Recent cosmic-ray anomalies and their interpretations

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LAPTh/LAPP

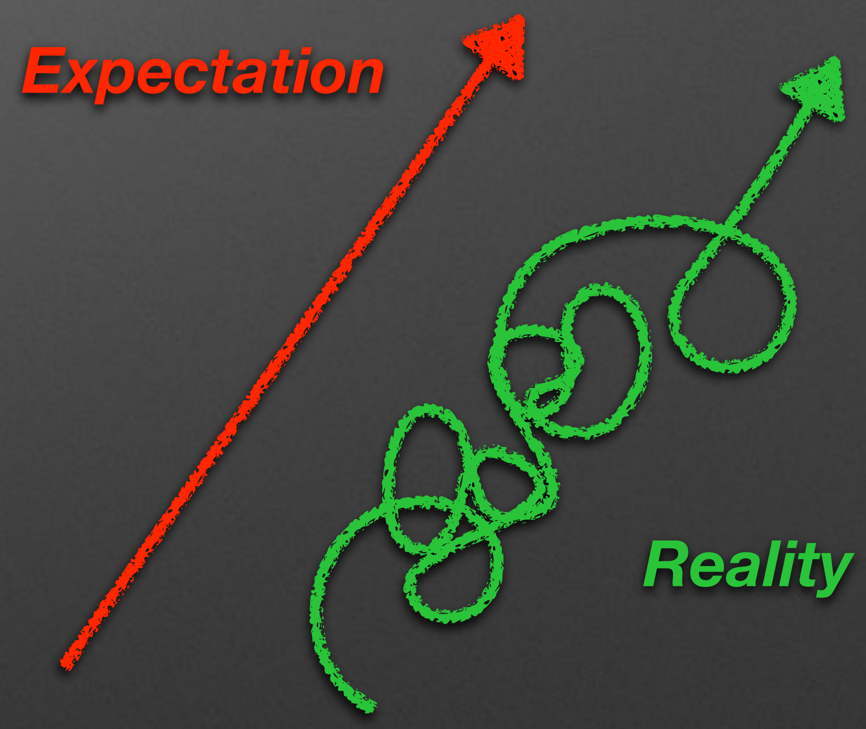
Disclaimer:
- Non-exhaustive list of models (and references)
- Recent examples given

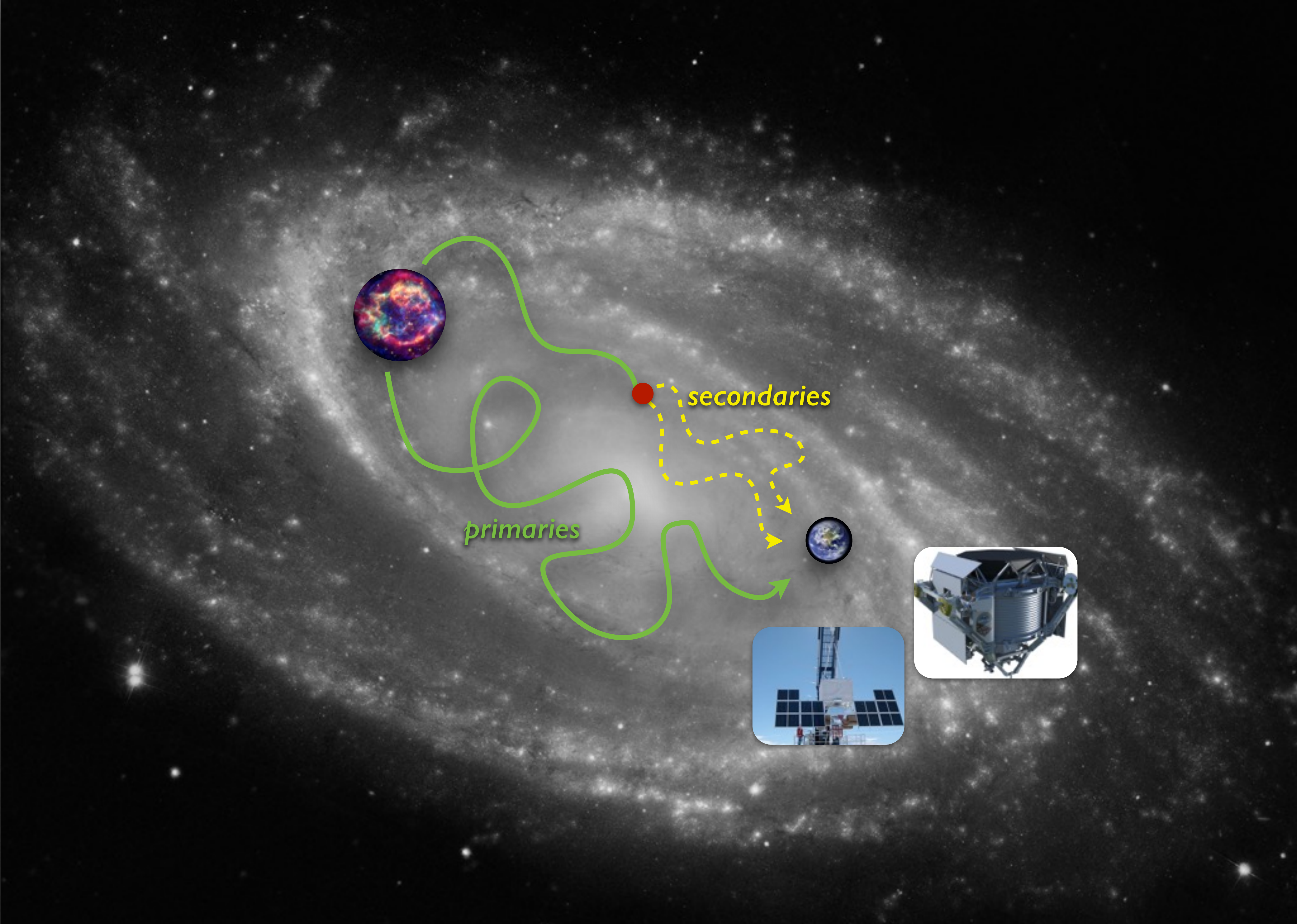
Outline

anomaly /ə'nɒm(ə)li/:
something that deviates from what is standard, normal, or ***expected***

[Dictionary]

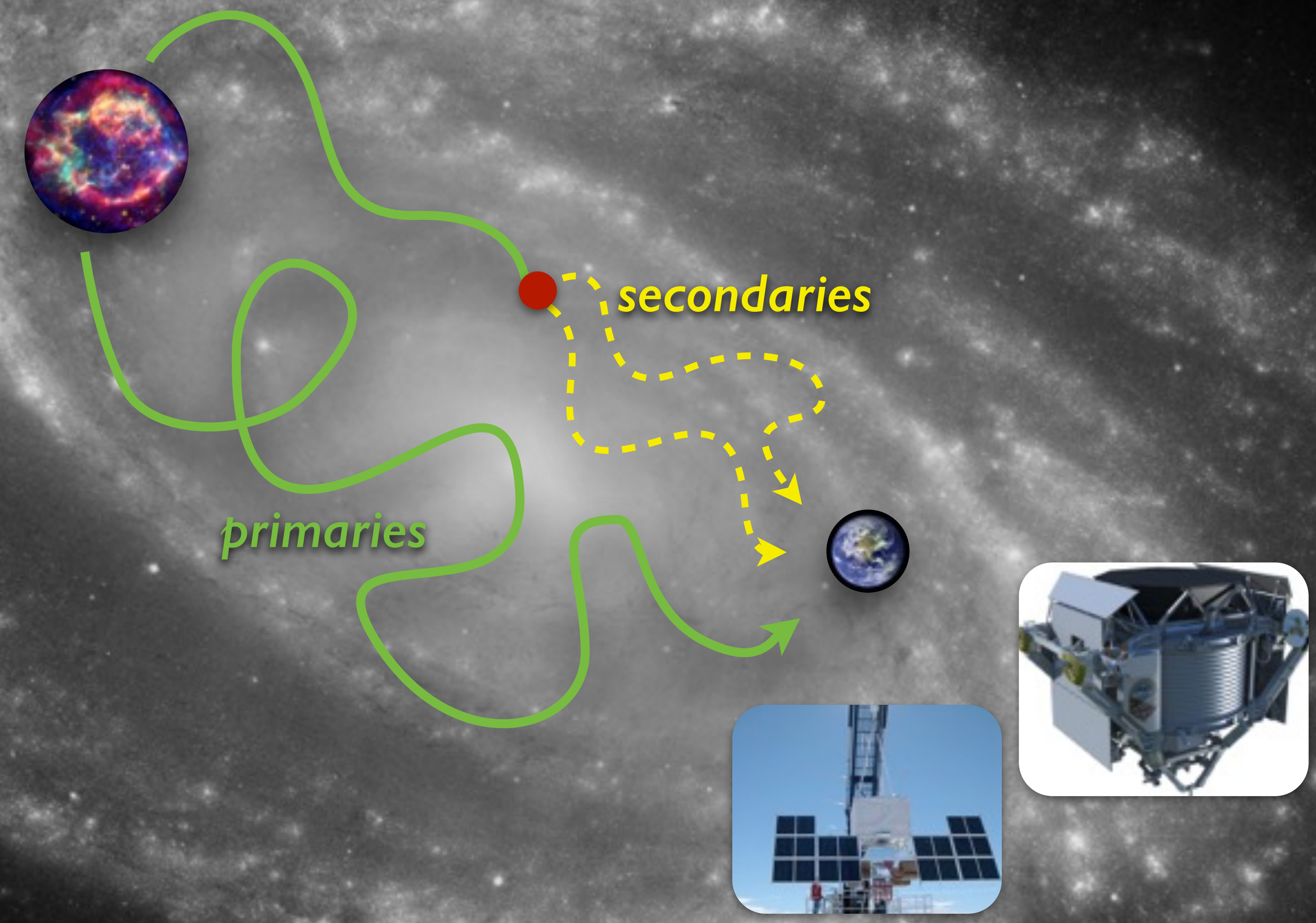
- What do we expect?
  → Diffusion model
- What deviates from our expectations?
  → Fluxes at GeV energies
- What can cause these deviations?
  → Propagation, acceleration, sources
- How can we test these hypotheses?
  → Multi-messenger approach

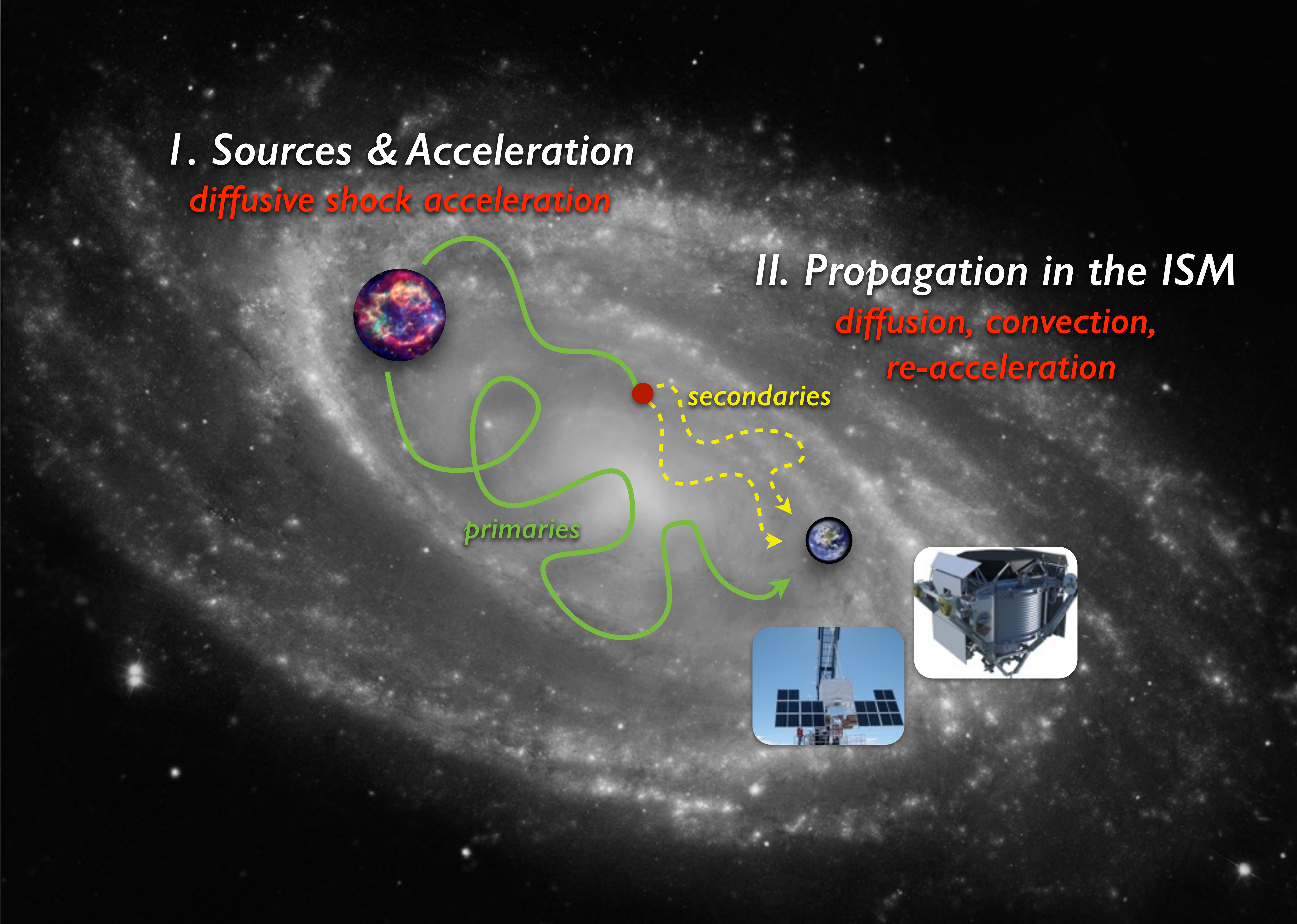


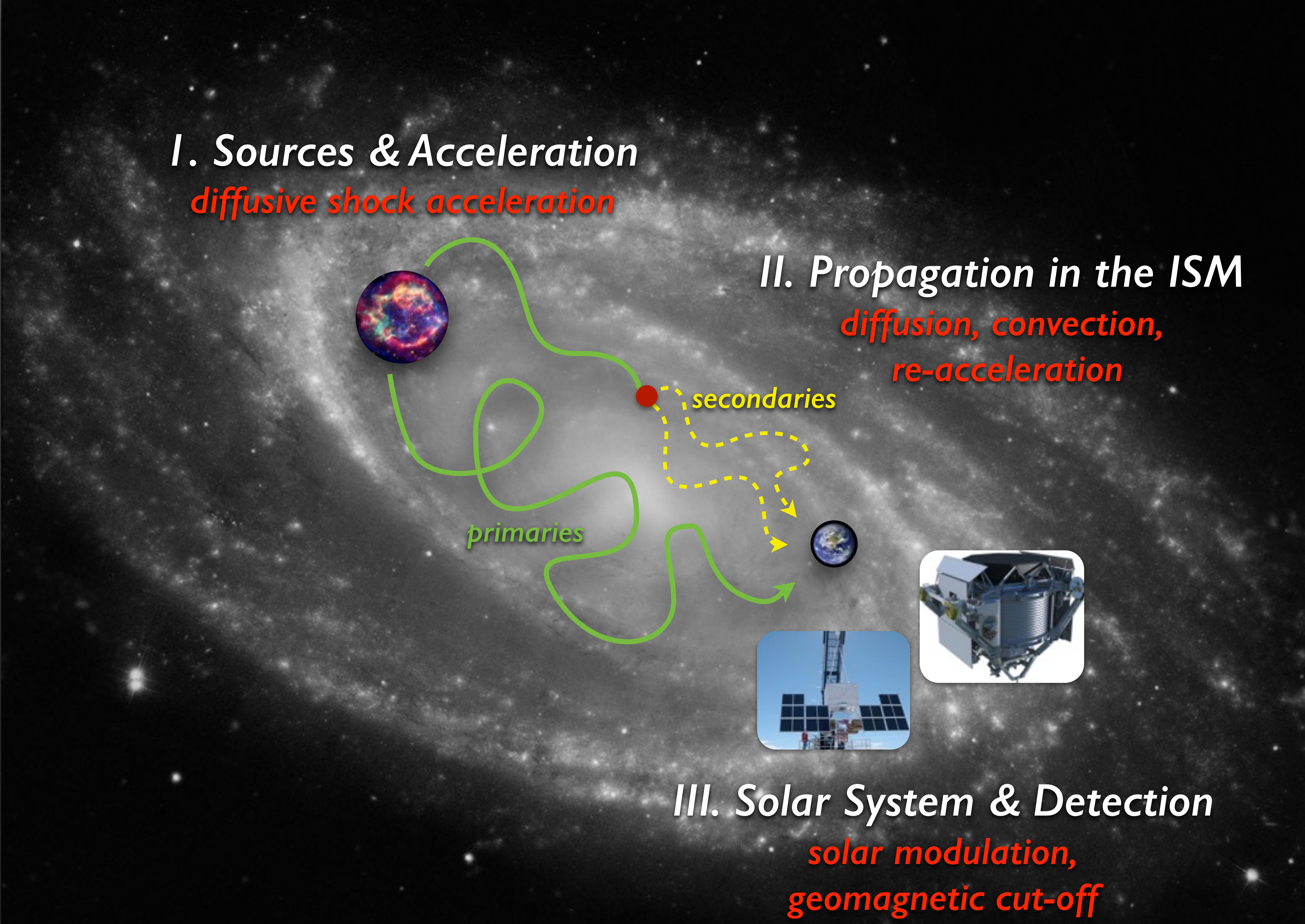

secondaries
primaries

1. Sources & Acceleration

diffusive shock acceleration




I. Sources & Acceleration
diffusive shock acceleration
II. Propagation in the ISM
diffusion, convection,
re-acceleration
secondaries
primaries


I. Sources & Acceleration
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diffusion, convection,
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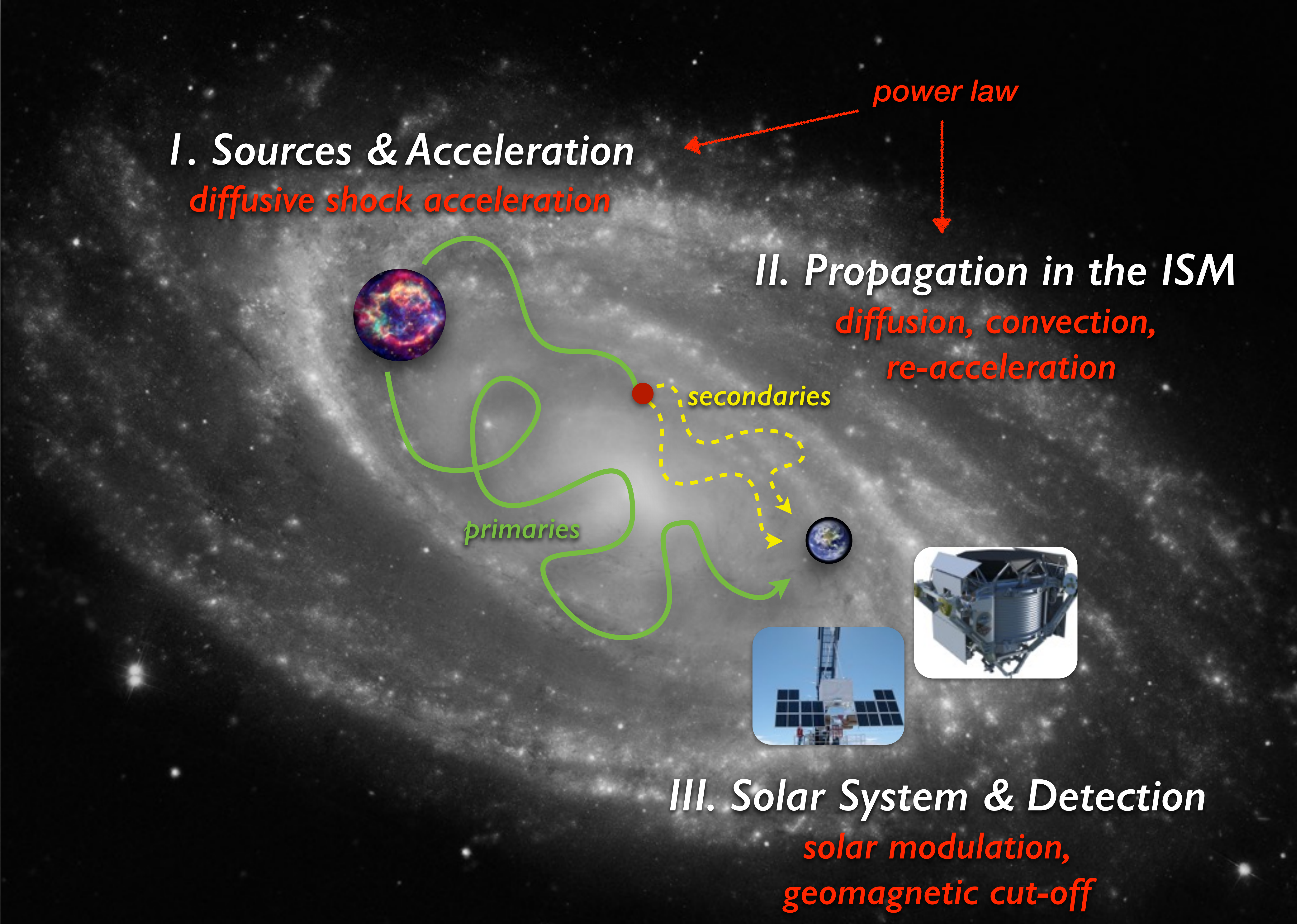
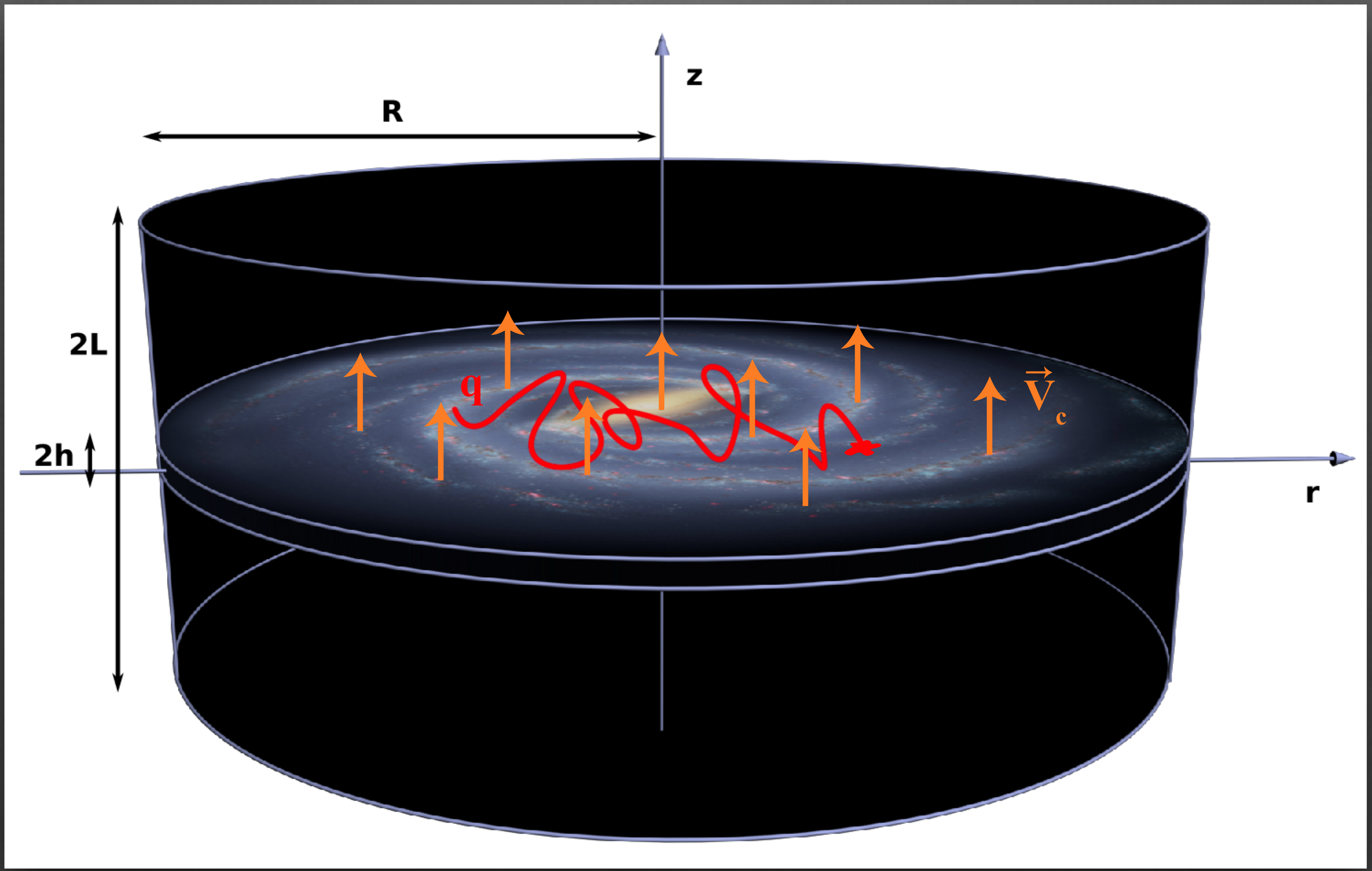
primaries
III. Solar System & Detection
solar modulation,
geomagnetic cut-off


power law
I. Sources & Acceleration
diffusive shock acceleration
II. Propagation in the ISM
diffusion, convection,
re-acceleration
secondaries
primaries
III. Solar System & Detection
solar modulation,
geomagnetic cut-off



$$\frac{\partial N}{\partial t} = \boxed{\underbrace{q}_{\text{sources}} + \vec{\nabla}\cdot(\hat{K}_{xx}\vec{\nabla}N} \underbrace{\vphantom{\vec{\nabla}} - \vec{V}_c N)}_{\text{spatial diffusion \& convection}} + \underbrace{\frac{\partial}{\partial p} p^2 K_{pp} \frac{\partial}{\partial p}\frac{1}{p^2} N}_{\text{momentum diffusion}}$$

$$- \underbrace{\frac{\partial}{\partial p}\left[\frac{\partial p}{\partial t} N - \frac{p}{3}\left(\vec{\nabla}\vec{V}_c\right) N\right]}_{\text{energy losses}} - \underbrace{\frac{1}{\tau_s} N}_{\text{spallation}} - \underbrace{\frac{1}{\tau_r} N}_{\text{radioactive decay}}$$

Cosmic-ray transport equation

talk by Evoli

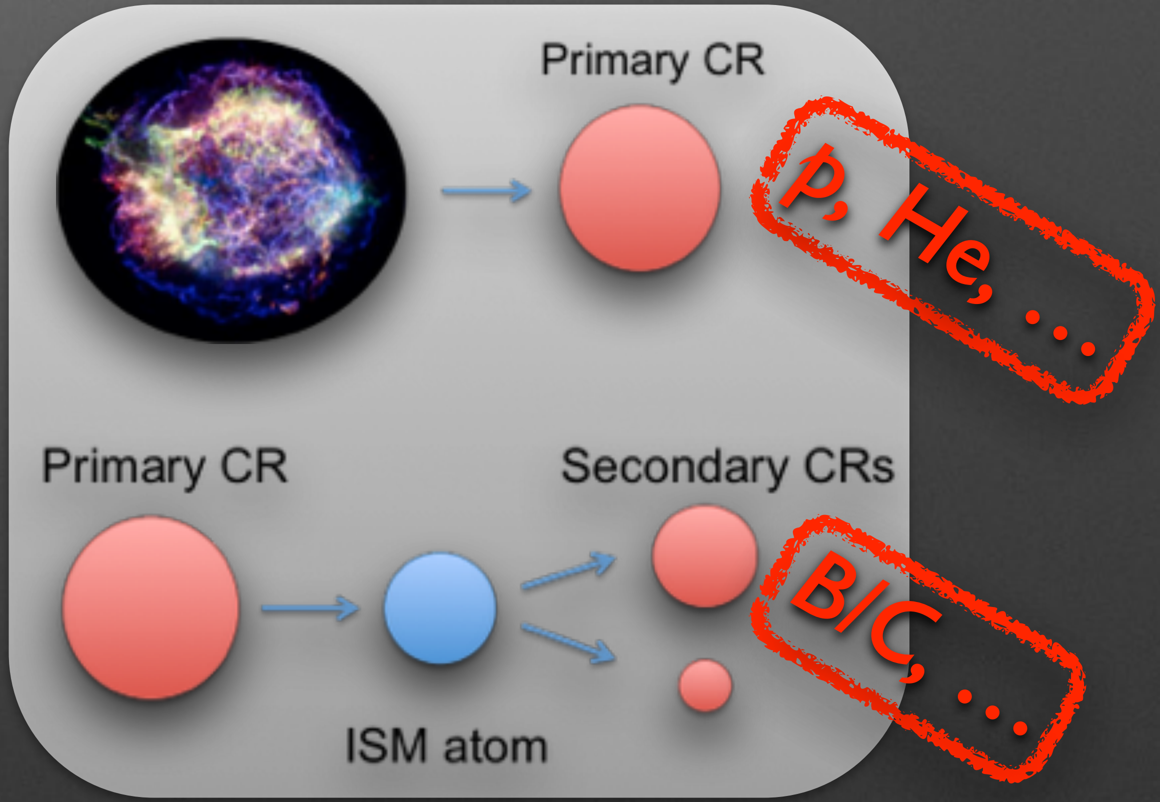
Parameters and observables

The most important parameters are linked to

- the acceleration mechanisms
  injection spectrum: $Q(R) \propto qR^{-\alpha}$

power law

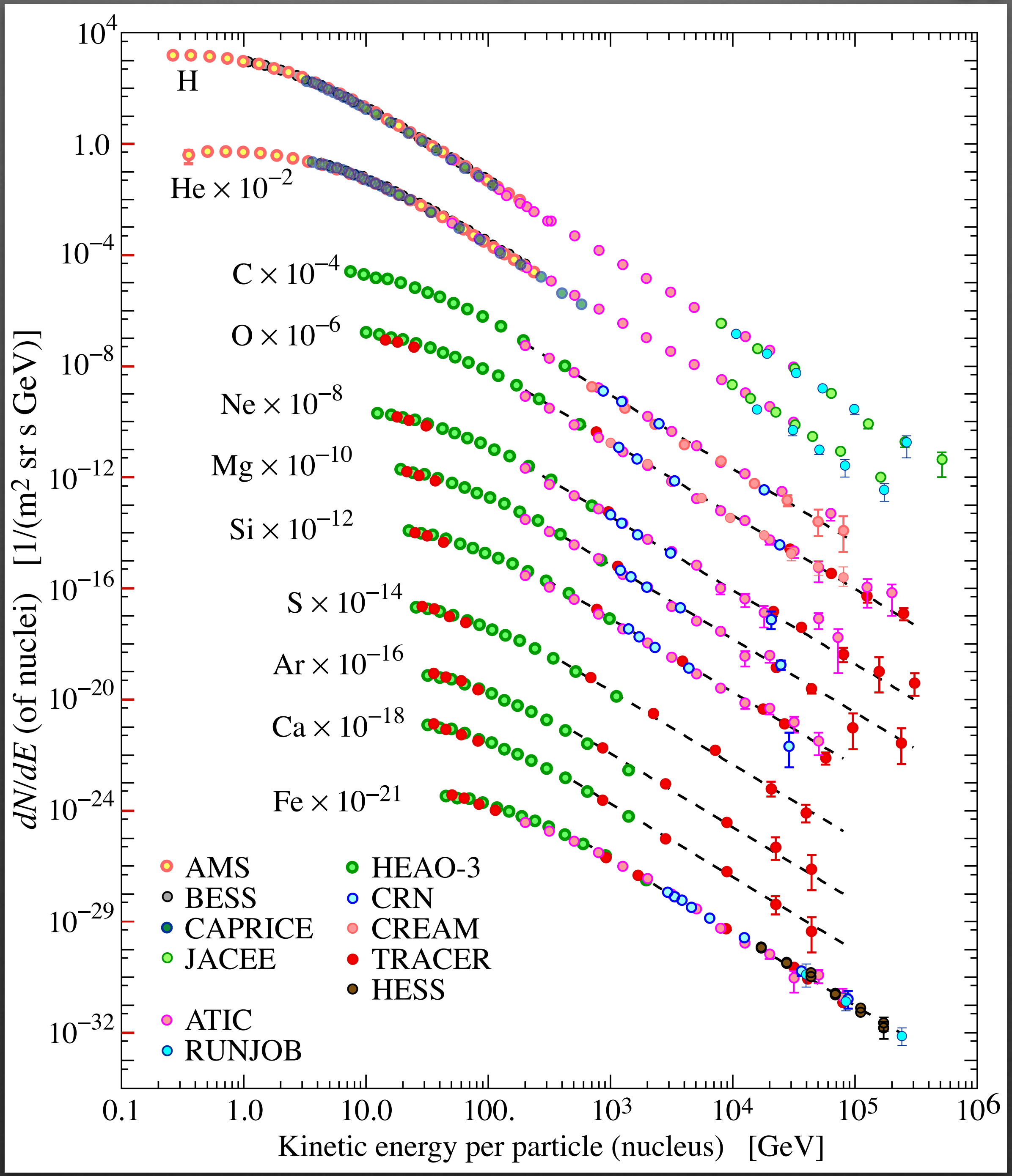
- the propagation mechanisms
  diffusion: $K(R) \propto K_0 R^{\delta}$
  convection: V_C
  re-acceleration: V_A



lpsc.in2p3.fr/cosmic-rays-db

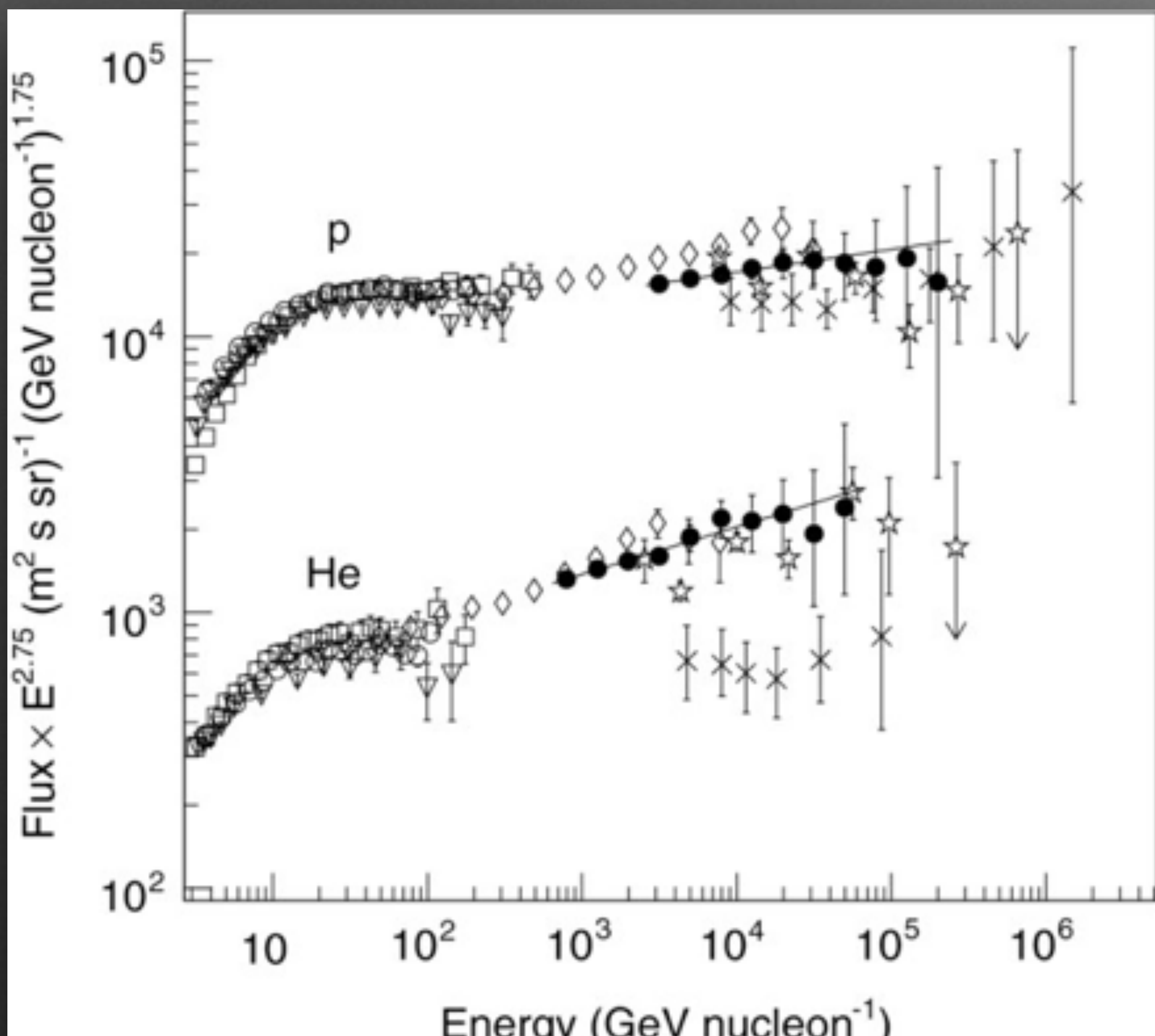
What do we expect?

featureless and universal power-law energy spectra

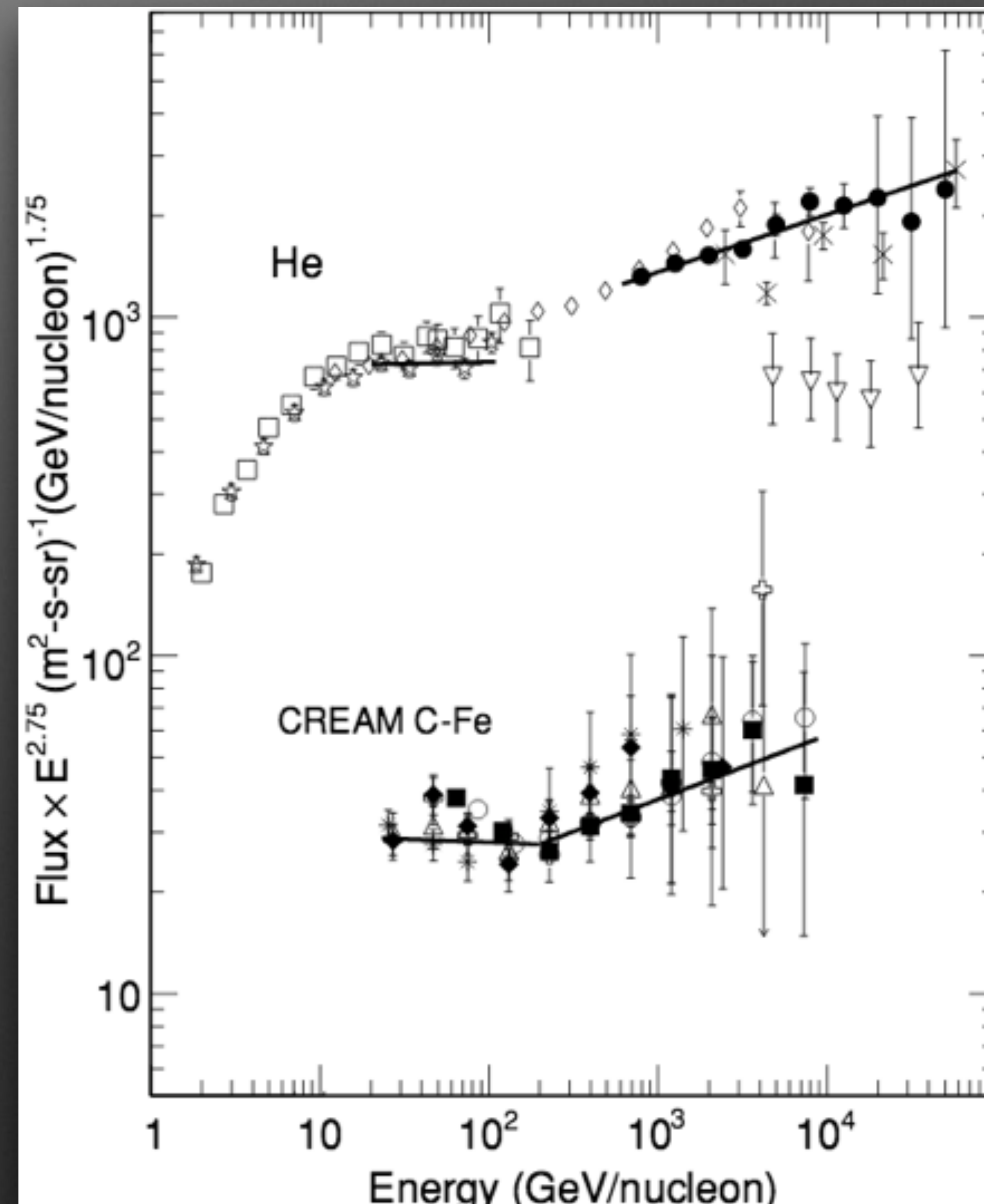


[Boyle & Müller, *PDG* (2014)]

What do we see?
Hints of a broken power law



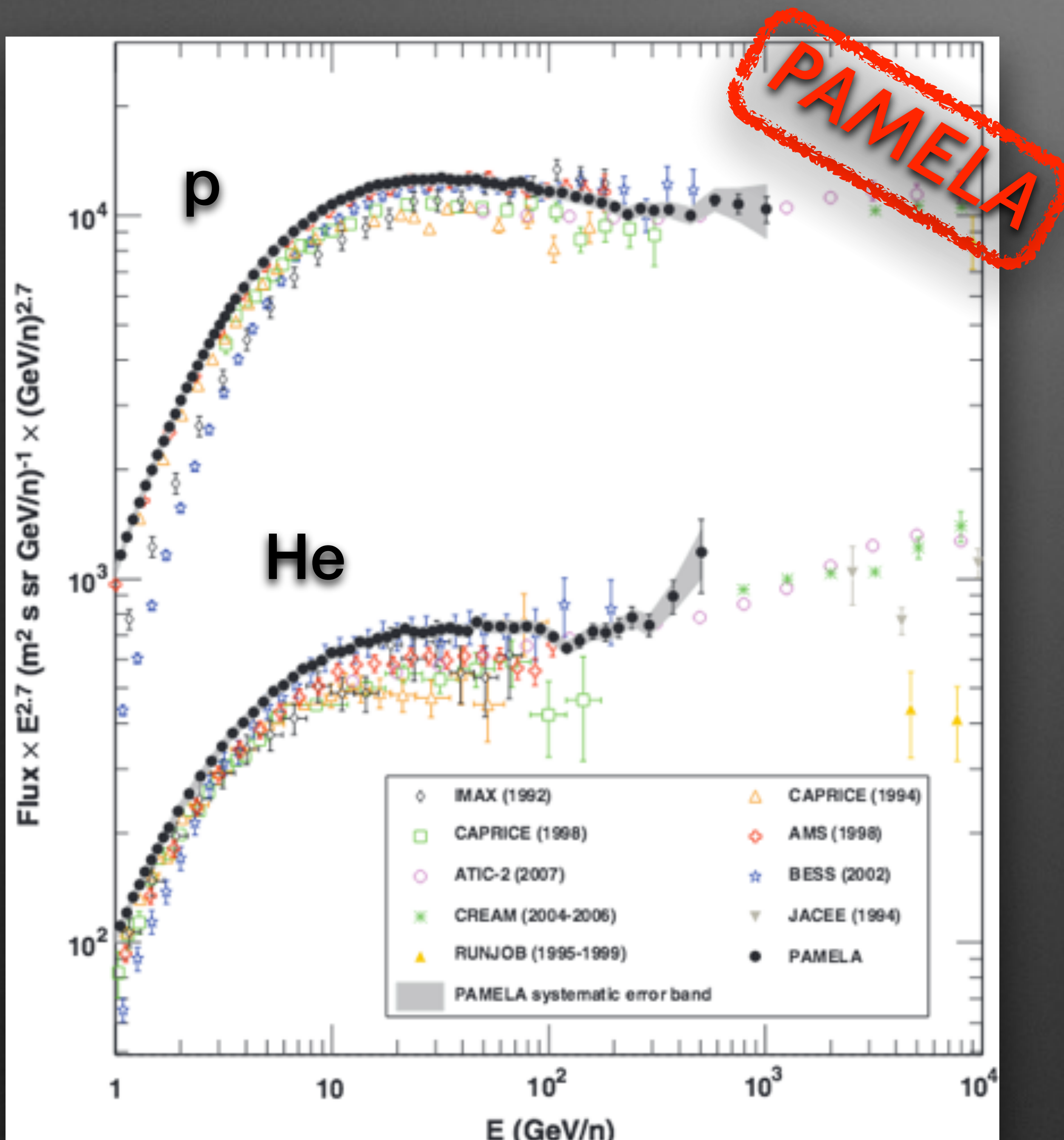
[Yoon et al., *ApJ* (2011)]



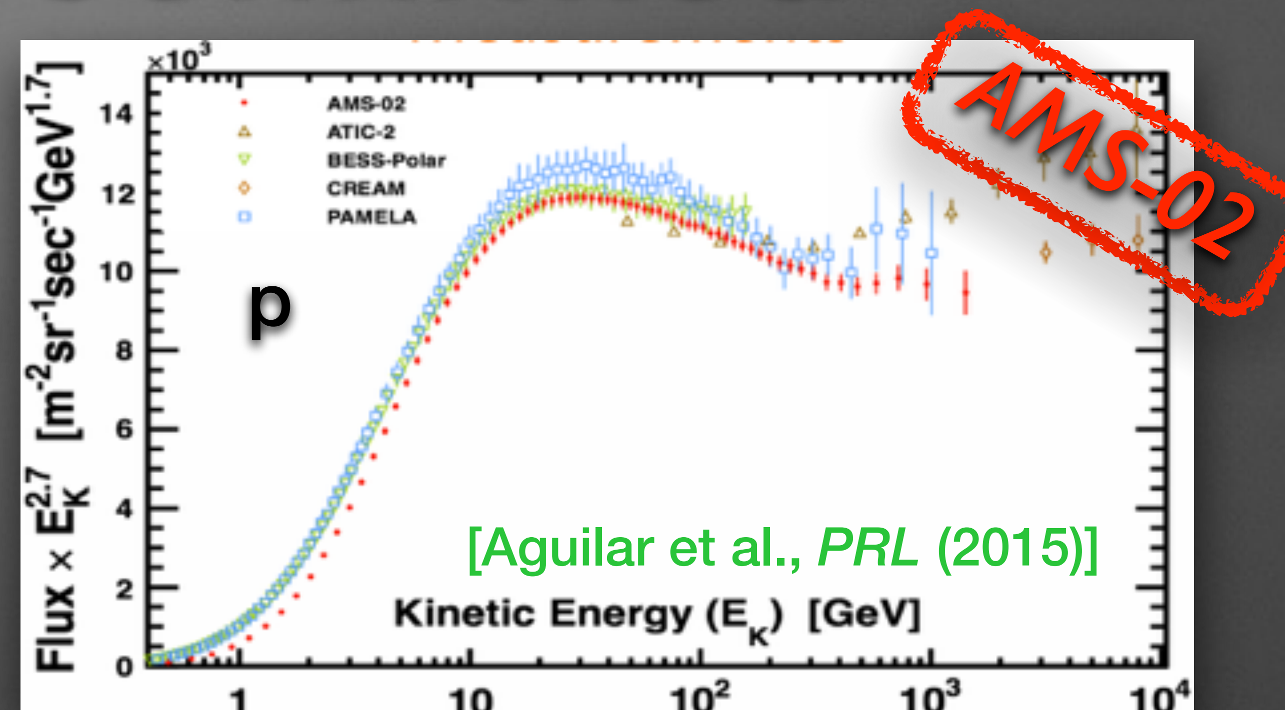
[Ahn et al., *ApJL* (2010)]

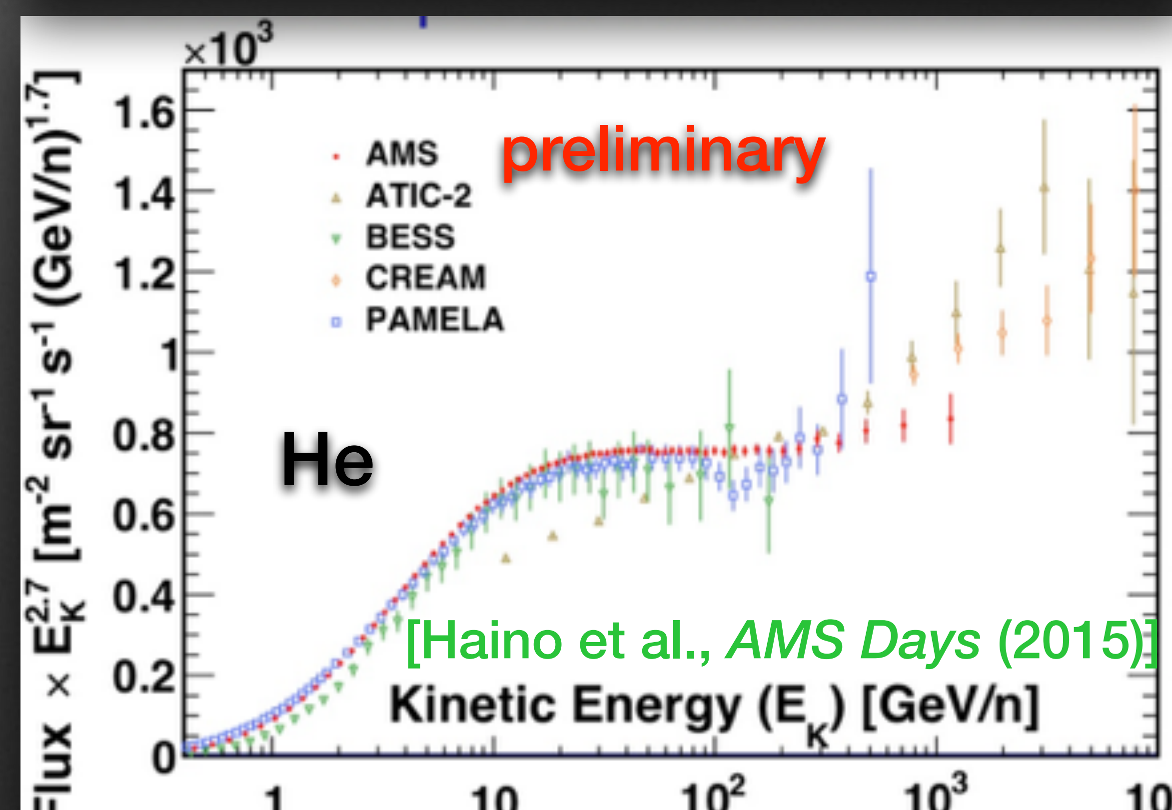
Balloon experiments (notably ATIC [◊] & CREAM [●]) observed a *hardening* in nuclei fluxes

What do we see? Hardening confirmed

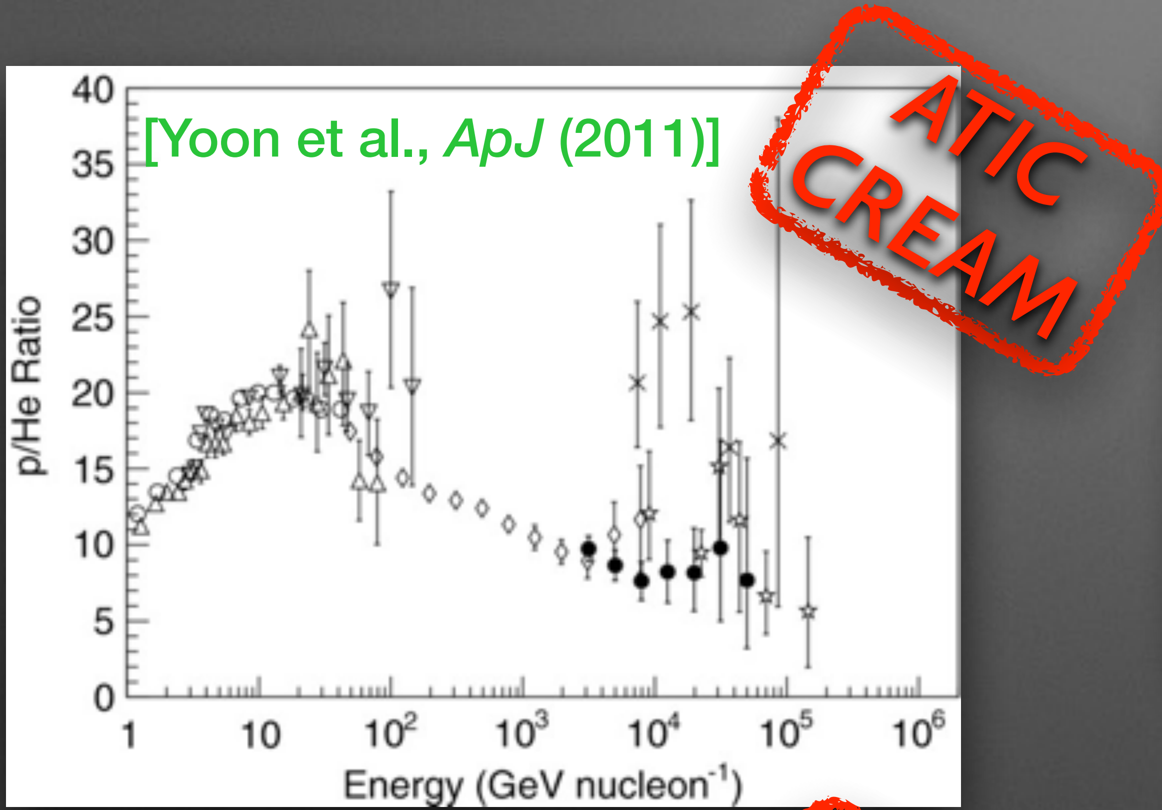


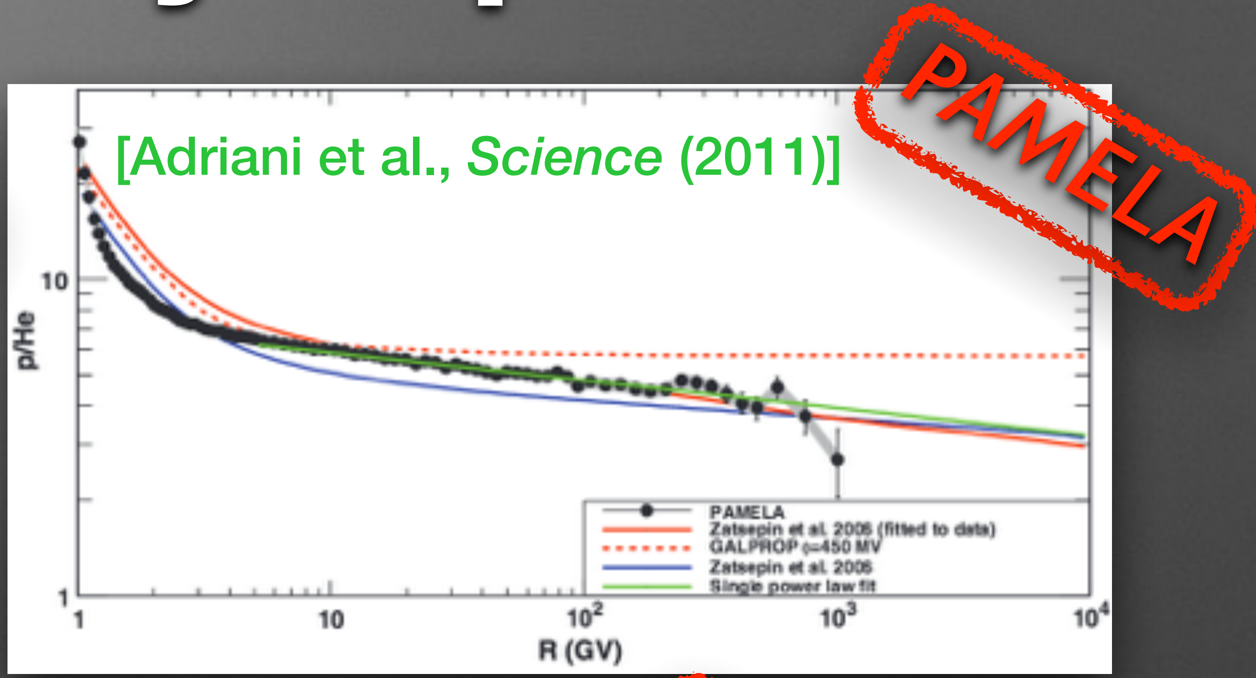
[Adriani et al., *Science* (2011)]

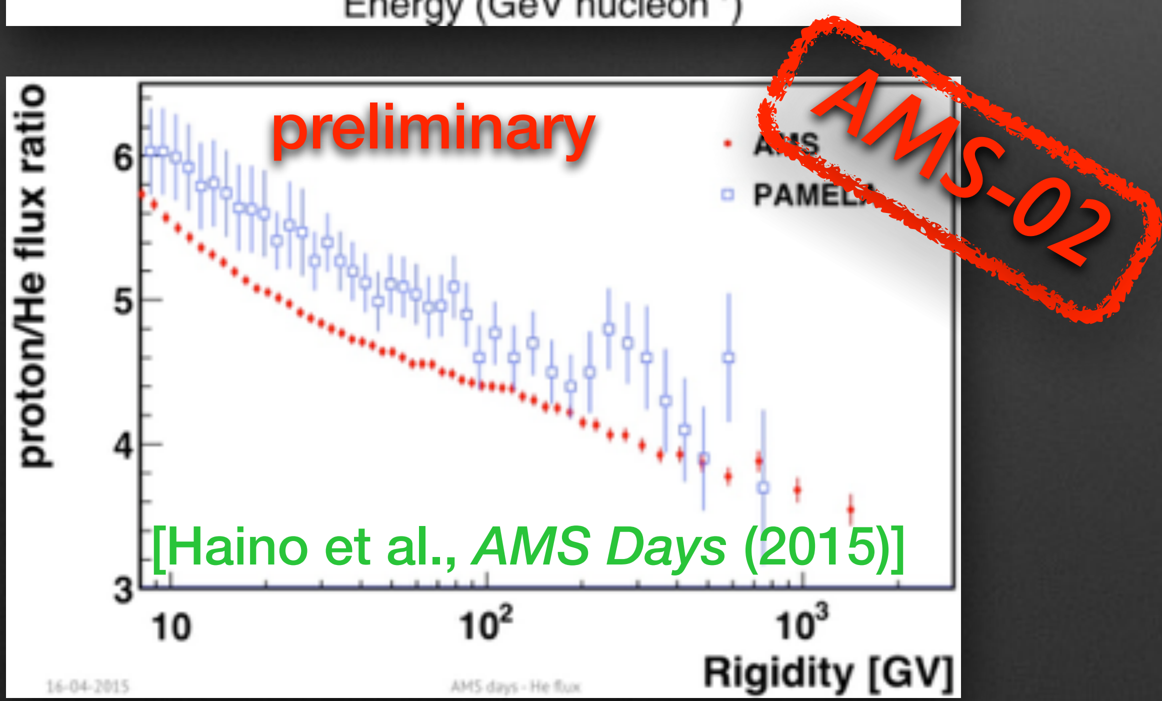


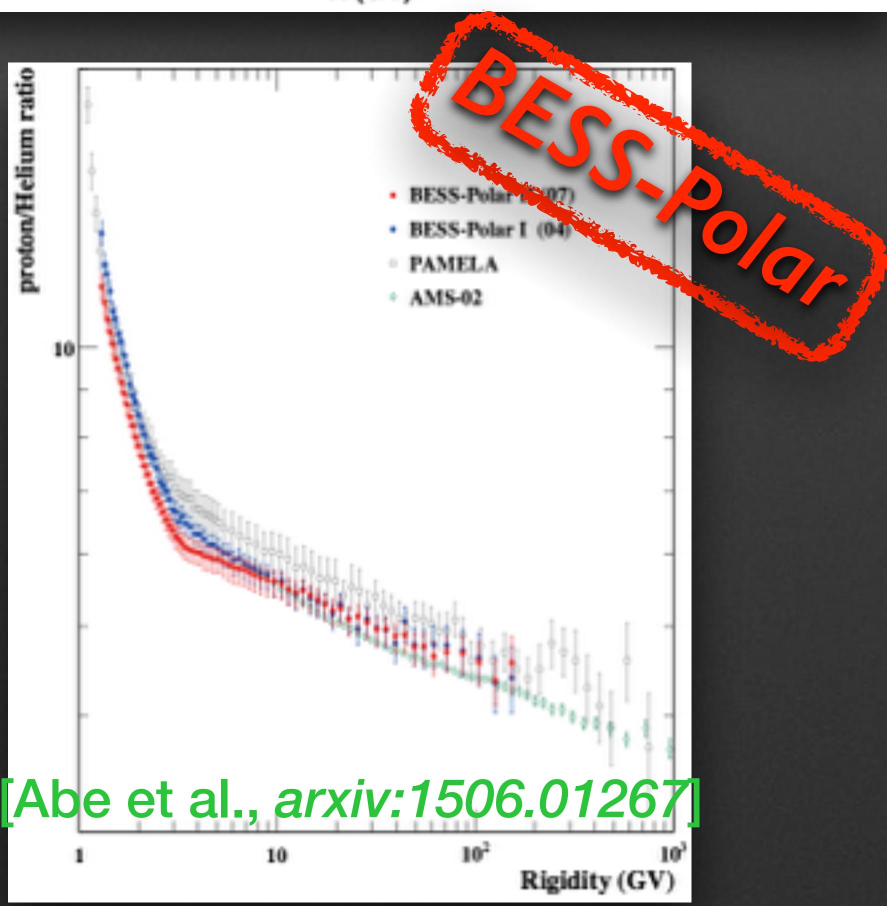


What do we see?
Non-universality: Δγ ~ 0.1

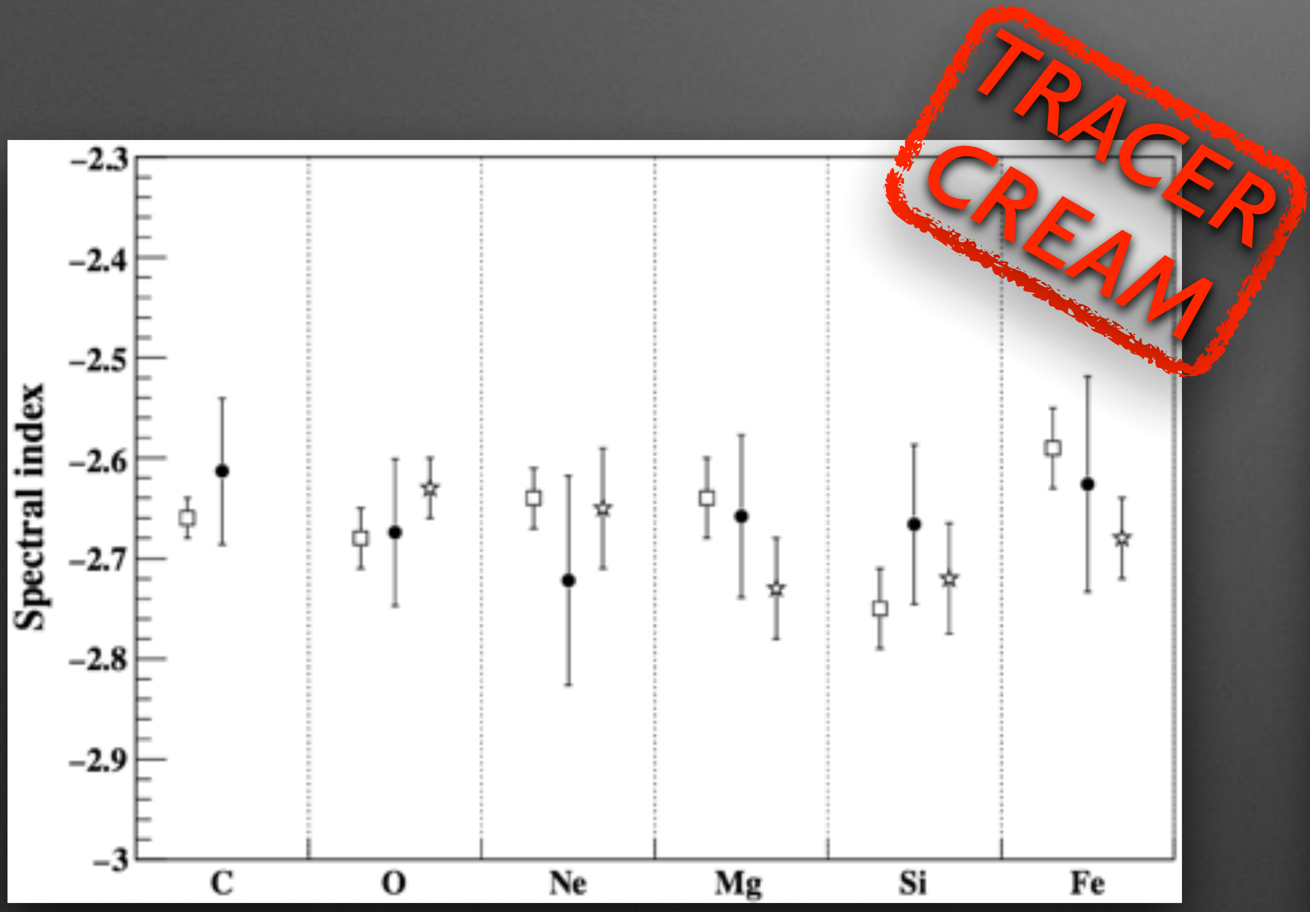




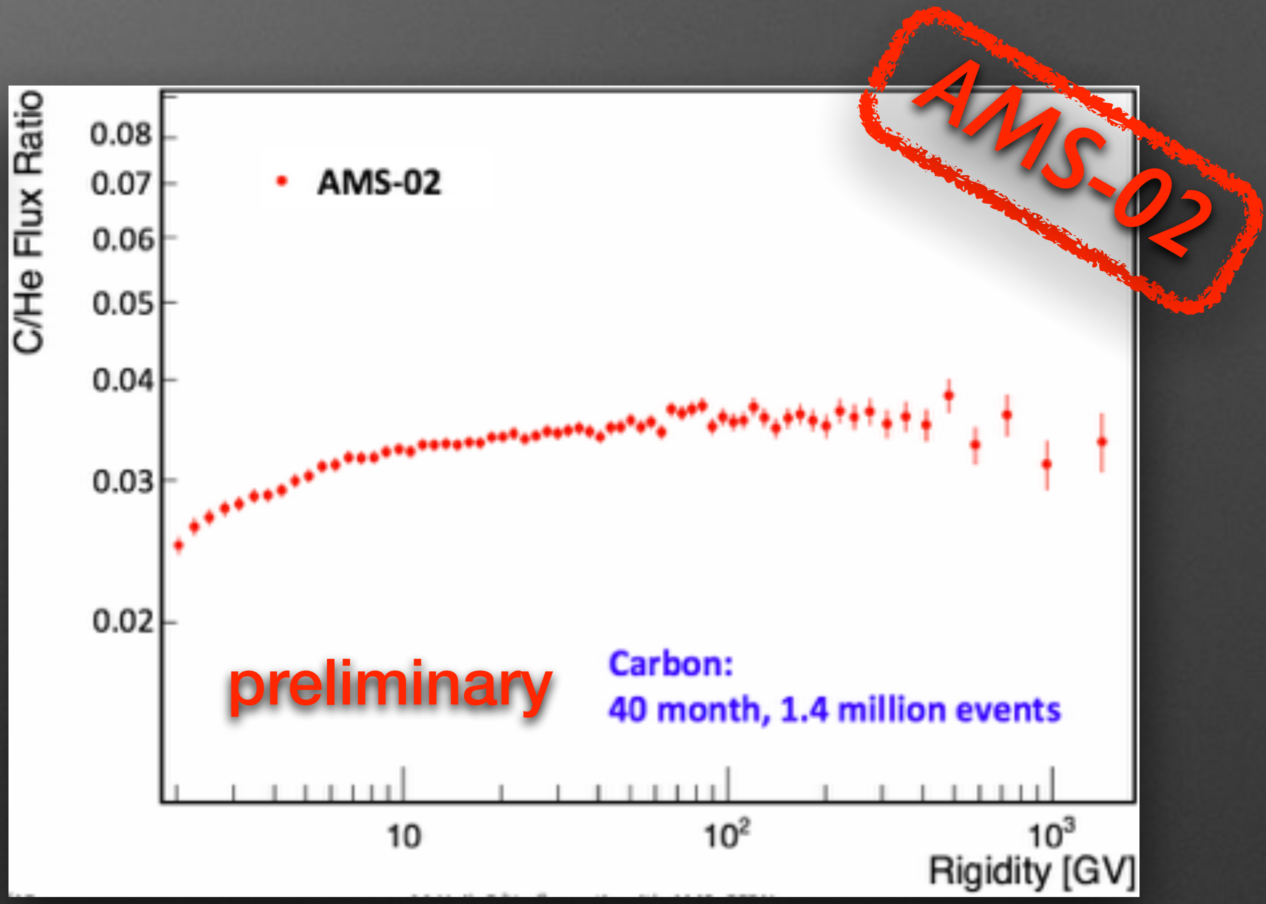




What do we see? Universality for Z > 1?

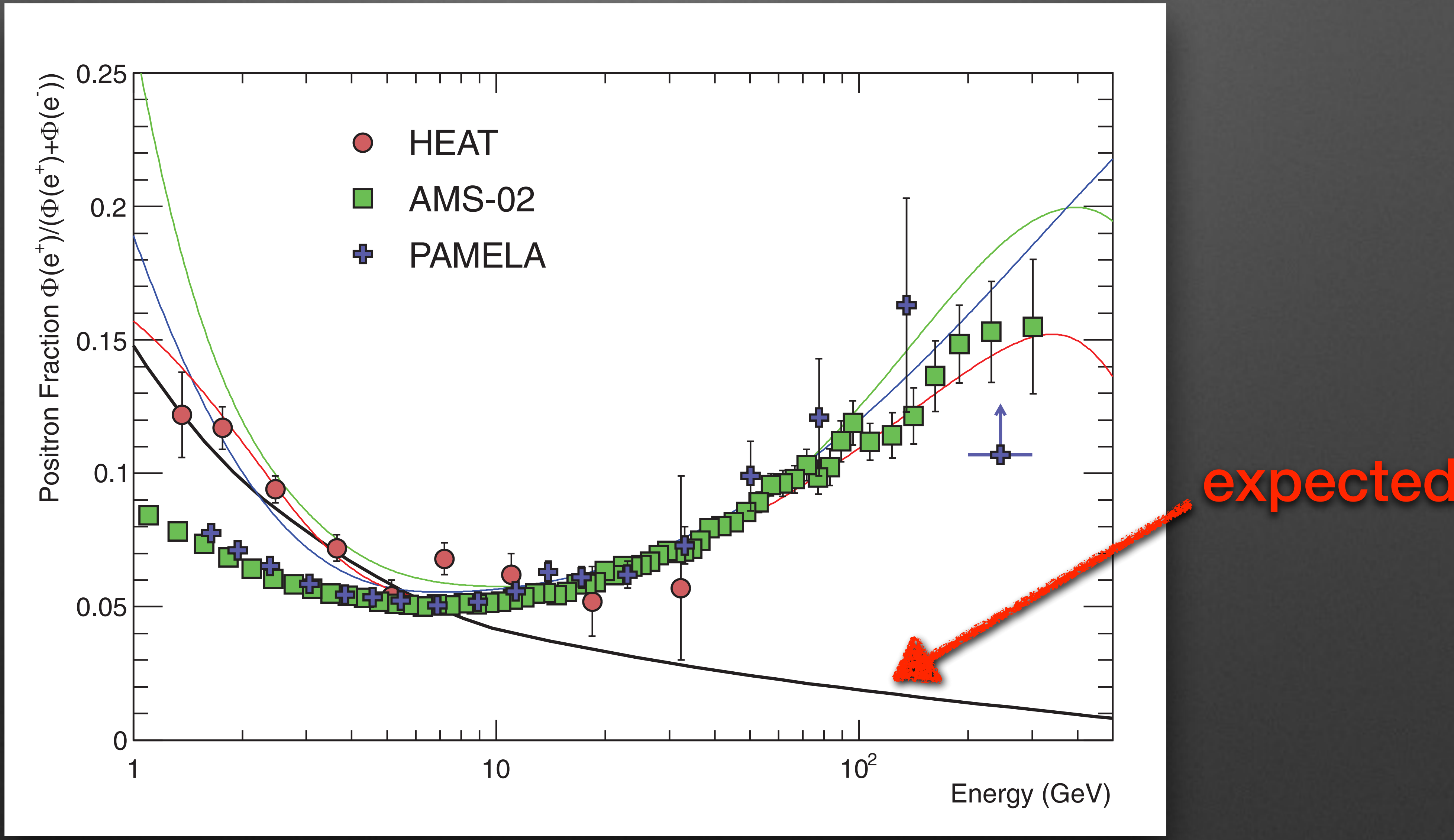


[Ahn et al., *ApJ* (2010)]



[Heil et al., *AMS Days* (2015)]

What do we see?
Rise in the positron fraction



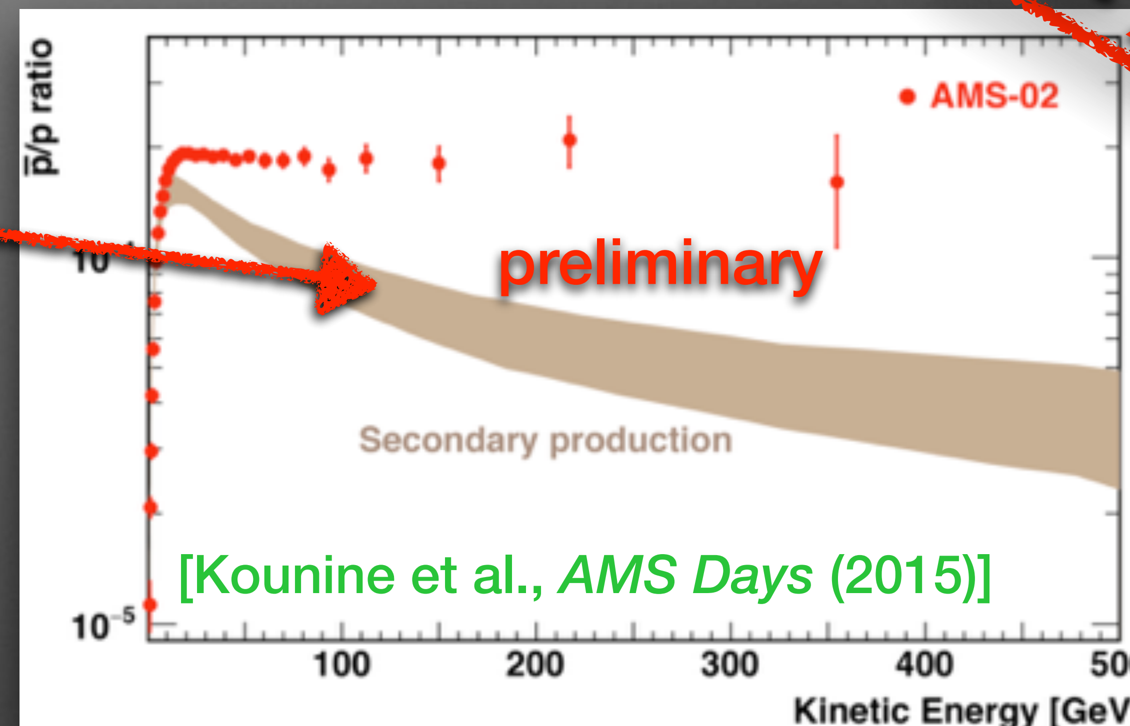
[Olive et al., *PDG* (2014)]

Hardening also seen in the individual electron and positron fluxes

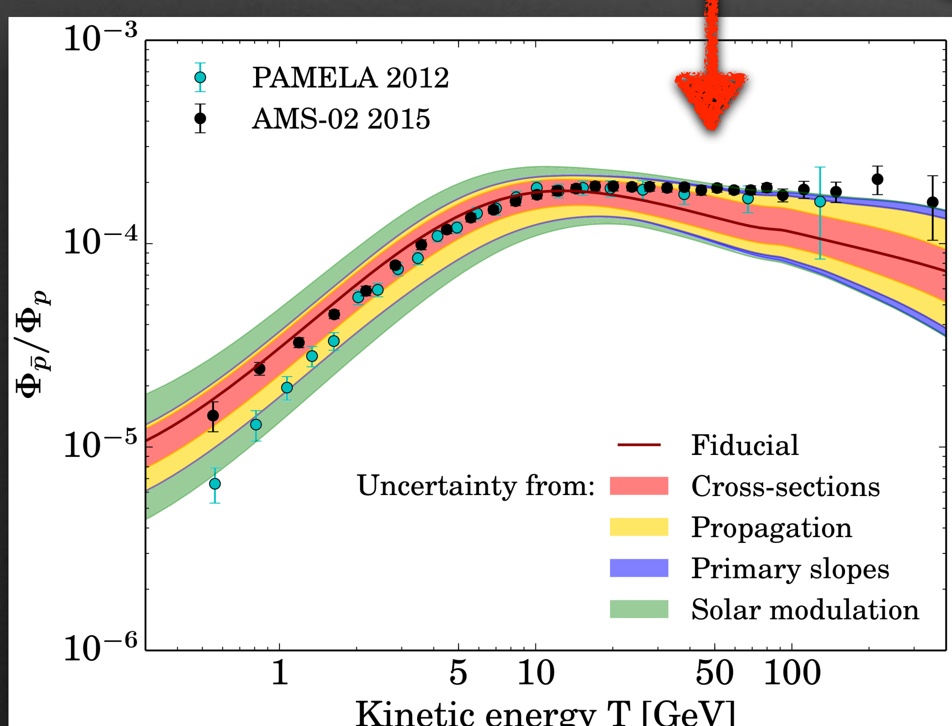
What do we see? Anomaly in antiprotons? Not yet!

Theoretical prediction based on pre-AMS knowledge

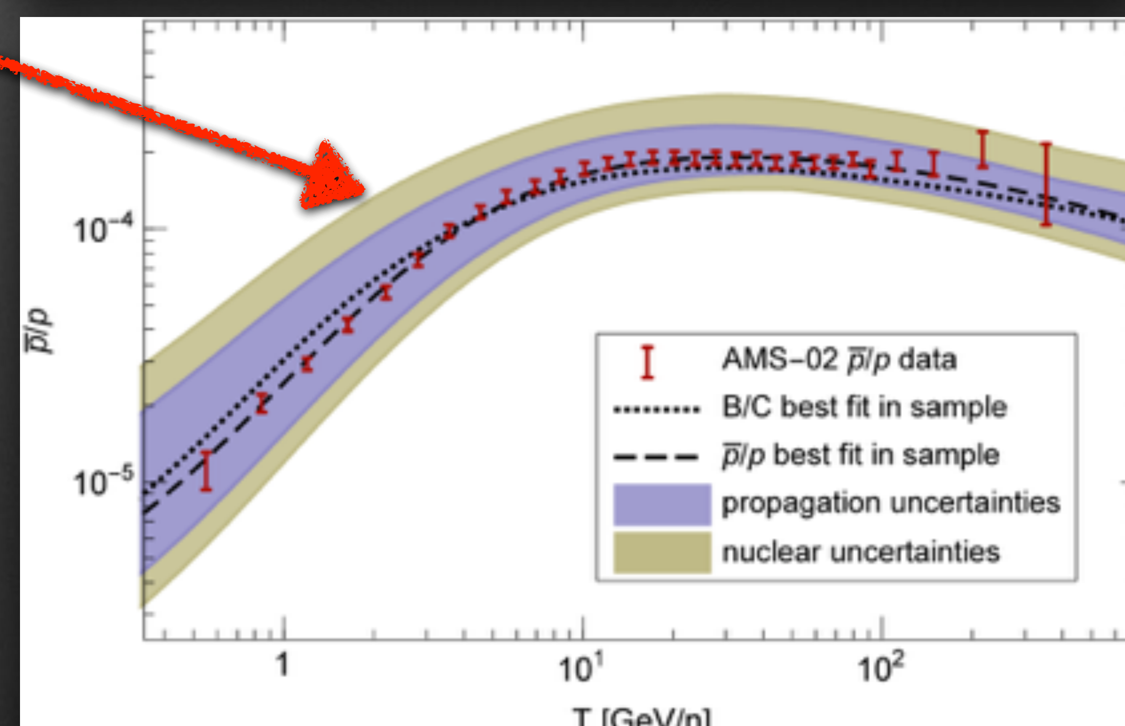
Updated secondary production and its uncertainties *not* in tension with antiproton-to-proton ratio



[Kounine et al., *AMS Days* (2015)]



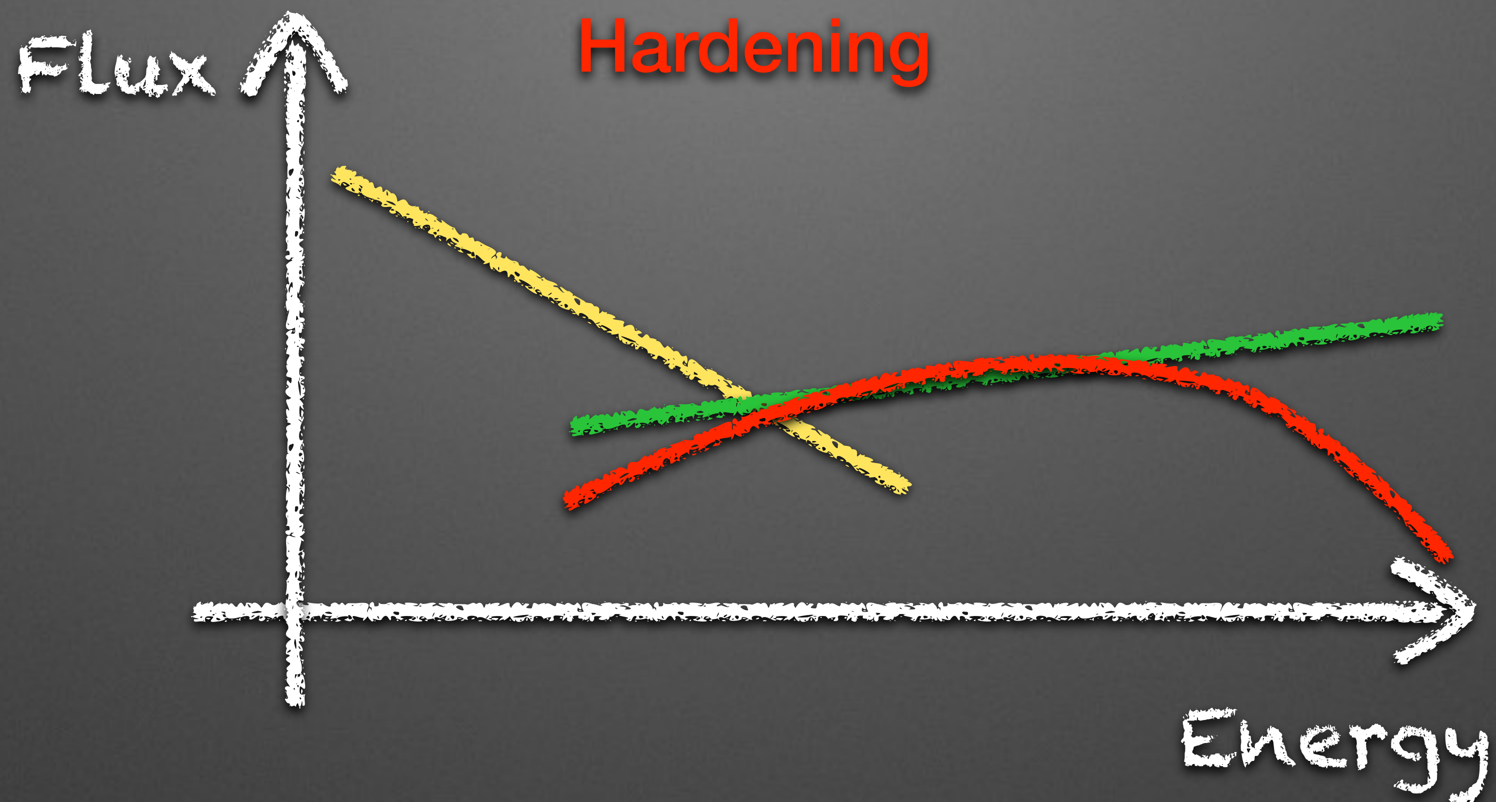
[Giesen et al., *JCAP* (2015)]



[Kappl et al., *JCAP* (2015)]

What can cause these anomalies?

Hardening



Non-universality

→ Propagation

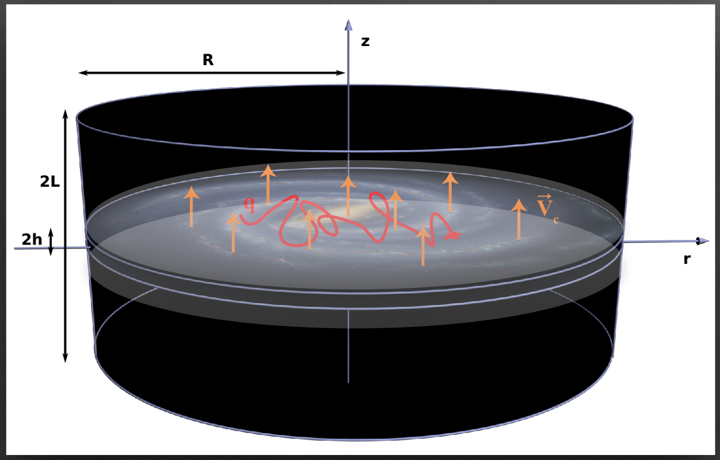
→ Acceleration

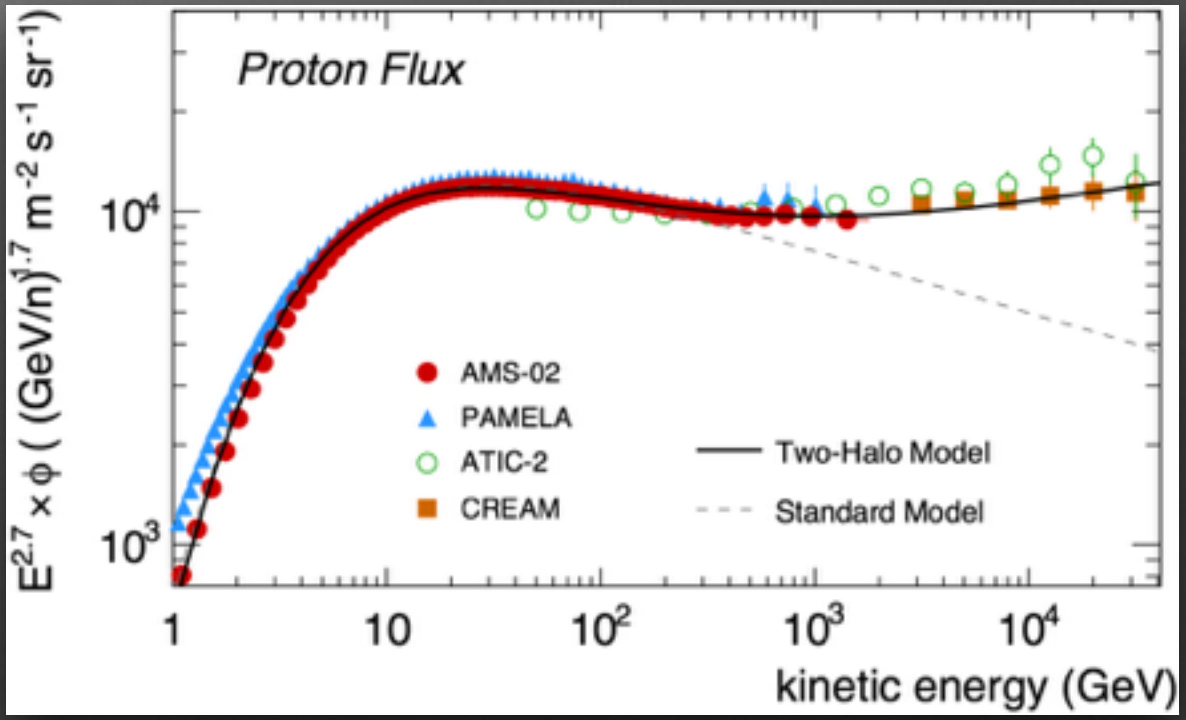
→ Sources

→ Dark Matter

Propagation
Two halo model

Assuming two halos (z ≲ 500 pc)
with different diffusion properties





[Tomassetti, *arxiv:1509.05775*]

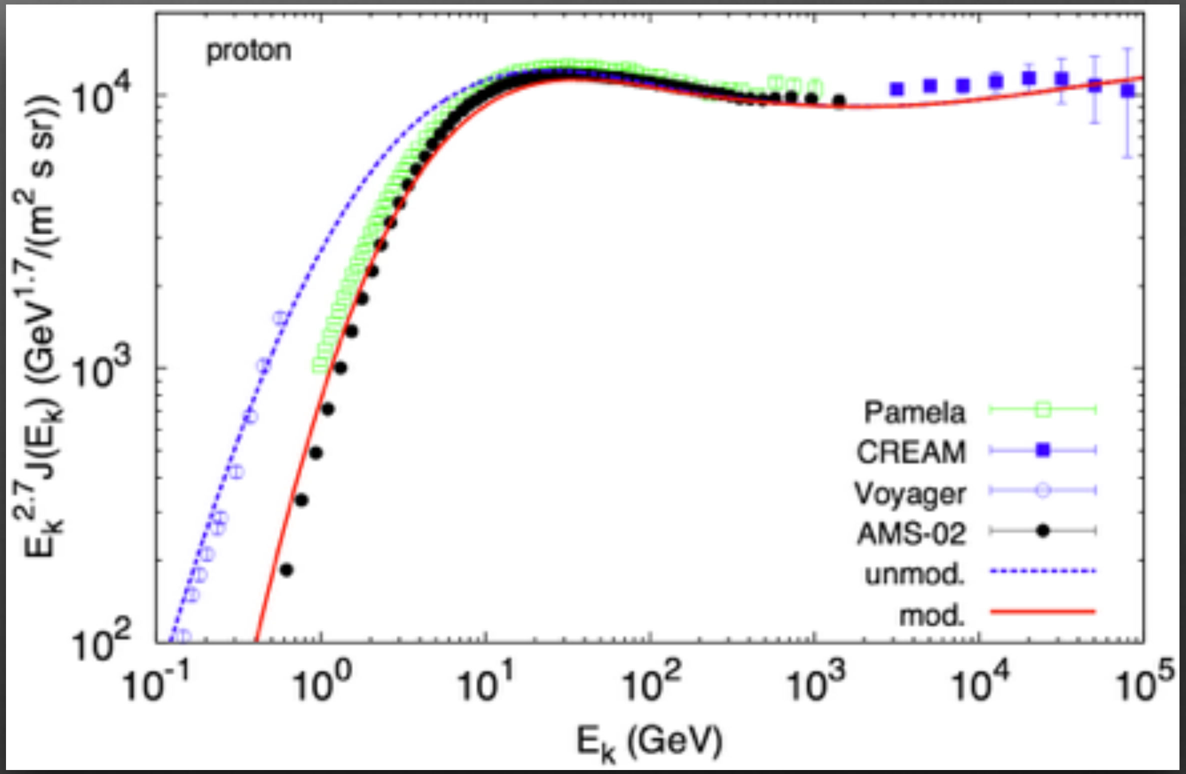
✅ explains hardening of nuclei and electron fluxes

⛔ fails to explain the positron flux/positron ratio
⛔ no parameters predicted a priori

Propagation
Non-linear coupling

Cosmic rays diffuse on

- self-generated waves at low energies
- external turbulences (e.g., SNRs) at high energies



[Aloisio et al., *arxiv:1507.00594*]

✅ explains hardening of nuclei fluxes
✅ transition arises naturally at ~ 300 GV

⛔ fails to explain the preliminary AMS-02 B/C ratio

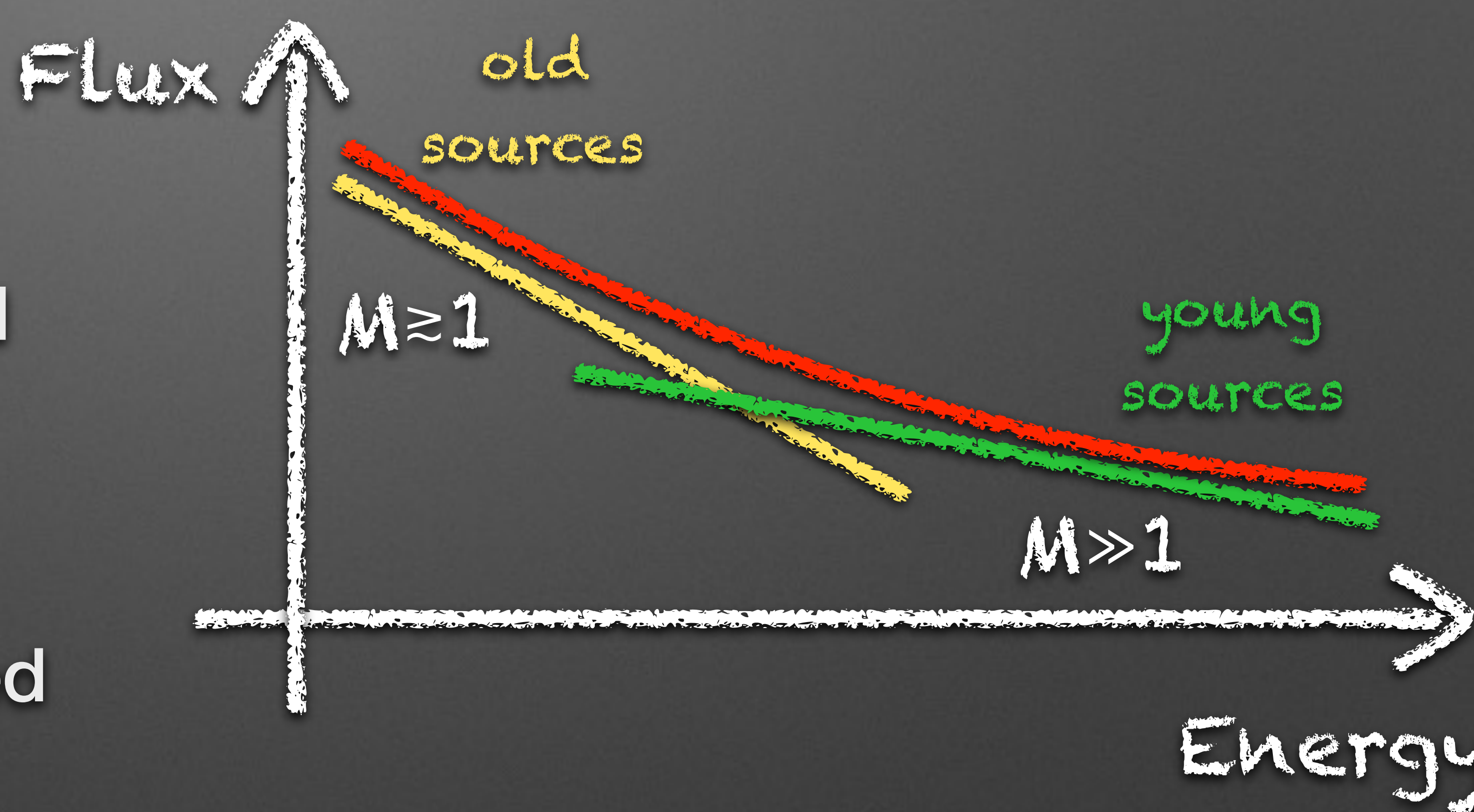
Acceleration
Evolution of the Mach number

Early stages (M≫1):

- injection index ~ 2
- mostly helium accelerated

Later stages (M≳1):

- injection index > 2
- mostly protons accelerated



✅ explains non-universality and change of slopes of energy spectra

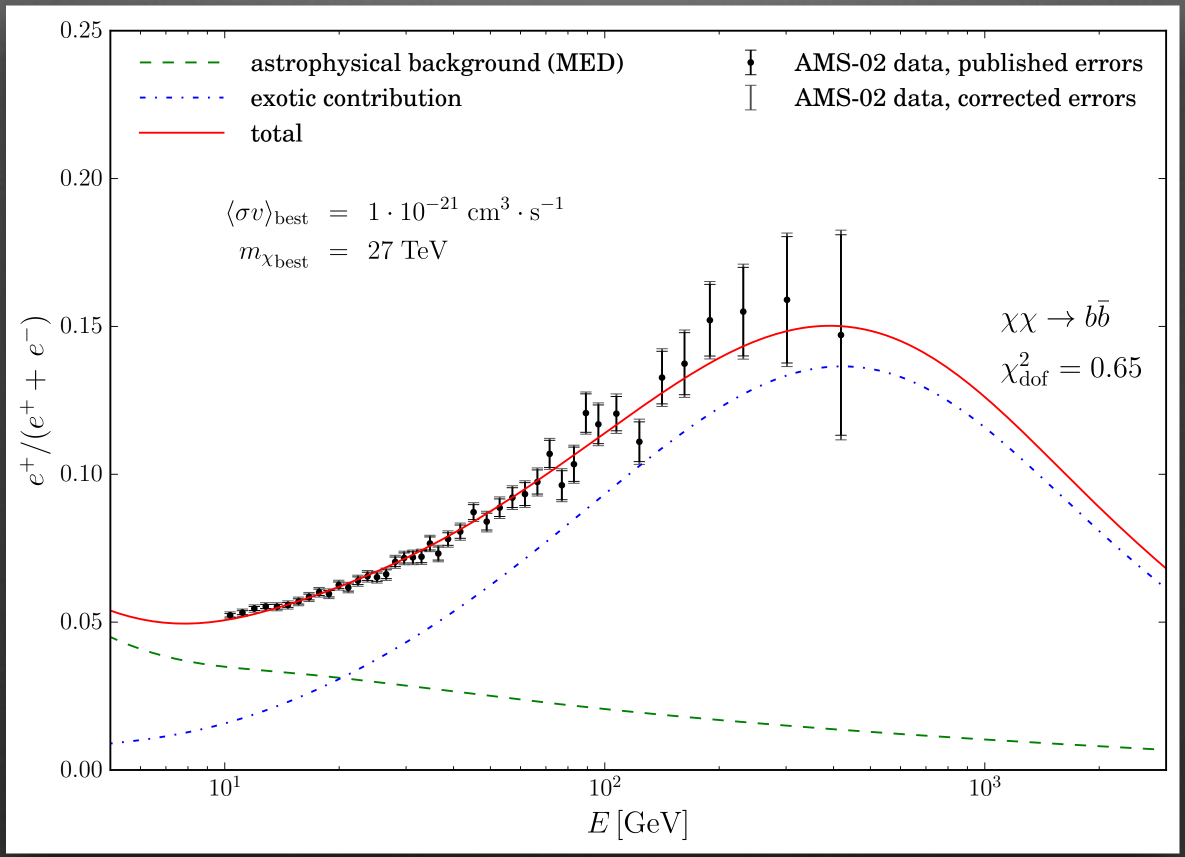
⛔ no clear break but smooth change of spectral slopes

⛔ no evident reason for early (late) helium (proton) acceleration

talk by Ohira

e.g. [Ohira et al., *arxiv:1506.01196*]

Sources
Dark matter

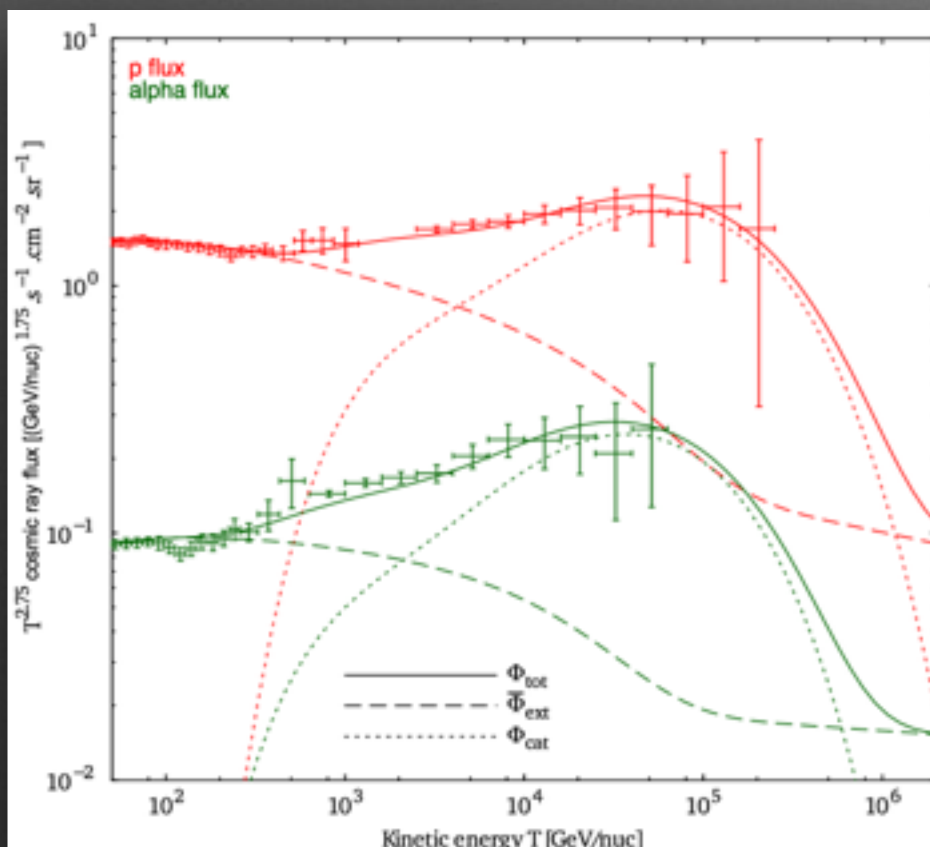


[Boudaud et al., *A&A* (2015)]

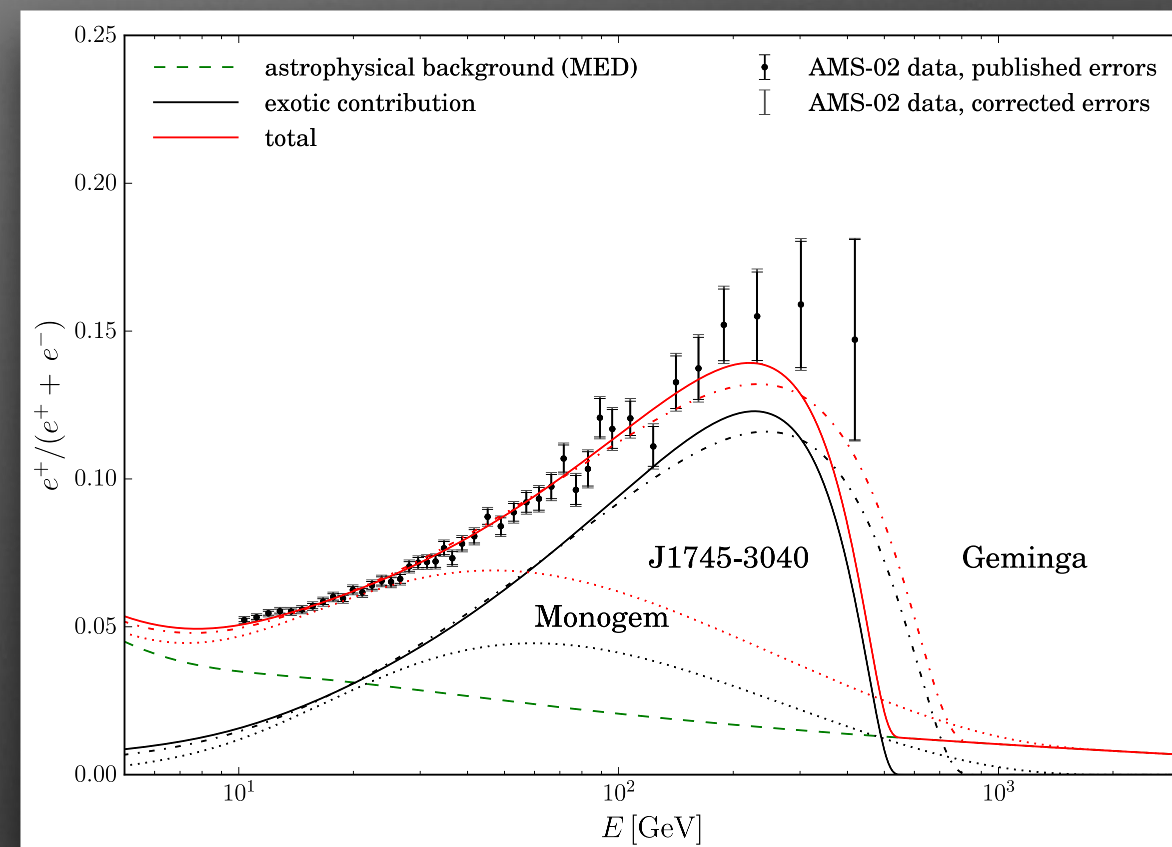
✅ explains lepton fluxes and positron fraction

⛔ needs large boost factors
⛔ in tension with other observables (antiprotons, gamma rays, CMB)

Sources
Nearby and young sources



[Bernard et al., *A&A* (2013)]



[Boudaud et al., *A&A* (2015)]

✅ explains hardening in nuclei fluxes
✅ explains lepton fluxes and positron fraction

⛔ needs small diffusion halos

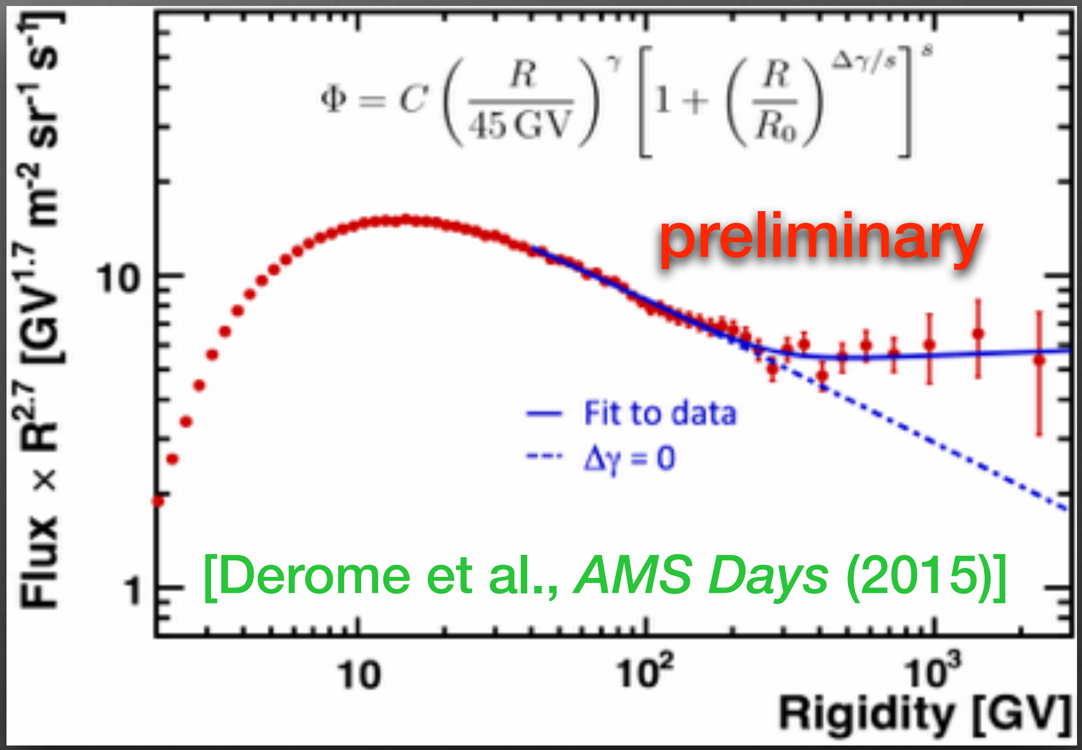
Testing the different hypotheses

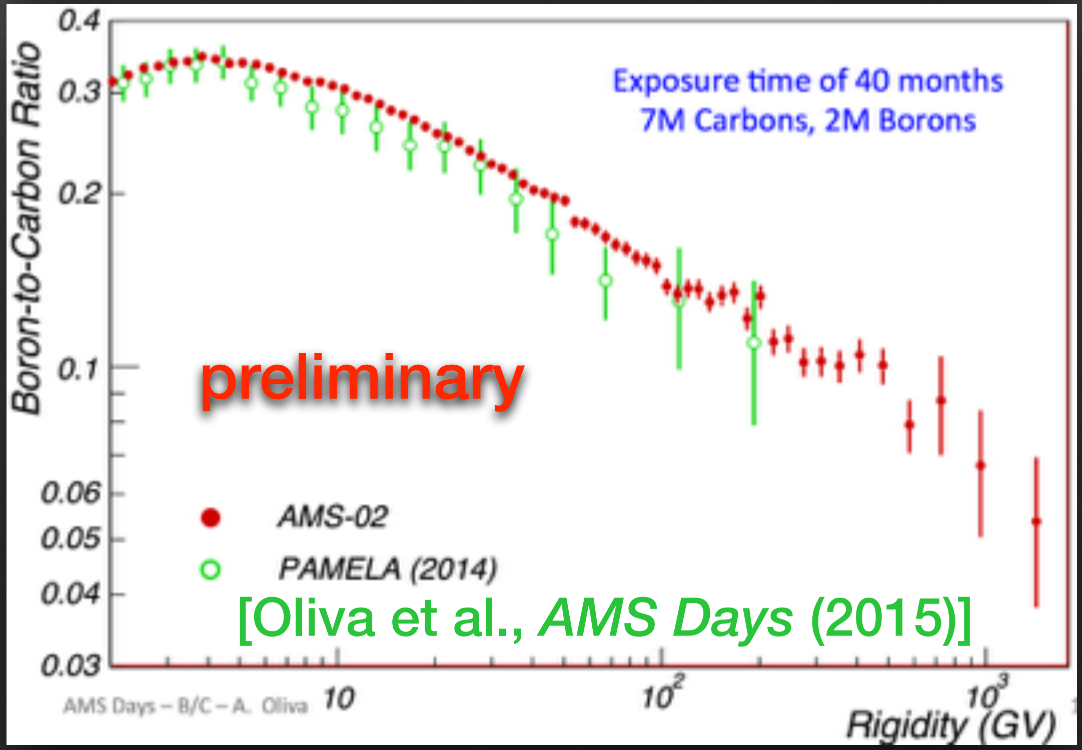
Hardening

- **Propagation**
  more pronounced break in secondaries → hardening in B/C
- **Acceleration**
  same hardening in primaries & secondaries → no feature in B/C
- **Discrete local sources**
  “bumpy” spectra

Non-universality

spectral indices of nuclei



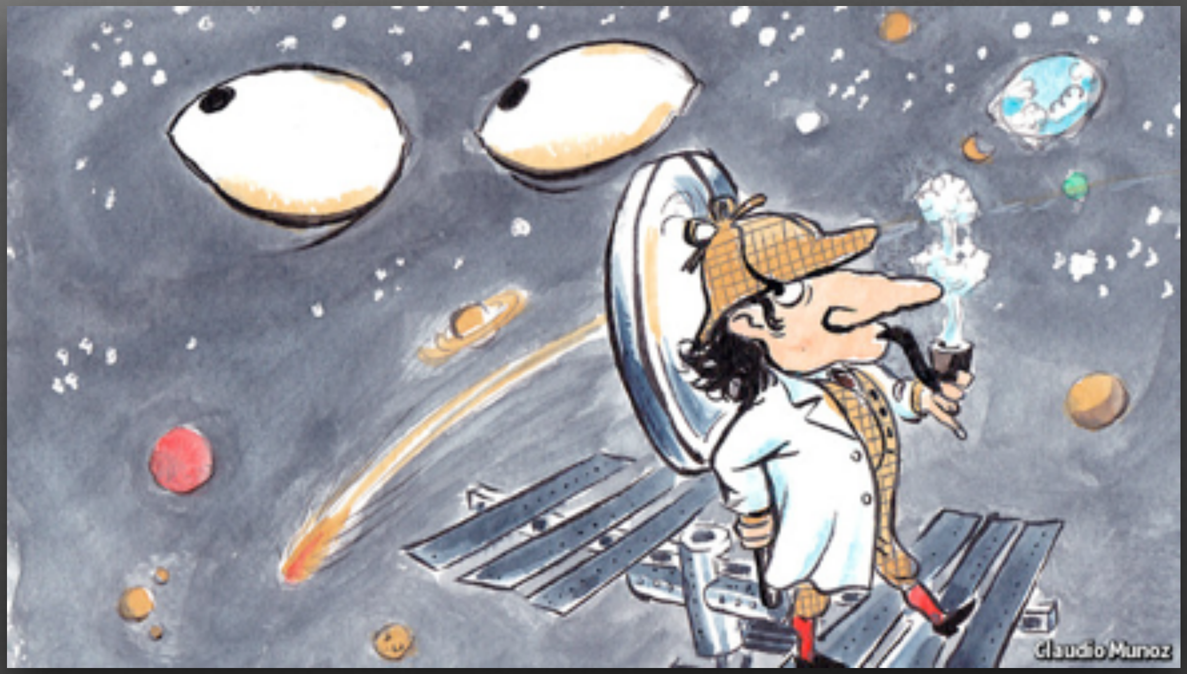


Conclusion

- More and more precise cosmic-ray data will be available soon
  Discrimination between model classes needs O(10%) precision at 1 TeV/nuc for firm conclusion!

- Multi-messenger approach necessary for individual model discrimination
  gamma ray flux, anisotropy

- Current propagation models suffer from large uncertainties on ingredients and hypotheses
  What you get out depends on what you put in…



Are you hunting for dark matter?

- Your dark matter candidate should reproduce all the available data
  → global fits
  → GAMBIT

talks by Scott & Weniger