2000-2001 ACADEMIC TRAINING PROGRAMME

SPEAKER : M. Spiro / CEA, Saclay, France
TITLE : Particle Physics and Experimentation in Space
TIME : 5, 6, 7, 8 and 9 February, from 11.00 – 12.00 hrs
PLACE : Main Auditorium, bldg. 500

ABSTRACT

The interplay between cosmology, high energy cosmic rays and particle physics is more and more obvious. Understanding particle physics helps to understand the Universe, as well as observing the Universe and the interactions of high energy cosmic rays helps to get a better knowledge of particle physics and of fundamental laws. The connection is not only valid for physics but also for instrumentation.

The achievement of LEP experiments, the preparation of a new generation of detectors for LHC experiments, and the advent and growth of new techniques for non-accelerator experiments have permitted developments of new detectors which are ready to be exported to experimentation in space.

In these lectures I will describe this type of instrumentation and review already achieved or planned space experiments which are using these opportunities and/or are somewhat particle physics inspired. I will describe the examples for cosmology of PLANCK (fluctuations of the cosmic microwave background), SNAP (study of distant supernovae). For cosmic rays I will discuss AMS (low to high energy cosmic rays), GLAST (high energy gamma ray astronomy), ACCESS (high to ultrahigh energy cosmic rays) EUSO (extreme high energy cosmic ray detection), and LISA (study of gravitational waves in the Universe) which all have deep connections with particle physics and with particle physicists.
COSMIC RAYS

Interaction

AMS : MEDIUM ENERGY

ACCESS : ULTRA HIGH ENERGY

EUSO : EXTREME ENERGY
ASTRONOMY WITH NEW MESSAGERS

GLAST - HIGH ENERGY GAMMA RAY ASTRONOMY

EUSO - NEUTRINO AND EXTREME ENERGY ASTRONOMY

LISA - GRAVITATIONAL WAVES
Fig. 1.6. The observed spectrum of the Cosmic Microwave Background (CBR) [11]. The points at wavelengths $\gtrsim$ 1 cm come from ground-based experiments. At shorter wavelengths the Earth's atmosphere is opaque and measurements must be made from balloons, rockets or satellites. The high precision points around the peak of the spectrum were made by the FIRAS instrument of the COBE satellite (1989-1995) [12]. Compilation courtesy of the Particle Data Group.
$e^- + p \rightleftharpoons H + \nu$

$\frac{n_p}{n_\nu} \sim 10^{-10}$

$T_{\text{decoupling}} \sim 3 \text{ eV}$
Fig. 7.10. Measurements of the spectrum of CBR anisotropies (7.162) as a function of angular scale (7.158). The large angular scale (small $l$) triangles are from the DMR instrument of the COBE satellite [144]. The small angular scale (large $l$) squares are the combined Boomerang and Maxima data [15]. The temperature fluctuations at large angular scales are roughly independent of $l$ at a value of $10^{-5}$ of the CBR temperature. The fact that the large angle fluctuations are independent of scale is evidence for scale-invariant primordial density fluctuations. The peak at $l \sim 200$ is generally interpreted as the first acoustic peak. Its position indicates that $\Omega_T \sim 1$. The curves correspond to calculations [149] assuming primordial adiabatic fluctuations. The solid line is the best fit yielding the parameters ($\Omega_T = 1.2, \Omega_\Lambda = 0.5, \Omega_b h^2 = 0.03$). The dashed line is the best $\Omega_T$ fit yielding the parameters ($\Omega_T = 1, \Omega_\Lambda = 0.7, \Omega_b h^2 = 0.03$). The dotted line is for an open universe with ($\Omega_T = 0.3, \Omega_\Lambda = 0.0, \Omega_b h^2 = 0.03$). For this model, the position of the peak is shifted to $200/\sqrt{\Omega_T} \sim 400$. [courtesy of K. Ganga.]
\[ T = 2.725 \, K + 3.36 \, mK \, \cos \Theta \]

\[ + \sum_{e, m} a_{e m} \, Y_{e m} (\Theta, \Phi) \left[ e \to \pi \Delta \theta \right] \]

\[ \langle \Delta T^2_{\Delta \theta} (\Theta_0, \Phi_0) \rangle = \frac{1}{4\pi} \sum_{\text{all } \Theta_0, \Phi_0} |a_{e m}|^2 |W_e (\Delta \theta)|^2 \]

\[ W_e (\Delta \theta) \text{ cuts off the sum for } e > \frac{1}{\Delta \theta} \]

\[ C_e = \left\langle |a_{e m}|^2 \right\rangle_m \]

\[ \langle \Delta T^2_{\Delta \theta} \rangle = \frac{1}{4\pi} \sum_{e} (2e+1) C_e |W_e (\Delta \theta)|^2 \]

small \( \Delta \theta \)

\[ \langle \Delta T^2_{\Delta \theta} \rangle = \frac{1}{2\pi} \int_0^\infty \frac{d \epsilon}{\epsilon} \, \epsilon^{(e+1)/2} \, C_e |W_e (\Delta \theta)|^2 \]

\[ \epsilon^{(e+1)/2} \, C_e \rightarrow \text{contribution per interval of } \epsilon \text{ to the temperature fluctuations} \]
CURVED SPACE
(homogeneous, isotropic)
2D SPHERE

CIRCLE CENTERED ON OBSERVER

\[ C = 2\pi R \]

\[ d = R \sigma \]

\[ \Delta s^2 = R^2(t) \left[ \frac{\Delta \sigma^2}{1 - \frac{\sigma^2}{R^2}} + \sigma^2 \Delta \phi^2 \right] \]

\[ \text{M} (\sigma, \phi) \]

\[ d_{o,m} (t) = R(t) \int_0^\sigma \frac{d\sigma}{\sqrt{1 - \sigma^2}} \]

\[ v(t) = \frac{\dot{R}(t)}{R(t)} d(t) \]

\[ \dot{H}(t) \]
3D (relativistic)

\[ \Delta s^2 = c^2 \Delta t^2 - R(t)^2 \left( \frac{\Delta \theta^2}{1 - \frac{\Delta \theta^2}{2 \Lambda R^2}} \right) \]

- \( k = 0 \) flat
- \( k = 1 \) spherical
- \( k = -1 \) hyperbolic

\[ \Delta s = 0 \text{ for light rays} \]

\[ H(t) = \frac{R'}{R} \text{ Hubble} \]

\[ q(t) = -\frac{R''}{R} \text{ Deceleration} \]

\[ S = 4\pi R^2 c^2 \Omega^2 \]

\[ Z = \frac{\lambda_0 - \lambda_e}{\lambda_e} = \frac{R(t_0)}{R(t_e)} - 1 \]

\[ \frac{1}{H^2} \text{ Hubble time} \]

\[ c/H = c H^{-1} \text{ Hubble distance} \]

\[ H_0 = 67 \pm 6 \text{ km/s/Mpc} \]

1 pc \( \approx 3.26 \) ly
Figure 50. World lines for calculating cosmic red shifts.

\[ 0 = c^2 \Delta t^2 - R^2(t) \frac{\Delta \sigma^2}{1 - k \sigma^2} \]

\[ \int_{t_0}^{t_e} \frac{dt}{R(t)} = \frac{1}{c} \int_{0}^{\sigma_e} \frac{d\sigma}{\sqrt{1 - k \sigma^2}} \text{ and } \int_{t_0 + \Delta t_0}^{t_e + \Delta t_e} \frac{dt}{R(t)} = \frac{1}{c} \int_{0}^{\sigma_e} \frac{d\sigma}{\sqrt{1 - k \sigma^2}} \]

\[ \Delta t_0 / R(t_0) = \Delta t_e / R(t_e) \]

with \( \lambda_0 = c \Delta t_0 \) and \( \lambda_e = c \Delta t_e \)

\[ z = \frac{R(t_0)}{R(t_e)} - 1 \]
AGES \[ t_u > t_x \]

OLD STARS:
\[ t_{GC} \sim 12 \pm 2 \pm 4/2 \text{ Gyr} \sim H_0 \]
Chaboyer et al.; Jimenez & Pagel; Gratton et al. '97

> 10 Gyr Shi et al '94; Jimenez '95

Radioactive Dating:
\[ t_N > 10 \text{ Gyr} \]
Meyer & UNS '86 Wasserburg & UNS '70

Disk of Galaxy:
\[ t_o \sim 10 \text{ Gyr} \]
Wingeet et al

Solar System:
\[ t_E = 4.6 \pm 0.1 \text{ Gyr} \]
Patterson '56
DEFINITIONS

Hubble Constant:

\[ H_o \equiv \frac{V(\text{km/s})}{R(\text{Mpc})} \]

[Mpc = 10^6 parsecs ~ 3 \times 10^6 \text{ Light Years}]

Density Parameter:

\[ \Omega_x \equiv \frac{\rho_x}{\rho_c} \]

Where

\[ \rho_c \equiv \frac{3H_0^2}{8\pi G} \]

= \(2 \times 10^{-29} h_o^2 \text{g/cm}^3\)

[h_o = H_o / 100 \text{ km/s/Mpc}]

Cosmological Constant:

\[ \Lambda_o = "\text{Density of the Vacuum}" \]
EINSTEIN-FRIEDMANN EQUATIONS

\[
\left( \frac{\dot{R}}{R} \right)^2 = \frac{8\pi G \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3} \\
d(\rho R^3) = -Pd(R^3)
\]

\[
\Omega = \frac{8\pi G \rho}{3H^2} = \frac{\rho}{\rho_c} \quad \rho_c = \frac{3H^2}{8\pi G}
\]

\[
\lambda = \frac{\Lambda}{3H^2} \quad , \quad \alpha = \frac{k}{R^2H^2}
\]

\[
\alpha = \Omega + \lambda - 1 \quad q = \Omega (1 + \frac{\lambda}{\rho})/2
\]

\[1 + \Omega_k = \Omega_m + \Omega_{\Lambda} = \Omega_T\]

CURVATURE DENSITY VACUUM

INFLATION PREDICTS

\[\alpha \text{  VERY  VERY  SMALL} \]

\[\sim k = 0\]
RADIATION ERA \( (R \to 0) \) → YESTERDAY

\( (z > 10^4 \text{ if } \Omega_0 = 1) \)

\[ P = \frac{\rho}{3} \Rightarrow \rho \propto R^{-4} \propto T^4 \]

\[ H \propto \frac{1}{R^2} \propto \frac{1}{t} \]

\[ R \propto \sqrt{t}, \quad d_n(t) = 2ct \]

\( (T \propto R^{-1}) \)

MATTER ERA → TODAY

\[ P = 0 \]

\[ \rho \propto R^{-3} \]

\[ H \propto \frac{1}{R^{2\Lambda}} \propto \frac{1}{t} \quad \Omega = \frac{\Omega}{2} \]

\[ R \propto t^{2/3}, \quad d_n(t) = 3ct \]

\( (T_H(z) \propto R^{-1}) \)

IF \( \Lambda = 0 \)

\[ \Omega = 1 + c^2 \left( \frac{1}{2} \right) R.E \]

\[ \alpha = \left\{ \begin{array}{ll}
\frac{1}{2} & \text{R.E.} \\
2/3 & \text{H.E.}
\end{array} \right. \]

VISIBLE STARS

AGE + EXPANSION

\[ 10^{-3} < \Omega_0 < 2 \quad \text{TO DAY} \]

\[ 0.5 < \Omega_{CUT} < 1.00 \ldots 01 \]
$1 + 2 = \frac{R(t_0)}{R(t_e)}$

If $\Omega_0 \approx 0.5$
**Horizon: Fixed \(0, \varphi\)**

\[
\Delta s^2 = c^2 \Delta t^2 - R^2(t) \frac{\Delta \varphi^2}{1-k\varphi^2}
\]

\[\Delta s = 0 \quad \text{for light rays}\]

\[D(t) = R(t) \int_0^T \frac{d\sigma}{\sqrt{1-k\varphi^2}}\]

\[\text{proper distance at a given time of comoving observers}\]

\[c \frac{dt}{R(t)} = \frac{d\sigma}{\sqrt{1-k\varphi^2}}\]

\[D_{\text{Hor}} = R(t) c \int_{t_0}^{t_{\text{today}}} \frac{dt}{R(t)}\]

**Radiative Era** \(z > 10^4\)

**R\alpha Ve** \(d_{\text{Hor}} = 2ct\)

**Matter Era** \(d_{\text{Hor}} = 3ct \quad (R \propto t^{2/3})\)

**Why is the Universe Isotropic?**

**(Causally Related)**
VACUUM ERA \Rightarrow TOMORROW?

\[ P = -\rho c^2 \quad \Rightarrow \quad H^2 = \frac{\Lambda}{3} = c^2 t \]

VAC. ENERGY: \quad \mathcal{S}_{\text{vac}} = \frac{\Lambda c^2}{8\pi G}

\[ R \propto e^{Ht} \]

\[ \Rightarrow \quad \frac{k c^2}{R^2} \quad \text{very small} \]

STANDARD SCENARIO

\[ T > \text{GUT} \Rightarrow \text{REL. ERA} \quad \Rightarrow \quad (\text{vacuum}) \Rightarrow \left\{ \begin{array}{l} \Omega = 1 \\ \Lambda = 0 \end{array} \right. \]

GUT \rightarrow z = 10^4 \quad \text{RELATIVISTIC ERA} \quad \Omega = 1

\begin{align*}
\text{few eV} & \quad \Rightarrow \quad z \gg \\
\quad & \quad \Rightarrow \quad z = 10^3 \\
\text{e^{-}p} & \rightarrow \text{H} + \gamma
\end{align*}

NOW \quad \Rightarrow \quad \Omega_{\text{bar}}, \Omega_{\text{gal}}?

H_0, \Omega_0, \Omega_\Lambda, \Omega_{\text{bar}}, \Omega_{\text{gal}}?
Fig. 5.7. Two points on the surface $\chi = \chi(z_{\text{rec}})$ with their horizons at $t_{\text{rec}}$. Pairs of points separated by more than $\sim 1$ deg on the sky were outside each other's horizon. The near equality of the temperatures of the two points could not have resulted from a causal process like heat diffusion.
INFLATION

$\text{Evac}$

$T > T_c$

$T = T_c$

$T < T_c$

$T_c \sim \text{GUT}$

$\left< \phi \right> \left< \phi \right>$

$T > T_{\text{cut}}$

REL. ERA

$T = T_{\text{cut}}$

VACUUM ERA $\rightarrow$ INFL.

REHEATING $\text{Evac} \downarrow 0$

$T < T_{\text{cut}}$

REL. ERA

MATTER ERA

$\text{Evac}$

$\left< \phi \right> \left< \phi \right>$

SLOW ROLL
COSMOLOGICAL CONSTANT

VACUUM ENERGY

$P_{\text{vac}} \text{ (GeV/m}^3\text{)}$

$10^0$

$10^2$

$10^4$

$10^6$

$10^{-35}$ $10^{-10}$ $10^{10}$ $10^{20}$

↑ $10^{15}$ GeV

↑ 500 GeV

↑ $P_{\text{vac}} < \text{few GeV/m}^3$

Now
$$\Lambda_0 \equiv \text{"Density of the Vacuum"}$$

\sim \text{UGLY!}

Einstein called it his biggest "Blunder". But, LeMaitre said it was Einstein's "Greatest contribution to Science".

**Vacuum Energy** $\propto 1/R^2$

(matter density $\propto 1/R^3$)

**Cosmologically Important Today only if**

$$\Lambda_0 / 3H_0^2 \sim 1$$

**But from a Physics Viewpoint**

**Vacuum Energy** $\propto (M_{\text{planck}})^4$

**Cosmologically Significant** $\Lambda_0 \Rightarrow$

**Energy Density** $\sim 10^{-121} (M_{\text{planck}})^4$

**AMAZING TUNING REQUIRED!**
Fig. 5.8. The energy density $\rho(a)$ in a simple inflationary scenario. The radiation and matter epochs are preceded by an inflationary epoch $a_2 < a < a_1$ when the universe is dominated by an effective vacuum energy. At the end of inflation, this energy must be partly transformed into radiation, providing the initial conditions for classical cosmology. This process will be described in Sec. 5.5.
TEMPERATURE OF THE UNIVERSE AS A FUNCTION OF TIME

From 1 GeV to $10^{19}$ GeV

Vacuum phase transition. The Grand Unified Symmetry is broken

$\bar{n}_p \neq n\bar{p}$
CP violation

$n_p = n_\epsilon$

Inflation period
somewhere between
$10^{-44}$ and $10^{-34}$ s
(An artist view)

Vacuum phase transition. The W and Z bosons acquire a mass

Explored

To be probed by LHC
$10^{-12}$ to $10^{-10}$ s

$1 \text{ GeV} \leq 10^{13}\text{ GeV}$
TEMPERATURE OF THE UNIVERSE AS A FUNCTION OF TIME

\[ T(K) = 2.7(2 + 1) \]

\[ \frac{n_e}{n_\gamma} \sim 10^{-9} \]

\[ \frac{n_p}{n_\gamma} \sim 10^{-9} \]

\[ T \sim t^{-1/2} \]

\[ e, \nu, \gamma \]

\[ \rho, \alpha, e, \gamma \]

\[ \text{Helium} \]

\[ \text{Radiation dominated} \]

\[ \text{Matter dominated} \]

\[ \text{H, He} \]

\[ T \sim t^{-2/3} \]

\[ T \sim 200 \text{ MeV} \]

Quarks bind into hadrons
Carnage of quarks and antiquarks
Universe opaque to color.

Carnage of electrons and positrons
Nucleosynthesis

\[ t(s) \]

Today \[ t \sim 10^{17} \text{ s} \]

Atom formation
Universe transparent to light
"recombination"
Fig. 7.11. The CBR photons that we observe come, on average, from the "last-scattering surface" at $\chi(z_{\text{rec}})$. The "surface" actually has a thickness of about 1/10 the Hubble distance at $t_{\text{rec}}$. The Hubble distance is shown (not to scale) and corresponds to an angle $\sim 1$ deg on the sky if $\Omega_T = 1$. Density inhomogeneities on the last-scattering surface generate temperature anisotropies. Photons from the dense region $a$ will be red-shifted climbing out of their potential well, but will have a higher initial temperature because of the greater compression. (The first effect dominates on large scales.) Photons coming from the underdense region $b$ will be blue-shifted as they fall off their potential hill but will be redshifted since the plasma is being accelerated towards the overdense region behind the last-scattering surface.
\[ \Delta \theta > \Theta_n \]

\[ \frac{\Delta T}{T} \sim G \frac{\Delta M}{d} \quad \text{Sachs-Wolfe} \]
\[ \quad \downarrow \text{climb the potential} \]
\[ \quad \downarrow \text{redshift} \]

\[ \frac{\Delta T}{T} \sim G \bar{\rho} \left( \frac{\Delta \rho}{\bar{\rho}} \right) \frac{4 \pi d^3}{3} \]

\[ \frac{\Delta T}{T} \quad \text{scale independent of} \quad \frac{\Delta \rho}{\bar{\rho}} \propto d^{-2} \]
\[ \quad = \Delta \frac{v}{d} \quad \text{INFLATION} \]

\[ \Delta V_g \quad \text{POTENTIAL FLUCTUATION} \]
\[ \text{INDEPENDENT OF} \quad d \quad \text{AND OF} \quad t \]

\[ \text{SINCE} \quad \rho \propto R(t)^n \]
\[ d^2 \propto R(t)^n \]
\[ \Delta \rho \propto R(t)^{n-2} \]
\[ \frac{\Delta \rho}{\rho} \propto R(t)^{n-2} \]
\[ n = 4 \quad \text{rad} \]
\[ n = 3 \quad \text{mol} \]
\[ n = 0 \quad \text{vacuum} \]
\[ \mathcal{P}(d,t) = \tilde{\mathcal{P}}(t) \left( 1 + \sum k \right) \]
\[ \sum k e^{i k d} \]
\[ \Delta M d = \int \frac{dk}{k} \Delta k^2 |W(kd)|^2 \]

**slow roll**
\[ \Delta_k (a_{\text{exit}}) = H \Phi = \text{cst} \]

**R** \( \rightarrow \) a notation

**k** = \( \frac{2\pi}{\text{length}} \)

**scale invariance**
\[ \Delta_k (a_{\text{enter}}) = \Delta_H \]

*Fig. 7.7.* The Hubble distance \( d_H \) in a model with inflation. A physical scale starts inside the Hubble radius, leaves at \( a_{\text{exit}} \) and then reenters at \( a_{\text{enter}} \). Small scales exit last and enter first. Mode \( k_a \) entered during the radiation epoch and mode \( k_b \) during the matter epoch. Mode \( k_c \) has not yet entered and never will if the vacuum energy continues to dominate.
\[ \ddot{\phi} + 3H \dot{\phi} + V'(\phi) = 0 \]

\[ \Delta(a_{\text{exit}}) = \Delta \phi \times V' = \text{cst} \]

\[ \Delta \phi \sim \frac{2\pi}{dH} \sim H(t_{\text{exit}}) \]

\[ \Delta_k(a_{\text{enter}}) = \left( \frac{H^2}{\dot{\phi}} \right)_{t_{\text{exit}}} \sim \text{cst} \]

\[ \Delta H = \left( \frac{\Delta T}{T} \right)_0 \gg \Theta_H \]

Fig. 7.8. An inflationary potential. The field rolls down the potential hill until it reaches the minimum. Inflation ends at \( \phi \sim \phi_1 \). A perturbed region with a field fluctuation \( \Delta \phi \) that places it higher up on the potential will stop inflating at a later time than the mean. For a short time \( \delta t_1 \) while the perturbed region is still inflating with a constant energy density, the rest of the universe is in the radiation epoch with a density \( \rho \propto a^{-4} \). When the perturbed region stops inflating, it will therefore have a radiation density greater than the mean, \( \Delta \rho/\rho \sim 4H_1 \Delta t_1 \).

\[ \Delta_H = 2 \times 10^{-5} \text{ and slow roll} \]

\[ \Rightarrow V(\phi)^{1/4} \sim T_{\text{inf}} \sim 10^{16} \text{ GeV} \]
SUSY 2nd order

\[ a_i^{-1}(\mu) \]

\[ a_z^{-1}(\mu) \]

\[ a_3^{-1}(\mu) \]

\( \mu [\text{GeV}] \)

\[ \chi^2 \]

\( M_{\text{SUSY}} [\text{GeV}] \)

\( M_{\text{GUT}} [\text{GeV}] \)

Fig. 2
INFLATION

- Solves Causality
- Solves Isotropy
- Solves Flatness

\[ \Delta_H \sim 9 \times 10^{-5} \quad (\Delta \theta > \theta_H) \]

\[ 10^{16} \text{ GeV} \]

Largest structure \( \sim 40 \text{ Mpc} \)

Why a today not solved!
BASICS OF COSMOLOGY

\[ \frac{\dot{R}^2}{R^2} + \frac{k}{R^2} = \frac{8\pi G}{3} \rho + \frac{\Lambda}{3} \]

- \( H = \frac{\dot{R}}{R} \)
- \( \Omega_k = \frac{k}{H^2 R^2} \)
- \( \Omega_M = \frac{8\pi G}{3H^2} \rho \)
- \( \Omega_{\Lambda} = \frac{\Lambda}{3H^2} \)

\[ 1 + \Omega_k = \Omega_M + \Omega_{\Lambda} \]

- \( q = -\frac{R \ddot{R}}{R^2} = \frac{\Omega_M}{2} - \Omega_{\Lambda} \)

Inflation scenario \( \rightarrow \Omega_k = 0 \quad (k=0) \)
\[ -P dR^3 = d(pR^3) \]

**Radiation Era** \( z > 10^4 \)

\[ P = \frac{p}{3} \]
\[ p \propto R^{-4} \]
\[ R \propto \sqrt{E} \]

**Matter Era** \( z \approx 1 \)

\[ P = 0 \]
\[ p \propto R^{-3} \]
\[ R \propto t^{2/3} \]

**Vacuum Era** \( z \approx 0 \)

\[ P = -\rho \]
\[ p = \frac{\Lambda}{8\pi G} \]
\[ R \propto t \]

**R(t)**

\[ k = 0 \]
\[ k = -1 \]
\[ \Lambda > 0 \]
\[ \Lambda = 0 \]
\[ \Lambda < 0 \]

\[ t_0 \]
Fig. 7.10. Measurements of the spectrum of CBR anisotropies (7.162) as a function of angular scale (7.158). The large angular scale (small \( l \)) triangles are from the DMR instrument of the COBE satellite [144]. The small angular scale (large \( l \)) squares are the combined Boomerang and Maxima data [15]. The temperature fluctuations at large angular scales are roughly independent of \( l \) at a value of \( 10^{-5} \) of the CBR temperature. The fact that the large angle fluctuations are independent of scale is evidence for scale-invariant primordial density fluctuations. The peak at \( l \sim 200 \) is generally interpreted as the first acoustic peak. Its position indicates that \( \Omega_T \sim 1 \). The curves correspond to calculations [149] assuming primordial adiabatic fluctuations. The solid line is the best fit yielding the parameters \( (\Omega_T = 1.2, \Omega_A = 0.5, \Omega_b h^2 = 0.03) \). The dashed line is the best \( \Omega_T \) fit yielding the parameters \( (\Omega_T = 1, \Omega_A = 0.7, \Omega_b h^2 = 0.03) \). The dotted line is for an open universe with \( (\Omega_T = 0.3, \Omega_A = 0.0, \Omega_b h^2 = 0.03) \). For this model, the position of the peak is shifted to \( 200/\sqrt{\Omega_T} \sim 400 \). [courtesy of K. Ganga.]

\[
\left( \frac{\Delta T}{T} \right)^2 = \frac{8 \pi G}{3} \frac{\rho}{\rho_c} = \frac{k}{R^2} + \frac{\Lambda}{3}
\]

\[
1 + \Omega_K = -\frac{M}{\Omega_T} = -\frac{\Omega_K}{\Omega_T}
\]

\[
\Omega_K = \frac{\Omega_T}{\Omega_T - 1}
\]

\[
\Delta T = \frac{\Delta \theta}{\Delta \theta}
\]

**ACOUSTIC PEAKS**

\( \Omega_b \sim 3 \). **COMPRESSION** \( \Omega_b \)}
too much baryons?
\[ 10^3 < \Omega_{\text{vis}} < 10^{-2} \]

**DARK MATTER**

\[ 10^2 < \Omega_{\text{baryon}} < 10^0 \]

**Baryonic**

- molecular clouds, hot intergalactic gas
- brown dwarfs
- red dwarfs...
- **massive compact objects**
- stellar remnants (black holes, neutron stars...)

**?**

**\( \Omega_{\Lambda} = 0.7 \)**

- axions
- neutrinos
- WIMP's

Nathalie Palanque-Delabrouille
Figure 2: A simulation of the CMB anisotropies as seen by Planck based on a $\Omega_0 = 1$ CDM model.
$\Delta T(\theta, \phi) = \sum a_{\ell m} Y_{\ell m}(\theta, \phi)$

Smoot et al. (COBE) + Balloon experiments

1999

Projected Satellite Errors

Hu et al.

Planck
Figure 3: This is a simulation (taken from W. Hu's web page) of the angular power spectrum of the CMB as recovered from Planck data. The simulation assumes a given spectrum for the sky (this is shown by the continuous line), then simulates the observation process (in this case using 3 LFI channels, 4 HFI channels and 3 HFI polarization channels). The vertical boxes show the uncertainty range in the recovery of each multipole (the corresponding angular scale is shown on the top horizontal scale). Recovery of the polarized CMB component is also shown. At large angular scales the uncertainties are limited by cosmic variance, while at small angular scales they are limited by the angular resolution and sensitivity of the instruments. This particular simulation did not take into account systematic effects and foreground removal, which would increase the size of the boxes.
Figure 3.7: (a) A three-dimensional view of the fully assembled payload module.
Figure 3.7: (b) A three-dimensional exploded view of the payload model
Model Payload

Worst-case shadow cone (defined by solar array)

Science data antenna beam (+/-15°)

Spin axis

Scan angle (70°)

Telescope Line-of-sight
Fig. 1.6. The observed spectrum of the Cosmic Microwave Background (CBR) [11]. The points at wavelengths $\gg 1$ cm come from ground-based experiments. At shorter wavelengths the Earth's atmosphere is opaque and measurements must be made from balloons, rockets or satellites. The high precision points around the peak of the spectrum were made by the FIRAS instrument of the COBE satellite (1989-1995) [12]. Compilation courtesy of the Particle Data Group.
## Goal Planck instrument characteristics (TBC)

<table>
<thead>
<tr>
<th>Telescope</th>
<th>1.3+0.2 m. (projected aperture) Gregorian; shared focal plane; system emissivity 1%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Viewing direction offset 80-85° from spin axis.</td>
</tr>
<tr>
<td>Center Frequency (GHz)</td>
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<td>Detector Technology</td>
<td>HEMT radio receiver arrays</td>
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<td>Detector Temperature</td>
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<td>Cooling Requirements</td>
<td>H$_2$ sorption cooler</td>
</tr>
<tr>
<td></td>
<td>H$_2$ sorption cooler + 4K J-T stage + Dilution system</td>
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<tr>
<td>Number of Detectors</td>
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<tr>
<td>Angular Resolution (°)</td>
<td>33</td>
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<tr>
<td>Optical Transmission</td>
<td>1</td>
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<tr>
<td>Bandwidth ($\Delta \nu / \nu$)</td>
<td>0.2</td>
</tr>
<tr>
<td>$\Delta T / T$ Sensitivity per res. element (12 months, $1\sigma$, $10^{-6}$ units)**</td>
<td>1.6</td>
</tr>
</tbody>
</table>

*Table last updated 11/12/1998

* Sensitivity to polarized signal is marked with a P
• Figure: A subsystem-level block diagram of the model payload, and a sketch of the geometric architecture of the payload.
<table>
<thead>
<tr>
<th>Table 3.1: Telescope Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main reflector (M1)</strong></td>
</tr>
<tr>
<td>shape</td>
</tr>
<tr>
<td>physical size</td>
</tr>
<tr>
<td>focal length</td>
</tr>
<tr>
<td>surface accuracy†</td>
</tr>
<tr>
<td>roughness‡</td>
</tr>
</tbody>
</table>

| **Sub-reflector (M2)**        |
| shape                         | off axis ellipsoid          |
| physical size                 | $0.761 \times 0.719$ m      |
| focal length                  | $0.514$ m                   |
| f-number                      | $1.36$                       |
| surface accuracy†             | $<10$ μm rms                |
| roughness‡                    | $<1$ μm rms                 |

| **Telescope**                 |
| focal length                  | $1.8$ m                     |
| main- to sub-reflector axis angle | $14^\circ$         |
| central feed to sub-reflector axis angle | $34^\circ.129$ |
| Total Wavefront§ Error        | $<40$ μm rms                |
| Total emissivity              | $0.01$                      |

† Deviation from best paraboloid/hyperboloid
‡ Average over spatial scales up to 0.8 mm
§ Not in-flight

Carbon fiber Honeycomb sandwich

$\rightarrow$ \{ low mass, stiffness, low thermal expansion \}
Figure 2: An isometric view of the HFI front-end or "cold box". At the top are the entrance horns, feeding radiation towards the bolometers. The body consists of nested radiation shields maintained at various temperatures (at 4 K, 1.6 K, and 0.1 K) by the active cooling system. Only the outermost shield at 4 K is shown. The bolometers are at 0.1 K.
Figure 3.6: (b) The principle of operation of the cryogenic dilution system.
Figure 1: Schematic layout of the HFI showing its main parts and their temperatures
THE HIGH FREQUENCY INSTRUMENT

\[ u(\nu, T) \, d\nu = \frac{\pi}{c^2} \frac{\hbar \nu^3 \, d\nu}{e^{\hbar \nu/kT} - 1} \]

\[ \sigma = 10^{-8} \, \text{W/m}^2/\text{K} \]

...corrugated, light guide, keep the polarization...

- Figure 4: Schematic of optical layout for a single HFI pixel with, at 0.1K (left), the bolometer, its horn, and its filters, at 1.6K (centre) filters, and at 4K (right) filters and back-to-back horns.
• **Figure 3**: A top view of the HFI front-end or "cold box", showing the layout of the entrance horns. Heavy lines indicate which channels contain polarizing filters and their direction.
BOLOMETERS

1) Crystal
\[ \Delta T = \frac{E}{C_v} \]

\[ n = \frac{1944 \cdot \frac{E}{V_{\text{air}}}}{E_{\text{air}}} \cdot \frac{1}{k} \]

\[ \text{Small volume, Low temperature} \]

2) Sensor
- Metal - Insulator near transition
- Normal - Super
- Supercond. tunnel junctions

\[ \downarrow \]

Spider web matched to λ

NTD Ge: R \( R \) will T
Wires Si: NO4 20μ Ω
+ 0.1μ Au

Picking time \( \approx 5 \text{ ms} \)
Table 3.3: Characteristics and Sensitivity of the HFI

<table>
<thead>
<tr>
<th></th>
<th>857</th>
<th>545</th>
<th>353</th>
<th>217</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Frequency (GHz)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Center Wavelength (mm)</td>
<td></td>
<td></td>
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<tr>
<td>Detector Temperature (K)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<td>Bandwidth ($\Delta\nu/\nu$)</td>
<td>0.37</td>
<td>0.37</td>
<td>0.37</td>
<td>0.37</td>
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<td>Bandwidth (GHz)</td>
<td>317</td>
<td>202</td>
<td>131</td>
<td>80</td>
<td>56</td>
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<td>Number of bolometers</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
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<tr>
<td>Angular Res. (FWHM, arcmin)*</td>
<td>4.37</td>
<td>4.37</td>
<td>4.37</td>
<td>7.11</td>
<td>10.29</td>
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<tr>
<td>No. pixels** on sky ($\times 10^6$)</td>
<td>7.76</td>
<td>7.76</td>
<td>7.76</td>
<td>2.93</td>
<td>1.40</td>
</tr>
<tr>
<td>$\text{NEP}_{bol}$ ($10^{-17}$ W/$\sqrt{Hz}$)</td>
<td>8.5</td>
<td>4.6</td>
<td>2.6</td>
<td>2.1</td>
<td>2.0</td>
</tr>
<tr>
<td>$\text{NEP}_{phot}$ ($10^{-17}$ W/$\sqrt{Hz}$) ♦</td>
<td>14.0</td>
<td>5.9</td>
<td>2.6</td>
<td>1.8</td>
<td>1.4</td>
</tr>
<tr>
<td>$\text{NEP}_{tot}$ ($10^{-17}$ W/$\sqrt{Hz}$)</td>
<td>16.4</td>
<td>7.5</td>
<td>3.7</td>
<td>2.8</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Nominal mission* (1σ sensitivities, per pixel*)

<table>
<thead>
<tr>
<th></th>
<th>4.7</th>
<th>4.7</th>
<th>4.7</th>
<th>12.5</th>
<th>26.2</th>
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</thead>
<tbody>
<tr>
<td>Average integ. time per bol. (sec.)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Array Sensit.§ ($\mu$K)</td>
<td>0.72</td>
<td>1.31</td>
<td>2.55</td>
<td>1.84</td>
<td>1.83</td>
</tr>
<tr>
<td>$\Delta T/T$ Sensit.† ($10^{-6}$)</td>
<td>4166</td>
<td>76.6</td>
<td>12.1</td>
<td>2.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Flux Sensit. (mJy)</td>
<td>26.4</td>
<td>19.3</td>
<td>15.8</td>
<td>11.4</td>
<td>11.3</td>
</tr>
<tr>
<td>$ySZ$ * ($10^{-6}$)</td>
<td>254</td>
<td>9.3</td>
<td>3.6</td>
<td>173.7</td>
<td>0.8</td>
</tr>
<tr>
<td>$N(H)_{b}$ ($10^{20}$ H/cm$^2$)</td>
<td>0.025</td>
<td>0.057</td>
<td>0.14</td>
<td>0.13</td>
<td>0.15</td>
</tr>
</tbody>
</table>

* 14 months of observations, or two full sky coverages

† Diffraction limited at frequencies below 350 GHz (effective telescope diameter = 1 m)

** A pixel is defined as a square whose side is the FWHM extent of the beam

♦ Telescope temperature = 100 K; total emissivity = 0.01

§ Rayleigh-Jeans temperature

† Thermodynamic temperature

‡ Sensitivity to the Sunyaev-Zeldovich $y$ parameter

§ Sensitivity to gas column density
Figure 1: (b) An isometric view of the LFI Front End Unit, showing the horn/receiver arrangement. The brown-colored unit in the center of the ring formed by the horns is a schematic representation of the HFI Front End Unit.
Figure 3.3: (b) Side and top view of the LFI, the former showing the horn/receiver arrangement, and the latter the layout of the feed apertures in the focal plane.
Table 1: Goal Characteristics and Sensitivity of the LFI

<table>
<thead>
<tr>
<th></th>
<th>30</th>
<th>44</th>
<th>70</th>
<th>100</th>
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</thead>
<tbody>
<tr>
<td>Center Frequency (GHz)</td>
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<td></td>
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<tr>
<td>Wavelength (mm)</td>
<td>10.0</td>
<td>6.8</td>
<td>4.3</td>
<td>3.0</td>
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<tr>
<td>Detector Temperature (K)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
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<tr>
<td>Bandwidth (%)</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
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<tr>
<td>Bandwidth (GHz)</td>
<td>6.0</td>
<td>8.8</td>
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<td>20.0</td>
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<tr>
<td>Number of Detectors</td>
<td>4</td>
<td>6</td>
<td>12</td>
<td>34</td>
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<tr>
<td>Angular Res. (FWHM, arcmin)</td>
<td>33</td>
<td>23</td>
<td>14</td>
<td>10</td>
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<td>$T_{\text{sys}}$ (K) (Diff. Rec.)</td>
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<td>15</td>
<td>22</td>
<td>31</td>
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<tr>
<td>Array $\Delta T_{\text{B}}$ (mK)</td>
<td>0.12</td>
<td>0.16</td>
<td>0.19</td>
<td>0.22</td>
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<tr>
<td>Polarized detector</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Nominal mission* (1σ sensitivities, per pixel)</td>
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<td></td>
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<tr>
<td>Average integ. time per det.(sec.)</td>
<td>213</td>
<td>103</td>
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<tr>
<td>$\Delta T_{\text{B}}$ per pixel (µK)</td>
<td>4</td>
<td>7</td>
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<tr>
<td>Sensitivity (x10^{-6})</td>
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<td>2.4</td>
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<td>4.3</td>
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<tr>
<td>Flux Sensit. per pixel (mJy)</td>
<td>13</td>
<td>19</td>
<td>25</td>
<td>27</td>
</tr>
</tbody>
</table>

* 12 months of observations, or two full sky coverages

- A pixel is a square whose side is the FWHM extent of the beam
- Antenna temperature
- Thermodynamic temperature.

\[
\nu(v, T) = \frac{\pi}{\nu^2} \frac{\hbar \nu^3}{e^{\hbar \nu / kT} - 1}
\]
Table 3.6: Real-time Science Data Acquisition Rates

<table>
<thead>
<tr>
<th>Inst.</th>
<th>Band (GHz)</th>
<th>No. Det.</th>
<th>Beam (arcmin)</th>
<th>Rate/Det. (wrd/s)</th>
<th>Rate/Band (kbit/s)</th>
<th>Rate/Inst. (kbit/s)</th>
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<td>4</td>
<td>30</td>
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<td>90</td>
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<td>217</td>
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<td>110</td>
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<td>Power (W)</td>
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<td>Shield &amp; Baffle</td>
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<td>BOB</td>
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<td>Harness</td>
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<tr>
<td>Total</td>
<td>304.5 kg</td>
<td>413 W</td>
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</table>
SN Ia
Search Strategy
Perlmutter et al. (1996a)

RESULT: ~100 SNe Ia Discovered
Before Maximum, at New Moon ⇒ Follow-up
Supernova 1998ba
Supernova Cosmology Project

5 Weeks Before

seen from
Space
Telescope

seen
from
Earth

Interence
Supernova Light Curves

Type Ia

IIp

Ib

Composite light curve for 15 Type Ia SNe
B Band

as measured

Calan/Tololo SNe Ia

light-curve timescale "stretch-factor" corrected

High-z SN search

1996E
z = 0.43

1996I
z = 0.57

1996K
z = 0.38

1997ce
z = 0.44

1995K
z = 0.48

1996H
z = 0.62

1996J
z = 0.30

1996U
z = 0.43

1997cj
z = 0.50

1997ck
z = 0.97
Time Series of Low-Redshift and High-Redshift Spectra

SN 1997ex at $z = 0.36$
Supernova Cosmology Project

Riess (1998)

-6 days

SN Cosmology Project

+14 days

High-Z SN Team

+17 days

High-Z SN Team

rest wavelength

3500 4000 4500 5000 5500 6000 6500
\[ l = \frac{L}{4\pi R^2(t_0) \sigma_e^2 (1+z)^2} \]

\[ 1+z \quad \text{Redshift} \]

\[ 1+z \quad \text{n.b. of photons per unit time} \]

\[ d_L = \frac{R(t_0) \sigma_e (1+z)}{g(z, \Omega_\Lambda, \Omega_k)} \]
SNe Ia
High-z SN Search

$\Omega_m = 0, \Omega_{\Lambda} = 0$
$\Omega_m = 1, \Omega_{\Lambda} = 0$
$\Omega_m = 0, \Omega_{\Lambda} = 1$
Figure 4.4: Le diagramme de Hubble pour les supernovae de type Ia [astro-ph/9805201]. Le diagramme du haut montre la différence entre la magnitude apparente et la magnitude absolue en fonction du redshift. Superposé sont les prédictions pour trois combinaisons de $\Omega_M$ et $\Omega_V$. La diagramme en haut montre la différence entre les observations et les prédictions pour la combinaison $\Omega_M = .2$ et $\Omega_V = 0$. On voit que les supernovae à $z = 0.5$ sont environ 20% moins lumineuses que prévu pour cette combinaison. Le trait plein montre les prédictions pour la combinaison $\Omega_M = .24$ et $\Omega_V = .76$. 

$\Omega_M = .3$
$\Omega_V = .7$
$\Omega_M = 1$
$\Omega_V = 0$
(\Omega_M, \Omega_A) =

(0, 0)
(1, 0)
(2, 0)

\Lambda = 0

Supernova Cosmology Project

Calan/Tololo
(Hamuy et al, A.J. 1996)

(a)

mag residual

(b)

standard deviation

(c)

redshift z
High-z SN search

\( \Omega_\Lambda \) vs. \( \Omega_M \) diagram showing different cosmological scenarios:
- **No Big Bang**
- **Accelerating**
- **Decelerating**
- **Expands to Infinity**
- **Recollapses**

Critical densities and contours:
- \( q_0 = 0 \)
- \( q_0 = 0.5 \)
- \( \Omega_{\Lambda} = 0 \)
- \( \Omega_{\text{tot}} = 1 \)

1. **Closed** universe
2. **Open** universe
3. **MLCS**
Supernova Cosmology Project

$\Omega_\Lambda$

$\Omega_M$

No Big Bang

68%

90%

95%

99%

expands forever

recollapses eventually

closed flat open
Figure 1.2: There is strong evidence for the existence of a cosmological vacuum energy density. Plotted are $\Omega_M-\Omega_A$ confidence regions for current SN, galaxy cluster, and CMB results. Their consistent overlap is a strong indicator for dark energy.

measurements. Perhaps surprisingly, these supernova measurements will provide stronger constraints on $\Omega_M$ and $\Omega_A$ than those expected from either LSS or CMB measurements, and constraints on curvature $\Omega_k$ that are comparable with those expected from MAP and Planck. The important cosmological test will be the cross comparison of these and other fundamental measurements — and it is even possible that cosmology
**Age of the Universe**

Supernova Cosmology Project
Perlmutter et al. (1998)

\[
\frac{H_0 t_0}{63 \text{ km s}^{-1} \text{ Mpc}^{-1}} = 19 \text{ Gyr} \quad 14.3 \text{ Gyr} \quad 11.9 \text{ Gyr} \quad 9.5 \text{ Gyr} \quad 7.6 \text{ Gyr}
\]

\[
\Omega_\Lambda
\]

\[
\Omega_M
\]

*Best fit age of universe:* \( t_0 = 14.5 \pm 1 \ (0.63/h) \) Gyr

*Best fit in flat universe:* \( t_0 = 14.9 \pm 1 \ (0.63/h) \) Gyr
$\frac{H_0 \Omega_0}{63 \text{ km s}^{-1} \text{ Mpc}^{-1}} = 19 \text{ Gyr}$

accelerating

decelerating

14.3 Gyr

11.9 Gyr

9.5 Gyr

7.6 Gyr
DUST
No,?

EVOLUTION
Possible
but unlikely?

NEARBY SNIA?
check

MYSTERIES

\[ I \]

\[ 0, 10, 20, 30 \]

Brighten \rightarrow Slow decline

Dimmer \rightarrow Fast decline
days
Fig. 3.— The residual of SN Ia distances from RPK96 plotted as a function of galaxy type. The offset between the early-type and late-type galaxies is 0.006 ± 0.07 mag.
Effect of Cosmological Constant on the Fate of the Universe

Universe with a Positive Cosmological Constant

Finite Universe

Borderline Universe

Eternal Universe

average distance between galaxies

time
SNAP Proposal

SNAP Proposal Signatories

D. Curtis, G. Goldhaber, J. Graham, S. Harris, P. Harvey, H. Heoekdorks, A. Kim,
M. Lampton, R. Lin, D. Pankow, C. Pennybacker, A. Spadafora, G. Smeel
University of California, Berkeley, CA, USA

R. Knop, R. LaVer, M. Levi (co-PI), P. Nugent, S. Perlmutter (PI), K. Robinson
Lawrence Berkeley National Laboratory, Berkeley, CA, USA

LPNHE, CNRS-IN2P3 and University Paris VI & VII, Paris, France

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SUPERNOVA / ACCELERATION PROBE
Purpose of SNAP

For a definitive measurement to provide a pillar of our cosmological theory requires

- a much larger statistical sample of supernovae
- with much better controlled measurements
- over a much larger range of redshifts

that cannot be obtained with existing or planned facilities.
SNAP: One year sample of 2000 SNe
Current ground-based data compared with binned simulated SNAP data.

**Dark Energy Models:**

- inverse tracker potential
- Albrecht & Skordis potential
- two D3-Brane potential
- double exponential potential
- pure exponential (fine tuned)
- Pseudo-Nambu-Goldstone Boson
- SUGRA potential
- exponential tracker potential
- $\Omega_m = 0.6$
- $\Omega_m = 0.8$
- SCDM ($\Omega_m = 1.0$)

Each SNAP point represents ~50-supernova bin
**Why a New Satellite?**

**Ground-based telescopes:**

A dedicated 8-meter with 9-square-degree imager...

- cannot discover SNe within 2 restframe days of explosion beyond $z = 0.6$.

- cannot measure SN plateau level (>45 days after peak) beyond $z = 0.7$.

- even limiting redshifts to $z = 0.6$, can only discover fewer than 300 SNe/year.
**Why a New Satellite?**

**Space-based (HST or NGST) telescopes:**

NGST targets different and complementary science — higher redshifts ($z \gg 1$), fewer (~100) SNe and fewer observations (~4) per SN.

- NGST 16-square-arcminute field of view too small to efficiently find SNe in the target redshift range.

- Using NGST to obtain spectroscopy of the SN discovered by SNAP would be wasteful: Most of the time for over half a year would be spent slewing the NGST.
SNAP Baseline Observing Strategy

Continuous monitoring (every 4 days) of
~2 sq. deg. to $m_{AB} (1\mu m) \approx 30$
~20 sq. deg. to $m_{AB} (1\mu m) \approx 28.5$

Discover every SN in these fields to $m_{AB}^{\text{limit}}$
### Observatory Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>~2.0 meter</td>
</tr>
<tr>
<td>Field-of-view</td>
<td>1° x 1°</td>
</tr>
<tr>
<td>Optical resolution</td>
<td>diffraction-limited at 1 μm</td>
</tr>
<tr>
<td>Wavelength</td>
<td>350nm - 1700nm</td>
</tr>
<tr>
<td>Solar avoidance</td>
<td>70°</td>
</tr>
<tr>
<td>Fields of study</td>
<td>North and South Ecliptic Poles</td>
</tr>
<tr>
<td>Image Stabilization</td>
<td>Feedback from Focal Plane</td>
</tr>
<tr>
<td>Focal Length</td>
<td>20 meter</td>
</tr>
</tbody>
</table>

Spacecraft is always at near normal incidence to sun
SNAP Instrumentation Suite

Key Instruments:
1) GigaCAM
   1 sq. deg FOV
   128 3kx3k CCD's

2) IR Photometer
   (small field of view)

3) 3-channel spectrograph
   350-600 nm,
   550-1000 nm,
   900-1700 nm
CHAPTER II. TELESCOPE

SIDE VIEW TMA BASELINE OPTIC

Figure 11.1: Side view of our baseline optical configuration, with a 2.0 meter primary mirror, a 0.45 meter secondary mirror, a folding flat, and a 0.7 meter tertiary mirror.

for this implementation are as follows:

PRIMARY: concave prolate ellipsoid
location (X,Y,Z) = (0, 0, 0);
diameter = 2.0 meters
curvature = -0.171580 reciprocal meters
shape = 0.0272532

SECONDARY: convex hyperboloid
location = (0, 0, -2.4)
diameter = 0.45
curvature = -0.7711666
## Optical Photometry Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field-of-view</td>
<td>1° x 1°</td>
</tr>
<tr>
<td>Plate Scale</td>
<td>1 pixel ~ 0.1 arcsec</td>
</tr>
<tr>
<td>Pixelization</td>
<td>32k x 32k CCD mosaic</td>
</tr>
<tr>
<td>Wavelength coverage</td>
<td>350nm - 1000nm</td>
</tr>
<tr>
<td>Detector Type</td>
<td>High-Resistivity P-channel CCD’s</td>
</tr>
<tr>
<td>Detector Architecture</td>
<td>2k x 2k, or 2k x 4k</td>
</tr>
<tr>
<td>Detector Temperature</td>
<td>150 K</td>
</tr>
<tr>
<td>Quantum Efficiency</td>
<td>65% 1000nm, 92% 900nm, &gt;85% 400-800nm</td>
</tr>
<tr>
<td>Read Noise</td>
<td>4 e- @100kHz</td>
</tr>
<tr>
<td>Exposure Time</td>
<td>up to 1000 sec (single exposures)</td>
</tr>
<tr>
<td>Number of Frames</td>
<td>1 to 24</td>
</tr>
<tr>
<td>Dark Current</td>
<td>0.08 e-/min/pixel</td>
</tr>
<tr>
<td>Readout Time</td>
<td>20 sec</td>
</tr>
<tr>
<td>Limiting Magnitude</td>
<td>30th magnitude in Z-band</td>
</tr>
<tr>
<td>Exposure control</td>
<td>Mechanical shutter</td>
</tr>
<tr>
<td>Filter Wheel</td>
<td>15 bands (U, V, R, I, Z, &amp; 10 special filters)</td>
</tr>
</tbody>
</table>
Figure 7: B band light curve sampling for SNAP SNe Ia and the supernova physics they address.
How do uncertainties improve as we extend the range of redshifts?

![Graph 1: Uncertainty in Curvature, $\Omega_k$ vs. Maximum redshift]

![Graph 2: Uncertainty in Equation-of-state ratio, $w$ vs. Maximum redshift, Flat Universe]
Figure 7.2: Example SN Ia spectrum with B-band bandpass superimposed.
BaBAR Silicon Vertex Detector (≈1m² Si)
GigaCAM, a one billion pixel array

- Depending on pixel scale approximately 1 billion pixels
- ~128 Large format CCD detectors required
- Looks like the SLD vertex detector in Si area (0.1 - 0.2 m²)
- Larger than SDSS camera, smaller than BaBar Vertex Detector (1 m²)
- Collaboration has lots of experience in building very large silicon detectors and custom readout electronics including radiation hard integrated circuits (should they be necessary).
**Typical CCD's**

**Front-illuminated CCD:**
- Poly gate electrodes
- 3-phase CCD structure
- p⁺ epi (20 to 50 Ω-cm)
- p⁺ substrate

**Thinned CCD with back-illumination:**
- n buried channel
- photo-sensitive volume (≈20μm)
- p⁻ epi (20 to 50 Ω-cm)

**Drawbacks:**
1. Poor blue response due to absorption in polysilicon gate electrodes
2. Poor near-IR response due to thinness of the epitaxial layer
3. Interference patterns due to gate structure

**Drawbacks:**
1. Thinning is difficult and expensive
2. Poor near-IR response
3. Interference (fringing)
4. Lateral diffusion in field-free region (degraded PSF)
CCD’s for GigaCam

- New kind of CCD developed at LBNL
- 2k x 2k (4 Megapixels/device) design successful, meets SNAP performance requirements
- Commercialization
- Current in house fabrication

2k x 4k for Eschellette Spectrograph and Imager (Keck)
Fully-Depleted CCD's

The New Approach:
Make a thick CCD on a high-resistivity n-type substrate, to operate fully depleted with rear illumination.

3-phase
CCD structure

Advantages:
1) Conventional MOS processes with no thinning
   => "inexpensive"
2) Full quantum efficiency to > 1 μm => no fringing
3) Good blue response with suitably designed rear contact
4) Radiation tolerant

Disadvantages:
1) Enhanced sensitivity to radiation (x-rays, cosmic rays, radioactive decay)
Photoactive region of standard CCD’s are 10-20 microns thick, while the photoactive region of Fully-Depleted CCD’s are 300 microns thick.
SNe Ia
High-z SN Search

Distance Modulus $m-M \propto \log d_L$

- $\Omega_m=0, \Omega_k=0$
- $\Omega_m=1, \Omega_k=0$
- $\Omega_m=0, \Omega_k=1$

$\Delta(m-M)$ vs Redshift $z$
B Band

as measured

$M_B - 5 \log (h/65)$

Calan/Tololo SNe Ia

days

light-curve timescale
"stretch-factor" corrected

$M_B - 5 \log (h/65)$

days

Kim, et al. 1997,
Figure 1.2: There is strong evidence for the existence of a cosmological vacuum energy density. Plotted are $\Omega_M - \Omega_A$ confidence regions for current SN, galaxy cluster, and CMB results. Their consistent overlap is a strong indicator for dark energy.

measurements. Perhaps surprisingly, these supernova measurements will provide stronger constraints on $\Omega_M$ and $\Omega_A$ than those expected from either LSS or CMB measurements, and constraints on curvature $\Omega_k$ that are comparable with those expected from MAP and Planck. The important cosmological test will be the cross comparison of these and other fundamental measurements — and it is even possible that cosmology
SNAP: One year sample of 2000 SNe

Baseline One-Year Sample
2000 SNe

"look-back" time
[billions of years before present]
Key Instruments:

1) GigaCAM
   - 1 sq. deg FOV
   - 128 3kx3k CCD’s

2) IR Photometer
   - (small field of view)

3) 3-channel spectrograph
   - 350-600 nm,
   - 550-1000 nm,
   - 900-1700 nm
Figure 7.3: B-band light-curve sampling for SNAP SNe Ia and the supernova physics they address.
CCD Status

- In house 2k x 2k (15 µm pixels) design successful, meets SNAP performance requirements
- Commercialization at CCD foundry
  2k x 2k (15 µm pixels) successful, in test at Lick
  Two separate processing runs (1) "standard"; (2) modified process recipe
  Current run of 4” wafers; will be followed immediately by run of 6” wafers
- Current in house fabrication completing now
  2k x 4k (15 µm pixels) for Eschellette Spectrograph and Imager (Keck)
  ~2k x 4k (12 µm pixels)
  ~2k x 4k (10.5 µm pixels)

- Requires further extensive radiation testing (already tested at LBNL 88” cyclotron to 20% of SNAP lifetime exposure w/o degradation) & large scale prototyping
- Complete commercialization
# 3-arm Spectrograph Requirements

## Optical:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrograph architecture</td>
<td>Integral field spectrograph, two arms</td>
</tr>
<tr>
<td>Wavelength coverage</td>
<td>350-600 nm, 550-1000 nm</td>
</tr>
<tr>
<td>Spatial resolution of slicer</td>
<td>0.07 arcsec</td>
</tr>
<tr>
<td>Field-of-View</td>
<td>2” x 2”</td>
</tr>
<tr>
<td>Resolution</td>
<td>15A, 30A, 100A selectable</td>
</tr>
<tr>
<td>Detector Type</td>
<td>CCD</td>
</tr>
<tr>
<td>Detector Architecture</td>
<td>2k x 2k</td>
</tr>
<tr>
<td>Detector Array Temperature</td>
<td>150 K</td>
</tr>
<tr>
<td>Quantum Efficiency</td>
<td>65% 1000nm, 92% 900nm, &gt;85% 400-800nm</td>
</tr>
<tr>
<td>Read Noise</td>
<td>$4 \text{ e}^- @ 100\text{kHz}$</td>
</tr>
<tr>
<td>Dark Current</td>
<td>0.08 e^-/min/pixel</td>
</tr>
</tbody>
</table>

## IR:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrograph architecture</td>
<td>Integral field spectrograph, one arm</td>
</tr>
<tr>
<td>Wavelength coverage</td>
<td>900 to 1700 nm</td>
</tr>
<tr>
<td>Spatial resolution of slicer</td>
<td>0.12 arcsec</td>
</tr>
<tr>
<td>Field-of-View</td>
<td>2” x 2”</td>
</tr>
<tr>
<td>Resolution</td>
<td>30A, 50A, 200A selectable</td>
</tr>
<tr>
<td>Detector Type</td>
<td>HgCdTe</td>
</tr>
<tr>
<td>Detector Architecture</td>
<td>2k x 2k</td>
</tr>
<tr>
<td>Detector Array Temperature</td>
<td>77 - 130 K (to achieve dark I)</td>
</tr>
<tr>
<td>Quantum Efficiency</td>
<td>56% @ 1000nm</td>
</tr>
<tr>
<td>Read Noise</td>
<td>$5 \text{ e}^- \text{ (multiple samples)}$</td>
</tr>
<tr>
<td>Dark Current</td>
<td>1 e^-/min/pixel</td>
</tr>
</tbody>
</table>
Figure 7.4: SN Ia spectroscopic regions relevant for identification and systematic studies.
CHAPTER 10. SPECTROSCOPY

Figure 10.3: Illustration of how various types of integral field units are used to reformat spatial and spectral information from an astronomical scene. The top row shows a pure microlens array IFU, the middle row shows a microlens array feeding optical fibers, and the last row shows in image slicer.
<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field-of-view</td>
<td>10' x 10'</td>
</tr>
<tr>
<td>Plate Scale</td>
<td>1 pixel ~ 0.1 arcsec</td>
</tr>
<tr>
<td>Wavelength coverage</td>
<td>1000nm - 1700nm</td>
</tr>
<tr>
<td>Detector Type</td>
<td>HgCdTe (1.7 μm cut-off)</td>
</tr>
<tr>
<td>Detector Architecture</td>
<td>Mosaic of 2kx2k</td>
</tr>
<tr>
<td>Detector Temperature</td>
<td>130K (to achieve dark I)</td>
</tr>
<tr>
<td>Read Noise</td>
<td>6 e- (multiple samples)</td>
</tr>
<tr>
<td>Dark Current</td>
<td>3 e-/min/pixel</td>
</tr>
<tr>
<td>Limiting Magnitude</td>
<td>30th magnitude (AB)</td>
</tr>
<tr>
<td>Exposure control</td>
<td>Mechanical shutter</td>
</tr>
<tr>
<td>Filters</td>
<td>J&amp;H, plus five special filters</td>
</tr>
</tbody>
</table>
In one year of study, as shown in Table 7.2, the satellite can discover, follow the light curve, and obtain spectra at peak brightness for 2366 supernovae. Most of these supernovae are obtained in the critical region of $0.5 < z < 1.2$ where the experiment has peak sensitivity to the value of the cosmological constant.

<table>
<thead>
<tr>
<th>Redshift</th>
<th>#SNe follow</th>
<th>Fields</th>
<th>Photometry</th>
<th>Spectroscopy [days/yr]</th>
<th>Color [days/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>14</td>
<td>20</td>
<td>8.4</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>44</td>
<td>20</td>
<td>8.4</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>82</td>
<td>20</td>
<td>8.4</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td>124</td>
<td>20</td>
<td>5.6</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>162</td>
<td>20</td>
<td>5.6</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td>196</td>
<td>20</td>
<td>5.6</td>
<td>1.15</td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>226</td>
<td>20</td>
<td>5.9</td>
<td>2.24</td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td>250</td>
<td>20</td>
<td>10.5</td>
<td>4.63</td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td>270</td>
<td>20</td>
<td>12.6</td>
<td>5.00</td>
<td>2.13</td>
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<tr>
<td>1.0</td>
<td>286</td>
<td>20</td>
<td>16.9</td>
<td>6.07</td>
<td>3.31</td>
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<tr>
<td>1.1</td>
<td>298</td>
<td>20</td>
<td>25.3</td>
<td>8.81</td>
<td>5.52</td>
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<tr>
<td>1.2</td>
<td>304</td>
<td>20</td>
<td>35.1</td>
<td>12.12</td>
<td>6.74</td>
</tr>
<tr>
<td>1.3</td>
<td>30</td>
<td>2</td>
<td>20.9</td>
<td>3.66</td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>30</td>
<td>2</td>
<td>29.1</td>
<td>4.95</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>22</td>
<td>2</td>
<td>28.8</td>
<td>4.77</td>
<td></td>
</tr>
<tr>
<td>1.6</td>
<td>16</td>
<td>2</td>
<td>28.4</td>
<td>2.14</td>
<td></td>
</tr>
<tr>
<td>1.7</td>
<td>12</td>
<td>2</td>
<td>28.0</td>
<td>2.03</td>
<td></td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>284</td>
<td>60</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.2: One-year SNAP supernova discovery and follow-up summary.

$\sim 100$ Terabytes/yr
What's wrong with a non-zero vacuum energy / cosmological constant?

Two coincidences:

- **Why so small?**
  
  Might expect $\Lambda \sim \frac{m_{\text{Planck}}^4}{8\pi G}$
  
  This is off by $\sim 120$ orders of magnitude!

- **"Why now?"**

  \[
  \frac{\dot{R}}{R} = -\frac{4\pi G}{3} (\rho + 3p)
  \]

  **MATTER:** $p = 0 \quad \rightarrow \quad \rho \propto R^{-3}$

  **VACUUM ENERGY:** $p = -\rho \quad \rightarrow \quad \rho \propto \text{constant}$

What are the alternatives?

New Physics:

“Dark energy”: Dynamical scalar fields, “quintessence”,...

- **COSMIC STRINGS:**

  \[ p = -\frac{1}{3} \rho \quad \rightarrow \quad \rho \propto R^{-2} \]

- **General Equation of State:**

  \[ p = w\rho \quad \rightarrow \quad \rho \propto R^{-3(1+w)} \]

  and $w$ can vary with time
How can we address these new questions?

*Greatly improve:*

![Graph showing Ω_A versus Ω_M](image)

*and:*

![Graph showing w(z) versus Ω_M](image)

...And look for details of \( w(z) \).

It is necessary but NOT sufficient to find and study
- more SNe Ia
- farther SNe Ia

because the statistical uncertainty is already within a factor of two of the systematic uncertainty.
CHAPTER 1. EXECUTIVE SUMMARY

Dark Energy
Unknown Component, $\Omega_U$, of Energy Density

Supernova Cosmology Project
Perlmutter et al. (1998)

$\Omega_M = 1 - \Omega_U$

SNAP Satellite
Target Statistical Uncertainty

Figure 1.3: Best-fit 68%, 90%, 95%, and 99% confidence regions in the $\Omega_M \ w$ plane for an additional energy density component, $\Omega_w$, characterized by an equation-of-state $w = p/\rho$. (If this energy density component is Einstein's cosmological constant, $\Lambda$, then the equation of state is $w = p_\Lambda/\rho_\Lambda = -1$.) Also shown is the expected confidence region allowed by SNAP.
How do uncertainties improve as we extend the range of redshifts?
COSMOLOGY

DONT PANIC ITS NOT THE END OF THE UNIVERSE

PLANCK: CMB

SNAP: TYPE Ia SUPERNOVAE

AMS: ANTI MATTER
COSMIC RAYS

Origin Interaction

AMS: MEDIUM ENERGY

ACCESS: ULTRA HIGH ENERGY

EUSO: EXTREME ENERGY
Figure A.4. Diversity of the techniques used for cosmic ray detections and measurements

Altitude (km)

10^{12} eV
10^{12} eV Cosmic ray

Primary interaction

Secondary particles

Cerenkov light

Photons

Optical reflector

Underground detector

10^{15} eV
10^{15} eV Cosmic ray

\pi^+ \pi^- \pi^0
e^+ e^- \gamma

10^{19} eV

Satellite

Balloon

Scintillation light for E > 10^{19} eV

High mountain emulsions

Fly's eye

Detector array

Hadron flux:
1 particle/m²/s @ TeV 10^{12} eV
1 particle/m²/day @ PeV 10^{15} eV
1 particle/km²/day @ EeV 10^{18} eV
1 particle/km²/century @ \epsilon 10^{20} eV

Authors.
Fluxes of Cosmic Rays

Galactic (remnants)

Extra galactic (AGN?)

Ankle
(1 particle per km$^2$-year)

Knee
(1 particle per m$^2$-year)

(1 particle per m$^2$-second)

Waiting for AUGER
now approved

Tevatron
Incognita
The diagram illustrates the energy spectrum of cosmic rays (CRs) as a function of energy. The spectrum is divided into three regions:

- **CR I** with a differential flux of $dF/dE \sim E^{-2.7}$.
- **CR II** with a differential flux of $dF/dE \sim E^{-3.0}$.
- **CR III** with a differential flux of $dF/dE \sim E^{-3.2}$.

The diagram also highlights various features:

- **Knee**, **2nd Knee**, and **Dip** are points of interest in the spectrum.
- **Flattening** and **Cutoff?** are other noteworthy characteristics.
- An **Expected Curve for Extragalactic Origins** is also shown.

The energy axis is logarithmic, covering a range from $10^3$ to $10^{22}$ eV.
ACCELERATION \( \frac{dN}{dE} \propto E^{-2} \)

DIFFUSION \( \beta \) \( \frac{dN}{dE} \propto E^{-2.7} \)

+ REINTERACTIONS

IRON \( \rightarrow \) STEEPER ?

EXTRA GALACTIC \( \rightarrow \) CUTOFF ?

+ FLATTER
Crab Nebula: A supernova remnant and pulsar in the constellation of Taurus. (Credit: NASA/CXC/SAO)

Caption: The explosion was seen on Earth in 1054 AD. At the center of the nebula is a rapidly spinning neutron star, or pulsar, that emits pulses of radiation 30 times a second. The image shows the central pulsar surrounded by tilted rings of high-energy particles that appear to have been flung outward over a distance of more than a light year from the pulsar. Perpendicular to the rings, jet-like structures produced by high-energy particles blast away from the pulsar. The diameter of the inner ring in the image is about a tenth of a light year, more than 200 times the diameter of our solar system. The X rays from the Crab nebula are produced by high-energy particles spiraling around magnetic field lines in the Nebula. The bell-shaped appearance of the Nebula could be due to the interaction of this huge magnetized bubble with clouds of gas and dust in the vicinity.

Chandra X-ray Observatory ACIS/HETG Image
Active Galactic Nucleus

Cygnus A
(3C 405)

Radio Optical

VLA - 6 cm

HST closeup

Bologna, December 13, 1999

L. Moscoso
Core of Galaxy NGC 4261

Hubble Space Telescope
AMS-01 on Discovery during STS-91 Flight

B. Alpat, May 21-27, 2000, Elba
Alpha Magnetic Spectrometer
First flight, STS-91, 2 June 1998 (10 days)
AMS-01

Construction of AMS-01

\[ p = mv \]

- **p:**
  - Silicon \( \Delta x = 10 \, \mu \) m
  - Magnet \( BL^2 = 0.14 \, TM^2 \)
  - Electronics 70,000 channels

*V:* Aerogel

Low Energy Particle Shield
AMS-01: STS-91 Flight Results

G.F.: ≈ 3000 cm².sr
MDR: ≈ 400 GV
Energy Range:
100 MeV/n < E_k < 300 GeV/n
Electronics channels: ≈ 70000
Power: ≈ 1 kW

- ≈30 hours before and ≈105 hours after rendezvous with MIR (total of ≈135 hours including ≈11 hours of albedo measurements)
- Shuttle altitude ranged from 320 to 390 km
- Latitudes ±51.7°, All longitudes (except S.A.A.)
- A total of 100 million events recorded with event rates ranging from 100 Hz to 700 Hz (corresponding to 95%÷40% DAQ livetime)

B. Alpat, May 21-27, 2000, Elba
AMS-01: STS-91 Flight Results

(2)

It was a successful flight!!

- Detector test in actual space conditions
  - Good performance of all subsystems

- Physics results:
  - Antimatter search
  - Charged cosmic ray spectra (p, π, e^±, D, He, N)
  - Geomagnetic effects on cosmic ray

B. Alpat, May 21-27, 2000, Elba
Cosmic rays measured by AMS in near Earth orbit:

- Originate from supernova explosions in our galaxy or produced in particle interactions with the interstellar media;

- Follow rigidity power law, with low energy part modified by solar wind;

- Low energy CR are deflected by geomagnetic field, with *Geomagnetic Rigidity Cutoff* varies with $\Theta_M$ from 60 to 0.4 GV;

- Interact with atmosphere and produce particles, which may be trapped in geomagnetic field for some time.
- High Statistics Measurement ($>6 \cdot 10^6$ Events);
- Power law fit: $\gamma_p = 2.78 \pm 0.025$;
- High Statistics Measurement (about $10^6$ Events):
- Power law fit: $\gamma_{He} = 2.74 \pm 0.02$;
AMS $\frac{e^+}{e^++e^-}$ measurement agrees well with same solar cycle earlier measurements.
Cosmic Deuteron Spectrum

\[ \phi_D = 650 \pm 20 \text{ MV}, \text{ agrees with that of } p, \text{ He.} \]

\[ \frac{D}{He} \text{ is compatible with CR models predictions.} \]
• $Z=2$ ($\bar{\text{He}}$) - discovery of a single nucleus - evidence of existence of primordial antimatter, as $\frac{\text{He}_{\text{sec}}}{\text{He}} < 10^{-12}$;
  
  – No candidates so far;

```
\text{AMS}
STS - 91
```

```
<table>
<thead>
<tr>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^5</td>
</tr>
<tr>
<td>10^4</td>
</tr>
<tr>
<td>10^3</td>
</tr>
<tr>
<td>10^2</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

```

```
\text{He} \quad 0 \text{ events}
```

```
\text{He} \quad 2.86 \times 10^6 \text{ events}
```

```
\text{Sign} \times \text{Rigidity} \quad \text{GV}
```

- "Same Spectrum" Limit: $\frac{3}{\int_{R_{\text{min}}}^{R_{\text{max}}}} \frac{\text{Flux}(R) \cdot \epsilon_{\bar{\text{He}}}(R) \cdot R}{\text{R}}$

  - AMS 98: $\frac{\text{He}}{\bar{\text{He}}} < 1.1 \cdot 10^{-6}; \text{R} < 100 \text{ GV}$
  - BESS 93-98: $\frac{\text{He}}{\bar{\text{He}}} < 1.0 \cdot 10^{-6}; \text{R} < 16 \text{ GV}$
- Substantial under cutoff flux is observed;
- Fluxes for downward and upward protons are equal;
- Equatorial increase of cutoff flux is seen.
- Substantial under cutoff $e^\pm$ flux is observed;
- Fluxes for downward and upward $e^\pm$ are equal;
- Equatorial increase of the undercutoff flux is seen:
$e^+/e^-$ fluxes ratio varies between 1 (pole) to 4 (equator).
• Undercutoff He flux was found at the level of $10^{-4}$ to $10^{-3}$ of the primary He flux;

• UnderCutoff He flux isotope composition was measured to be $\frac{\text{He}^3}{\text{He}} > 0.9$ at 90 % CL.
A TeV accelerator/interactor in Space

V: $e^\pm$

V: He$^4$, Be

P: $e^\pm$, $\gamma$

ToF

Veto

RICH

Calorimeter

AM
AMS-02 on ISS

ISS ATTACHED PAYLOAD ENVELOPES

AMSO2 PAYLOAD ASSEMBLY

ISS TRUSS

B. Alpat, May 21-27, 2000, Elba
AMS01 AND AMS02 AT THE SAME SCALE

- $e^+, e^-$ up to 3 TeV
- Separate $e$ from $p$ up to 300 GeV

AMS02

- Velo Counter
- RICH
- Calorimeter
- $e, \gamma, E$ and Identification
- $\beta, Z^2$: Identify isotopes

AMS01

- Honeycomb
- Silicon
- Scintillators
- Low energy particle field
- Veto Counters
- Magnet
- Aerogel
AMS-02 Superconducting Magnet (1)

The superconducting AMS-02 Magnet (1)

Identical magnet configuration between AMS-01 and AMS-02

Both have
1- Same Inner radius
2- Dipole moment = 0
3- B at 2.0 M ≤ 60 G

AMS-01

AMS-02

B = 0.5G

BL² = 0.14 TM²

B. Alpat, May 21-27, 2000, Elba
AMS-02 Construction

The Transition Radiation Detector (TRD)
(AMS Proposal .164)

Aachen I (K. Luebelsmeyer), CIEMAT (C.Ma–‡), MIT (U.Becker)

Measuring $V$ when $V \rightarrow C$ (velocity of light)

1. TRD: $e^{\pm}$ / hadron rejection $> 10^3$

2. Tracking: 28 points are measured for each track:
   20 points (top TRD) + 8 (tracker)
A three-dimensional sampling calorimeter

AMS Proposal p.320

To measure P or the energy of $\gamma$, $e^\pm$

Italy (C. Vannini), France (J.P. Vialle), China (H.S. Chen)
AMS-02 Electromagnetic Calorimeter (2)

Active detector characteristics

- **Pankake characteristics:**
  - Density: $6.95 \pm 0.05 \text{ to } 0.15 \text{ g/cm}^3$
  - Radiation Length:
    $$X_0 = 0.98 \pm 0.01 \text{ cm}$$

- **Superlayer:**
  - 10 Scintillating fiber planes
  - Thickness: $18.2 \pm 0.3 \text{ mm}$

- **Active Detector:**
  - Dimensions:
    $$658 \times 658 \times 163.8 \text{ mm}^2$$
  - Weight: 482 kg
  - 10 Scifi planes/Superlayer
  - Total Rad Length: $16.5 \times X_0$
AMS-02 Time of Flight System (2)

AMS II TOF SYSTEM

B. Alper, May 21-27, 2000, Elba
Aim:

- Rigidity (P/Ze) measurements
- Sign of Charge
- Absolute Charge (dE/dX, in addition to ToF system)

Tracker detector based on 8 thin layers of double-sided silicon microstrips, with a spatial resolution better than 10 μm, ≈ 200,000 of electronics channel and ≈ 800 W of power.

A complex detector, qualified for operation in space, with its ≈ 6 m² of active surface will be the largest ever built before the LHC @ CERN.
AMS-02 Tracker (2)

- Operating Temperature: -10/+25 °C
- Power Dissipation on the Detector: 1 W/ladder, in total 192 ladders
- $dP/P = \approx 2 \% @ 1 \text{ GeV} (\approx 8\% \text{ in AMS-01})$ (for protons)
- The planes alignment will be monitored by a IR laser alignment system (as in case of AMS-01).
- INFN Perugia

B. Alpat, May 21-27, 2000, Elba
AMS-02 Ring Imaging Cerenkov Detector (3)

Construction of the Ring Imaging Cerenkov Counter (RICH)

(AMS Proposal, p.316)

Measuring $v$ ($v < c$) to the accuracy of 0.1%,
to identify $^{3}\text{He}$, $^{4}\text{He}$, ...
Résultats des tests sur faisceau d'ions 12C de 0.6 à 1.5 GeV/n (mars 1999)

mesure de la vitesse $\beta$

$[\delta\beta/\beta]_c = 1.9 \times 10^{-3}$

mesure de la charge $Z$

B. Alpat, May 21-27, 2000, Elba
AMS-02 DAQ System (1)

- **Link Speed:**
  - Max raw link speed is 100 Mbps
  - Max raw data transfer rate is \( \approx 10 \text{ Mbytes/sec} \)
  - Data transfer rate w/ overhead is \( \approx 5 \text{ Mbytes/sec} \)

- **Input data rate:**
  - Max event rate is \( \approx 2 \text{ kHz} \)
  - Average data size is \( \approx 2 \text{ Kbytes} \)
  - Max input data rate is \( \approx 4 \text{ Mbytes/sec} \)
  - Total 20-24 crates, max input data rate from each crate is \( \approx 2 \text{ Kbytes/sec} \)

- **Output data rate:**
  - Max output data rate is 100 Mbps
  - Two links for data transfer

- Further data reduction on board with Level-3 algorithm (Solutions: DSP 01 PowerPC750 from Lockheed Martin)

- IEEE1355 (Space Wire) standard at all board and crate level communications

---

B. Alpat, May 21-27 2006, Elba
## AMS-02 Physics on ISS (3)

### Expected data statistics for AMS on SS

<table>
<thead>
<tr>
<th>Above</th>
<th>&gt; 1 GeV/c</th>
<th>&gt; 5 GeV/c</th>
<th>&gt; 10 GeV/c</th>
<th>&gt; 100 GeV</th>
<th>&gt; 1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrons</td>
<td>1.4 x 10^8</td>
<td>7.3 x 10^7</td>
<td>6.8 x 10^6</td>
<td>7.2 x 10^4</td>
<td>5.4 x 10^2</td>
</tr>
<tr>
<td>Positrons</td>
<td>9 x 10^6</td>
<td>3.8 x 10^6</td>
<td>3 x 10^5</td>
<td>1.6 x 10^3</td>
<td>6</td>
</tr>
<tr>
<td>Antiprotons</td>
<td>1.5 x 10^6</td>
<td>1.1 x 10^6</td>
<td>1.4 x 10^4</td>
<td>3.2 x 10^3</td>
<td>5.8 x 10^2</td>
</tr>
<tr>
<td>Helium</td>
<td>6.4 x 10^8</td>
<td>4.3 x 10^6</td>
<td>2.1 x 10^6</td>
<td>7.3 x 10^6</td>
<td>1.7 x 10^5</td>
</tr>
</tbody>
</table>

B. Alpat, May 21-27, 2000, Elba
Physics Objectives for AMS-02

Search for Dark Matter

AMS e^+, e^- Measurement

AMS e^+, e^- Measurement

AMS e^+, e^- Measurement

AMS sensitivity to Dark Matter

\( \chi + \chi \rightarrow e^+ + \ldots \)
\( \rightarrow e^- + \ldots \)

B. Alpat, May 21-27, 2000, Elba
Figure A.4. Diversity of the techniques used for cosmic ray detections and measurements.

Altitude (km)

10^12 eV
Cosmic ray

10^15 eV

Satellite

10^6 eV → few GeV

Balloon

10^18 eV

Cerenkov light

Primary interaction

Secondary particles

\( \pi^+ \pi^- \pi^0 \)

\( e^+ e^- \gamma \)

Scintillation light for \( E > 10^{18} \text{ eV} \)

High mountain emulsions

Fly's eye

Optical reflector

Charged particles

Detector array

Underground detector

Hadron flux:

- 1 particle/m^2/s
- 1 particle/m^2/day
- 1 particle/km^2/day
- 1 particle/km^2/century

- TeV
- PeV
- EeV
- \( 10^{20} \text{ eV} \)

1/m^2/s → TeV
1/m^2/day → PeV
1/km^2/day → EeV
1/km^2/century → 10^{20} eV

Authors.
AMS01 AND AMS02 AT THE SAME SCALE

AMS01

- Scintillators
- Low energy detector shield
- Honeycomb
- Silicon
- Magnet
- Aerogel

AMS02

- e^+ e^- up to 3 TeV
- e^+ e^- up to 300 GeV
- SRD
- TRD
- ToF
- β, Z^2
- Veto Counter
- Tracker
- Magnet, Cals & Structure
- RICH
- β, Z^2: Identify isotopes
- Calorimeter
- e, γ: E and Identification

AMS01

AMS02
ACCESS

Advanced Cosmic-ray Composition Experiment for the Space Station

- ENERGY SPECTRA of individual elements $1 \leq Z \leq 28$ to $\sim 10^{15}$ eV.
  - Based on plausible extrapolations of known spectra, see about ten each of H, C, Fe above $\sim 10^{15}$ eV.

- ELEMENT ABUNDANCES for all elements heavier than Fe, with
  - excellent individual-element resolution and
  - excellent statistics up to $\text{^{82}Pb}$
    - $\sim 2000$ $\text{^{38}Sr}$, $\sim 300$ $\text{^{56}Ba}$,
    - $\sim 400$ total $\text{^{76}Os}$ through $\text{^{83}Bi}$
    - $\sim 10$ actinides
**ACCESS - High-energy measurements**

- Particle fluxes fall steeply with increasing energy
  - Figure shows all-particle spectrum from air-shower measurements
  - Abscissa is energy per nucleus
- Expect limit of supernova shock acceleration near the “knee”.
  - Expect composition to change as energy approaches $10^{15}$ eV

3/26/99  
M.H. Israel presentation to AASC Gaisser panel
ACCESS -- Acceleration Limit for a supernova remnant

- Rigidity-dependent acceleration limit implies changes in element composition.

- Maximum energy for typical supernova parameters is about $2 \times 10^{14} \text{ eV} \times Z$

- Additional source needed above about $10^{16} \text{ eV}$
ACCESS instrument concept -- three main components

- Measures abundances of individual elements $1 \leq Z \leq 83$

- Measures energy spectra of individual elements $4 \leq Z \leq 28$ with good statistics to $10^{15}$eV

- Measures energy spectra of individual elements $1 \leq Z \leq 26$ to $10^{15}$eV with good statistics for $Z < 10$
  Also measures electrons to about $10^{13}$eV

Mount on S3UI attach point in 2006 after AMS comes off

3/26/99  M.H. Israel presentation to AASC Gaisser panel
ACCESS - High-charge measurements

- Particle fluxes fall steeply with increasing nuclear charge
  - Figure shows relative fluxes at energies around a few GeV/nucleon from HEAO-3 and Ariel-6.
  - For $30 \leq Z \leq 60$ only even-Z elements have been measured.
  - For $Z > 60$ only element groups have been measured relative to Fe. (Trek has resolved Pt-Pb region.)

- Abundances of individual elements, including odd-Z will distinguish among sources of cosmic-ray nuclei.

3/26/99 M.H.Israel presentation to AASC Gaisser panel
ACCESS -- Charge identification

- Silicon detector dE/dx with Cherenkov velocity and scintillating fiber trajectory give individual-element charge resolution over the entire periodic table.

- 3-year exposure gives definitive measurement of almost every element up through $^{82}$Pb (but only about 10 actinides).
ACCESS -- Baseline transition radiation detector

- Six layers of transition fiber radiator with Xe-filled multi-wire proportional-counter (MWPC) tubes.
- MWPC detects ionization from penetrating particle plus transition-radiation x-rays.
- Transition radiation measures Lorentz factor to \( \sim 3 \times 10^4 = 1.5 \times 10^{15} \) eV for Fe.
Shown here is the TRACER tube design which is a starting point for ACCESS.

- Mylar Tube, .001" wraps, inside surface is aluminized
- 2 cm diameter
- Aluminum cigar tube
- Noryl 30% glass filled
- Eccobond 45LU
- Urabond or RTV
- Section A-A

Center wire not shown

~245 cm
ACCESS -- Baseline calorimeter

- Graphite target gives ~1 interaction length without much shower development.
- Bismuth Germanate (BGO) scintillators give about 26 radiation lengths of active detector to measure resulting shower energy.
- Alternate approach, also under study, uses layers of scintillating fibers between layers of heavy metal.
Calorimeter Exploded View

Si Detector

Graphite Targets

Scintillator Hodoscopes w/ Graphite Target

Scintillator Hodoscope

BGO Crystal Target

ACCESS
A 10 EeV Extensive Air Shower (EAS)

12 km

6 km

100 billion particles at sea level
photons, electrons (99%), muons (1%)
• Ground Array stations
AGASA
120 km² sr

Akene observatory - 7 years operation
6 events ≥ 10²⁰ eV

F 2.7 K → Nπ

111 2.2 m² scintillation detectors

separation ~ 1 km

To be published PRL
Recent data on UHE Cosmic Rays

Former results from: Volcano Ranch, Haverah Park, Yakutsk, Fly's Eye

<table>
<thead>
<tr>
<th>Experiment (site)</th>
<th>Technique</th>
<th>$\Delta E/E$</th>
<th>$\Delta \theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGASA (Japan)</td>
<td>EAS array</td>
<td>30%</td>
<td>3°</td>
</tr>
<tr>
<td>111 scintillators (2.2 m²) deployed over 100 km²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HI-RES (Utah, USA)</td>
<td>Fluorescence detector</td>
<td>10%</td>
<td>0.4°</td>
</tr>
<tr>
<td>(2nd detector in 2000 binocular fly's eye)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Both experiments have similar sensitivities above $10^{20}$ eV:

$\sim 1000 \text{ km}^2 \times \text{sr} \times \text{yr}$

Both have 7 events with $E > 10^{20}$ eV

BEYOND THE GREisen-ZATSEpin-KUZMIN cutoff.

[AGASA Spectrum]
supergalactic plane \((z \leq 0.02)\)

arrival direction of \(\sim 10^2\) EeV c-rays

\[ \begin{align*}
\text{FR-I Radio Galaxies} & \quad \text{FR-II Radio Galaxies} \\
\text{Starburst Galaxies} & \quad \text{Quasars} \\
\text{Galactic Disk} &
\end{align*} \]

\[ \mathcal{P} \mathcal{Y} \rightarrow \mathcal{N} \pi \]

\[ \lambda = 40 \text{ Mpc} \]

NEEDS FOR LARGE SCALE FACILITIES
(AUGER PROJECT = 5000 RM$^2$) GROUND + ATM.
## Mission Design Cycle

### Scientific Objectives

- Study of (> $10^{20}$ eV) cosmic rays
- What are the particles?
  - Protons, heavy nuclei, photons, or neutrinos
- Where are their sources?
- How are they produced?
  - In an extraordinary acceleration process?
  - From the decay of topological defects?

### Capabilities

- $3 \times 10^4$ km$^2$ target, (0.05°)$^2$/pixel
- 8% "On-time"
- Collecting power for E > $2 \times 10^{20}$ eV
  - $3 - 5 \times 10^5$ km$^2$-sr
- Sampling time (1-3) microseconds
- 0.1R_{e} (638 km), 28 degree orbit with
  - 5 year operational life

### Requirements

- Sensitivity for > $3 \times 10^{18}$ eV
- Measure shower profiles, find energy
  - Essential for particle identification
- Determine arrival directions to < 1°
  - Localize sources
- Energy resolution <30% for precise spectrum analysis
- Reject background events
  - Lightning, meteors, man-made sources, etc.
Orbiting Wide-angle Light-collectors
An Earth Orbiting Experiment to Study Airshowers
Initiated by $> 10^{20}$ eV Particles

Objective:
Determine Origin of the Highest Energy Particles
"Bottom Up": Acceleration From Below
"Top Down": Decay of Massive Particles

Approach:
- Use the atmosphere as a vast calorimeter, observe atmospheric fluorescence light of giant air showers from ABOVE. (John Linsley)
- Determine arrival direction, $\approx 1^\circ$
  - Stereo view from two satellites, observe cascade development in atmosphere
- Measure shower profile, determine energy and depth of interaction with atmosphere
  - Particle identity
Observation of UHE Cosmic Rays from Space

Naive extrapolation of various spectra indicates 700 - 1000 events above $10^{20}$ eV / 10$^5$ km$^2$-sr-year of effective exposure.


NASA/GSFC
Extreme Universe Space Observatory

Vincent Van Gogh, "The starry night"

An Explorative Mission
Probing the Extremes of the Universe
using the Highest Energy Cosmic Rays and Neutrinos

A Proposal for the ESA F2/F3 Missions
ISS - The International Space Station

ESA
Columbus Module

EUSO: Extreme Universe Space Observatory
EUSO principle of operation

Viewed at some instant from a distance, an EAS appears as a relatively small disc-shaped luminous object. When it is viewed continuously, the object moves on a straight path with the speed of light. As it does so, the disc luminosity changes from so faint to be undetectable, up to a maximum followed by a gradual fading.

The general goal of the EUSO space mission is to acquire the dynamic image of events that occur when an individual energetic particle strikes the Earth atmosphere producing UV fluorescence light as the end-result of the complex relativistic cascade process.

The UV fluorescence produced by cosmic rays (protons, nuclei, gamma rays, neutrinos, ...) can be disentangled from the general background and measured as other phenomena as Gamma Ray Bursts (GRB), auroras, lightning, atmospheric flashes, distribution of minor components in the atmosphere, can also be observed and studied.
EUSO, with its unconventional approach for cosmic ray observations, offers the possibility to conjugate Astrophysics and Particle Physics. By using the calorimeter property of the Earth atmosphere it provides the advantages given by the vast target watched from a space vehicle orbit: geometrical factor of the order of $10^6$ km$^2$ sr, corresponding to an air mass target of $10^{13}$ tons. It represents the necessary evolution of experimental investigation of Cosmic Ray and Neutrino High Energy Astrophysics.

![Graph showing effective area for various experiments.](image)
EUSO requirements

EUSO, originally proposed to ESA for a free-flyer LEO mission, has been approved for the “accomodation study” on the ISS International Space Station.

Under the assumption of both a LEO (≈ 500 km altitude) free-flyer mission or the ISS accommodation (400 km average altitude), the coverage of the observable atmosphere surface at the scale of thousands kilometers across and the measurement of very fast and faint phenomena like those EUSO is interested in, requires:

• **optical system** with large collecting area (because of the faint fluorescence signal) and wide equivalent field of view covering a sizable half opening angle around the local Nadir (to reach geometrical factor of $10^6 \, \text{km}^2 \, \text{sr}$),

• **focal plane detector** with high segmentation (single photon counting and high pixelization), high resolving time (≈ 10 ns), weight and power contained,

• **trigger and read-out electronics** prompt, simple, efficient, modular, capable to handle hundreds of thousands of channels, and comprehensive of a sophisticated on-board image processor acting as a trigger.
EUSO Payload

- Electronic system
- Focal plane detector
- Optics system
- Support structure
Fig. 2.2 - The proposed EUSO optical system. It consists of 2 curved Fresnel lenses and a spherical focal surface. The entrance pupil is 2.6 m.
EUSO principle of operation

The measurement of the height $X_{\text{max}}$, where the maximum shower size $N_{\text{max}}$ is present, is based on the Cherenkov light, isotropically diffuse by the land or sea surface: the time difference between the arrival of the fluorescence light from the primary track and the back reflected Cherenkov flash localizes the height of the event.

\[
\#pe \propto \text{shower size} \\
\text{UV integral} \propto \text{EECR energy} \\
N_{\text{max}} \propto \text{EECR energy}
\]

Showers initiated very deep in the atmosphere (low $X_{\text{max}}$) indicate an origin by neutrinos because of neutrino-air nuclei interaction cross section hundreds times lower than the cross sections for protons, nuclei, or photons.

\[
X_{\text{max}} \leftrightarrow \text{EECR nature}
\]
Event simulation

Showers are simulated taking into account geometric parameters as well as the depth of penetration of the Primary Cosmic Ray into the atmosphere.

The longitudinal development of the shower is calculated via a parametrization formula. An atmosphere standard model has been included in our calculation which considers the temperature dependence with altitude and consequently, the scale height variation with altitude.

Shower profile representation.

$N_e$ refers to the number of electrons calculated via the parametrization; $p_e$ is the number of fluorescence UV photoelectrons detected at the abscissa slant depth.
Fig. 1.6 – *EUSO* effective trigger aperture.

Fig. 1.7 – *EUSO* expected counting rate (10% duty cycle).
Effective trigger aperture as a function of the primary particle energy for three different cloud levels. Clouds have been considered for estimating the corresponding response of the system.
<table>
<thead>
<tr>
<th><strong>Orbital Parameter</strong></th>
<th><strong>Height</strong></th>
<th><strong>Inclination</strong></th>
<th><strong>LEO 500 km nominal</strong></th>
<th><strong>10°-15° Equatorial</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ground Station</strong></td>
<td><strong>Equatorial</strong></td>
<td></td>
<td>Kourou (French Guiana), Malindi (Kenya)</td>
<td></td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td>Payload Module</td>
<td>1050 kg</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Service Module</td>
<td>775 kg</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td><strong>Satellite Mass</strong></td>
<td>1825 kg</td>
<td></td>
<td></td>
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<tr>
<td><strong>Power</strong></td>
<td>Payload Module</td>
<td>400 Watt</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Service Module</td>
<td>1300 Watt</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Satellite Power</strong></td>
<td>1700 Watt</td>
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<td></td>
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<tr>
<td><strong>Telemetry</strong></td>
<td>Rate during ground contact (10 min)</td>
<td>100 KBit/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Attitude and Pointing</strong></td>
<td>3 Axis Stabilised</td>
<td>&lt;200 arcsec (1/2 pixel)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Basic *EUSO* mission characteristics.

<table>
<thead>
<tr>
<th><strong>Field of View</strong></th>
<th>60°</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Entrance Pupil Diameter</strong></td>
<td>2.6 m</td>
</tr>
<tr>
<td><strong>Operating wavelengths</strong></td>
<td>330-400 nm</td>
</tr>
<tr>
<td><strong>Angular resolution</strong></td>
<td>~ 0.1°</td>
</tr>
<tr>
<td><strong>Pixel diameter (and spot size)</strong></td>
<td>~ 6 mm</td>
</tr>
<tr>
<td><strong>Number of pixels</strong></td>
<td>~ 2.5 × 10^5</td>
</tr>
<tr>
<td><strong>Pixel size on ground</strong></td>
<td>1 km</td>
</tr>
</tbody>
</table>

Basic *EUSO* payload characteristics.
After EUSO

Problems open:

- Spectral details around $3 \times 10^{19}$ eV
  * calibration with ground based experiments (Auger, HiRes, ...)
  * absolute calibration with pile-up induced by the GZK effect
- More detailed reconstruction of EASs
- Neutrino statistics

To deal with these problems we need

"LARGER SIGNAL"
After *EUSO*

The goal is to decrease the detection threshold of a factor from 5 to 10 from $\sim 3 \times 10^{19}$ eV to $\sim 10^{19}$ eV or better to $\sim 3 \times 10^{18}$ eV.

Starting from the planned *EUSO* configuration on the ISS, larger signals can be obtained using a larger collecting optics. This can allow a gain of 5 to 10 from the 4 m diameter of *EUSO* to 15÷30 meters (S/N proportional to the diameter of the collecting surface). **OR APD, HPD**

**Conclusion:**

"*Grand Observatories Deployment in Space*"

*from the International Space Station ISS*
UHE Neutrinos via Air Fluorescence

- Large Aperture ($10^{12}$ tons of effective atmospheric target) opens the door for observing ultra-high energy neutrinos interactions

- Horizontal Airshowers initiated deep ($> 1500$ g/cm$^2$) in the atmosphere provide a signature of neutrino interactions which are well-separated from hadronic and electromagnetic showers, $\lambda_\nu \sim 10^{10}$ cm, $\lambda_p \sim 10^4$ cm

(Air at STP, $E = 10^{20}$ eV)
Neutrino and hadron error boxes

Neutrino error box is limited only by the EUSO angular resolution while the proton error box is dominated by the intergalactic magnetic field.

\[ <B> = 1 \text{nGauss} \]
\[ <d> = 30 \text{ Mpc} \]

proton
\( (E=10^{20} \text{ eV}) \)
> 40 GeV, earth opaque to $\nu$'s, except...

**Tau Neutrino Regeneration**

A cosmological long-baseline muon $\to$ tau neutrino oscillation appearance experiment
...\( \nu \)'s via Cherenkov spot... much lower threshold!

Upward Airshower Flux Sensitivity

The Earth's crust is a huge neutrino target
(1 km\(^3\) of ice \(\sim 10^9\) ton-ster \(\nu\) Aperture)

<table>
<thead>
<tr>
<th>Tau Energy</th>
<th>(\gamma c \tau_\tau)</th>
<th>(\nu) Aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^{14}) eV</td>
<td>5 m</td>
<td>(10^9) ton-ster</td>
</tr>
<tr>
<td>(10^{15}) eV</td>
<td>50 m</td>
<td>(10^{10}) ton-ster</td>
</tr>
<tr>
<td>(10^{16}) eV</td>
<td>500 m</td>
<td>(10^{11}) ton-ster</td>
</tr>
<tr>
<td>(10^{17}) eV</td>
<td>5 km</td>
<td>(\leq 10^{12}) ton-ster</td>
</tr>
</tbody>
</table>
GLAST : recouvrement sol-espace

OVERLAP GROUND - SPACE

(a) 50 heures, >10 événements
(b) après un an de balayage

Crab Nebula

Jacques Paul
Prospective IN2P3 / DAPNIA
5 octobre 2000
EGRET All Sky Map (>100 MeV)

- Cygnus Region
- 3C279
- Vela
- Geminga
- Crab
- PKS 0528+134
- LMC
- PSR B1706-44
- PKS 0208-512
- Cosmic Ray Interactions With ISM
Gamma-Ray Quasars

- EGRET sees most blazars only when they flare
- What is the population of high-energy blazars?
- What is the nature of the quiescent emission?
- What is the relation to radio luminosity and variability?
- What are the high-latitude unidentifieds?

○ = EGRET blazars seen sometimes
● = EGRET blazars seen always
· = EGRET unidentified high-latitude variables
○ = Simulated GLAST 20σ AGN detections
Unidentified Sources

- 172 unidentified sources in 3rd EGRET catalog
- Mystery of unidentifieds since 1970s
- Galactic unidentifieds may be SNRs, Gemingas, massive stars, molecular clouds, or new phenomenon!
- Mid-latitude sources are separate population from low-latitude sources (Nature, March 23rd issue)
The Sky in the light of >300 GeV photons

13 sources (+1 GRB?), 4 confirmed sources

Galactic Sources:
- Plerions
- Shell-type Supernova Remnants
- X-ray Binary

Extragalactic Sources
- Blazars

Non-Detections
- Galactic Plane
- Pulsars
- Non-Blazar type AGNs
Preliminary evaluation from CELESTE data of the Crab Nebula around 60 GeV
Mrk 501 broad-band SED in April 1997

$\nu F(\nu)$ SED for “low” and high-flaring activities

Leptonic models are favoured (Synchrotron Self Compton, ...
GLAST LAT

Complete GLAST
4 x 4 Array of Towers

Gamma Ray

1.68 m

Anticoincidence Shield

Ultra-low Mass Tray Backbone

Lead

Silicon

9.2 cm

201 μm Pitch

12 Trays with 0.025 Radiation Length Pb Converters

4 Trays with 0.25 Radiation Length Pb Converters

2 Trays without Converters

SI Stelp Detector

Protons Mounted on Vertical Edge of Tray

Grid

Imaging Colorimeter (P ri)
**Si-Pb Tracker**
- Pitch = 201 µm
- $12 \times 2.5\% X_0$
- $+ 4 \times 25\% X_0$
- $+ 2$

**CsI Calorimeter**
- $8.6 X_0$
- $8 \times 12$ bars
- $2.0 \times 2.8 \times 35.1$ cm

**GLAST**
- 10 MeV - 1 TeV
- 2560 kg, 520 W
- $1.73 \times 1.06$ m

**ACD**
- Scintillator tiles
- 0.9997 efficiency
GLAST

Candidacy for the status of

*CERN—Recognized Experiment*

GLAST is a robust gamma detector
of about 1.73 m$^2$ total area $(1.4$ m$^2$ efficient)
subdivided in $4 \times 4 = 16$ towers,

with:

- a tracker: 18 x–y layers of silicon–strip, with 0.2mm resolution
  (60 m$^2$ of Si, $10^6$ channels in total)
- a calorimeter: 4 x, 4 y layers of CsI rods, for 8.6 R.L. in depth
  (1.5 tons, 1536 rods)
- an outer shell veto.

Constraints:

- total mass=2.56 tons, total power = 520 watts;
- life time (without maintenance) = 5 + 5 years.
Gamma Ray Large Area Space Telescope

Theme: Exploring Sites of Particle Acceleration in the Universe

- Launch in 2005
- 20 MeV to 300 GeV
- Wide-field imaging telescope
- NASA cost is $326 M
- http://glast.gsfc.nasa.gov/
<table>
<thead>
<tr>
<th></th>
<th>EGRET</th>
<th>GLAST</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>50 MeV - 30 GeV</td>
<td>10 MeV - 1 TeV</td>
</tr>
<tr>
<td><strong>Sensitive Area</strong></td>
<td>1500 cm²</td>
<td>12 900 cm²</td>
</tr>
<tr>
<td><strong>Field of view</strong></td>
<td>0.6 sr</td>
<td>2.4 sr</td>
</tr>
<tr>
<td><strong>1-yr sensitivity</strong></td>
<td>&gt; 10⁻⁷ γ cm² s⁻¹</td>
<td>&gt; 2.3 10⁻⁹ γ cm² s⁻¹</td>
</tr>
<tr>
<td><strong>Localization</strong></td>
<td>0.5°</td>
<td>20° - 7°</td>
</tr>
</tbody>
</table>
**Science Capabilities: Sensitivity**

- **200 γ bursts per year**
  - prompt emission sampled to > 20 μs

- **AGN flares > 2 min**
  - time profile +ΔE/E ⇒ physics of jets and acceleration

- **γ bursts delayed emission**

- **All 3EG sources + 80 new in 2 days**
  - ⇒ periodicity searches (pulsars & X-ray binaries)
  - ⇒ pulsar beam & emission vs. luminosity, age, B

- **10^4 sources in 1-yr survey**
  - ⇒ AGN: logN-logS, duty cycle, emission vs. type, redshift, aspect angle
  - ⇒ extragalactic background light (γ + IR-opt)
  - ⇒ new γ sources (μQSO, external galaxies, clusters)
• EGRET source positions are ~ 0.5° in size, too large for counterpart searches

• GLAST will provide much more accurate source positions, 30 arcsec to 5 arcmin

Image from NVSS 1.4 GHz survey, Condon et al. (1998)
SNR Origin of Cosmic Rays

- Supernova shock acceleration models predict correct spectra and energetics

- Evidence of TeV electrons in non-thermal X-ray emission and ground-based gamma-ray observations

- Smoking gun would be an extended gamma-ray source, such as an interstellar cloud, located next to a SNR, which may be the case for Gamma Cygni

- This would provide proof that nuclei as well as electrons are accelerated as predicted
2691 BATSE Gamma-Ray Bursts

Fluence, 50-300 keV (ergs cm$^{-2}$)
# GBM vs. BATSE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BATSE</th>
<th>GBM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy Range</strong></td>
<td>25 keV - 1.9 MeV (LAD)</td>
<td>5 keV - 1 MeV (LED)</td>
</tr>
<tr>
<td></td>
<td>7 keV - 10 MeV (SD)</td>
<td>150 keV - 30 MeV (HED)</td>
</tr>
<tr>
<td><strong>Detectors</strong></td>
<td>NaI</td>
<td>NaI/BGO</td>
</tr>
<tr>
<td><strong>FOV</strong></td>
<td>Full Sky</td>
<td>8.6 sr</td>
</tr>
<tr>
<td><strong>Location Accuracy</strong></td>
<td>2° - 5°</td>
<td>1.5° - 3°</td>
</tr>
<tr>
<td><strong>Burst Sensitivity</strong></td>
<td>0.2 ph cm(^{-2}) s(^{-1})</td>
<td>0.6 ph cm(^{-2}) s(^{-1})</td>
</tr>
</tbody>
</table>
# AGILE

## Spacecraft and Satellite Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Equatorial orbit, 550 km Malindi (Kenya)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal orbital parameters</td>
<td></td>
</tr>
<tr>
<td>Possible ground station</td>
<td></td>
</tr>
<tr>
<td>Spacecraft + payload mass</td>
<td>180-200 kg</td>
</tr>
<tr>
<td>Payload required power</td>
<td>~60 W</td>
</tr>
<tr>
<td>Downlink telemetry rate</td>
<td>~500 kbit/sec</td>
</tr>
<tr>
<td>Pointing configuration</td>
<td>3 - axes</td>
</tr>
<tr>
<td>Pointing accuracy</td>
<td>0.5 - 1 degree</td>
</tr>
<tr>
<td>Satellite expected life</td>
<td>~3 years</td>
</tr>
</tbody>
</table>
Space Gamma Ray Astronomy

CGRO

INTEGRAL

HETE

Swift

AGILE

GLAST

VIRGO: Sensibilité

Limite inférieure au bruit de l'instrument:
- ∅ bruit introduit par les asservissements, l'électronique ou les défauts de l'ITF
- Ne rend pas compte du bruit excédentaire ("bruit non gaussien")
VIRGO : Sensibilité vs sources attendues
| Coalescence of massive black holes during collisions between galaxies, perhaps in formation of massive black holes, probing the central engines powering quasars. |
| Black holes orbiting massive black holes, providing precision tests of gravitational theory in the high-field limit. |
| Hundreds of galactic binary star systems, many containing neutron stars or black holes including several known binary systems. |
LASER INTERFEROMETER SPACE ANTENNA

[Diagram showing relative orbit of spacecraft and distances involved.]
LASER INTERFEROMETER SPACE ANTENNA

**Figure 1**
- Laser
- Beam Splitter
- Mass 1
- Photodetector

**Figure 2**
- Laser
- Beam Splitter
- Mass 1
- Photodetector

**Figure 3**
- Laser
- Beam Splitter
- Mass 1
- Photodetector
Pixel Detectors

Atlas and CMS Pixel VTX systems:

- ~1 - 2 m²; 10⁸ channels
- Pixel size ~ 50*400 μ² - 150*150 μ²
- τ_{peak} ~ 25ns; C_{input} < 100fF

- Noise < 200e⁻; Power/pix ~ 60μW
- complex chip functionality demonstrated
- (relatively) low noise operation achieved
- integration problem solved (bump-bond)

Possible use as X-ray detector?
Pixel Detectors

Direct coupling of each pixel to electronics allows:

Pixel self triggering & time stamp
< 1μs time resolution
vs. ~ 20ms CCD collection time

“Clean” read-out
(in CCD charge collection continues even)
(as stored signals are shifted through the sensor)
(to the electronics)

Fast (< 1μs vs. ~2ms) and possibly
“dead-timeless” read-out

Marcello Mannelli: Silicon Sensors in HEP with possible interest for astrophysics
CERN-ESA Workshop April 2000
Pixel Detectors

Further remarks:

• Separate chip & sensor => freedom of choice for sensor material & geometry
  (bump ~ few fF =>only a small noise penalty)

• if p-on-n, may use 6” wafers to obtain large ~ 90cm² vs. 36cm² active area

=> fewer cracks & dis-homogeneity if used in large area multi-module device

• may consider very high $\rho$, thicker wafer or even different s.c. material (CdTe)

=> improved sensitivity to high energy X-rays ~10 KeV - 10MeV (?)
The Liquid Xenon Time Projection Chamber

- A homogeneous, self-triggered detector which combines high detection efficiency and low background with calorimetry and tracking capability.
- Xe ionization and scintillation signals are used to measure energy and 3-D spatial information for each gamma-ray interaction taking place in the sensitive volume.
- Ideal to visualize the complex histories of MeV gamma-rays and to image them as a Compton telescope.
Xe – ACT: 
Low Density (0.15 g·cm$^{-3}$) Xe TPC Version

<table>
<thead>
<tr>
<th>Instrument Characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range (Compton imaging)</td>
<td>0.3 – 10 MeV</td>
</tr>
<tr>
<td>(extendable using pair production events)</td>
<td>10 – 100 MeV</td>
</tr>
<tr>
<td>Energy resolution (FWHM)</td>
<td>5 keV @ 1 MeV</td>
</tr>
<tr>
<td>Position resolution (1 $\sigma$)</td>
<td>0.3 mm (3 dimensions)</td>
</tr>
<tr>
<td>Angular resolution (1 $\sigma$)</td>
<td>8 arcmin at 2 MeV</td>
</tr>
<tr>
<td>Field-of-view</td>
<td>$\sim 2\pi$</td>
</tr>
<tr>
<td>Effective area at (0.8 – 2 MeV)</td>
<td>$\sim 6000$ cm$^2$</td>
</tr>
<tr>
<td>Sensitivity ($3 \sigma$, $t_{obs} = 10^6$ s)</td>
<td>$\sim 1 \times 10^{-7}$ $\gamma$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Narrow line source ($\leq 5$ keV)</td>
<td>$\sim 3 \times 10^{-7}$ $\gamma$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Broadened line source (30 – 40 keV)</td>
<td>$\sim 1 \times 10^{-6}$ $\gamma$ cm$^{-2}$ s$^{-1}$ MeV$^{-1}$</td>
</tr>
</tbody>
</table>

| Compton Telescope Configuration |                |
| Event imaging technique | Time projection chamber |
| Background rejection: | Factor $> 100$ improvement |
| 3D event imaging and | over COMPTEL |
| Compton electron tracking |                |
| Instrument volume | $2 \times 2 \times 2$ m$^3$ |
APD

Major recent development, driven by CMS ECAL requirements:

- Radiation hard, operation in 4T field
  - tot. noise term < 40Mev (after irr.)
    - gain stability < 0.5%
  - PbWO₄ light yield ~ 20γ/cm²/ MeV
    (at instrumented crystal face)

- maximize Q.E.
- maximize surface
- minimize noise
- provide gain!
- minimize gain variation w.r.t. HV and Temp

Marcello Mannelli: Silicon Sensors in HEP with possible interest for astrophysics
CERN-ESA Workshop April 2000
APD

Advantages compared to PIN diode

- Lower capacitance at equal surface:
  (~70pF vs. ~300 pF)
- Gain eg. ~ 50!

=> Very large noise reduction:
  eg. from ~1000e\(^-\) to ~50e\(^-\) @ \(t_{\text{shape}} \sim 1\mu\text{s}\)
(probably better if tune to specific application)

---

For CsI(Tl) could potentially
extend sensitivity <1MeV
(while retaining large dynamic range)

---

Principle difficulty:
require HV (~400V) & Temp. stability
Strip Detectors in Astro-physics

- Development is already parallel between HEP and Astro-physics. The two largest examples are:

- AMS: very large volume tracking in magnetic field, for momentum determination & P.ID. of charged cosmic ray flux

- GLAST: very large volume γ-ray conversion & tracking, for time-resolved burst measurements, with source identification by pointing

  \[ \text{NB. DC courses \& need to reduce costs?} \]
Space-CMS comparison

Charge particles

Protons in space

Protons in tracker

Pions in tracker

Cavern

Muon Chambers

Calorimeters

Tracker

Charged Hadrons Flux (particles/cm²/10 years)

1.0E+05 1.0E+07 1.0E+09 1.0E+11 1.0E+13 1.0E+15

Neutrons

Neutrons in Atmosphere (~15 km)

Cavern

Muon Chambers

Calorimeters

Tracker & Forward Cal.

Neutron Flux - E>100 keV (n/cm²/10 years)

1.0E+07 1.0E+09 1.0E+11 1.0E+13 1.0E+15 1.0E+17

Basic Radiation effects on electronic devices, VLSI circuits

• **Long-term damaging effects**
  – Total Dose effects TID
    • caused by ionizing particles
    • affects all CMOS and bipolar integrated circuits
  – Displacement damage
    • neutrons and all charged hadrons
    • affects bipolar circuits, APD, silicon detector

• **Single Event Effects SEE**
  – event caused by nuclear spallation: hadron-silicon atom or single ion strike.
    • single event latch-up: hard failure
    • single event upset: soft failure
    • SEGR, burnout...

# Technologies for LHC ASICs

**Current Situation**

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>Pixel</th>
<th>Tracker</th>
<th>Calorimeter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 000 chips</td>
<td>SCT 60 000 chips</td>
<td>DMILL TEMIC</td>
</tr>
<tr>
<td></td>
<td>1000x 6” wafers</td>
<td>TRT 30 000 chips</td>
<td>100x 6” wafers</td>
</tr>
<tr>
<td>ATLAS</td>
<td>DMILL TEMIC</td>
<td>TRT 30 000 chips</td>
<td>COTS...</td>
</tr>
<tr>
<td></td>
<td>SOI-CMOS</td>
<td>DMILL TEMIC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Honeywell</td>
<td>RICMOS Honeywell</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maxim bipolar</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CMS</th>
<th>Pixel</th>
<th>Tracker</th>
<th>Calorimeter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 000 chips</td>
<td>100 000 chips</td>
<td>DMILL TEMIC</td>
</tr>
<tr>
<td>CMS</td>
<td>1000x 6” wafers</td>
<td>500x 8” wafers</td>
<td>Honeywell CHFET</td>
</tr>
<tr>
<td>CMS</td>
<td>DMILL TEMIC</td>
<td>DMILL TEMIC</td>
<td>HARRIS bipolar</td>
</tr>
<tr>
<td></td>
<td>SOI-CMOS</td>
<td>HARRIS CMOS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Honeywell</td>
<td>0.25 μm CMOS</td>
<td></td>
</tr>
</tbody>
</table>

**LHCb and ALICE also concerned**

For all LHC experiments > 4000 wafers x 6”, 2000 x 8”

Radiation hardened or radiation tolerant wafers

---

Simulation - GEANT4

Object-oriented toolkit
Worldwide collaboration
Geometry description of complex detectors
Detailed physics processes
Applications outside high-energy physics
Software Quality

Functionality, correctness, robustness
- Experience, requirements, software process

Ease of entry for physicists
- Documentation, clear architecture, training, mentors

Maintainability
- Documentation, software process

Flexibility
- Changing environment, new requirements

Performance
- Few O(0) re-processings, CPU, memory, IO

CERN-ESA Workshop, 5-7 April 2000