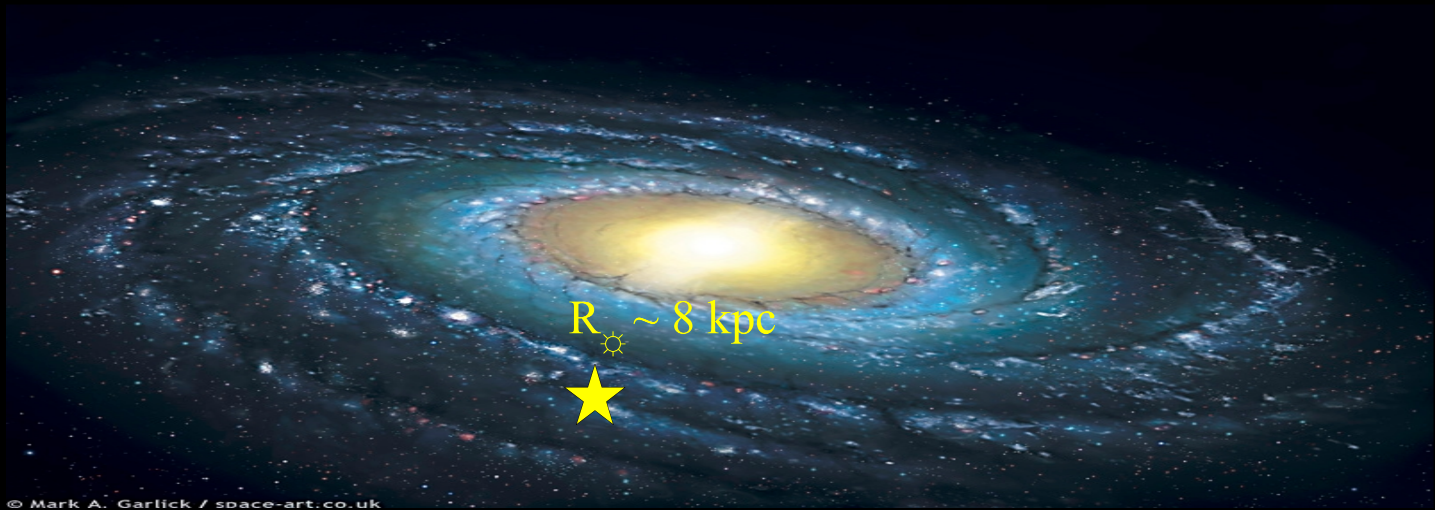
Indirect searches with Galactic Cosmic Rays

N.B.: dark matter candidate in the GeV-TeVmass range

David Maurin (LPSC)
dmaurin@lpsc.in2p3.fr

News from the Dark
LUPM, Montpellier
31/10/2013

Charged cosmic rays in the Galaxy

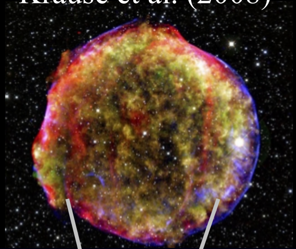


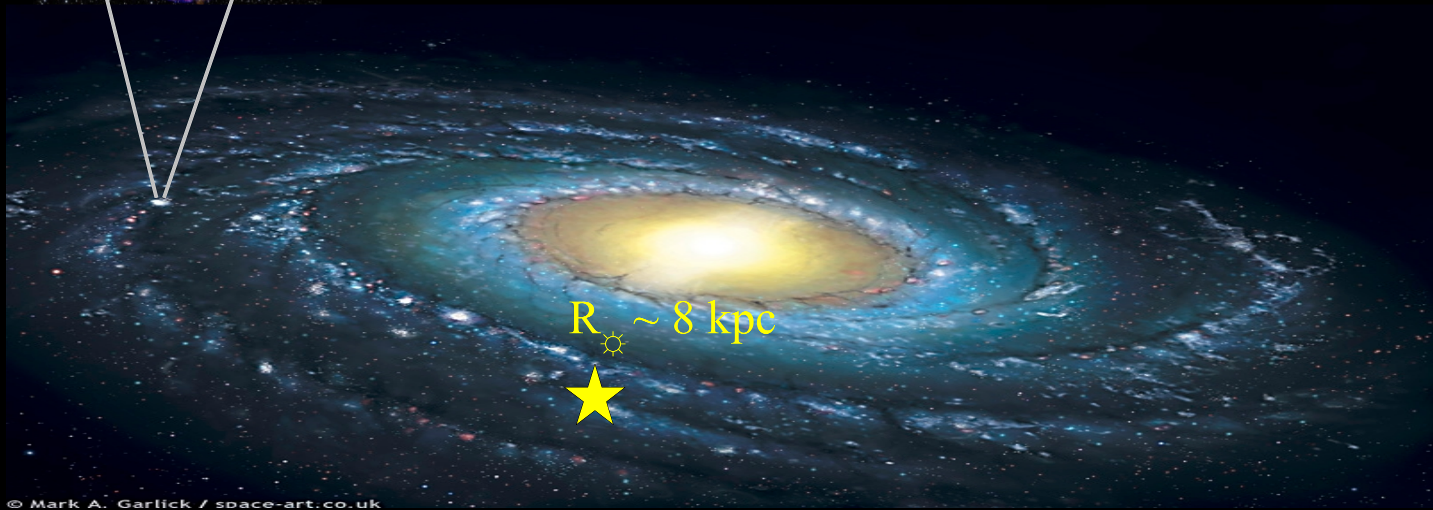
Charged cosmic rays in the Galaxy

1. Source injection

- spectrum ~ R^{-2}
- abundances

Krause et al. (2008)



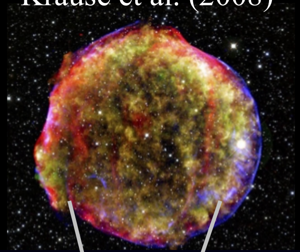


Charged cosmic rays in the Galaxy

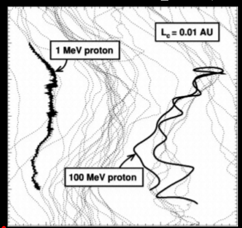
1. Source injection

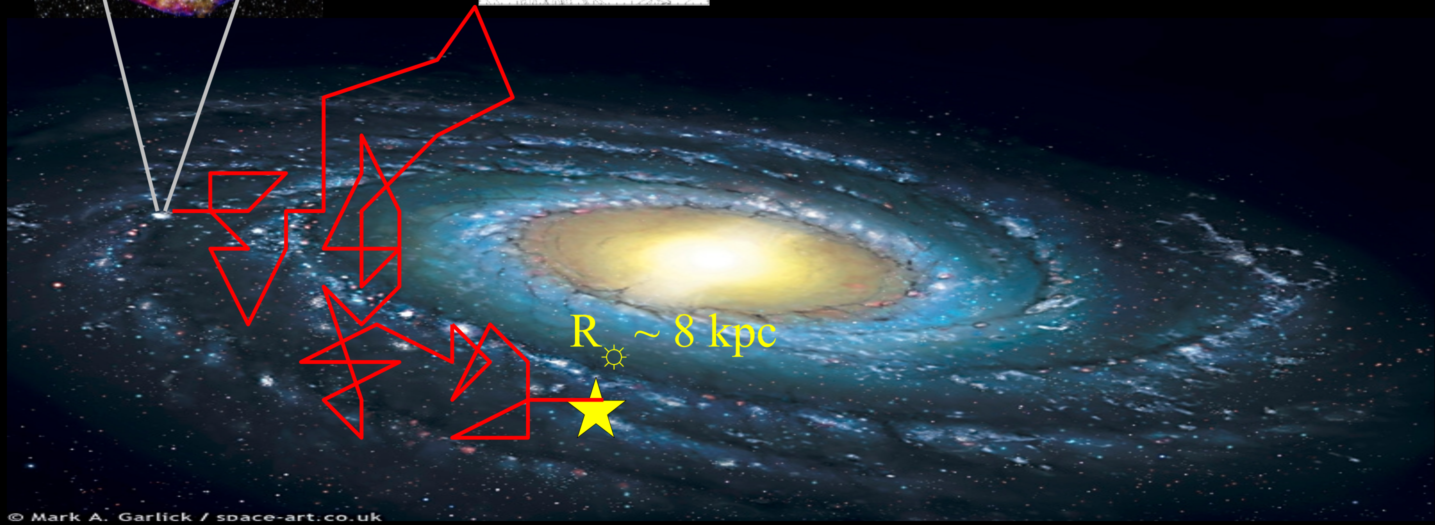
- spectrum ~ R^{-2}
- abundances

Krause et al. (2008)



Giacalone et Jokipii (1999)



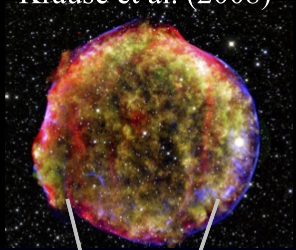


Charged cosmic rays in the Galaxy

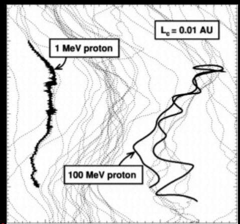
1. Source injection

- spectrum ~ R^{-2}
- abundances

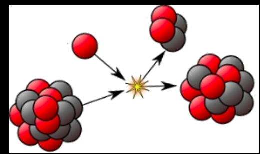
Krause et al. (2008)

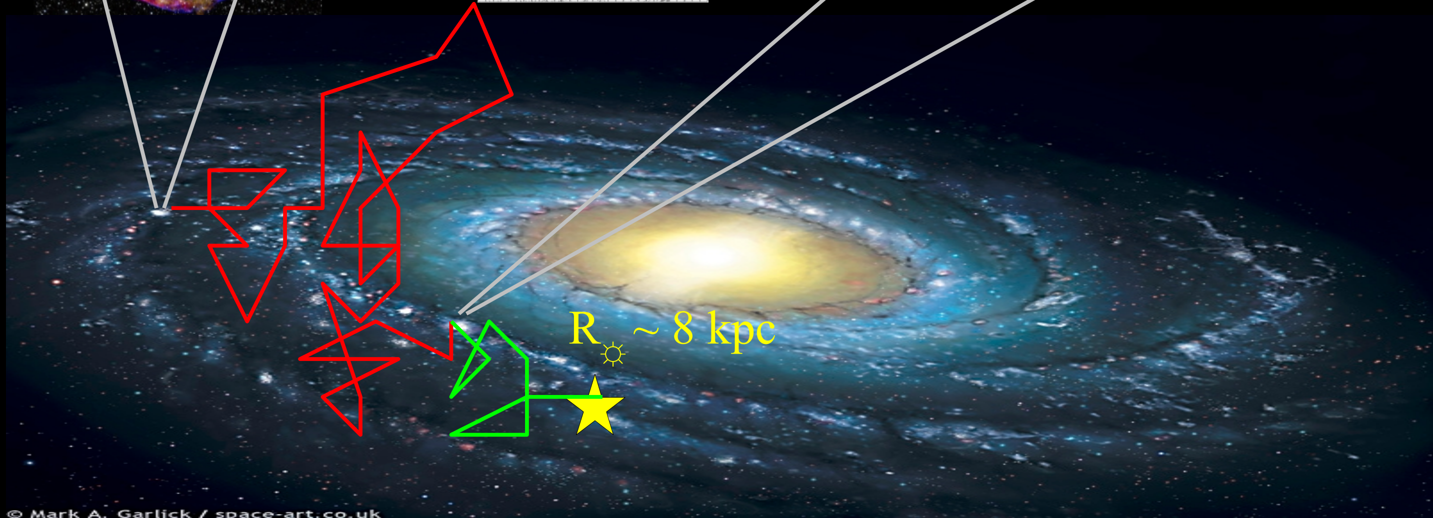


Giacalone et Jokipii (1999)



Webber et al. (2003)



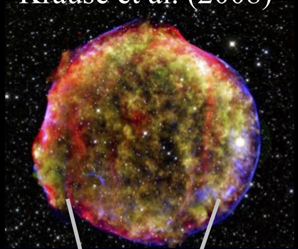


Charged cosmic rays in the Galaxy

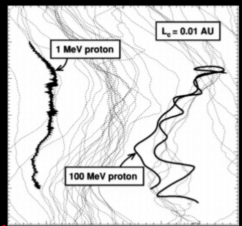
1. Source injection

- spectrum ~ R^{-2}
- abundances

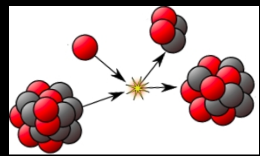
Krause et al. (2008)

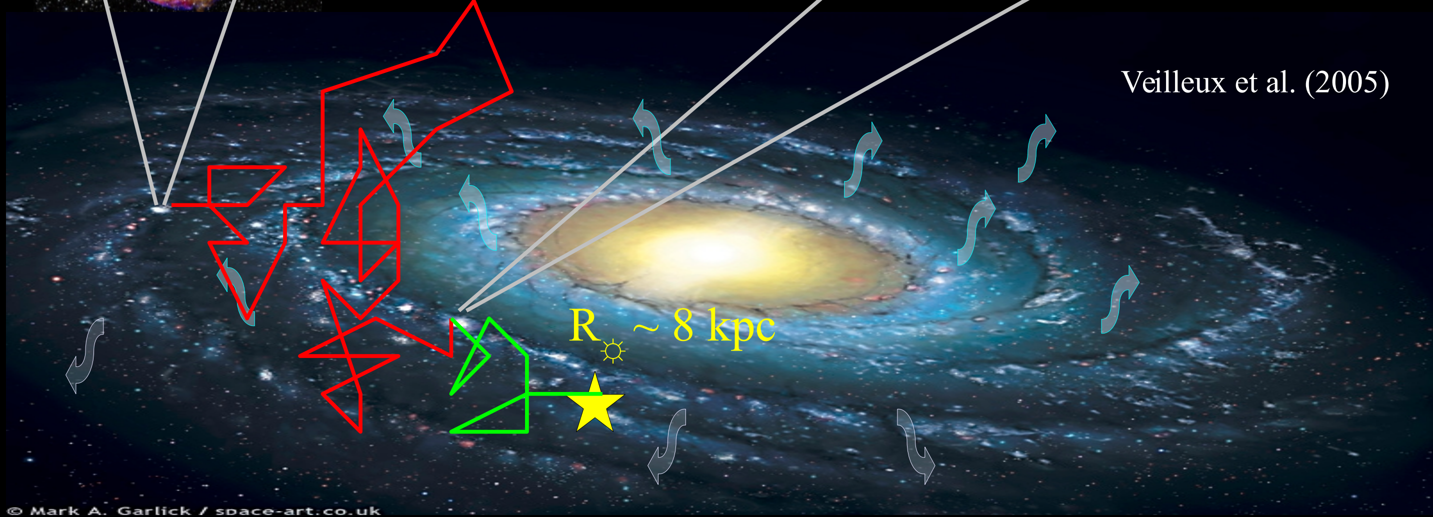


Giacalone et Jokipii (1999)



Webber et al. (2003)



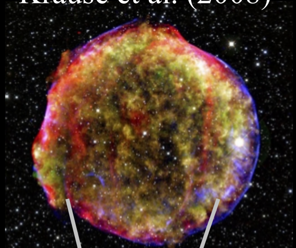


Charged cosmic rays in the Galaxy

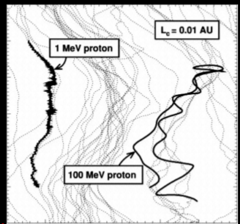
1. Source injection
- spectrum ~ R^{-2}
- abundances

2. Transport in the Galaxy
- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/decay

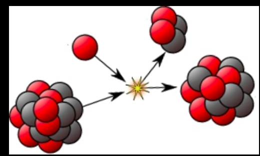
Krause et al. (2008)

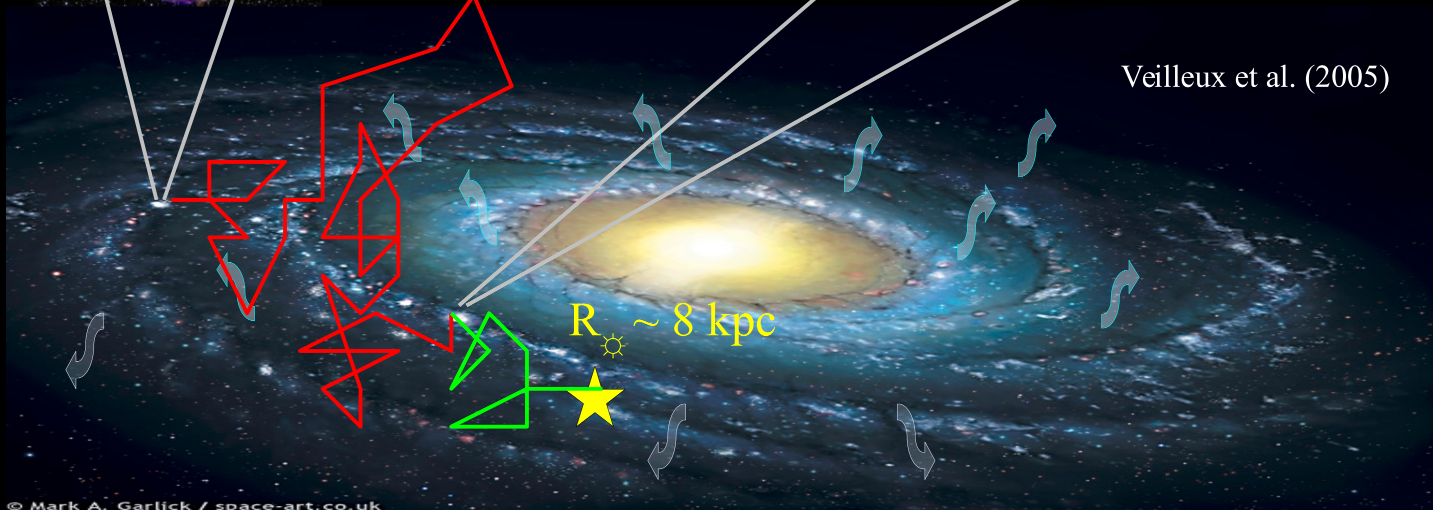


Giacalone et Jokipii (1999)



Webber et al. (2003)



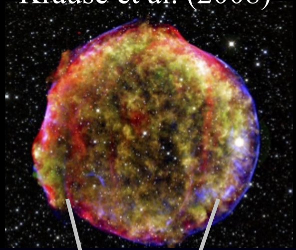


Charged cosmic rays in the Galaxy

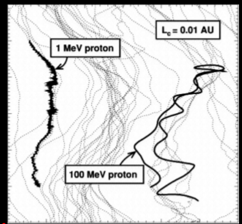
1. Source injection
- spectrum ~ R^{-2}
- abundances

2. Transport in the Galaxy
- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/decay

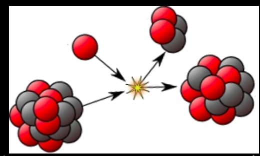
Krause et al. (2008)

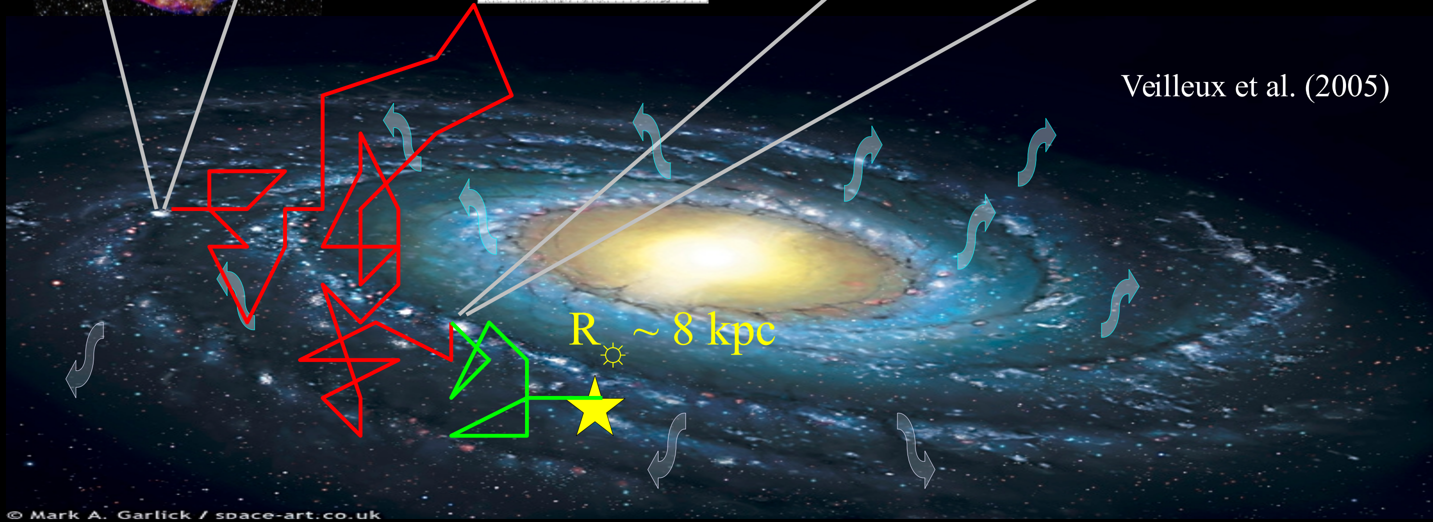


Giacalone et Jokipii (1999)



Webber et al. (2003)





Veilleux et al. (2005)

Particles reaching Earth come from:

- whole diffusive volume for stable species
- small volume (~ 100 pc) for radioactive nuclei and high energy electrons

→ different species sample different regions of the Galaxy

Taillet & Maurin (2003)
Maurin & Taillet (2003)

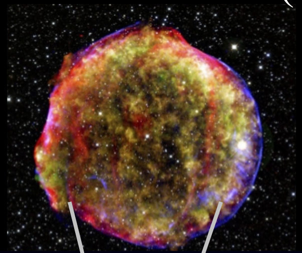
Charged cosmic rays in the Galaxy

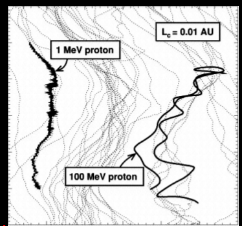
1. Source injection
- spectrum ~ R^{-2}
- abundances

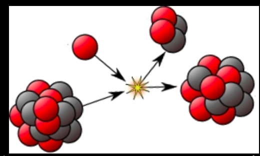
2. Transport in the Galaxy
- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/decay

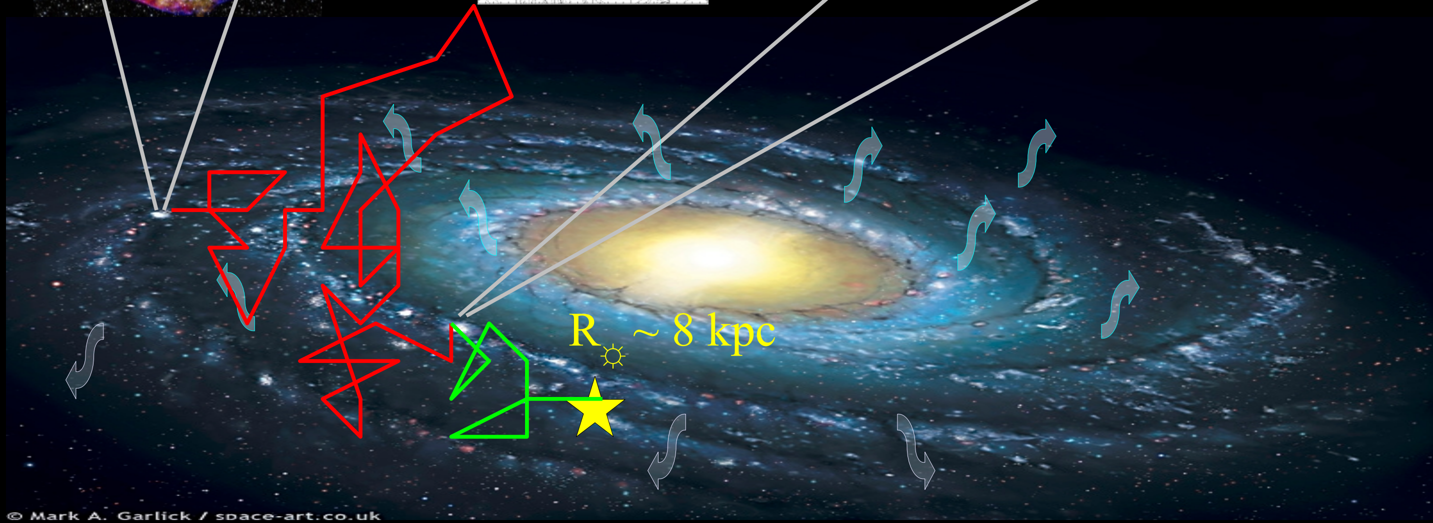
(MHD)

(nuclear physics)









(astrophysics + particle physics)

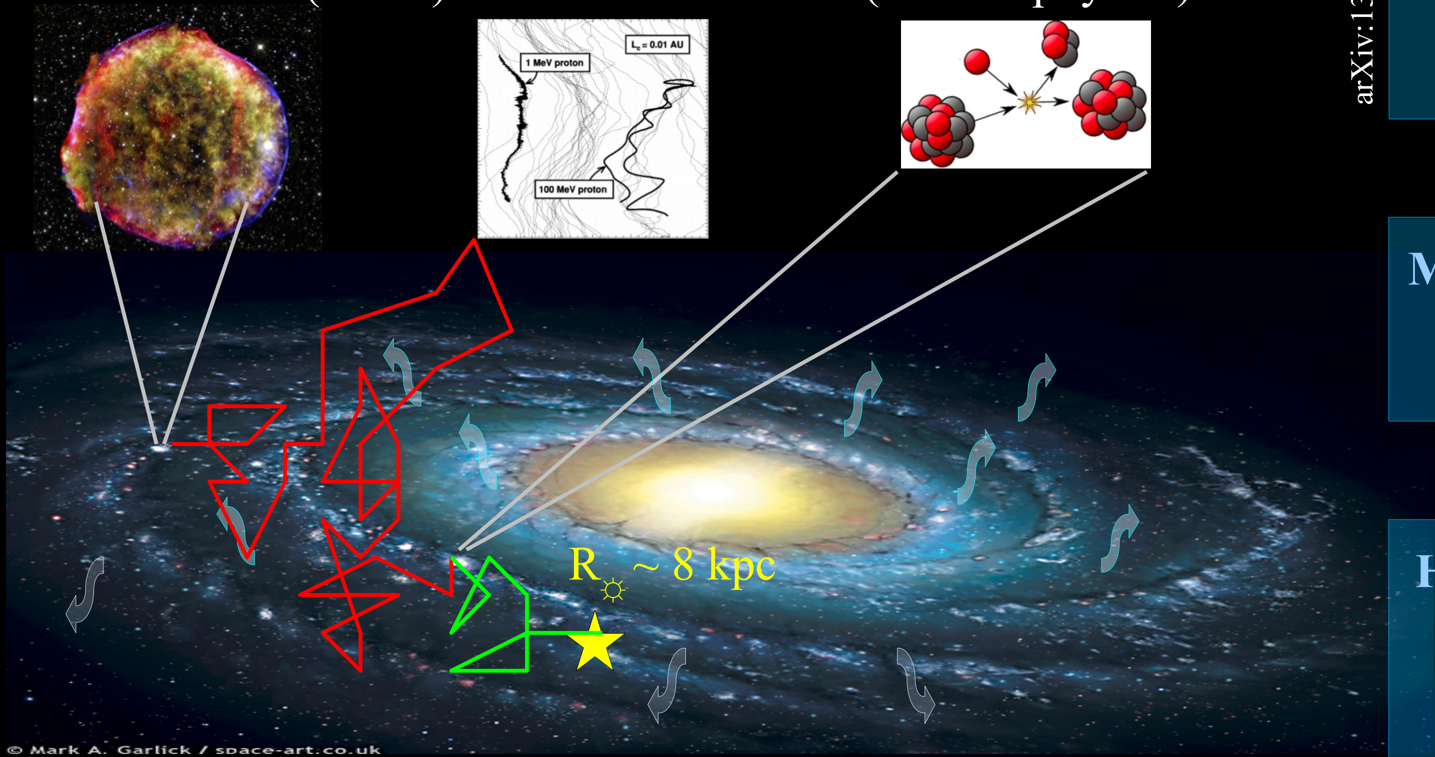
Charged cosmic rays in the Galaxy

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

2. Transport in the Galaxy
- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/decay

(MHD)

(nuclear physics)



(astrophysics + particle physics)

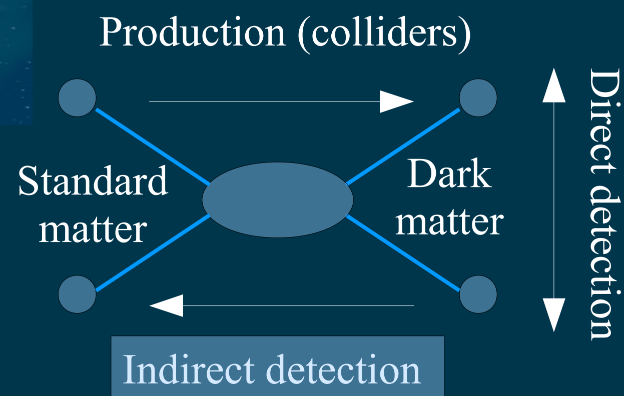
What about dark matter?

arXiv:1302.5076

Universe (after Planck)
- 68.3 % dark energy
- 26.8 % dark matter
- 4.9 % ordinary matter

Milky-way dark matter halo
- ~ spherical halo
- radius ~300 kpc

How to detect dark matter?



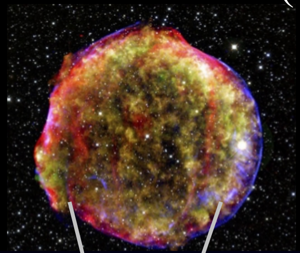
Charged cosmic rays in the Galaxy

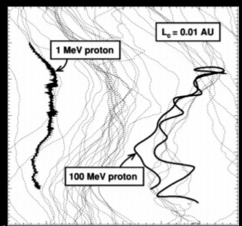
1. Source injection
- spectrum ~ R^{-2}
- abundances

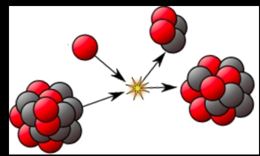
2. Transport in the Galaxy
- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/decay

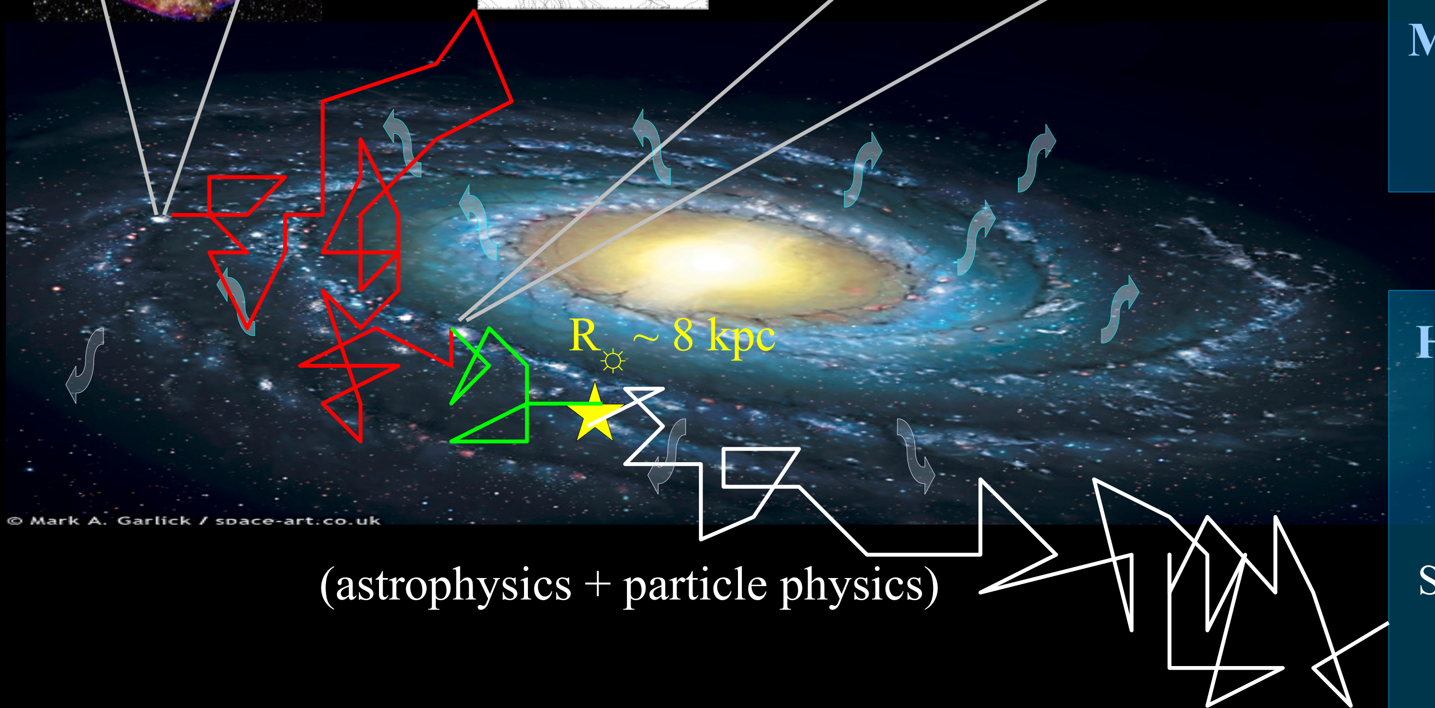
(MHD)

(nuclear physics)









(astrophysics + particle physics)

→ Sources for DM-induced cosmic rays from DM halo [same "transport"]

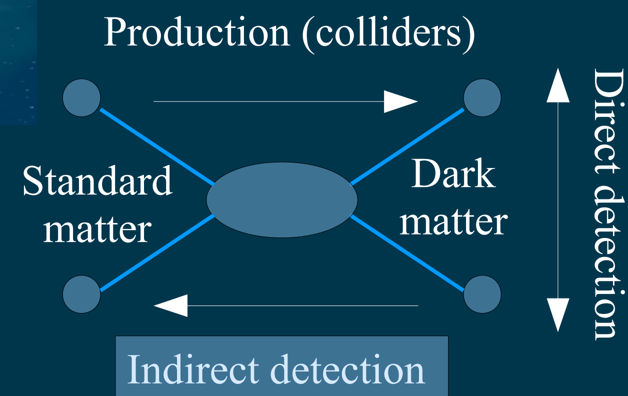
What about dark matter?

arXiv:1302.5076

Universe (after Planck)
- 68.3 % dark energy
- 26.8 % dark matter
- 4.9 % ordinary matter

Milky-way dark matter halo
- ~ spherical halo
- radius ~300 kpc

How to detect dark matter?



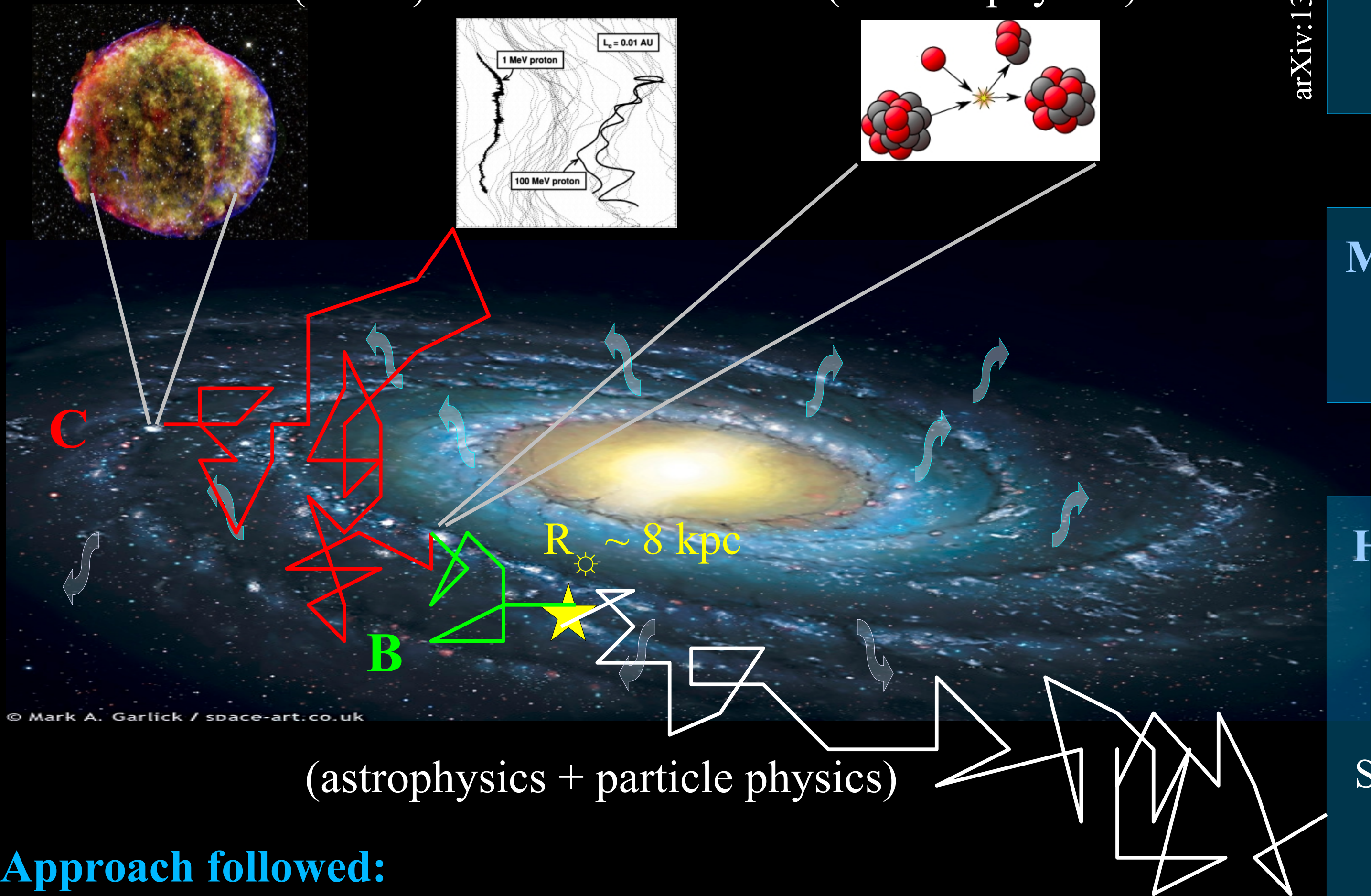
Charged cosmic rays in the Galaxy

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

2. Transport in the Galaxy
- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/decay

(MHD)

(nuclear physics)



(astrophysics + particle physics)

Approach followed:

→ Calibrate transport (model vs data): B/C, $^{10}Be/^{9}Be$

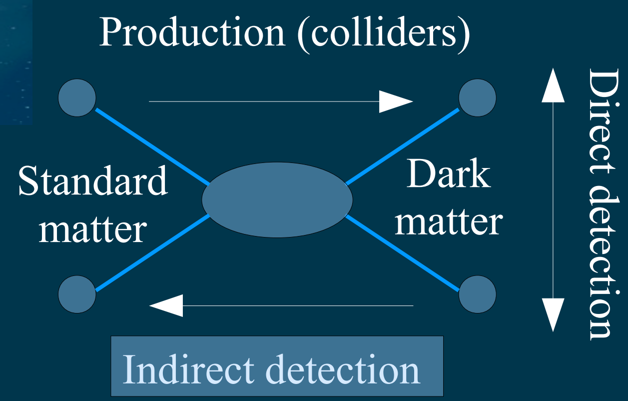
What about dark matter?

arXiv:1302.5076

Universe (after Planck)
- 68.3 % dark energy
- 26.8 % dark matter
- 4.9 % ordinary matter

Milky-way dark matter halo
- ~ spherical halo
- radius ~300 kpc

How to detect dark matter?



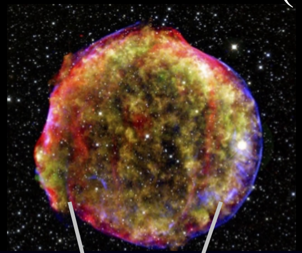
Charged cosmic rays in the Galaxy

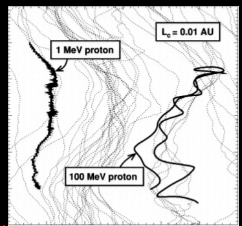
1. Source injection
- spectrum ~ R^{-2}
- abundances

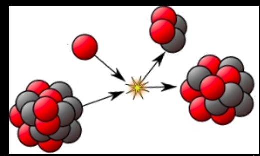
2. Transport in the Galaxy
- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/decay

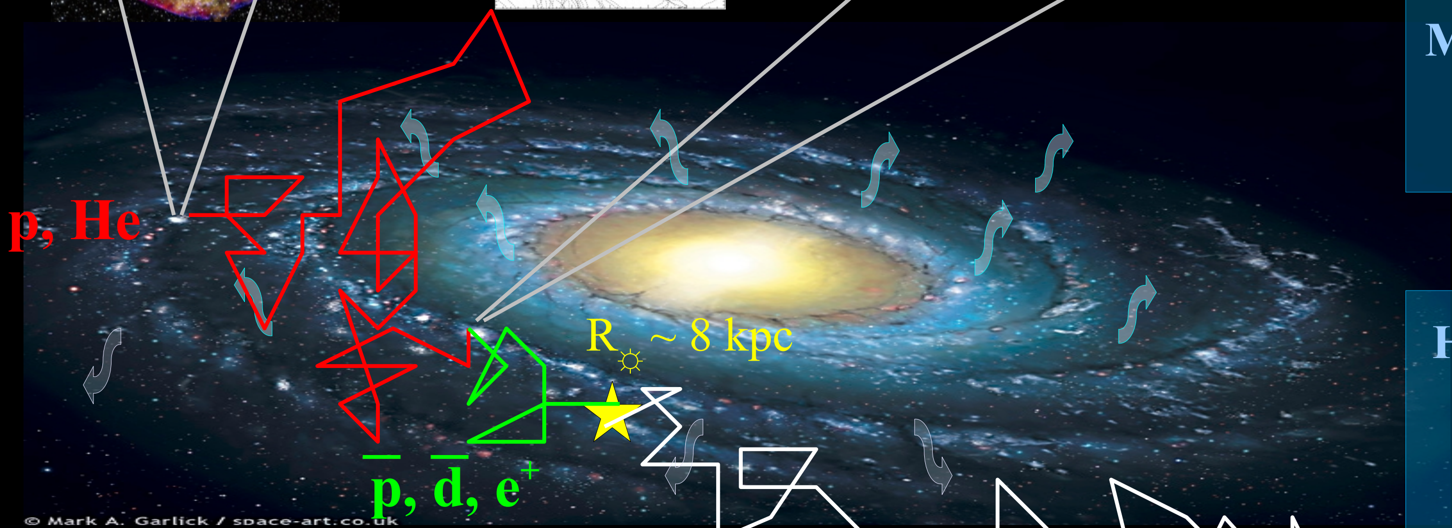
(MHD)

(nuclear physics)









(astrophysics + particle physics)

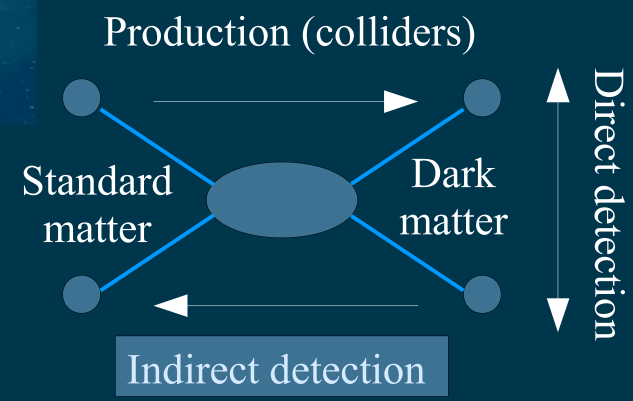
What about dark matter?

arXiv:1302.5076

Universe (after Planck)
- 68.3 % dark energy
- 26.8 % dark matter
- 4.9 % ordinary matter

Milky-way dark matter halo
- ~ spherical halo
- radius ~300 kpc

How to detect dark matter?



Approach followed:

→ Calibrate transport (model vs data): B/C, $^{10}Be/^{9}Be$

→ Calculate rare secondary fluxes (e^+, anti-p, anti-d, diffuse γ-rays)

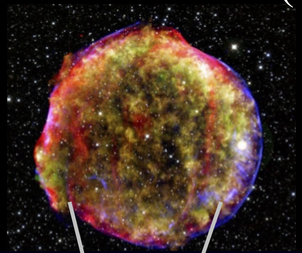
Charged cosmic rays in the Galaxy

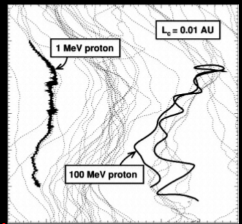
1. Source injection
- spectrum ~ R^{-2}
- abundances

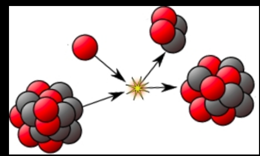
2. Transport in the Galaxy
- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/decay

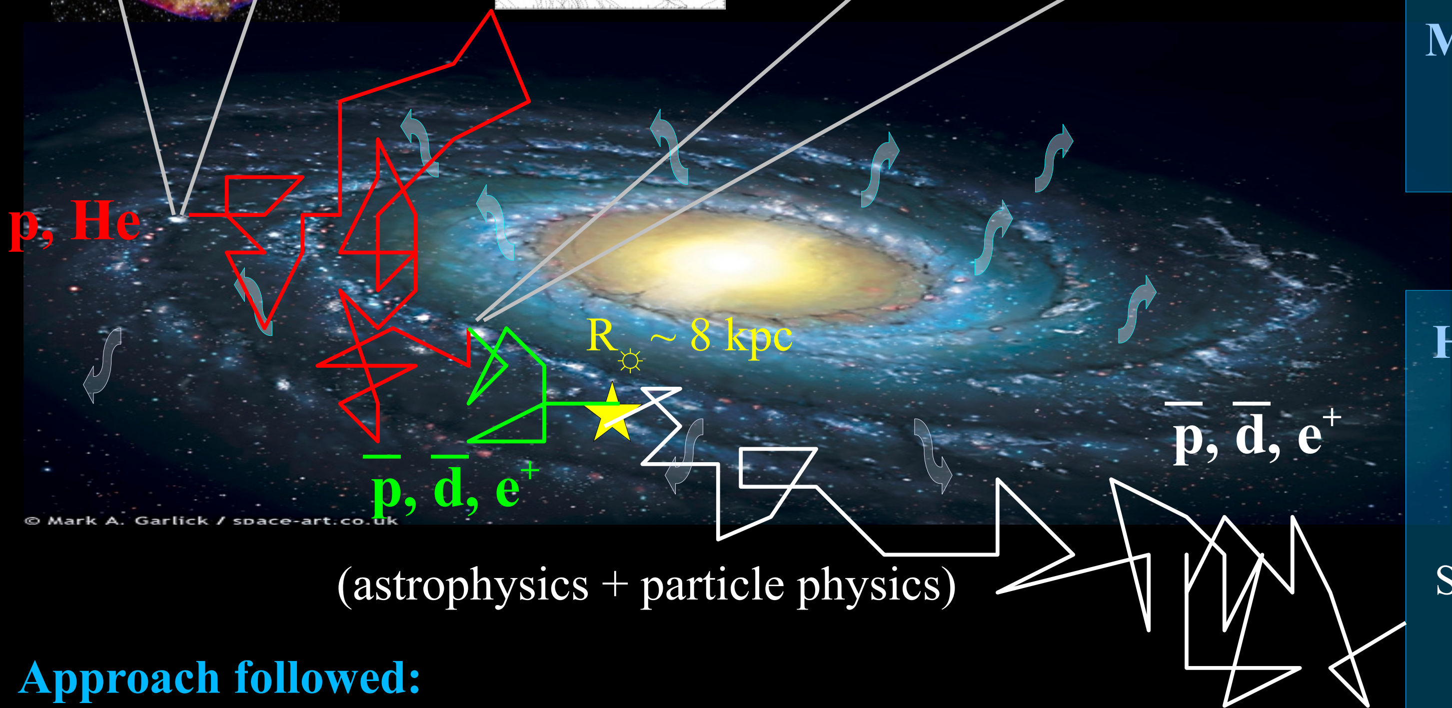
(MHD)

(nuclear physics)









(astrophysics + particle physics)

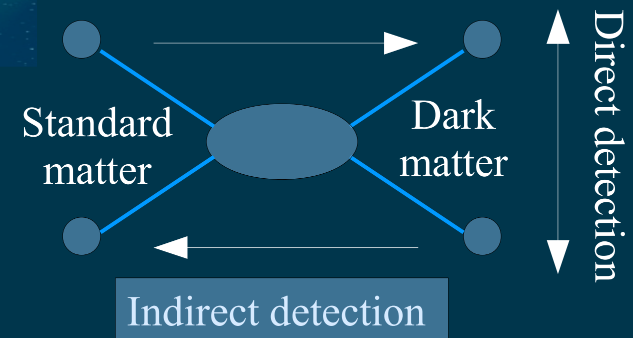
What about dark matter?

arXiv:1302.5076

Universe (after Planck)
- 68.3 % dark energy
- 26.8 % dark matter
- 4.9 % ordinary matter

Milky-way dark matter halo
- ~ spherical halo
- radius ~300 kpc

How to detect dark matter?



Approach followed:

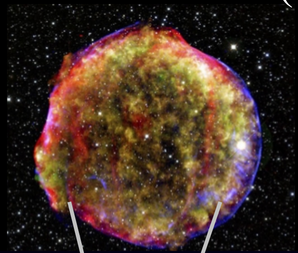
→ Calibrate transport (model vs data): B/C, ^{10}Be/^{9}Be
→ Calculate rare secondary fluxes (e^+, anti-p, anti-d, diffuse γ-rays)
→ Excess from DM annihilation?

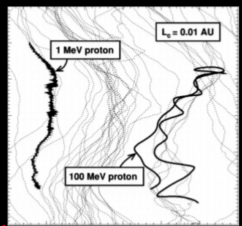
Charged cosmic rays in the Galaxy

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

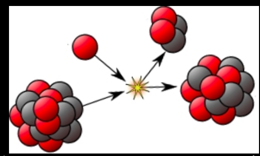
2. Transport in the Galaxy
- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/deca

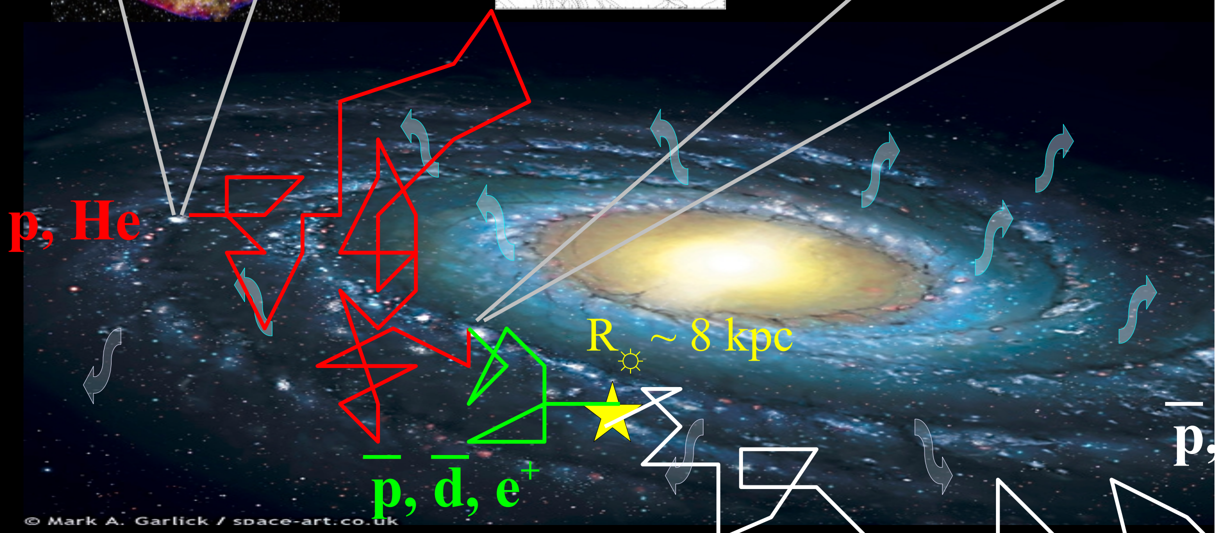
(MHD)





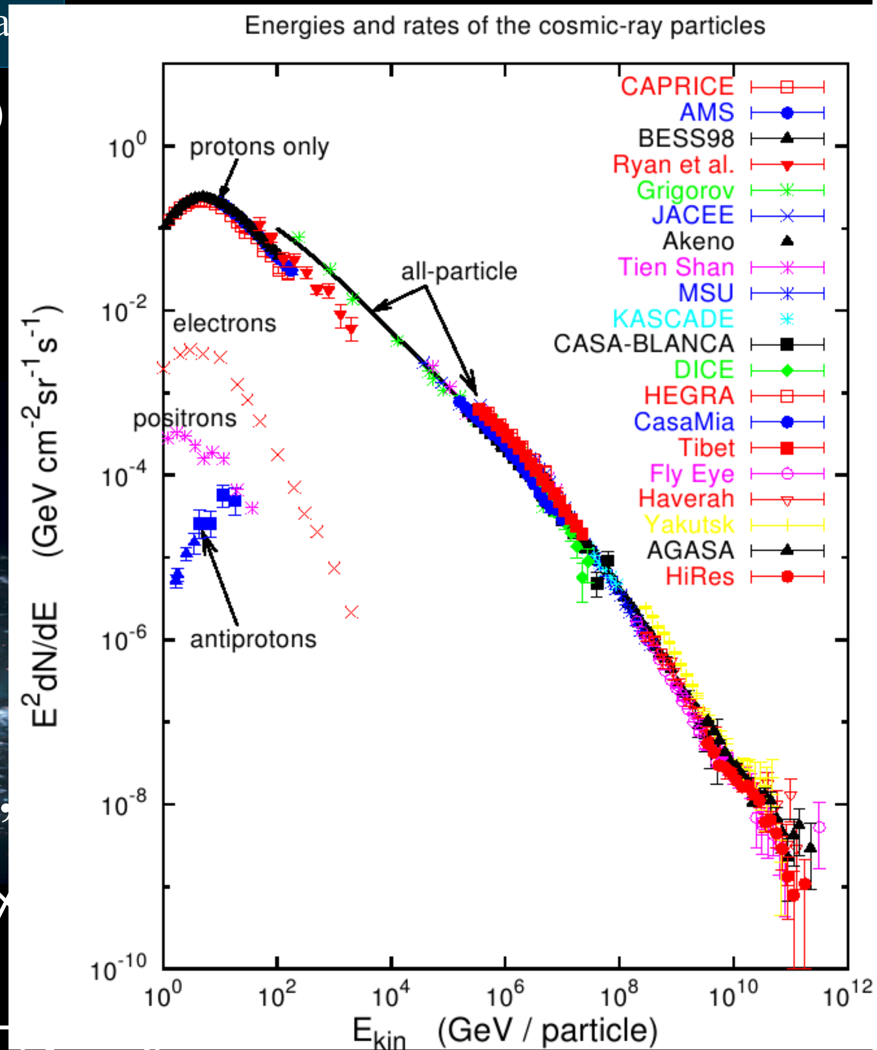
(nuclear physics)





(astrophysics + particle physics)

Hillas (astro-ph/0607109)



Approach followed:

→ Calibrate transport (model vs data): B/C, $^{10}Be/^{9}Be$

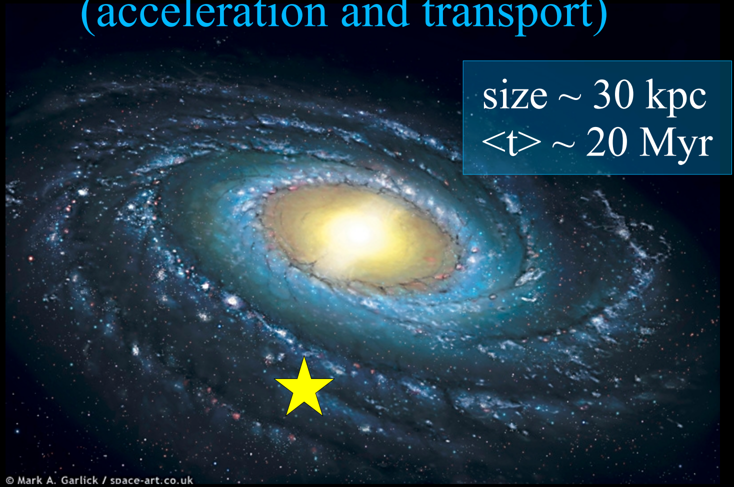
→ Calculate rare secondary fluxes (e^+, anti-p, anti-d, diffuse γ-rays)

→ Excess from DM annihilation?

An unexpected journey: processes and typical scales

1. Cosmic rays in the Galaxy

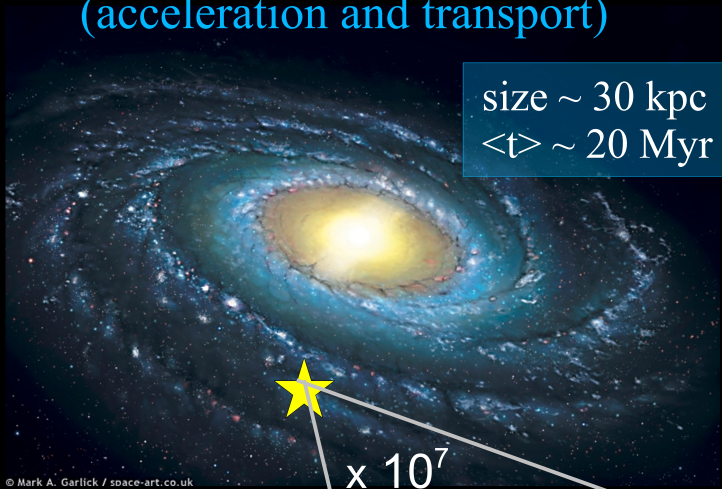
→ Spectra and abundances (acceleration and transport)



An unexpected journey: processes and typical scales

1. Cosmic rays in the Galaxy

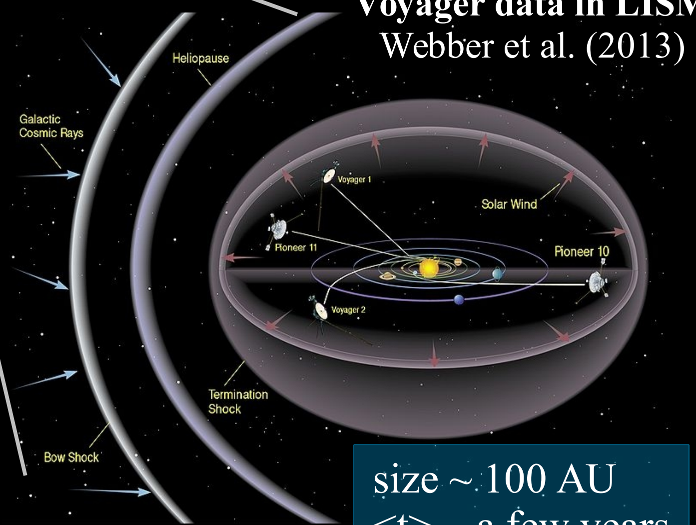
→ Spectra and abundances
(acceleration and transport)



size ~ 30 kpc
<t> ~ 20 Myr

x 10^7

Voyager data in LISM
Webber et al. (2013)



size ~ 100 AU
<t> ~ a few years

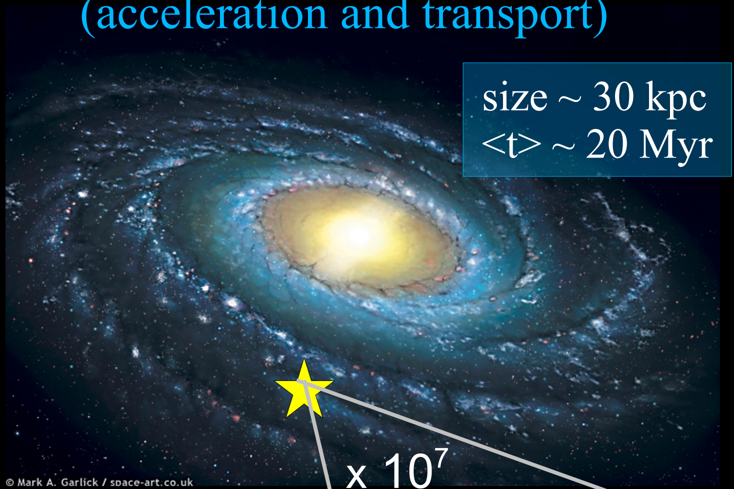
2. Transport in the Solar cavity

→ flux modulation < 10 GeV/n
→ time dependence

An unexpected journey: processes and typical scales

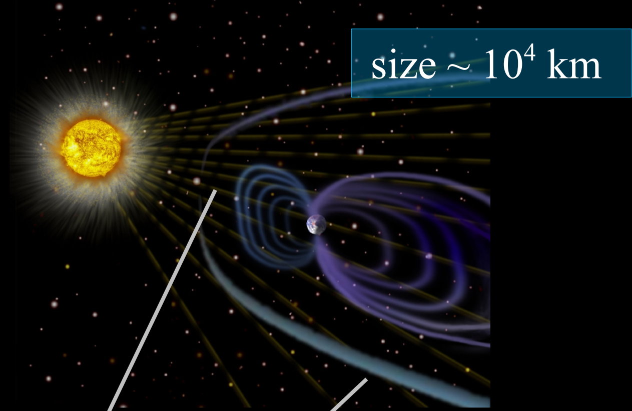
1. Cosmic rays in the Galaxy

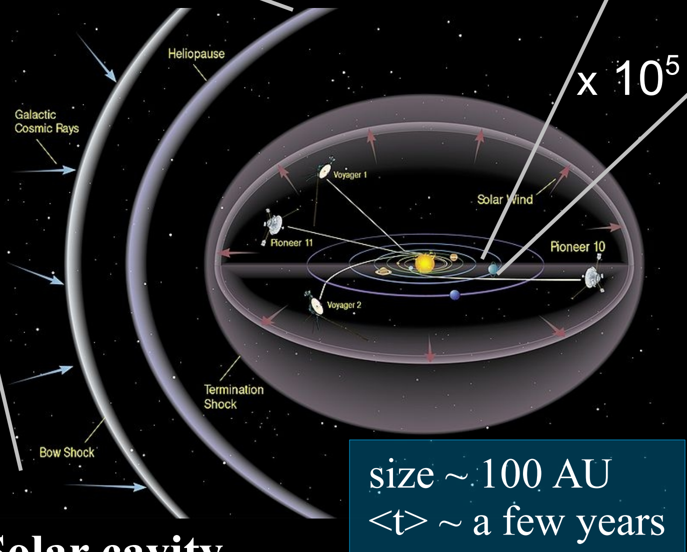
→ Spectra and abundances (acceleration and transport)



3. Earth magnetic shield

→ Cut-off rigidity for detectors





2. Transport in the Solar cavity

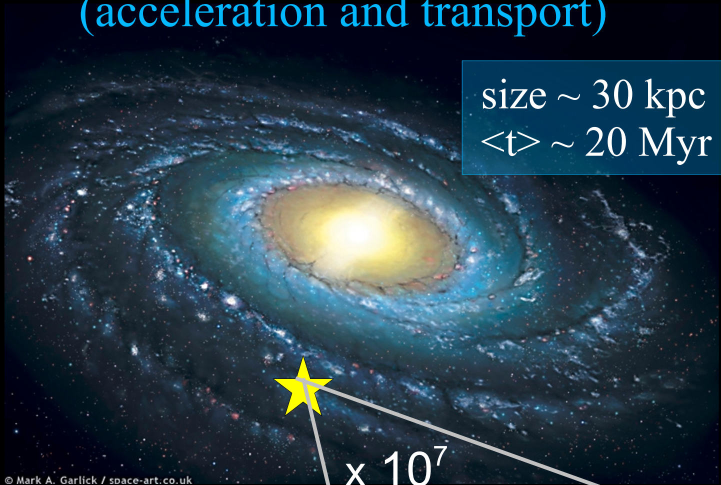
→ flux modulation < 10 GeV/n

→ time dependence

An unexpected journey: processes and typical scales

1. Cosmic rays in the Galaxy

→ Spectra and abundances (acceleration and transport)

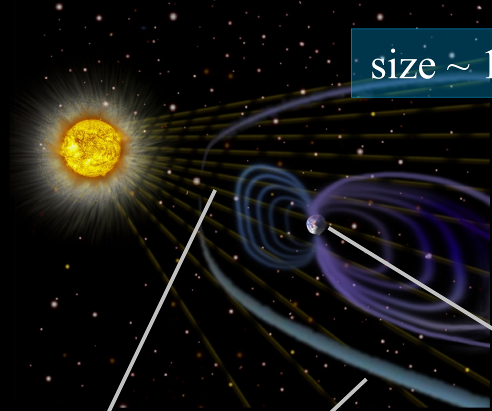


size ~ 30 kpc
<t> ~ 20 Myr

x 10^7

3. Earth magnetic shield

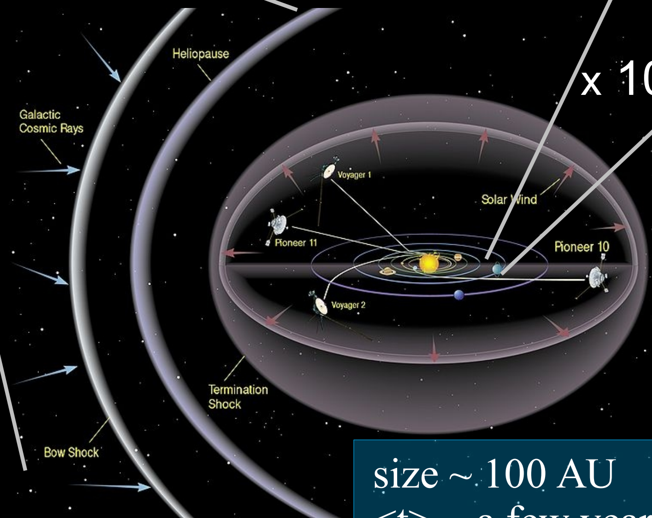
→ Cut-off rigidity for detectors



size ~ 10^4 km

x 10^2

x 10^5

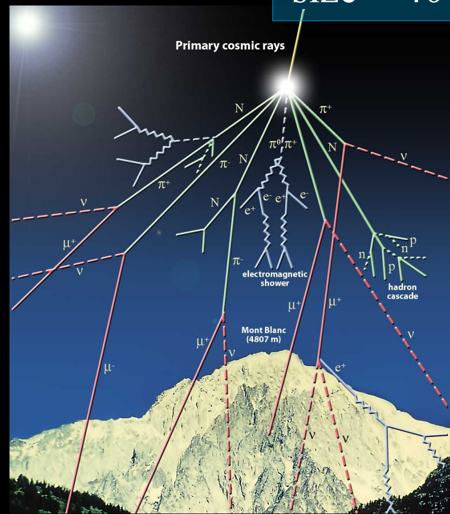


size ~ 100 AU
<t> ~ a few years

2. Transport in the Solar cavity

→ flux modulation < 10 GeV/n
→ time dependence

size ~ 40 km

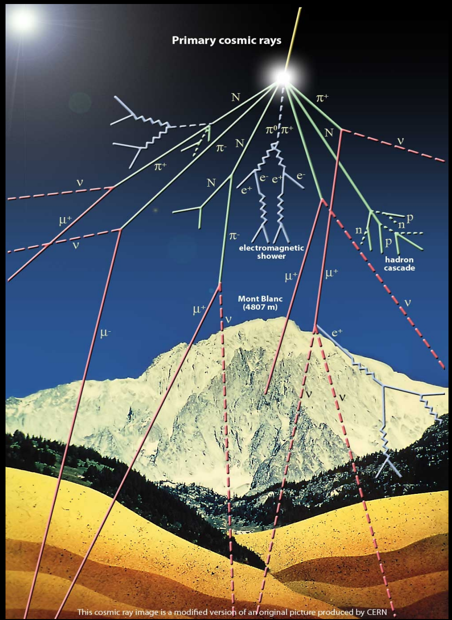


4. Atmospheric showers

→ Ground-based detection
→ Solar activity monitoring
[N.B.: Čerenkov flash ~ 10^{-8} s]

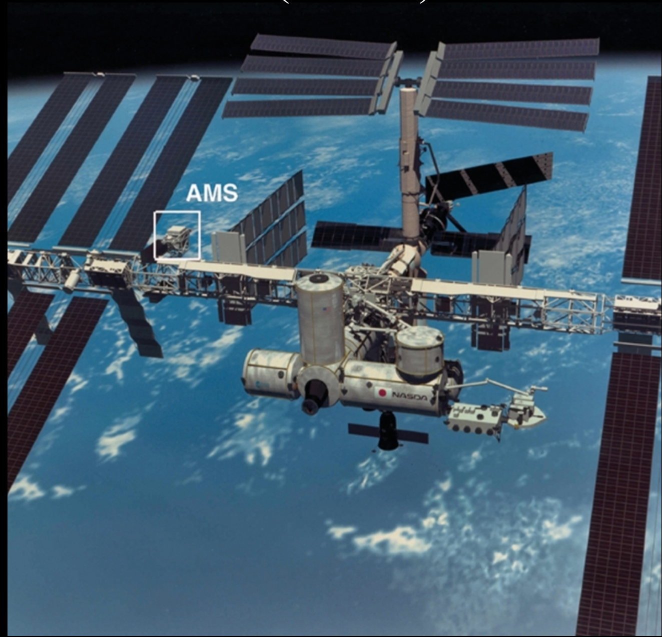
A brief history of cosmic-ray measurements

Mountain altitude < 5 km



CREAM balloon ~ 40 km

AMS-02 (on ISS) ~ 300 km



CR discovery — 1910

1930 — 1950 — 1980 — 2000

e^-, e^+ — Diffuse γ — $\bar{p}$ — TeV astronomy — ν — $\bar{d}$?

e^+, μ, π , K, Λ

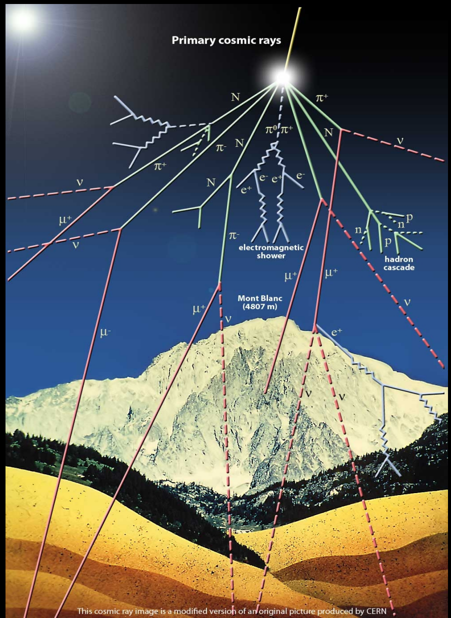
Elements up to U

^{10}Be - ^{54}Mn

Cosmic rays = Particle physics → Particle physics / Astrophysics } + astroparticle physics

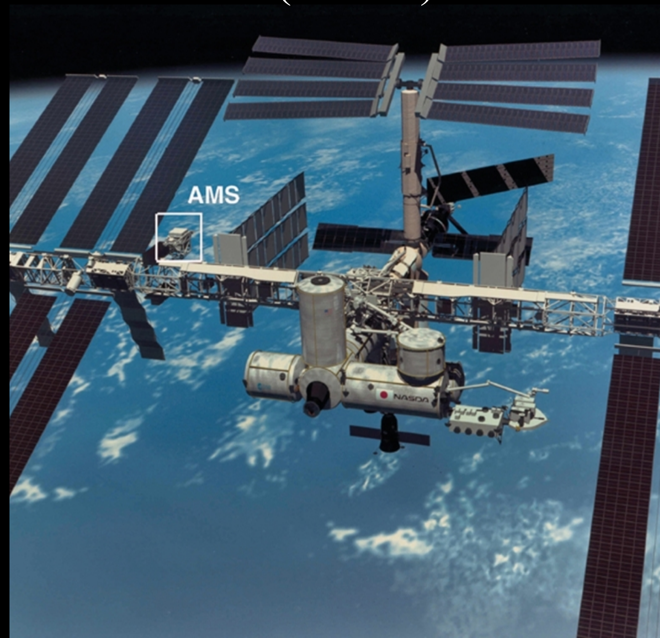
A brief history of cosmic-ray measurements

Mountain altitude < 5 km



CREAM balloon ~ 40 km

AMS-02 (on ISS) ~ 300 km



CR discovery — 1910

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

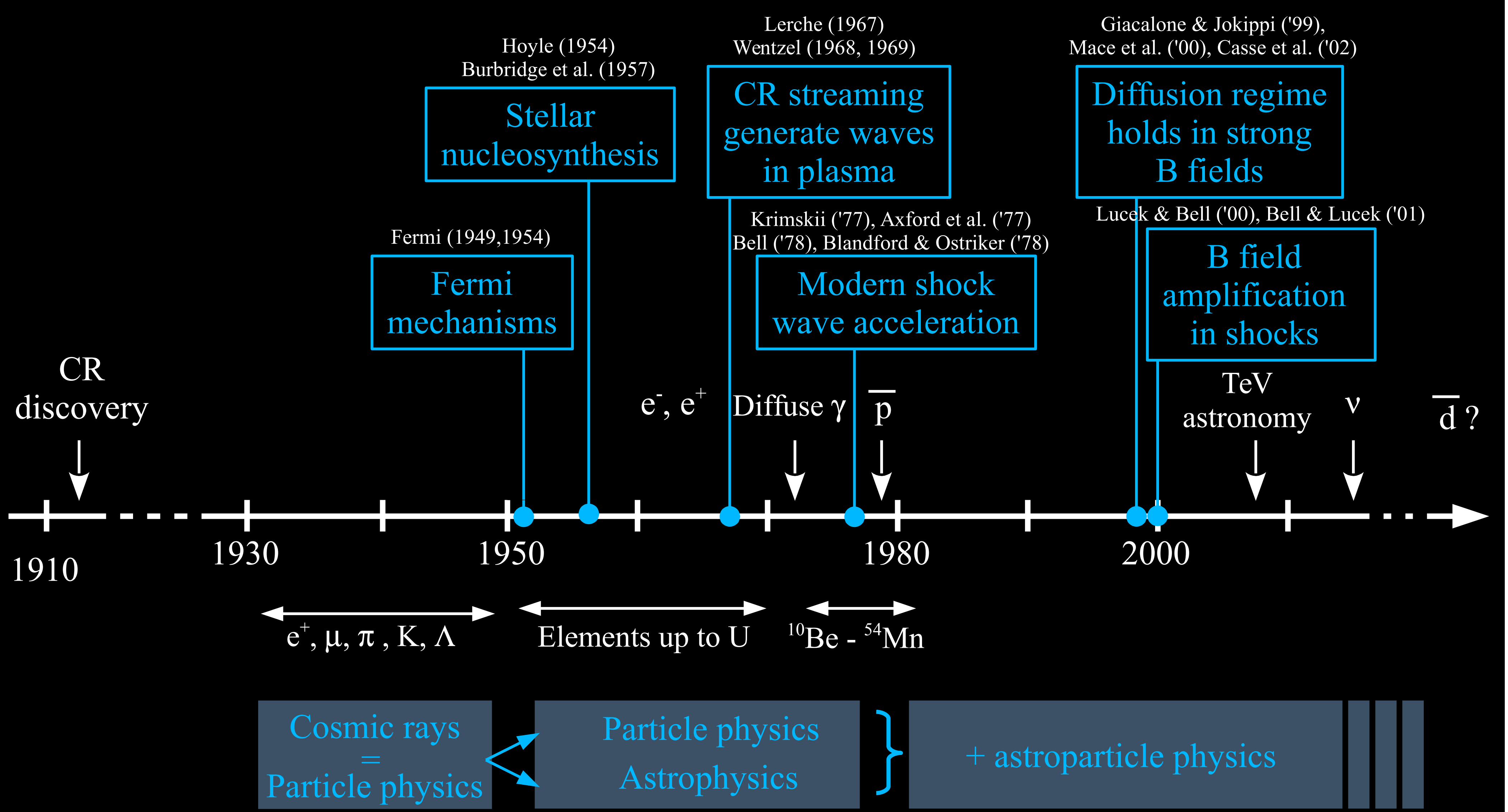
Database (arXiv:1302.5525)
http://lpsc.in2p3.fr/crdb

Cosmic rays = Particle physics

Particle physics
Astrophysics

+ astroparticle physics

A brief history of cosmic-ray theory

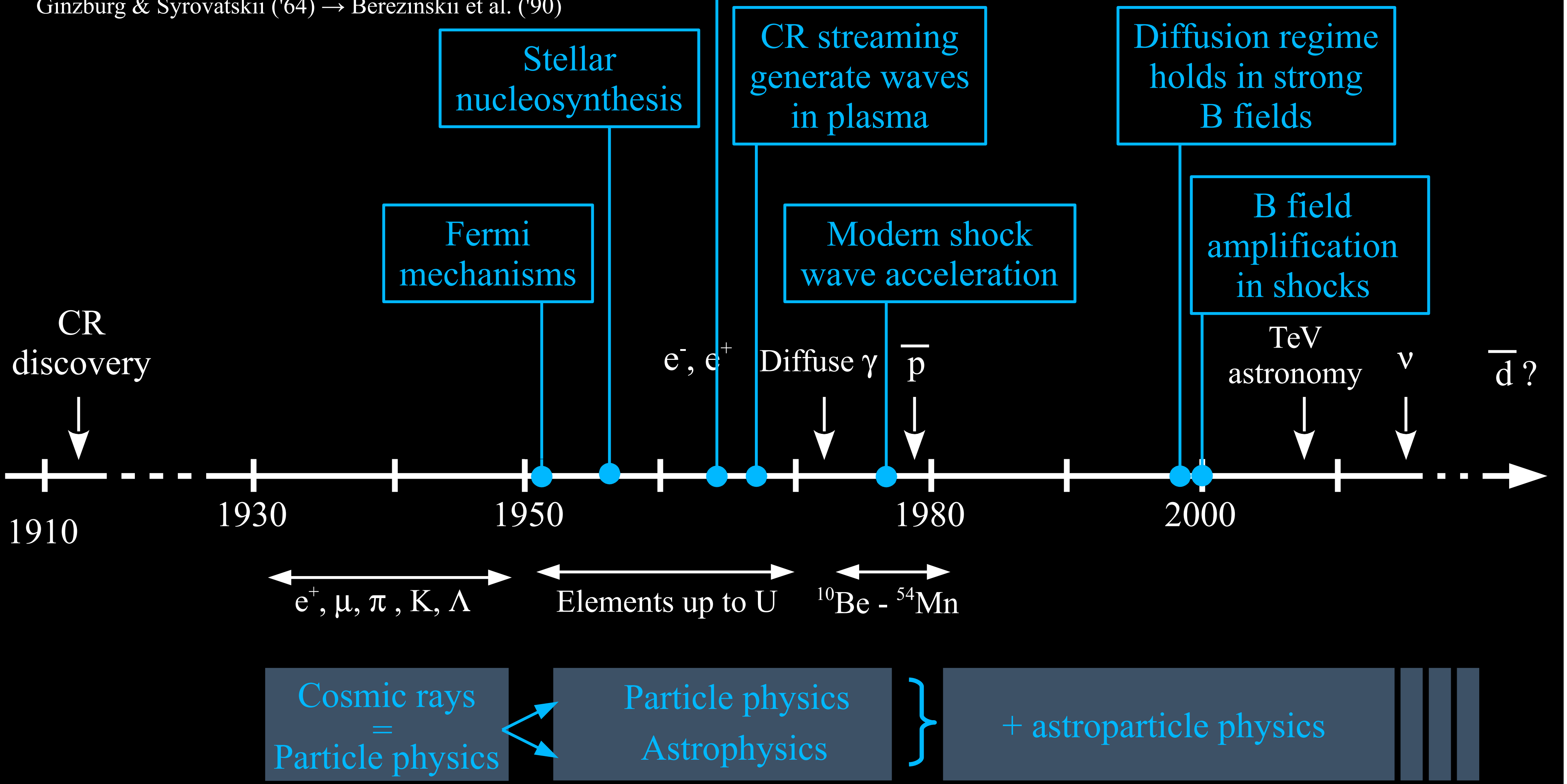


A brief history of cosmic-ray theory

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

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

Parker ('65), Jokipii ('66), Gleeson & Axford ('67, '68)
Ginzburg & Syrovatskii ('64) → Berezinskii et al. ('90)

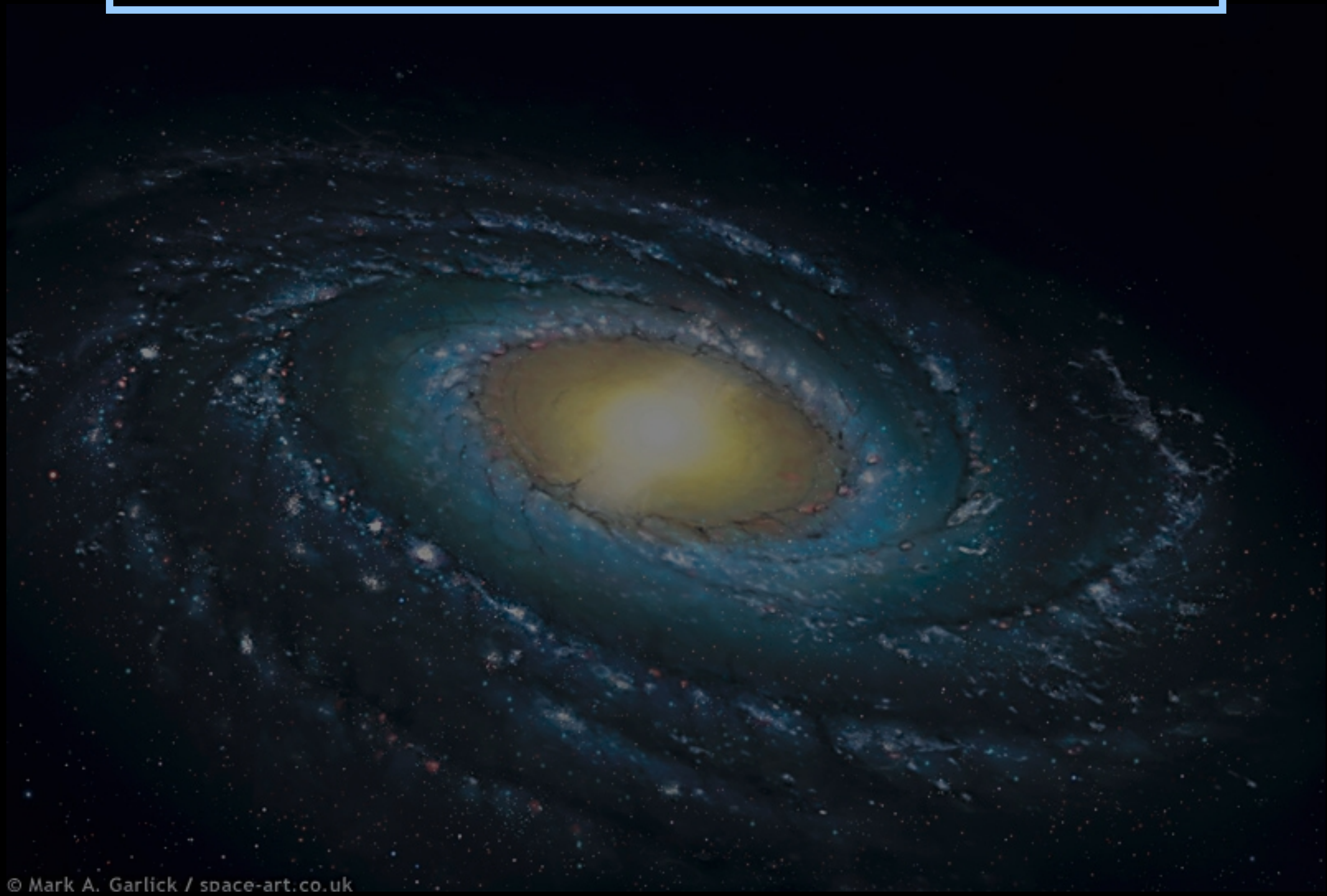


I – Galactic cosmic rays (GCR)

II – GCR phenomenology: basics

II – Status of recent measurements

III – Conclusions



Transport equation: ingredients and solutions

1. Transport equations

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

- Coupled set of second order differential equation (space and momentum)
- All nuclear species to consider

2. Ingredients

- Nuclear physics
- 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,...]

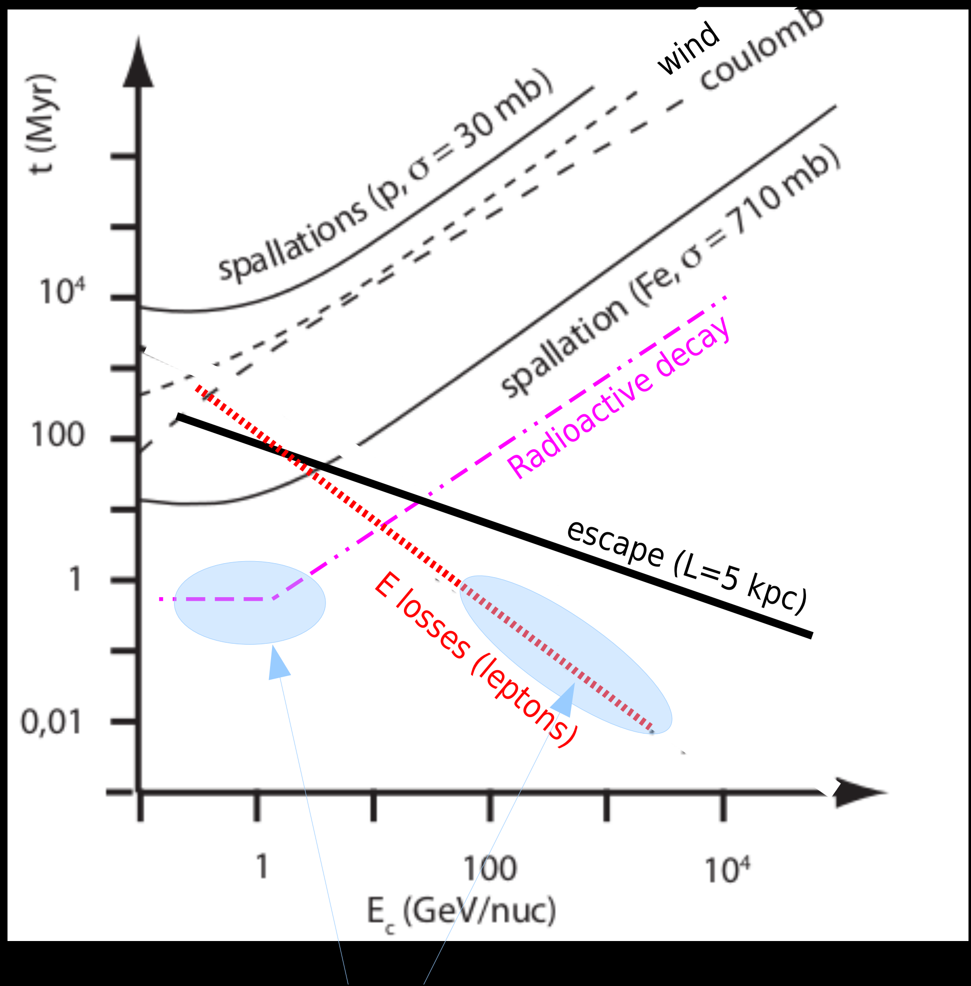
GALPROP: Strong et al. (1998)
DRAGON: Evoli et al. (2008)

Faharat et al. (2008)

USINE: Maurin et al. (2001)

Transport equation: typical timescales

Adapted from Taillet (2010)

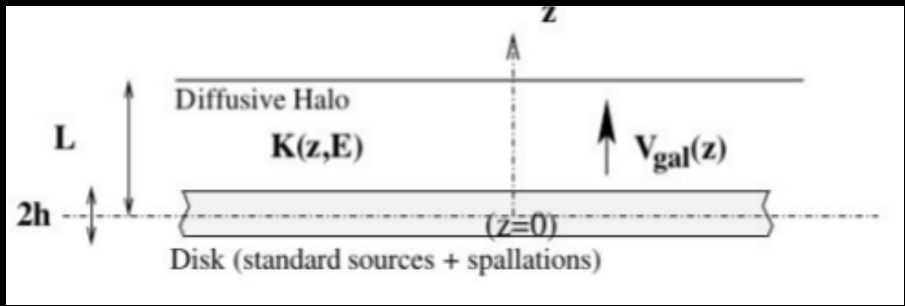


→ "Local" origin (~ 100 pc)
[local source or production]

Transport equation: 2 zone (thin disc+thick halo) model

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

Webber, Lee & Gupta (1992)



$$-\frac{d}{dz}\left\{K(z)\frac{dN}{dz}\right\} + \frac{d}{dz}[V_{\rm gal}(z)N] + nv\sigma 2h\delta(z)N = q(z,E)$$

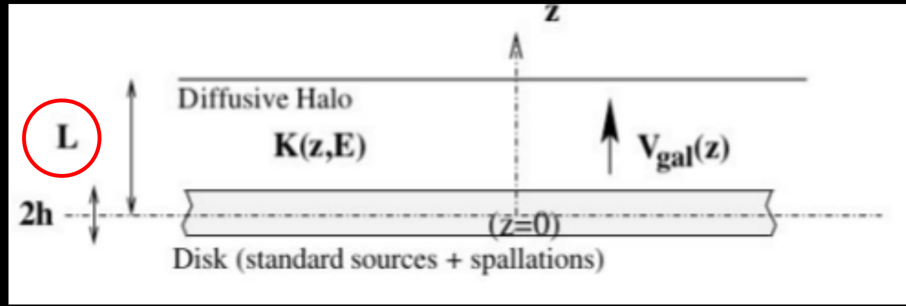
→ simple, but captures all the physics

K0/L degeneracy: impact on dark matter signal

$$-\frac{d}{dz}\left\{K(z)\frac{dN}{dz}\right\} + \frac{d}{dz}[V_{\rm gal}(z)N] + nv\sigma 2h\delta(z)N = q(z,E)$$

+ isotropic diffusion
+ no galactic wind

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



Transport parameters from B/C analysis

$$-KN'' + nv\sigma 2h\delta(z)\times N = 2h\delta(z)Q(E)$$

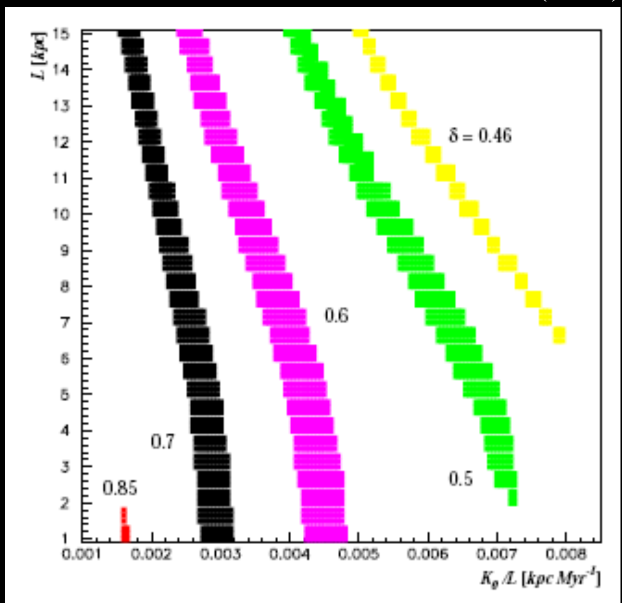
$$\frac{N^s}{N^p}(z=0) \propto \frac{L}{K_0}\mathcal{R}^{-\delta}$$

Maurin et al. (2001)

Parameters matching B/C data

↓

K0/L degeneracy

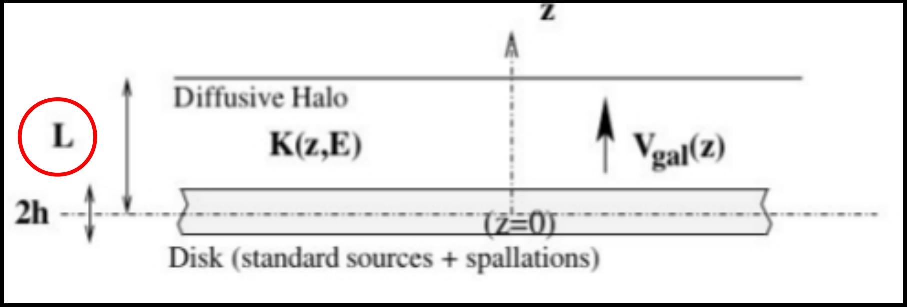


K0/L degeneracy: impact on dark matter signal

$$-\frac{d}{dz}\left\{K(z)\frac{dN}{dz}\right\} + \frac{d}{dz}[V_{\rm gal}(z)N] + nv\sigma 2h\delta(z)N = q(z,E)$$

+ isotropic diffusion
+ no galactic wind

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



Transport parameters from B/C analysis

$$-KN'' + nv\sigma 2h\delta(z)\times N = 2h\delta(z)Q(E)$$

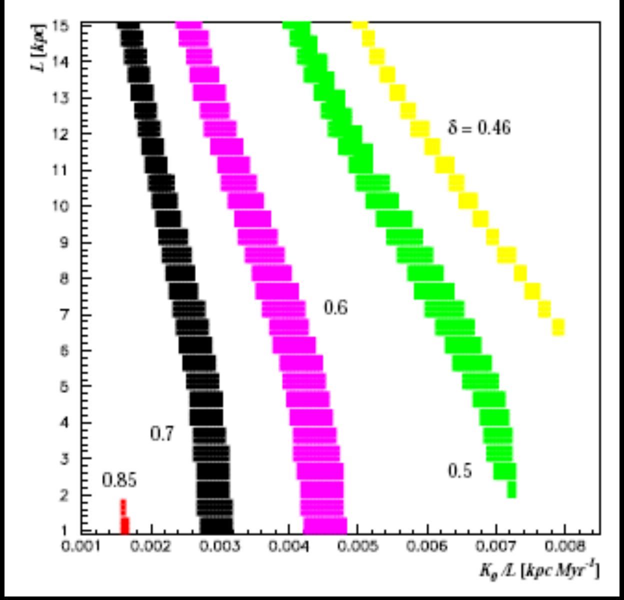
$$\frac{N^s}{N^p}(z=0) \propto \frac{L}{K_0}\mathcal{R}^{-\delta}$$

Maurin et al. (2001)

Parameters matching B/C data

↓

K0/L degeneracy



Dark matter signal

$$-KN'' = q \quad \Rightarrow \quad N_{(\bar{p},\bar{d})}(z=0) = \frac{q\,L^2}{2K}$$

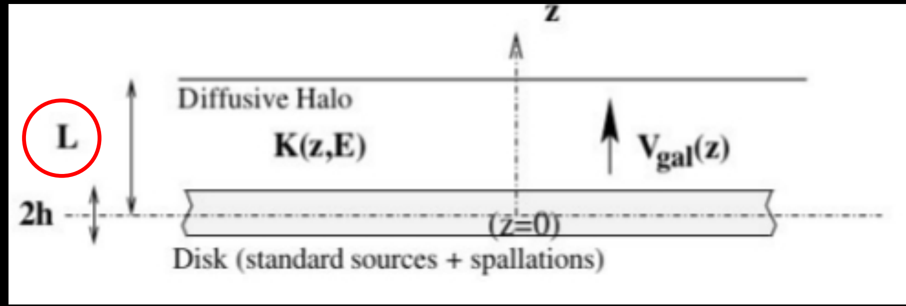
→ for fixed K0/L (from B/C), signal scales with L, hence the min/med/max parameters

K0/L degeneracy: impact on dark matter signal

$$-\frac{d}{dz}\left\{K(z)\frac{dN}{dz}\right\} + \frac{d}{dz}[V_{\rm gal}(z)N] + nv\sigma 2h\delta(z)N = q(z,E)$$

+ isotropic diffusion
+ no galactic wind

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



Transport parameters from B/C analysis

$$-KN'' + nv\sigma 2h\delta(z) \times N = 2h\delta(z)Q(E)$$

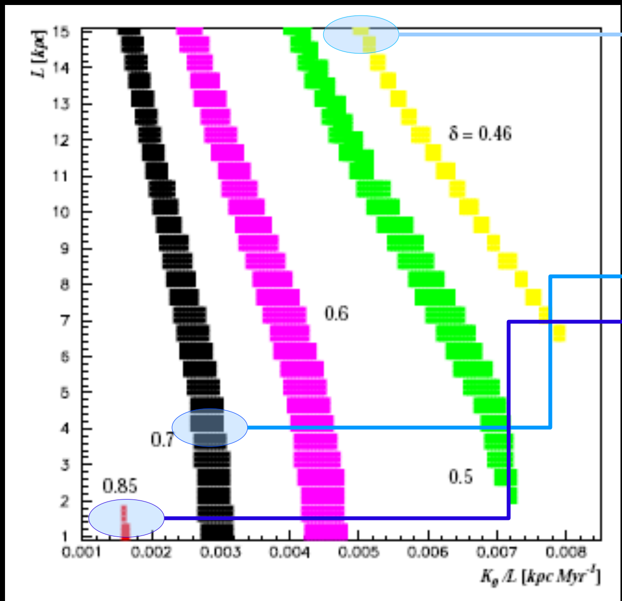
$$\frac{N^s}{N^p}(z=0) \propto \frac{L}{K_0}\mathcal{R}^{-\delta}$$

Maurin et al. (2001)

Parameters matching B/C data

↓

K0/L degeneracy



Dark matter signal

$$-KN'' = q \quad \Rightarrow \quad N_{(\bar{p},\bar{d})}(z=0) = \frac{q\,L^2}{2K}$$

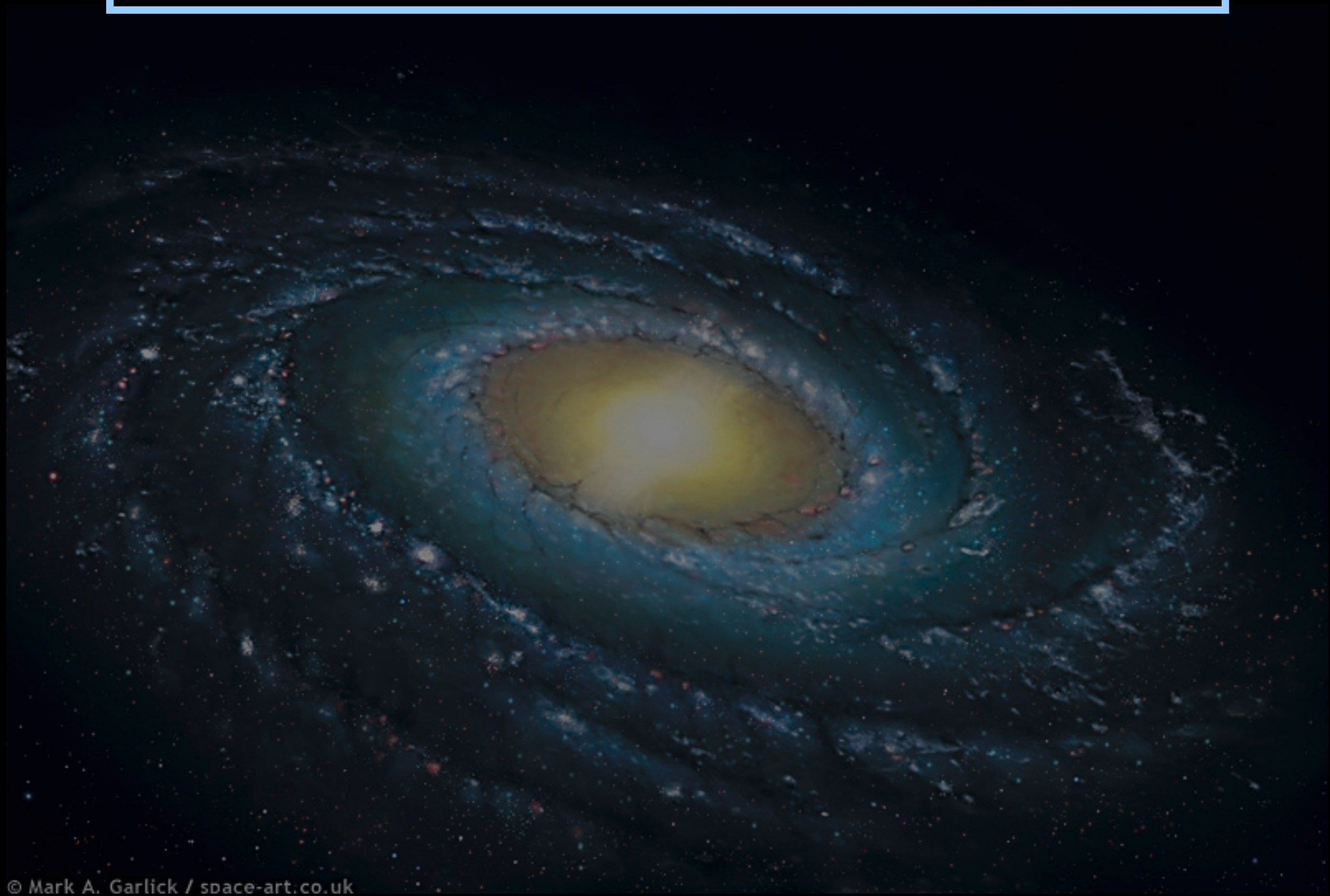
→ for fixed K0/L (from B/C), signal scales with L, hence the min/med/max parameters

Donato et al. (2004)

Case	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/s)	V_A (km/s)	$\chi^2_{\rm B/C}$
max	0.46	0.0765	15	5	117.6	39.98
med	0.70	0.0112	4	12	52.9	25.68
min	0.85	0.0016	1	13.5	22.4	39.02

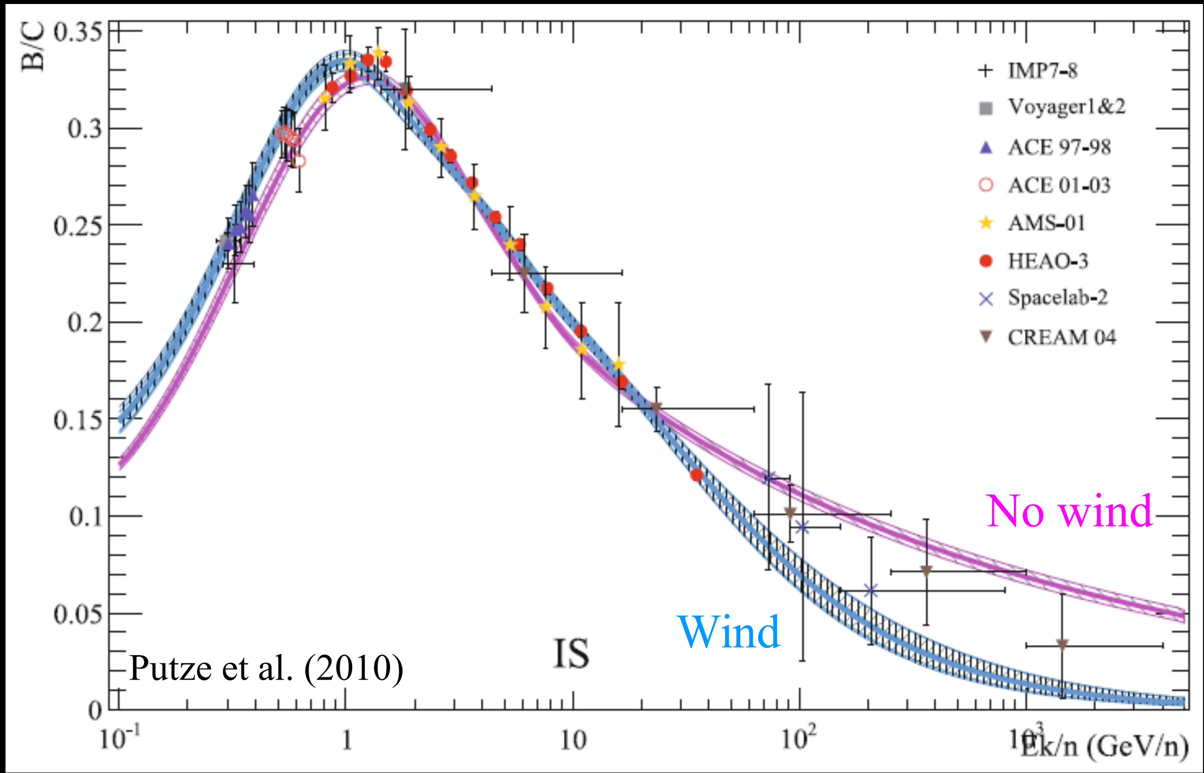
N.B.: K0/L degeneracy also broken for positrons
Delahaye et al. (2009)

I – Galactic cosmic rays (GCR)
II – GCR phenomenology: basics
II – Status of recent measurements
III – Conclusions



Determination of transport parameters and uncertainties

MCMC analysis (USINE: Putze et al. '09,'10,'11 + GALPROP: Trotta et al.' 11)



Results and issues

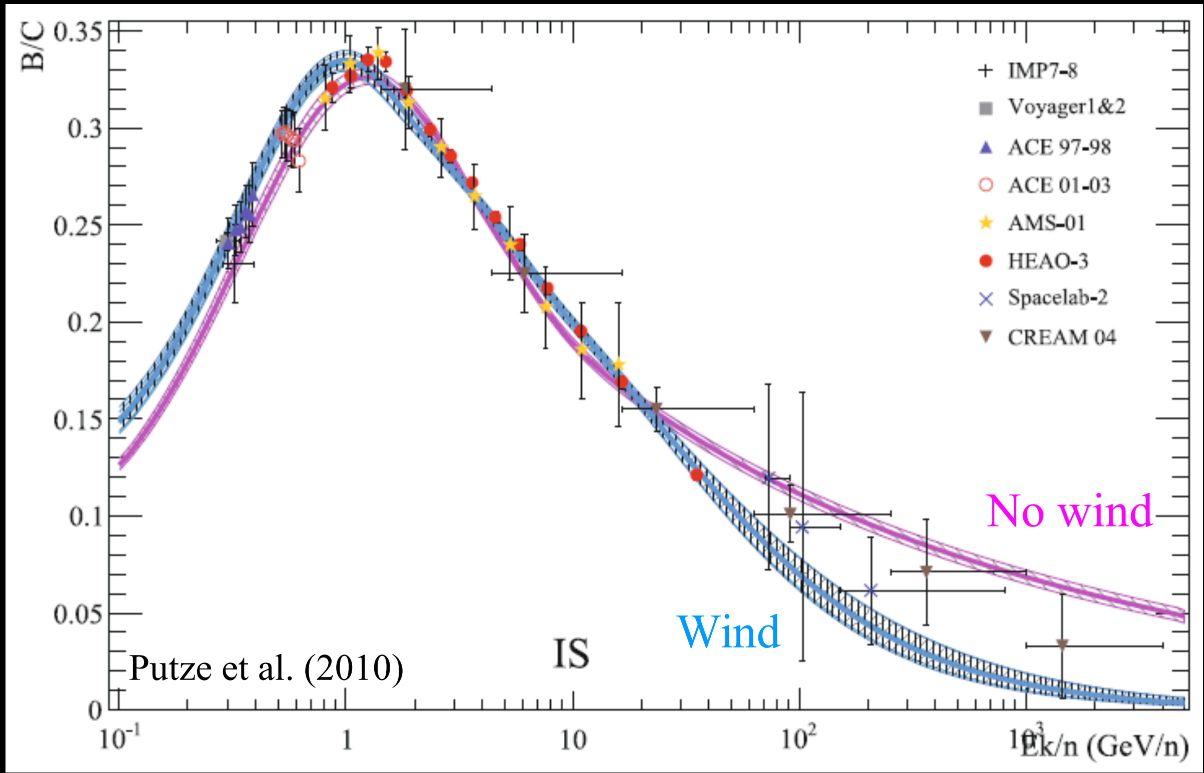
1. Degenerate transport parameters

Solution considered

- Use radioactive clocks ^{10}Be → Ptuskin et Soutoul '98; Donato et al. '03, Putze et al. '10
- Use secondary e^+ → Lavalle et al., in prep

Determination of transport parameters and uncertainties

MCMC analysis (USINE: Putze et al. '09,'10,'11 + GALPROP: Trotta et al.' 11)



Results and issues

1. Degenerate transport parameters

2. Systematic errors from nuc. phys.

Maurin et al. (2010)

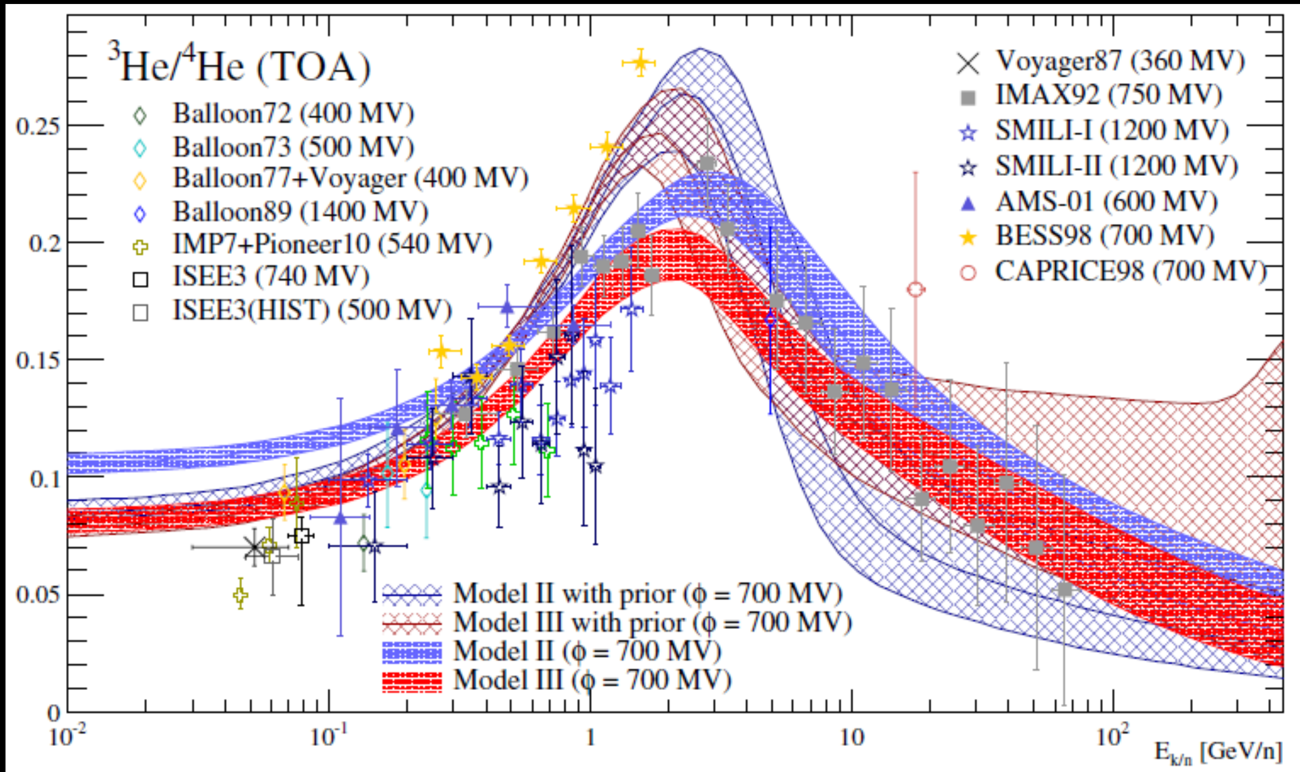
Solution considered

- Use radioactive clocks ^{10}Be → Ptuskin et Soutoul '98; Donato et al. '03, Putze et al. '10
- Use secondary e^+ → Lavalle et al., in prep

- Improve cross-sections → Hard to achieve
- Use of quartet ratio → Works well!
- Use AMS Li flux → In progress...

Determination of transport parameters and uncertainties

Coste et al. (2012)



Results and issues

1. Degenerate transport parameters

2. Systematic errors from nuc. phys.

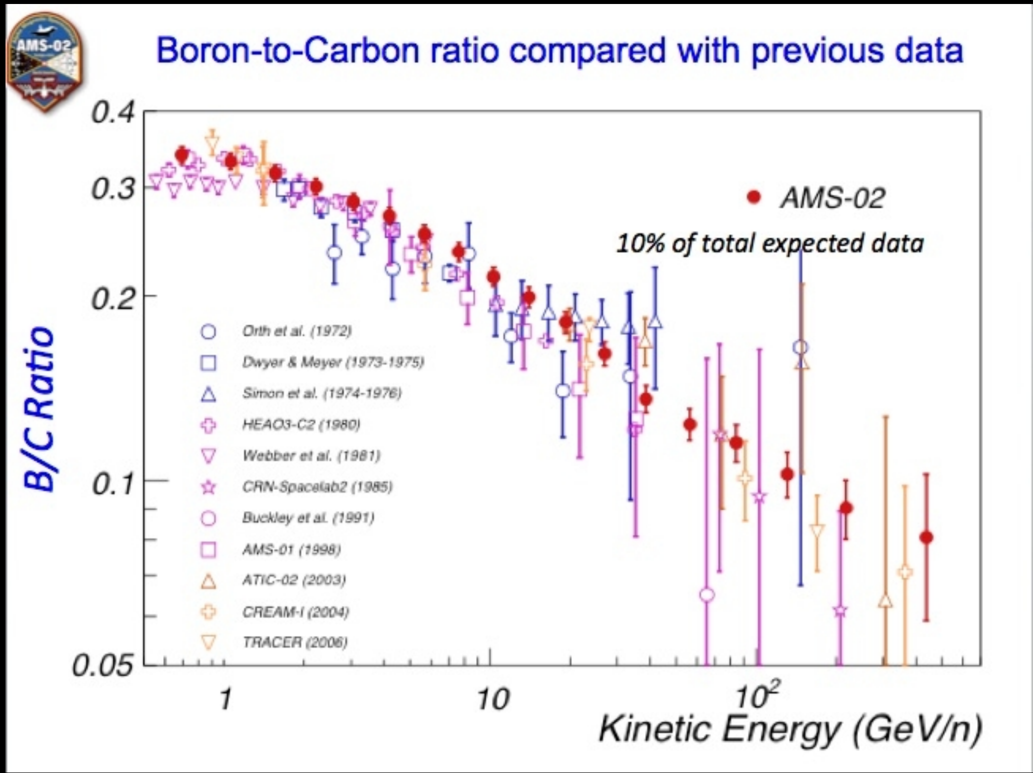
Solution considered

- Use radioactive clocks ^{10}Be → Ptuskin et Soutoul '98; Donato et al. '03, Putze et al. '10
- Use secondary e^+ → Lavalle et al., in prep

- Improve cross-sections → Hard to achieve
- Use of quartet ratio → Works well!
- Use AMS Li flux → In progress...

Determination of transport parameters and uncertainties

→ B/C: better data from AMS-02 (preliminary) + CREAM high energy data



Results and issues

1. Degenerate transport parameters

2. Systematic errors from nuc. phys.

Solution considered

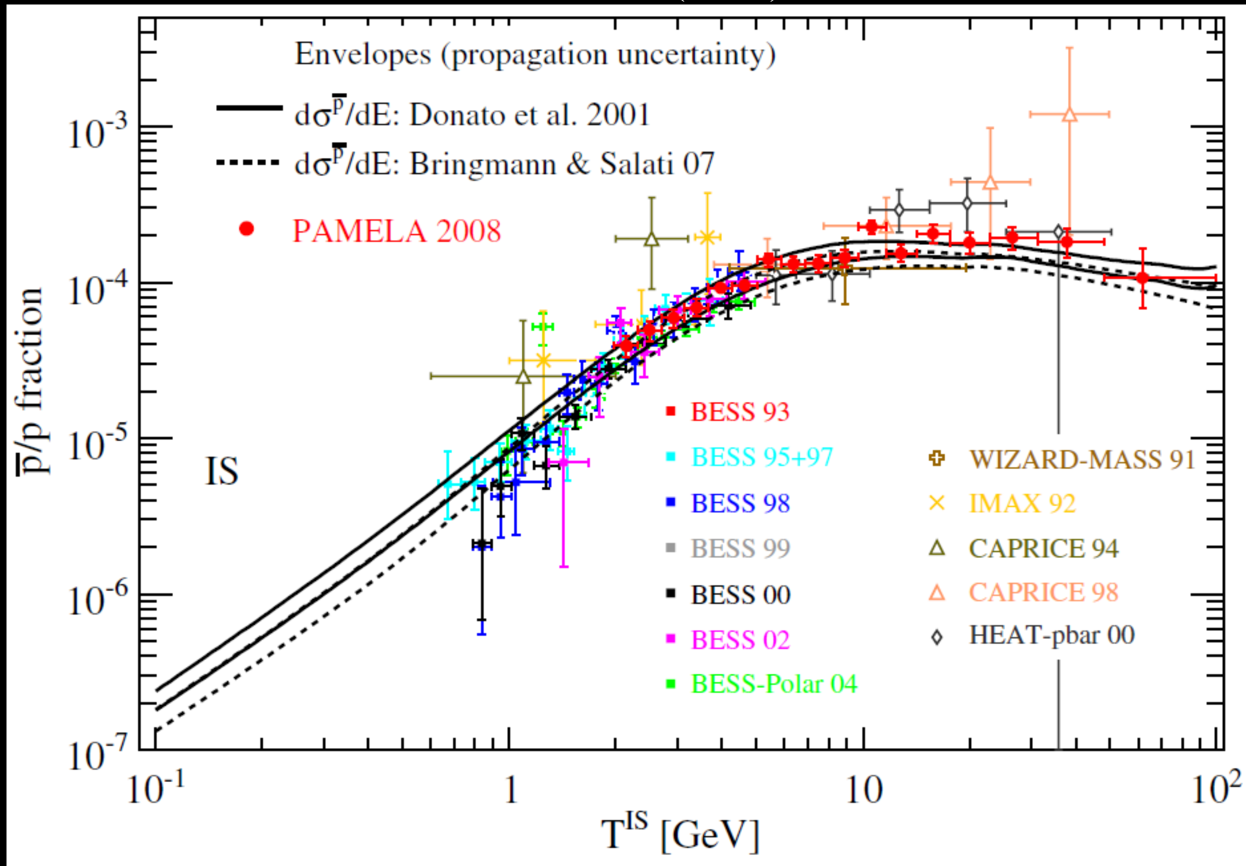
- Use radioactive clocks ^{10}Be → Ptuskin et Soutoul '98; Donato et al. '03, Putze et al. '10
- Use secondary e^+ → Lavalle et al., in prep

- Improve cross-sections → Hard to achieve
- Use of quartet ratio → Works well!
- Use AMS Li flux → In progress...

Anti-matter from dark matter: antiprotons

Previous B/C transport parameters (no free parameters) + nuclear X-sections

Donato et al. (2009)



1. Good agreement between model and data (no dark matter needed)
2. Small propagation uncertainties (similar history as B/C)
3. Nuclear physics uncertainties > propagation uncertainties

→ Even with AMS-02 data, constraints on non-detection difficult to improve (still a window at high energy, i.e. TeV dark matter candidates)

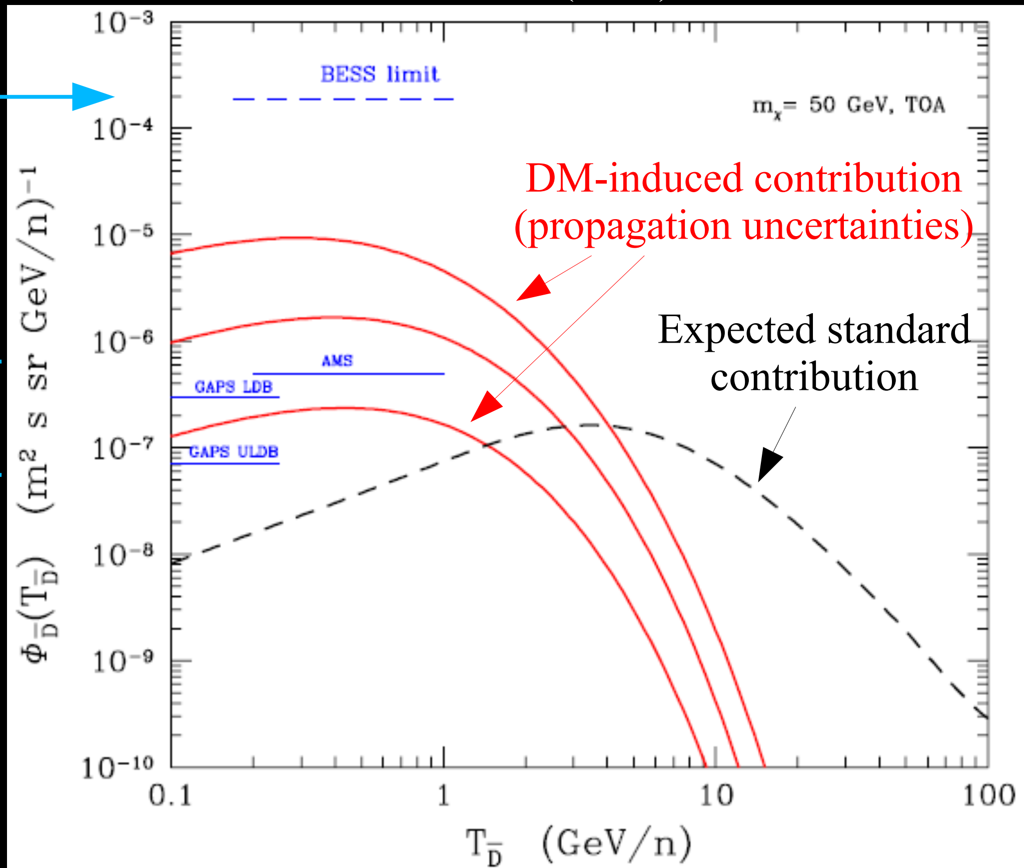
Anti-matter from dark matter: antideuterons

Previous transport parameters (no free parameters) + nuclear X-sections [Duperray et al., 2004]

Donato et al. (2008)

Current limit

Sensitivity future instruments



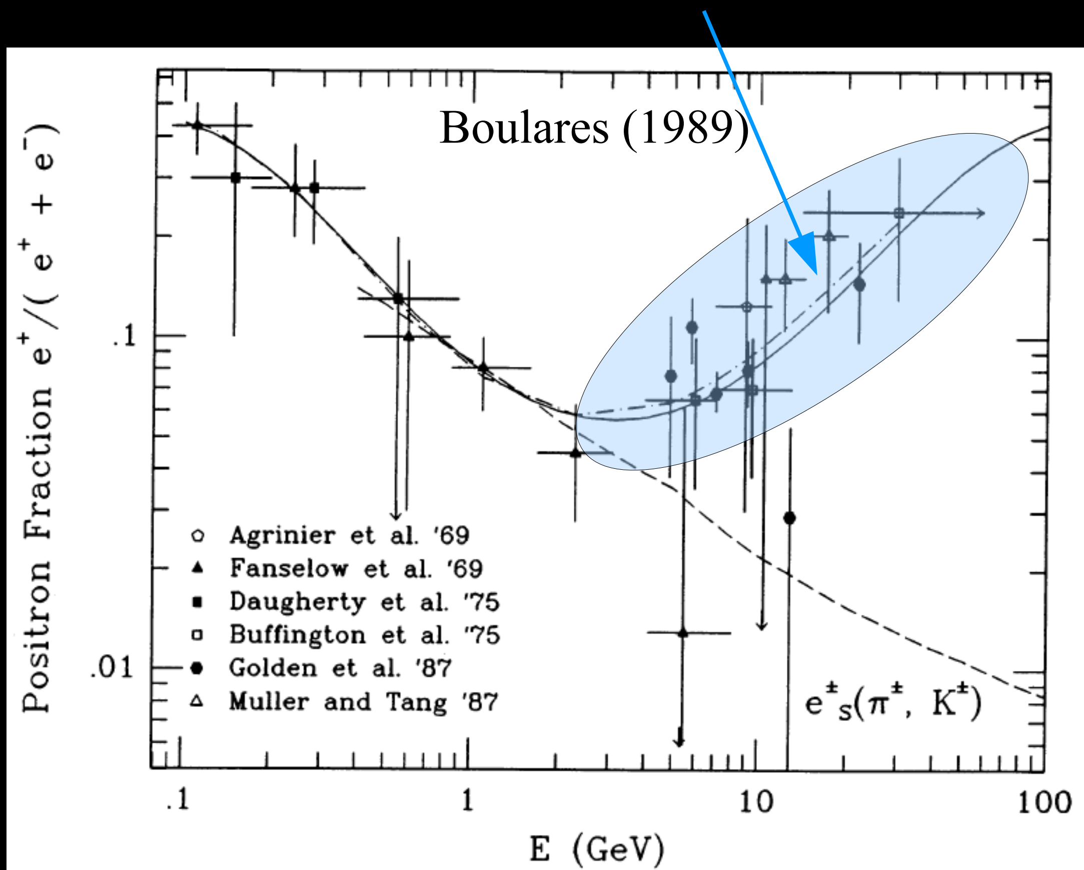
Enhanced production for Heavy DM
Kadastik et al. (2010)
Dal & Kachelriess (2012)

1. Nuclear physics uncert. > propagation uncert. (worse than for antiprotons)
2. Propagation uncertainties for 'exotic' contrib. >> prop. uncert. 'standard' contrib.

→ Antideuterons can exclude more DM models than antiprotons
[However, AMS-02 limits have to be reconsidered (with permanent magnet)]
→ My favoured choice for DM constraints (~ 100 improvement w.r.t. current limits)

Anti-matter from dark matter: positrons

Positron fraction: origin of the rise at high energy

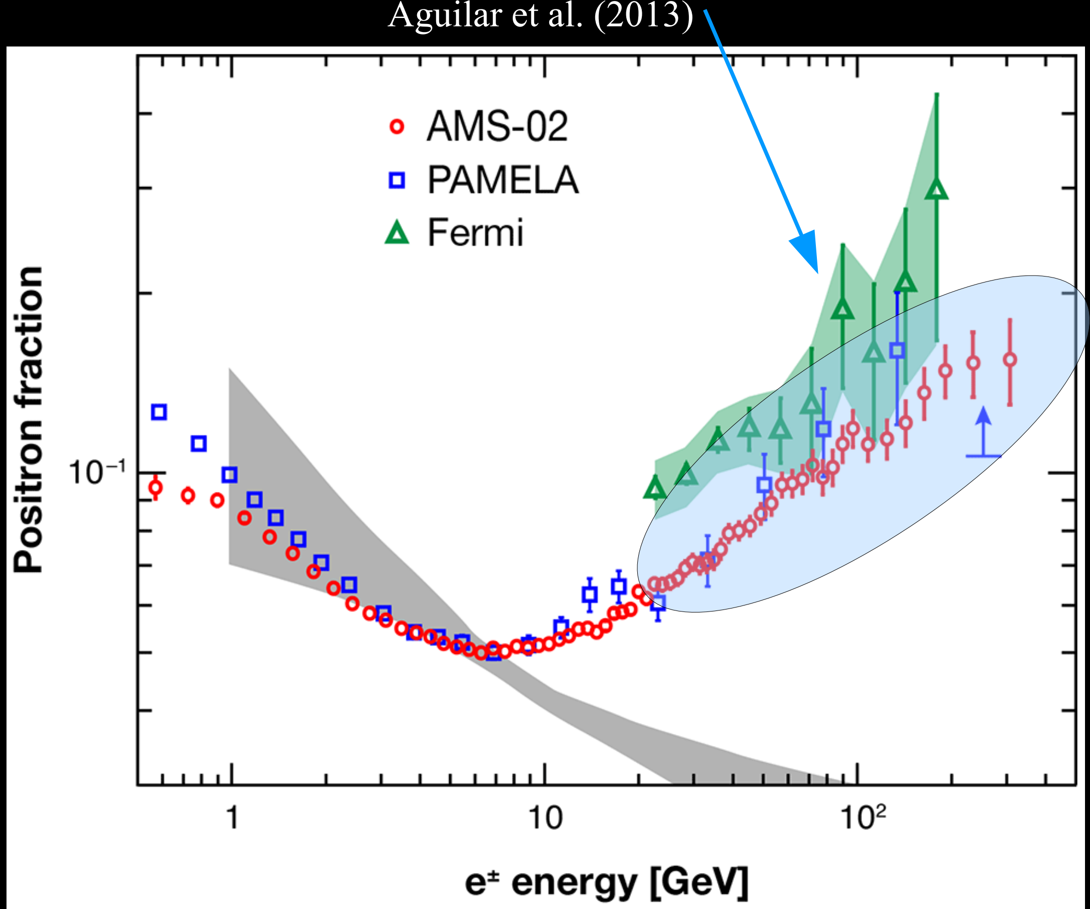


→ 'Natural' astrophysical prediction (local SNRs, pulsars)

Anti-matter from dark matter: positrons

Positron fraction: origin of the rise at high energy

Aguilar et al. (2013)



'Natural' astrophysical prediction [Delahaye et al. (2010)]

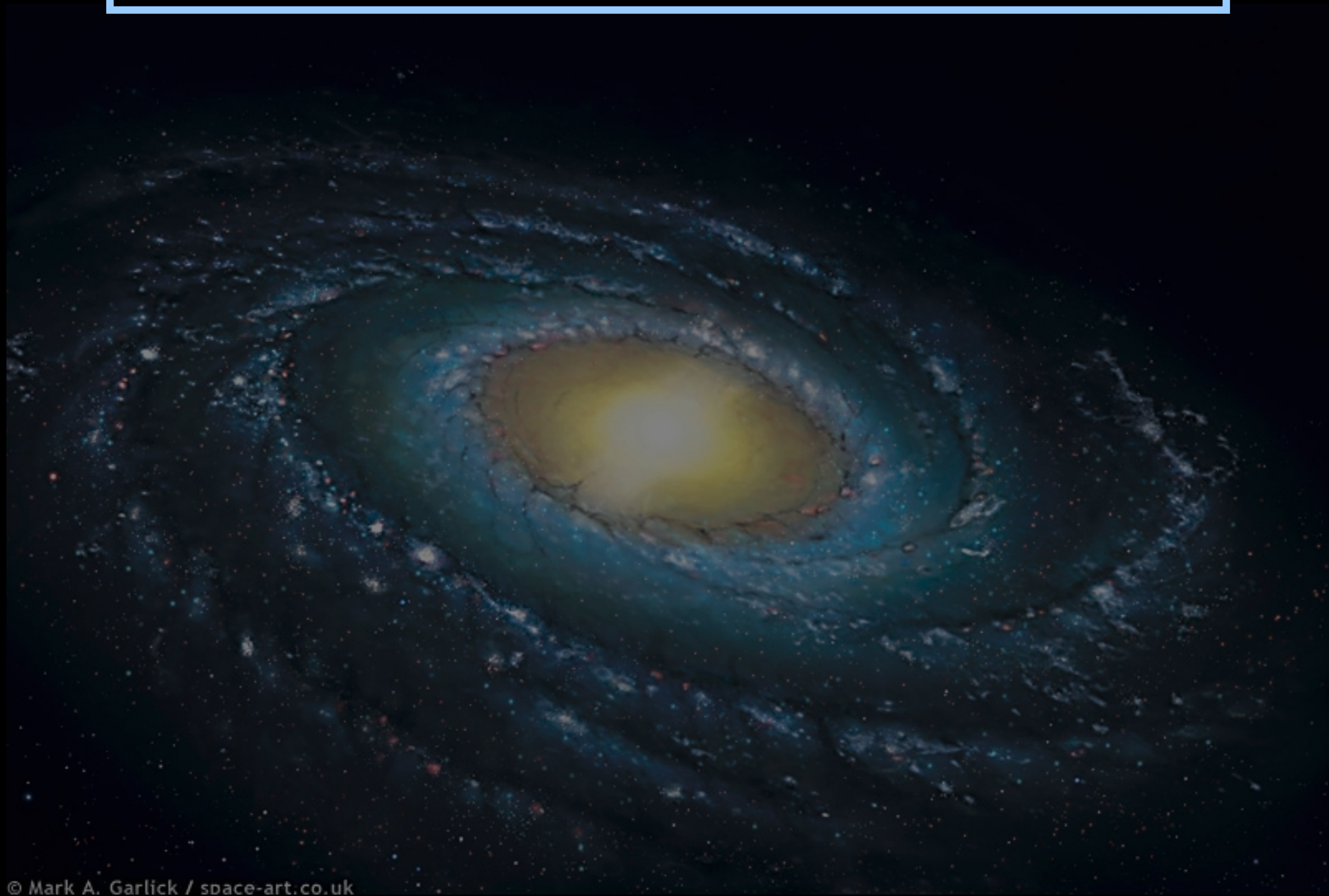
vs

"fine-tuned" leptophilic boosted dark matter post-diction

[N.B.: no boost from dark matter substructures [Lavalle et al. 2008]]

→ maybe worse place to look for dark matter (local sources): no control on astro. background!

I – Galactic cosmic rays (GCR)
II – GCR phenomenology: basics
II – Status of recent measurements
III – Conclusions



Indirect dark matter crisis?

No signal yet! And we are reaching limitations in many channels...

→ Still room for high mass candidates in antiproton flux
→ Antideuterons best target left for DM discovery
→ If large L favoured, stronger constraints on DM candidates

[not discussed: multi-wavelength and multi-messenger studies]

Larger perspective: why so many improper claims for DM discovery?

Scarce data, data in extreme range of instrument capabilities, detector issue

- 1 GV & 10 GeV antiproton excess (in the 80's and 90's)
- 10 GeV HEAT positron fraction bump (in the 90')
- 10 GeV EGRET excess (in the 00')
- 500 GeV ATIC excess (in 2008)

Correct data, but too biased to see the astrophysics

- 511 keV annihilation line (INTEGRAL/SPI)
- Rise of the positron fraction (PAMELA/AMS-02)

Correct, but too much data for our own good (Fermi-LAT, AMS-02 era)

- 10 GeV annihilation line in the galactic centre
- 130 GeV line in the Galactic center
- 110 and 130 GeV line in galaxy cluster

Exquisite AMS-02 data in the coming years...