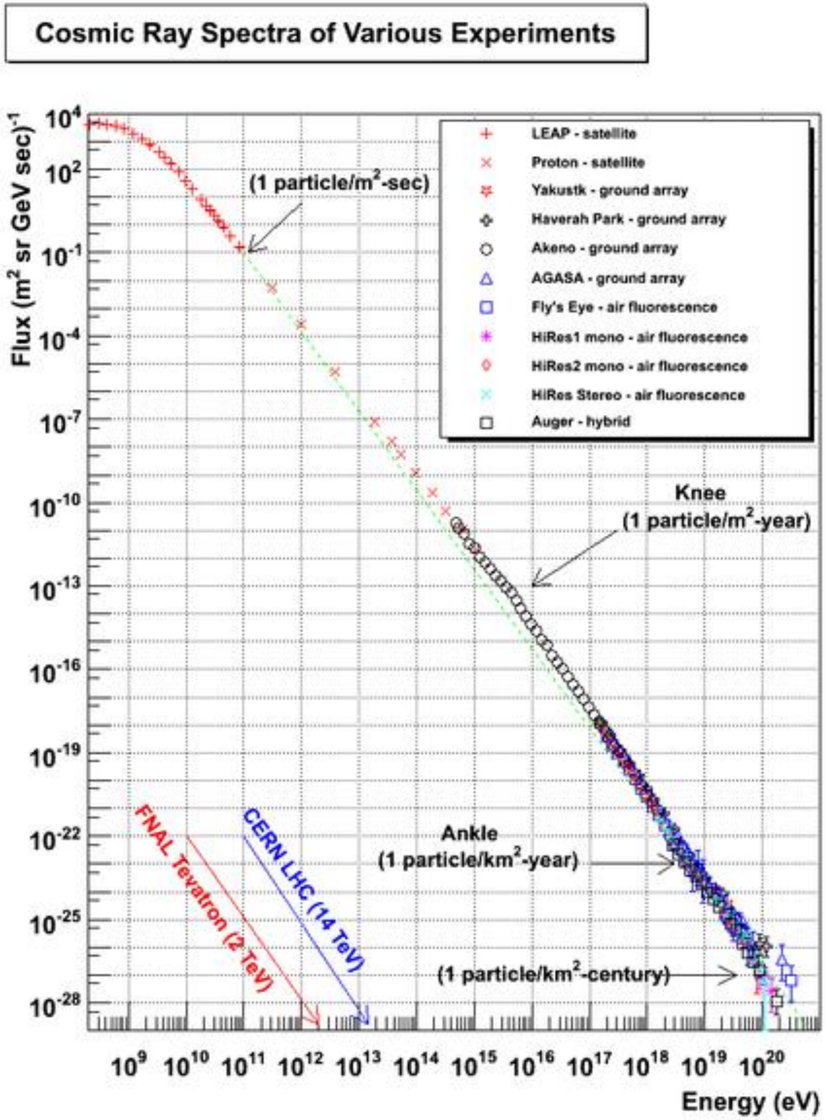
FYST17 Lecture 13
The cosmic connection

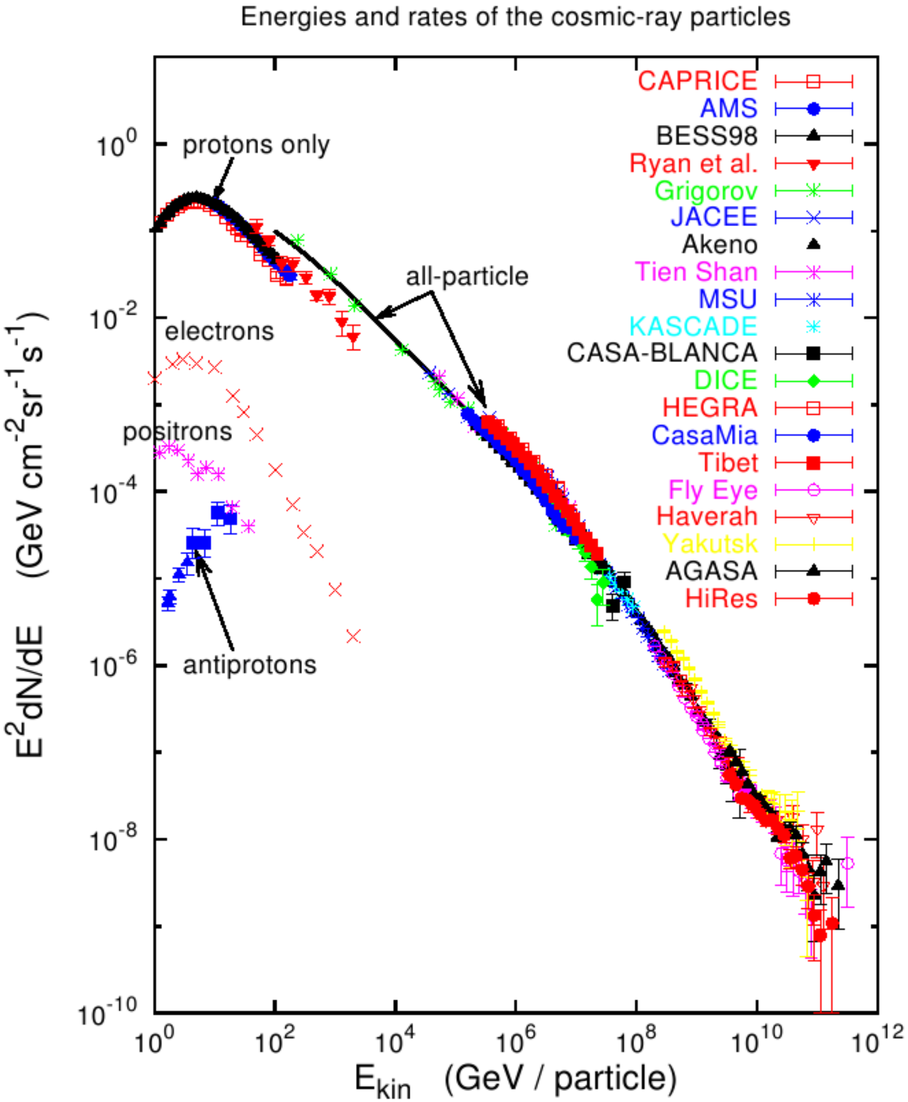
Thanks to R. Durrer, L. Covi

Today's outline

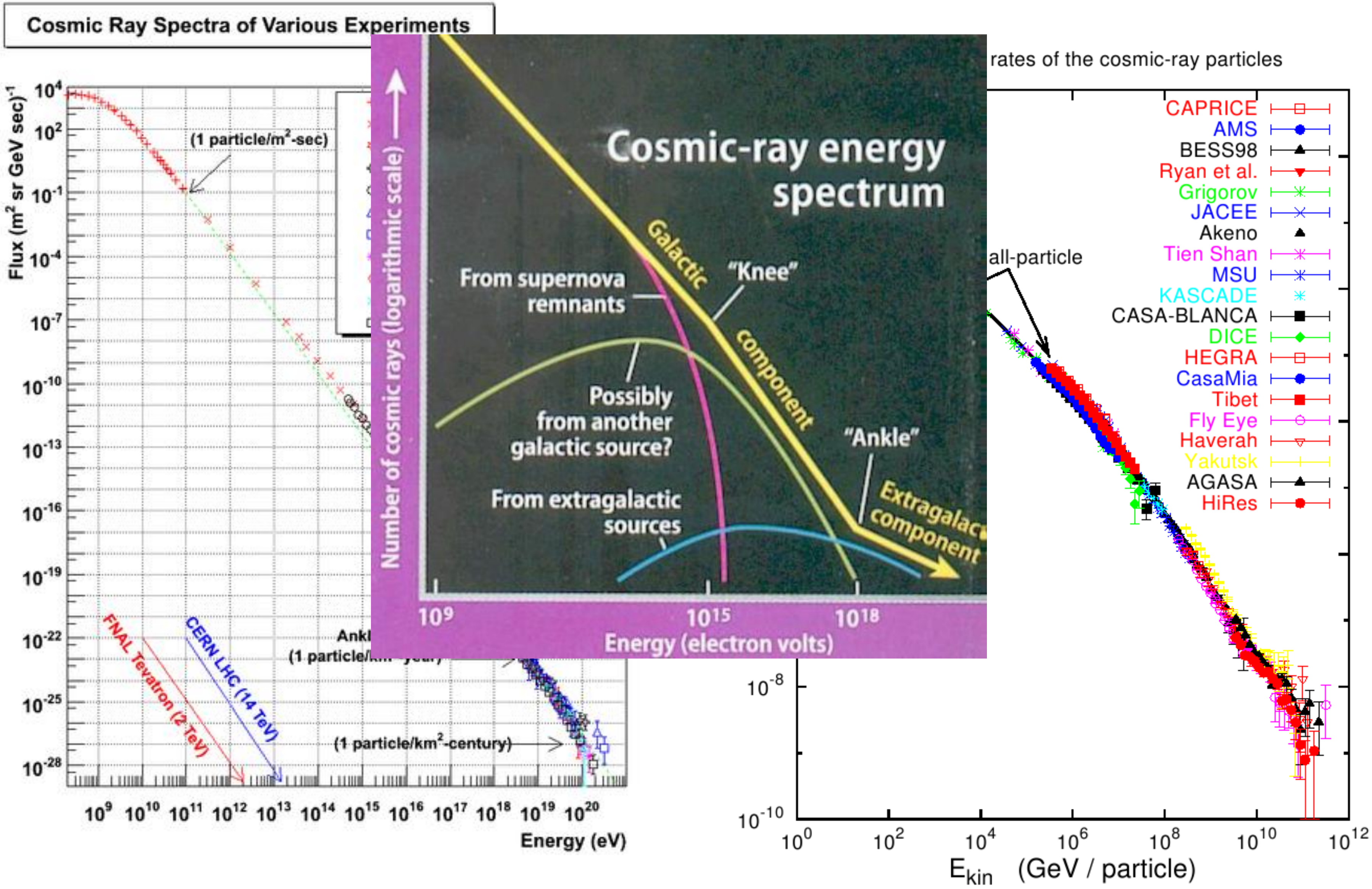
- High energy cosmic rays
  - GKZ cut-off
- Detectors in space
  - The PAMELA signal
- Some words on the expansion of the Universe
- Some words on the exam + evaluation

Cosmic rays


Cosmic Ray Spectra of Various Experiments
Flux (m^2 sr GeV sec)$^{-1}$
10^4
10^2
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
10^{-22}
10^{-25}
10^{-28}
10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
Energy (eV)
LEAP - satellite
Proton - satellite
Yakustk - ground array
Haverah Park - ground array
Akeno - ground array
AGASA - ground array
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes Stereo - air fluorescence
Auger - hybrid
(1 particle/m^2-sec)
Knee
(1 particle/m^2-year)
Ankle
(1 particle/km^2-year)
(1 particle/km^2-century)
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)


Energies and rates of the cosmic-ray particles
E^{2}dN/dE (GeV cm^{-2}sr^{-1}s^{-1})
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^0 10^2 10^4 10^6 10^8 10^{10} 10^{12}
E$_{kin}$ (GeV / particle)
protons only
all-particle
electrons
positrons
antiprotons
CAPRICE
AMS
BESS98
Ryan et al.
Grigorov
JACEE
Akeno
Tien Shan
MSU
KASCADE
CASA-BLANCA
DICE
HEGRA
CasaMia
Tibet
Fly Eye
Haverah
Yakutsk
AGASA
HiRes

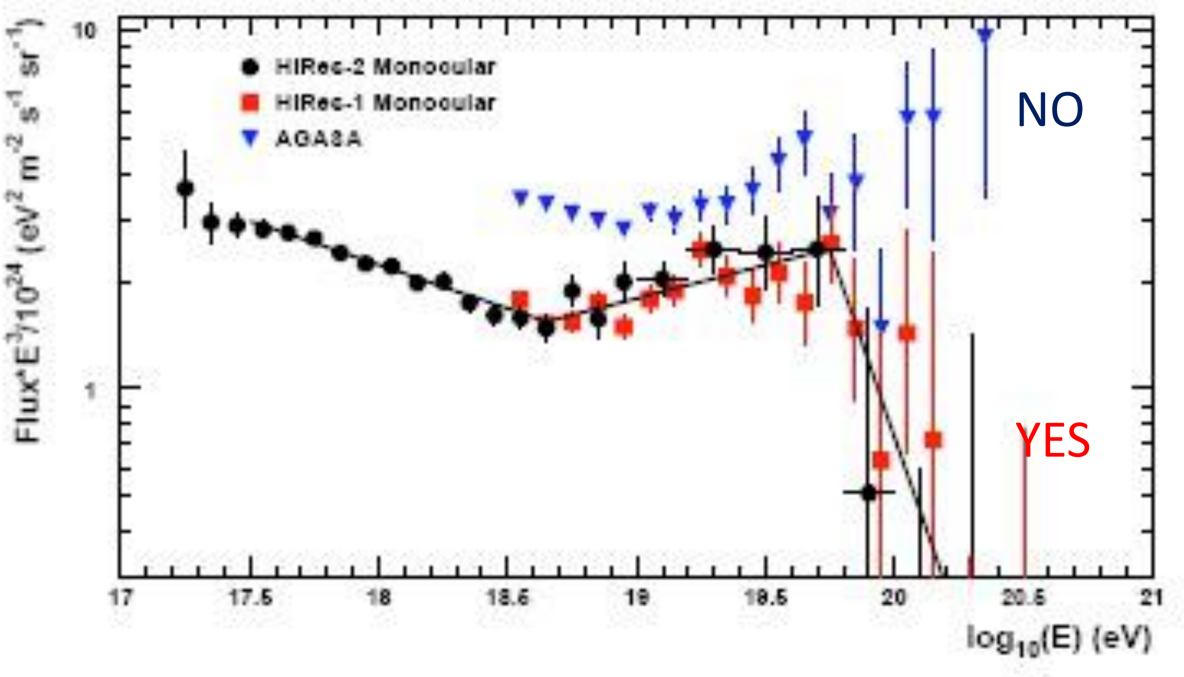
Cosmic rays


Cosmic Ray Spectra of Various Experiments
Flux (m^2 sr GeV sec)$^{-1}$
10^4
10^2
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
10^{-22}
10^{-25}
10^{-28}
(1 particle/m^2-sec)
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)
Ankl
(1 particle/k
(1 particle/km^2-century)
10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
Energy (eV)
Cosmic-ray energy spectrum
Number of cosmic rays (logarithmic scale)
Galactic component
"Knee"
From supernova remnants
Possibly from another galactic source?
"Ankle"
From extragalactic sources
Extragalac component
10^9
10^{15}
10^{18}
Energy (electron volts)
rates of the cosmic-ray particles
all-particle
CAPRICE
AMS
BESS98
Ryan et al.
Grigorov
JACEE
Akeno
Tien Shan
MSU
KASCADE
CASA-BLANCA
DICE
HEGRA
CasaMia
Tibet
Fly Eye
Haverah
Yakutsk
AGASA
HiRes
10^{-8}
10^{-10}
10^0 10^2 10^4 10^6 10^8 10^{10} 10^{12}
E_{kin} (GeV / particle)

GZK cut-off?

Greisen-Zatsepin-Kuzmin (sometimes GKZ)

Predict cuf-off in cosmic ray energies around 5×10^{19} eV if they result from protons. (protons have to origin max 30 Mpc from our Galaxy)

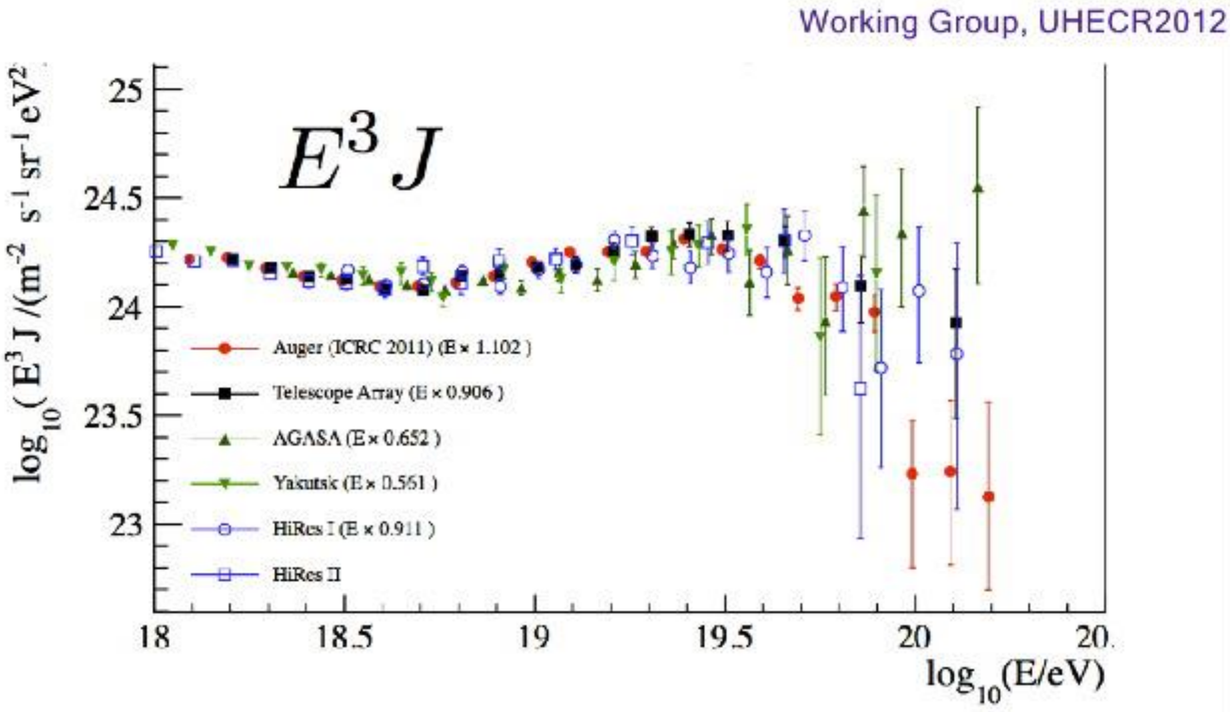


At very high energy the CMB γs interact with the protons to produce pions ($\gamma + p \rightarrow \pi^+ + n$ etc.) $\Rightarrow$ leptons + high energy neutrinos

GZK cut-off?

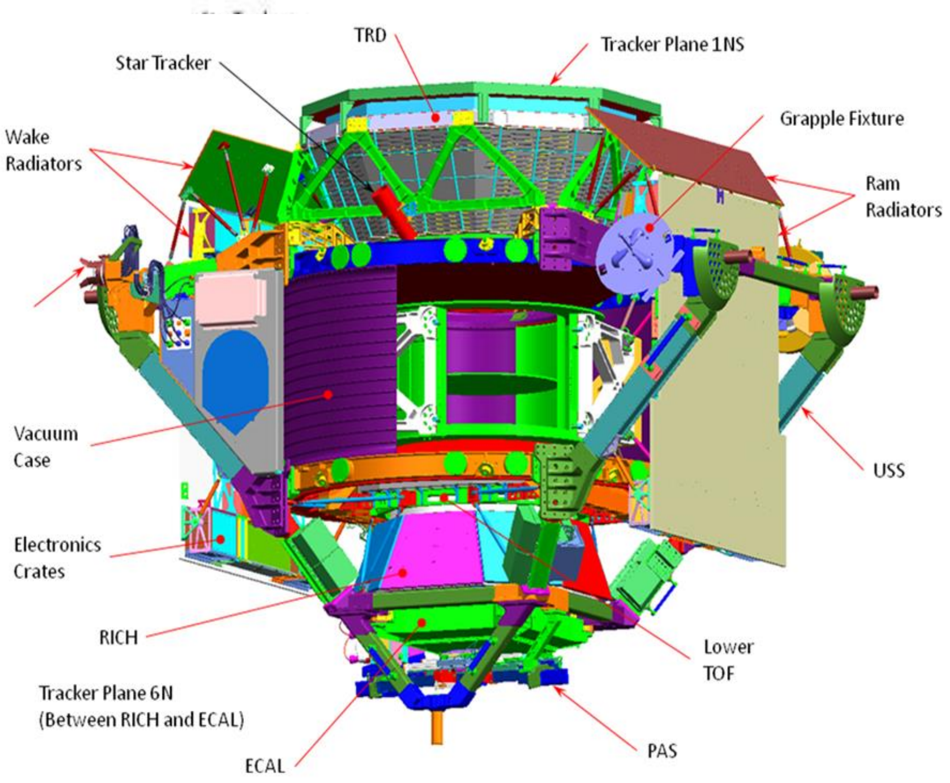
Difference probably due to calibration problem, with recalibration spectrum seems to be cut-off .

But GZK pions produce both photons and neutrinos – need spectrum for both!



And then of course has to be proven that cut-off due to GZK mechanism …

Detectors in space: AMS-02



Magnet *bends in opposite directions charged particles/antiparticles*

Transition Radiation Detector (TRD) *identifies electrons and positrons among other cosmic-rays*

Time-of-Flight System (ToF) *warns the sub-detectors of incoming cosmic-rays*

Silicon Tracker (Tracker) *detects the particle charge sign, separating matter from antimatter*

Ring-Imaging Cherenkov Detector (RICH) *measures with high precision the velocity of cosmic-rays*

Electromagnetic Calorimeter (ECAL) *measures energy of incoming electrons, positrons and γ-rays*

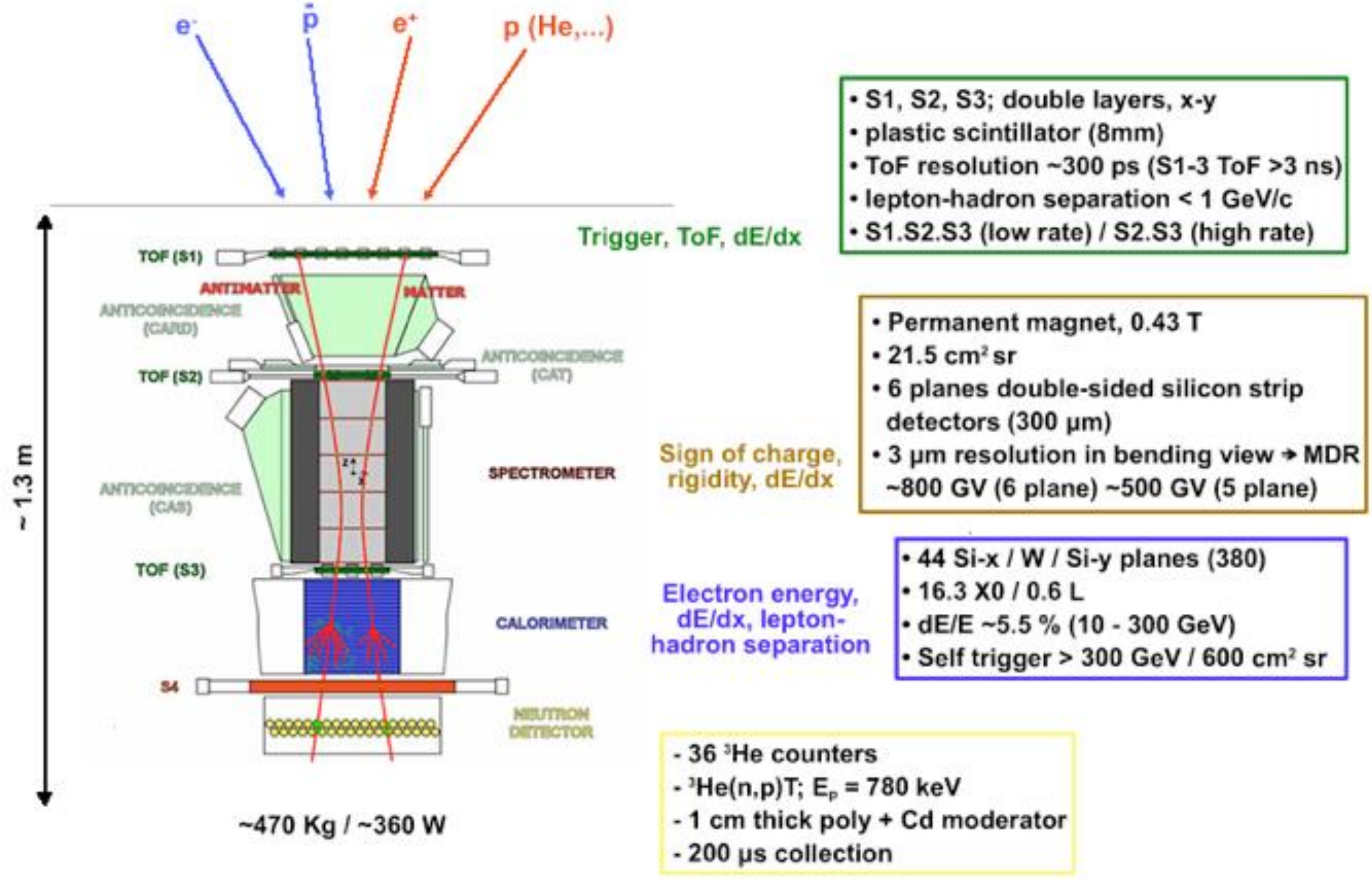
Anti-Coincidence Counter (ACC) *rejects cosmic rays traversing the magnet walls*

Tracker Alignment System (TAS) *checks the Tracker alignment stability*

Star Tracker and GPS *defines the position and orientation of the AMS-02 experiment*

Electronics *transform the signals detected by the various particle detectors into digital information to be analyzed by computers*

PAMELA Satelite



Trigger, ToF, dE/dx

- S1, S2, S3; double layers, x-y
- plastic scintillator (8mm)
- ToF resolution ~300 ps (S1-3 ToF >3 ns)
- lepton-hadron separation < 1 GeV/c
- S1.S2.S3 (low rate) / S2.S3 (high rate)

Sign of charge, rigidity, dE/dx

- Permanent magnet, 0.43 T
- 21.5 cm^2 sr
- 6 planes double-sided silicon strip detectors (300 µm)
- 3 µm resolution in bending view → MDR ~800 GV (6 plane) ~500 GV (5 plane)

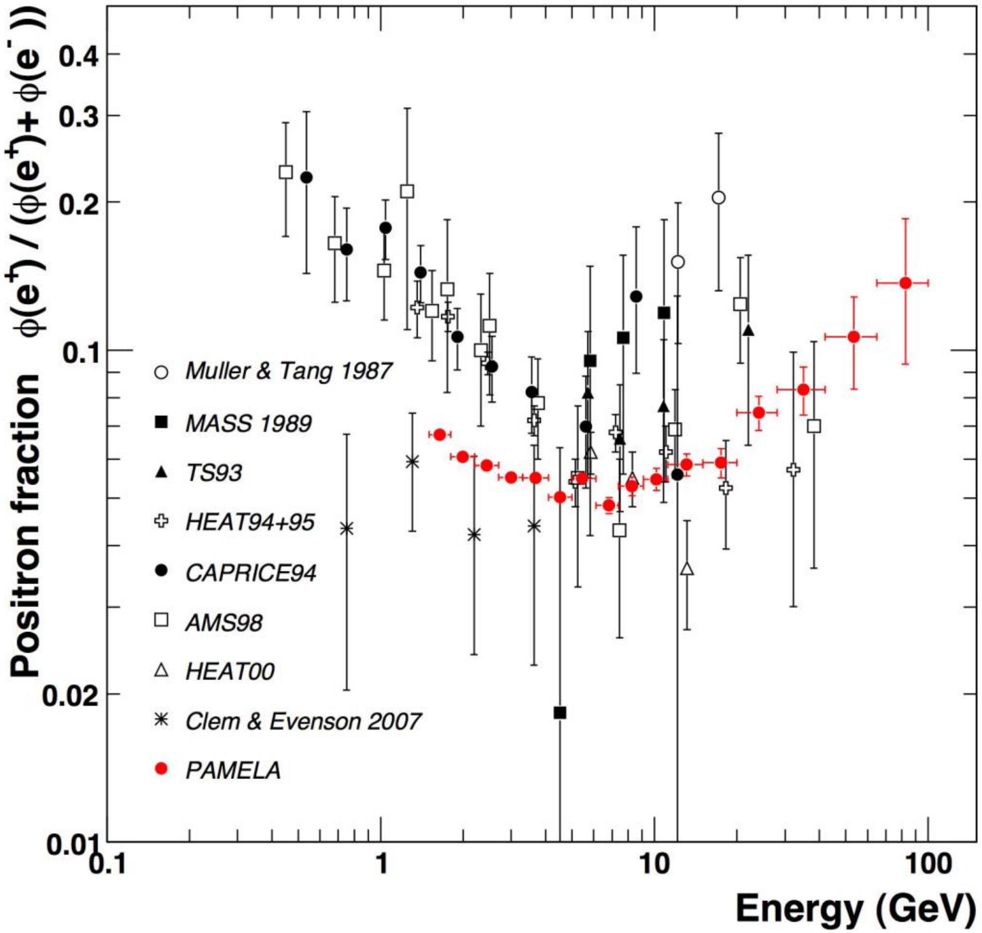
Electron energy, dE/dx, lepton-hadron separation

- 44 Si-x / W / Si-y planes (380)
- 16.3 X_0 / 0.6 L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm^2 sr

- 36 ^{3}He counters
- ^{3}He(n,p)T; E_p = 780 keV
- 1 cm thick poly + Cd moderator
- 200 µs collection

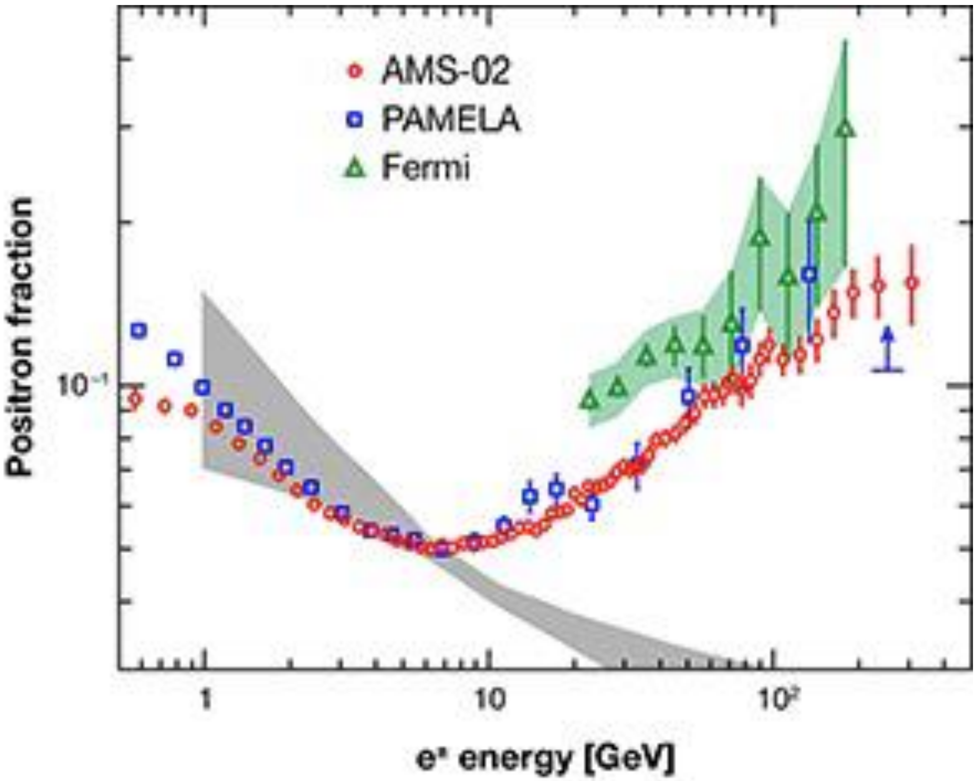
The PAMELA signal

The big news of 2003 was the positron excess observed by PAMELA:



Confirmed by AMS and Fermi

Rising spectrum doesn't fit secondary positron hypothesis

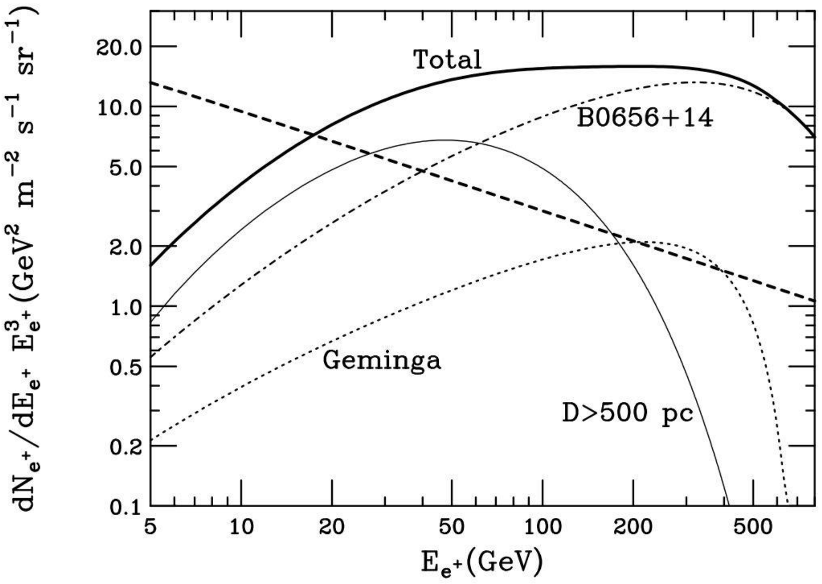


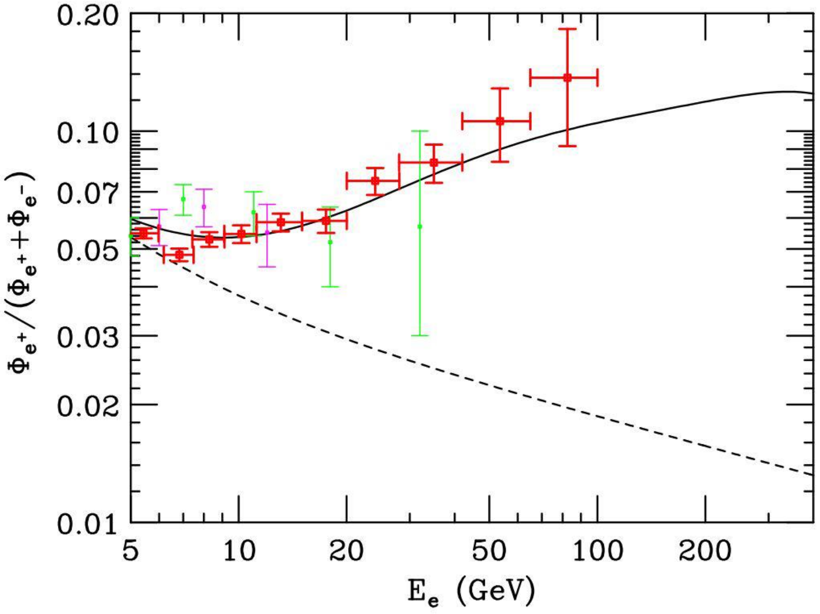
What is this? Need new source of positrons and not too far away

Is it perhaps from Dark matter annihilation?!!

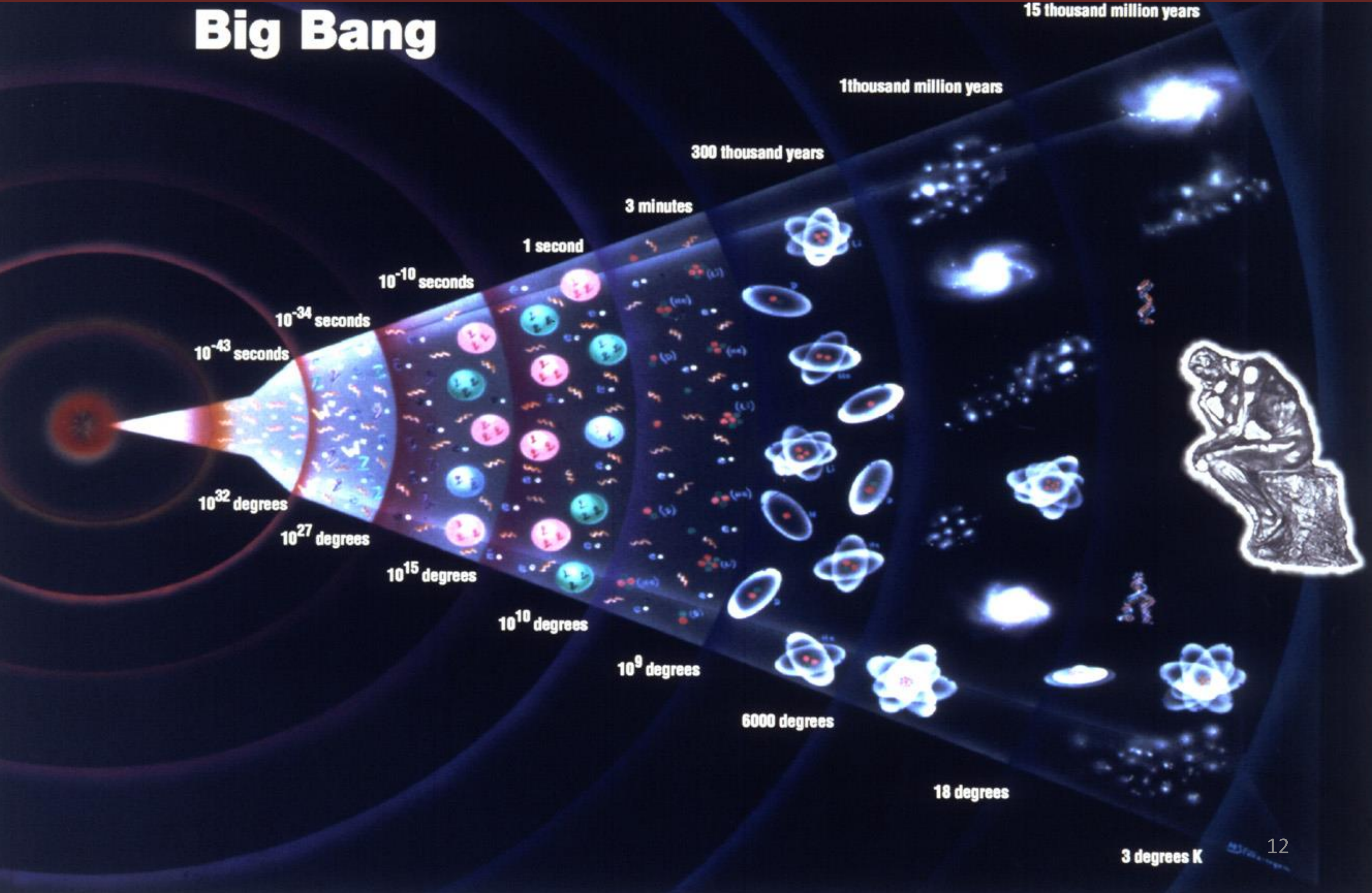
The positron excess

- Dark Matter annihilation hypothesis by now excluded by the PLANCK experiment
- Could it be a local pulsar?

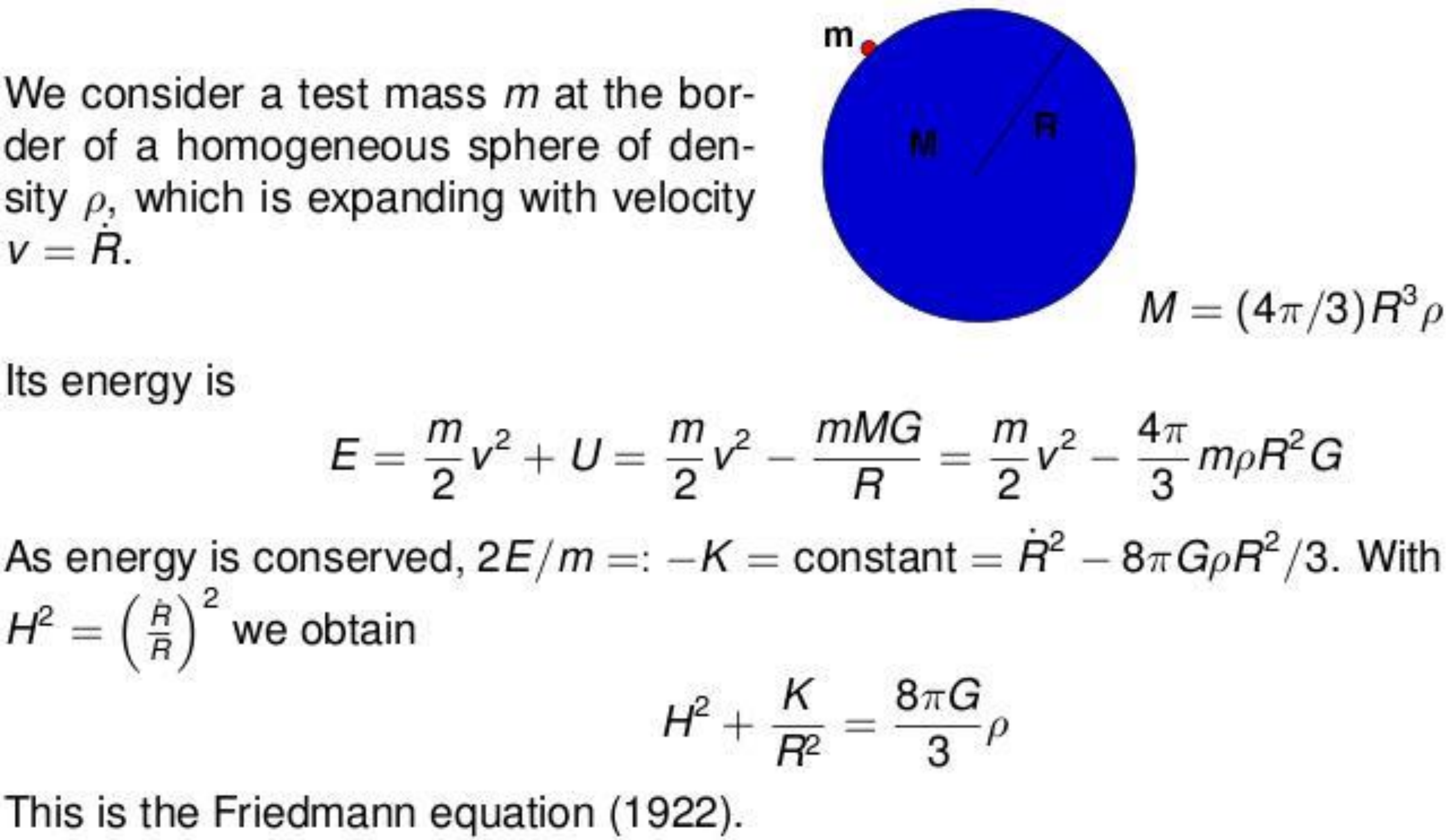




The expanding Universe



Understanding the expansion of the Universe within Newtonian gravity



We consider a test mass m at the border of a homogeneous sphere of density ρ, which is expanding with velocity $v = \dot{R}$.

$$M = (4\pi/3)R^3\rho$$

Its energy is

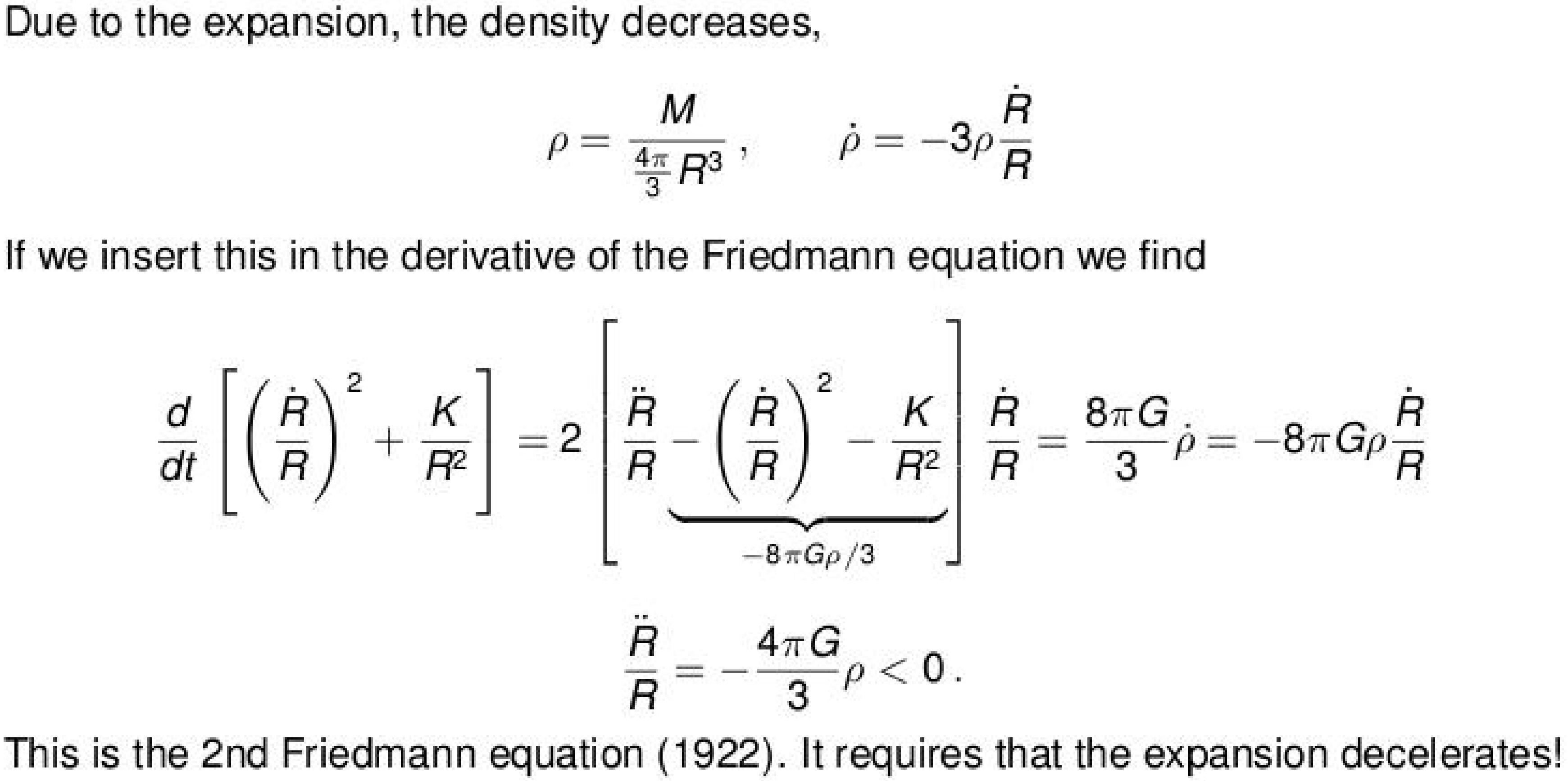
$$E = \frac{m}{2}v^2 + U = \frac{m}{2}v^2 - \frac{mMG}{R} = \frac{m}{2}v^2 - \frac{4\pi}{3}m\rho R^2 G$$

As energy is conserved, $2E/m =: -K = \text{constant} = \dot{R}^2 - 8\pi G\rho R^2/3$. With $H^2 = \left(\frac{\dot{R}}{R}\right)^2$ we obtain

$$H^2 + \frac{K}{R^2} = \frac{8\pi G}{3}\rho$$

This is the Friedmann equation (1922).

Understanding the expansion of the Universe within Newtonian gravity



Due to the expansion, the density decreases,

$$\rho = \frac{M}{\frac{4\pi}{3}R^3}\,, \qquad \dot{\rho} = -3\rho\frac{\dot{R}}{R}$$

If we insert this in the derivative of the Friedmann equation we find

$$\frac{d}{dt}\left[\left(\frac{\dot{R}}{R}\right)^2 + \frac{K}{R^2}\right] = 2\left[\frac{\ddot{R}}{R}\underbrace{-\left(\frac{\dot{R}}{R}\right)^2 - \frac{K}{R^2}}_{-8\pi G\rho/3}\right]\frac{\dot{R}}{R} = \frac{8\pi G}{3}\dot{\rho} = -8\pi G\rho\frac{\dot{R}}{R}$$

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}\rho < 0\,.$$

This is the 2nd Friedmann equation (1922). It requires that the expansion decelerates!

Expansion within General Relativity

Including general relativity these equations are modified:

$$\begin{aligned} \left(\frac{\dot{R}}{R}\right)^2 + \frac{K}{R^2} &= \frac{8\pi G}{3c^2}\rho_E + \frac{\Lambda}{3} \\ \frac{\ddot{R}}{R} &= -\frac{4\pi G}{3c^2}(\rho_E + 3P) + \frac{\Lambda}{3} \end{aligned}$$

P is the pressure and Λ is the cosmological constant,
ρ_E is the energy density. For ordinary matter $\rho_E = c^2\rho$, and c is the speed of light.
K now has a new interpretation. It is the curvature of space.

Introducing the 'density' parameters

$$\Omega_m = \frac{8\pi G\rho_E}{3c^2H^2}, \qquad \Omega_K = -\frac{K}{R^2H^2}, \qquad \Omega_\Lambda = \frac{\Lambda}{3H^2},$$

the first Friedmann eqn. becomes

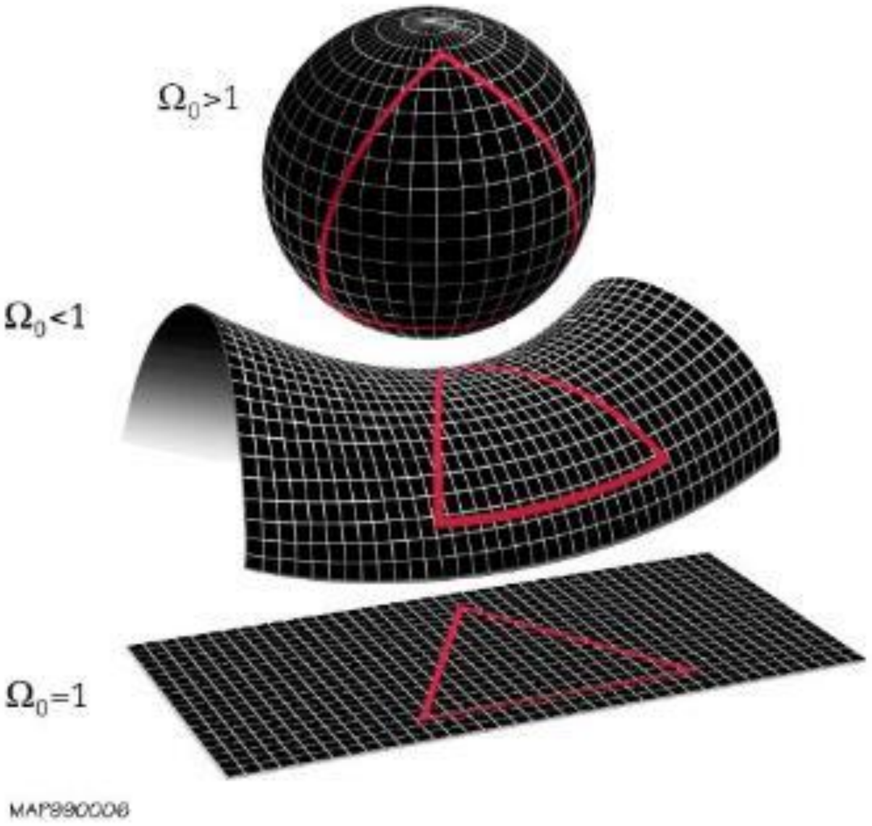
$$\Omega_m + \Omega_\Lambda + \Omega_K = 1 .$$

Curvature

$K > 0$ ($\Omega_K < 0$): spherical space,

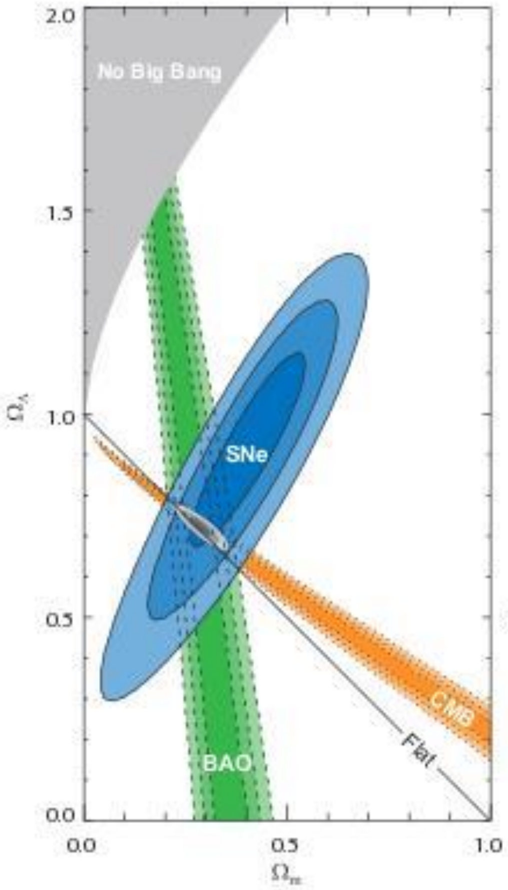
$K < 0$ ($\Omega_K > 0$): pseudo-spherical space (saddle),

$K = 0$ ($\Omega_K = 0$): flat space.

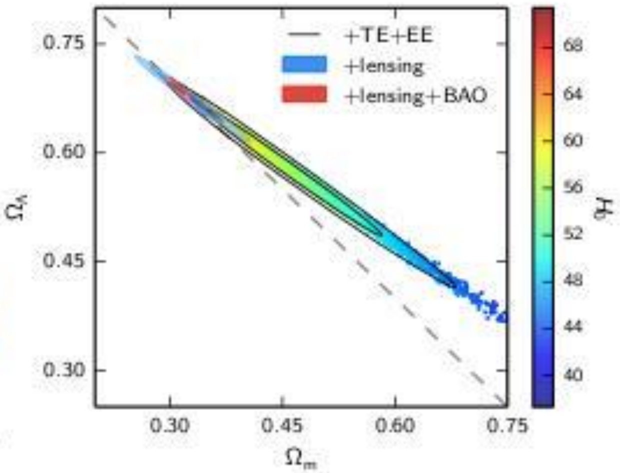


The Universe is accelerating

Matter, Ω_m, and cosmological constant, Ω_Λ (dark energy).



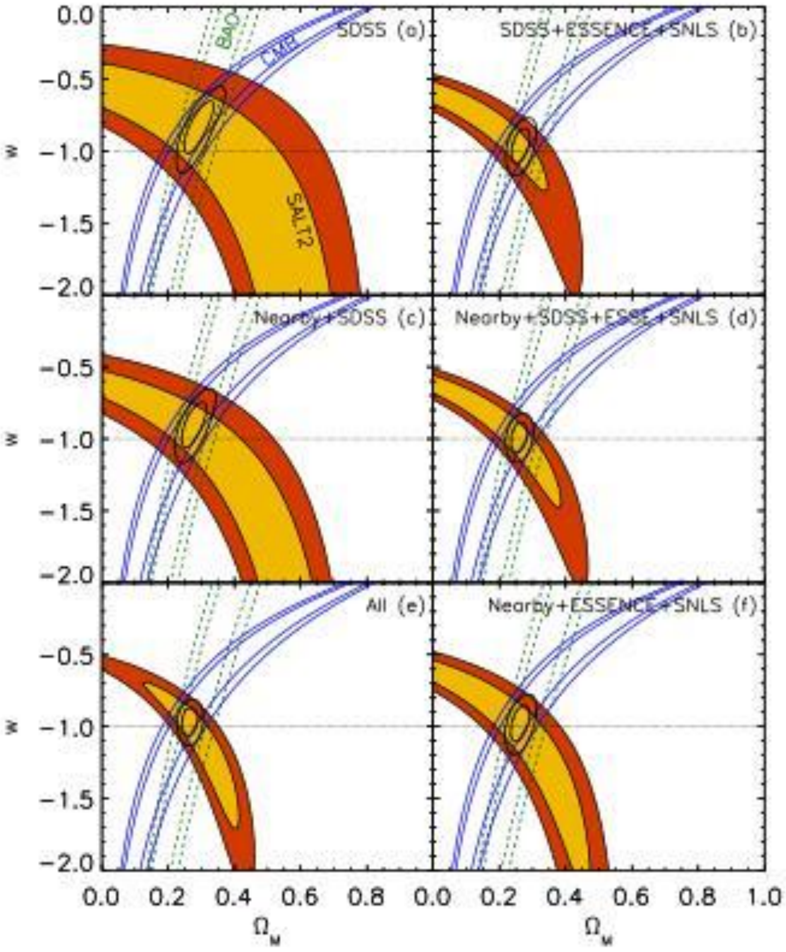
Supernova Cosmology Project, Suzuki et al. 2011



Planck 2015

The Universe is accelerating

If pressure is negative, $P = w\rho_E$ with $w < -1/3$ we can have accelerated expansion ($\ddot{R} > 0$) without a cosmological constant. Such a component is called dark energy. A cosmological constant corresponds to a dark energy component with $w = -1$.



The matter fraction and the parameter *w* of dark energy (Kessler et al. ’09).

Summary / outlook

- **Particle physics exploration started out with cosmic rays and we are still exploring that source!**
- Complementary searches particle physics and astro-particle physics
  - Similar techniques
  - Pros and cons of working ”directly” with the Universe

- Input from cosmology has huge implications for particle physics model building!

Exam info

- Pick up
  - **Monday March 14 at 10:00**

- Turn in:
  - **Wednesday March 16 at 10:00**

Learning outcomes

- The purpose of this course is to provide advanced knowledge of current aspects of experimental particle physics
  - Current status and challenges
  - Experimental programs current and future
  - Basic statistical methods in particle physics
- Students should also:
  - Learn to acquire scientific knowledge, including reading scientific papers
  - Improve their problem solving skills in the area
  - Improve communication skills, both written and oral