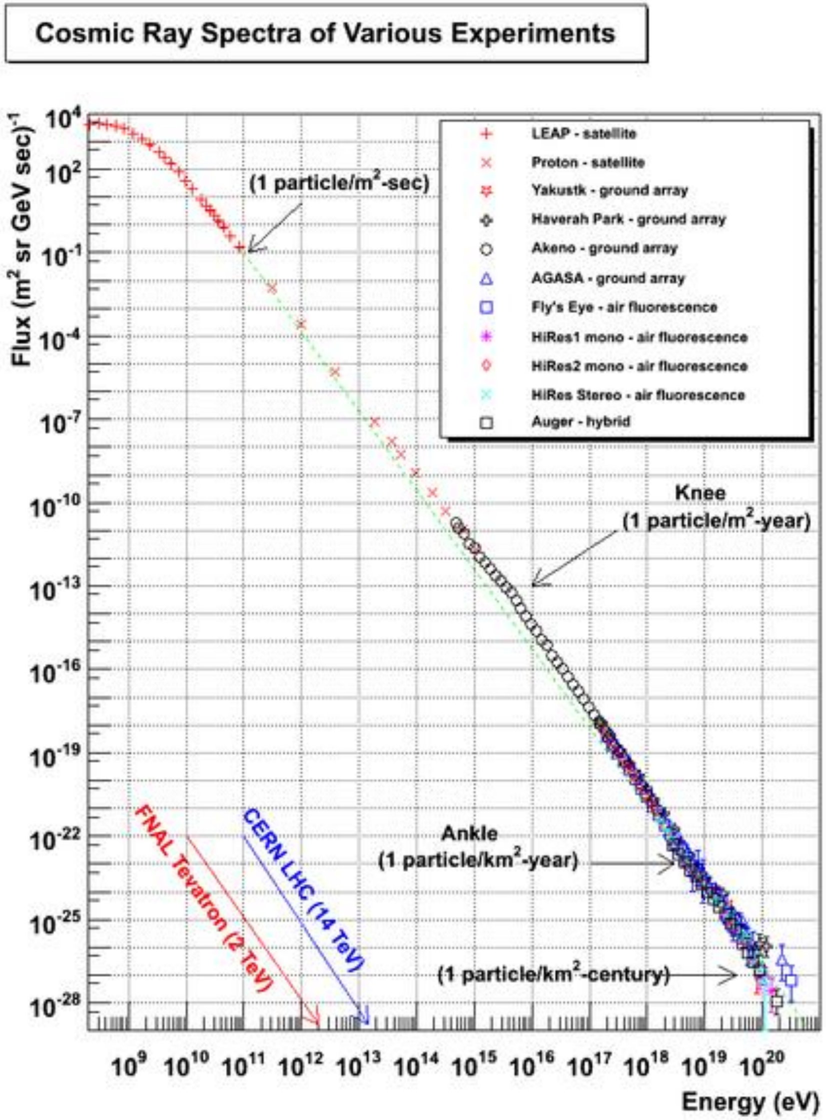
FYST17 Lecture 13
The cosmic connection

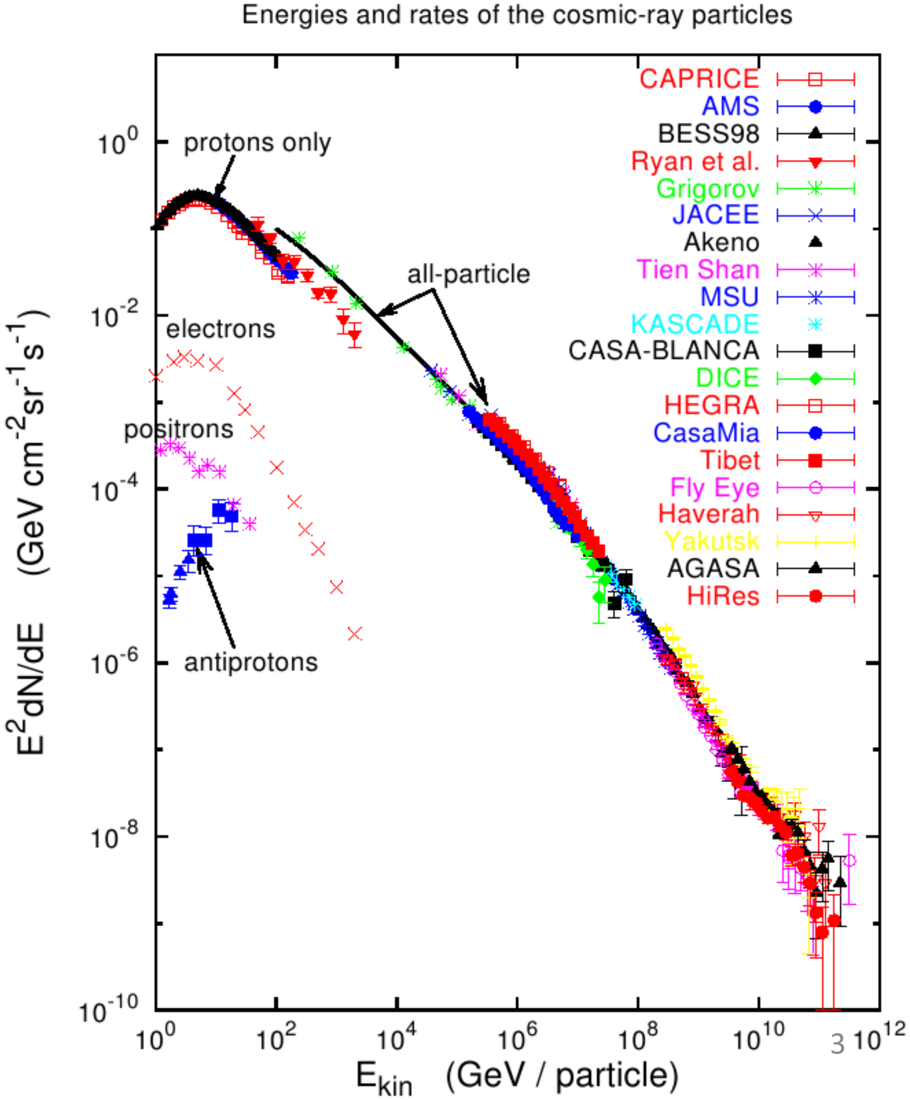
Thanks to R. Durrer, L. Covi, S. Sakar

Today’s outline

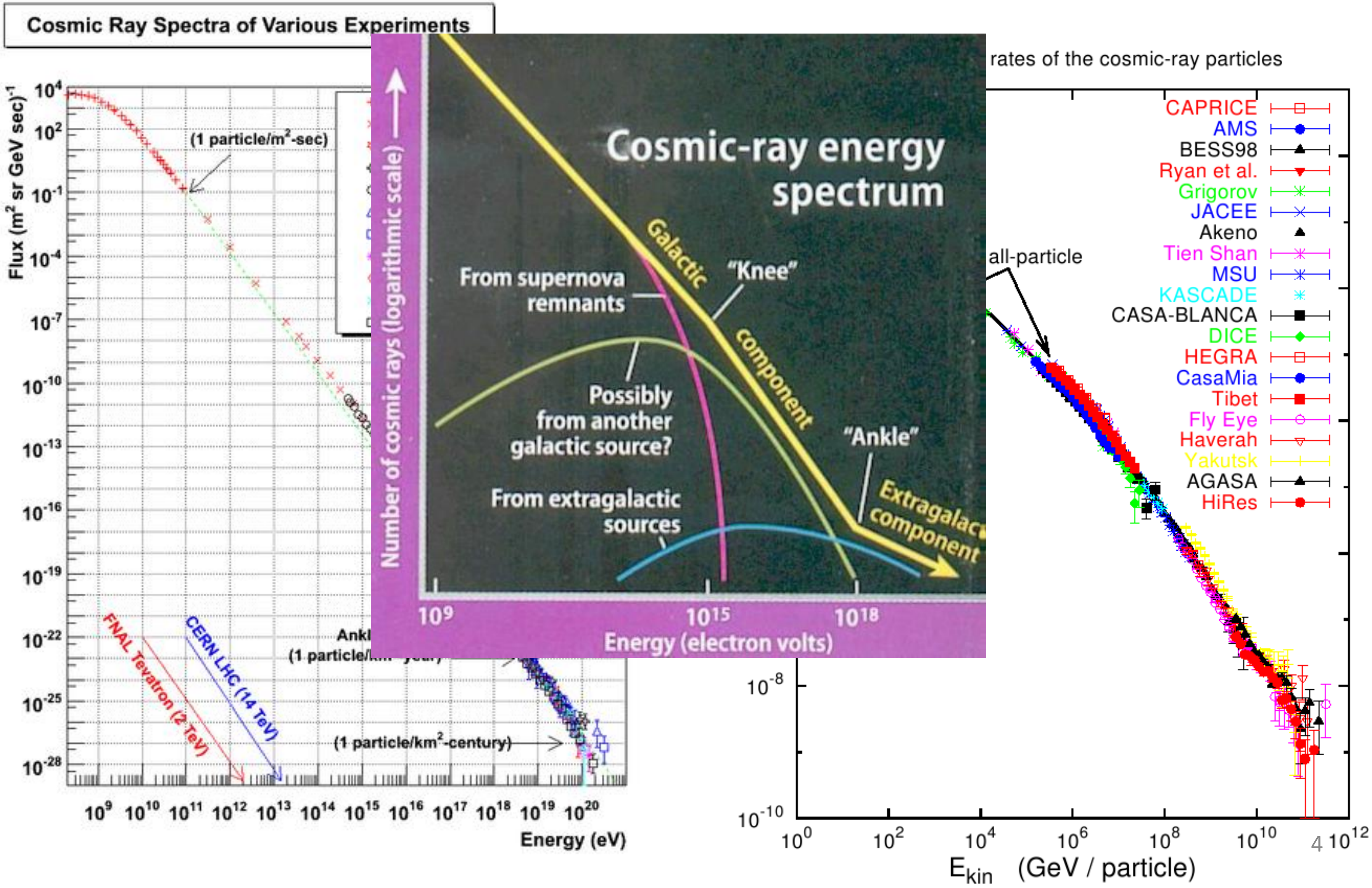
- High energy cosmic rays
  - GKZ cut-off
- Detectors in space
  - The PAMELA signal
- Some words on the expansion of the Universe
- Controversy
- Some words on the exam + evaluation

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^2dN/dE (GeV cm^-2sr^-1s^-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

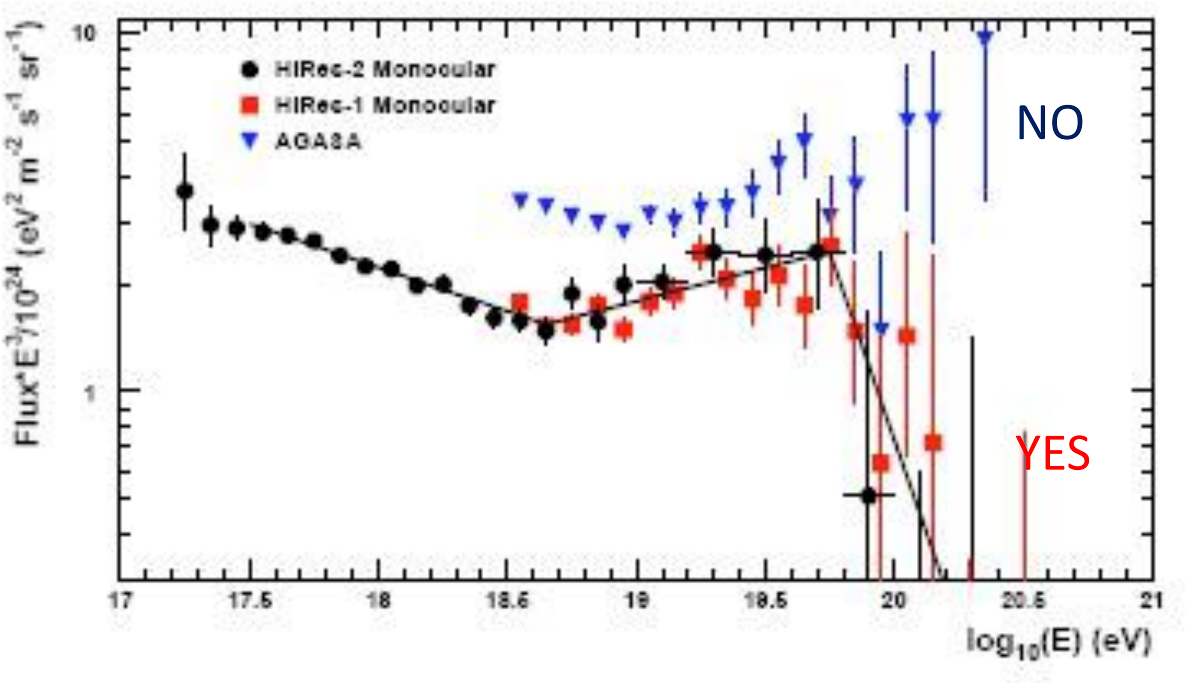
Cosmic rays


Cosmic Ray Spectra of Various Experiments
Flux (m^2 sr GeV sec)$^{-1}$
(1 particle/m^2-sec)
Ankl
(1 particle/km^2-year)
(1 particle/km^2-century)
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)
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
Extragalactic 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 5x10^{19} eV if they result from protons. (protons have to origin max 30 Mpc from our Galaxy)



NO

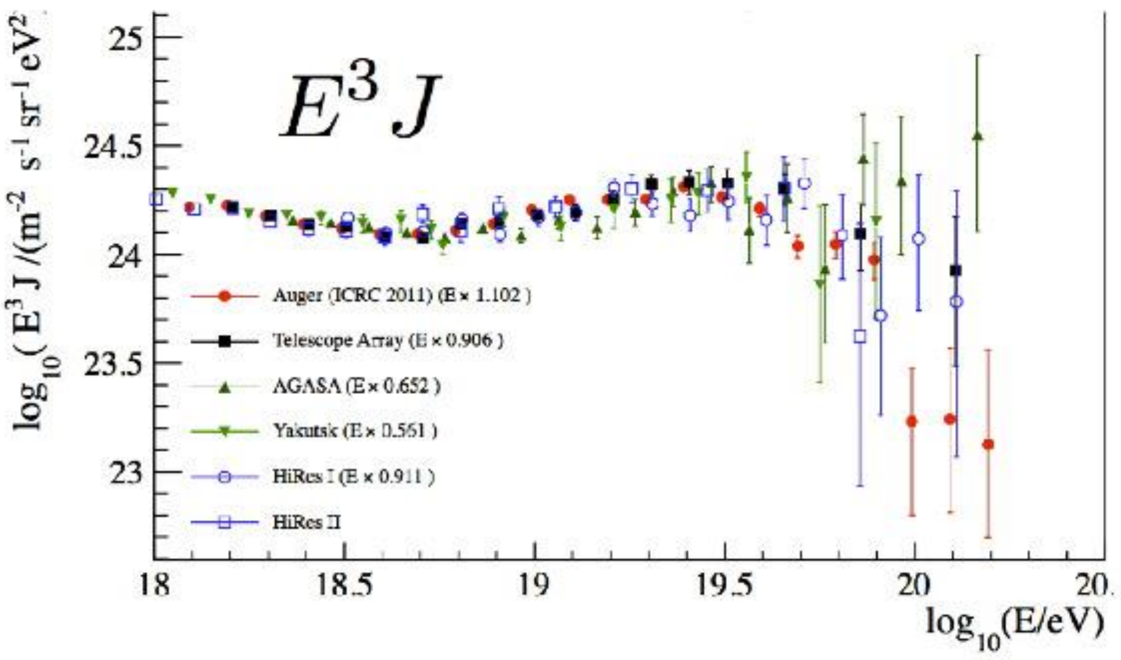
YES

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 .

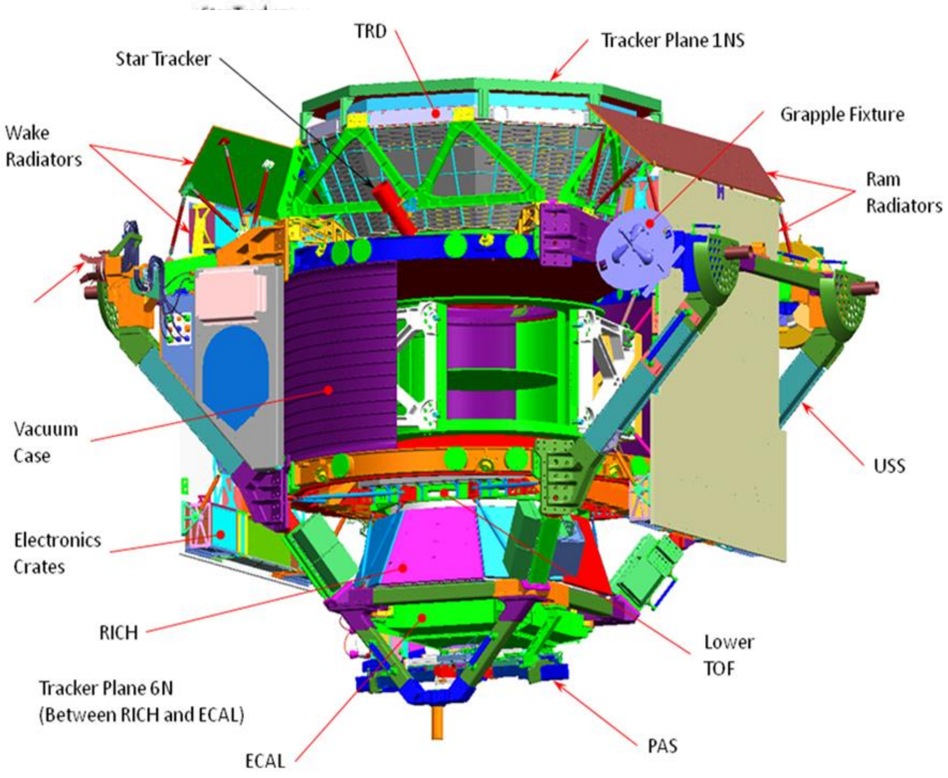
But GZK pions produce both photons and neutrinos – need spectrum for both!

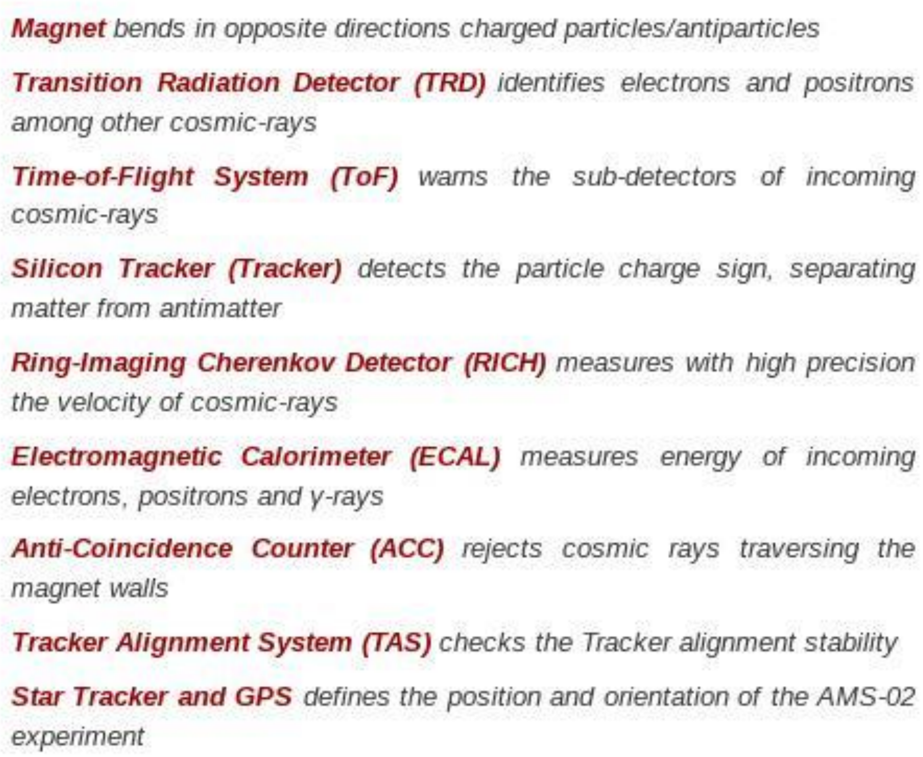


Working Group, UHECR2012

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

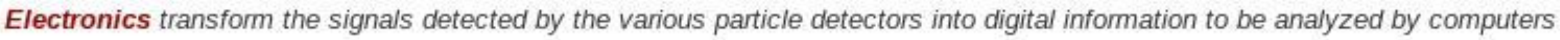
Ring-Imaging Cherenkov Detector (RICH) measures with high precision the velocity of cosmic-rays

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

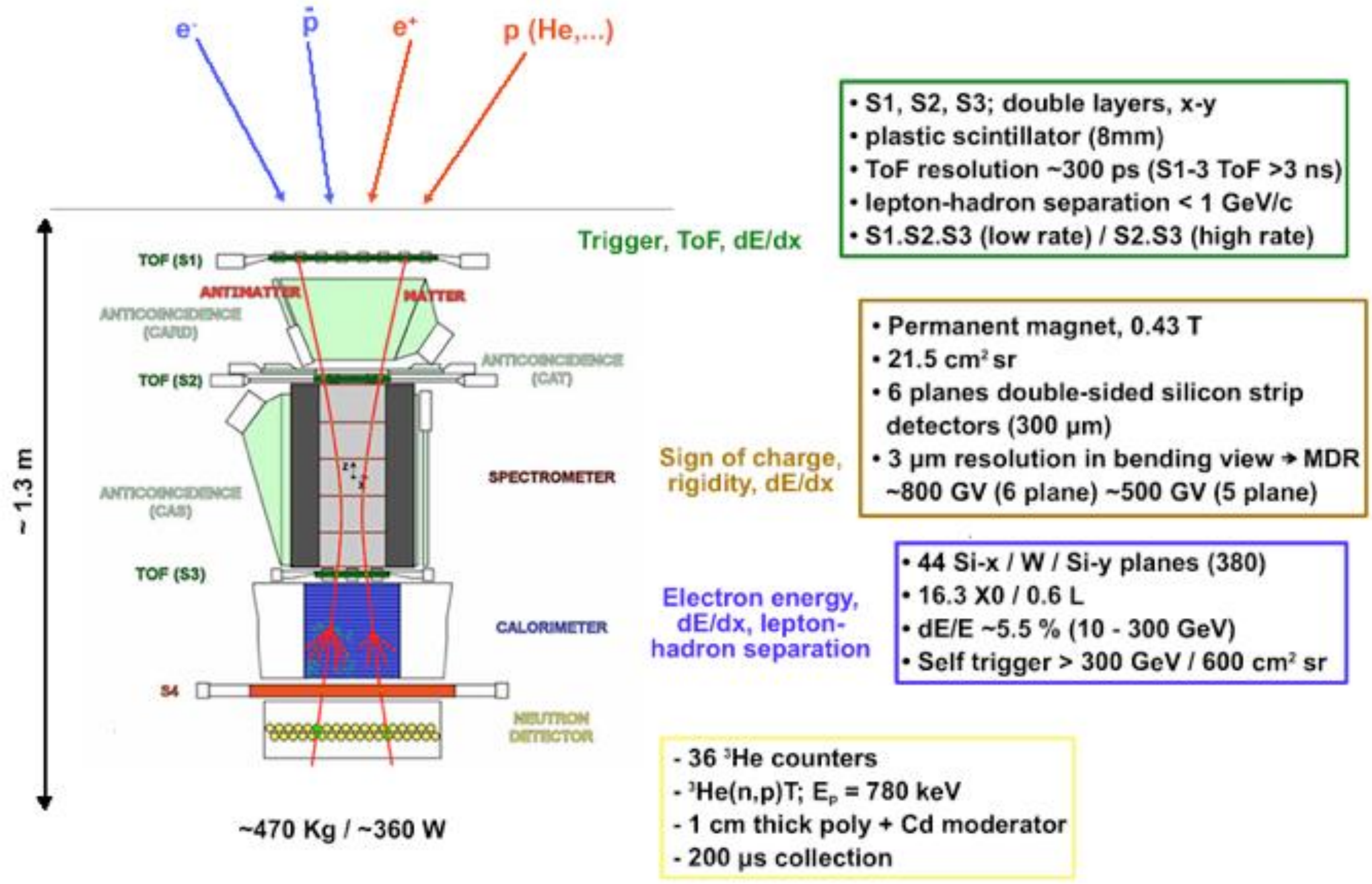
Anti-Coincidence Counter (ACC) rejects cosmic rays traversing the magnet walls

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)

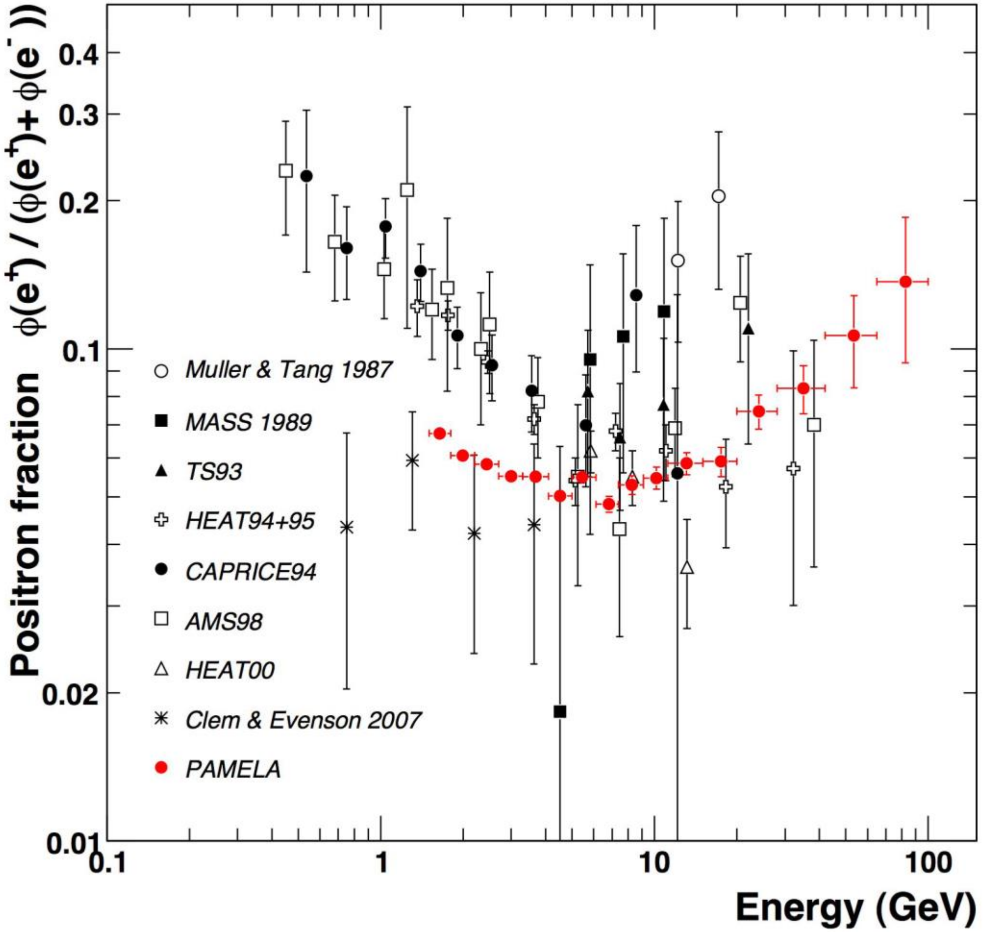
Electron energy, dE/dx, lepton-hadron separation

- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 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

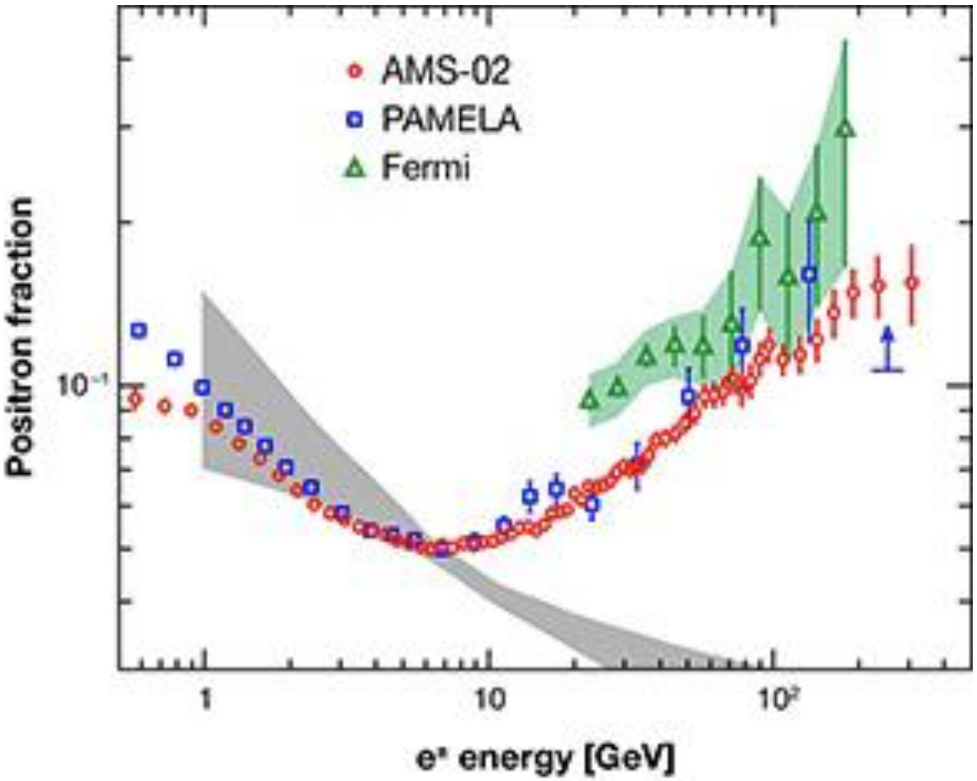
The PAMELA signal

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

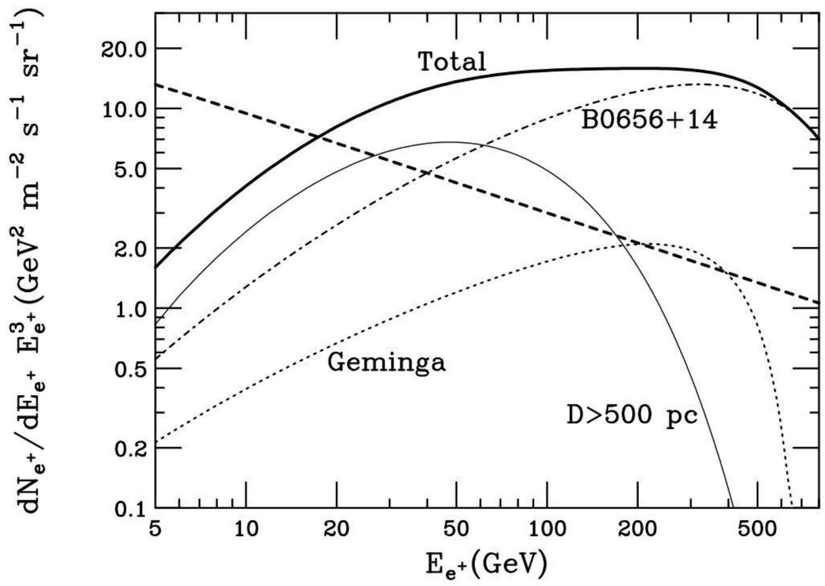


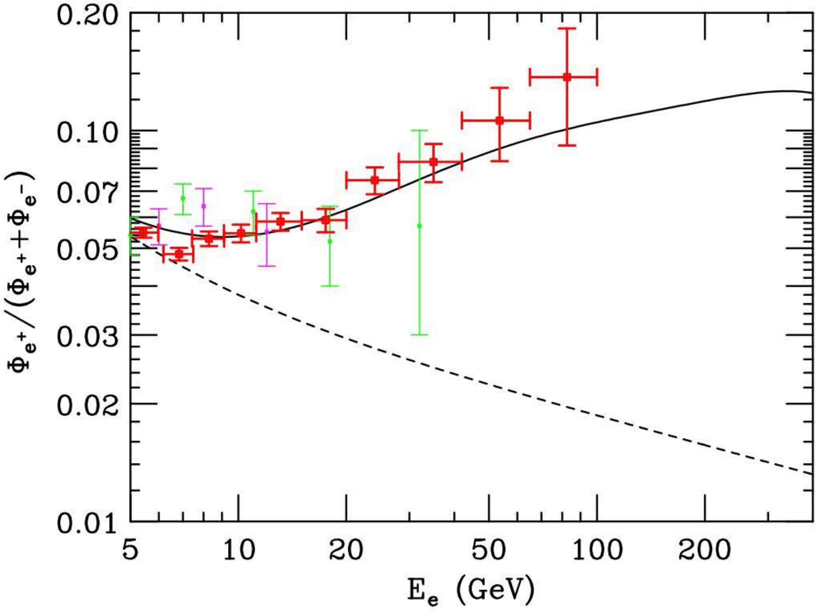
What is this? Need new source of positrons and not too far away

Is it perhaps from Dark matter annihilation?!!

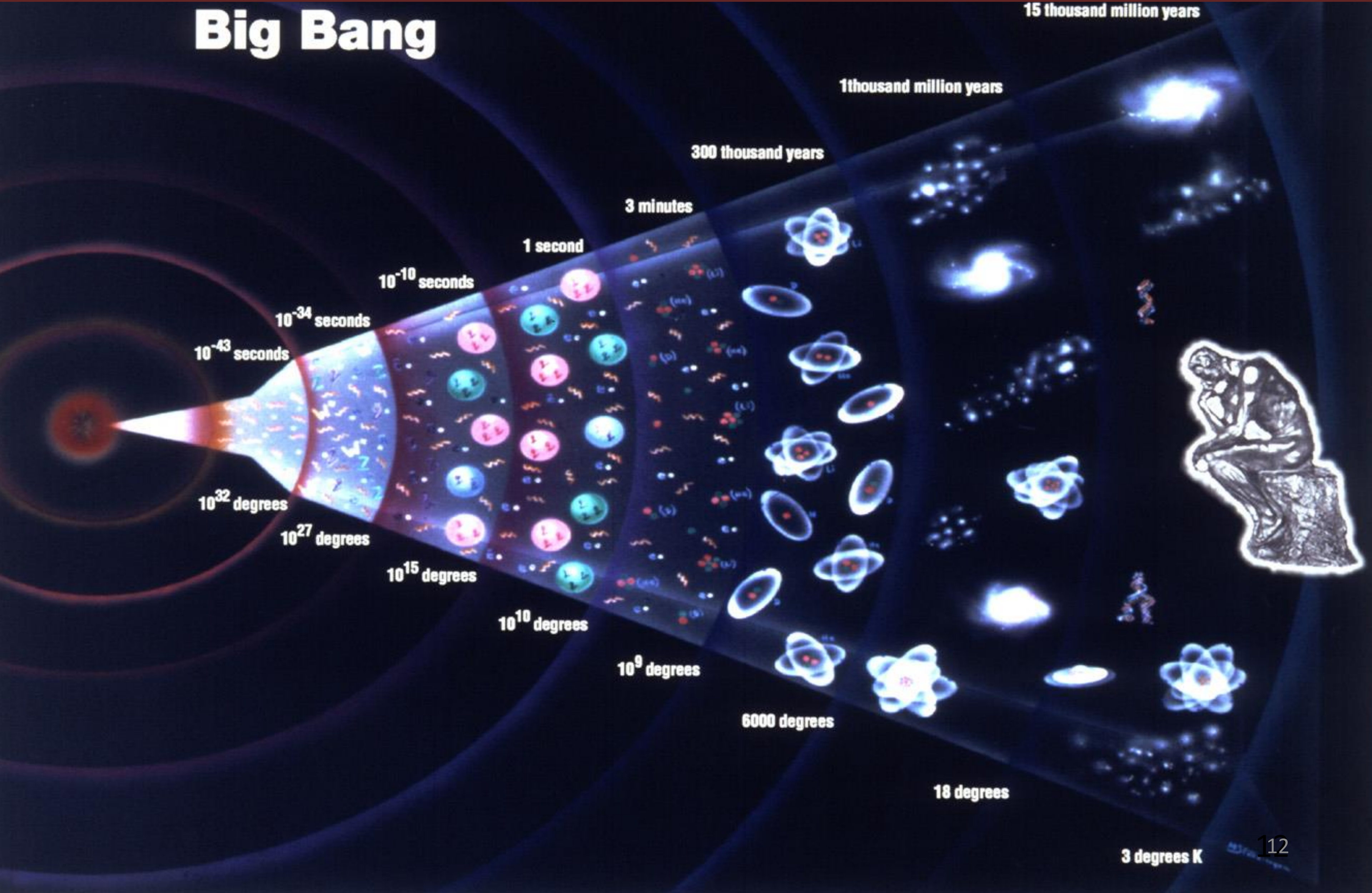
The positron excess

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



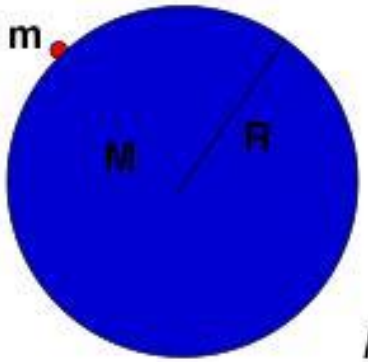


The expanding Universe



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

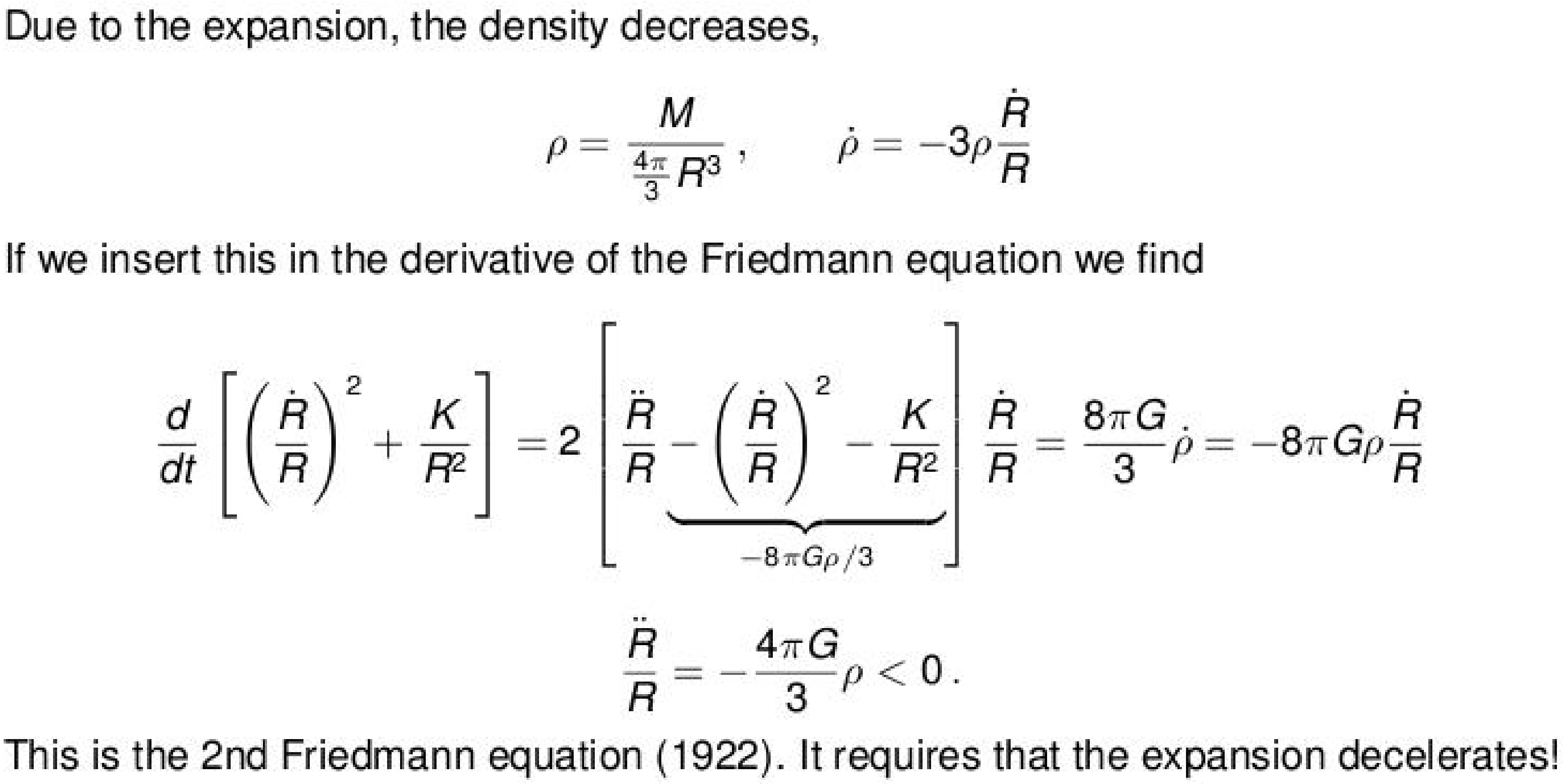
$$E = \frac{m}{2}v^2 + U = \frac{m}{2}v^2 - \frac{mMG}{R} = \frac{m}{2}v^2 - \frac{4\pi}{3}m\rho R^2 G$$

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:

$$\left(\frac{\dot{R}}{R}\right)^2 + \frac{K}{R^2} = \frac{8\pi G}{3c^2}\rho_E + \frac{\Lambda}{3}$$

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3c^2}(\rho_E + 3P) + \frac{\Lambda}{3}$$

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

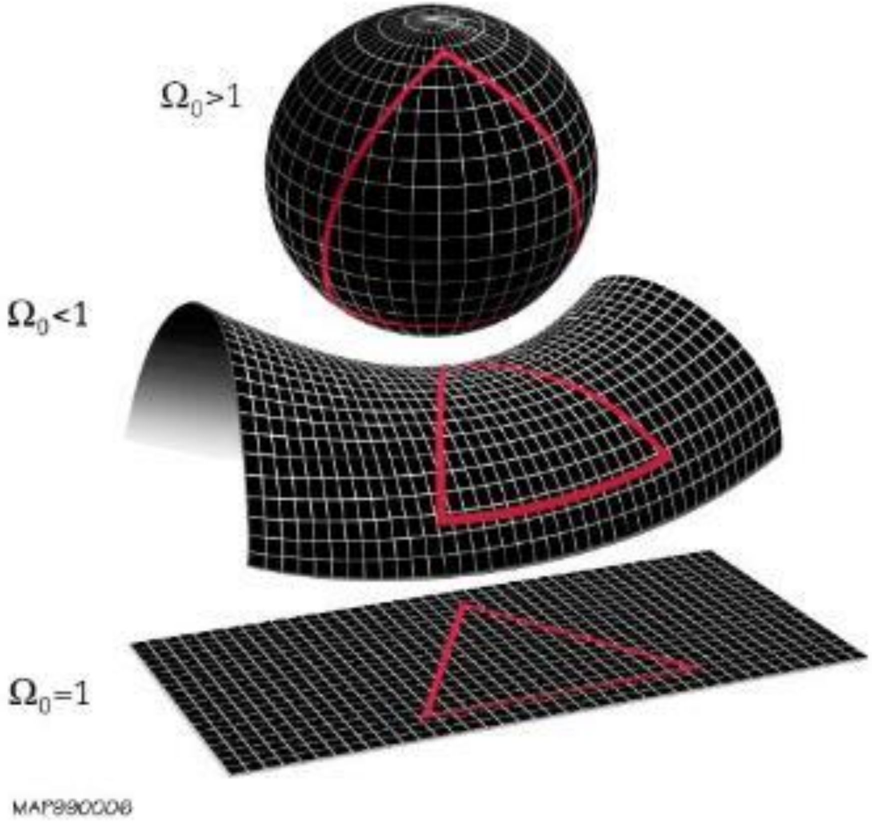
$$\Omega_m + \Omega_\Lambda + \Omega_K = 1\,.$$

Curvature

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

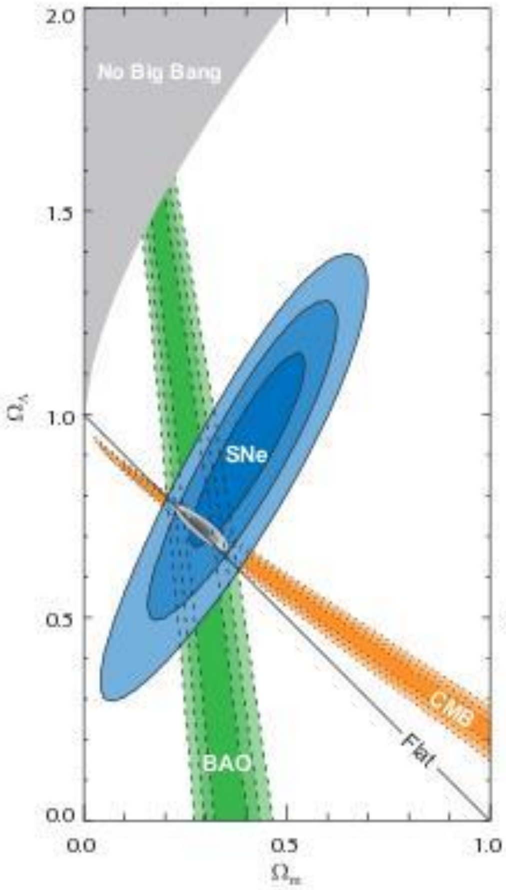
$K < 0$ ($\Omega_K > 0$): pseudo-spherical space (saddle),

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

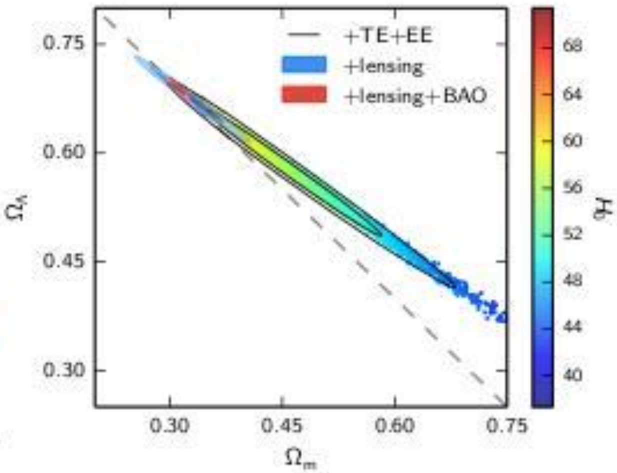


The Universe is accelerating

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



Supernova Cosmology Project, Suzuki et al. 2011

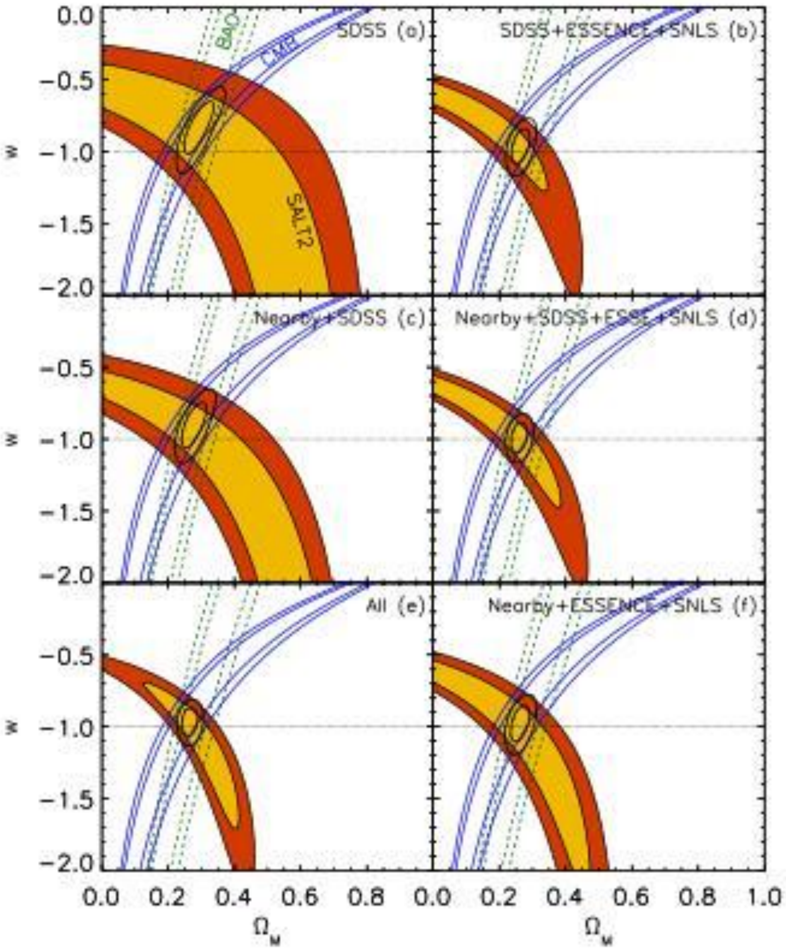


Planck 2015

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).

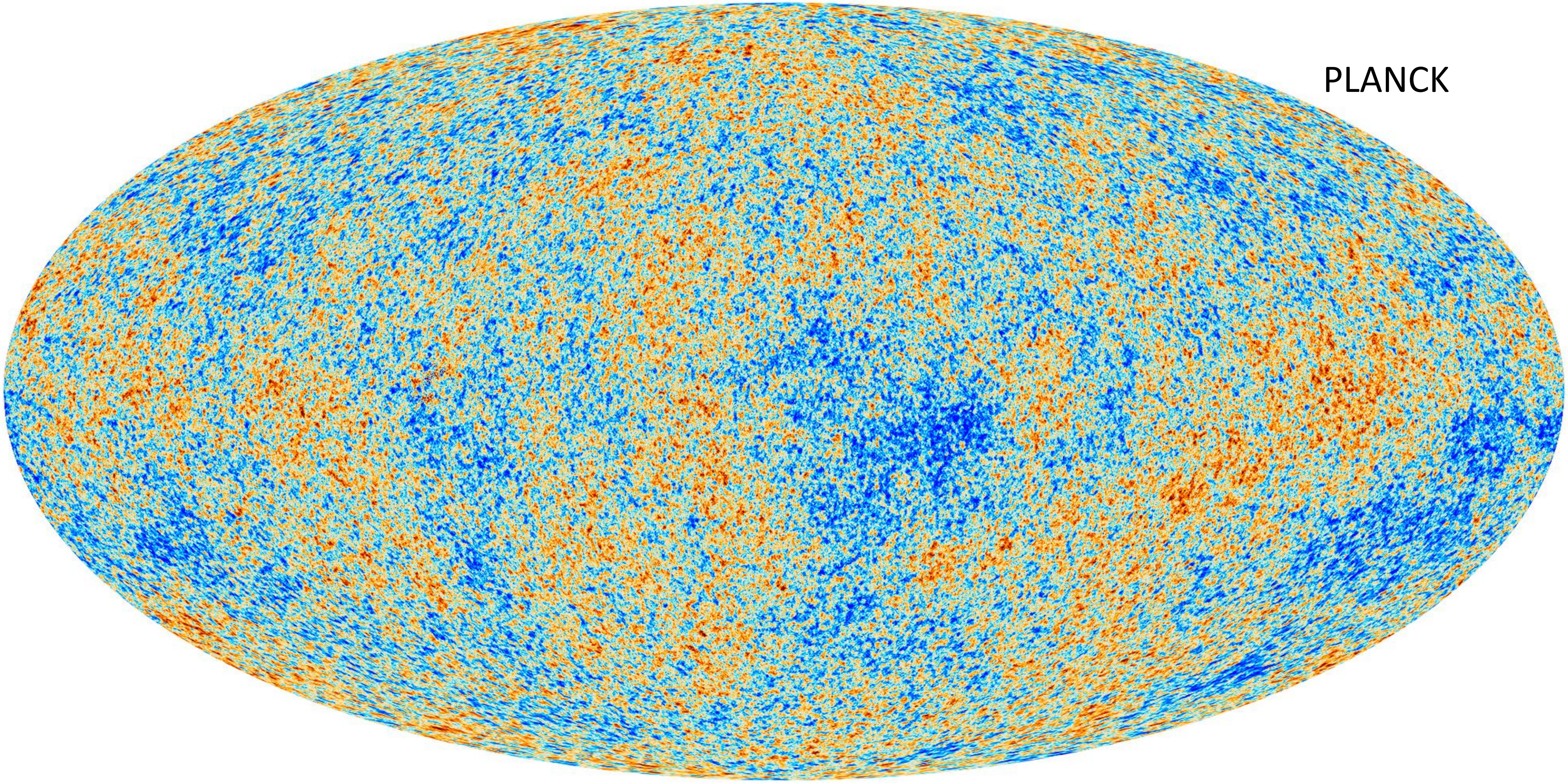


Cosmic Microwave Background

Remnant photons from when the Universe became transparent to radiation

Small fluctuations at particle levels boosted into galaxy-scale structures by inflation

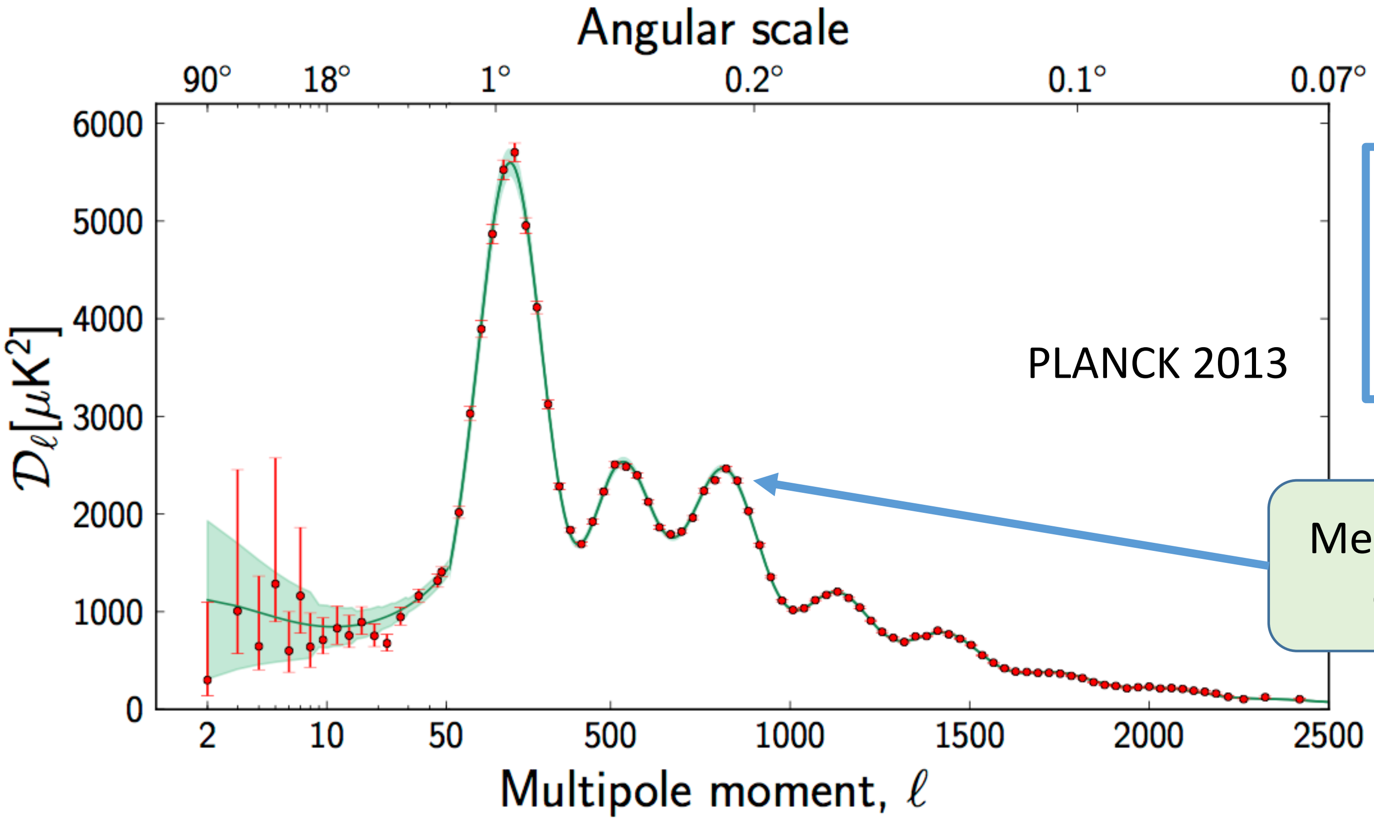
Cosmic Microwave Background


PLANCK

The sound of the CMB

CMB photons behaves like gas, carry sound waves caused by gravity (seen as hot and cold spots in the sky map)

Big gravitational events, like inflation, should be audible in the spectrum. Inflation predicts a set of harmonics with frequency ratios of 1:2:3

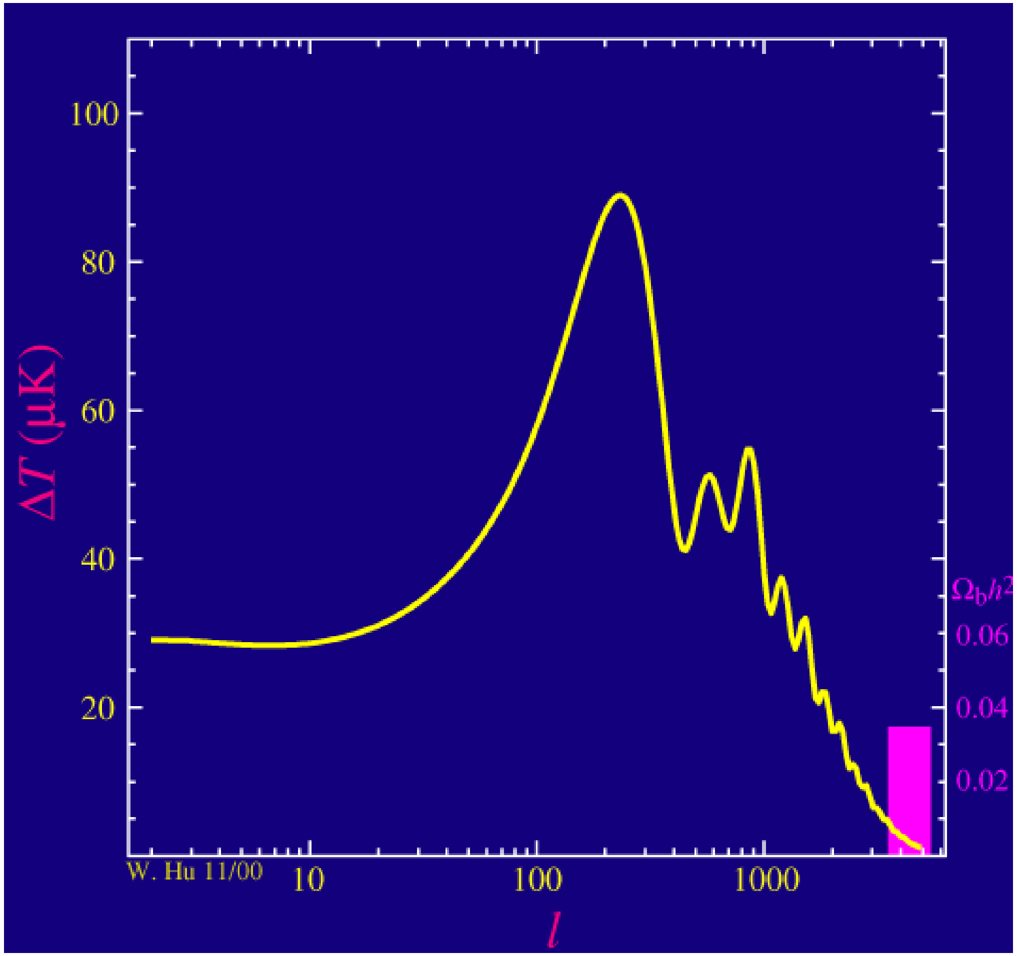


PLANCK 2013

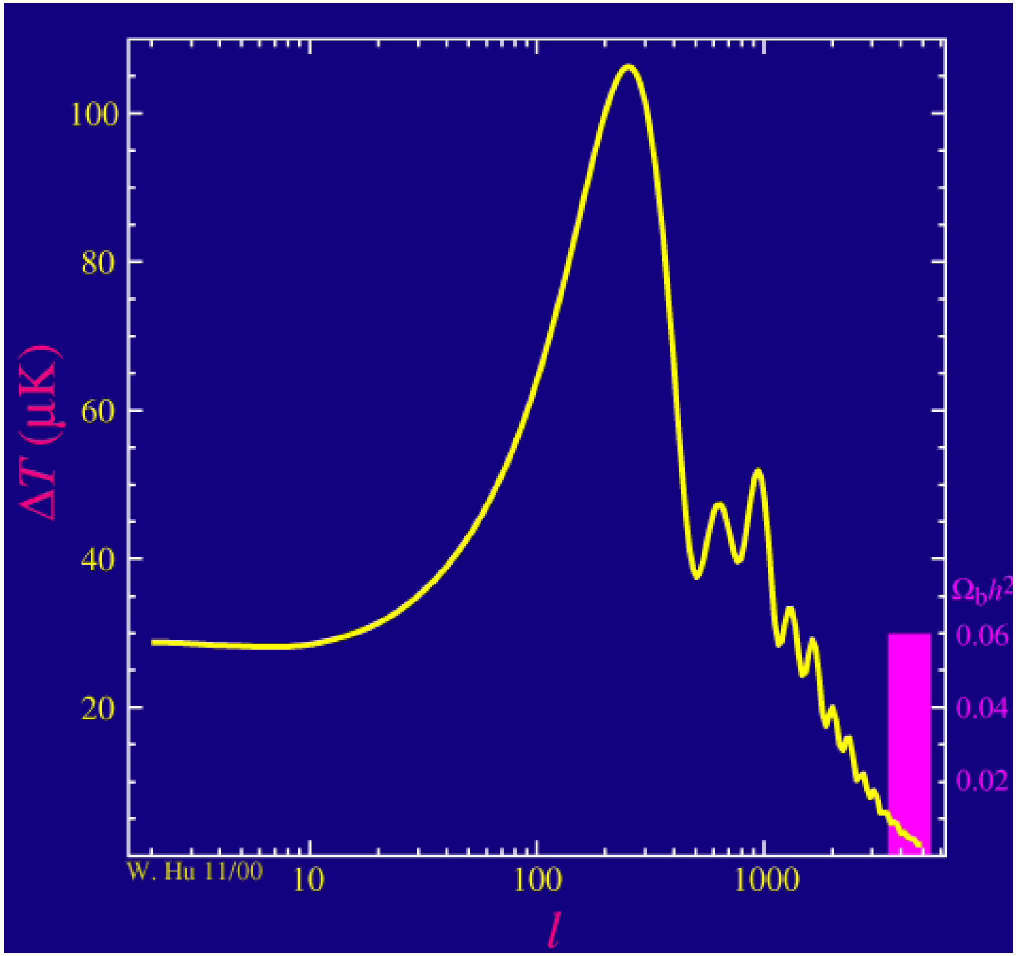
Dark Energy barely affects this picture
Dark Matter mainly indicated in 3rd peak

Measure physical density of the Dark Matter

Peak amplitudes sensitive to baryon density



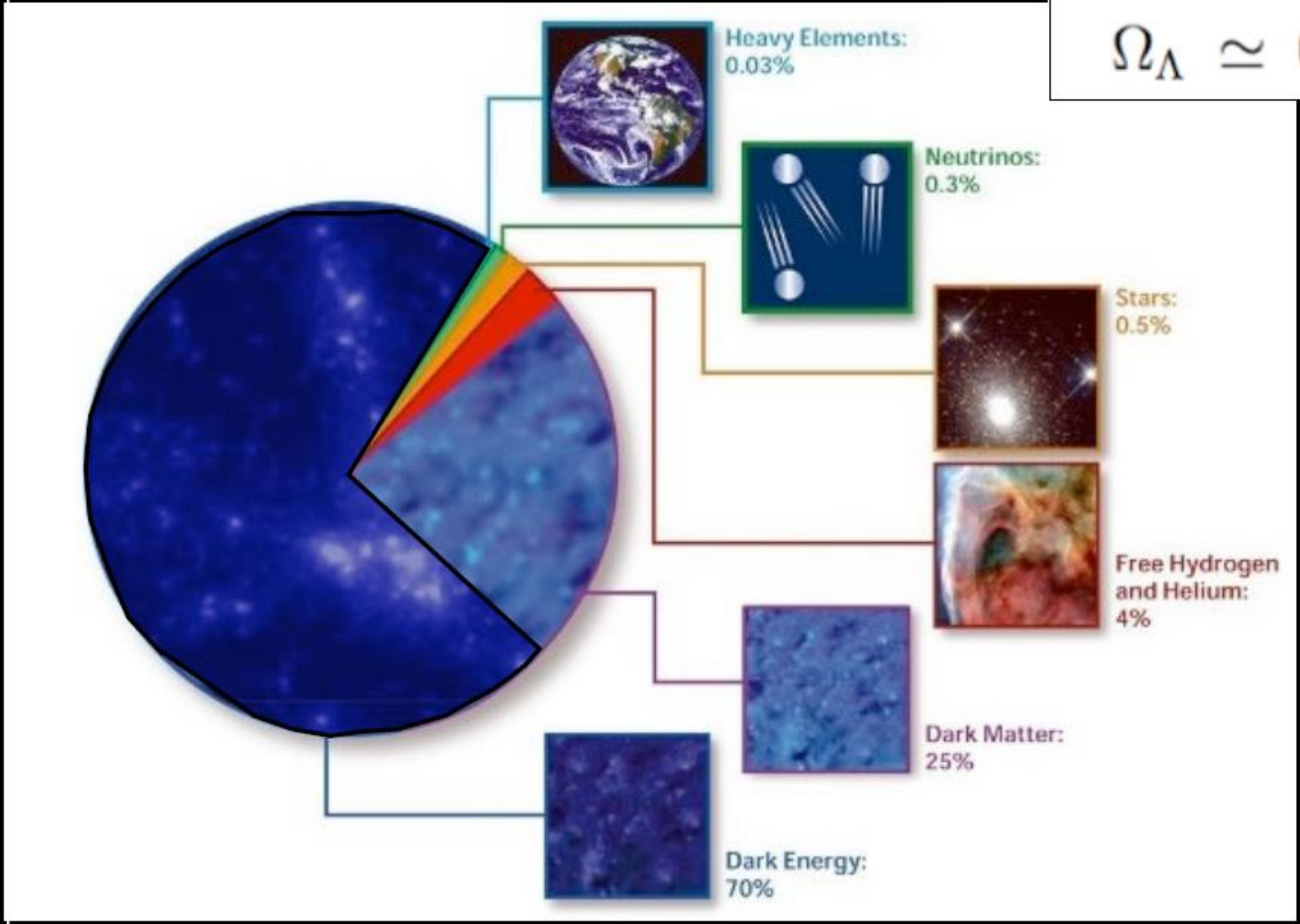
Peak amplitudes sensitive to baryon density



The Standard Model of Cosmology

$$\begin{aligned}\Omega_{\rm B} &\simeq 0.0456 \pm 0.0016\\ \Omega_{\rm DM} &\simeq 0.227 \pm 0.014\\ \Omega_{\Lambda} &\simeq 0.728 \pm 0.015\ .\end{aligned}$$

E. Komatsu et al., Astrophys. J. Suppl 192 (2011) 18



Dark Matter is ~23% of the universe.

Controversy

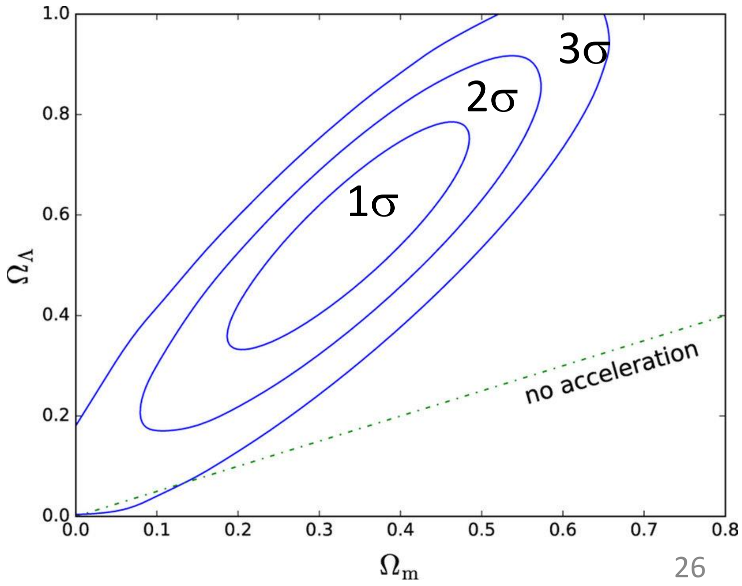
(as seen by a non-expert)

How well do we know what we know about Dark Energy?

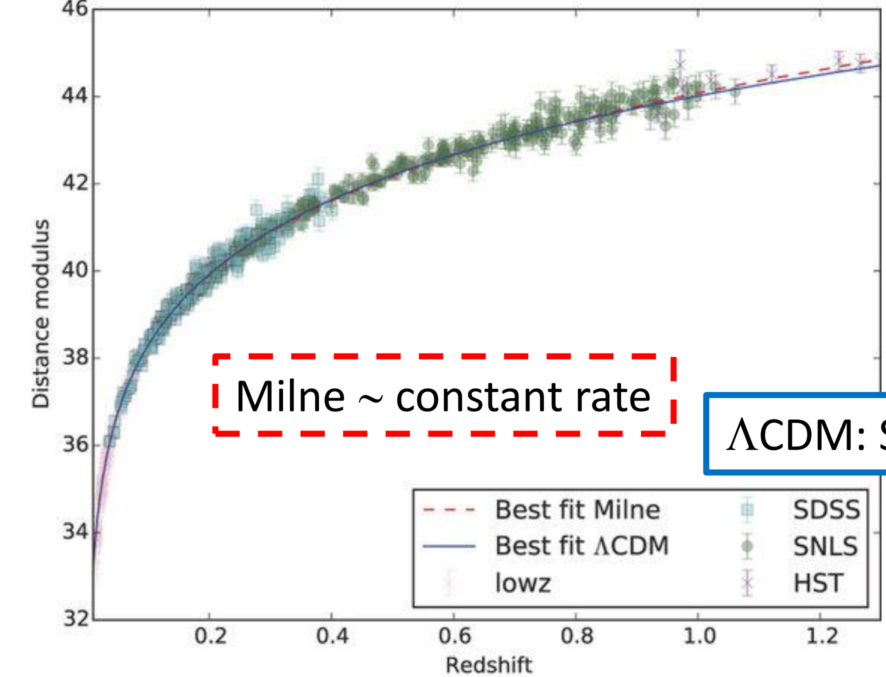
- Paper by S. Sakar et al [Nature Scientific reports 6:35596] claims that the evidence for Dark Energy is in fact less than 3 σ
  - e.g. constant acceleration rate not yet excluded!
- Original analysis used Type Ia supernovae as "standard candles". Main argument against is that nowadays there are many more of these known $\Rightarrow$ one can use more rigorous statistical methods instead of assuming all have the same light profile.
- New analysis use maximum likelihood estimator to get best fit to the (now large) dataset

$$p_{\mathrm{cov}} = \int_0^{-2\,\log\,\mathcal{L}/\mathcal{L}_{\max}} f_{\chi^2}(x;\nu)\,\mathrm{d}x,$$

(where f is pdf of χ^2 random variable with ν degrees of freedom)

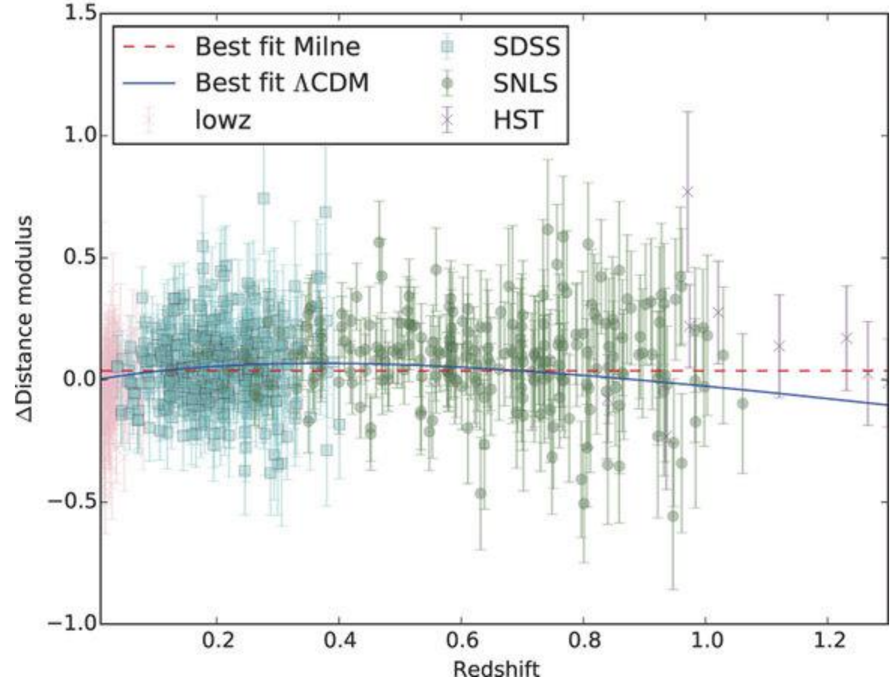


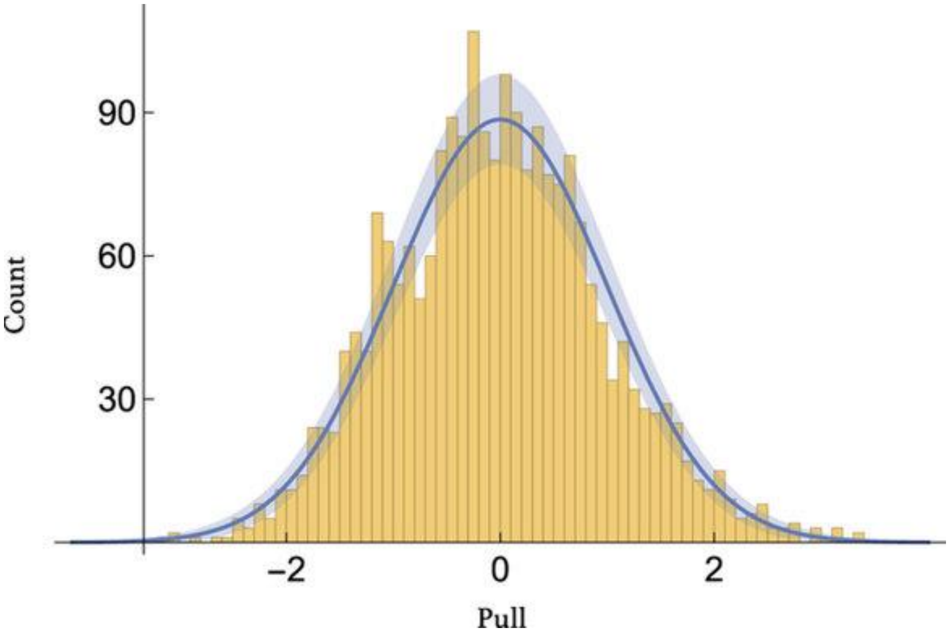
Looking closer at the data



Milne ~ constant rate

ΛCDM: SM cosmology with accelerating rate





Distribution of pulls (normalized residuals) for the best fit model compared to a Gaussian

Conclusion?

Other people working on the statistics argument

– some still see $> 3\ \sigma$

No official resolution yet. Other evidence for accelerating expansion means that mainstream community still prefers Dark Energy hypothesis

To resolve it:

More data $\Rightarrow$ better understanding of the light profile of Type Ia SN

Several experiments ongoing (for instance CODEX) that should be sensitive to this

Alternatives to Dark Matter?

Can other models do what dark matter can?

According to E. Verlinde [arXiv 1611.02269] can attribute gravity effects of DM to effects of dark energy :

ordinary matter ↔ dark energy

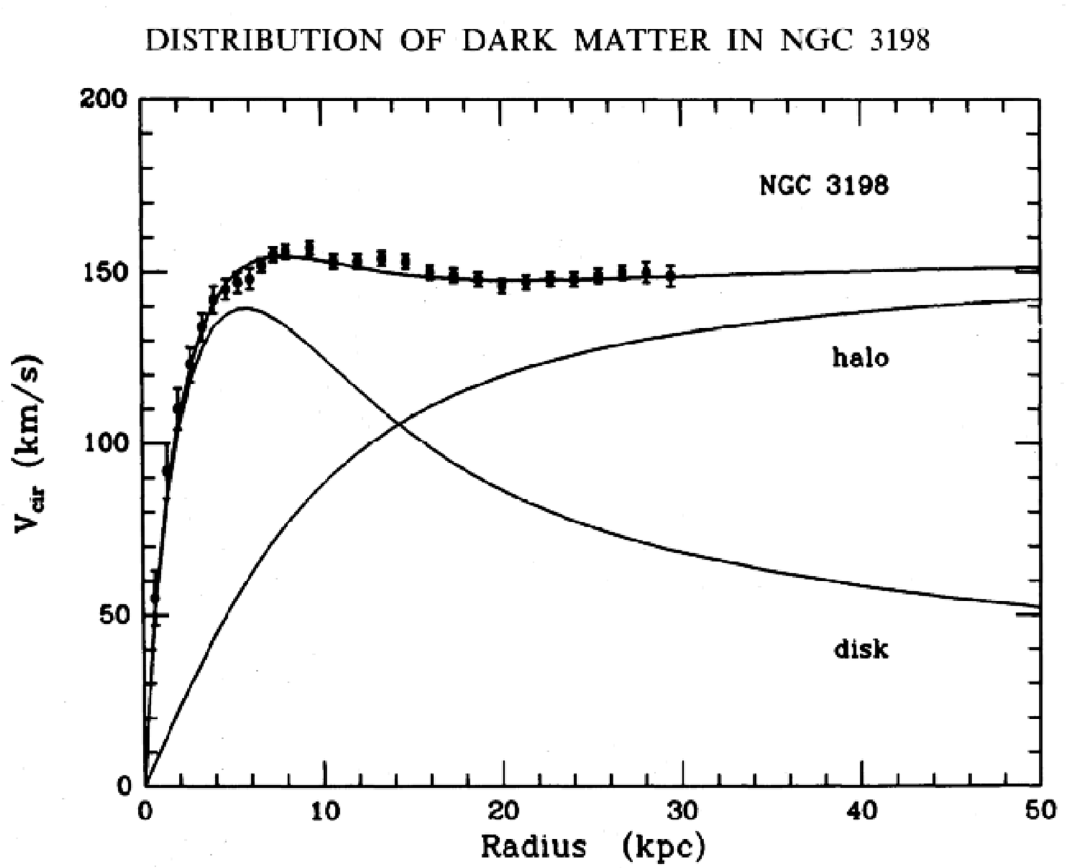
"Emergent gravity"

Other models have challenging DM hypothesis: for instance modified Newtonian gravity (MONDs)

- Assume changes to gravitational acceleration for small accelerations.
- Experimental tests (testing gravity in the laboratory!) have not yet confirmed nor excluded MOND
- Other possibilities: G is time-dependent: Yukawa mass terms for low values of a

What is actually the evidence?
A few examples

Rotational curves



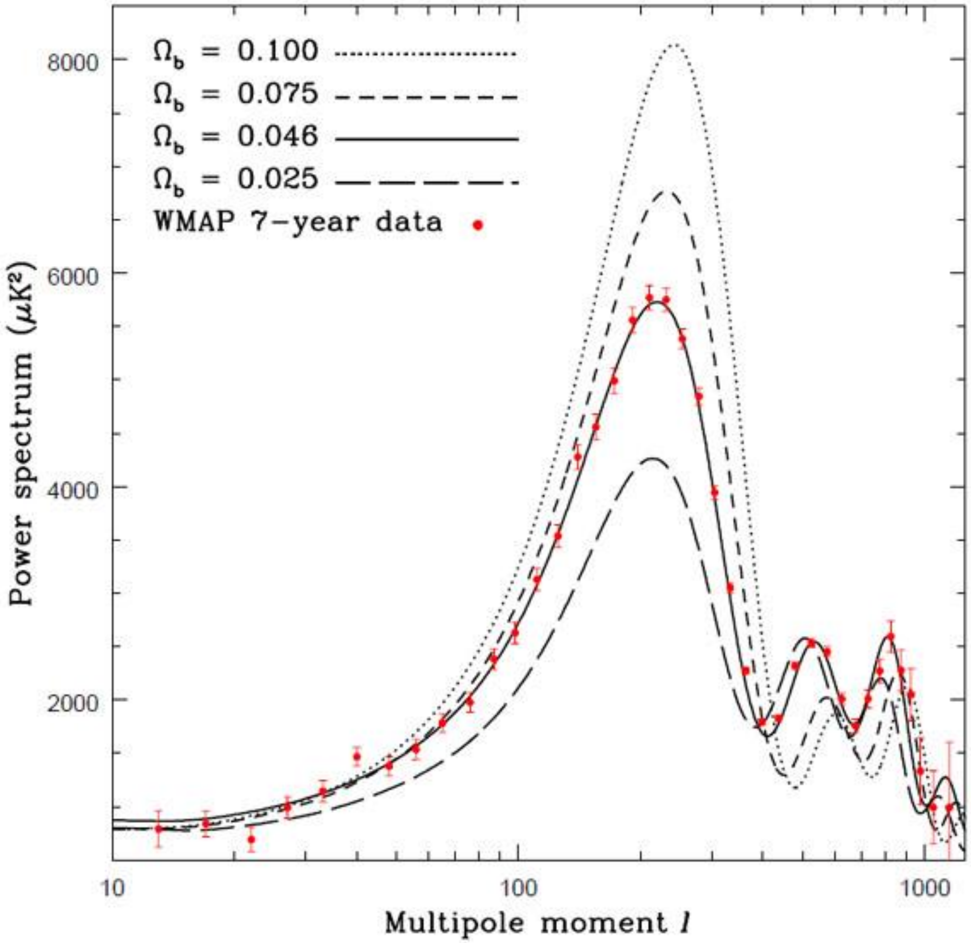
Hypothesis	explained
Dark Matter	y
MOND	partial
EmGrav	Y

The “bullet cluster” and similar

(NASA/Chandra/Magellan/Hubble)

Hypothesis	**explained**
Dark Matter	y
MOND	no
EmGrav	not yet?

CMB oscillations



Hypothesis	explained
Dark Matter	y
MOND	no
EmGrav	not yet?

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
- As far as I can tell, dark matter and dark energy are still the best hypotheses given the data
  - We really don’t know enough about gravity
  - But indeed, more data would help!
- **Input from cosmology has huge implications for particle physics model building!**

Exam info

- 5 exercises whereof
  - At least 1 on HI
  - At least 1-2 on relativistic kinematics
  - At least 1 on statistical methods
- Pick up
  - **Tuesday March 14 at 11:00 A426**
- Turn in:
  - **Thursday March 16 at 11:00 A426**
  - *Electronic version by email also ok – but make sure you receive a confirmation of reciept from me!*

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