The simplest and yet the most unorthodox explanation for the PAMELA anomaly - Galactic Arm SNRs

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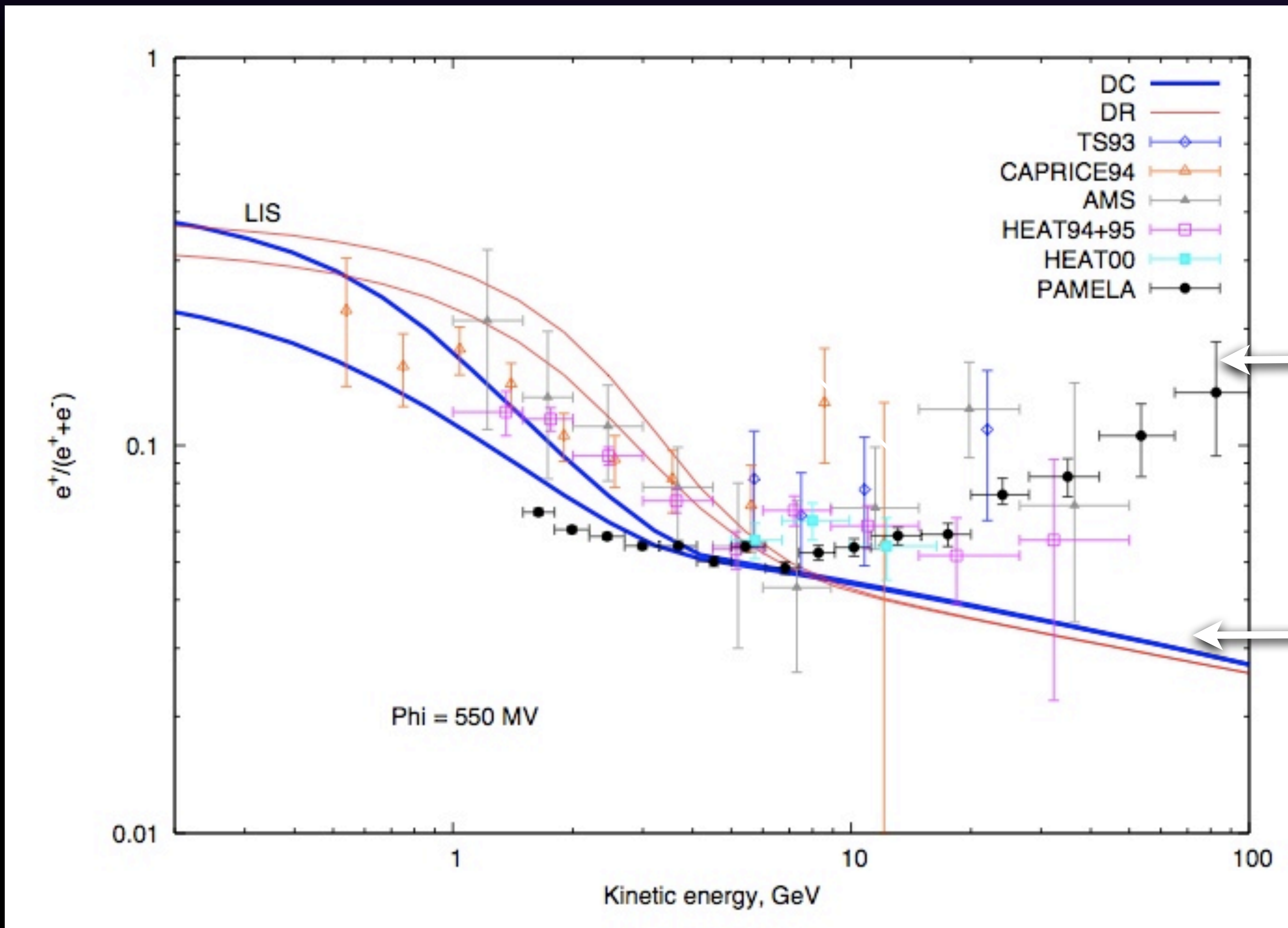
Ehud Nakar (Tel Aviv U) **Astro-ph/09020376**

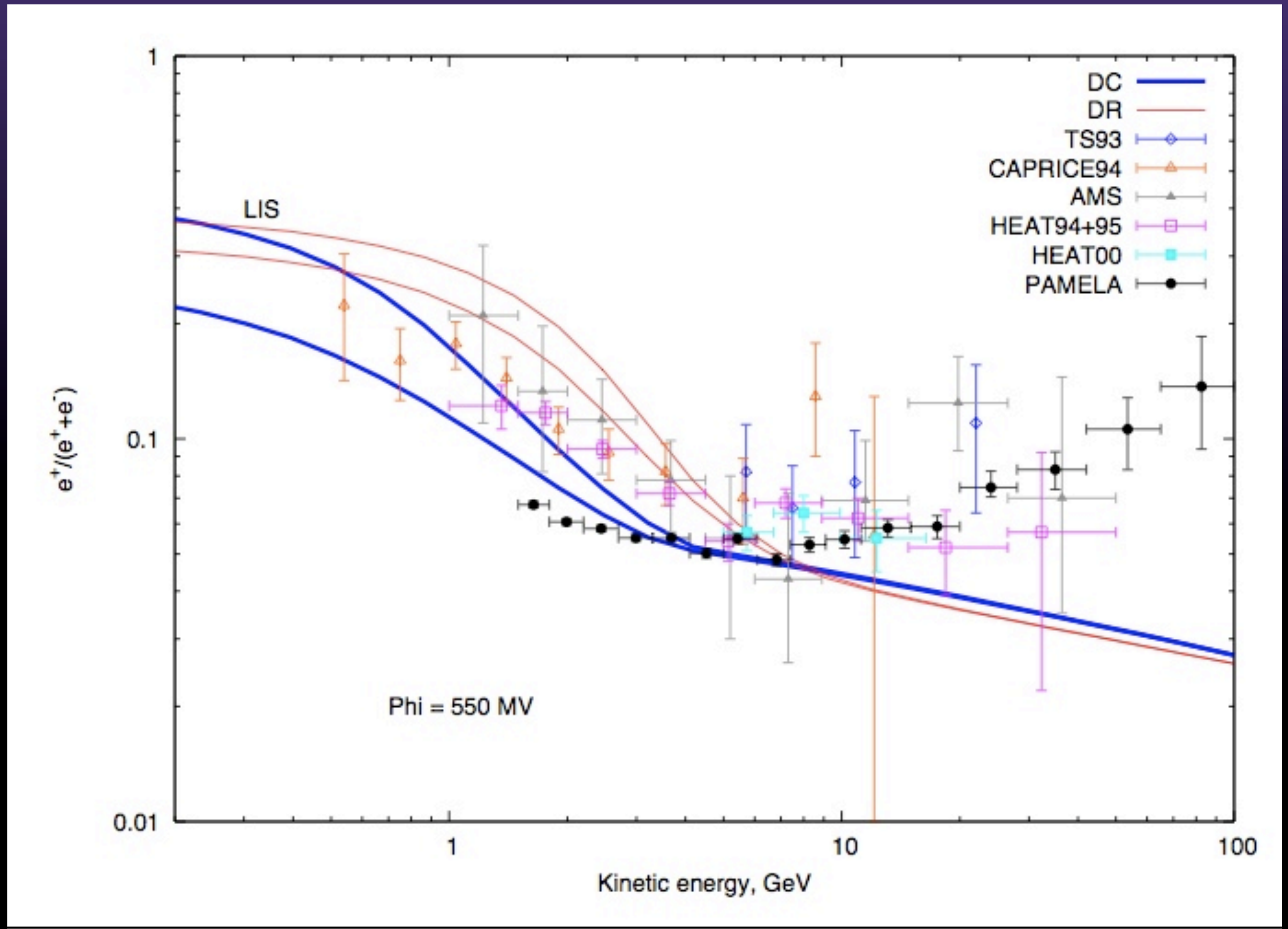
Phys. Rev. Lett. 2009

The PAMELA's anomaly:



The Observations

The Model

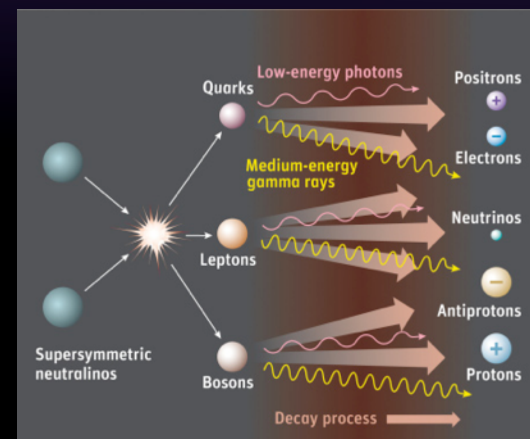


A new source of positrons (and electrons) that becomes dominant at ~10 GeV

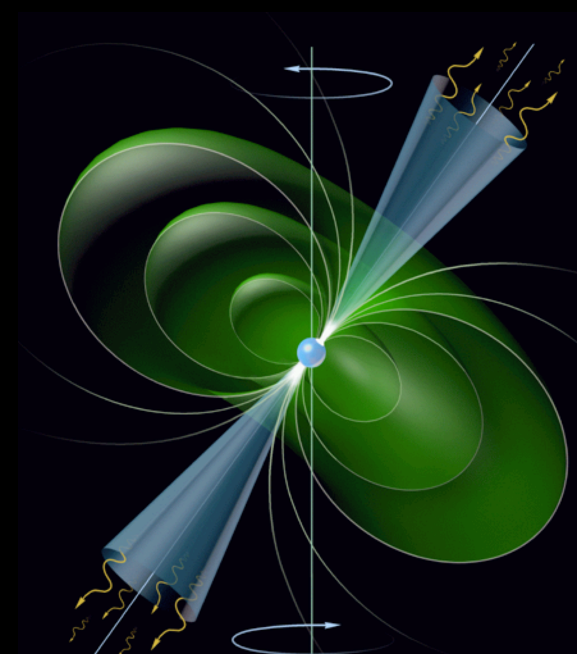
- The standard solutions require

Dark Mater - NEW PHYSICS

or



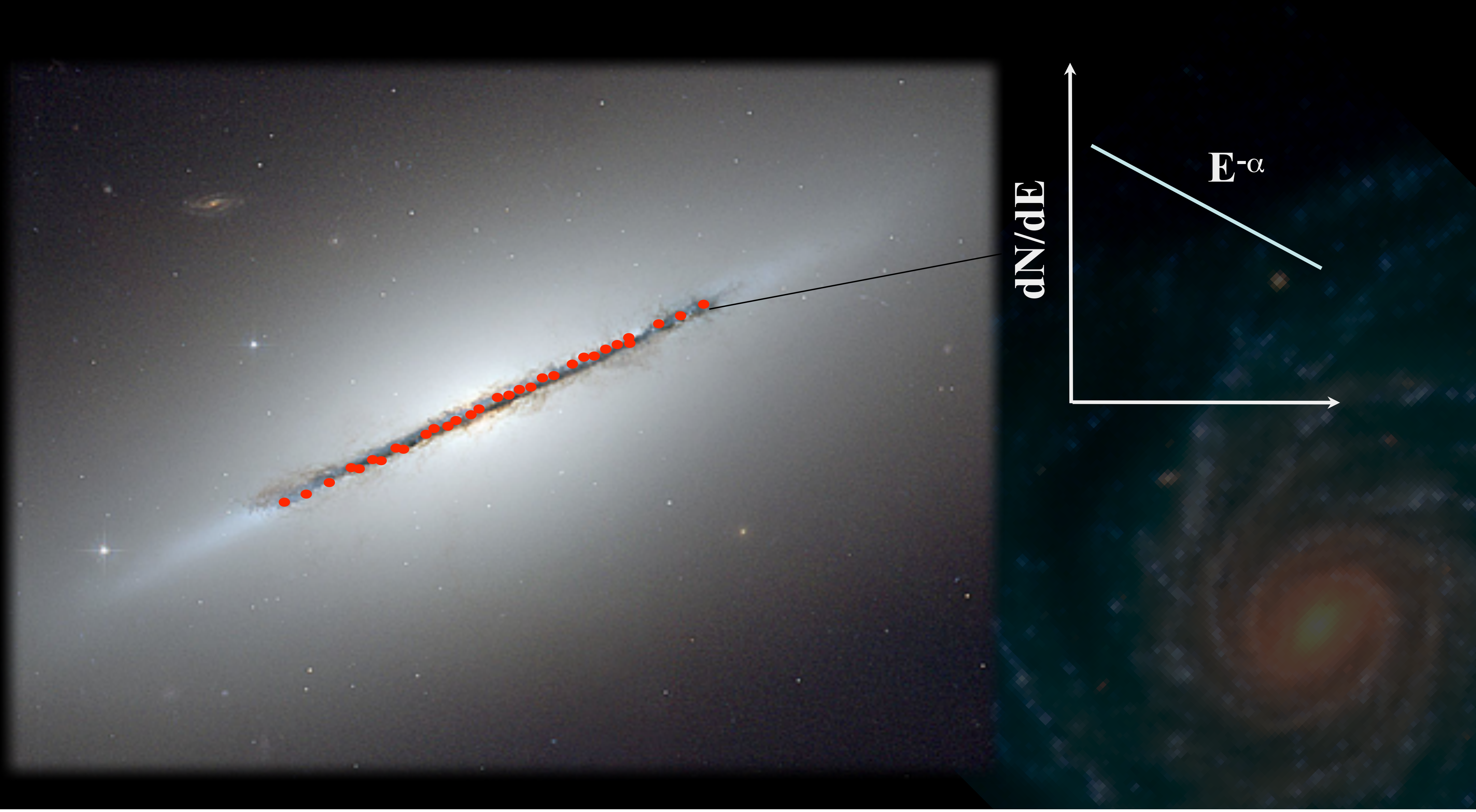
Pulsars - NEW ASTROPHYSICS



- Is there a simpler solution?

The Standard Model

(e.g. review by Strong, Moskalenko & Ptuskin)



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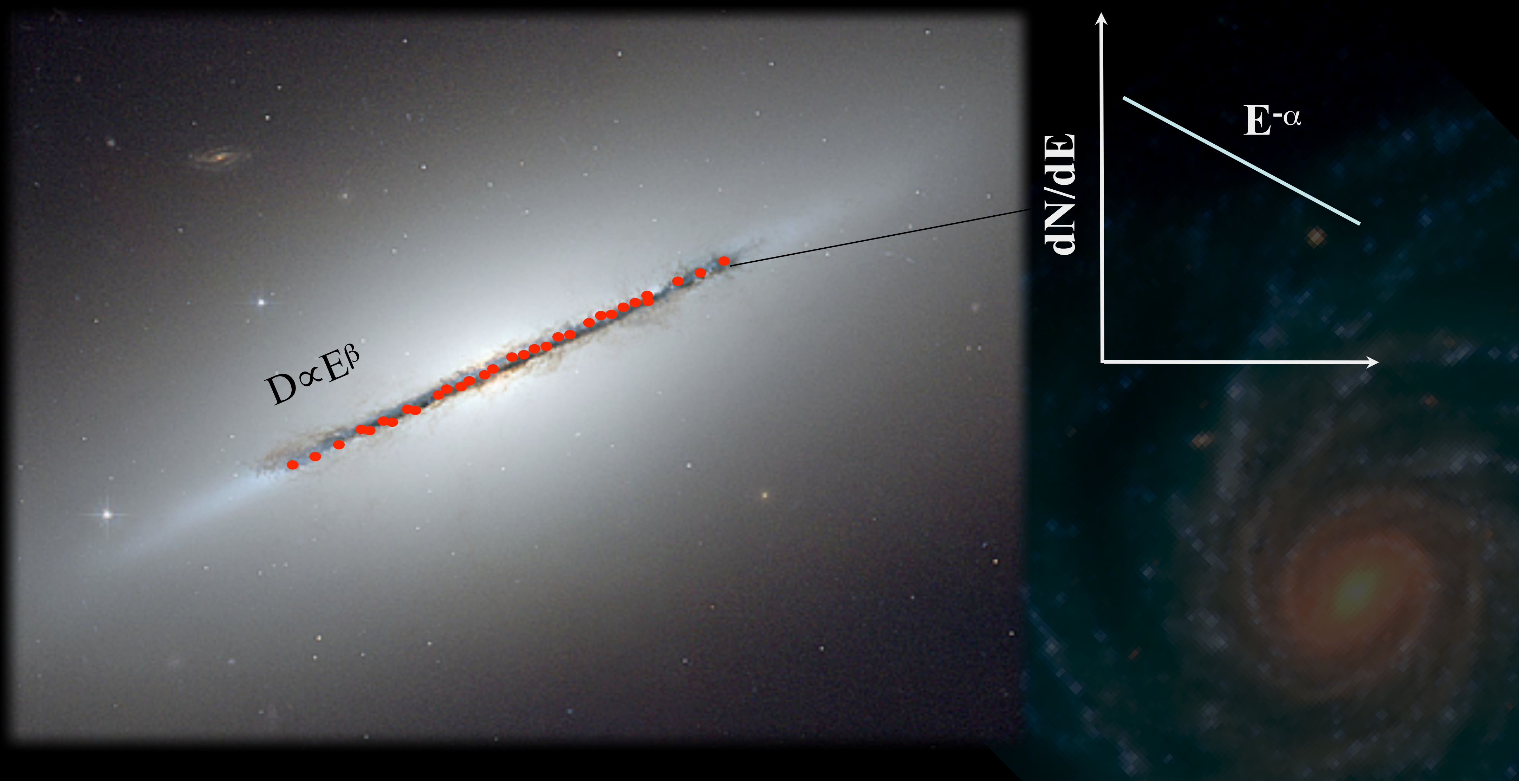

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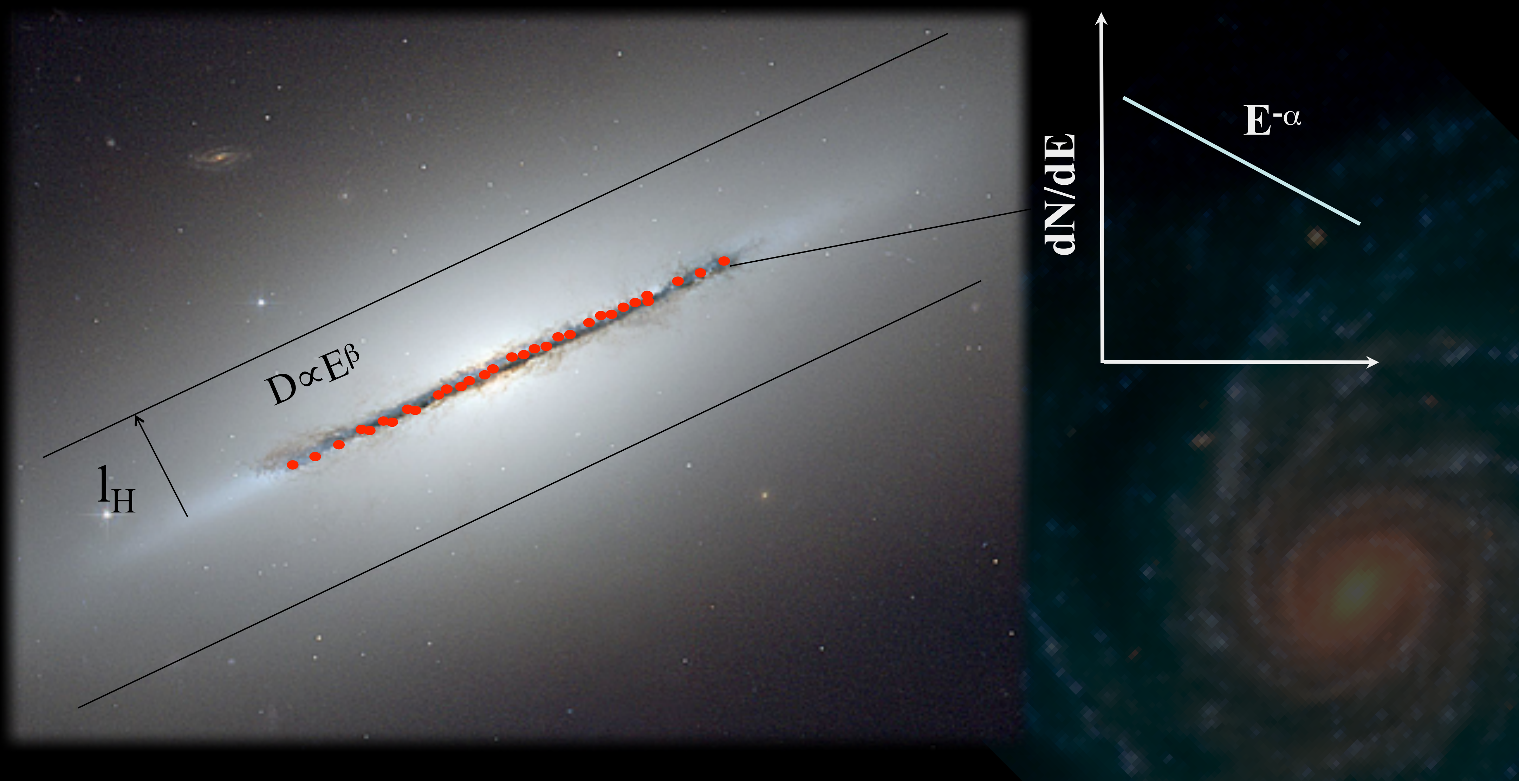

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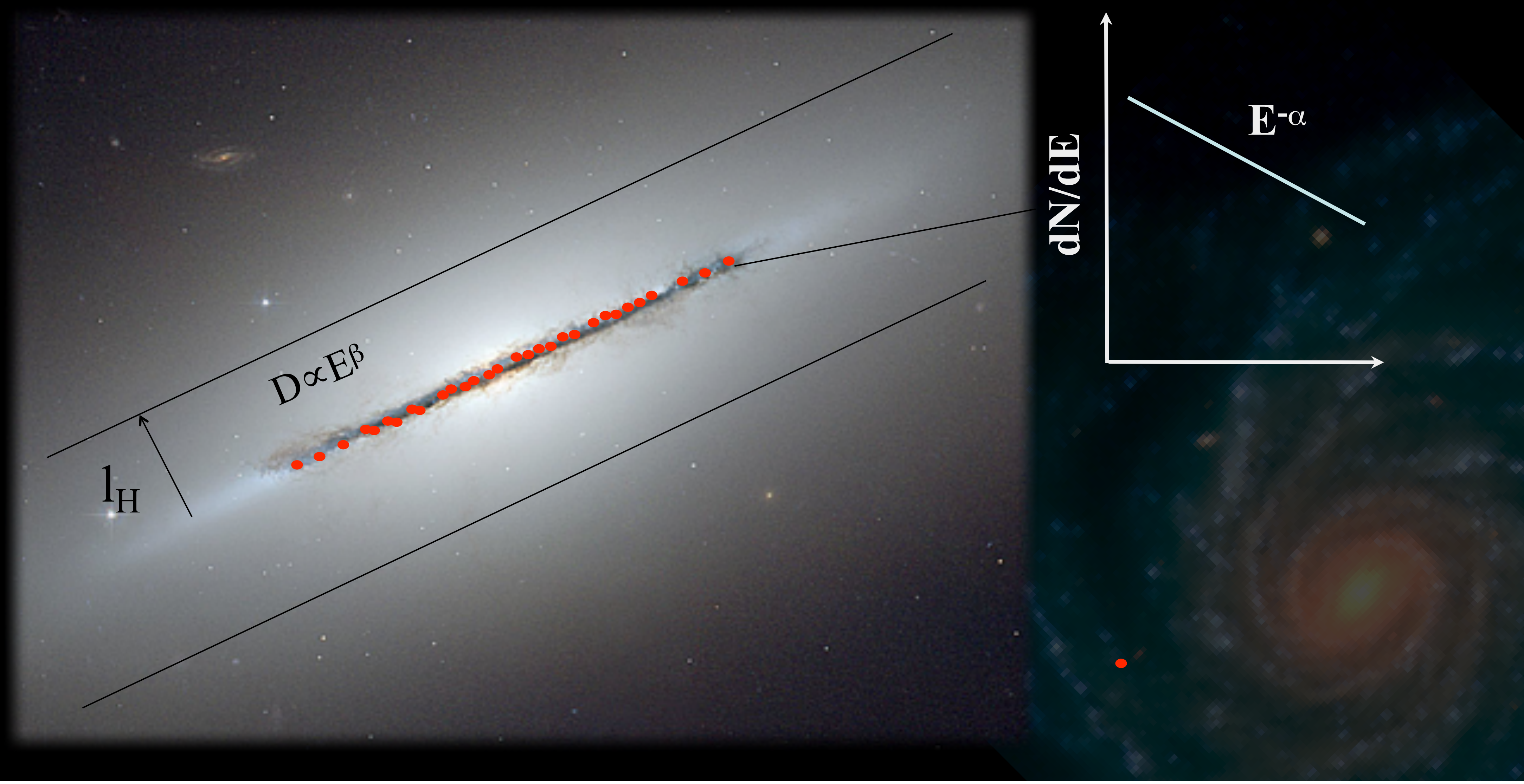

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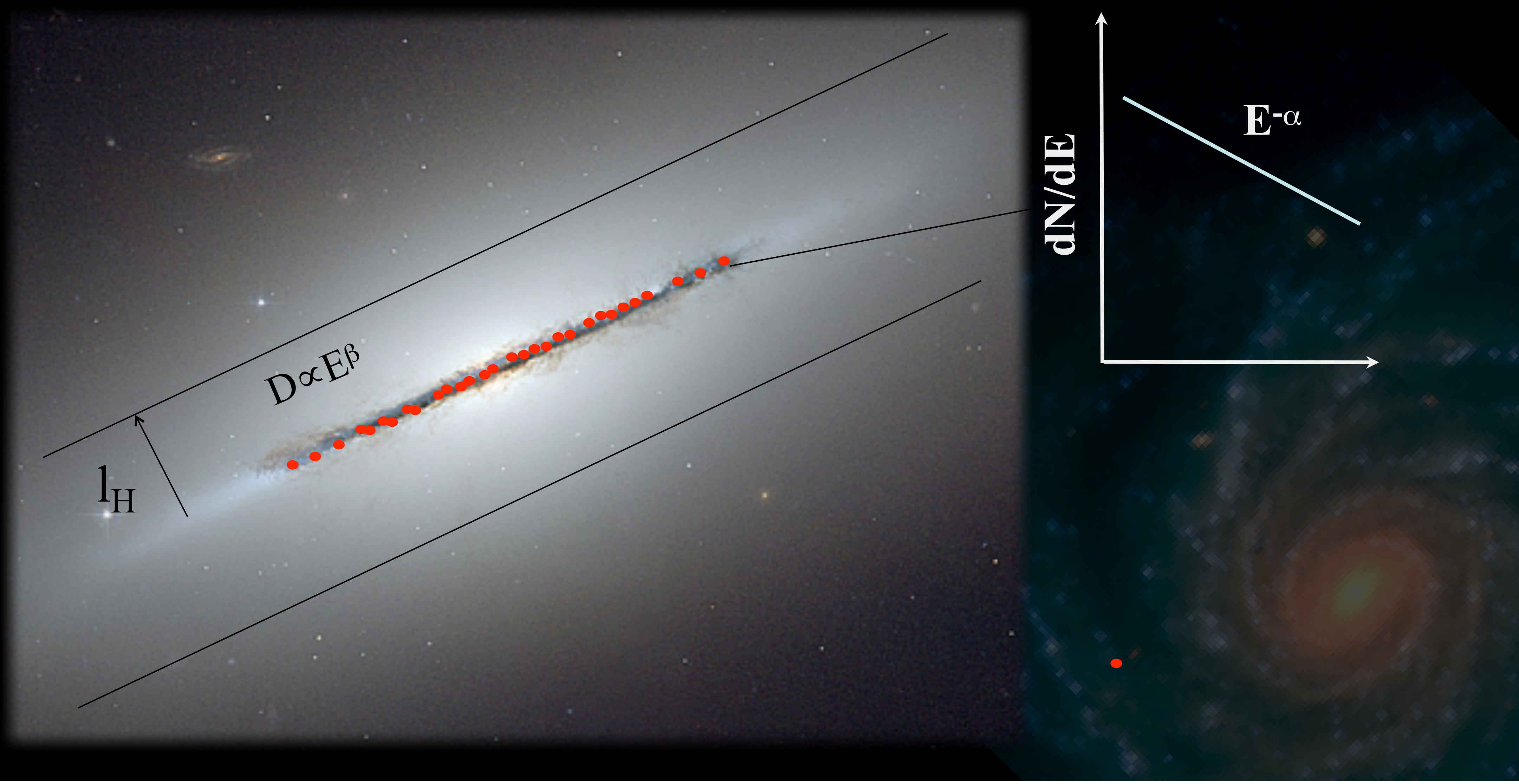
- Possible additions: galactic wind



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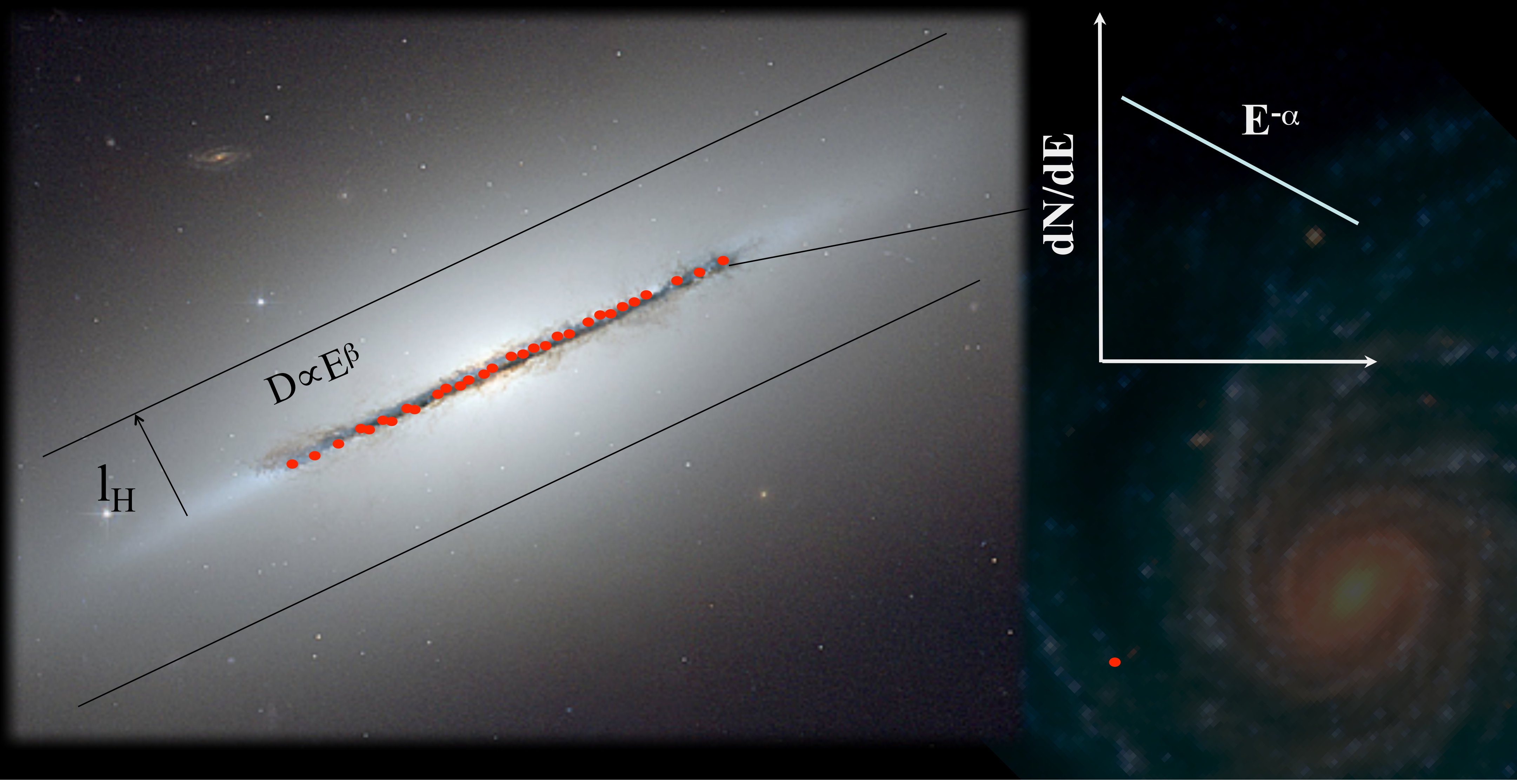
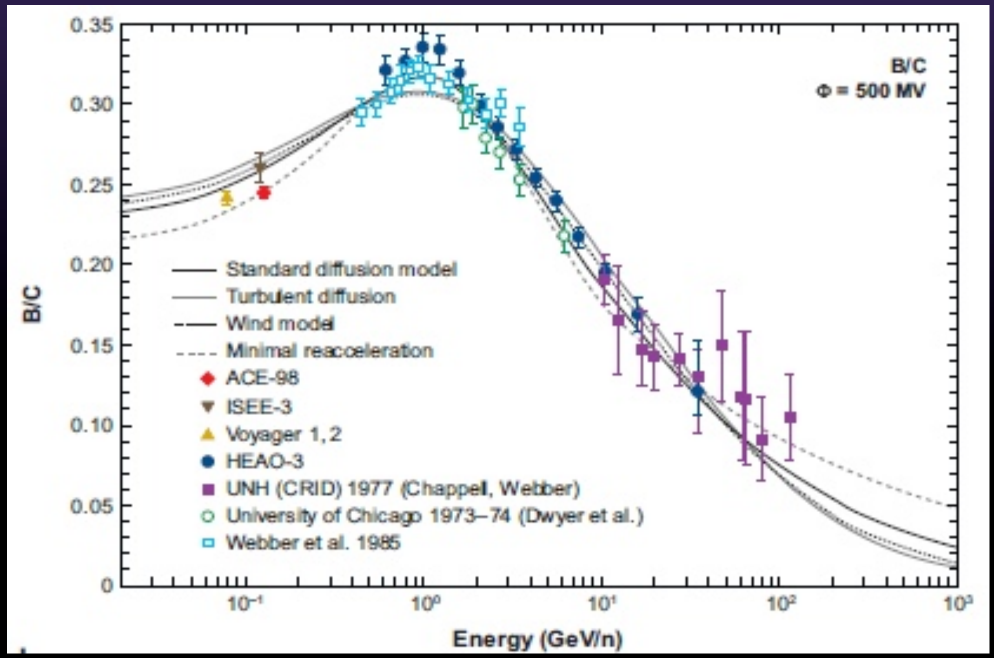
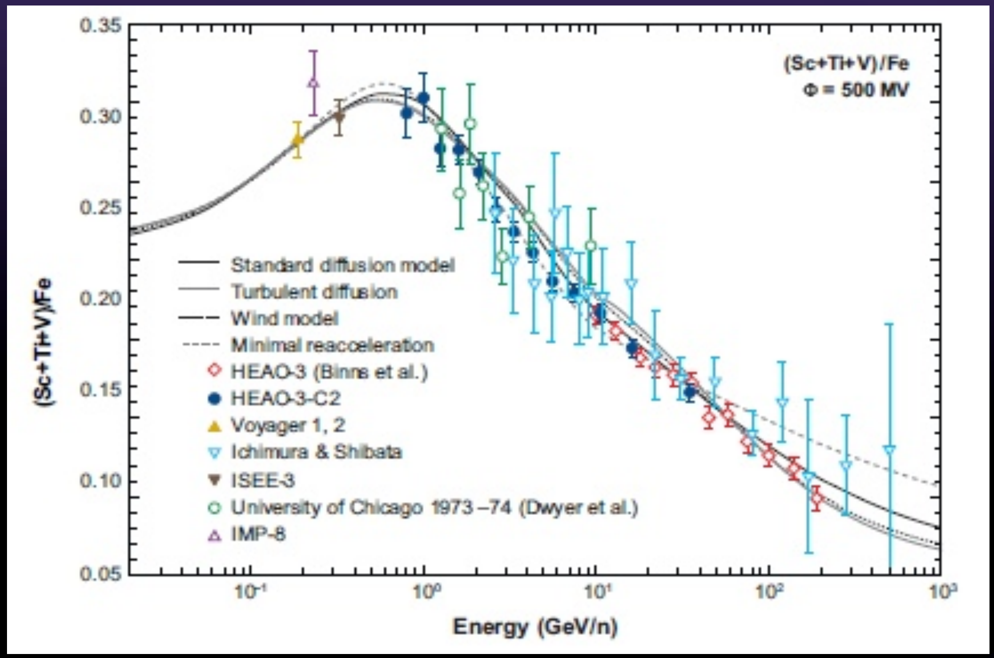


These models fit the data well





Typical parameter values

$$D(E>E_0) = D_0\,(E/E_0)^{\delta}$$

$$D_0 = 3\text{-}5 \times 10^{28}\ \mathrm{cm^2/s}$$

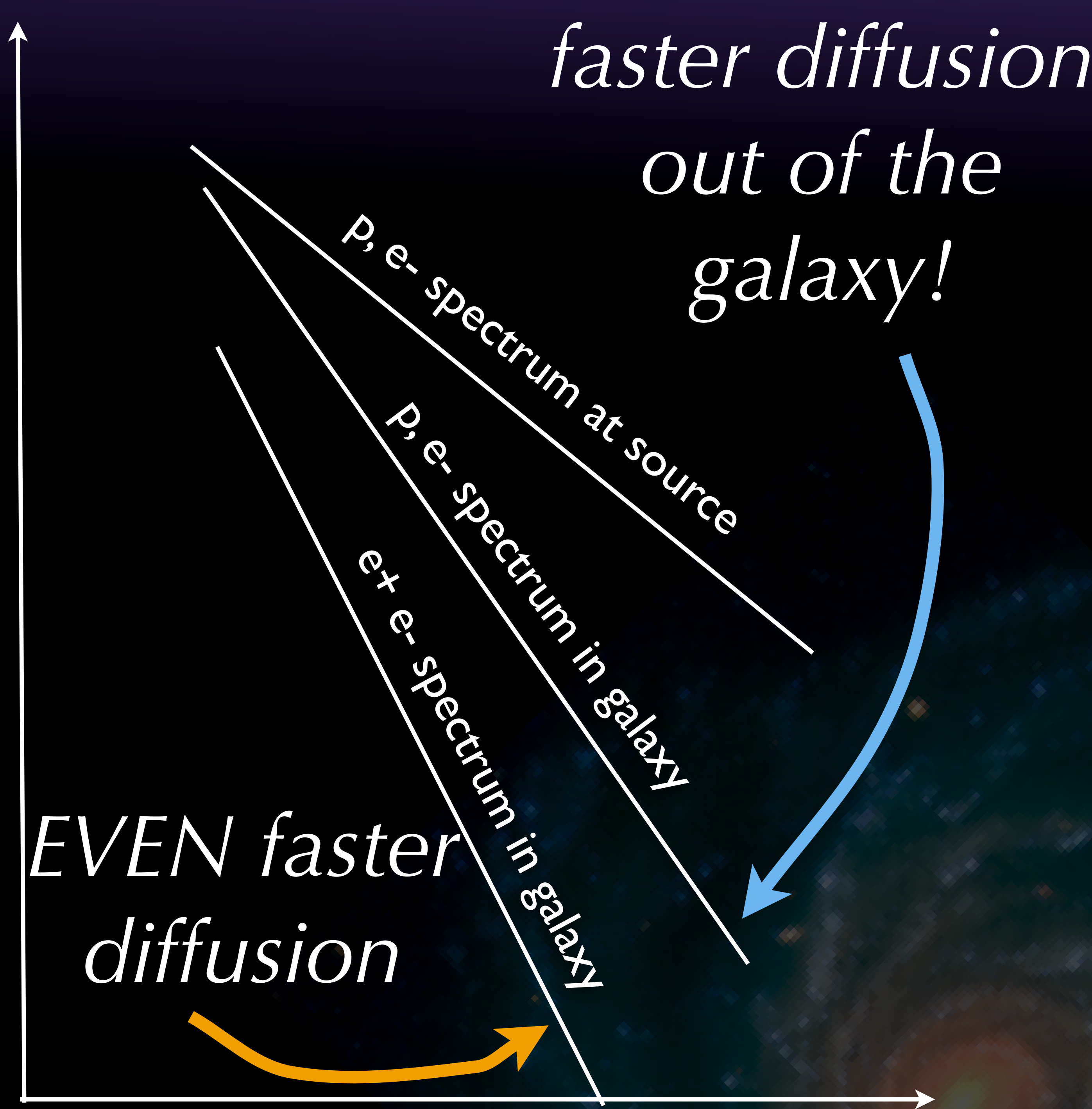
$$E_0 \sim 3\ \mathrm{GeV}$$

$$\delta = 0.3\text{-}0.6$$

$$l_H = 2\text{-}4\ \mathrm{kpc}$$

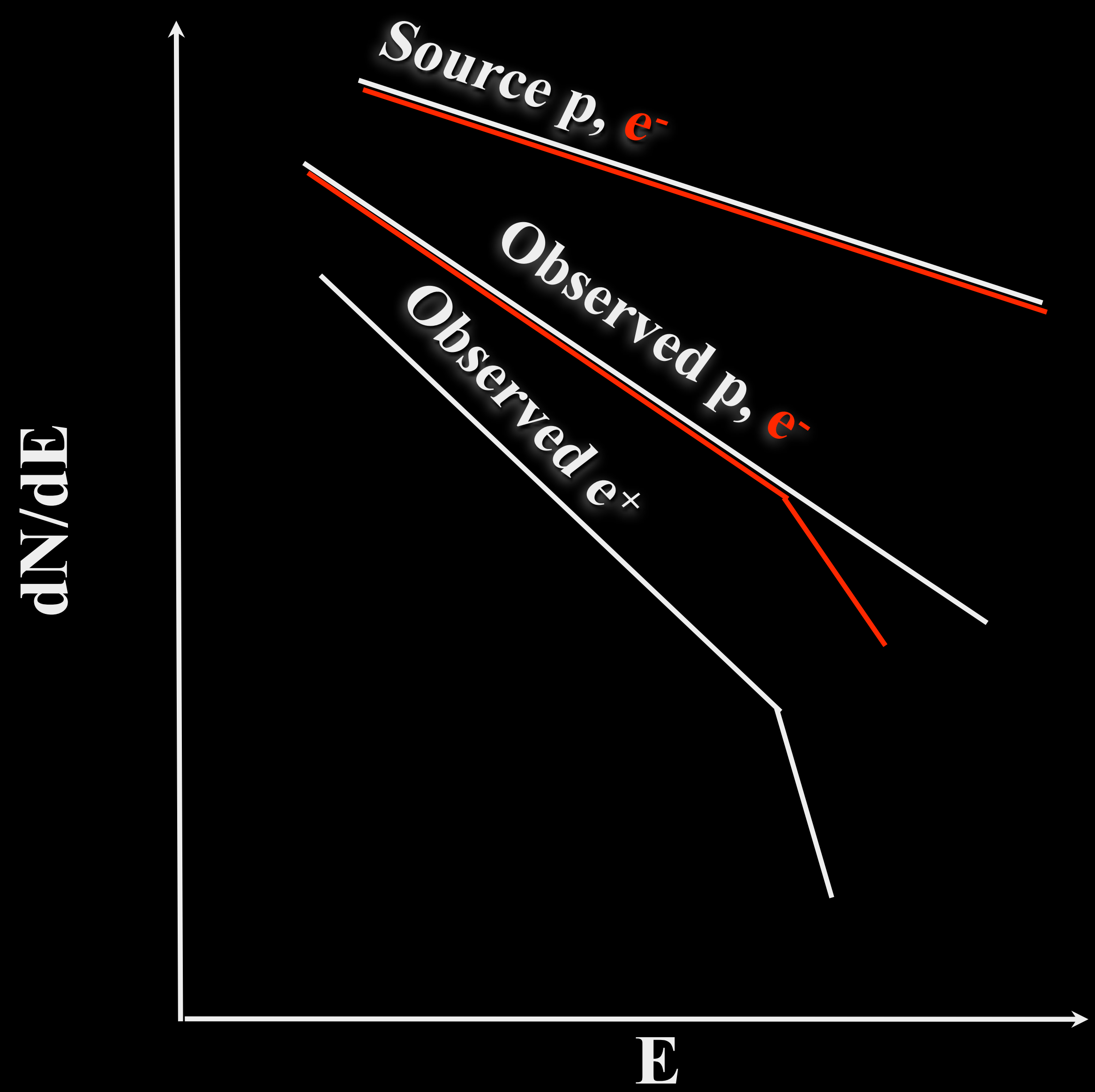
Standard View

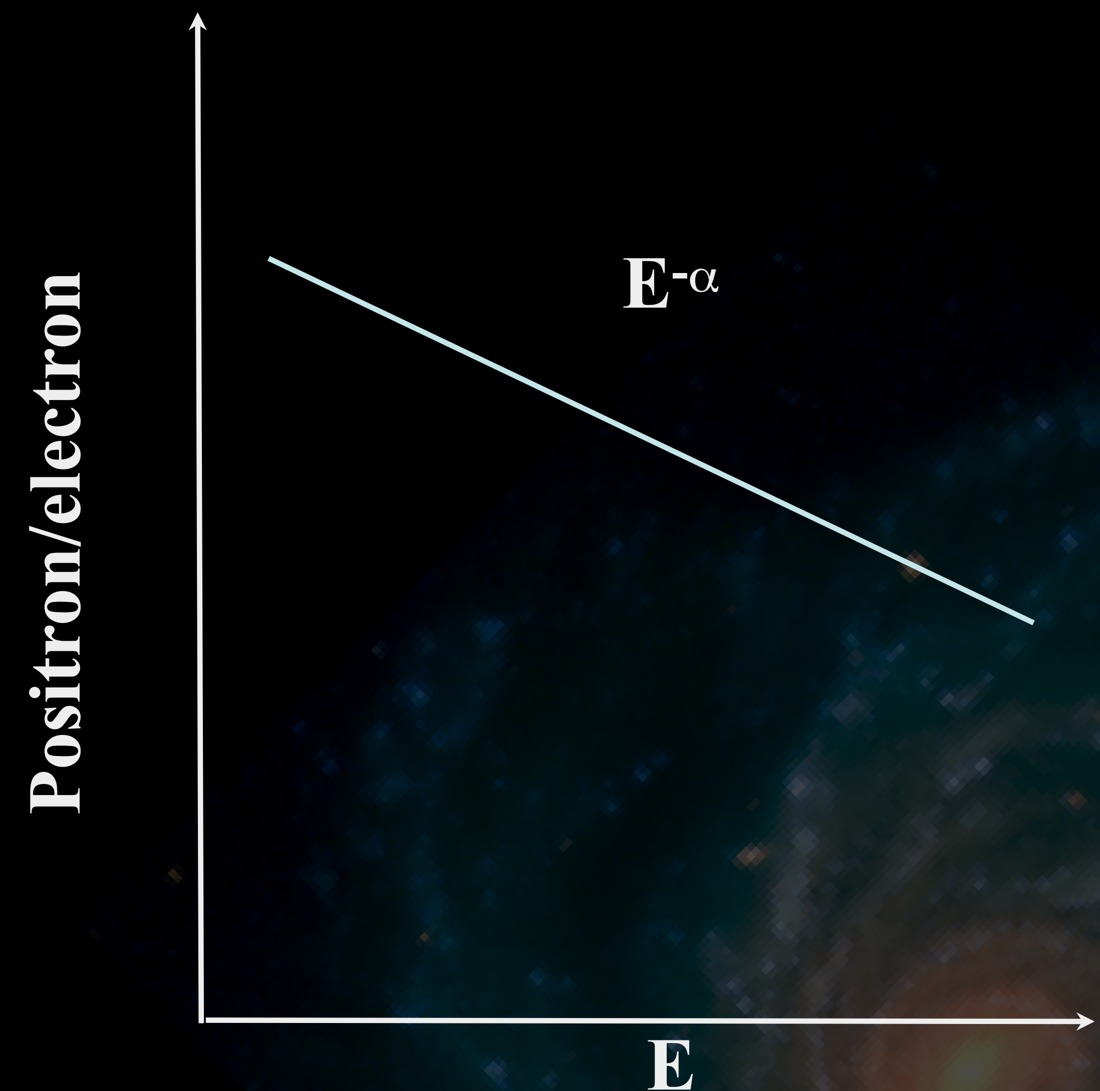
- **Electrons and Protons are mostly accelerated by supernova/ interstellar medium (ISM) shocks.**
- **Pairs (and hence Positrons) are produced by CR protons interacting with the ISM (Positrons are secondaries)**
- **Positron/Electron ratio should decrease with energy!**
- **Cooling affect electrons and positrons in the same way.**



Standard model predictions for electron and positron spectrum

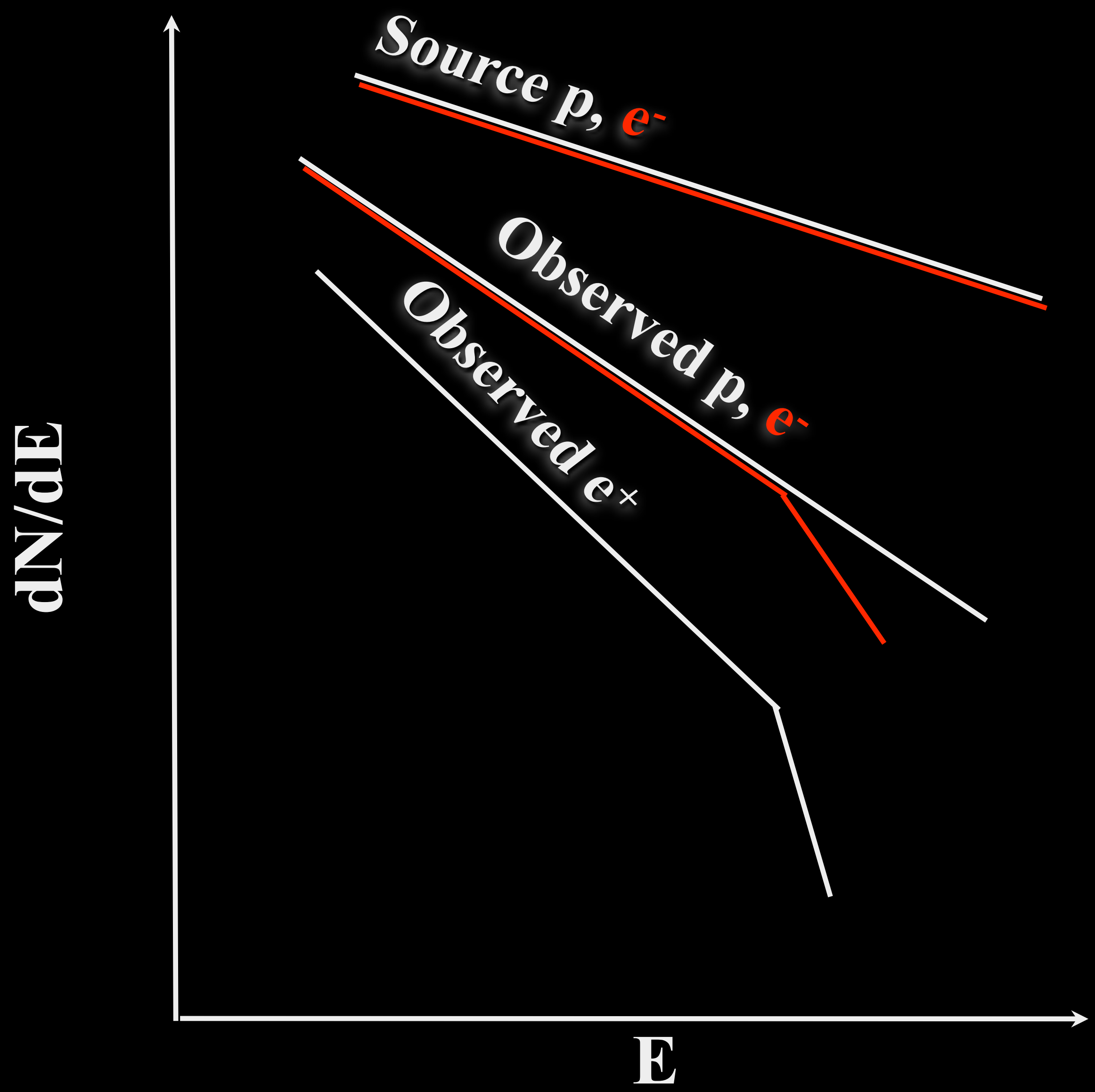
Positrons are secondaries : CR+ISM → pairs

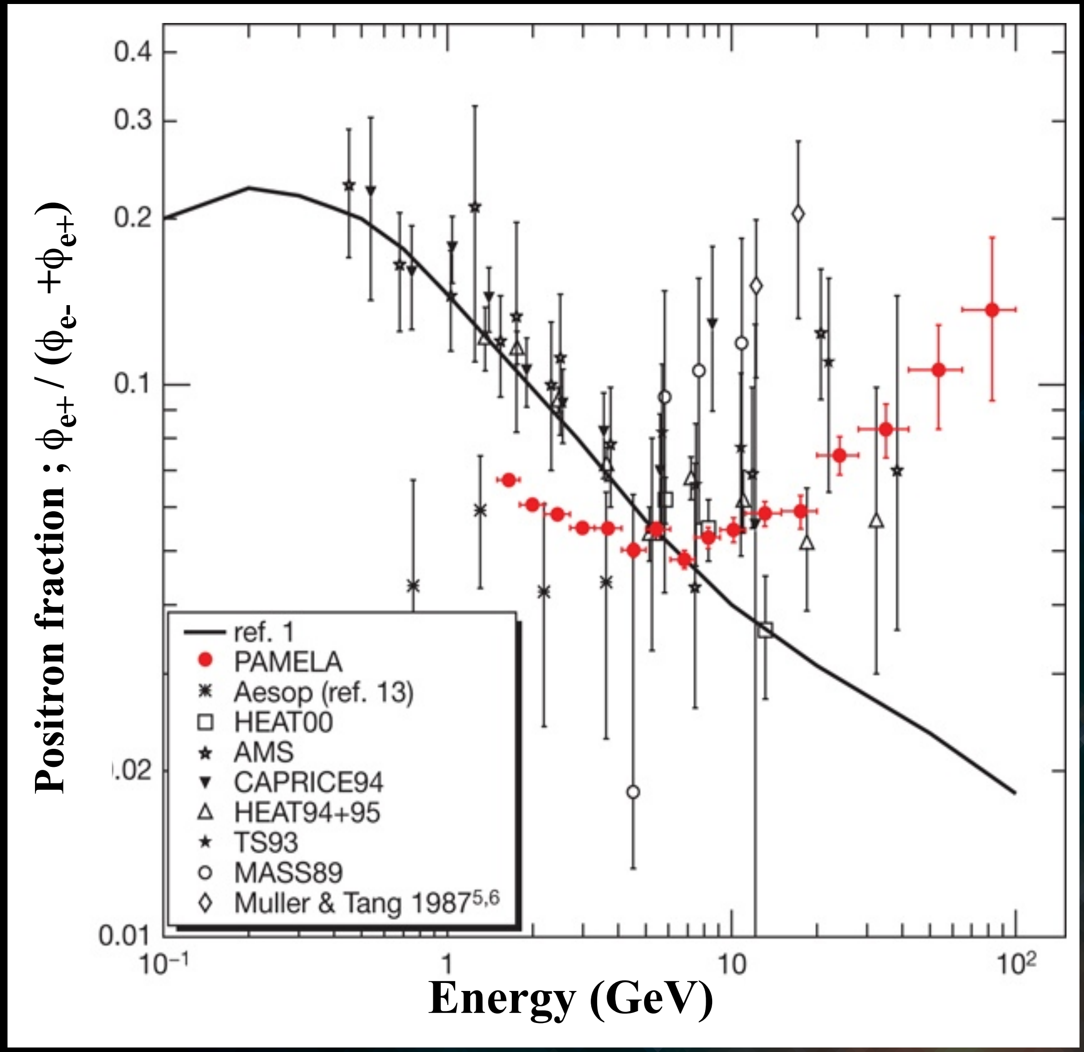


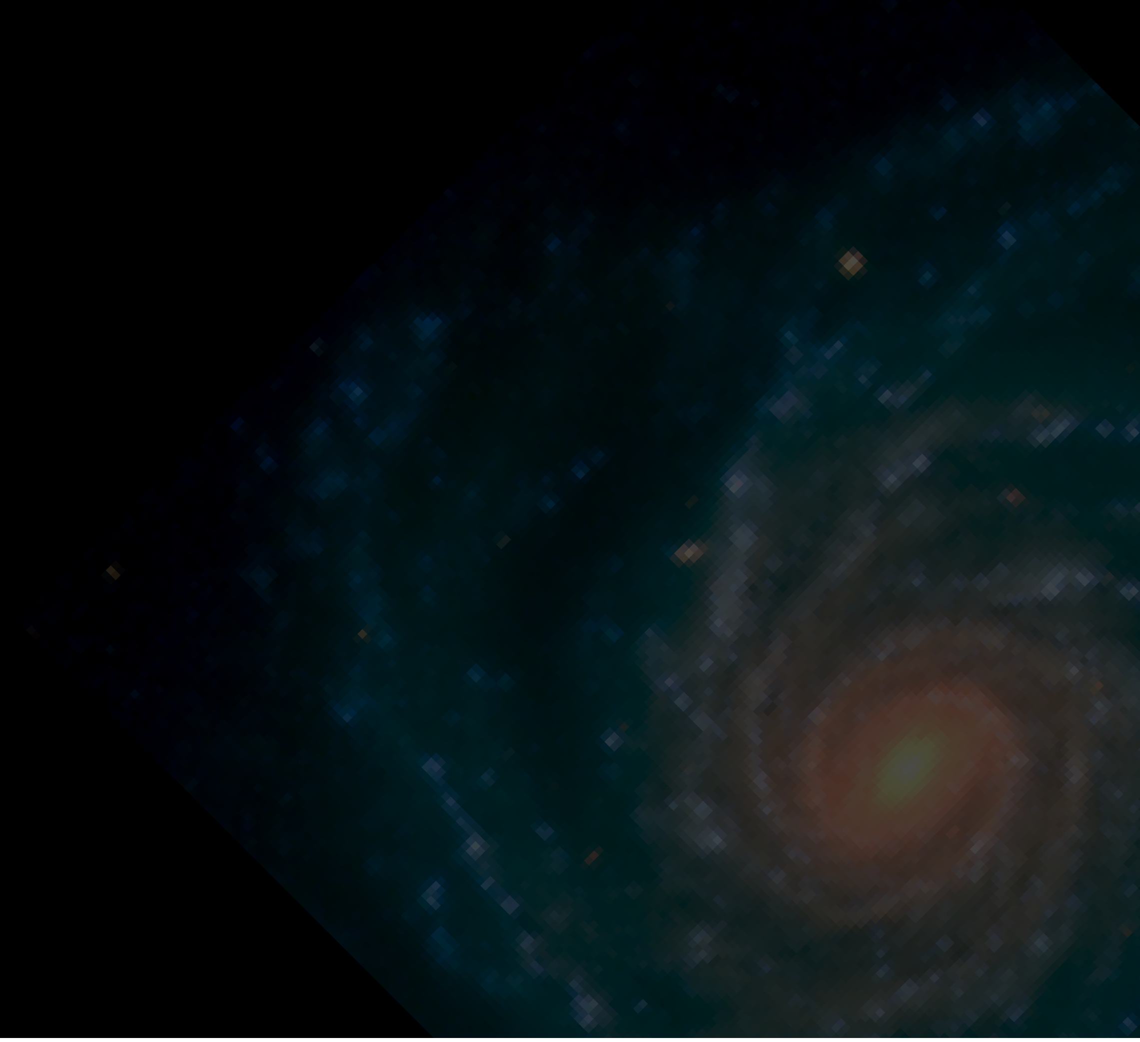


Standard model predictions for electron and positron spectrum

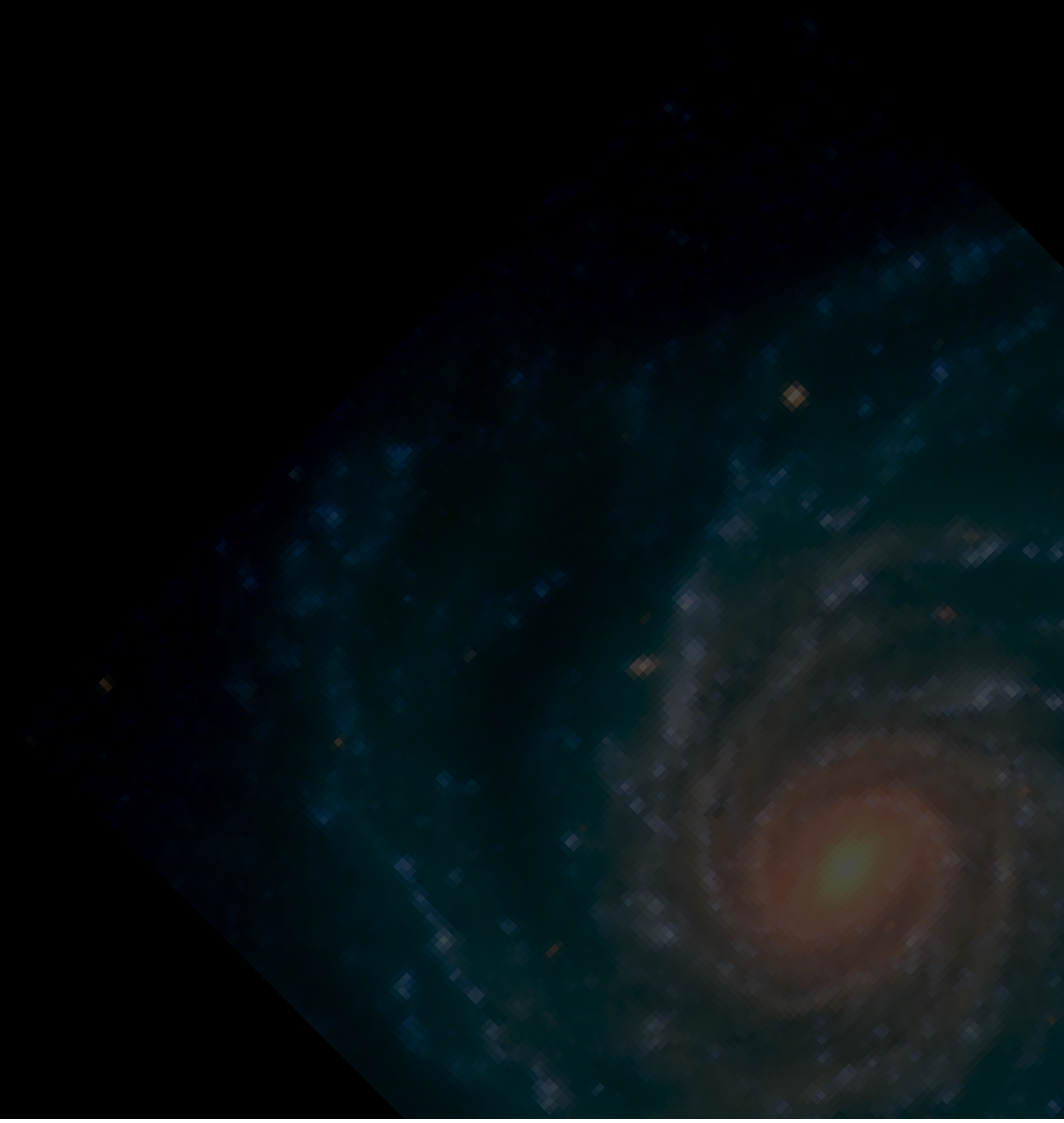
But - PAMELA





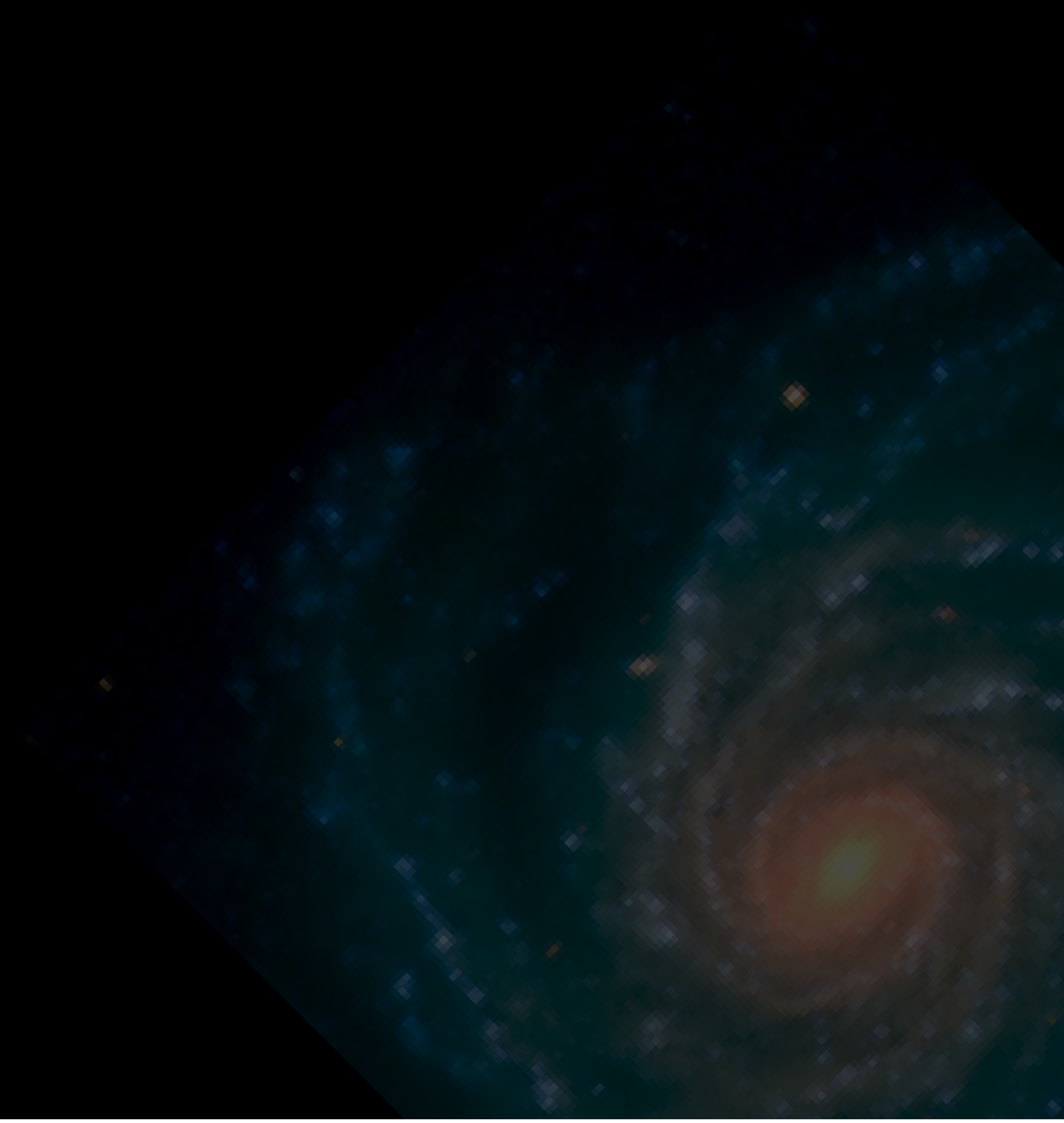


Some of the standard CR model assumptions



Some of the standard CR model assumptions

- **A** <u>uniform</u> CR source distribution in the gaseous disk



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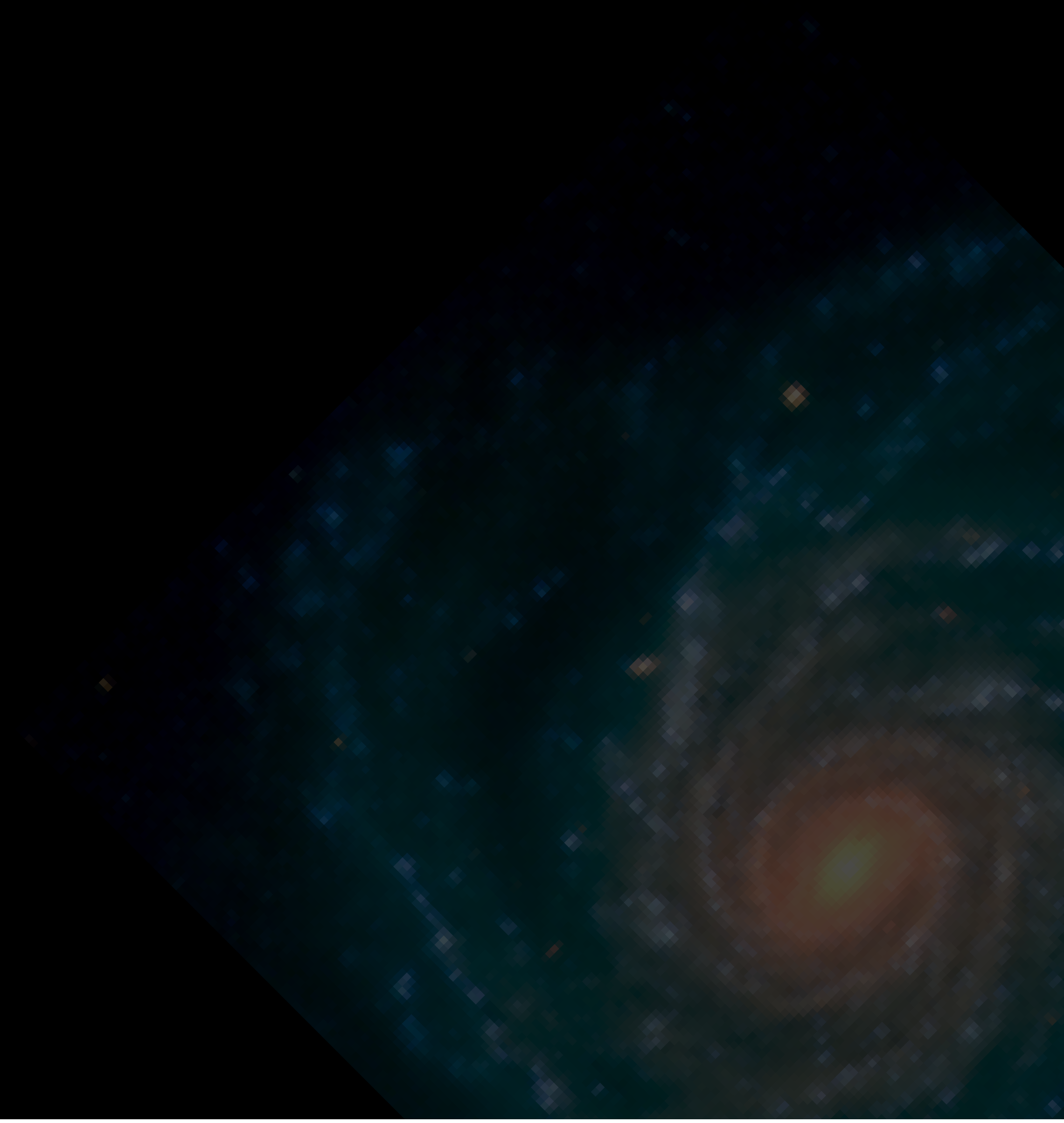

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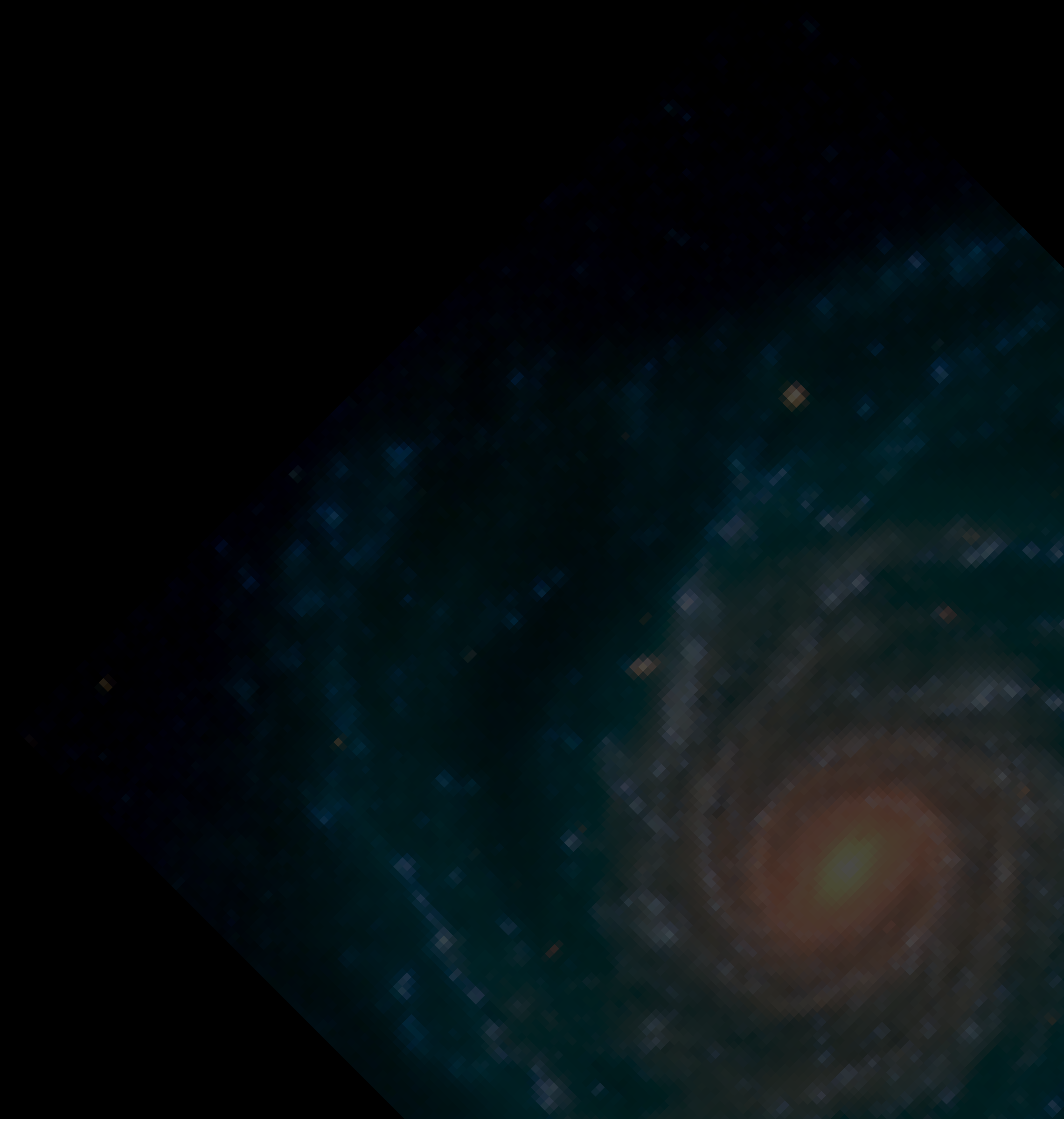
•CRs diffuse isotropically with a rigidity dependent (but spatially constant) diffusion coefficient - **$D(E>E_0) = D_0\ (E/E_0)^{\delta}$**



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The PAMELA anomaly

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The PAMELA anomaly

⇓

At least one of the model assumptions is wrong

The standard CR model unconfirmed assumptions

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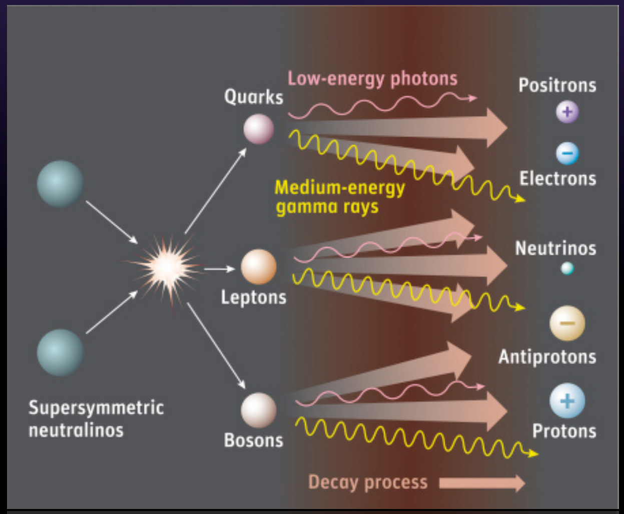
- ~~Positrons are produced only as secondaries by CR-ISM interaction outside of the acceleration site~~

The most popular solution (measured by # of papers)

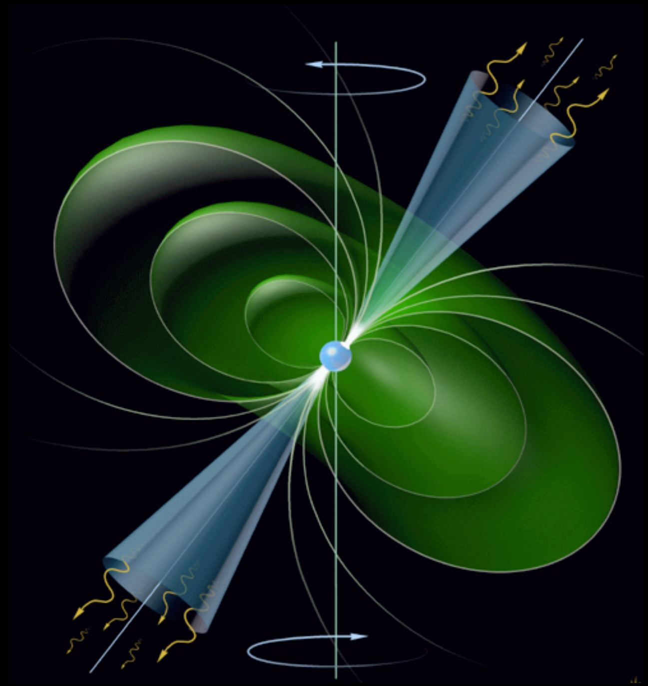
A new, yet unaccounted for, primary source of pairs

Dark Mater - NEW PHYSICS



or

Pulsars - NEW ASTROPHYSICS



also GRBs...

The standard CR model unconfirmed assumptions

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• Positrons are produced only as secondaries by CR-ISM interaction outside of the acceleration site

↑

There are no observations that directly rule out this assumption (Delahaye et al 09, Katz et al. 09).

The PAMELA anomaly can be explained in many ways by violating one or more of these assumptions.

The standard CR model unconfirmed assumptions

- A <u>uniform</u> CR source distribution in the gaseous disk
- Sources accelerate *p* and e^- to a <u>Similar</u> power-law spectrum
- CRs diffuse isotropically with a rigidity dependent (but <u>spatially constant</u>) diffusion coefficient - $\mathbf{D(E>E_0) = D_0\ (E/E_0)^{\delta}}$
- CRs diffuse in a halo with <u>an energy independent scale height</u> $l_H \sim$ kpc, i.e. all CRs can escape once they reach a height l_H above the disk.
- Positrons are produced <u>only as secondarie</u>s by CR-ISM interaction ~~outside of the acceleration site~~

Production of secondaries within the acceleration site

(Blasi 09; Blasi & Serpico 09)

The standard CR model unconfirmed assumptions

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Nested sources

(Cowsik & Burch 09)

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- CRs diffuse in a halo with an energy independent scale height l_H ~ kpc, i.e. all CRs can escape once they reach a height l_H above the disk.
- Positrons are produced only as secondaries by CR-ISM interaction outside of the acceleration site

Inhomogebeity in the SNR distribution

(Shaviv, Nakar & Piran 09)

SNR are the canonical sources of CRs

- Mechanism exists (1st order diffusive / shock acceleration)
- Ginzburg & Syrovatskii (1963) - Energy requirements agree with CR density/lifetime (assuming ~ 3% - 10% efficiency)
- Observations of Synchrotron from SNe reveals efficient electron acceleration

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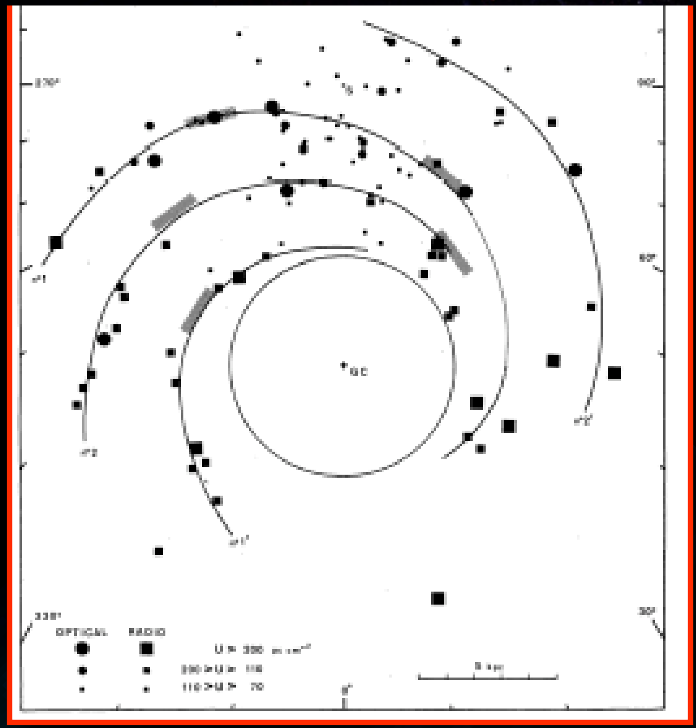
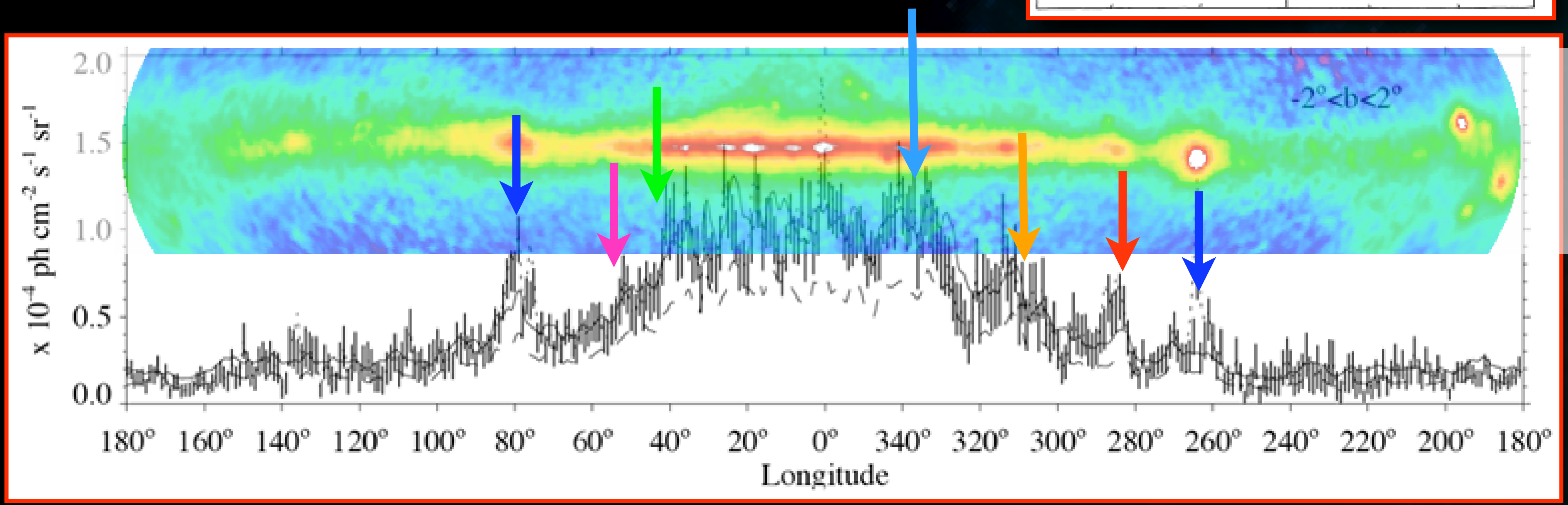
Most SNe occur in the spiral arms

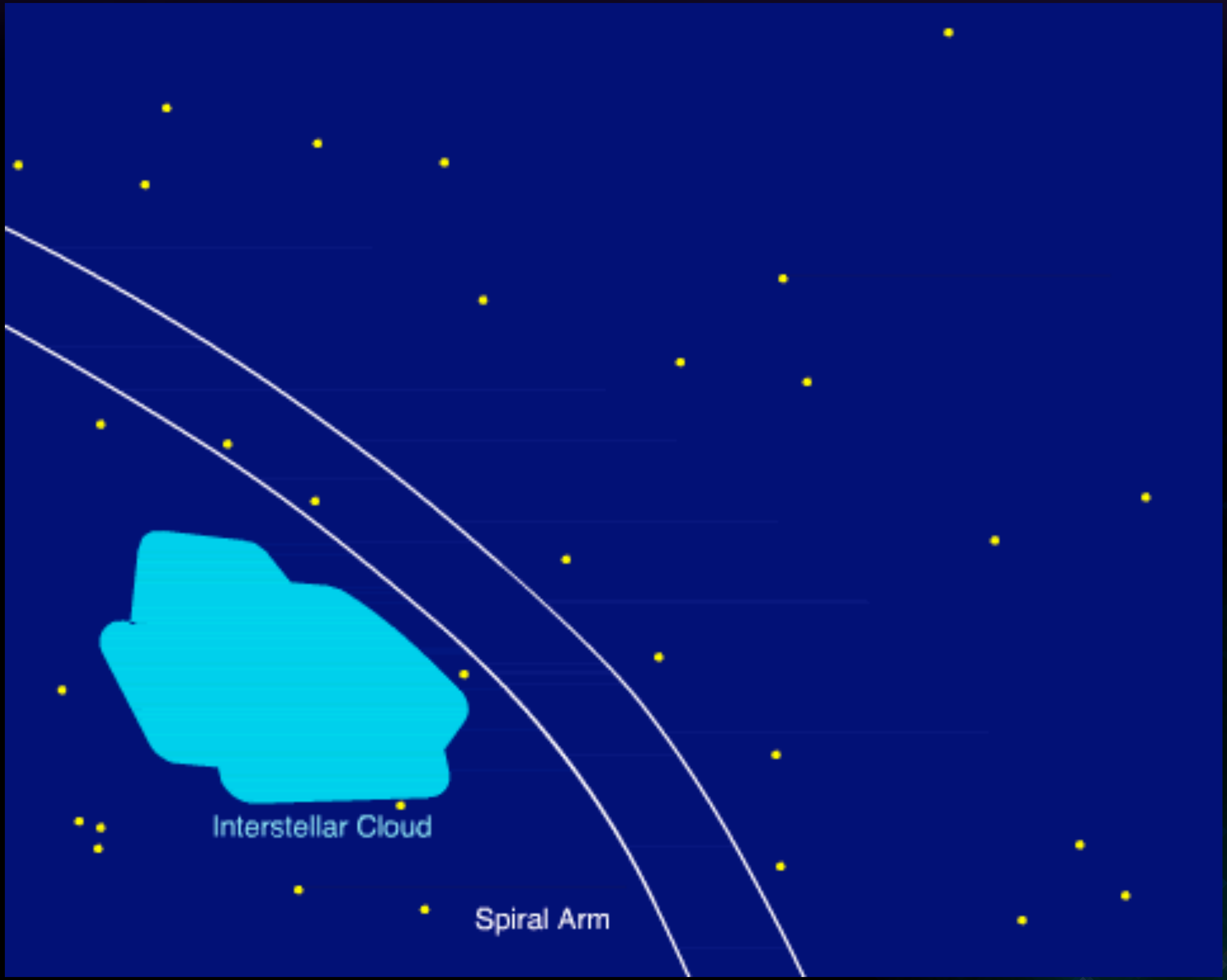
- In the Milky Way: Almost all SNe are non-Type Ia, and occur where almost all star formation takes place: In the Spiral Arms
- Meteorites: Show that density changes by a factor of > 2.5
- Deconvolved Synchrotron: Shows arm to inter-arm ratio of ~ 3



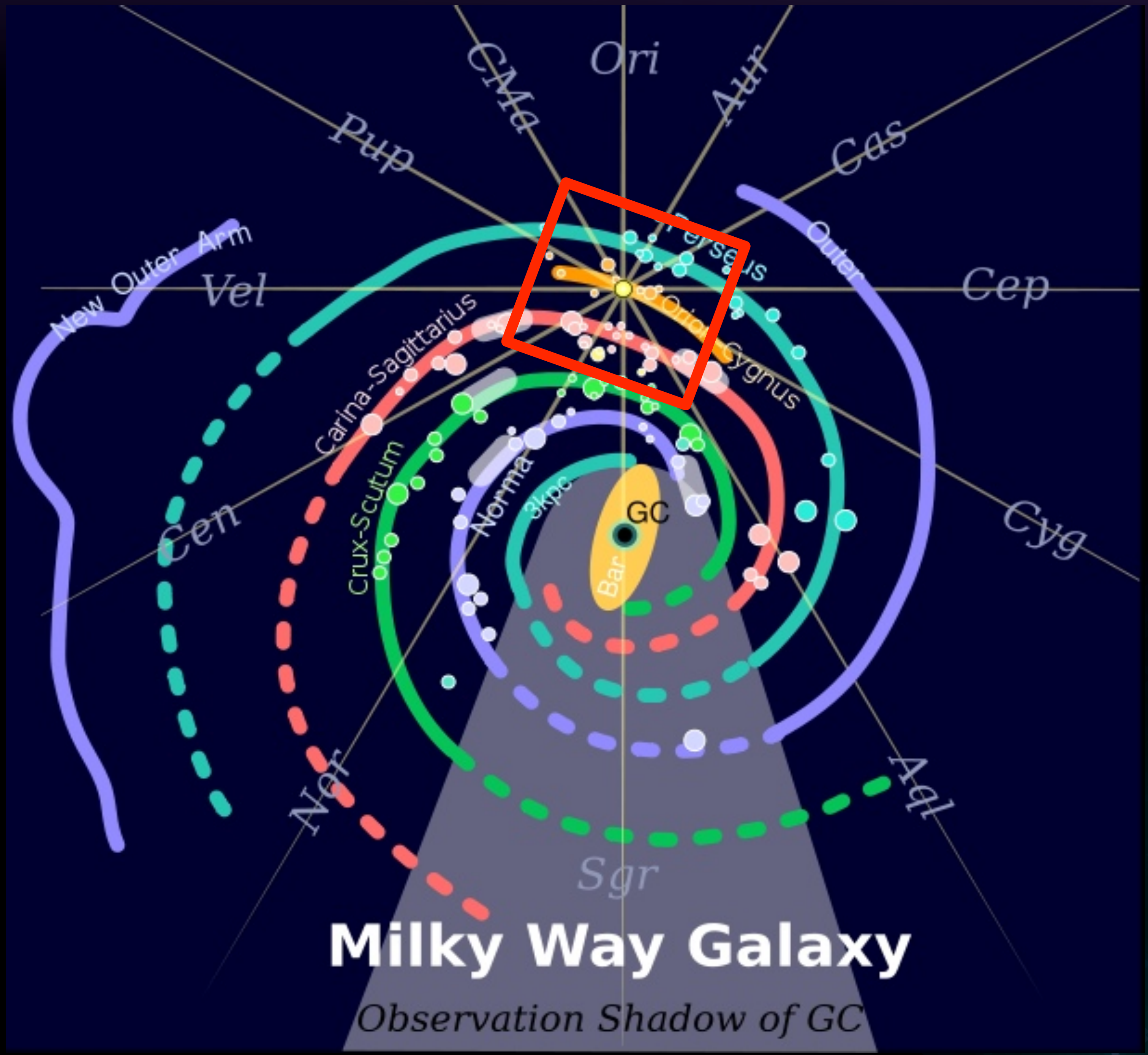


What are Spiral Arms?

Why Primarily Spiral Arms?



The nearest spiral arms are Sagittarius-Carina and Perseus at a distance of ~1-2 kpc:



Consider a localized Source of CR electrons at a distance d

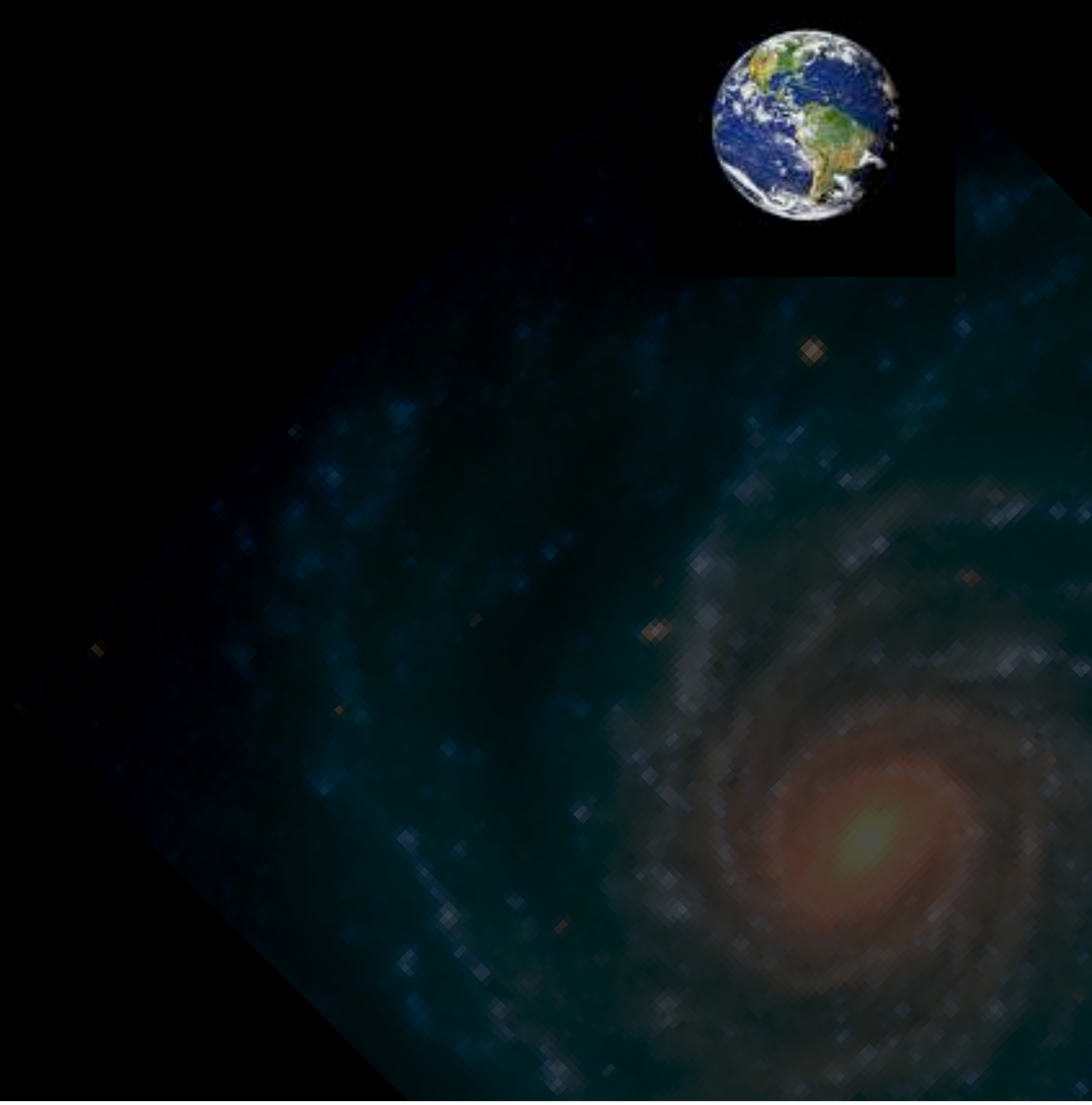
- **Above some energy, the electrons don't have enough time to reach us before cooling.**

$$t_{cool}(E,d)=t_{diffuse}(E,d)$$

d ≈ 1 kpc for E ≈ 20 GEV

This means that...

- Above E_b ~ 20 GeV, the electrons will start cooling and disappear.
- Positrons however, form continousely along the way from proton-ISM interactions.
- Therefore the positron/electron ratio will increase



- Primary electron cool and disappear before reaching earth

- Primary electron cool and disappear before reaching earth
- Secondary electron/positron form nearer and can reach earth before cooling

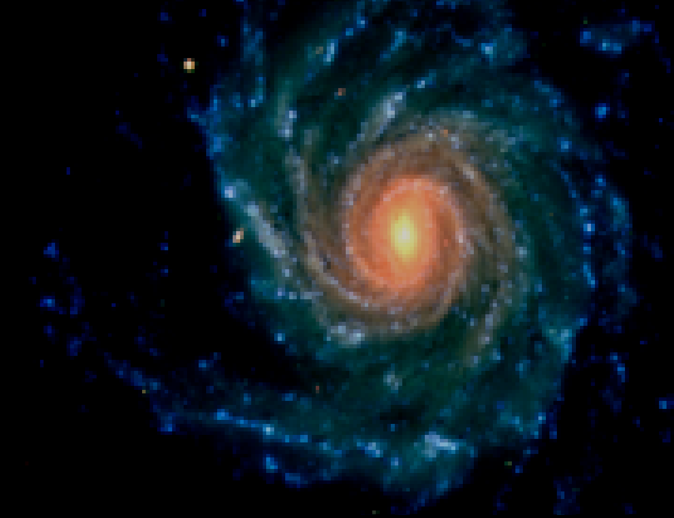
Technical Complications

- **CRs escape from the galaxy at a vertical hight of ~1kpc**

$$\Phi_{e^-}(x) \propto \frac{\exp\left[-2\sqrt{\tau_x/\tau_c + \tau_x/\tau_e}\right]}{D\sqrt{1+\tau_e/\tau_c}}$$

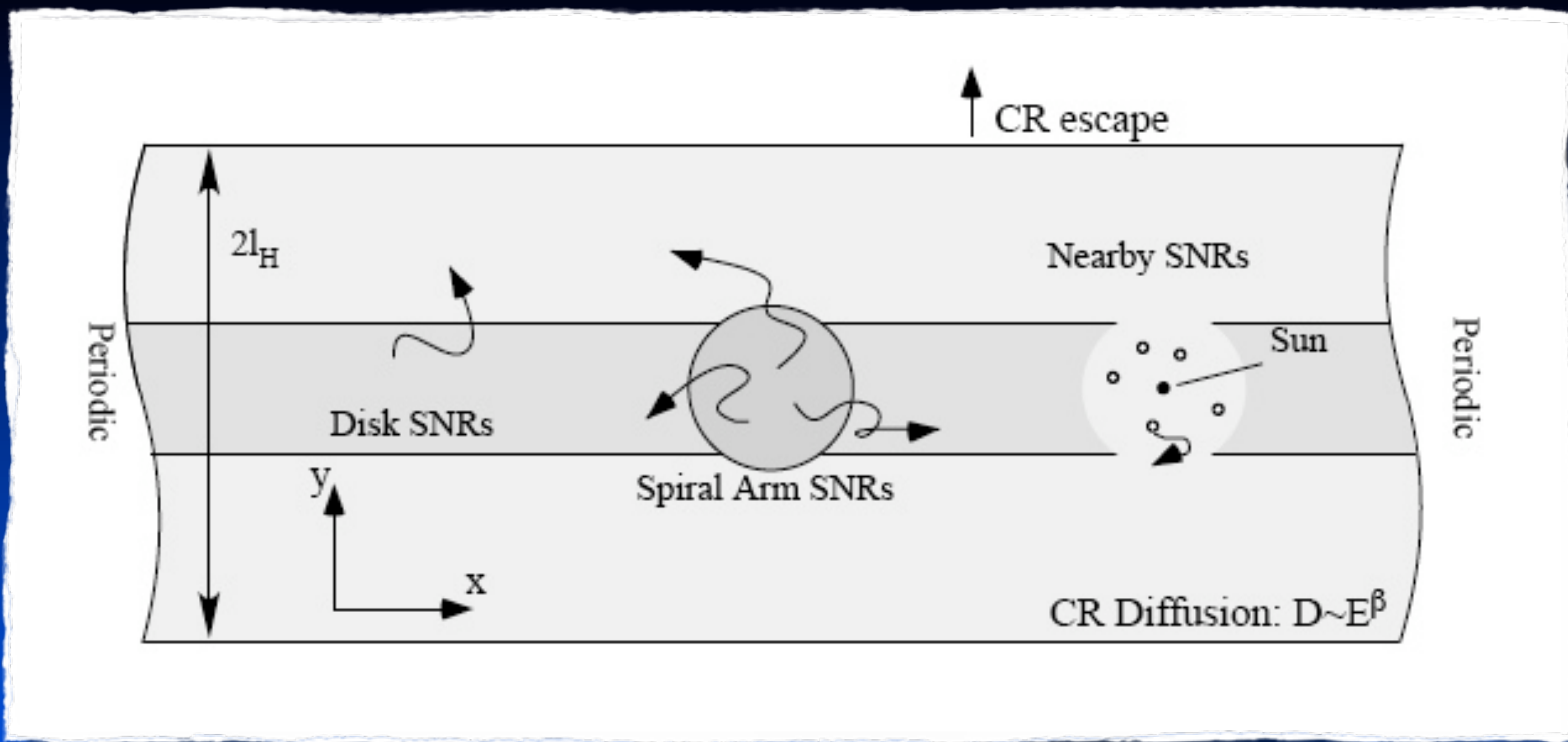
- **And the production of positrion/electrons by protons**

$$\Phi_{e^+}(x) \propto \frac{\tau_c}{D}\left(\exp\left[-\sqrt{\frac{2\tau_x}{\tau_e}}\right] - \frac{1}{\sqrt{1+\tau_e/\tau_c}}\exp\left[-\sqrt{\frac{2\tau_x}{\tau_c}+\frac{2\tau_x}{\tau_e}}\right]\right).$$



Eqs. 3 and 4 show that for a source at a distance d from Earth, a turnover in ϕ^+/ϕ^- is observed at E_b which satisfies $\tau_c(E_b) \approx \min\{\tau_x(E_b), (\tau_e(E_b)\tau_x(E_b))^{1/2}\}$. ϕ^+/ϕ^- for $E < E_b$ decreases, while it increases for $E > E_b$. At the same time the typical age of CR protons with energy E_b is $a \sim \max\{\tau_e, (\tau_e\tau_d)^{1/2}\}$. Therefore a natural prediction of the model is $a(E_b) \gtrsim \tau_c(E_b)$ and a comparison of the two observables can be used as a consistency test for the model. Moreover, over a wide range of the parameter space for which $d \gtrsim l_H$, the model predicts $a(E_b) \approx \tau_c(E_b)$ regardless of the value of the diffusion coefficient D.

A simplied Model

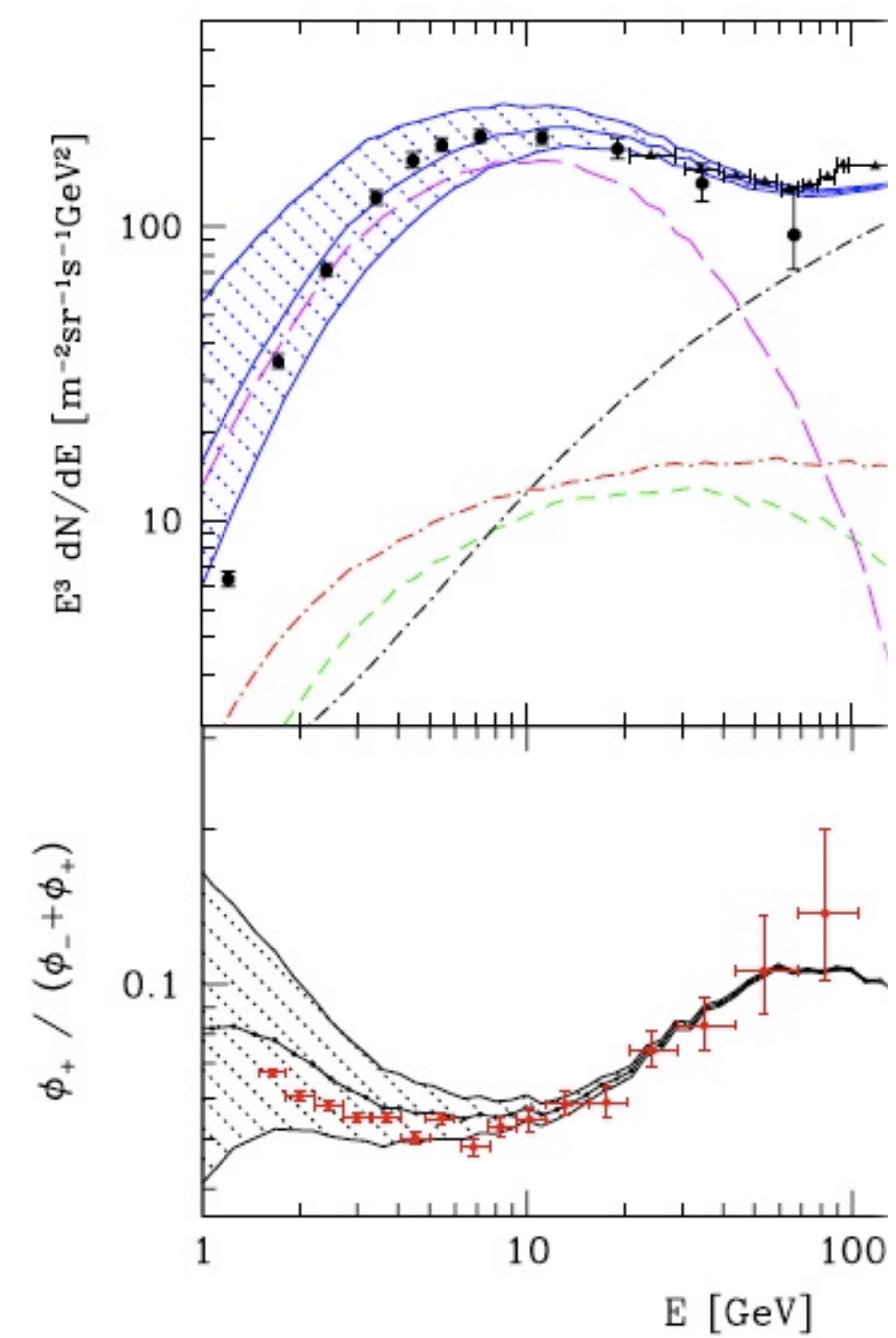


d=1 kpc

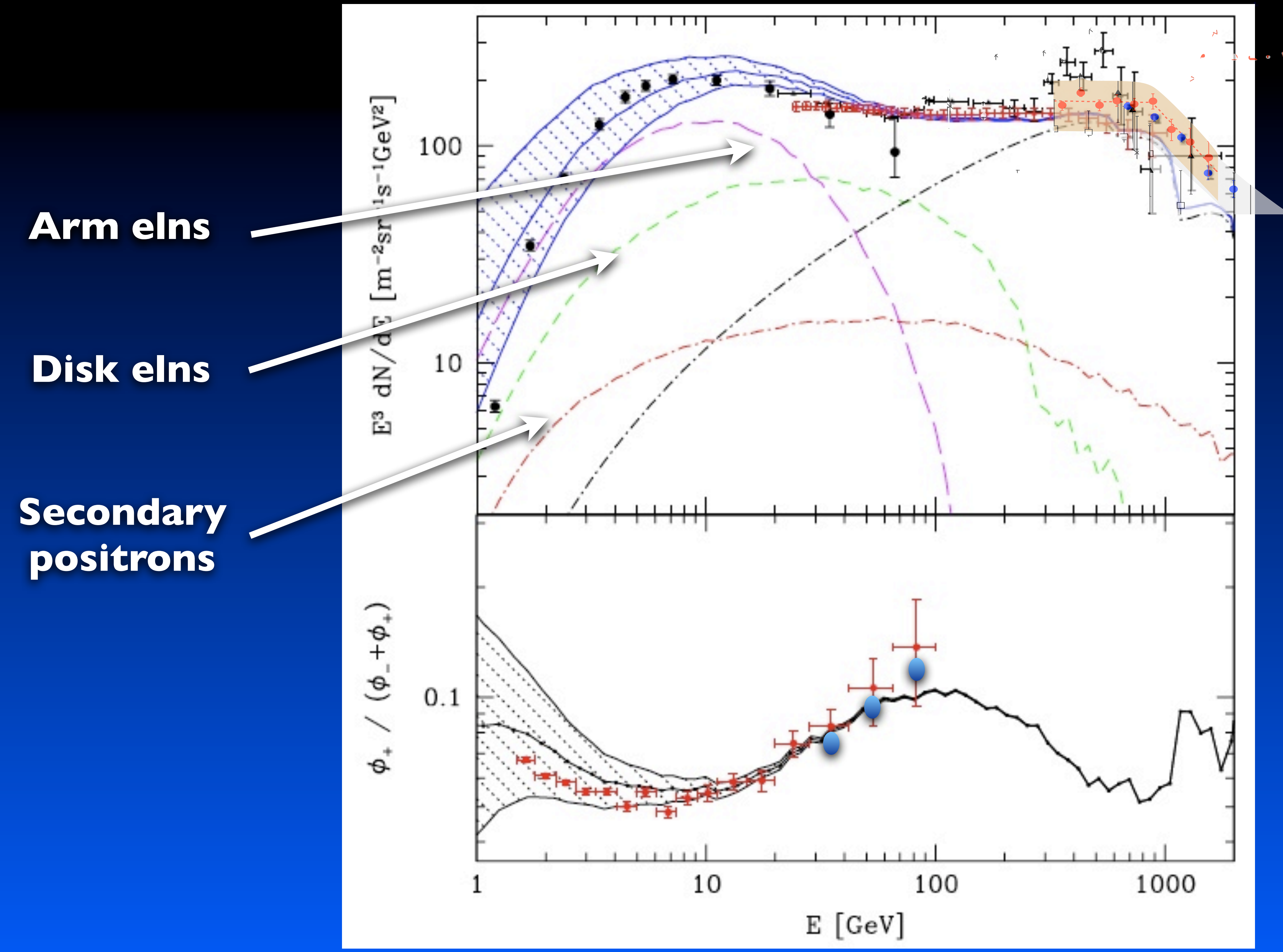
δ=1/3

$$\frac{R_{arm}}{R_{disk}} = 4$$

$e^+/(e^+ + e^-)$ ratio and e^- spectrum



$e^+/(e^++e^-)$ ratio and e^- spectrum

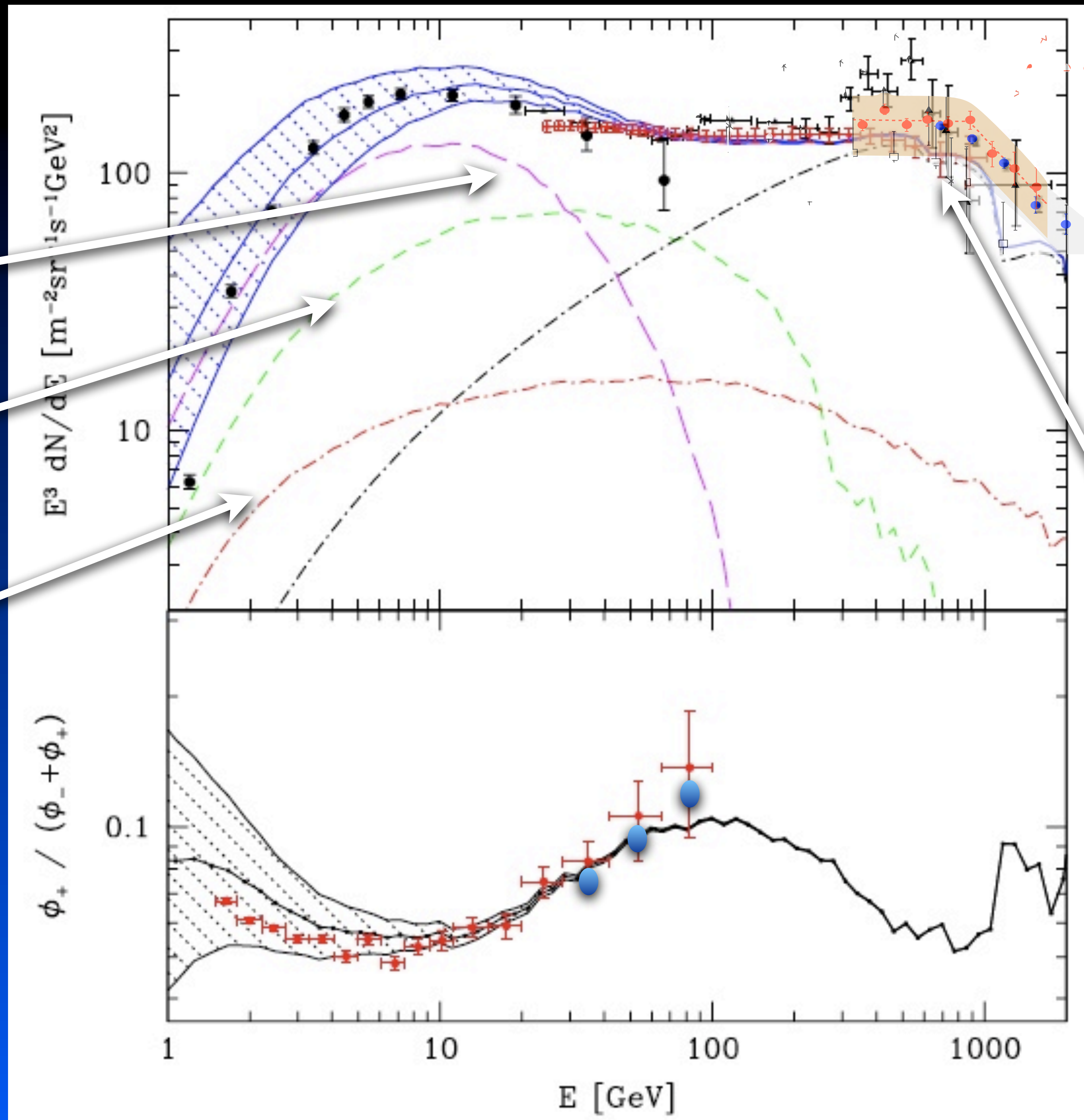


$e^+/(e^++e^-)$ ratio and e^- spectrum

Arm elns

Disk elns

Secondary positrons



Contribution from nearby KNOWN young SNRs: **Geminga, Monogem, Gela LoopI and Cygnus Loop**

Short scale inhomogeneities

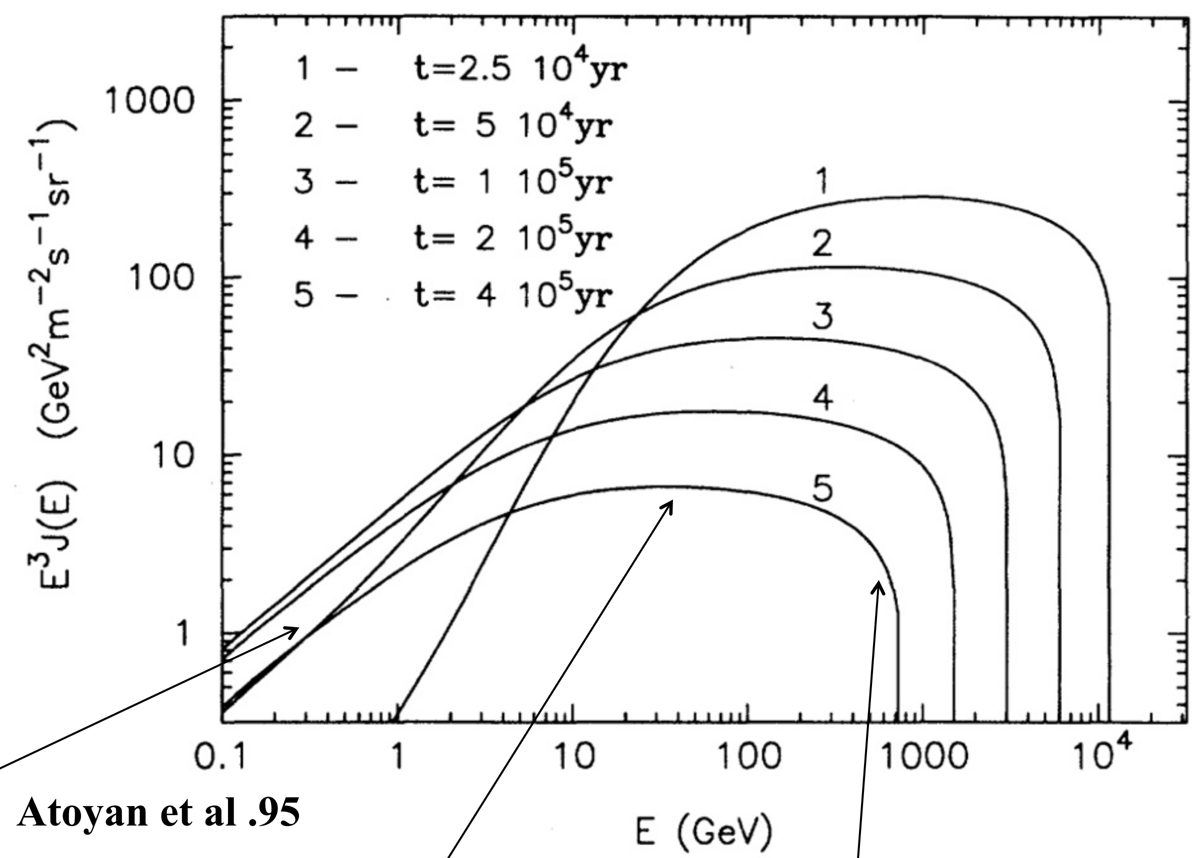
In the near vicinity (<0.5 kpc, <0.5 Myr) the discrete nature of the sources must be taken into account

Nearby SNRs

SNR	R(kpc)	T(yr)
Cygnus Loop	0.44	2.0×10^4
Vela	0.30	1.1×10^4
Monogem	0.30	8.6×10^4
Loop1	0.17	2.0×10^5
Geminga	0.4	3.4×10^5

Yoshida et al. 03

Single SNR observed e^- spectrum



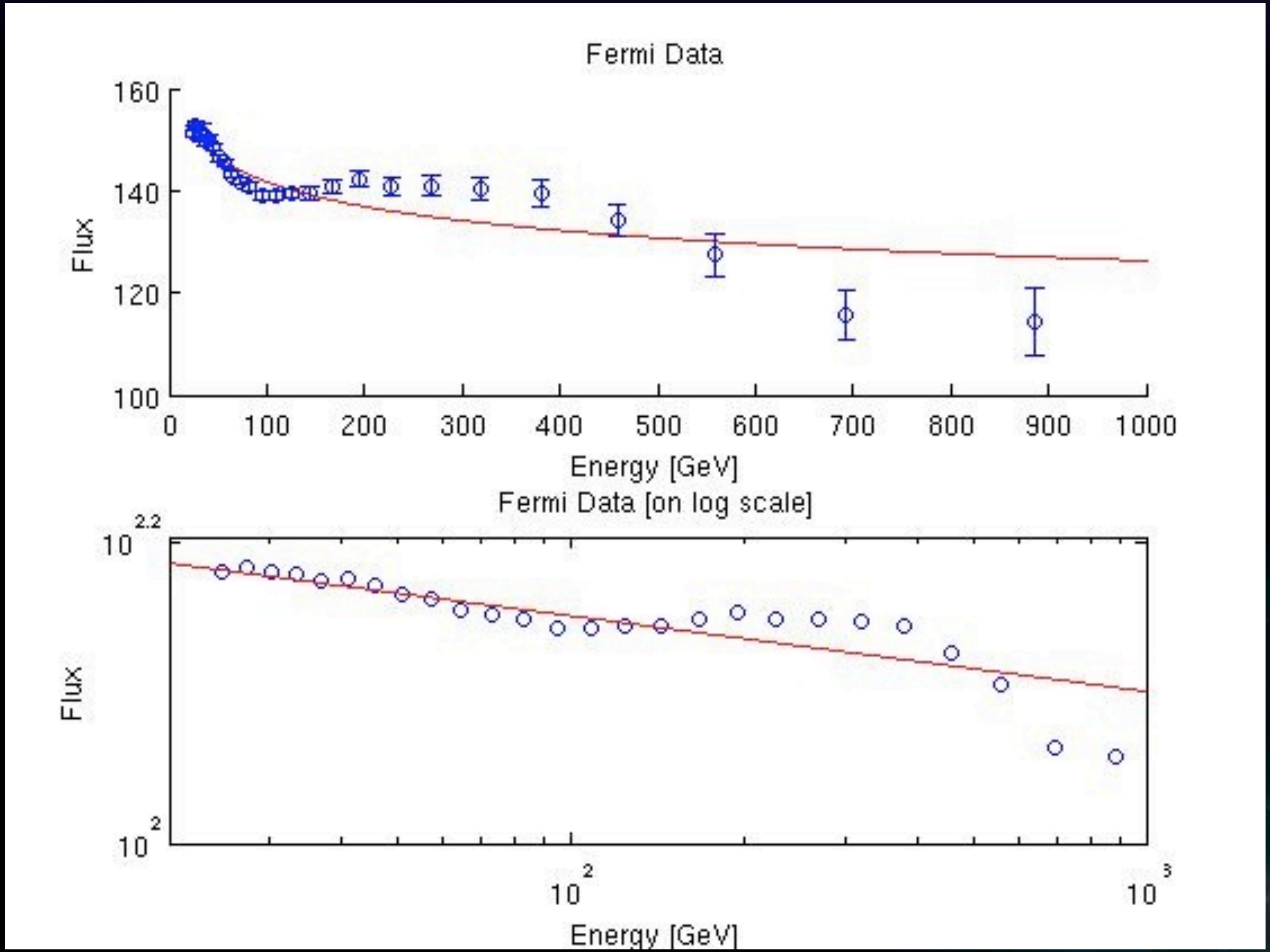
Atoyan et al .95

Didn't reach us yet

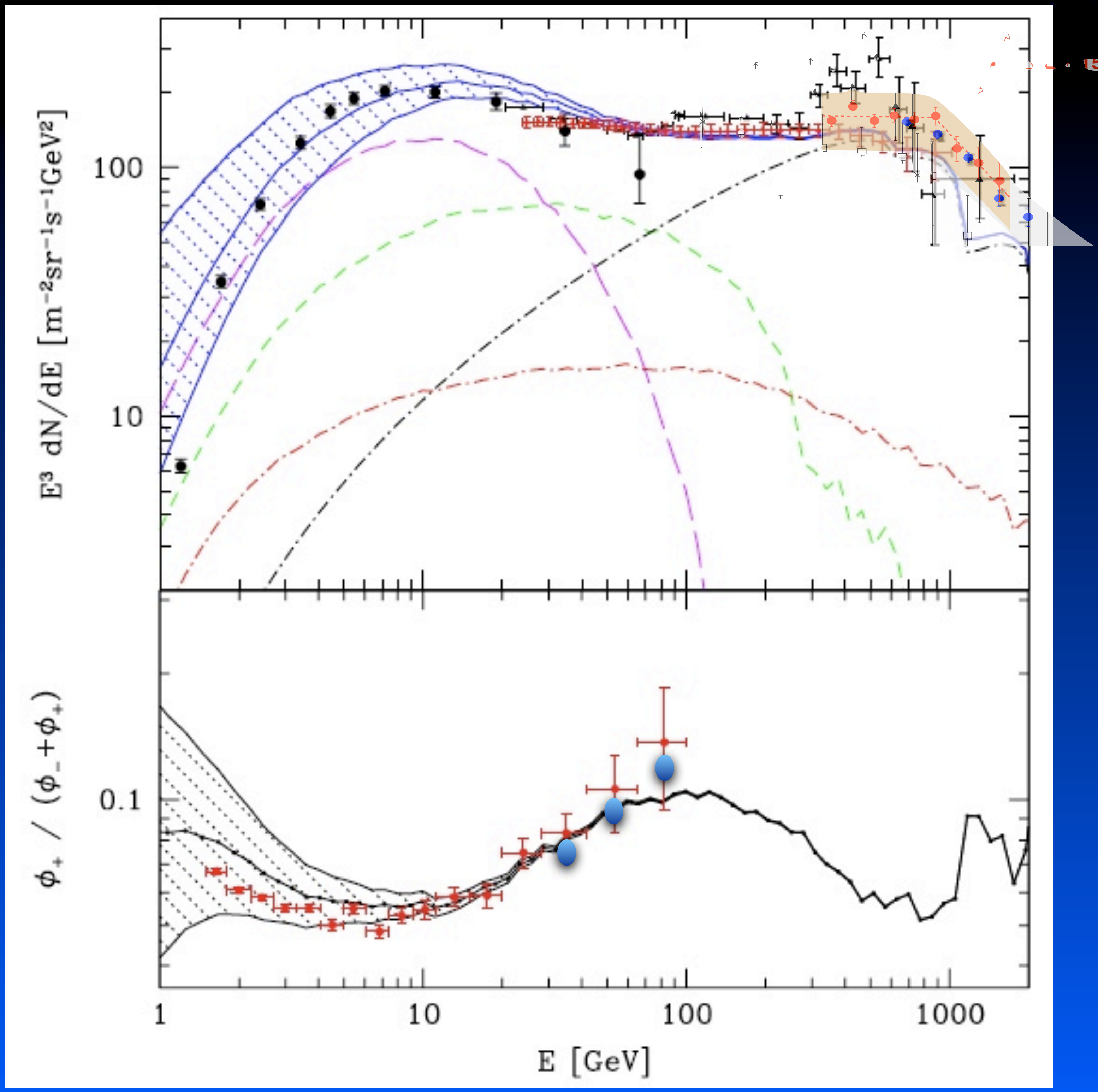
reached us

Already cooled down

Wiggles in the Fermi Data



$e^+/(e^++e^-)$ ratio and e^- spectrum



Dark matter

Pros:

- Can explain the data

Cons:

- Require a revolution in physics while it is based on weak supporting evidence
- non-standard model (many degrees of freedom)

Predictions:

- Rising positron fraction above 100 GeV

Pulsars:

Pros:

• A known site where relativistic pairs are produced

Cons:

• Unknown fraction of energy and spectrum of the pairs escaping to the ISM

Predictions:

• Rising positron fraction above 100 GeV

Galactic Arm SNRs:

Pros:

- No new source or physics is required
- If Core collapse SNe are major CR source then the effect must be there at some level
- Predict CR age (10 GeV) ≈ cooling time (10 GeV)

Cons:

- Affect the whole set of CR observations and therefore must be confronted with all available data
- The effect is not dominant for all the parameter space allowed by the observations.

Predictions:

- A flattening and then a falling positron fraction above a few hundred GeV

Conclusions

- The observed rising e^+/e^- ratio requires revisions in one or more of the standard model for CR positron
- There are well known astrophysical effects that can potentially produce the observations.

The Galactic Arms SNR model:

- A *realistic* distribution of SNRs must be included in the models, even if this is not the main source of rising e^+/e^- ratio
- This model is the only one (so far) that explains PAMELA+Fermi+H.E.S.S. and predicts a flat and later decrease in $e^+/(e^++e^-)$ ratio above a few hundred GeV.

The End ?