

# *Open issues in cosmic-ray astrophysics and indirect dark matter searches*

*I – Evidence for dark matter*

*II – Indirect detection: principle*

*III – Targets and experiments for  $\gamma$ -rays*

*IV – Targets and experiments for charged particles*

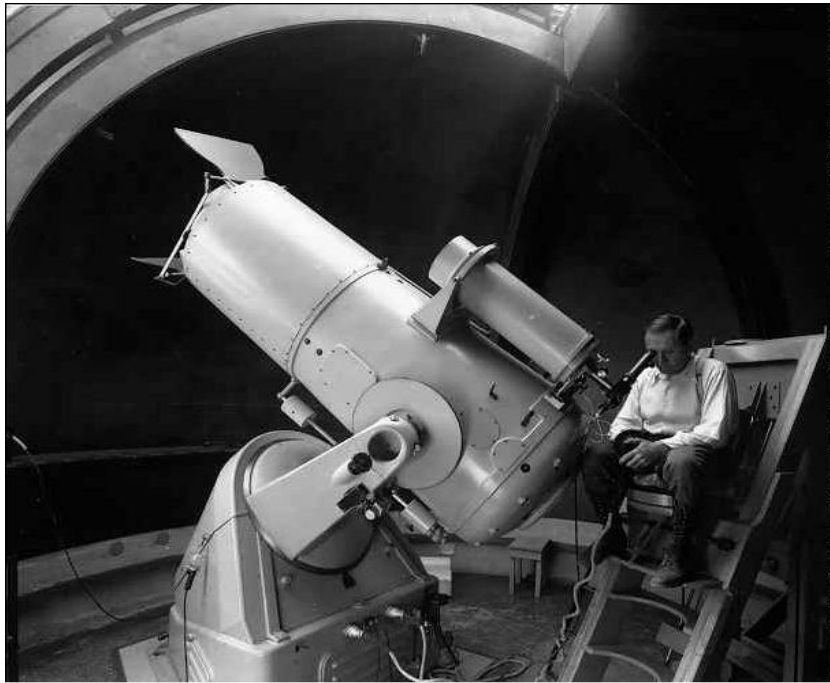
*V – Conclusion: status and challenges*



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17/04/2013

# First evidence for dark matter (DM)



Fritz Zwicky at the Mt. Wilson 24 inch Telescope

In 1933, Zwicky measures velocity of galaxies in clusters to estimate the mass of that cluster. The mass estimated from the former is far more larger than the mass estimated from counting all stars in all galaxies in this cluster.



So what...

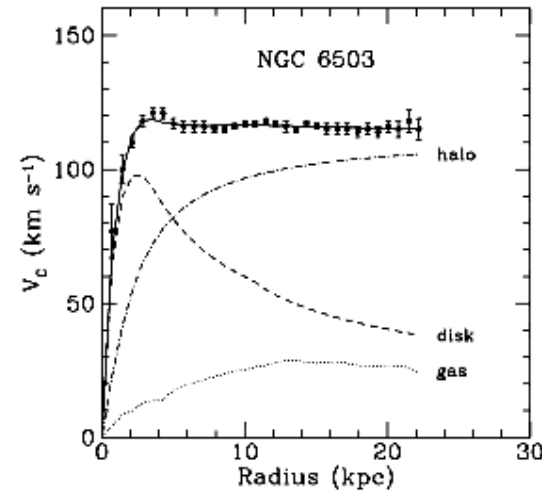
1. Error in measurements?
2. Some feebly luminous undetectable matter (planets, brown dwarfs, cold gas, dark matter?)
3. The theory used to interpret the data is wrong (departure from Newtonian Dynamics?)

# Dark matter: from Galactic to cluster scale

DM exists both within and between galaxies

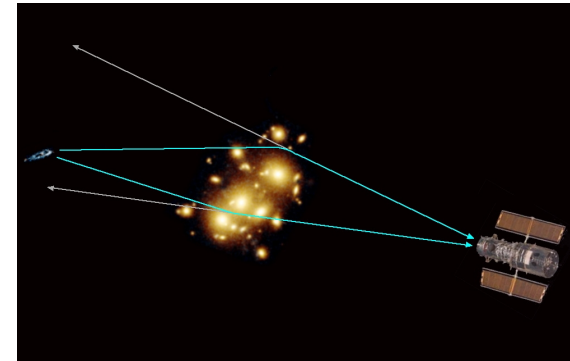
## - Galaxies: flat rotation curves

- Distribution is “mapped” in more than 1000 galaxies
- Excess is about 10 times and can be even more (also depends on the type)



## - Clusters: velocity dispersion, X-ray, and lensing measurements

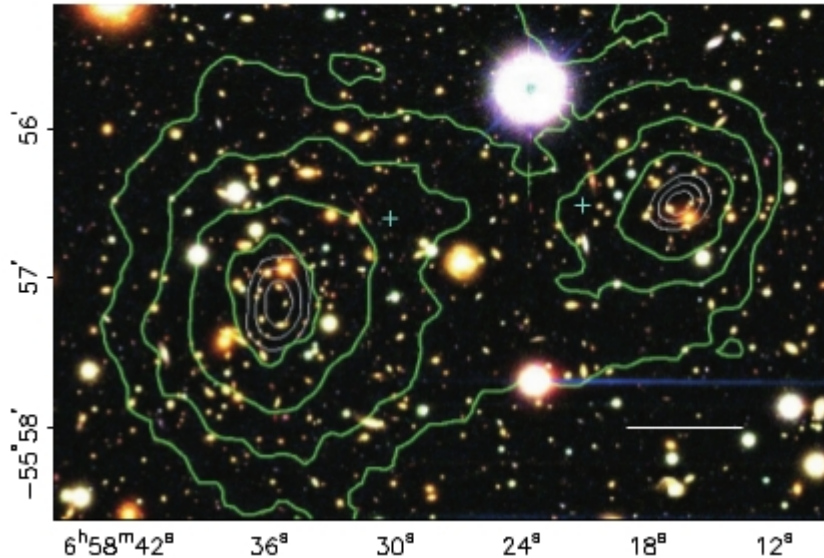
Three independent methods all in agreement  
DM is ~90% of the total matter



# Dark matter: MOND takes a bullet

Cluster merger 1E 0657–558 (bullet cluster)

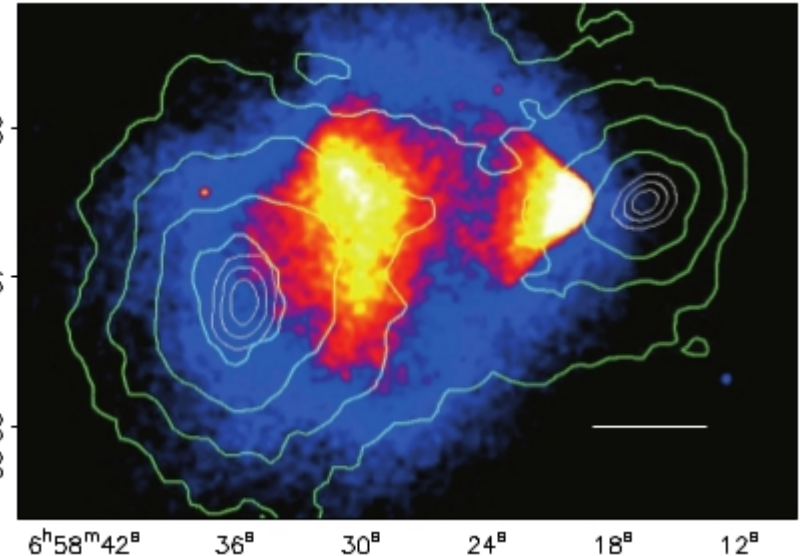
*Clowe et al., ApJL 648, 109 (2006)*



Gravitational lensing map (HST)

→ traces gravitational potential  
(galaxies are collisionless particles)

$$m_{\text{galaxies}} \ll m_{\text{gas}}$$



X-ray image (Chandra)

→ traces fluid-like intracluster plasma  
(gas experiences ram pressure)

**Most of the mass must be dark matter**

*[MOND seems to fail, although MOND people do not agree]*

# Dark matter: cosmology and $\Lambda$ CDM

## - SNIa survey: Super Novae Legacy Survey

*SNLS: Astier et al., A&A 447, 31 (2006)*

## - Galaxy surveys (formation of structures): 2dF, SDSS

*SDSS: Tegmark et al., PRD 74, 123507 (2007)*

## - Cosmic Microwave Background (CMB): Planck

Almost perfect "black body" radiation (2.73 K).

Deviations from the mean of about a part in million!

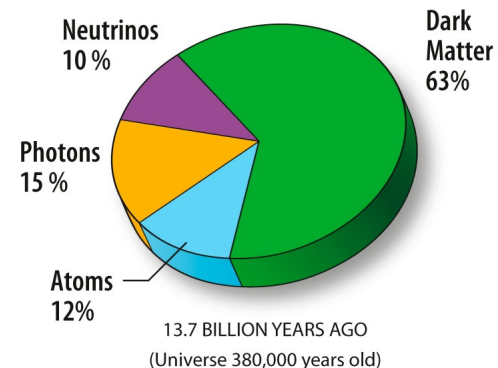
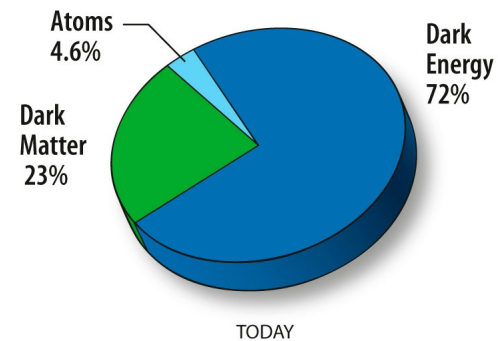
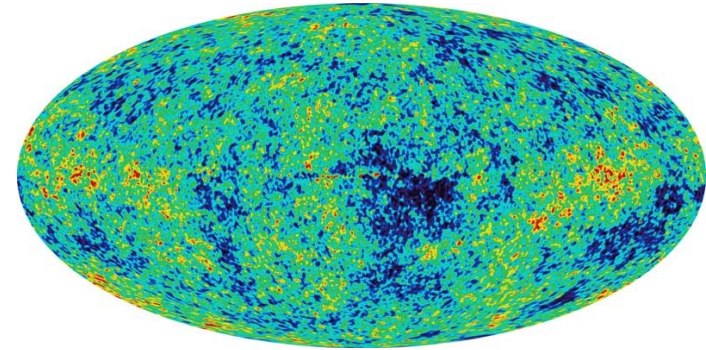
*Planck Collaboration, arXiv:1303.5076 (2013)*

+ BAO, Weak lensing, Ly $\alpha$ ...

## → Content of the universe

Relative constituents of the universe today (top), and for the universe 13.7 billion years ago (bottom). Neutrinos used to be a larger fraction of the energy of the universe than they are now.

Dark energy is yet another puzzle...  
But what is dark matter made of?



Credit: WMAP Science Team

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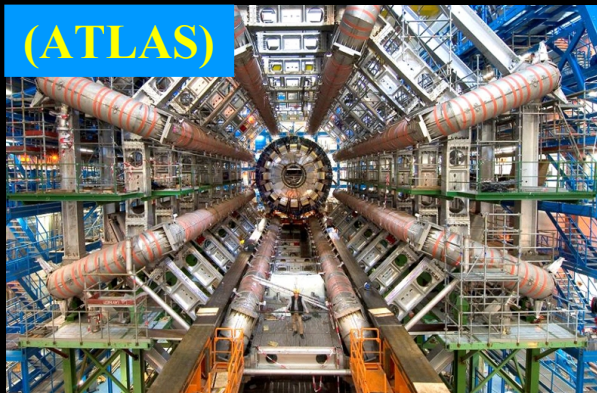
*V – Conclusion: status and challenges*



# Back on Earth: how to detect DM/new physics?

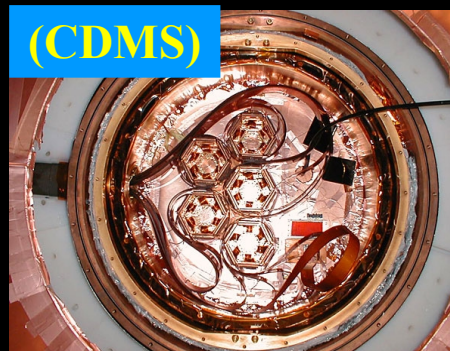
## *Colliders*

LHC, TeVatron, etc.



## *Direct detection*

Underground  
experiments



## *Indirect detection*

Astroparticle  
experiments



N.B.: complementarity of WIMP searches, but

- different technical challenges
- different couplings and different 'backgrounds'
- direct vs indirect sensitive to local vs global DM density

Reminder: new particles to be discovered in colliders are not necessarily DM!

# DM direct detection: principle

**1. There is DM in the Galaxy** [Weakly Interacting Massive Particles  $\sim$  at rest]

**2. Neutralino  $\chi$  (from SUSY theory) is a good candidate** [ $m_\chi \sim \text{GeV-TeV}$ ]

- solves DM and particle physics problems
- self-annihilate:  $\chi + \chi \rightarrow \gamma, e^+, \nu, \text{anti-protons} \dots$  (annihilation rate  $\langle \sigma v \rangle \sim 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ )

**$\rightarrow$  We look for annihilation products in the Galactic cosmic radiation**



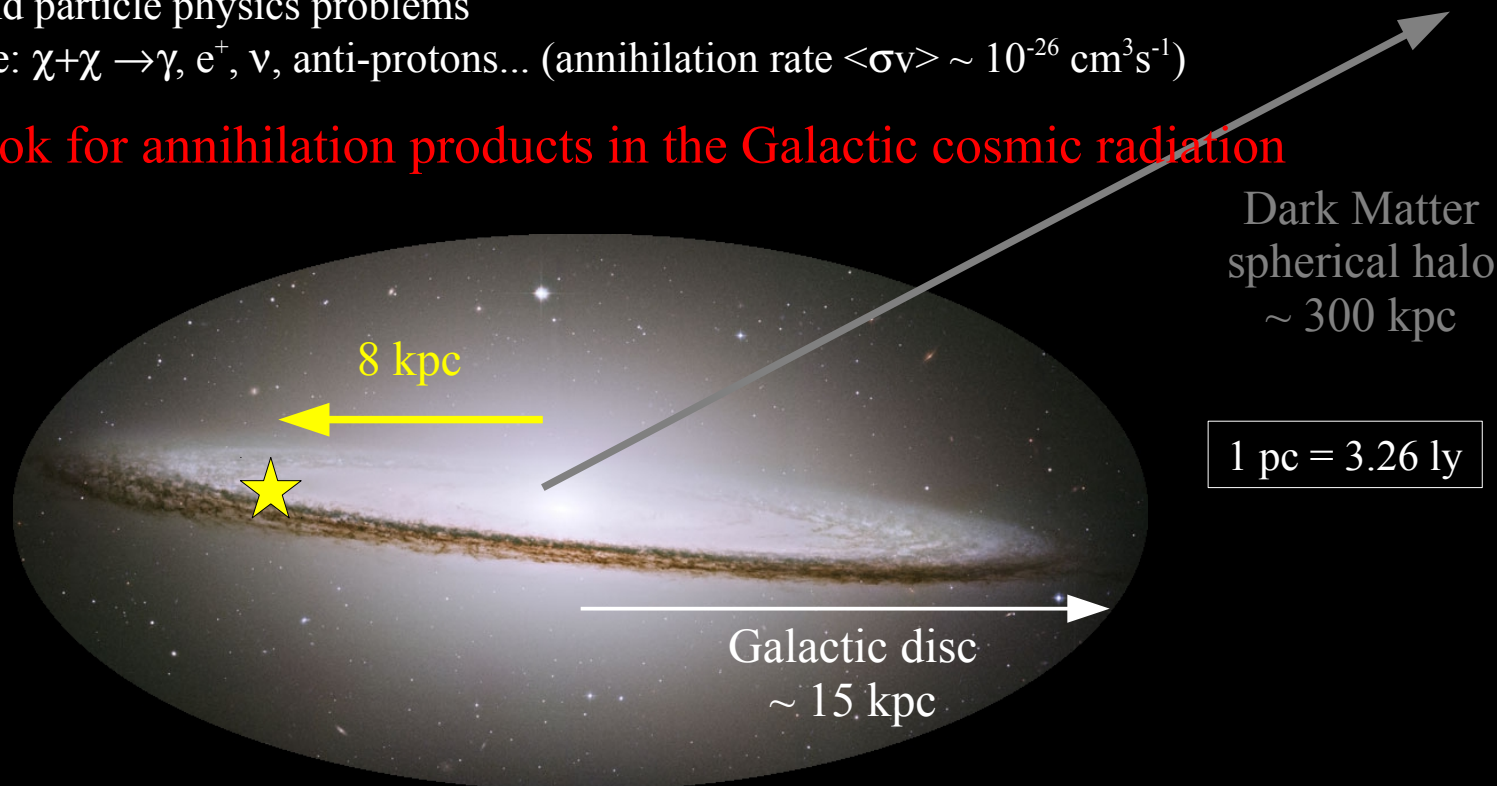
# DM direct detection: principle

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→ We look for annihilation products in the Galactic cosmic radiation



**Other approaches (not discussed):**

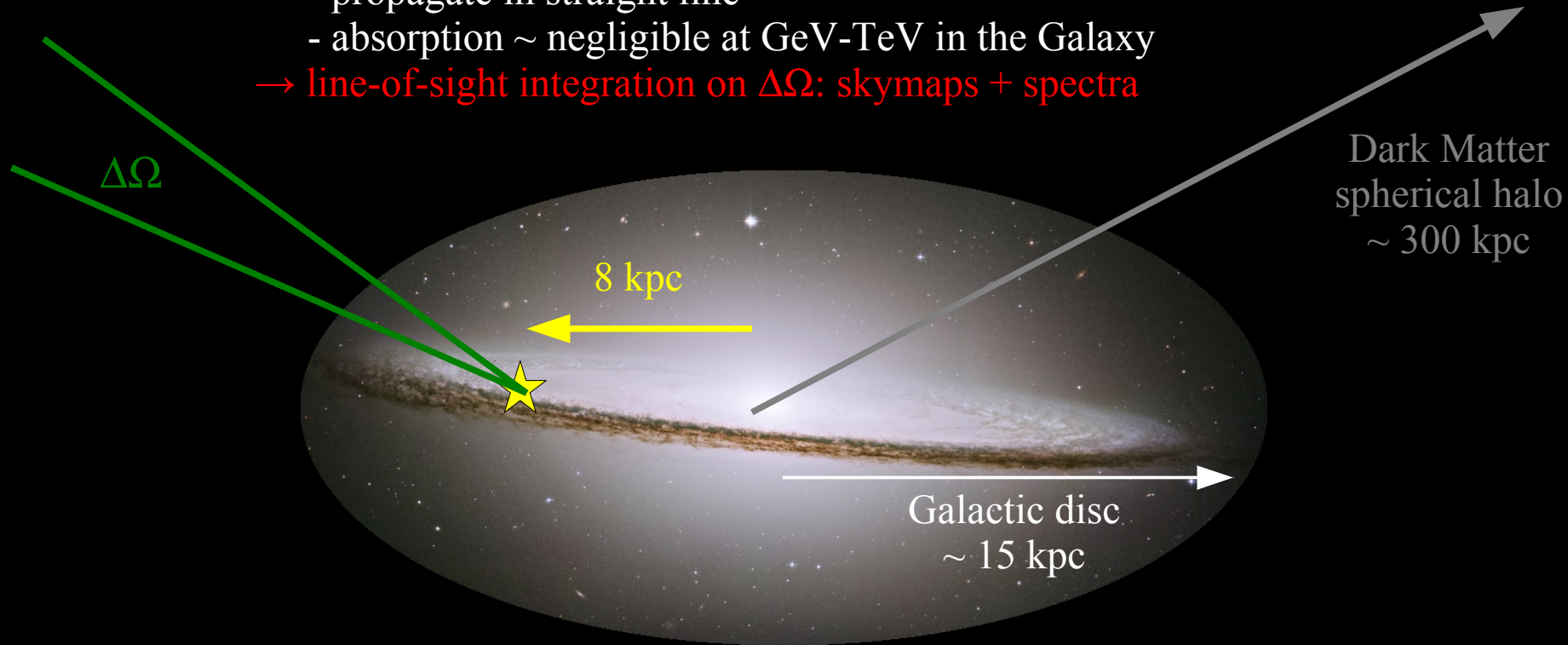
- annihilations in the early Universe (impact on BBN, first stars...)
- annihilations from  $\chi$  captured in the Sun
- Multiwavelength (from radio to  $\gamma$ -rays) and multi-messenger (combine all channels) analyses

II – Indirect detection: principle

# Transport from the “source” to the detector (I)

## Neutral particles:

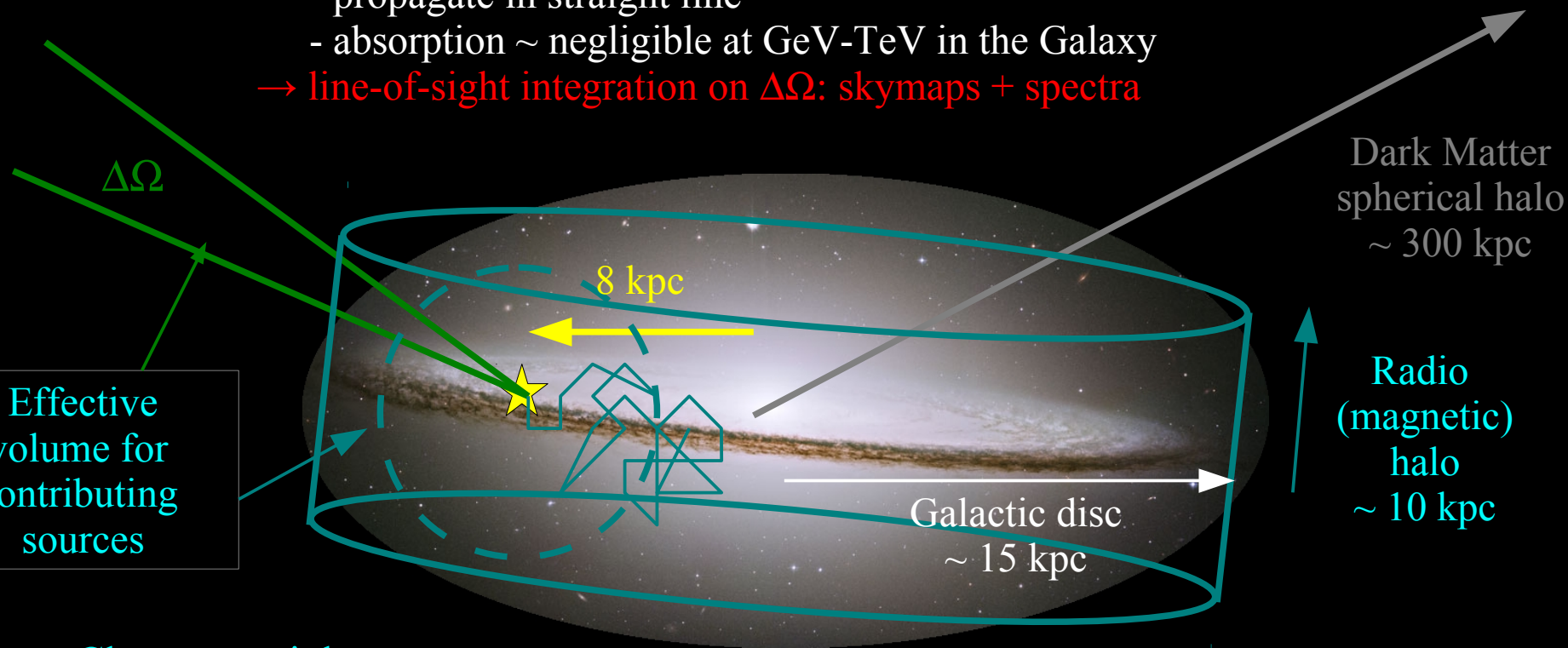
- propagate in straight line
  - absorption  $\sim$  negligible at GeV-TeV in the Galaxy
- line-of-sight integration on  $\Delta\Omega$ : skymaps + spectra



# Transport from the “source” to the detector (II)

## Neutral particles:

- propagate in straight line
- absorption  $\sim$  negligible at GeV-TeV in the Galaxy
- $\rightarrow$  line-of-sight integration on  $\Delta\Omega$ : skymaps + spectra



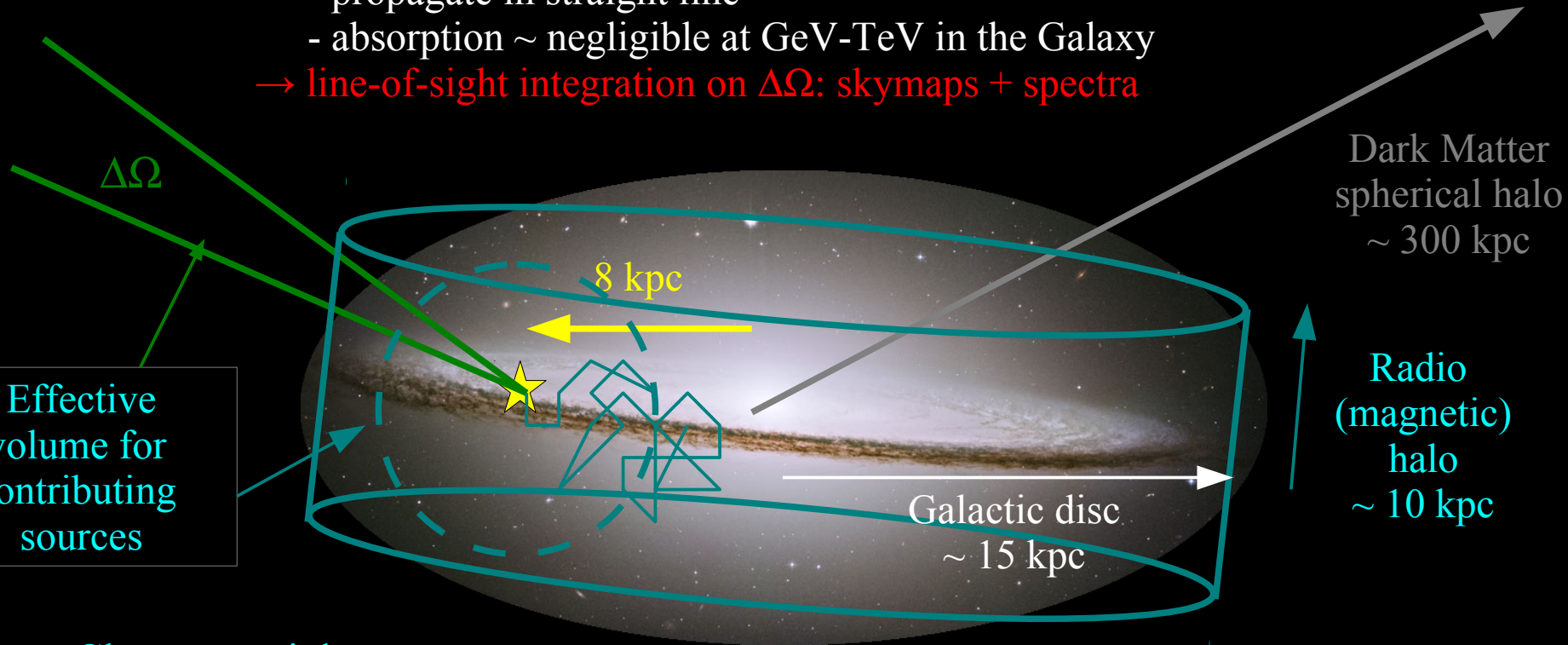
## Charge particles:

- diffusion in turbulent B, E losses, nuclear interactions
- $\rightarrow$  diffusion equation: spectrum for all charged species + anisotropy

# Transport from the “source” to the detector (III)

## Neutral particles:

- propagate in straight line
- absorption  $\sim$  negligible at GeV-TeV in the Galaxy
- line-of-sight integration on  $\Delta\Omega$ : skymaps + spectra



## Charge particles:

- diffusion in turbulent B, E losses, nuclear interactions
- diffusion equation: spectrum for all charged species + anisotropy

### **Difficulties:**

- 1. Astrophysical background** [p (CR) + H (ISM)  $\rightarrow$  antiprotons,  $e^+$ ,  $\gamma$ ...]
- 2. Charged particle transport** [same for any source type]

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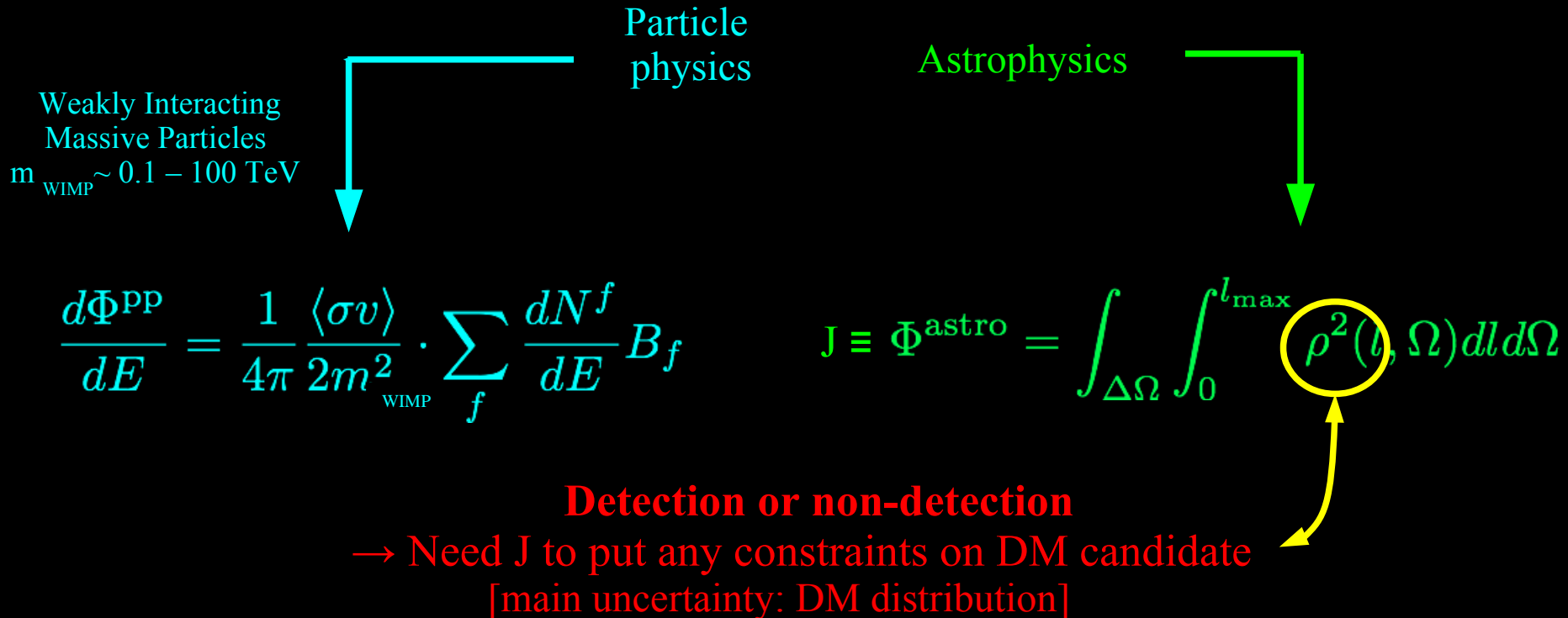
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# $\gamma$ -ray flux from DM annihilation

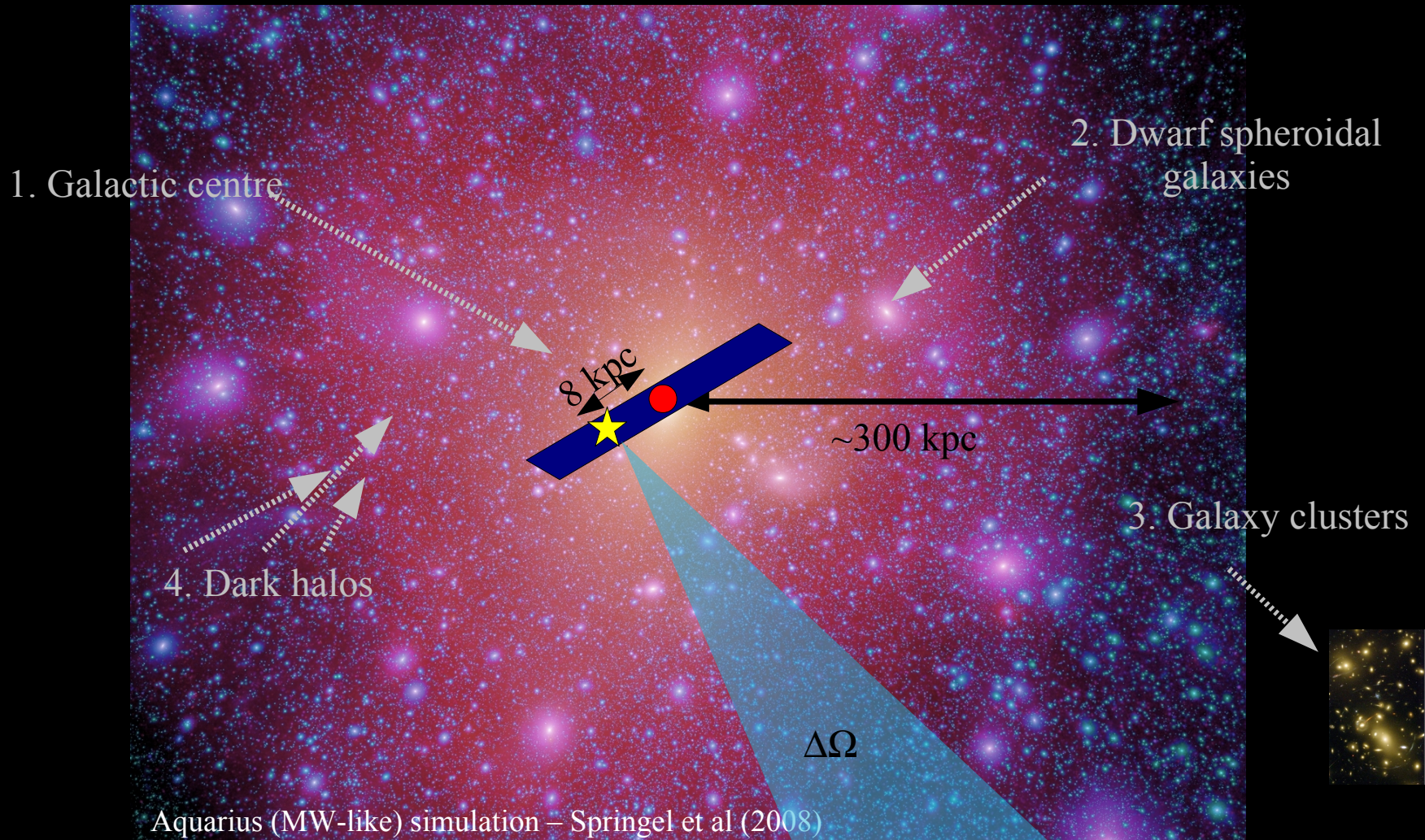
The  $\gamma$ -ray flux is given by

$$\frac{d\Phi}{dE}(E, \phi, \theta, \Delta\Omega) = \frac{d\Phi^{\text{pp}}}{dE}(E) \times \Phi^{\text{astro}}(\phi, \theta, \Delta\Omega)$$



# Best targets for $\gamma$ -ray searches?

Strategy: dense ( $\sim \int \rho^2$ ) + close ( $1/d^2$ ) + no astrophysical background





# Detection: 'direct' and 'indirect' measurements



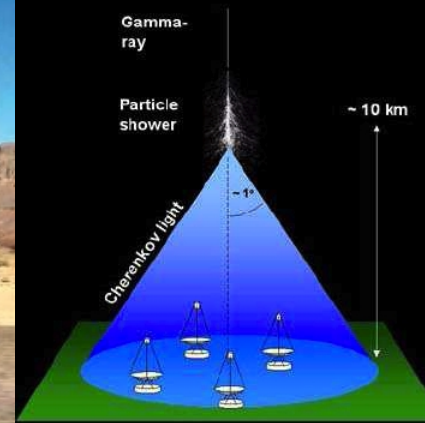
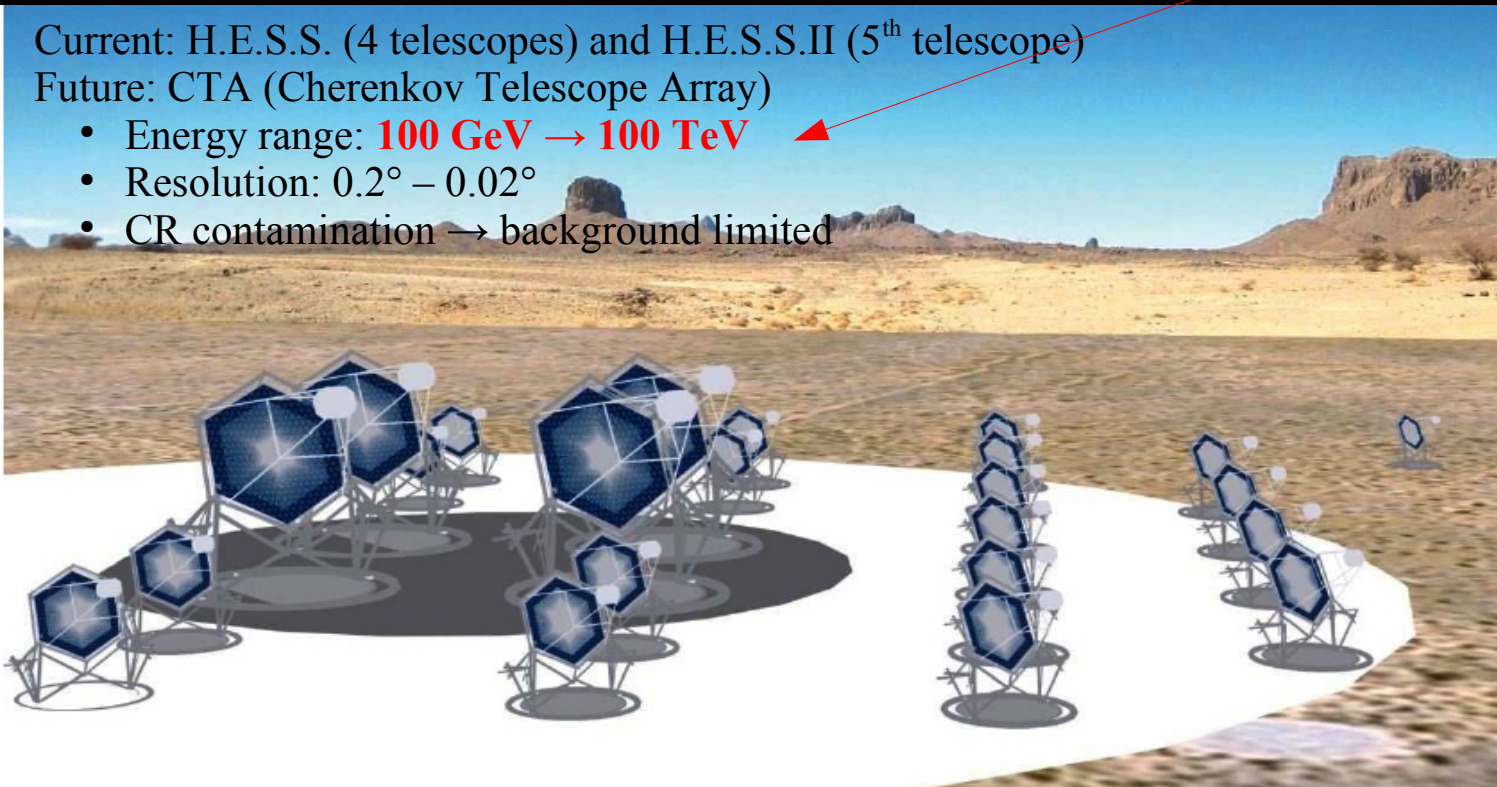
Fermi-LAT: space-borne

- Energy range: **30 MeV – 300 GeV**
- Resolution:  $1^\circ - 0.1^\circ$
- Fullsky

DM mass constrained:  $\langle E_\gamma \rangle \sim m_\chi / 10$

Current: H.E.S.S. (4 telescopes) and H.E.S.S.II (5<sup>th</sup> telescope)  
Future: CTA (Cherenkov Telescope Array)

- Energy range: **100 GeV → 100 TeV**
- Resolution:  $0.2^\circ - 0.02^\circ$
- CR contamination → background limited





# Recent results and limits on $\langle\sigma v\rangle$

## 1. Galactic centre: dominated by astro. bkgd

H.E.S.S.: Aharonian et al., A&A 425, L13 (2004)

## 2. Dwarf spheroidal galaxies : clean targets

Fermi-LAT: Abdo et al., ApJ 712, 147 (2010),

Ackermann et al., PRL 107, 1320 (2012)

[+H.E.S.S., VERITAS,...]

## 1. Galactic centre halo: no bkgd expected

H.E.S.S.: Abramowski et al., PRL 106, 1301 (2011)

$$3 \cdot 10^{-25} \text{ cm}^3 \text{ s}^{-1}$$
$$M_\chi = 1 \text{ TeV}$$

$$8 \cdot 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$
$$m_\chi = 100 \text{ GeV}$$

$$5 \cdot 10^{-24} \text{ cm}^3 \text{ s}^{-1}$$
$$m_\chi = 100 \text{ GeV}$$

$$2 \cdot 10^{-24} \text{ cm}^3 \text{ s}^{-1}$$
$$m_\chi = 100 \text{ GeV}$$

## 4. Dark halos: blind searches (no counterparts)

Fermi-LAT: Ackermann et al., ApJ 747, 121 (2012)

## 3. Galaxy clusters: no signal (bkgd expected)

Fermi-LAT: Ackermann et al., ApJ 717, 71 (2010) and

JCAP 05, 025 (2010)

Aquarius (MW-like) simulation – Springel et al (2008)

$\Delta\Omega$

+ Other searches: isotropic diffuse emission,  $\gamma$ -ray line searches...

→ only start to reach interesting  $\langle\sigma v\rangle$  regions for SUSY models

III –  $\gamma$ -rays from DM

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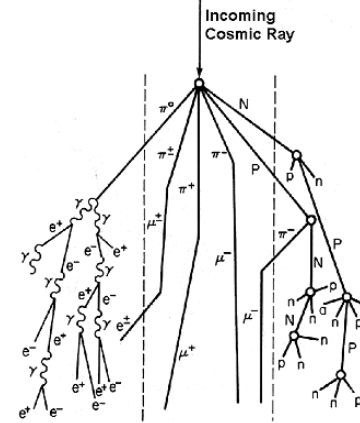


# Galactic Cosmic Rays (GCRs): century-old questions

**1912: cosmic radiation from outer space (V. Hess, Nobel prize 1936)**

**1912–1950: particle physics with CRs**

- Positron: Anderson (1932)
- Muon: Anderson & Neddermeyer (1936)
- Pion: Powell (1947)
- Kaon [strange particle]: Rochester & Butler (1947)
- Lambda [first hyperon]: Danysz & Pniewski (1951)



**1952–1954 : first GeV accelerators built**



**1950–1980: astrophysics with CRs (GeV–TeV)**

- Stable nuclei:  $Z < 30$  (1948),  $Z \geq 30$  (1967),  $Z > 90$  (1970)
- Radioactive isotopes:  $^{10}\text{Be}$  (1973),  $^{54}\text{Mn}$  (1979),  $^{36}\text{Cl}$  (1981),  $^{26}\text{Al}$  (1982)
- Leptons: electrons (1960), positrons (1964)
- Antiprotons (1979), anti-deuterons (????)
- $\gamma$ -ray diffuse emission (1972)

**Collider (particle) physics**



**1980–20XX: astrophysics, and astro-particle physics**

# Many yet unsolved questions

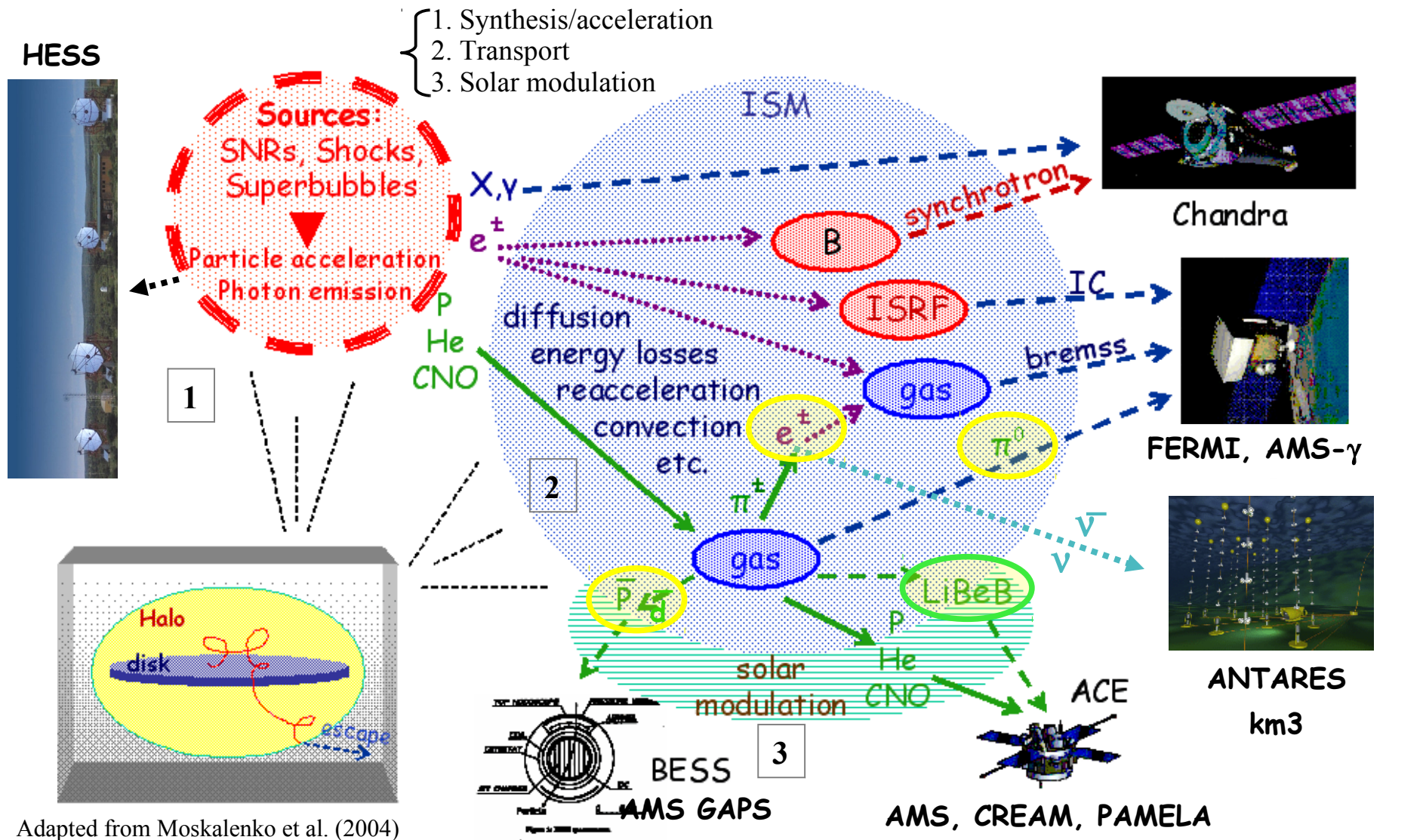
## 1. Do we understand the “standard” galactic fluxes?

- Sources (SN, pulsars, SB...)
- Nucleosynthesis (r and s-process for heavy nuclei)
- Acceleration mechanisms (injection, B amplification)
- Propagation mechanisms (link to turbulence, spatial dependence, isotropy)
- Magneto-cosmico-gaseo properties of the Galaxy (MHD description)
  - i) GCRs here/in the whole Galaxy (linked to diffuse emissions)
  - ii) GCRs now/in the past/future (linked with massive extinctions?)

## 2. Are GCRs a good laboratory to search for new physics?

- Dark matter/new physics ?
- Just standard astrophysics?

# Modern picture: CR journey in 3 steps



→ Search for DM where “standard” production is rare

→ Use LiBeB to calibrate transport

IV – Charge CRs and transport

# Transport/propagation equation

## 1. What is the transport equation?

- Real life transport is in turbulent and regular B: MHD problem
- In the limit  $\delta B \ll B$ , it is possible to show that we have a diffusion/convection equation

$$\frac{\partial \psi}{\partial t} = q(r, p) + \nabla \cdot (D_{xx} \nabla \psi - V \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[ \dot{p} \psi - \frac{p}{3} (\nabla \cdot V) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

- Coupled set of second order differential (space and momentum) equations

N.B.: for different species and different energies, the dominant “process” can change  
[for CR nuclei, the steady-state approximation is often used]

## 2. What are the ingredients?

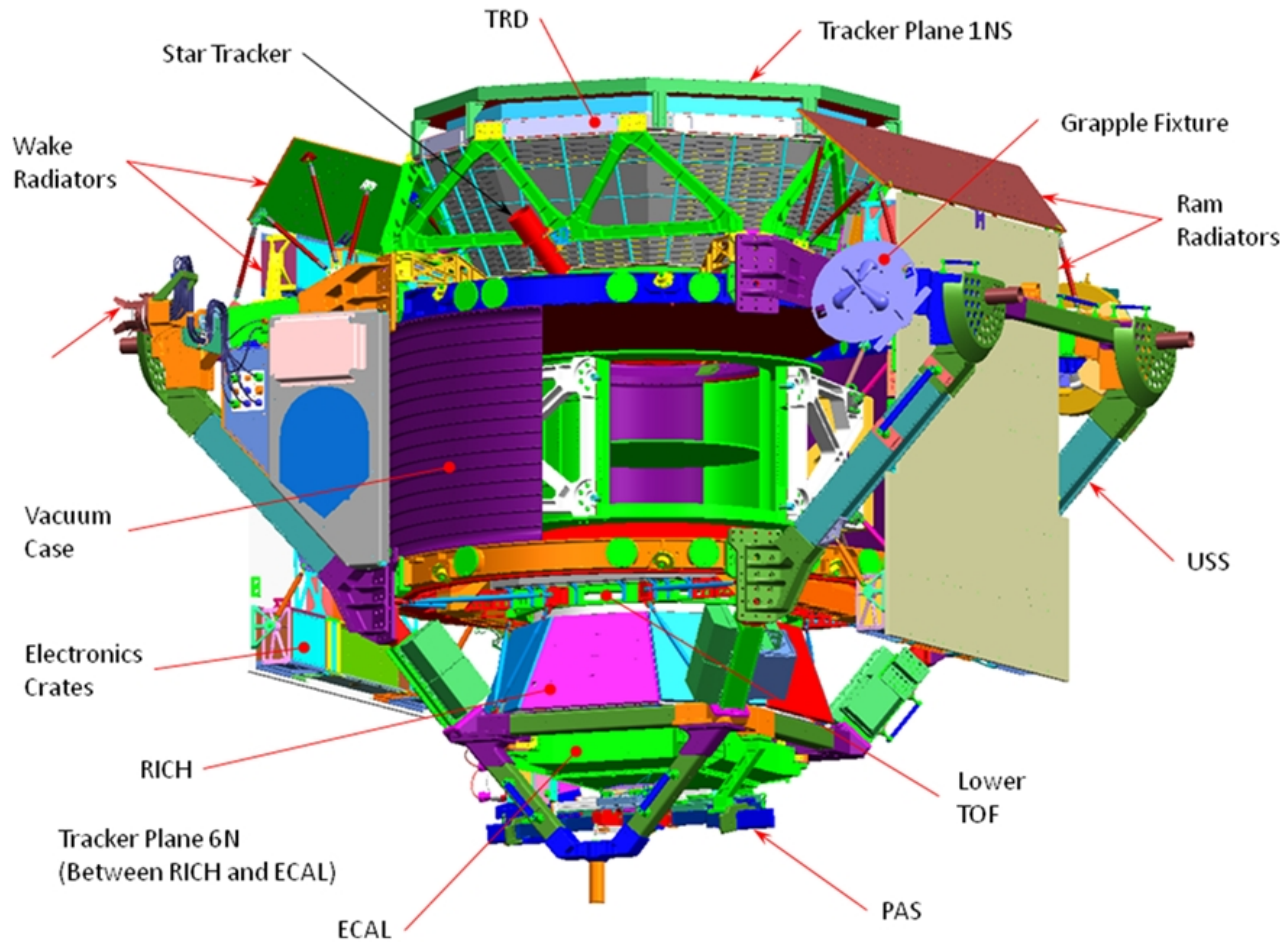
- Nuclear physics [<https://indico.in2p3.fr/conferenceDisplay.py?confId=7012>]
- Solar physics [same transport equation, different environment/geometry/boundary conditions]
- Astrophysics environment [sources, gas distribution, radiation field in Galaxy, magnetic fields]

## 3. How to solve the transport equation?

- Numerical solution [discretisation using explicit or implicit schemes]
- Monte Carlo diffusion [forward and backward stochastic equation]
- Semi-analytical solutions [solve for simplified geometry: Green functions, Bessel expansion,...]



# AMS-02: a particle physics detector in space



- On ISS since May 2011
- Energy range:  
 $1 \text{ GeV} \rightarrow 1 \text{ TeV}$
- Measure:  
 $H \rightarrow \text{Fe}, e^-, e^+, p\text{bar}, \gamma$

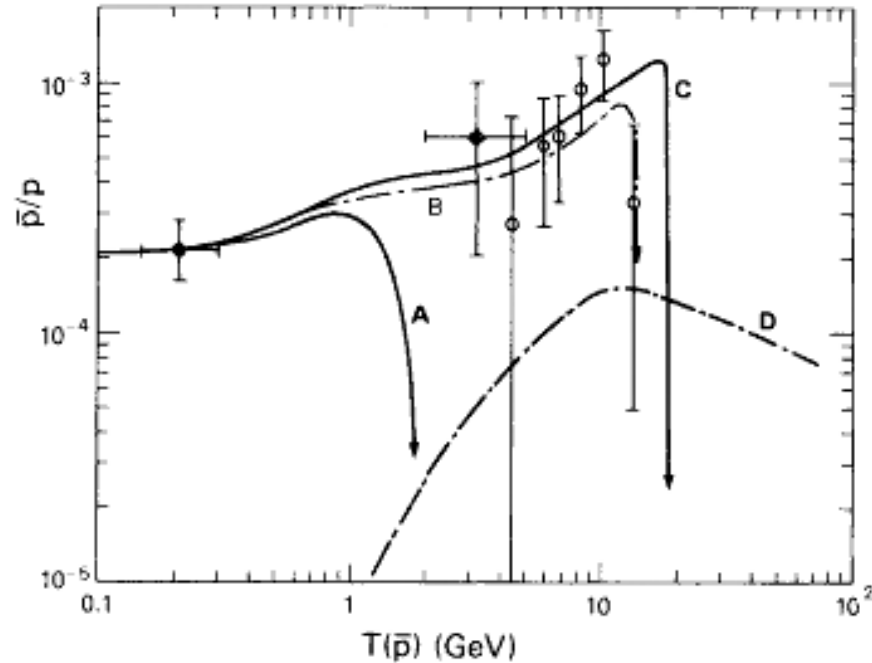
**Huge coverage/increase  
of statistics compared to  
previous experiments**

Exp.	#events/day	flight dates	Total #events
$N_{\text{HEAO-3}}$	$\sim 2.6 \cdot 10^4$ /day	[10/79-06/80]	$\rightarrow 7 \cdot 10^6$ events ( $4 < Z < 30$ )
$N_{\text{PAMELA}}$	$\sim 2.2 \cdot 10^6$ /day	[07/06-...]	$\rightarrow 5 \cdot 10^9$ events ( $Z < 6$ )
$N_{\text{AMS-02}}$	$\sim 4.6 \cdot 10^7$ /day	[04/11-...]	$\rightarrow 3 \cdot 10^{10}$ events (all $Z$ )

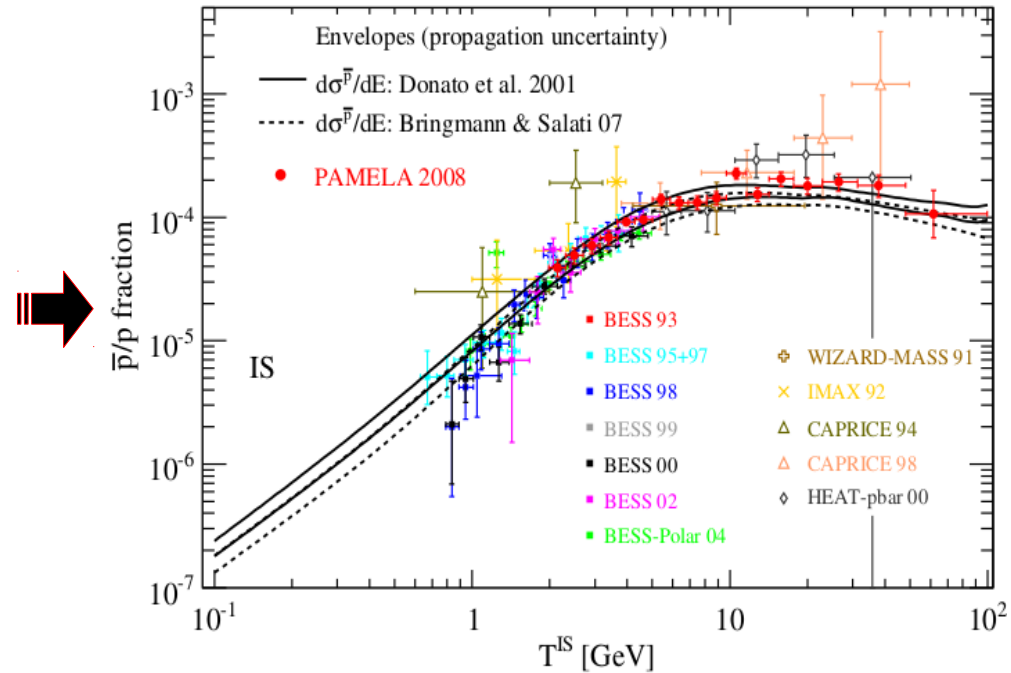


# Antiproton flux 1979 → 2010

Silk & Srednicki, PRL **53**, 624 (1984)  
Stecker, Rudaz & Walsh, PRL **55**, 2622 (1985)



Donato et al., PRL **102**, 071301 (2009)



- No excess: consistent with standard production
- Main uncertainty (for background) comes from nuclear physics
- No stringent exclusion limit (dominated by propagation uncertainties)

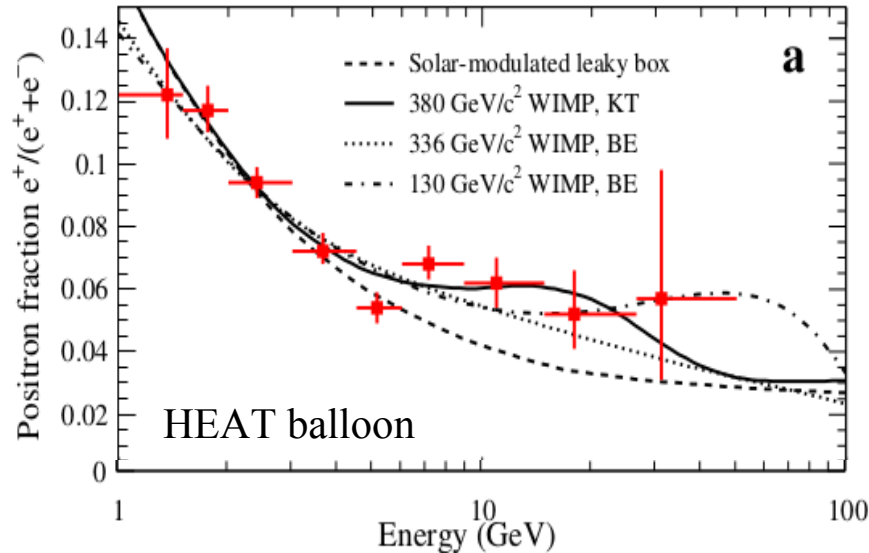
## Future developments:

- Higher precision measurement from AMS-02
- Decrease propagation uncertainties from AMS-02 data on nuclear species
- Search for anti-deuterons: more constraining than antiproton, but difficult

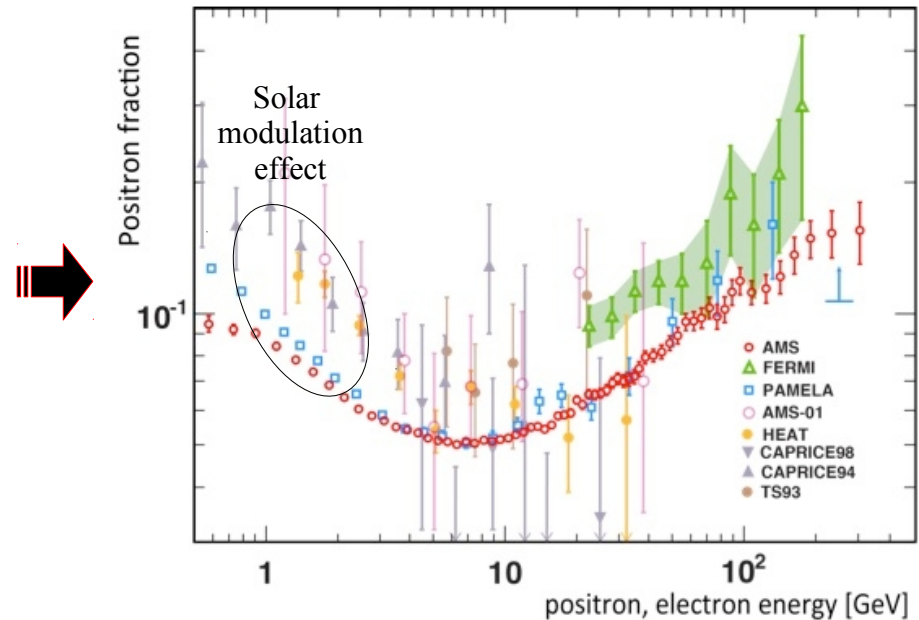
# Positron fraction 1990 → 2013

N.B.: due to important E losses, high energy leptons are “local” ( $\sim$  kpc)

Coutu et al., *Aph* **11**, 429 (1999)



AMS collaboration, *PRL* **110**, 1102 (2013)



- Rise of the positron fraction confirmed by PAMELA and AMS-02
- Naturally explained by local pulsars [e.g., Boulares (1989), Delahaye et al. (2010)]
- Non-natural DM models required (leptophilic, boosted)

## Future developments:

- Go to higher energy with AMS-02 (search for sharp cutoff)
- Study separately  $e^-$  and  $e^+$  spectra, combine with antiproton constraints
- Refine pulsars and propagation description

N.B.: positrons are probably the worse place to look for DM

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**N.B.: many collaborations theory/pheno/exp. between LAPP/LAPTh/LPSC**

- Members of AMS-02, H.E.S.S., C.T.A.
- Studies on CR propagation
- Studies on DM annihilation and constraints

# Anomalies in GCRs as DM signal: déjà vu?

## Antiprotons

- first measurements, be it at low energy or at high energy, proven wrong
- first theoretical calculation underestimated
  - *Present status: no excess from PAMELA data*

## $\gamma$ -ray GeV excess

- EGRET excess (1997-2008): astrophysical or DM?
- High latitude excess proven wrong by FERMI data
  - *Present status: several FERMI papers from non-detection (dSphs, diffuse...)*
  - *But many claims of detection @ 10 GeV, 120 GeV, etc. from non-Fermi members*

## Positron fraction

- Rise at 10 GeV (HEAT) controversial, if DM, needed large boosts
- Clumpiness found unable to boost the signal
- Rise from PAMELA data: if DM, requires leptophilic DM + particle physics boost
- Rise confirmed by AMS-02 with better accuracy
  - *People seem to come back to reality: local sources very likely to explain data*

## TeV electron flux

- First measurement ATIC& PPP-BETS (2008)
- Local sources, DM [ $\sim O(100)$  papers], or incorrect measurements?
  - *Status: neither confirmed by HESS nor by FERMI, local sources as for positrons*

## 511 keV line

- Variable source, then positronium fountain (OSEE), then light DM (SPI/INTEGRAL)
- Hundreds of papers on light dark matter!!!
  - *Present status: spatial correlation LMXB (issues with intensity?)*

→ Astrophysics backgrounds are complicated: not a clean environment

→ Better data, better ingredients, and better models are required

V – Conclusions