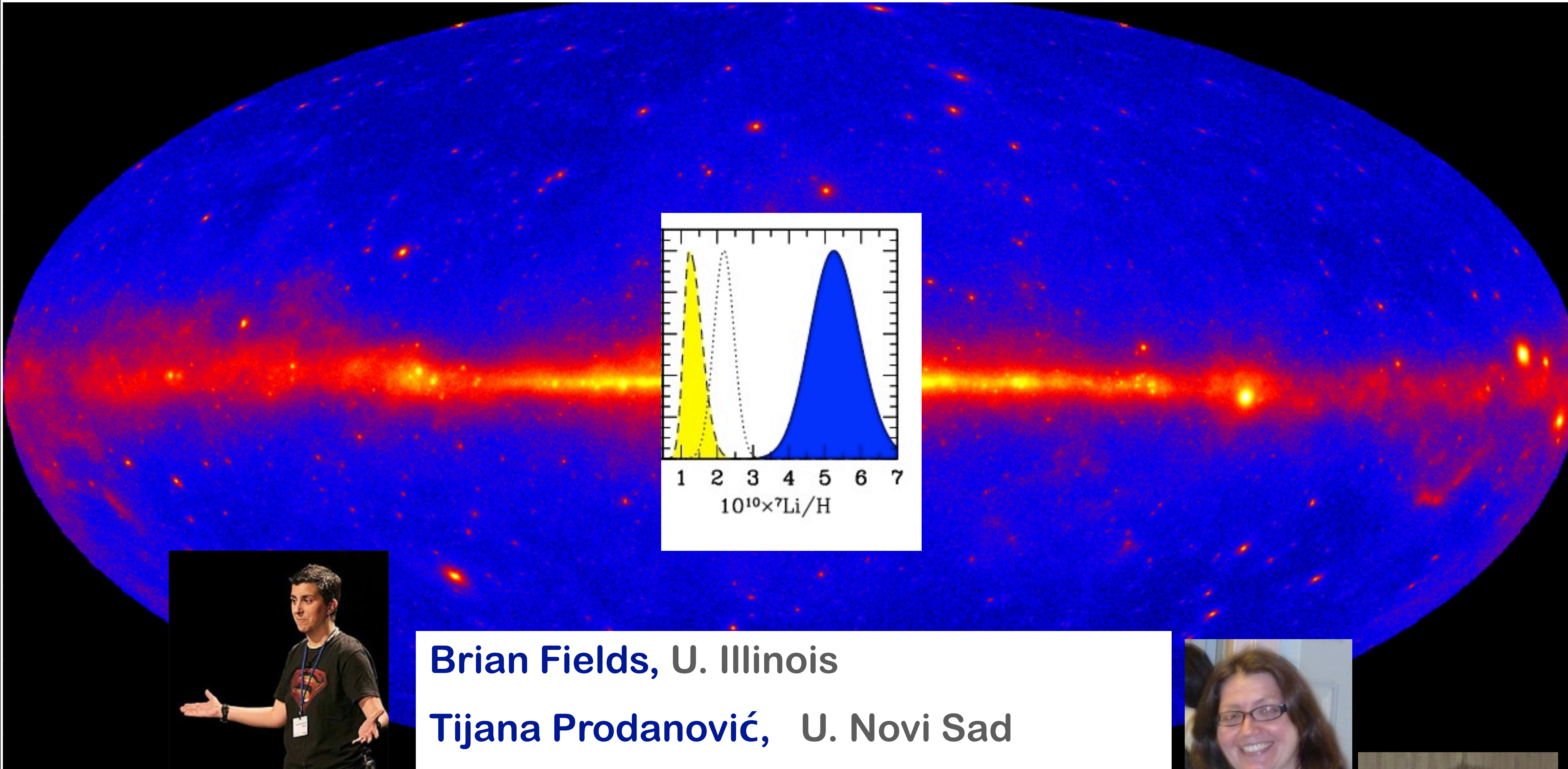
Cosmic Rays and the Lithium Problems



Brian Fields, U. Illinois

Tijana Prodanović, U. Novi Sad

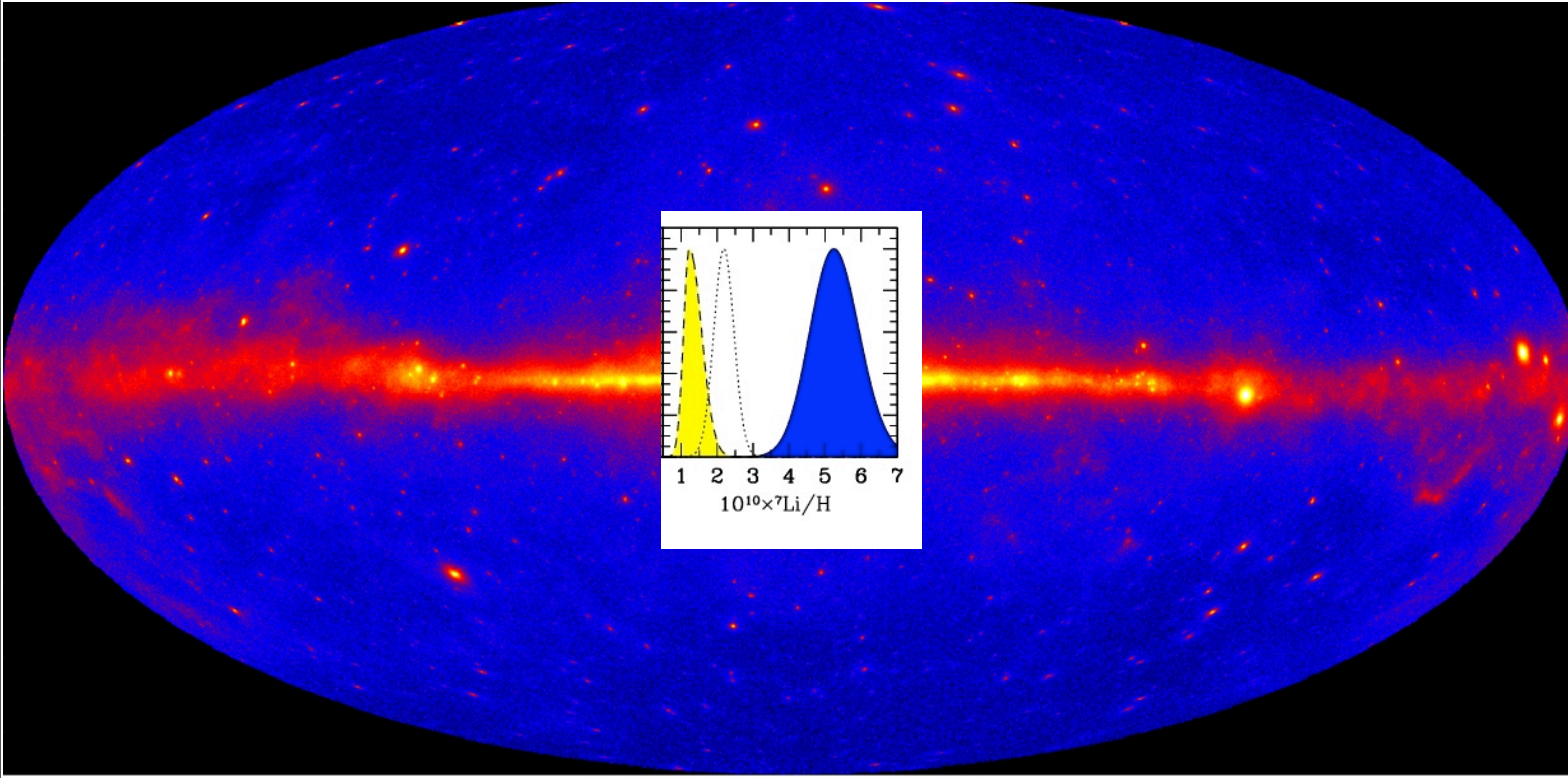
Vasiliki Pavlidou, U. Crete & MPA Bonn

Keith Olive, U. Minnesota

Elisabeth Vangioni, IAP

Michel Cassé, IAP & Saclay

Orphans of Nucleosynthesis



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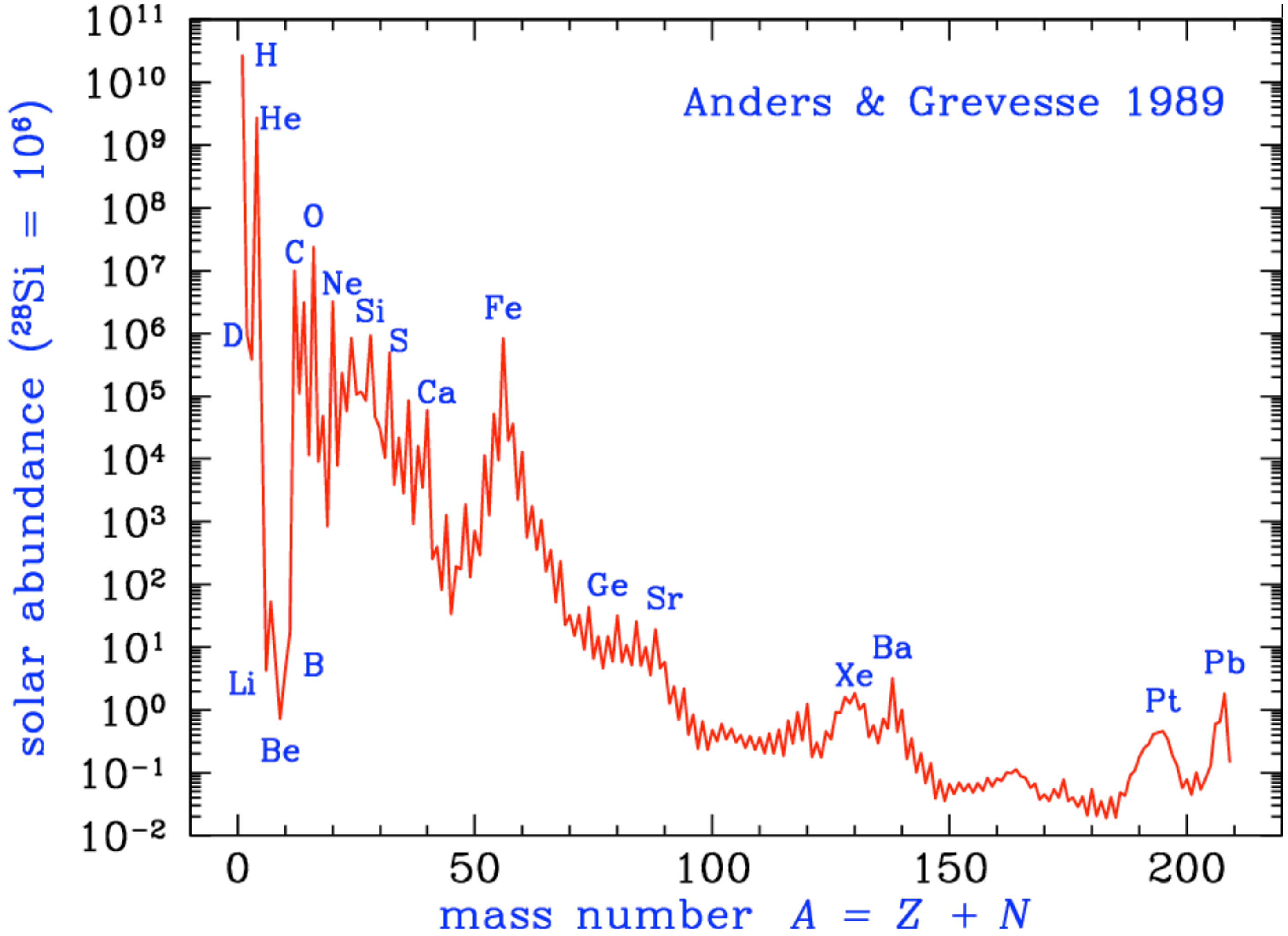
The Big Picture, circa 1967



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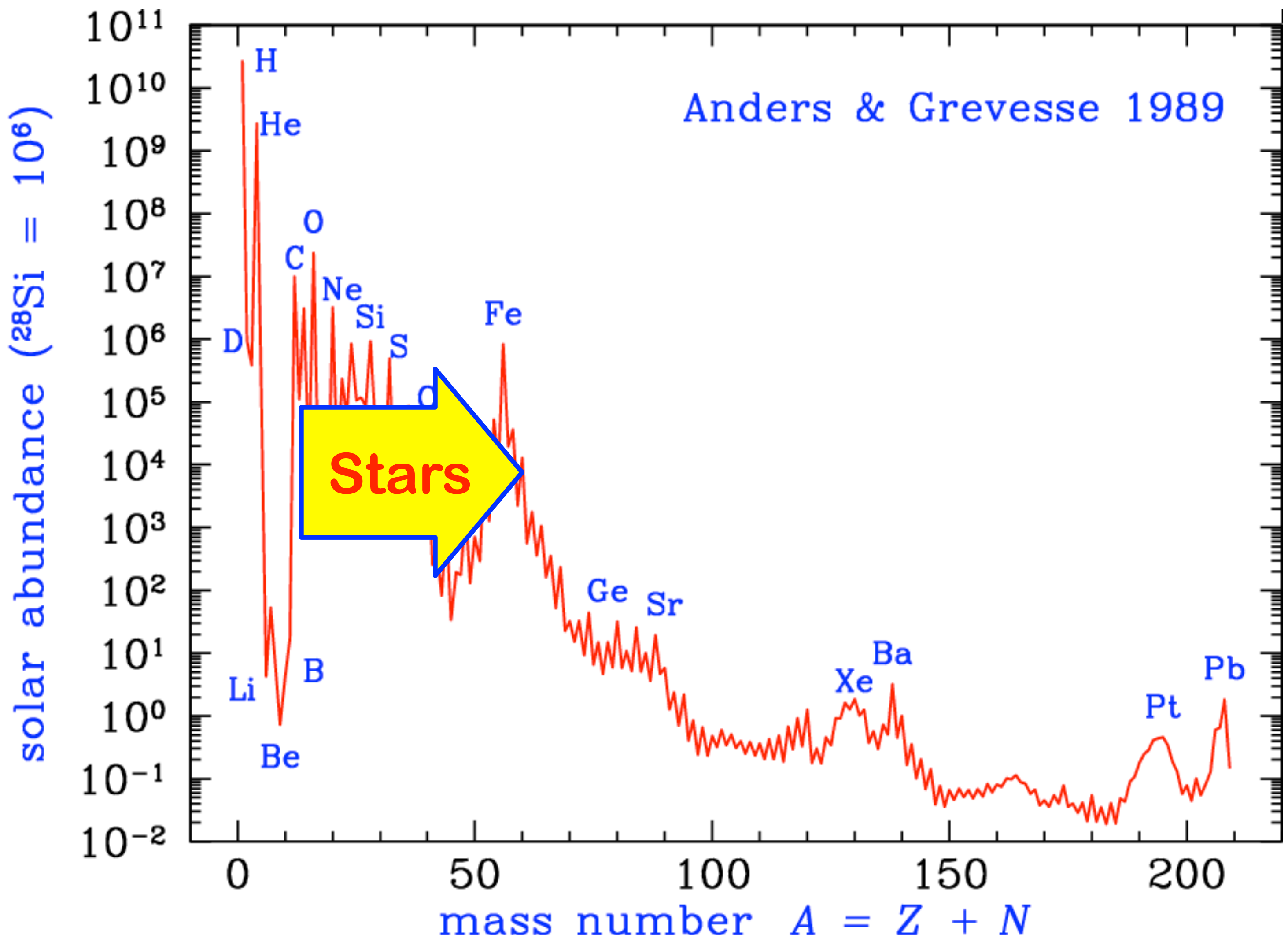
Heavy elements:

- **stars** BBFH57, Cameron 57



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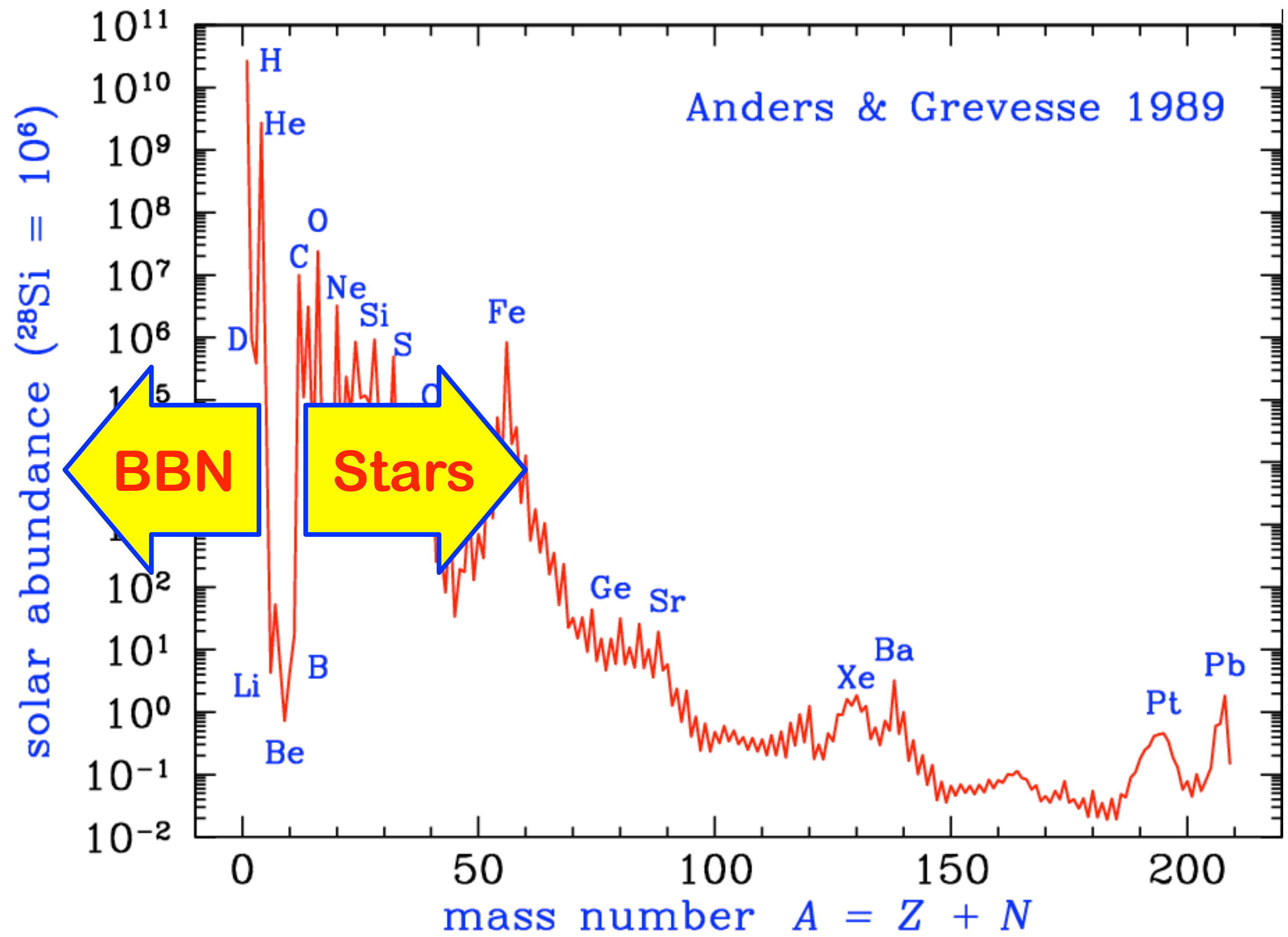

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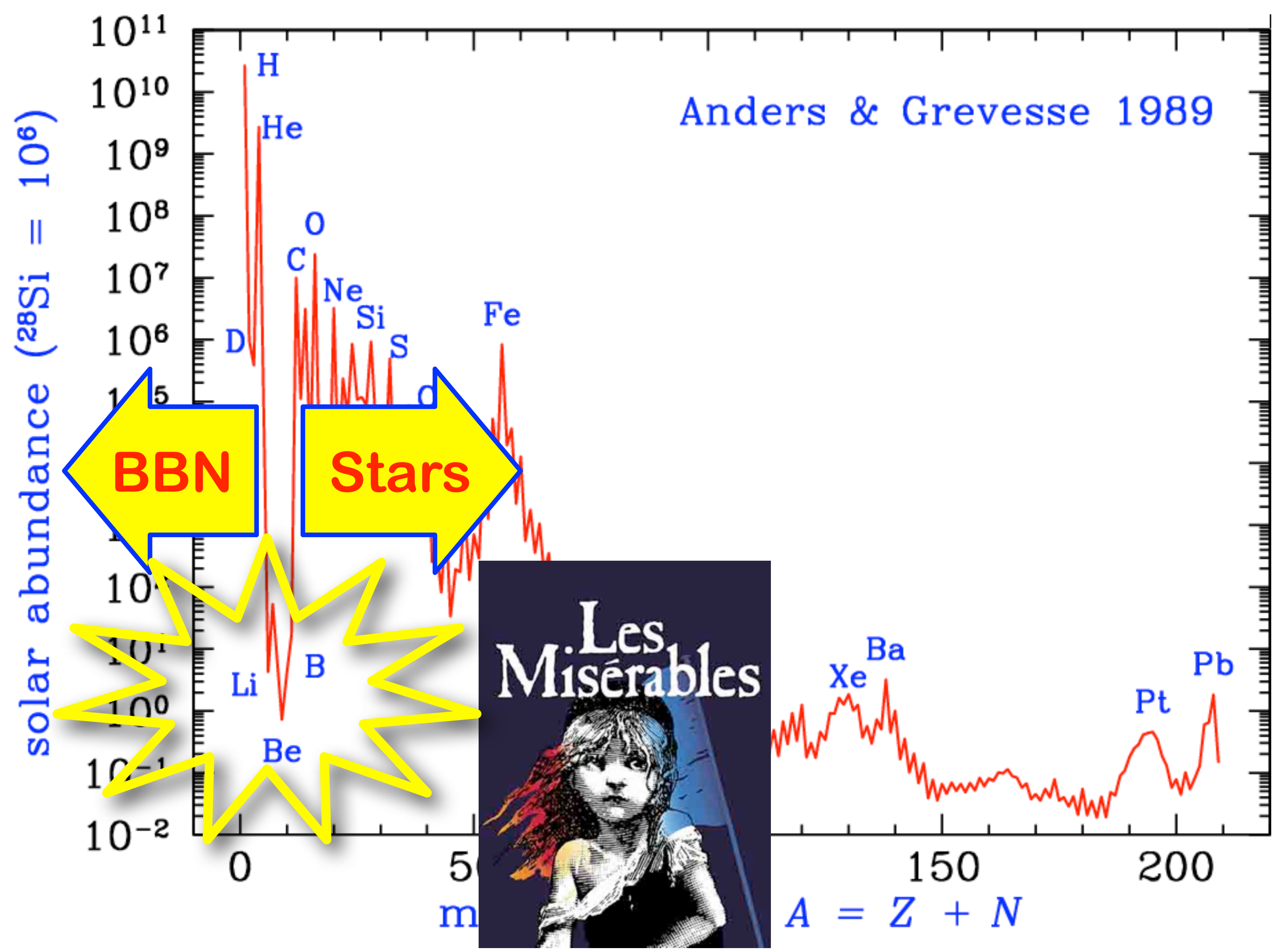
- all of ^{6}Li and Be and B



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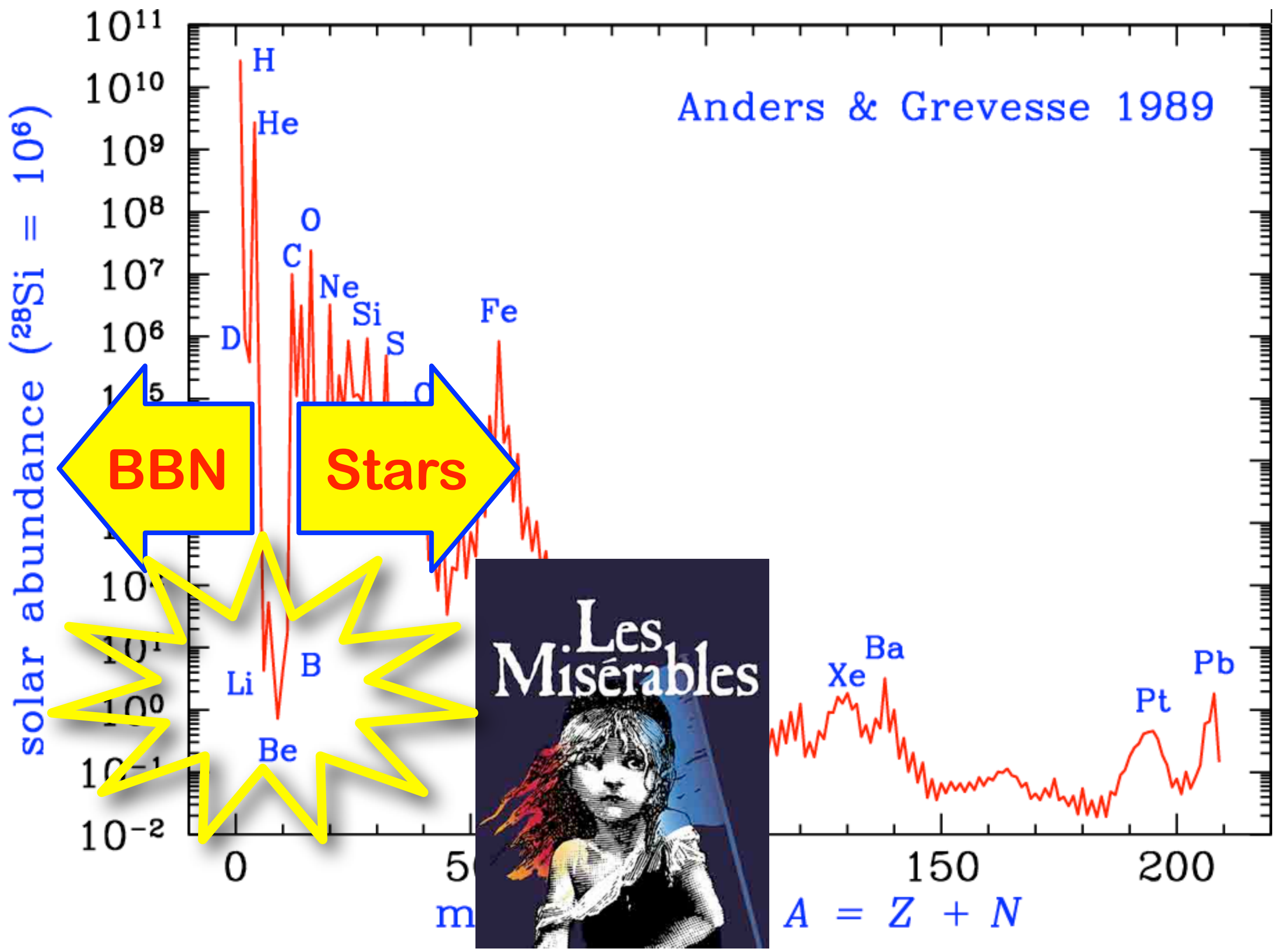
- lowest binding after D
- stars destroy at ~2.7 x 10^{6} K

Need non-thermal origin



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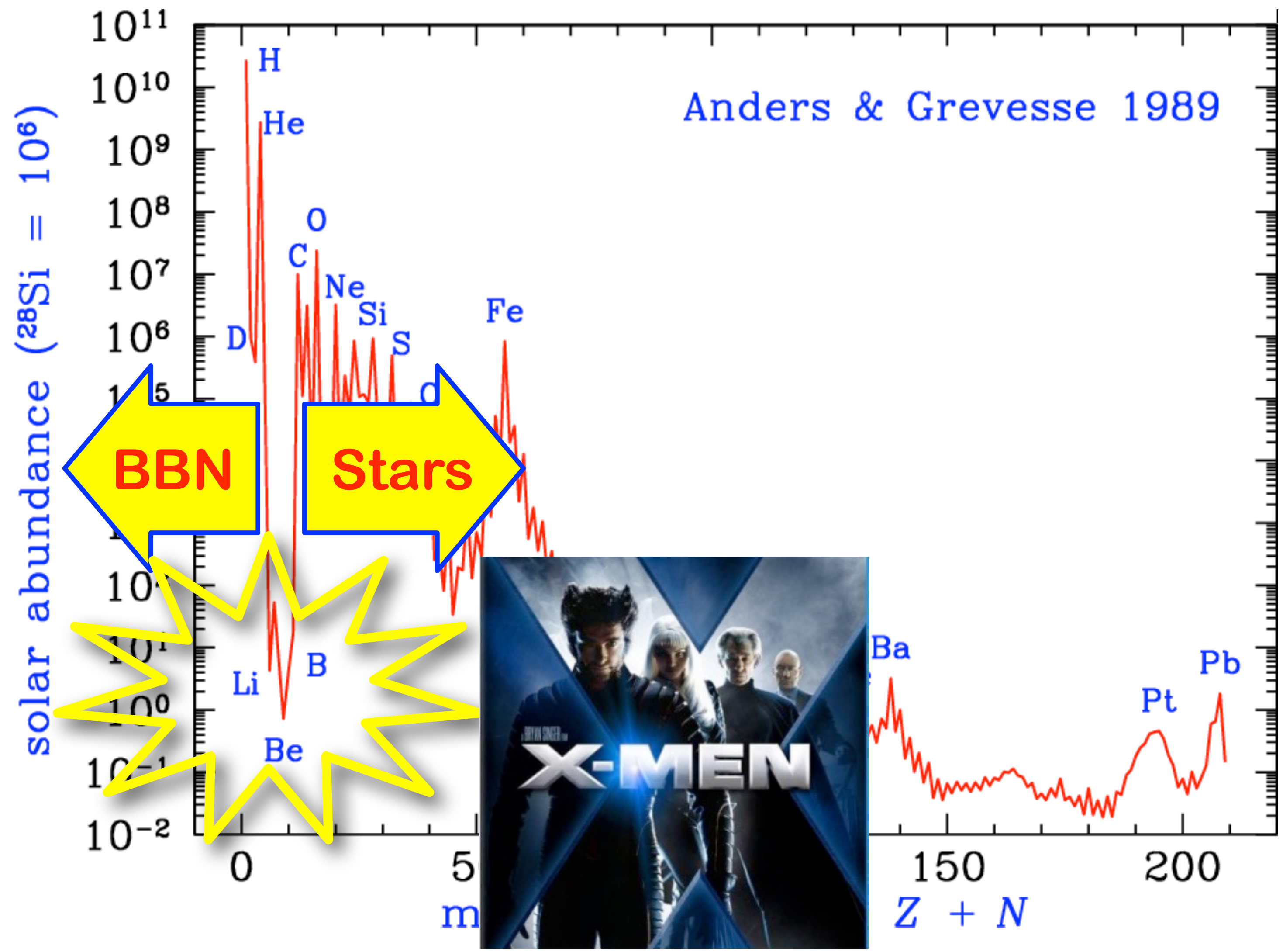

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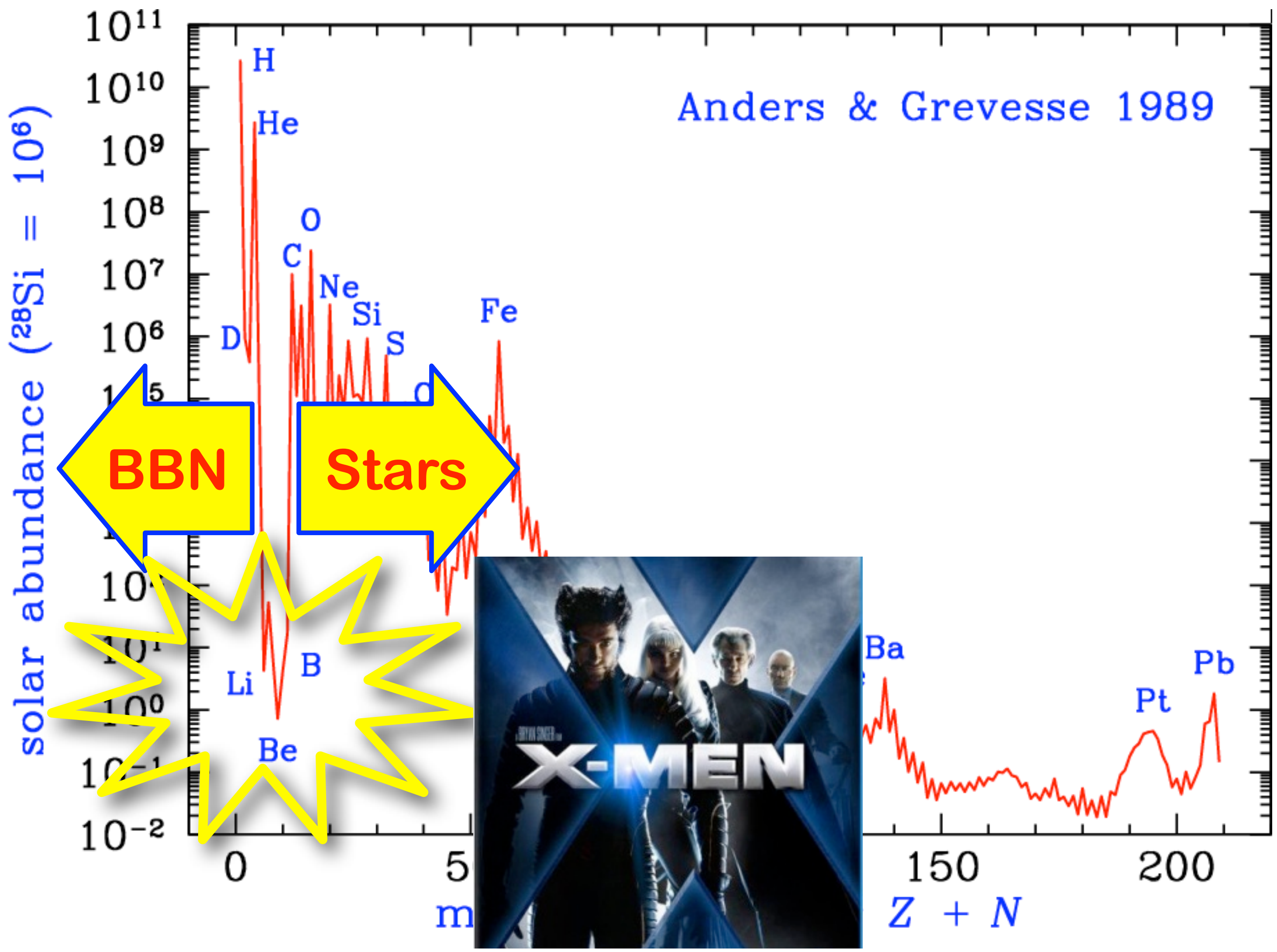
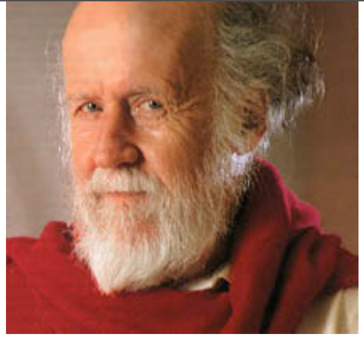
- protostars (T-Tauri)

Fowler Greenstein & Hoyle 62





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Key hint:

- LiBeB abundances anomalously high in cosmic rays

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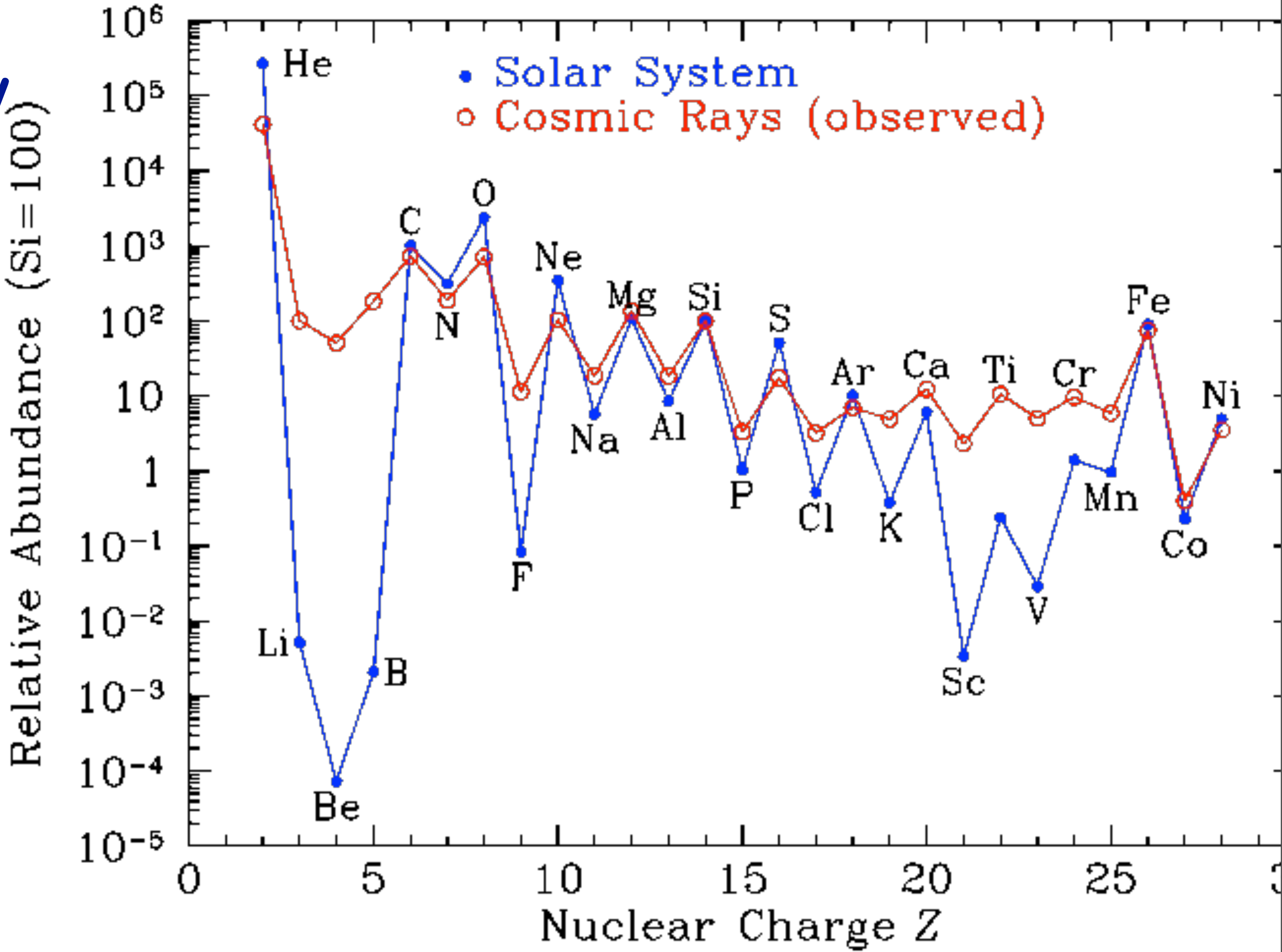

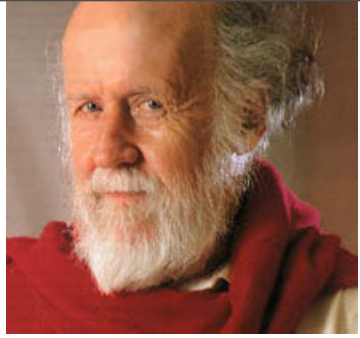

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C,N,O → H, He → LiBeB

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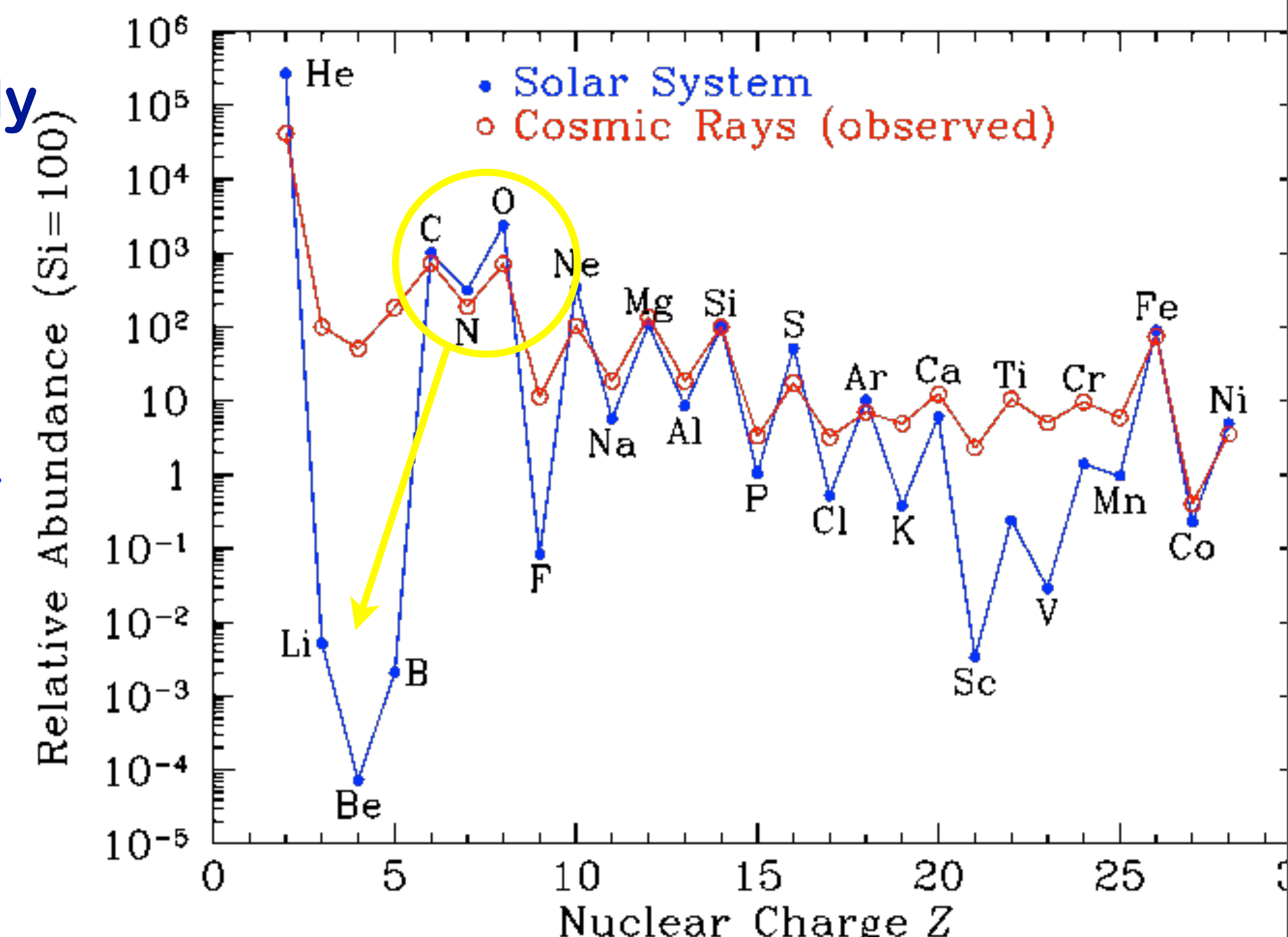

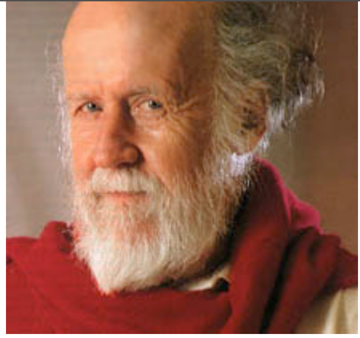

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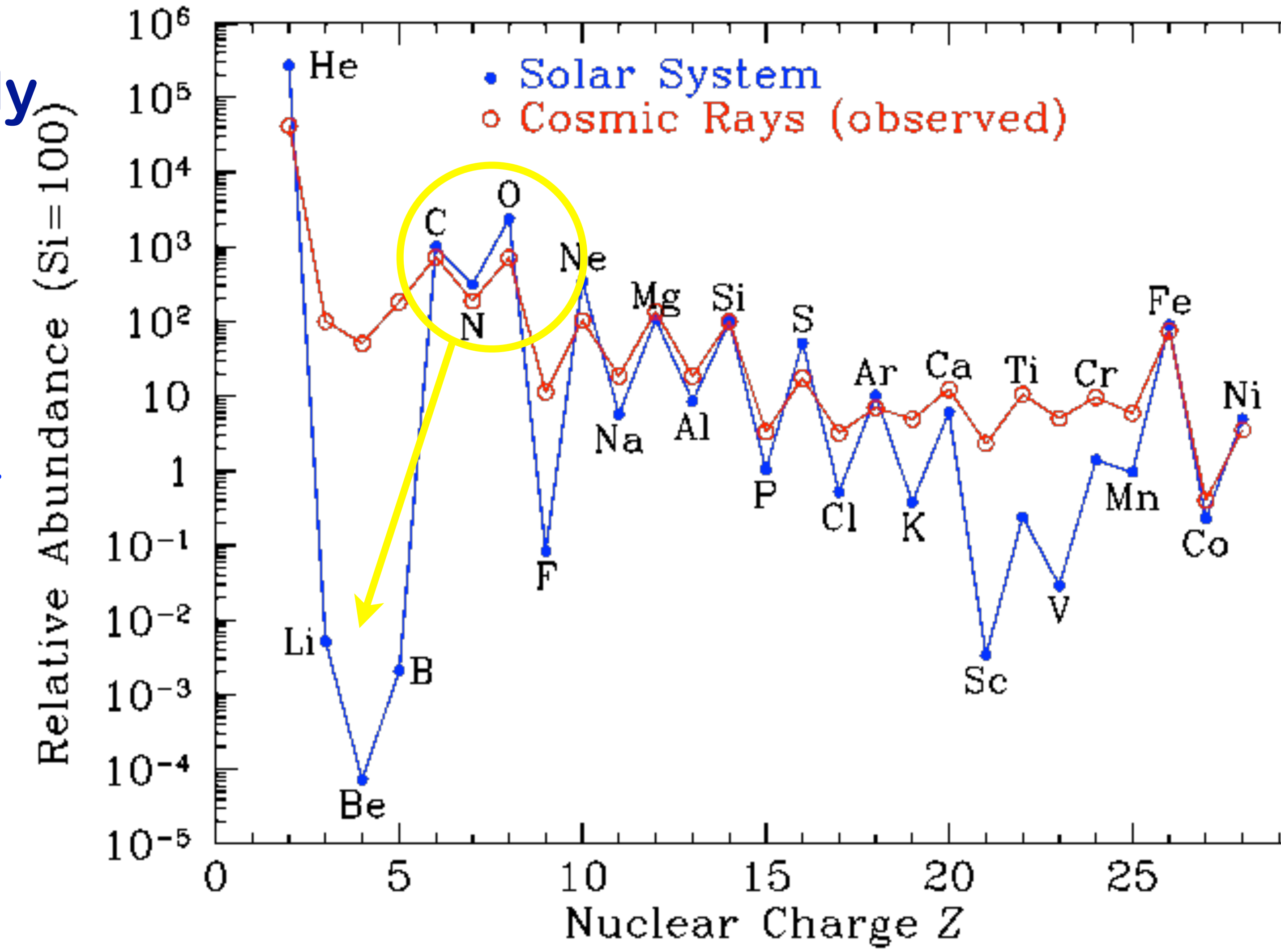

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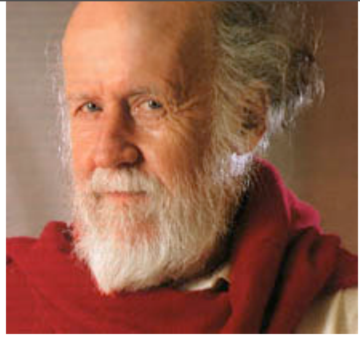

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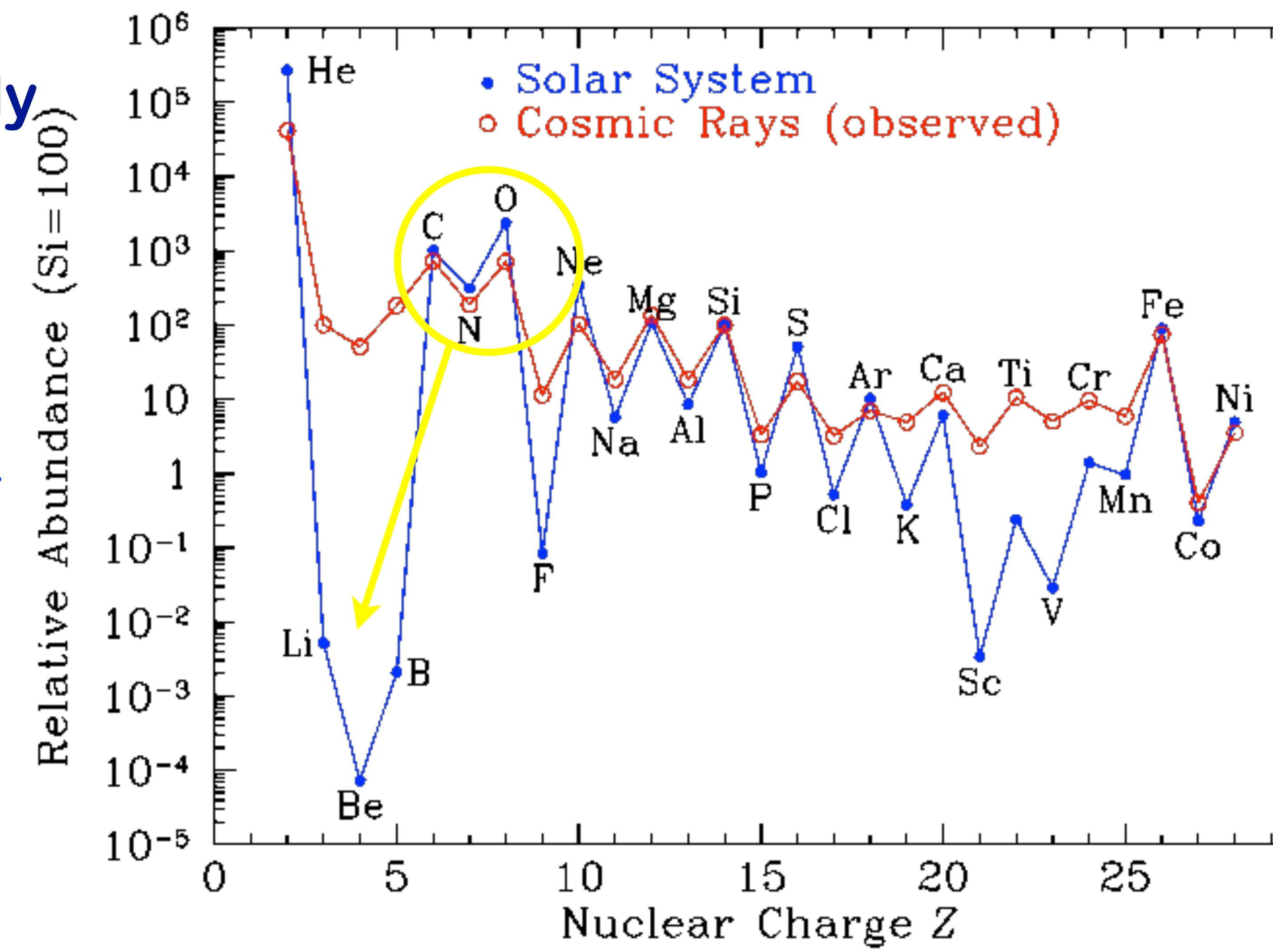

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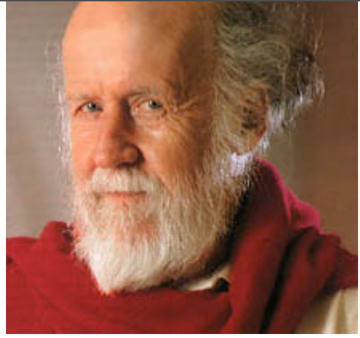

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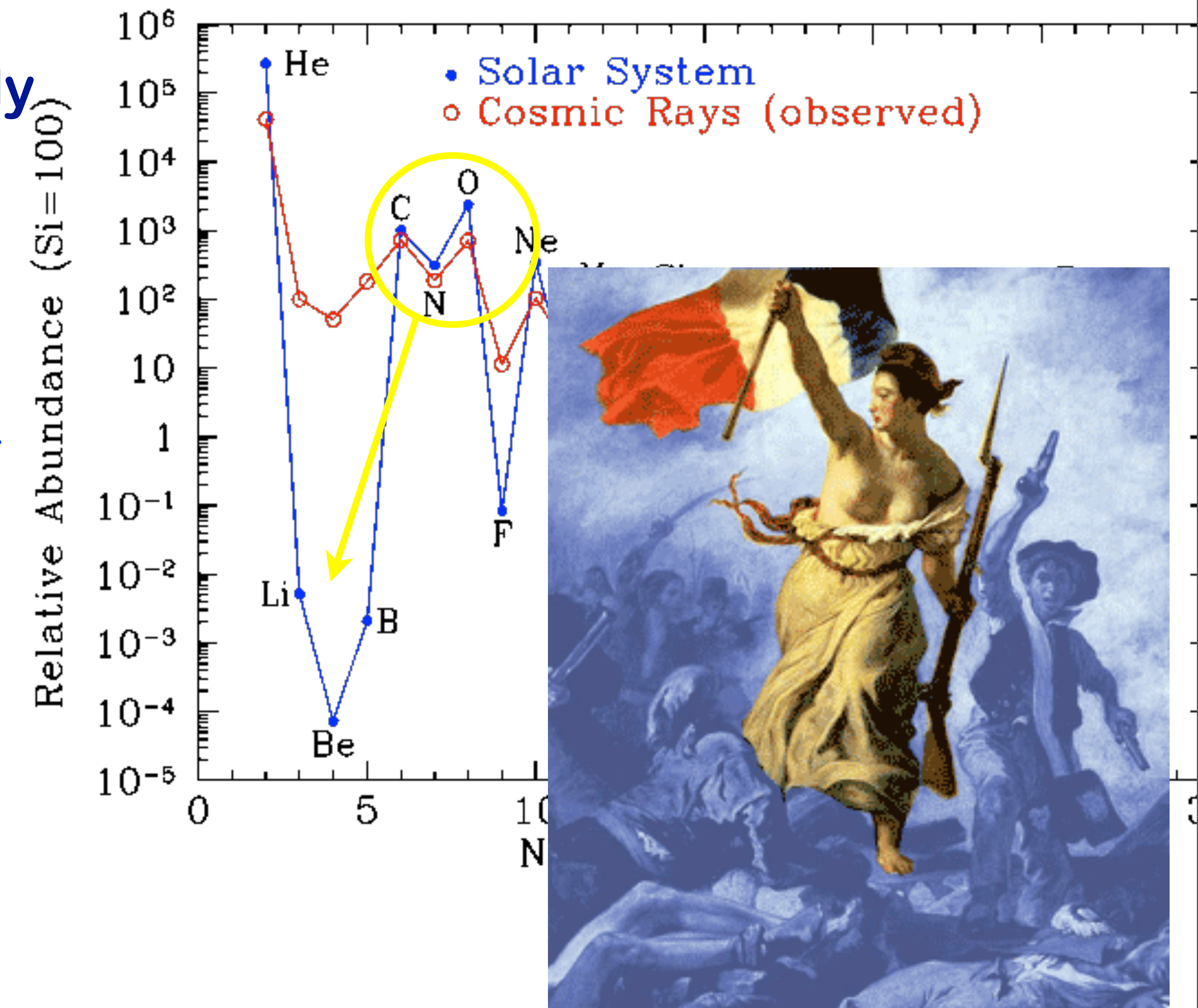

Cosmic-Ray Nucleosynthesis

Reeves, Fowler, Hoyle 1970; Meneguzzi, Audouze, Reeves 1971; Walker, Mathews, Viola

Cosmic Rays interact with ISM

Interstellar gas: beam dump

- Observe in gamma-ray sky

$$p_{\rm cr} + p_{\rm gas} \to pp\pi^0$$
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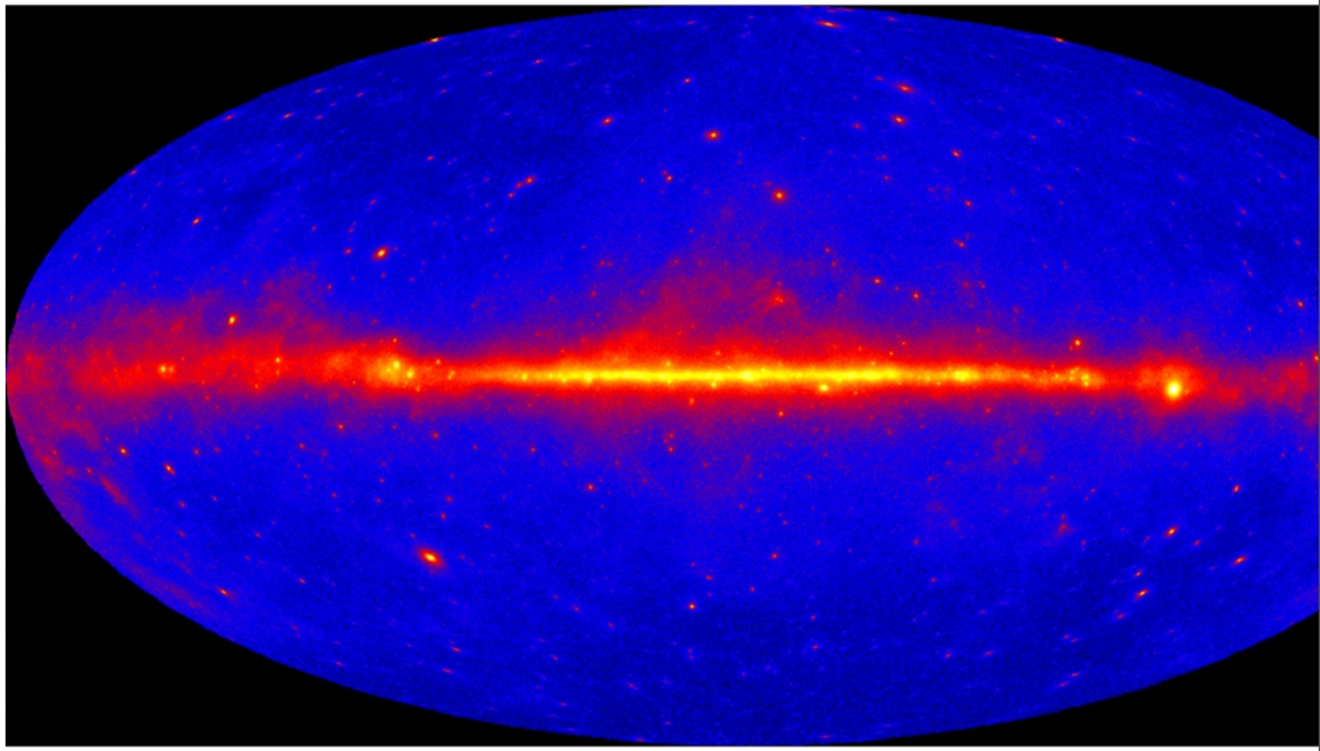

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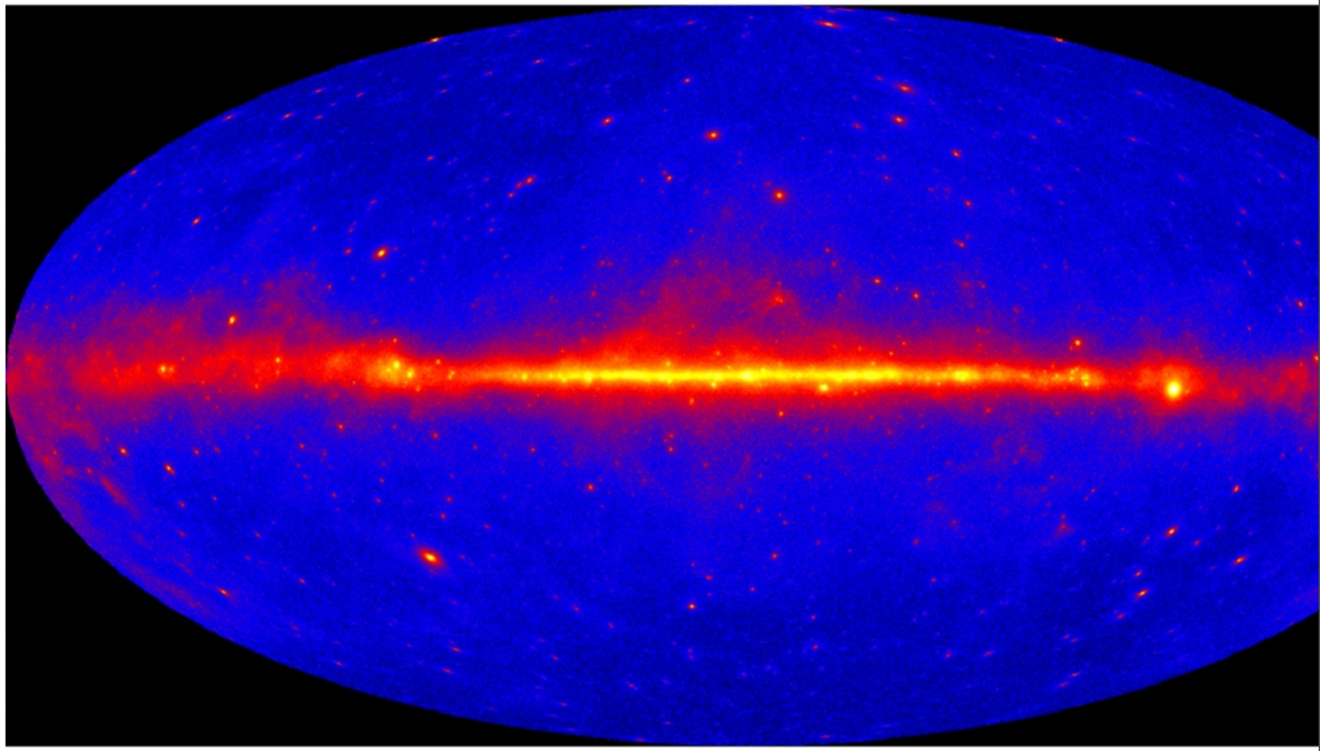

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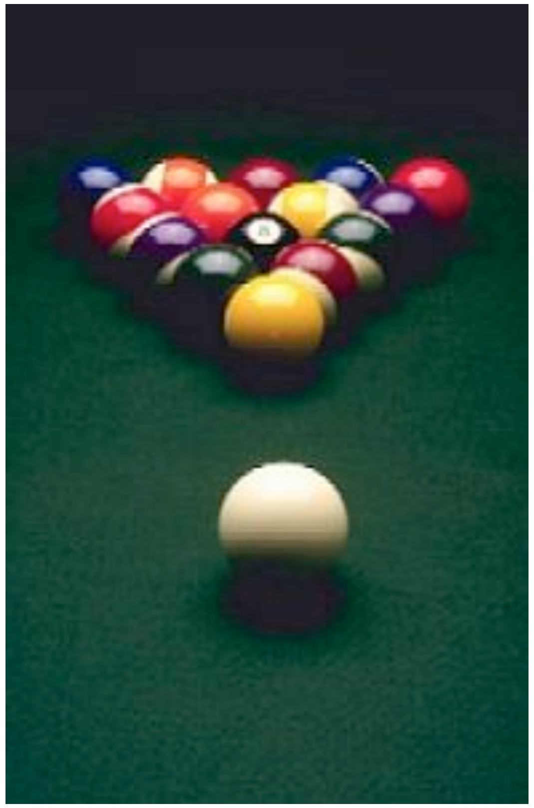

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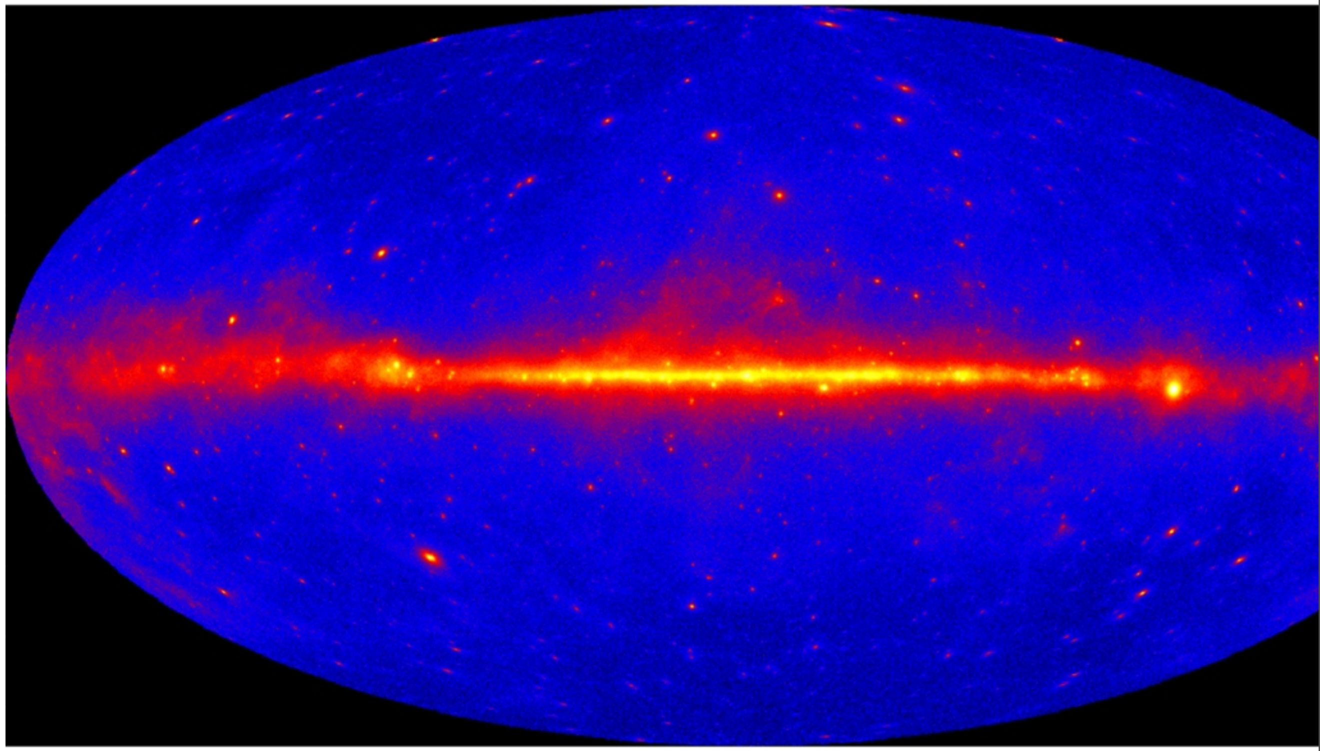

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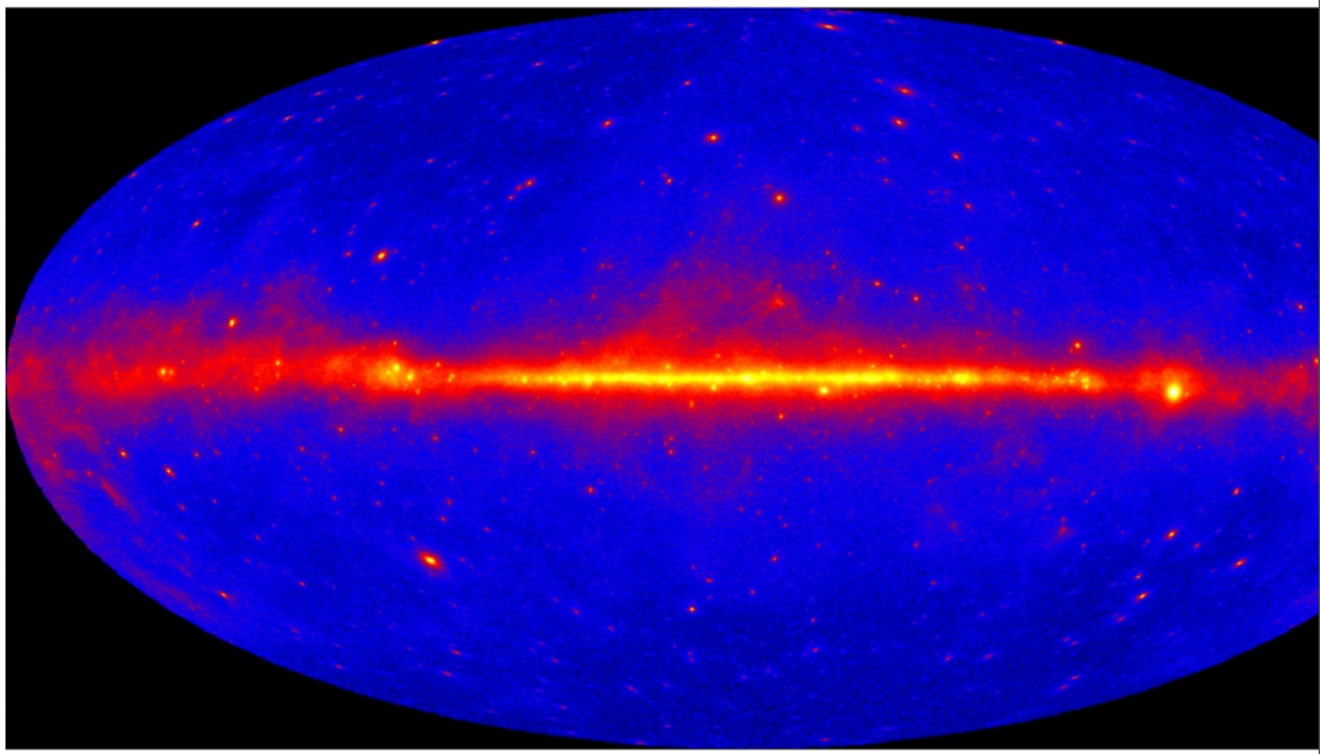

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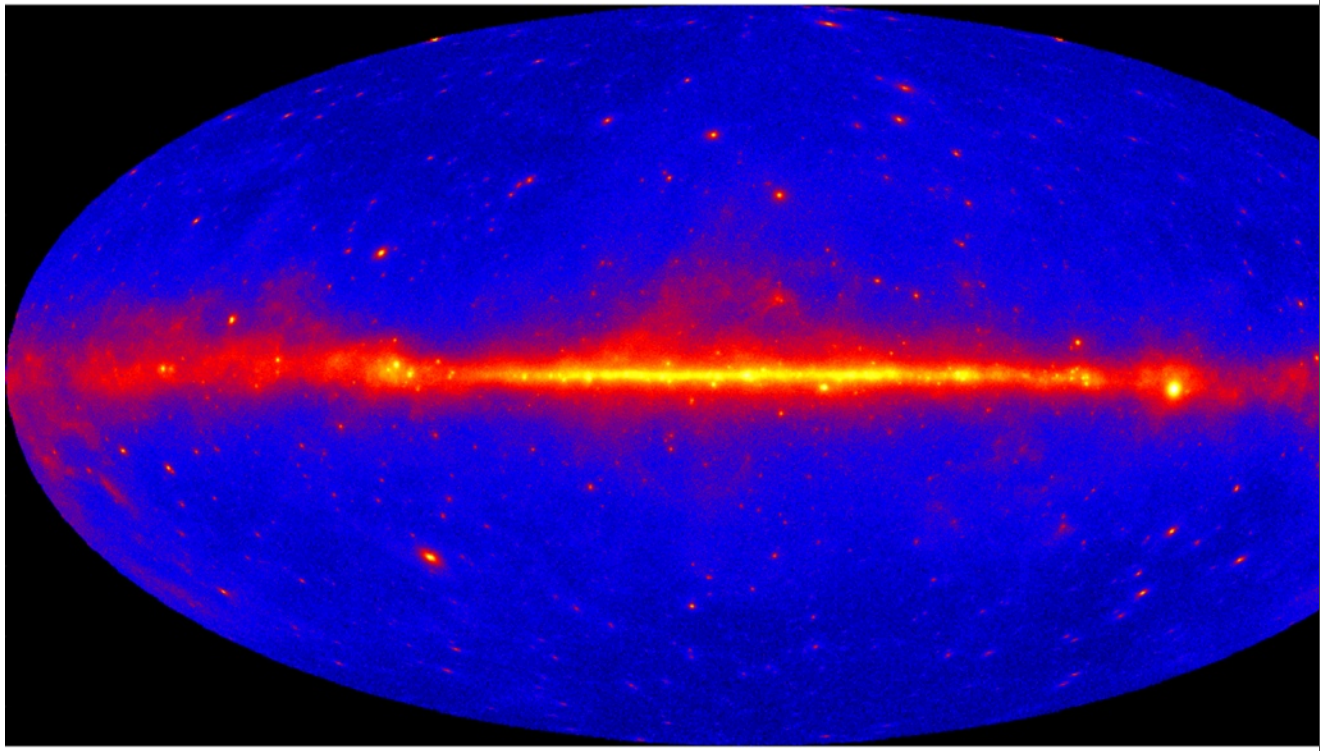

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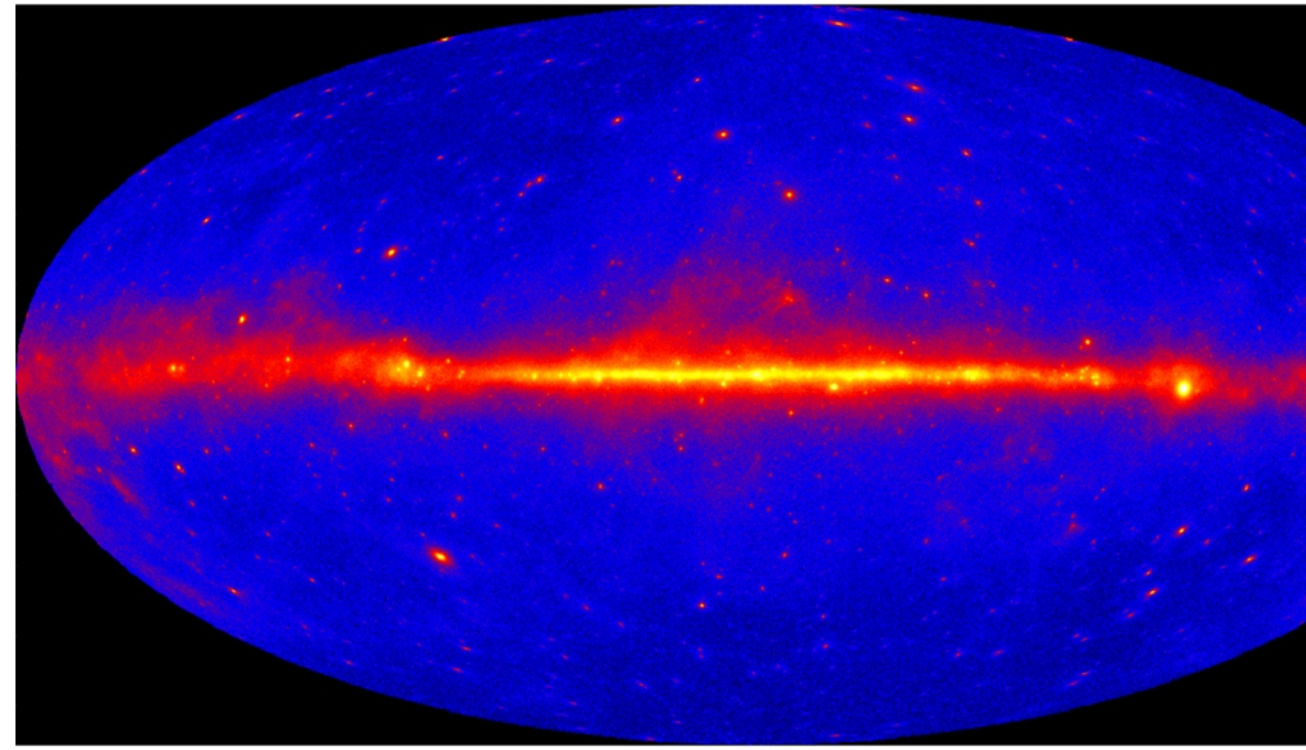

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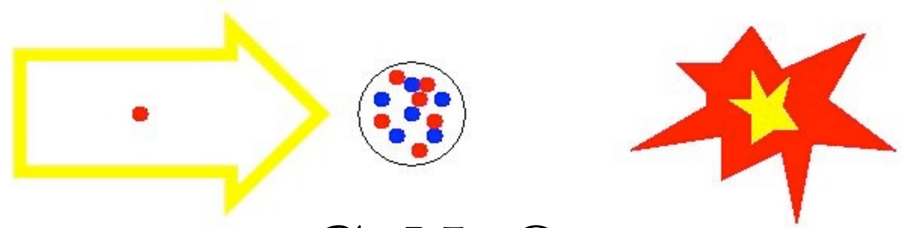

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no metals required--helium is primordial

Cosmic Ray Acceleration: Astrophysical Shocks

In magnetized collisionless shocks:

- ★ shock deceleration
  - ⇨ converging flows
- ★ charged particles scatter off magnetic inhomogeneities
- ★ repeatedly cross shock,

  gain energy

  with some chance of escape
- ★ result: power-law spectrum

$$dN/dE \propto E^{-(2+4/\mathcal{M}^2)} \rightarrow E^{-2}$$

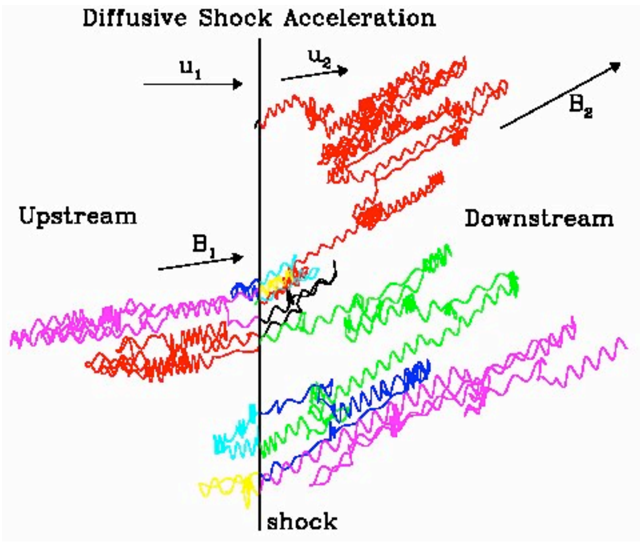
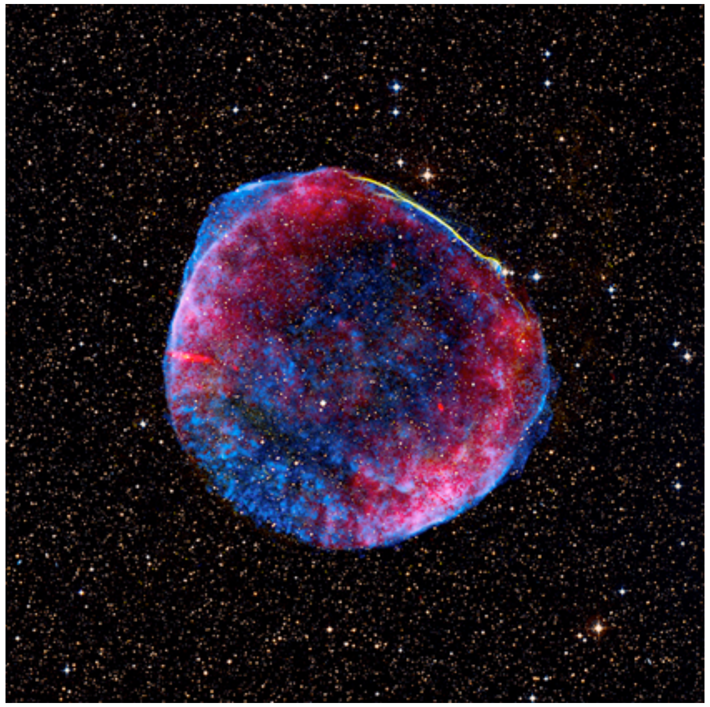


Image: Matthew Baring



SN 1006 X-ray/Radio/Optical

Galactic Cosmic Rays

composition: mostly protons

- heavier nuclei in roughly ISM proportions

spectrum: nonthermal

- power law with breaks

sources: Supernovae

- Galactic CR flux:

- SNe also sites of metal production:

Li production:

- rate
- abundance

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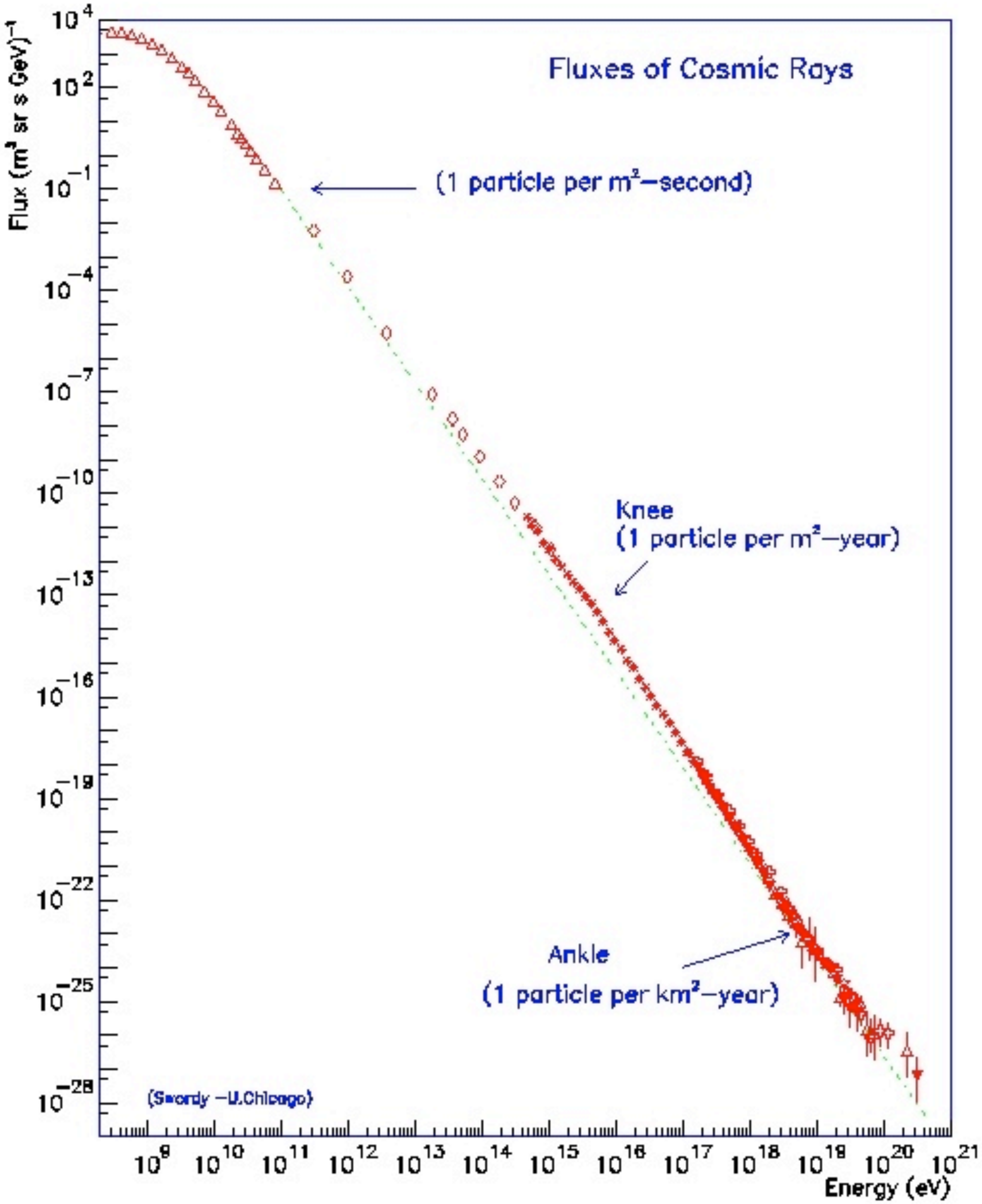

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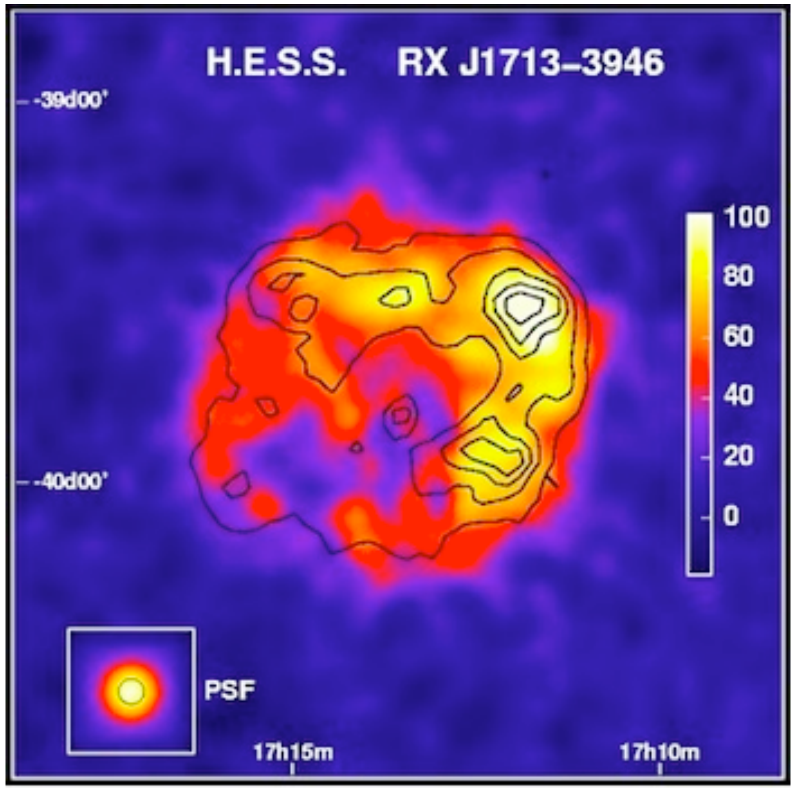

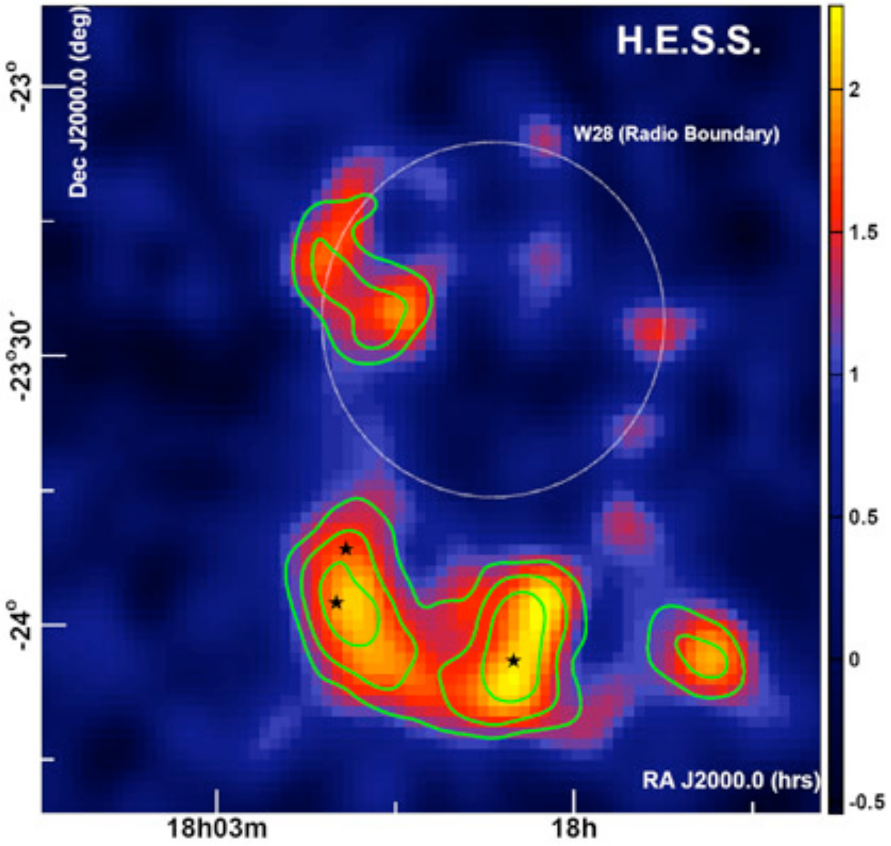

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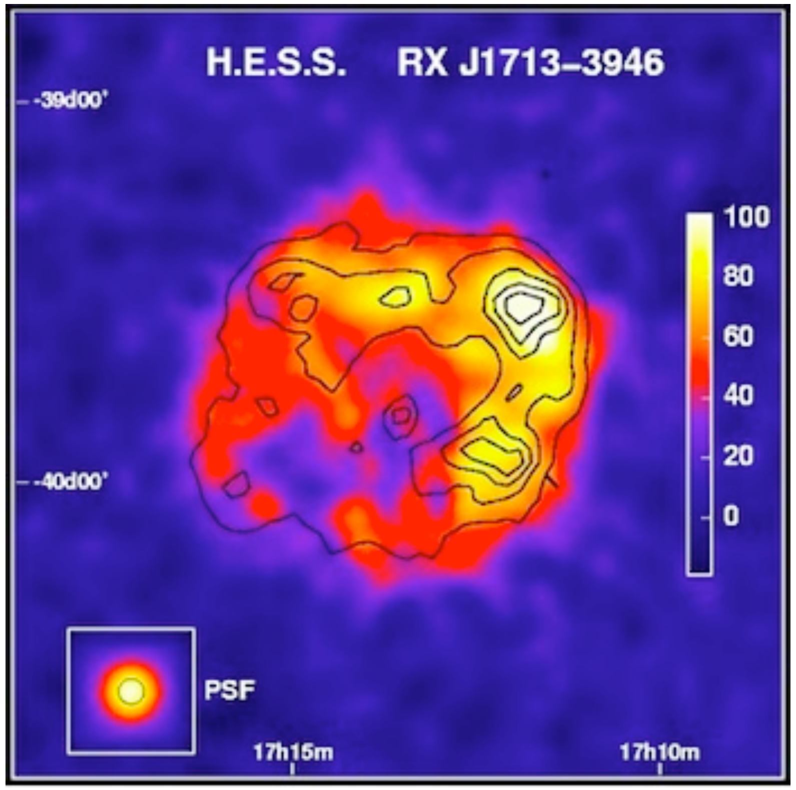

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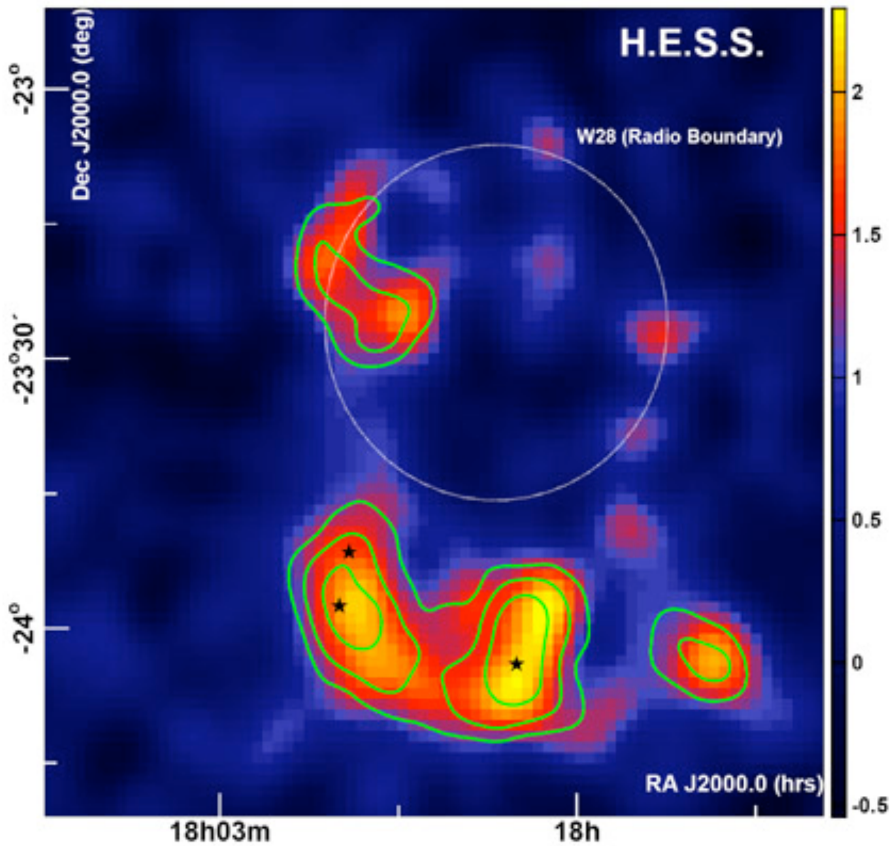
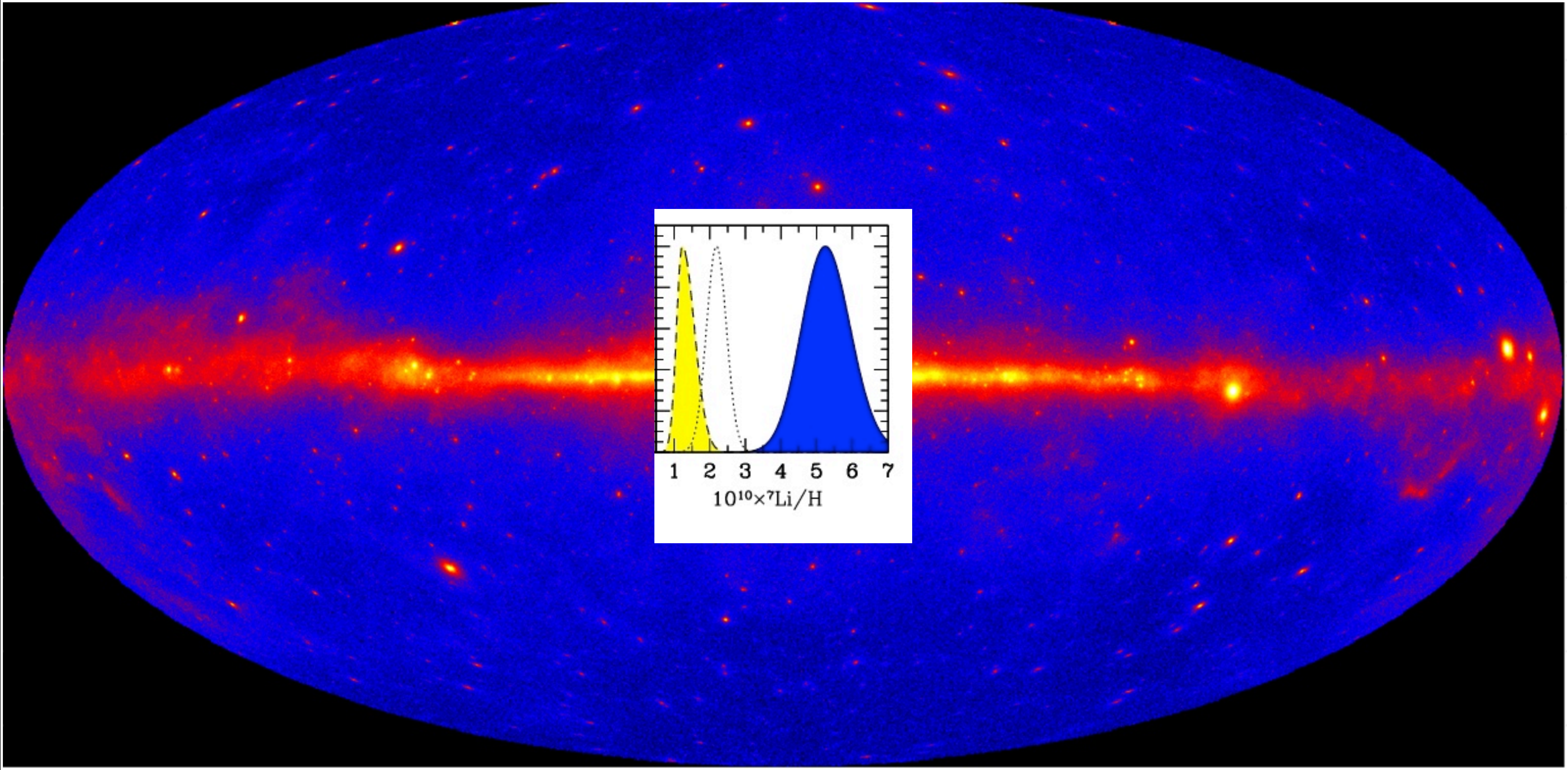


Li production: $\alpha\alpha \to {}^6{\rm Li} + \cdots$

- rate $\frac{d}{dt} {\rm Li}|_{\rm gcr} \sim \Phi_\alpha \sigma_{\alpha\alpha} \propto \frac{d}{dt} Z$
- abundance $\boxed{{\rm Li}|_{\rm gcr} \propto Z}$

Cosmic Rays and LiBeB Evolution



Galactic Cosmic Rays: Archaeology

Prantzos, Cassé, Vangioni-Flam 1993; Walker et al 1993; BDF Olive & Schramm 1994; Ramaty, Kozlovsky, & Lingenfelter 1996

LiBeB as Cosmic Ray Dosimeters

Solar LiBeB: cumulative irradiation at Sun birth

Galactic cosmic rays are only conventional ^{6}Li,^{9}Be,^{10}B source

neutrino spallation in supernovae (nu process) also makes ^{7}Li, ^{11}B

LiBeB in halo stars: cosmic-ray fossils

Cosmic rays present in early Galaxy!

LiBeB probe cosmic ray origin & history

Cosmic Rays explain

- Be evolution over entire measured metallicities

  latest data: "primary" linear Be vs O slope

  points to metal-rich cosmic rays

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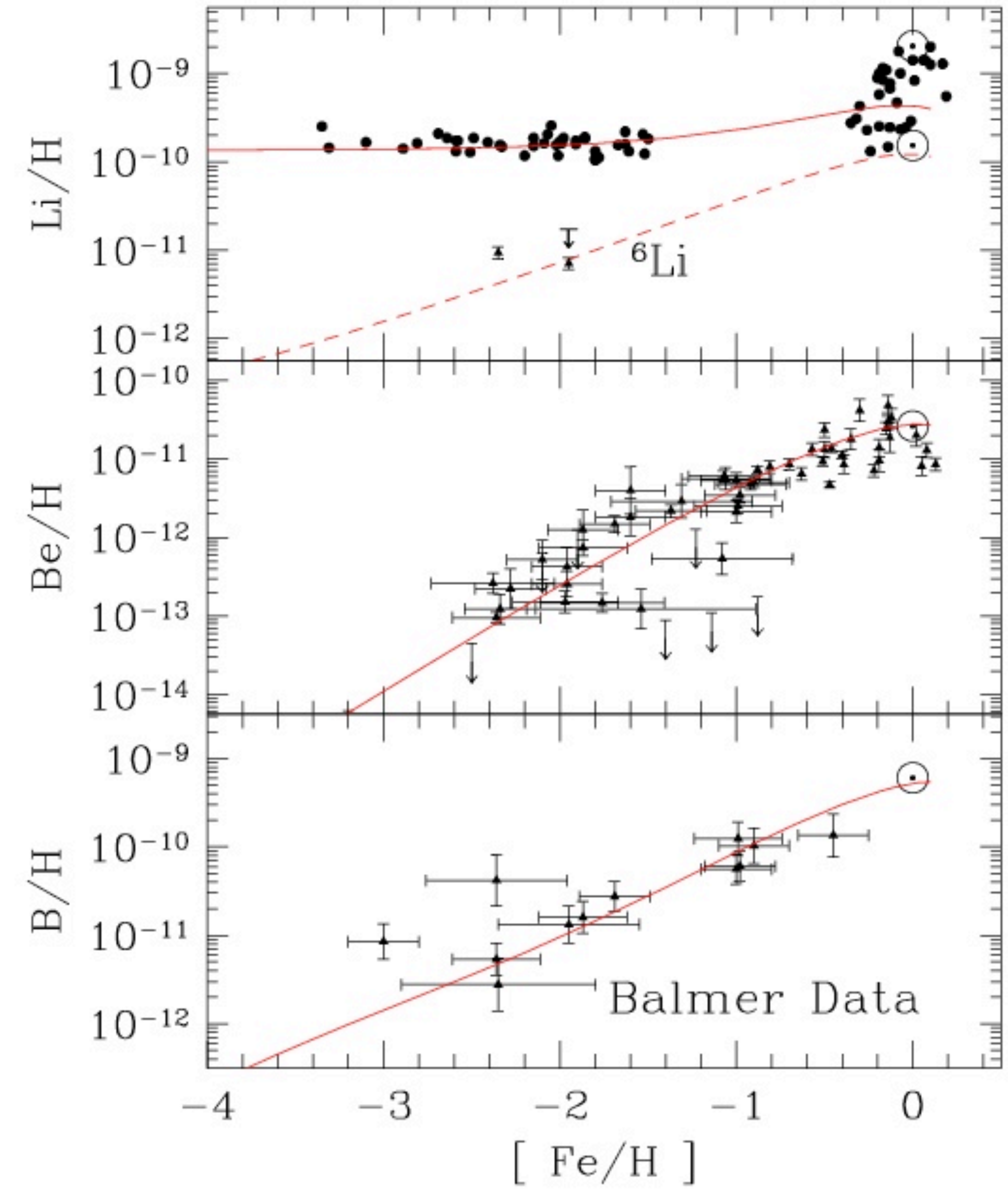

BDF & Olive 99

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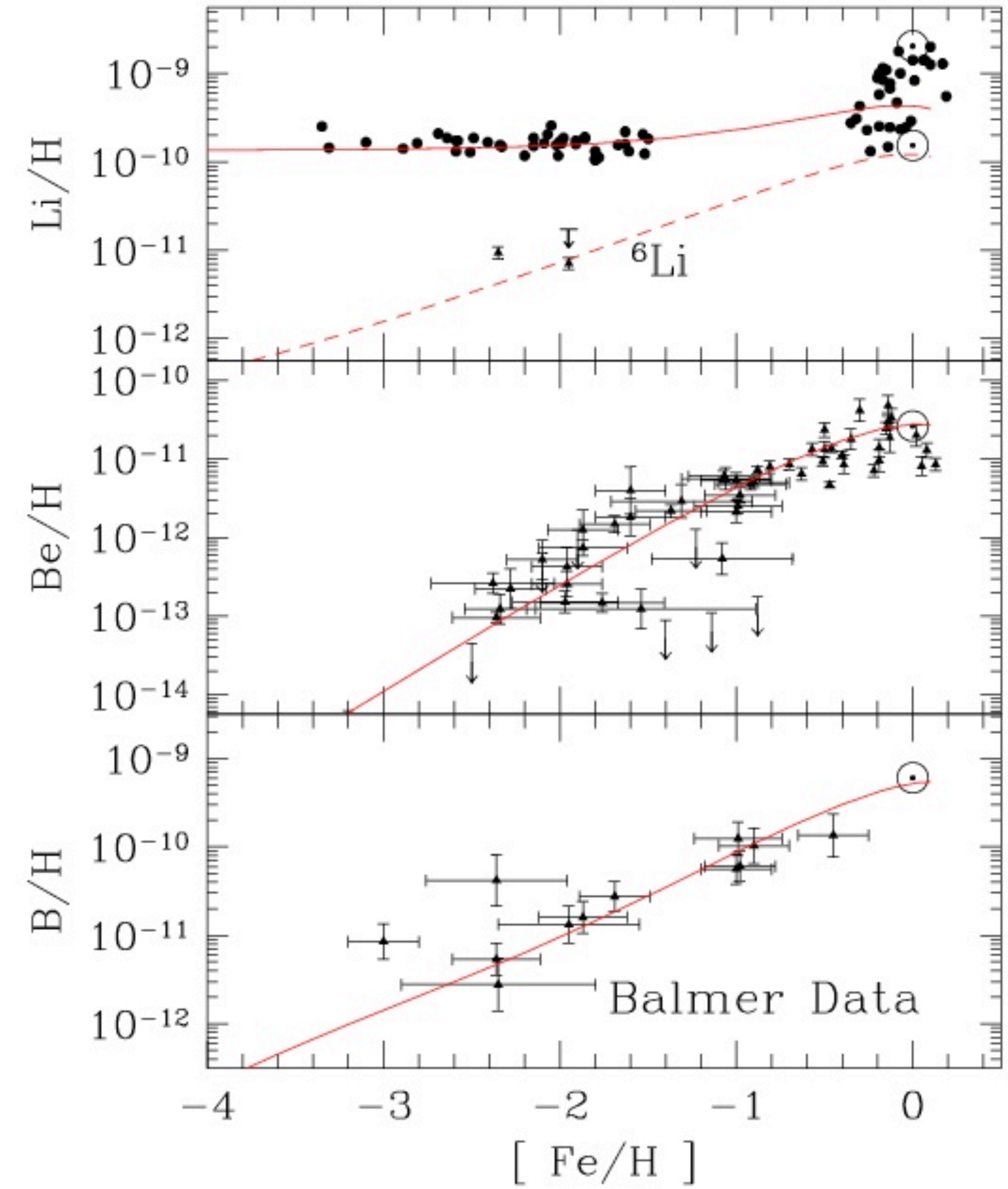

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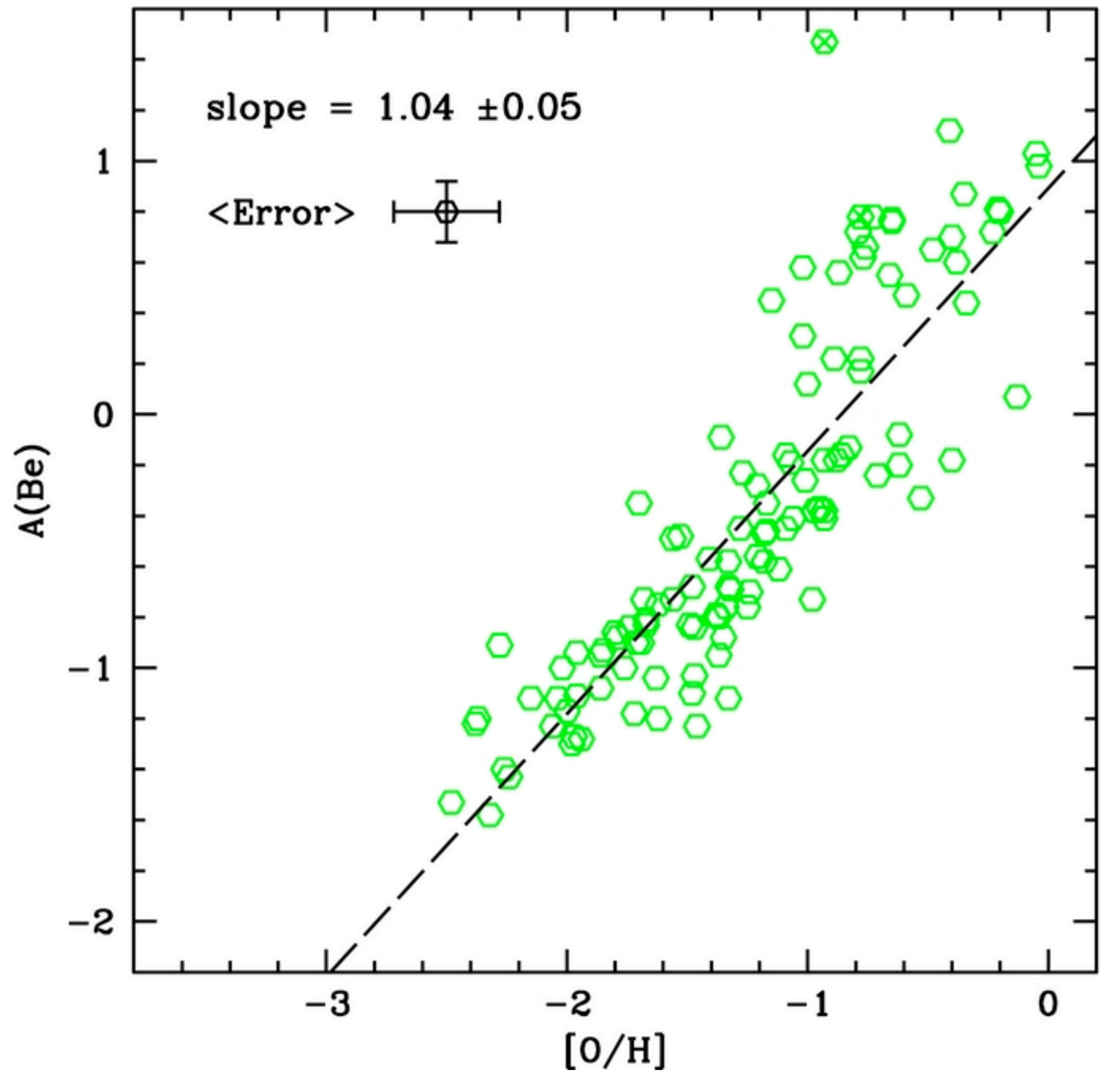

Boesgaard, Rich, Levesque, Bowler 2011

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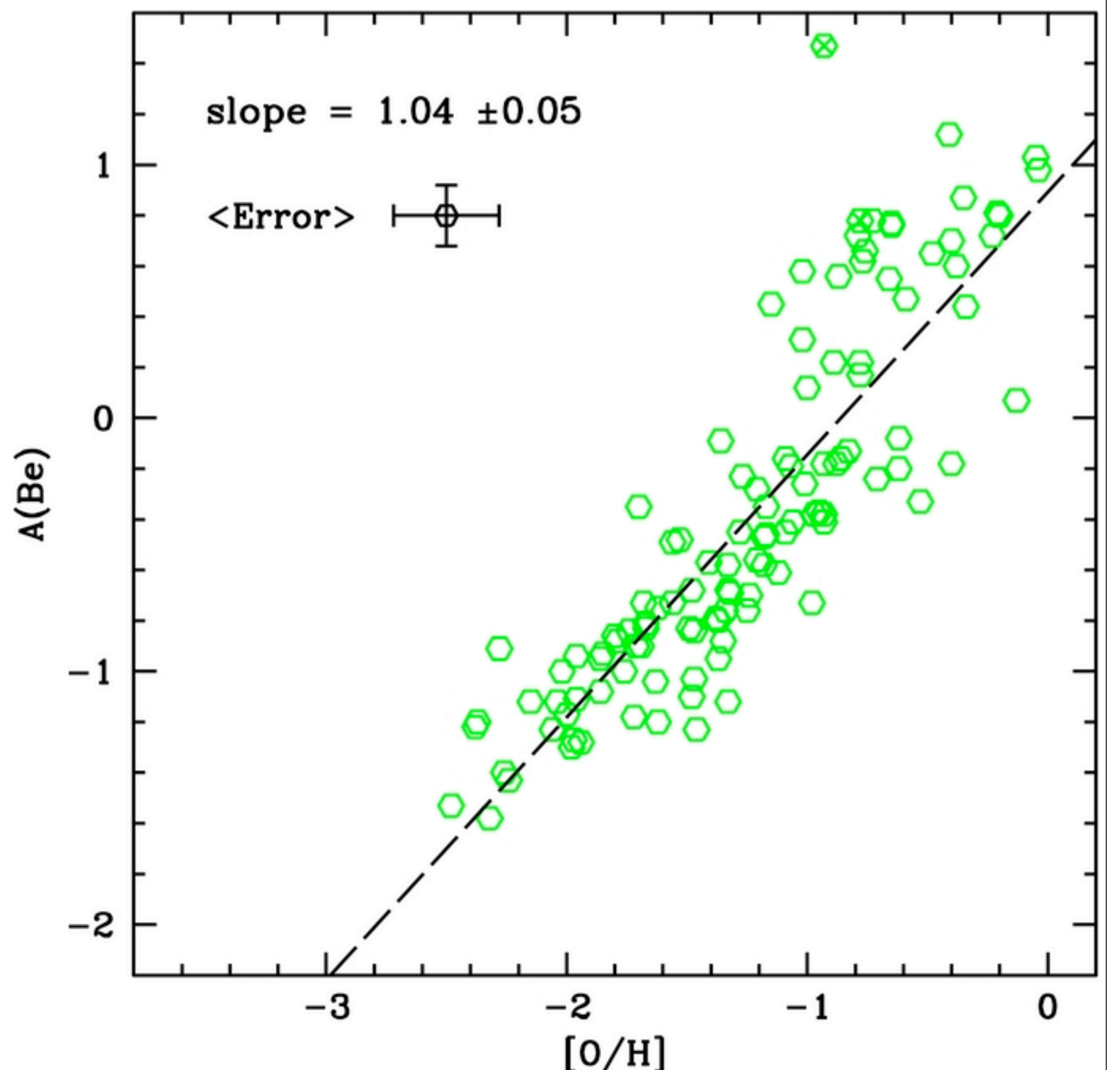

Boesgaard, Rich, Levesque, Bowler 2011

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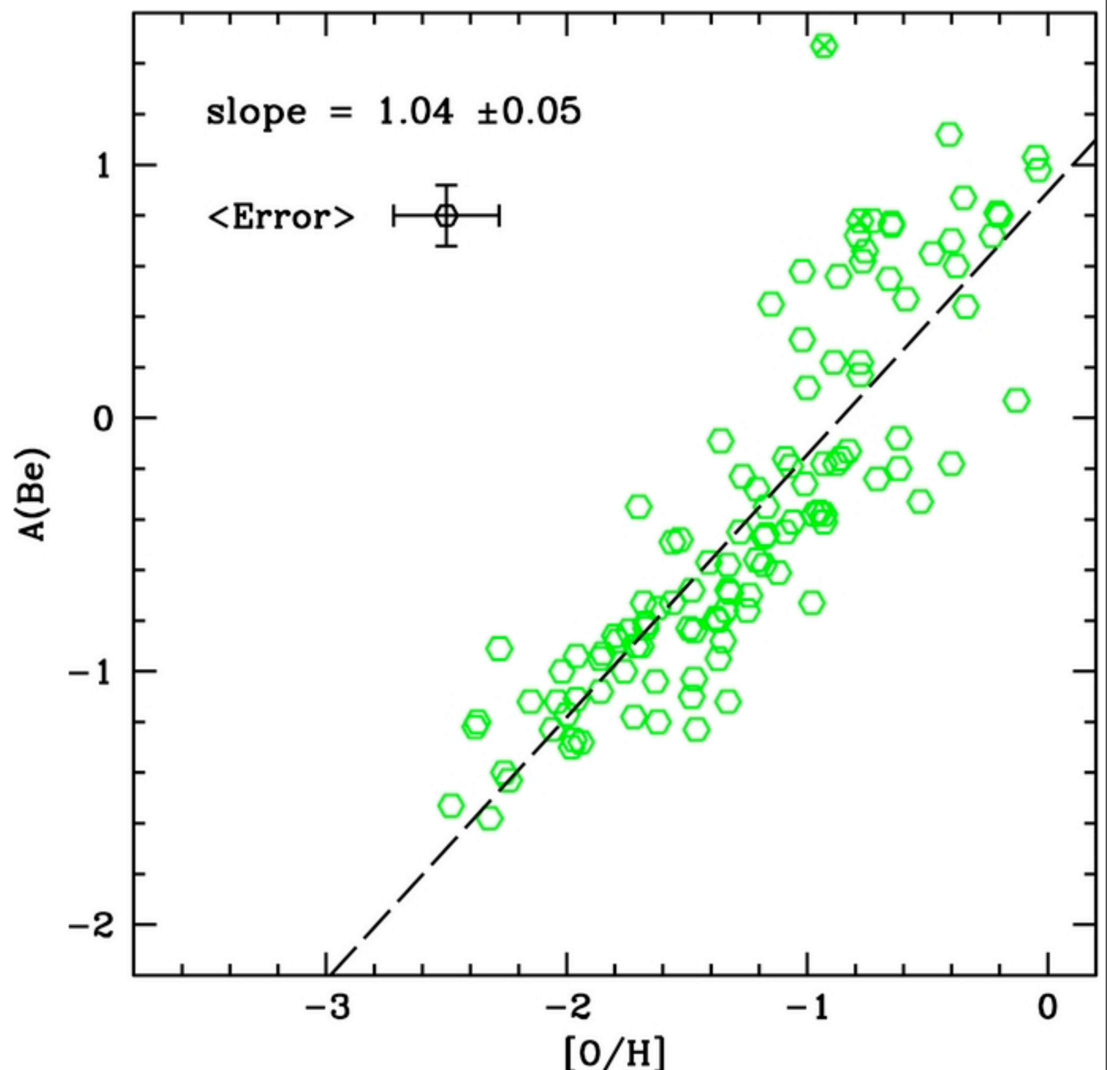

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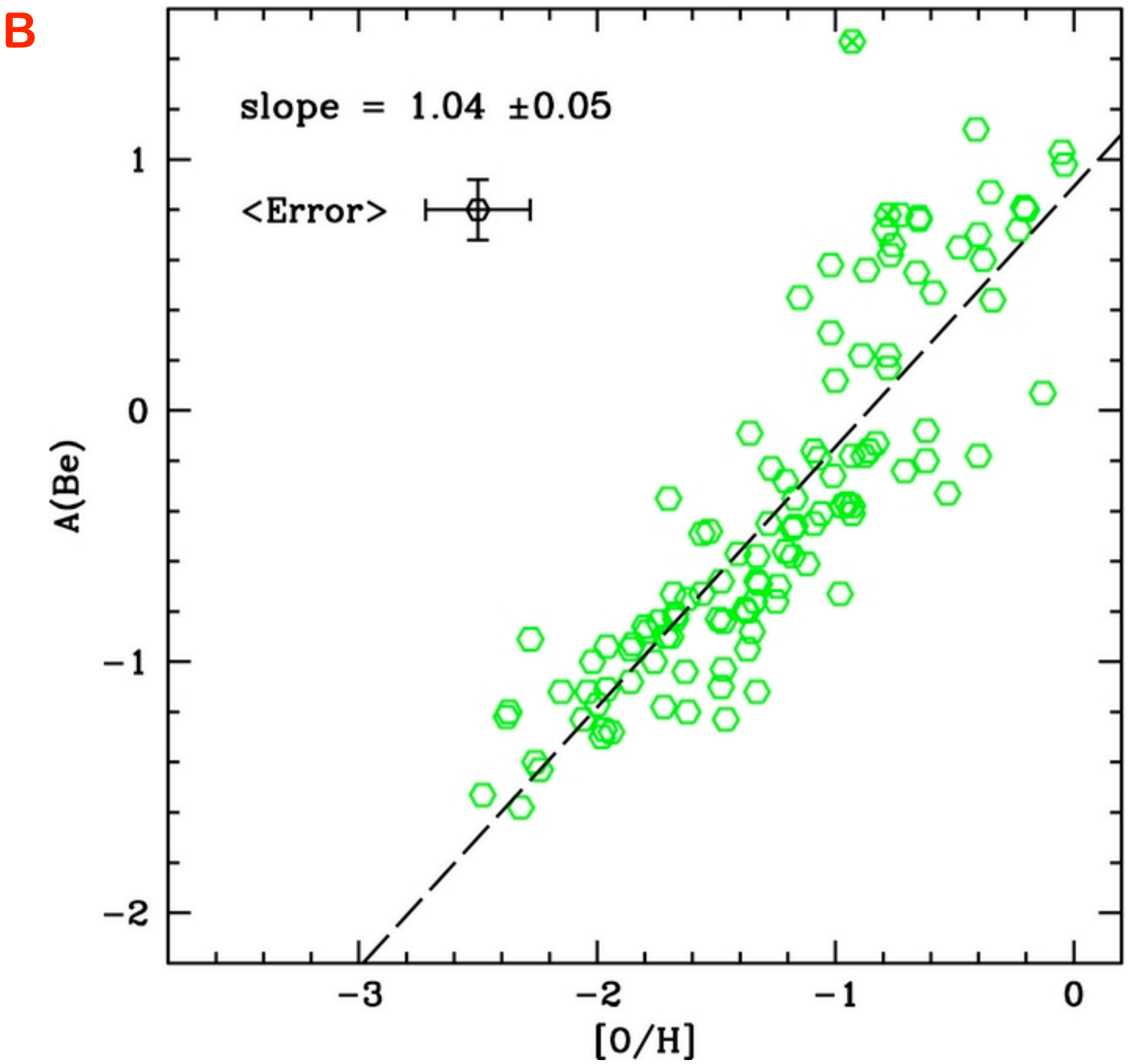

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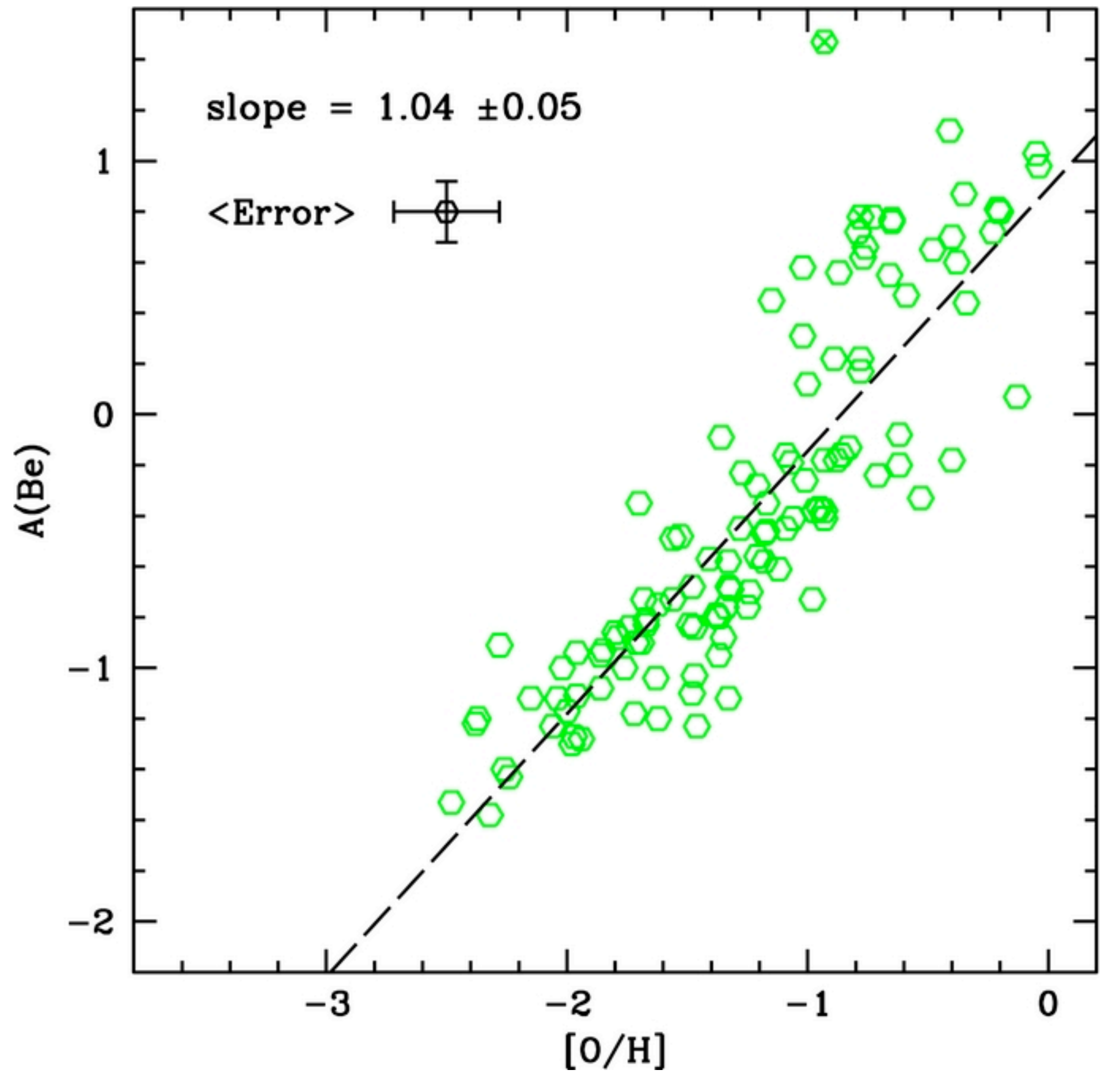

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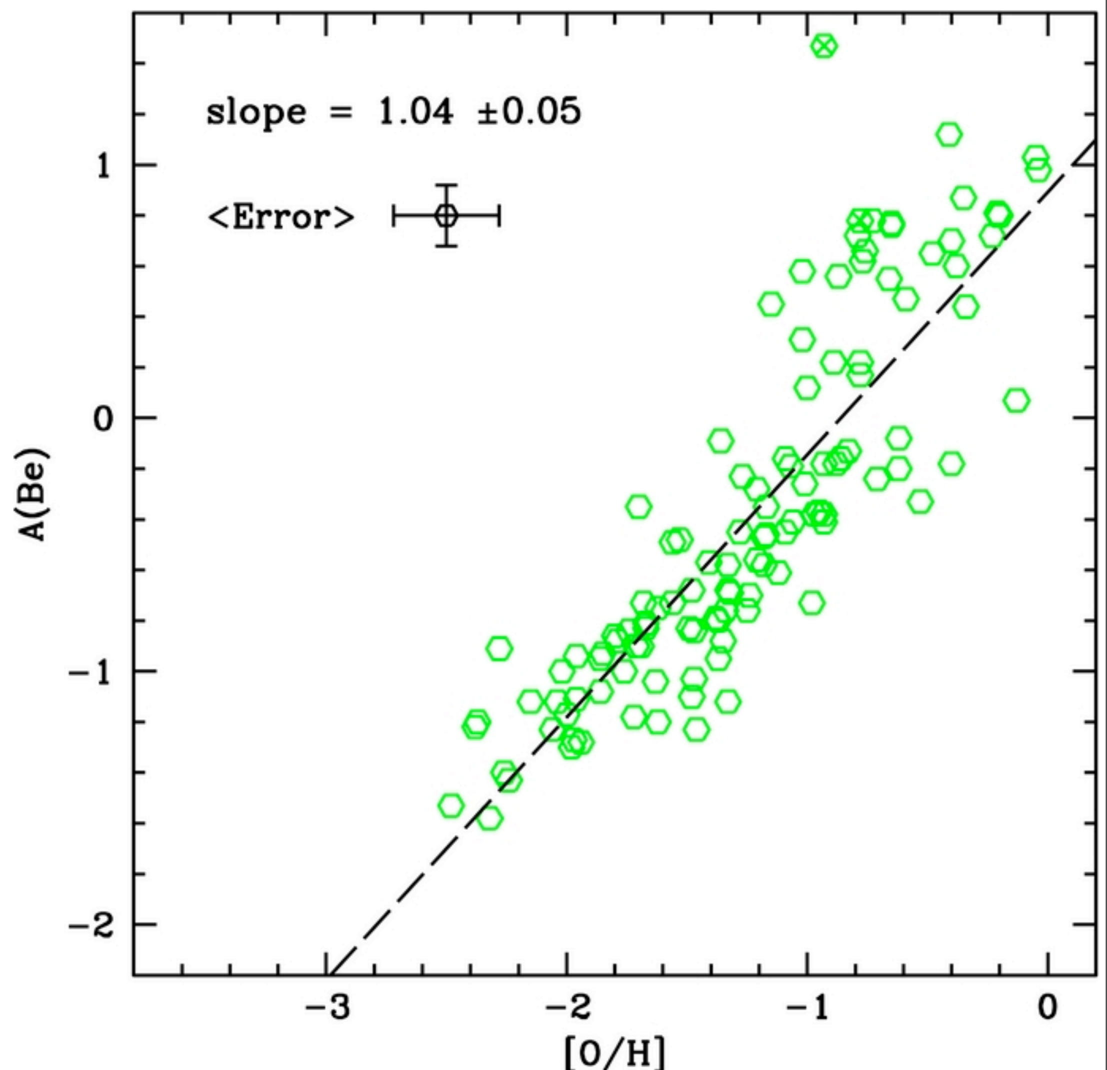
- cosmic rays + neutrinos underproduce solar ^{7}Li: need another source



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Galactic Cosmic Rays and Halo Star Lithium

- Cosmic rays pollute primordial Li

  $^{7}\mathrm{Li}_{\mathrm{observed}} = {}^{7}\mathrm{Li}_{\mathrm{CR}} + {}^{7}\mathrm{Li}_{\mathrm{BBN}}$

  But $^{6}\mathrm{LiBeB}_{\mathrm{GCR}} \Rightarrow {}^{6,7}\mathrm{Li}_{\mathrm{GCR}}$

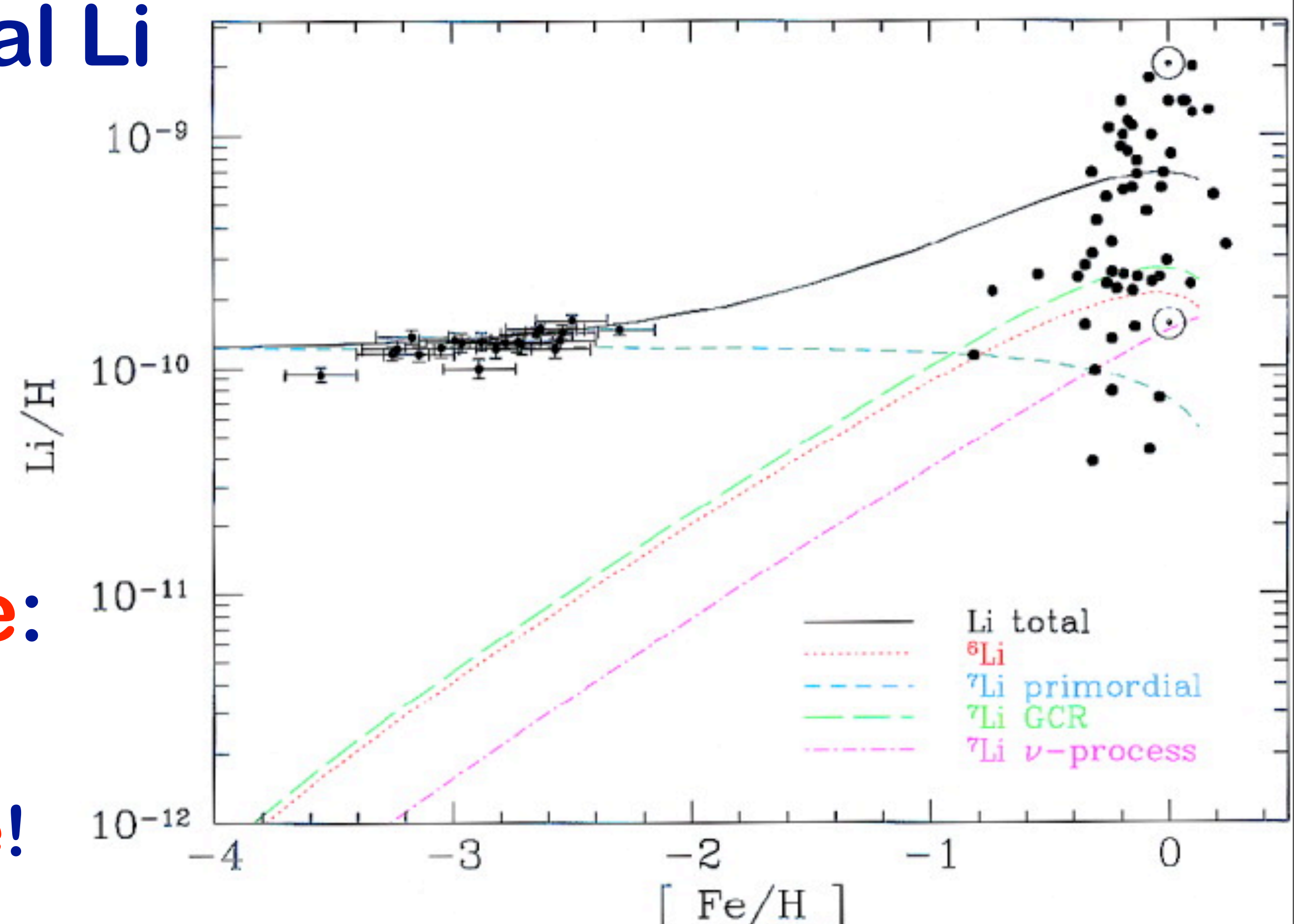
  Infer true $^{7}\mathrm{Li}_{\mathrm{BBN}}$!

- Consequences
  - predict small positive slope:

$$\mathrm{Li} = \mathrm{Li}_{\mathrm{bbn}} + \left.\frac{d\mathrm{Li}}{d\mathrm{Fe}}\right|_{\mathrm{cr}} \mathrm{Fe}$$

  - makes ^{7}Li problem slightly worse!

    ~10% downwards correction at [Fe/H]=-3



Ryan, Olive, Beers, BDF, Norris 2000

^{6}Li and Cosmic Rays

Cosmic-Ray prediction:

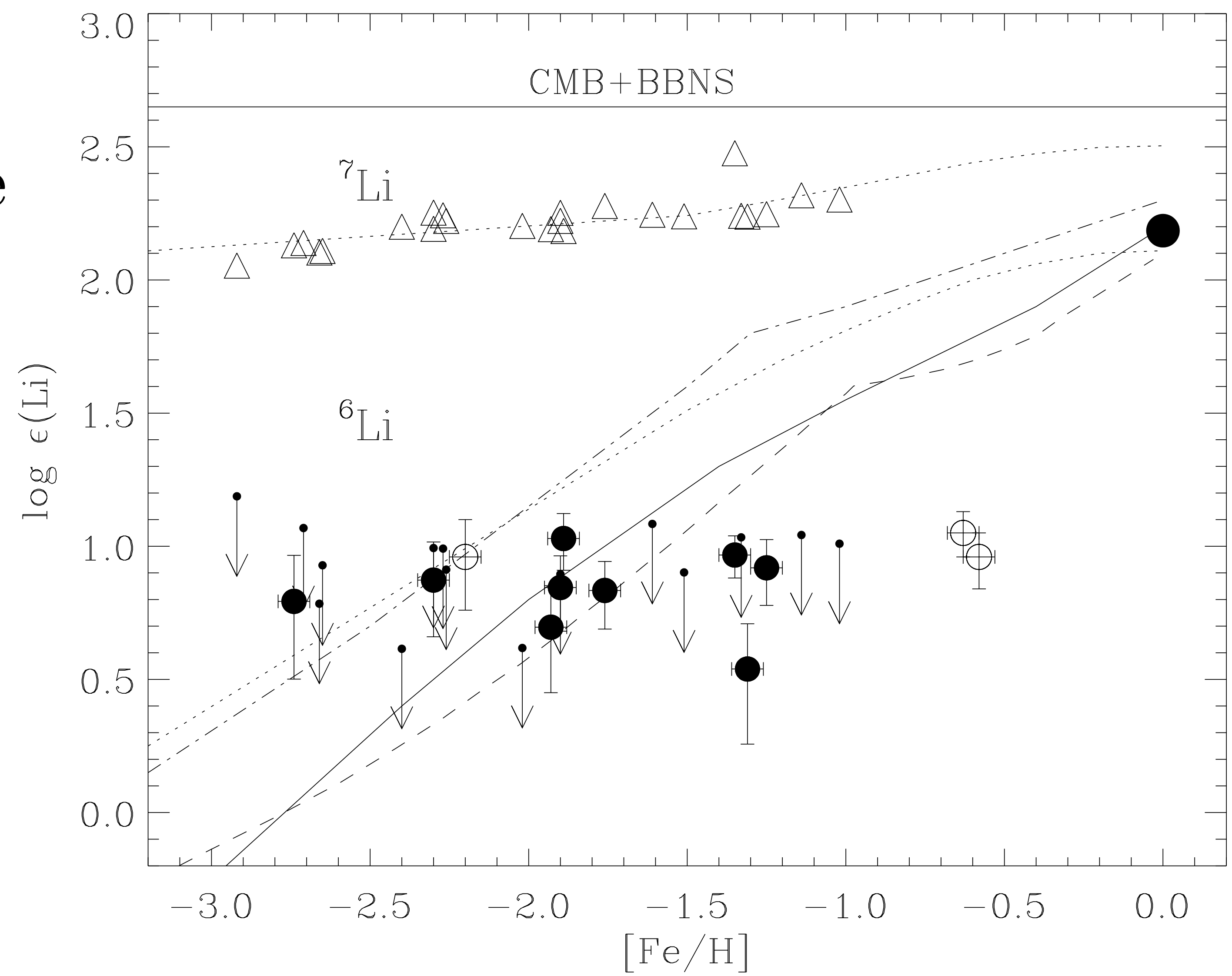
- **linear metal scaling**

$$^6\mathrm{Li} = \left.\frac{d^6\mathrm{Li}}{d\mathrm{Fe}}\right|_{\mathrm{cr}} \mathrm{Fe}$$

inconsistent with a ^{6}Li plateau!

because CR interactions unavoidable:

- **^{6}Li non-detection at [Fe/H]>-1.5 disagrees with CR prediction**
- **suggests depletion must operate at least in this regime**



Data: Asplund et al 2006

Pre-Galactic Cosmic Rays: Pop III Stars

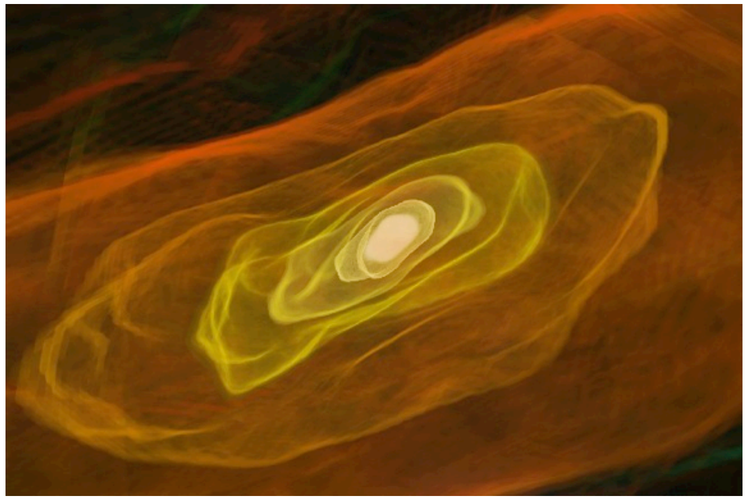
First stars (PopIII)

- Zero metallicity star formation
- thought to lead to ~few stars per halo
- massive to supermassive

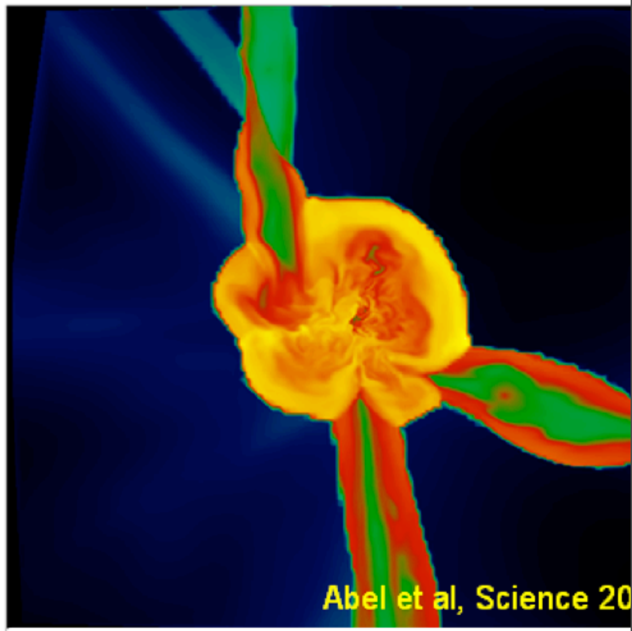
Explosions would be sources of cosmic rays

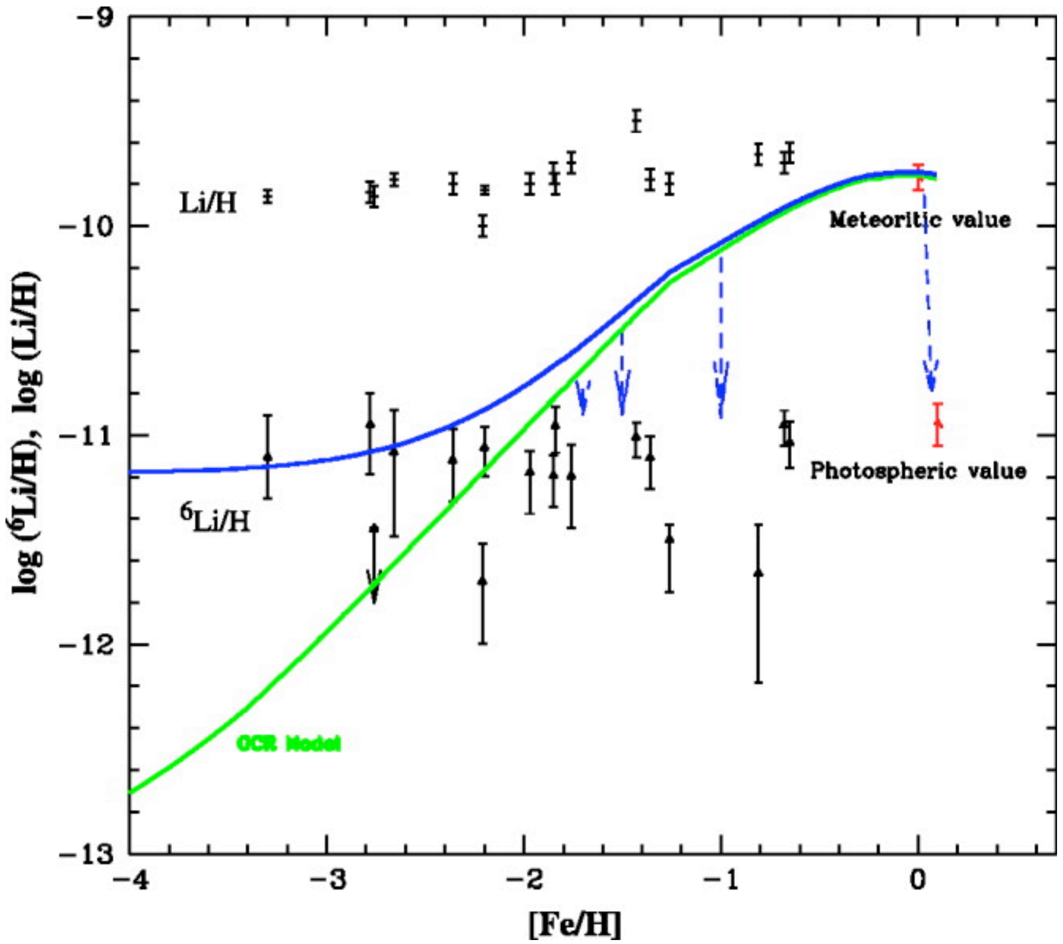
Rollinde, Vangioni, Olive, Silk; Kusukabe

- once outside of birth remnant, produce lithium in metal-free environment
- can give ^{6}Li "plateau" without substantial disruption to ^{7}Li
- gamma-ray signal redshifted, small



Abel, Bryan, & Norman





Rollinde, Vangioni, & Olive 2006

Shock Power for Acceleration of Cosmological Cosmic Rays

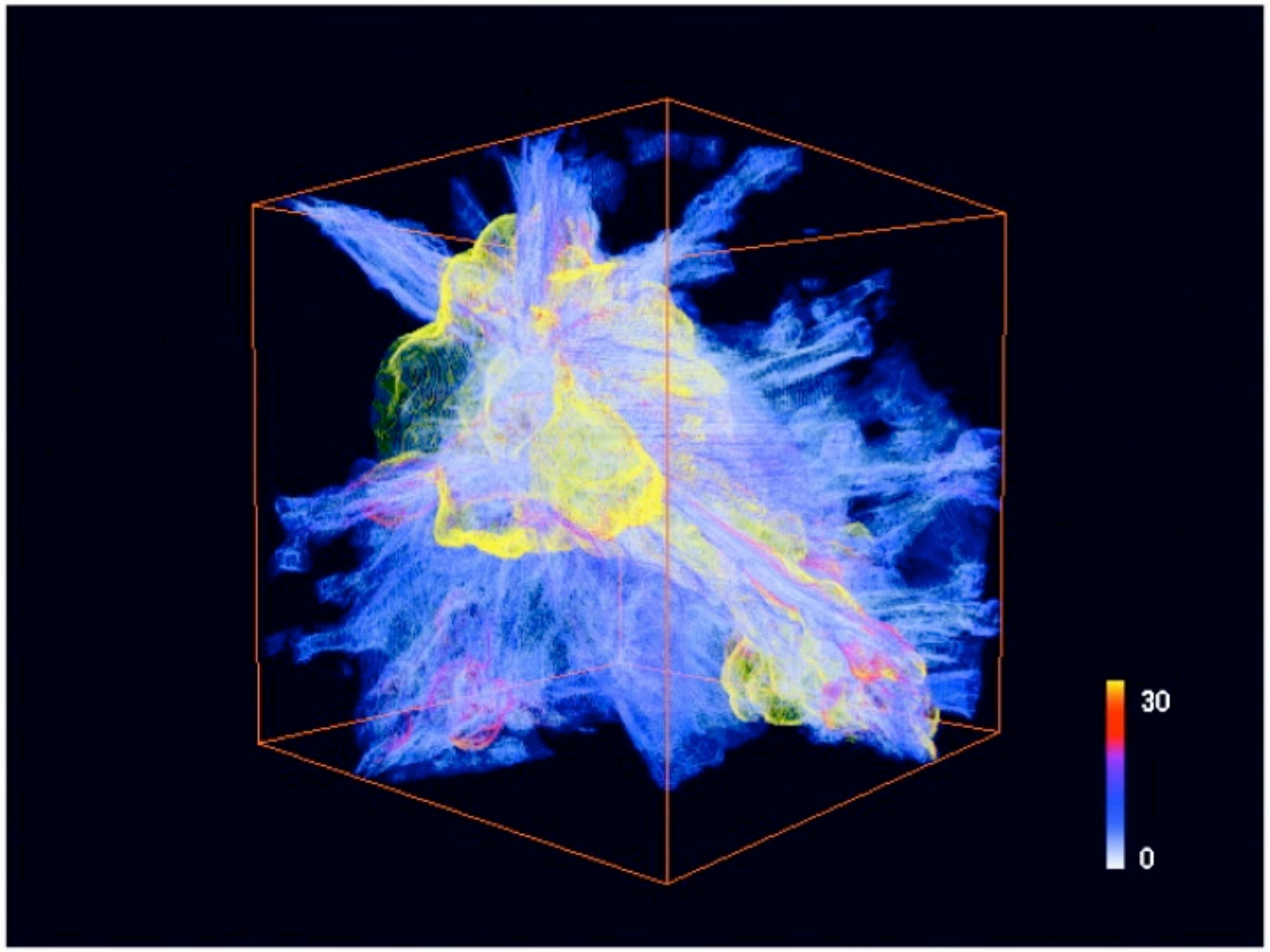
dark matter potentials drive baryon flows

If flow speed > sound speed: shocks

Cosmic accretion shocks:

- ✓ High Mach
- ✓ Long-lived
- ✓ Large power

Ideal sites for particle acceleration!



Ryu et al 2003

Shock surfaces, Mach colors

$(25\ h^{-1}\ \mathrm{Mpc})^3$ simulation

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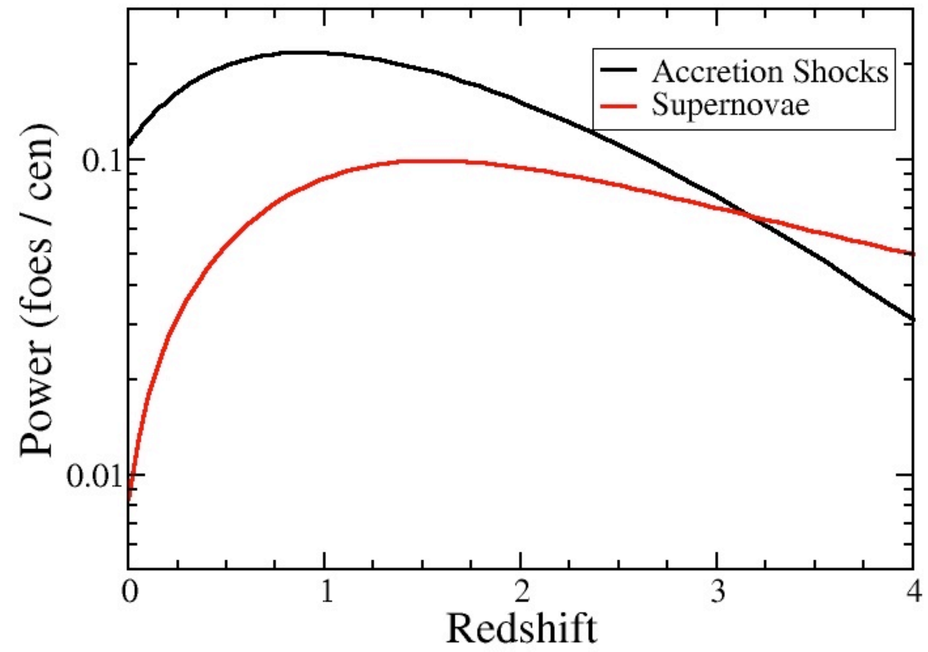
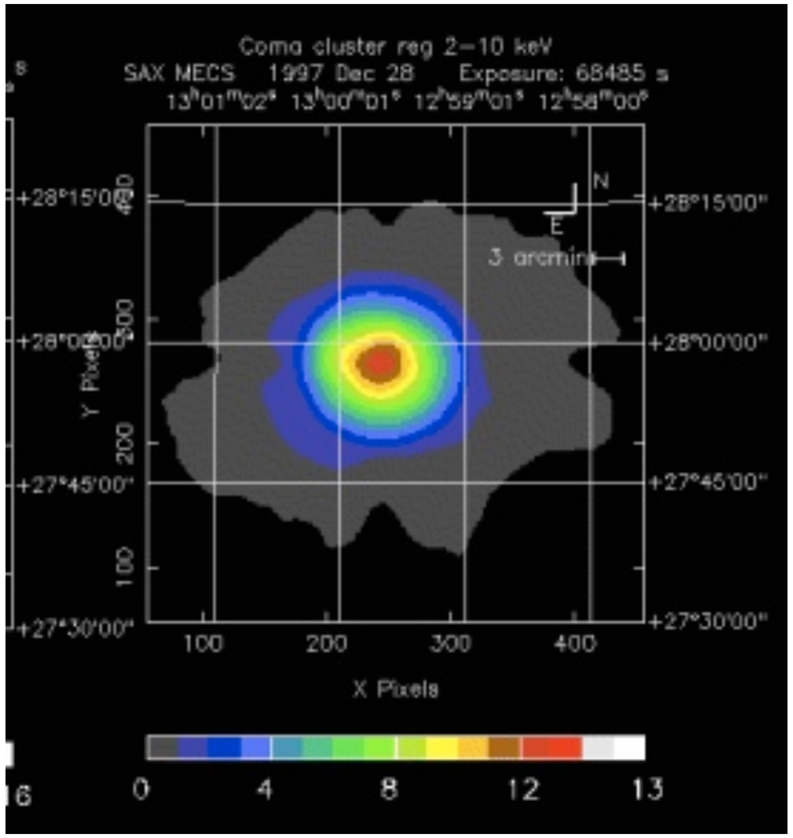
Structure Formation Cosmic Rays

- An inevitable fact of baryonic life?
- Acceleration begins before galaxy birth?
- Galaxy clusters:
  - nonthermal radio Fusco-Femiano et al 99
  - but no gamma rays Ackermann et al 2010



Pavlidou & BDF 2006



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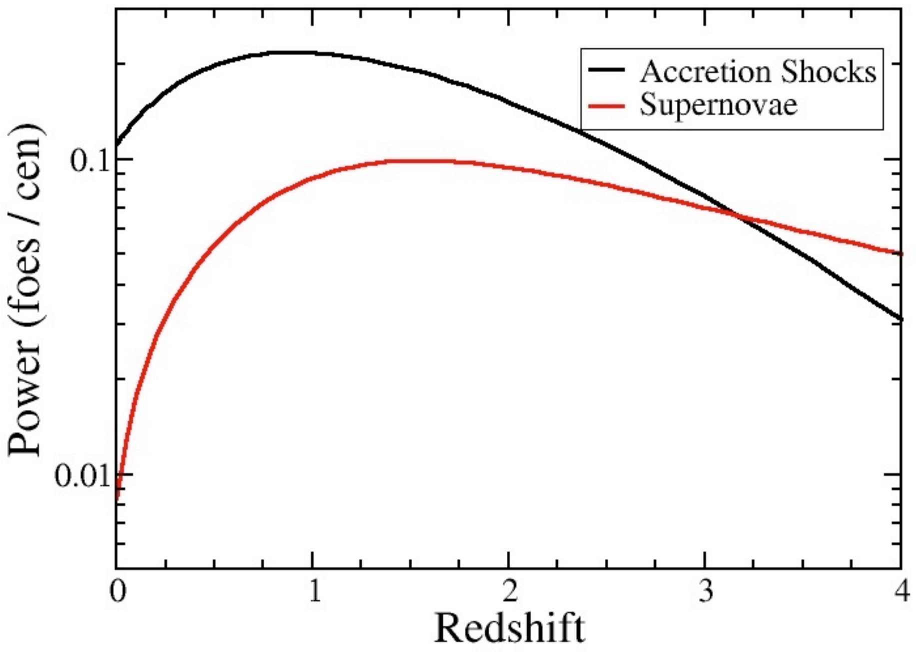

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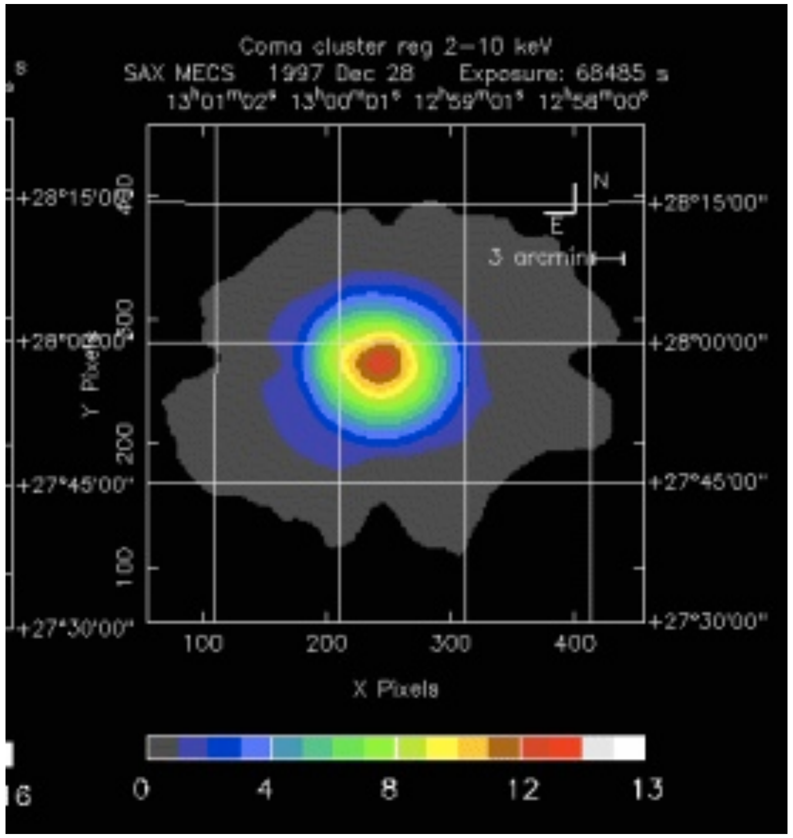

Structure Formation CR Nuke

Primordial beam, targets:

- ✓ produce ^{6}Li and ^{7}Li only,
- ✓ no Be & B
- ✓ no correlation with metals

Plateau candidate!

also see Prodanović poster

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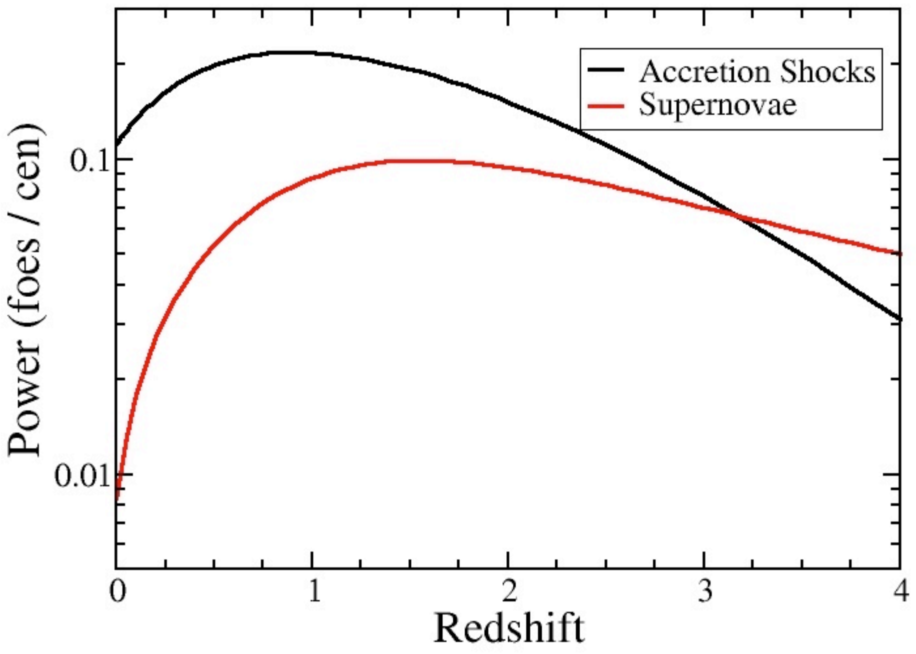

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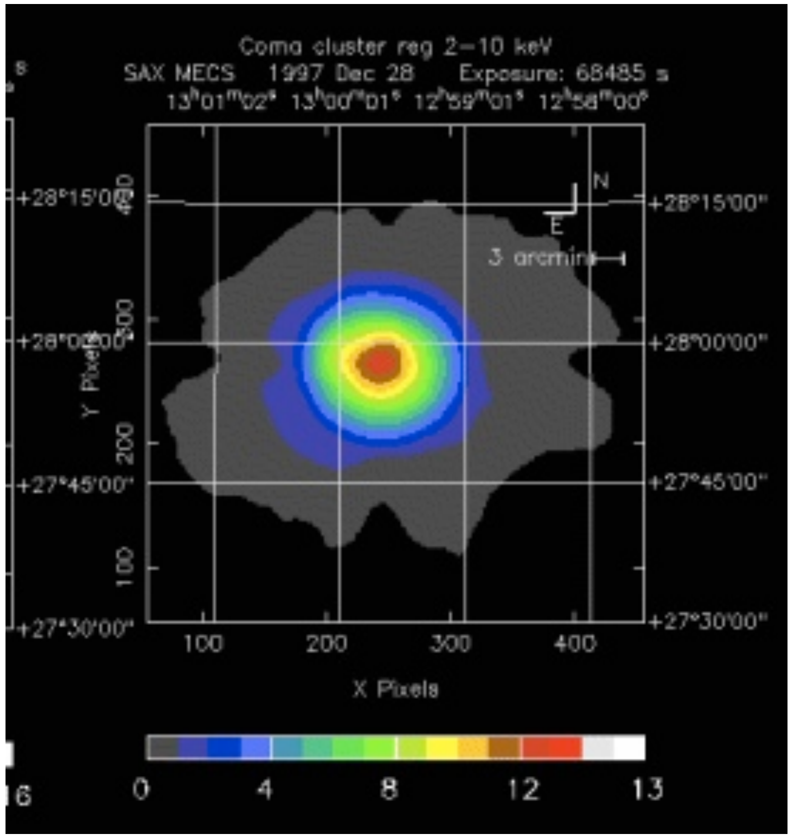

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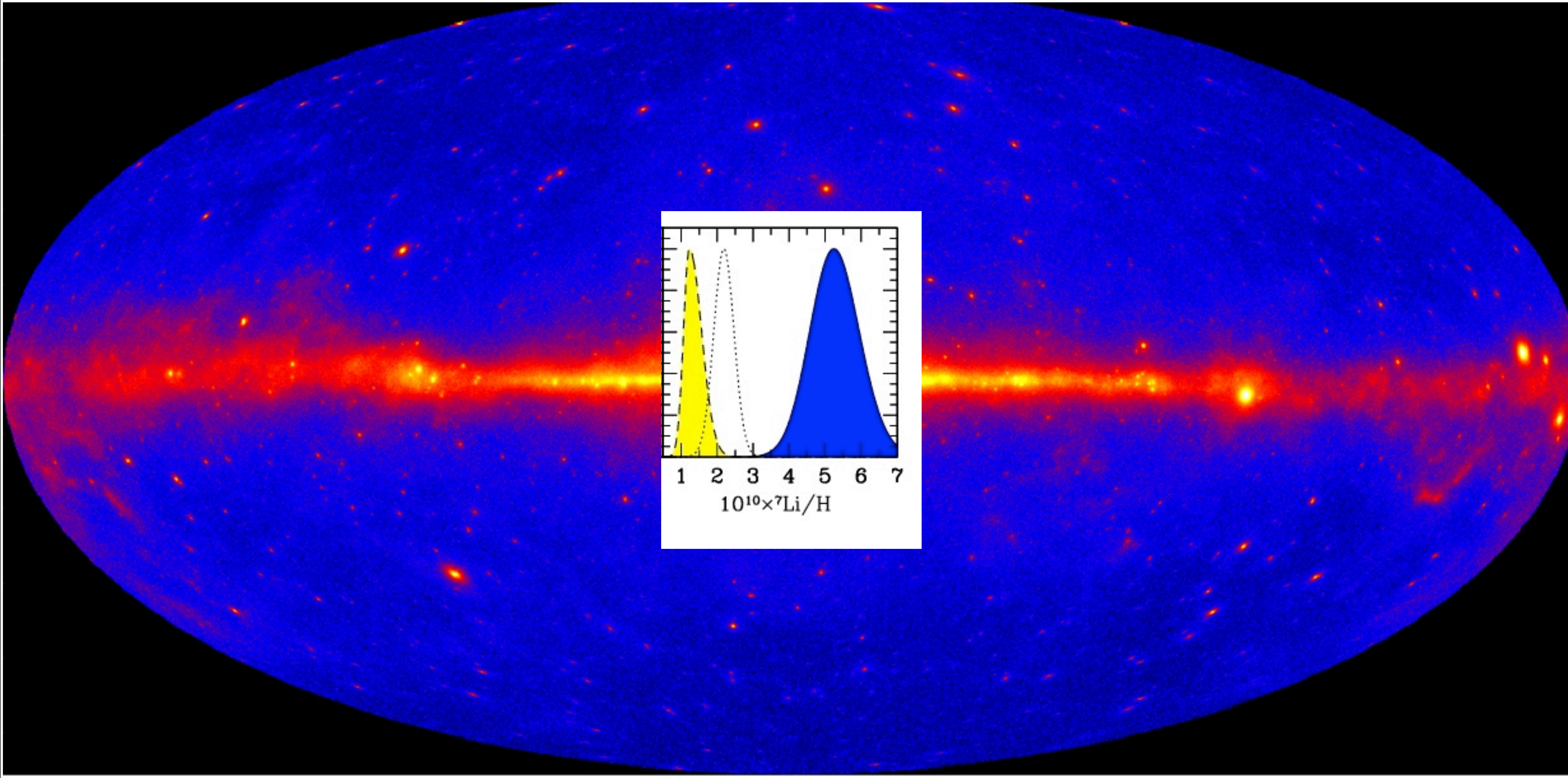
But how disentangle primordial Li?

The Fermi Era



Paleolithography:
Gamma-Ray Probes of Cosmic-Ray History

Prodanovic & BDF

Fermi

Hadronic gamma production
inevitably means ***lithium synthesis***

Observables

star-forming galaxies: new source class!

- probes global cosmic-ray/ISM interactions

gamma background: measure mean CR fluence across universe

lithium abundance: measures local CR fluence

Complementary:

use one to probe the other

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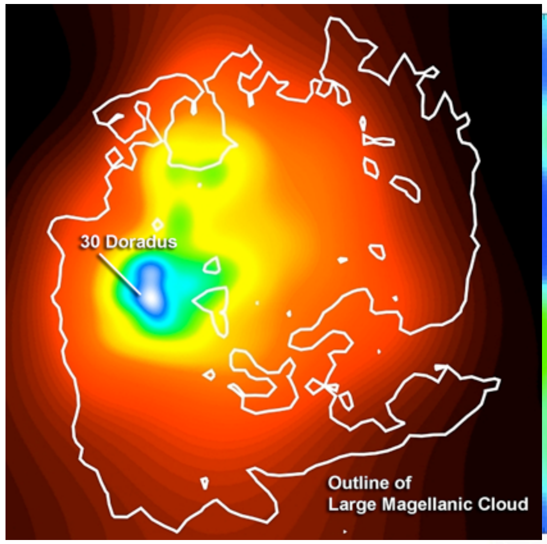
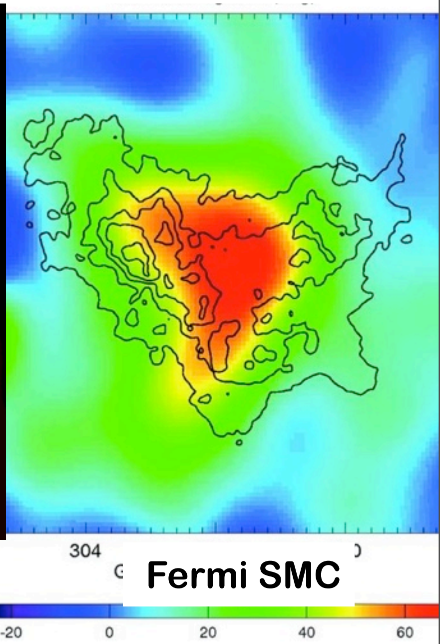


Fermi LMC



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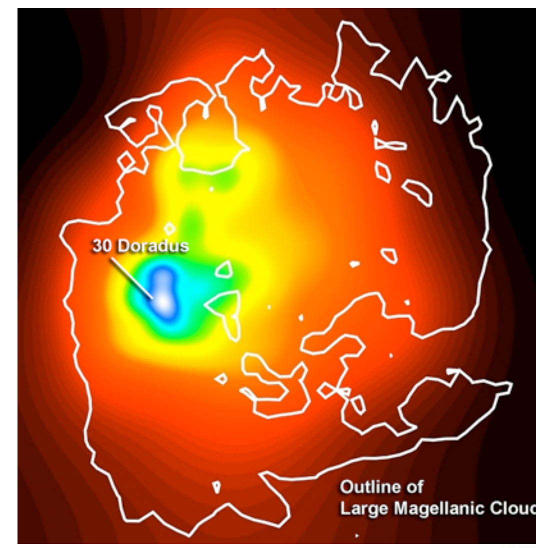

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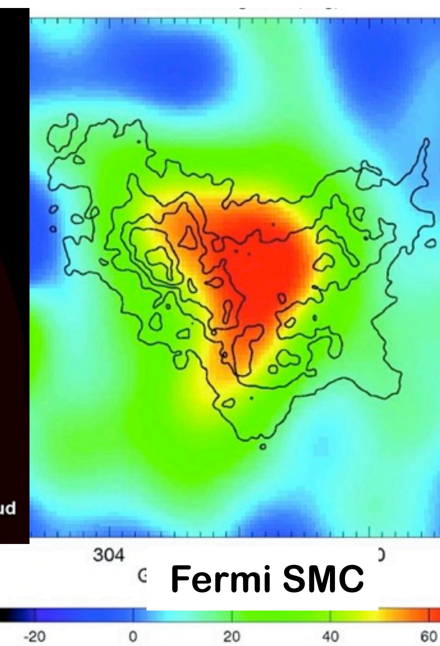

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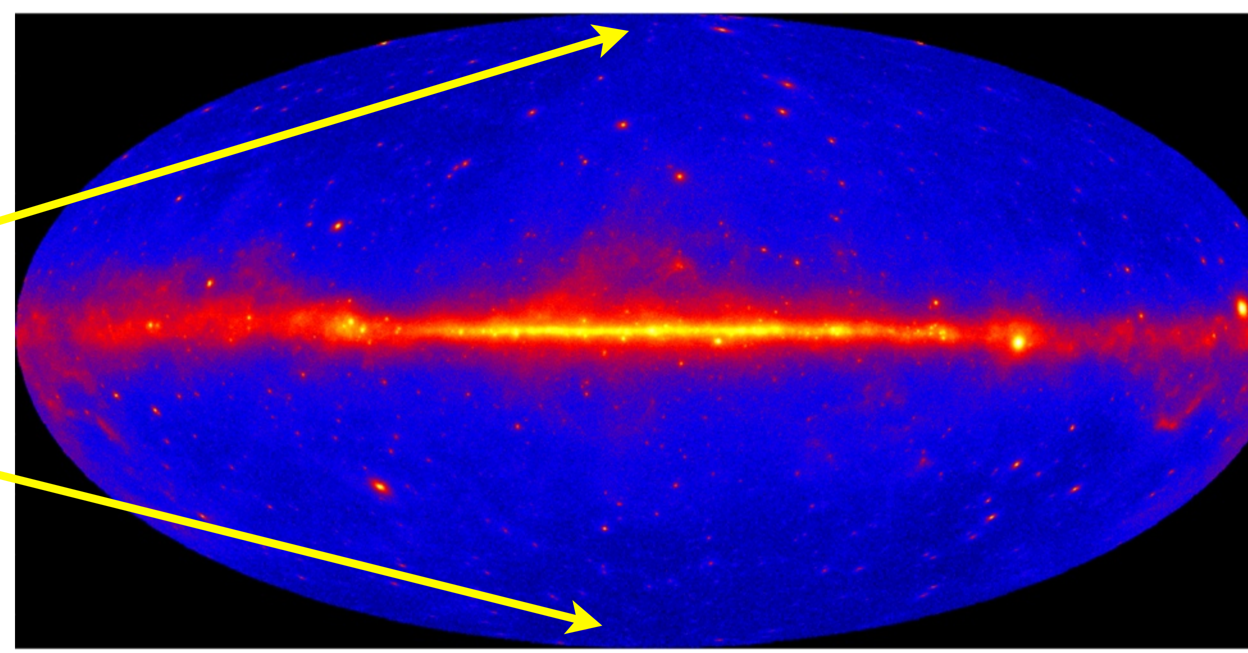

All-Sky, 2-years, >100 MeV
Fermi LAT

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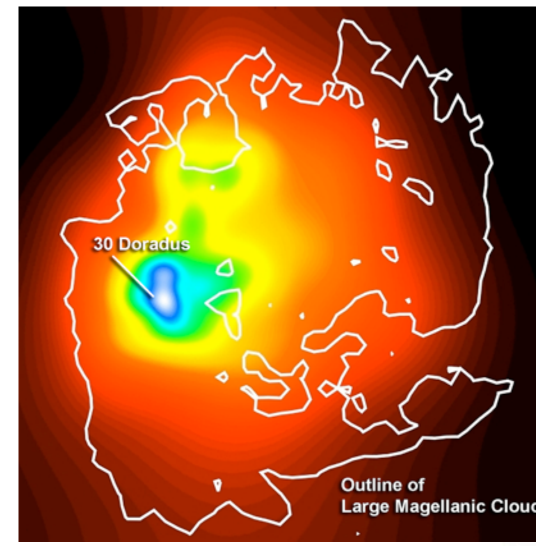

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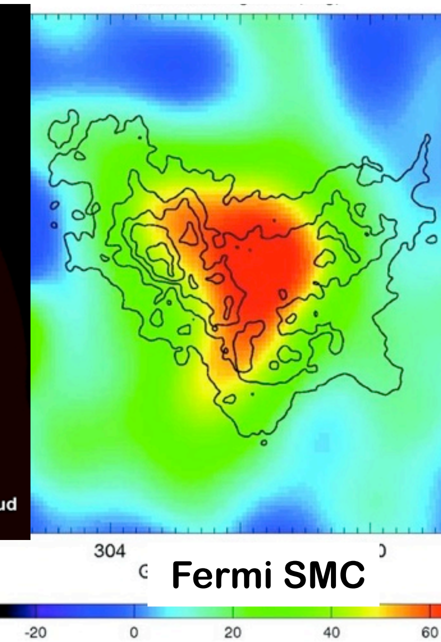

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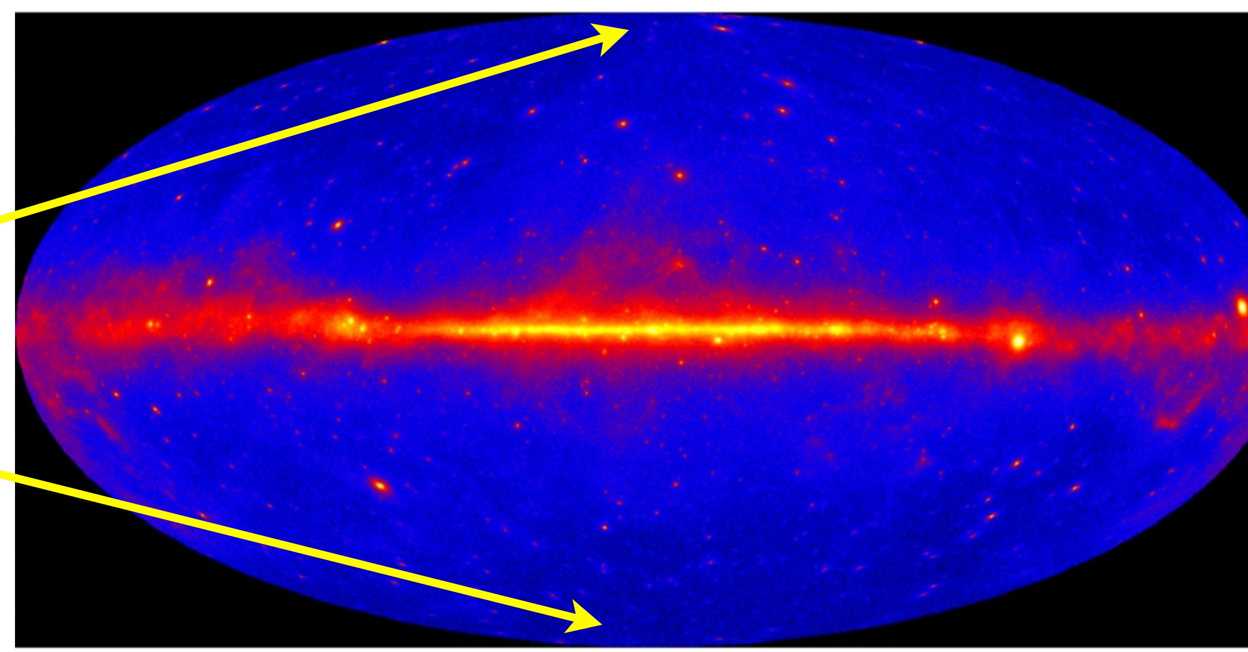

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Diffuse Gamma-Ray Background

Diffuse Gamma-Ray Background
Unresolved Normal Galaxies?

working hypothesis:
supernovae are engines of cosmic-ray acceleration

star formation → SN → cosmic rays

√ gamma signal:

$$I \sim \int_{\rm los} (\text{cosmic star form}) \times (\text{ISM targets})$$

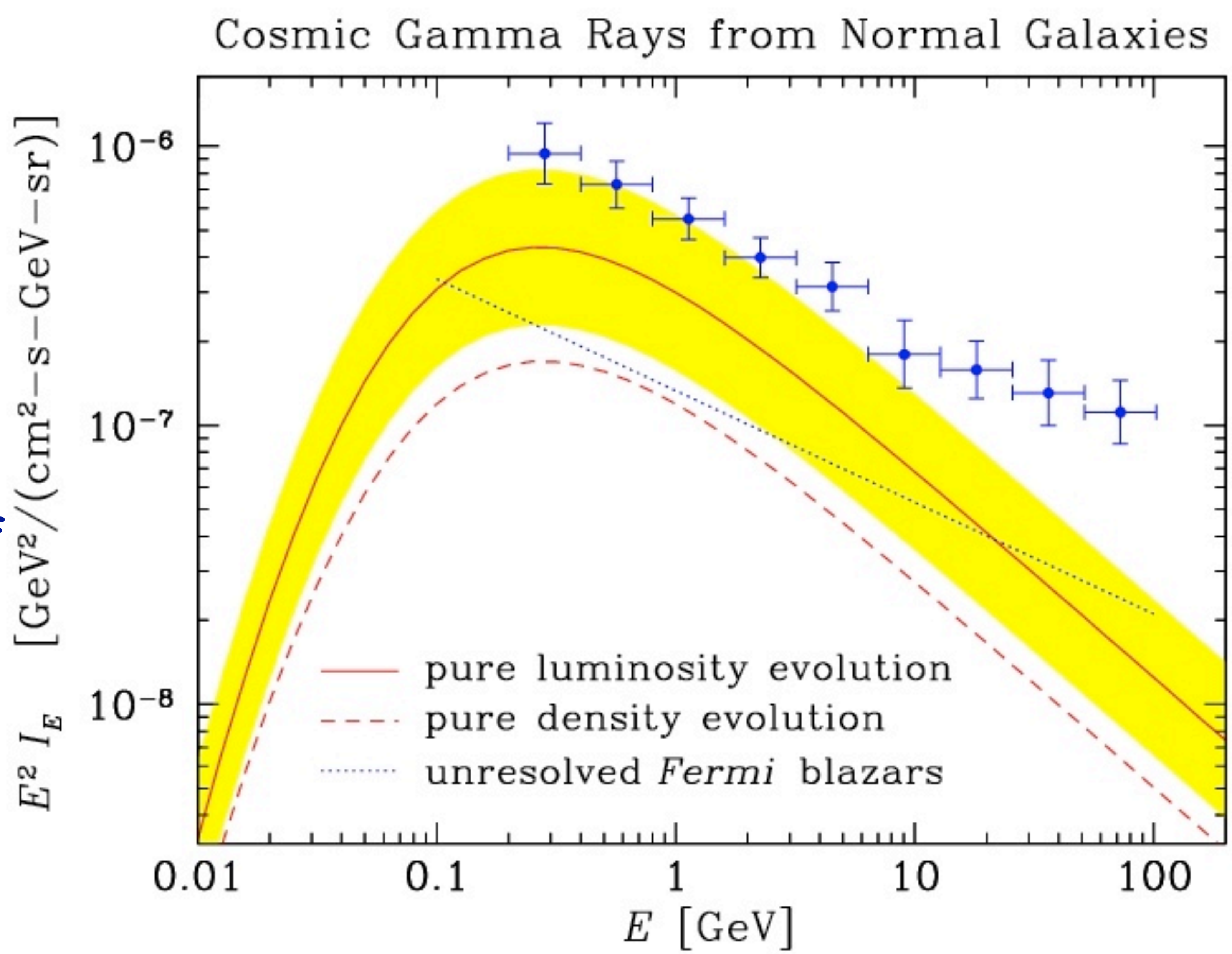
√ shape: Galactic/pionic feature redshifted

√ amplitude: substantial part of preliminary Fermi signal

√ Fits! Can saturate but does not overproduce background

√ consistent with solar lithium

√ limits cosmic-ray activity not associated with star formation (e.g., structure form)



Curves: BDF, Pavlidou, Prodanovic 2010

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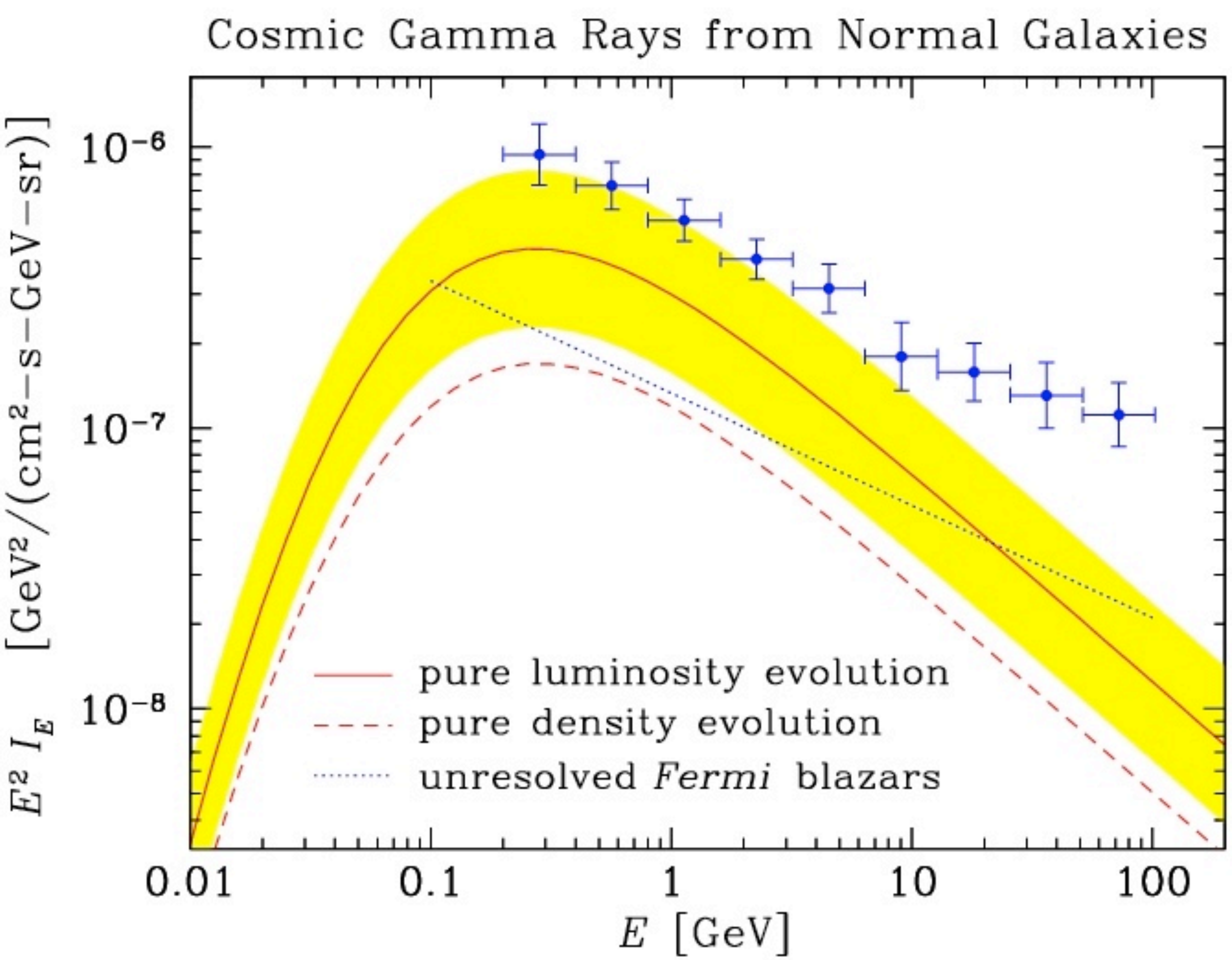

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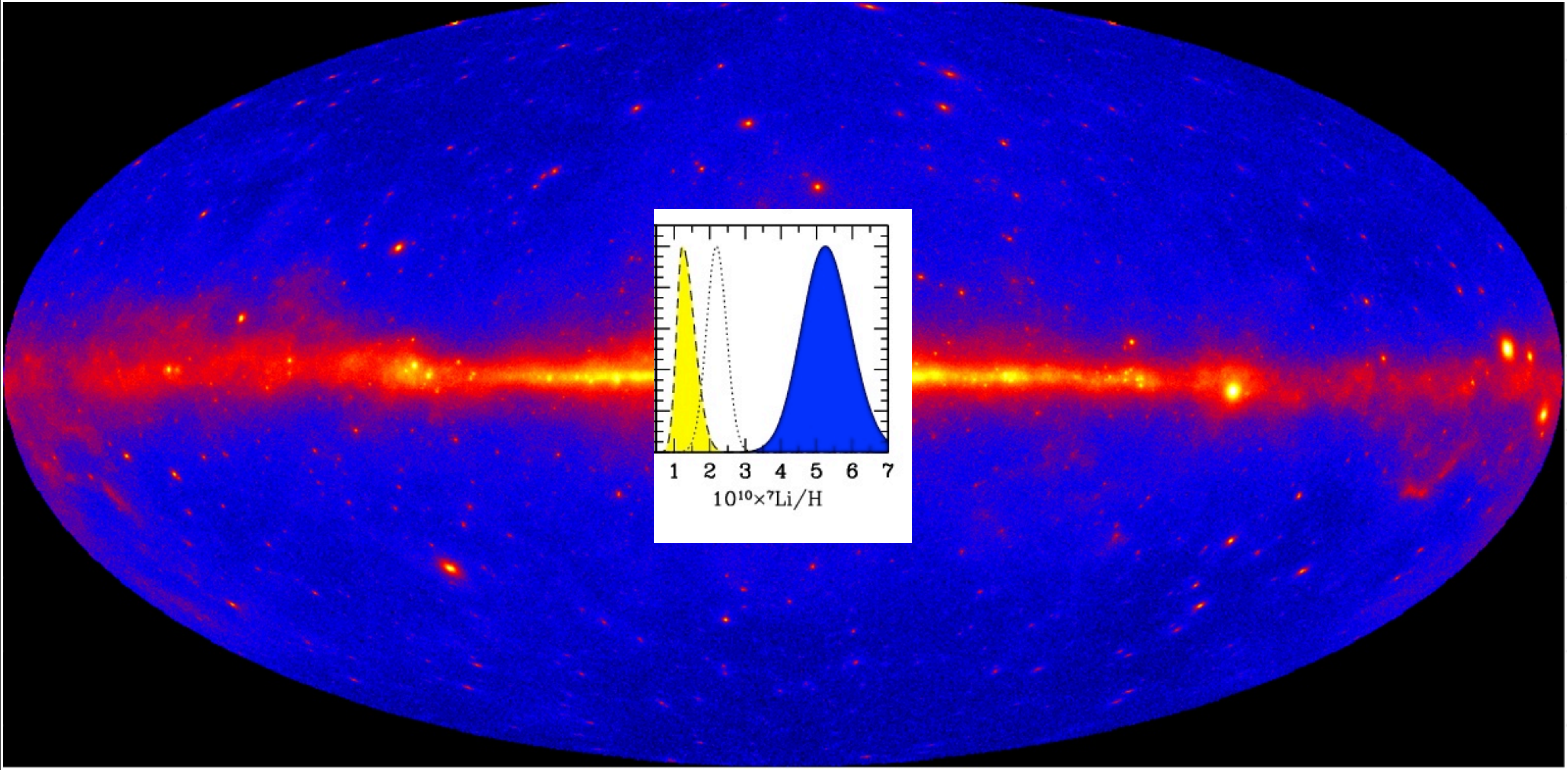
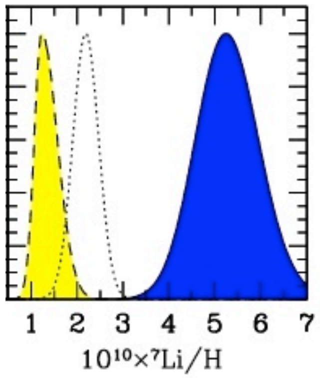
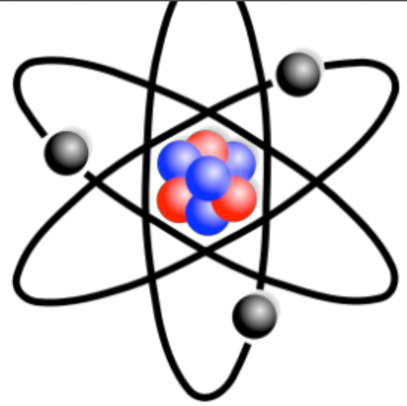
Points: Fermi (Abdo et al 2010)

Implications and Outlook



Outlook





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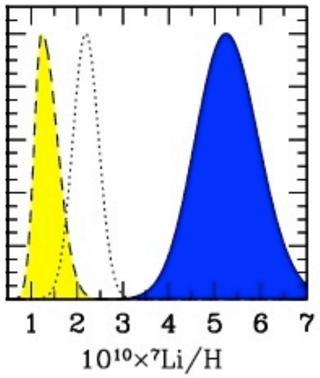

Cosmic-ray interactions with diffuse gas unavoidably produce lithium

- only conventional source of ^{6}Li, ^{9}Be, ^{10}B
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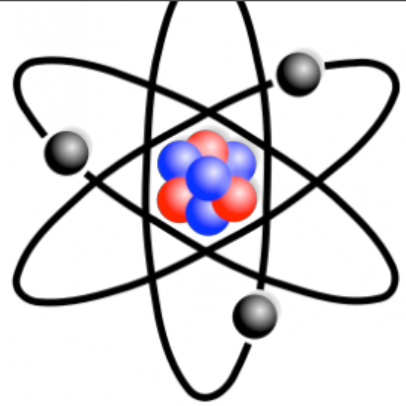
- nucleosynthesis of last resort



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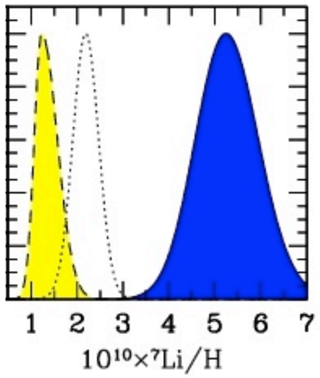

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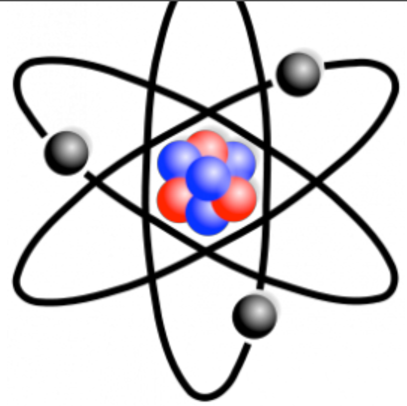

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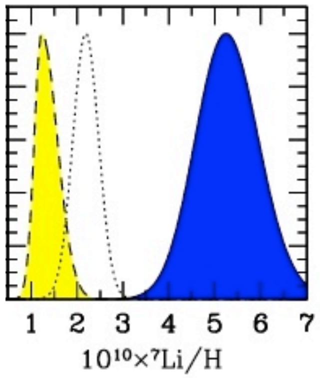

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  but also makes problem more pressing and interesting

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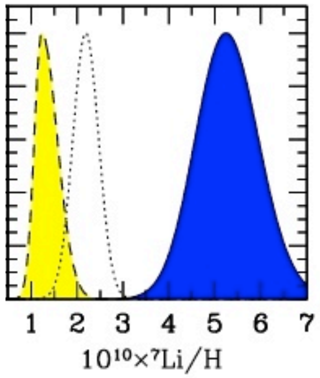

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The Fermi Era

- Gamma-rays produced by same cosmic-ray interactions
- probe Galactic and pre-Galactic synthesis

Thanks to the Organizers!

Vive le Lithium!