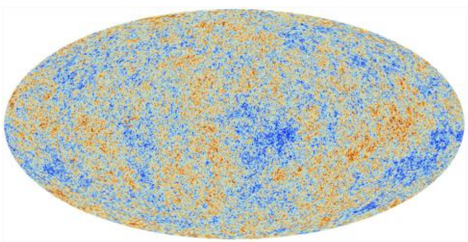
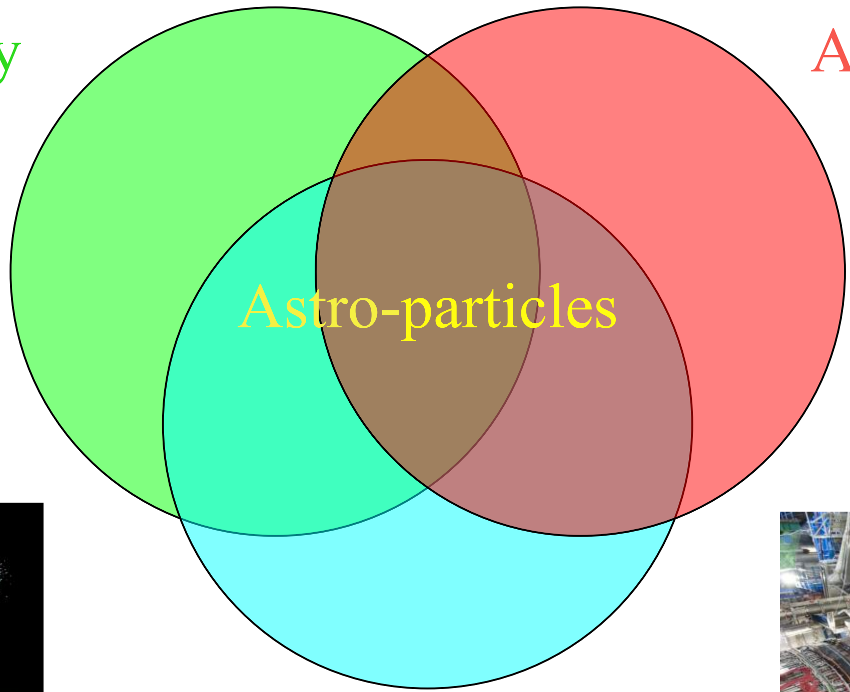
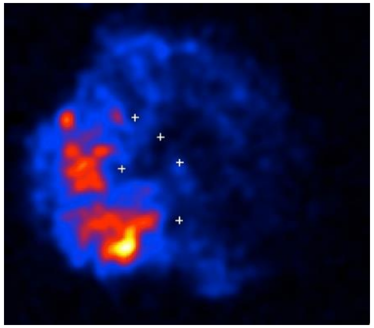
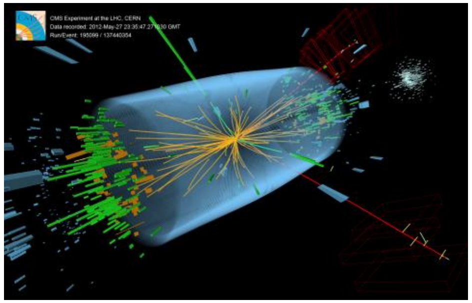
Introduction to Astroparticle Physics – theory

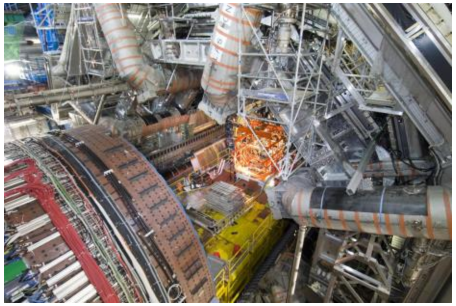
Pierre Salati – Université de Savoie & **LAPTH**









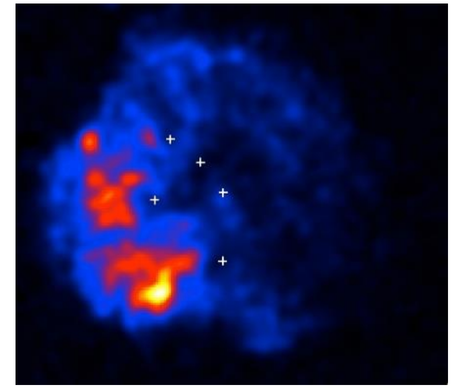


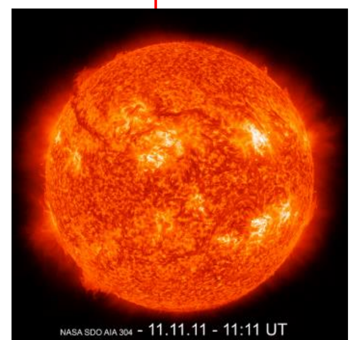
Graduate School in Particle & Astroparticle physics – Annecy-le-Vieux – 23 & 24 July

Astroparticle physics inherits from various fields

Genealogical Tree

stellar sources

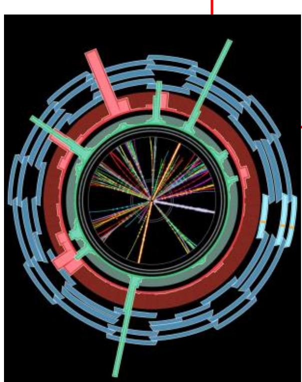


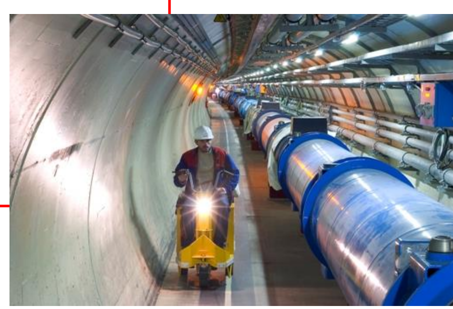


cosmic rays

cosmology & big–bang

accelerators





Particle Astrophysics

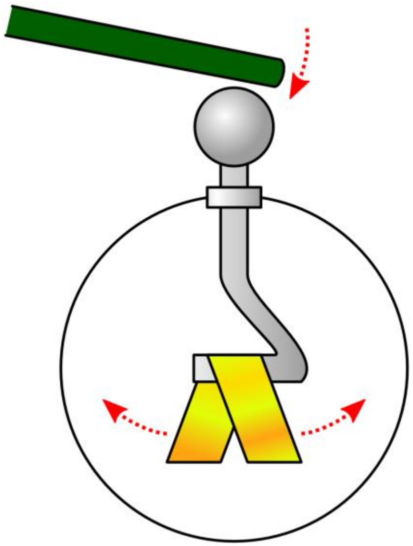
Outline

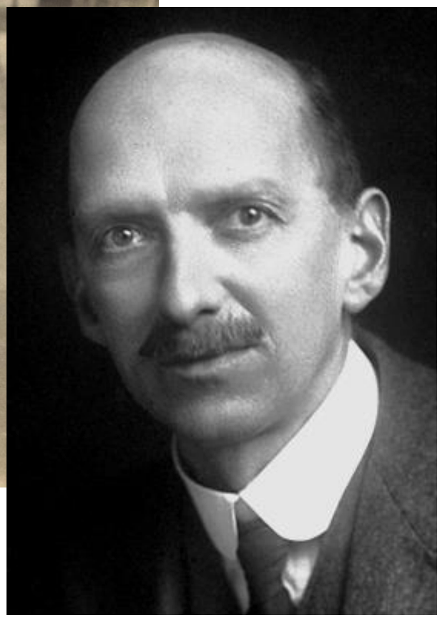
Outline

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.





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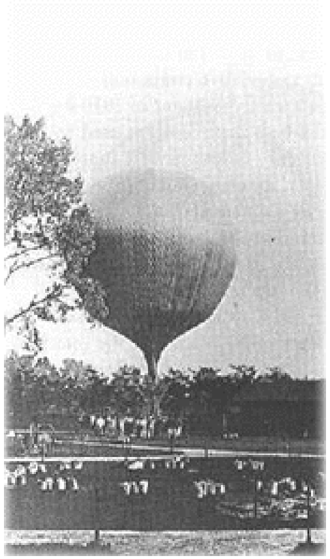
- **1911 to 1912** – V.F. Hess measures the atmospheric ionization with electroscopes during balloon flights at various altitudes. The ionization **increases**.



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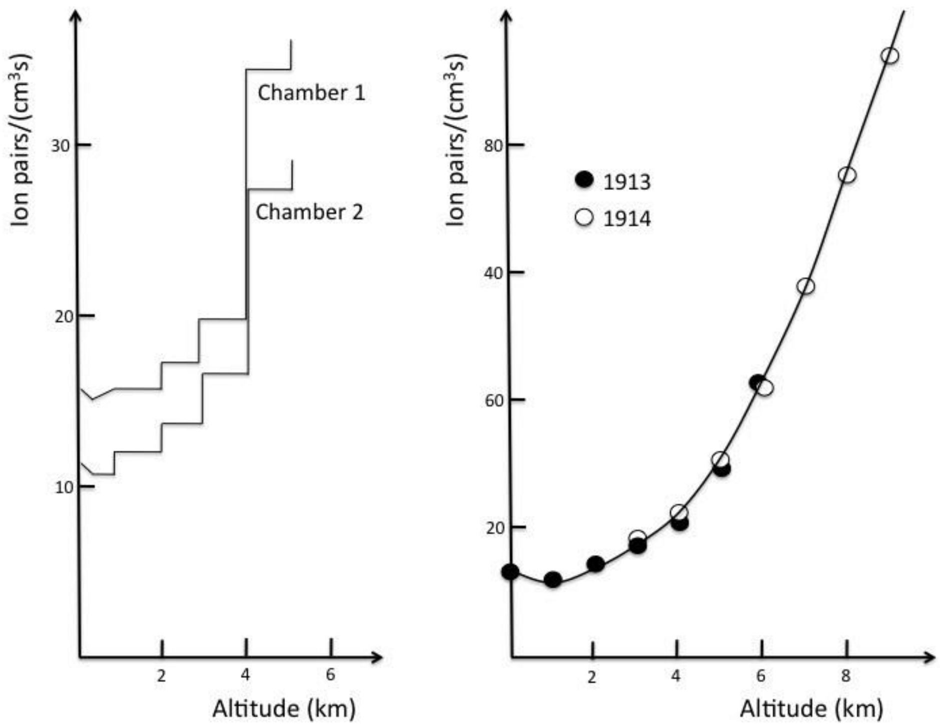
- **1914** – These results are confirmed and extended by W. Kolhörster with flights up to an elevation of 9200 meters.



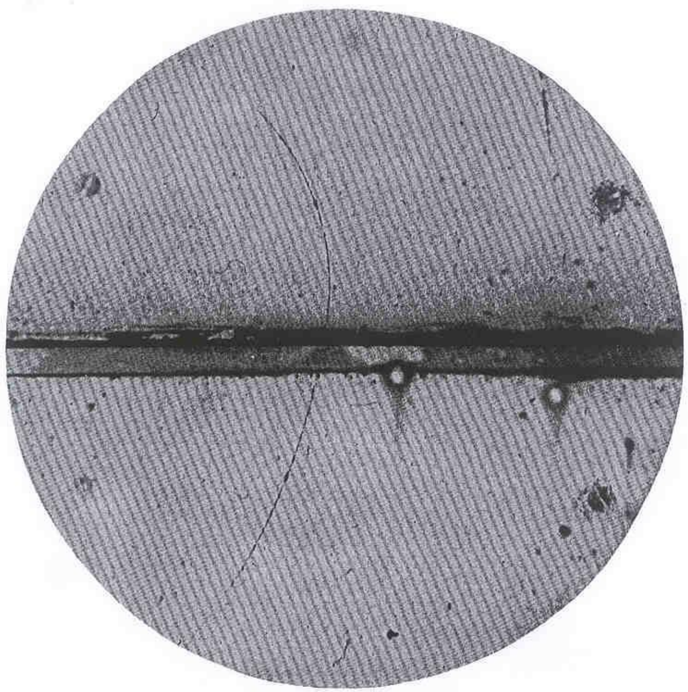
Cosmic rays and particle physics

- **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.



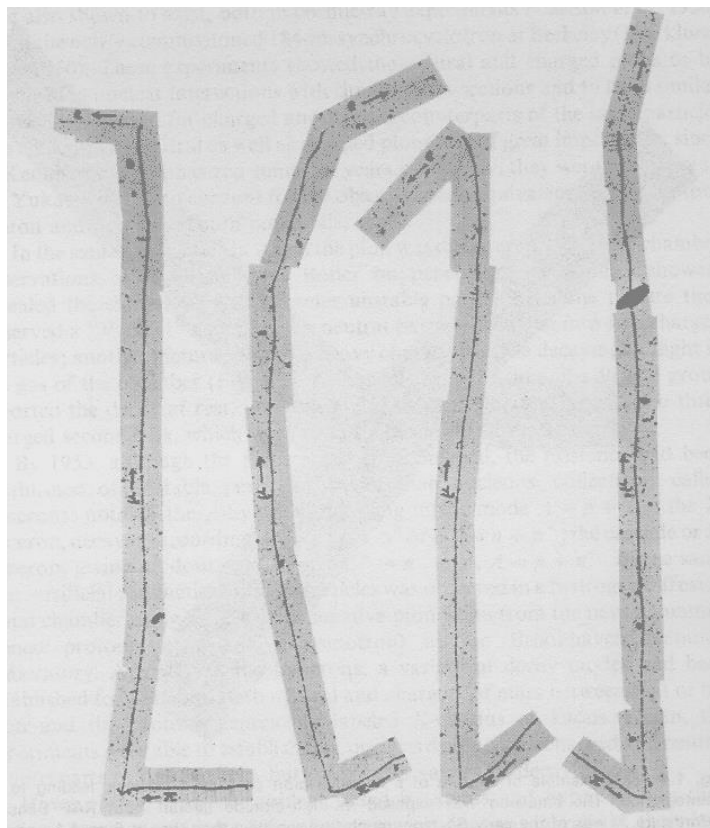
Cosmic rays and particle physics

• **1936** – The muon is discovered by C.D. Anderson and S. Nedermeyer in cosmic rays. This particle is quite penetrating.

• **1947** – Charged pions are discovered by C. Powell, C. Lattes and G. Occhialini at the University of Bristol.

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

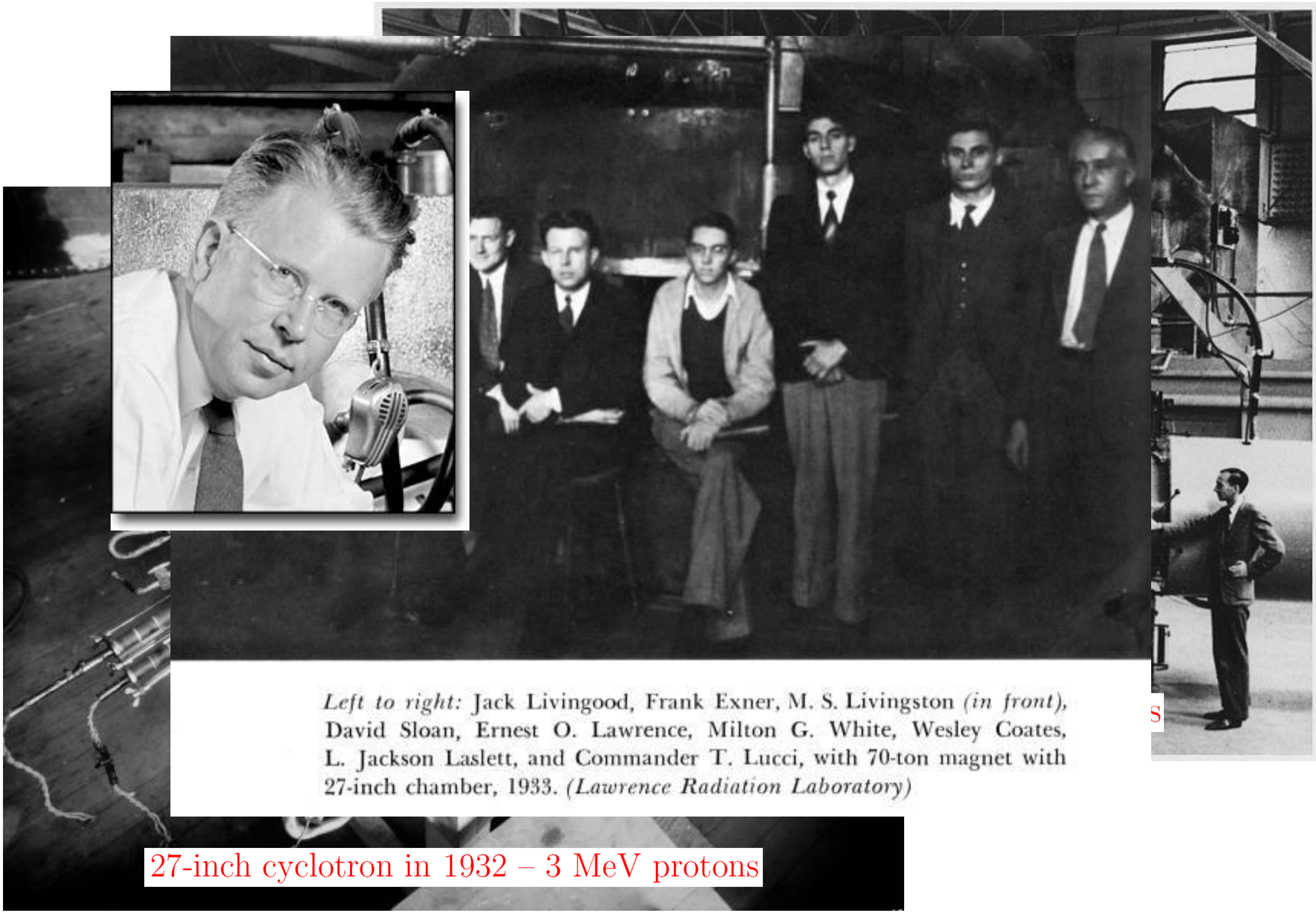


Cosmic rays are replaced by accelerators where particles are artificially produced

Five inch cyclotron held by Glenn Seaborg

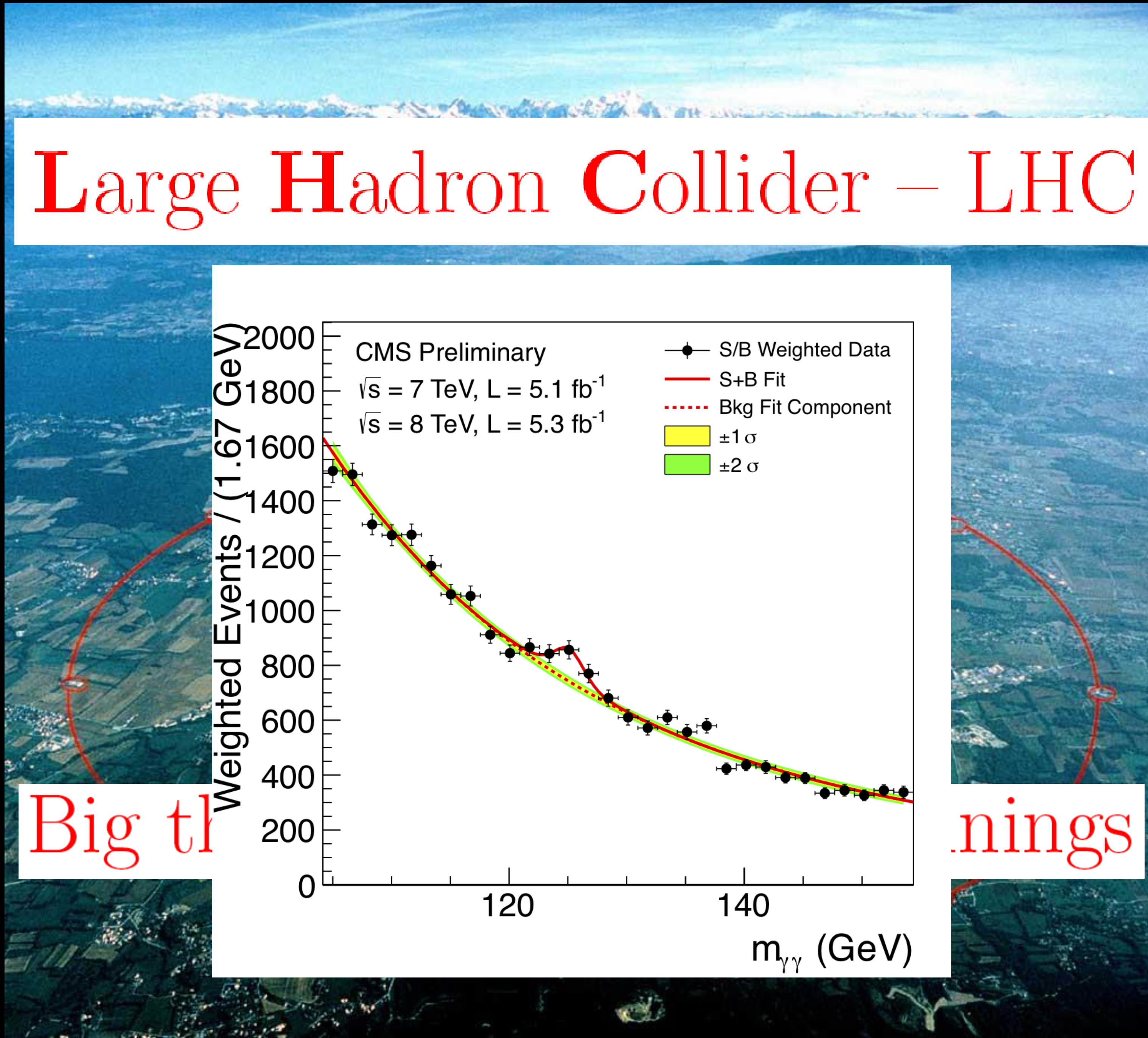
Operated first on January 2, 1931 – 70 keV protons

Cosmic rays are replaced by accelerators where particles are artificially produced

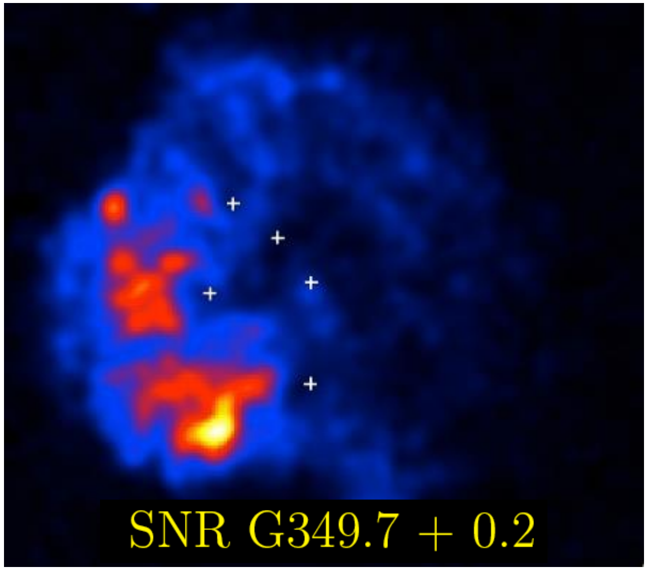


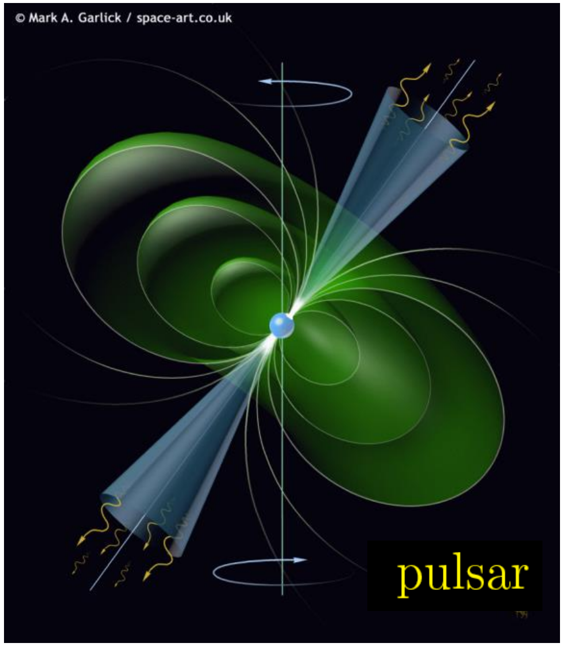
Cosmic rays are replaced by accelerators where particles are artificially produced

Large Hadron Collider – LHC



Cosmic rays and astrophysical accelerators



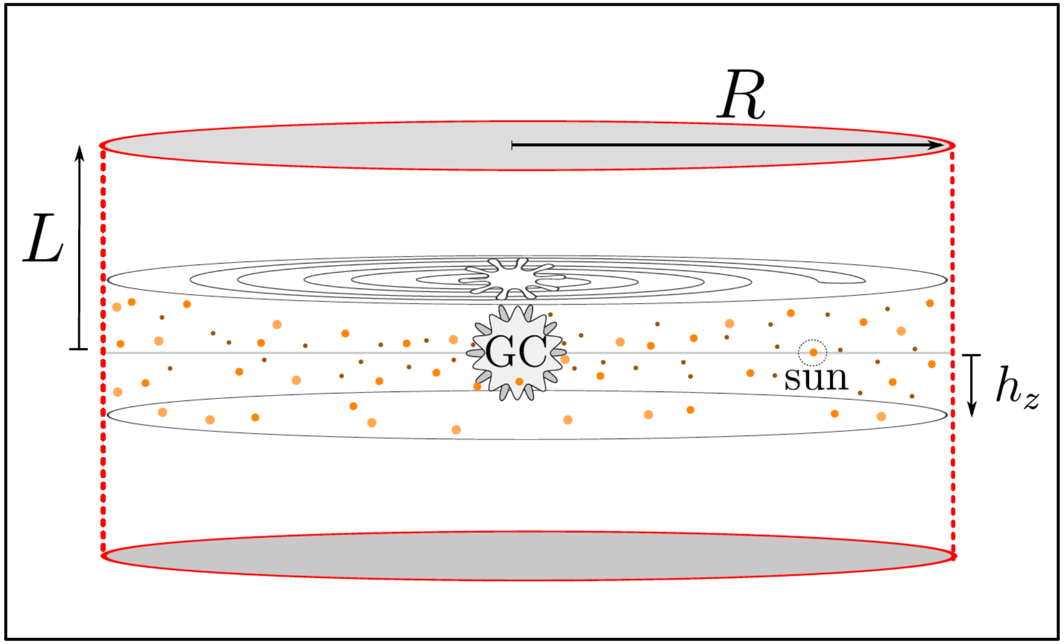


- Supernova driven shock waves accelerate the elements of the interstellar medium through a first order Fermi mechanism. Nuclei and electrons are injected.

- 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.

Cosmic rays and Galactic propagation

Lineros' PhD thesis (2008)



- Diffusion and convection in space $\vec{J} = -K\,\vec{\nabla}\psi + \psi\,\vec{V_C}$.
- Energy losses and second order Fermi mechanism.

$$J_E = b^{\rm loss}(E)\,\psi - D_{EE}(E)\,\partial_E\psi$$

- Steady state holds – not always. . .

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

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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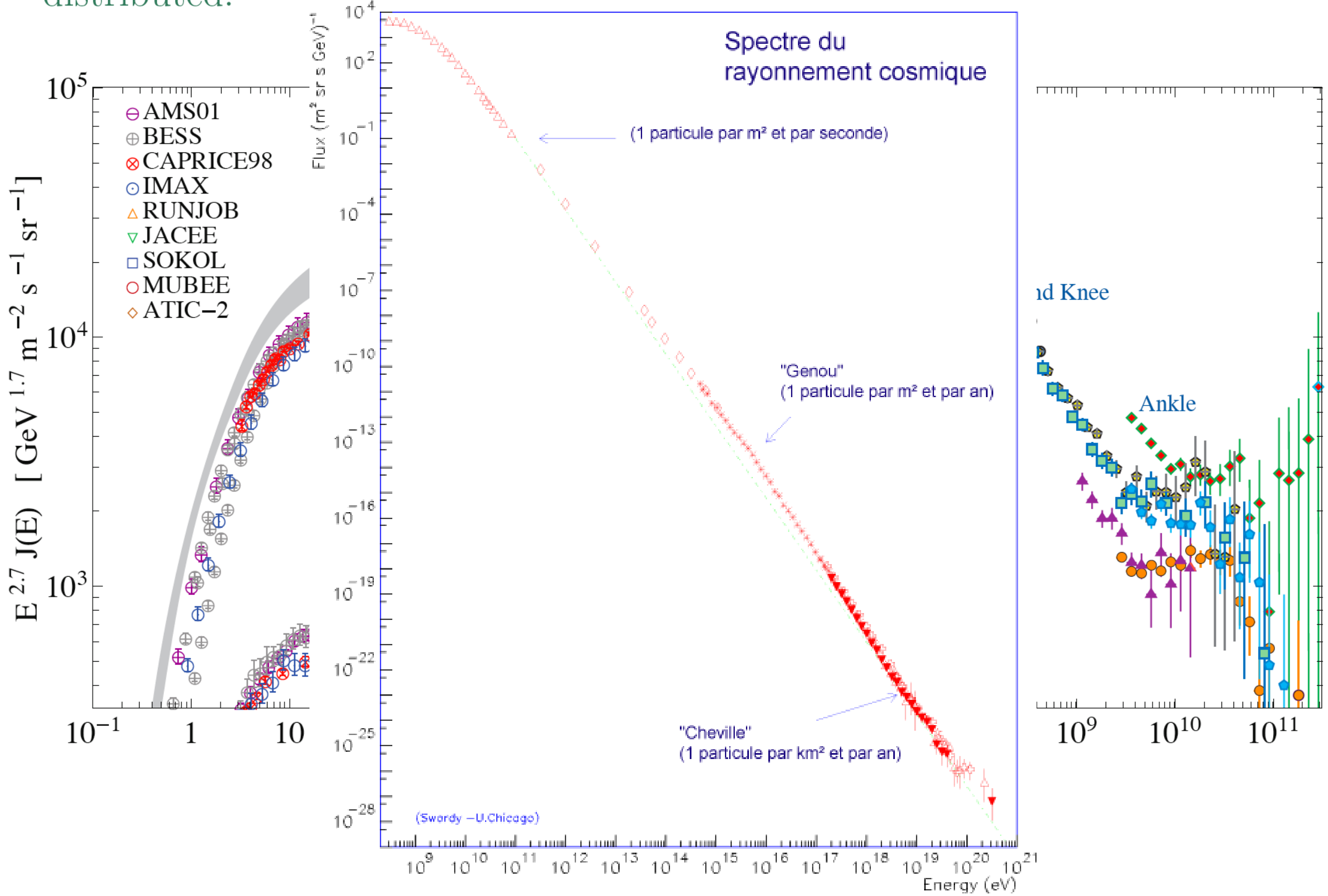
V in

Ultra–high energy cosmic rays from extra–galactic origin

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



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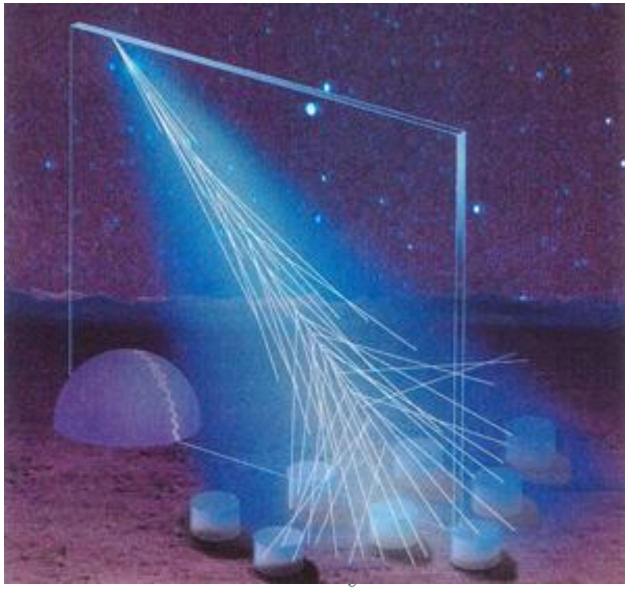
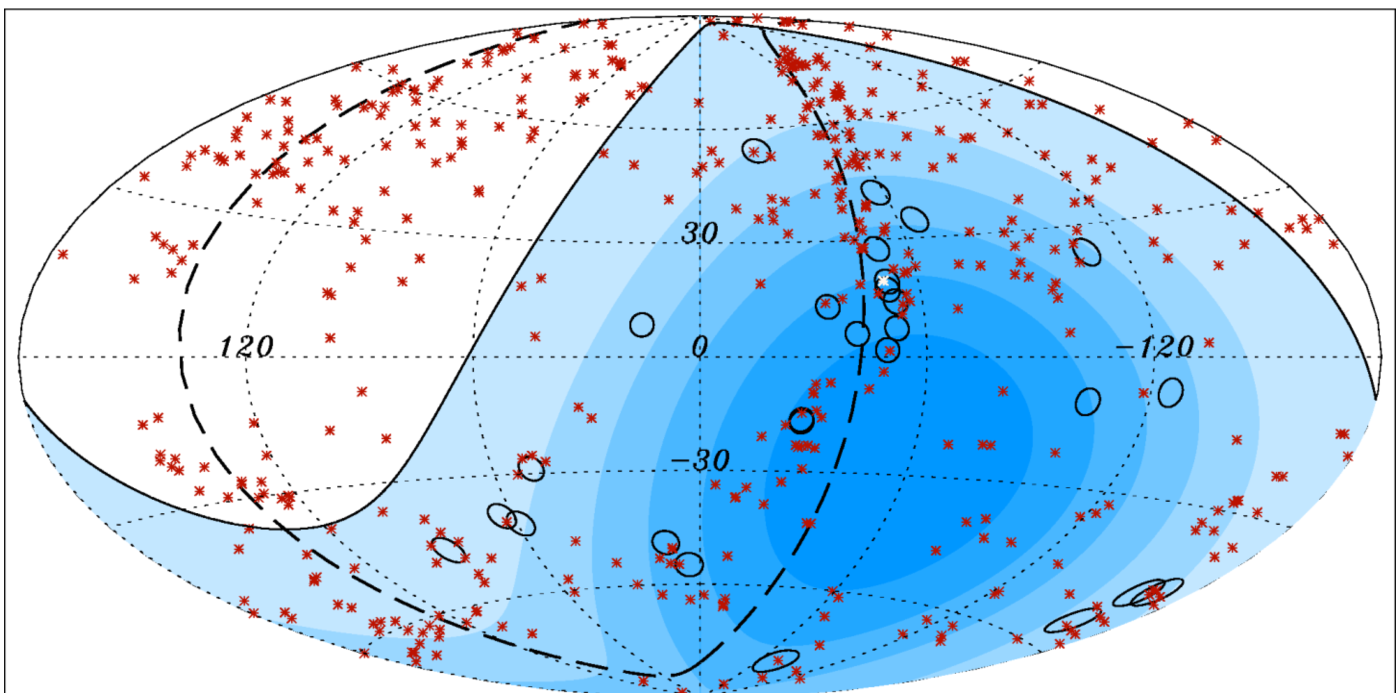


Kuzmin and G. Zatsepin show that abov
duces a pion on the CMB so that its
epth does not exceed ∼ 70 Mpc – GZK

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

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

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



Outline

Shock acceleration – First order Fermi mechanism

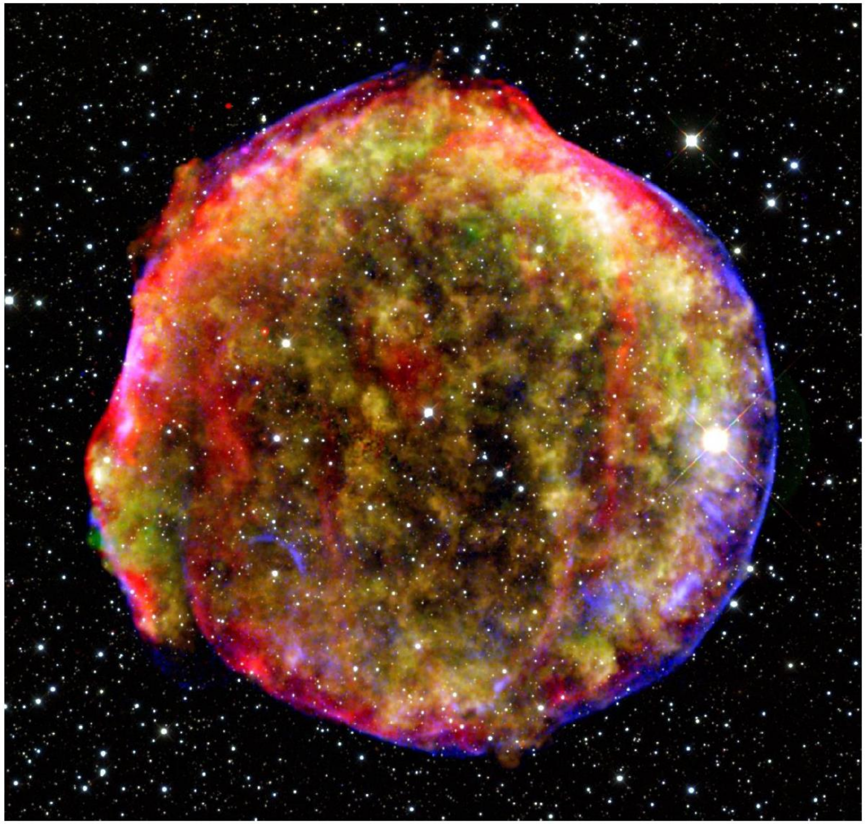
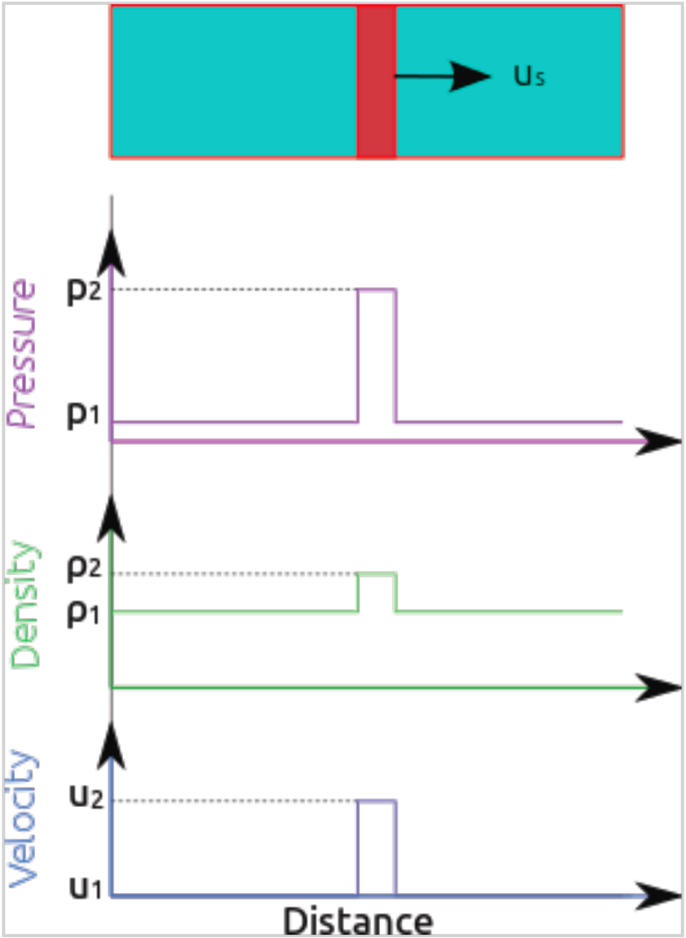


FIGURE 3.11: Restes de la SN de Tycho (1572)

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



One-dimensional shock wave in a medium. The shock moves with a velocity u_s. The coordinate system has been chosen to move with the shock so that the particle velocities outside the shock are zero. The shock front does not change with time in a stationary shock.

$$\rho_1 \, u_s = \rho_2 (u_s - u_2) \qquad \text{Conservation of mass}$$

$$p_2 - p_1 = \rho_2 \, u_2 \, (u_s - u_2) = \rho_1 \, u_s \, u_2 \qquad \text{Conservation of momentum}$$

$$p_2 \, u_2 = \rho_1 \, u_s \, \left(\tfrac{1}{2} u_2^2 + E_2 - E_1\right) \qquad \text{Conservation of energy}$$

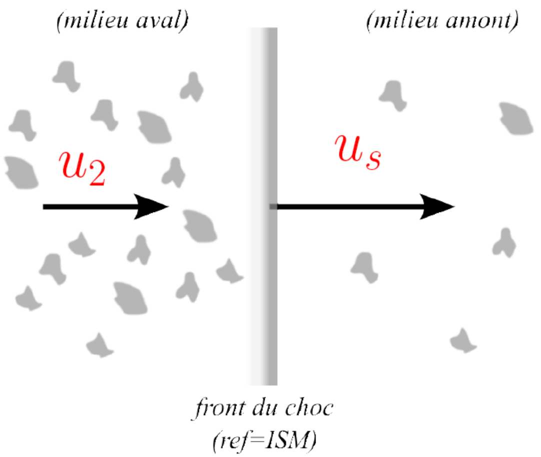


FIGURE 3.8: Référentiel du milieu interstellaire.

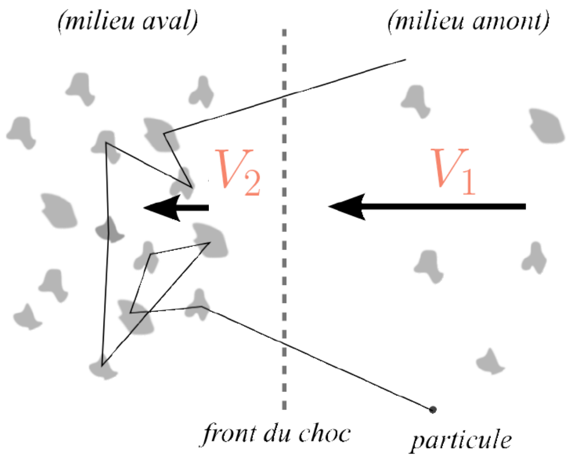


FIGURE 3.9: Référentiel de l'onde de choc.

courtesy Damir Buskulic

$$
\begin{aligned}
\rho_1 V_1 &= \rho_2 V_2 \quad \text{(mass)} \\
P_1 + \rho_1 V_1^2 &= P_2 + \rho_2 V_2^2 \quad \text{(momentum)} \\
\frac{P_1}{\rho_1} + e_1 + \frac{V_1^2}{2} &= \frac{P_2}{\rho_2} + e_2 + \frac{V_2^2}{2} \quad \text{(energy)} \\
P &= (\gamma - 1)\rho\, e \quad \text{(EOS)}
\end{aligned}
$$

$$
\frac{V_1}{V_2} = \frac{\rho_2}{\rho_1} = \frac{(\gamma-1)P_1 + (\gamma+1)P_2}{(\gamma-1)P_2 + (\gamma+1)P_1} = \frac{\gamma+1}{\gamma-1} \sim 4
$$

• A relativistic particle with momentum p_0 enters the shock from the upstream region. In the downstream frame, its momentum is p'. In the shocked medium, it is deflected and reflected. It crosses back the shock and is seen in the ISM frame with momentum

$$p_1 = p_0 \left(1 + \frac{u_2}{c}\right)^2$$

• Very crudely, a sixth of the particles cross the shock from the upstream medium. As seen from the shock frame, a fraction η of the particles that have ventured in the downstream region do not turn back and are convected away. They are lost.

$$\eta = \frac{6V_2}{c} \text{ so that } P_{\text{surv}} = 1 - \eta$$

• Particles that have undergone n cycles forth and back the shock are characterized by

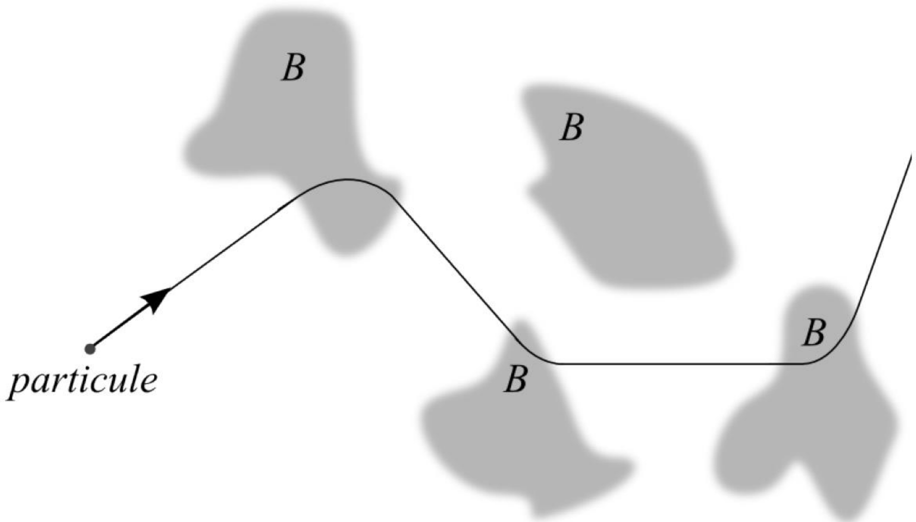
$$\log\left(\frac{N_n}{N_0}\right) = -\frac{3V_2}{V_1 - V_2} \log\left(\frac{p_n}{p_0}\right)$$

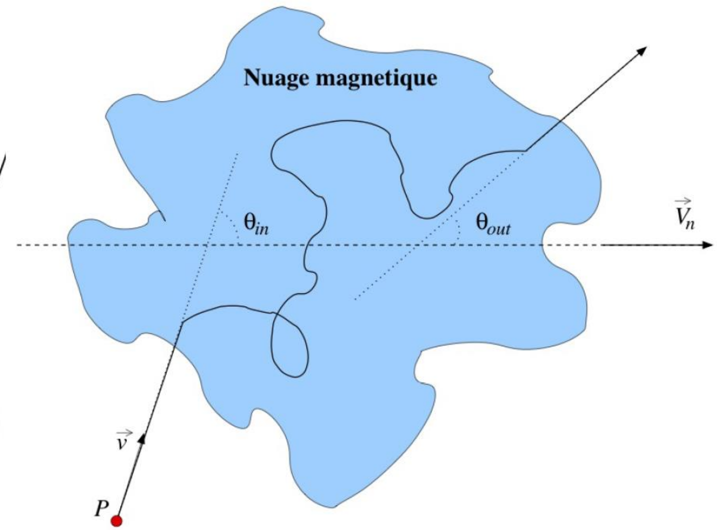
• The energy spectrum at the source can be readily inferred from

$$q(p) \propto \frac{dN}{dp} \propto p^{-2}$$

Stochastic acceleration – Second order Fermi mechanism

Fermi E., Phys. Rev. **75** 1169 (1949)





courtesy Damir Buskulic

- Particles are stochastically deflected by magnetic clouds that move with a velocity V_a with respect to the Galaxy. The deflections are elastic in the cloud frame – not in the Galactic frame !

• Assume naively that the magnetic clouds move along the x axis just like cosmic rays. Assume also that a particle has equal chance to be deflected forward and backward in the cloud frame. Lorentz invariance implies

$$E_1 \; = \; E_0 \; (50\%) \text{ and } E_1 \; = \; E_0 \; \left(1 \pm 2\beta_a \beta + 2\beta_a^2\right) \; (50\%)$$

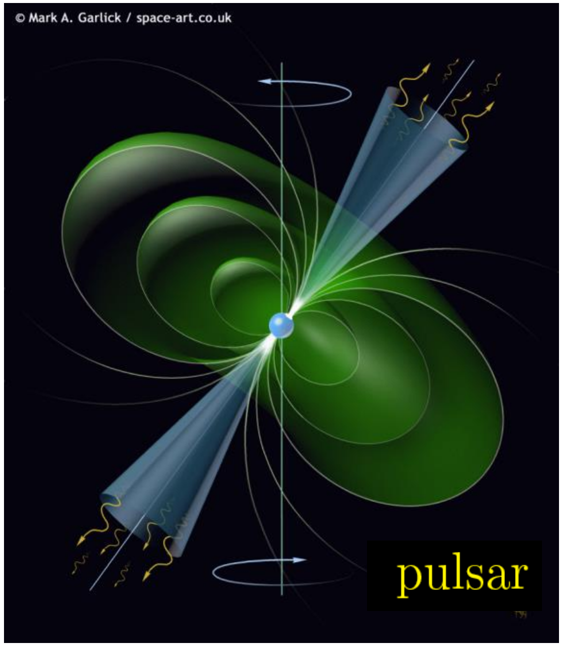
• A second order acceleration – proportional to V_a^2 – takes place with a rate related to the coefficient K of diffusion on the magnetic clouds

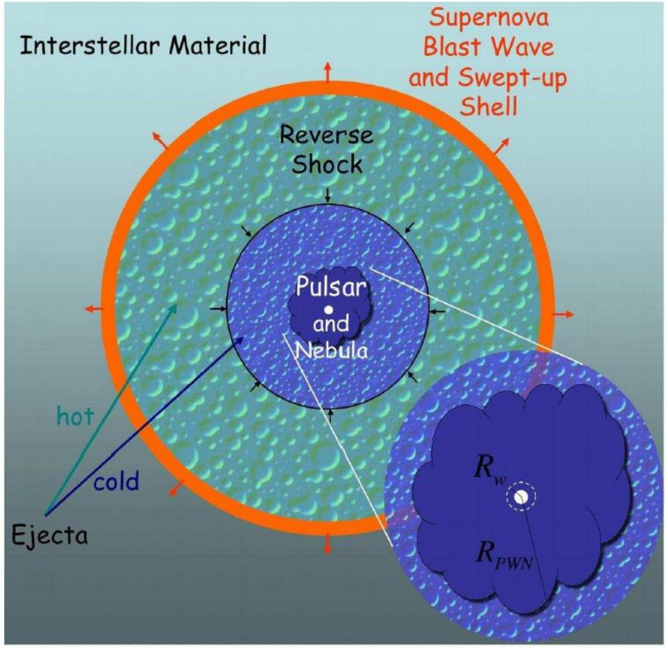
$$\frac{\langle \Delta E \rangle}{\Delta t} = \frac{V_a^2}{3K} \beta^2 E \text{ where } K = \tfrac{1}{3} \lambda \, \beta \, c$$

• A diffusion in energy also takes place with coefficient

$$D_{EE} = \frac{\left\langle (\Delta E)^2 \right\rangle}{\Delta t} = \frac{2}{3} \frac{V_a^2}{K} \beta^4 E^2$$

Acceleration by electromagnetic induction – Pulsars

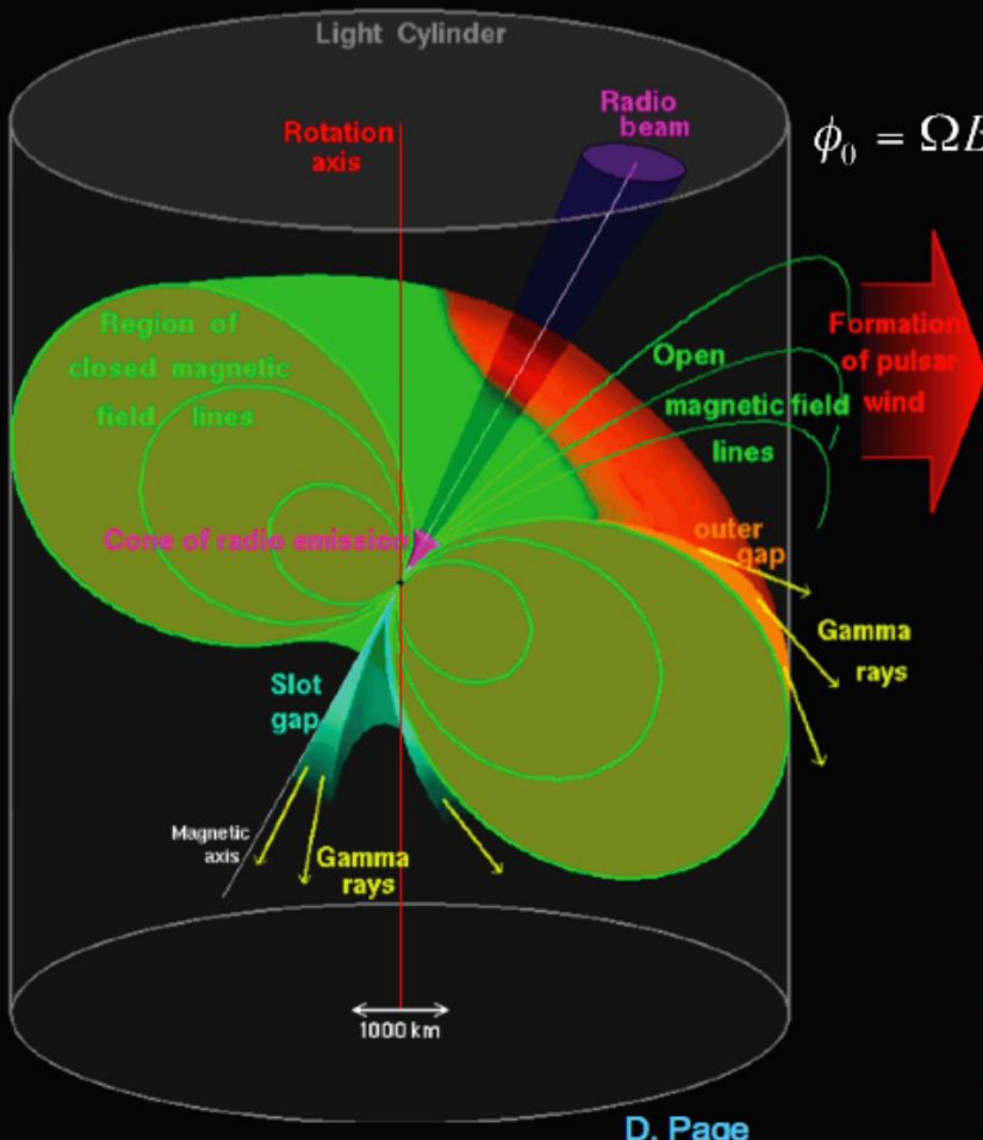




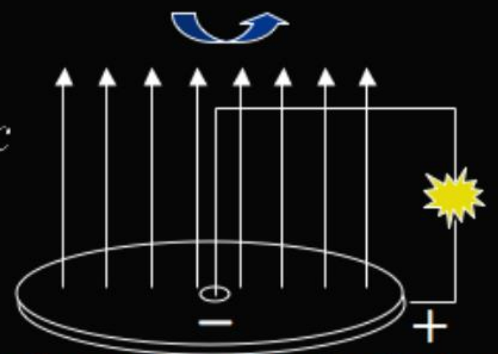
courtesy Solène Le Corre

• 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.

Courtesy of Anatoly Spitkovsky – Princeton



$$\phi_0 = \Omega B a^2 / c$$



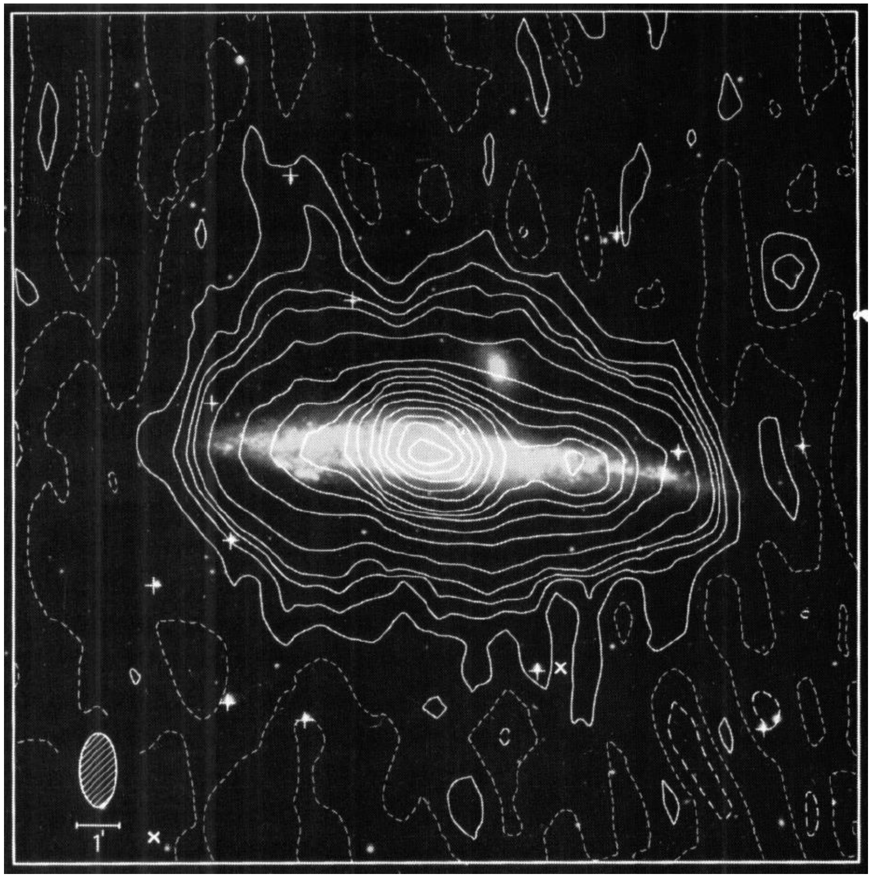
Faraday disk: unipolar induction

- *but pulsars are not in vacuum!*
- *Equator-pole potential difference (10^{15}V for Crab)*
- *Charge extraction from the surface (E field >> gravity)*
- *Currents, strong magnetization*
- *Corotating zone; Light cylinder*
- *Throwing away toroidal field -- energy loss (Poynting flux)*
- *Plasma currents modify field. How can we model this?*

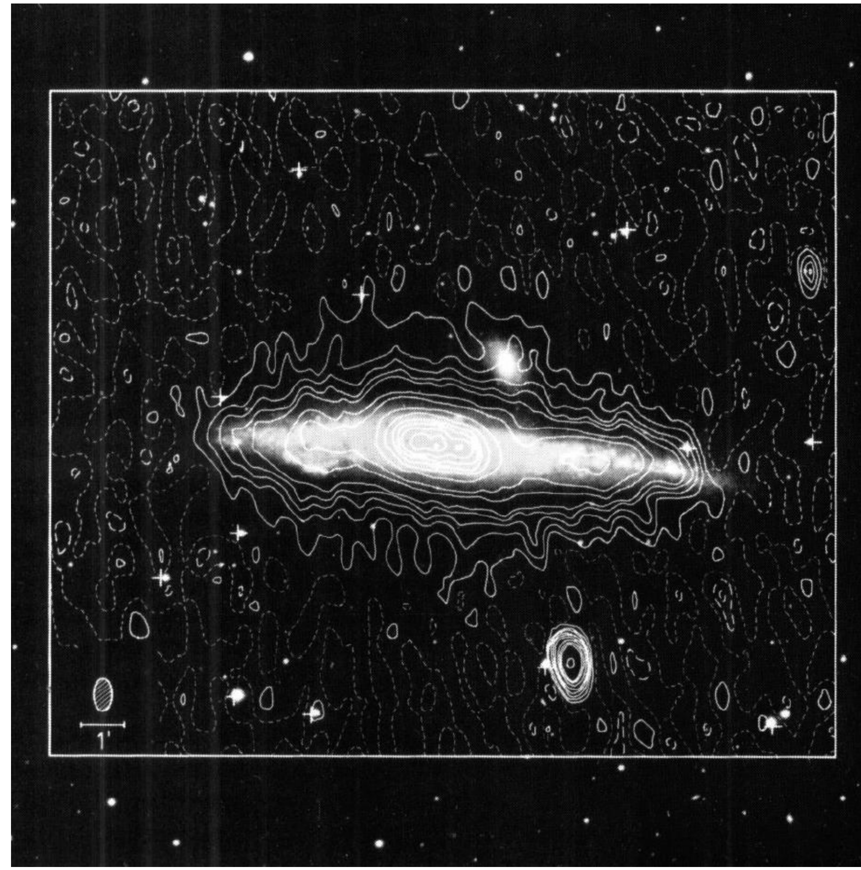
Outline

Propagation of particles inside the Galaxy

610 MHz



1412 MHz



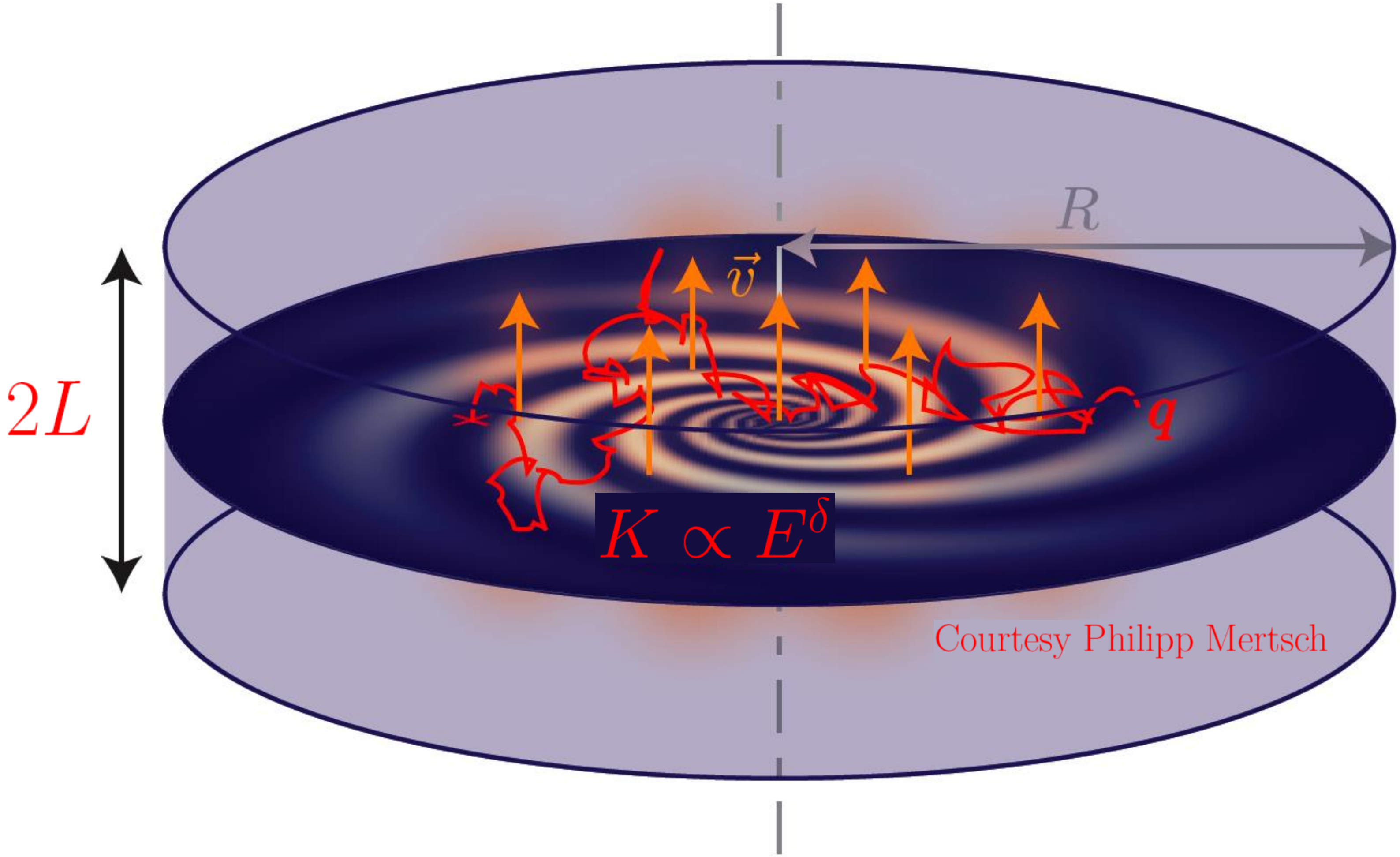
The Radio Continuum Halo in NGC 4631

R. D. Ekers and R. Sancisi

Astron. Astrophys. 54, 973—974 (1977)

Milky–Way seen by a cosmic–ray physicist

Cosmic rays propagate inside a diffusive halo



D. Maurin, R. Taillet, F. Donato, P. Salati, A. Barrau and G. Boudoul, *Galactic cosmic ray nuclei as a tool for astroparticle physics*, [astro-ph/0212111].

Cosmic–rays diffuse in space and energy

- A propagation model is characterized by the set δ, K_0, L, V_C, V_a

Case	δ	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

- Different methods to solve the CR diffusion equation

  The semi–analytic approach – radial Bessel expansion & Green functions

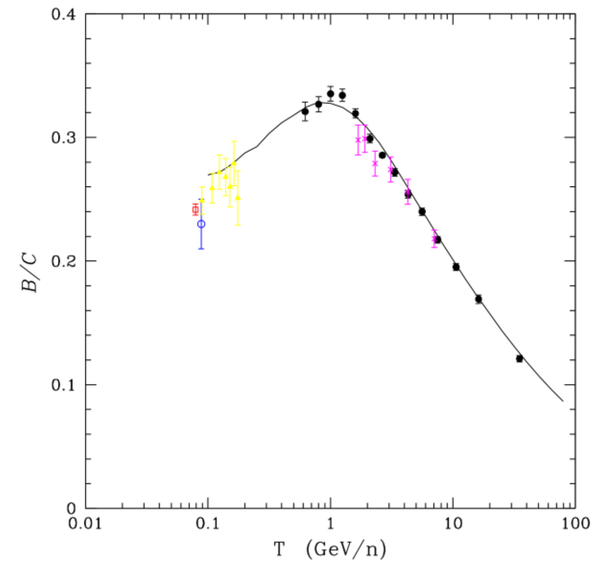
  The numerical Galprop code – Crank–Nicholson semi–implicit scheme

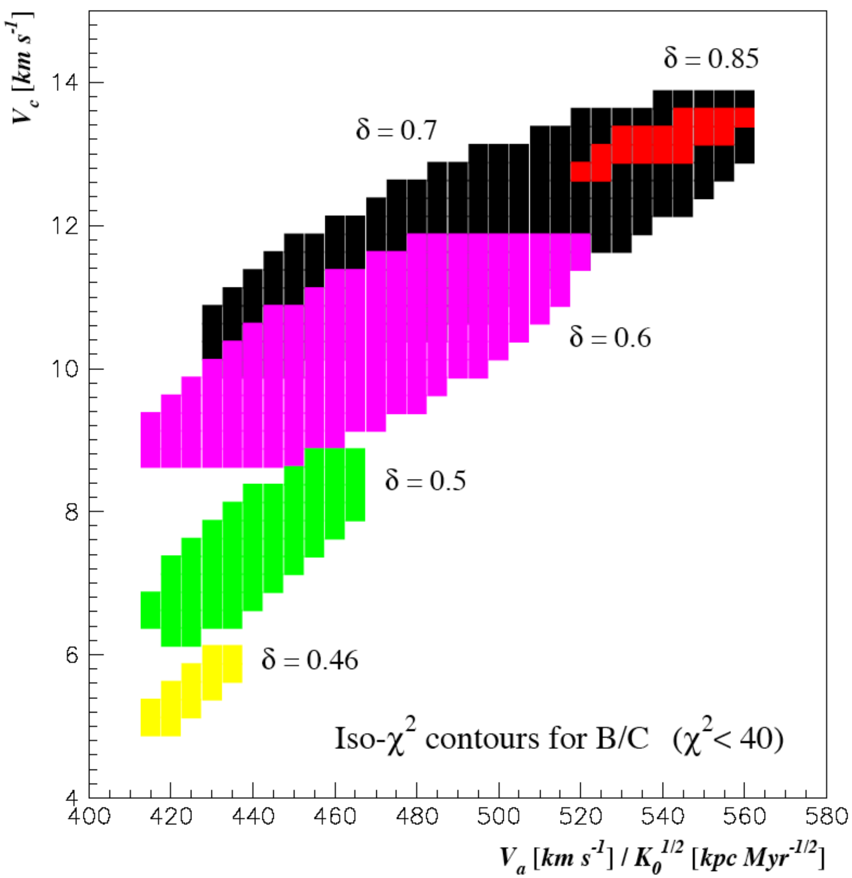
- Constraints from the typical secondary to primary B/C ratio

$$V_C \partial_z \Psi \; - \; K \, \Delta\Psi \; + \; \partial_E \left\{ b^{\text{loss}}(E) \, \Psi \; - \; K_{EE}(E) \, \partial_E \Psi \right\} \; = \; Q$$

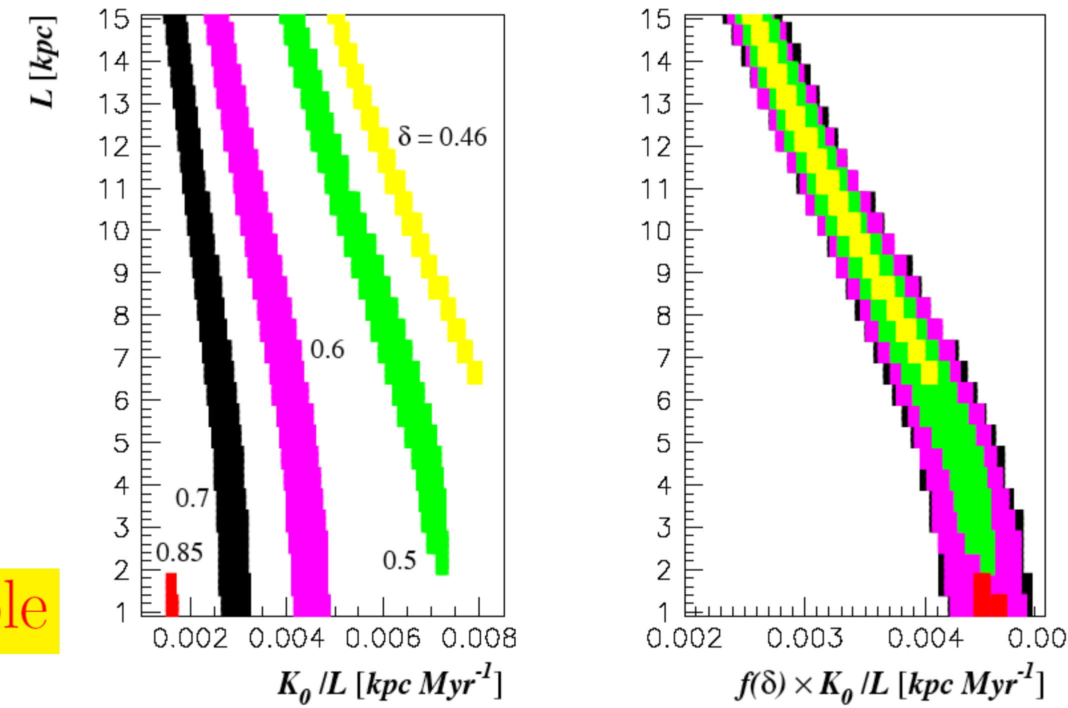
B/C ratio analysis – D. Maurin et al.

THE ASTROPHYSICAL JOURNAL, 555:585–596, 2001 July 10





Iso-χ^2 contours for B/C ($\chi^2 < 40$)



~ 1,600 models are compatible

Prehistoric leaky box model and the B/C ratio

$$\dot{\psi}_C = q_C - \frac{\psi_C}{\tau_{\rm esc}} - (\sigma v n_H)\,\psi_C \quad \text{and} \quad \dot{\psi}_B = -\frac{\psi_B}{\tau_{\rm esc}} + (\sigma v n_H)\,\psi_C$$

$$\psi_C = \frac{\tau_{\rm esc}}{1 + (\sigma\lambda/m_H)} \times q_C \quad \text{and} \quad \psi_B = \frac{\sigma\lambda}{m_H} \times \psi_C$$

$$\text{grammage } \lambda = 1.6 \text{ g cm}^{-2} \times \beta \times \left\{ \frac{\tau_{\rm esc}}{1 \text{ Myr}} \right\}$$

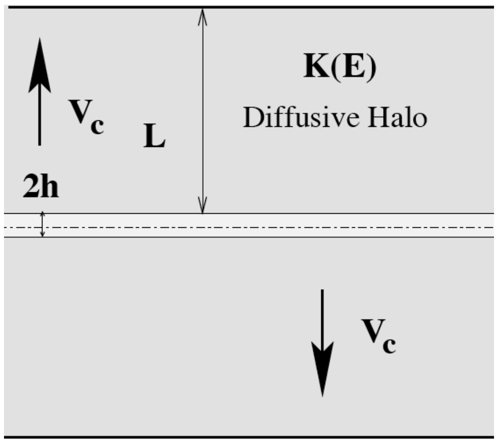
Infinite slab and 1D vertical (over)simplified CR model

$$\dot{\psi} + \vec{\nabla} \cdot \left\{ - K \vec{\nabla}\psi + \psi \vec{V}_C \right\} = Q$$

$$- K\, \partial_z^2 \psi + \partial_z(\psi\, V_C) = 2h\, \delta(z)\, Q$$

$$\psi(0) = \tau_{\rm esc} \times Q$$

$$\tau_{\rm esc} = \frac{h}{V_C} \left\{ 1 - e^{-V_C L/K} \right\}$$

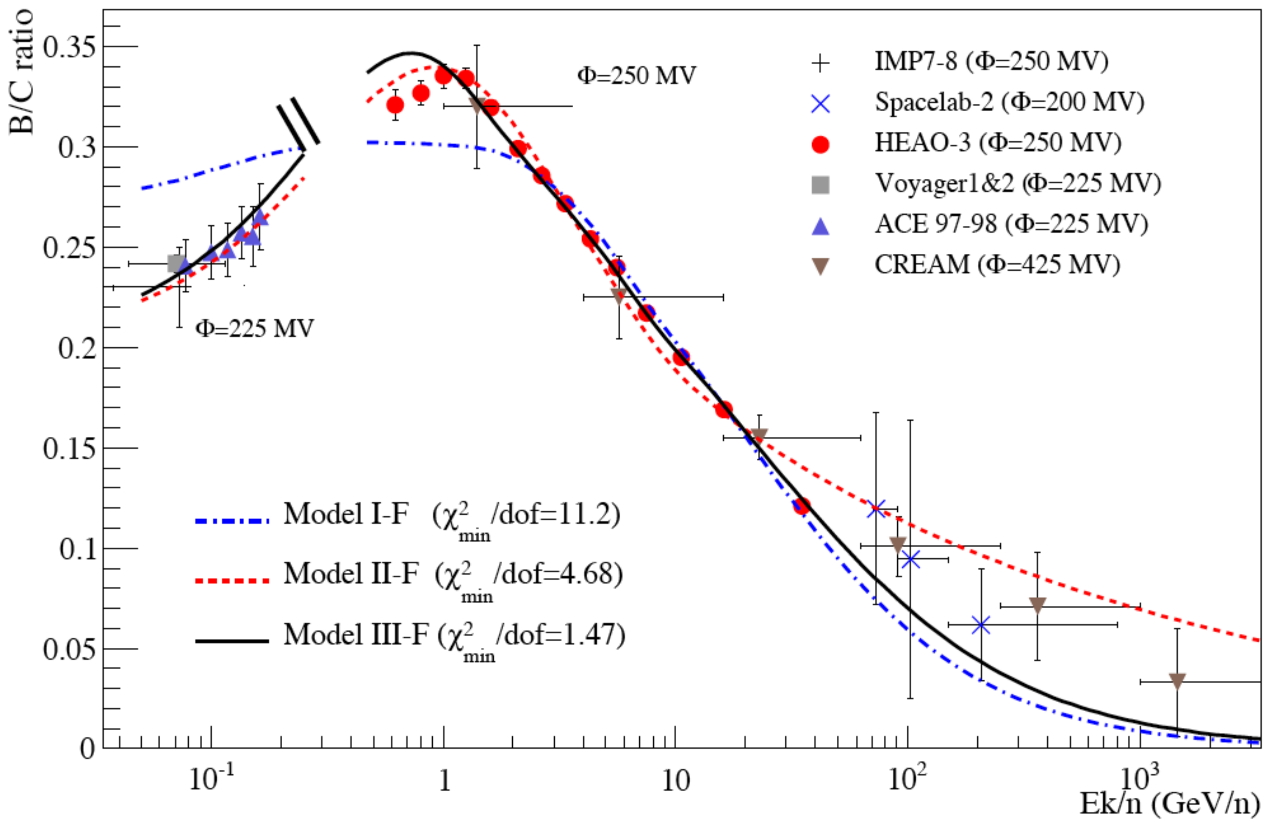


$$\tau_{\rm esc}(\text{low T}) = \frac{h}{V_C} \quad \text{while} \quad \tau_{\rm esc}(\text{high T}) = \frac{hL}{K} \propto \mathcal{R}^{-\delta}$$

A Markov Chain Monte Carlo technique to sample transport and source parameters of Galactic cosmic rays

II. Results for the diffusion model combining B/C and radioactive nuclei

A. Putze[1,2], L. Derome[2], and D. Maurin[3,4,5]



USINE code soon public !

arXiv:1001.0551v1 [astro-ph.HE] 4 Jan 2010

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A. Putze[1,2], L. Derome[2], and D. Maurin[3,4,5]

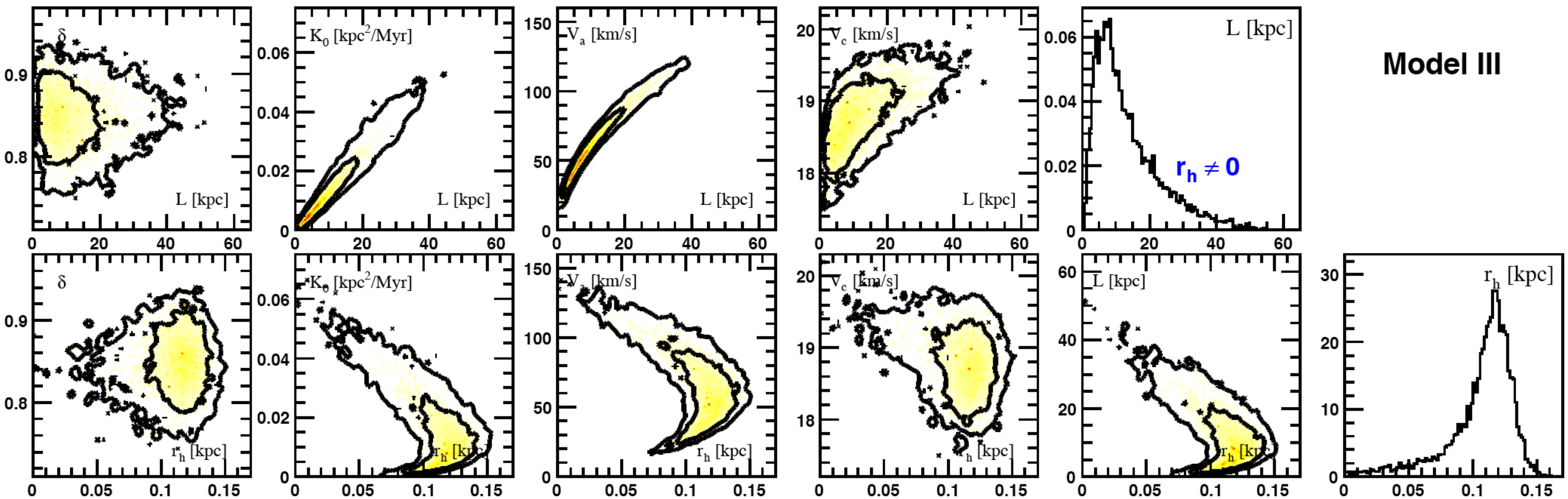


Fig. 7. Model III (diffusion/convection/reacceleration): same as in Fig. 6. The transport parameters are now δ, K_0, V_a and V_c, with the geometrical parameters L and r_h.

	$K_0 \times 10^2$ (kpc^{2}Myr^{-1})	δ	V_c (km s^{-1})	V_a (km s^{-1})	L (kpc)	r_h (pc)
III	$0.8^{+1}_{-0.7}$	$0.86^{+0.03}_{-0.04}$	$18.7^{+0.5}_{-0.4}$	55^{+31}_{-21}	8^{+8}_{-7}	120^{+20}_{-20}

arXiv:1001.0551v1 [astro-ph.HE] 4 Jan 2010

Outline

Cosmology – the dark matter problem

Fritz Zwicky and the Coma cluster – 1933

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 86 OCTOBER 1937 NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

The determination of the masses of extragalactic nebulae constitutes at present one of the major problems in astrophysics. Masses of nebulae until recently were estimated either from the luminosities of nebulae or from their internal rotations. In this paper it will be shown that both these methods of determining nebular masses are unreliable. In addition, three new possible methods will be outlined.

Cosmology – the dark matter problem

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

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

average square of the velocities of the individual nebulae which con-
stitute this cluster.[5] But even if we drop the assumption that clus-

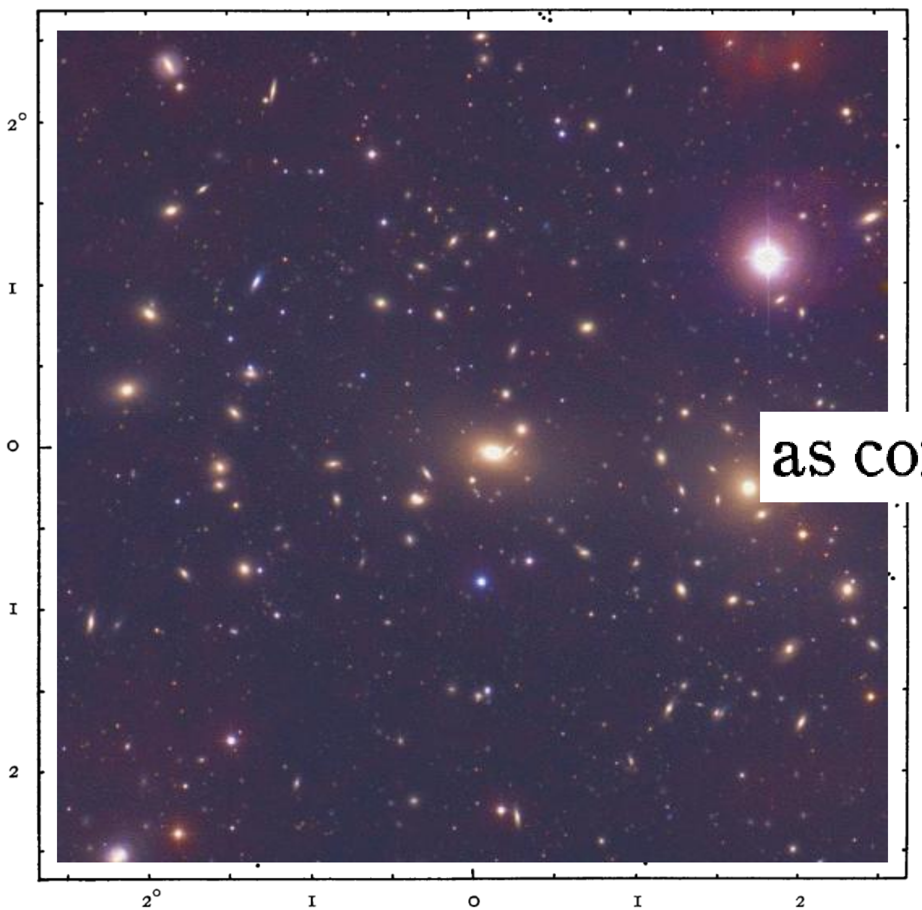


FIG. 3.—The Coma cluster of nebulae

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

$$\gamma = 500$$

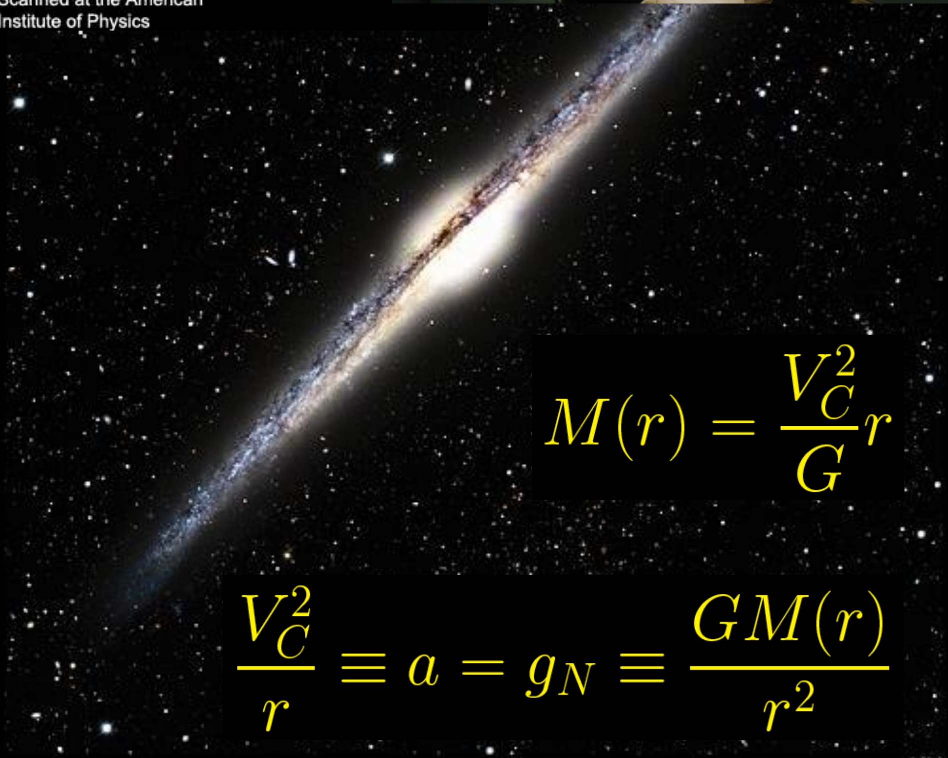
as compared with about $\gamma' = 3$

Zwicky's legacy

In principle the virial theorem may also be applied to describe the mechanical conditions in an individual nebula. Actually a direct application is difficult, since it is not possible to measure separately, as in the case of a cluster of nebulae, the velocities of the individual units of mass which constitute a nebula. The average square velocity (21) might be derived from the shape of the spectral lines in the light from nebulae. Unfortunately, the practical determination of such shapes is at present exceedingly difficult, if not impossible. In addition the spectral lines in the light of nebulae are doubtless of complex origin, and the interpretation even of well-known shapes of lines is by no means an easy task.

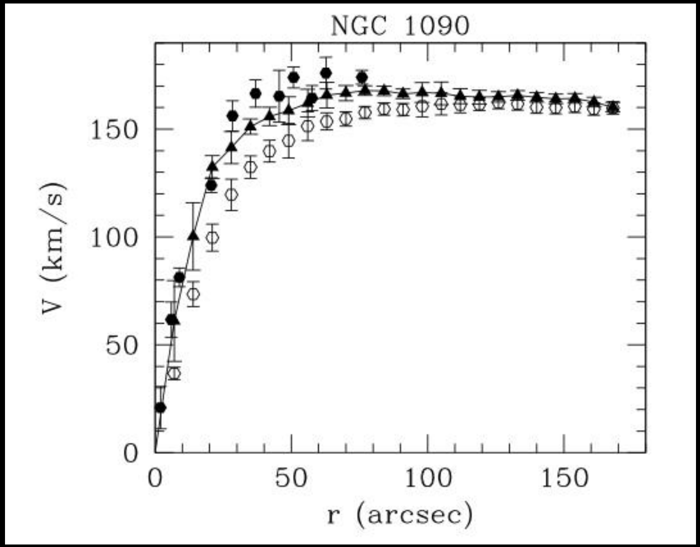
Flat rotation curves of spiral galaxies

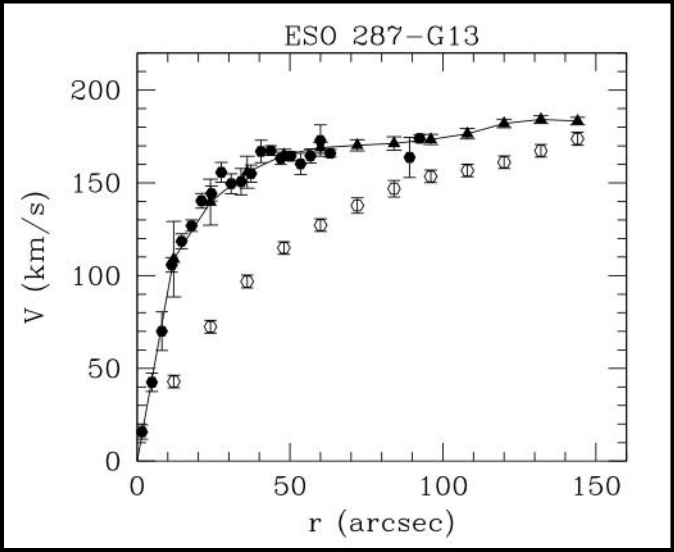
Scanned at the American Institute of Physics



$$M(r) = \frac{V_C^2}{G} r$$

$$\frac{V_C^2}{r} \equiv a = g_N \equiv \frac{GM(r)}{r^2}$$



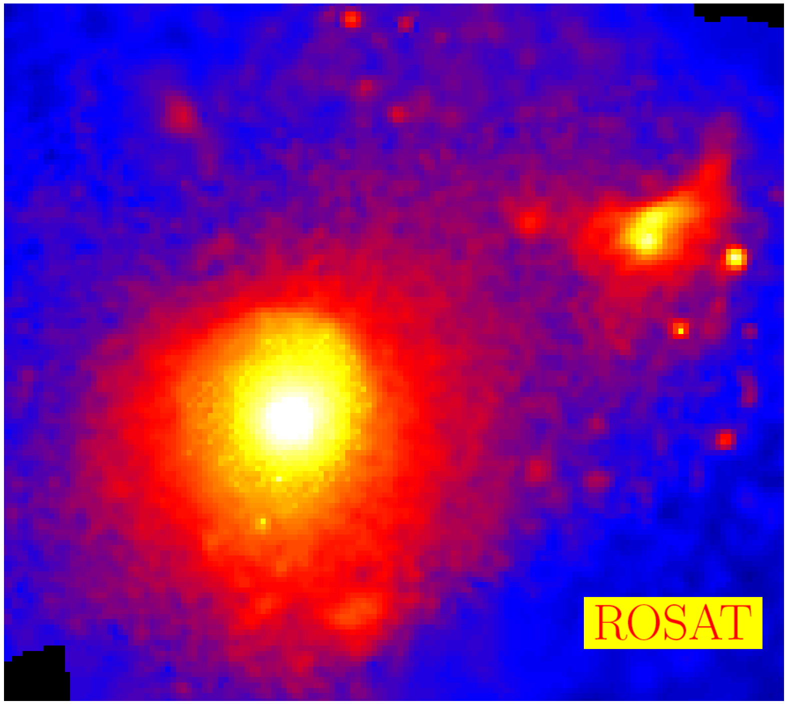


Cosmology – the dark matter problem

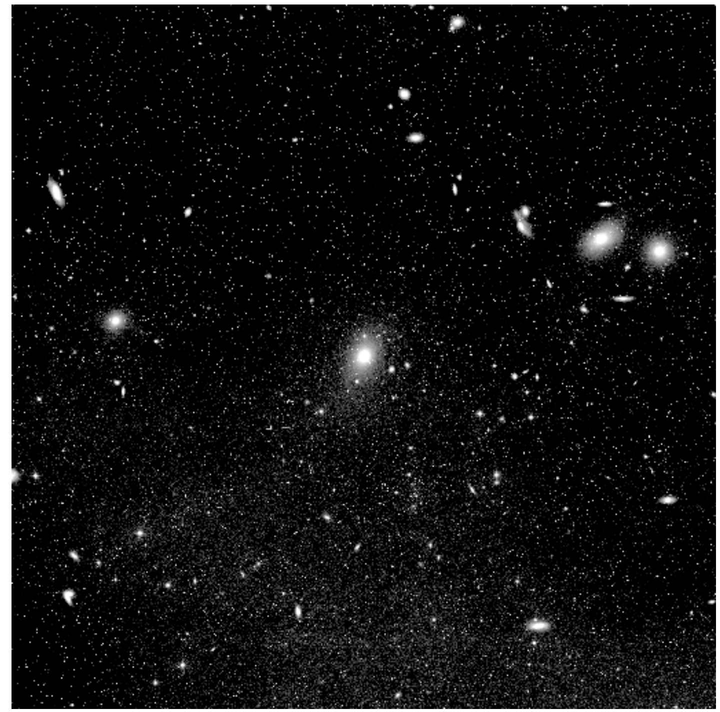
- X–ray observations $\Rightarrow$ presence of hot gas (T, n_e)

$$v \sim 500 \text{ km s}^{-1} \Rightarrow 10^{13}\ \mathrm{M}_\odot \text{ in the inner 100 kpc}$$

M87 – X ray image

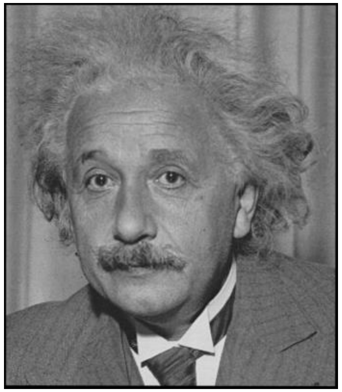


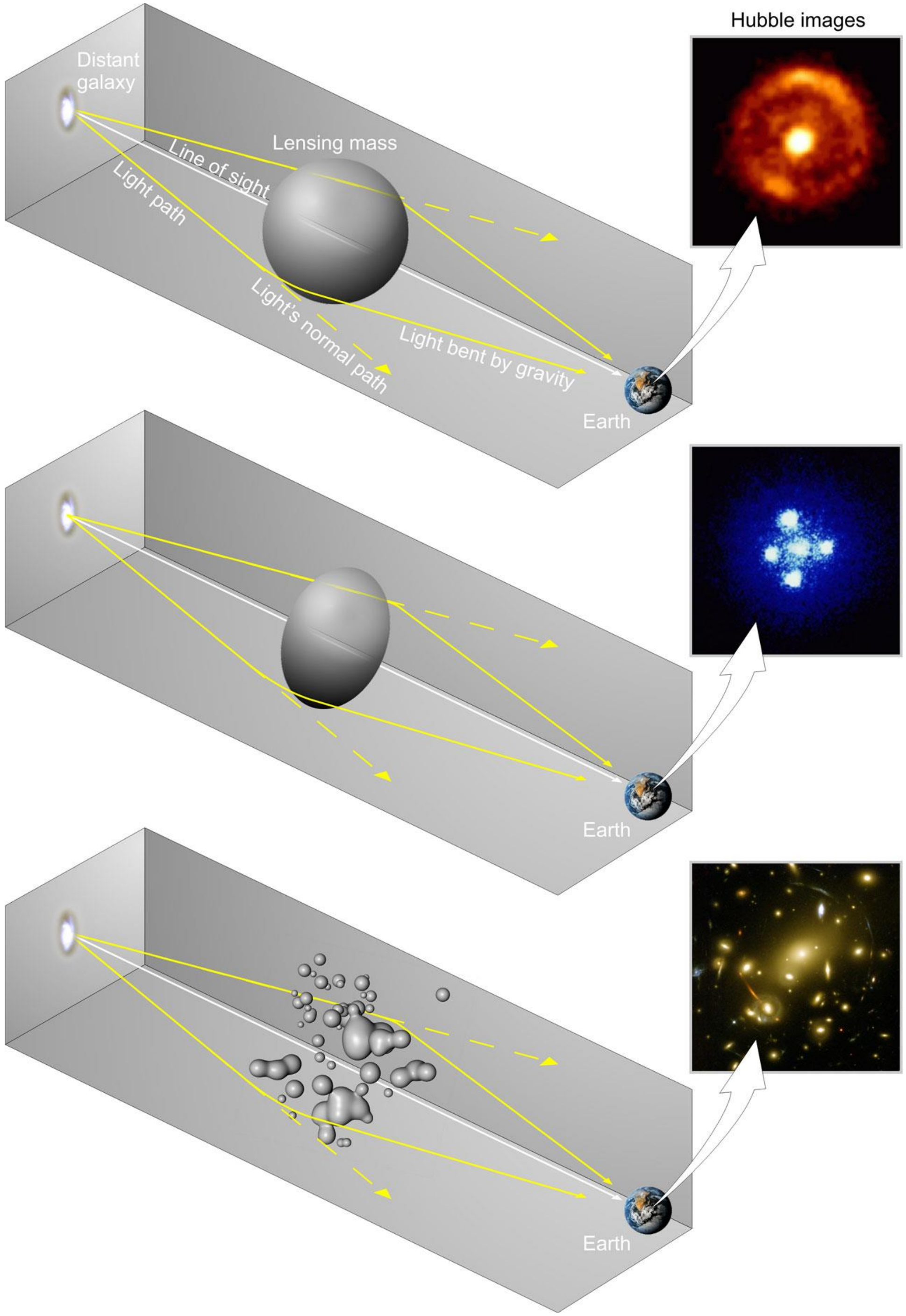
M87 – Optical



$$M_{\rm tot}(r) = -\frac{k\,T}{G\,\bar{\mu}}\,r\left\{\frac{d\ln n_e}{d\ln r} + \frac{d\ln T}{d\ln r}\right\} \quad >> \quad M_{\rm gas+stars}$$

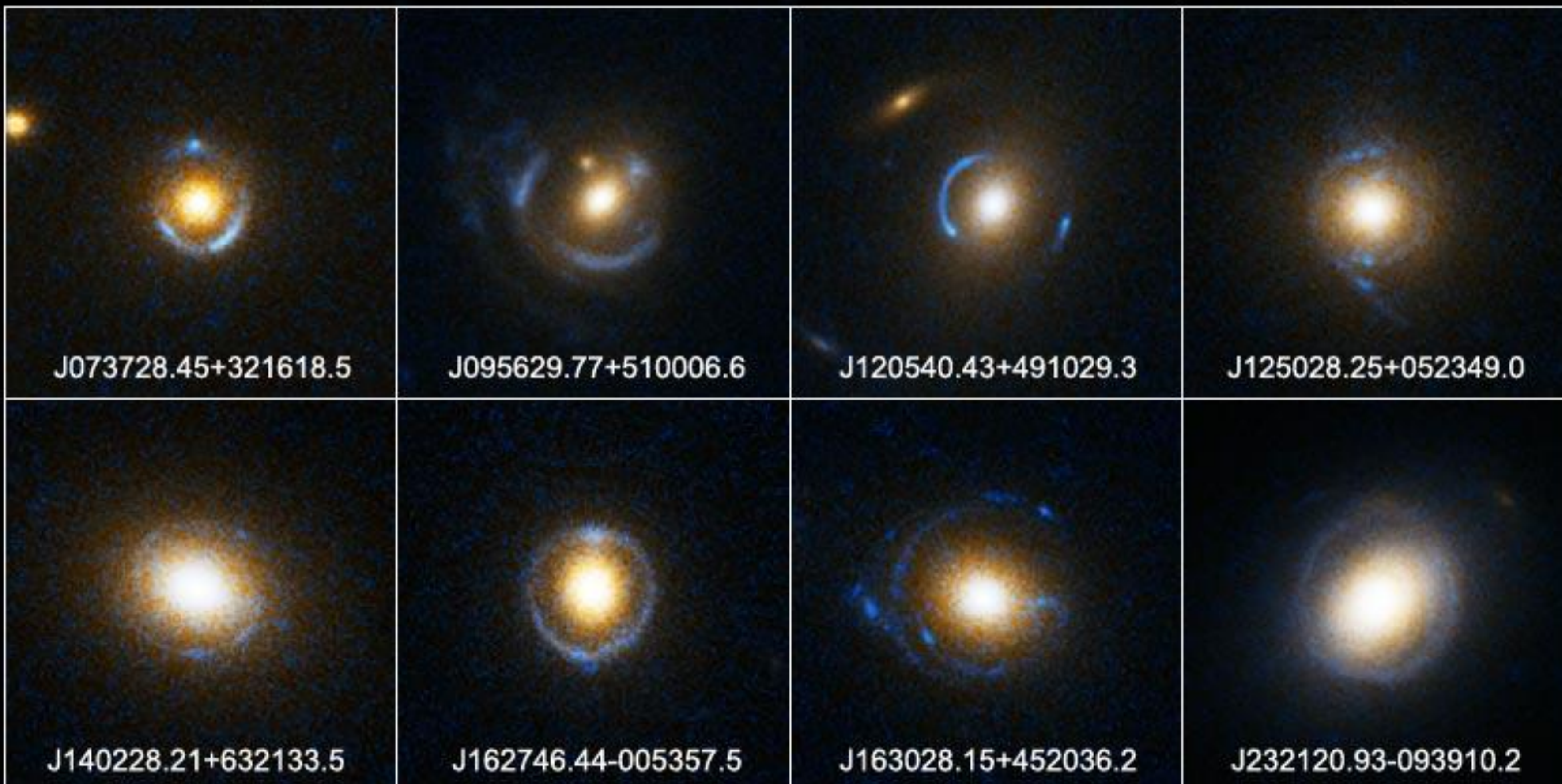
Spherical cluster in hydrostatic equilibrium




Hubble images
Distant galaxy
Lensing mass
Line of sight
Light path
Light's normal path
Light bent by gravity
Earth
Earth
Earth

Einstein Ring Gravitational Lenses

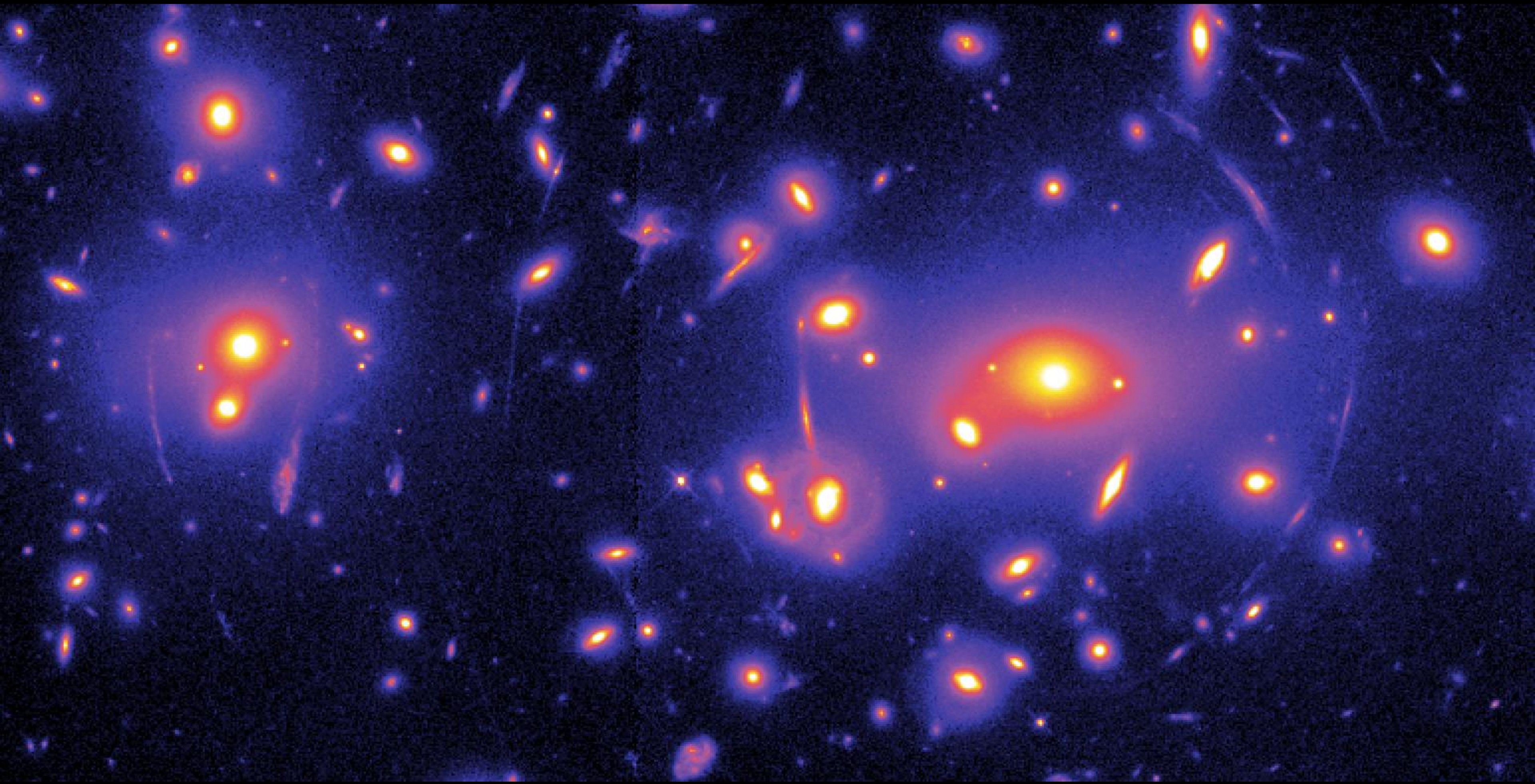
Hubble Space Telescope ▪ ACS



NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team

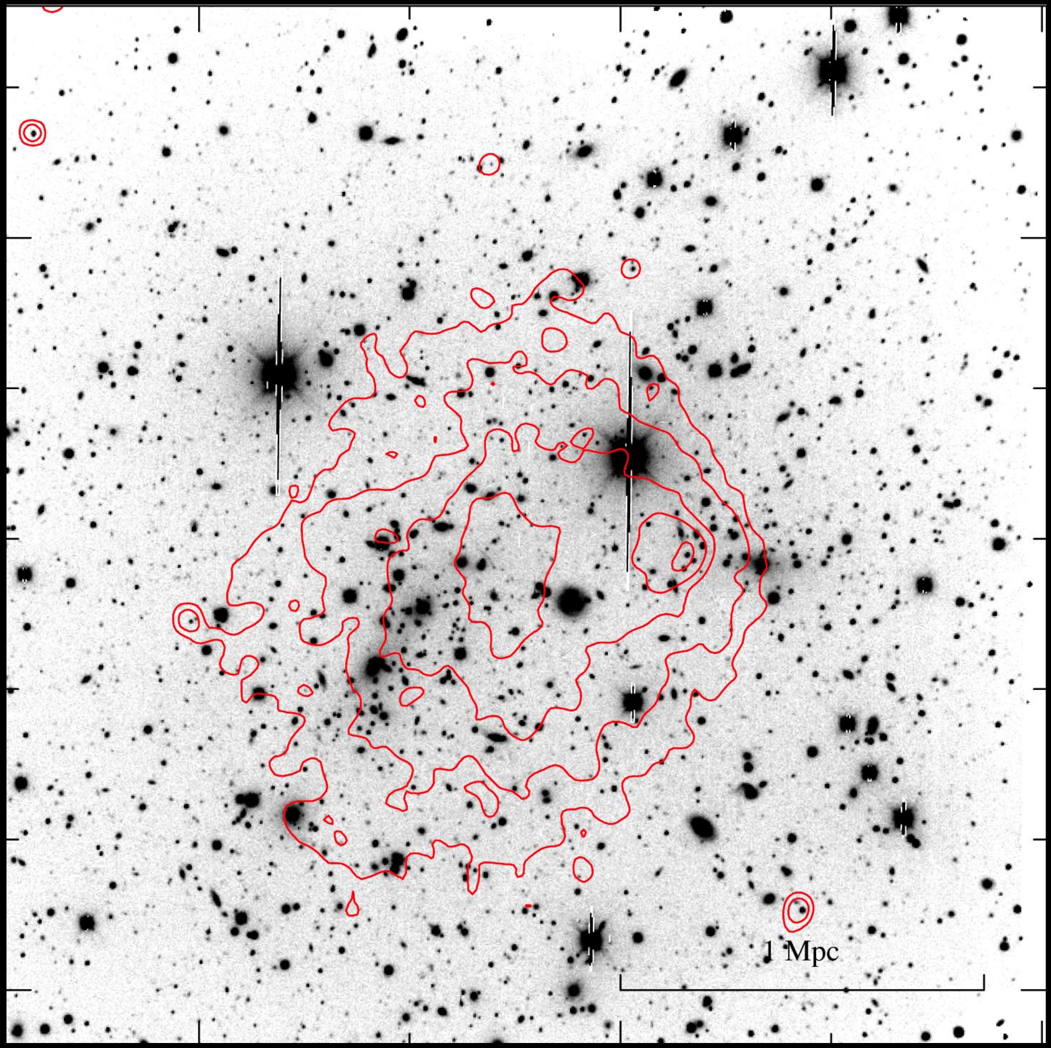
STScI-PRC05-32

Abell 2218 is located at 1 Gpc in Draco



Dougl ... ndall[4],

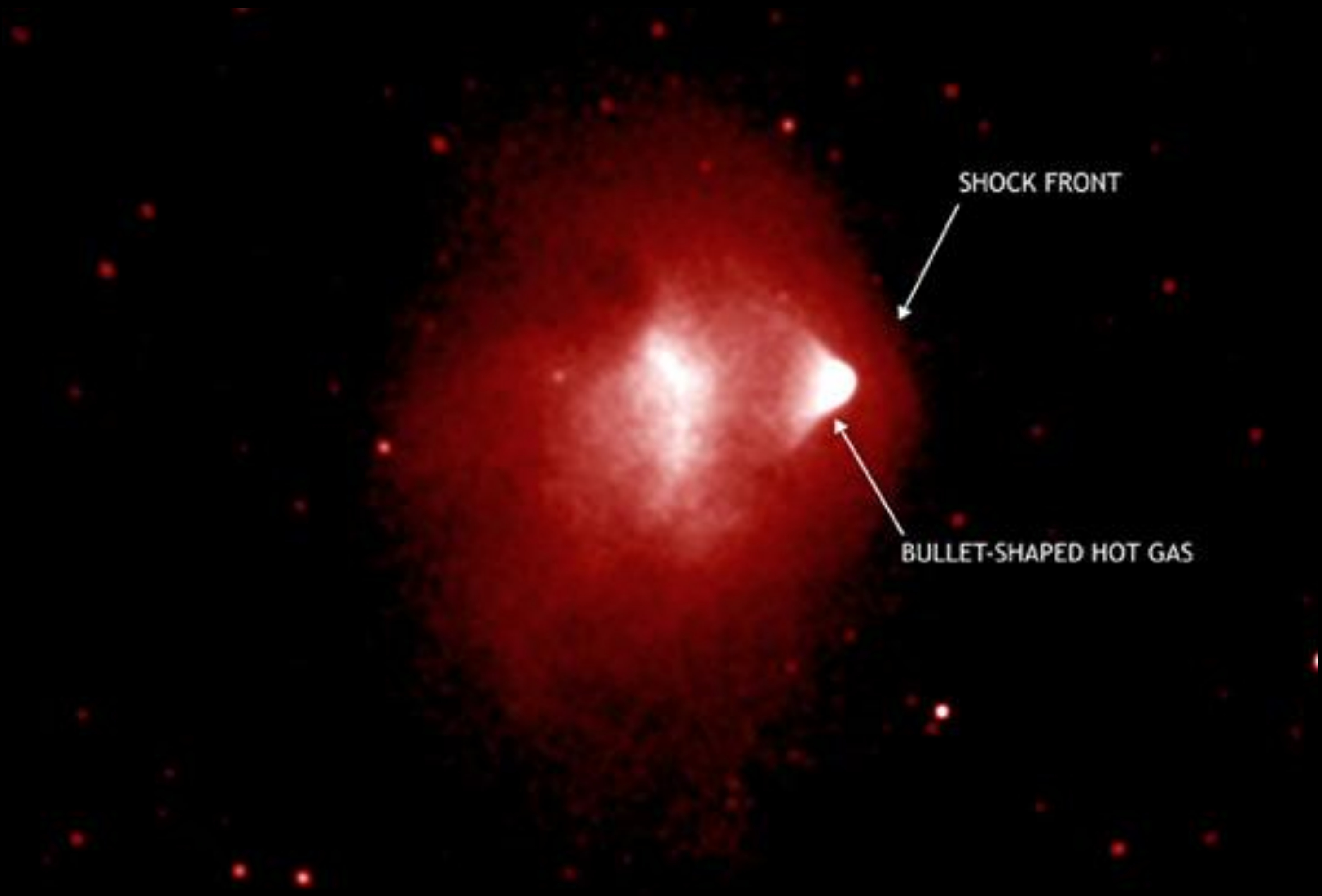
Optical Image with Chandra X–ray Contours



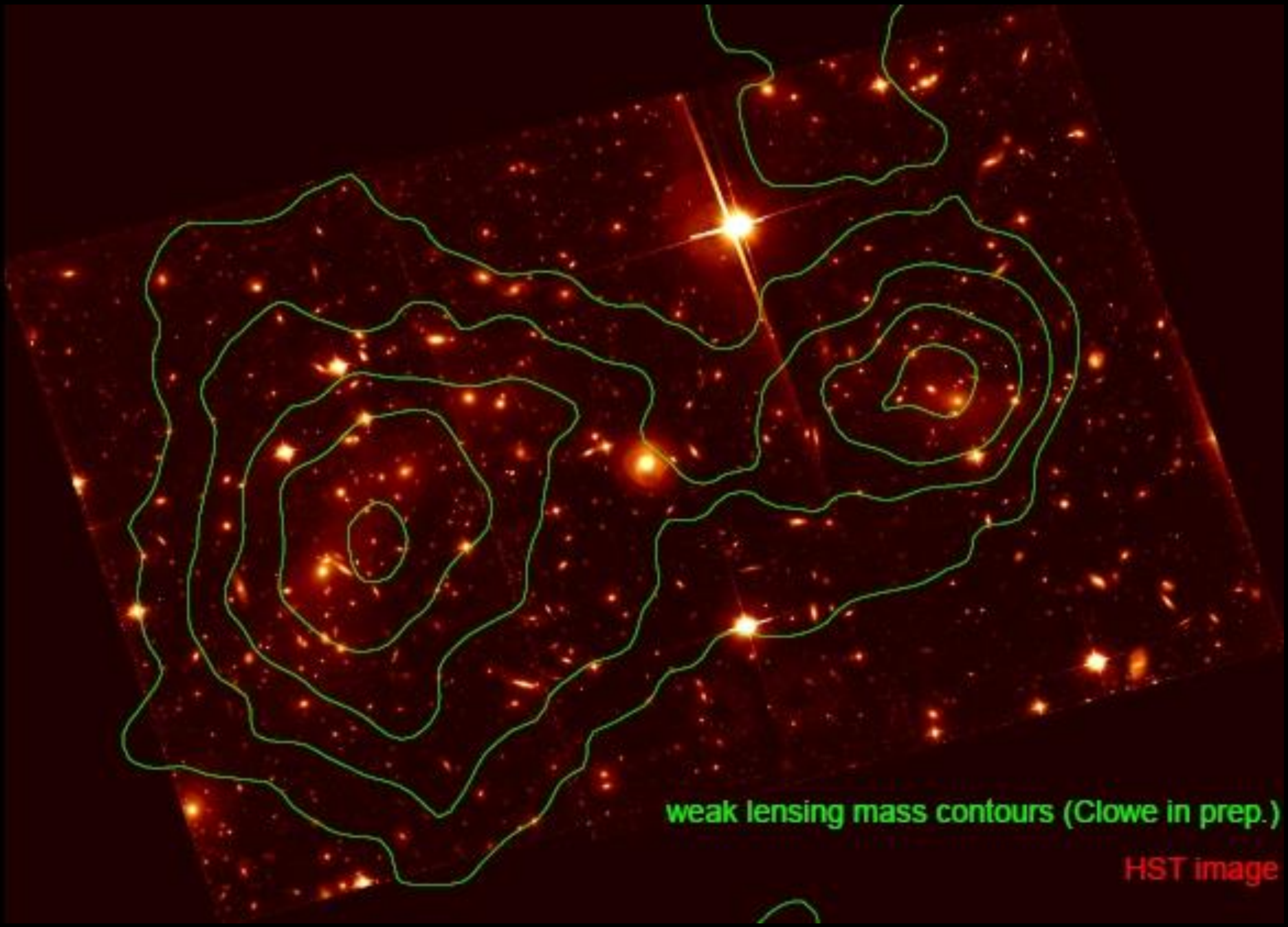
NASA Chandra

ESO NTT

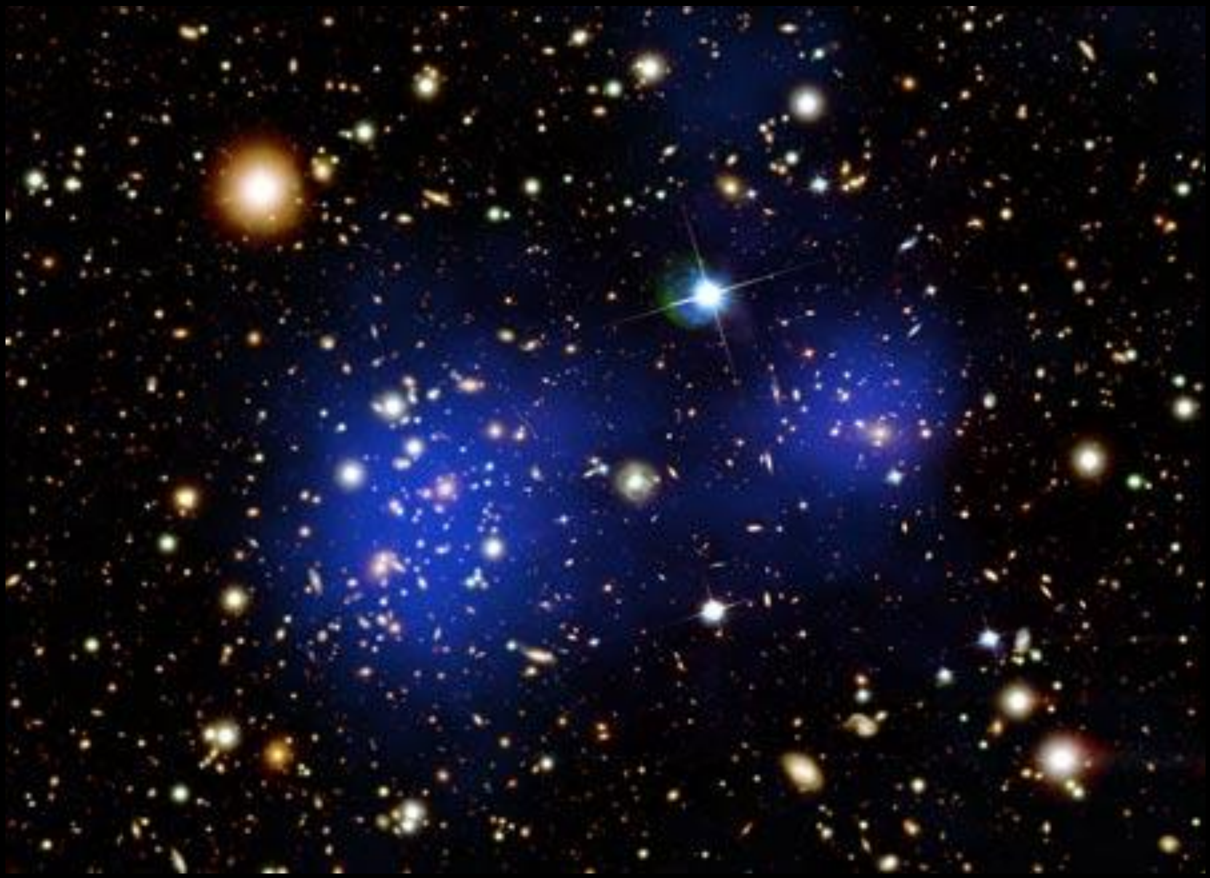
The bullet cluster : hot gas



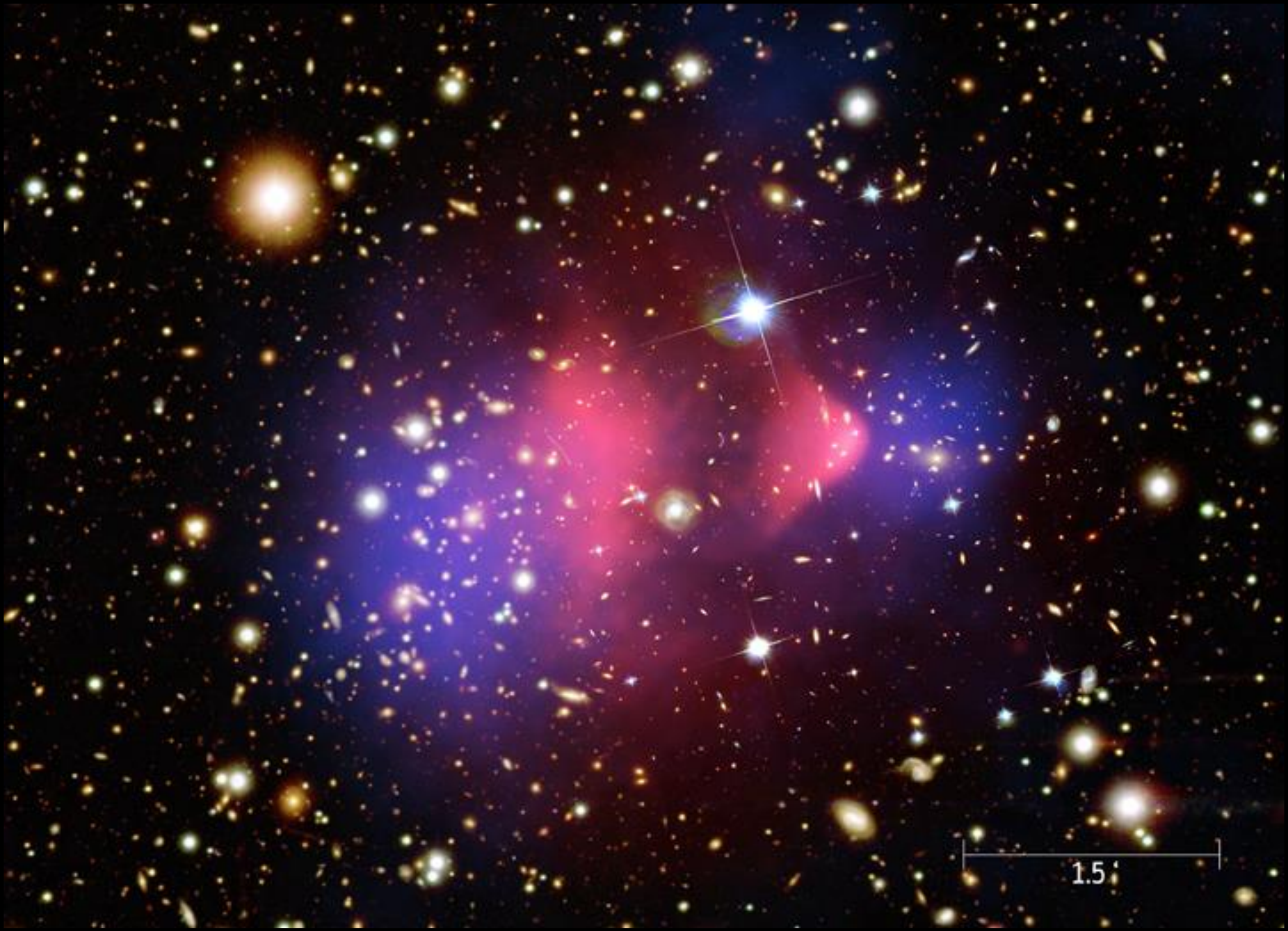
HST Image with κ-Map Contours



The bullet cluster : optical + dark matter



Dark matter and hot gas are different !



Cosmological micro–wave background

Cosmological micro–wave background

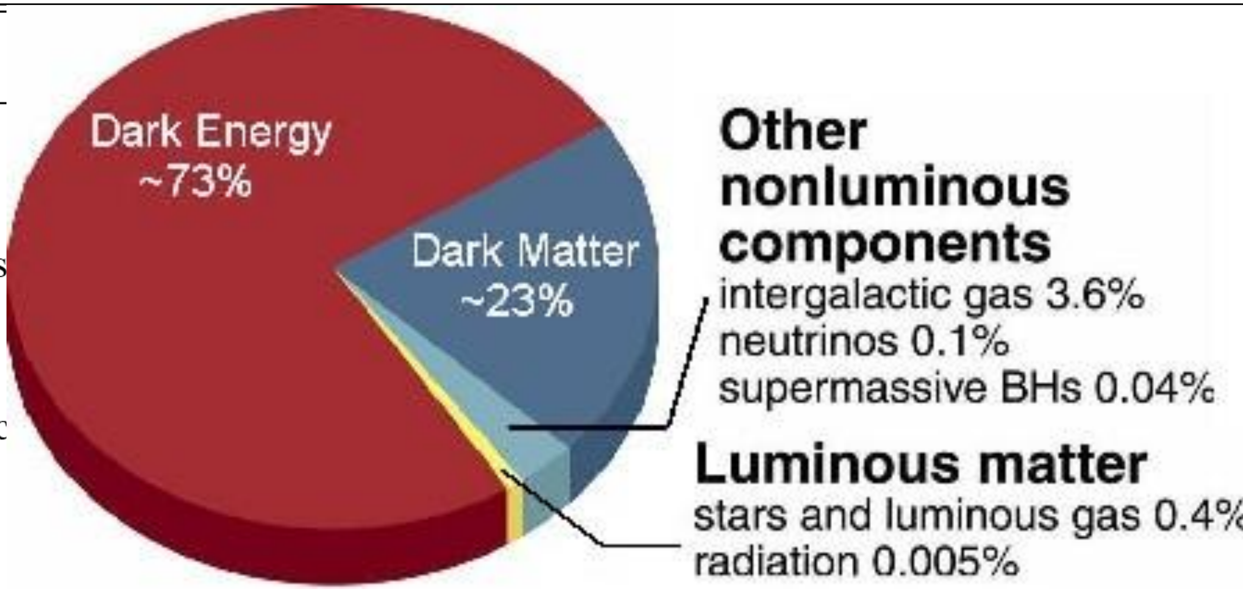
Cosmological micro–wave background

From primordial sound waves to today's galaxies

The Universe identity card

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		0.1×10^{-7}
Matter density		0.009
Matter density		0.04



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

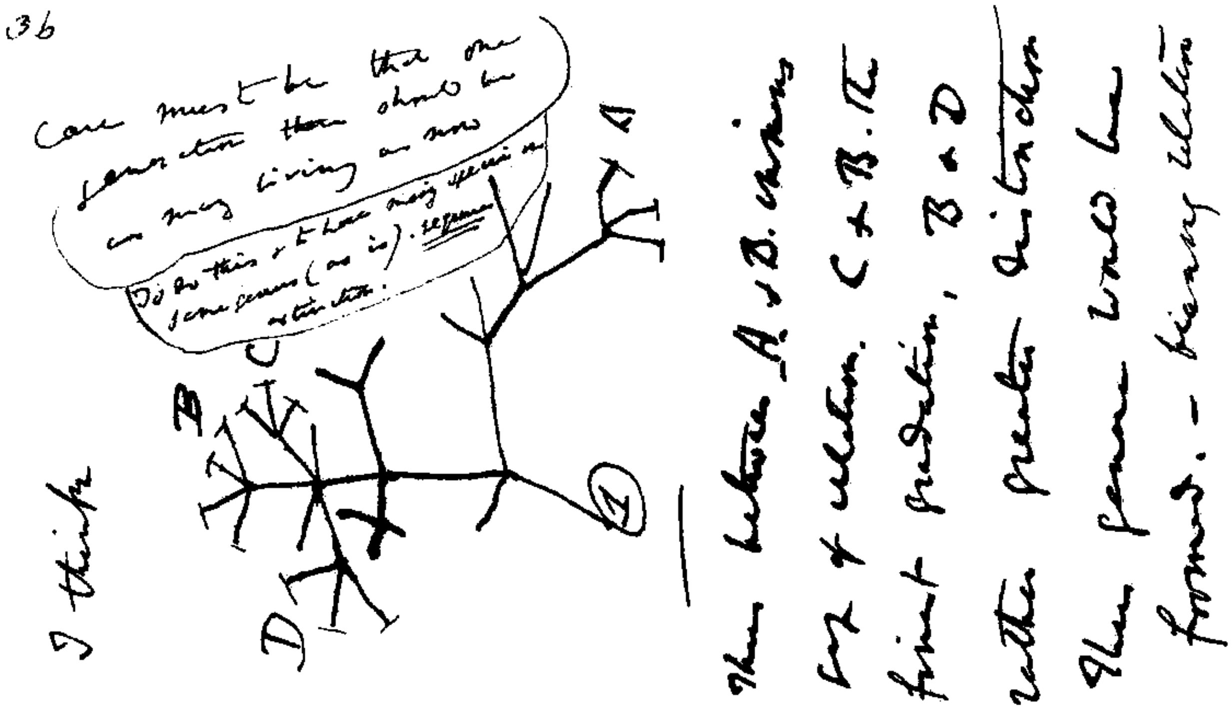
$$\Omega_{\text{M}} = 0.27 > \Omega_{\text{B}} = 0.044$$

Outline

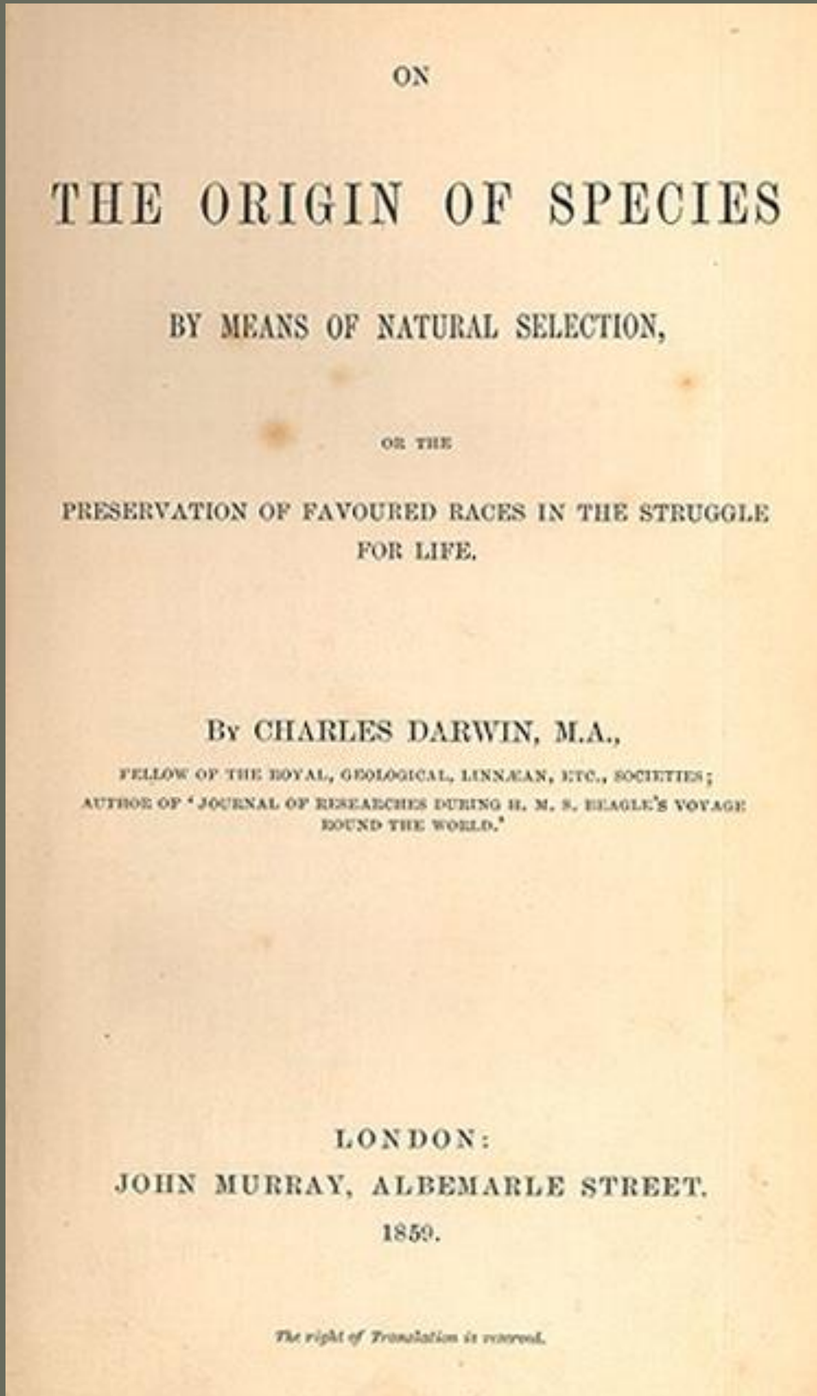
A rich bestiary of dark matter species

A few guidelines to help us classifying the bestiary

The bestiary of DM species contains a large variety of objects which have been accumulating for more than 30 years.



A classification is necessary – like in zoology !


ON

THE ORIGIN OF SPECIES

BY MEANS OF NATURAL SELECTION,

OR THE

PRESERVATION OF FAVOURED RACES IN THE STRUGGLE FOR LIFE.

BY CHARLES DARWIN, M.A.,

FELLOW OF THE ROYAL, GEOLOGICAL, LINNÆAN, ETC., SOCIETIES;
AUTHOR OF 'JOURNAL OF RESEARCHES DURING H. M. S. BEAGLE'S VOYAGE ROUND THE WORLD.'

LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1859.

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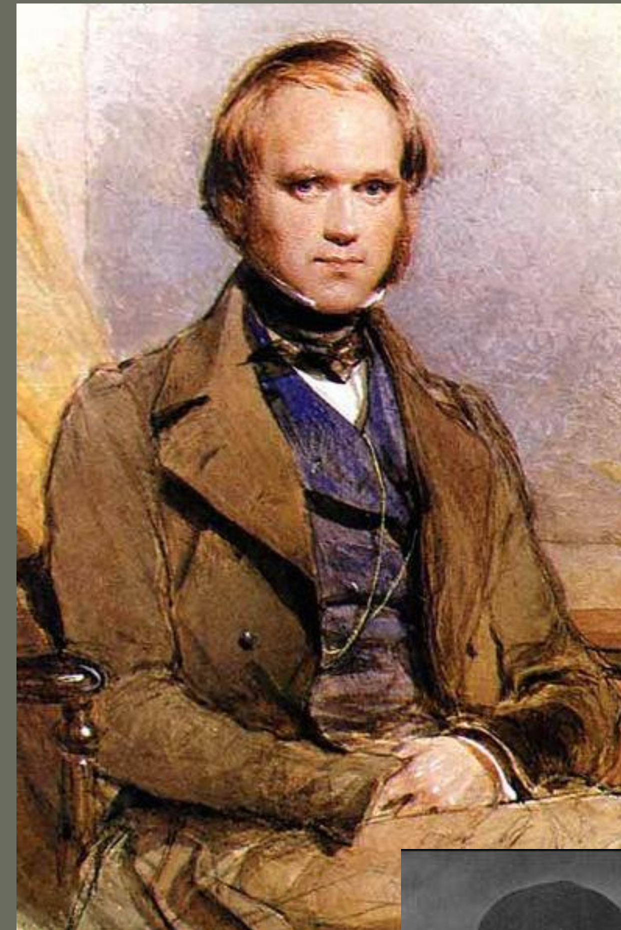

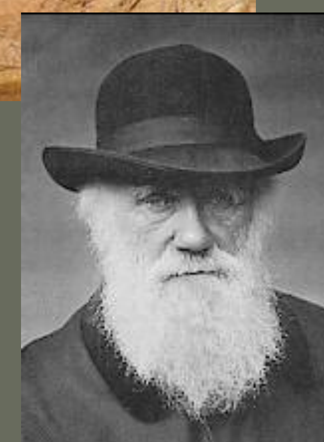

Charles Robert Darwin (1809-1882)

ON

THE ORIGIN OF DARK MATTER SPECIES

BY MEANS OF NATURAL OBSERVATION

OR THE

PRESERVATION OF FAVOURED CANDIDATES IN THE STRUGGLE FOR DATA

By CHARLES DARWIN, M.A.,

FELLOW OF THE ROYAL, GEOLOGICAL, LINNÆAN, ETC., SOCIETIES;
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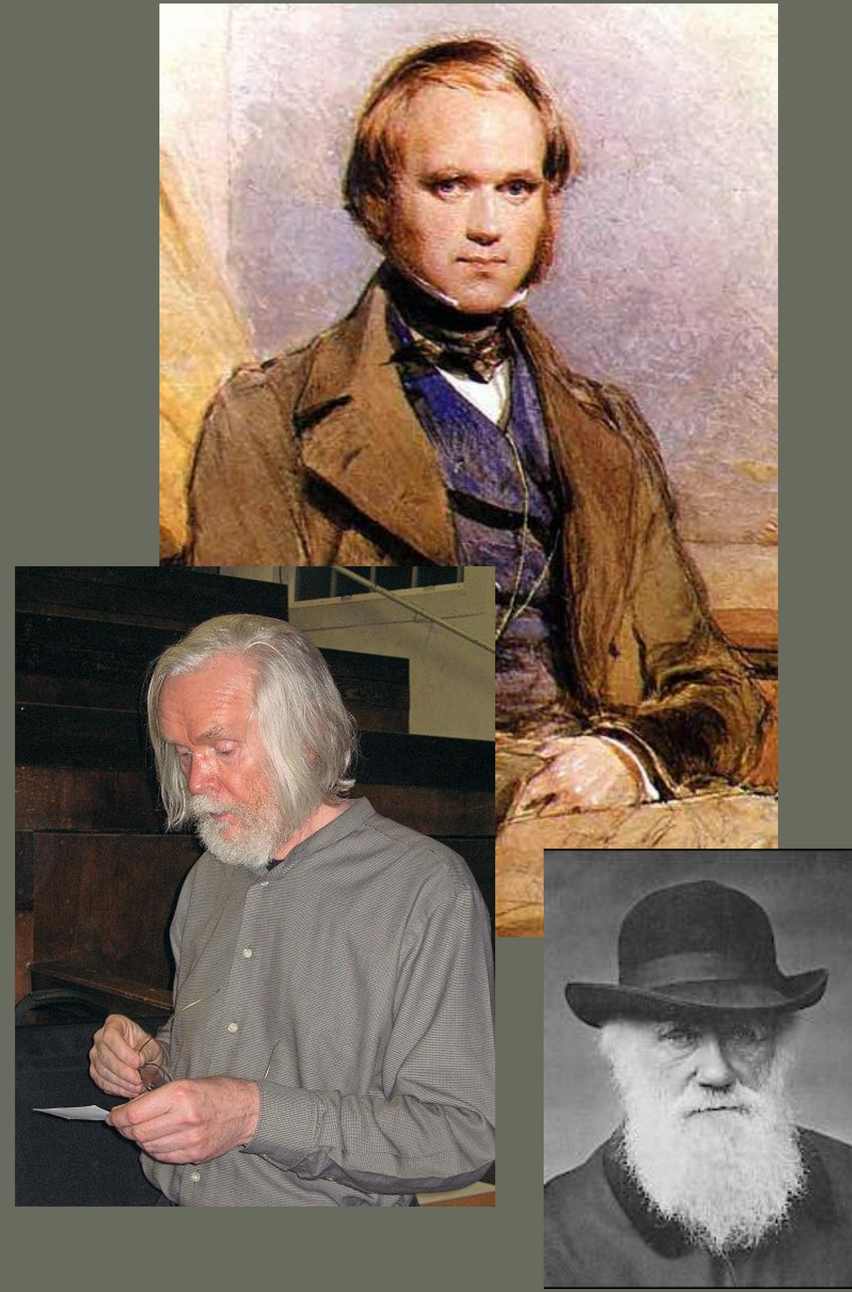


Charles Robert Darwin (1809-1882)

A few guidelines to help us classifying the bestiary

- **Theoretical motivations**

  Independently suggested by particle physics (strong incentive)

  Astrophysical – built to solve the DM issue (ad–hoc)

- **Stability** : The lifetime $\tau \geq 10^{10}$ yr $\Rightarrow \Gamma \simeq 2 \times 10^{-42}$ GeV

  The DM species needs to be **protected** from decay otherwise fine–tuning

  - ✓ Symmetry as in SUSY or extra–dimension models
  - ✓ Topological reasons as for monopoles or strings
  - ✓ Inner dynamics as in Q–balls

- **Production mechanism**

  Equilibrium at early time – thermal or chemical decoupling

  Out of equilibrium – from heavier species decay or vacuum fluctuations

- **Signatures**

Selection by means of observation

WIMPs

Weakly Interacting Massive Particles
A species predicted by most extensions of the SM

- 10 to 1000 times heavier than the proton
- no electric charge
- produced during the big-bang at early times
- abundance compatible with $\Omega_{\rm DM} \sim 0.23$
- interacts weakly – like a neutrino

L'ylem de Gamow ou le plasma primordial

Energy density

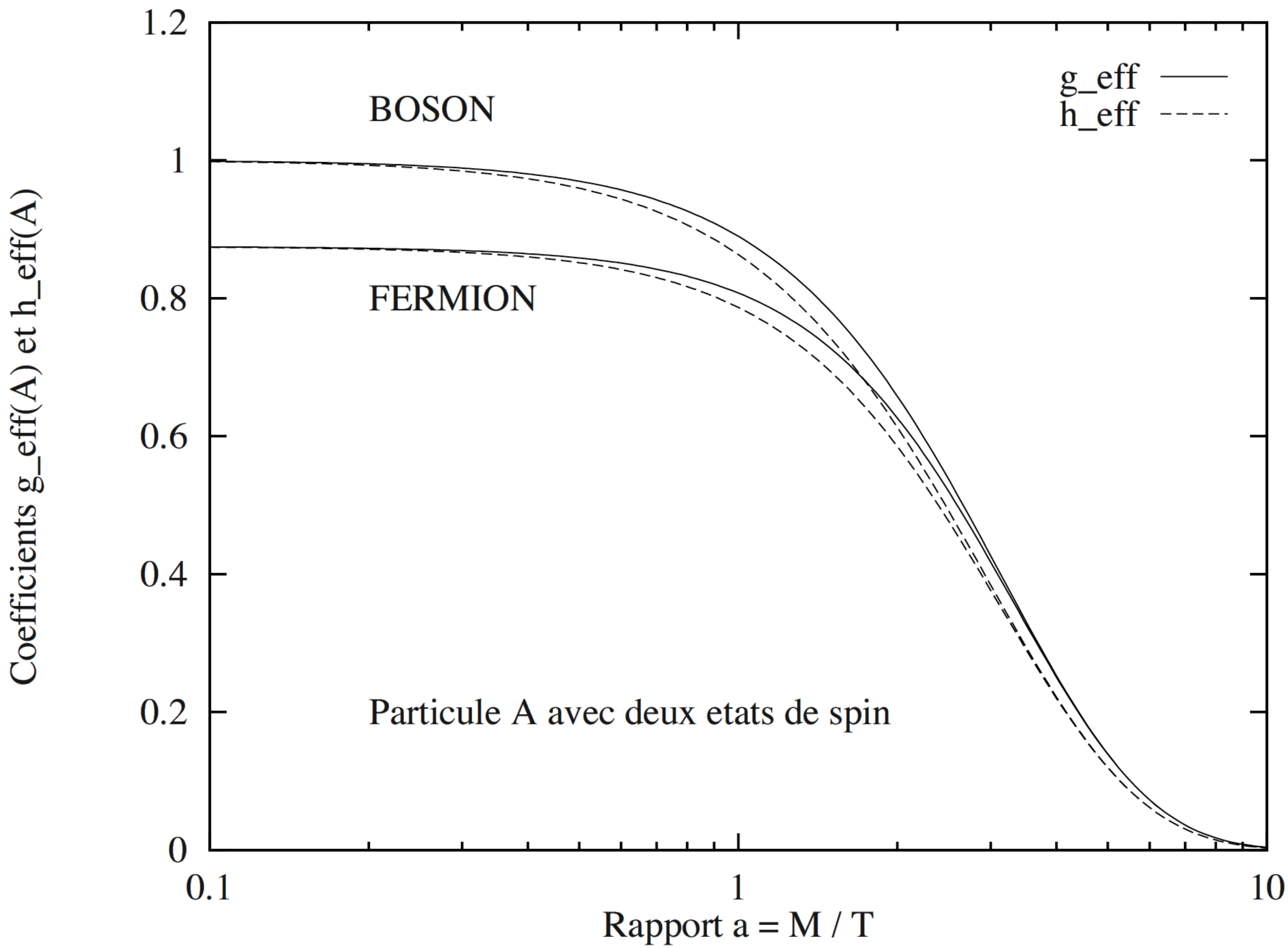
$$\rho_A \;=\; \frac{g_A}{2\pi^2}\, T^4 \int_0^\infty x^2\, dx\, \left(\frac{y}{e^y - \epsilon} \right)$$

$$g_{\rm eff}(A) \;=\; \frac{\rho_A}{\rho_\gamma}$$

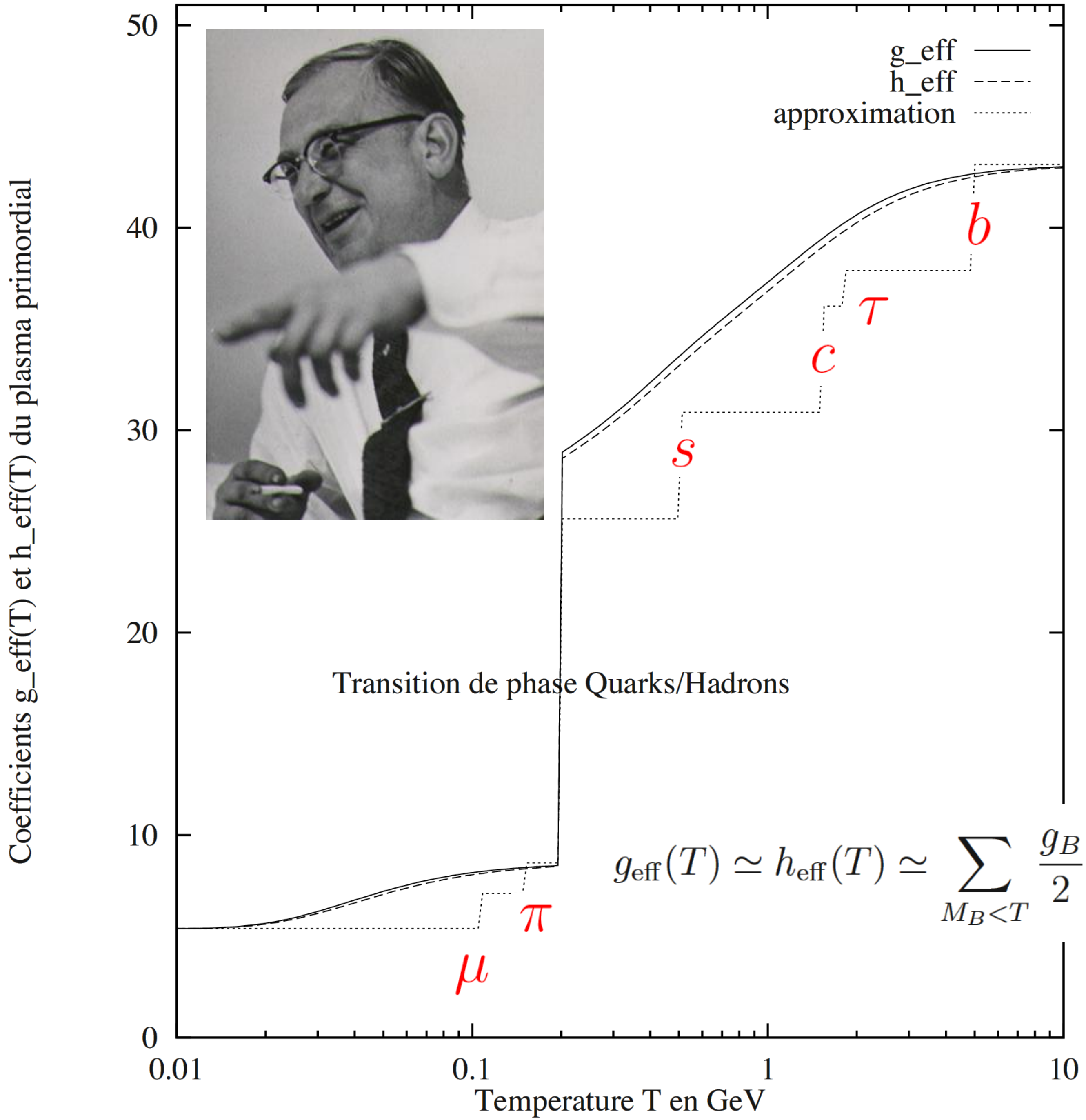
Entropy density

$$\sigma_A \;=\; \frac{g_A}{2\pi^2}\, T^3 \int_0^\infty x^2\, dx\, \left\{ y + \frac{x^2}{3y} \right\} \{e^y - \epsilon\}^{-1}$$

$$h_{\rm eff}(A) \;=\; \frac{\sigma_A}{\sigma_\gamma}$$



1.2
1
0.8
0.6
0.4
0.2
0
0.1
1
10
Coefficients g_eff(A) et h_eff(A)
Rapport a = M / T
g_eff
h_eff
BOSON
FERMION
Particule A avec deux etats de spin



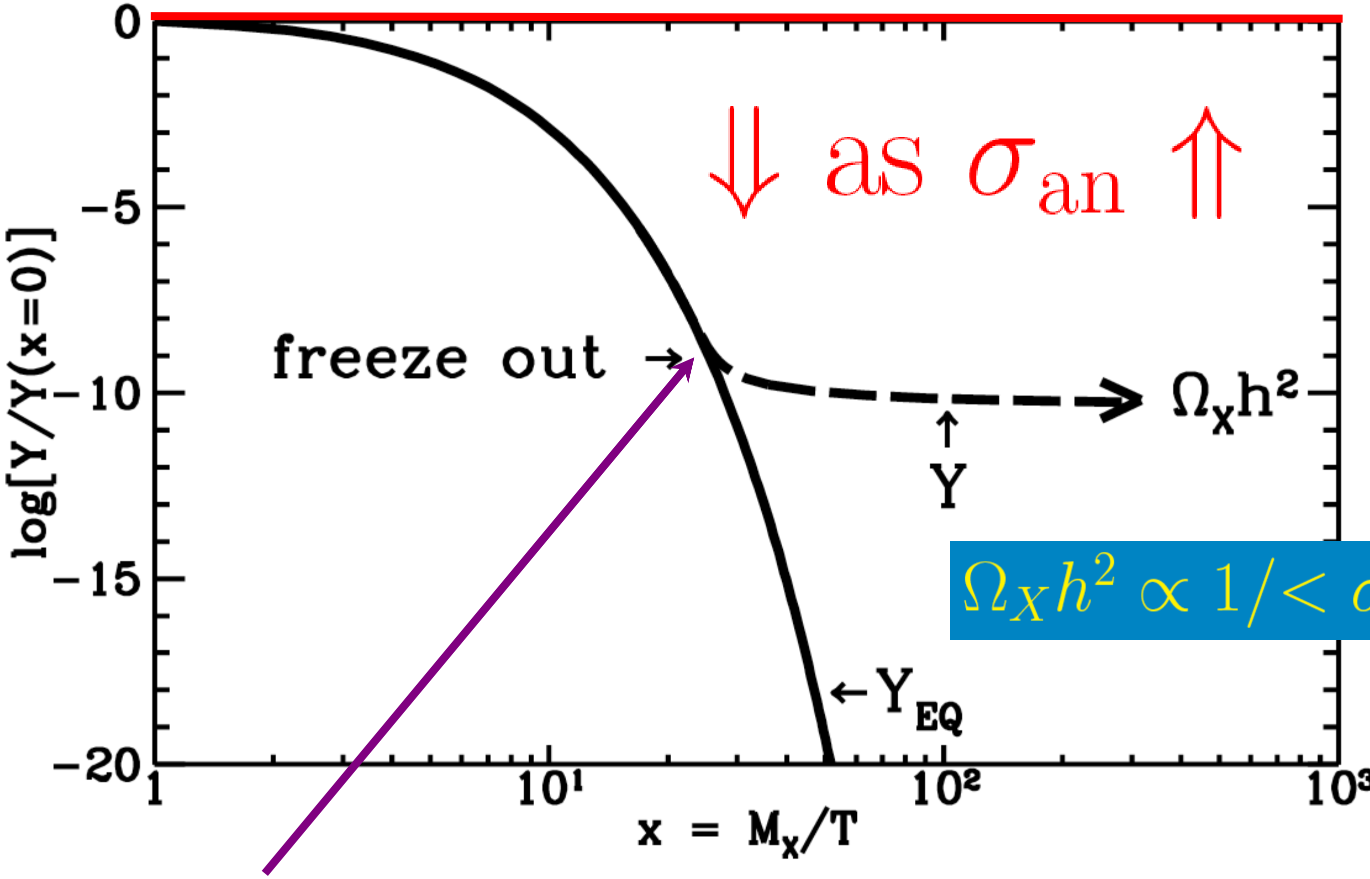
$$g_{\text{eff}}(T) \simeq h_{\text{eff}}(T) \simeq \sum_{M_B<T} \frac{g_B}{2} + \sum_{M_F<T} \frac{7\,g_F}{16}$$

Thermodynamical equilibrium production

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

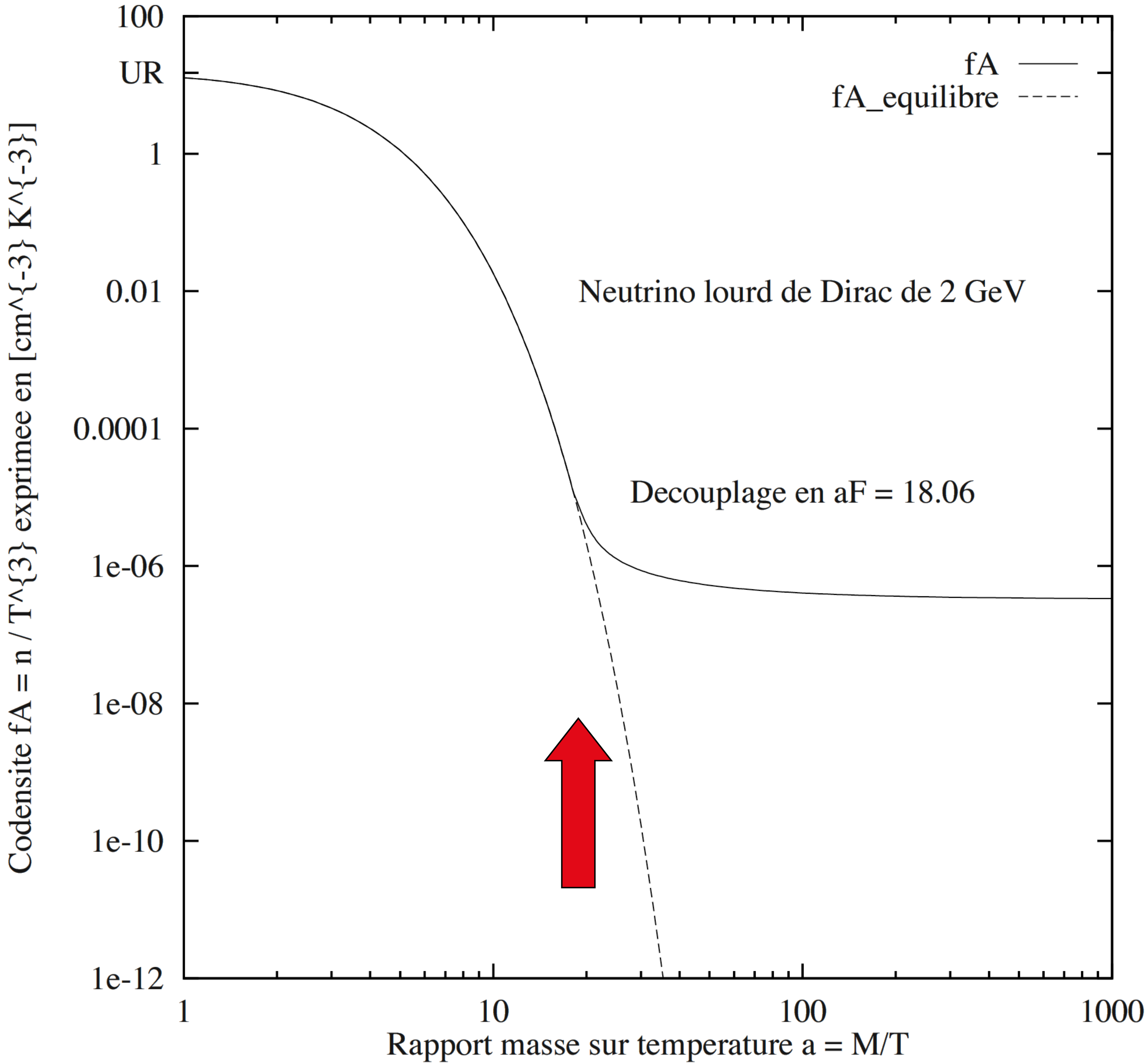
$$\frac{dn_X}{dt} = -3Hn_X - <\sigma_{\rm an} v> {n_X}^2 + <\sigma_{\rm an} v> {n_X^0}^2$$

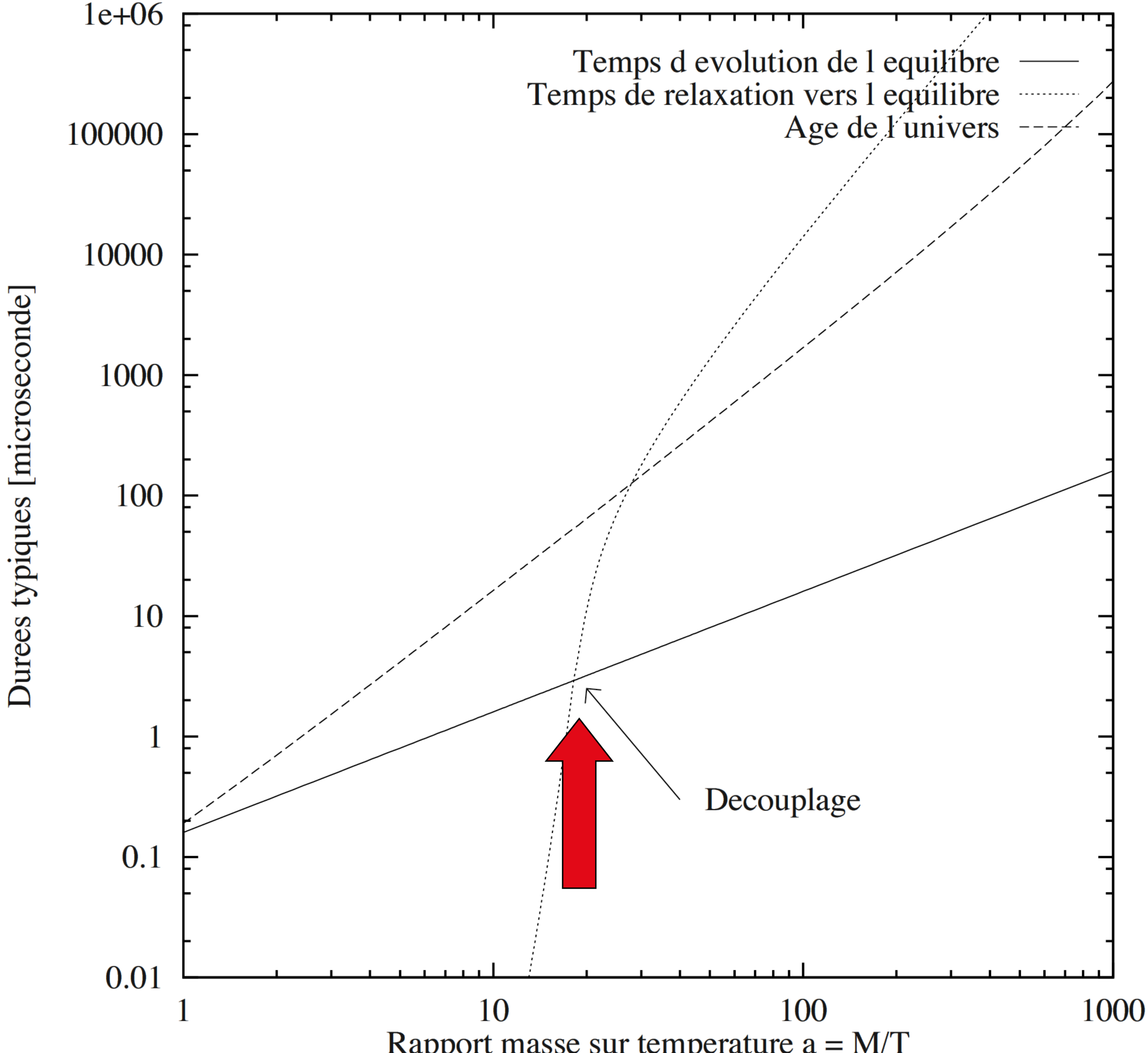
thermal decoupling when $\Gamma_{\rm coll} \sim H_F$ (UR)



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

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


100
UR
1
0.01
0.0001
1e-06
1e-08
1e-10
1e-12
1
10
100
1000
fA
fA_equilibre
Neutrino lourd de Dirac de 2 GeV
Decouplage en aF = 18.06
Codensite fA = n / T^{3} exprimee en [cm^{-3} K^{-3}]
Rapport masse sur temperature a = M/T



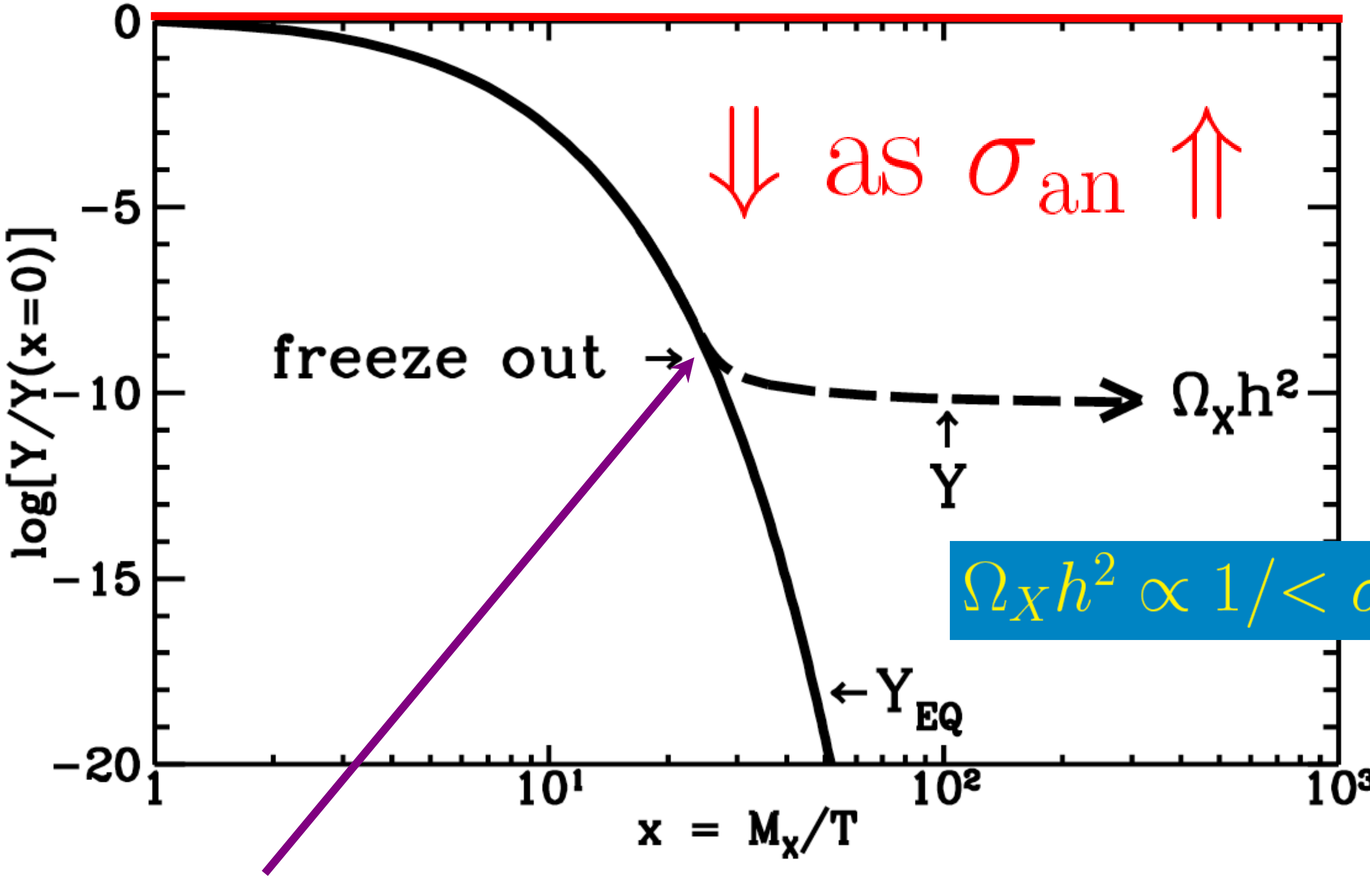
1e+06
100000
10000
1000
100
10
1
0.1
0.01
1
10
100
1000
Durees typiques [microseconde]
Rapport masse sur temperature a = M/T
Temps d evolution de l equilibre
Temps de relaxation vers l equilibre
Age de l univers
Decouplage

Thermodynamical equilibrium production

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

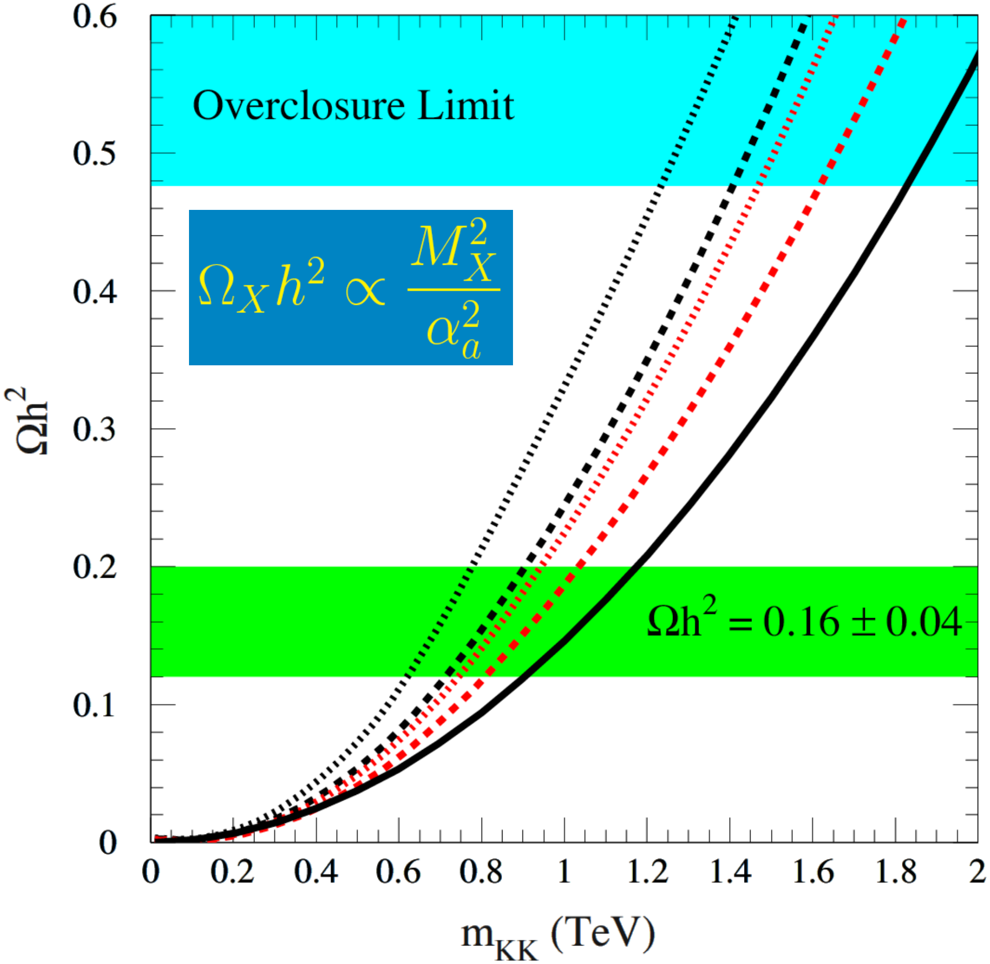
$$\frac{dn_X}{dt} = -3Hn_X - <\sigma_{\rm an} v> {n_X}^2 + <\sigma_{\rm an} v> {n_X^0}^2$$

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]

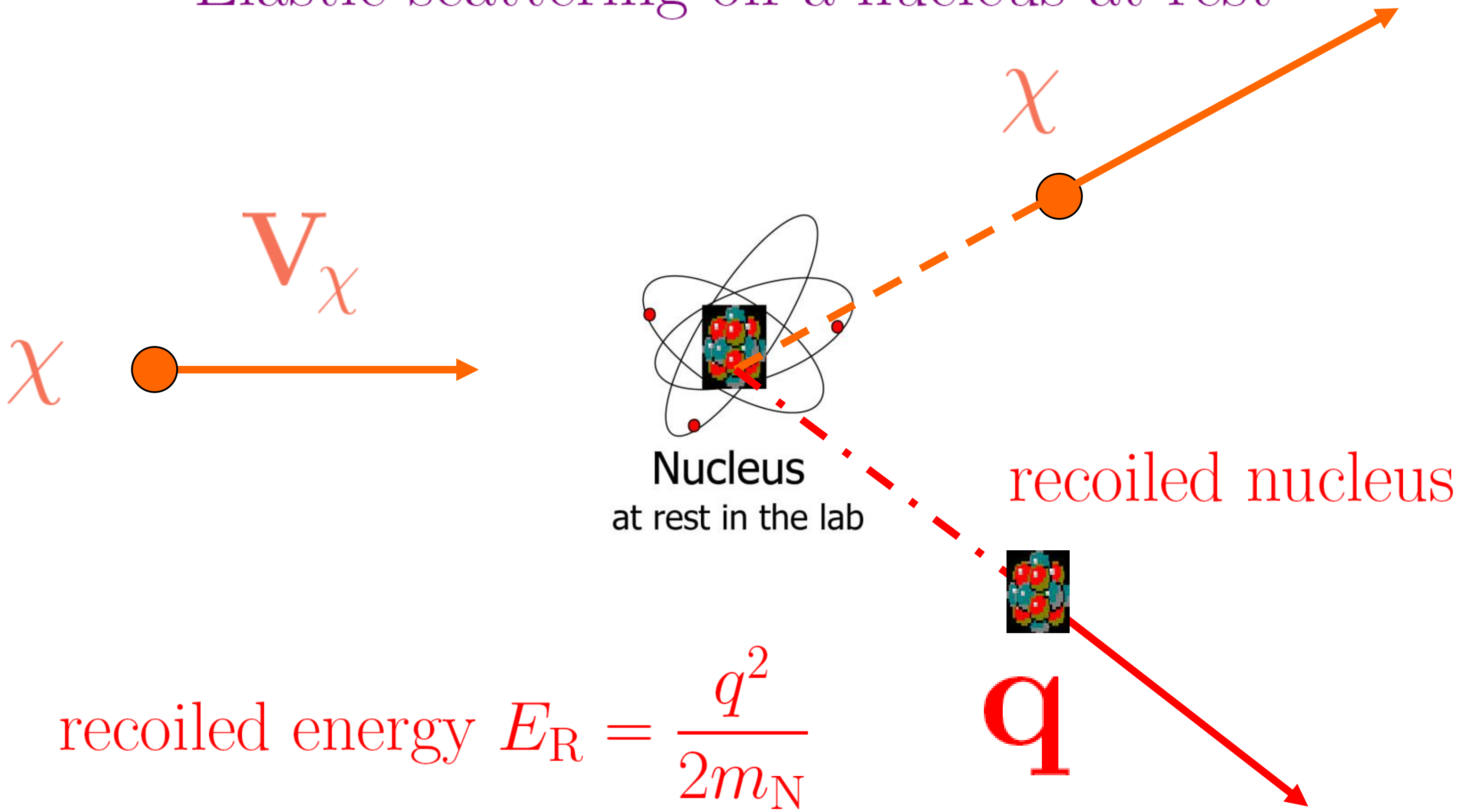
Figure 3: Prediction for $\Omega_{B^{(1)}} h^2$ as in Figure 1. The solid line is the case for $B^{(1)}$ alone, and the dashed and dotted lines correspond to the case in which there are one (three) flavors of nearly degenerate $e_R^{(1)}$. For each case, the black curves (upper of each pair) denote the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

Outline

Direct signatures of WIMPs

Laboratory Frame

Elastic scattering off a nucleus at rest

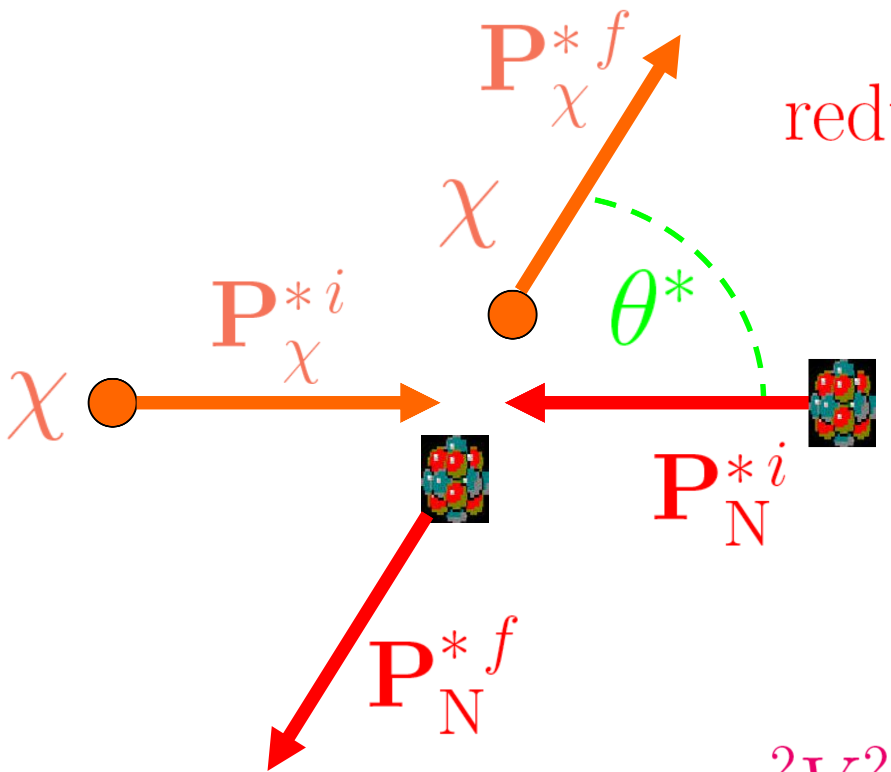


recoiled energy $E_{\mathrm{R}} = \dfrac{q^2}{2m_{\mathrm{N}}}$

This is the signal !

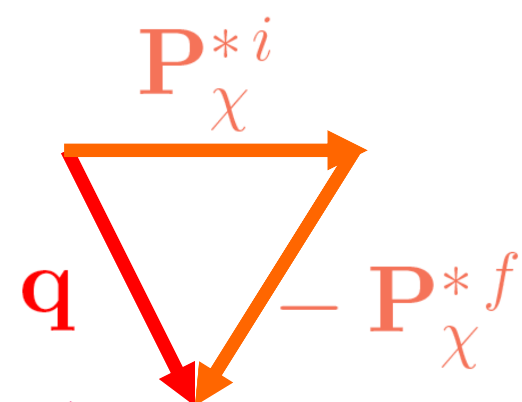
Center of Mass Frame

The CMF is defined by $(m_\mathrm{N} + m_\chi)\mathbf{V}_\mathrm{CMF} = m_\chi \mathbf{V}_\chi$



reduced mass $\mu = \dfrac{m_\chi m_\mathrm{N}}{m_\chi + m_\mathrm{N}}$

$$P^* = \mu V_\chi$$

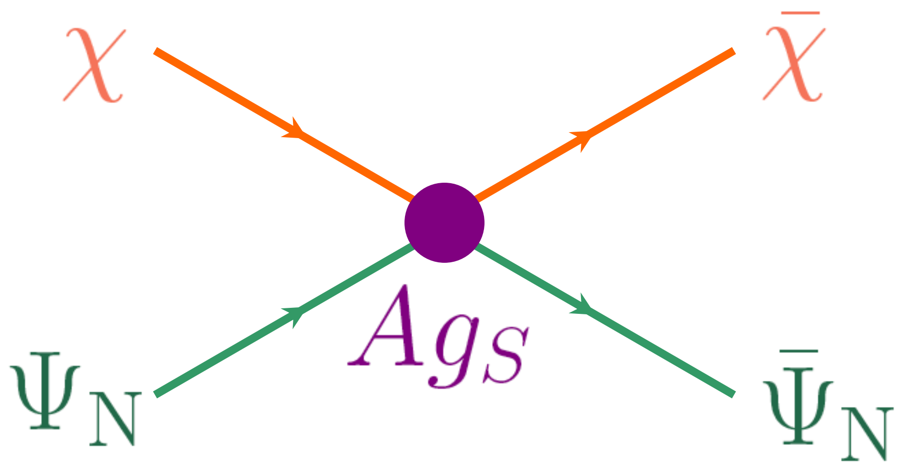


$$E_\mathrm{R} = \frac{\mu^2 V_\chi^2}{m_\mathrm{N}}(1 - \cos\theta^*)$$

$m_\chi = m_\mathrm{N} = 100$ GeV & $V_\chi = 220$ km s^{-1} yield $E_\mathrm{R}^\mathrm{max} \simeq 27$ keV

A (not too) naive toy model

$$\mathcal{L}_{\rm scalar} = A\, g_S \,\{\bar{\chi}\chi\} \cdot \{\bar{\Psi}_{\rm N}\Psi_{\rm N}\}$$



- Coherent interaction on the A nucleons of the nucleus N
- Effective scalar coupling $g_S \sim \dfrac{\alpha_{\rm em}}{M^2}$

$g_S \sim 7.3 \times 10^{-9}$ GeV^{-2} for a scale $M = 1$ TeV

Exercise – Level **[3]** *: The cross section for the scattering process*

$$\chi\,(P_1)\;+\;\text{nucleus}\,(k_1) \longrightarrow \chi\,(P_2)\;+\;\text{nucleus}\,(k_2)\quad , \tag{1}$$

is generically given by the well–known relation

$$d\sigma \cdot |\mathbf{V}_\chi - \mathbf{V}_\mathrm{N}| \;=\; \frac{1}{2\,P_1^0}\,\frac{1}{2\,k_1^0}\int d\tilde{P}_2\;d\tilde{k}_2\;(2\pi)^4\,\delta(P_1 + k_1 - P_2 - k_2)\;\mathcal{A}\quad , \tag{2}$$

where $\mathcal{A}$ denotes the average over the initial spin states and the sum over the final spin states of the square of the amplitude. Show that the later may be expressed as

$$\mathcal{M}_{\,\text{scalar}} \;=\; \sqrt{\kappa}\cdot A\,g_S \cdot \bar{u}(P_2)u(P_1)\cdot\bar{u}(k_2)u(k_1)\quad . \tag{3}$$

The κ coefficient is equal to 1 for Dirac fermions and to 4 for Majorana species. In the NR limit where the velocities of the particles are negligible with respect to their energies, establish that $\mathcal{A}$ is given by

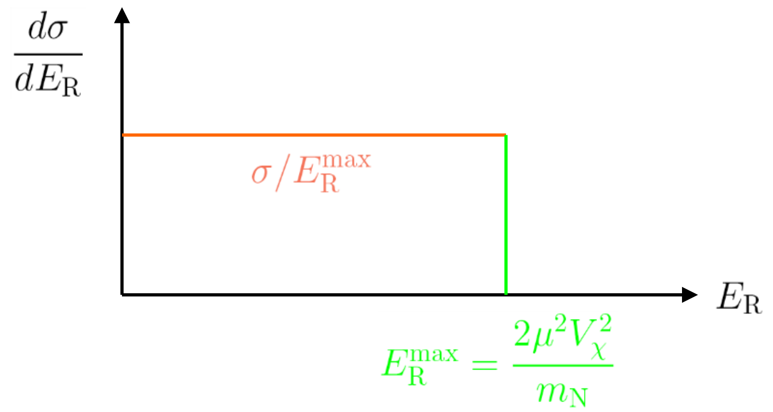
$$\mathcal{A} \equiv \frac{1}{4}\sum_{\text{spins}} |\mathcal{M}_{\,\text{scalar}}|^2 \;=\; 16\,\kappa\,A^2\,g_S^2\,m_\chi^2\,m_\mathrm{N}^2\quad . \tag{4}$$

Compute the integral (2) in order to derive the differential cross section in the CMF

$$\frac{d\sigma}{d\Omega^*} \;=\; \frac{\kappa}{4\pi^2}\,A^2\,g_S^2\,\mu^2\quad . \tag{5}$$

A few consequences ensue

(i) Because the scattering is **isotropic** in the CMF, the differential cross section is **flat** as a function of the recoil energy $E_{\rm R}$



$$\sigma \; = \; \frac{\kappa}{\pi} A^2 \, g_S^2 \, \mu^2$$

(ii) In order to compare among the various experiments, the **spin independent** cross section on a **single nucleon** is defined as

$$\sigma_{\rm p}^{\rm SI} = \lim_{m_\chi \to \infty} \sigma \left\{ m_{\rm N} = m_{\rm p}, m_\chi \right\} = \frac{\kappa}{\pi} \, g_S^2 \, m_{\rm p}^2$$

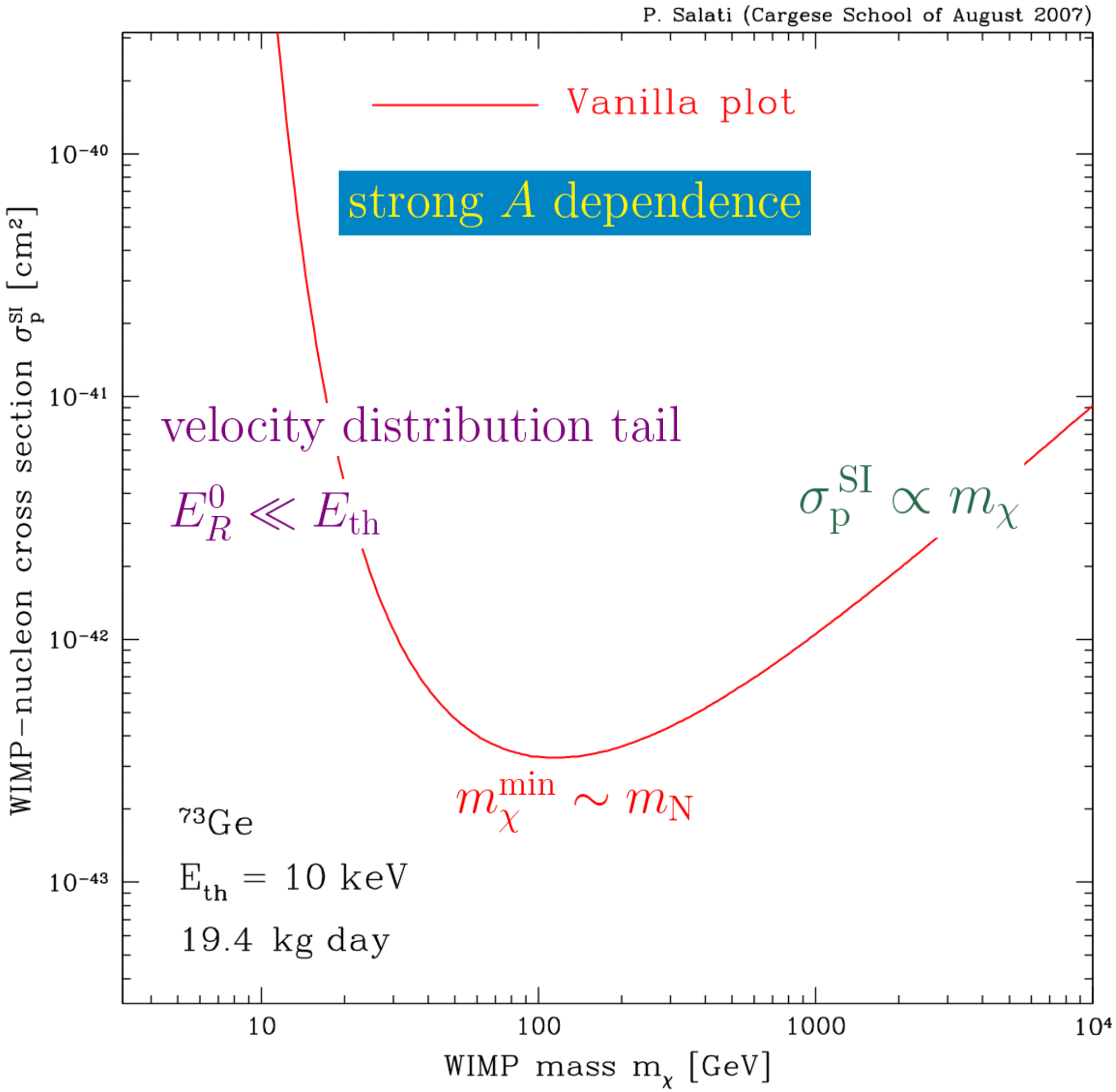
$\sigma_{\rm p}^{\rm SI} \sim 23.3$ zeptobarns* for a scale $M = 1$ TeV

(iii) The total scattering cross section varies with the atomic number A of the target nucleus as

$$\frac{\sigma}{\sigma_{\rm p}^{\rm SI}} \; = \; A^4 \left\{ 1 + \frac{m_{\rm N}}{m_\chi} \right\}^{-2} \longrightarrow A^4 \text{ when } m_\chi \gg m_{\rm N}$$

$*$ 1 zeptobarn (zp) $= 10^{-9}$ picobarn $= 10^{-45}$ cm^2

We require that $n_{\rm theo} \leq 2.3$ (90% CL for a null observation)

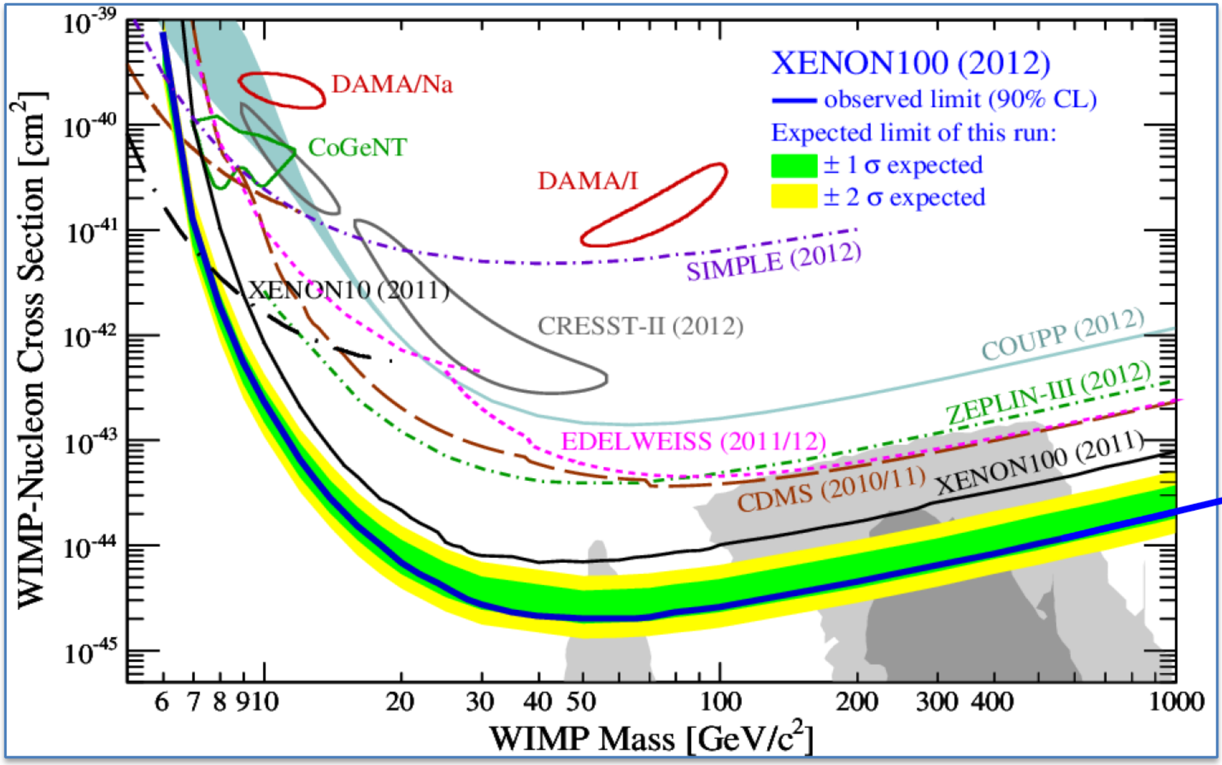


the heavier, the better !

Latest SI limit from XENON100 :

Lowest limit for M_χ = **55 GeV/c²**:

2.0 • 10⁻⁴⁵ cm² (90% C.L.)



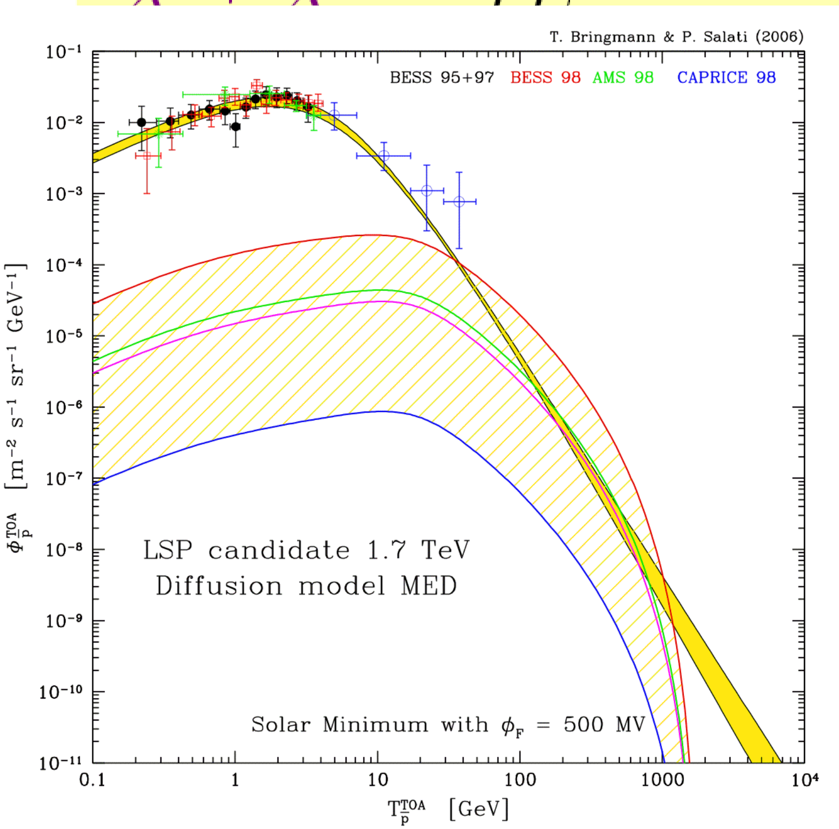
XENON100
Spin-independent
WIMP-nucleon
cross-section

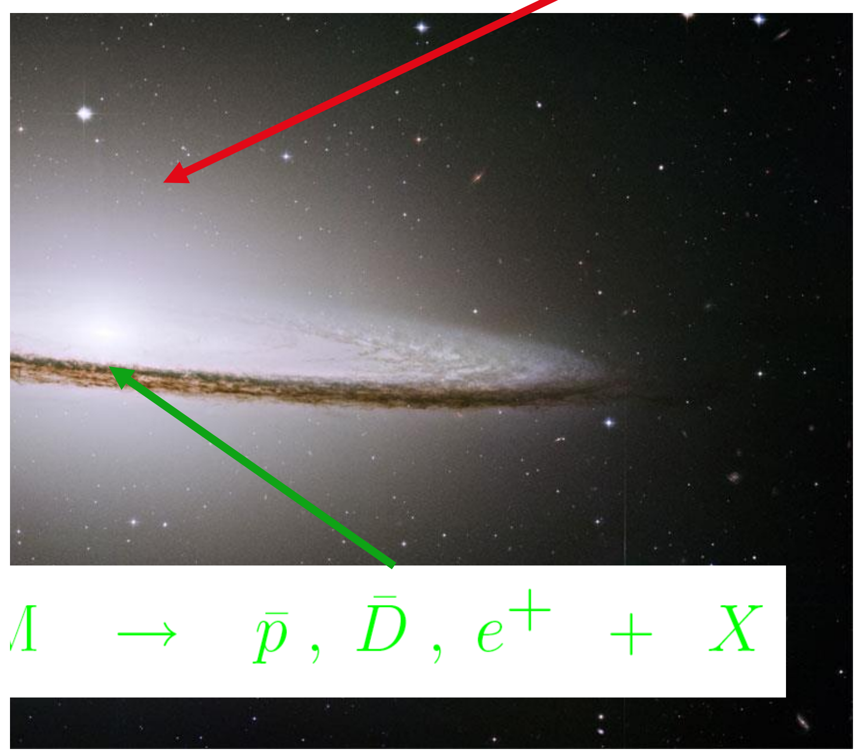
E. Aprile et al. (XENON100), Phys. Rev. Lett. 109, 181301 (2012)

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 :

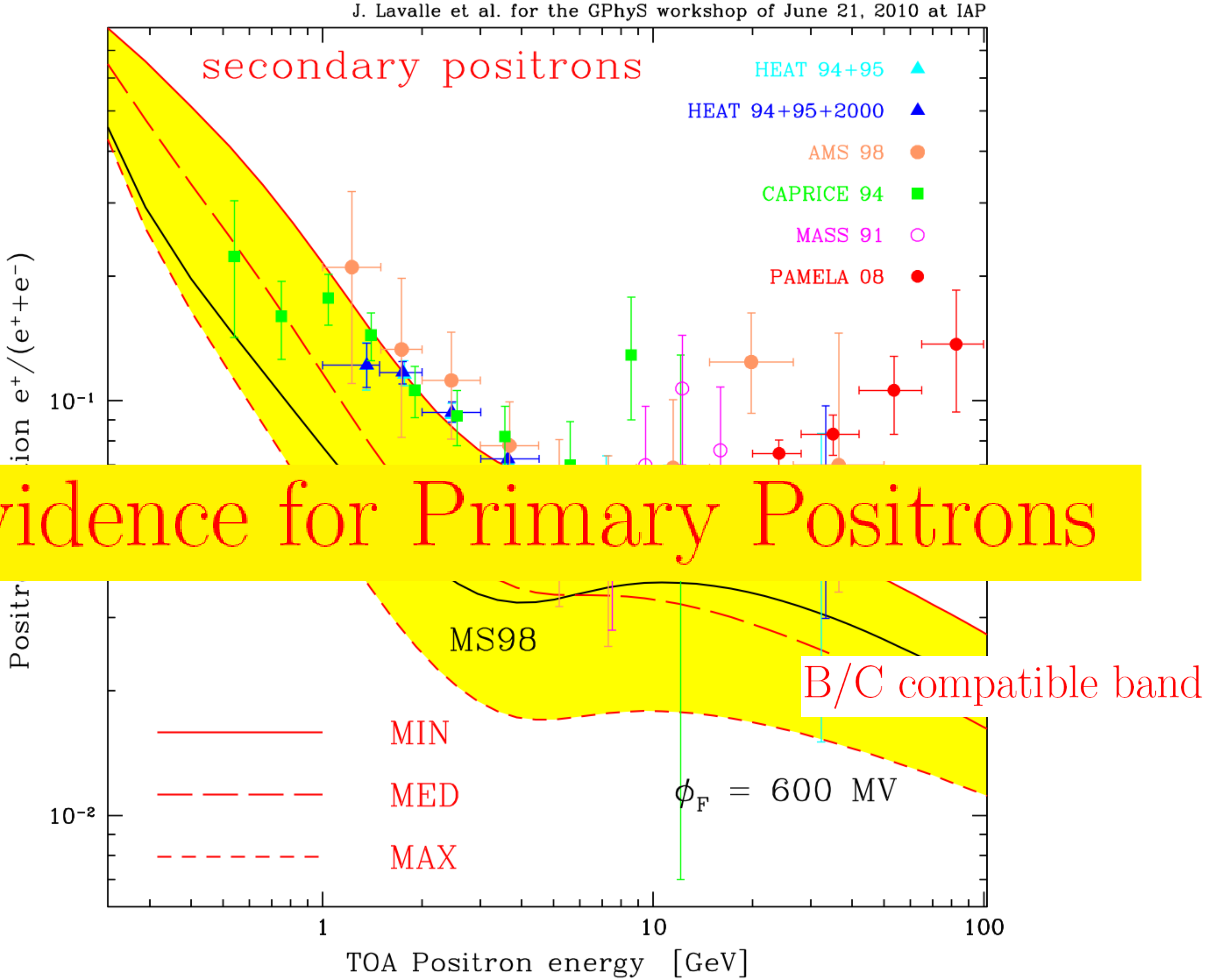
$$\chi + \chi \to q\bar{q}, W^+W^-, \ldots \to \gamma, \bar{p}, \bar{D}, e^+ \;\&\; \nu's$$





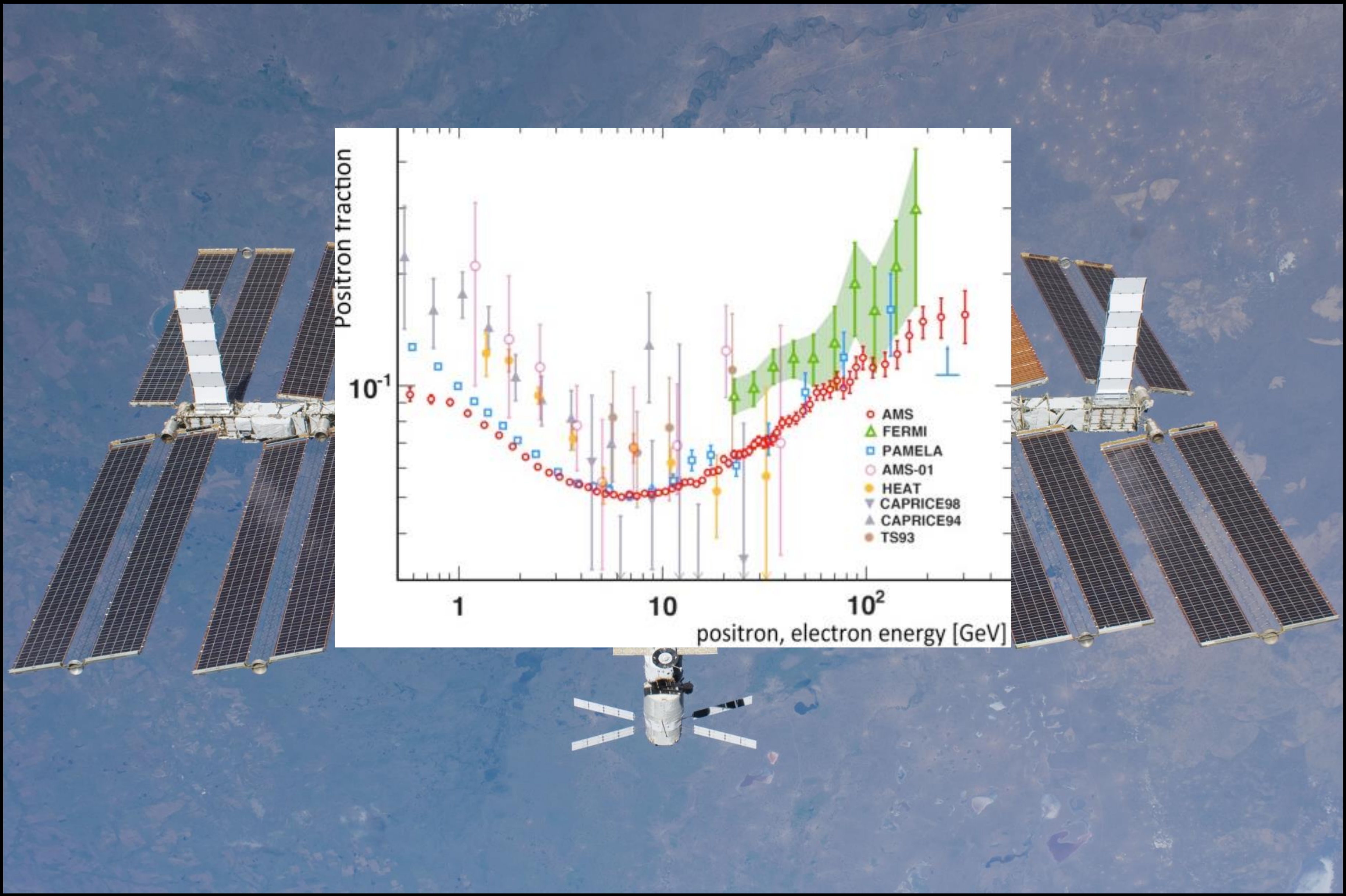
Antimatter is already manufactured inside the galactic disk

Evidence for Primary Positrons



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

AMS–02



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

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

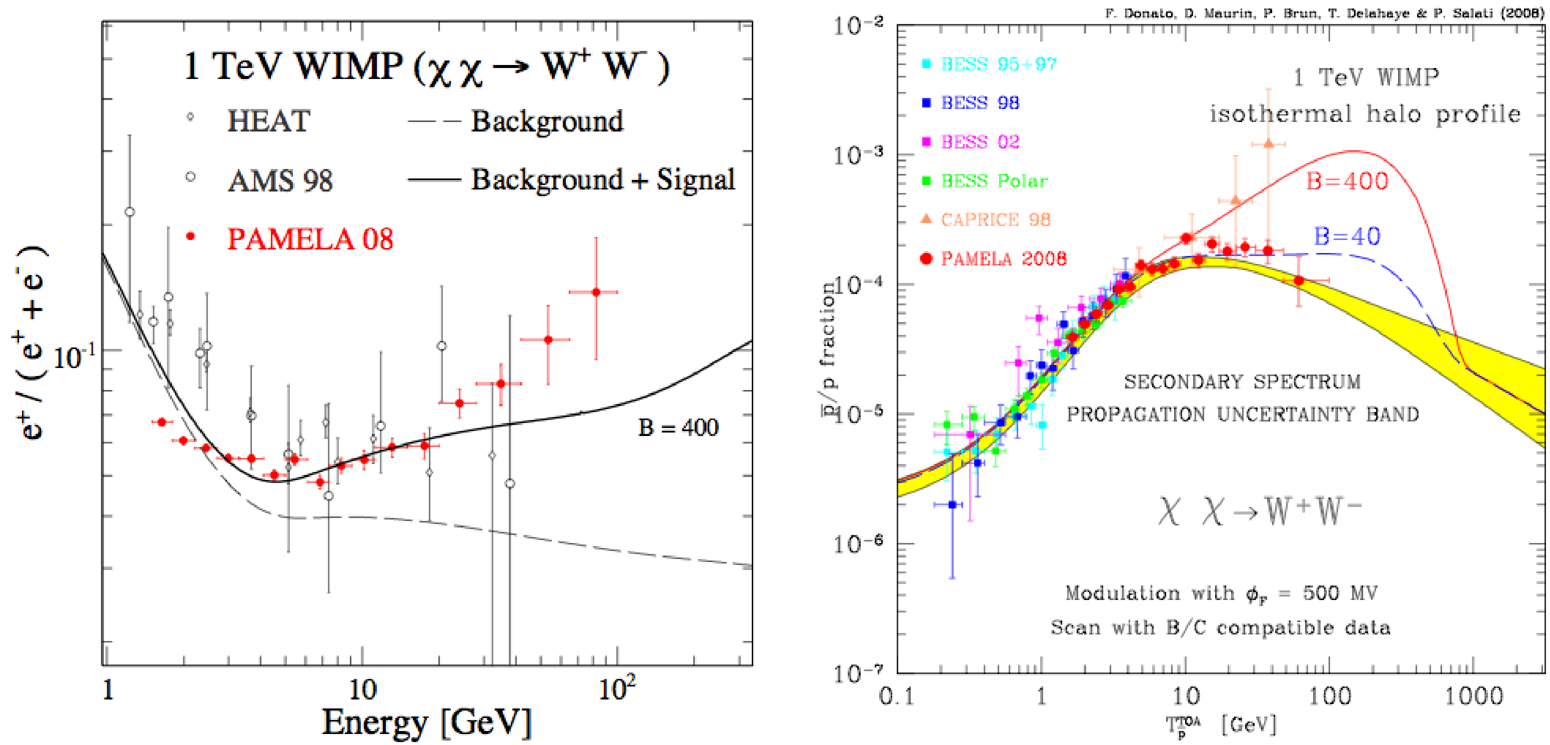
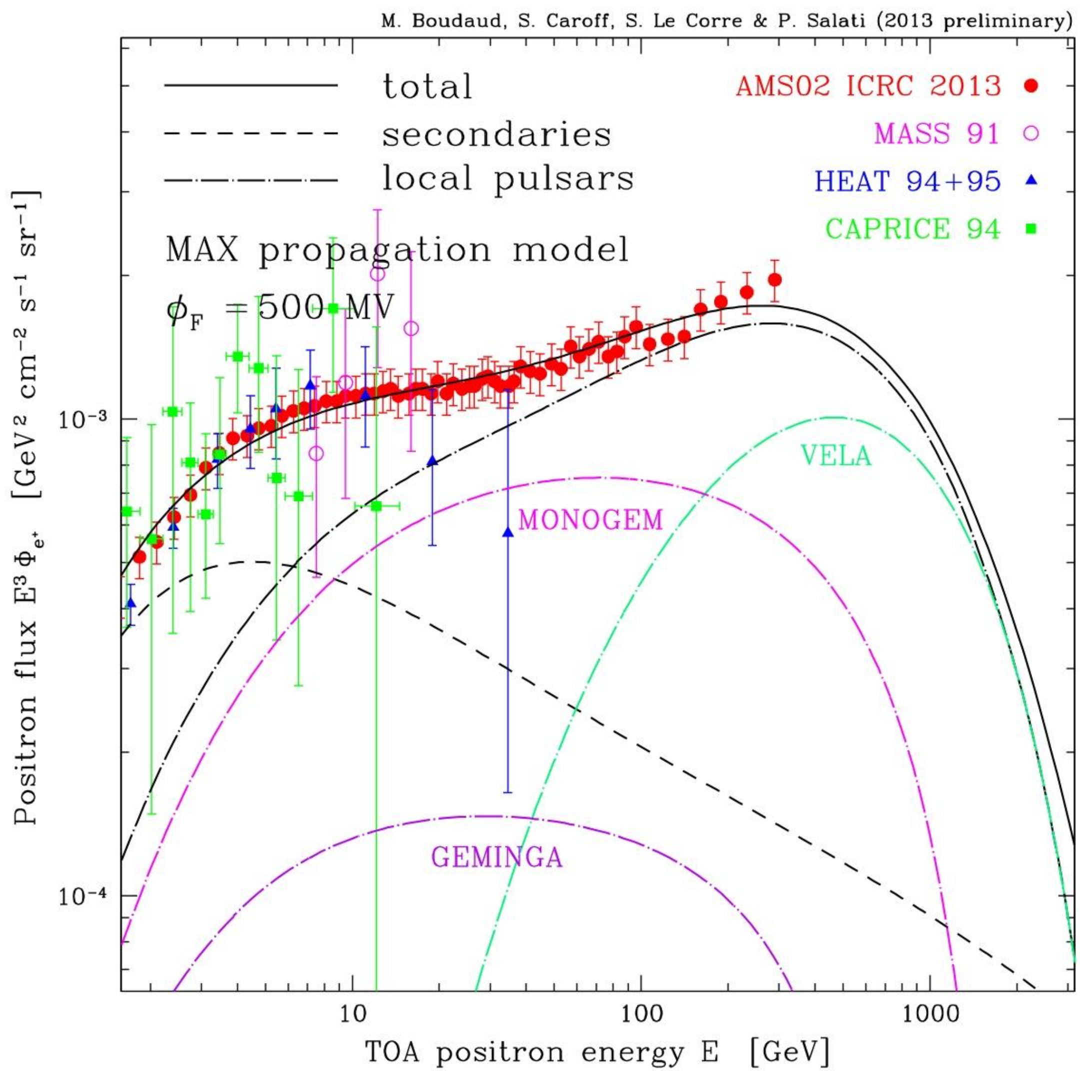


FIG. 3: The fiducial case of a 1 TeV LSP annihilating into a W^+W^- pair is featured. In the left panel, the positron signal which this DM species yields has been increased by a factor of 400, hence the solid curve and a marginal agreement with the PAMELA data. Positron fraction data are from HEAT [18], 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

Positrons could be injected by pulsars



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 !