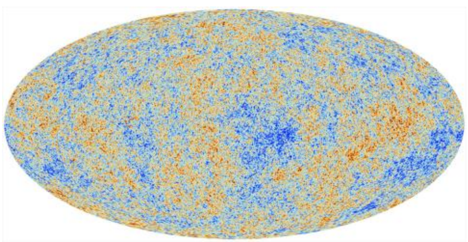
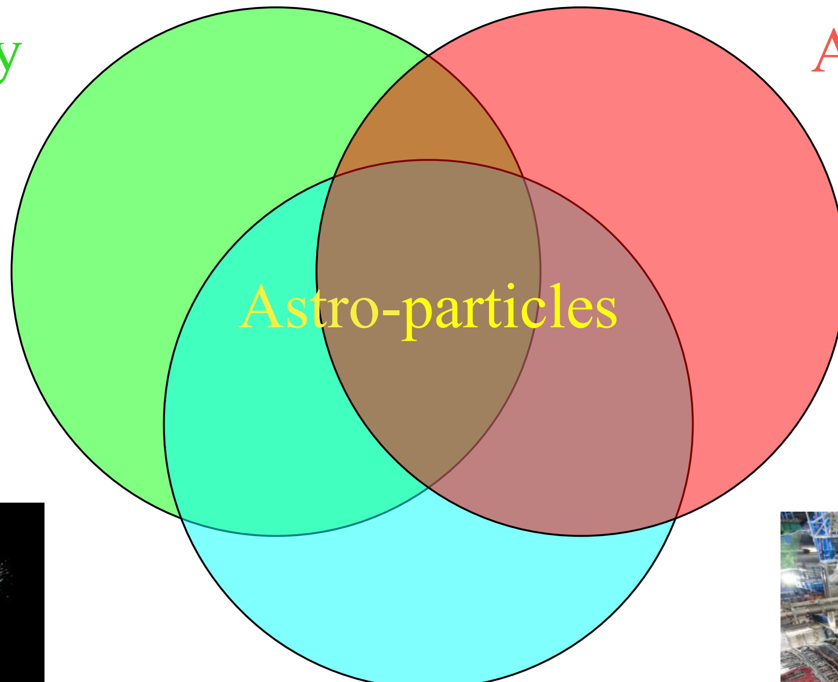
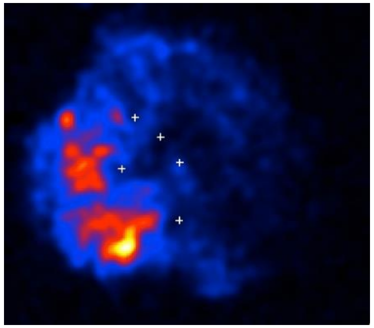
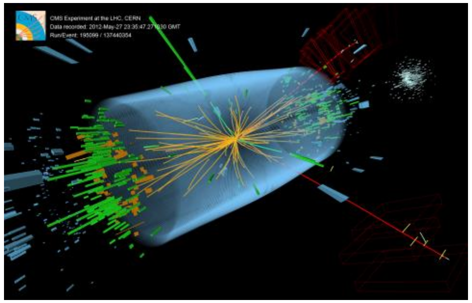
Introduction to Astroparticle Physics – Theory

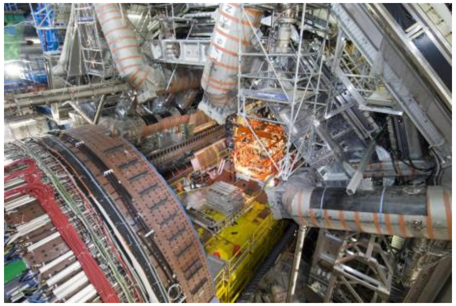
Pierre Salati – **LAPTh** & Université Savoie Mont Blanc





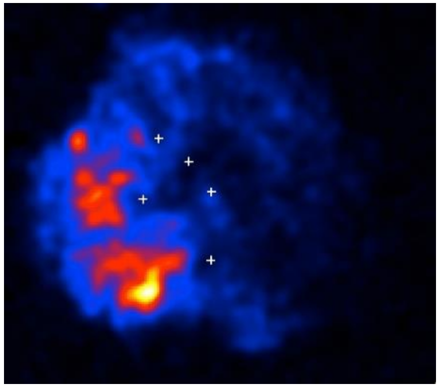




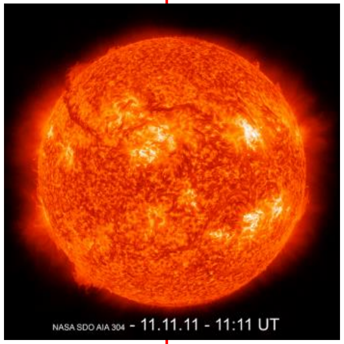


Astroparticle physics inherits from various fields

Genealogical Tree



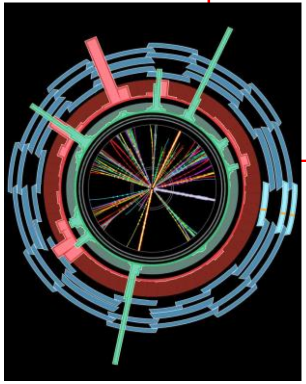
stellar sources

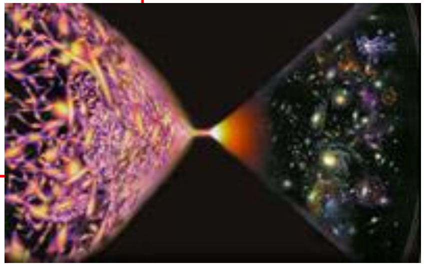


cosmic rays

cosmology & big–bang

accelerators





Particle Astrophysics

The Astronomical Dark Matter Problem

or the Hunt for eluding Particles

Outline

1 – Zwicky's legacy

- **a.** The historical discovery
- **b.** Galaxies and clusters of galaxies
- **c.** Cosmological observations

2 – The bestiary of dark matter species

- **a.** Following Charles Darwin
- **b.** Kaluza-Klein particles in extra-D theories
- **c.** The WIMP miracle

3 – Particle astrophysics and the search for dark matter particles

- **a.** Direct detection experiments – underground searches
- **b.** Indirect signatures – the search for cosmic ray anomalies
- **c.** A status on the recent antiproton measurements

4 – Dark matter searches at the LHC

Outline

1 – Zwicky's legacy

http://adsabs.harvard.edu/abs/1937ApJ....86..217Z

a. The historical discovery

b. Galaxies and clusters of galaxies

c. Cosmological observations

2 – The bestiary of dark matter species

a. Following Charles Darwin

b. Kaluza-Klein particles in extra-D theories

c. The WIMP miracle

3 – Particle astrophysics and the search for dark matter particles

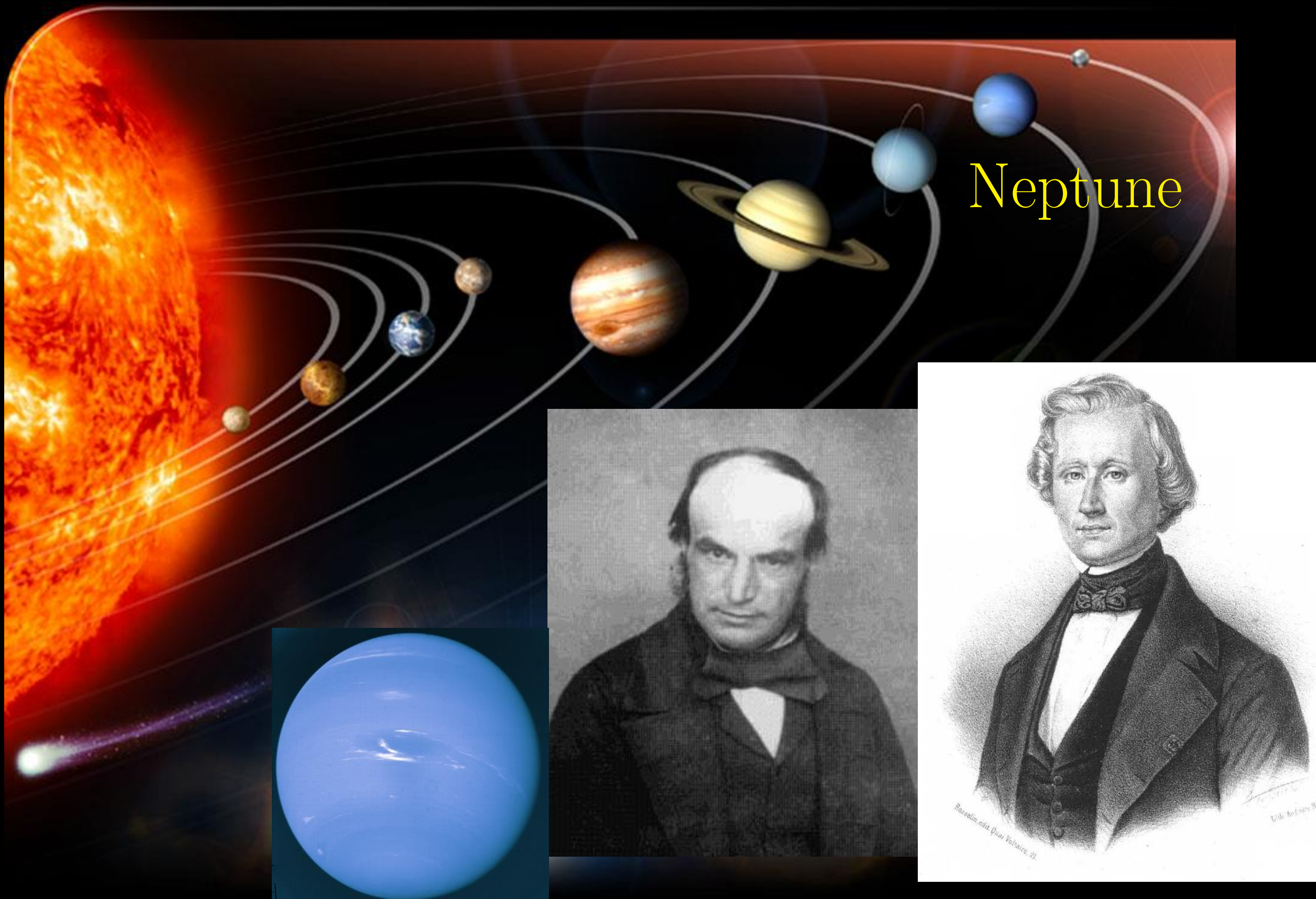
a. Direct detection experiments – underground searches

b. Indirect signatures – the search for cosmic ray anomalies

c. A status on the recent antiproton measurements

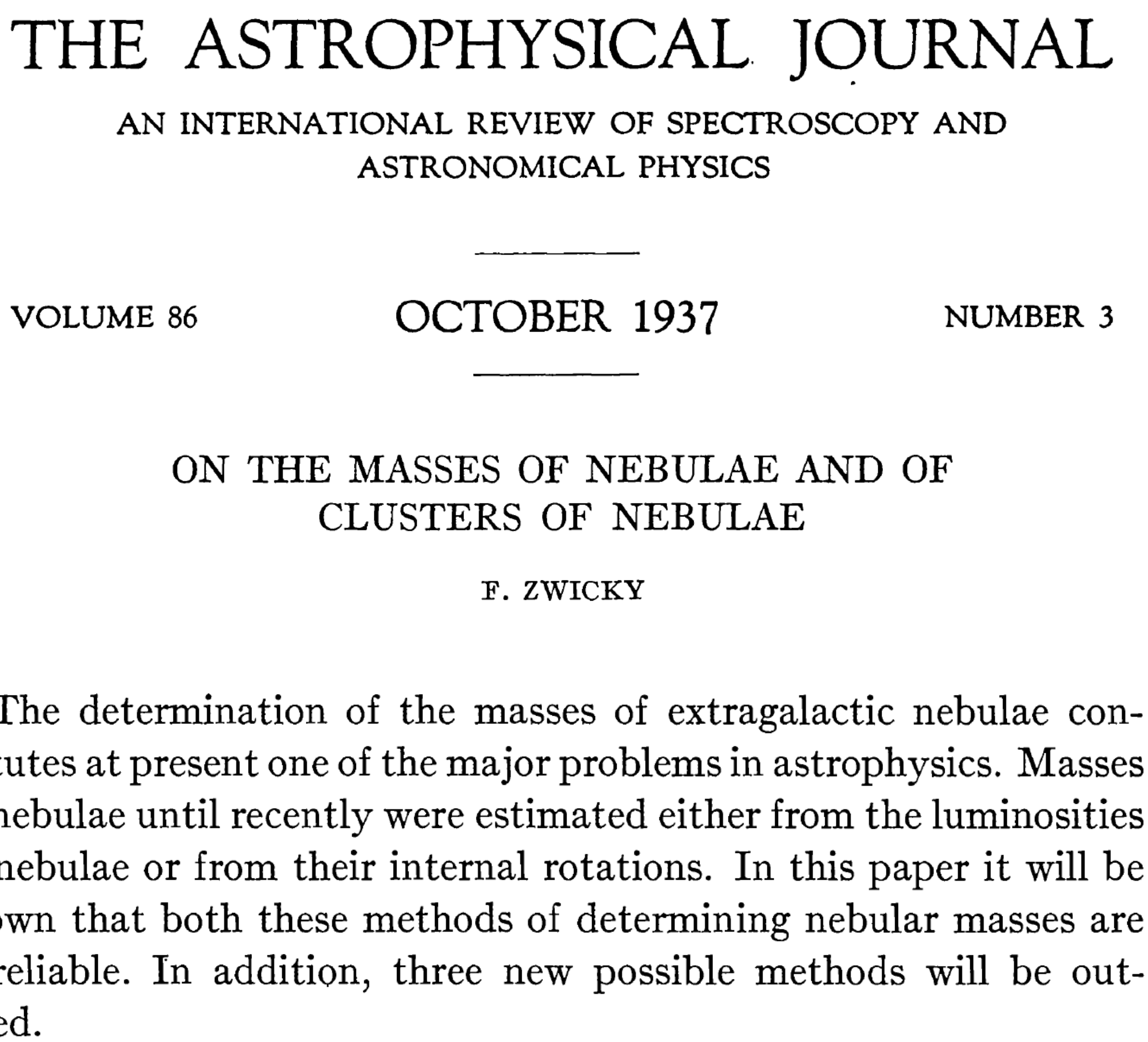
4 – Dark matter searches at the LHC

The discovery of Neptune – a historical precedent



Monsieur Le Verrier vit le nouvel astre au bout de sa plume (Arago)

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.

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-

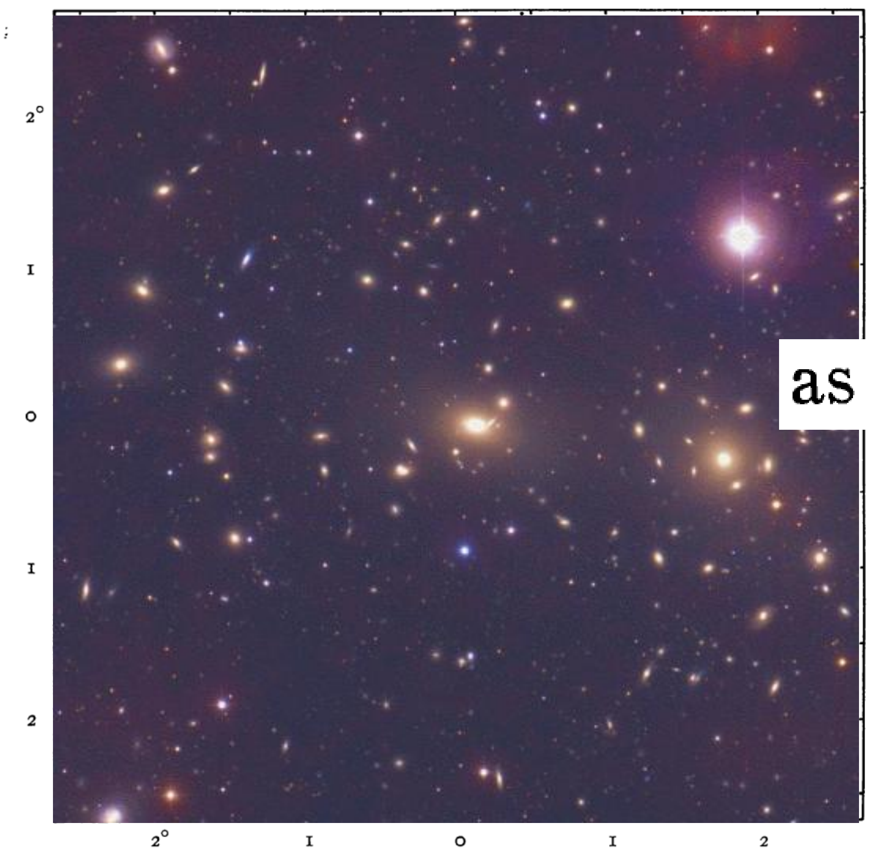


FIG. 3.—The Coma cluster of nebulae

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

$$\gamma = 500$$

as compared with about $\gamma' = 3$

Outline

1 – Zwicky's legacy

http://lapth.cnrs.fr/pg-nomin/salati/APP_ENS_11.pdf

a. The historical discovery

b. Galaxies and clusters of galaxies

c. Cosmological observations

2 – The bestiary of dark matter species

a. Following Charles Darwin

b. Kaluza-Klein particles in extra-D theories

c. The WIMP miracle

3 – Particle astrophysics and the search for dark matter particles

a. Direct detection experiments – underground searches

b. Indirect signatures – the search for cosmic ray anomalies

c. A status on the recent antiproton measurements

4 – Dark matter searches at the LHC

Outline

1 – Zwicky's legacy

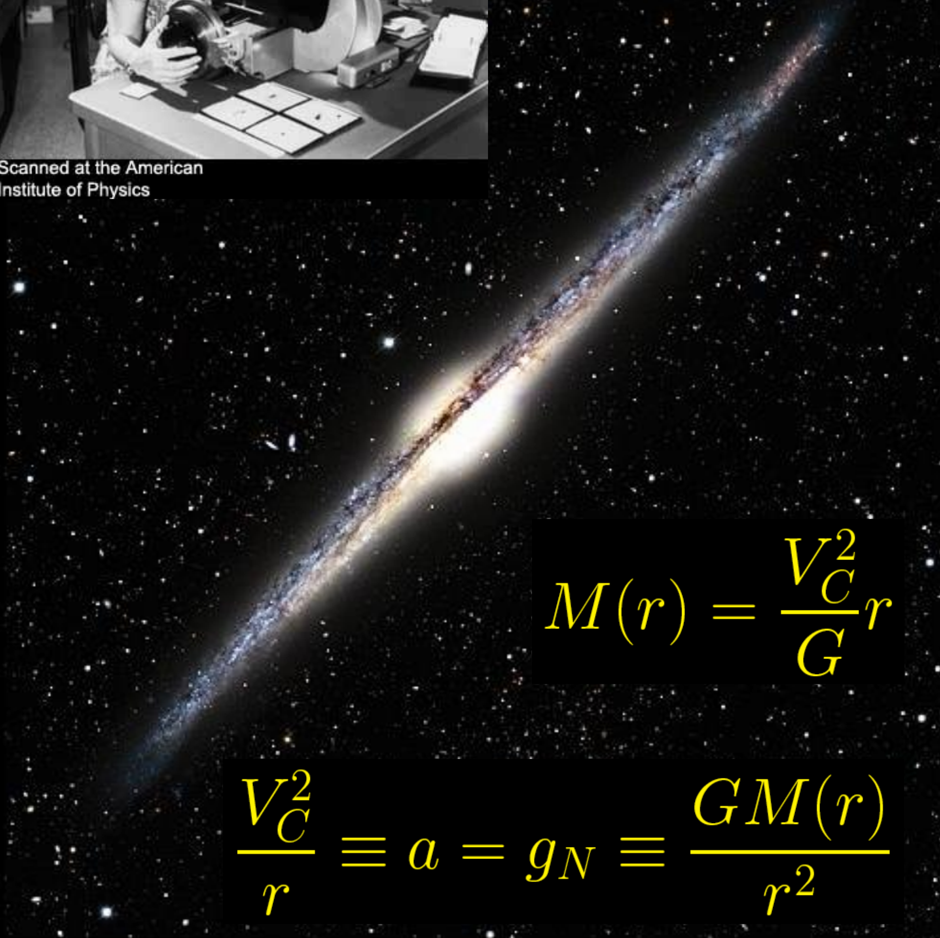
a. The historical discovery

b. Galaxies and clusters of galaxies

Fritz Zwicky and the Coma cluster – 1933

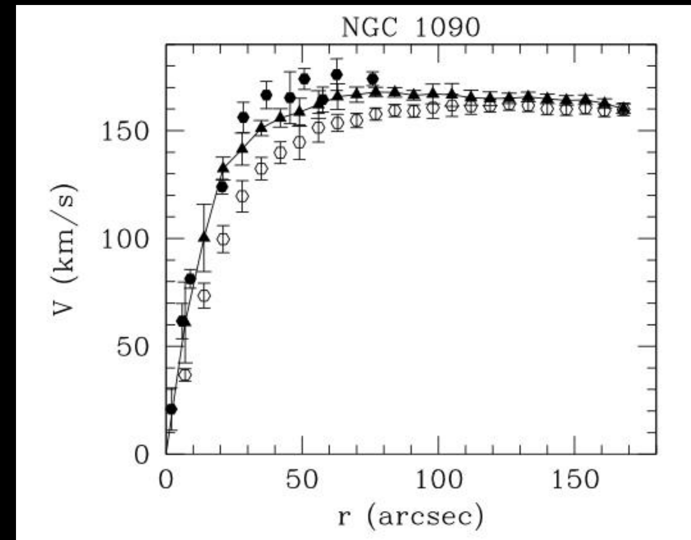
In principle the virial theorem may also be applied to describe the mechanical conditions in an individual nebula. Actually a direct application is difficult, since it is not possible to measure separately, as in the case of a cluster of nebulae, the velocities of the individual units of mass which constitute 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.

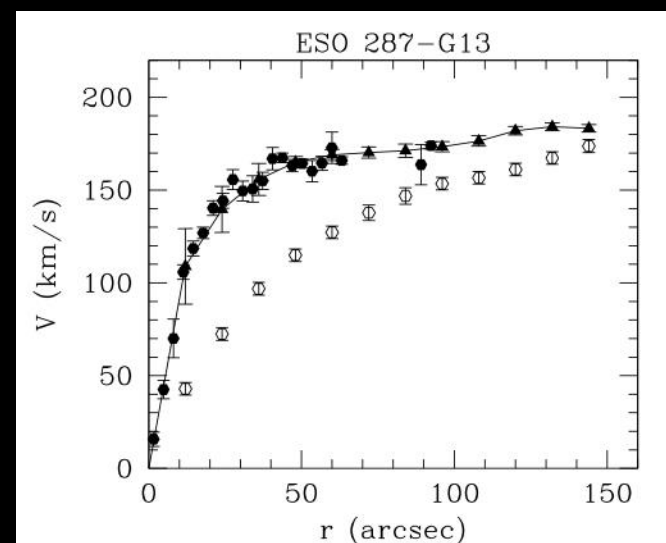
Spiral galaxies have flat rotation curves



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

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





Outline

1 – Zwicky's legacy

a. The historical discovery

b. Galaxies and clusters of galaxies

Fritz Zwicky and the Coma cluster – 1933

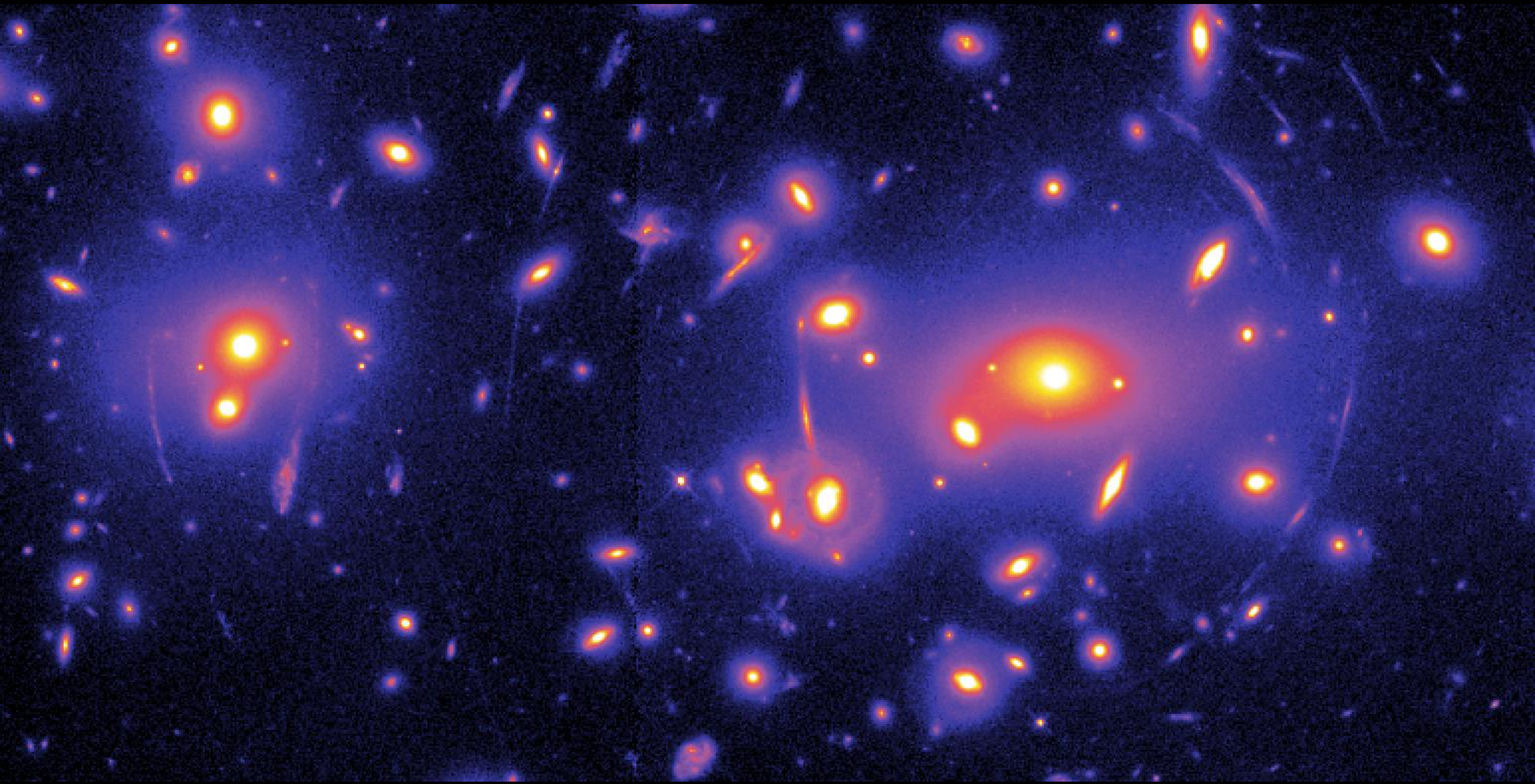
In sections iii, iv, and v three new methods for the determination of nebular masses are discussed, each of which makes use of a different fundamental principle of physics.

Method iii is based on the *virial theorem* of classical mechanics. The application of this theorem to the Coma cluster leads to a minimum value $\bar{M} = 4.5 \times 10^{10} M_{\odot}$ for the average mass of its member nebulae.

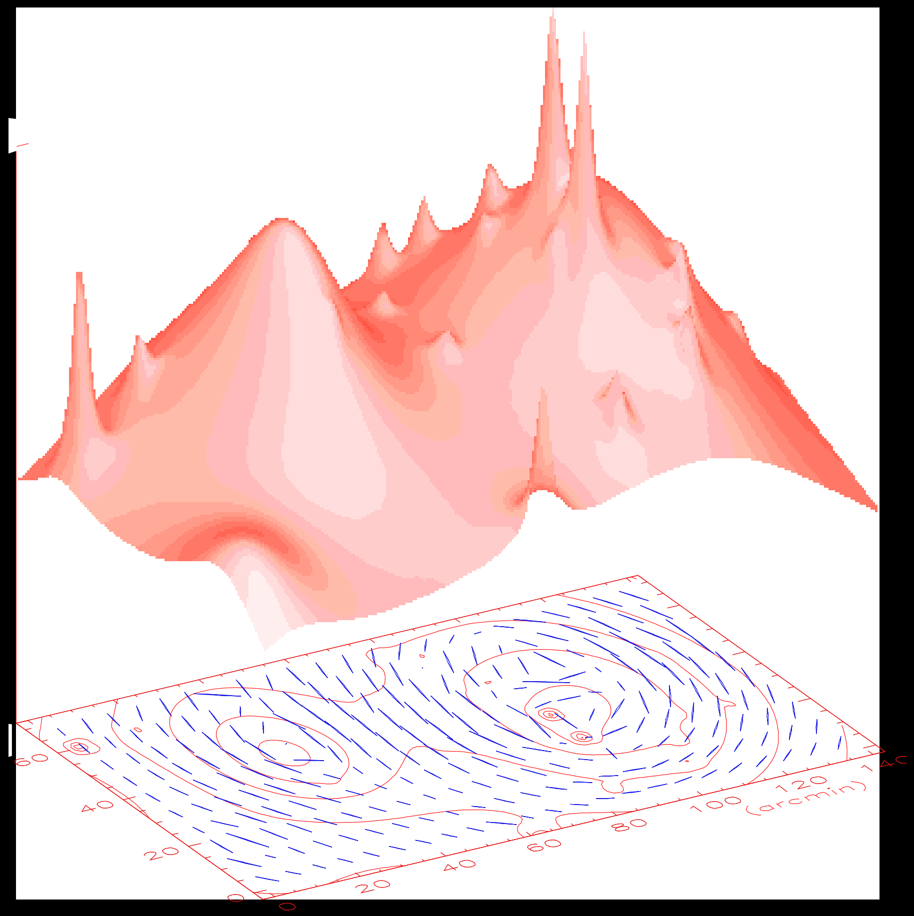
Method iv calls for the observation among nebulae of certain *gravitational lens* effects.

Section v gives a generalization of the principles of ordinary *statistical mechanics* to the whole system of nebulae, which suggests a new and powerful method which ultimately should enable us to determine the masses of all types of nebulae. This method is very flexible and is capable of many modes of application. It is proposed, in particular, to investigate the distribution of nebulae in individual great clusters.

Abell 2218 is located in the Dragon constellation at 1 Gpc



Abell 2218 is located in the Dragon constellation at 1 Gpc



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

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

$$\Downarrow$$

$$T_{\text{gaz}} = \frac{m_B\,\sigma^2}{k} \sim 3 \times 10^7 \text{ K}$$

$$e^- + p \rightarrow e^- + p + \gamma$$

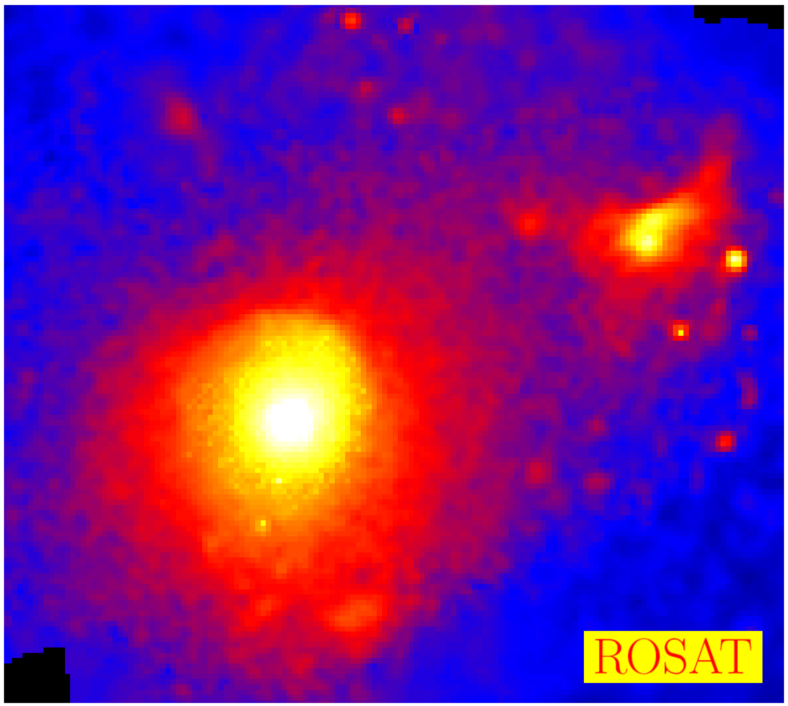
M87 – Optical

$M_{\text{gas+stars}}$

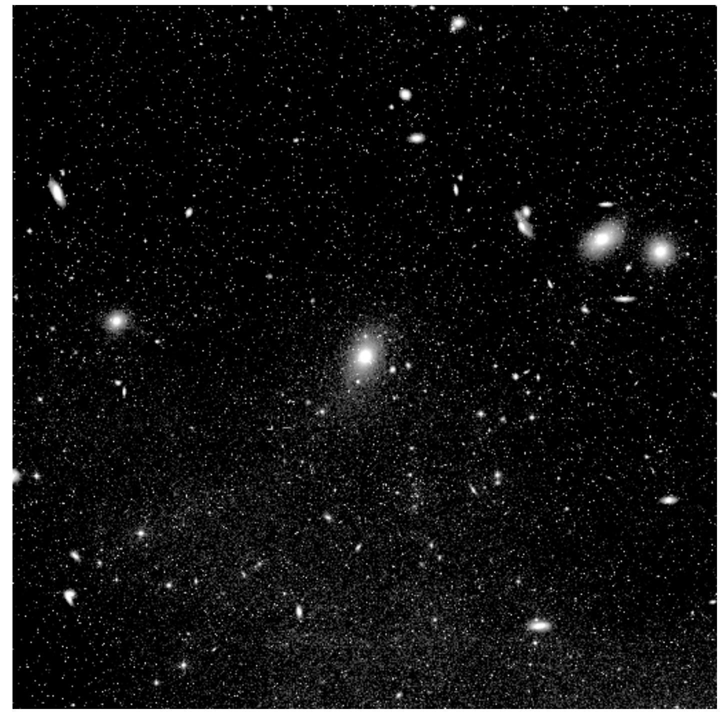
- X–ray observations $\Rightarrow$ presence of hot gas (T, n_e)

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

M87 – X ray image

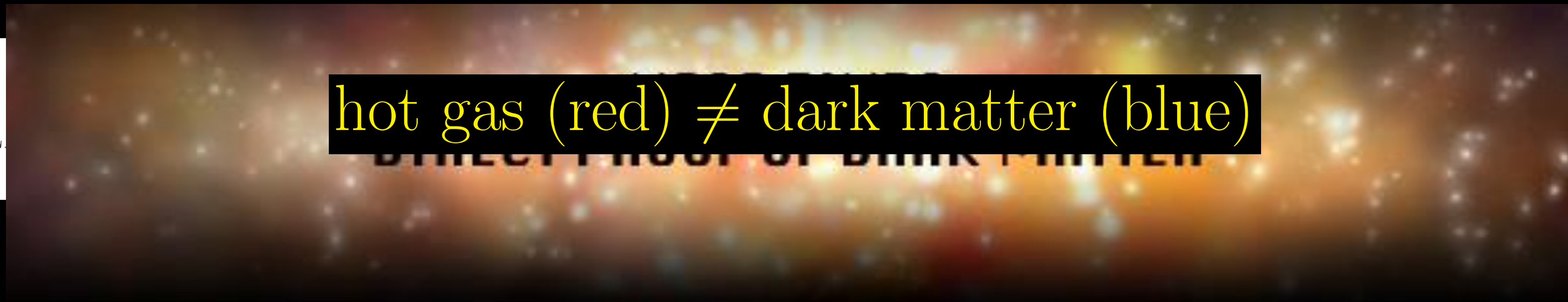


M87 – Optical



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

Spherical cluster in hydrostatic equilibrium

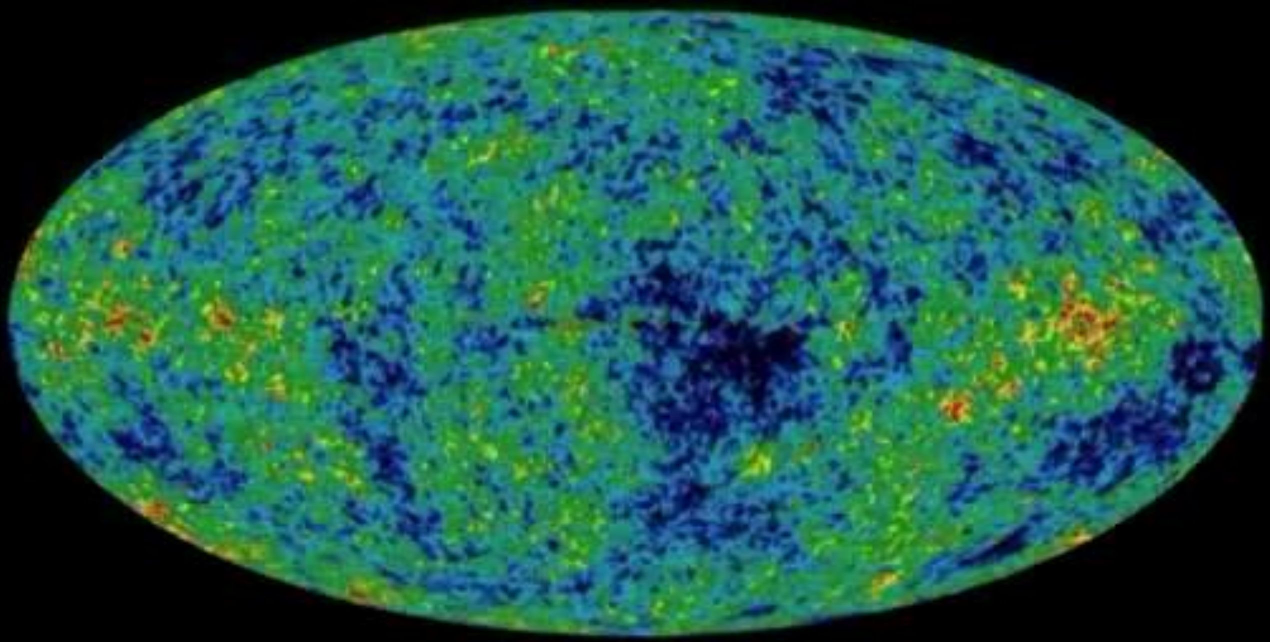


hot gas (red) $\neq$ dark matter (blue)

Outline

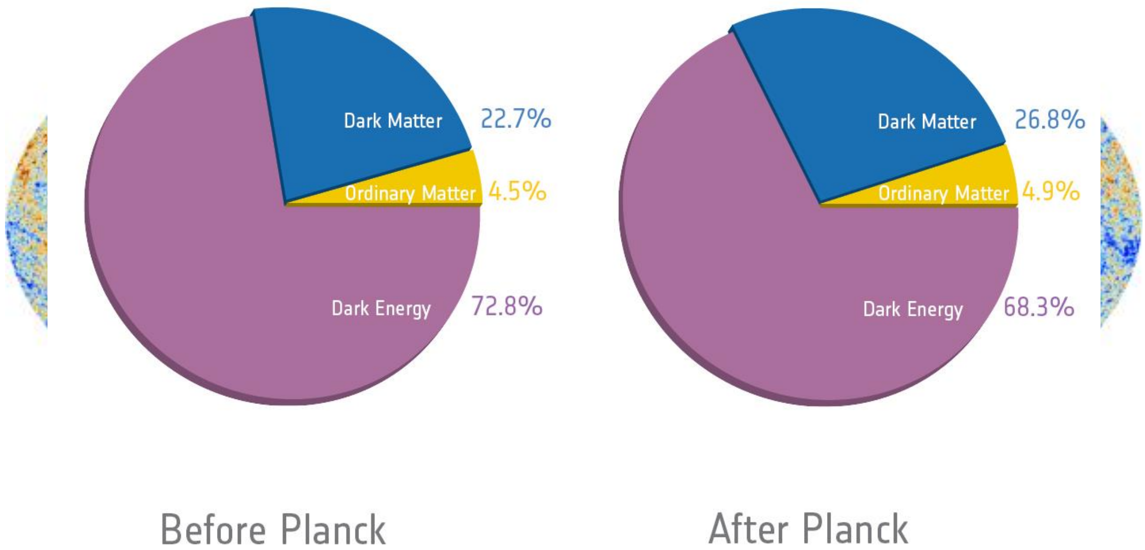
The Cosmological Microwave Background (CMB)

From primordial sound waves to galaxies



The CMB allows to identify the universe properties

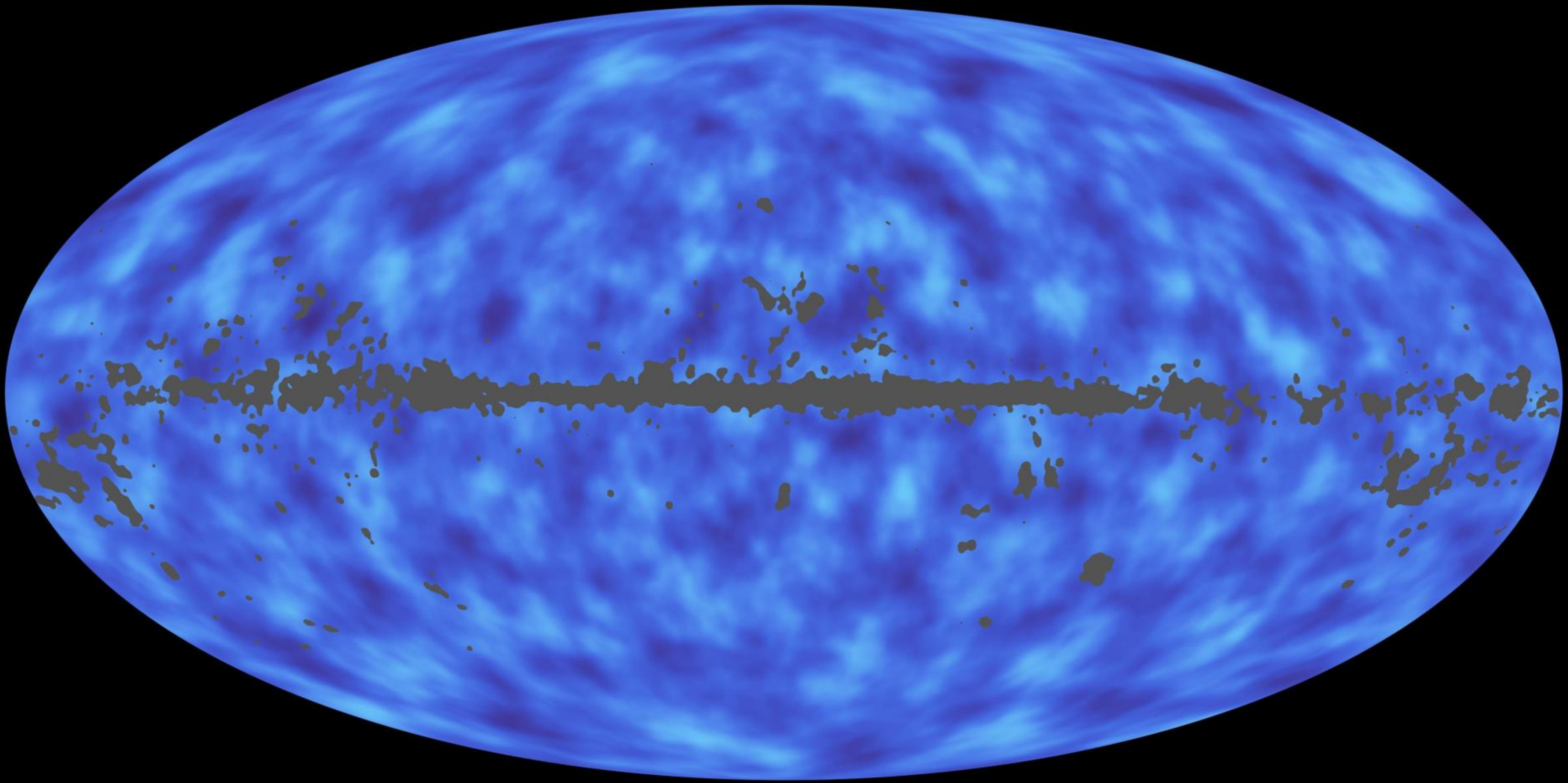
Anisotropies in the cosmic micro-wave background (CMB)



- Dark matter is also detected at cosmological scales.
- This component contributes substantially to the mass of the universe.
- Last but not least, its nature is unknown.

$$\Omega_{\rm DM} h^2 = 0.1196 \pm 0.0031$$

A noisy map of the DM cosmological distribution



Outline

1 – Zwicky's leg

a. The historica

b. Galaxies and

c. Cosmologica

2 – The bestiary of dark matter species

a. Following Charles Darwin

b. Kaluza-Klein particles in extra-D th

c. The WIMP miracle

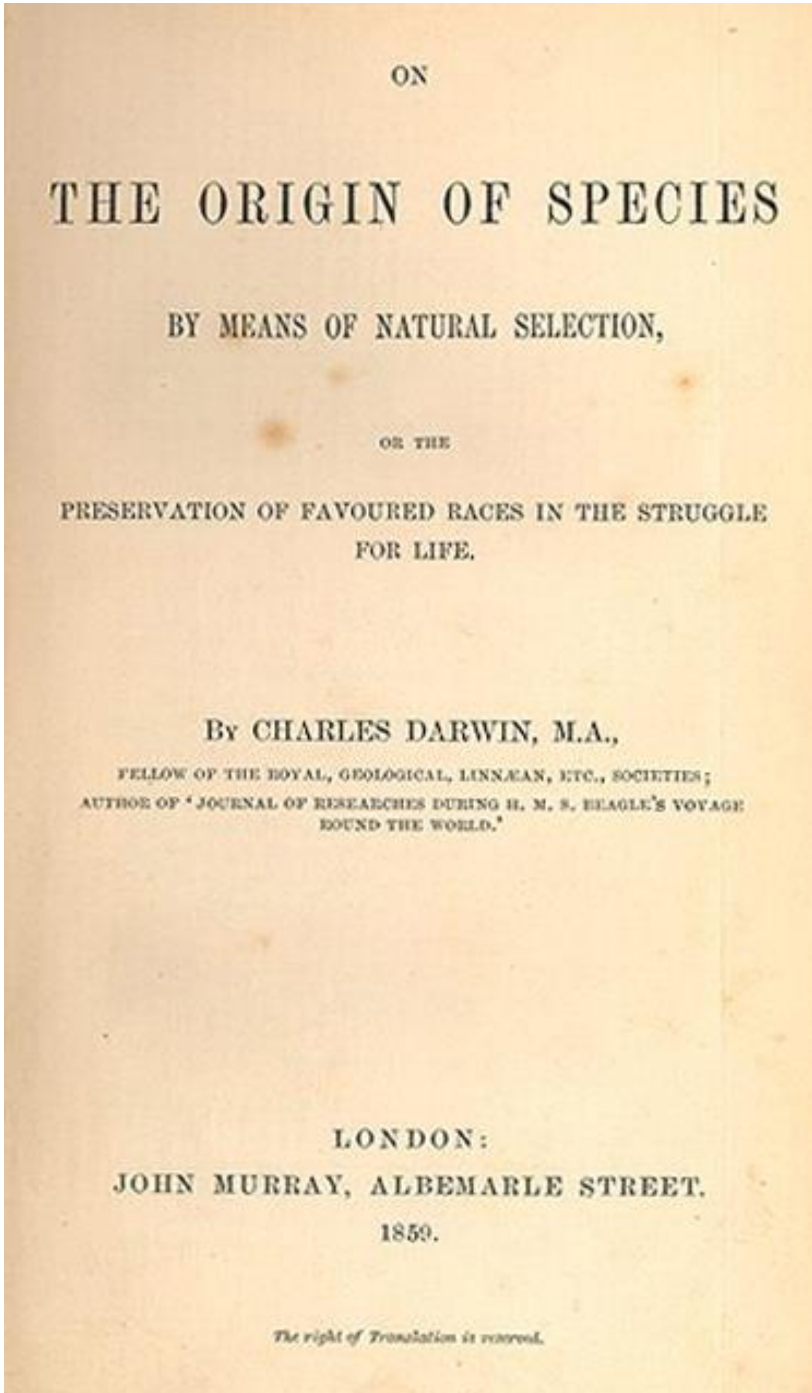
3 – Pa ar s

a. Di le

b. In r c

c. A measurements

4 – Da C



ON

THE ORIGIN OF SPECIES

BY MEANS OF NATURAL SELECTION,

OR THE

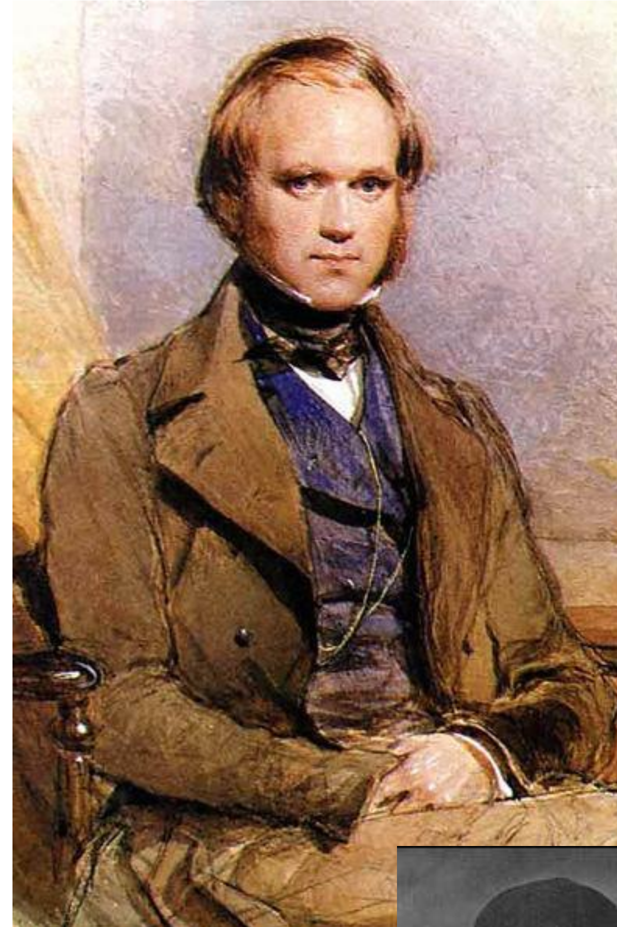
PRESERVATION OF FAVOURED RACES IN THE STRUGGLE FOR LIFE.

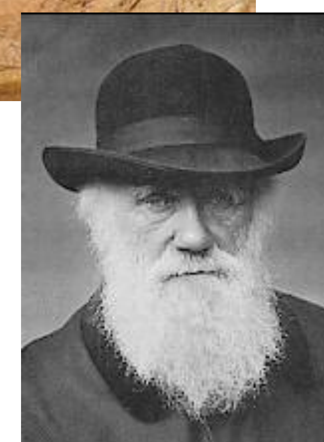
By CHARLES DARWIN, M.A.,

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

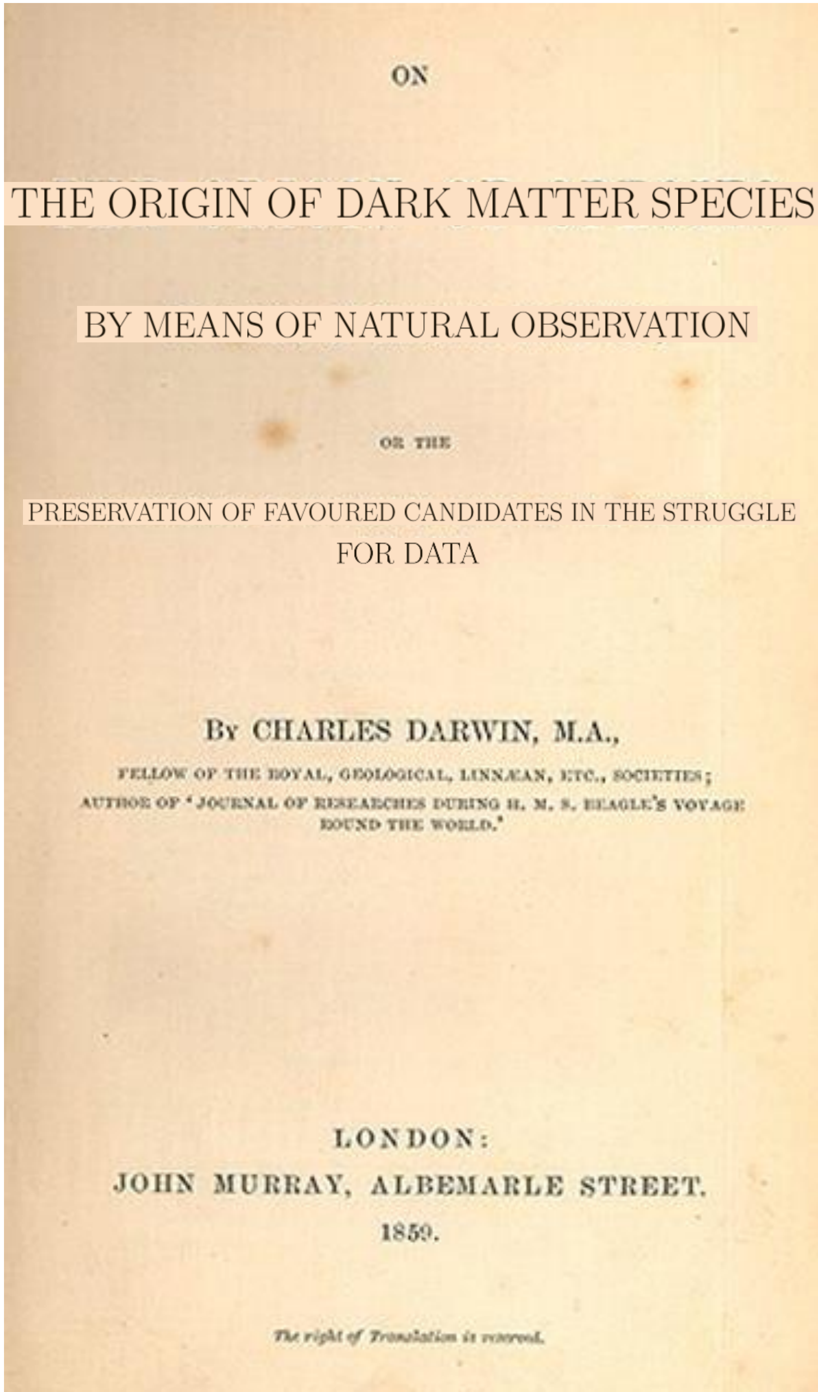
LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1859.

The right of Translation is reserved.





Charles Robert Darwin (1809-1882)



ON

THE ORIGIN OF DARK MATTER SPECIES

BY MEANS OF NATURAL OBSERVATION

OR THE

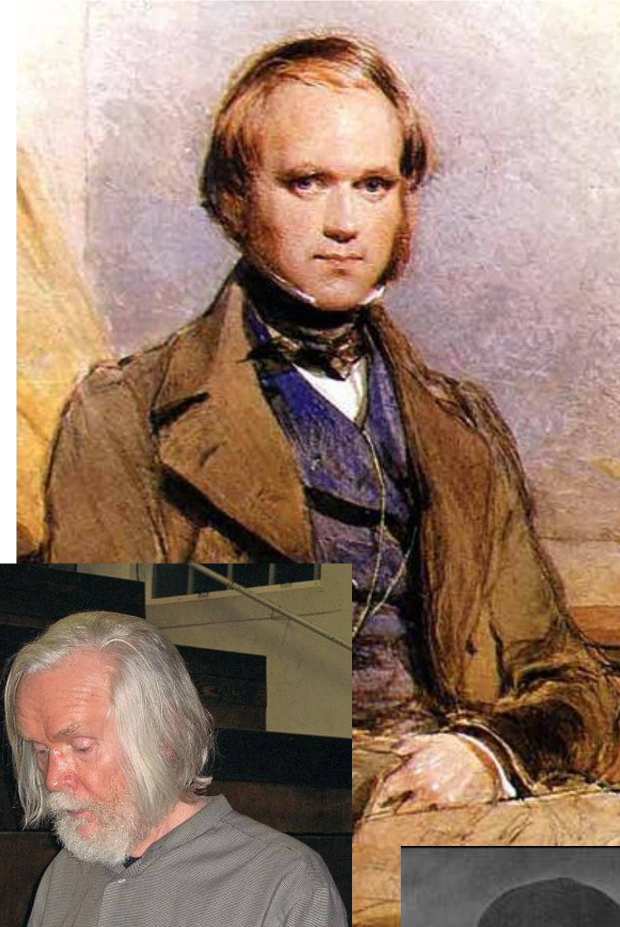
PRESERVATION OF FAVOURED CANDIDATES IN THE STRUGGLE FOR DATA

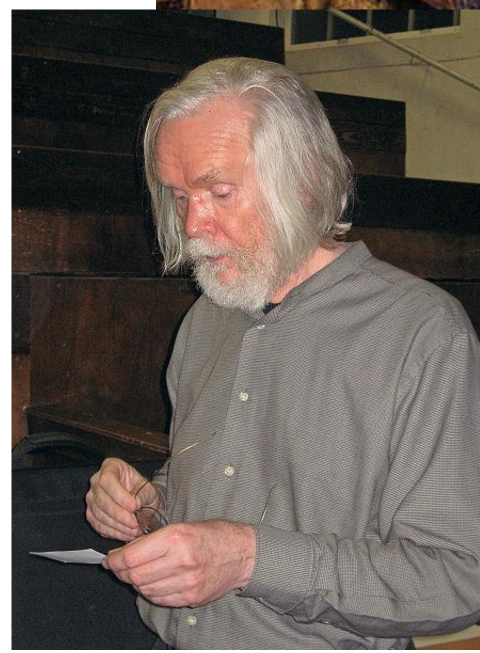
BY CHARLES DARWIN, M.A.,

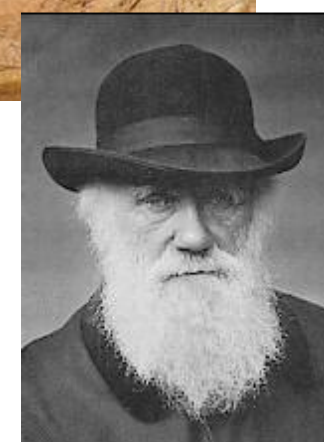
FELLOW OF THE ROYAL, GEOLOGICAL, LINNÆAN, ETC., SOCIETIES;
AUTHOR OF 'JOURNAL OF RESEARCHES DURING H. M. S. BEAGLE'S VOYAGE ROUND THE WORLD.'

LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1859.

The right of Translation is reserved.



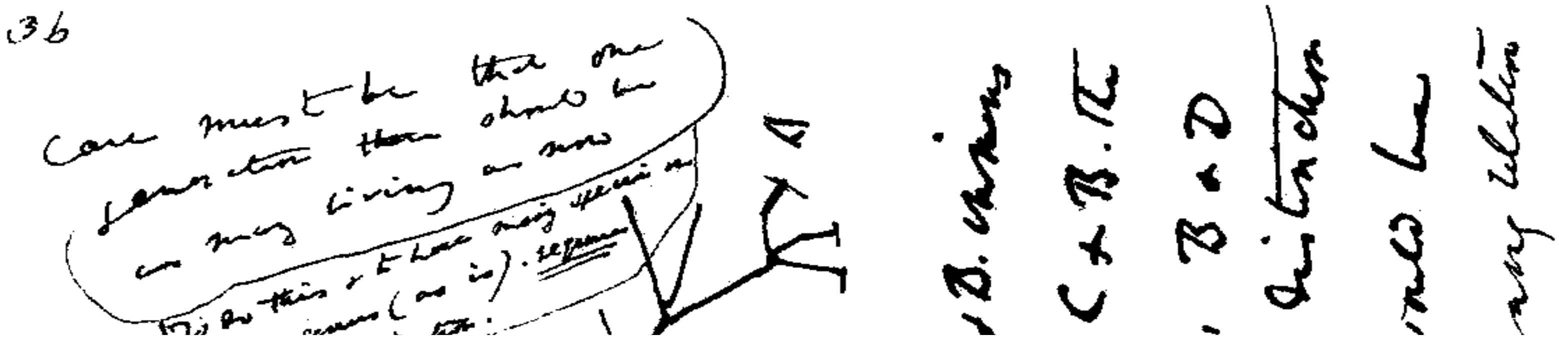




Charles Robert Darwin (1809-1882)

• The nature of Dark Matter is still unresolved. For more than 30 years, physicists have been creating a rich bestiary of possible – if not plausible – candidates.

• In order to classify the various members of that zoo, a few guidelines would be helpful.



DM species	TH motivated	Stable	Production	Signatures
neutralino	✓ (hierarchy)	R parity	thermal	✓ ✓
KK WIMP	✓ (hierarchy)	KK parity	thermal	✓ ✓
gravitino	✓ (GMSB)	R parity	non–TH + NLSP decay	no
axion	✓ (CP)	no	symmetry–B or non–TH	✓ ✓
light DM (MeV)	no	ad hoc	thermal	γ–lines
wimpzillas	no	ad hoc	vacua or non–TH	no
defects	✓ ($G \to H$)	topology	symmetry–B	CMB
Bose condensate	no	ad hoc	?	galactic RC

• The nature of Dark Matter is still unresolved. For more than 30 years, physicists have been creating a rich bestiary of possible – if not plausible – candidates.

• In order to classify the various members of that zoo, a few guidelines would be helpful.

- ✓ Strong theoretical incentive and not just ad'hoc construction
- ✓ Stability needs to be automatically ensured (quantum number or topology)
- ✓ Natural production mechanism
- ✓ Observational signatures should be detectable ≠ metaphysics

Supersymmetric or Kaluza-Klein candidates

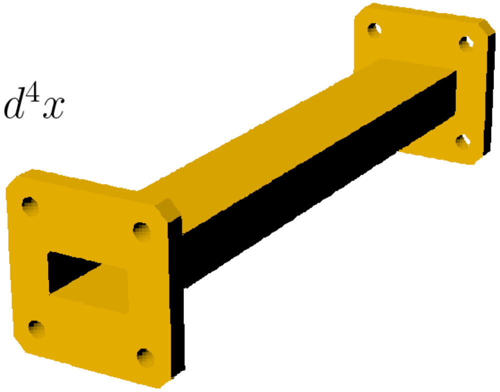
• This species are predicted by supersymmetric or extra-dimensional theories – which are natural extensions to the Standard Model of particle physics. They are **electrically neutral**, **interact weakly** and have a mass of order **GeV to TeV**.

Weakly interacting massive particle – WIMP ou neutralino

Outline

Kaluza–Klein species in extra–dimension theories

Could the **true** Planck mass be O(1) TeV ?



• In Kaluza–Klein theories, the universe has extra–dimensions.
The real Planck mass μ is smaller than the canonical value of $M_P \sim 10^{19}$ GeV since

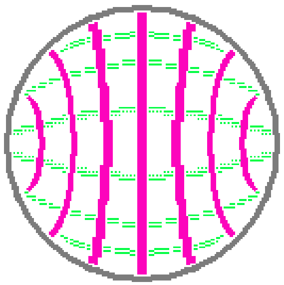
$$\mathcal{S} = \frac{{M_P}^2}{16\,\pi} \int \mathcal{R}\,\sqrt{g}\;d^4x = \frac{\mu^3}{16\,\pi} \int \mathcal{R}\,\sqrt{\tilde{g}}\;d^5y = \frac{\mu^3\,L}{16\,\pi} \int \mathcal{R}\,\sqrt{g}\;d^4x$$

$$\Downarrow$$

$${M_P}^2 \; = \; \mu^3\,L$$

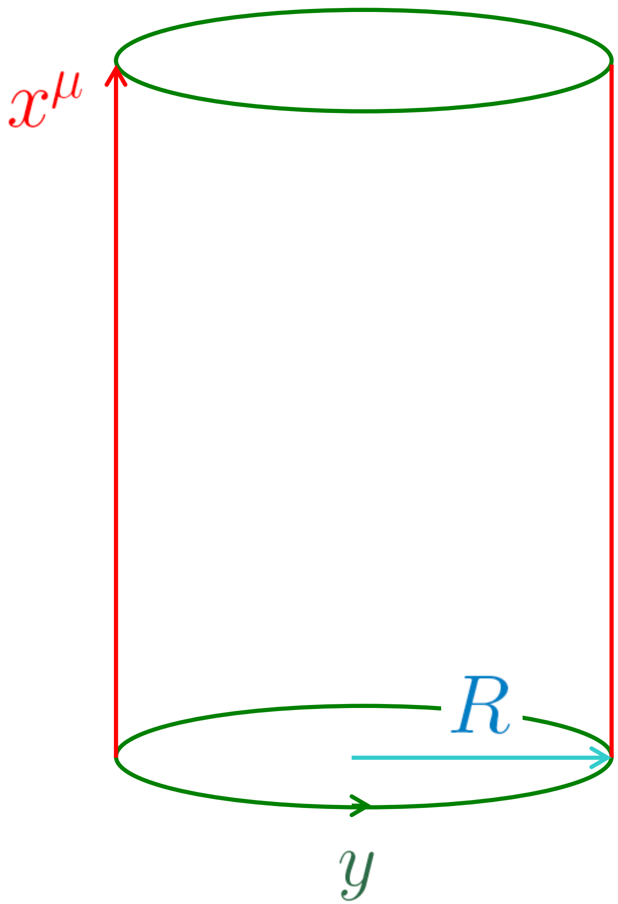
We can play with the number and length of extra–dimensions to lower the gravity scale

$$L^{-1} \sim 1 \text{ TeV} \quad \Rightarrow \quad \mu \sim 5 \times 10^{13} \text{ GeV}$$



• Extra–dimensions behave as a wave–guide. Explanation of the masses.

Universal Extra Dimension Theories – UED



$$\phi\,(x^\mu, y) \;=\; \sum_{n=-\infty}^{+\infty} \phi^{(n)}(x^\mu) \quad exp\left\{\frac{i\,n\,y}{R}\right\}$$

$$\left(\partial^A \partial_A + m^2\right)\phi = 0$$

$$\Downarrow$$

$$\left(\partial^\mu \partial_\mu \;+\; \left\{m^2 + \frac{n^2}{R^2}\right\}\right)\phi^{(n)}(x) = 0$$

Kaluza–Klein tower of states

The y–momentum $P_5 \equiv -\,i\,R\,\partial_y$ is conserved $\;\Rightarrow\;$ $P_5\,\phi^{(n)} = n\,\phi^{(n)}$

However !

• For $D = 5$ – odd – the Dirac spin 1/2 representation of $SO(4,1)$ is irreducible and non–chiral

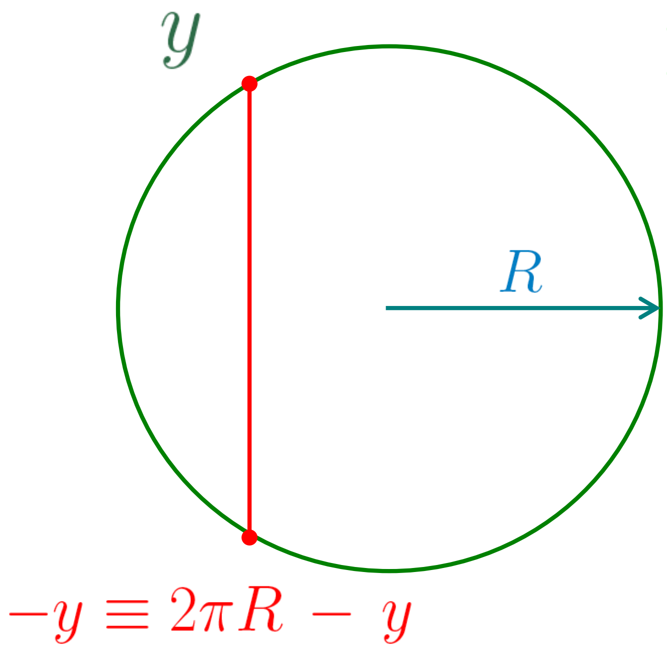
• The fifth–component of the 5–dimensional vector field A_M may be expanded as

$$A_5\,(x, y) \;=\; \sum_{n=-\infty}^{+\infty} A_5^{(n)}(x) \;\; \exp\left\{\frac{i\,n\,y}{R}\right\}$$

The zero mode $A_5^{(0)}$ behaves as a massless scalar field under the 4–D usual lorentz transformation.

Where is it ?

Orbifold Compactification



Parity Operator $\mathcal{P}$: $y \;\Rightarrow\; -y$

- Even eigenstates

$$\phi_{\mathrm{E}} = \phi^{(0)} + \sum_{n=1}^{+\infty} \phi_{\mathrm{E}}^{(n)} \cos\left\{\frac{n\,y}{R}\right\}$$

- Odd eigenstates

$$\phi_{\mathrm{O}} = \sum_{n=1}^{+\infty} \phi_{\mathrm{O}}^{(n)} \sin\left\{\frac{n\,y}{R}\right\}$$

The gauge invariance of the electromagnetic field translates into

$$A_M \;\Rightarrow\; A'_M = A_M + \partial_M \theta$$

$A'_\mu = A_\mu + \partial_\mu \theta$ is even whereas $A'_5 = A_5 + \partial_y \theta$ is odd

The Kaluza–Klein parity $\mathcal{P} = \pm 1$ is conserved

The Lightest Kaluza–Klein Particle LKP is stable !

Outline

http://lapth.cnrs.fr/pg-nomin/salati/APP_ENS_11.pdf

PHYSICAL REVIEW LETTERS

VOLUME 39 — 25 JULY 1977 — NUMBER 4

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] *Batavia, Illinois 60510*

and

Steven Weinberg[c]
Stanford University, Physics Department, Stanford, California 94305

(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

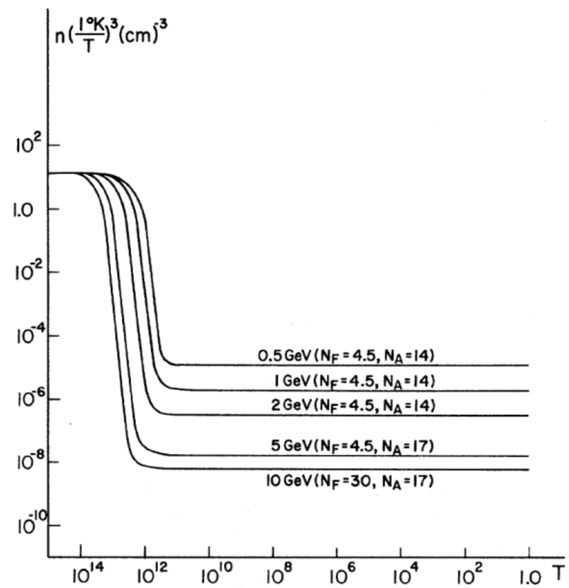


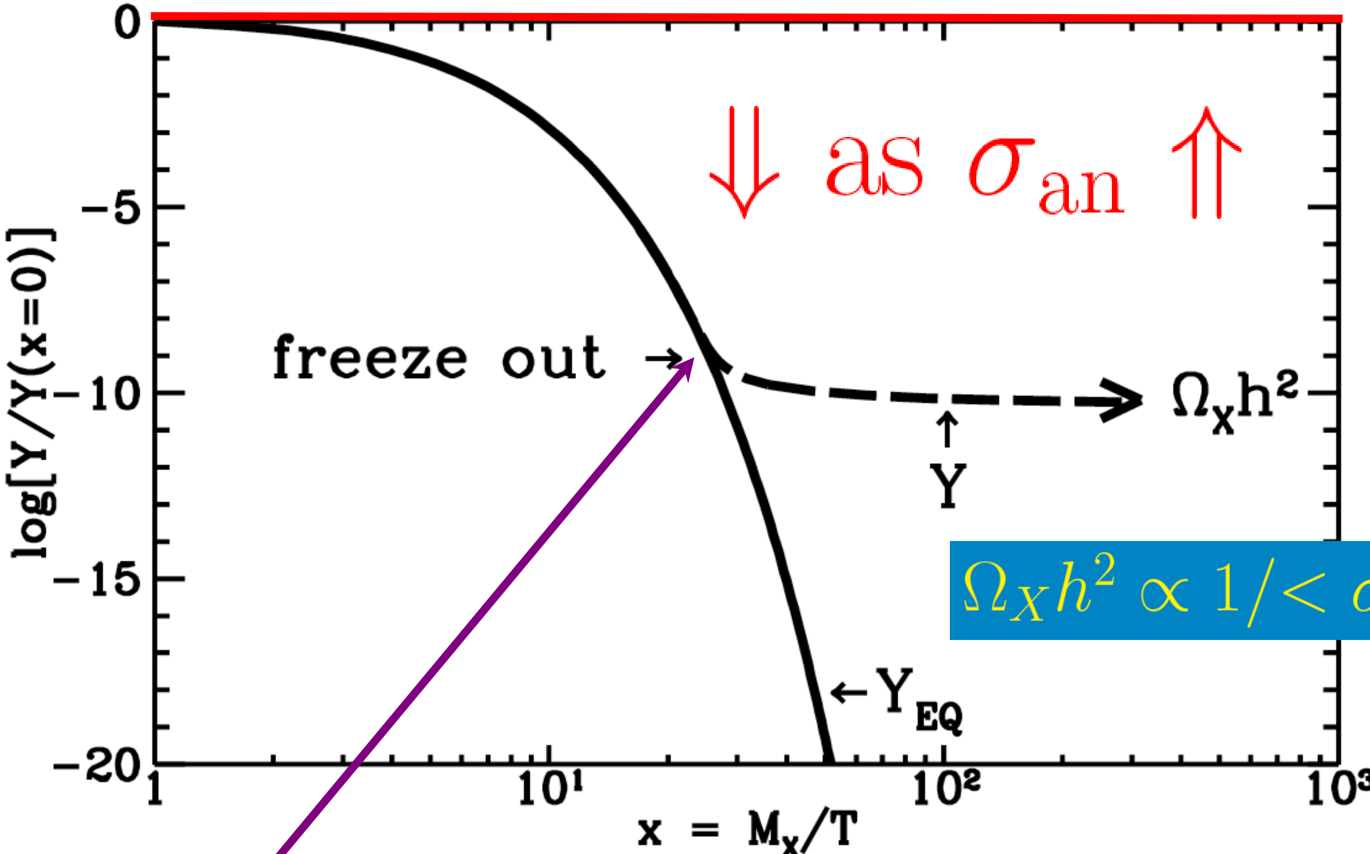
FIG. 1. n/T^3 vs T for a variety of special cases of m_L, N_F, and N_A.

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)

Lightest Kaluza–Klein Particle

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

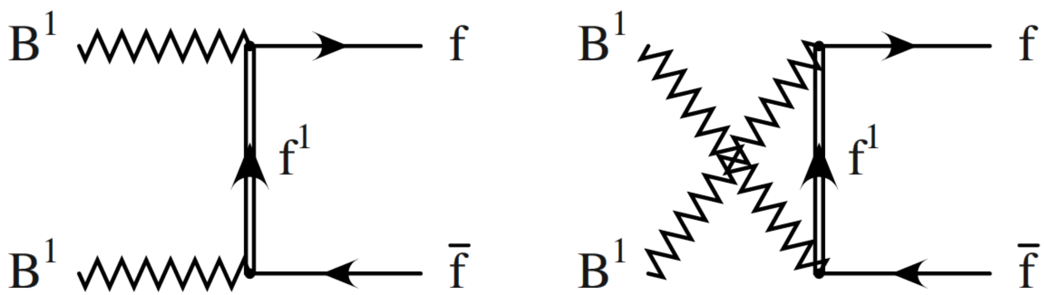


Figure 4: Feynman diagrams for $B^{(1)}B^{(1)}$ annihilation into fermions.

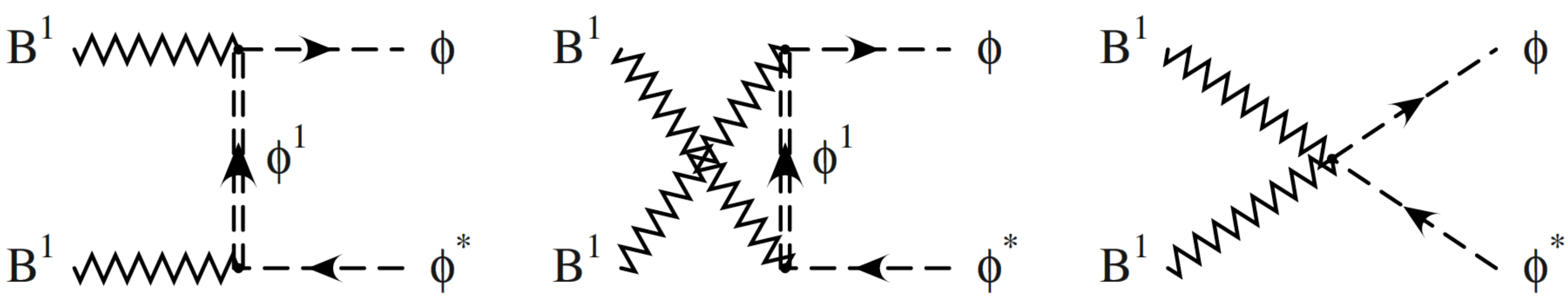
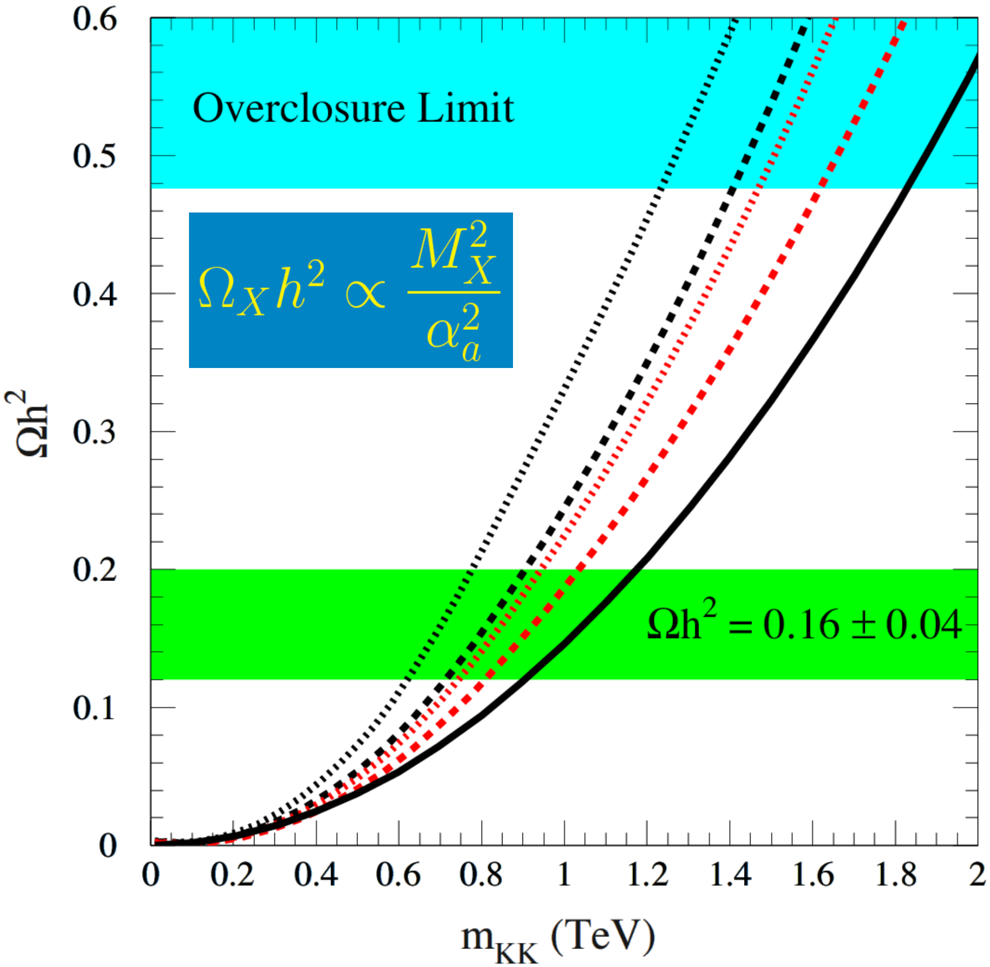


Figure 5: Feynman diagrams for $B^{(1)}B^{(1)}$ annihilation into Higgs scalar bosons.



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) $\Delta = 0.05$.

Thermodynamical equilibrium production

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

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

$$\Omega_X h^2 \sim 0.1 \;\; \Leftrightarrow \;\; \langle \sigma_{\rm an} v \rangle \sim 3 \times 10^{-26} \; {\rm cm}^3 \, {\rm s}^{-1}$$

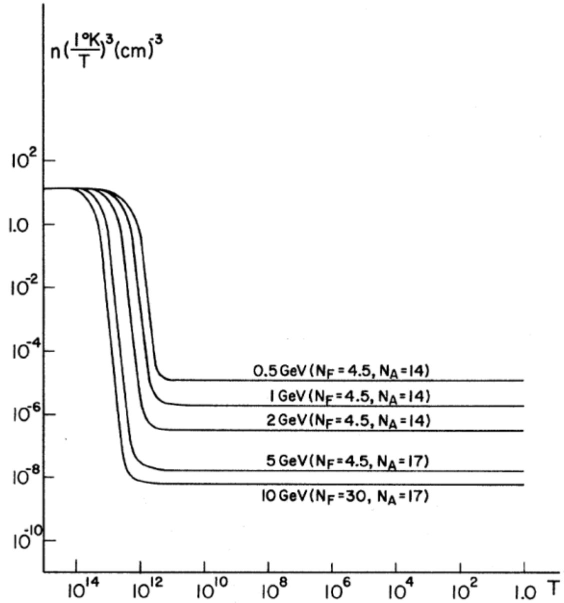


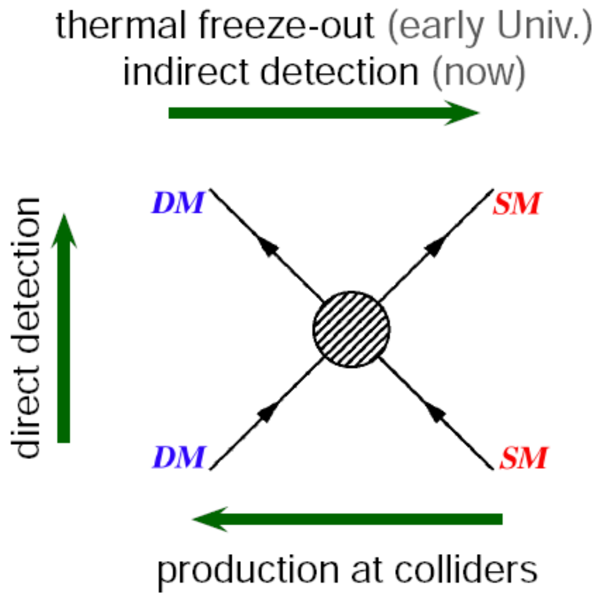
FIG. 1. n/T^3 vs T for a variety of special cases of m_L, N_F, and N_A.

Thermodynamical equilibrium production

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

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

$$\Omega_X h^2 \sim 0.1 \;\; \Leftrightarrow \;\; \langle \sigma_{\rm an} v \rangle \sim 3 \times 10^{-26} \ {\rm cm}^3 \ {\rm s}^{-1}$$



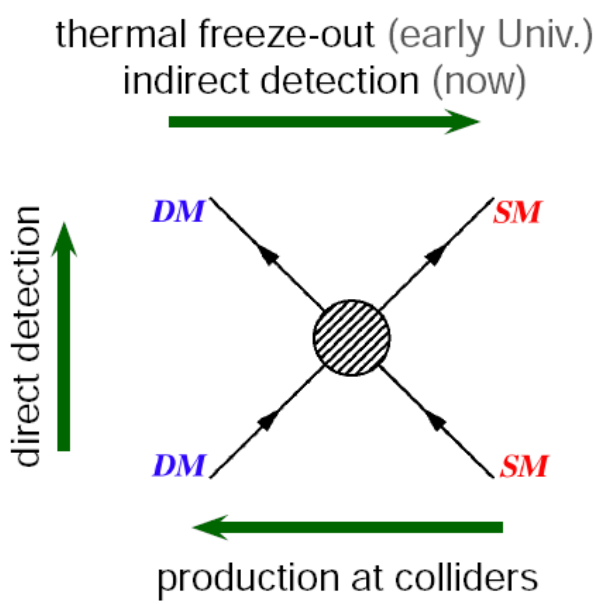
WIMP search strategies

• Direct Detection – Observing the impact of a cosmic WIMP on a nucleus through the energy transferred by the collision.

$$\chi + \text{quark} \rightarrow \chi + \text{quark}$$

• Indirect Detection – WIMPs continuously annihilate and produce SM particles such as gamma-rays, neutrinos, but also rare antimatter species like positrons, antiprotons and even antideuterons.

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



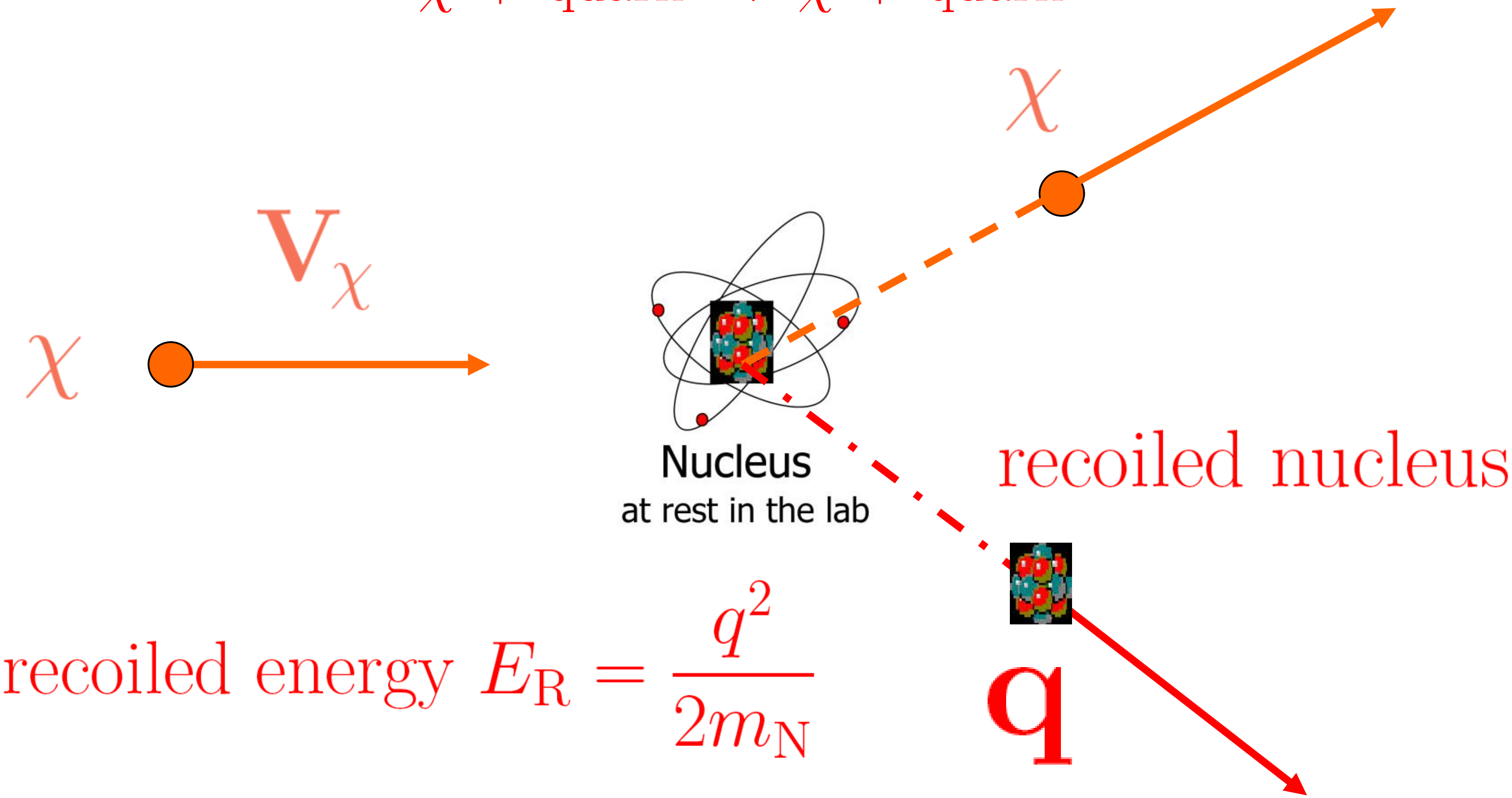
Outline

http://lapth.cnrs.fr/pg-nomin/salati/salati_cargese_2007.pdf

WIMP search strategies

- Direct Detection – Observing the impact of a cosmic WIMP on a nucleus through the energy transferred by the collision.

$$\chi + \text{quark} \rightarrow \chi + \text{quark}$$

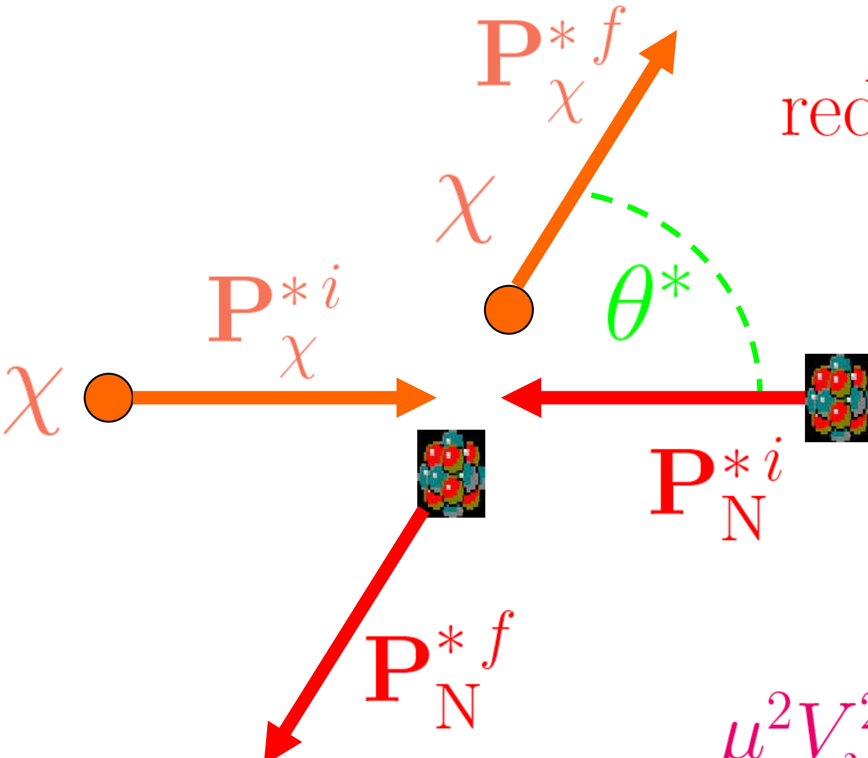


recoiled energy $E_{\rm R} = \dfrac{q^2}{2 m_{\rm N}}$

Elastic scattering off a nucleus at rest

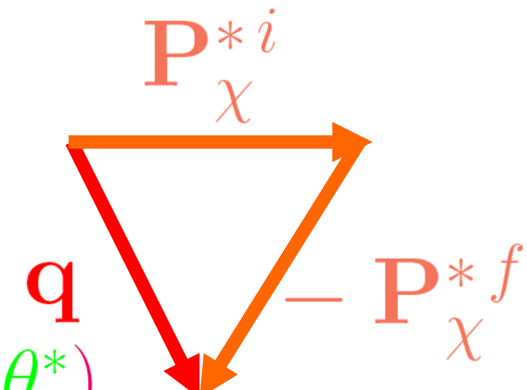
Center of Mass Frame

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



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

$P^* = \mu V_\chi$

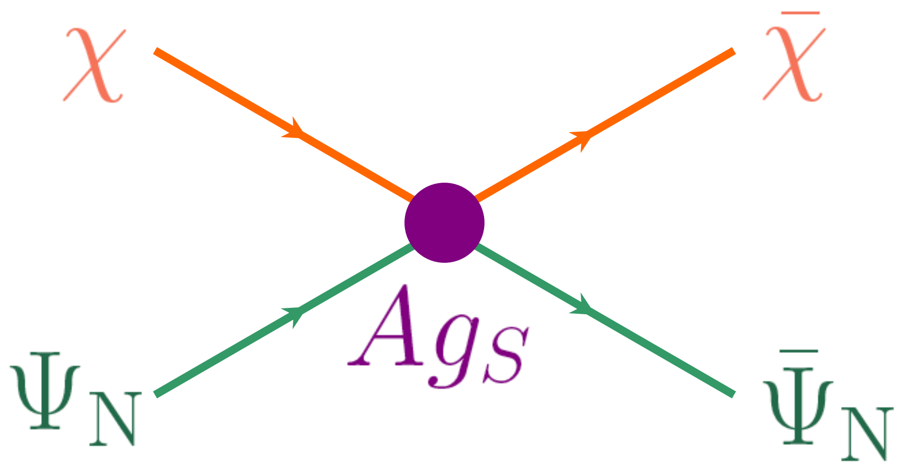


$$E_{\rm R} = \frac{\mu^2 V_\chi^2}{m_{\rm N}}(1 - \cos\theta^*)$$

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

A (not too) naive toy model

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



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

$g_S \sim 7.3 \times 10^{-9}\ \text{GeV}^{-2}$ 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

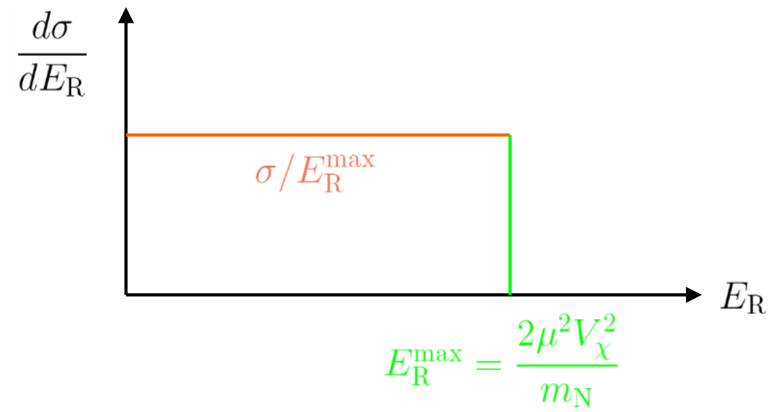
$$\mathcal{A}\equiv\frac{1}{4}\sum_{\text{spins}}|\mathcal{M}_{\,\text{scalar}}|^2\;=\;16\,\kappa\,A^2\,g_S^2\,m_\chi^2\,m_\mathrm{N}^2\quad. \tag{4}$$

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 $E_{\rm R}$



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

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

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

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

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

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

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

The recoil spectrum

• The terrestrial detector is embedded inside a stream of neutralinos. Each nucleus may undergo a collision whose probability per unit time and unit of recoil energy is given by

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E_{\mathrm{R}}} = \frac{\rho_{\odot}}{m_{\chi}} \cdot \int_{v_{\min}(E_{\mathrm{R}})}^{v_{\max}} \mathrm{d}^3\mathbf{v}\ \mathrm{f}(\mathbf{v})\ v\ \frac{d\sigma}{dE_{\mathrm{R}}}$$

• In the limit where the recoil spectrum is flat, the rate of collision **per unit mass of the detector** may be expressed as the product

$$\boxed{\frac{\mathrm{d}R}{\mathrm{d}E_{\mathrm{R}}} = \frac{\rho_{\odot}}{m_{\chi}} \cdot \frac{\sigma}{\sqrt{\pi}\mu^2 V_C} \cdot \mathcal{T}(E_R)}$$

where the integral $\mathcal{T}(E_R)$ depends on the velocity distribution of the neutralinos

$$\mathcal{T}(E_R) = \frac{\sqrt{\pi}}{2} V_C \int_{v_{\min}(E_{\mathrm{R}})}^{v_{\max}} \frac{\mathrm{d}^3\mathbf{v}}{v}\ \mathrm{f}(\mathbf{v})$$

Exercise – Level **[2]** *: In the absence of collisions, point–like particles under the action of the gravitational potential* Φ *behave in phase–space like an incompressible fluid whose density* $\mathrm{f}(\mathbf{r}, \mathbf{v}, t)$ *follows the* **Vlasov** *equation*

$$\frac{\partial \mathrm{f}}{\partial t} + (\mathbf{v} \cdot \nabla)\,\mathrm{f} - (\nabla\Phi \cdot \nabla_v)\,\mathrm{f} \;=\; 0 \quad . \tag{1}$$

Show that any function f *of the mechanical energy per unit mass* $E = v^2/2 + \Phi(\mathbf{r})$ *is a stationary solution of (1). Let us choose the Maxwell–Boltzmann distribution* $f = C\,\exp(-E/\nu^2)$, *where* ν *denotes the typical velocity dispersion of the particles. By integrating out the velocities, establish that the mass density is given by*

$$\rho\,(\mathbf{r}) = \rho_c\,\exp\{-\,\Phi(\mathbf{r})/\nu^2\} \quad . \tag{2}$$

Assuming spherical symmetry, solve the Poisson equation

$$\Delta\Phi \;=\; \frac{1}{r^2}\,\frac{d}{dr}\left\{r^2\,\frac{d\Phi}{dr}\right\} \;=\; 4\,\pi\,G\,\rho(r) \quad . \tag{3}$$

for the scale invariant solution $\rho = A\,r^{\alpha}$. *Compute* A *and* α *in order to derive the specific form for the mass density of an isothermal sphere*

$$\rho(r) \;=\; \frac{\nu^2}{2\,\pi\,G}\,\frac{1}{r^2} \quad . \tag{4}$$

Show that if the dark matter inside a spiral galaxy follows that profile and if it dominates the dynamics of the system, the rotation curve is flat with velocity $V_C = \sqrt{2}\,\nu$.

• DM particles need to have a large enough velocity in order to transfer the recoil energy E_R

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

$$\Downarrow$$

$$\boxed{\frac{2\mu^2 v_{\rm min}^2}{m_{\rm N}} = E_R}$$

• A **Maxwellian distribution** of velocity is assumed here for simplicity

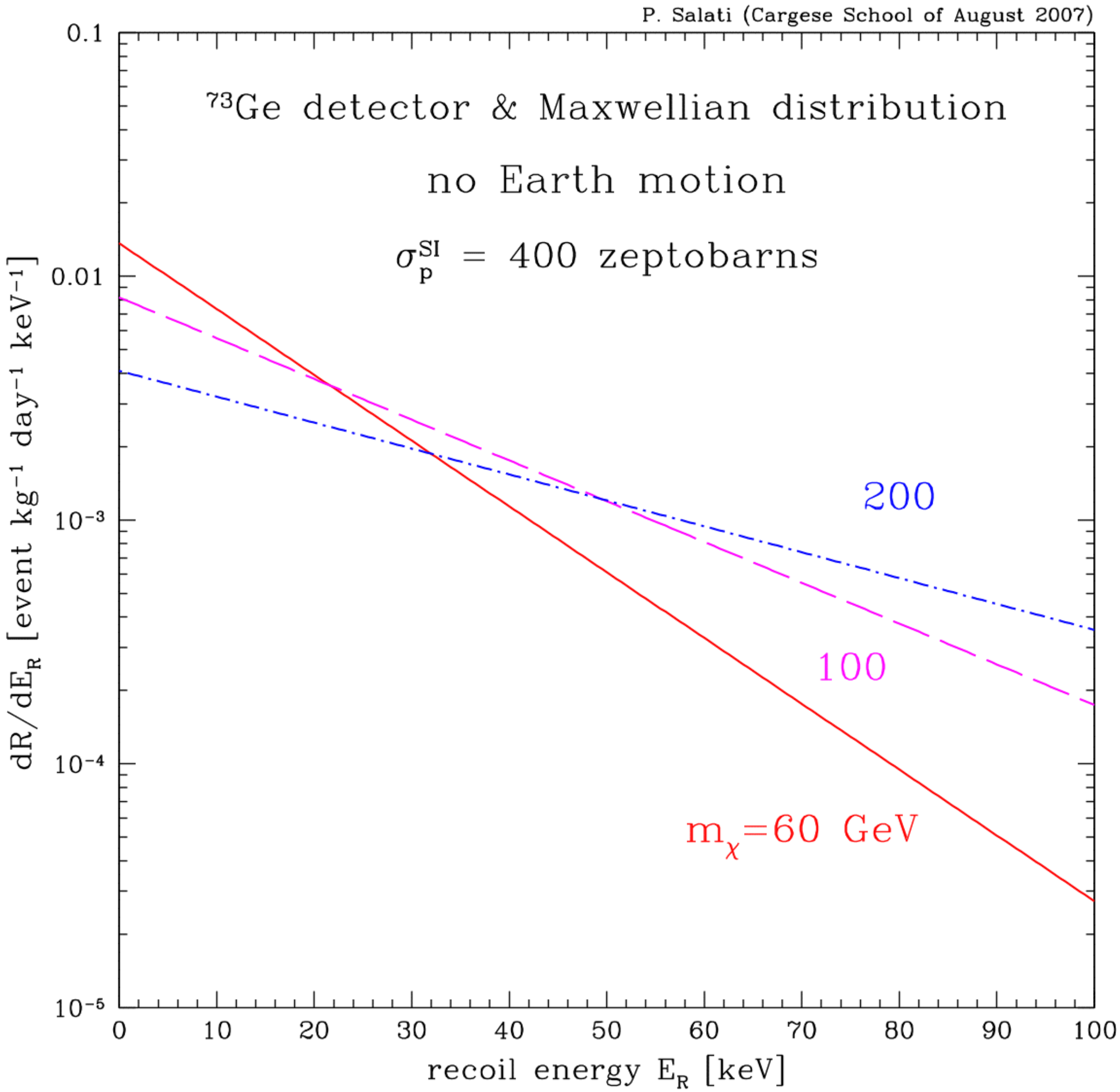
$$\boxed{\mathrm{f}(\mathbf{v}) = \left(\pi V_C^2\right)^{-3/2} \exp(-v^2/V_C^2)}$$

$$\Downarrow$$

$$\boxed{\mathcal{T}(E_R) = \exp(-v_{\rm min}^2/V_C^2)}$$

$$\boxed{\mathcal{T}(E_R) = \exp(-E_R/E_R^0) \text{ where } E_R^0 = 2\mu^2 V_C^2/m_{\rm N}}$$

The recoil spectrum decreases exponentially with a variation scale set by E_R^0.
For ^{73}Ge and a 60 GeV neutralino, $E_R^0 = 16$ keV


P. Salati (Cargese School of August 2007)
^{73}Ge detector & Maxwellian distribution
no Earth motion
σ_p^{SI} = 400 zeptobarns
200
100
m_χ=60 GeV
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
dR/dE_R [event kg^{-1} day^{-1} keV^{-1}]
0
10
20
30
40
50
60
70
80
90
100
recoil energy E_R [keV]

Expected number of events $n_{\rm theo}$

• The exposure of the detector is defined as

$$\mathcal{E} = \text{Mass} \times \text{Duration}$$

and is expressed in units of kg $\times$ day.

• Events are detected above the threshold $E_{\rm th}$ up to an energy $E_{\rm max}$. During the period of observation – characterized by the exposure $\mathcal{E}$ – a number $n_{\rm theo}$ is expected

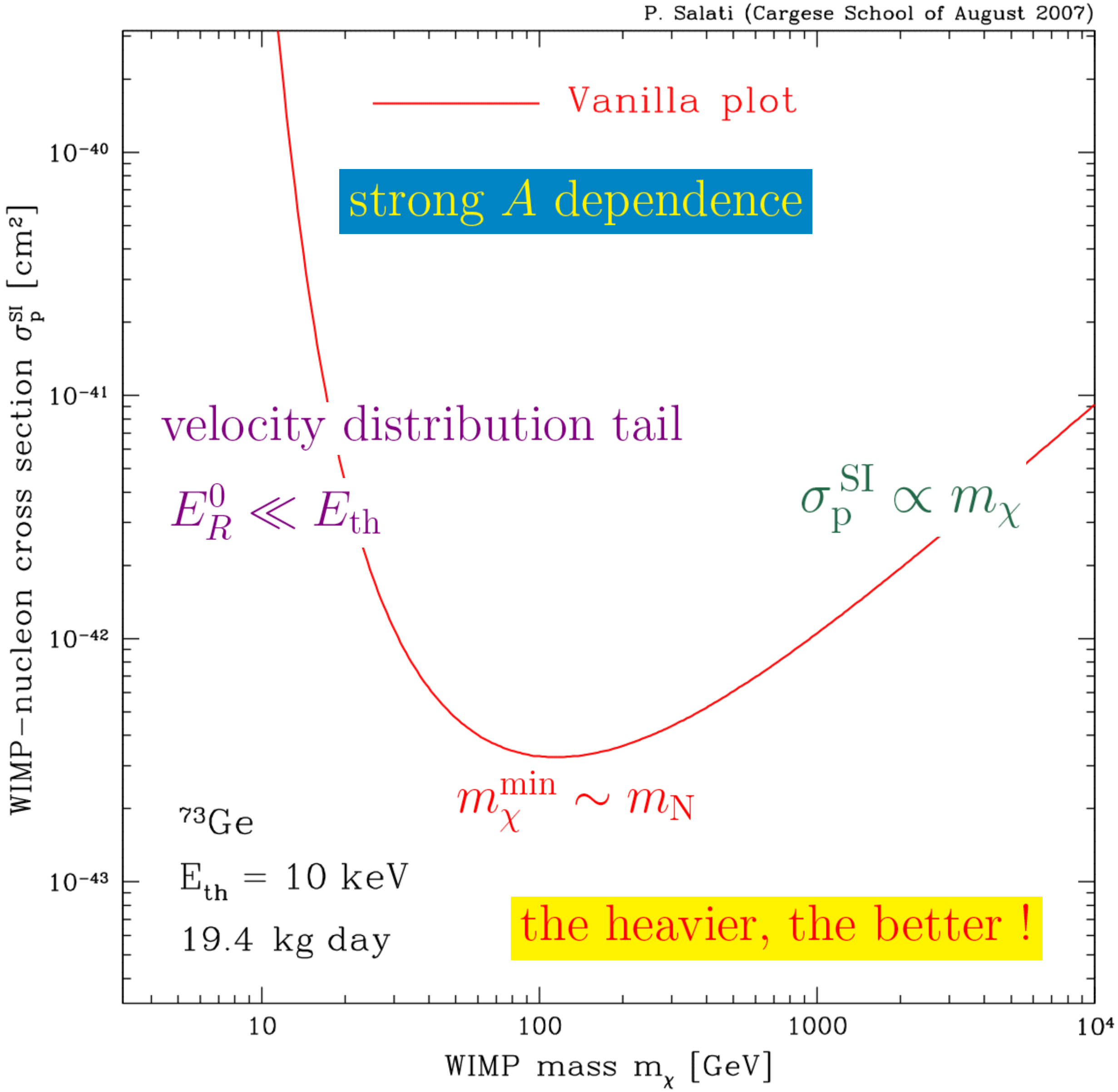
$$n_{\rm theo} = \mathcal{E} \times \int_{E_{\rm th}}^{E_{\rm max}} \frac{{\rm d}R}{{\rm d}E_{\rm R}} \, {\rm d}E_{\rm R}$$

• In the naive approach where the Earth motion is neglected and setting the upper bound $E_{\rm max}$ at infinity, the number of events simplifies into

$$n_{\rm theo} \simeq 4.14 \times 10^{-7} \;\text{events kg}^{-1}\,\text{day}^{-1} \times \left\{ \frac{\sigma_{\rm p}^{\rm SI}}{1\,\text{zb}} \right\} \times A^2 \times \left\{ \frac{\sqrt{x}-1}{x} \right\} \times e^{-\alpha x}$$

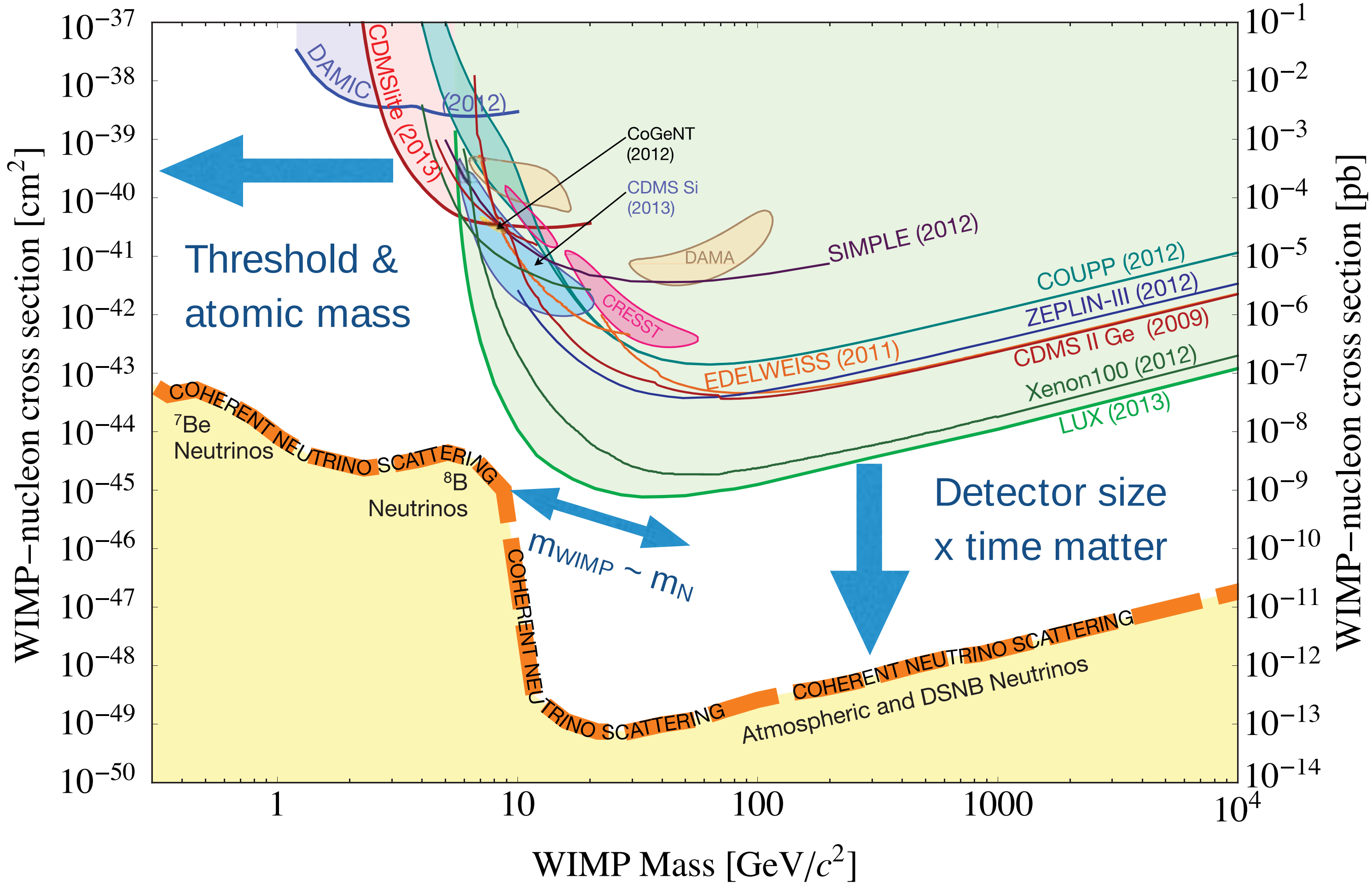
$$\text{where} \quad x = \left\{ 1 + \frac{m_{\rm N}}{m_\chi} \right\}^2 \quad \& \quad \alpha = \frac{E_{\rm th}}{2 m_{\rm N} V_C^2}$$

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



Laura Baudis
University of Zurich

The WIMP landscape in 2015



Outline

http://arxiv.org/pdf/1205.1004v2.pdf

1 – Zwicky's legacy

- **a.** The historical discovery
- **b.** Galaxies and clusters of galaxies
- **c.** Cosmological observations

2 – The bestiary of dark matter species

- **a.** Following Charles Darwin
- **b.** Kaluza-Klein particles in extra-D theories
- **c.** The WIMP miracle

3 – Particle astrophysics and the search for dark matter particles

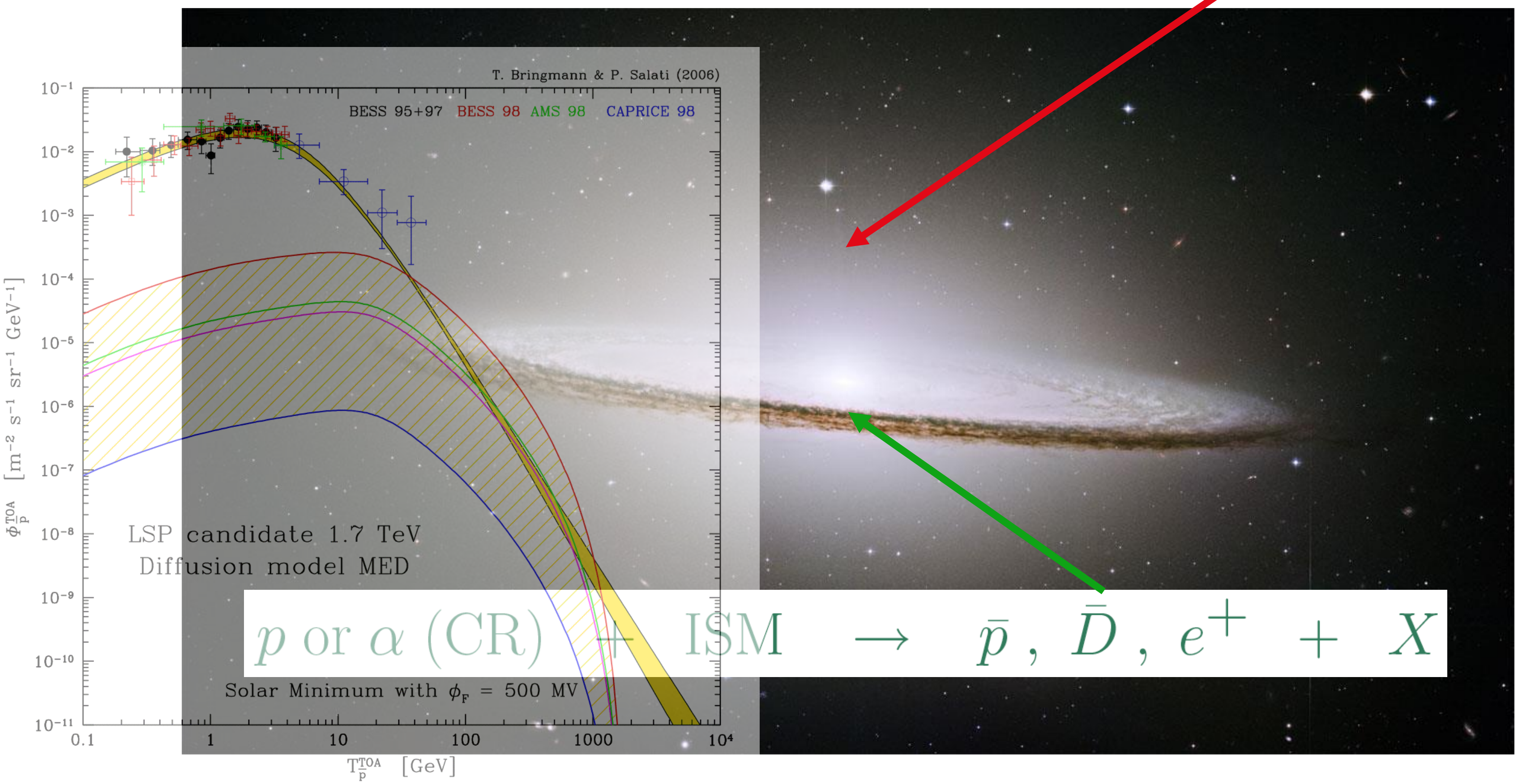
- **a.** Direct detection experiments – underground searches
- **b.** Indirect signatures – the search for cosmic ray anomalies
- **c.** A status on the recent antiproton measurements

4 – Dark matter searches at the LHC

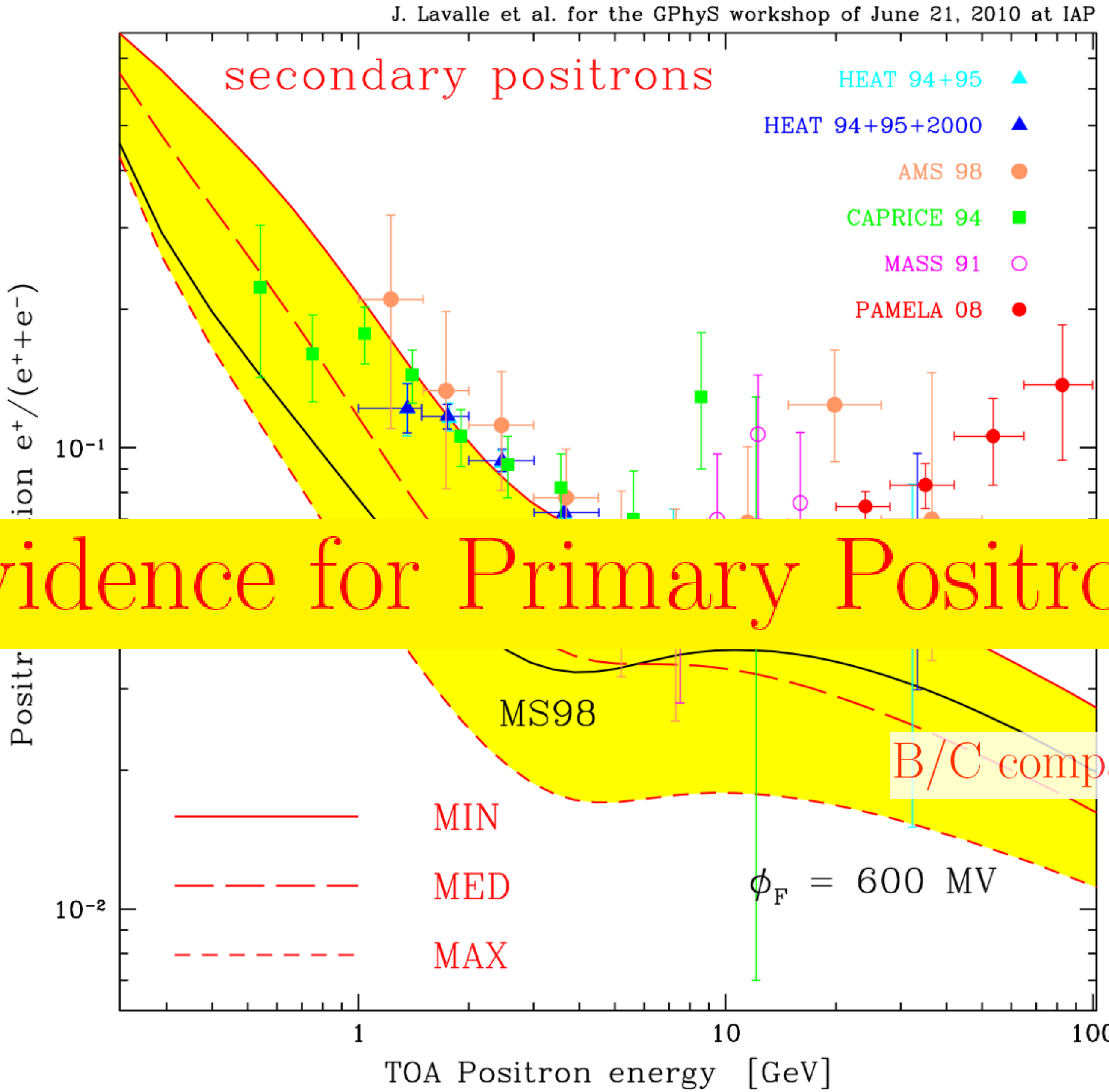
WIMP search strategies

- Indirect Detection – WIMPs continuously annihilate and produce SM particles such as gamma-rays, neutrinos, but also rare antimatter species like positrons, antiprotons and even antideuterons.

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



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



Evidence for Primary Positrons

Outline

http://arxiv.org/pdf/1504.04276.pdf

1 – Zwicky's legacy

- **a.** The historical discovery
- **b.** Galaxies and clusters of galaxies
- **c.** Cosmological observations

2 – The bestiary of dark matter species

- **a.** Following Charles Darwin
- **b.** Kaluza-Klein particles in extra-D theories
- **c.** The WIMP miracle

3 – Particle astrophysics and the search for dark matter particles

- **a.** Direct detection experiments – underground searches
- **b.** Indirect signatures – the search for cosmic ray anomalies
- **c.** A status on the recent antiproton measurements

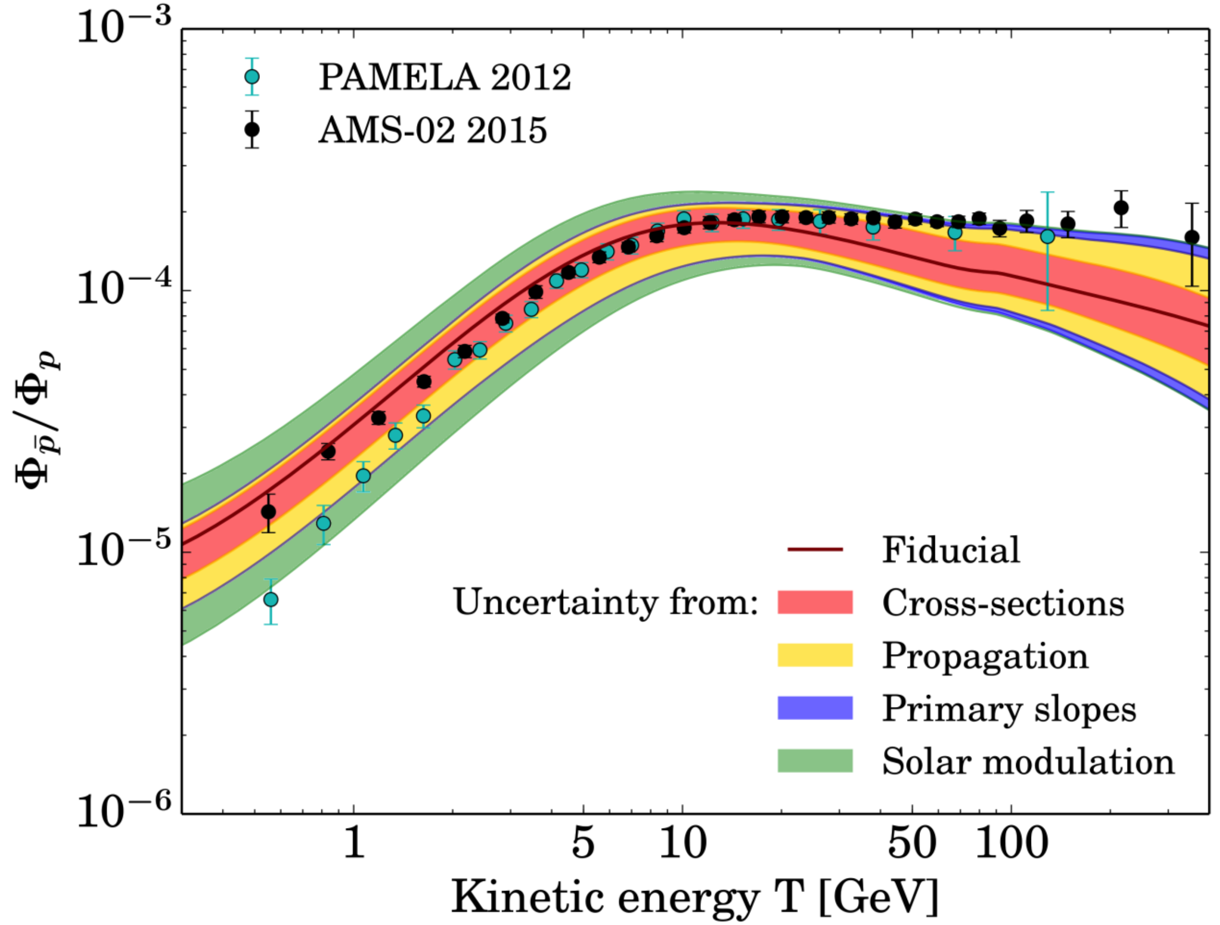
4 – Dark matter searches at the LHC

AMS Collaboration
CERN, Geneva, 15 April 2015

"**A**MS Days at CERN" and Latest Results from the AMS Experiment on the International Space Station

Backgrounds to a putative DM signal need to understood

Production cross sections – solar modulation – cosmic ray propagation



Antiprotons Production in the Galaxy

• **Secondary** antiprotons are produced through the spallations of cosmic–ray protons and He nuclei on the interstellar material.

$$p\,(\mathrm{CR}) \;+\; H\,(\mathrm{ISM}) \;\rightarrow\; \bar{p} \;+\; X$$

$$\Downarrow$$

$$q_{\bar{\mathrm{p}}}^{\mathrm{sec}}(r, E_{\bar{\mathrm{p}}}) \;=\; 4\pi \int_{E_{\mathrm{p}}^{0}}^{+\infty} \frac{d\sigma_{\mathrm{pH}\rightarrow\bar{\mathrm{p}}}}{dE_{\bar{\mathrm{p}}}} \{E_{\mathrm{p}} \rightarrow E_{\bar{\mathrm{p}}}\}\; n_{\mathrm{H}}\, \Phi_{\mathrm{p}}(r, E_{\mathrm{p}})\, dE_{\mathrm{p}}$$

New developments since 2008

– CR p and He fluxes measured with improved accuracy.

$$\Phi_{\bar{\mathrm{p}}}^{\mathrm{sec}}(E_{\bar{\mathrm{p}}}) \;\propto\; q_{\bar{\mathrm{p}}}^{\mathrm{sec}}(E_{\bar{\mathrm{p}}}) \;\propto\; \Phi_{\mathrm{p}}(E_{\mathrm{p}} \sim 10 \times E_{\bar{\mathrm{p}}})$$

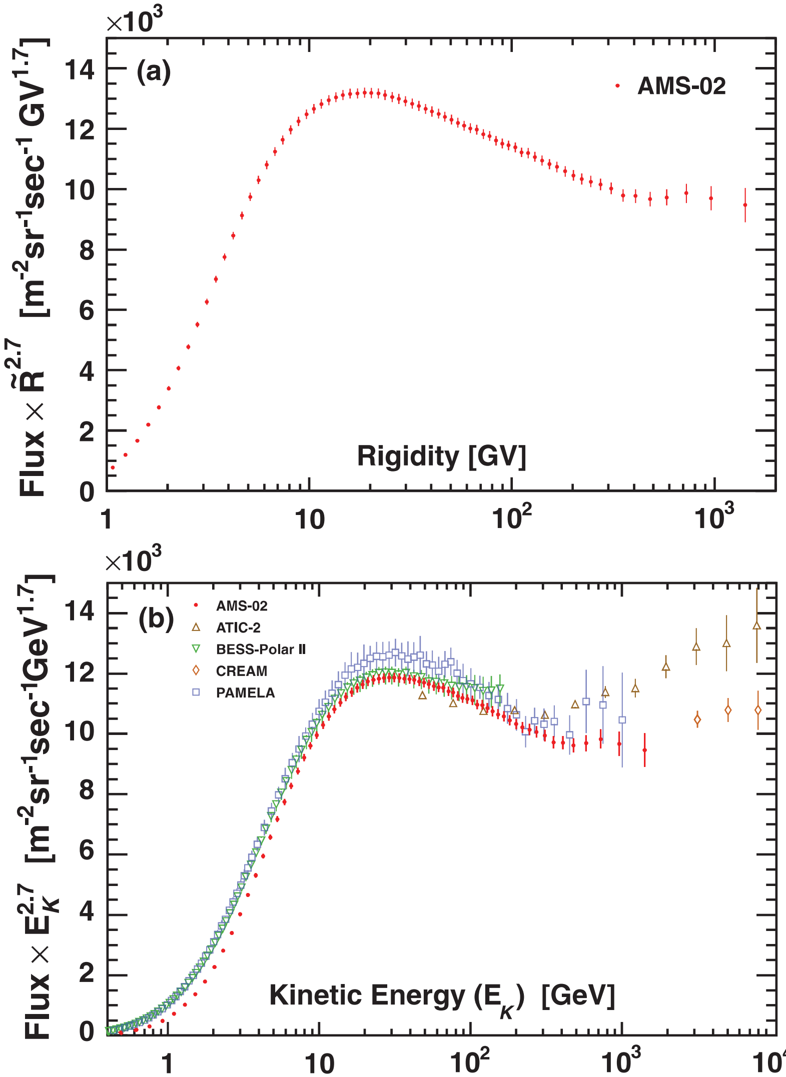
$$\Downarrow$$

$$\bar{\mathrm{p}}/\mathrm{p}(E) \;\propto\; \Phi_{\mathrm{p}}(\sim 10 \times E)/\Phi_{\mathrm{p}}(E) \;\propto\; 10^{-\alpha}$$

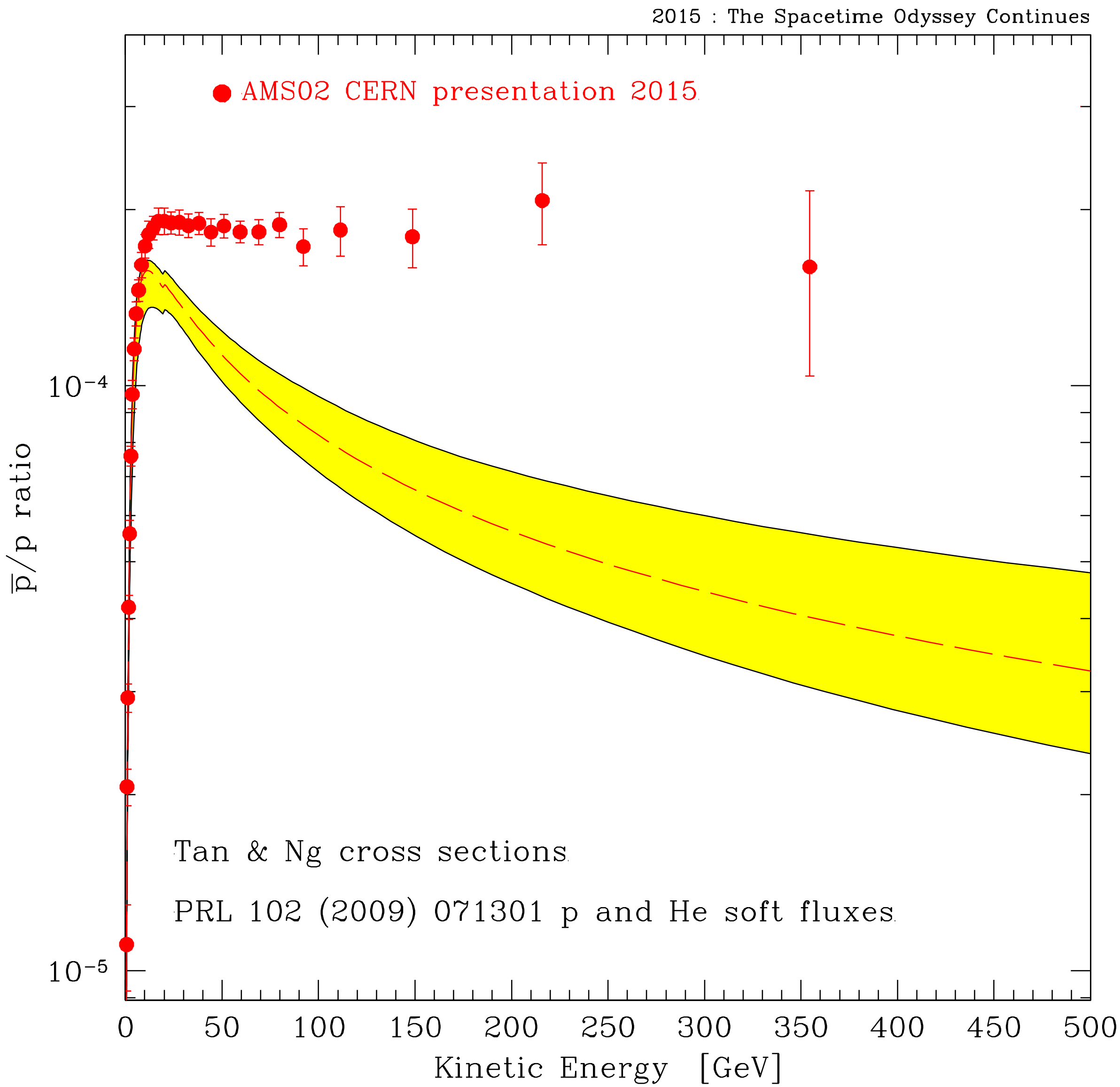
$\bar{\mathrm{p}}/\mathrm{p}$ depends on the CR proton spectral index α

PRL **114,** 171103 (2015) PHYSICAL REVIEW LETTERS week ending 1 MAY 2015

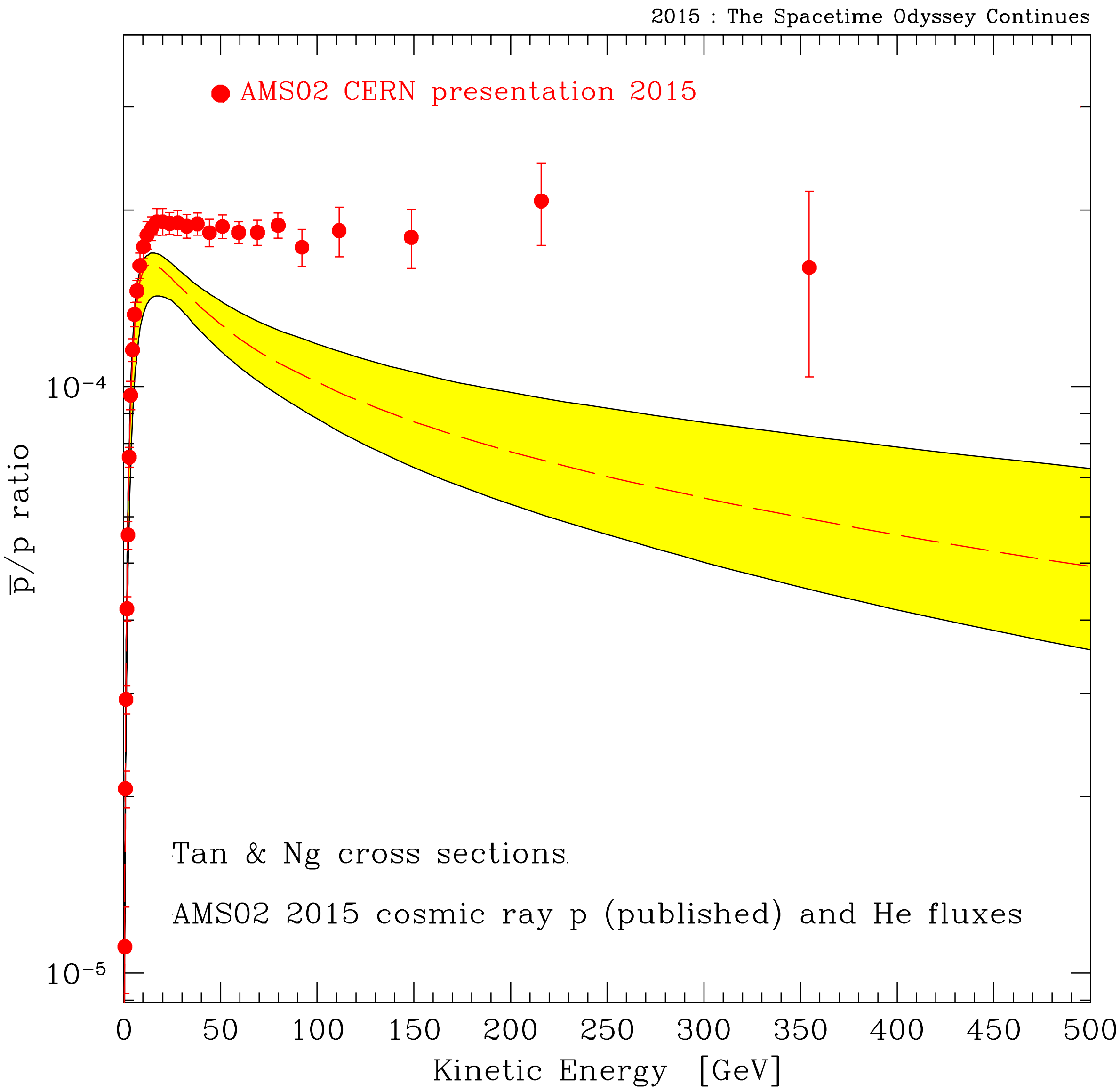
Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station



New developments since 2008



New developments since 2008



Antiprotons Production in the Galaxy

• **Secondary** antiprotons are produced through the spallations of cosmic–ray protons and He nuclei on the interstellar material.

$$p\,(\mathrm{CR}) \; + \; H\,(\mathrm{ISM}) \; \rightarrow \; \bar{p} \; + \; X$$

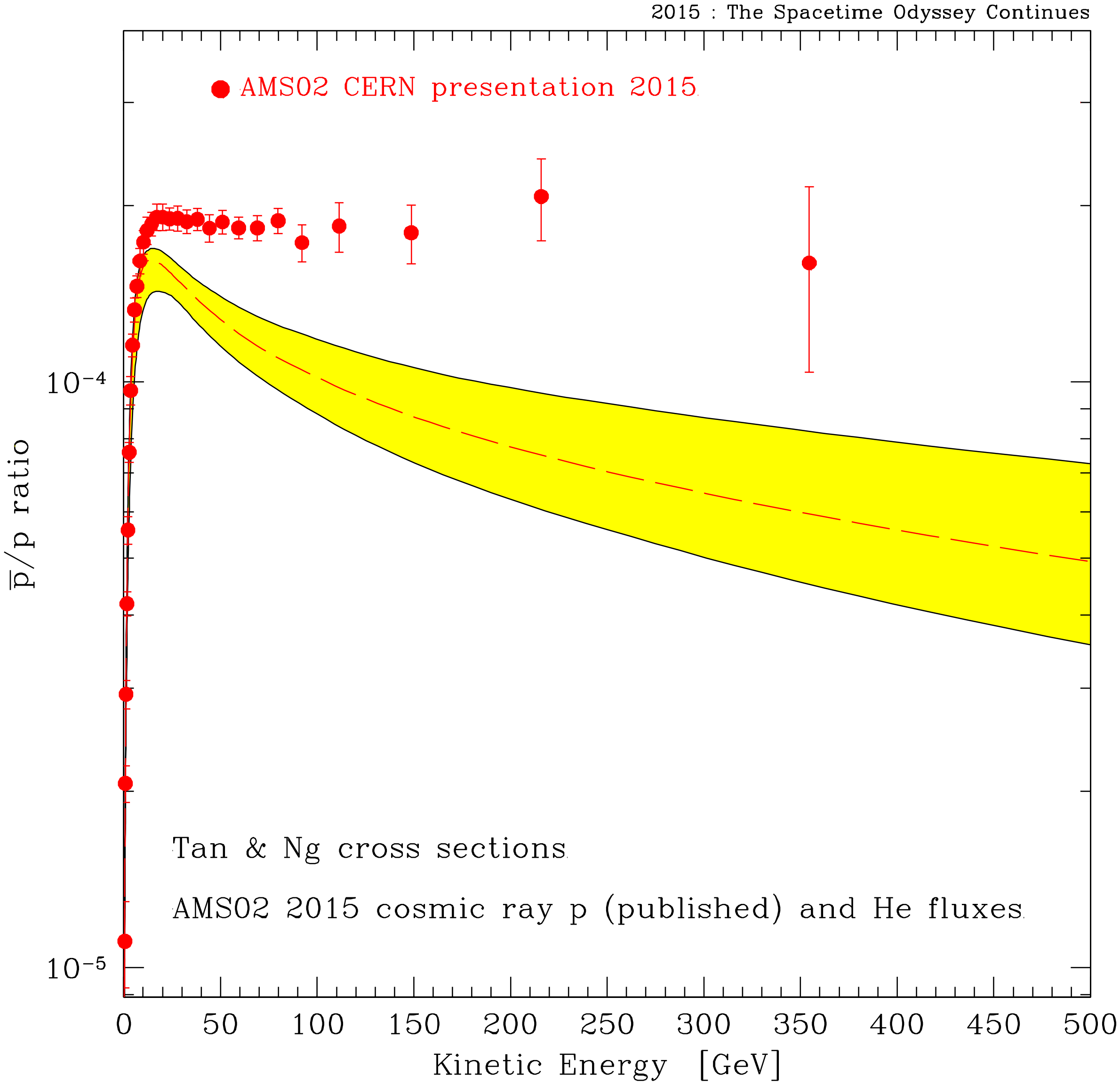
$$\Downarrow$$

$$\boxed{q_{\bar{\mathrm{p}}}^{\mathrm{sec}}(r, E_{\bar{\mathrm{p}}}) \; = \; 4\pi \int_{E_{\mathrm{p}}^{0}}^{+\infty} \frac{d\sigma_{\mathrm{pH}\rightarrow\bar{\mathrm{p}}}}{dE_{\bar{\mathrm{p}}}} \left\{ E_{\mathrm{p}} \rightarrow E_{\bar{\mathrm{p}}} \right\} \, n_{\mathrm{H}} \, \Phi_{\mathrm{p}}(r, E_{\mathrm{p}}) \, dE_{\mathrm{p}}}$$

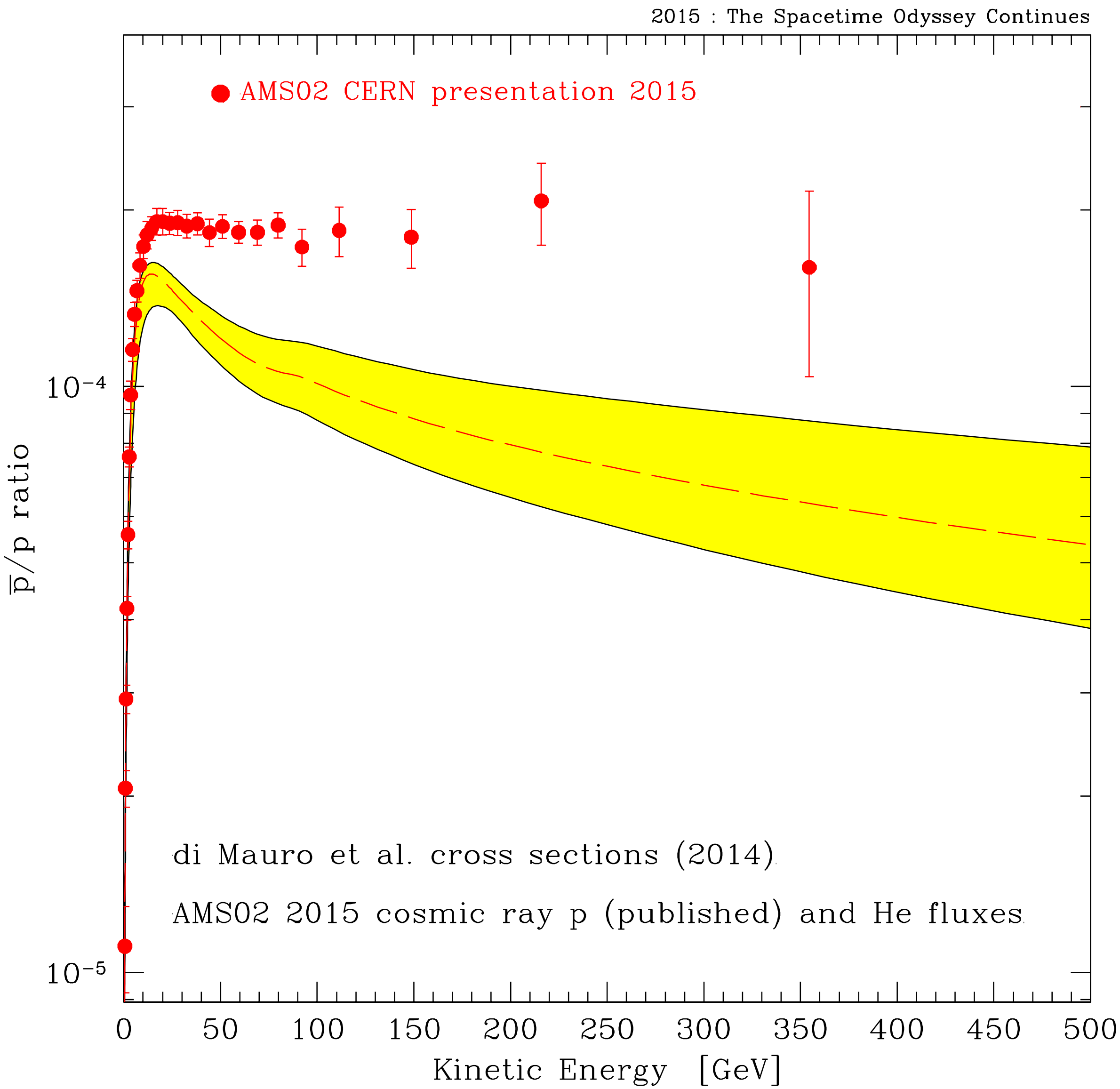
New developments since 2008

– New parameterization of $d\sigma_{\mathrm{pH}\rightarrow\bar{\mathrm{p}}}/dE_{\bar{\mathrm{p}}}$ from BRAHMS and NA49.

New developments since 2008



New developments since 2008



Antiprotons Production in the Galaxy

• **Secondary** antiprotons are produced through the spallations of cosmic–ray protons and He nuclei on the interstellar material.

$$p\,(\mathrm{CR}) \;+\; H\,(\mathrm{ISM}) \;\rightarrow\; \bar{p} \;+\; X$$

$$\Downarrow$$

$$\boxed{q_{\bar{\mathrm{p}}}^{\mathrm{sec}}(r, E_{\bar{\mathrm{p}}}) \;=\; 4\pi \int_{E_{\mathrm{p}}^{0}}^{+\infty} \frac{d\sigma_{\mathrm{pH}\rightarrow\bar{\mathrm{p}}}}{dE_{\bar{\mathrm{p}}}} \left\{E_{\mathrm{p}} \rightarrow E_{\bar{\mathrm{p}}}\right\} \, n_{\mathrm{H}} \, \Phi_{\mathrm{p}}(r, E_{\mathrm{p}}) \, dE_{\mathrm{p}}}$$

New developments since 2008

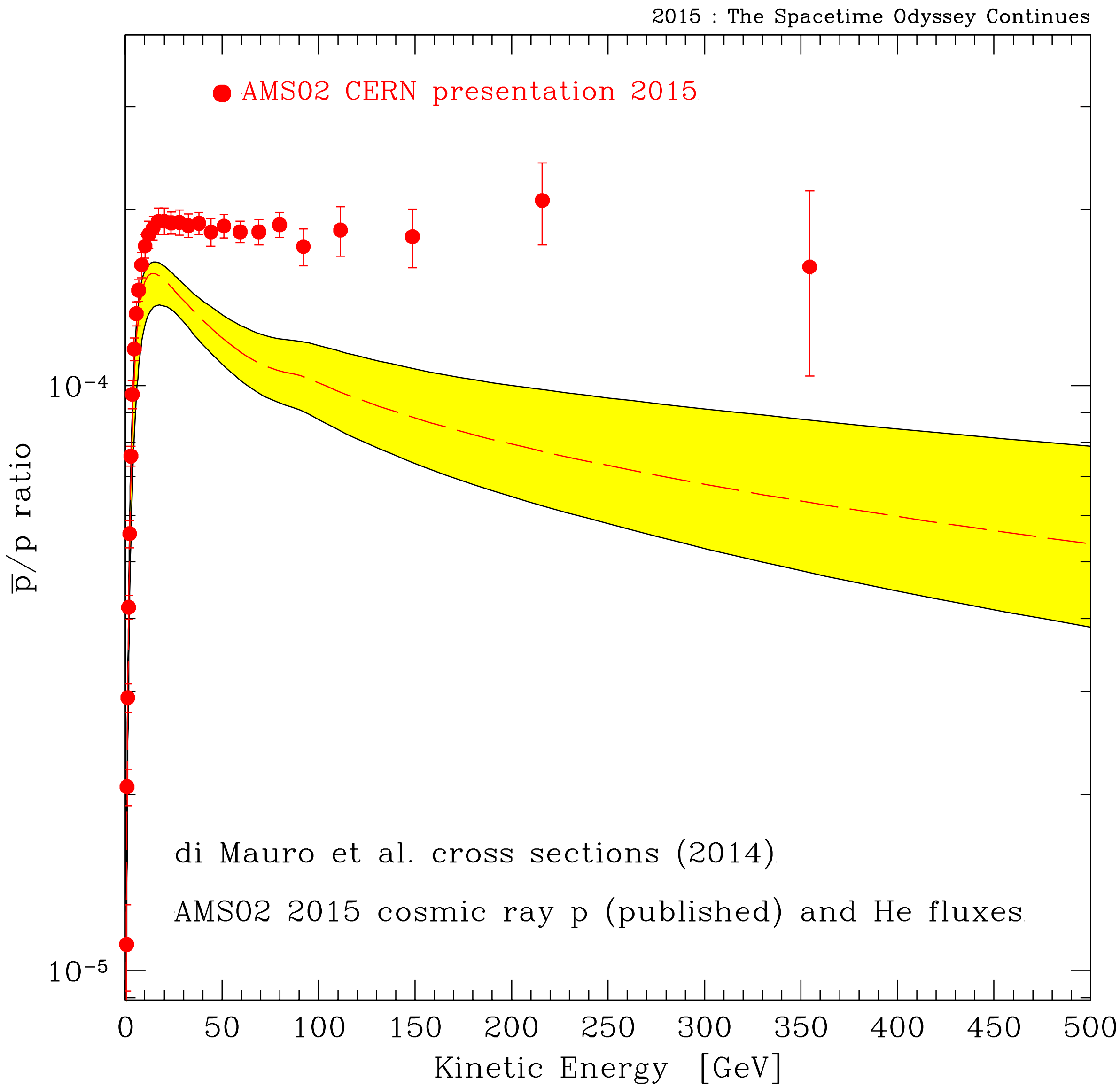
– Proton collisions yield more antineutrons than antiprotons.

$$d\sigma_{\mathrm{pp}\rightarrow\bar{\mathrm{n}}}/dE_{\bar{\mathrm{p}}} \equiv d\sigma_{\mathrm{pn}\rightarrow\bar{\mathrm{p}}}/dE_{\bar{\mathrm{p}}}$$

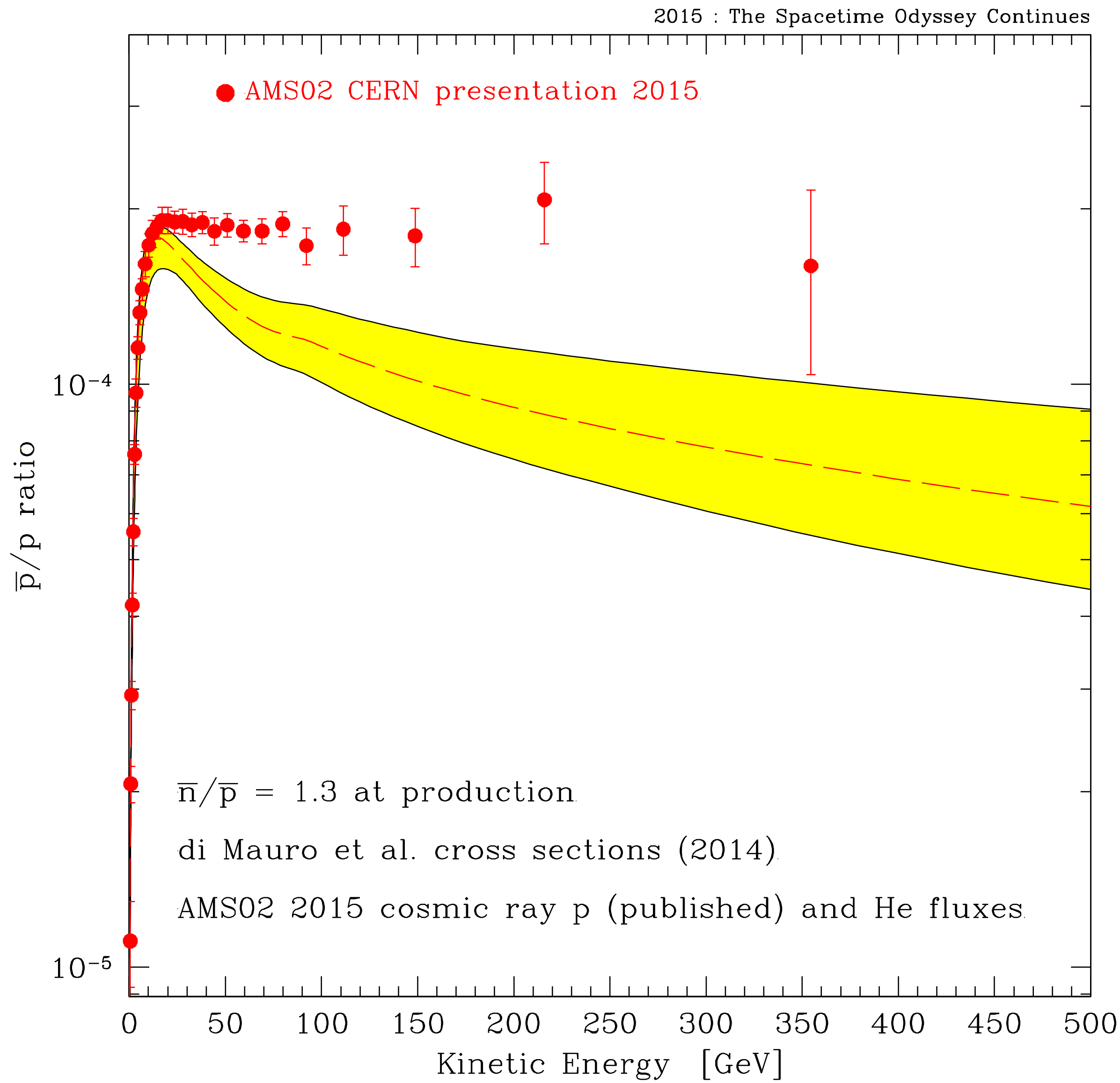
$$\Downarrow$$

$$d\sigma_{\mathrm{pp}\rightarrow\bar{\mathrm{n}}}/d\sigma_{\mathrm{pp}\rightarrow\bar{\mathrm{p}}} \simeq 1.3$$

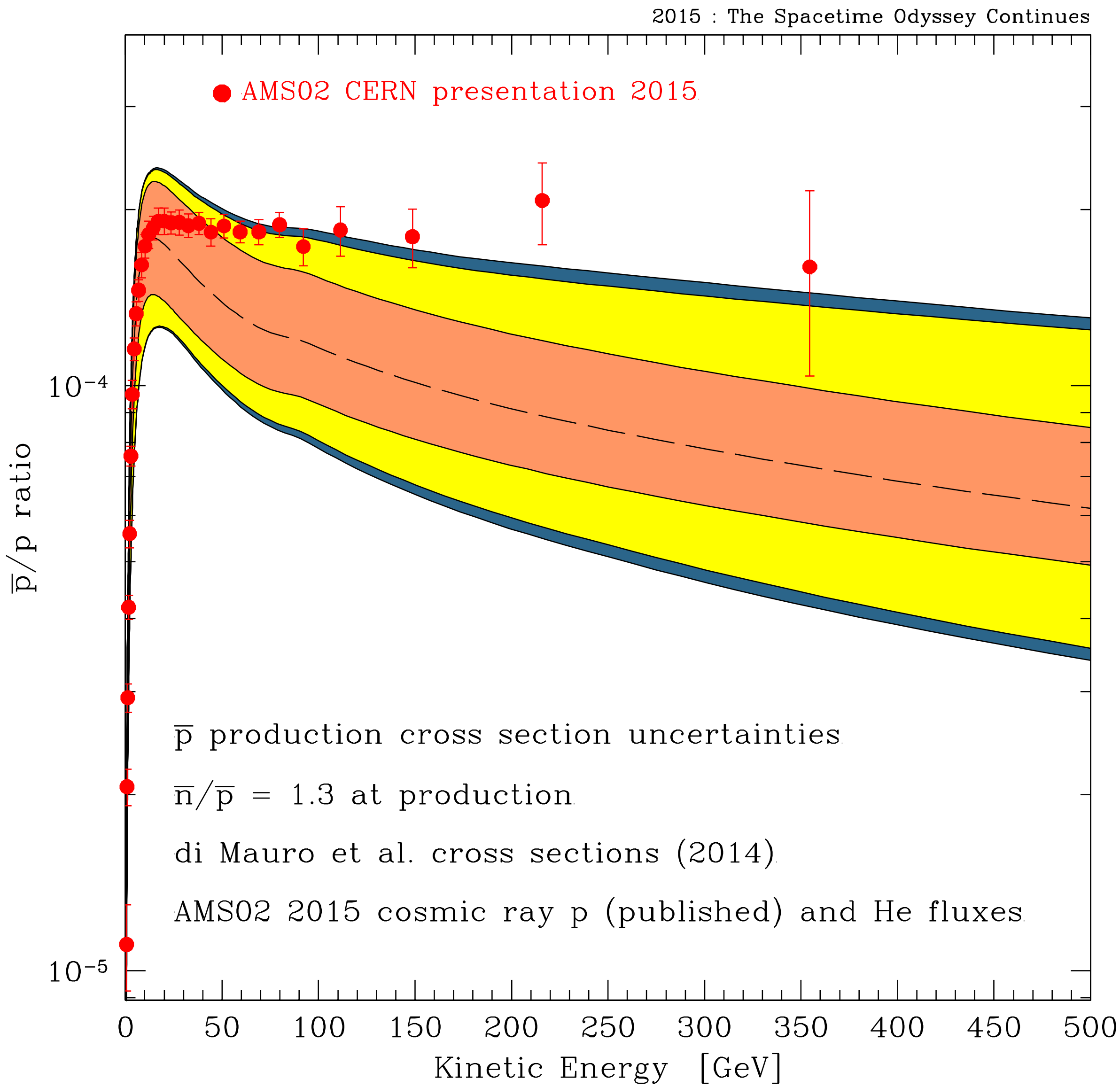
New developments since 2008



New developments since 2008

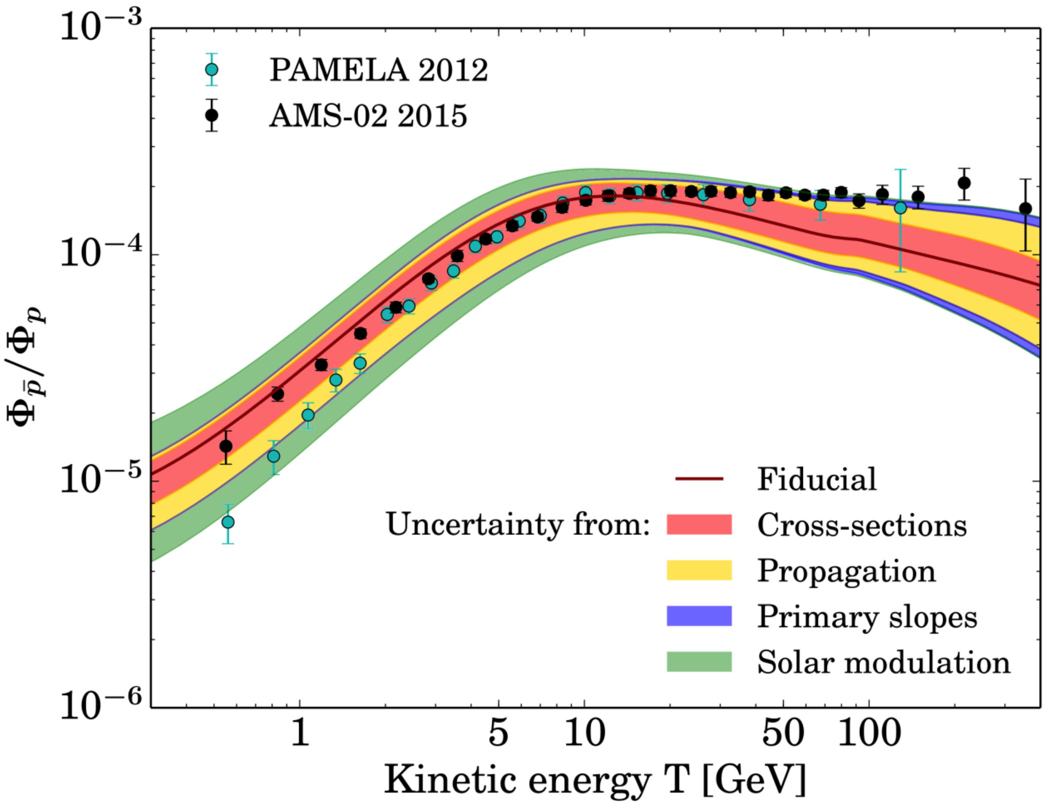


New developments since 2008



Antiproton data are compatible with the background

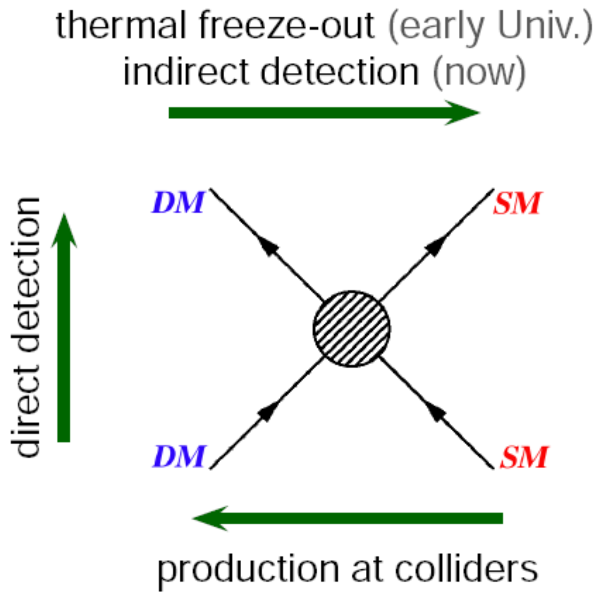
No $\bar{\mathrm{p}}$ excess



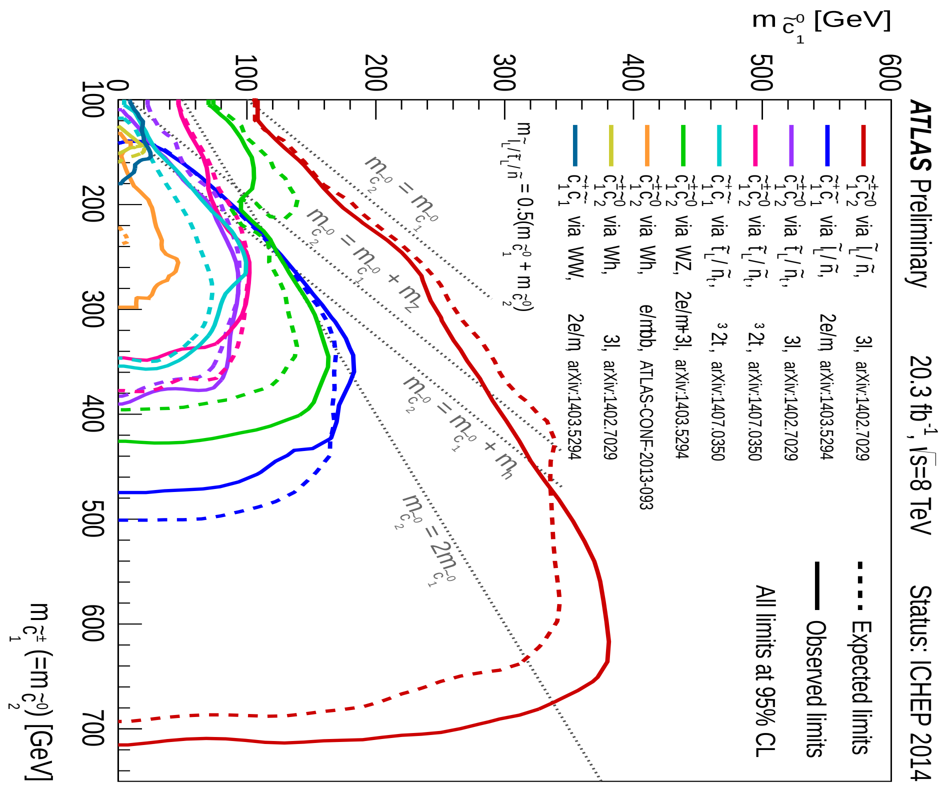
But measurements are on the upper side

Outline

• The Large Hadron Collider (LHC) is the ultimate tool of high energy physics with which the Higgs boson has been at last discovered – a scalar particle with mass 126 GeV whose branching ratios into fermions pairs are currently measured very carefully.



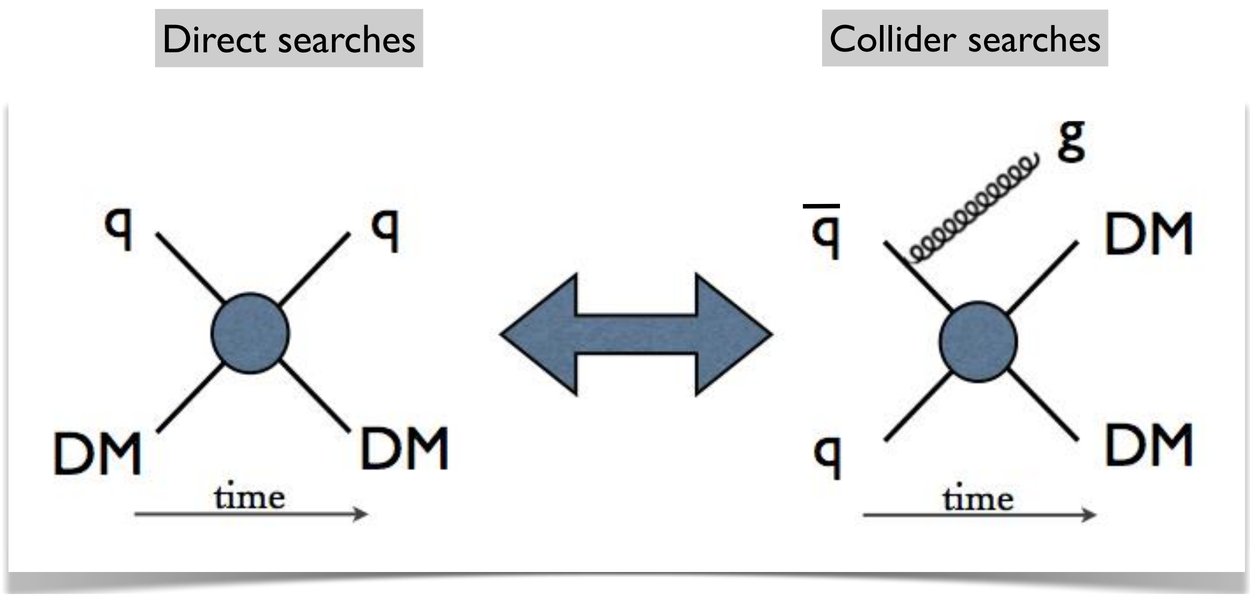
• So far, none of the species predicted by supersymmetry or extra-d theories has been detected at the LHC. The new particles – should they exist – must be heavier than ~ 1 TeV.



Light Neutralino Dark Matter > 24 GeV from LHC

• So far, none of the species predicted by supersymmetry or extra-d theories has been detected at the LHC. The new particles – should they exist – must be heavier than ~ 1 TeV.

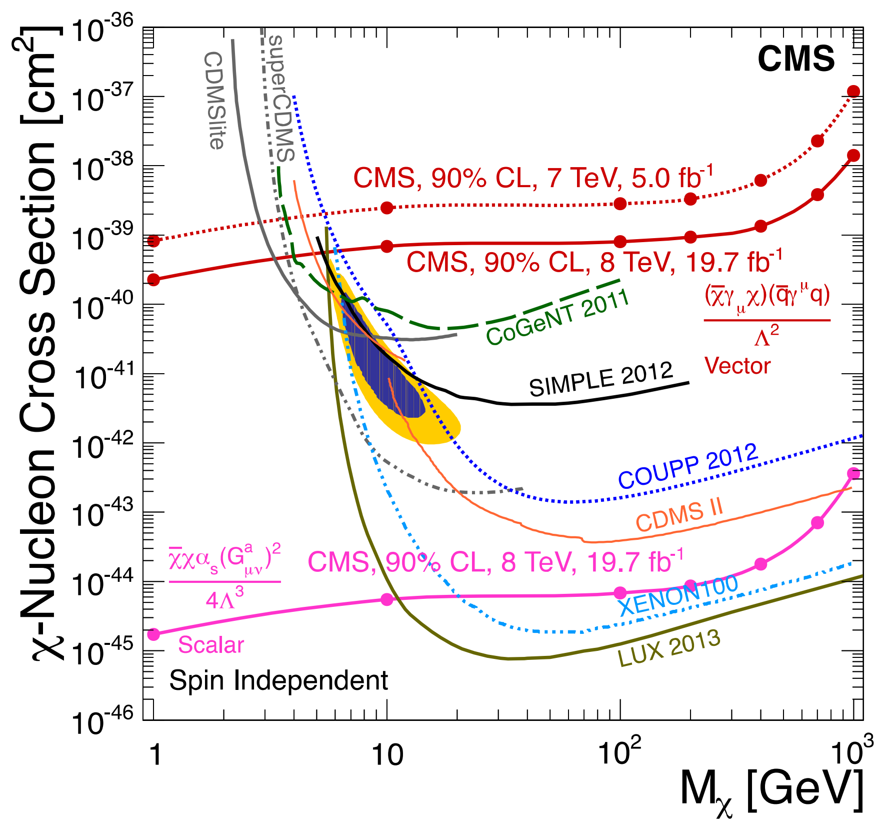
• The LHC and direct detection are complementary techniques.



Courtesy Sarah Alam Malik from the CMS collaboration

- So far, none of the species predicted by supersymmetry or extra-d theories has been detected at the LHC. The new particles – should they exist – must be heavier than ~ 1 TeV.

- The LHC and direct detection are complementary techniques.



Conclusion

• The astronomical dark matter has been discovered by Fritz Zwicky in 1933 and is still a puzzle yet to be solved.

• The nature of that component is unresolved. High energy physicists have imagined a plethora of candidates. In particular, weakly interacting massive particles – independently predicted by supersymmetric or Kaluza-Klein extensions of the Standard Model – provide an exciting possibility worth being explored.

• This species are actively searched at the LHC – with no evidence so far. The second run of the machine is impatiently expected.

• Direct and indirect searches are more and more precise and will eventually explore the entire parameter space predicted by theory. But what if nothing is discovered ?

"entia non sunt multiplicanda praeter necessitatem"
Guillaume d'Occam

• Modified gravity is in that respect a very important line of research.

Introduction to Astroparticle Physics – Theory

The Astronomical Dark Matter Problem
or the Hunt for eluding Particles

Pierre Salati – **LAPTh** & Université Savoie Mont Blanc

http://lapth.cnrs.fr/pg-nomin/salati/GraSPA_salati_150716.pdf

Introduction to Astroparticle Physics – Theory

The Astronomical Dark Matter Problem or the Hunt for eluding Particles

Pierre Salati – **LAPTh** & Université Savoie Mont Blanc

http://lapth.cnrs.fr/pg-nomin/salati/GraSPA_salati_150716.pdf