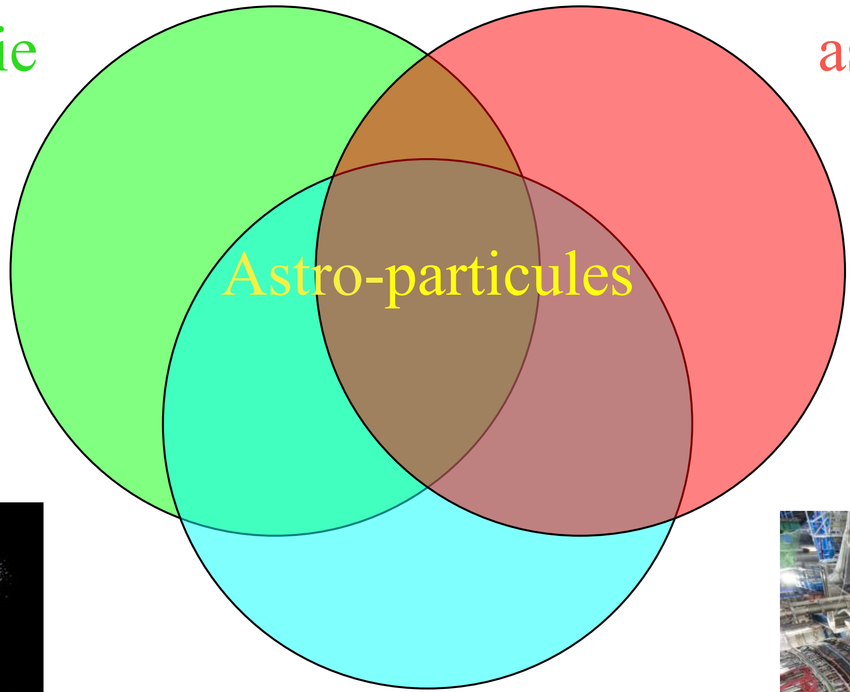
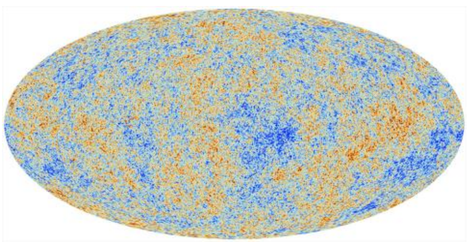
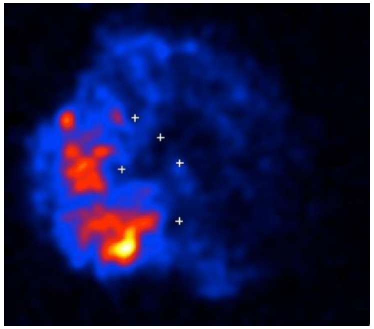
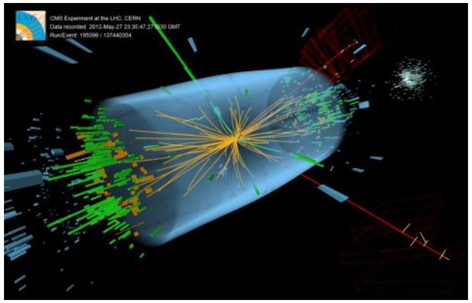
# Introduction à la physique des astro–particules

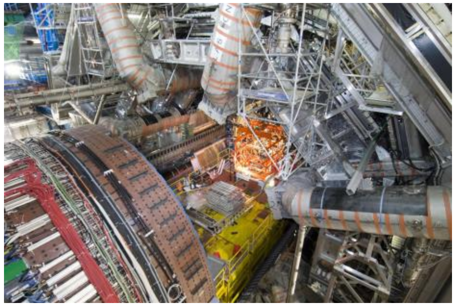
Pierre Salati – Université de Savoie & **LAPTH**





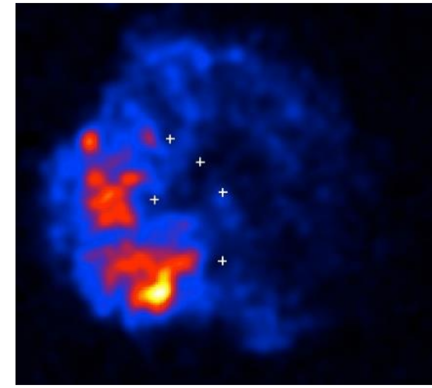




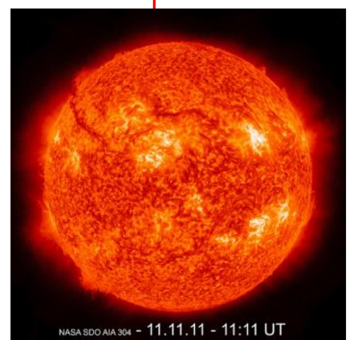
Société Française de Physique – Les deux infinis – Marseille le 2 juillet 2013

# Discipline fille de plusieurs champs de recherche

## Arbre généalogique



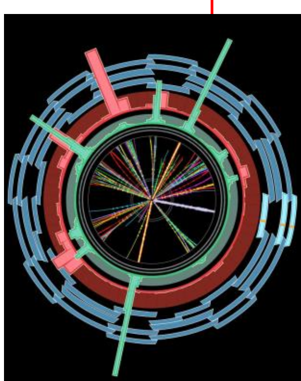
sources stellaires

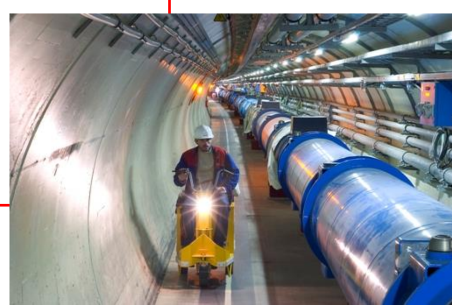


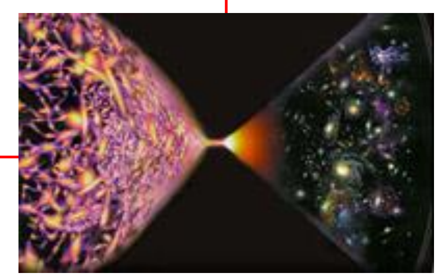

rayons cosmiques

cosmologie & big–bang

accélérateurs







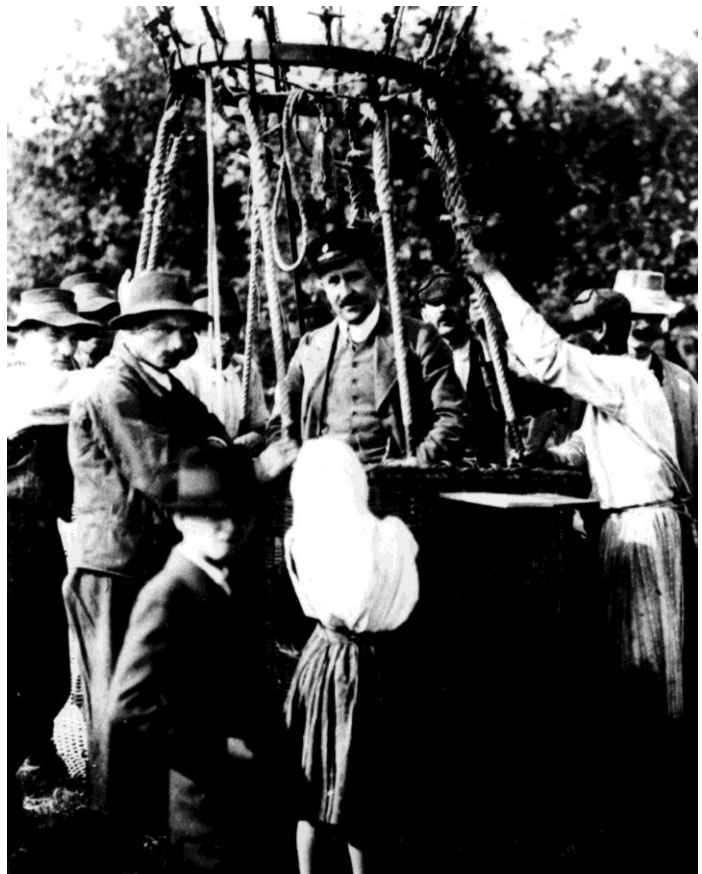
astrophysique des particules

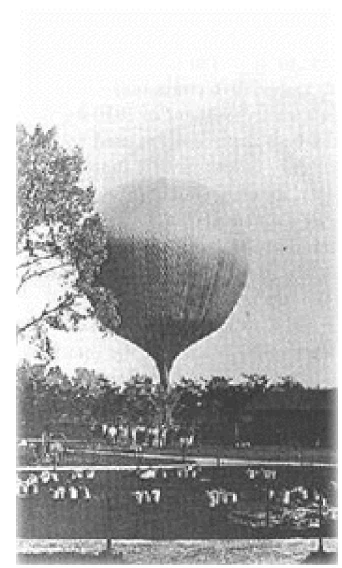
# Cosmic rays

- **1736-1806** – Charles Augustin de Coulomb observes that a sphere initially charged and isolated loses its electric charge. No explanation at the time.

- **1900** – C.T.R. Wilson discovers the continuous atmospheric ionization. It is believed to be due to the natural radiation of the Earth.

- **1911 to 1912** – V.F. Hess measures the atmospheric ionization with electroscopes during balloon flights at various altitudes. The ionization **increases**.





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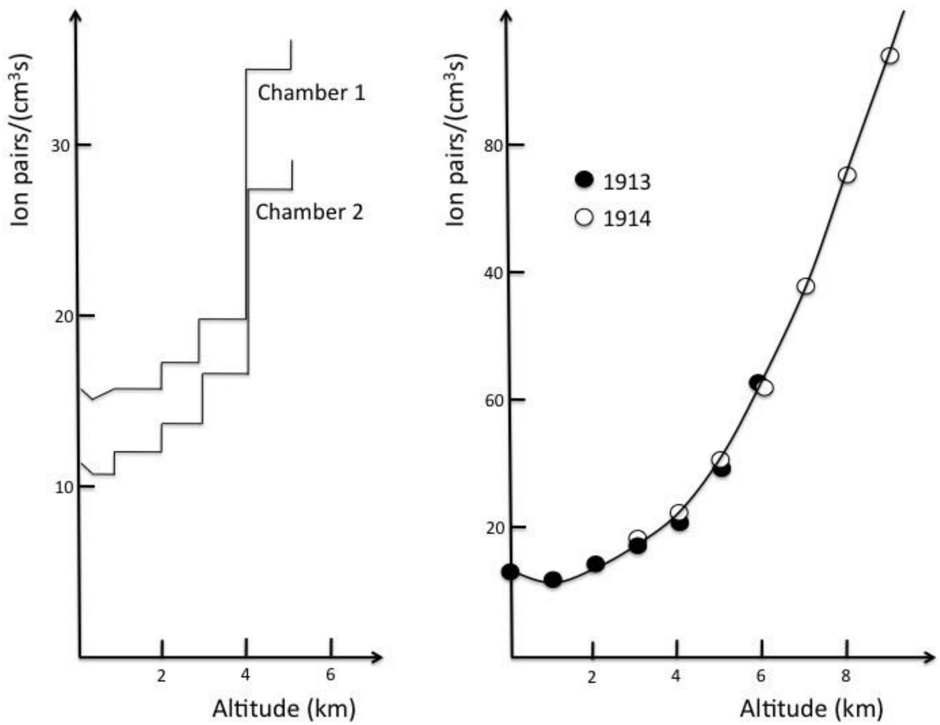
- **1914** – These results are confirmed and extended by W. Kolhörster with flights up to an elevation of 9200 meters.



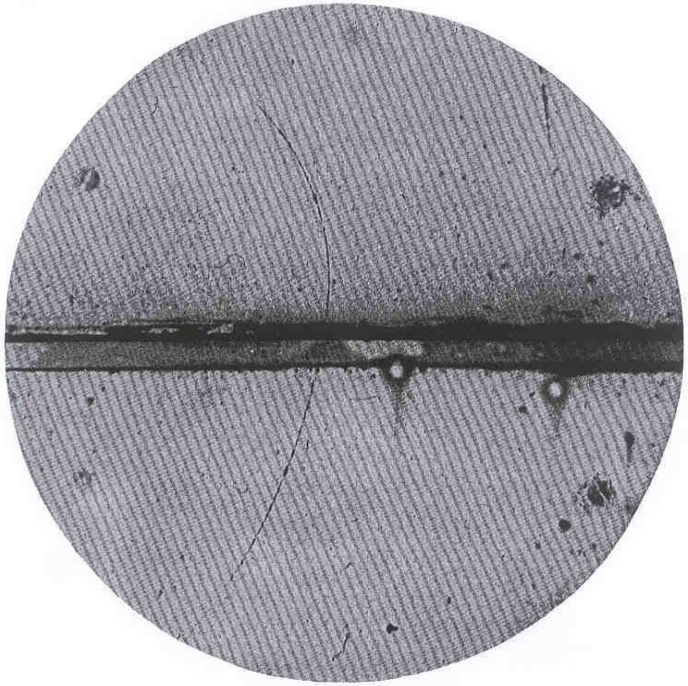
# Cosmic rays and particle physics

- **1928** – P.A.M. Dirac finds a relativistic wave equation which describes the electron within the framework of quantum mechanics.

- **May 1931** – P.A.M. Dirac makes a small step forward.

*"A hole, if there were one, would be an entirely new kind of particle, unknown to experimental physics, having the same mass, and opposite charge of the electron."*

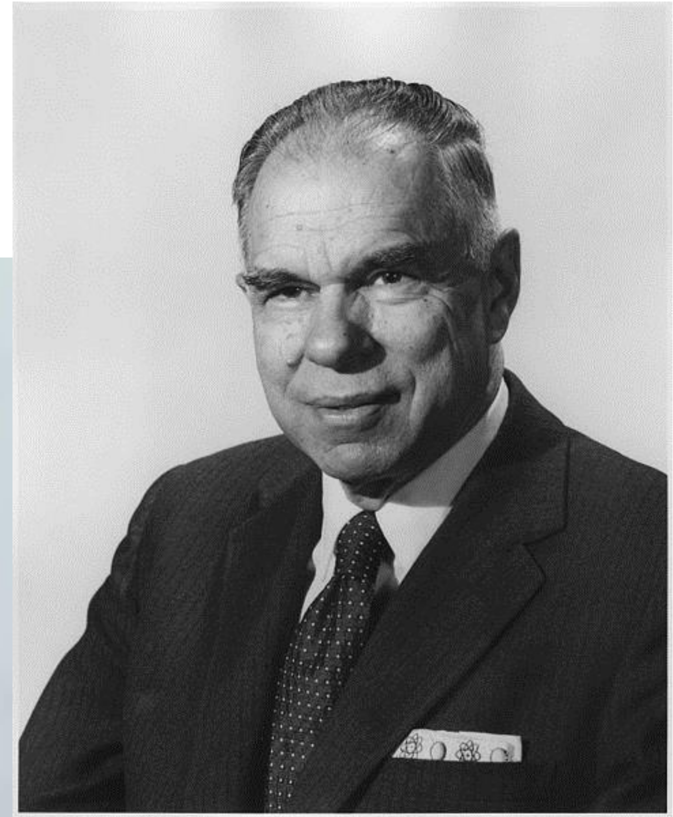
- **August 1932** – C.D. Anderson discovers the positron in the cosmic radiation. He publishes his work in February 1933.



Cosmic rays are replaced by accelerators where particles are artificially produced

Five inch cyclotron held by Glenn Seaborg

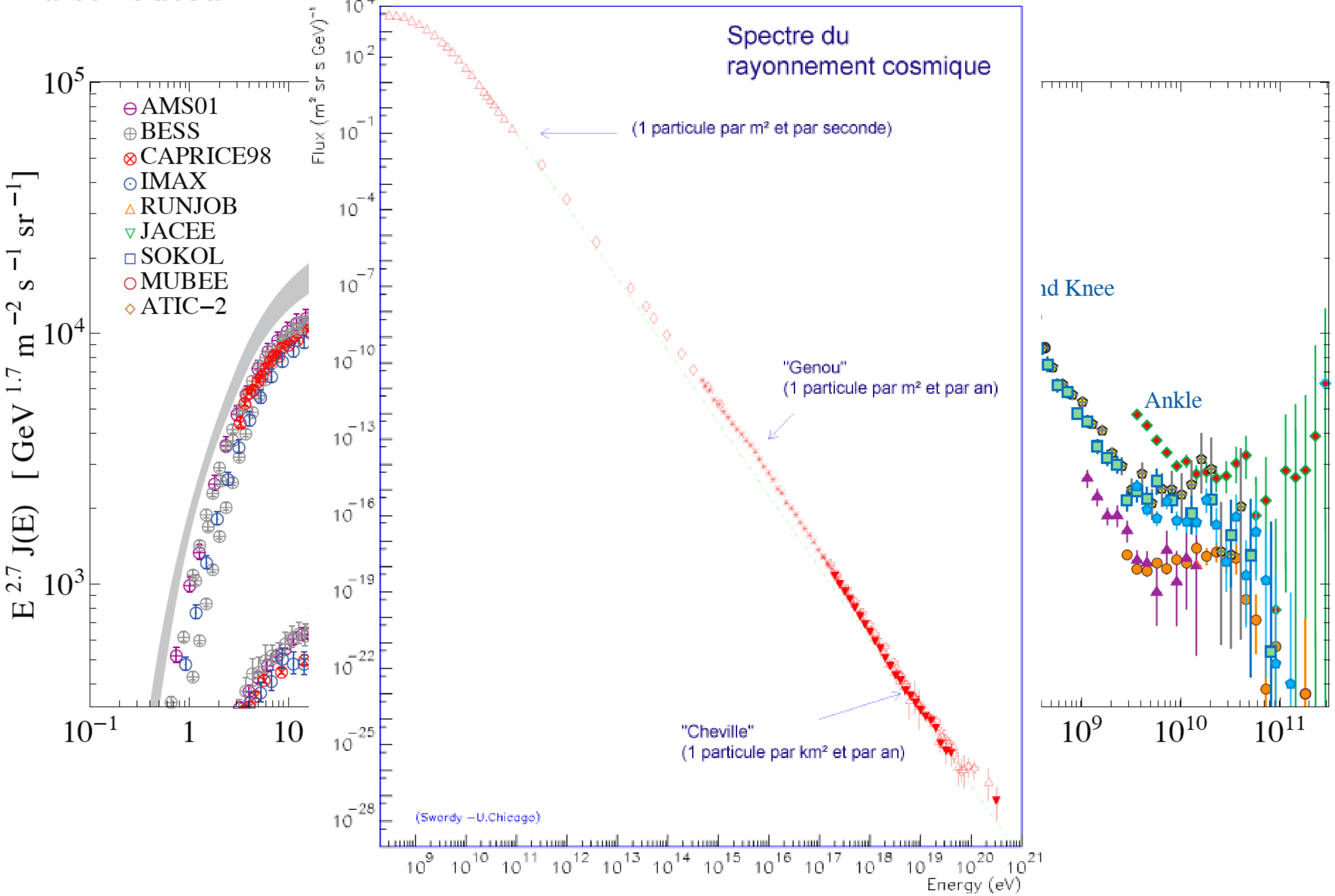
Operated first on January 2, 1931 – 70 keV protons



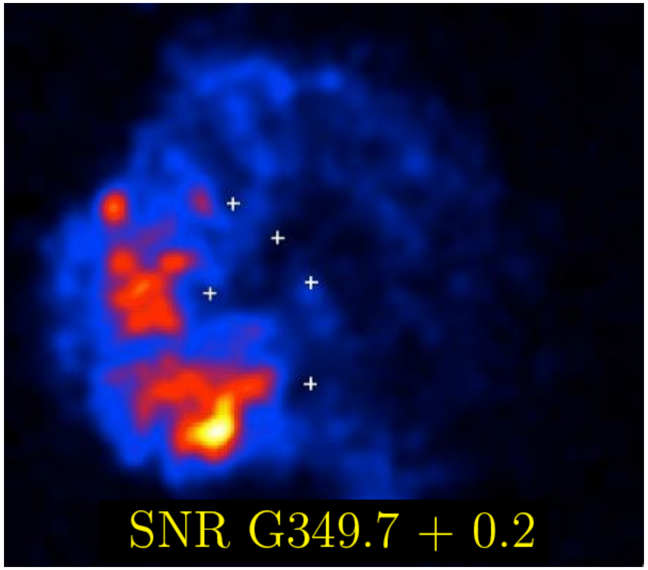
Cosmic rays are replaced by accelerators where particles are artificially produced

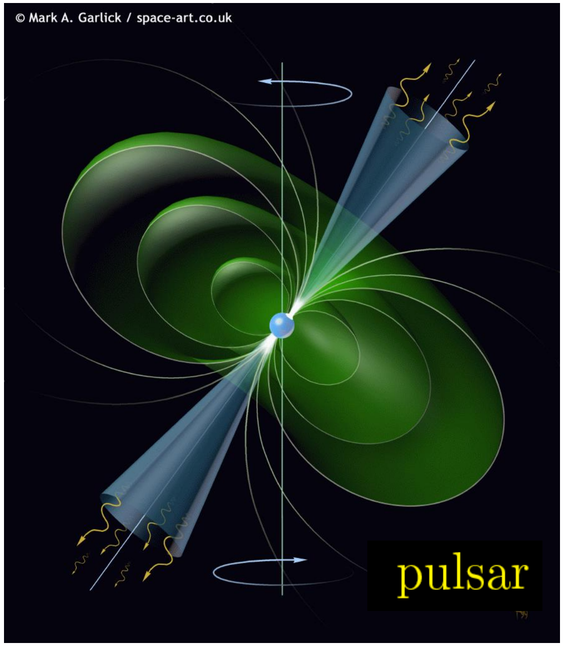
# Ultra–high energy cosmic rays from extra–galactic origin

• Above $3 \times 10^{15}$ eV, cosmic rays diffuse weakly inside the Milky Way magnetic fields. Above $3 \times 10^{17}$ eV, they come from outside the Galaxy. Their Larmor radii exceed the size of the Galaxy and yet they are isotropically distributed.



# Cosmic rays and astrophysical accelerators



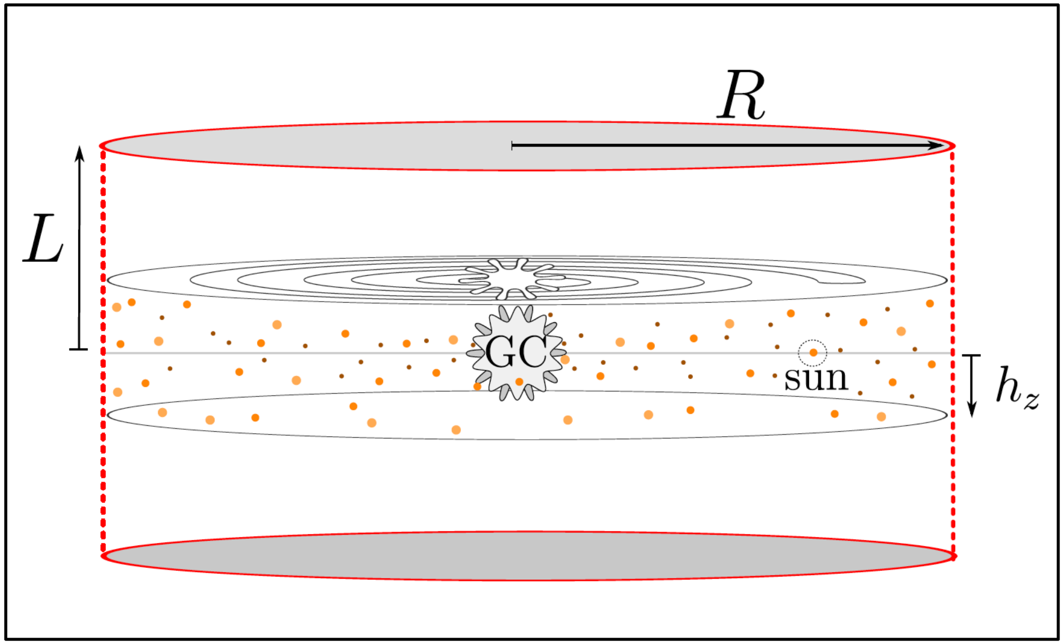

- Supernova driven shock waves accelerate the elements of the interstellar medium through a first order Fermi mechanism. Nuclei and electrons are injected.

- Misaligned magnetized neutron stars accelerate electrons which interact with photons – light and magnetic field – to initiate an electromagnetic cascade. Pulsars inject electrons and positrons exclusively, not protons or nuclei.

Jonathan Biteau David Sanchez

# Cosmic rays and Galactic propagation

Lineros' PhD thesis (2008)




Thickness $L$

$$K(E) = K_0 \beta \times \mathcal{R}^{\delta}$$

$$K_{EE} = \frac{2}{9} {V_a}^2 \frac{E^2 \beta^4}{K(E)}$$

$$\partial_z (V_C \psi) - K \Delta\psi + \partial_E \left\{ b^{\text{loss}}(E)\, \psi - D_{EE}(E)\, \partial_E \psi \right\} = q_S$$

- A propagation model is characterized by the set $\delta, K_0, L, V_C, V_a$

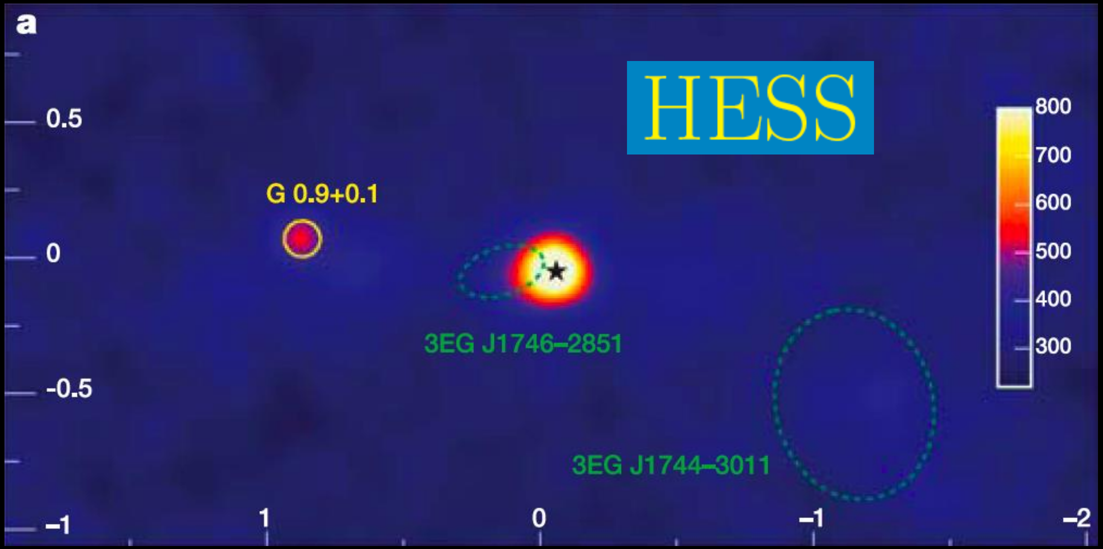
| Case | $\delta$ | $K_0$ [kpc$^2$/Myr] | $L$ [kpc] | $V_C$ [km/s] | $V_a$ [km/s] |
|---|---|---|---|---|---|
| max | 0.46 | 0.0765 | 15 | 5 | 117.6 |
| med | 0.70 | 0.0112 | 4 | 12 | 52.9 |
| min | 0.85 | 0.0016 | 1 | 13.5 | 22.4 |

- Isotopic ratios provide indications on the CR parameters

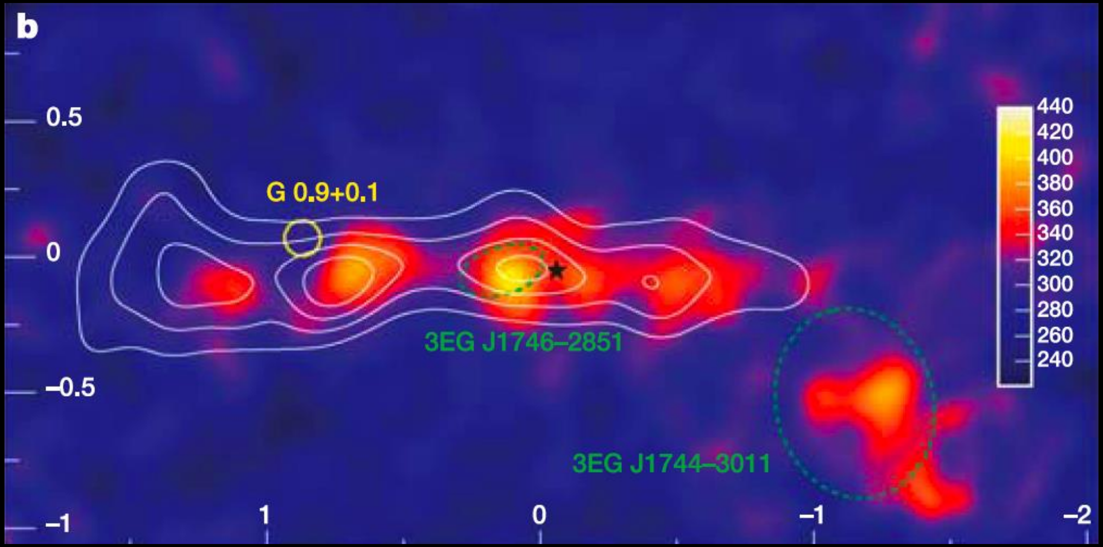
B/C is proportional to $L/K_0$ and varies with $\delta$

$^{10}$Be/$^{9}$Be is related to K

# The center of the Milky Way




Laura Core




supermassive black hole

## Ultra–high energy cosmic rays from extra–galactic origin

- **December 1932** – Strong debate between R.A. Millikan and A.H. Compton over whether cosmic rays (CR) are composed of high-energy photons (Millikan's view) or charge
already exist !

- **1933** – P. Auger and L
CR intensity at the equato
are **charged** particles !

- **1934** – P. Auger and L
tween east and west. Mor
rays are predominantly **po**

- **1938** – P. Auger discove
lated detectors hit at the s

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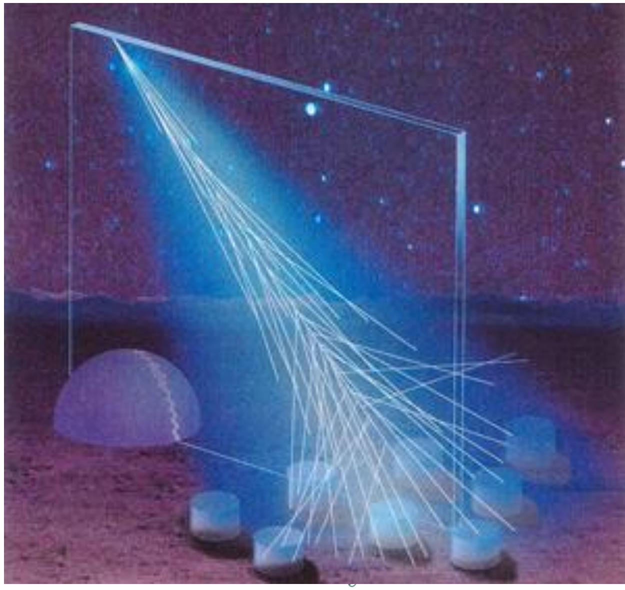
# Ultra–high energy cosmic rays from extra–galactic origin



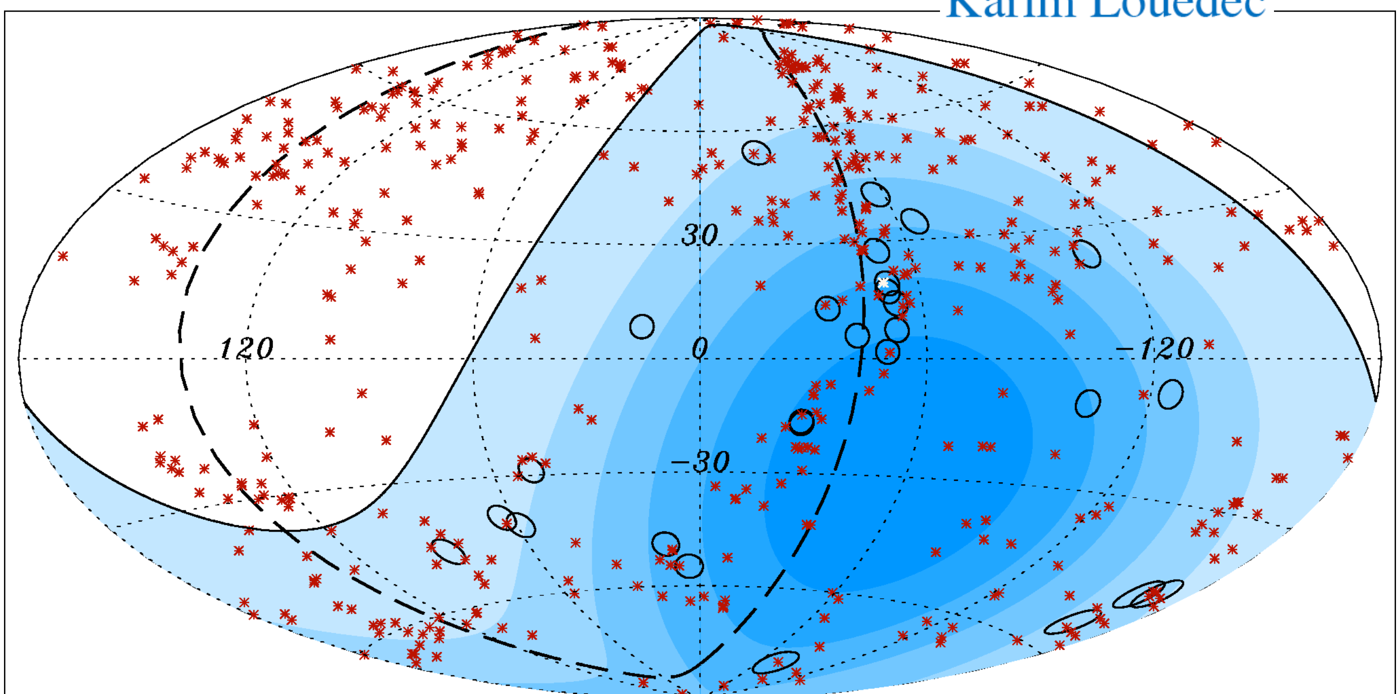
Kuzmin and G. Zatsepin show that abov
oduces a pion on the CMB so that its
epth does not exceed $\sim$ 70 Mpc – GZK

$$+ p \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$

$$+ p \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$

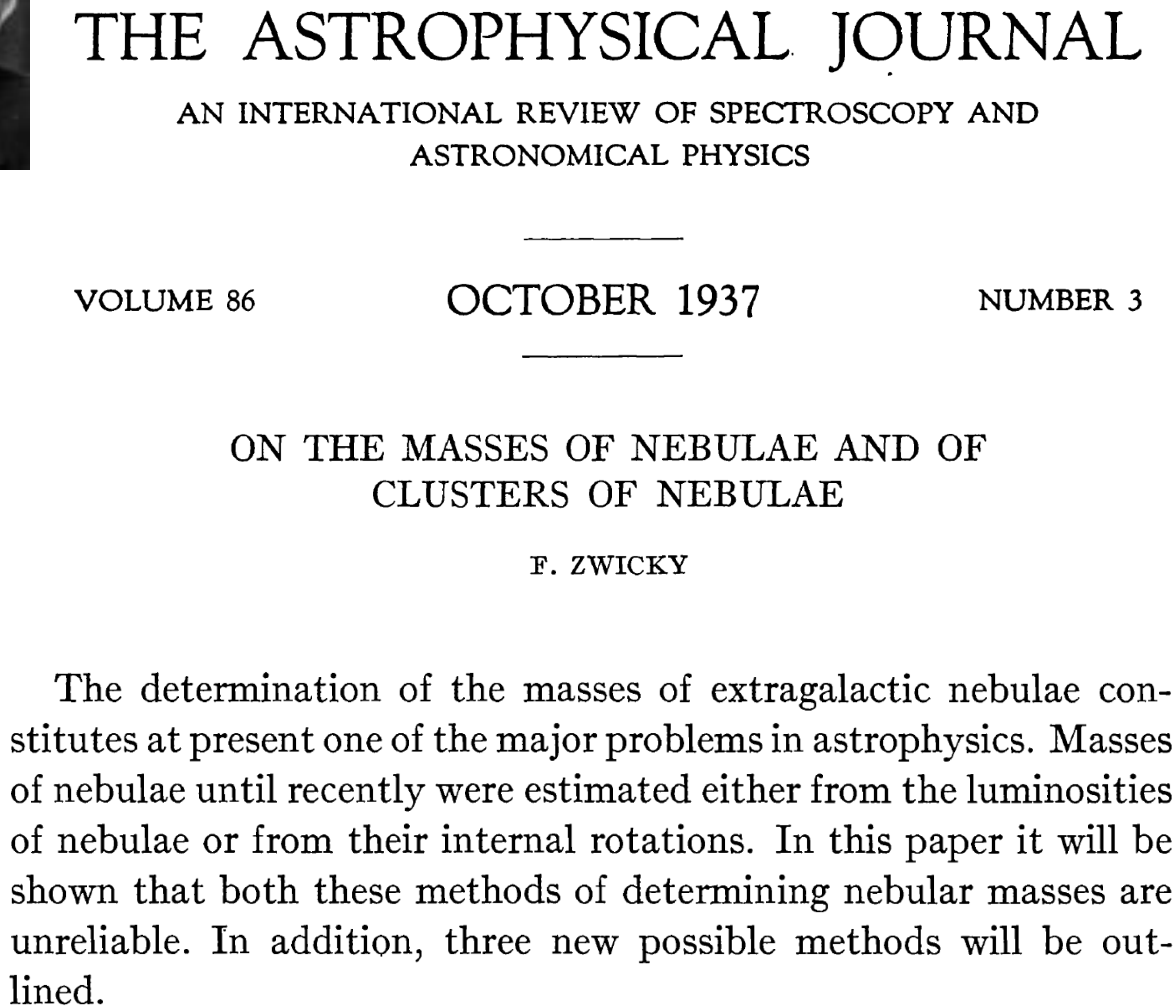
uger Collaboration announces that activ
ly candidate for the sources of the highe
GZK cut–off.

Karim Louedec



Cosmology – the dark matter problem

# Fritz Zwicky and the Coma cluster – 1933



As a first approximation, it is probably legitimate to assume that

$$-\overline{E_p} = 2\overline{K_T} = \overline{\sum_\sigma M_\sigma v_\sigma^2} = \sum_\sigma M_\sigma \overline{v_\sigma^2}$$

stitute this cluster.[5] But even if we drop the assumption that clus-

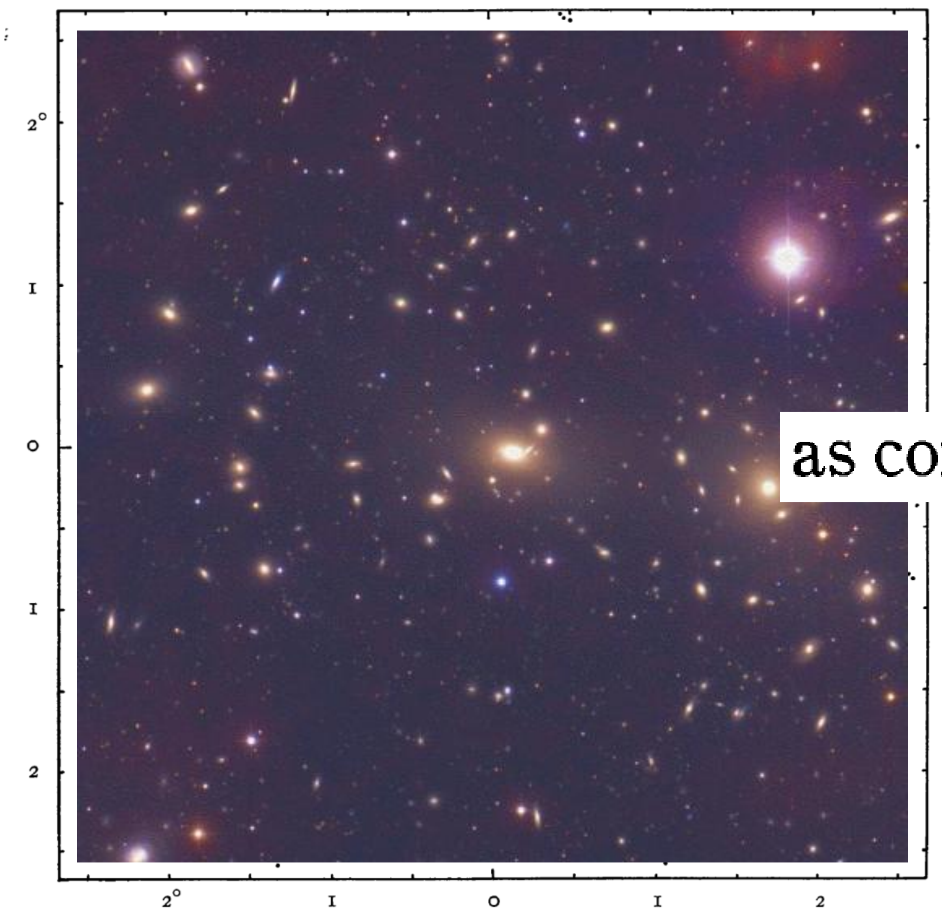



FIG. 3.—The Coma cluster of nebulae

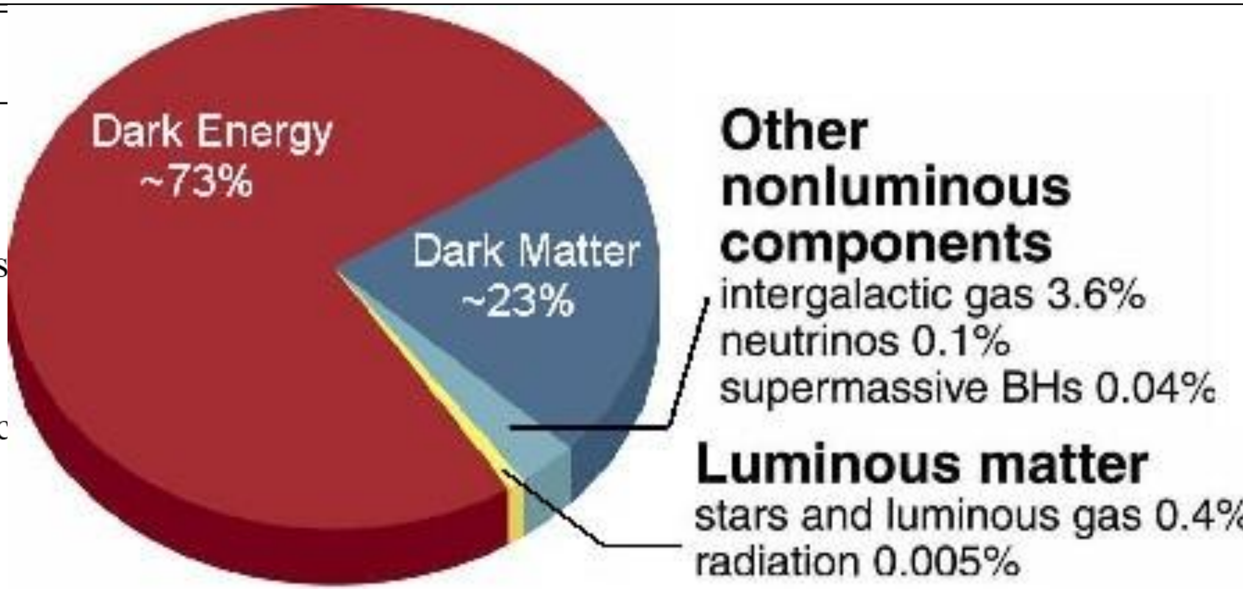
$$\mathcal{M} = \frac{5R\overline{\overline{v^2}}}{3\Gamma}$$

$$\gamma = 500$$

as compared with about $\gamma' = 3$

# WMAP observations

| | | y | – uncertainty |
|---|---|---|---|
| Total density | | | 0.02 |
| Equation of state | | | — |
| Dark energy dens | | | 0.04 |
| Baryon density | | | 0.0009 |
| Baryon density | | | 0.004 |
| Baryon density (c | | | $0.1 \times 10^{-7}$ |
| Matter density | | | 0.009 |
| Matter density | | | 0.04 |




- The Univers is **flat** $\Omega_{\mathrm{tot}} = 1.02$
- A new intriguing component – dark energy – $\Omega_\Lambda = 0.73$
- Dark and **exotic** matter on cosmological scales since

$$\Omega_{\mathrm{M}} = 0.27 > \Omega_{\mathrm{B}} = 0.044$$

# The bestiary of dark matter candidates

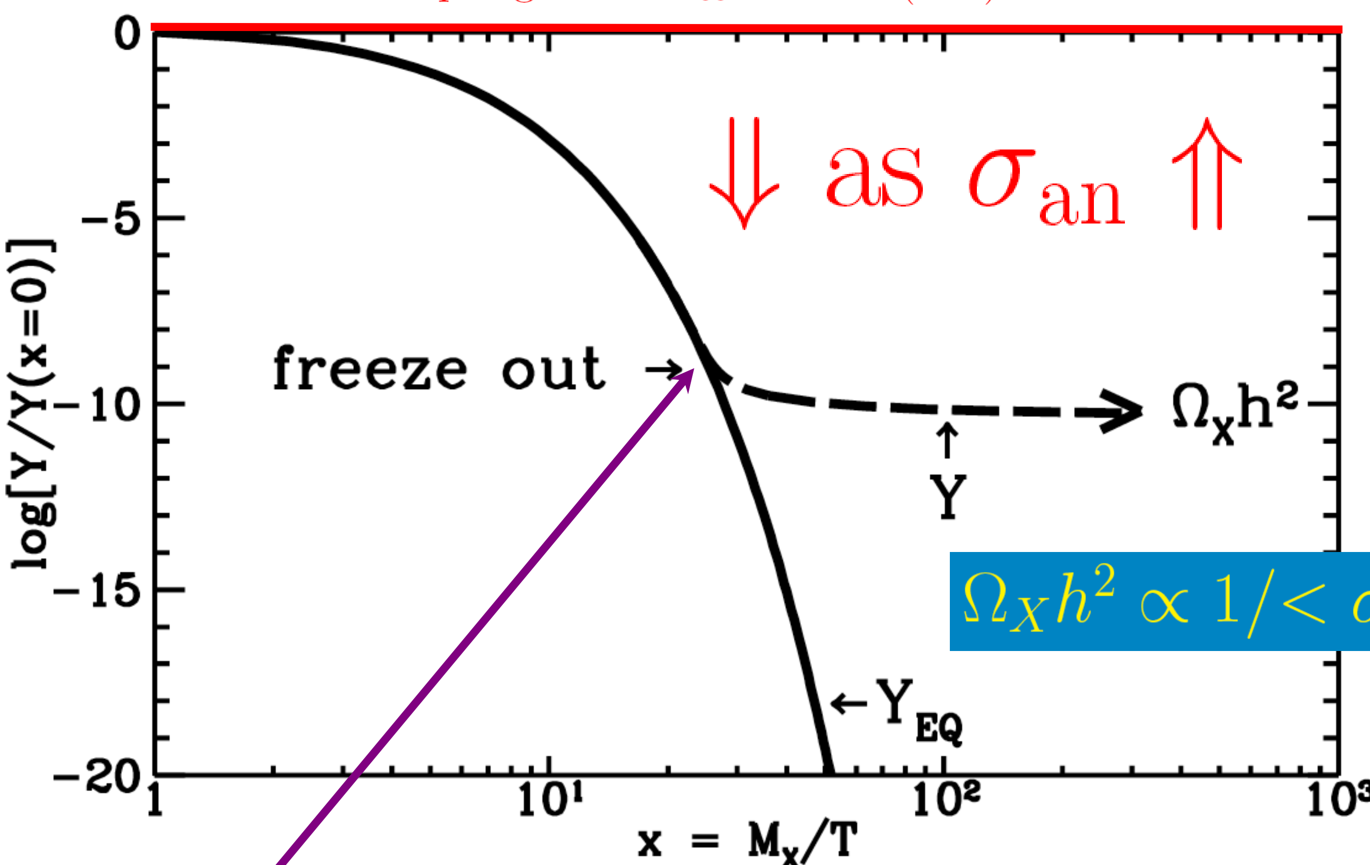
- The popular beasts : SUSY and extra–dimensions
- The light candidates : gravitinos, axions and MeV particles
- The heavy objects : Wimpzillas
- The social species : topological defects and Boson DM

# Thermodynamical equilibrium production

$$X + \bar{X} \rightleftharpoons f + \bar{f}$$

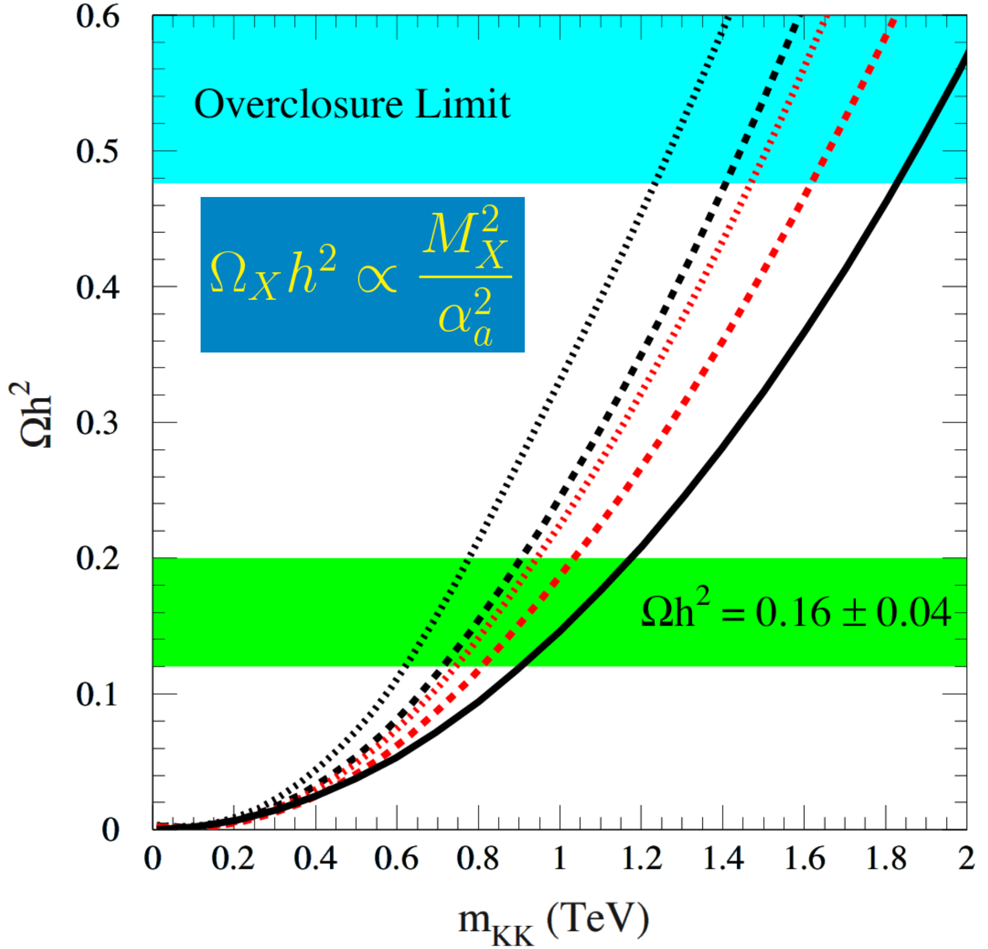
$$\frac{dn_X}{dt} = -3Hn_X - <\sigma_{\rm an}v> {n_X}^2 + <\sigma_{\rm an}v> {n_X^0}^2$$

thermal decoupling when $\Gamma_{\rm coll} \sim H_F$ (UR)




$$\Omega_X h^2 \propto 1/<\sigma_{\rm an}v>$$

chemical decoupling when $<\sigma_{\rm an}v> n_X \sim H_F$ (NR)



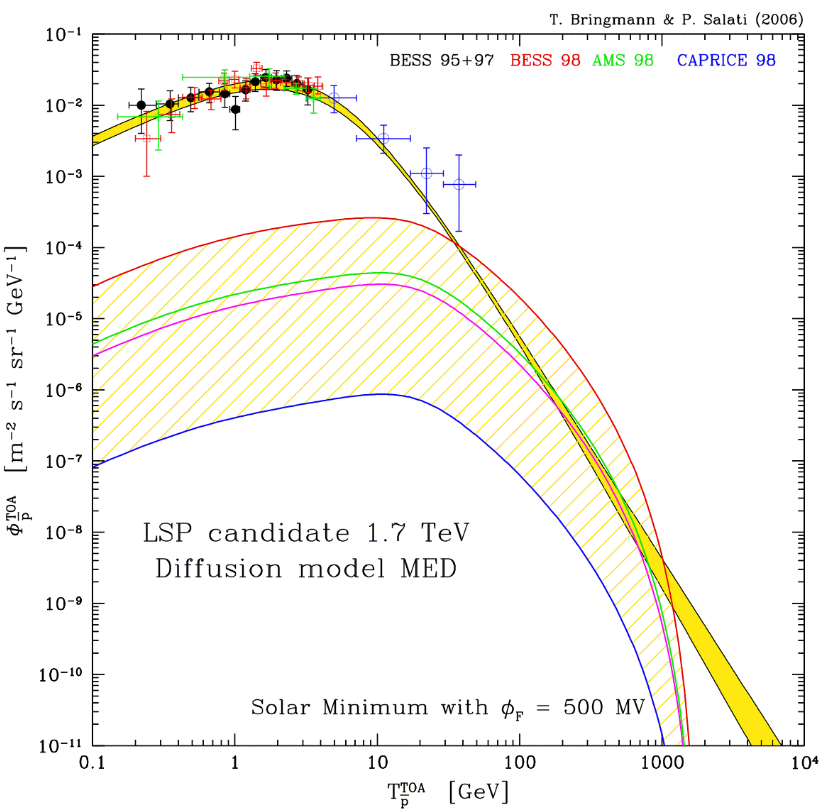

Géraldine Servant [a,b] and Tim M.P. Tait [a]

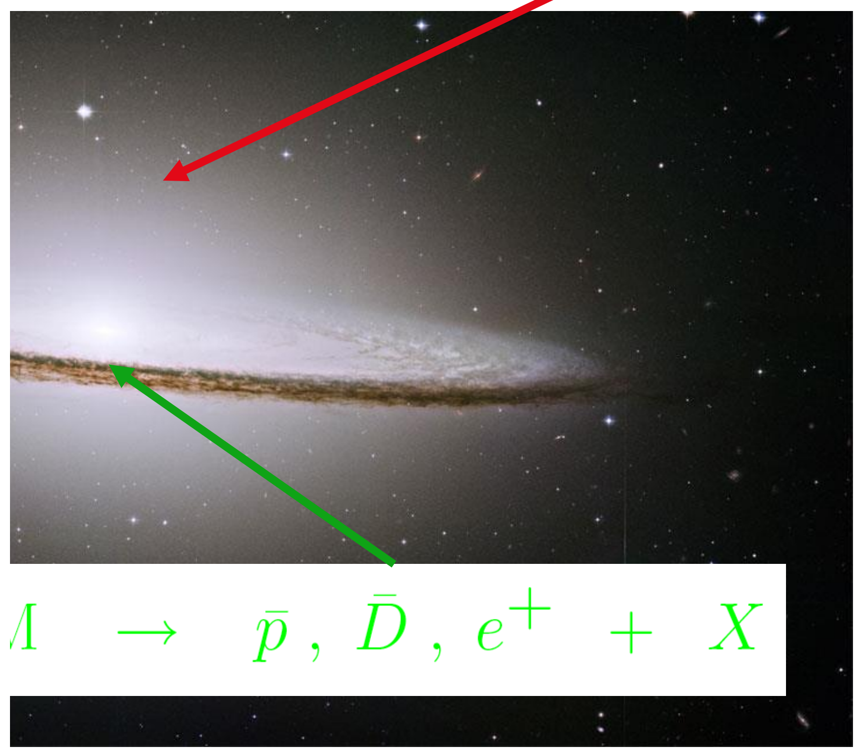
Figure 3: Prediction for $\Omega_{B^{(1)}} h^2$ as in Figure 1. The solid line is the case for $B^{(1)}$ alone, and the dashed and dotted lines correspond to the case in which there are one (three) flavors of nearly degenerate $e_R^{(1)}$. For each case, the black curves (upper of each pair) denote the case $\Delta = 0.01$ and the red curves (lower of each pair) $\Delta = 0.05$.

# Indirect signatures of DM species

Weakly Interacting Massive particles – WIMPs – may be the major component of the haloes of galaxies. Their mutual annihilations would produce an indirect signature of high–energy cosmic rays :

$$\chi + \chi \rightarrow q\bar{q}, W^{+}W^{-}, \ldots \rightarrow \gamma, \bar{p}, \ \bar{D}, \ e^{+} \ \& \ \nu' s$$



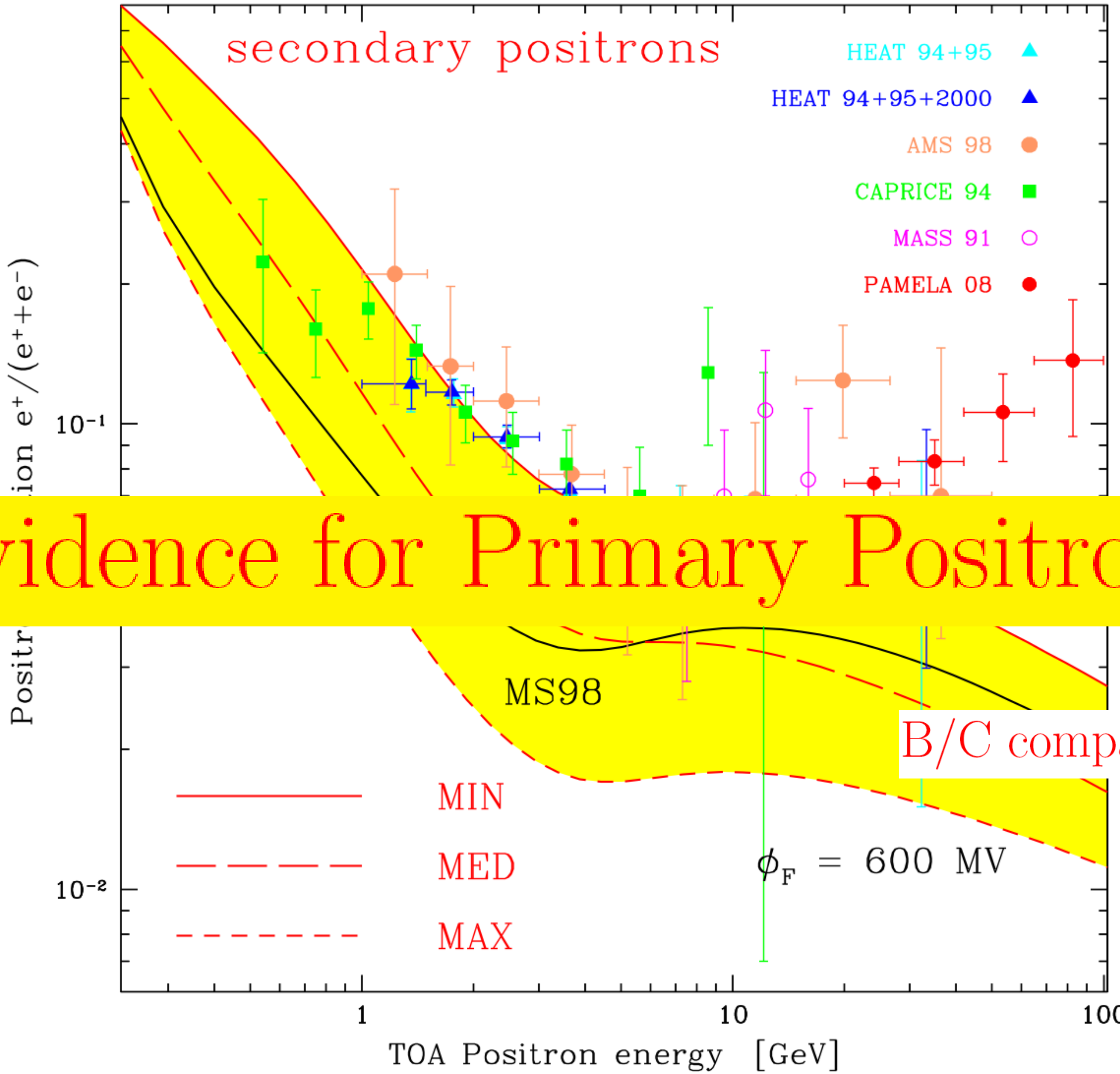



$$M \rightarrow \bar{p}\,,\ \bar{D}\,,\ e^{+} + X$$

Antimatter is already manufactured inside the galactic disk

# Cosmology and particle physics – the dark matter problem

J. Lavalle et al. for the GPhyS workshop of June 21, 2010 at IAP




**Evidence for Primary Positrons**

B/C compatible band

Delahaye T. et al. – arXiv:0809.5268 – **A&A** 501 (2009) 821

# PAMELA positron excess

May be the first indirect hint that DM species annihilate in the MW

$$q_{e^+} = \frac{1}{2} \langle \sigma v \rangle \times \left\{ n_\chi \equiv \frac{\rho_\chi}{m_\chi} \right\}^2 \times \frac{dN_e}{dE_e}$$

A few remarks are in order

**(i)** The WIMP mass $m_\chi \sim 100$ GeV (PAMELA) up to 1 TeV (Fermi)

**(ii)** The annihilation rate needs to be considerably enhanced

- Thermal freeze–out cross section $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm$^3$ s$^{-1}$
- Local e$^+$ production means DM density given by $\rho_\odot = 0.3$ GeV cm$^{-3}$

$$m_\chi = 1 \text{ TeV needs } \Gamma_{\rm ann} \equiv \frac{1}{2} \langle \sigma v \rangle \times \frac{\rho_\chi^2}{m_\chi^2} \text{ boosted by } B = 10^3$$

**(iii)** DM species are **leptophilic**, id est $q$ channels are suppressed

## (iii) DM species are **leptophilic**, id est $q$ channels are suppressed

M. Cirelli et al., Nucl. Phys. **B 813** (2009) 1

**Constraints on WIMP Dark Matter from the High Energy PAMELA $\bar{p}/p$ data**

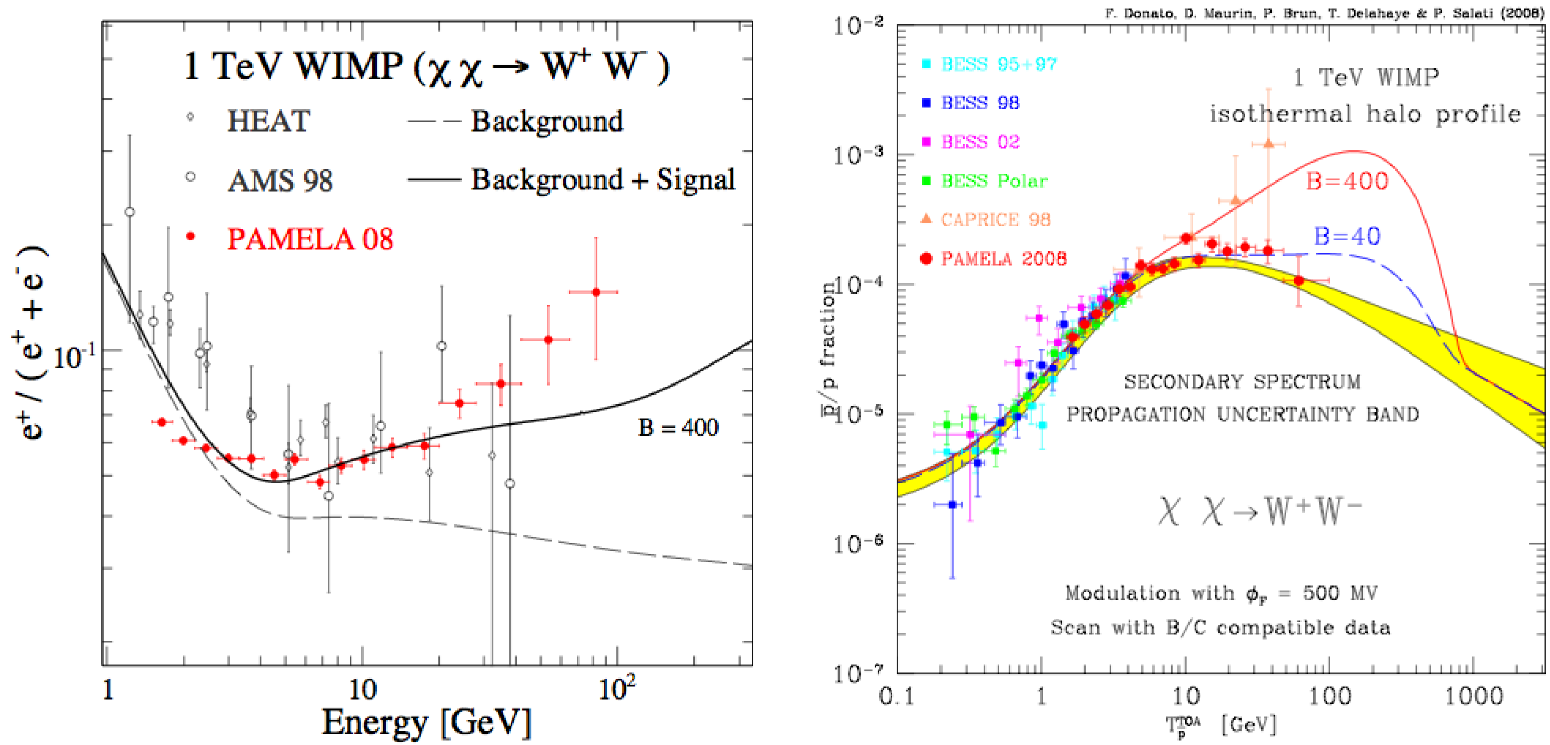
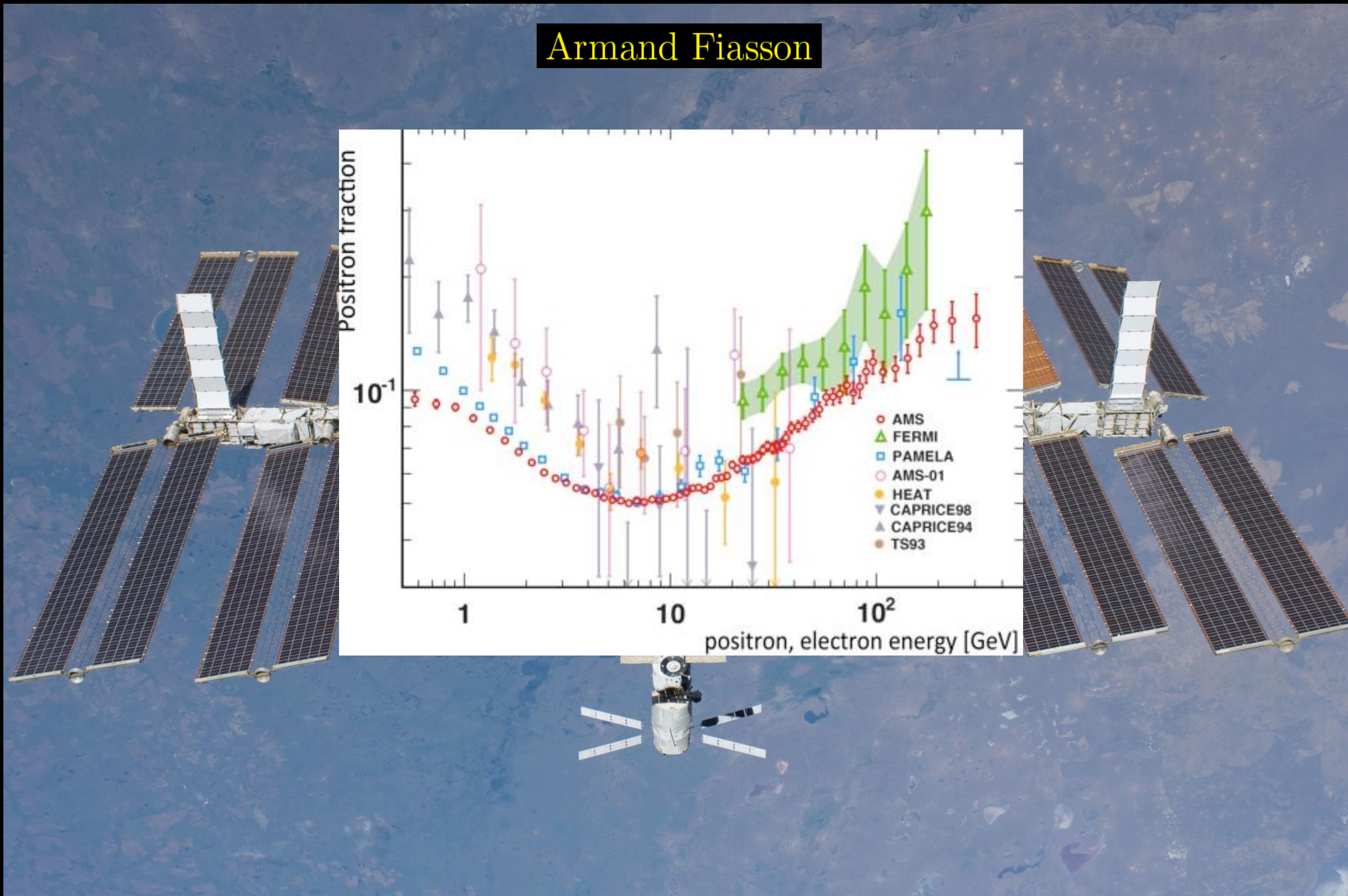



FIG. 3: The fiducial case of a 1 TeV LSP annihilating into a $W^+W^-$ pair is featured. In the left panel, the positron signal which this DM species yields has been increased by a factor of 400, hence the solid curve and a marginal agreement with the PAMELA data. Positron fraction data are from HEAT [18], AMS-01 [5, 22] and PAMELA [2]. If the so–called Sommerfeld effect [7] is invoked to explain such a large enhancement of the annihilation cross section, the same boost applies to antiprotons and leads to an unacceptable distortion of their spectrum as indicated by the red solid line of the right panel.

F. Donato et al. – PRL **102** (2009) 071301

# AMS–02


Armand Fiasson
Positron fraction
$10^{-1}$
1
10
$10^2$
positron, electron energy [GeV]
AMS
FERMI
PAMELA
AMS-01
HEAT
CAPRICE98
CAPRICE94
TS93

# Perspectives

• Particle astrophysics is a very rich domain nutured by various fields – particle physics, astrophysics and cosmology.

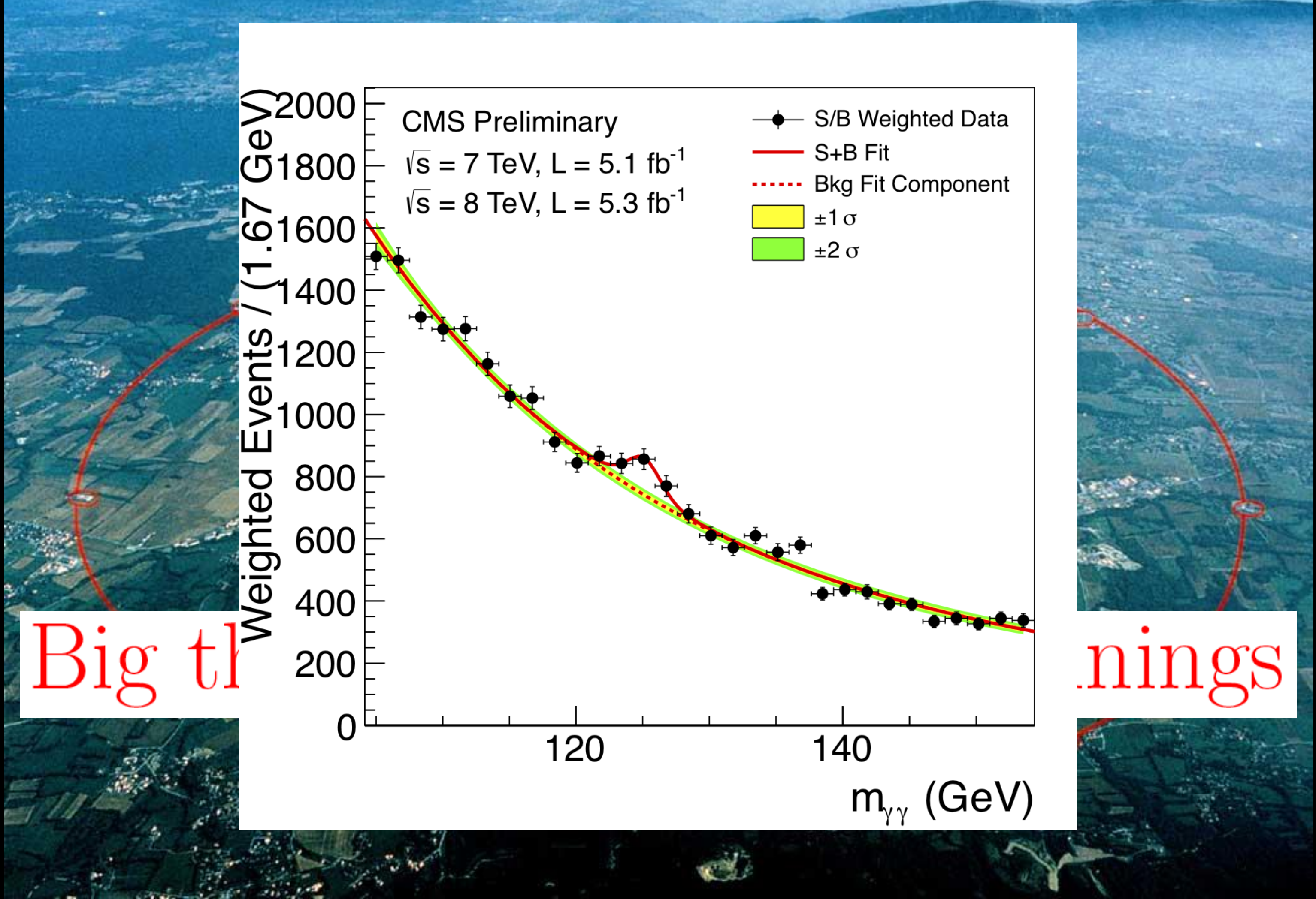
• A central theme is provided by cosmic rays. What are their sources ? How do they propagate ? Many current experiments try to answer that question.

• The dark matter puzzle is also a key issue whose solution may come from the heavens – if not from the LHC.

• The domain has proved to be very successfull. Remember that neutrino oscillations have been discovered in the Sun !

Cosmic rays are replaced by accelerators where particles are artificially produced

# Large Hadron Collider – LHC

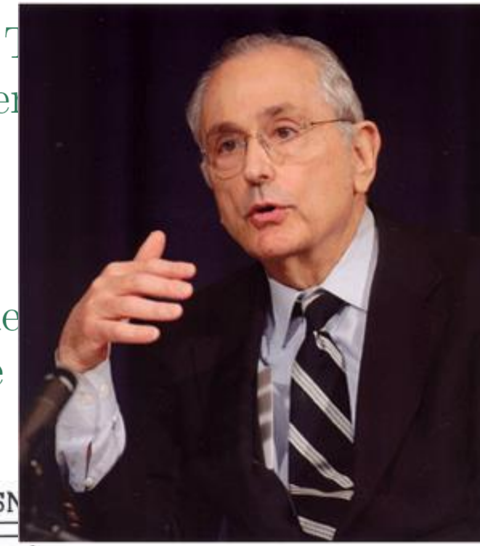


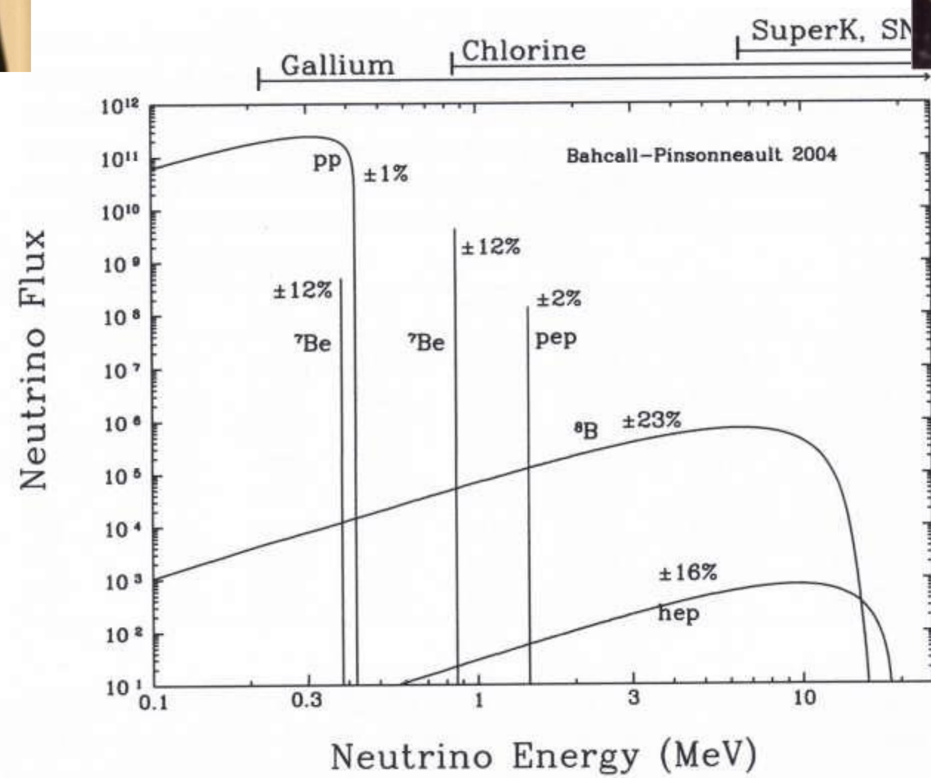
# Particle physics and astrophysics – the solar neutrino puzzle

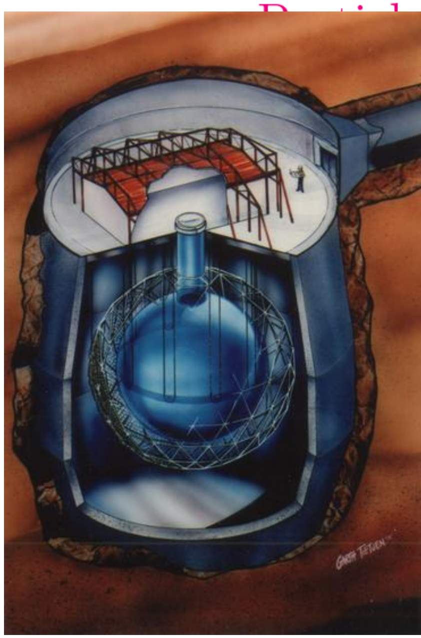
wered by the fusion of hydrogen into helium. T
production of deuterium through a weak inter

$$p + p \rightarrow D + e^{+} + \nu_e + 0.26\,\mathrm{MeV}$$

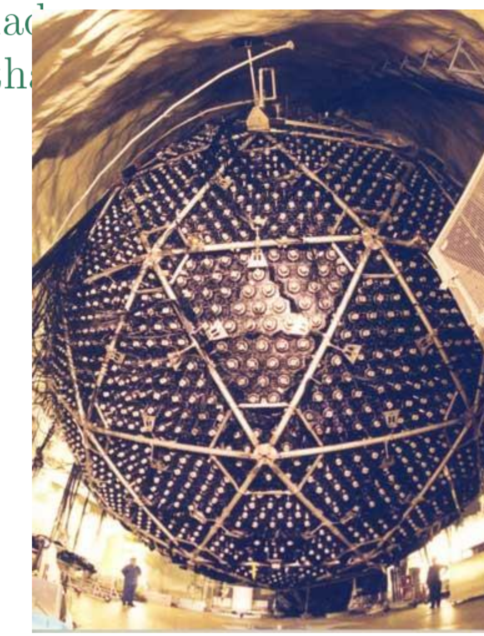
avis's and J.N. Bahcall's Homestake experime
flux of neutrinos from the Sun through the
A deficit is detected.







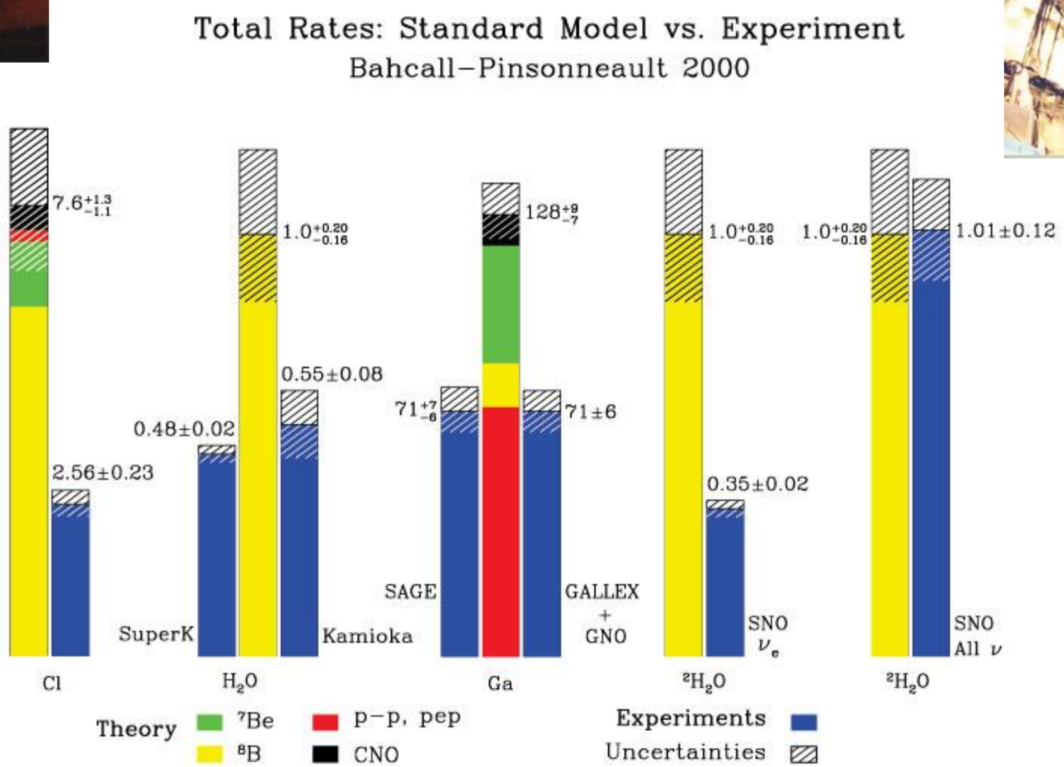
e Subdury Neutrino Observatory (SNO) in Canad
eutrinos by using heavy water $D_2O$ and proves th
heir way from the Sun to the Earth.



$$D + \nu_e \rightarrow p + p + e^- \ (\textbf{CC})$$

$$D + \nu_X \rightarrow p + n + \nu_X \ (\textbf{NC})$$

$$\nu_X + e^- \rightarrow \nu_X + e^- \ (\textbf{ES})$$

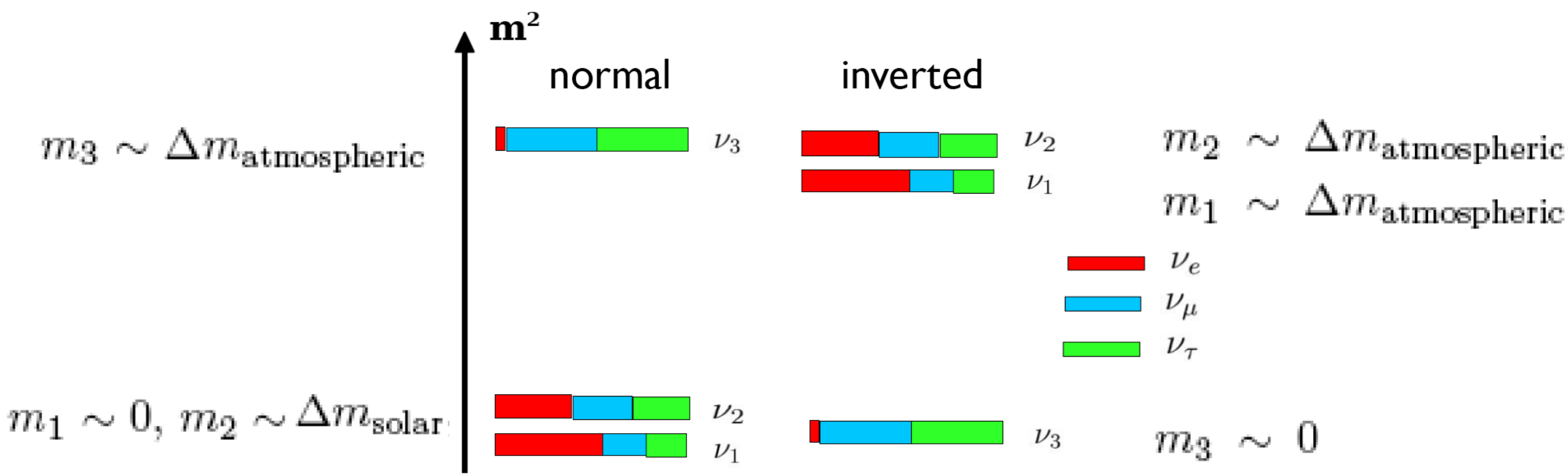


# Particle physics and astrophysics – the solar neutrino puzzle

- $\sin^2(2\theta_{13}) = 0.092 \pm 0.017$[12]
- $\tan^2(\theta_{12}) = 0.457^{+0.040}_{-0.029}$. This corresponds to $\theta_{12} \equiv \theta_{sol} = 34.06^{+1.16}_{-0.84}$° ("sol" stands for solar)[13]
- $\sin^2(2\theta_{23}) > 0.92$ at 90% confidence level, corresponding to $\theta_{23} \equiv \theta_{atm} = 45 \pm 7.1$° ("atm" stands for atmospheric)[13]
- $\Delta m^2_{21} \equiv \Delta m^2_{sol} = 7.59^{+0.20}_{-0.21} \times 10^{-5}$ eV$^2$[13]
- $|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \equiv \Delta m^2_{atm} = 2.43^{+0.13}_{-0.13} \times 10^{-3}$ eV$^2$[13]
- $\delta$, $\alpha_1$, $\alpha_2$, and the sign of $\Delta m^2_{32}$ are currently unknown

Oscillation probabilities for an initial electron neutrino

## If neutrino masses are hierachical:




## However, neutrino masses could also be degenerate:

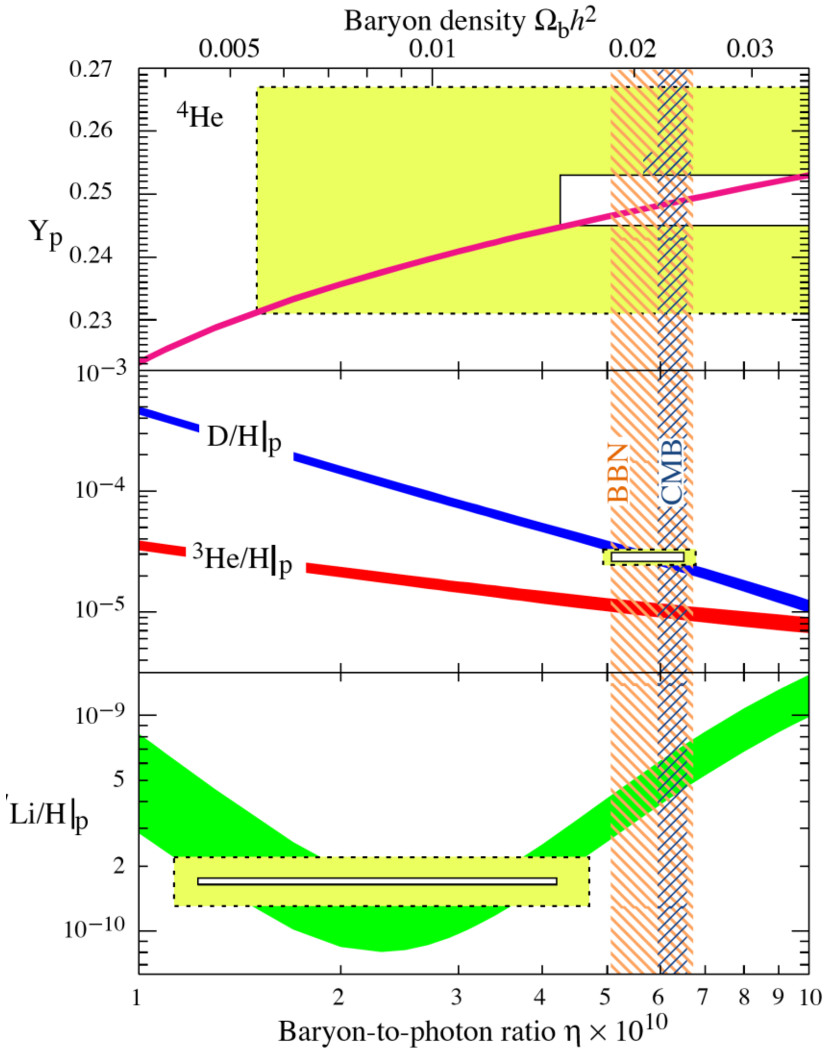
$$m_1 \sim m_2 \sim m_3 \gg \Delta m_{\rm atmospheric}$$

L/E (km/GeV)

# Particle physics and cosmology – the number of neutrino species

- Big-bang nucleosynthesis predicts the abundance of light elements and sets limits on the number of light neutrino families. Additional degrees of freedom with respect to the SM are constrained – but not very strongly.

$$|\Delta Y_p| \le 0.009 \;\Rightarrow\; |\Delta N_\nu| \le 0.82$$

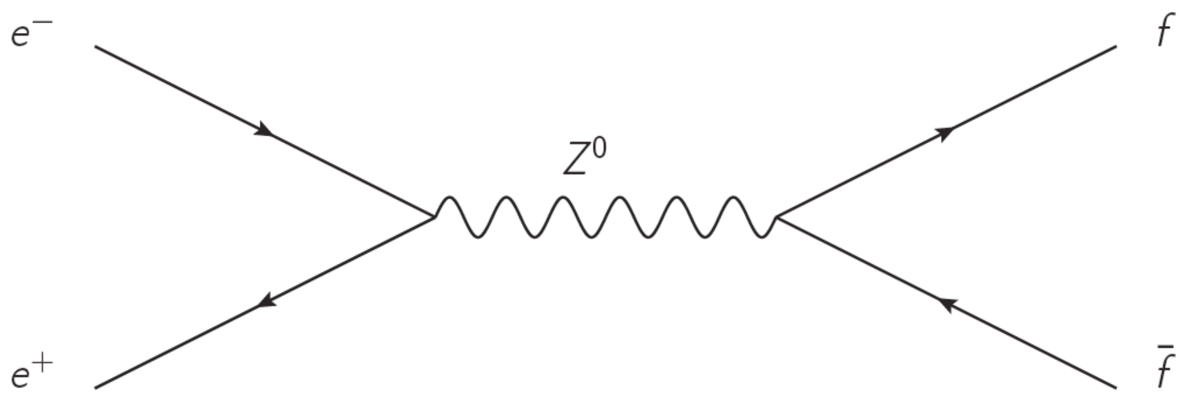


# Particle physics and cosmology – the number of neutrino species

- **1990** – The $Z^0$ boson is resonantly produced at LEP. From the Breit–Wigner fit of the resonance, the $Z^0$ width is measured and the number of neutrino species – that couple to the boson – is determined.

$$\sigma = \sigma^0 \frac{s\,\Gamma_Z^2}{(s - M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2} \quad \text{with} \quad \sigma^0 = 12\,\pi \frac{\Gamma_{\rm ee}\Gamma_{\rm had}}{M_Z^2\Gamma_Z^2}$$

$$\Gamma_Z = \Gamma_{\rm had} + 3\Gamma_{\rm l^+l^-} + N_\nu\Gamma_\nu$$



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$$M_Z = 91.175 \pm 0.027 \pm 0.030 \text{ GeV}$$

$$N_\nu = 3.01 \pm 0.15_{exp} \pm 0.05_{theor}$$

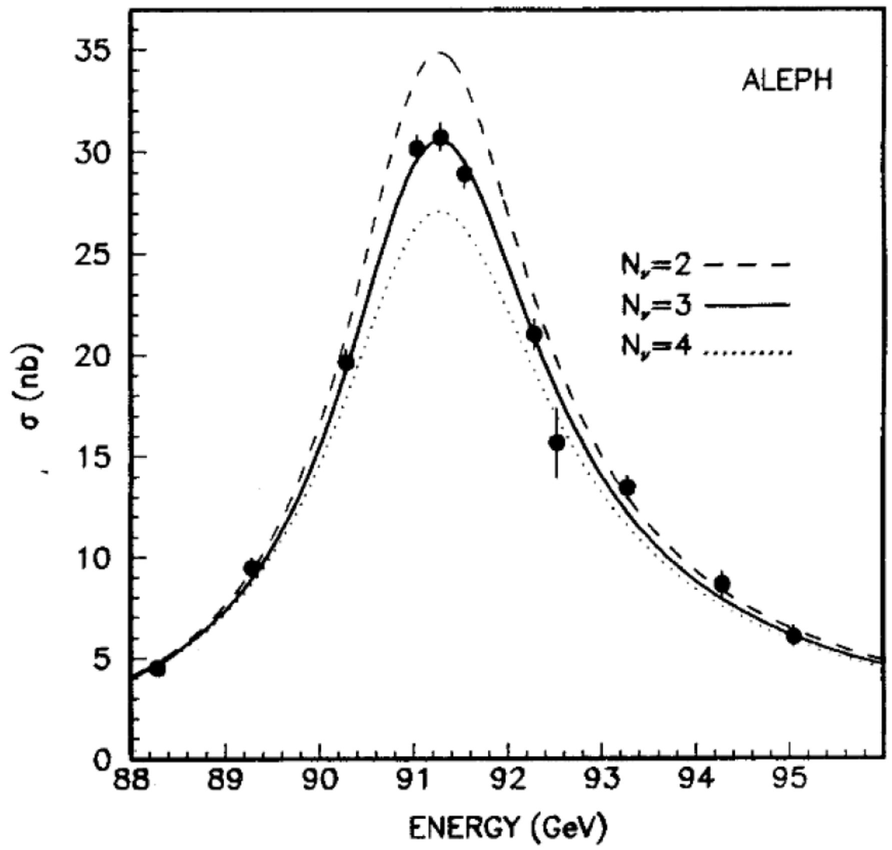


Figure: Hadronic cross-section as a function of $\sqrt{s}$