Modelling of astrophysical foreground

It's about galactic cosmic rays (GCR)!

1. A brief historical perspective
2. CR journey: global picture
3. DM indirect detection: foreground and targets
4. Simplex, complex, multiplex: GCR "model"
5. Detailed uncertainties for anti-protons
6. Positron fraction: a severe case of memory loss
7. γ-rays: fun facts about diffuse emissions

David Maurin
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HAP Dark Matter 2015
Karlsruhe
23 Sept. 2015

Modelling of astrophysical foreground

→ *Foreground depends on messenger!*
→ *Foreground depends on wavelength!*
→ *Foreground depends on instrument!*

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1. Historical perspective

How cosmic rays were discovered and why they received this misnomer
Adv. in Space Res. 53 (2014) 1388–1404
Dorman & Dorman

As many great discoveries, **the phenomenon of cosmic rays was discovered mainly accidentally, during investigations that sought to answer another question**: what are sources of air ionization? This problem became interesting for science about 230 years ago in the end of the 18th century, when physics met with a problem of leakage of electrical charge from very good isolated bodies. [...] These discoveries were recognized among greatest in the 20th Century and were awarded by Nobel Prize.

End of 19^{th} century – J.J. Thomson
Electric conductivity of gasses strongly increases under the influence of X-rays and radiation from radioactive elements
→ Theory of ionic conductivity of gasses

Start of 20^{th} century (improved electroscope designs...)

- *Radiation constantly ionizing the air*
- *Discharge of an electroscope explained by an insignificant number of ions in air*

→ **What is the nature of the unknown source of ions?**

1. Historical perspective: proof of extraterrestrial radiation

- **A decade of unrewarded efforts...**

  1902-1909 – Improvements of apparatus, data at ground, sea, mountain level... w/o shielding

  Review of Kurtz (1909)

  - γ-radiation from the earth's crust;
  - ~~radiation coming from the atmosphere;~~
  - ~~radiation from space.~~

  } Resolutely rejected as improbable!

- **Ionisation constant with altitude (whereas decrease expected)**

  1909-11 – A. Gockel: 3 balloon flights @ 4500 m (unpressurised detector)
  1909-10 – T. Wulf: electroscope + measurements at Eiffel tower
  1909-12 – D. Pacini: underwater (require non-terrestrial radiation)

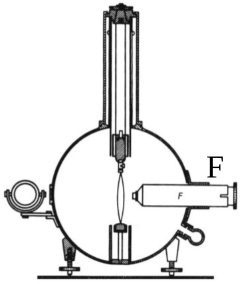


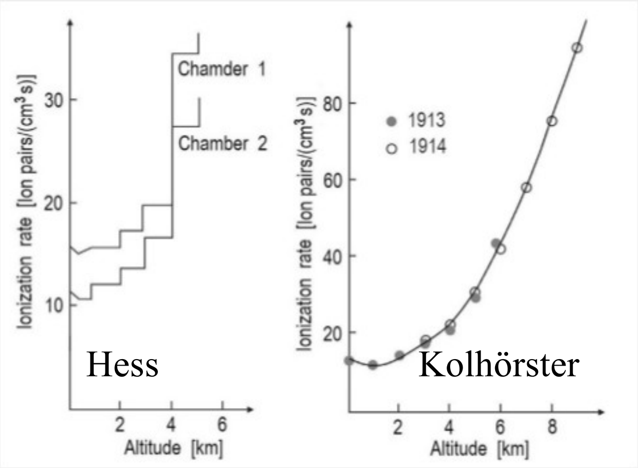
Fig. 6. Electroscope of Wulf (1909).

Electroscope: speed of discharge related to distance change between the wires (microscope F)

- **Proof of existence: V. Hess (1911-1912)** → *"ultra-gamma radiation"*

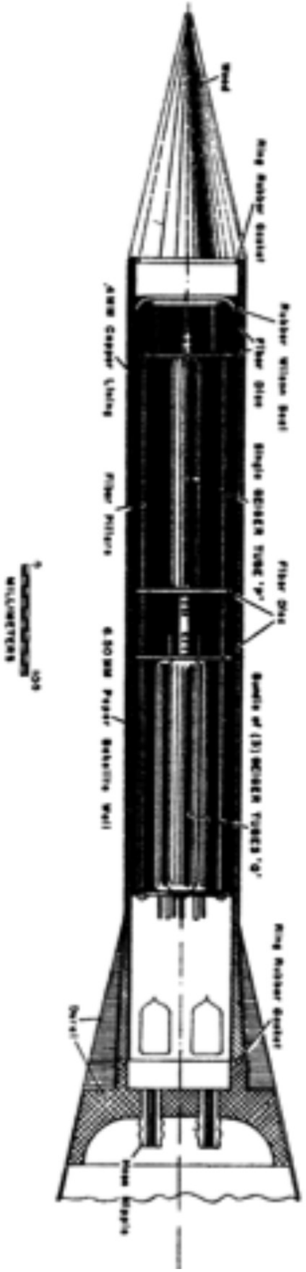
  1911: First measure of γ-ray attenuation in air, predict absorption for d≥500 m
  → *"there should be other source of a penetrating radiation in addition to γ-radiation from radioactive substances in earth crust"*

  1912: flights at ≠ times, ≠ atmospheric conditions (wind, pressure, T)
  3 Wulf electroscopes: (non-)hermetic, w/o shield (sensitive to γ-rays)
  → *"can be explained by the assumption that radiation of the big penetrating ability is coming into our atmosphere from above and even its bottom layers"*



… and confirmation by Kolhörster (1913-1914)

1. Historical perspective: opening the space age...

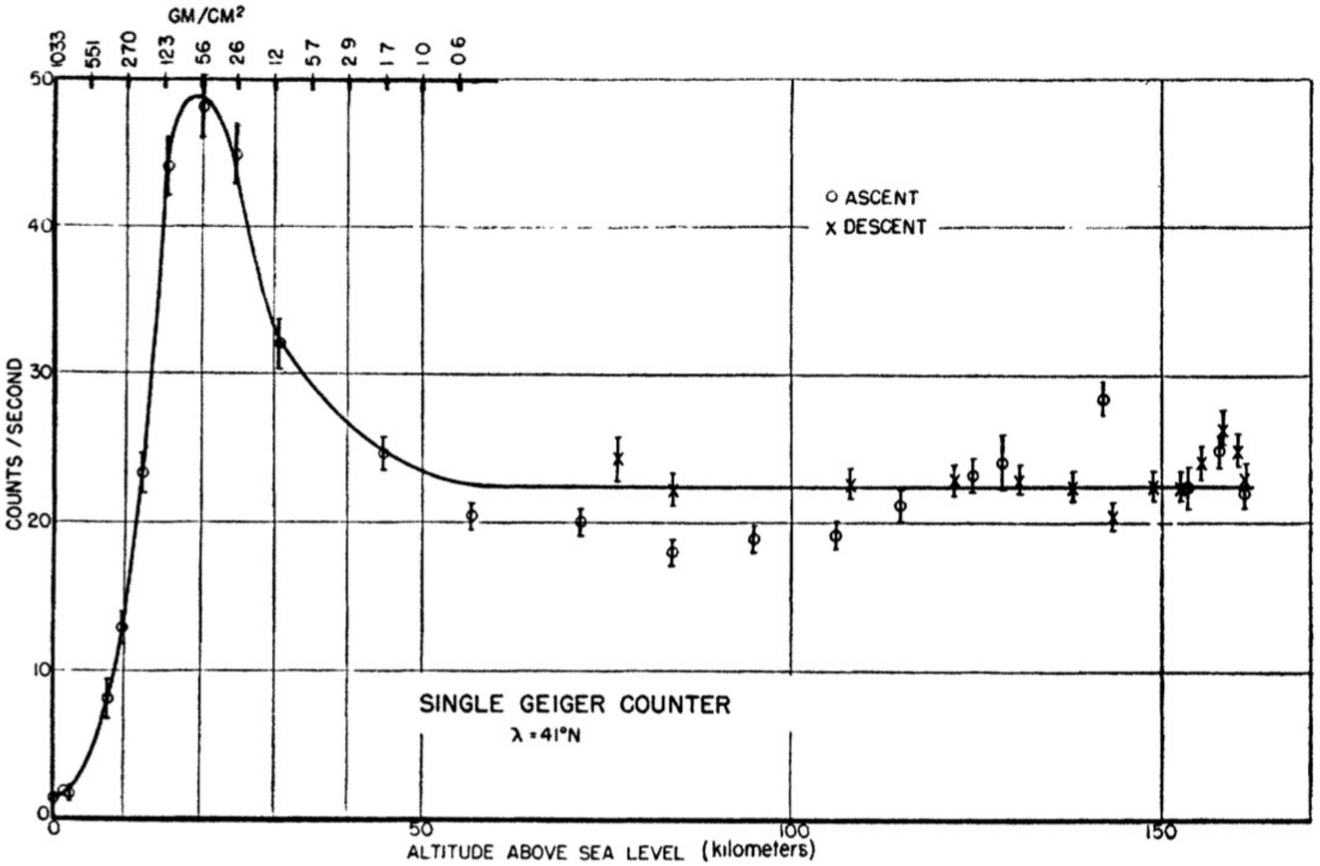


PHYSICAL REVIEW VOLUME 73, NUMBER 3 FEBRUARY 1, 1948

The Cosmic-Ray Counting Rate of a Single Geiger Counter from Ground Level to 161 Kilometers Altitude

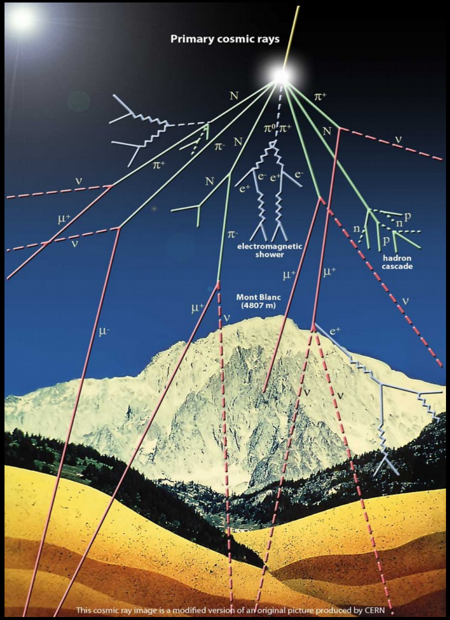
J. A. Van Allen and H. E. Tatel*
Applied Physics Laboratory, Johns Hopkins University, Silver Spring, Maryland

(Received October 16, 1947)



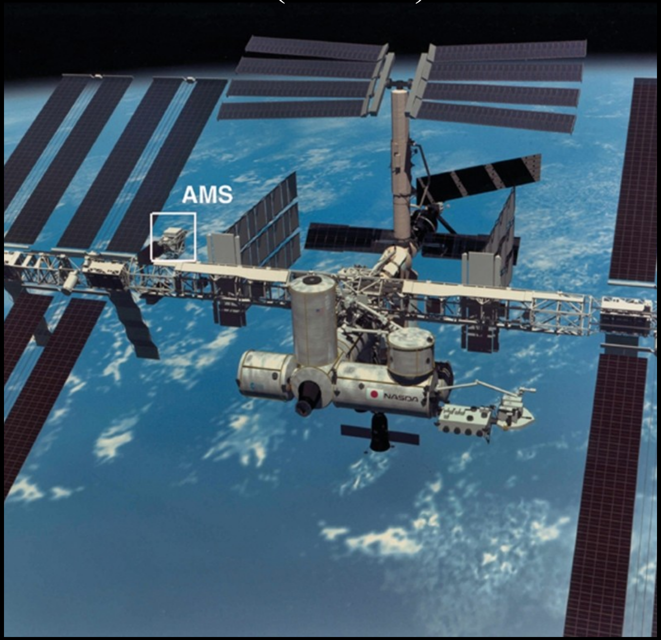
1. Timeline: cosmic-ray identification

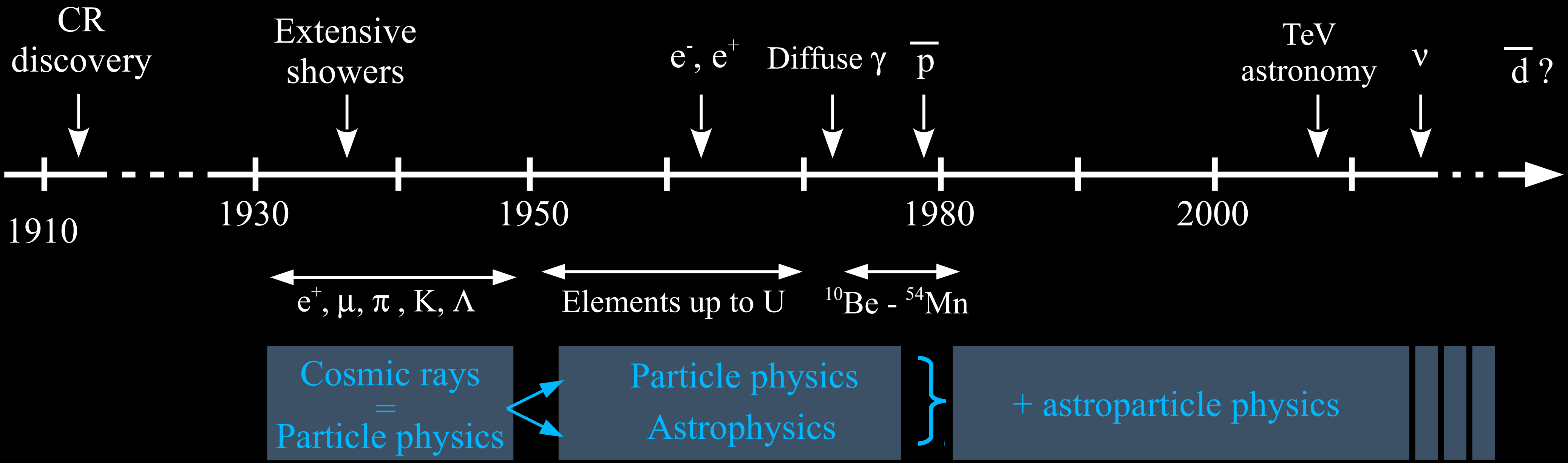
Mountain altitude < 5 km



CREAM balloon ~ 40 km

AMS-02 (on ISS) ~ 300 km





CR discovery

Extensive showers

e^-, e^+

Diffuse γ

$\bar{p}$

TeV astronomy

ν

$\bar{d}$?

1910

1930

1950

1980

2000

e^+, μ, π , K, Λ

Elements up to U

^{10}Be - ^{54}Mn

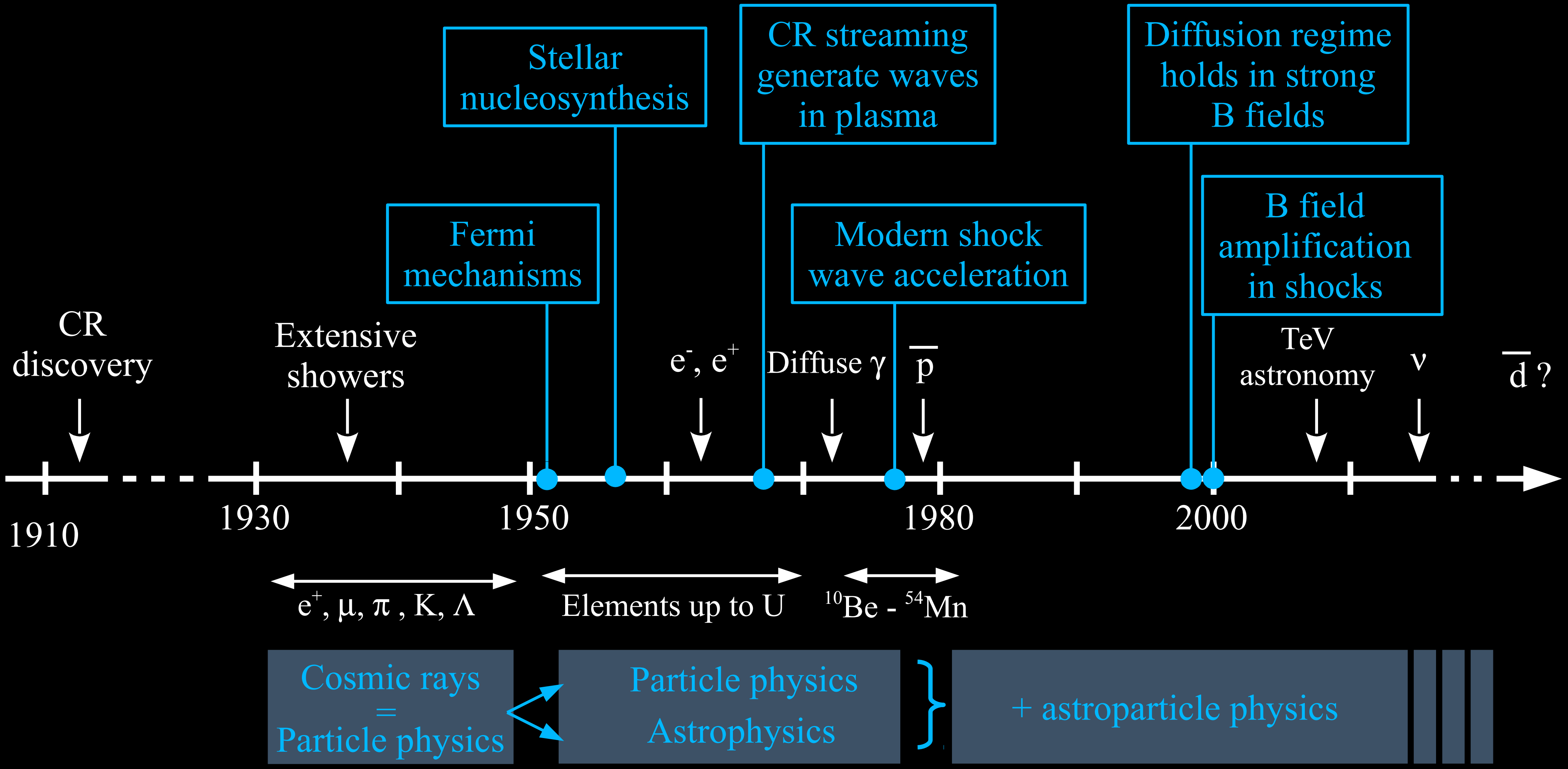
Cosmic rays = Particle physics

Particle physics

Astrophysics

+ astroparticle physics

1. Timeline: establishing a theory of CRs



Stellar nucleosynthesis

CR streaming generate waves in plasma

Diffusion regime holds in strong B fields

Fermi mechanisms

Modern shock wave acceleration

B field amplification in shocks

CR discovery

Extensive showers

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Cosmic rays = Particle physics

Particle physics

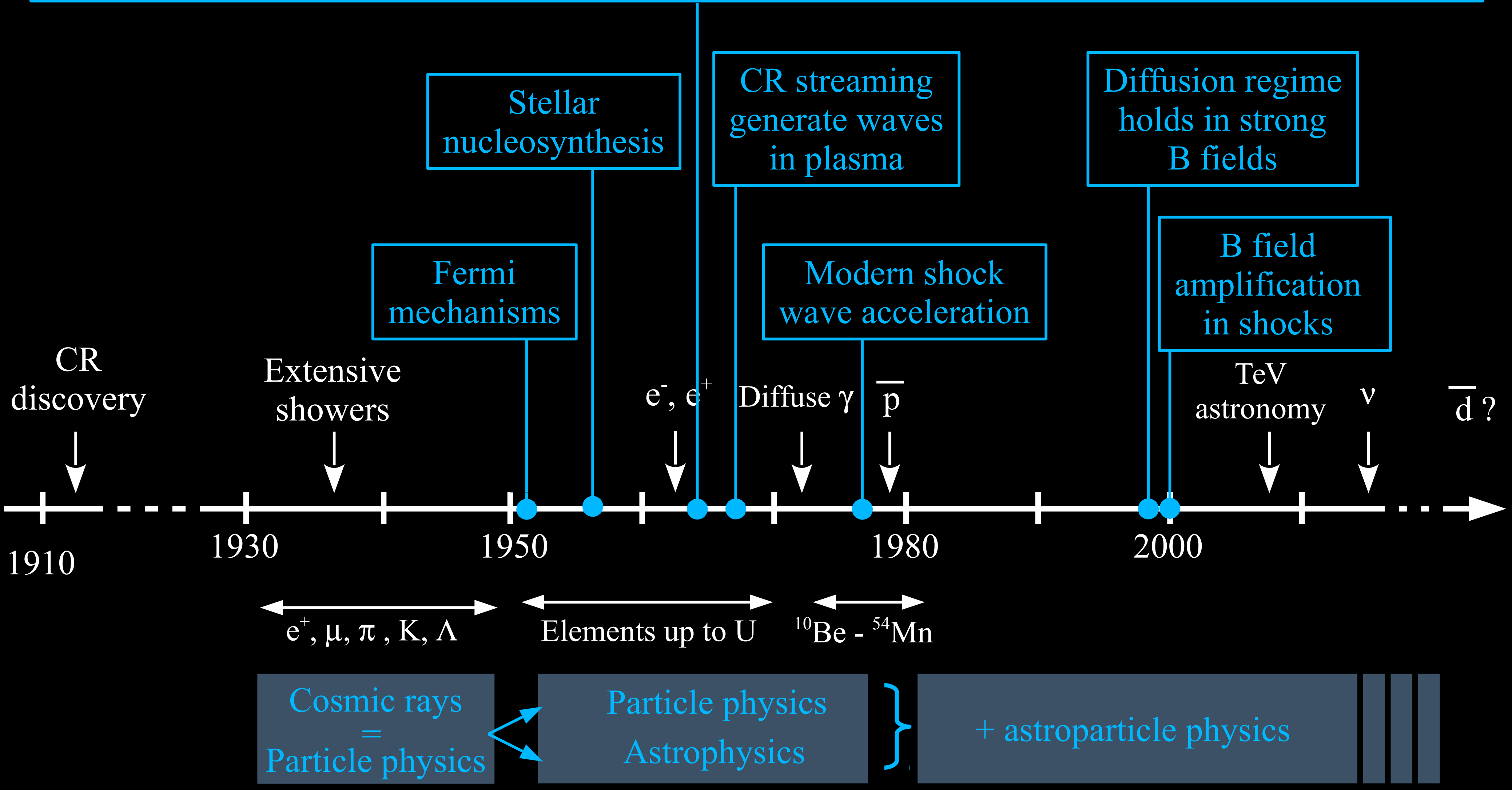
Astrophysics

+ astroparticle physics

1. Transport equation

Transport parameters: K_0 and δ (diffusion normalisation and slope), L (diffusive halo size), V_c (convection)

$$\overbrace{\frac{\partial N^j}{\partial t}}^{\text{Variation}} + \overbrace{\left(-\vec{\nabla}\cdot\left(K(E,\vec{r})\vec{\nabla}\right)+\vec{\nabla}\cdot\vec{V}(\vec{r})\right)}^{\text{Transport (diff+conv)}} N^j + \overbrace{\left(\Gamma_{\rm rad}+\Gamma_{\rm inel}\right)}^{\text{catastrophic losses}} N^j + \overbrace{\frac{\partial}{\partial E}\left(b^j N^j - c^j\frac{\partial N^j}{\partial E}\right)}^{\text{E gain/losses}} = \overbrace{Q^j(E,\vec{r}) + \sum_{m_i>m_j} \Gamma^{i\to j} N^i}^{\text{Sources (prim+sec)}}$$



Stellar nucleosynthesis

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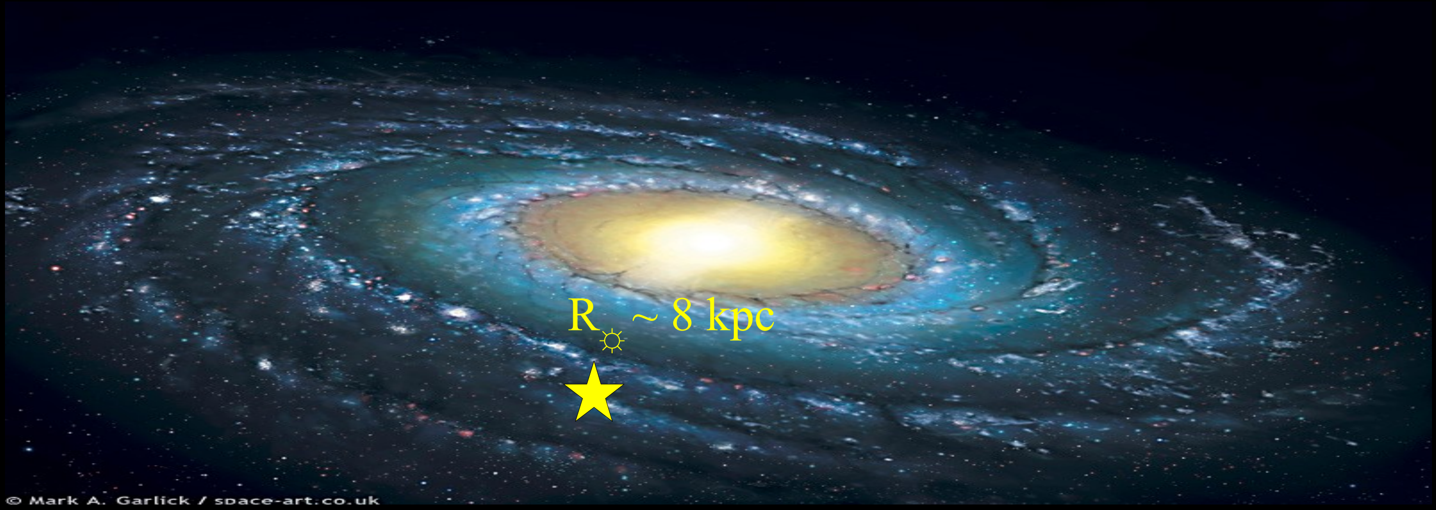
2. Journey of a charged particle in the Galaxy



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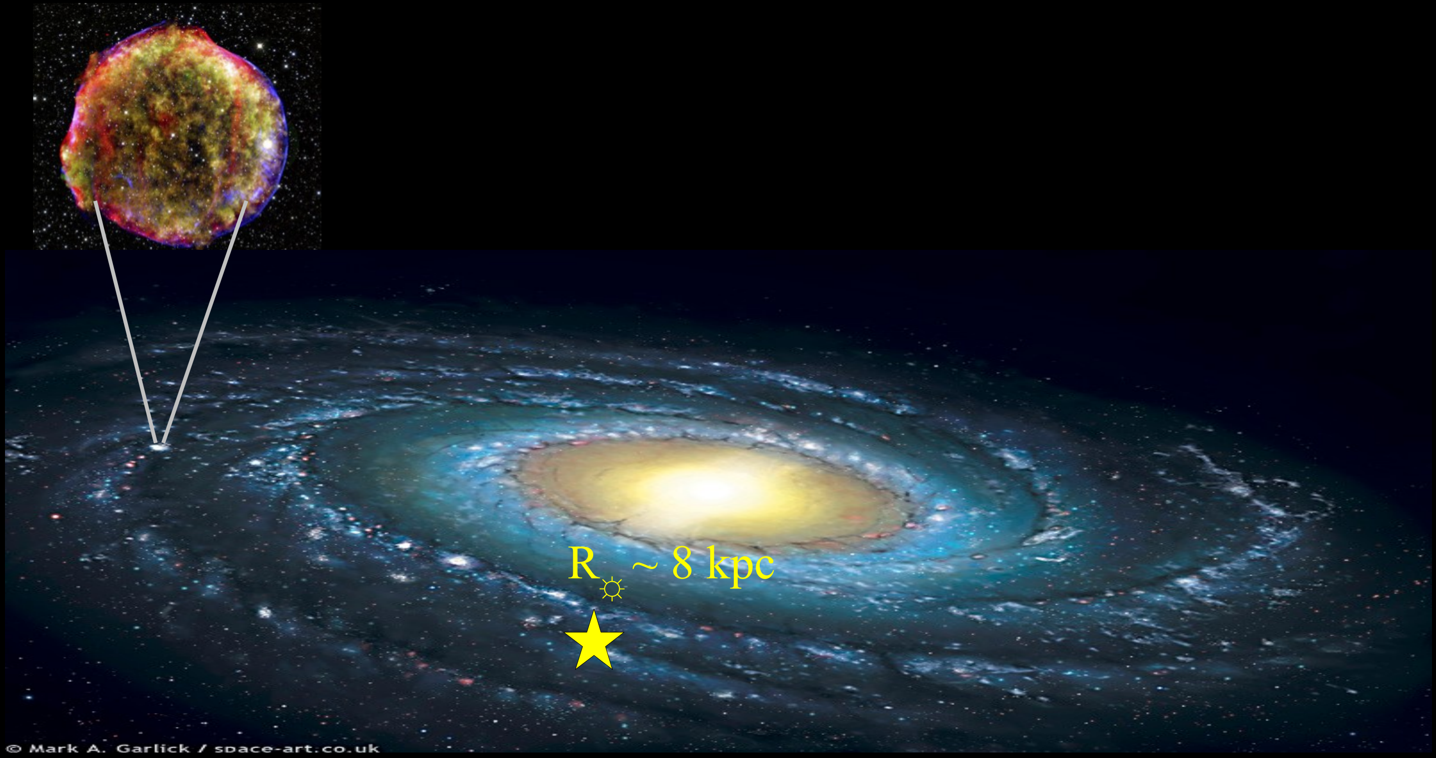
2. Charged GCRs: sources

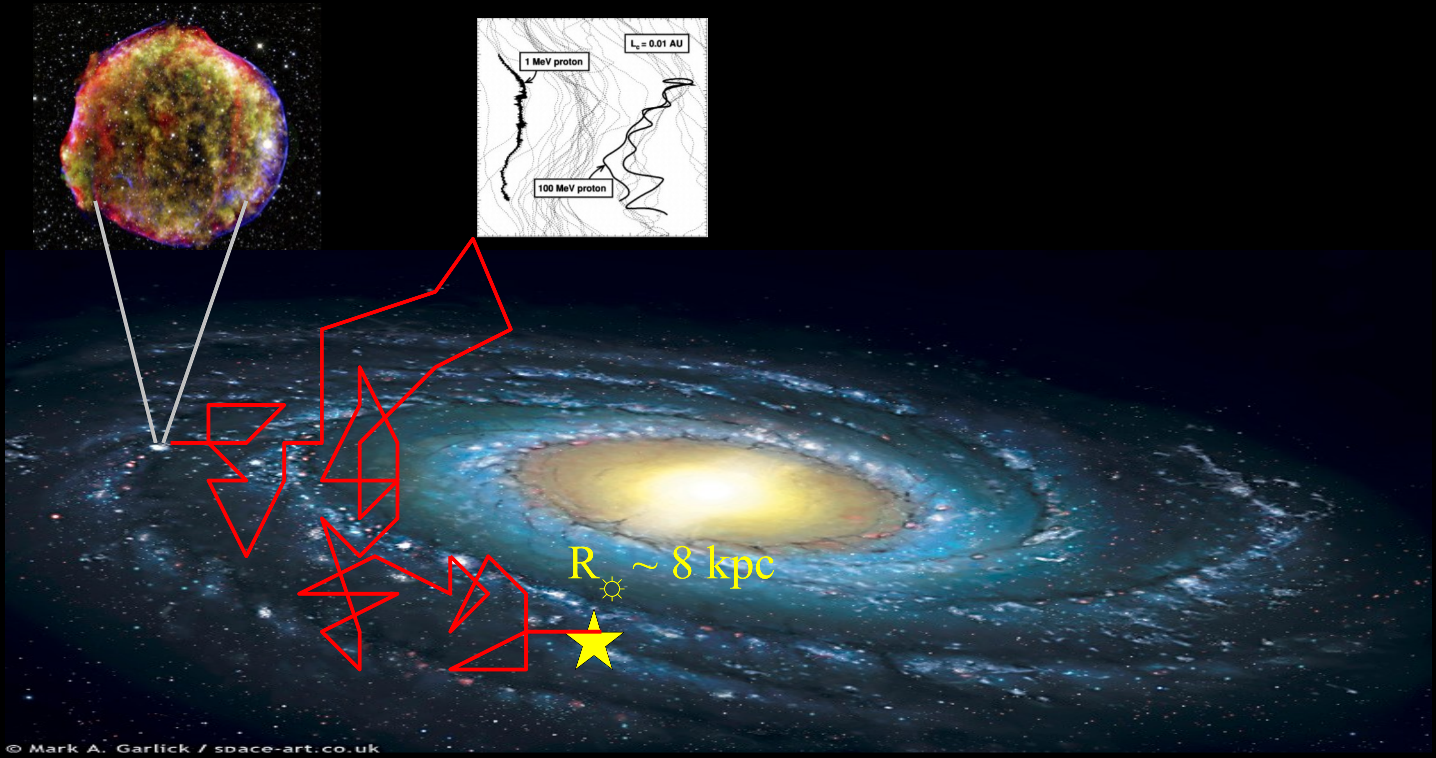
1. Source injection
- spectrum ~ R^{-2}
- abundances



2. Charged GCRs: diffusion

1. Source injection

- spectrum ~ R^{-2}
- abundances



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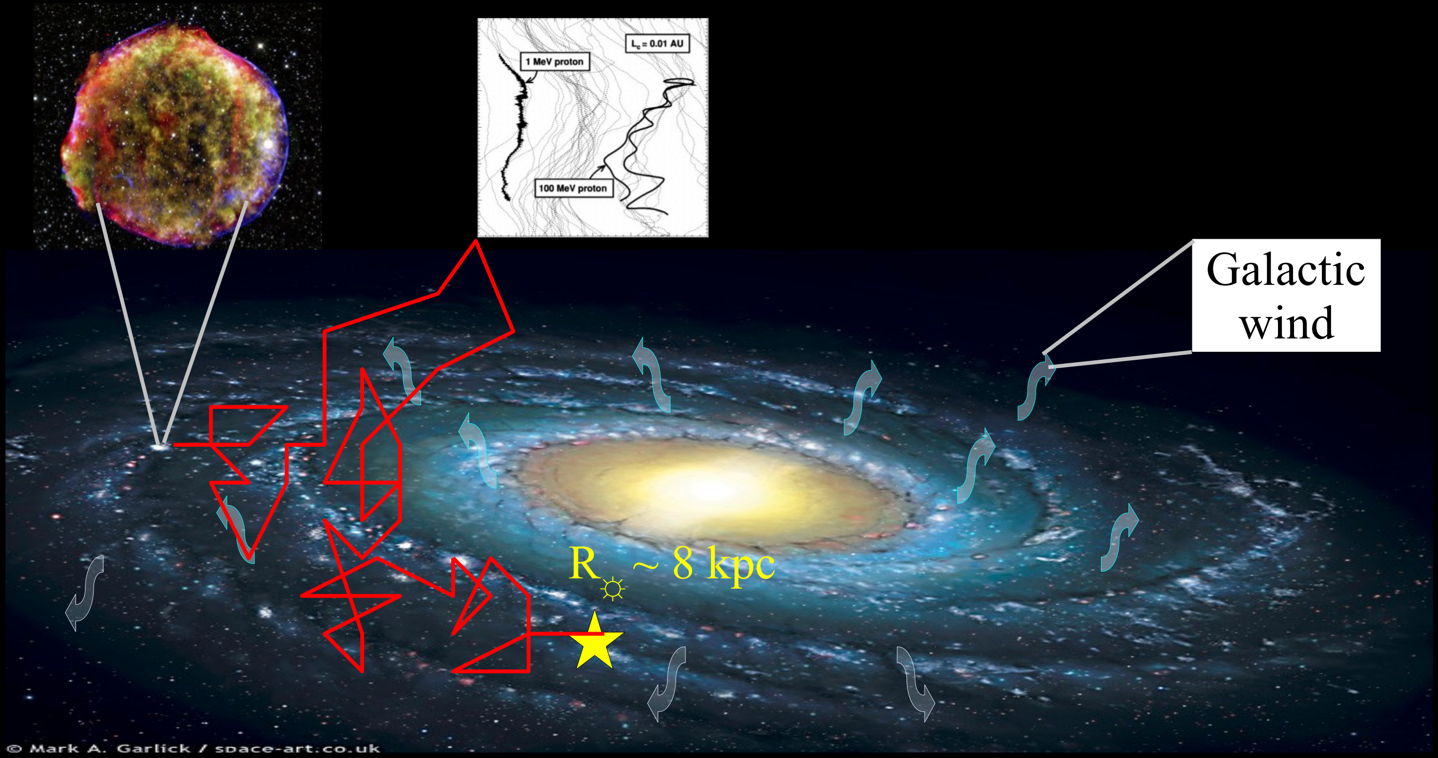
2. Charged GCRs: convection

1. Source injection

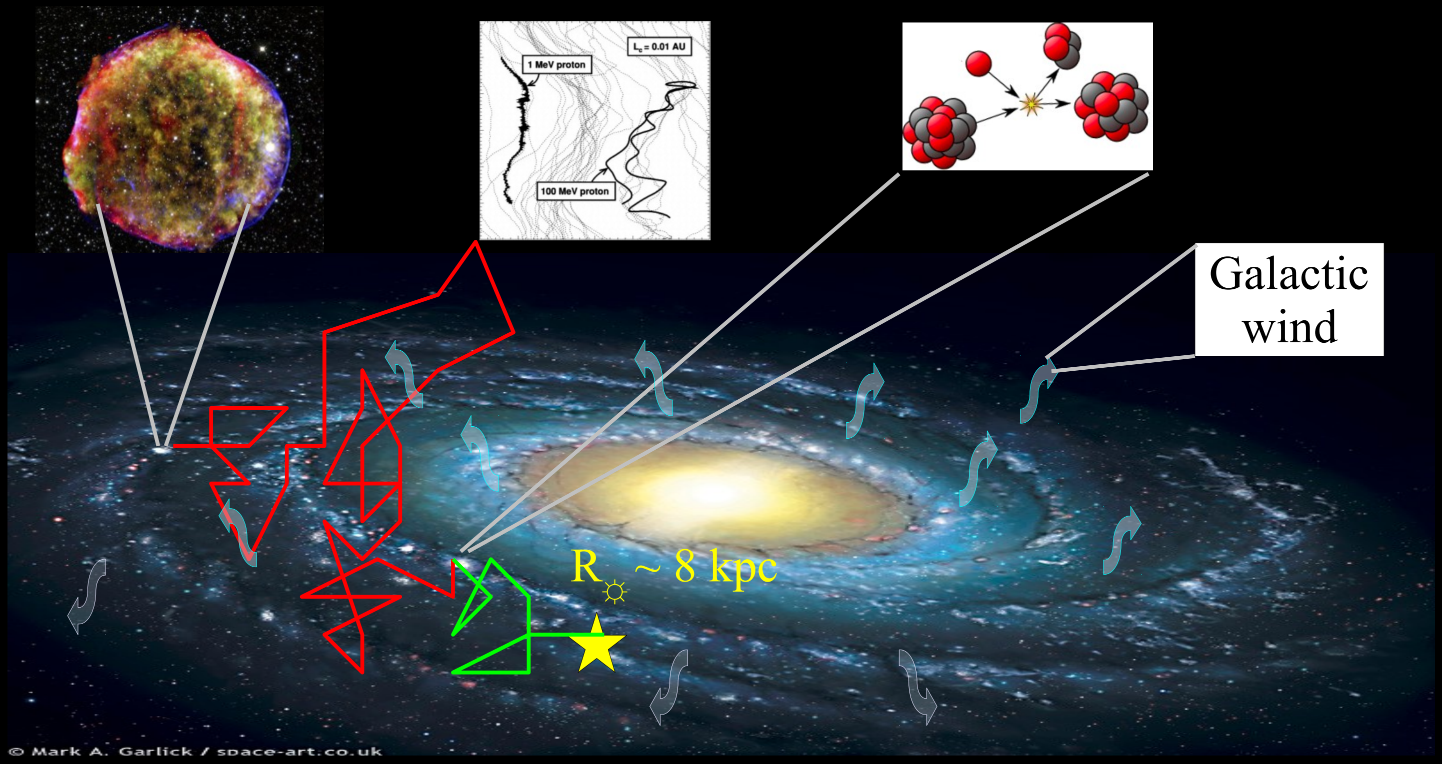
- spectrum ~ R^{-2}
- abundances



2. Charged GCRs: nuclear interactions

1. Source injection

- spectrum ~ R^{-2}
- abundances



Galactic wind

$R_\odot \sim 8$ kpc

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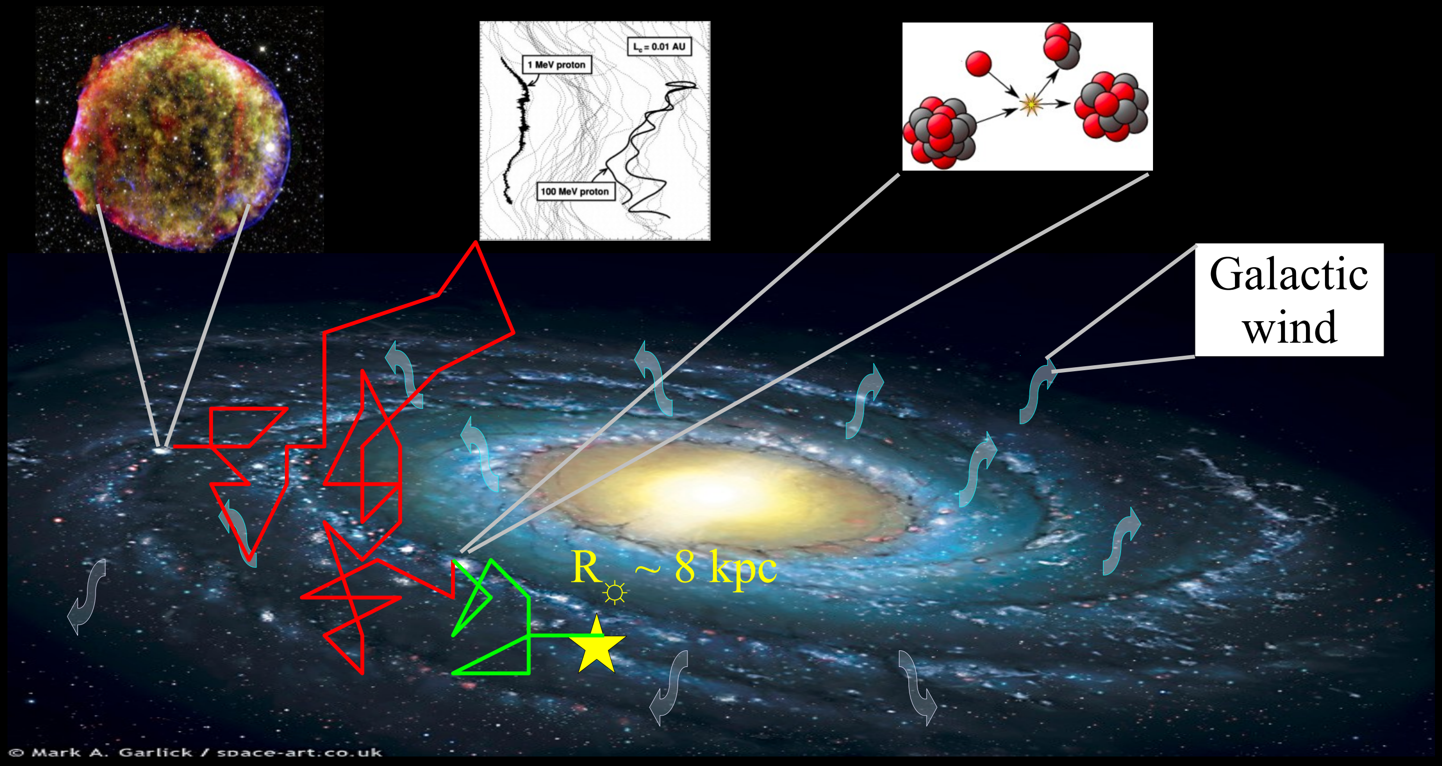
2. GCR transport

1. Source injection

- spectrum ~ R^{-2}
- abundances

2. Transport in the Galaxy

- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/decay



2. GCR transport

1. Source injection

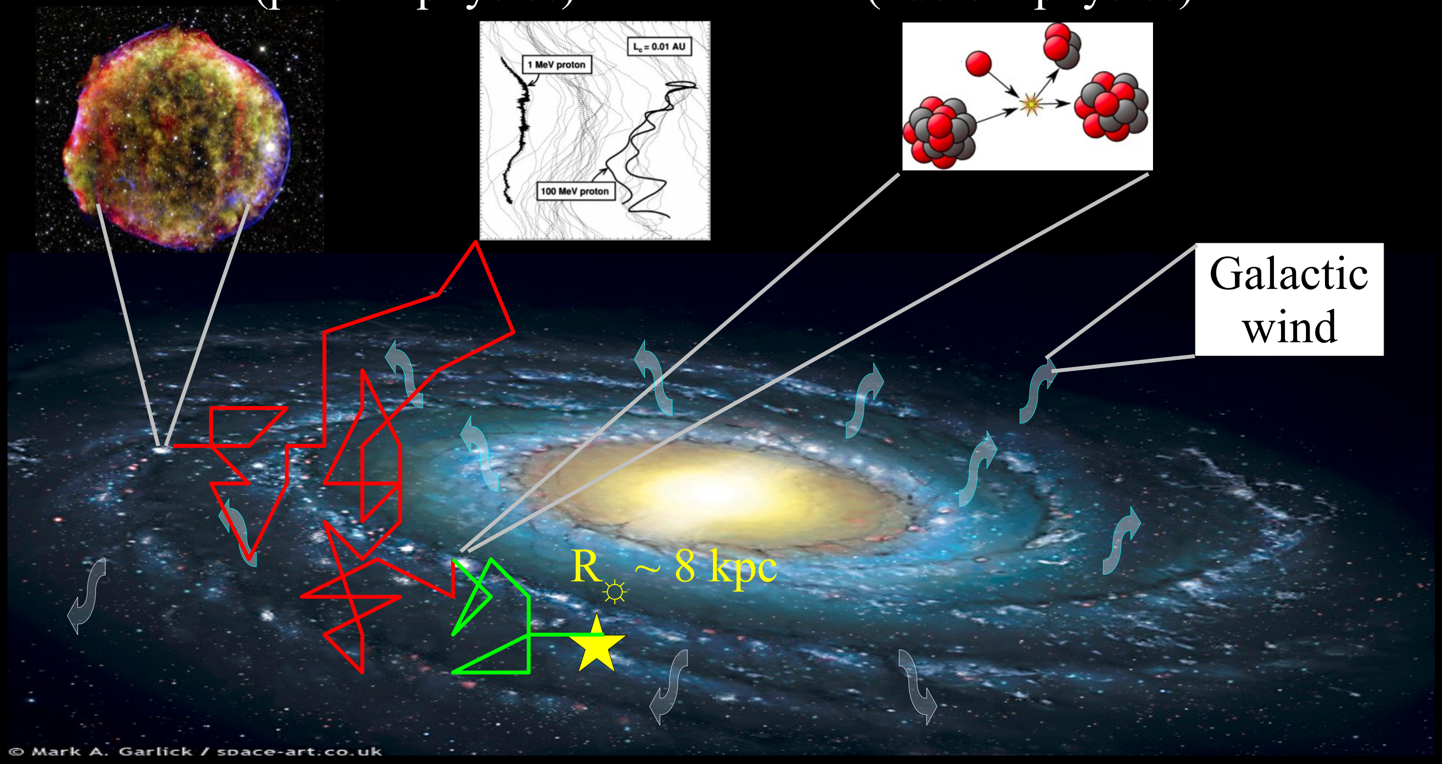
- spectrum ~ R^{-2}
- abundances

2. Transport in the Galaxy

- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/decay

(plasma physics)

(nuclear physics)



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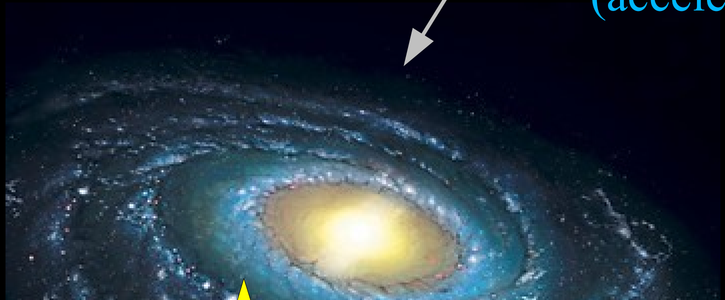
(astrophysics + particle physics)

2. Spectrum: galactic and extragalactic CRs

Galactic cosmic rays or extra-galactic

→ Spectra and abundances
(acceleration and transport)



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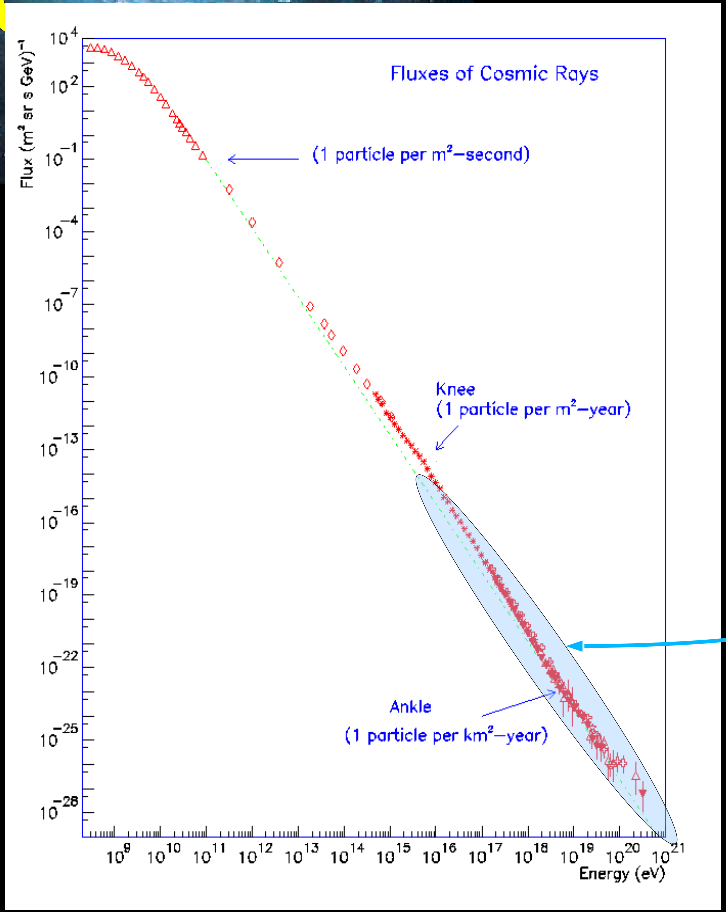
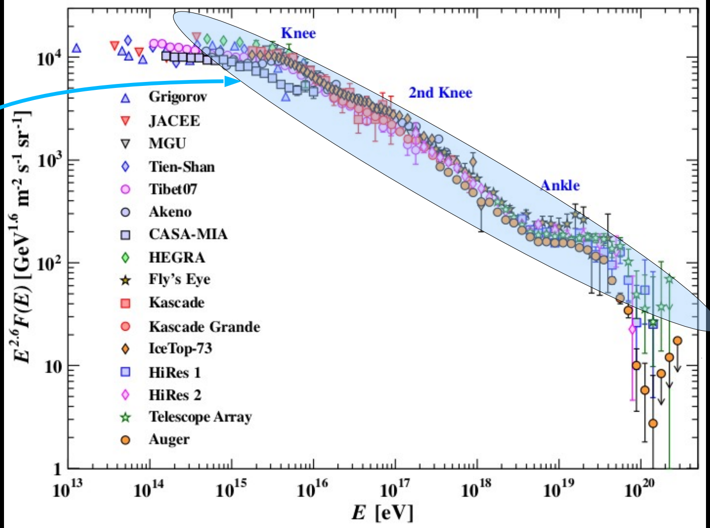


→ Origin of spectral features, composition, anisotropy?
→ Sources of the UHECRs
→ Transport in the cluster and inter-cluster medium



2. Spectrum and abundances: GCRs

1. Cosmic rays in the Galaxy

→ Spectra and abundances (acceleration and transport)

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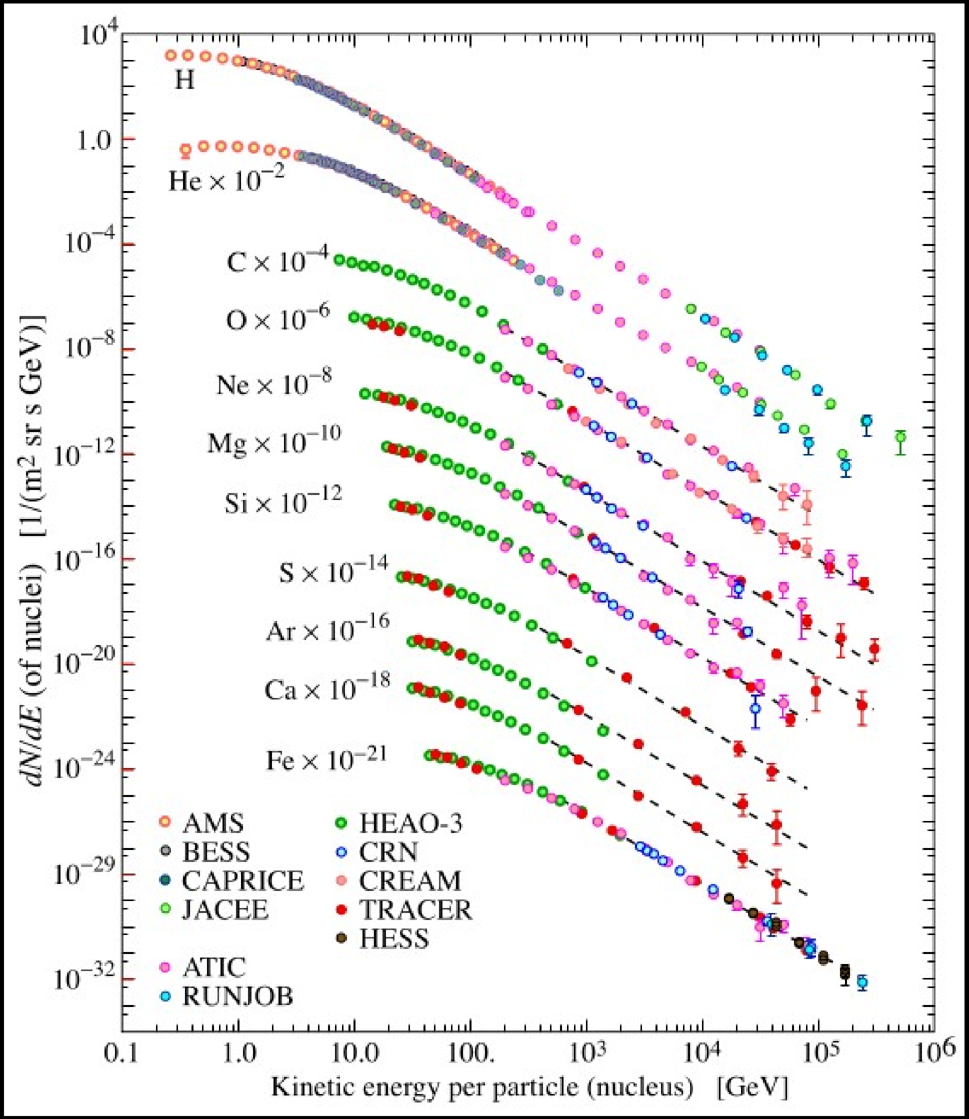
→ Source: nucleosynthesis + acceleration (injection/efficiency)

→ Transport: parameters required to provide the right abundances

Universal power-law = Fermi 1st order

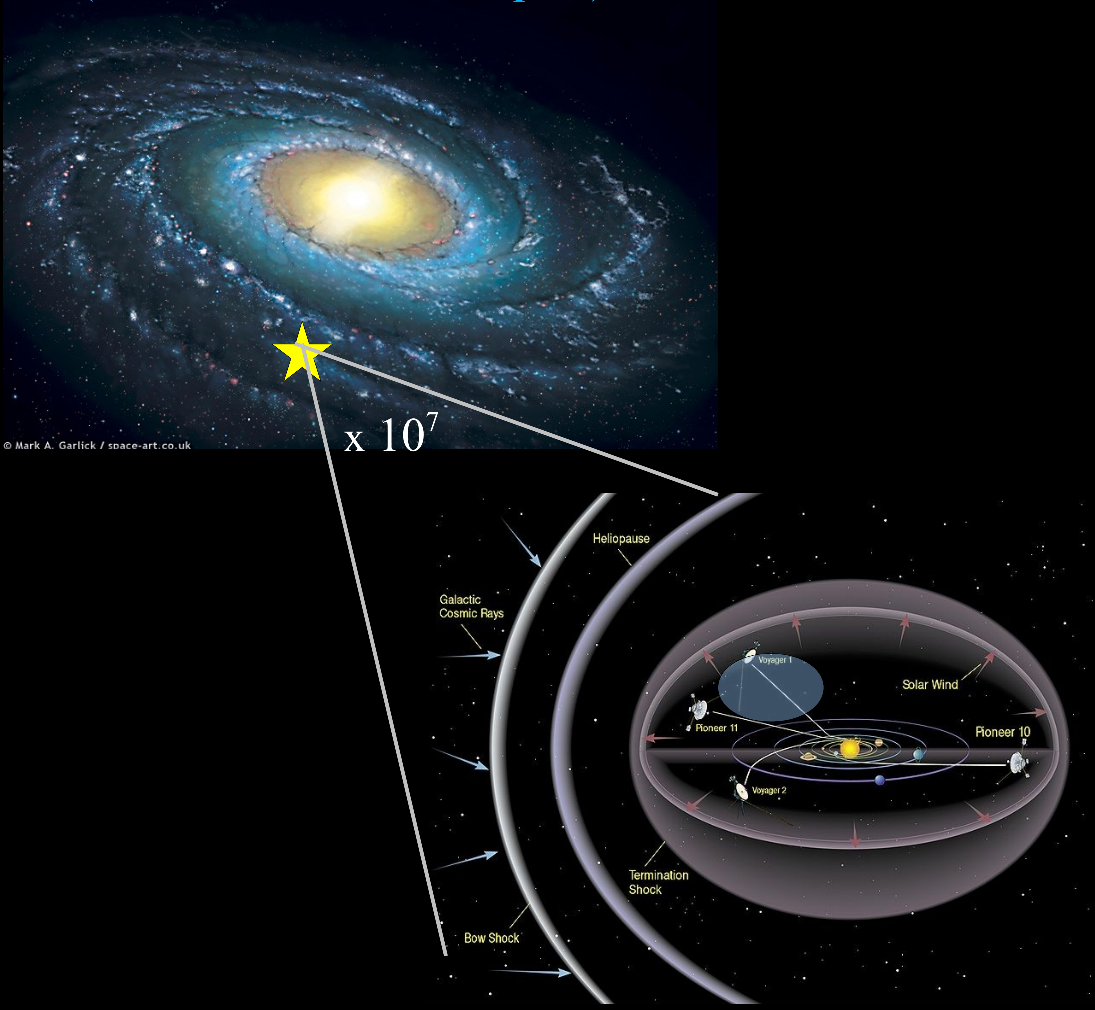


Beringer et al. (PDG), PR D86, 010001 (2012)

2. Spectrum: Solar Cosmic Rays

1. Cosmic rays in the Galaxy

→ Spectra and abundances (acceleration and transport)

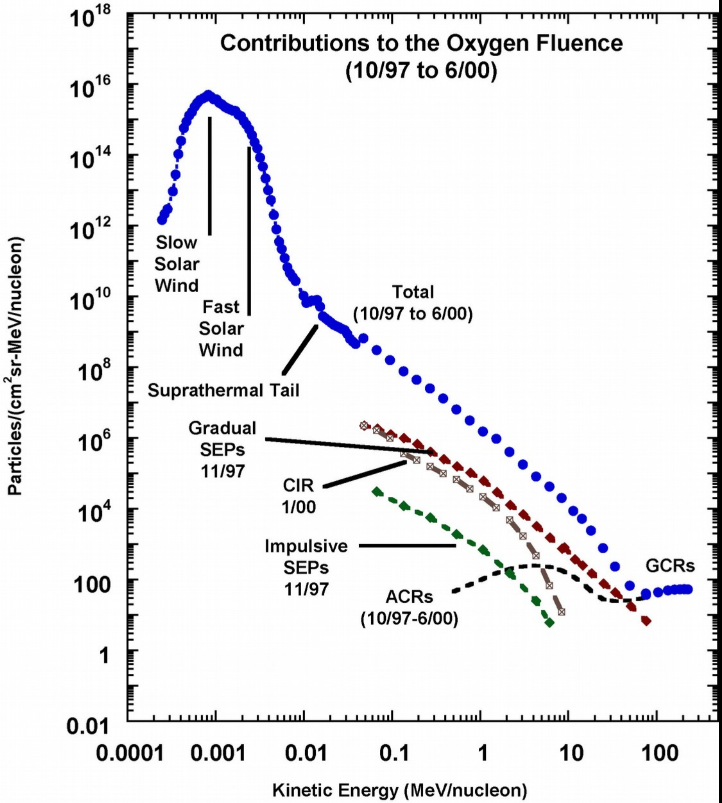


2. Transport in the Solar cavity

→ flux modulation < 10 GeV/n

→ time dependence

N.B.: the Solar cavity is the first place where acceleration and propagation theories are tested



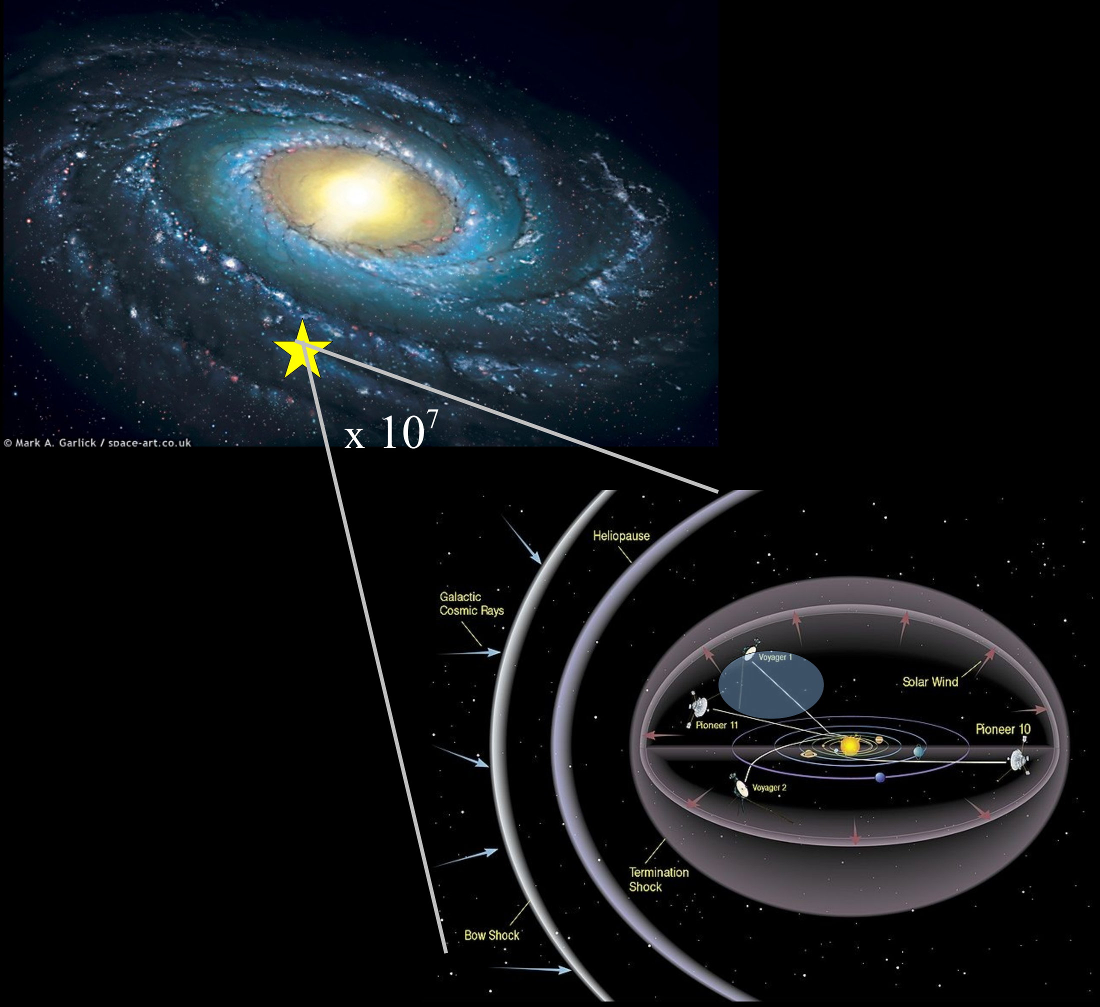
→ Plenty of different components at low energy (transient and continuous)

→ Indirect effect of Solar Cosmic rays: solar modulation

2. Charged GCRs: Solar modulation

1. Cosmic rays in the Galaxy

→ Spectra and abundances (acceleration and transport)



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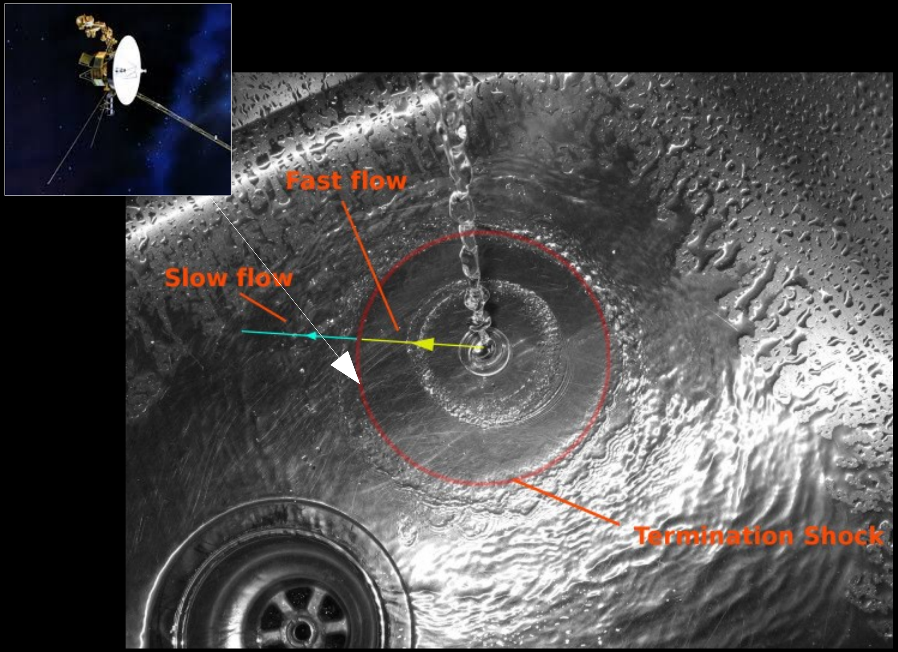
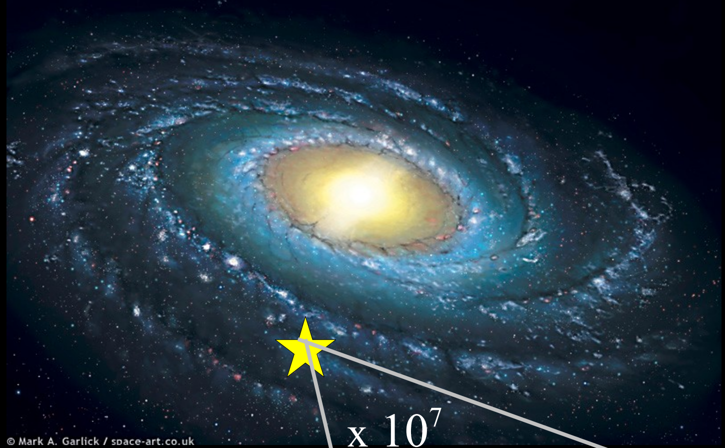


2. Charged GCRs: Solar modulation

1. Cosmic rays in the Galaxy

→ Spectra and abundances
(acceleration and transport)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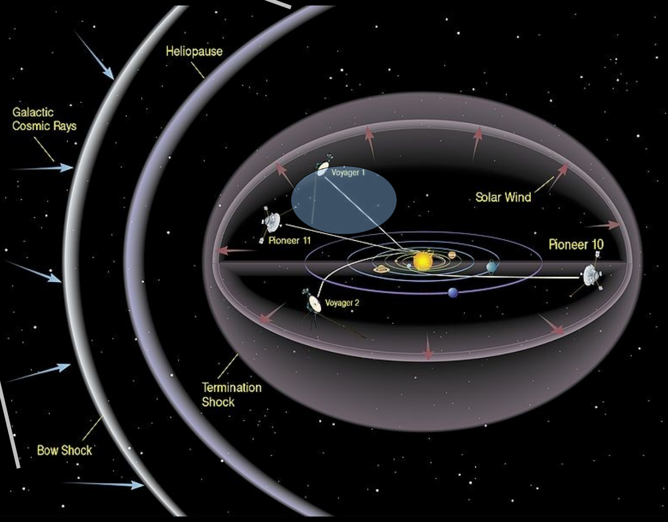
x 10^7



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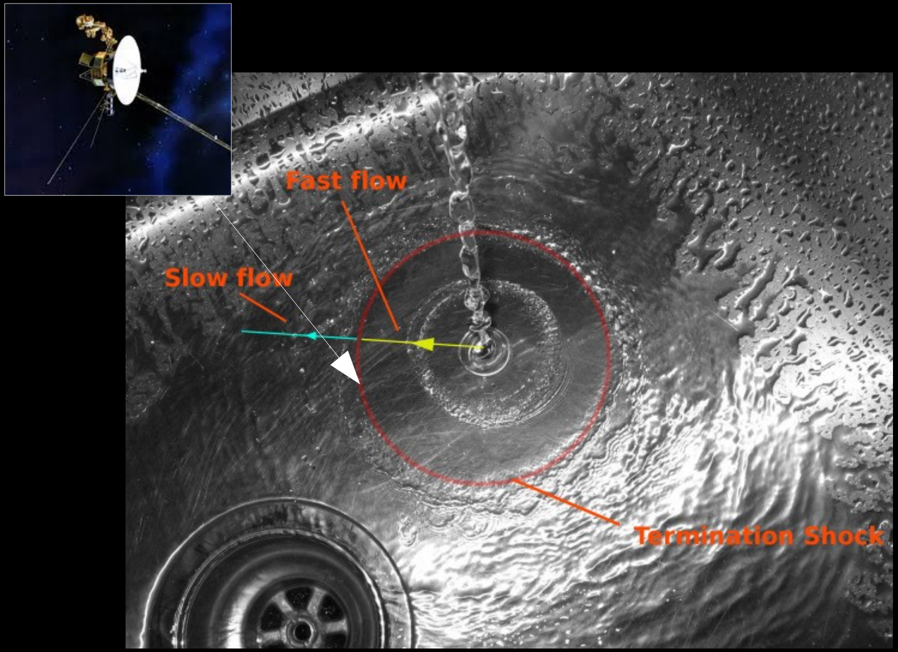
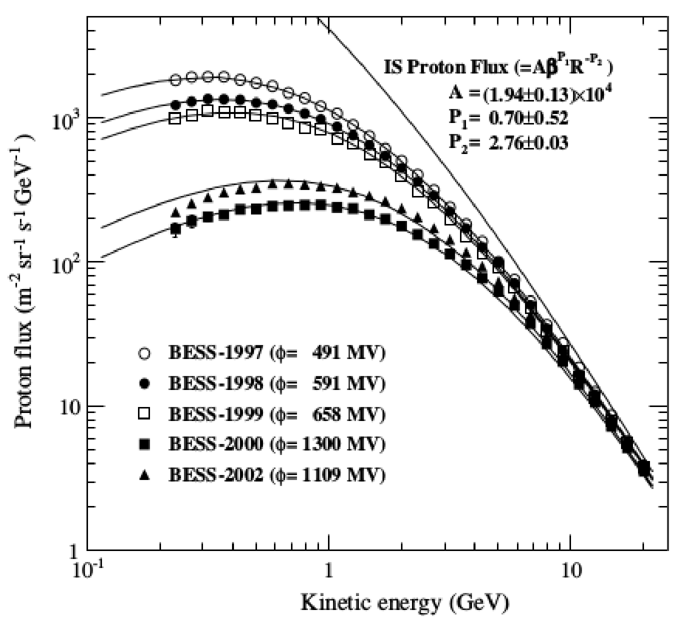


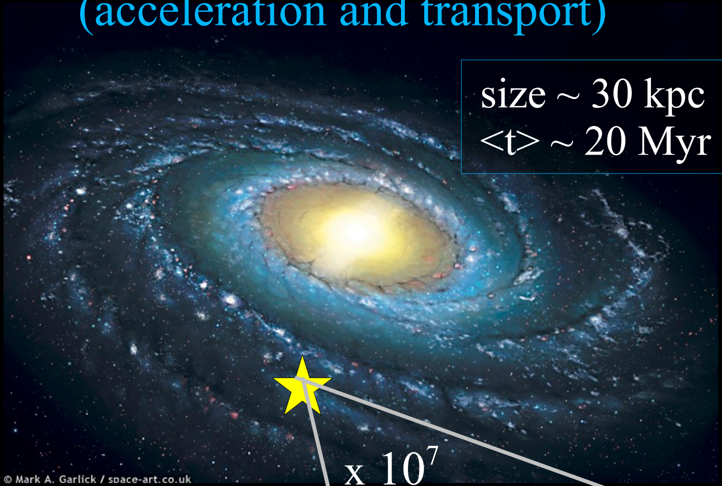


→ Solar modulation

2. GCRs: need high statistics experiments!

1. Cosmic rays in the Galaxy

→ Spectra and abundances (acceleration and transport)


size ~ 30 kpc
<t> ~ 20 Myr

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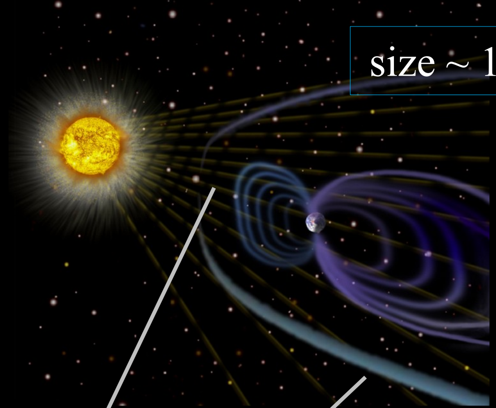
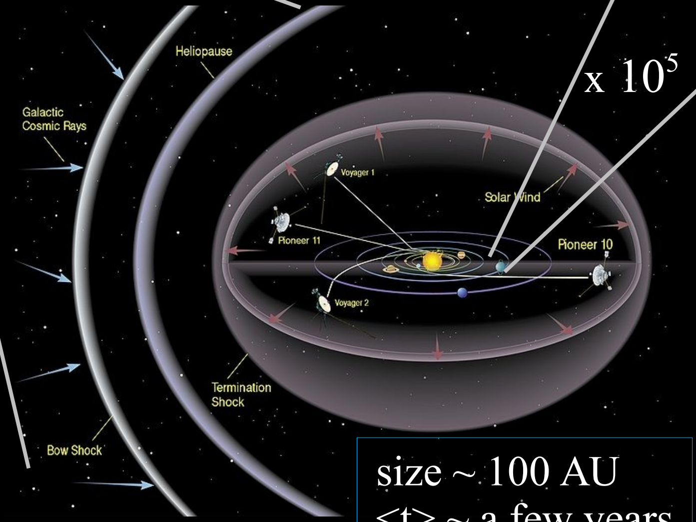
x 10^7

3. Earth magnetic shield

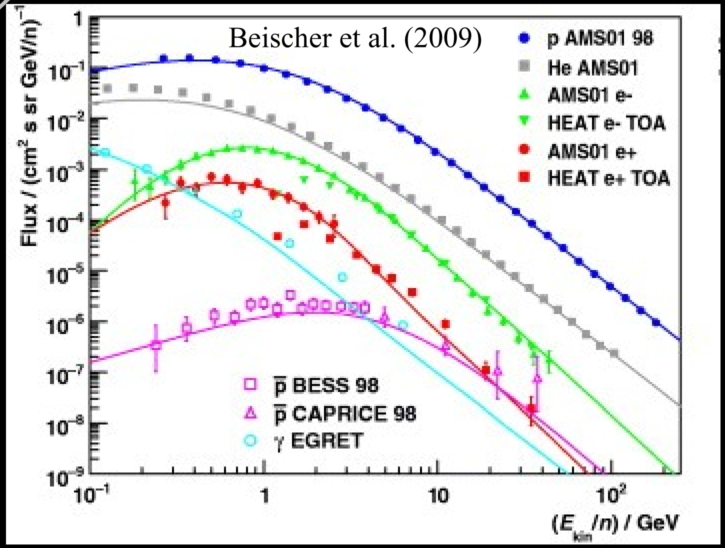
→ Cut-off rigidity for detectors


size ~ 10^4 km

x 10^5



size ~ 100 AU
<t> ~ a few years


Beischer et al. (2009)

2. Transport in the Solar cavity

→ flux modulation < 10 GeV/n
→ time dependence

→ Spectrum pbar, diffuse γ-rays, e^- and e^+
→ CR anisotropy $\delta<10^{-3}$ (≠ E and species)

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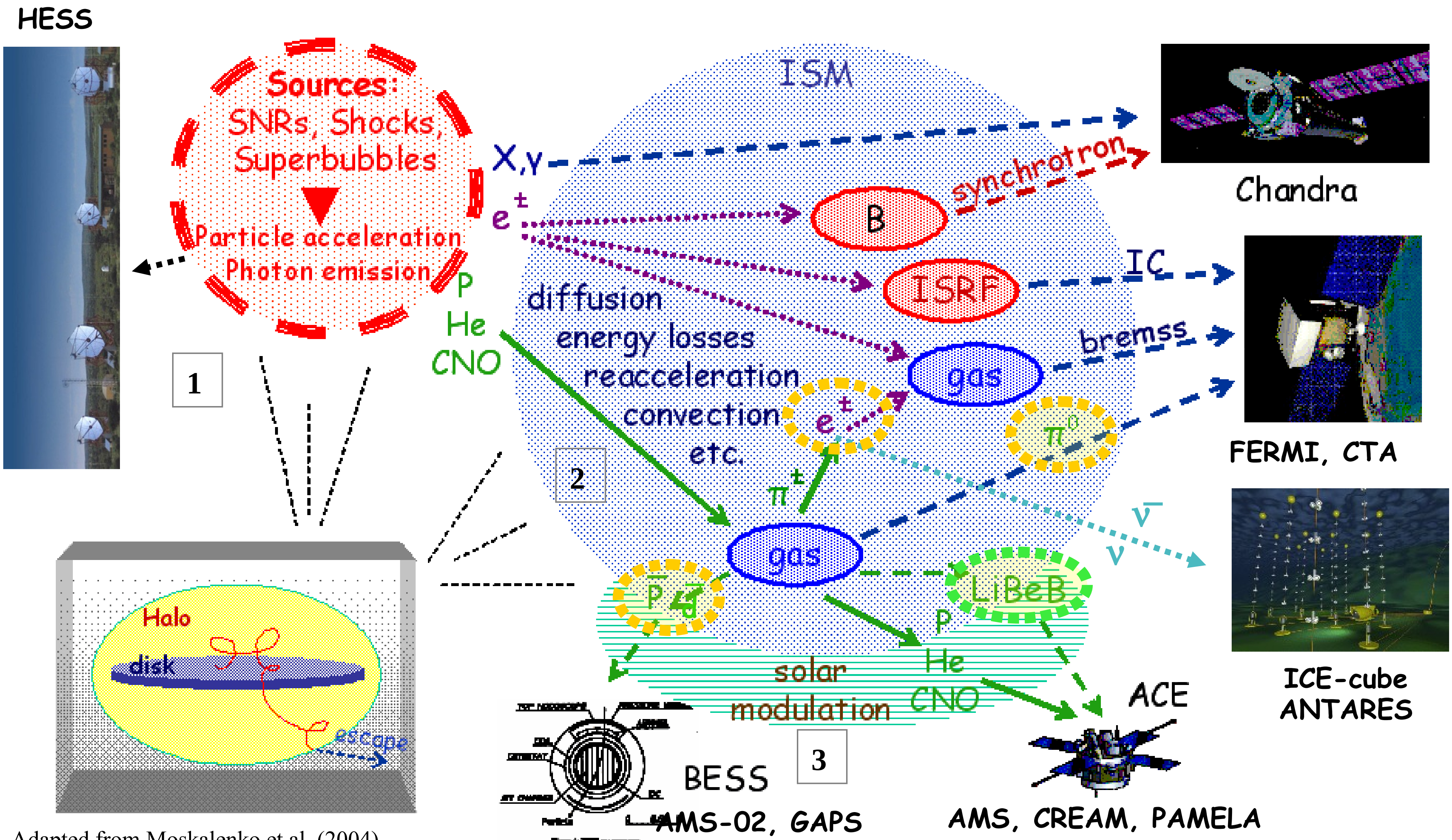
3. Primary and secondary "rare" emissions



Adapted from Moskalenko et al. (2004)

→ Search for DM where "standard" production is rare

→ Use LiBeB to calibrate transport

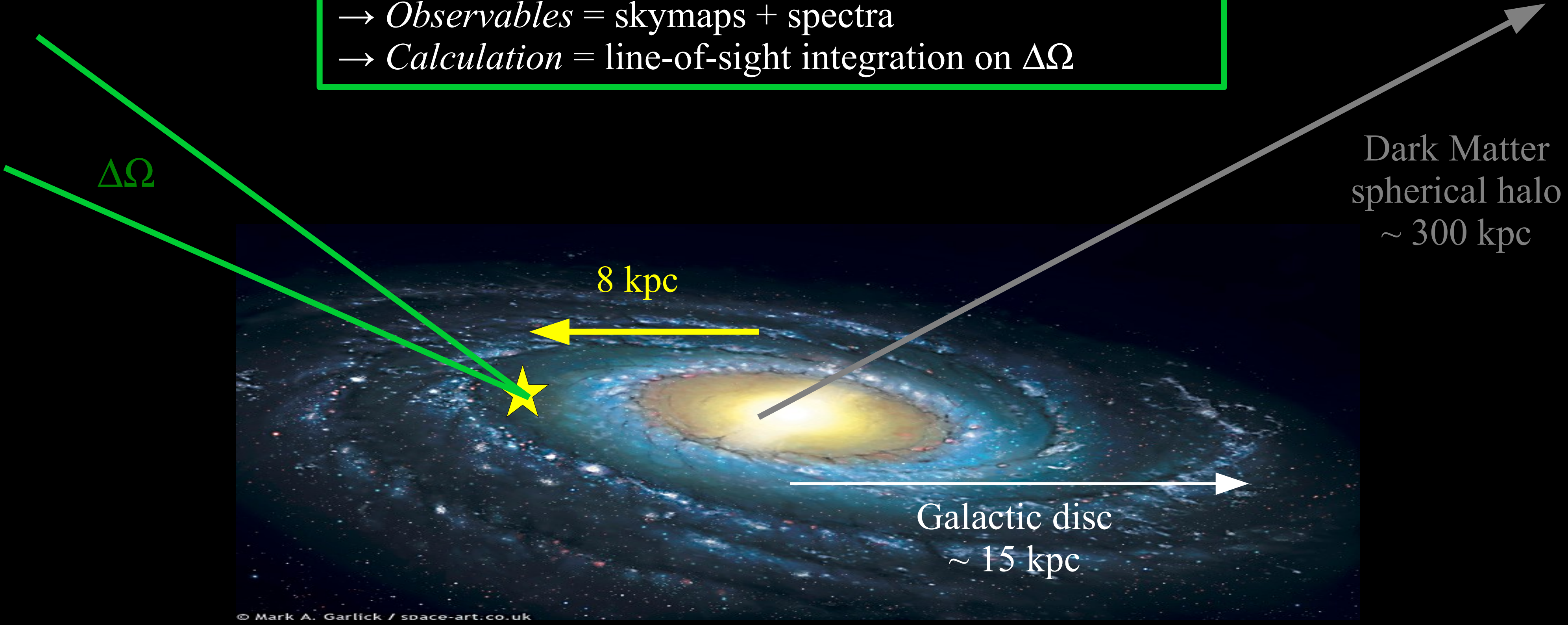
3. "Transport" for neutral particles

Neutral particles

- propagate in straight line
- absorption ~ negligible at GeV-TeV in the Galaxy

→ *Observables* = skymaps + spectra

→ *Calculation* = line-of-sight integration on $\Delta\Omega$



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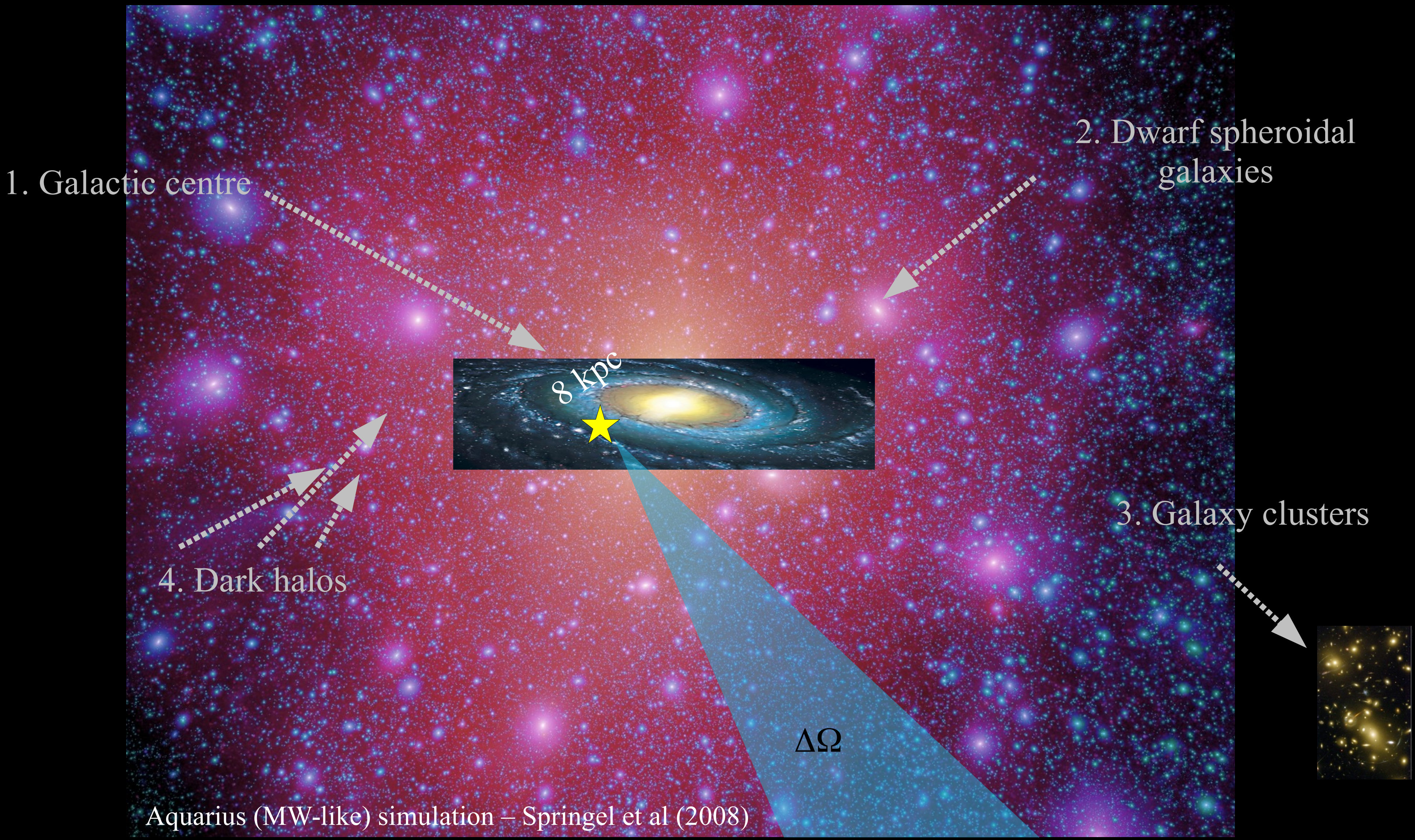
3. Best targets for indirect detection of γ and ν?

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



1. Galactic centre

2. Dwarf spheroidal galaxies

3. Galaxy clusters

4. Dark halos

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

→ Background = diffuse emissions, unresolved sources, etc.

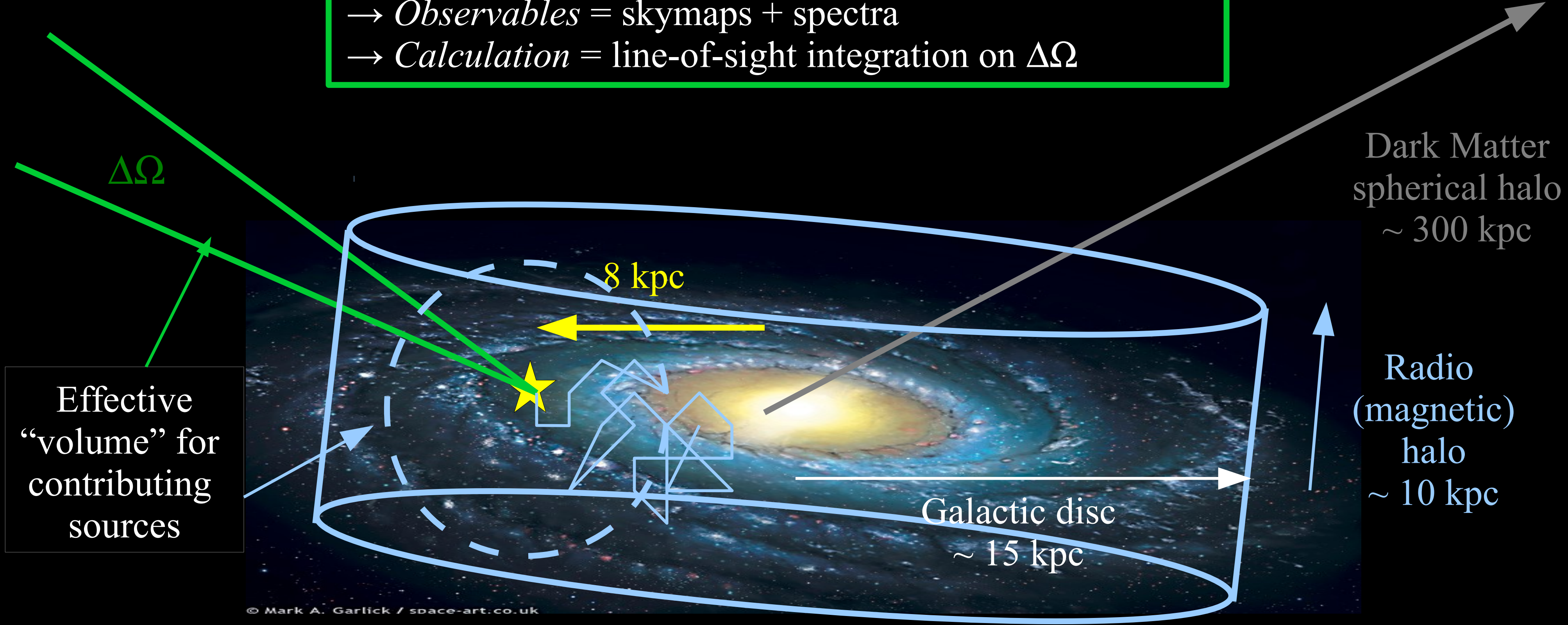
3. Transport for charged particles

Neutral particles

- propagate in straight line
- absorption ~ negligible at GeV-TeV in the Galaxy

→ *Observables* = skymaps + spectra

→ *Calculation* = line-of-sight integration on ΔΩ



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Charge particles

- diffusion in turbulent B
- continuous and catastrophic losses

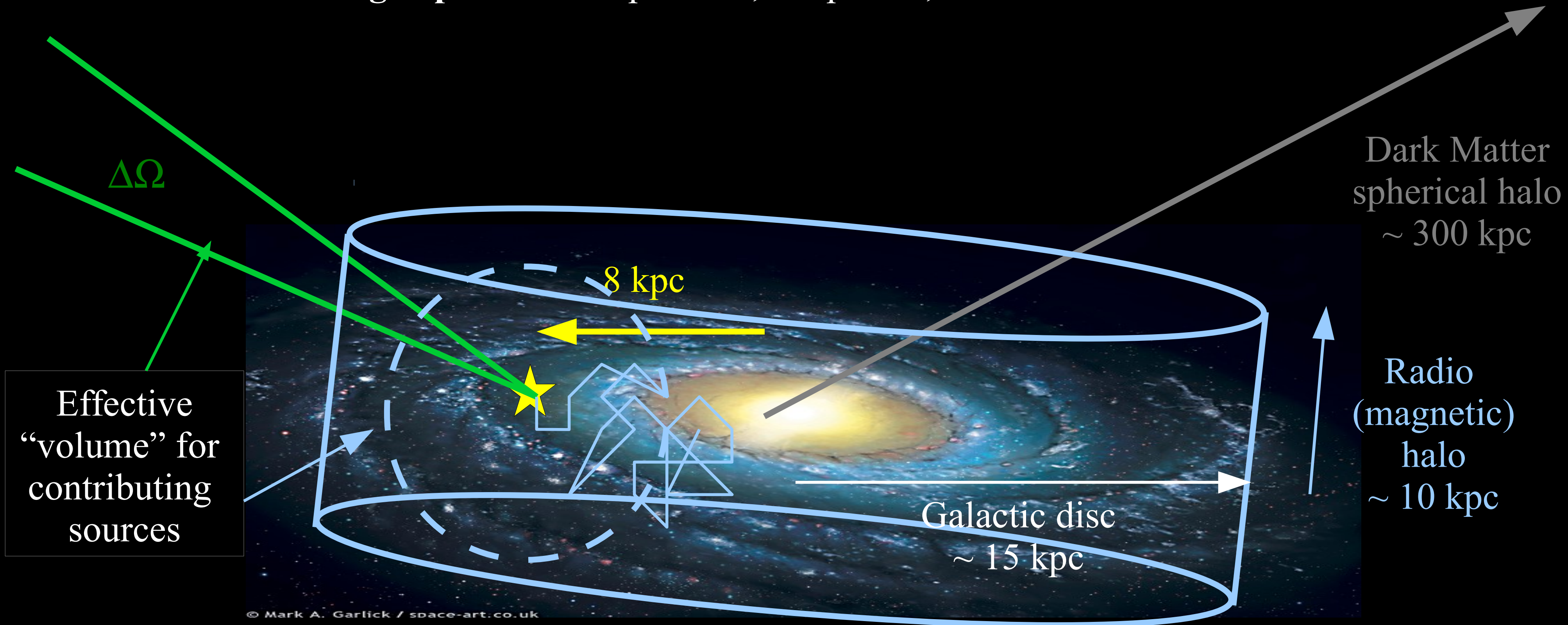
→ *Observables* = spectra (all species) + anisotropy

→ *Calculation* = diffusion equation (same for DM)

3. Clean and nice laboratory?

Indirect detection targets

γ → high signal (DM density)/background (sources/diffuse) regions
charged particles → positron, antiproton, antideuteron fluxes

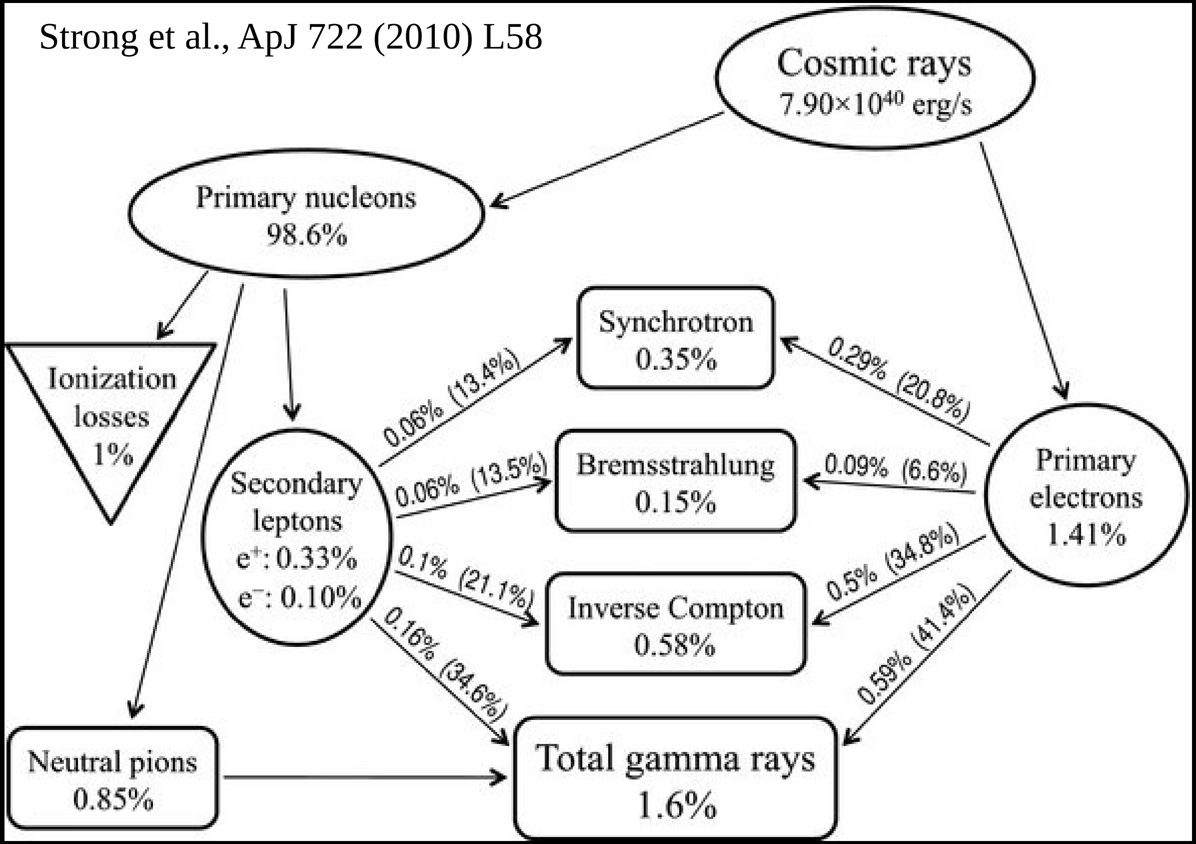


Do we understand the "standard" fluxes (everywhere and anytime)?

- Sources (SN, pulsars, ...)
- Nucleosynthesis (r and s-process for heavy nuclei)
- Acceleration mechanisms (injection, B amplification, E_{max})
- Propagation mechanisms (turbulence, spatial dependence, isotropy)
- Magneto-cosmico-gaseo properties of the Galaxy (MHD description)

3. Neat and nice electromagnetic calorimeter!

→ GALPROP run (exact numbers depend on the model used)



Strong et al., ApJ 722 (2010) L58

→ Very inefficient for protons (escape)
→ Very efficient for electrons (convert e^- to radiation)

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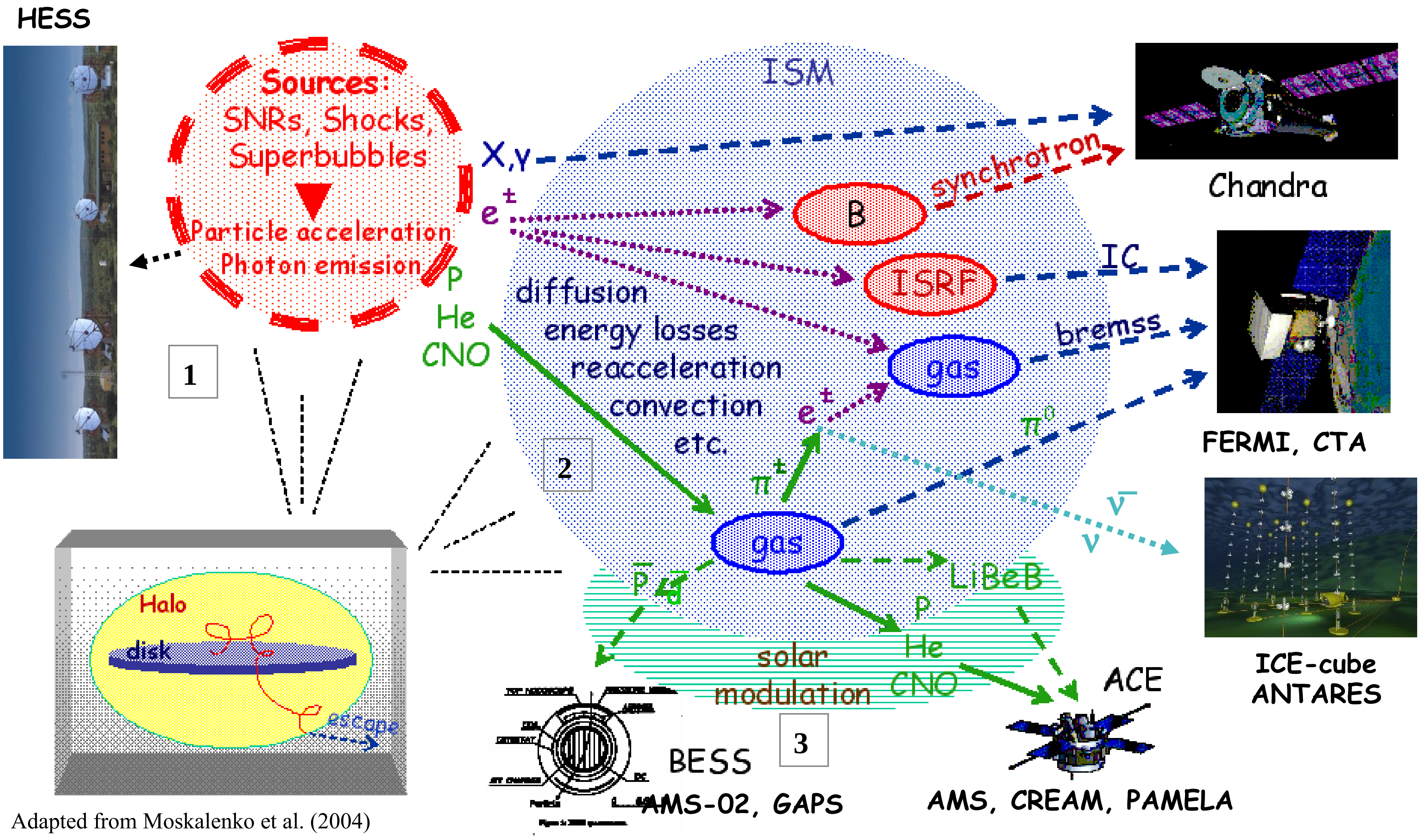
4. Acceleration, then transport (solar modulation later)



Adapted from Moskalenko et al. (2004)

1. Synthesis/acceleration
2. Transport
3. Solar modulation

4. Acceleration: diversity of sources!

Damiano Caprioli (ICRC 2015)

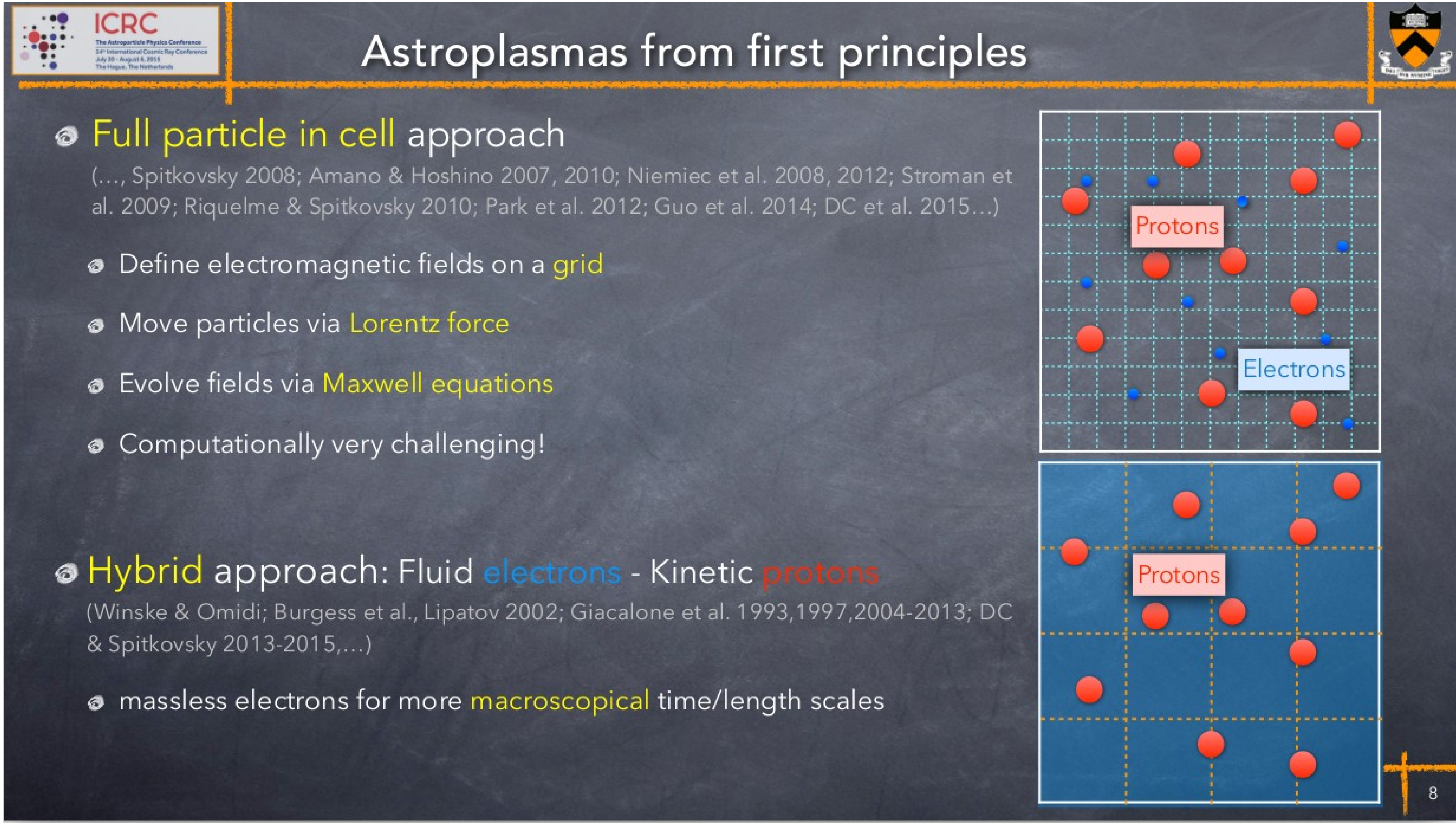
ICRC
The Astroparticle Physics Conference
34th International Cosmic Ray Conference
July 30 - August 6, 2015
The Hague, The Netherlands

Collisionless shocks

- Mediated by collective electromagnetic interactions
- Show prominent non-thermal activity
- Now studied in laboratory with laser experiments!

4. Acceleration: how to simulate it?

Damiano Caprioli (ICRC 2015)



Astroplasmas from first principles

- Full particle in cell approach

  (…, Spitkovsky 2008; Amano & Hoshino 2007, 2010; Niemiec et al. 2008, 2012; Stroman et al. 2009; Riquelme & Spitkovsky 2010; Park et al. 2012; Guo et al. 2014; DC et al. 2015…)

  - Define electromagnetic fields on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally very challenging!

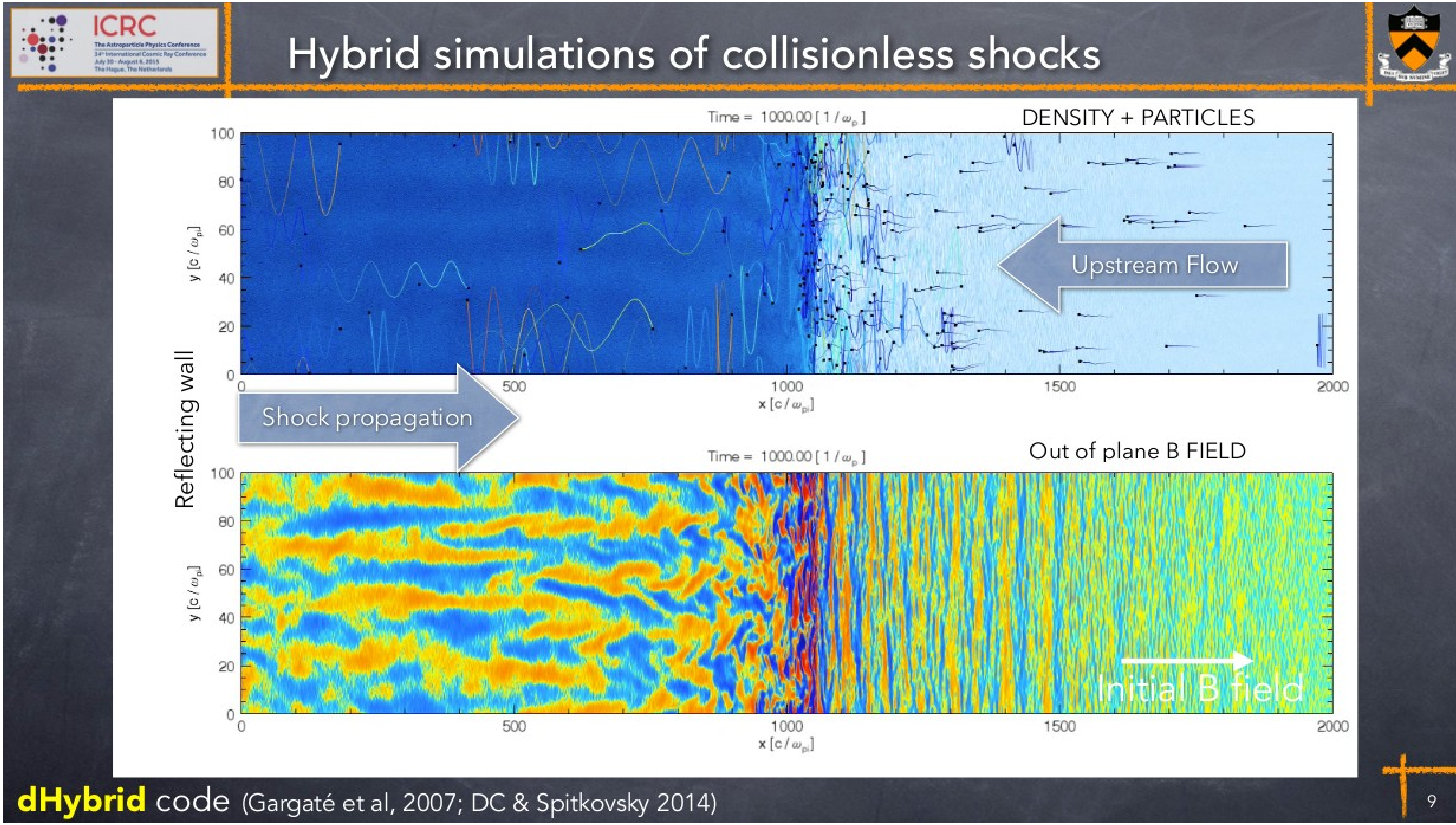
- Hybrid approach: Fluid electrons - Kinetic protons

  (Winske & Omidi; Burgess et al., Lipatov 2002; Giacalone et al. 1993,1997,2004-2013; DC & Spitkovsky 2013-2015,…)

  - massless electrons for more macroscopical time/length scales

4. Acceleration: blockbuster(s)

Damiano Caprioli (ICRC 2015)



Hybrid simulations of collisionless shocks

dHybrid code (Gargaté et al, 2007; DC & Spitkovsky 2014)

→ **So far, in most (if not all) propagation models:**

- **Power-law or broken power-law (with cut-off at HE)**
- **No time-dependence in fluxes (except for HE)**

4. From microphysics to diffusion

[Adapted from R. Tautz (CRISM 2014)]

- **Physics problem:** motion in a turbulent field
- **Ansatz:** diffusion equation $\frac{\partial f}{\partial t} - S = \nabla \cdot \left(\kappa_{nj} \cdot \nabla f - \boldsymbol{v}\, f \right) + \frac{\partial}{\partial \boldsymbol{p}} \left(p^2 D_p \frac{\partial}{\partial \boldsymbol{p}} \frac{f}{p^2} - \dot{\boldsymbol{p}}\, f \right) + \ldots$

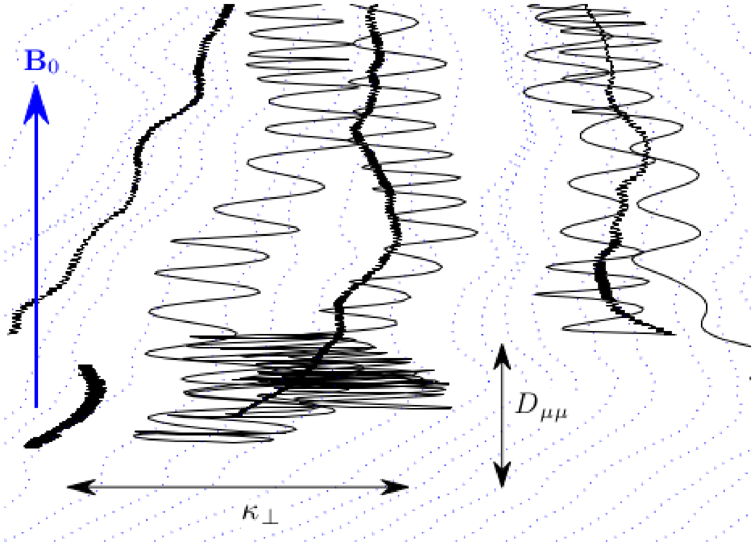
$$\boldsymbol{\kappa} = \begin{pmatrix} \kappa_\perp & \kappa_\mathrm{A} & 0 \\ -\kappa_\mathrm{A} & \kappa_\perp & 0 \\ 0 & 0 & \kappa_{||} \end{pmatrix}$$

$\kappa_{||}$: Diffusion *along*[2] ***B***

$\kappa_\perp$: Diffusion *across*[3] ***B***

κ_A: Drift effects[4]

<u>Reality</u>: resonant wave-particle interaction with stochastic motion



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$\kappa_\perp$: Diffusion *across*[3] ***B***

κ_A: Drift effects[4]

Analytical calculation

- Mean free path $\lambda_\parallel \propto \kappa_\parallel \propto \int_{-1}^{1} \mathrm{d}\mu \, \frac{(1-\mu^2)^2}{D_{\mu\mu}(\mu)}$

  Pitch angle $\mu = \cos(\widehat{\boldsymbol{v}, \boldsymbol{B}_0})$

- Fokker-Planck coefficient $D_{\mu\mu} = \int_0^\infty \mathrm{d}t \, \langle \dot{\mu}(t)\, \dot{\mu}^\star(0) \rangle$

  Taylor-Green-Kubo formula

- Equation of motion (Lorentz) $\dot{\mu} = \frac{\partial}{\partial t}\left(\frac{v_\parallel}{v}\right) \overset{\text{static}}{=} \frac{\dot{v}_\parallel}{v}$

  Unknown $v_{x,y}$, *unknown position in* $\delta B_{x,y}$

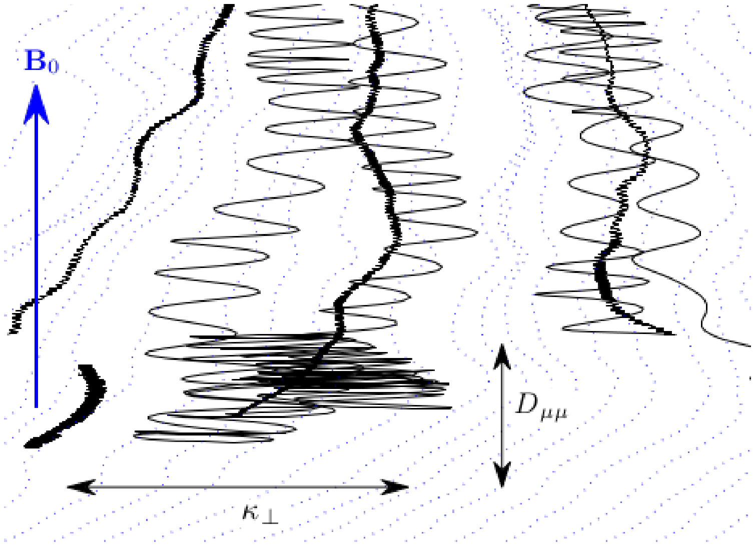
$$= \frac{\Omega}{v}\left(v_x \frac{\delta B_y}{B_0} - v_y \frac{\delta B_x}{B_0} \right)$$

→ Can only be solved in ideal situations

- Quasi-Linear Theory ($\delta B \ll B$): QLT
- 2nd order QLT: SOQLT
- Non-linear guiding centre: NLGC

Numerical simulations

Reality: resonant wave-particle interaction with stochastic motion



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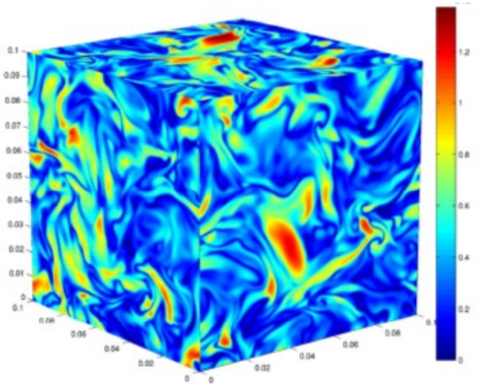
- Quasi-Linear Theory ($\delta B \ll B$): QLT
- 2nd order QLT: SOQLT
- Non-linear guiding centre: NLGC

Numerical simulations

Reality: resonant wave-particle interaction with stochastic motion... turbulence model requires:

- Energy spectrum (diff.eq. for wave!): $W \propto k^{-s}$
- Geometry
- Dynamical behaviour
  - Instabilities
  - Damped waved
  - Intermittency



Diffusion in MHD turbulence

4. A simple (and mostly) successful model

$$\overbrace{\frac{\partial N^j}{\partial t}}^{\text{Variation}} + \overbrace{\left(-\vec{\nabla}\cdot\left(K(E,\vec{r})\vec{\nabla}\right)+\vec{\nabla}\cdot\vec{V}(\vec{r})\right)}^{\text{Spatial transport: diffusion+convection}} N^j + \overbrace{\left(\Gamma_{\rm rad}+\Gamma_{\rm inel}\right)}^{\text{Catastrophic losses}} N^j + \overbrace{\frac{\partial}{\partial E}\left(b^j N^j - c^j \frac{\partial N^j}{\partial E}\right)}^{\text{E gains/losses}} = \overbrace{Q^j(E,\vec{r}) \quad + \sum_{m_i>m_j} \Gamma^{i\to j} N^i}^{\text{Source term: prim.+sec.}}$$

4. Simple geometry and ingredients: “base” model

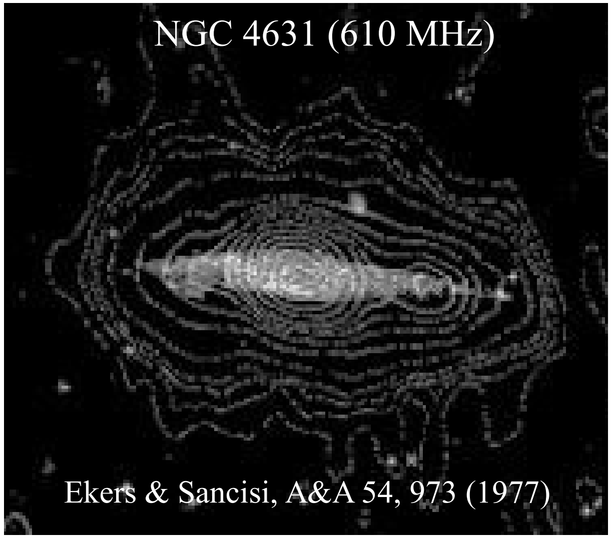
$$\overbrace{\frac{\partial N^j}{\partial t}}^{\text{Variation}} + \overbrace{\left(-\vec{\nabla}\cdot\left(K(E,\vec{r})\vec{\nabla}\right)+\vec{\nabla}\cdot\vec{V}(\vec{r})\right)}^{\text{Spatial transport: diffusion+convection}} N^j + \overbrace{\left(\Gamma_{\rm rad}+\Gamma_{\rm inel}\right)}^{\text{Catastrophic losses}} N^j + \overbrace{\frac{\partial}{\partial E}\left(b^j N^j - c^j\frac{\partial N^j}{\partial E}\right)}^{\text{E gains/losses}} = \overbrace{Q^j(E,\vec{r}) \quad + \sum_{m_i>m_j}\Gamma^{i\to j}N^i}^{\text{Source term: prim.+sec.}}$$

Magnetic fields

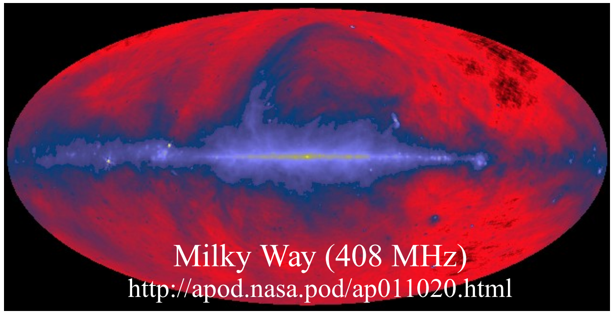
- Everywhere: planetary → galaxy clusters
- Typical amplitudes: ~ μG – nT
- Two components (comparable strength):
  - ✓ Regular B0 (large scale)
  - ✓ Turbulent δB (small scale), i.e. <δB>=0

Diffusion coefficients

Diffusion+ confinement = geometry


NGC 4631 (610 MHz)

Ekers & Sancisi, A&A 54, 973 (1977)


Milky Way (408 MHz)

http://apod.nasa.pod/ap011020.html

Usual simplifying assumptions

- Isotropic (no preferred diffusion direction)
- Standard (no sub-diffusion, Levy flights...)
- Spatial-independent diffusion coefficient
- Wind: ⊥ to galactic plane (cst or linear)
- “Minimal” reacceleration (VA mediated)

$\langle(\Delta x)^2\rangle \propto t^{\alpha+1}$

with α=0

→ D = β D0 R$^\delta$

→ DEE µ (pVA)^2/D

“Minimal” model
5 free parameters
D0, δ, VA, L, Vc

Geometry = camembert box

→ Diffusive halo half-height ~ L

4. Techniques/codes to solve the transport equation

$$\overbrace{\frac{\partial N^j}{\partial t}}^{\text{Variation}} + \overbrace{\left(-\vec{\nabla}\cdot\left(D(E,\vec{r})\vec{\nabla}\right) + \vec{\nabla}\cdot\vec{V}_c(\vec{r})\right)}^{\text{Spatial transport: diffusion+convection}} N^j + \overbrace{\frac{\partial}{\partial E}\left(b^j N^j - D_{EE}\frac{\partial N^j}{\partial E}\right)}^{\text{E losses and gains}} + \overbrace{\left(\Gamma_{\rm rad} + \Gamma_{\rm inel}\right)}^{\text{Catastrophic losses}} N^j = \overbrace{Q^j(t,E,\vec{r})}^{\text{Source}}$$

	(Semi-)analytical	*Numerical*	*Monte Carlo*
Approach	Simplify the problem: • keep dominant effects only • simplify the geometry	Finite difference scheme: • discretise the equation • scheme (e.g., Crank-Nicholson)	Follow each particle: • N particles at t=0 • evolve each of them to t+1 $1\text{D} : \Delta z = \pm\sqrt{2D\Delta t}$
Tools	• Green functions, • Fourier/Bessel expansion • Differential equations	• Numerical recipes/solvers (NAG, GSL libraries)	• Stochastic differential equations (Markov process) + MPI
Pros	• Useful to understand the physics • Fast (MCMC analyses "simple")	• Very simple algebra • Any new input easily included	• Statistical properties (along path) • No grid but t step (for/back)-ward
cons	• Only solve approximate model • New solution for new problem	• Slower, memory for high res. • "Less" insight in the physics	• Even slower (+ statistical errors) • Massively parallel problem
Codes and/or references	Webber (1970+) Ptuskin (1980+) Schlickeiser (1990+) **USINE (2000+)**	GALPROP (Strong et al. 1998) DRAGON (Evoli et al. 2008) PICARD (Kissmann et al., 2013)	Webber & Rockstroh (1997) Farahat et al. (2008) Kopp, Büshing et al. (2012)

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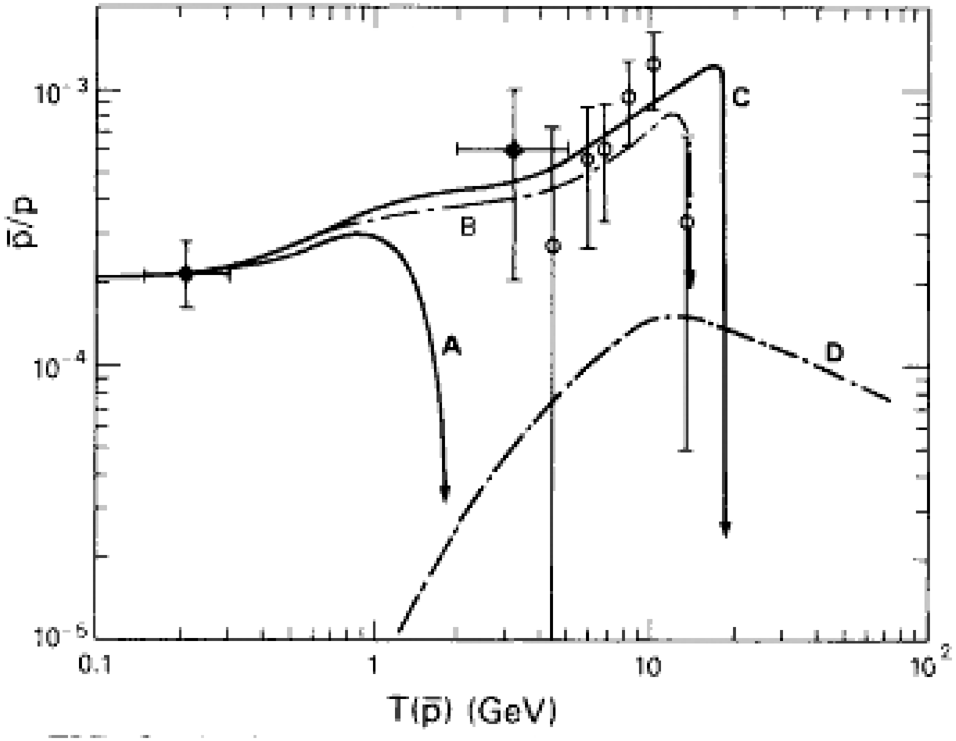
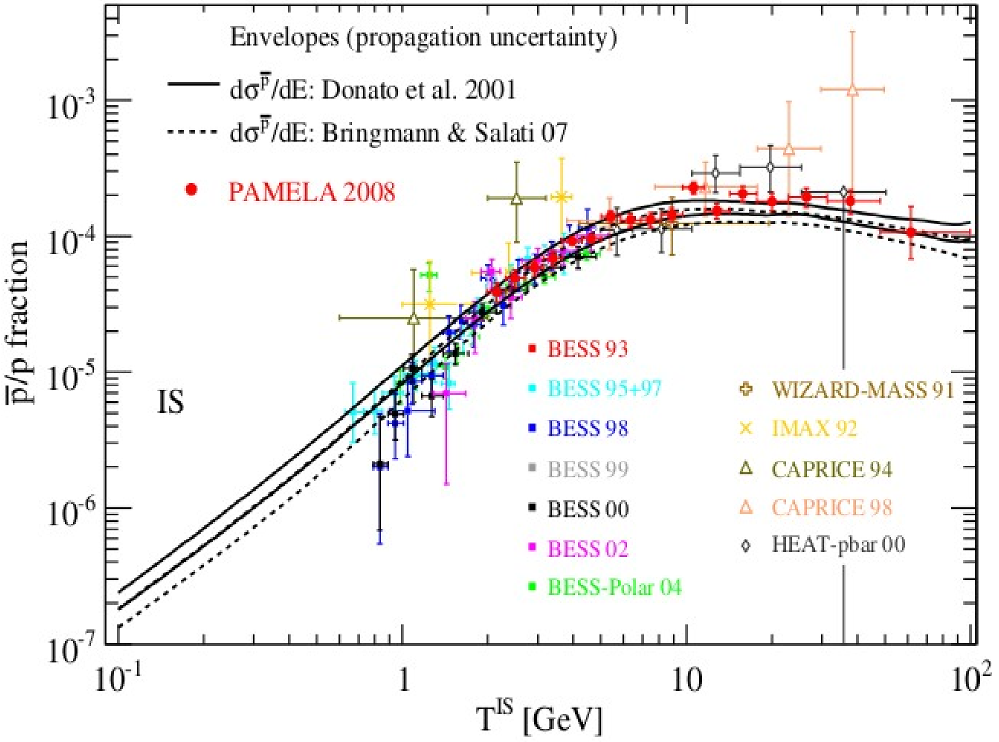
7. γ-rays: fun facts about diffuse emissions

5. Antiprotons: 1979 → 2010



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



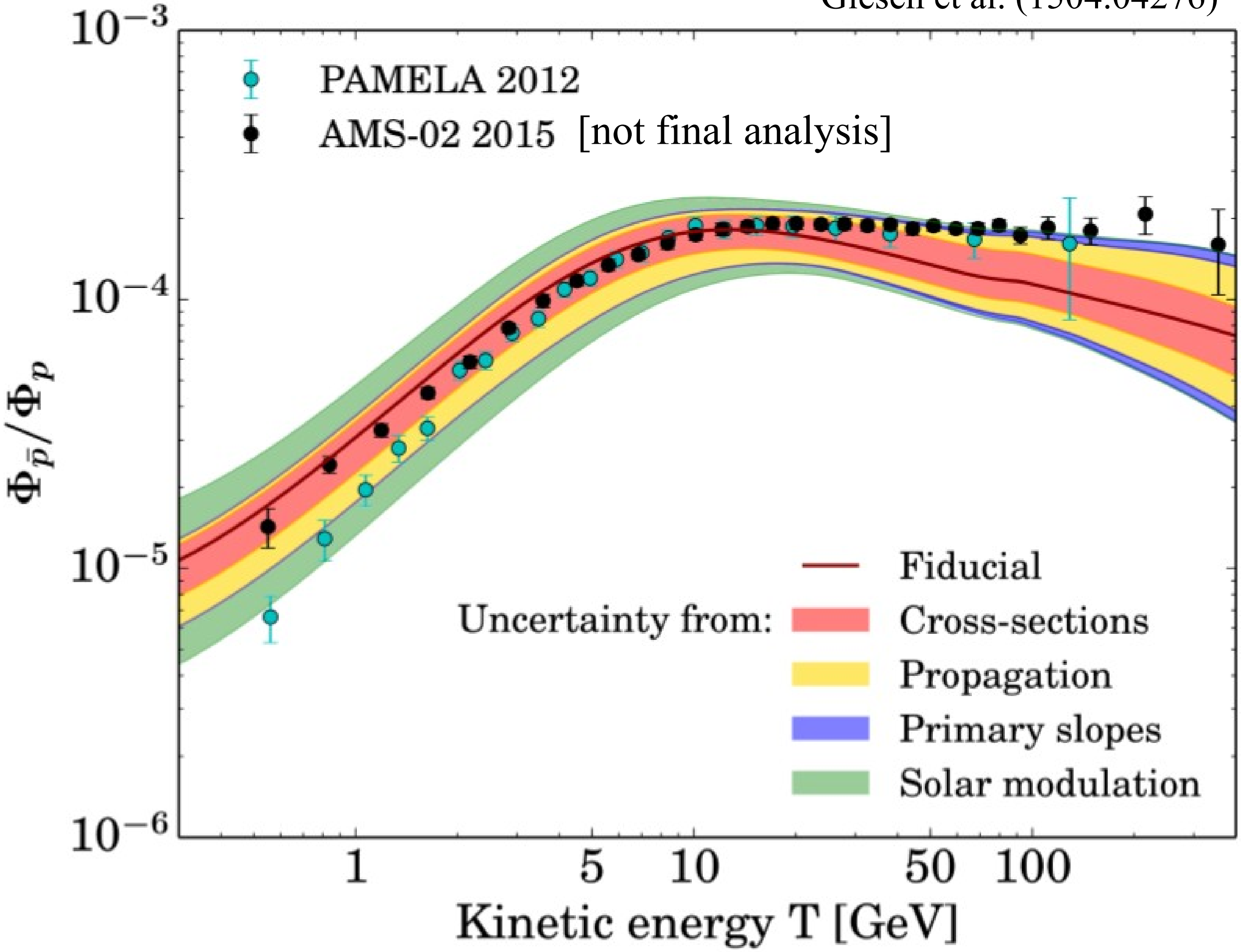
Donato et al., PRL **102**, 071301 (2009)

→ 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

5. Antiprotons: today's status

Giesen et al. (1504.04276)



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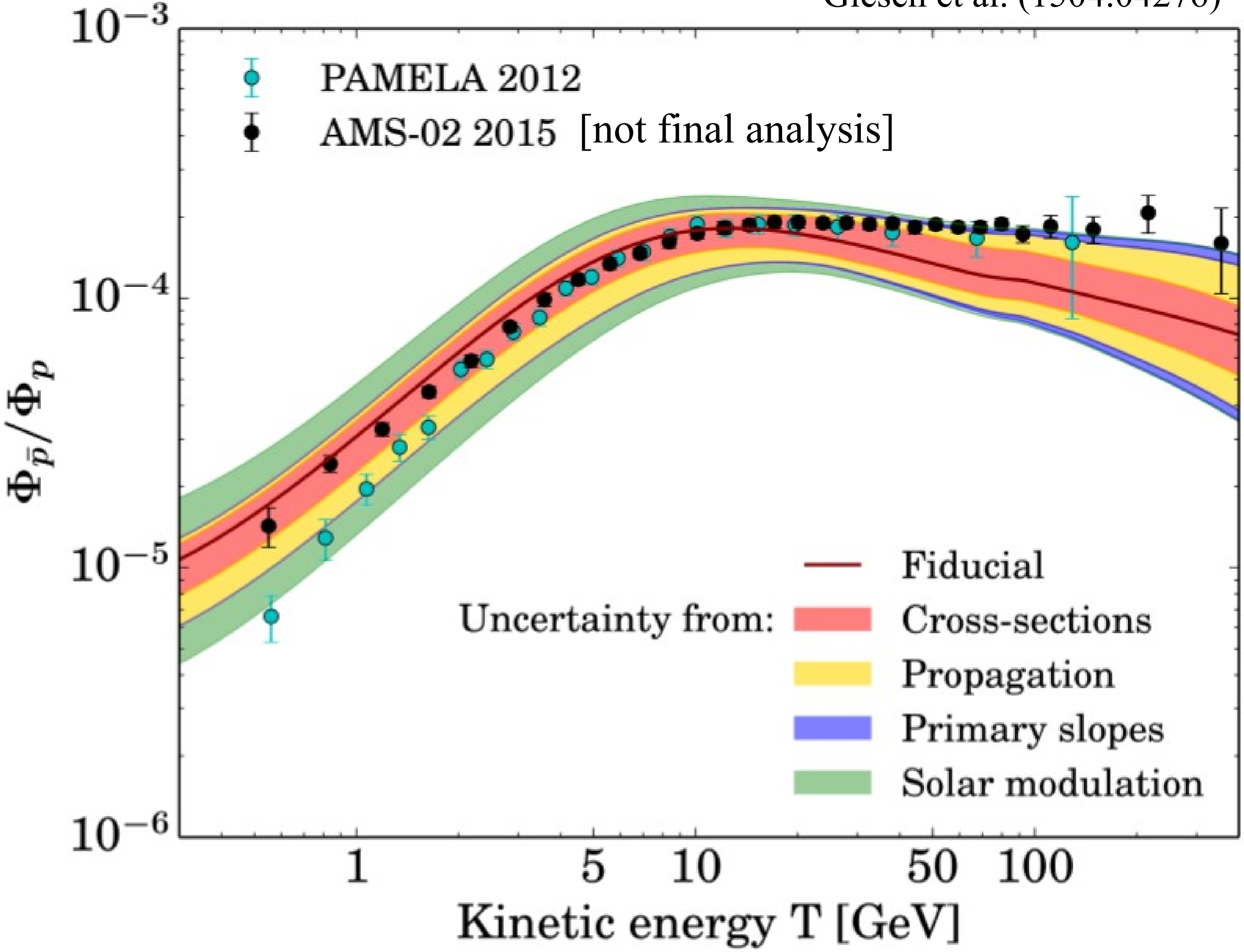

$$Q^{\rm sec}(T_{\bar{p}}) = 2 \sum_{\rm i=CRs}^{\rm p,He,CNO} \sum_{\rm j=ISM}^{\rm H,He,CNO} 4\pi n_j \int_{\rm m_{thresh}}^{\infty} \frac{d\sigma^{\rm i+j}}{dT_{\bar{p}}} \times (T_{\bar{p}}, T_i)\Phi_i(T_i)dT_i,$$

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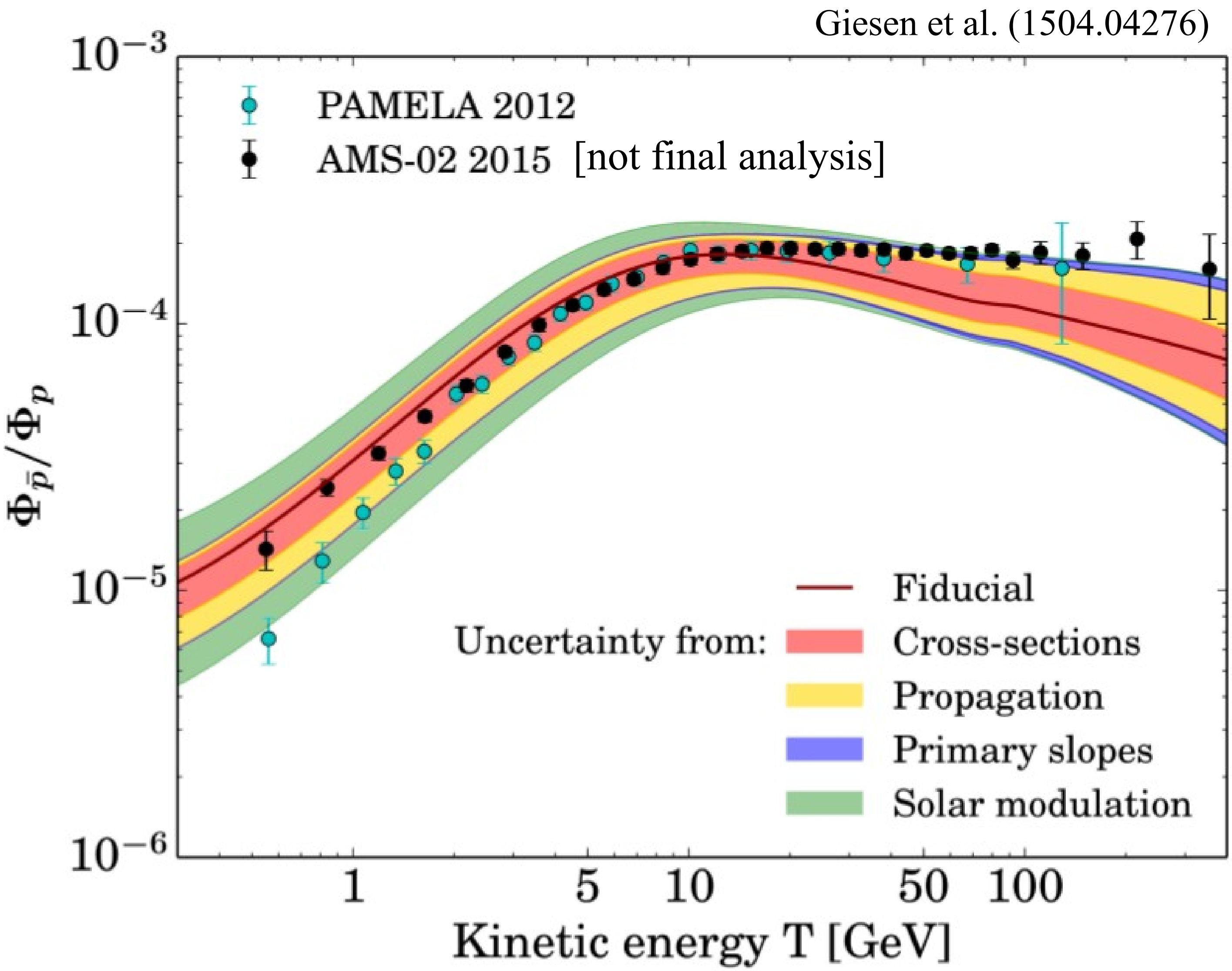
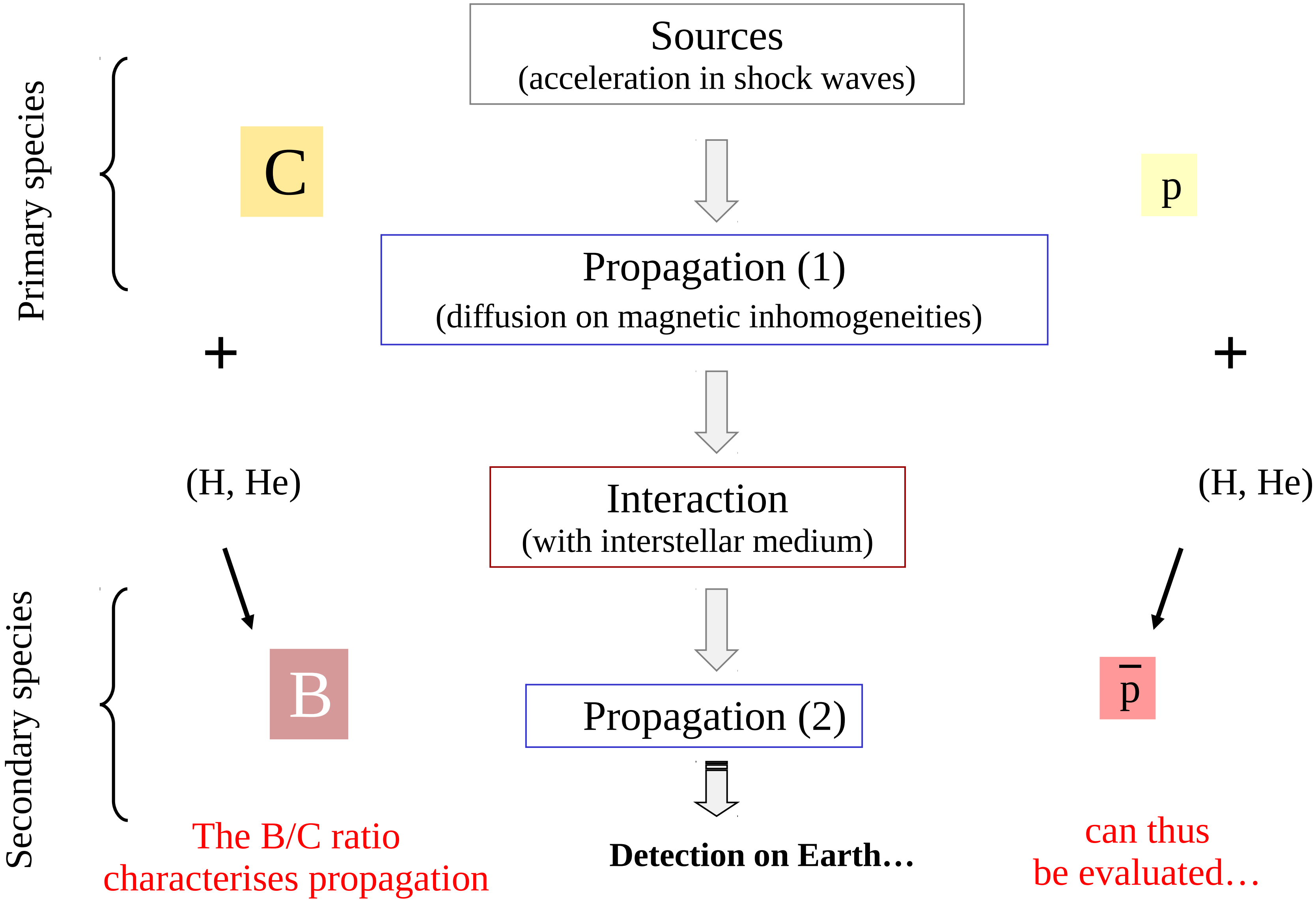


→ Primary source (subdominant): He AMS-02 flux published soon + HE measurements
→ Cross-sections (dominant): need new measurements (NA49/61, LHC-b…)

https://agenda.infn.it/contributionListDisplay.py?confId=9748

5. Propagation uncertainty



Sources
(acceleration in shock waves)

Propagation (1)
(diffusion on magnetic inhomogeneities)

Interaction
(with interstellar medium)

Propagation (2)

Detection on Earth…

Primary species

C

+

(H, He)

Secondary species

B

The B/C ratio
characterises propagation

p

+

(H, He)

$\bar{p}$

can thus
be evaluated…

→ Same propagation history
(can also use ^{2}H, ^{3}He, Li, Be, Sub-Fe...)

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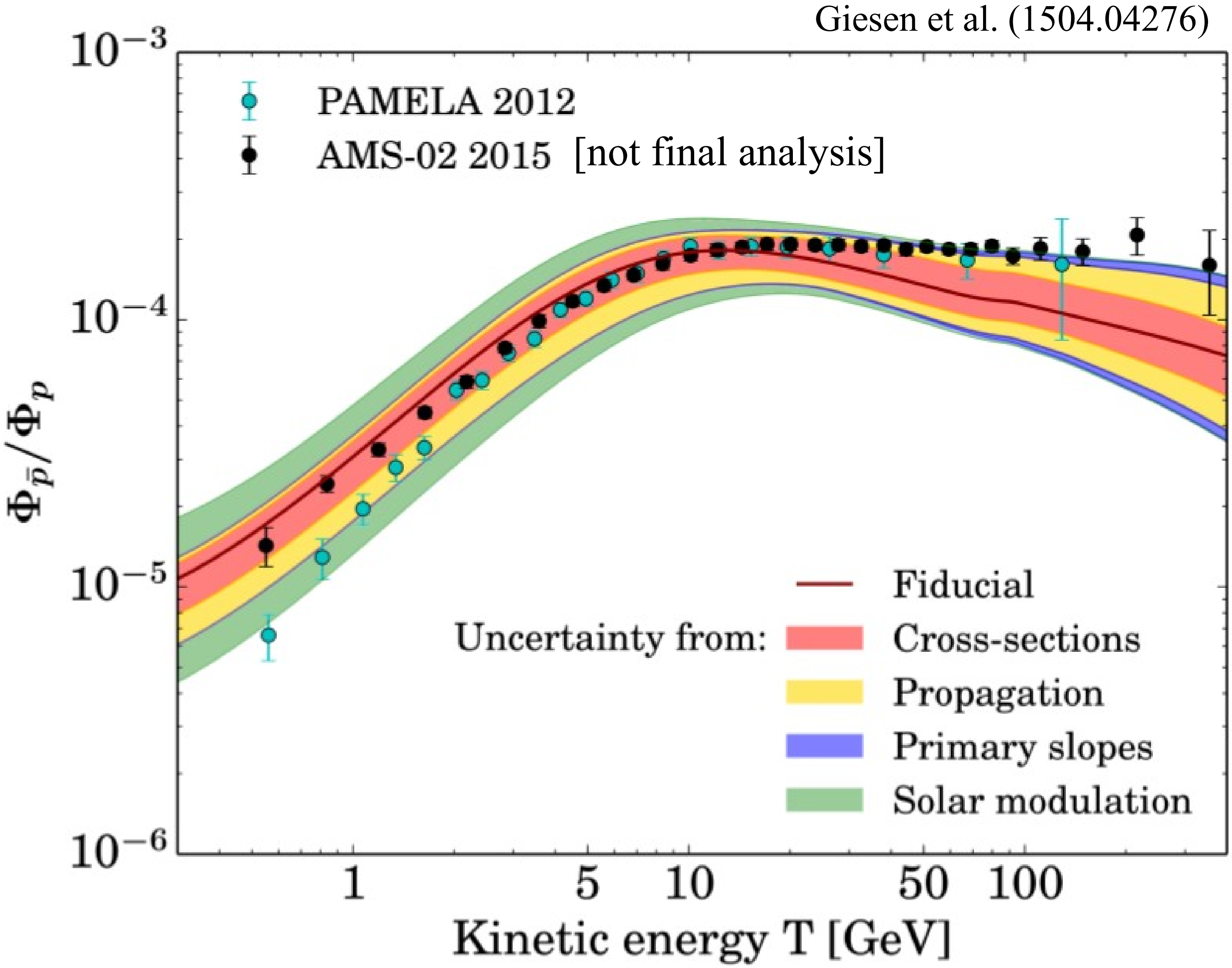

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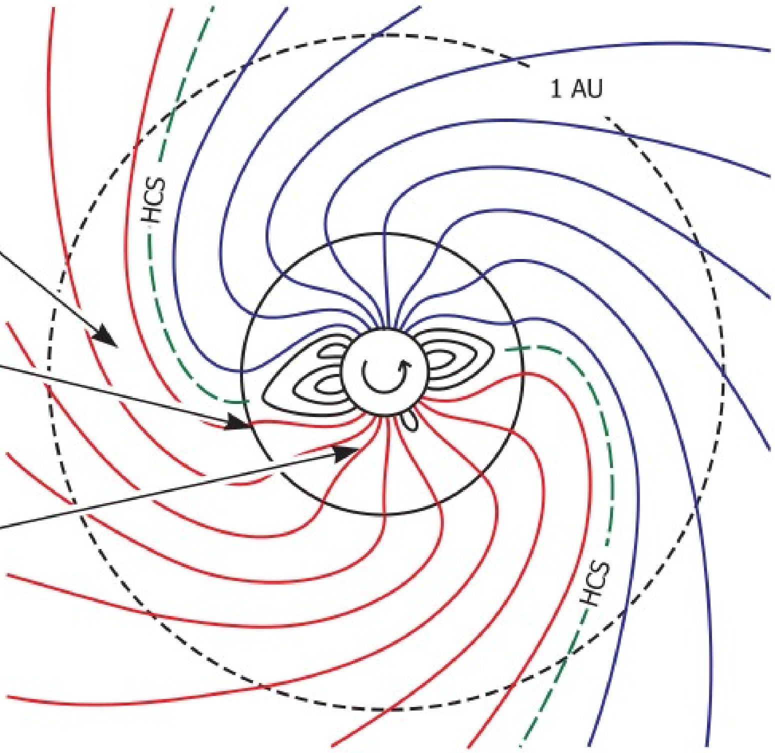
→ Propagation uncertainty: better data soon (AMS-02) and several species necessary

5. Solar modulation: B archimedian structure

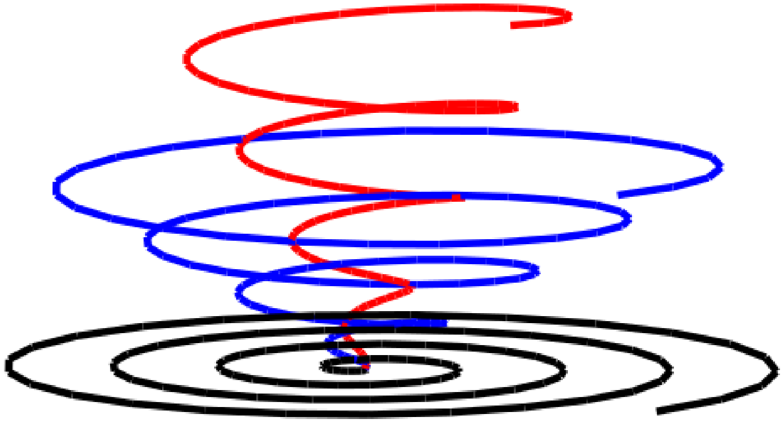
Magnetic field is assumed to be frozen in solar wind plasma
→ Archimedean spiral in the solar equatorial plane
Parker, AJ 128 (1958), 664



Heliosphere
$\vec{B} = B_R \hat{R} + B_\phi \hat{\phi}$
$\vec{V} = V_R \hat{R}$

Source surface
$\vec{B} = B_R \hat{R}$
$\vec{V} = V_R \hat{R}$

Super-radial expansion
$\vec{B} = B_R \hat{R} + B_\theta \hat{\theta} + B_\phi \hat{\phi}$
$\vec{V} = V_R \hat{R} + V_\theta \hat{\theta} + V_\phi \hat{\phi}$



Ideal Parker spiral magnetic field lines between 0 and 25 AU for a solar wind speed of 450 km s^{-1}. Black, blue, and red lines show heliographic latitudes of 0, 30, and 60 degrees, respectively

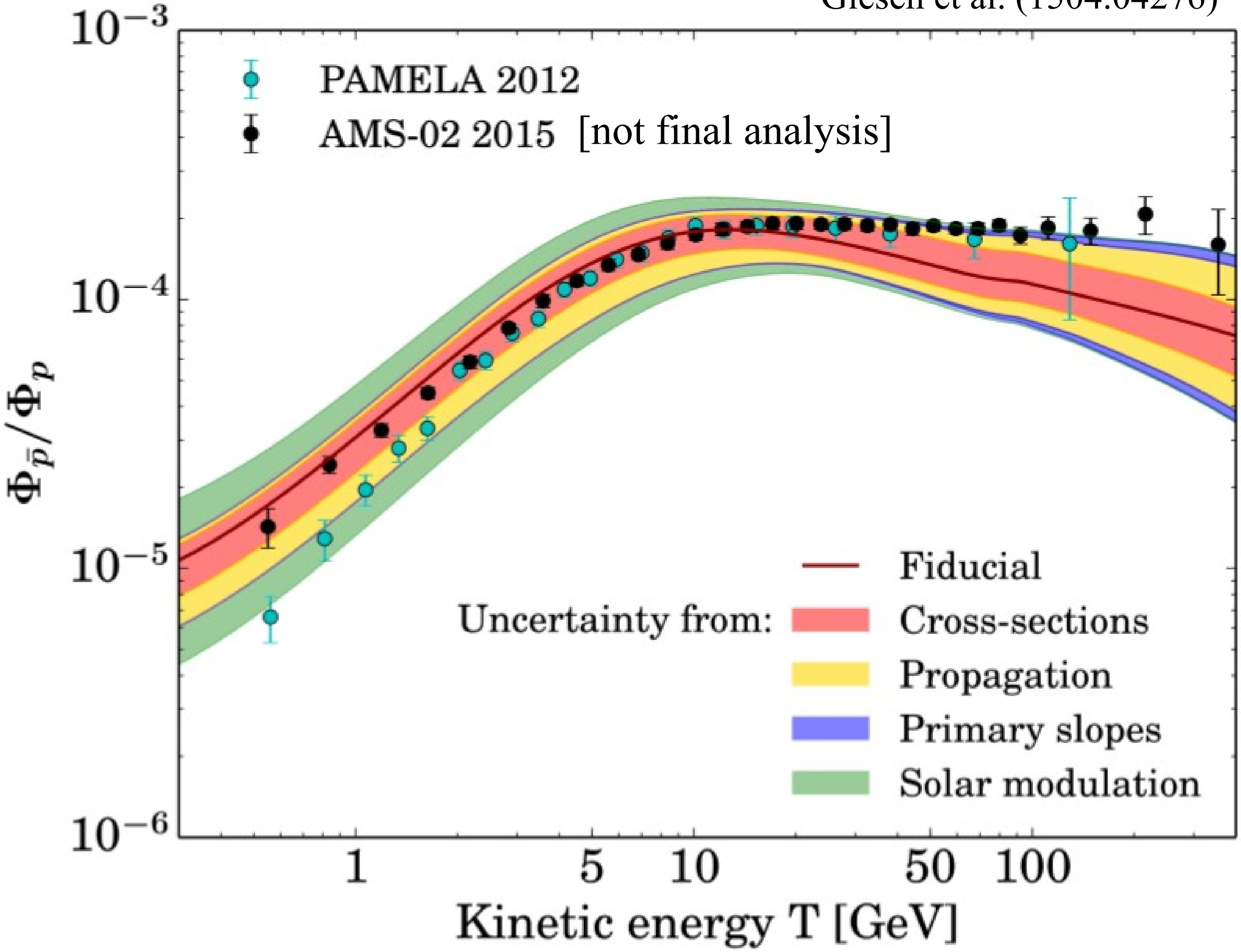
$$V(r,\theta) = V_0 \left[1 - \exp\left(13.33\left(\frac{r_\odot - r}{r_0}\right)\right)\right] \left[1.475 \mp 0.4 \tanh\left(6.8\left(\theta - \frac{\pi}{2} \pm \theta\right)\right)\right] \left[\left(\frac{s+1}{2s}\right) - \left(\frac{s-1}{2s}\right) \tanh\left(\frac{r - r_{\mathrm{TS}}}{L}\right)\right]$$

$$\mathbf{B} = B_o \left(\frac{r_0}{r}\right)^2 (\mathbf{e}_r - \tan\psi\, \mathbf{e}_\phi)$$

$$\tan\psi = \frac{\Omega\,(r - r_\odot)\sin\theta}{V}$$

5. Antiprotons: today's status

Giesen et al. (1504.04276)



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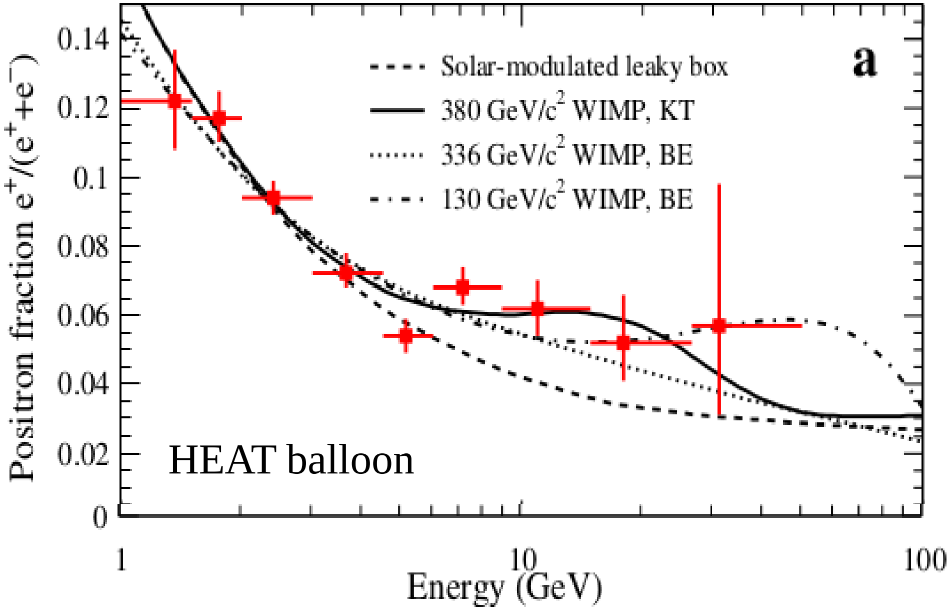
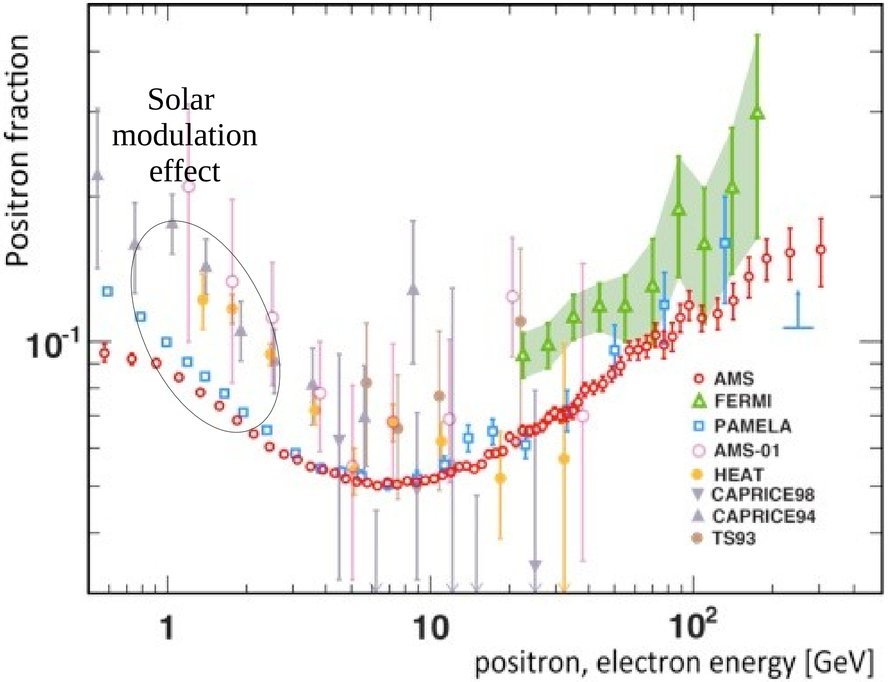
6. Positron fraction: same game… but different!

→ Rise of the positron fraction confirmed by PAMELA and AMS-02

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



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



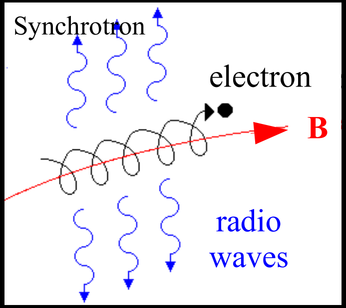
→ Uncertainties

- Production cross-sections: ~factor of 2-3 above a few 10 GeV (positron flux)
- Slope of the electron spectrum: ~ factor of 4 at 100 GeV (positron fraction)
- Transport: larger propagation uncertainties on positrons than on antinuclei

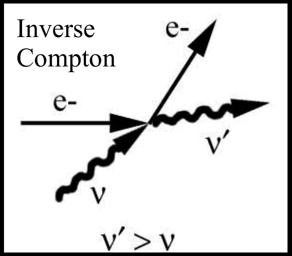
Delahaye et al., A&A 501 (2009) 821

N.B.: due to severe E losses, high energy leptons are “local” (~ kpc)

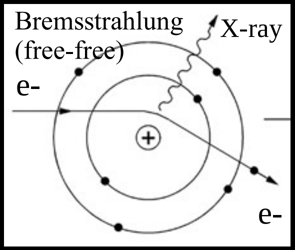
6. Energy losses…



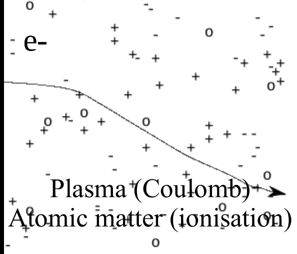
$$-\frac{dE}{dt}_{\rm sync} \propto \sigma_{\rm T} B_\perp^2 \gamma^2$$



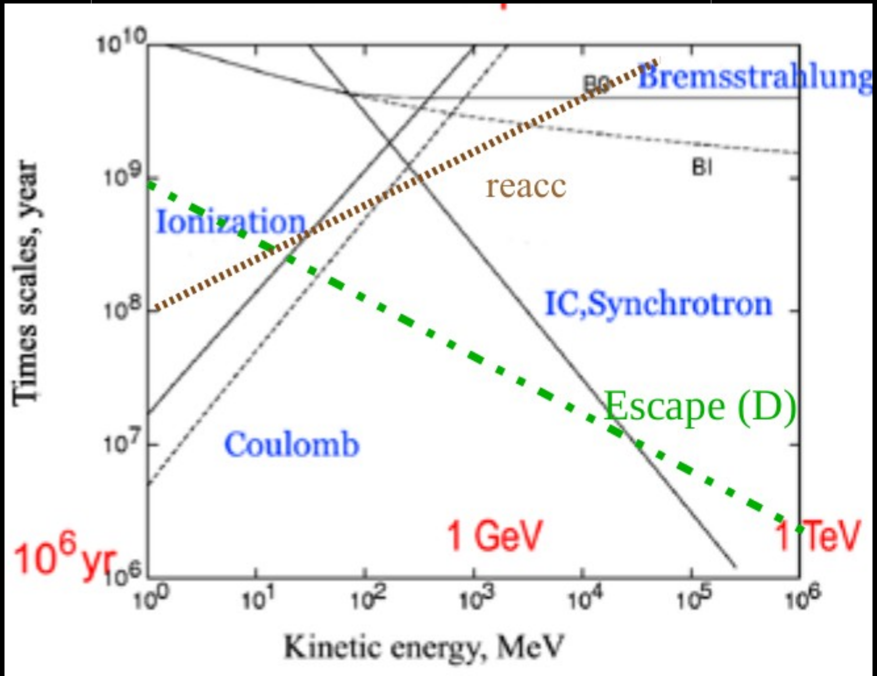
$$-\frac{dE}{dt}_{IC} \propto \sigma_{\rm T} U_{\rm rad} \gamma^2$$



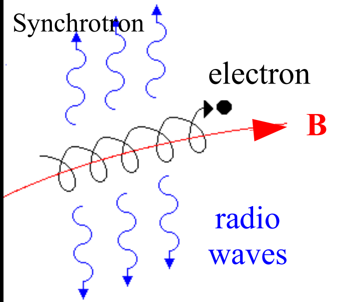
$$-\frac{dE}{dt}_{\rm brem} \propto \sigma_{\rm T} n_{\rm ISM} \gamma$$



$$-\frac{dE^{\rm ion}}{dt}_{\rm Coulomb} \propto \sigma_{\rm T} n^{\rm ISM}_{\rm plasma}$$



6. Energy losses… and sources of uncertainties



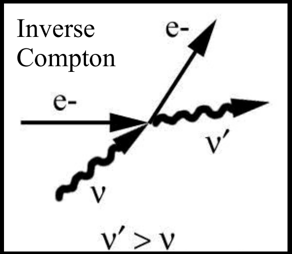
$$-\frac{dE}{dt}_{\rm sync} \propto \sigma_{\rm T} B_\perp^2 \gamma^2$$

B tracers

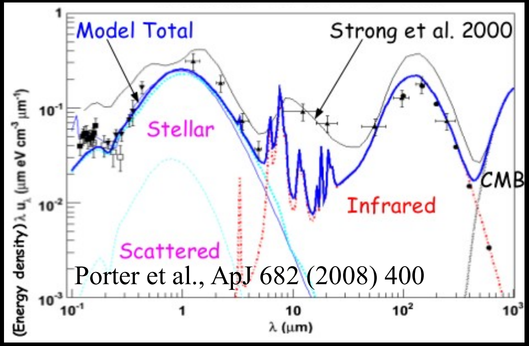
- Faraday rotation: free e^- (ionised regions)
- Synchrotron emission: CR e^-
- Zeeman splitting: lines (neutral regions)
- Dust thermal emission, starlight polar.

Uncertainties [2 μG < $B_{\rm sync}$ < 6 μG]

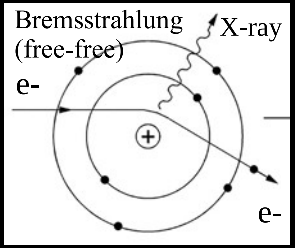
- Geometry (z dependence)
- Arm-interarm strength
- Regular vs irregular component



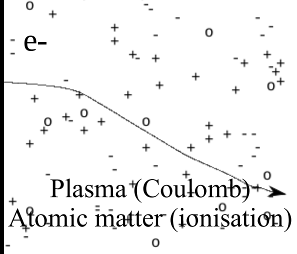
$$-\frac{dE}{dt}_{IC} \propto \sigma_{\rm T} U_{\rm rad} \gamma^2$$



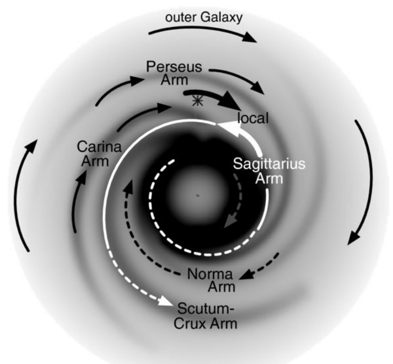
Porter et al., ApJ 682 (2008) 400



$$-\frac{dE}{dt}_{\rm brem} \propto \sigma_{\rm T} n_{\rm ISM} \gamma$$



$$-\frac{dE^{\rm ion}}{dt}_{\rm Coulomb} \propto \sigma_{\rm T} n^{\rm ISM}_{\rm plasma}$$

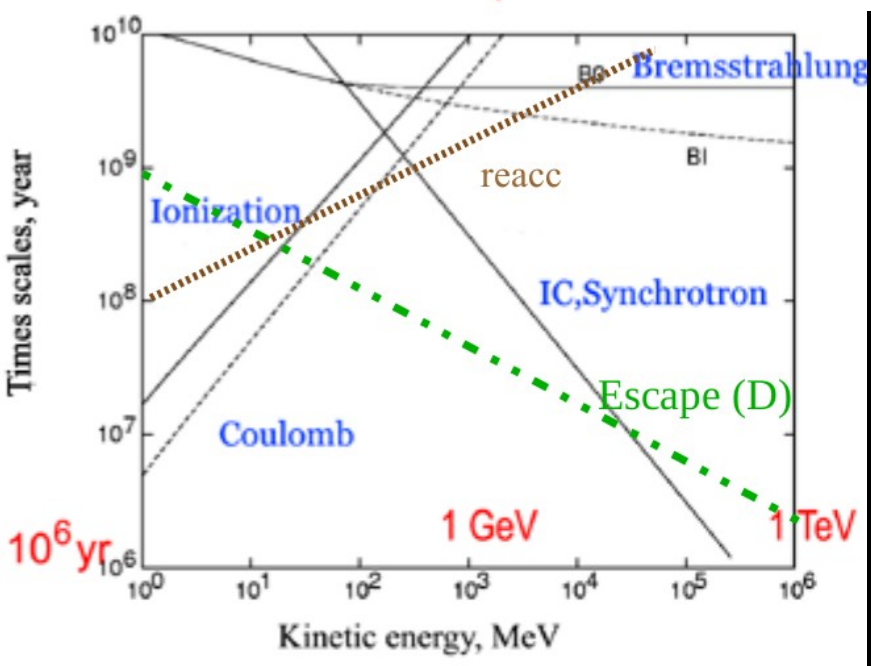


Van Eck et al. ApJ 728 (2011) 97

$n_{\rm disc}$ ~ 1 – 2 cm^{-3}

- Distribution of HI, HII, H2, He…
- Geometry: radial and z-dependence
- Arm-interarm contrast

→ Crucial for γ-ray emissions

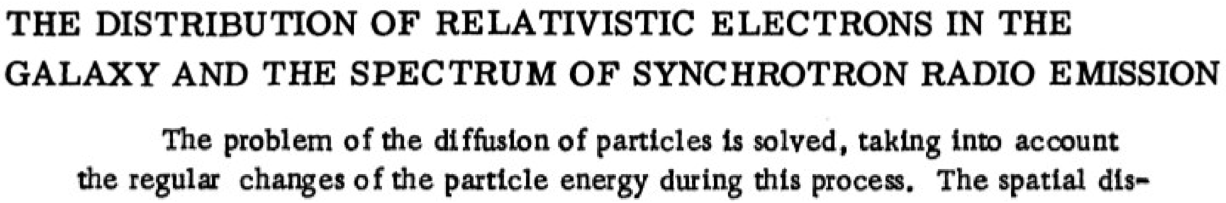


6. Transport equation/solution for leptons

$$\frac{\partial N^j}{\partial t}+\left(-\vec{\nabla}\cdot\left(D(E,\vec{r})\vec{\nabla}\right)+\cancel{\vec{\nabla}\cdot\vec{V}_c(\vec{r})}\right)N^j+\frac{\partial}{\partial E}\left(b^jN^j-\cancel{D_{EE}\frac{\partial N^j}{\partial E}}\right)+\cancel{(\Gamma_{\rm rad}+\Gamma_{\rm inel})}N^j=Q^j(t,E,\vec{r})$$

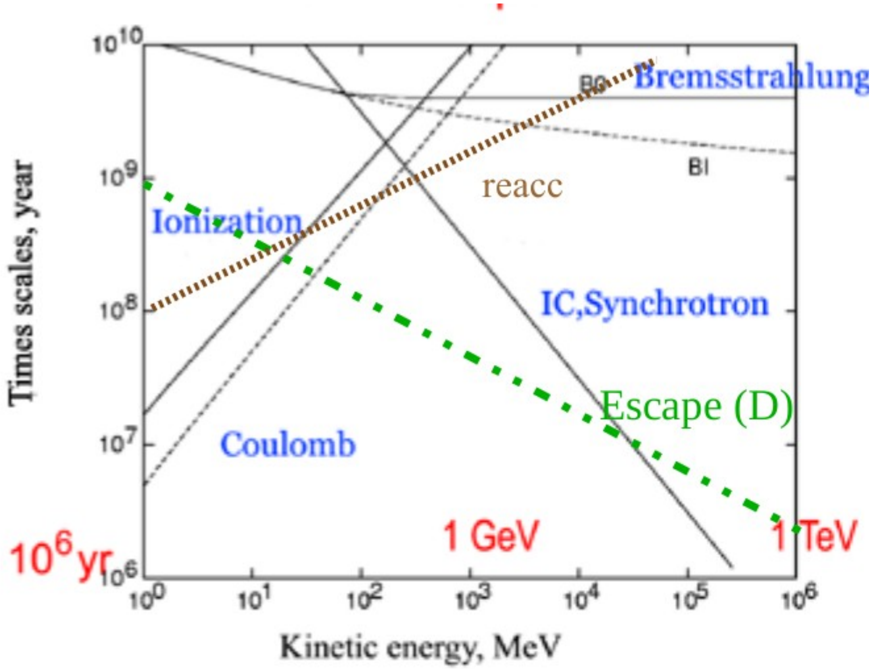
General time-dependent solution

Syrovatskii, Soviet Astronomy 3 (1959) 22



THE DISTRIBUTION OF RELATIVISTIC ELECTRONS IN THE GALAXY AND THE SPECTRUM OF SYNCHROTRON RADIO EMISSION

The problem of the diffusion of particles is solved, taking into account the regular changes of the particle energy during this process. The spatial dis-



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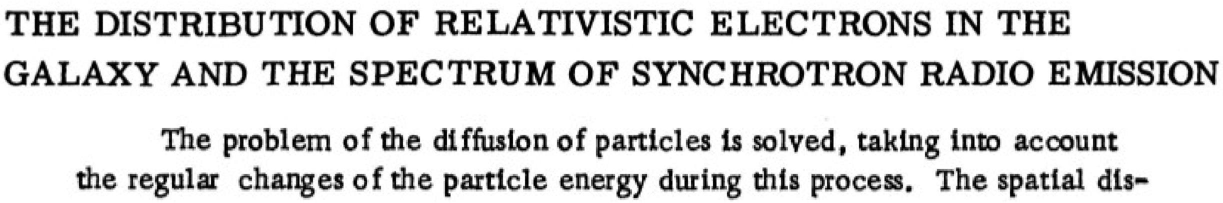

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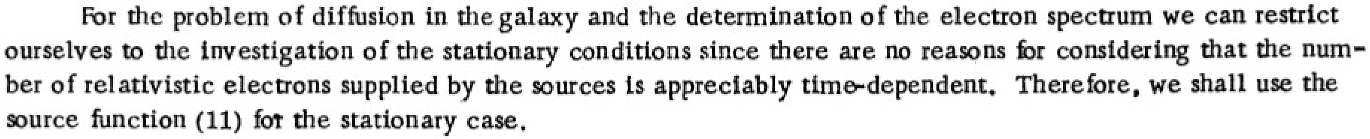
But no data to support time-dependent behaviour



For the problem of diffusion in the galaxy and the determination of the electron spectrum we can restrict ourselves to the investigation of the stationary conditions since there are no reasons for considering that the number of relativistic electrons supplied by the sources is appreciably time-dependent. Therefore, we shall use the source function (11) for the stationary case.

Synchrotron: B ~ 6 μG
IC: negligible

6. Transport equation/solution for leptons (1970)

$$\cancel{\frac{\partial N^j}{\partial t}}+\left(-\vec{\nabla}\cdot\left(D(E,\vec{r})\vec{\nabla}\right)+\cancel{\vec{\nabla}\cdot\vec{V}_c(\vec{r})}\right)N^j+\frac{\partial}{\partial E}\left(b^j N^j-\cancel{D_{EE}\frac{\partial N^j}{\partial E}}\right)+\cancel{(\Gamma_{\mathrm{rad}}+\Gamma_{\mathrm{inel}})}N^j=Q^j(t,E,\vec{r})$$

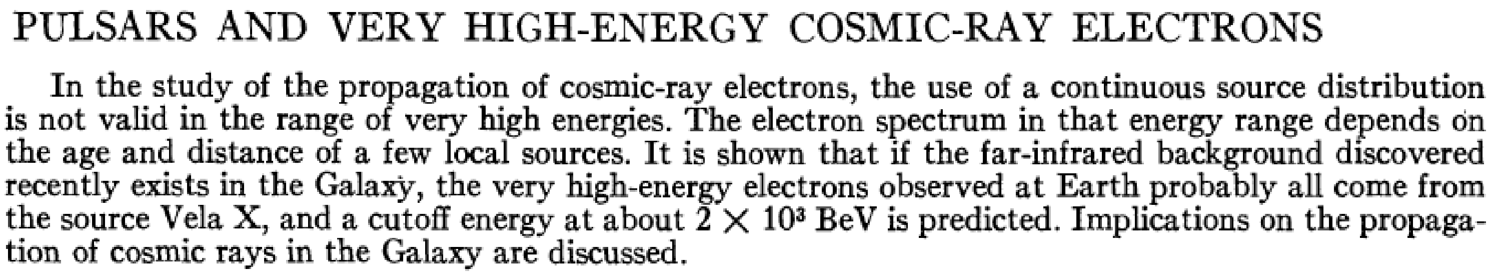
Origin of high energy electrons (TeV)

- $t_{IC}\sim$ 0.3 Myr
- $d_{max}\sim(2Dt)^{1/2}$

$\rightarrow d_{max}\sim$ 1 kpc

Singe source and cut-off in HE spectrum
→ very sensitive to D

Shen, ApJ 162 (1970) 181



PULSARS AND VERY HIGH-ENERGY COSMIC-RAY ELECTRONS

In the study of the propagation of cosmic-ray electrons, the use of a continuous source distribution is not valid in the range of very high energies. The electron spectrum in that energy range depends on the age and distance of a few local sources. It is shown that if the far-infrared background discovered recently exists in the Galaxy, the very high-energy electrons observed at Earth probably all come from the source Vela X, and a cutoff energy at about 2 × 10³ BeV is predicted. Implications on the propagation of cosmic rays in the Galaxy are discussed.

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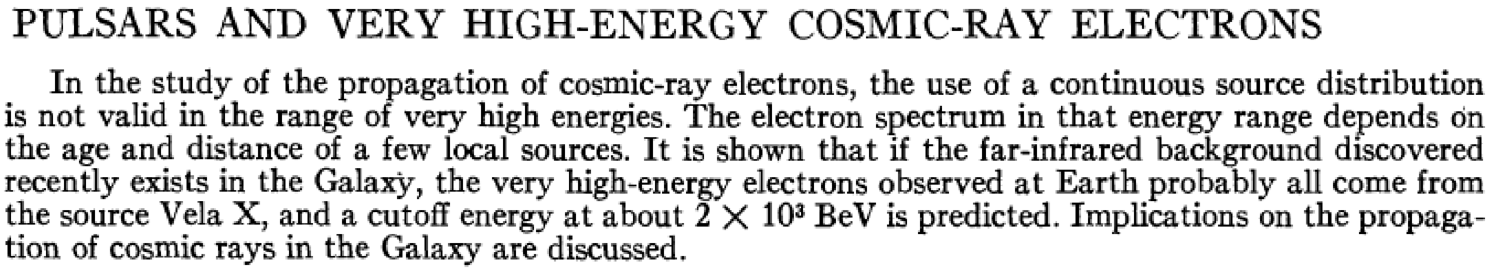

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Procedure (use of 50 pulsars)

→ sources @ r>1kpc: continuous space-time distribution

→ sources @ r<1kpc

6. Transport equation/solution for leptons (1970)

$$\cancel{\frac{\partial N^j}{\partial t}} + \left(-\vec{\nabla}\cdot\left(D(E,\vec{r})\vec{\nabla}\right) + \cancel{\vec{\nabla}\cdot\vec{V}_c(\vec{r})}\right)N^j + \frac{\partial}{\partial E}\left(b^j N^j - \cancel{D_{EE}\frac{\partial N^j}{\partial E}}\right) + \cancel{(\Gamma_{\rm rad}+\Gamma_{\rm inel})}N^j = Q^j(t,E,\vec{r})$$

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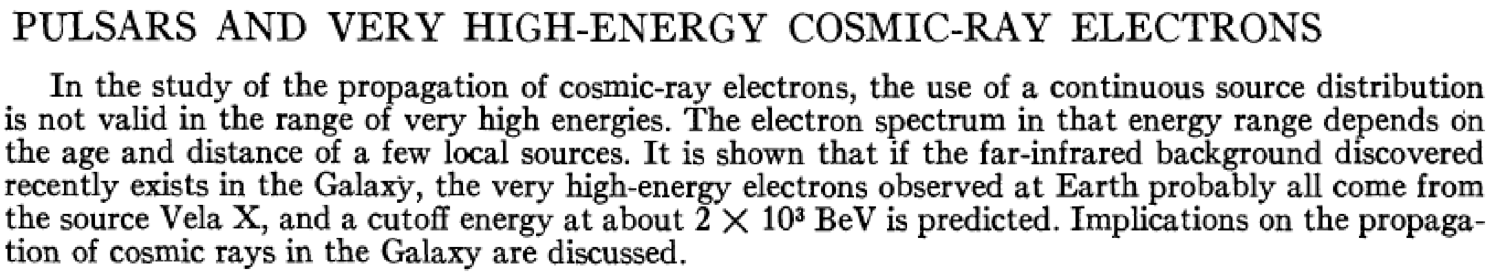

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Procedure (use of 50 pulsars)

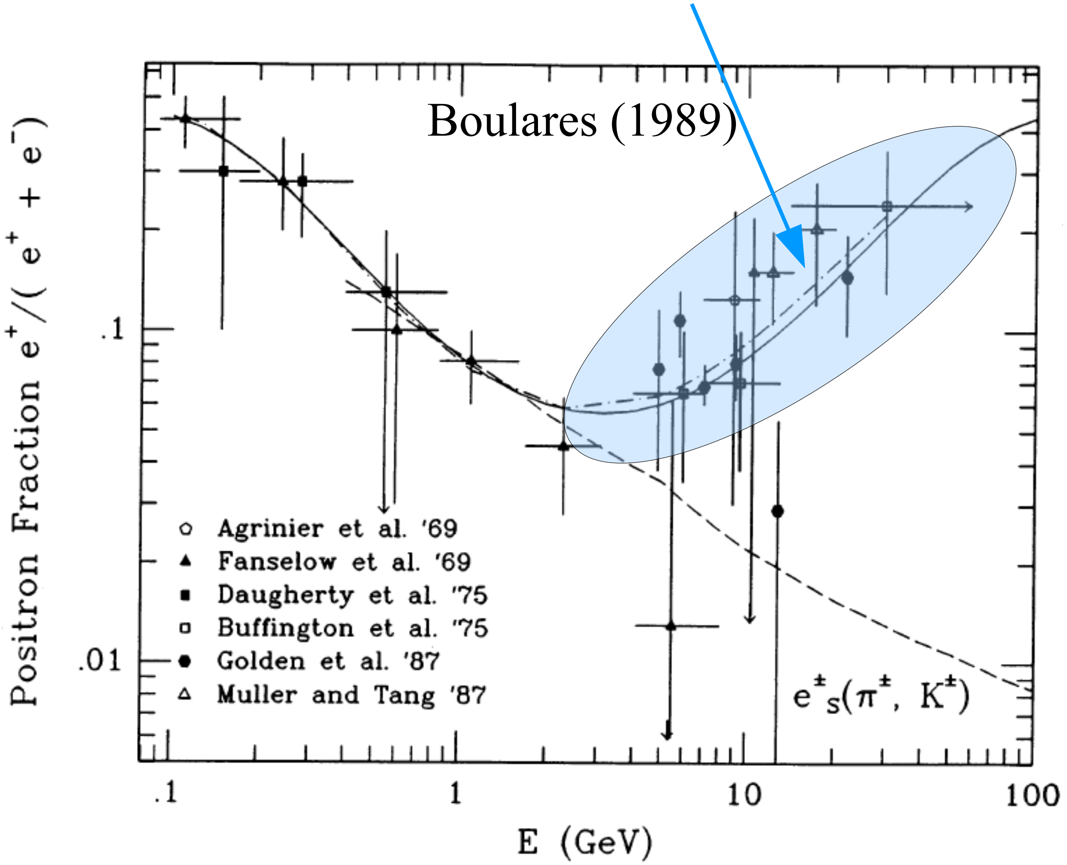
→ sources @ r>1kpc: continuous space-time distribution
→ sources @ r<1kpc

Atoyan, Aharonian &Völk, PRD 52 (1995) 3265
Electrons and positrons in the galactic cosmic rays

→ Apply procedure of Shen (1970)
→ More general solutions and analysis

6. So, there was this guy...

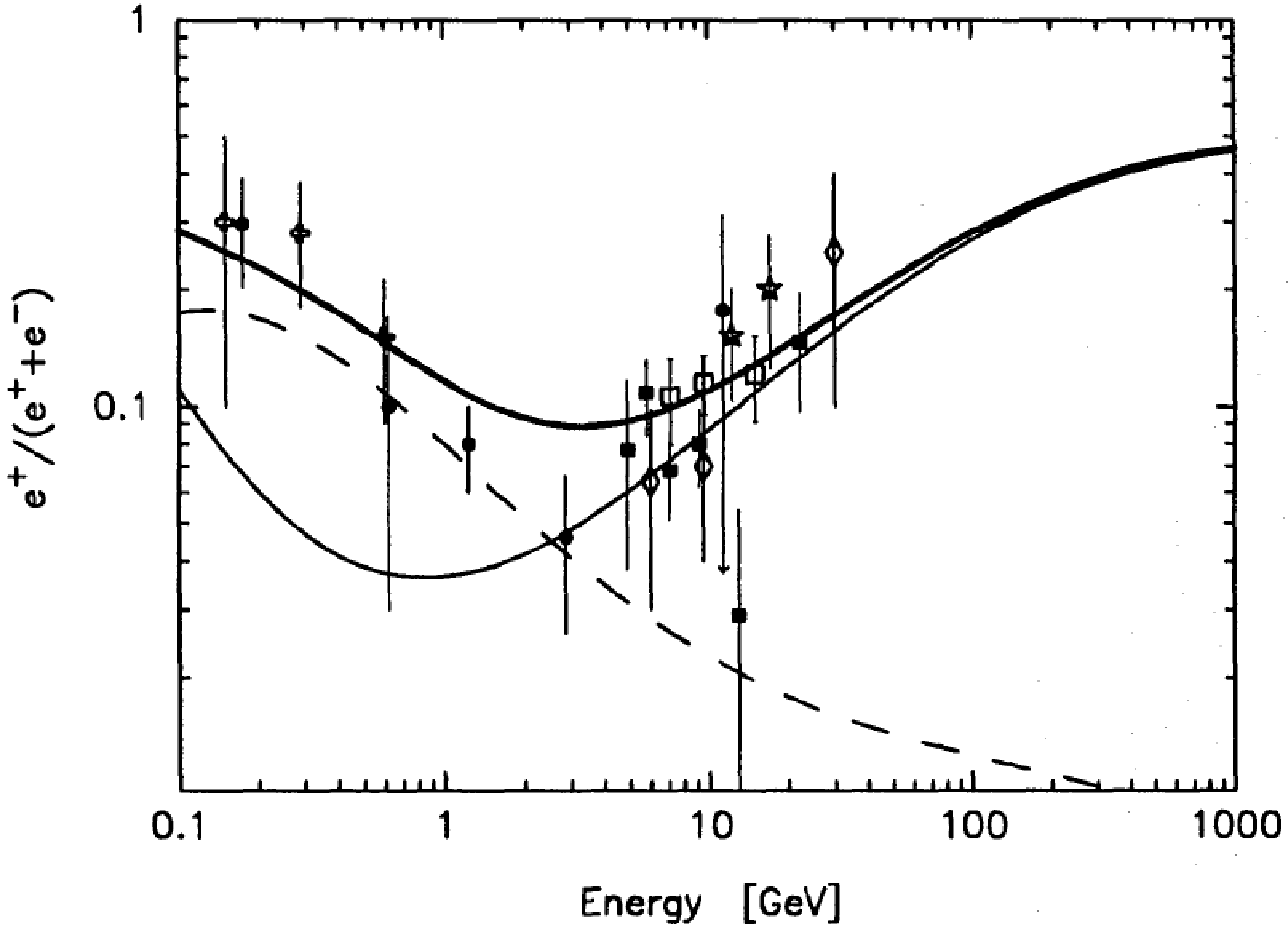
Positron fraction: origin of the rise at high energy



→ 'Natural' astrophysical prediction (local SNRs, pulsars)

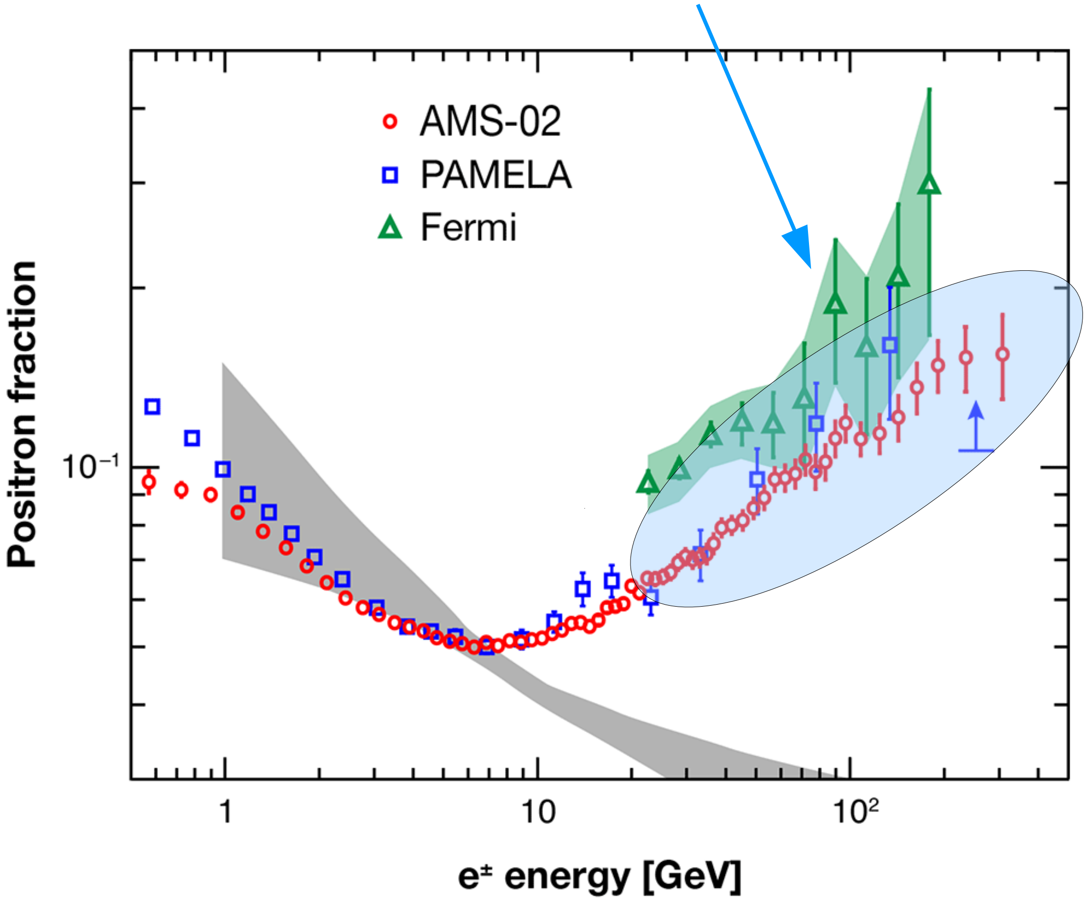
6. And then some other guys...

Aharonian et al., A&A 26 (1995) 41



6. So what would you bet on?

Positron fraction: origin of the rise at high energy



→ Not much control yet on the astrophysical background!

Next steps

→ 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

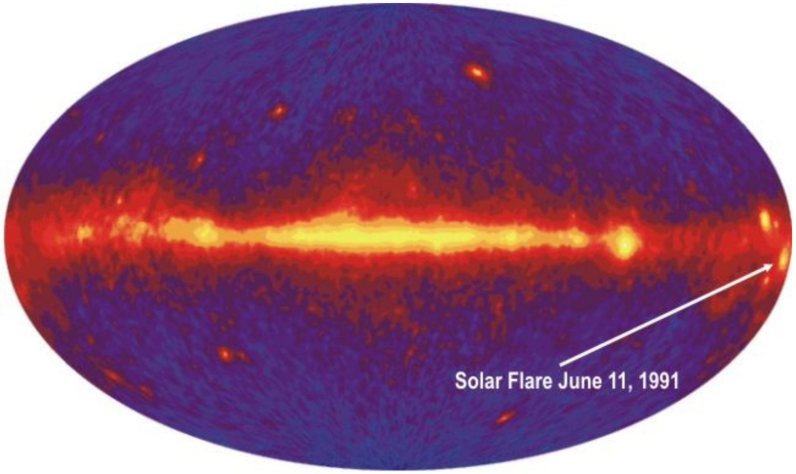
...positrons are probably the worse place to look for DM

1. A brief historical perspective
2. CR journey: global picture
3. DM indirect detection: foreground and targets
4. Simplex, complex, multiplex: GCR “model”
5. Detailed uncertainties for anti-protons
6. Positron fraction: a severe case of memory loss
7. γ-rays: fun facts about diffuse emissions

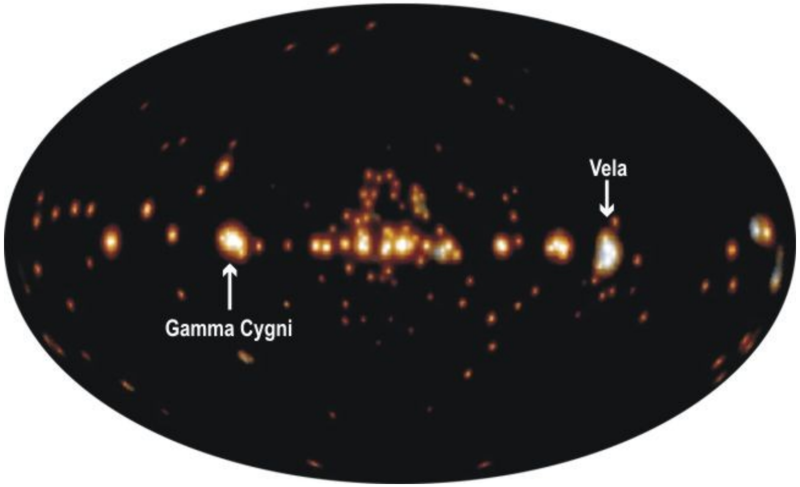
7. Diffuse emission for dummies

1) Count the number of
(photons-instrument background)

EGRET >100 MeV

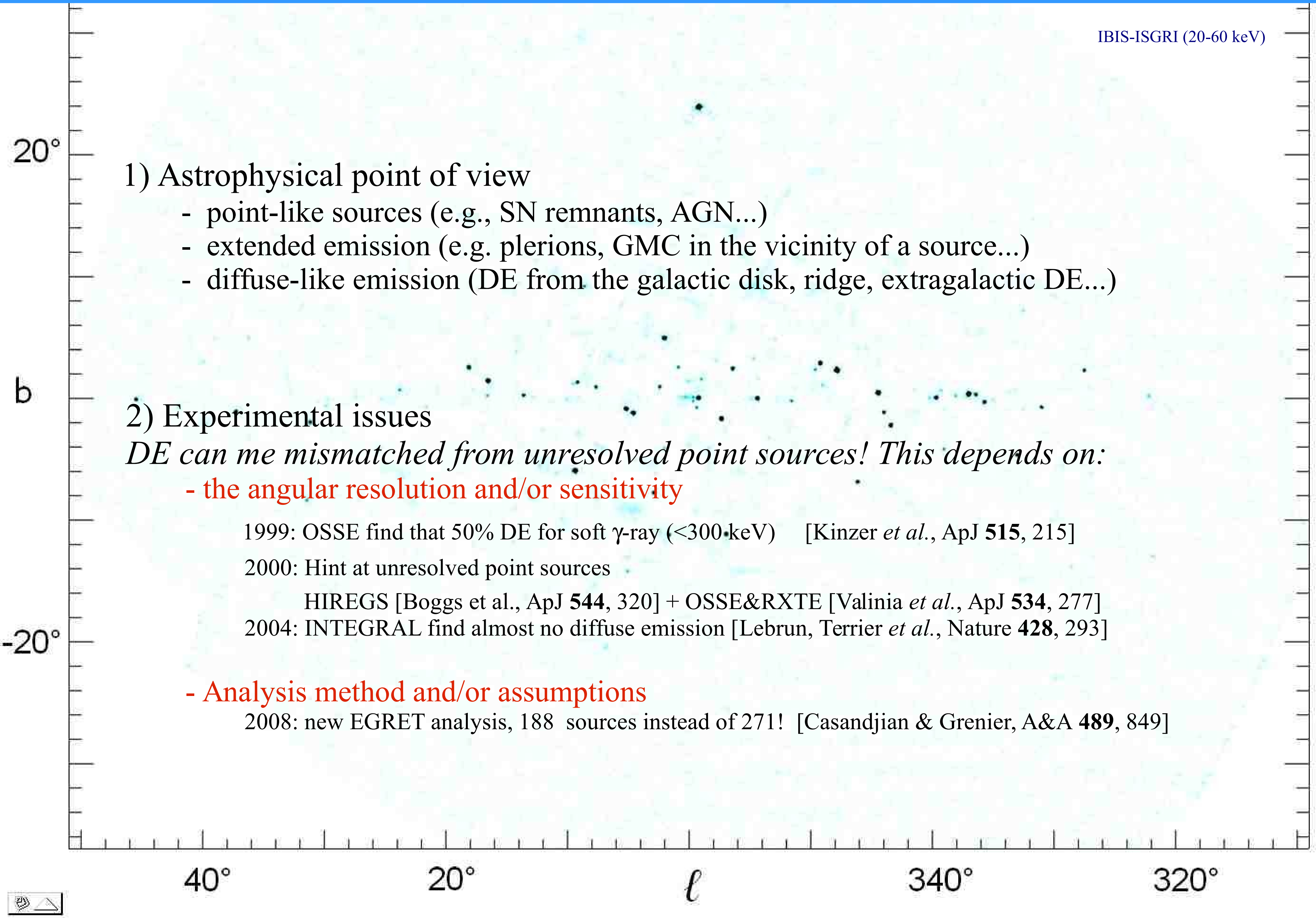


2) Subtract point sources



→ Hopefully, what remains is the diffuse emission

7. Control on diffuse emissions?



1) Astrophysical point of view

- point-like sources (e.g., SN remnants, AGN...)
- extended emission (e.g. plerions, GMC in the vicinity of a source...)
- diffuse-like emission (DE from the galactic disk, ridge, extragalactic DE...)

2) Experimental issues

DE can me mismatched from unresolved point sources! This depends on:

- the angular resolution and/or sensitivity

1999: OSSE find that 50% DE for soft γ-ray (<300 keV) [Kinzer *et al.*, ApJ **515**, 215]

2000: Hint at unresolved point sources

HIREGS [Boggs et al., ApJ **544**, 320] + OSSE&RXTE [Valinia *et al.*, ApJ **534**, 277]
2004: INTEGRAL find almost no diffuse emission [Lebrun, Terrier *et al.*, Nature **428**, 293]

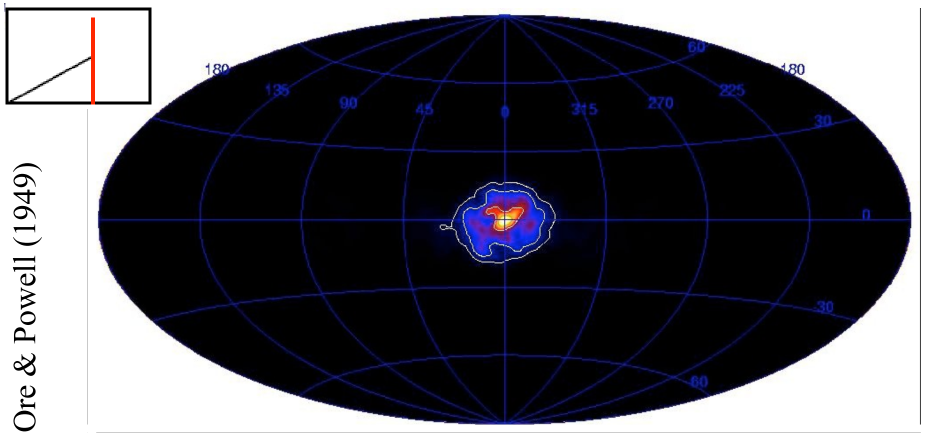
- Analysis method and/or assumptions

2008: new EGRET analysis, 188 sources instead of 271! [Casandjian & Grenier, A&A **489**, 849]

7. The soft γ-ray sky and the 511 keV line

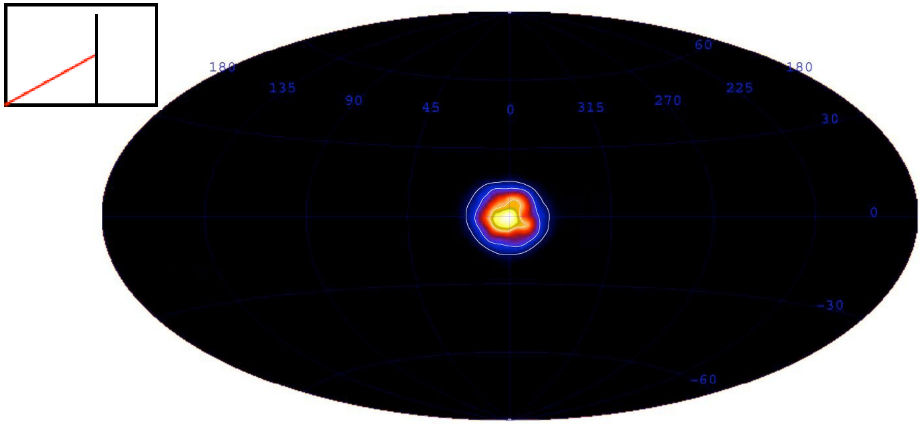
First results

Knödlseder *et al.*, A&A **441**, 513 (2003)



Ore & Powell (1949)

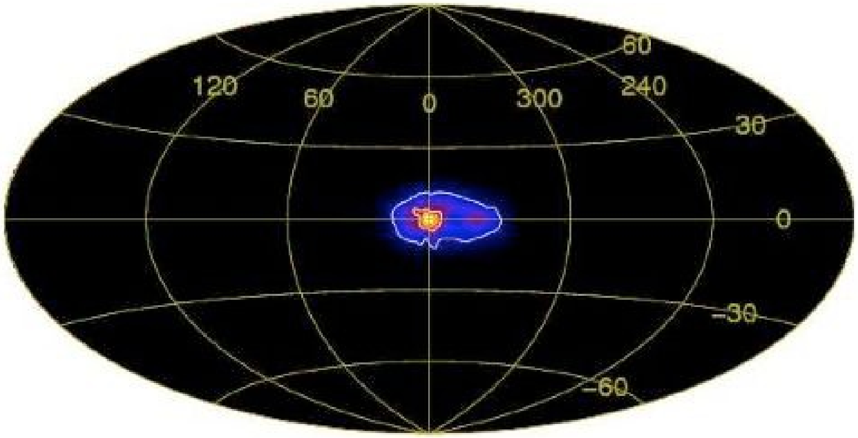
Weidenspointner *et al.*, A&A **450**, 1013 (2006)

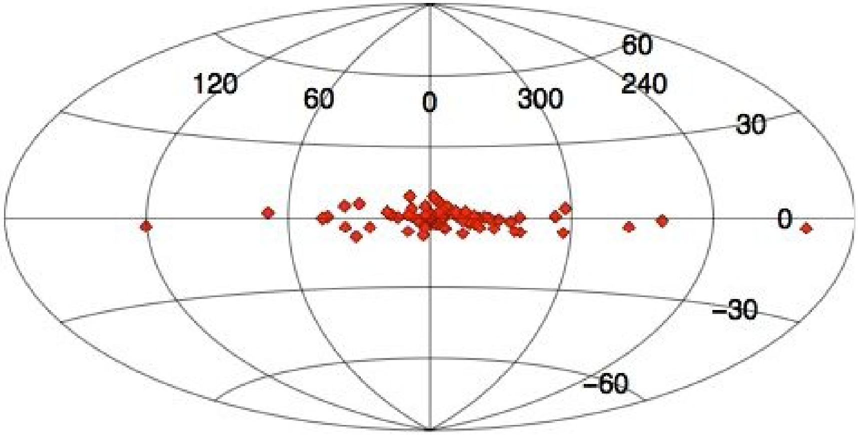


→ Light Dark matter?

Latest results

Weidenspointner *et al.*, Nature **451**, 159 (2008)





→ Correlation with LMXB?

Conclusions

Status of "Simple" propagation models (homogeneous diffusion)

- *Anti-protons*: consistent with astrophysics only
- *Anti-deuterons*: astrophysics background level within reach soon (GAPS, AMS-02)
- *High energy e^+/e^-*: local sources may reproduce any feature seen in data
- *Diffuse γ-rays*: can be tuned to reproduce Fermi-LAT data (GALPROP)

→ Uncertainties from production cross-sections are a limiting factor!

But some features…

- Break in p and He spectra et ~ 300 GV (PAMELA, AMS-02)
- GeV γ-rays: Fermi bubble + p flux variability from molecular clouds
- GeV γ-rays: H.E.S.S. galactic centre signal dominated by "one" active source

→ Looking at small scales (high angular resolution) requires to go beyond the "averaged" picture

Experimentally: need high precision measurement up to the highest energy + multi-wavelength observation
→ may provide clues on specific E scales and phenomena indicating non-universal features of injection, acceleration, escape (from the source) and/or propagation

For more, see Pasquale Serpico's talk @ ICRC
Possible physics scenarios behind cosmic ray "anomalies"