

EGU 2026 - Vienna
May 8, 2026



Acceleration of He and Heavy Ions at Collisionless Shocks

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University of Chicago

with L. Orusa (Columbia), M. Cernetic, C. Haggerty (Hawai'i) and B. Ostler



Shock Acceleration: From Helio to Cosmological Scales



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Earth's bow shock



HELIOSPHERIC



Solar flares and helio shocks

Shock Acceleration: From Helio to Cosmological Scales

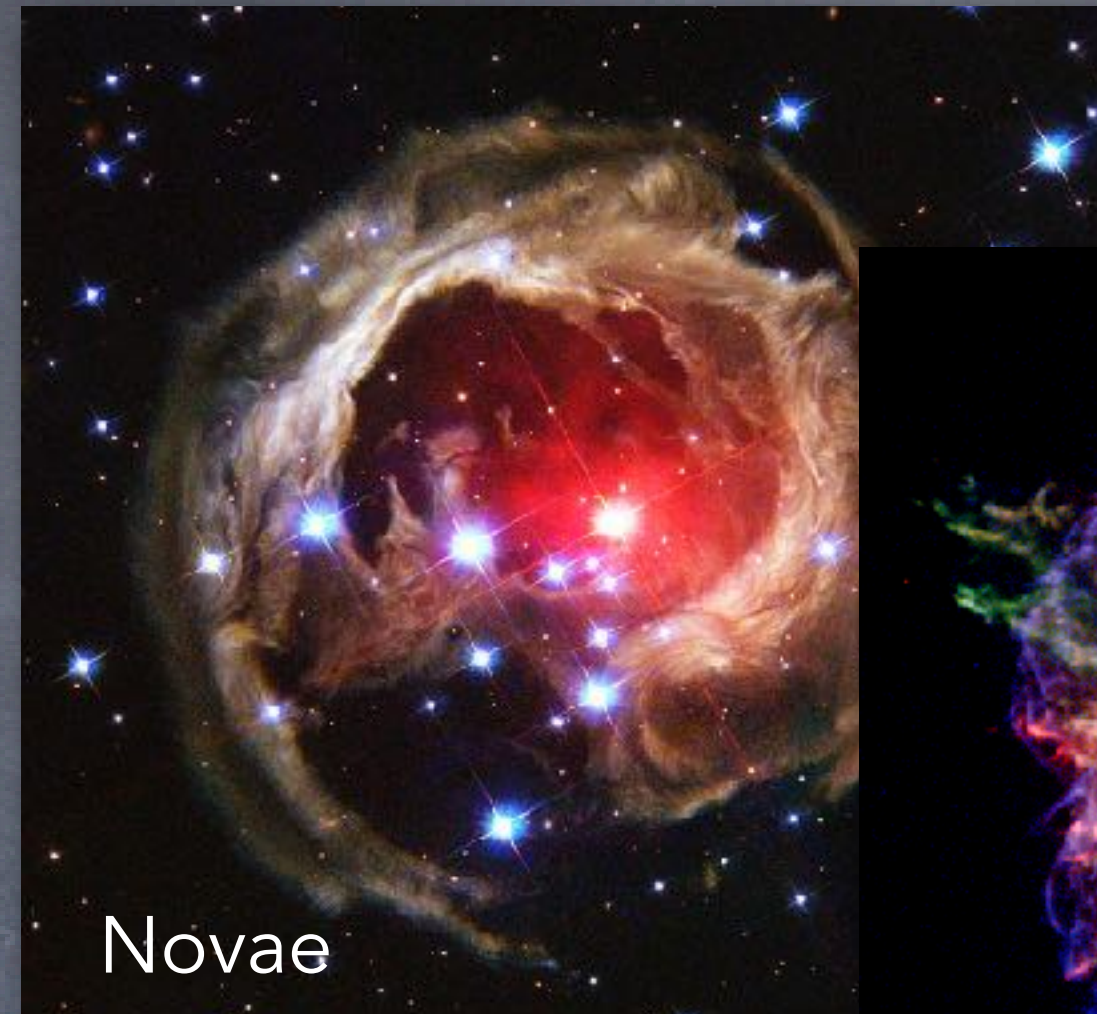


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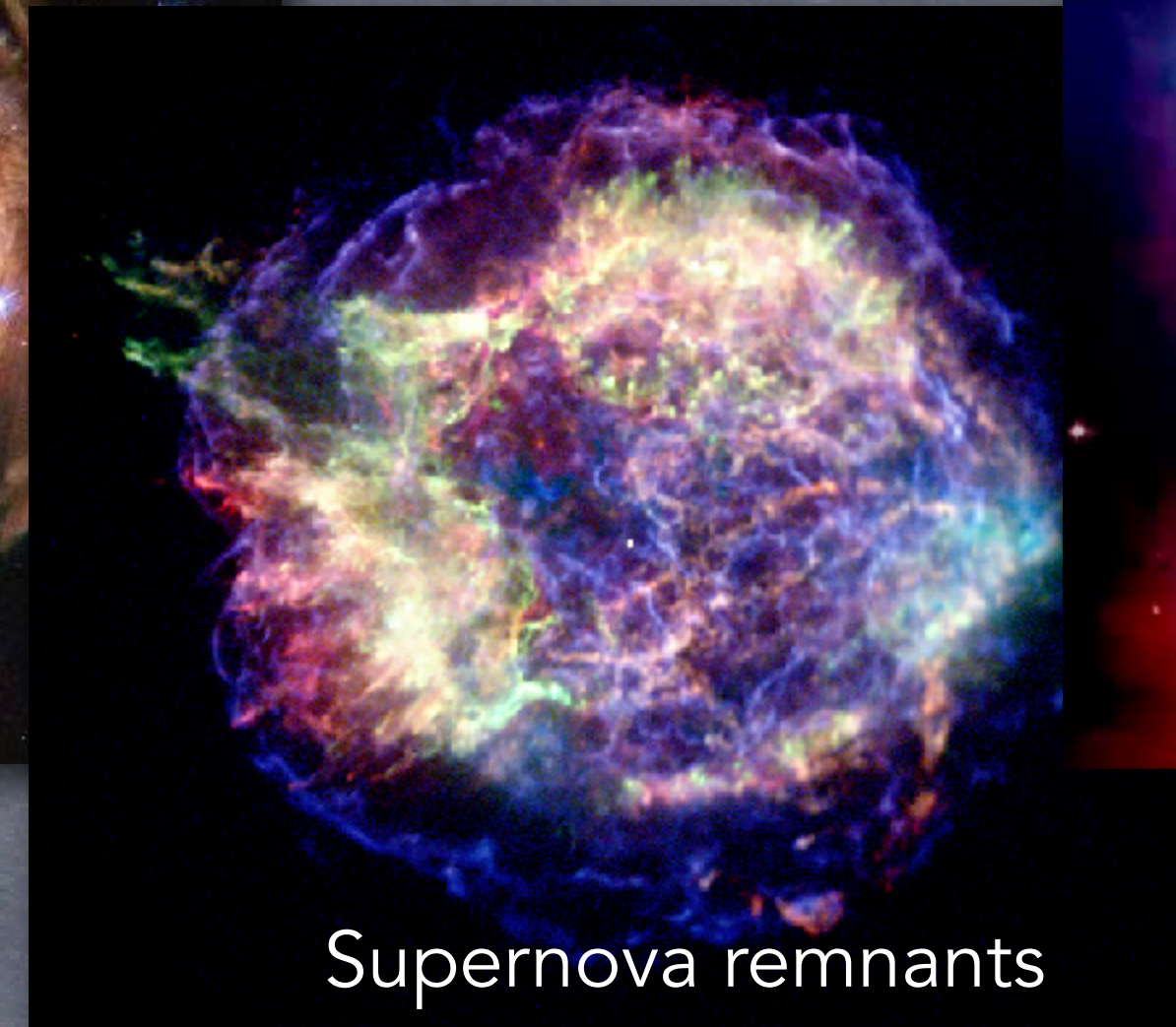


Solar flares and helio shocks

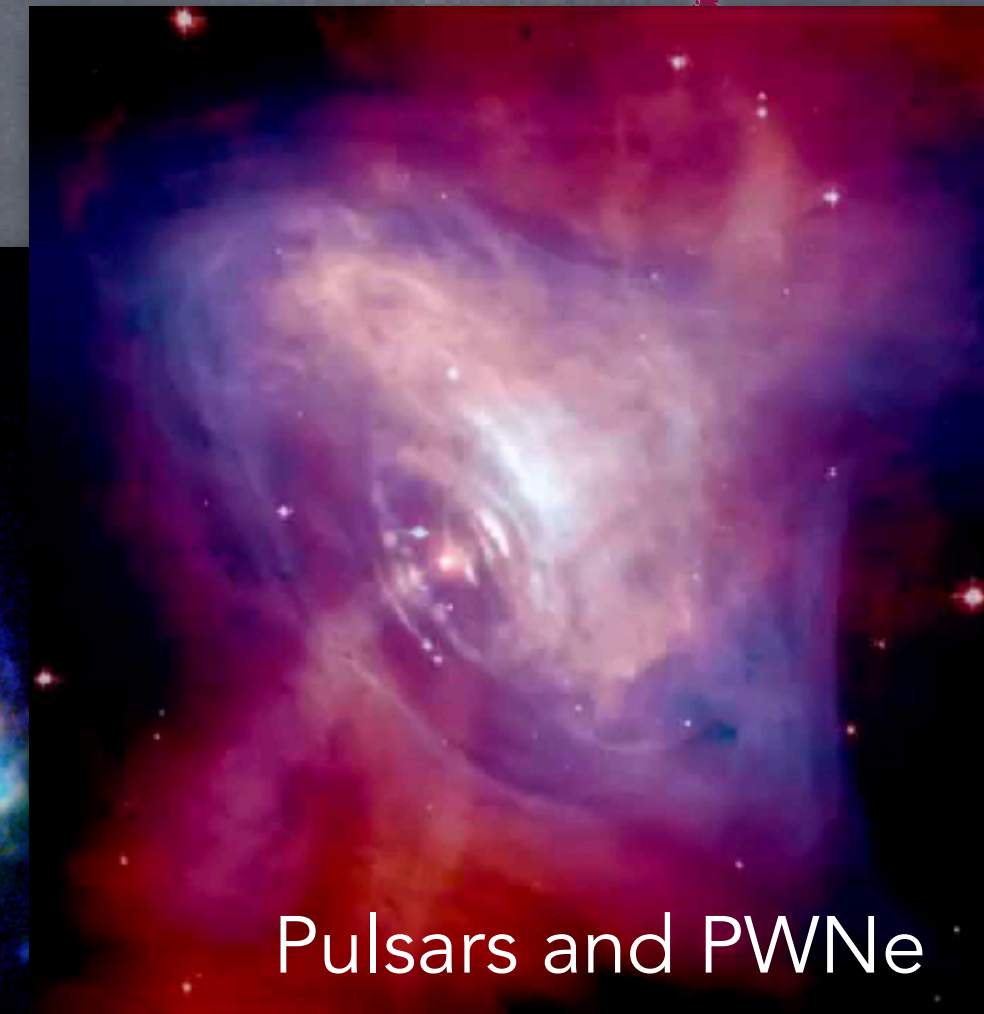


Novae

GALACTIC



Supernova remnants



Pulsars and PWNe



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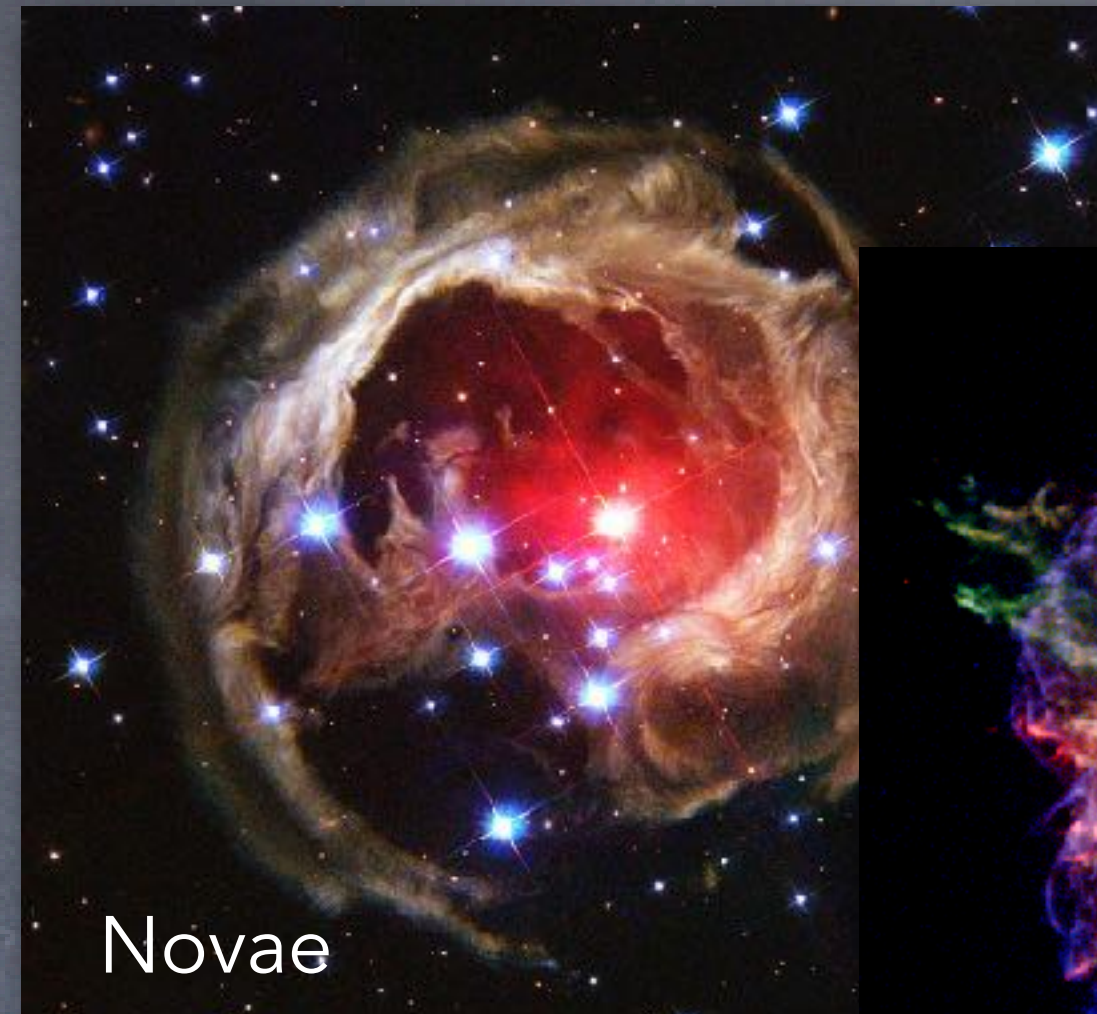


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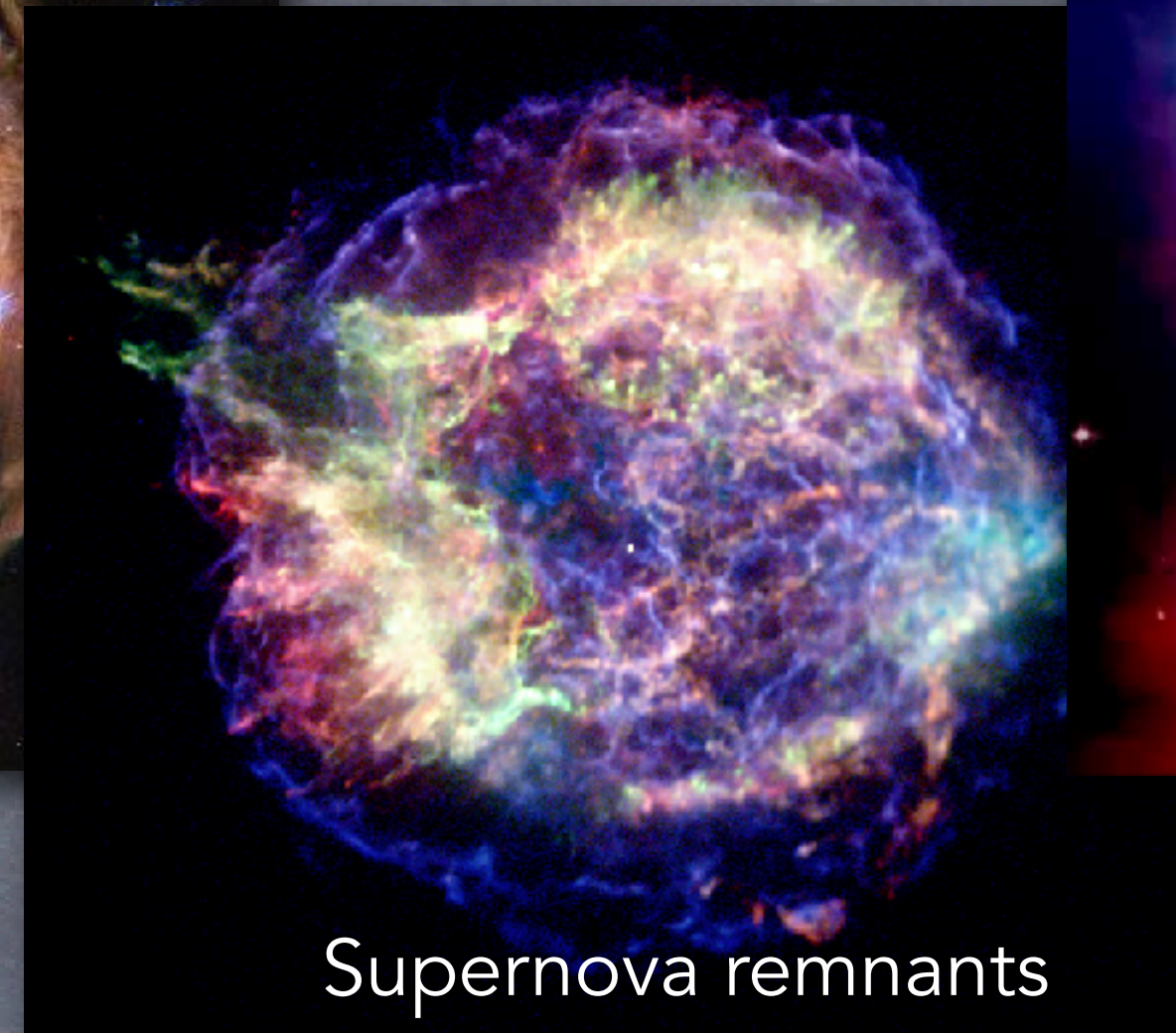


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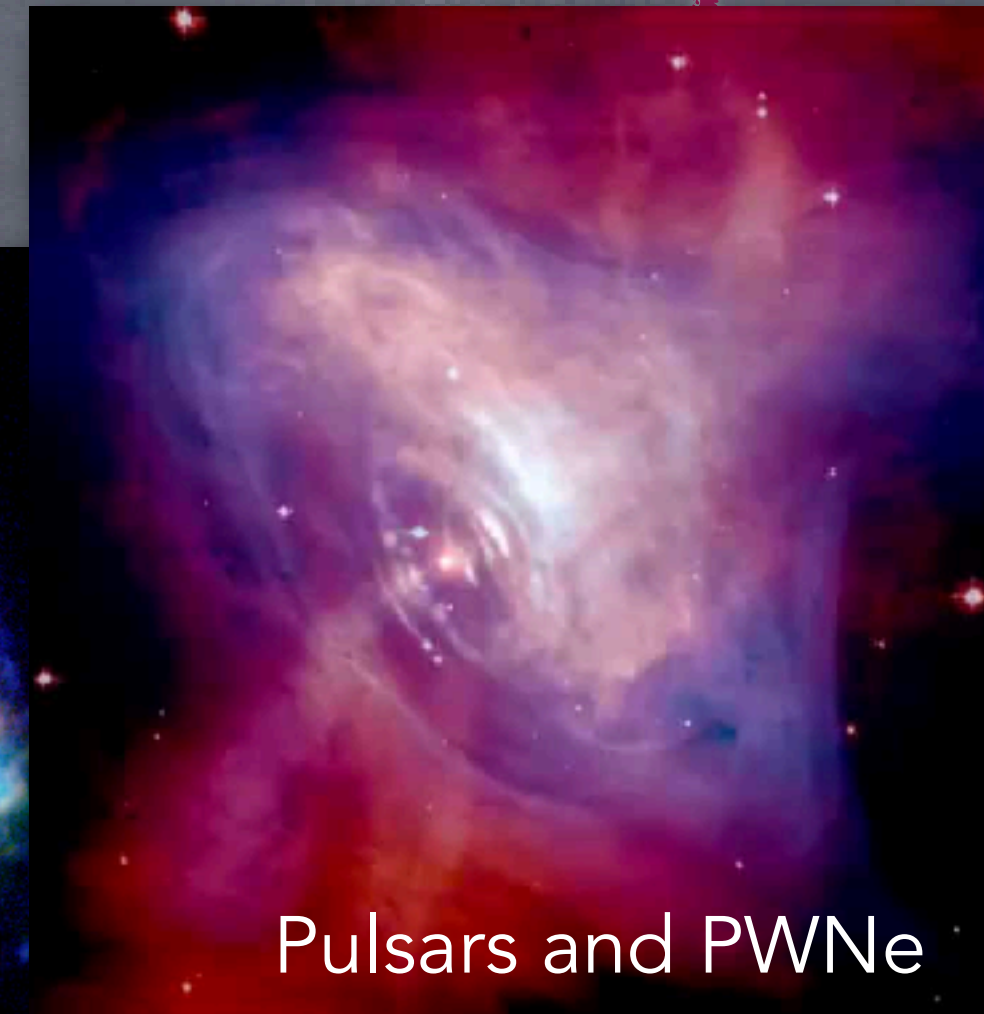


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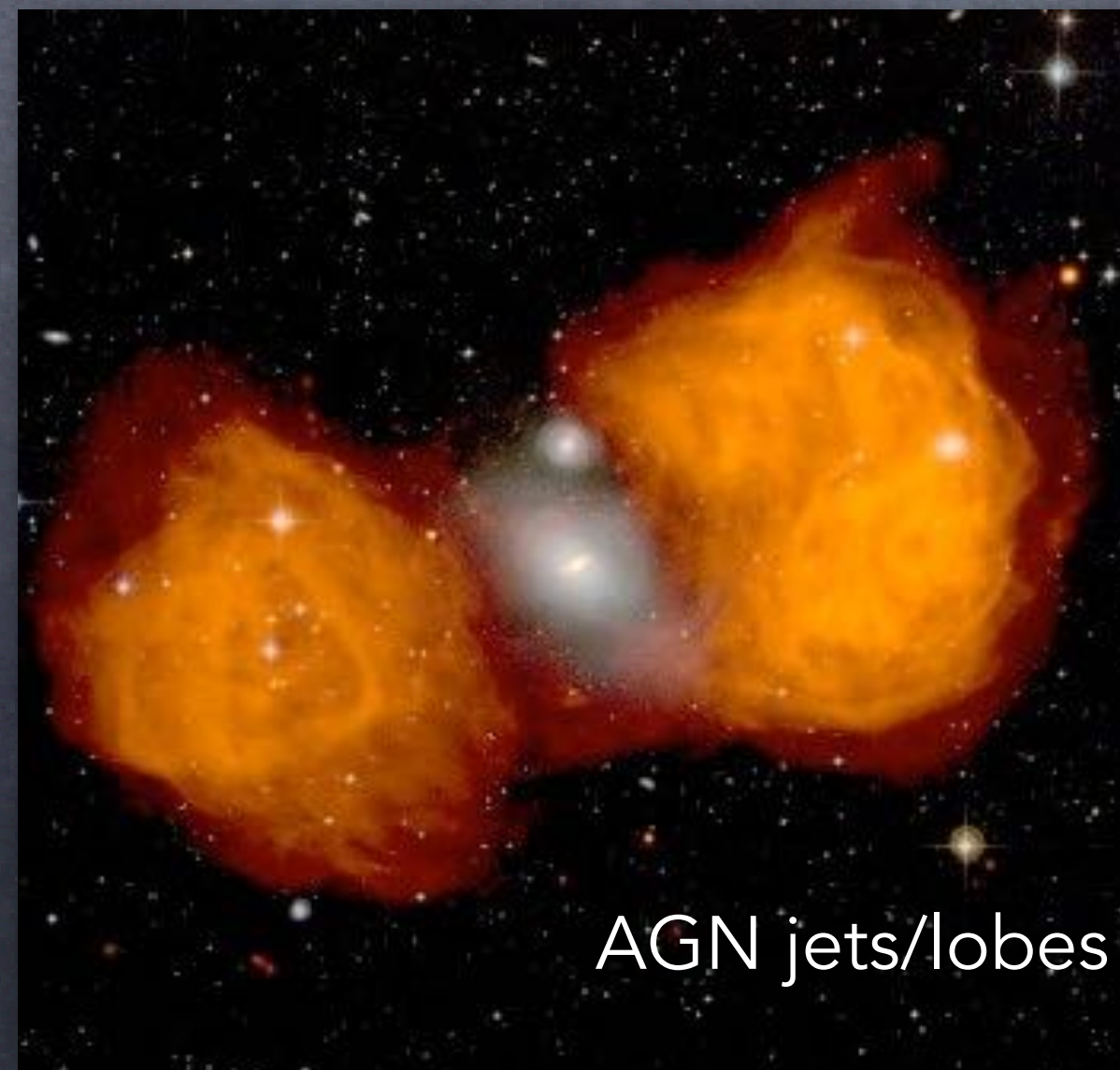
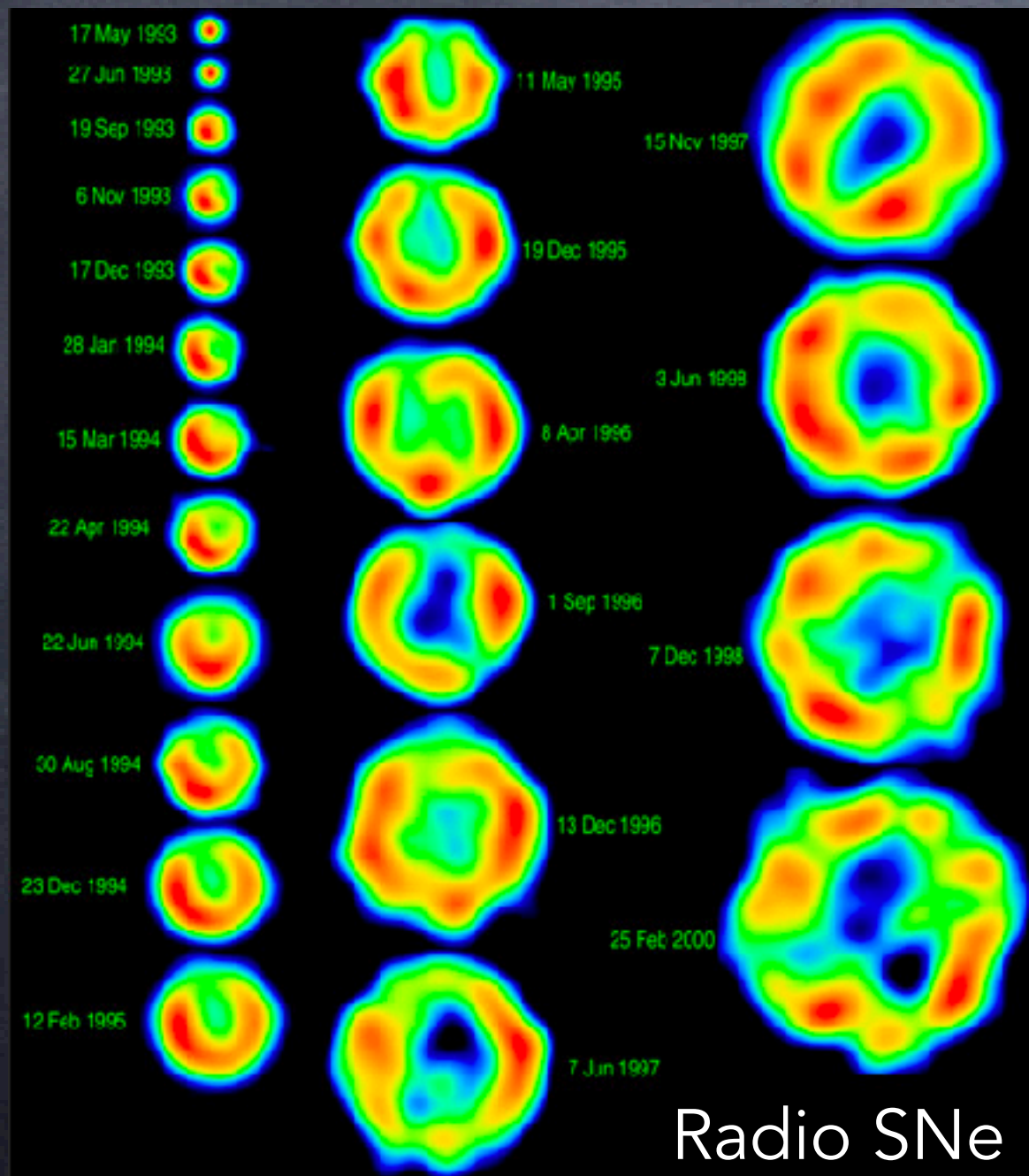


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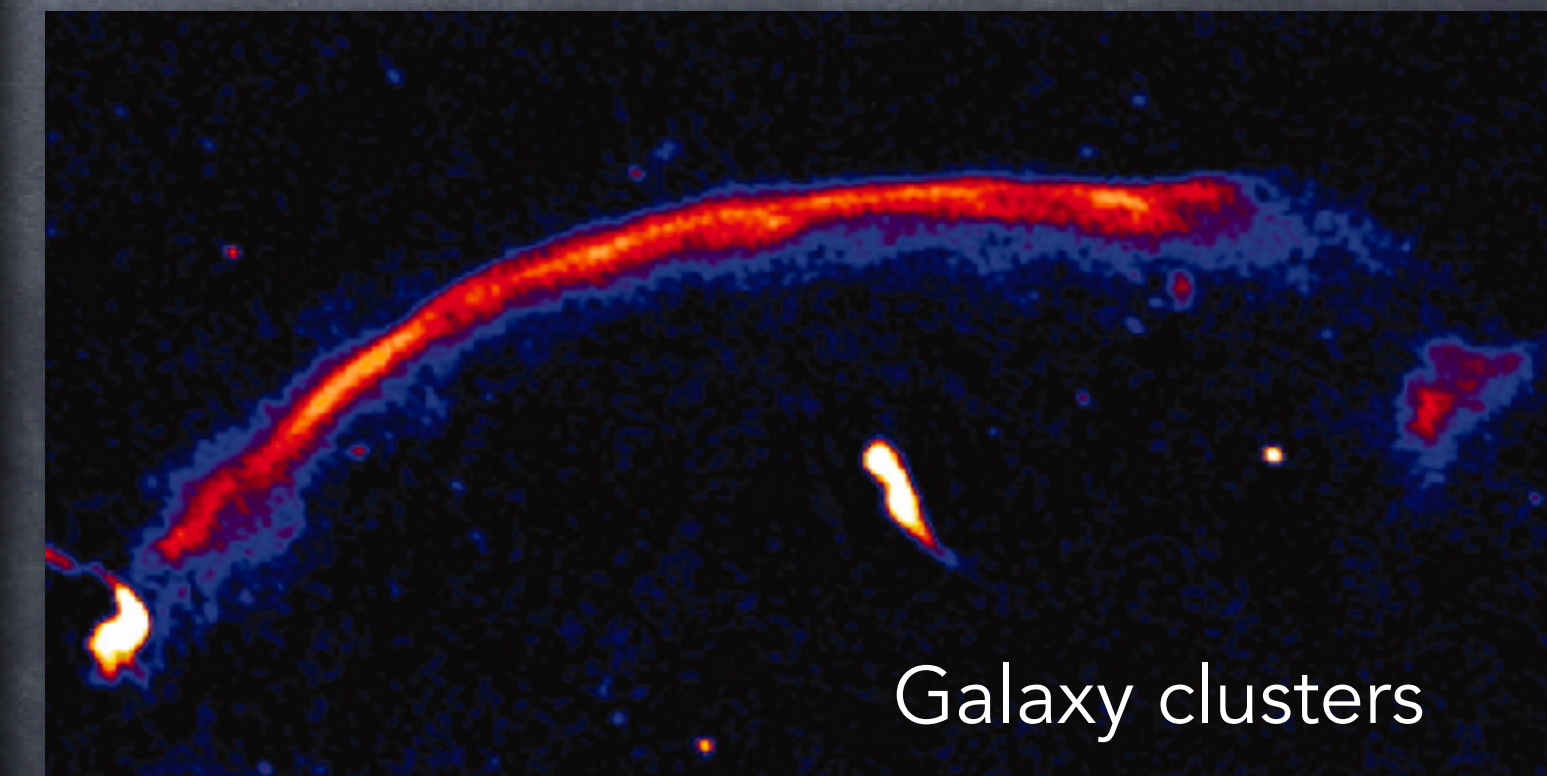
EXTRA-GALACTIC



AGN jets/lobes



AGN Winds



Galaxy clusters



Shock Acceleration: From Helio to Cosmological Scales



In situ

Earth's bow shock

HELIOSPHERIC

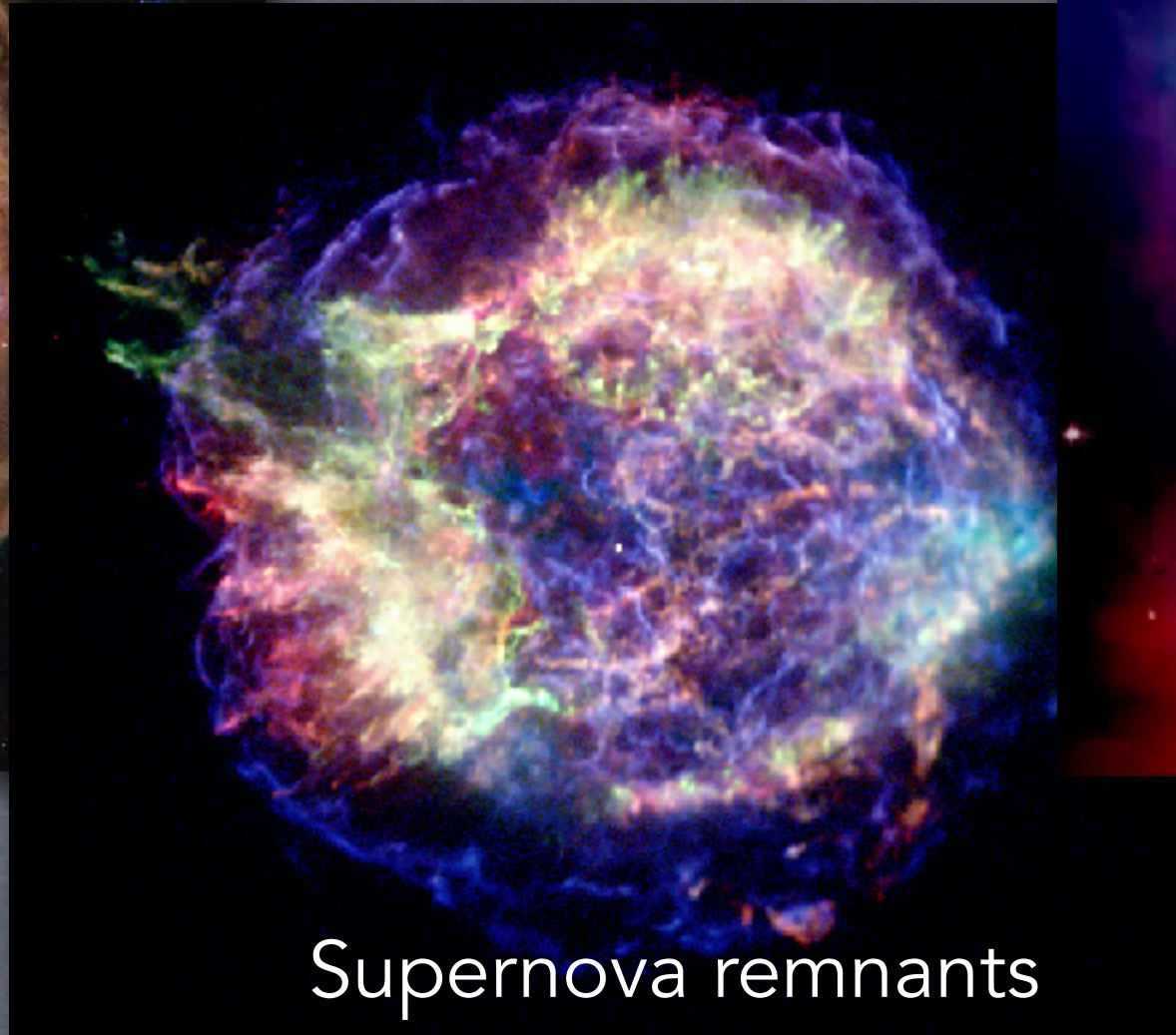


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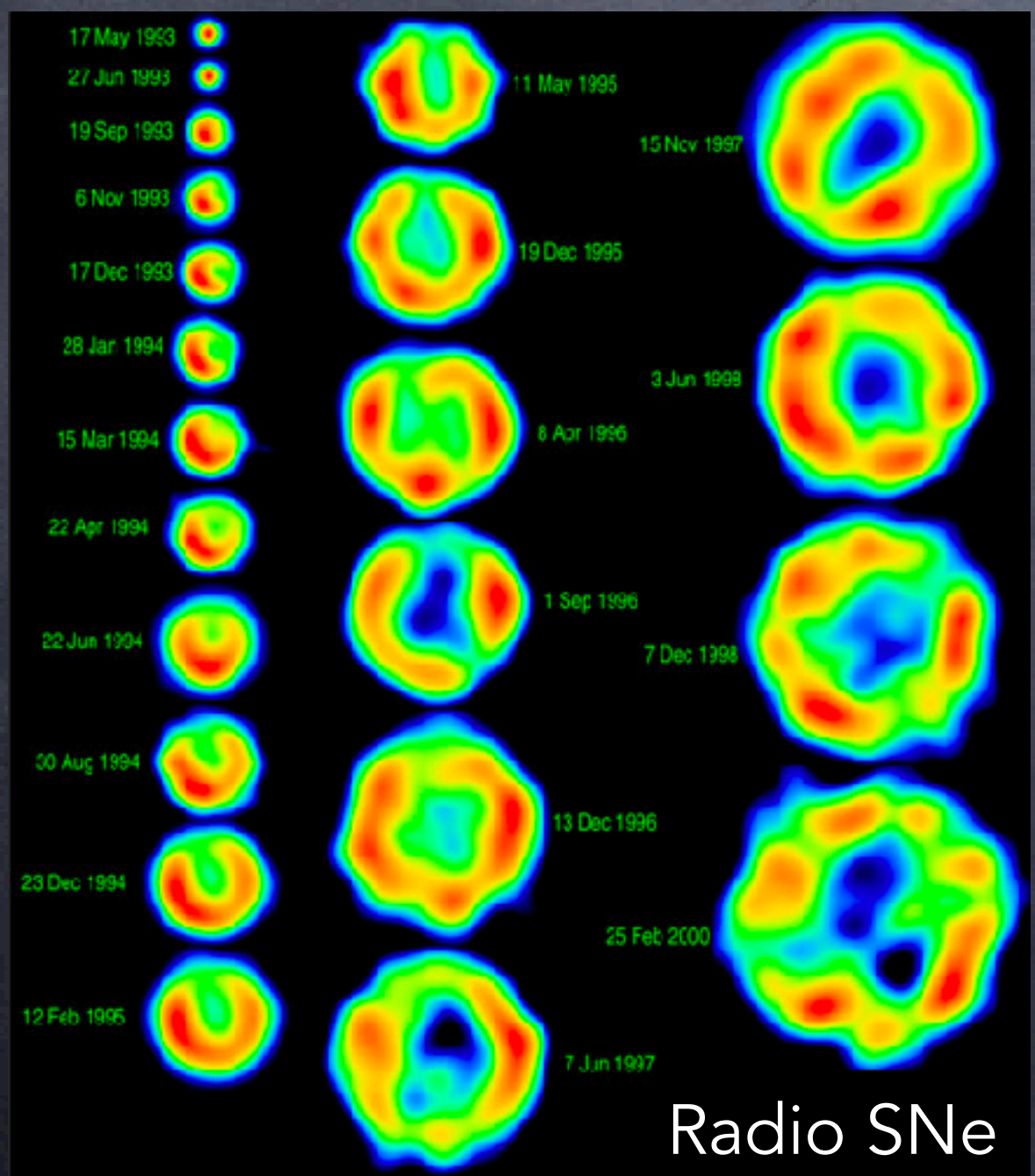


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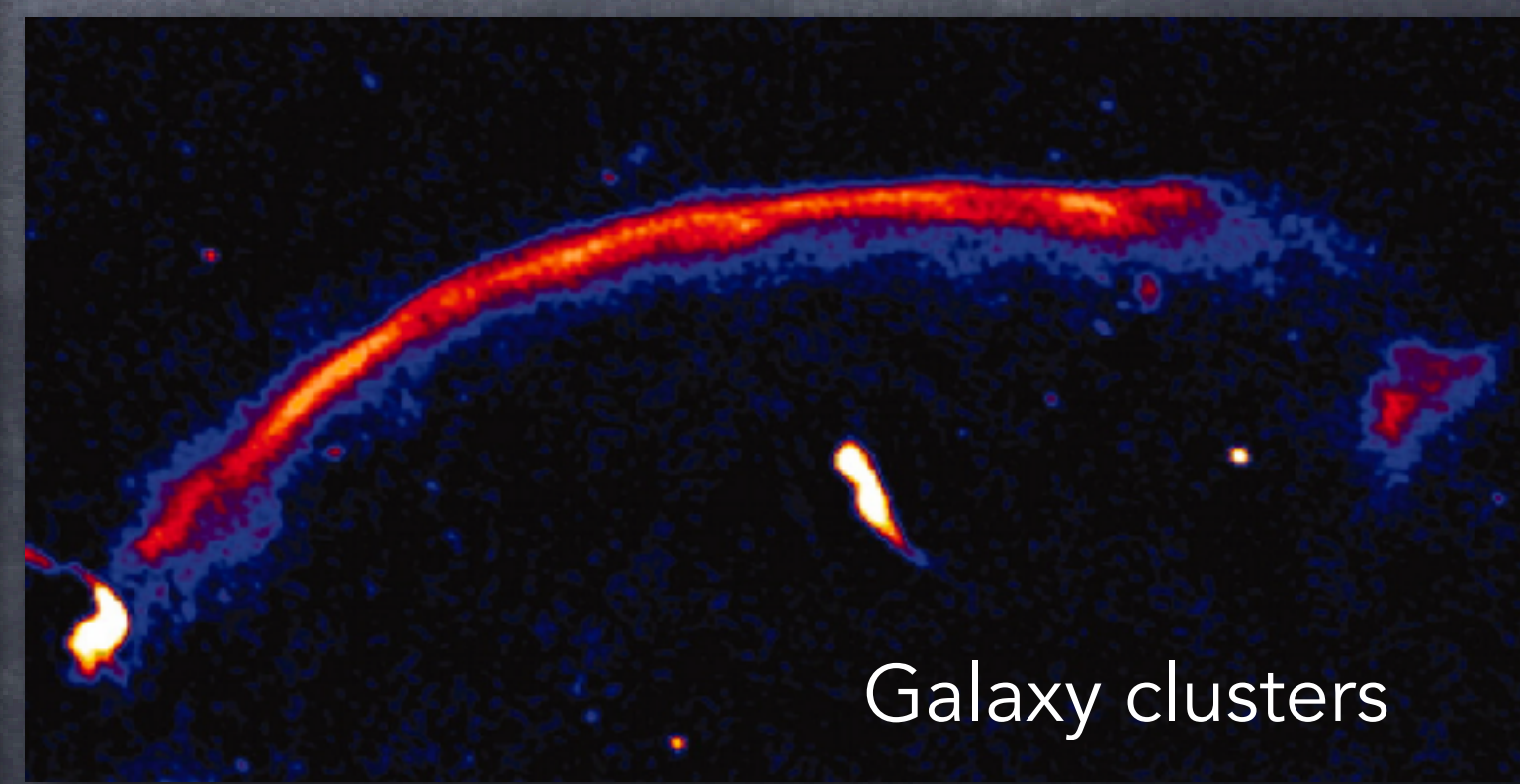
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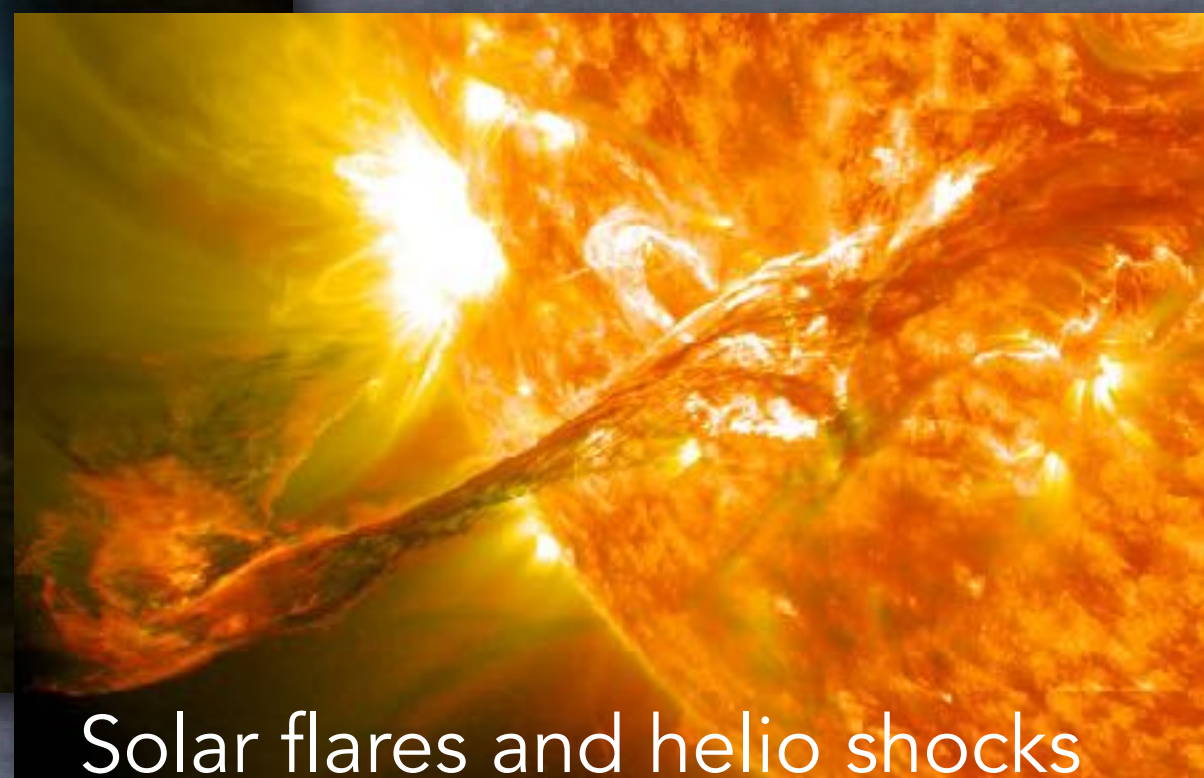
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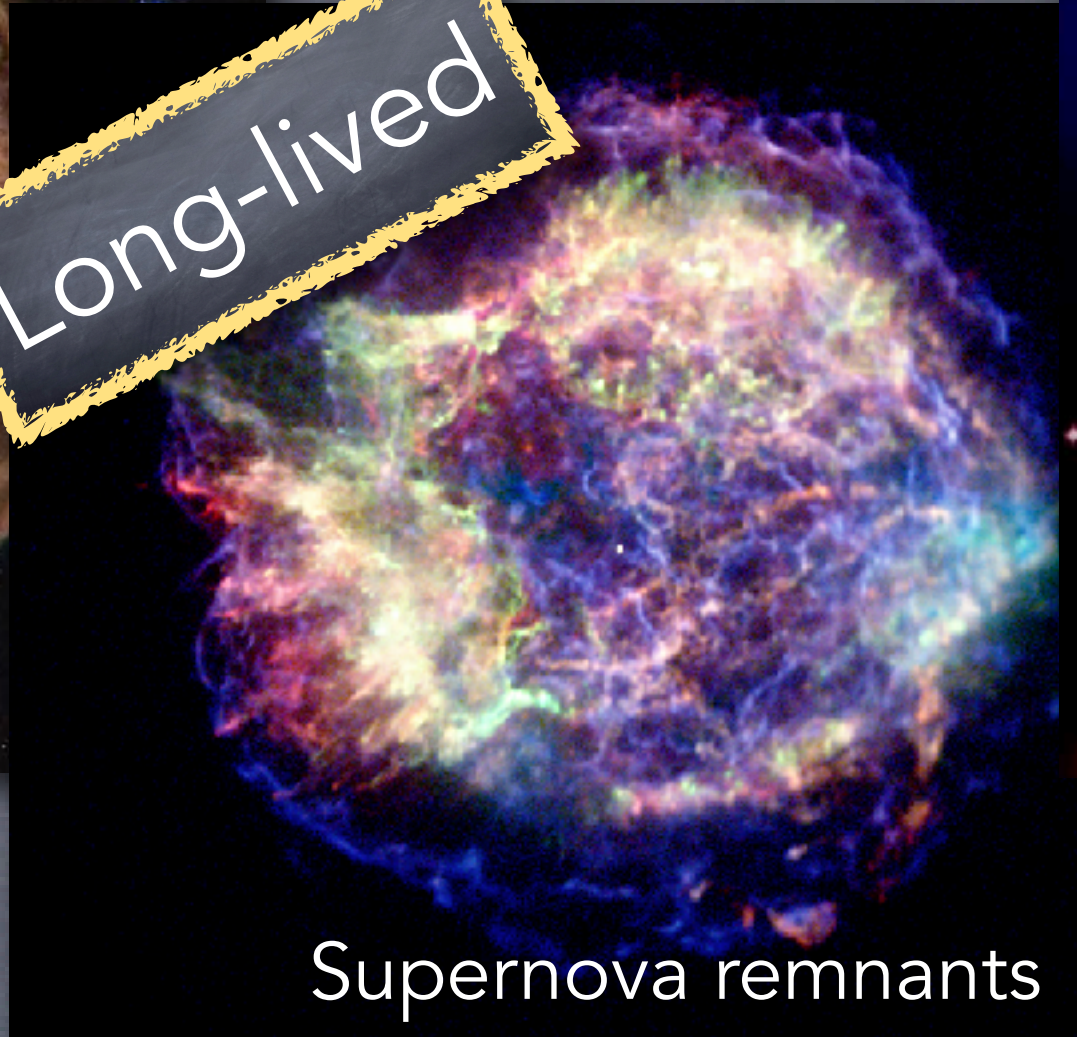
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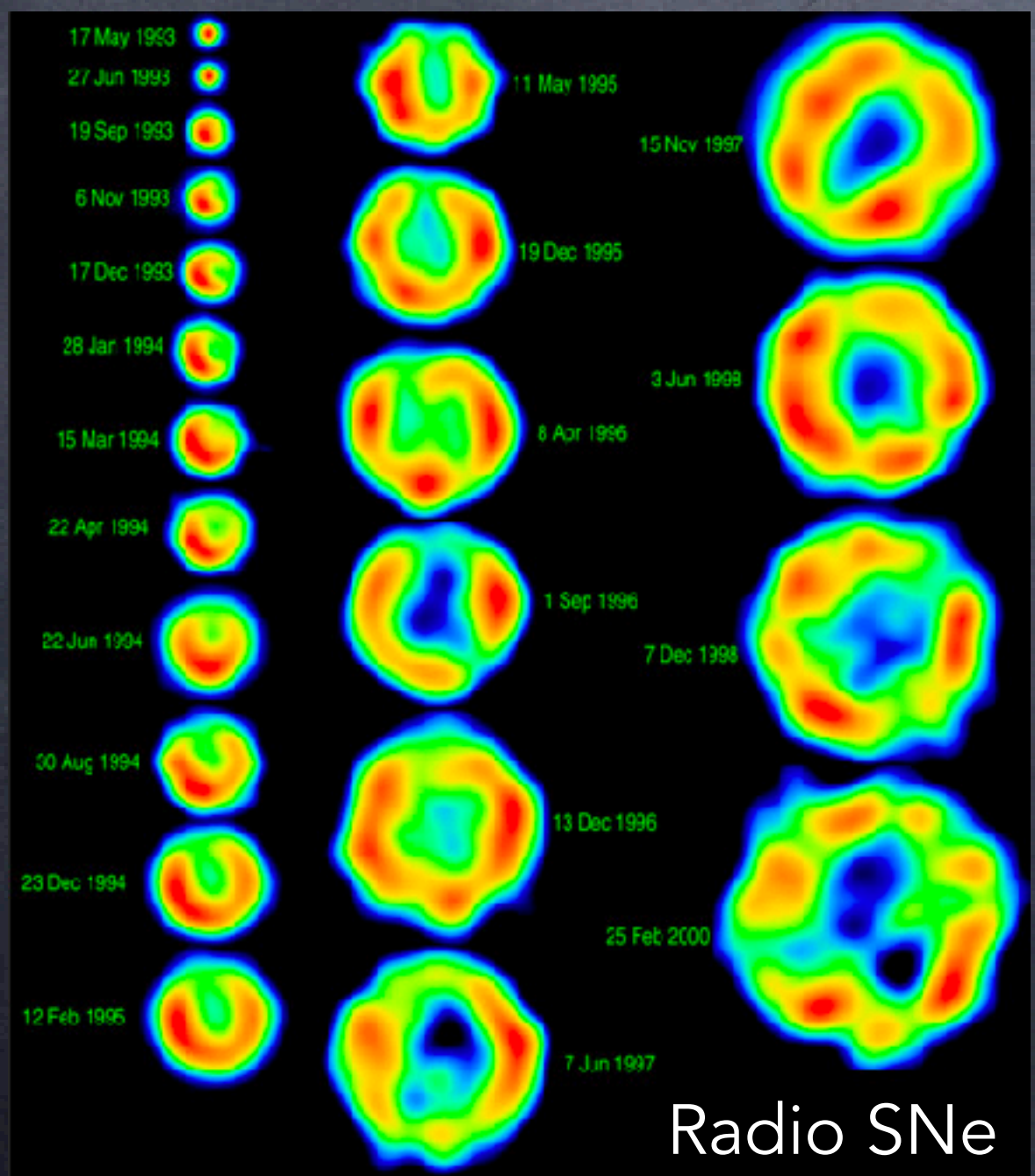
Long-lived



Supernova remnants

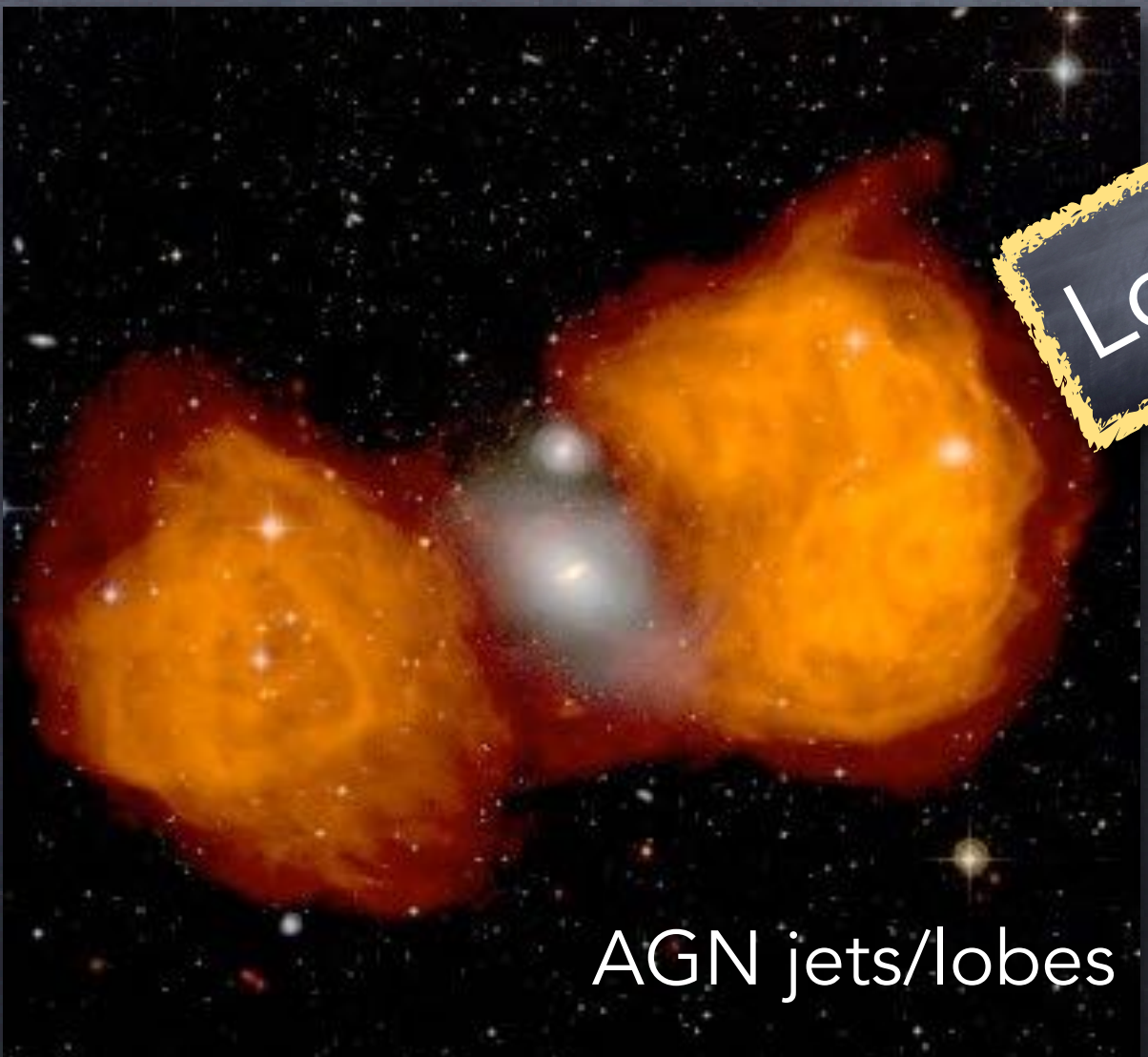


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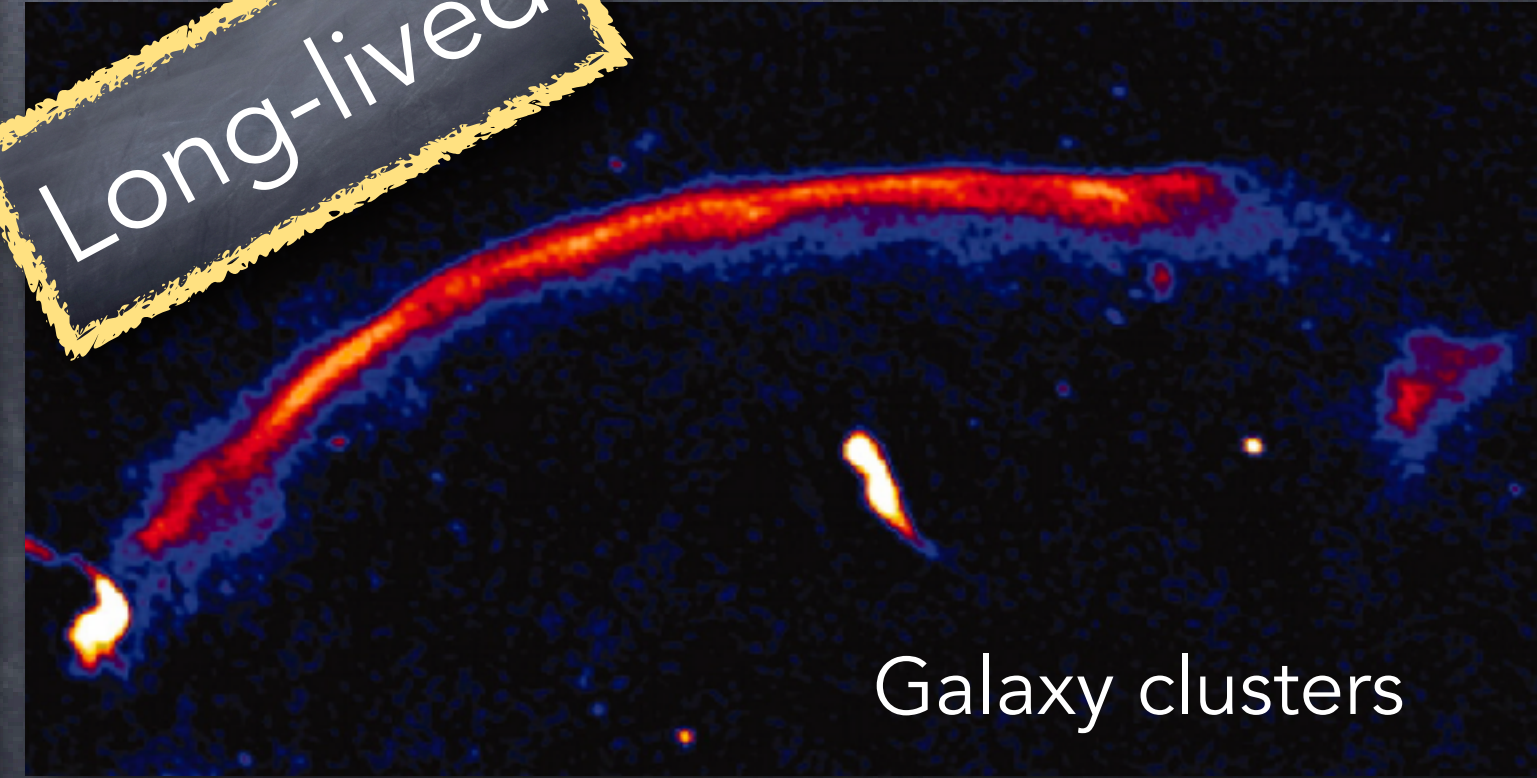


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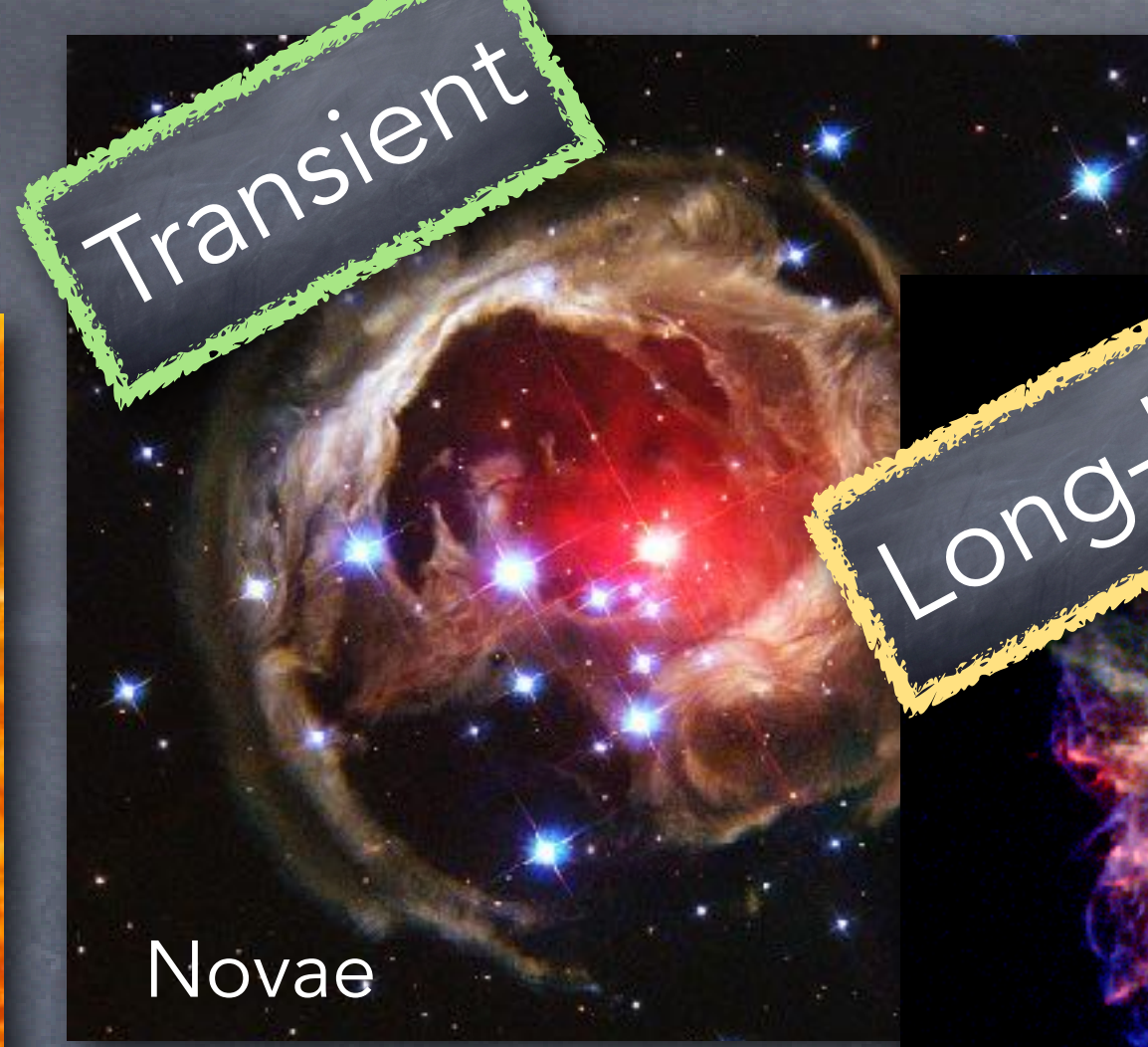
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Transient

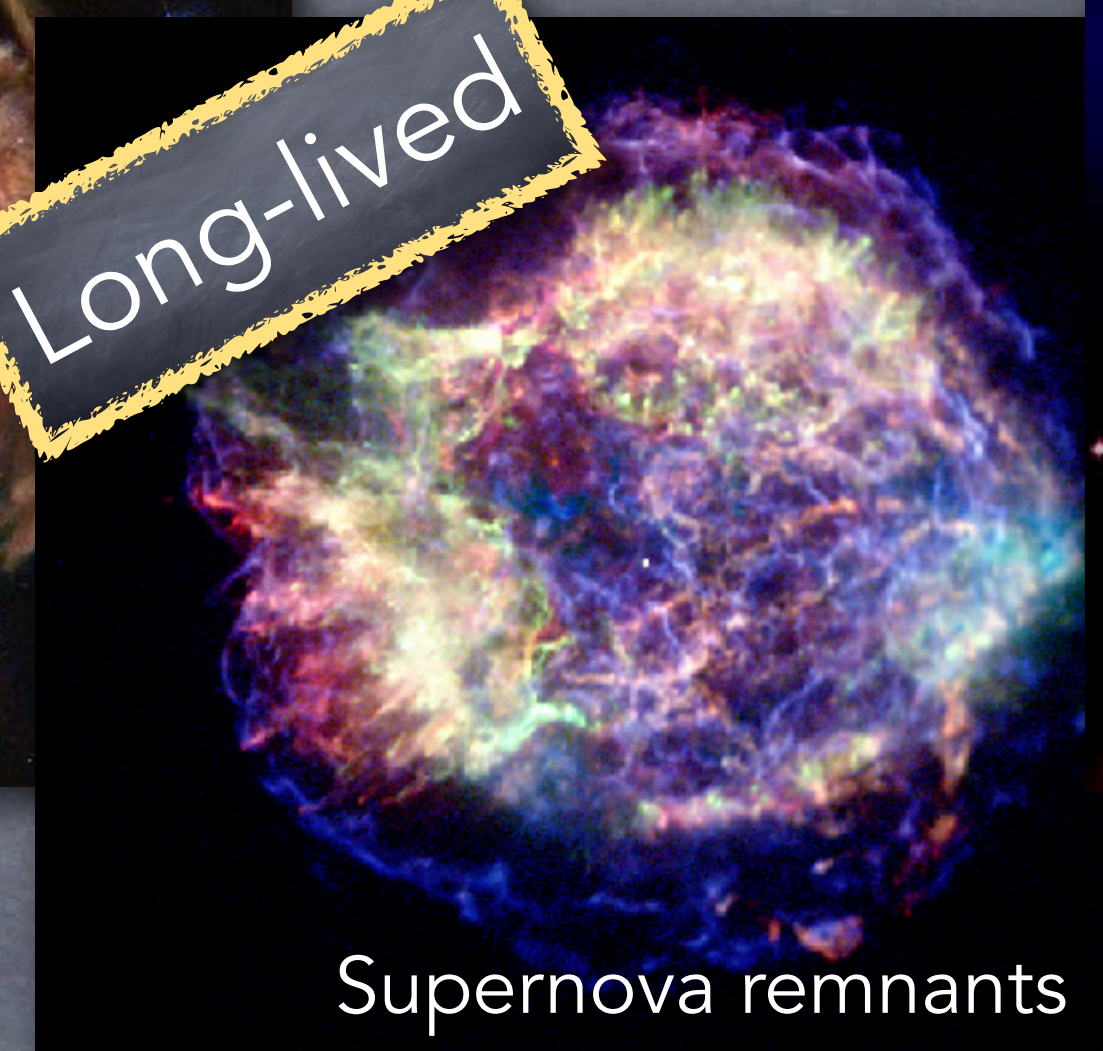
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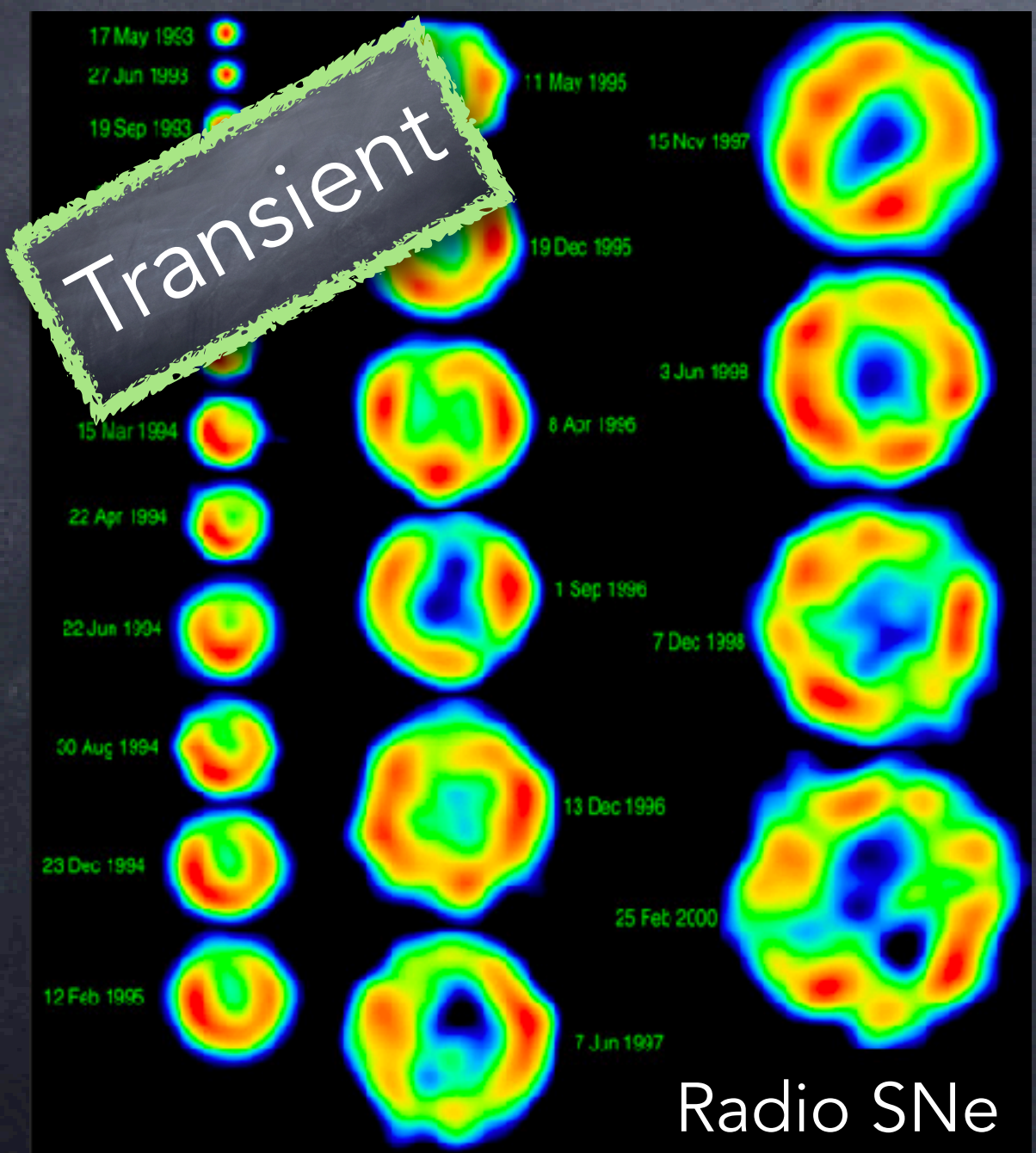


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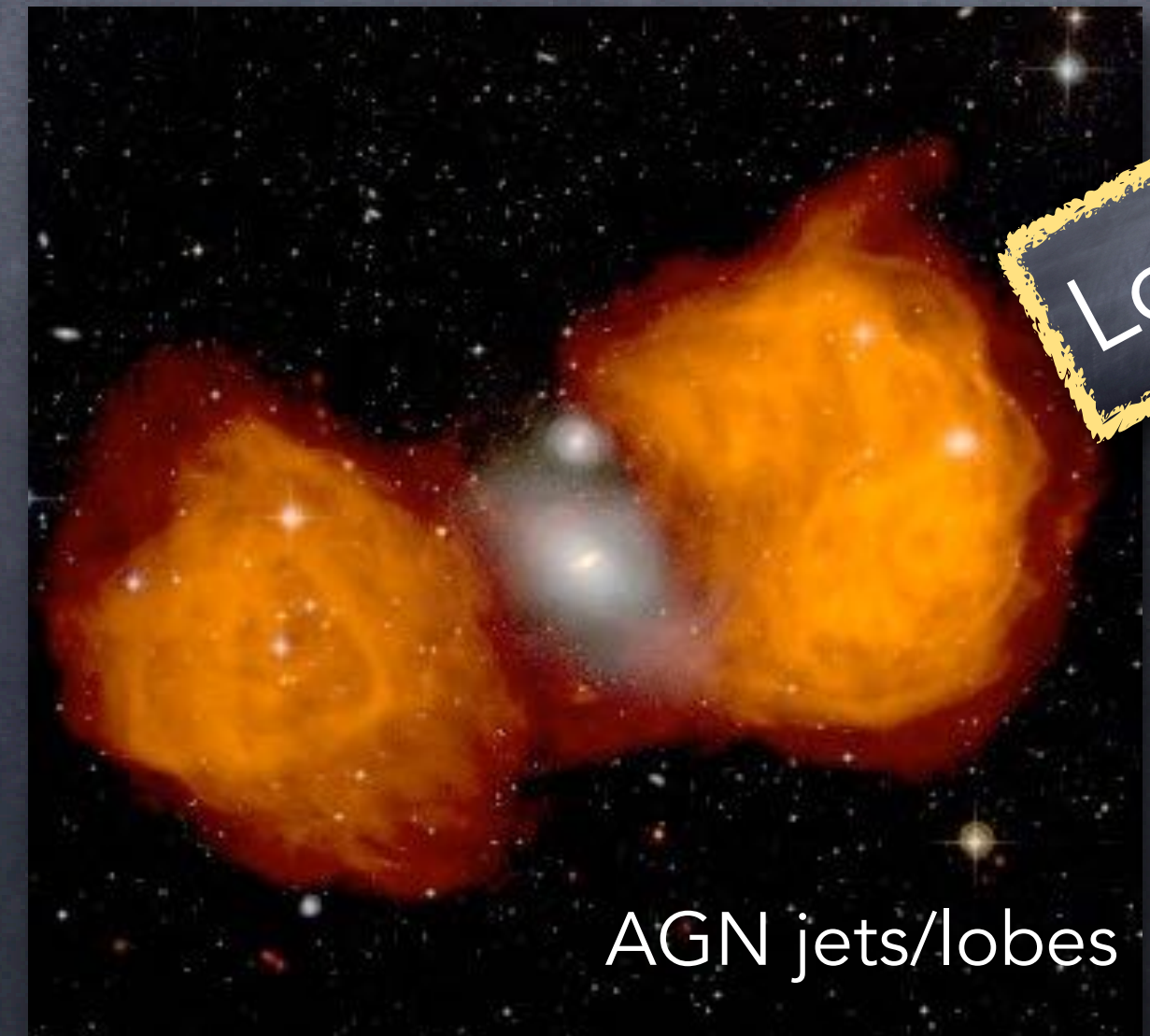
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Radio SNe

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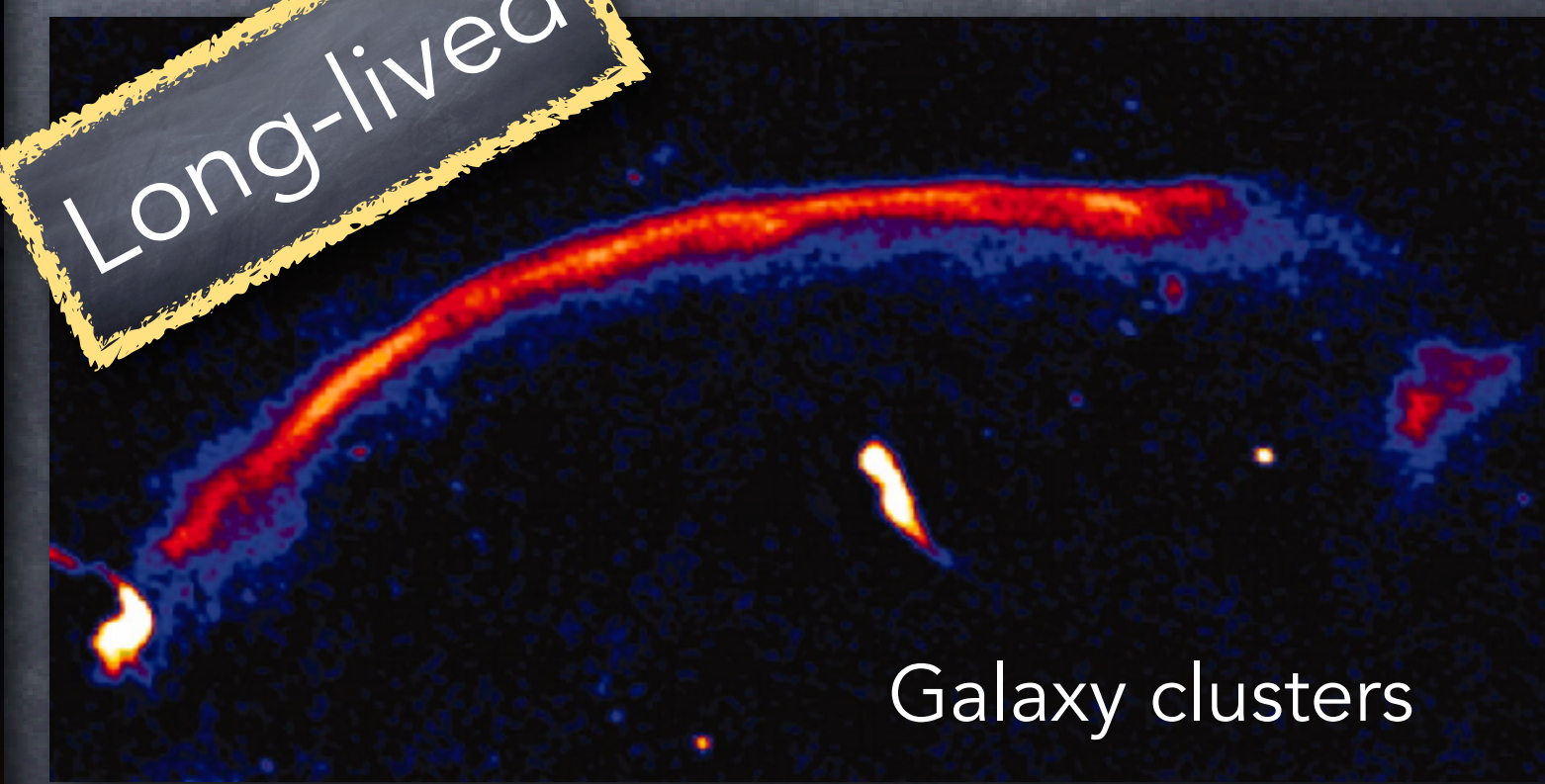


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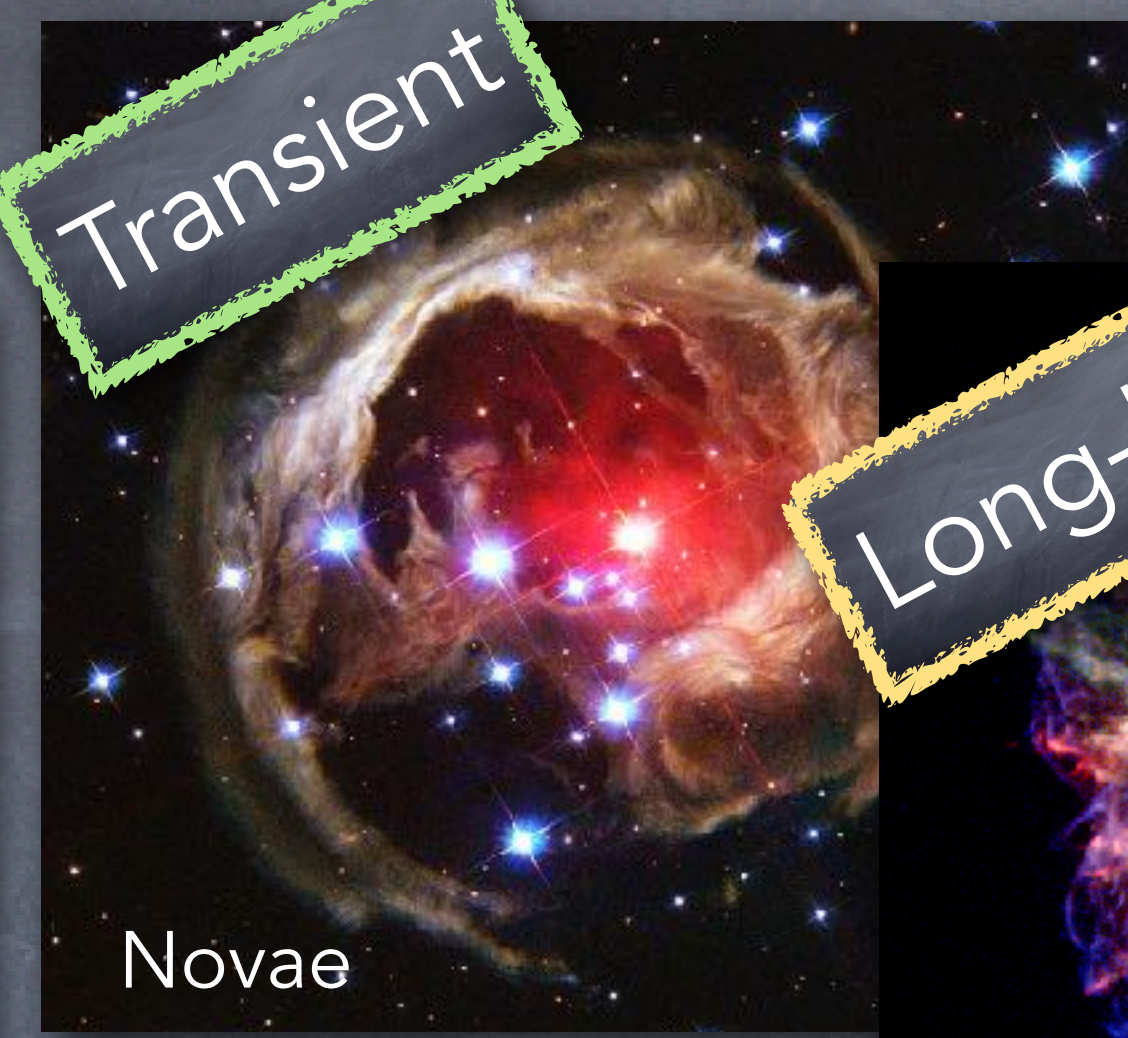
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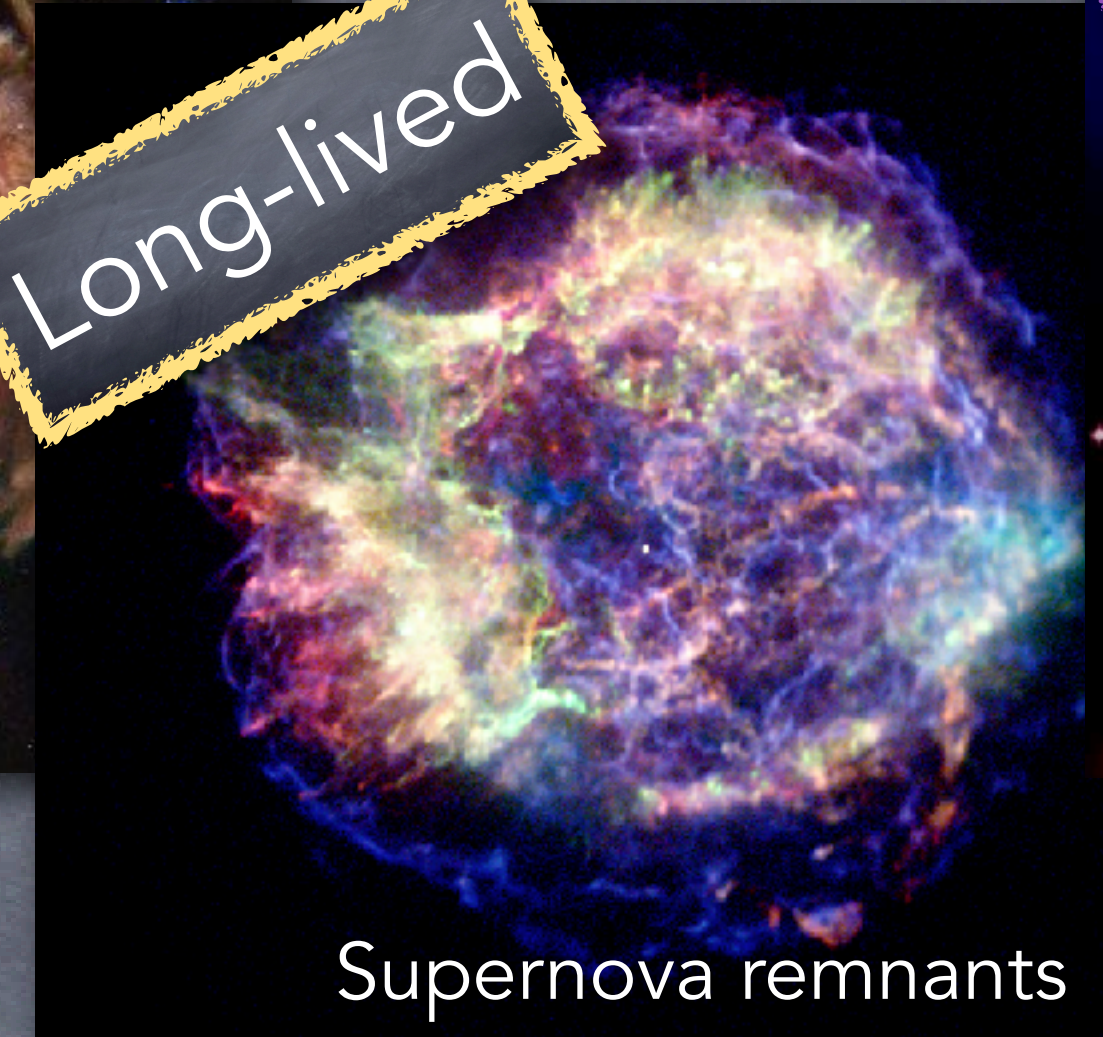
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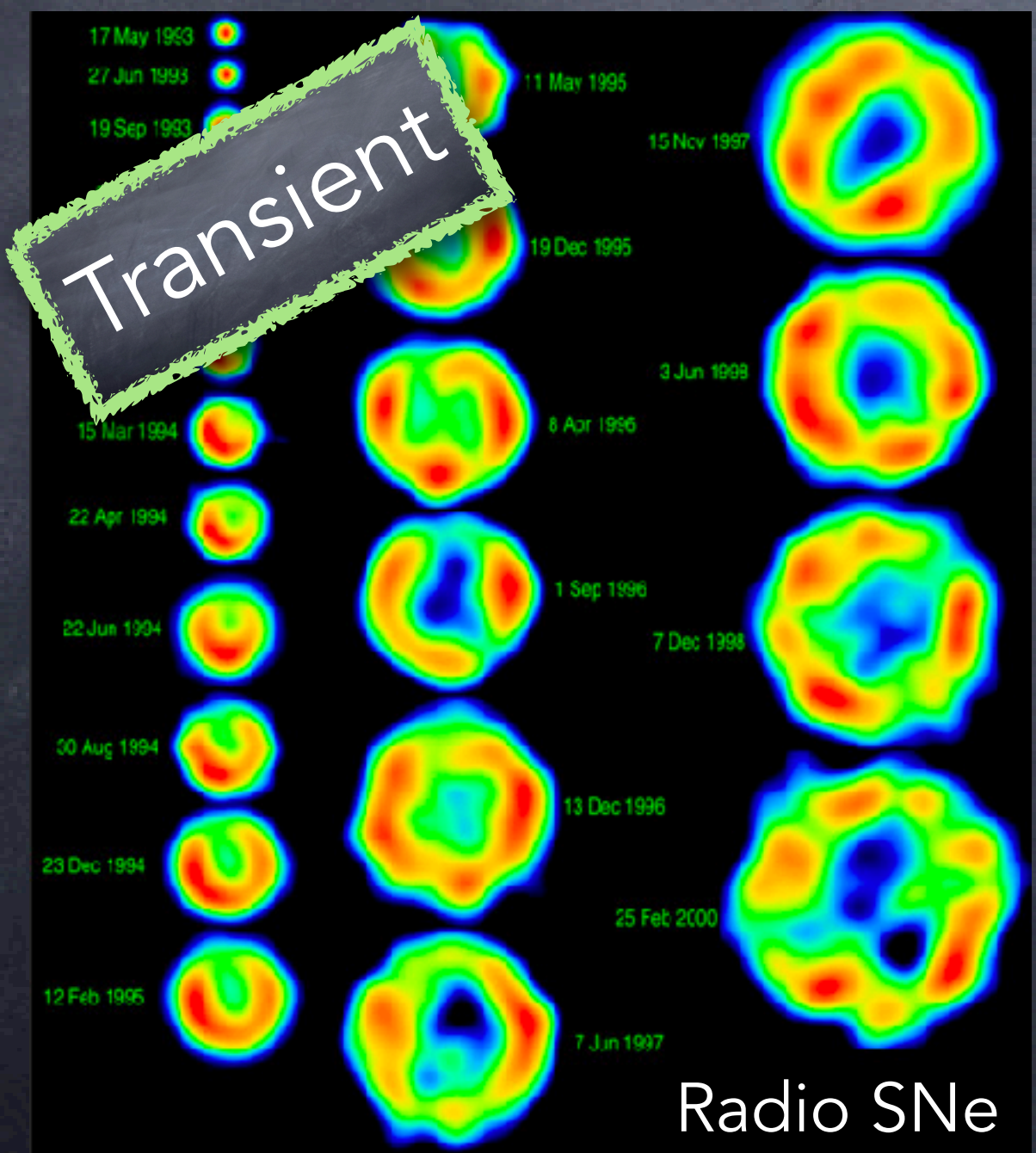
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Flaring

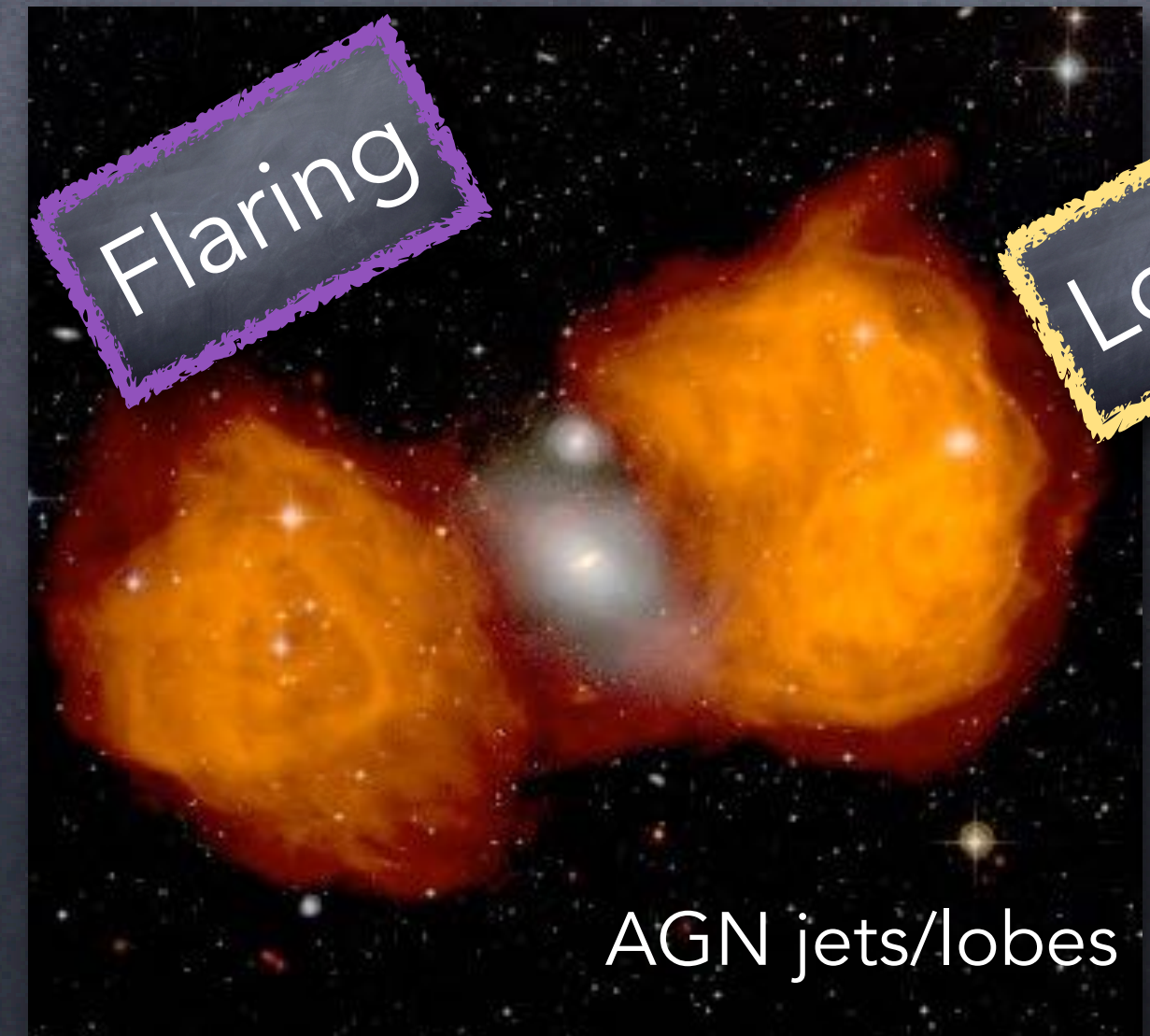
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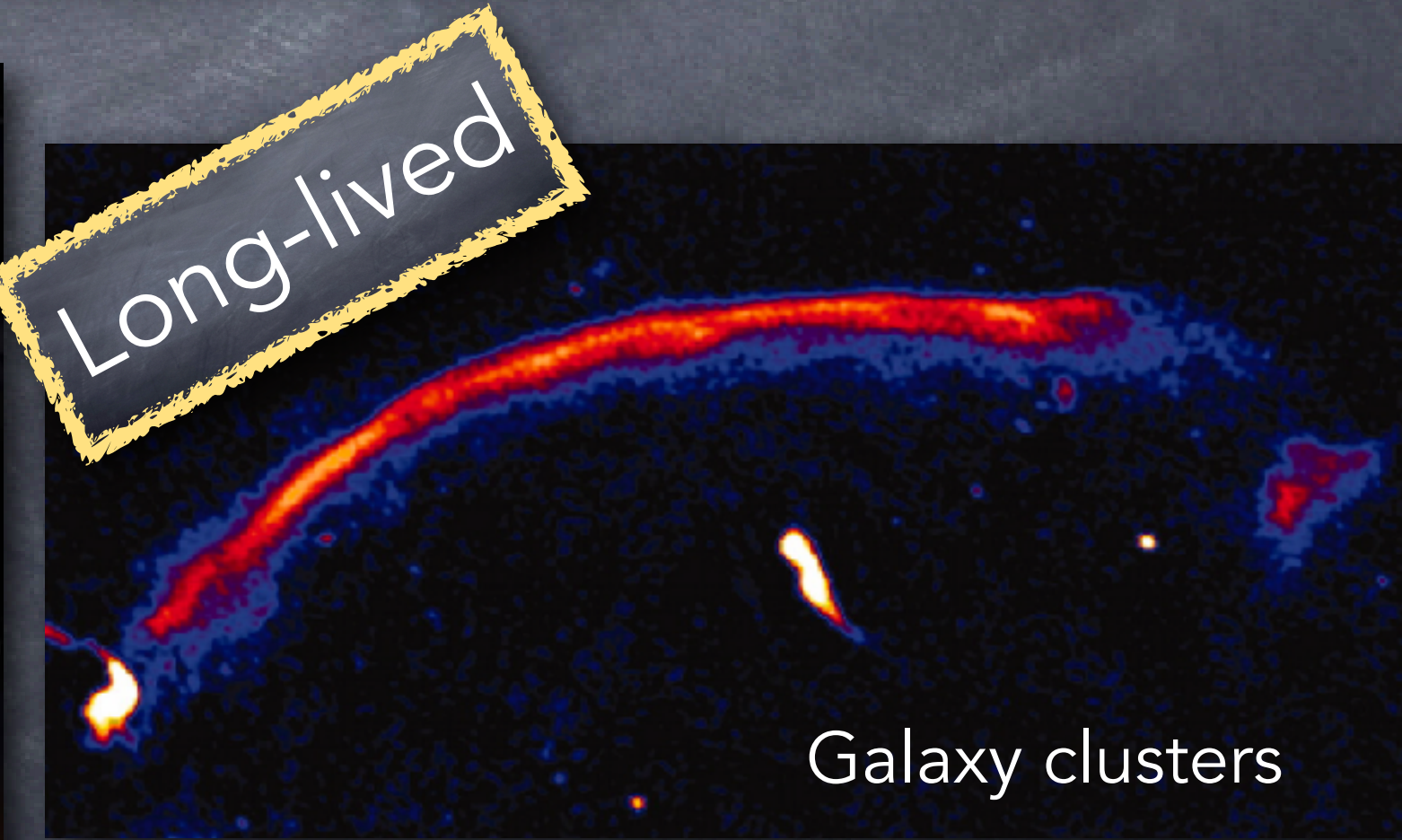
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A universal acceleration mechanism



A universal acceleration mechanism



- **Fermi mechanism** (Fermi, 1949): random elastic collisions lead to energy gain

PHYSICAL REVIEW

VOLUME 75, NUMBER 8

APRIL 15, 1949

On the Origin of the Cosmic Radiation

ENRICO FERMI

Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received January 3, 1949)

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A universal acceleration mechanism



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- In **shocks**, particles gain energy at any interaction (Krymskii77; Blandford & Ostriker; Bell; Axford+78)

Diffusive Shock Acceleration (DSA)

A universal acceleration mechanism

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Diffusive Shock Acceleration (DSA)



Downstream (post-shock)

Upstream (pre-shock)

Test-particle
squeezed
between
converging
flows

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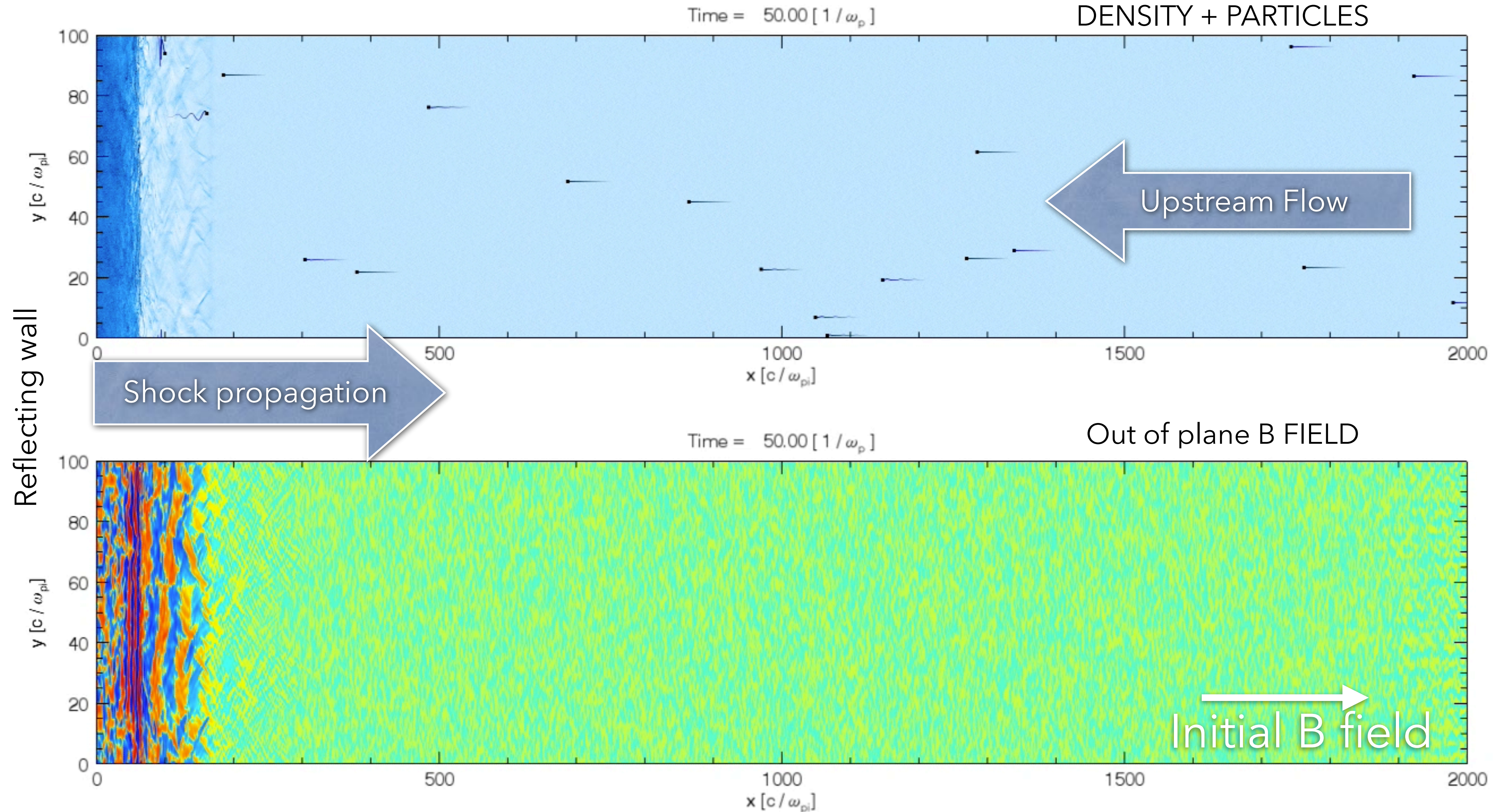
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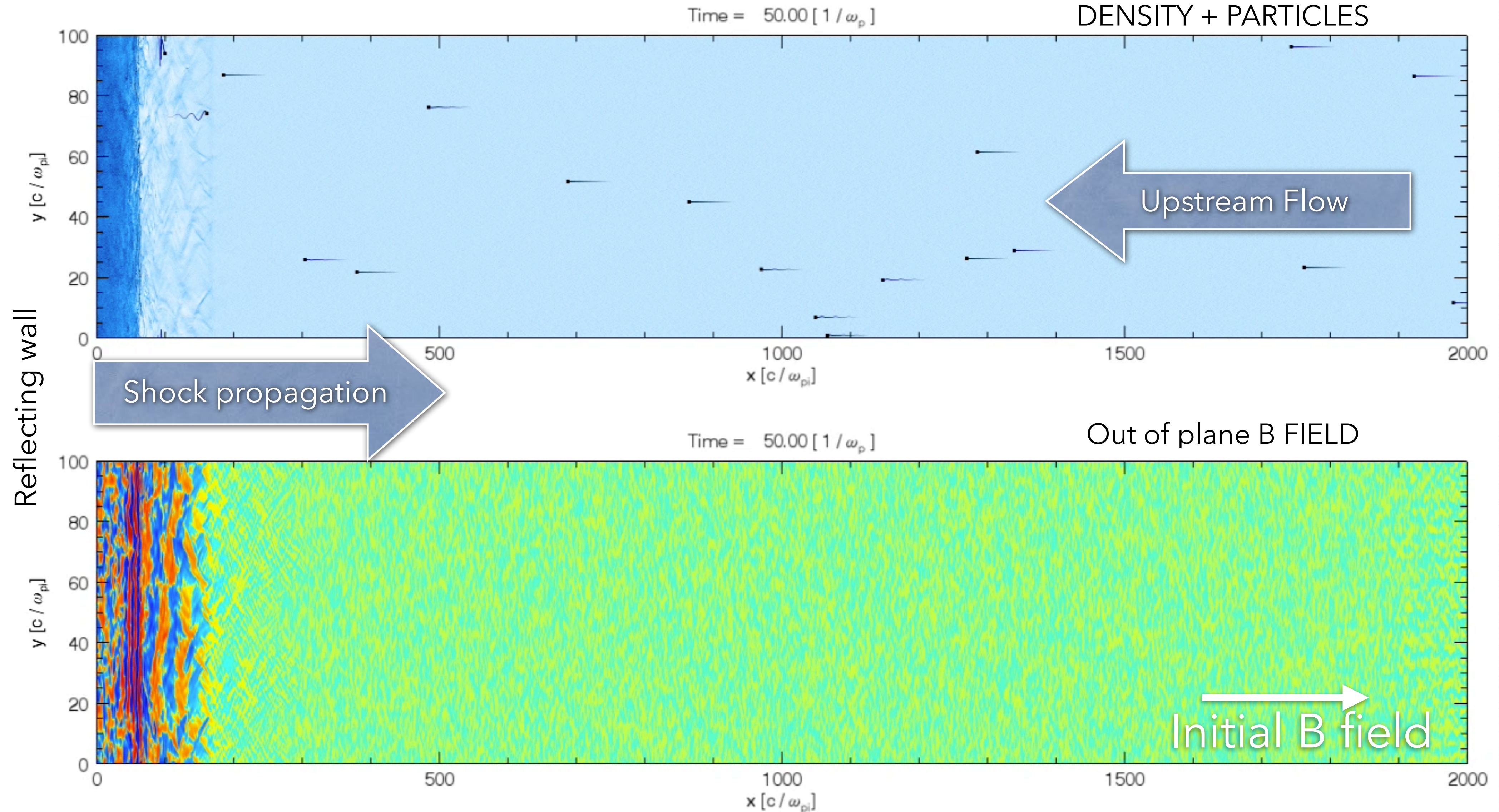
$$R = \frac{4M_s^2}{M_s^2 + 3} \quad \alpha = \frac{3R}{R - 1}$$

- For strong shocks (Mach number $M_s = V_{sh}/c_s \gg 1$): $R = 4$ and $\alpha = 4$

Hybrid Simulations of Collisionless Shocks

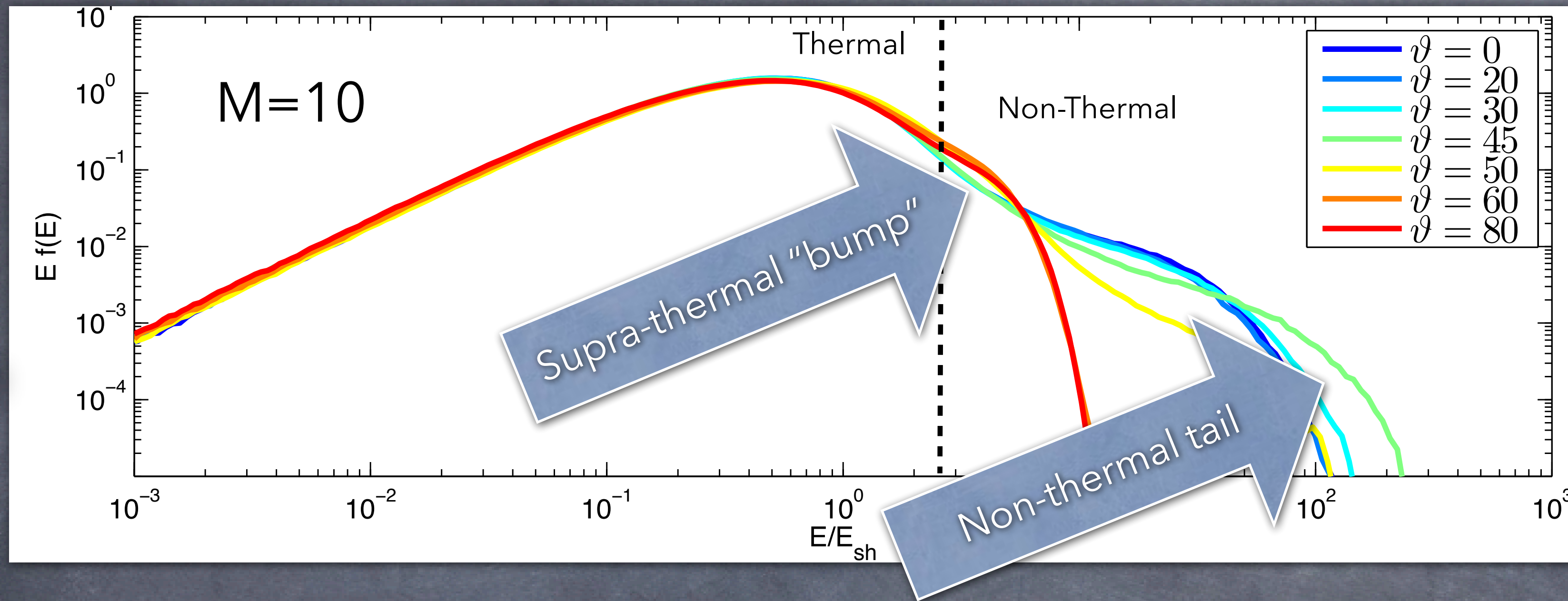
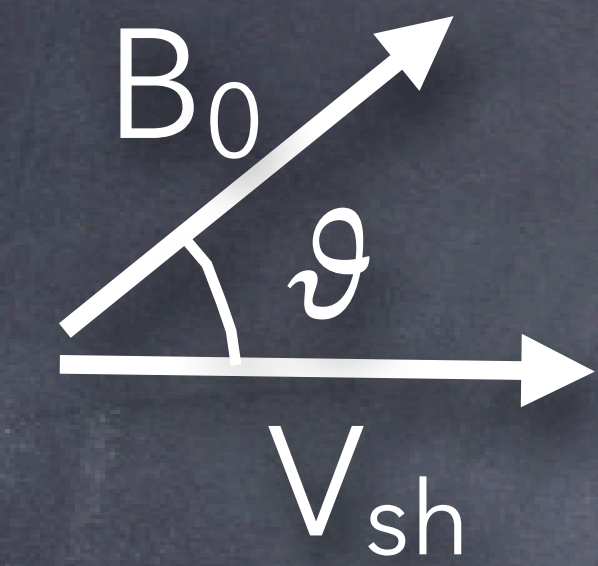


Hybrid Simulations of Collisionless Shocks



Parallel vs Oblique shocks

Shock inclination

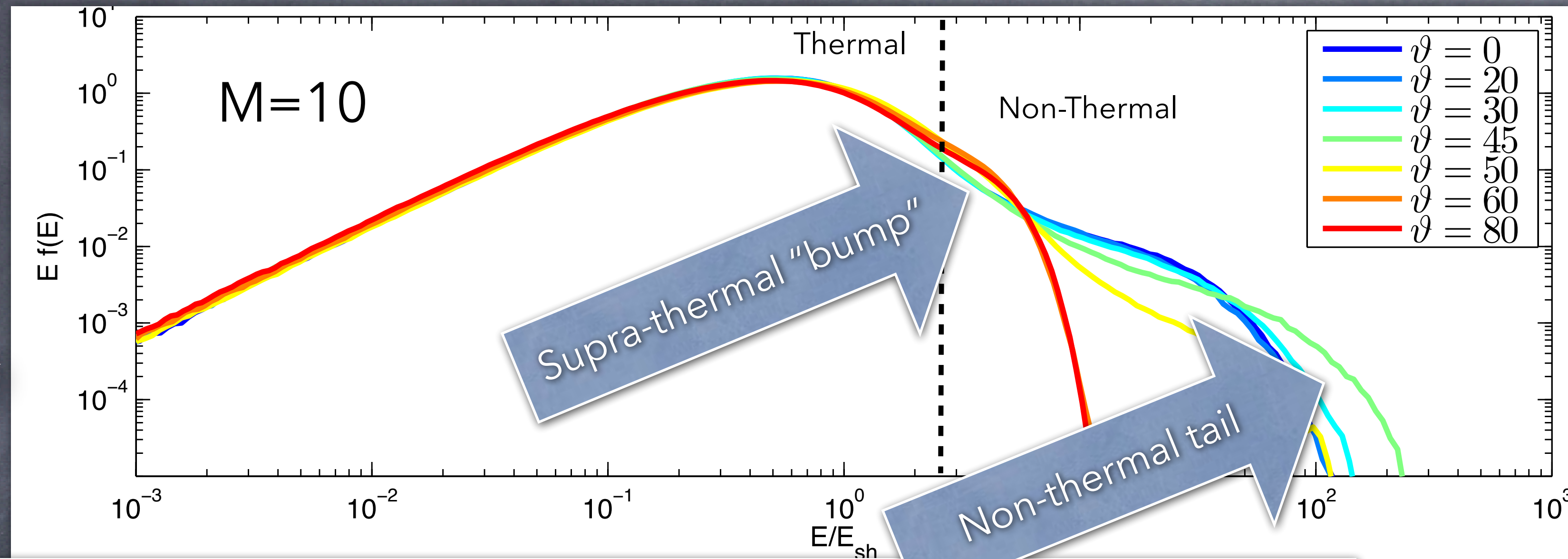
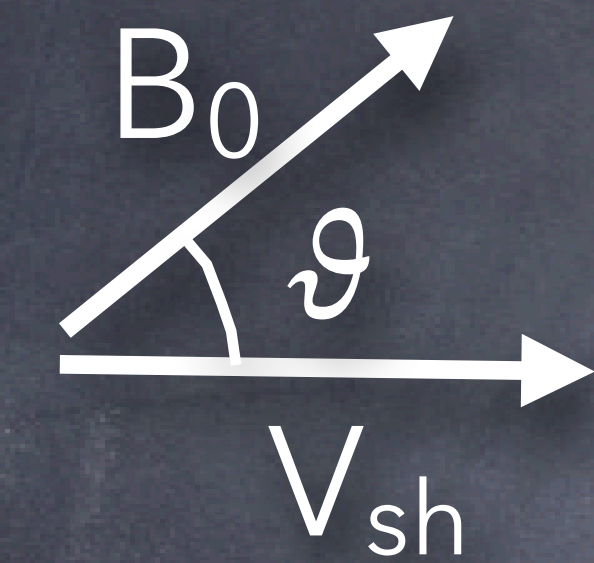


Ion acceleration correlates with B-field amplification

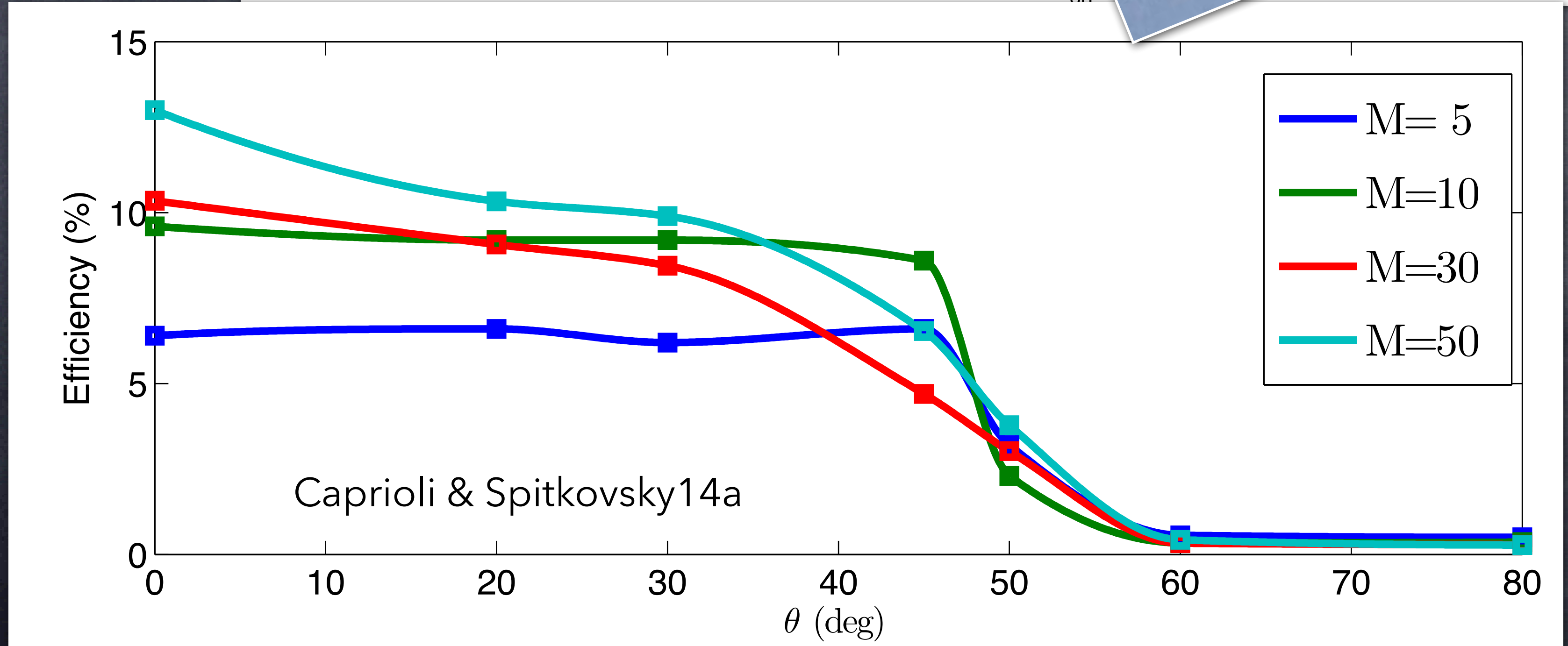


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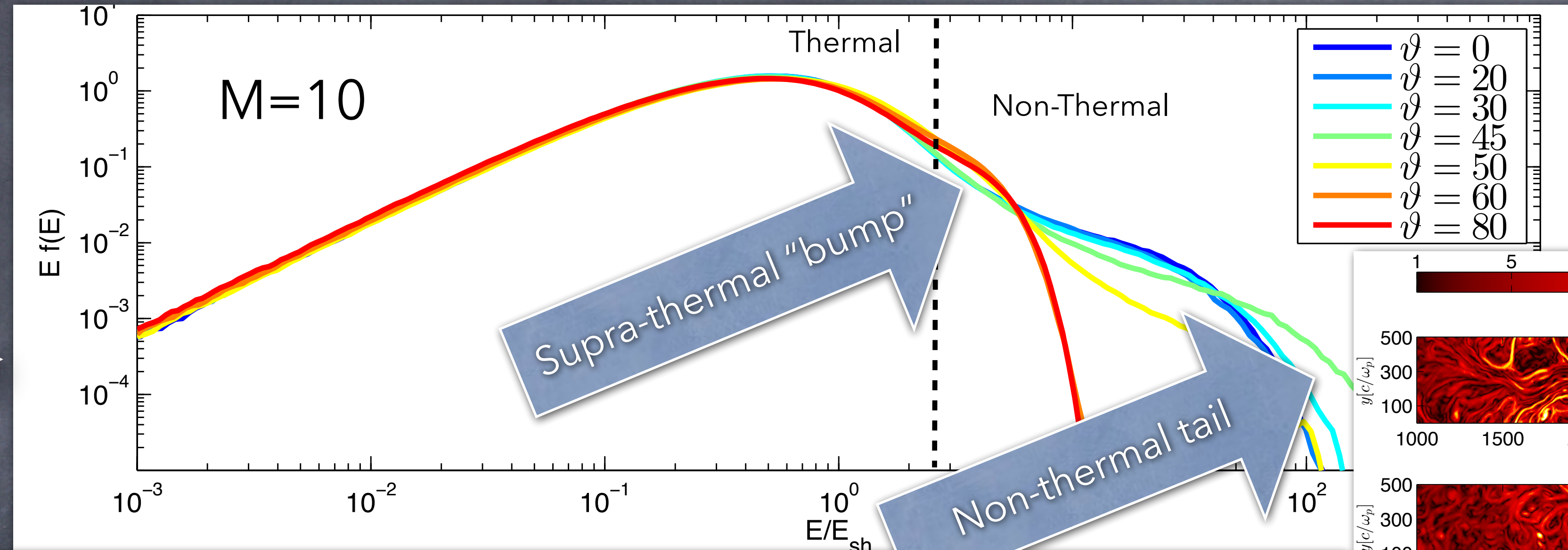
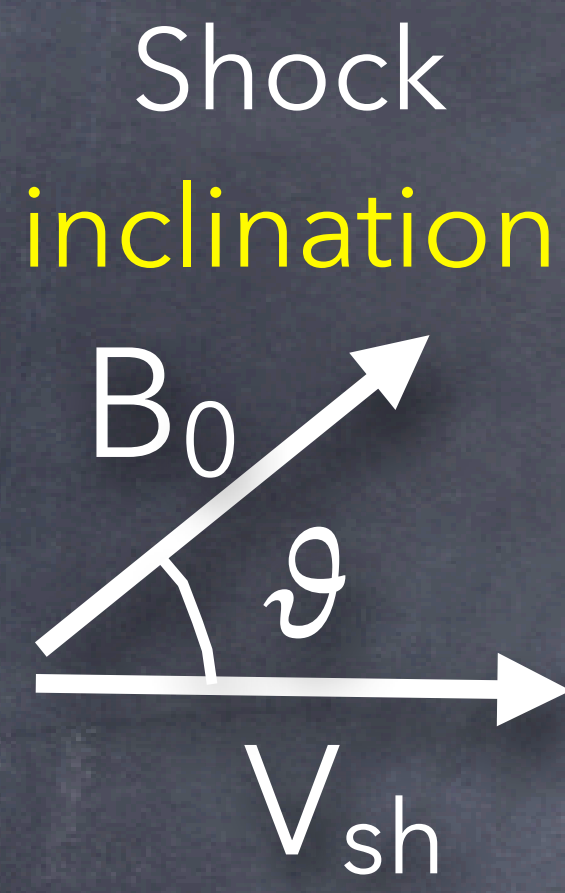


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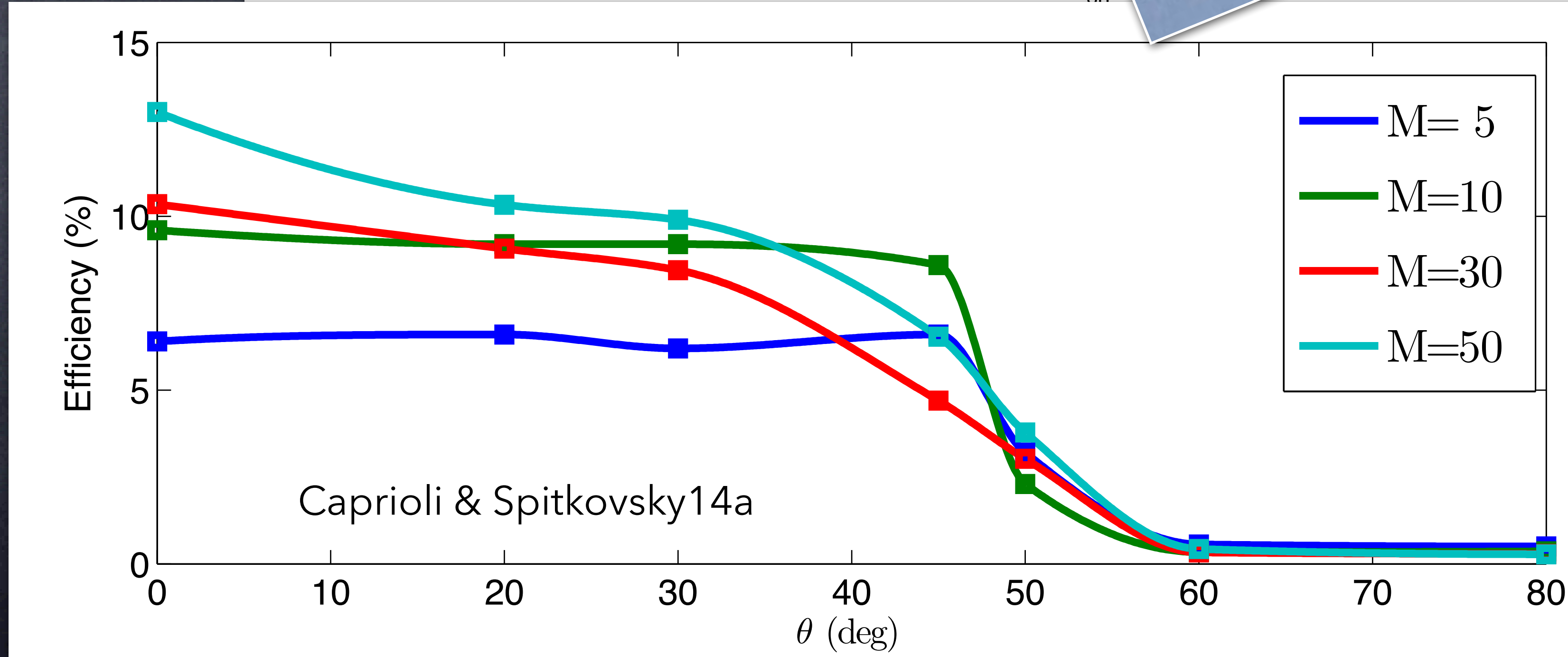
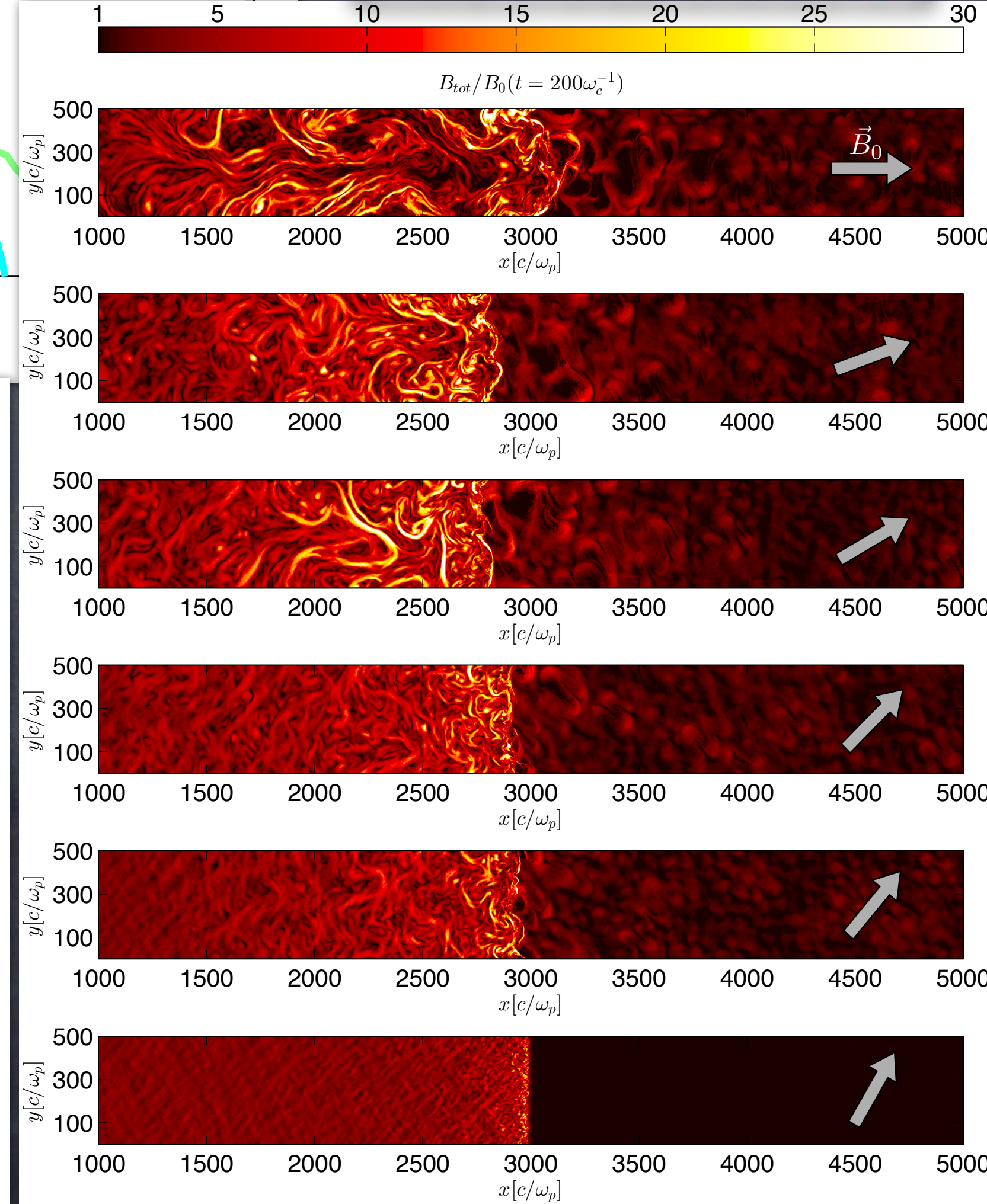




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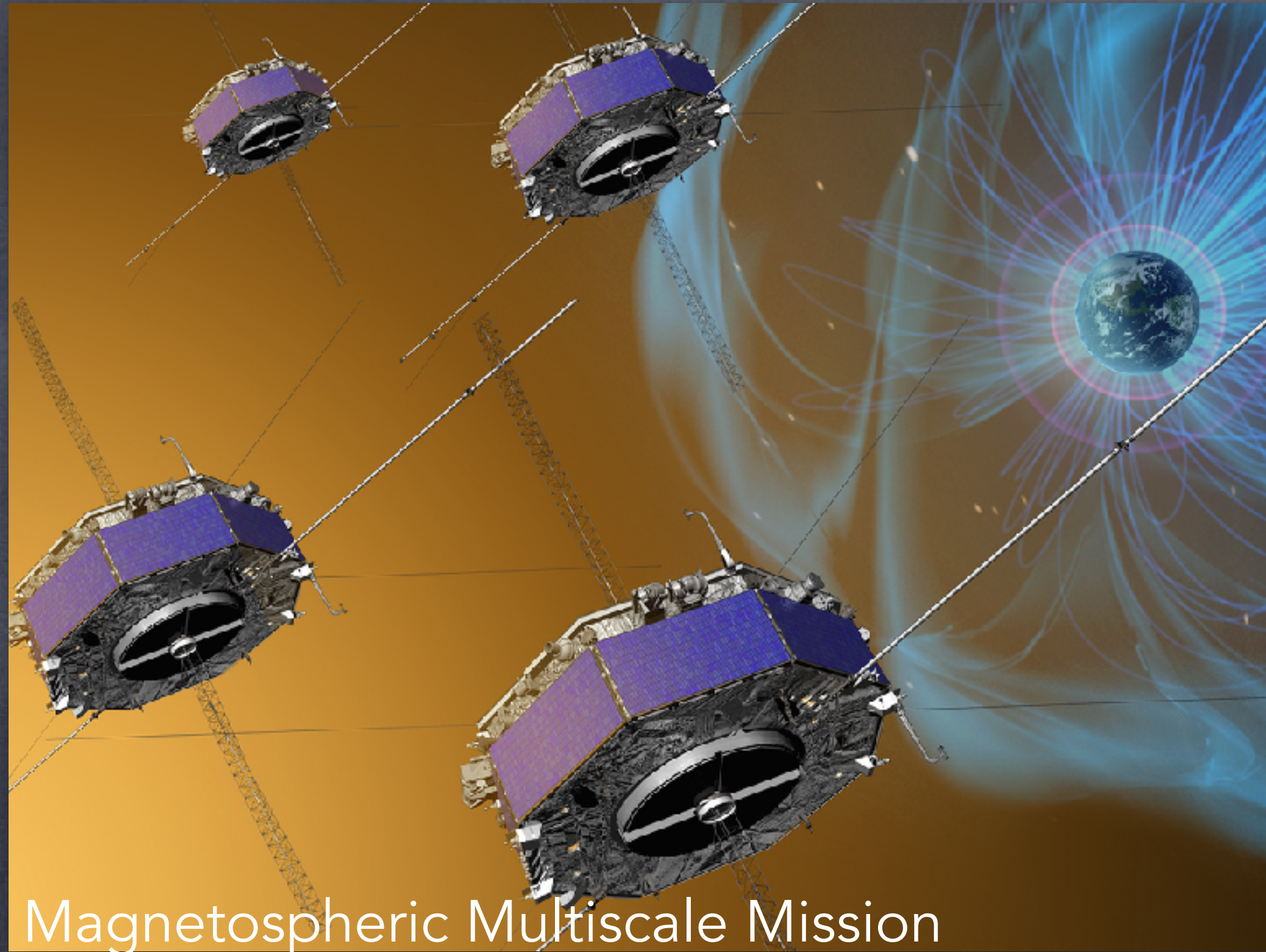


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Ion DSA at the Earth Bow Shock

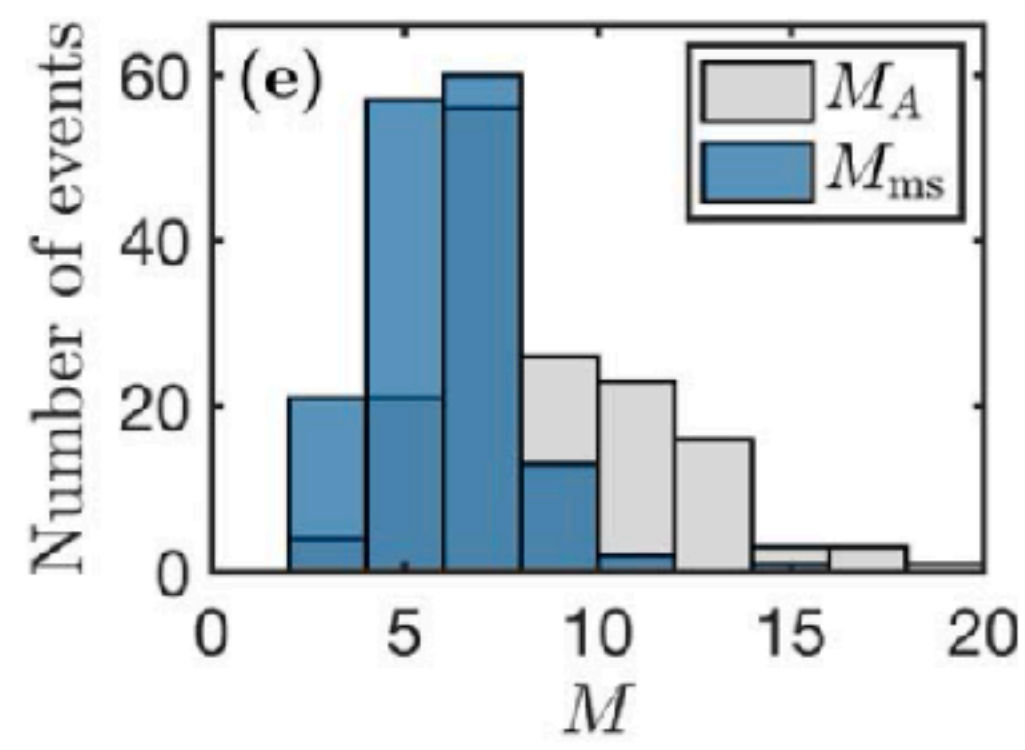
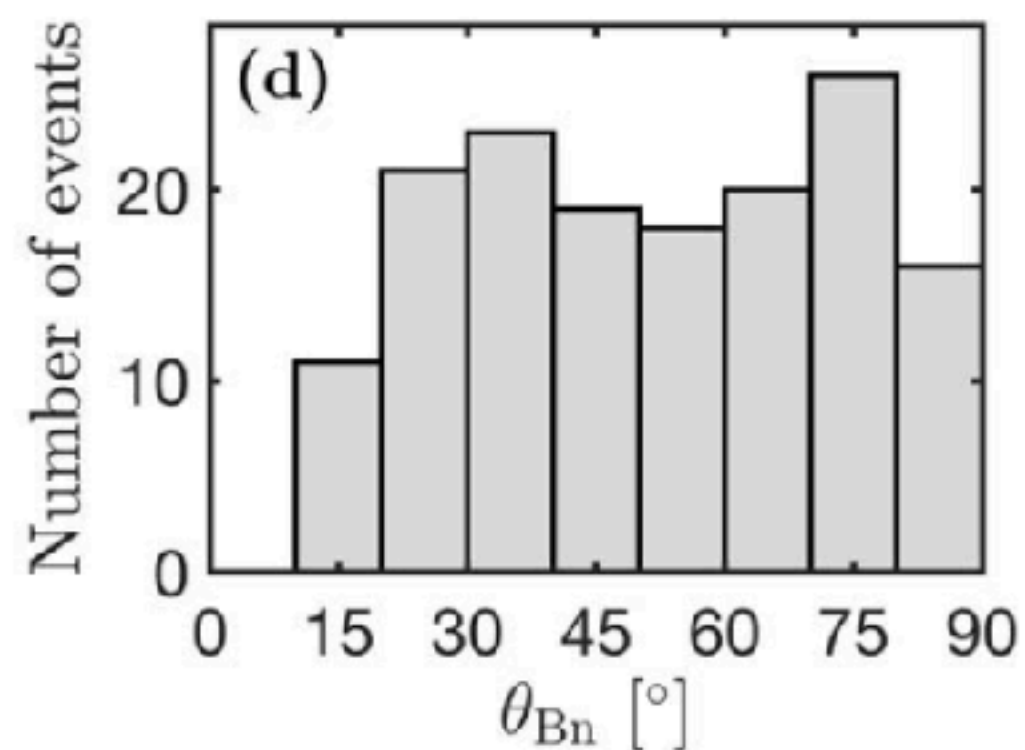
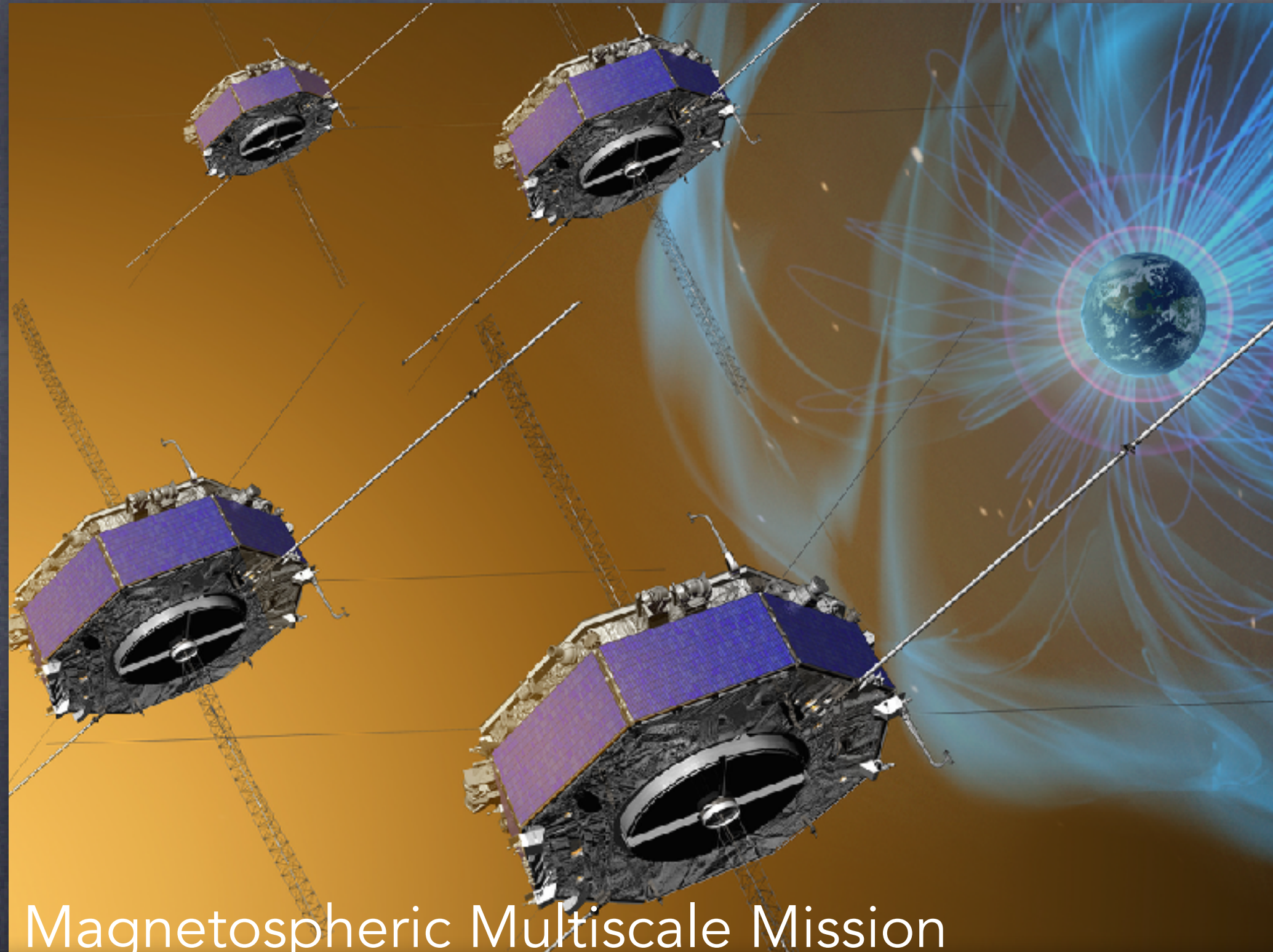
- **MMS** confirms that DSA is efficient **at quasi-parallel** shocks (Johlander, Caprioli+21)



Magnetospheric Multiscale Mission

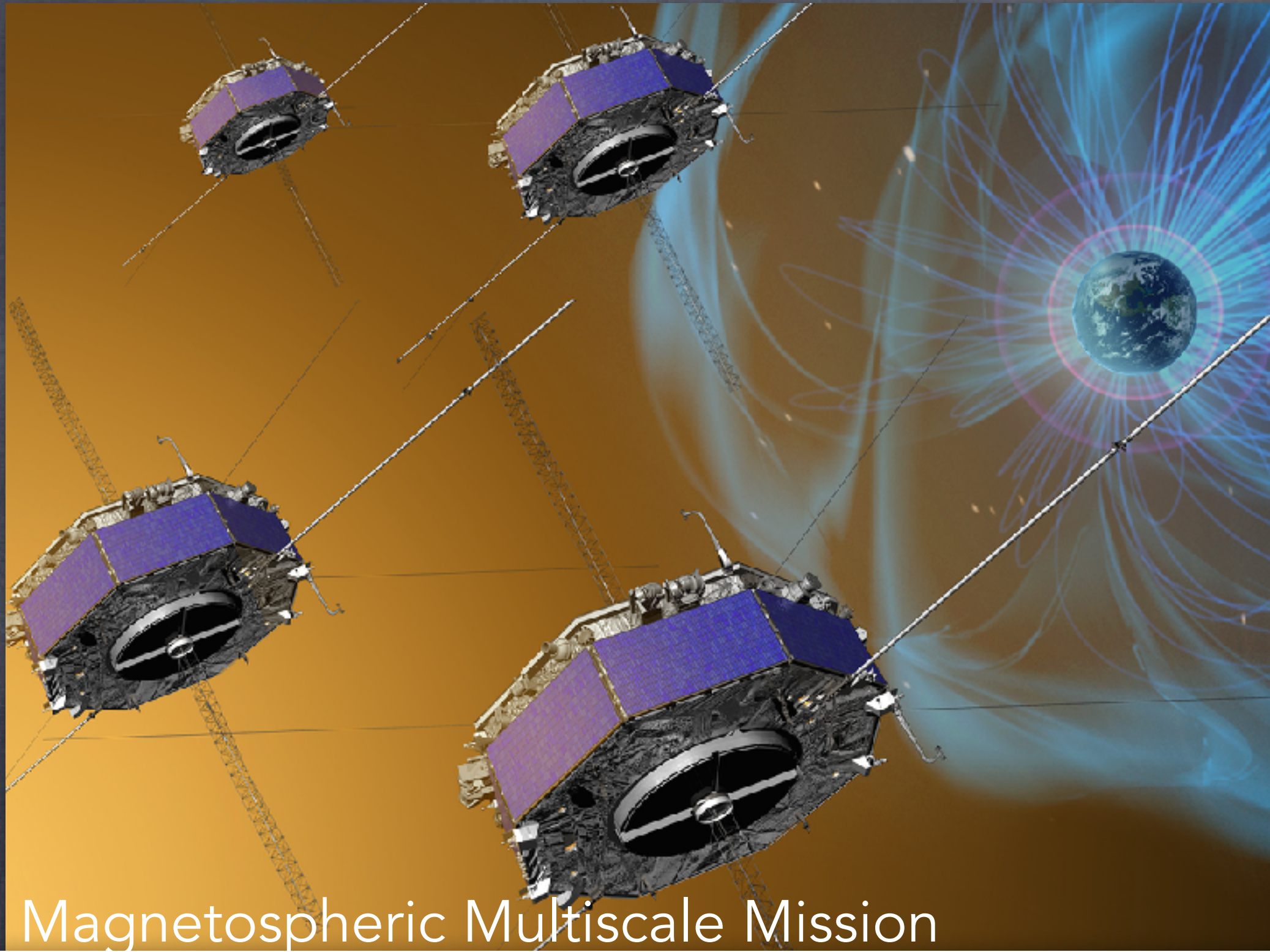
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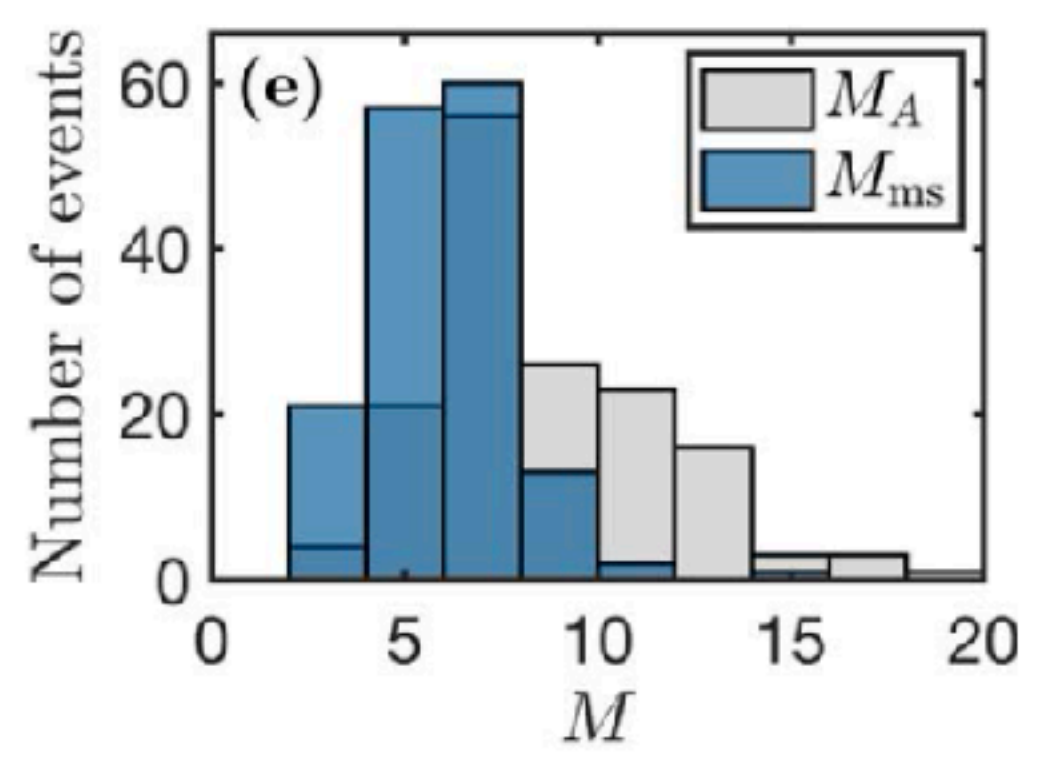
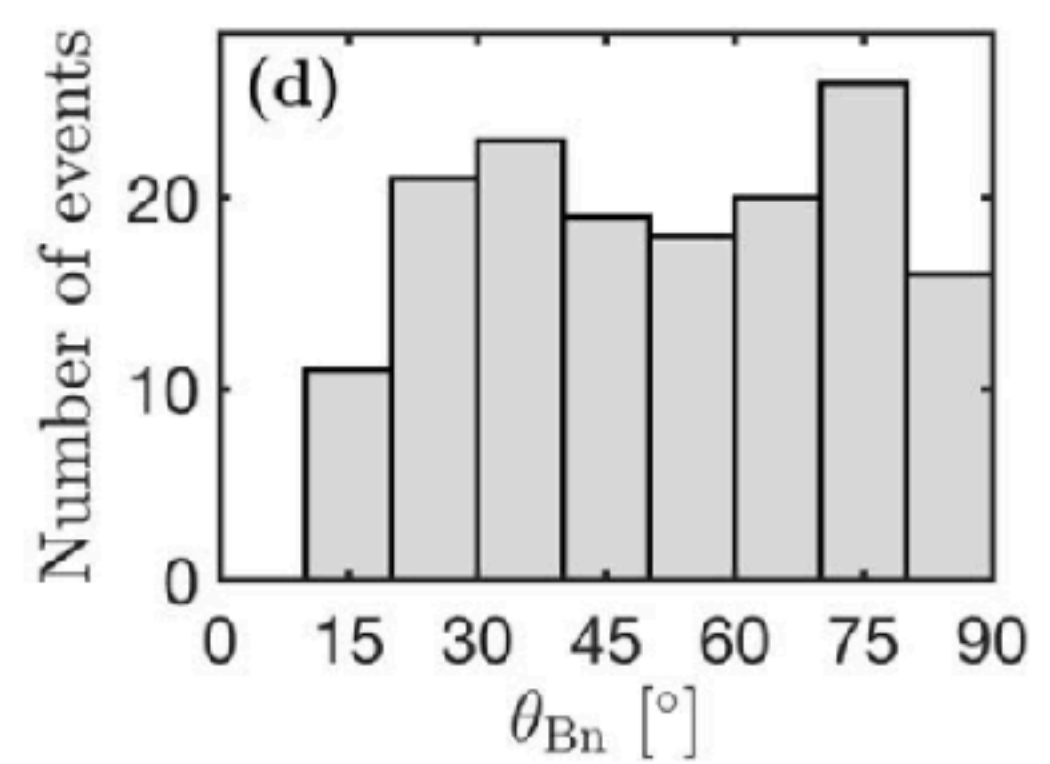
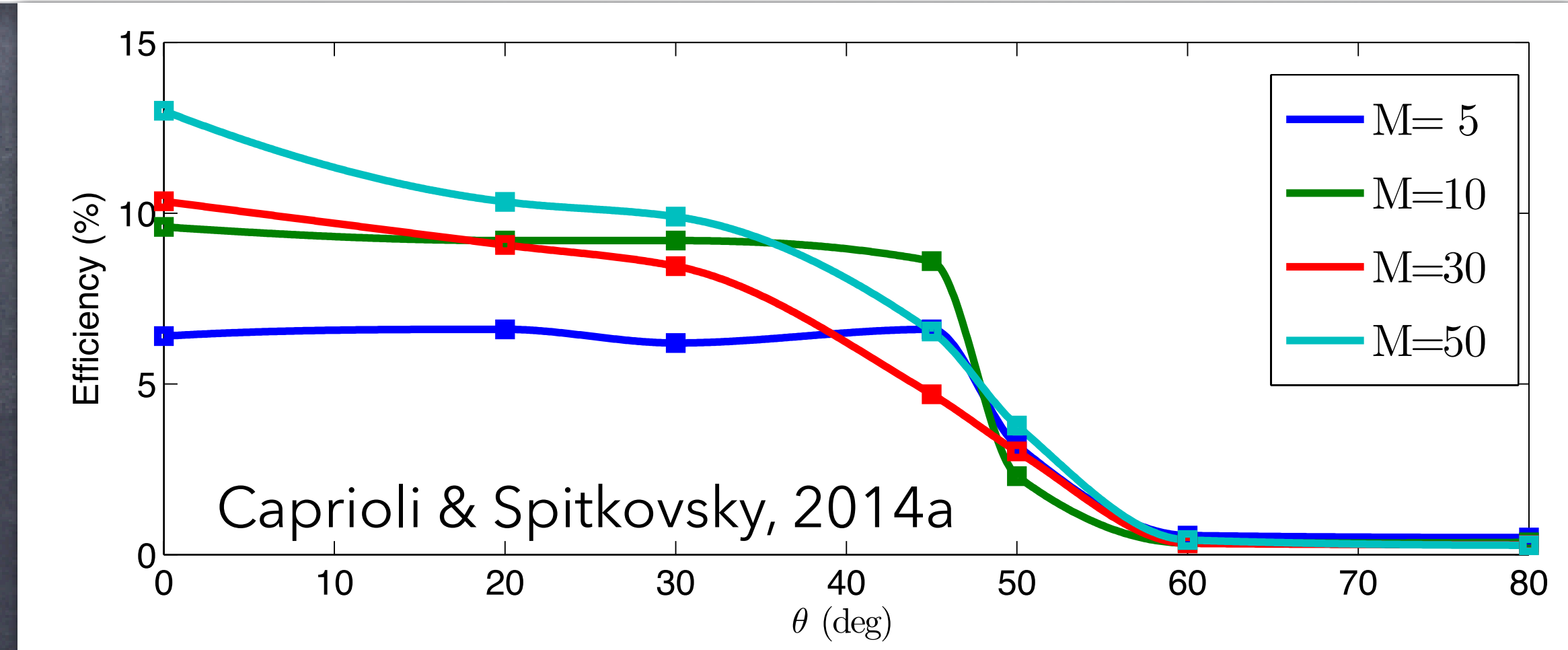
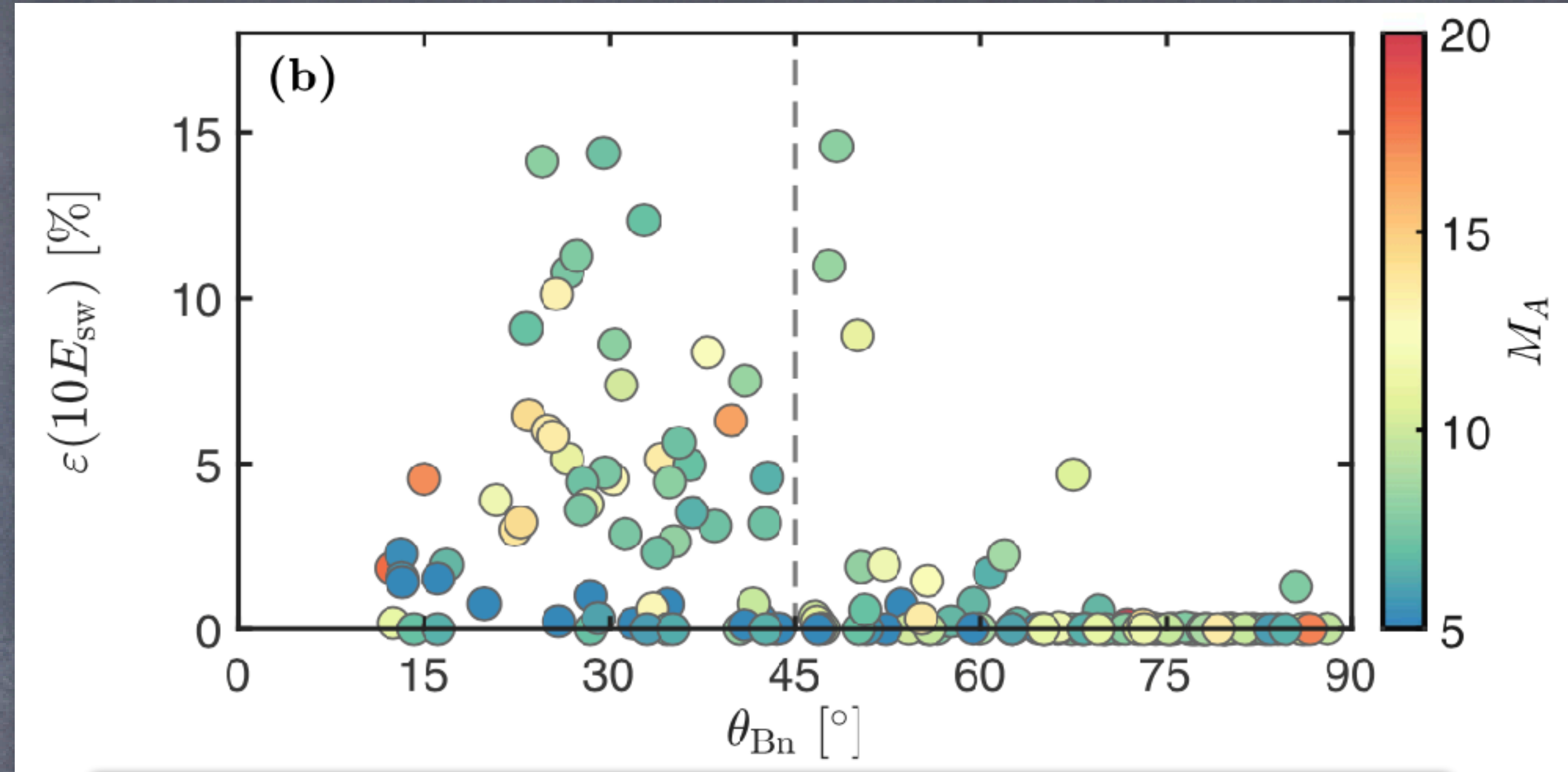


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Magnetospheric Multiscale Mission



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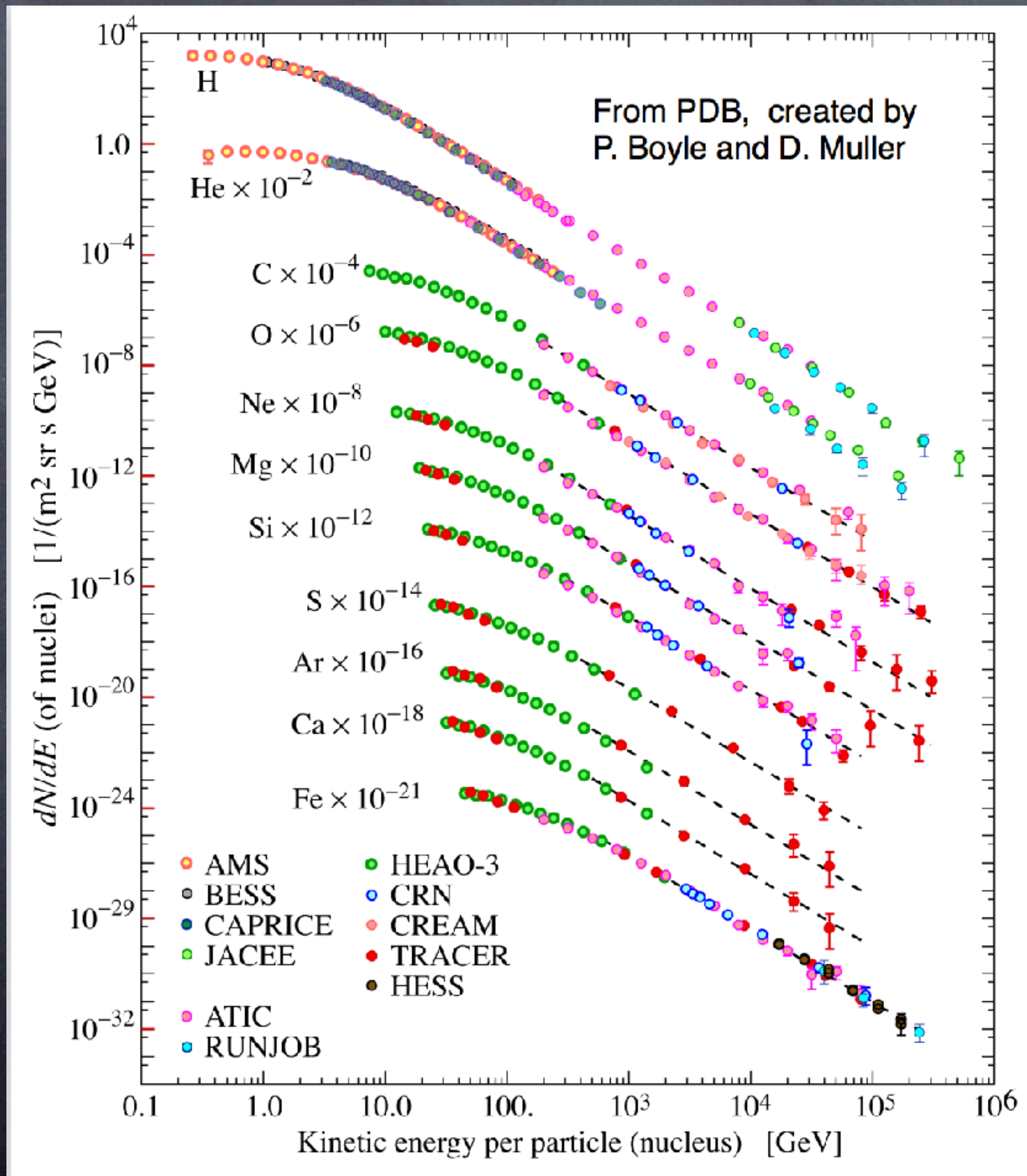
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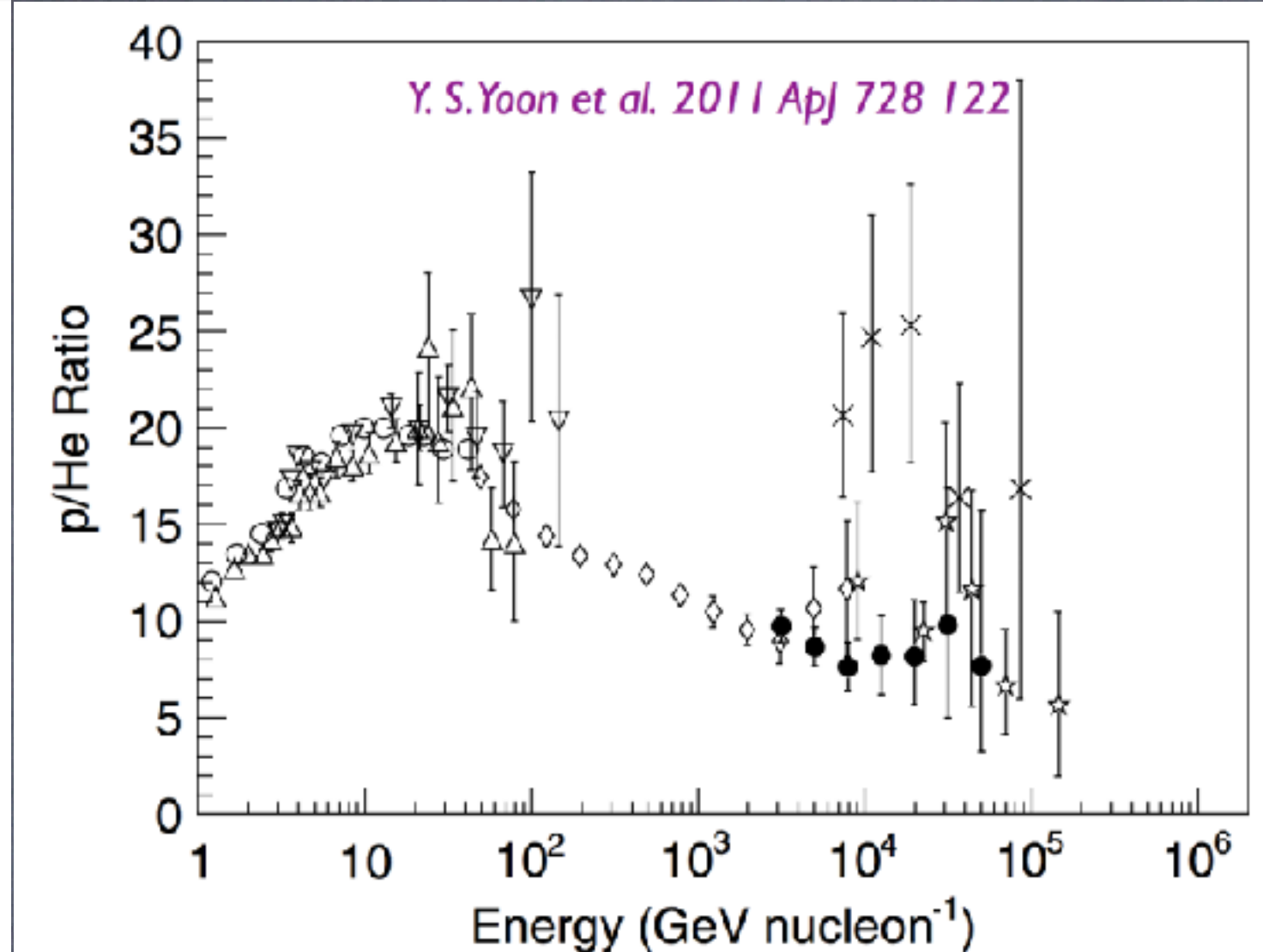
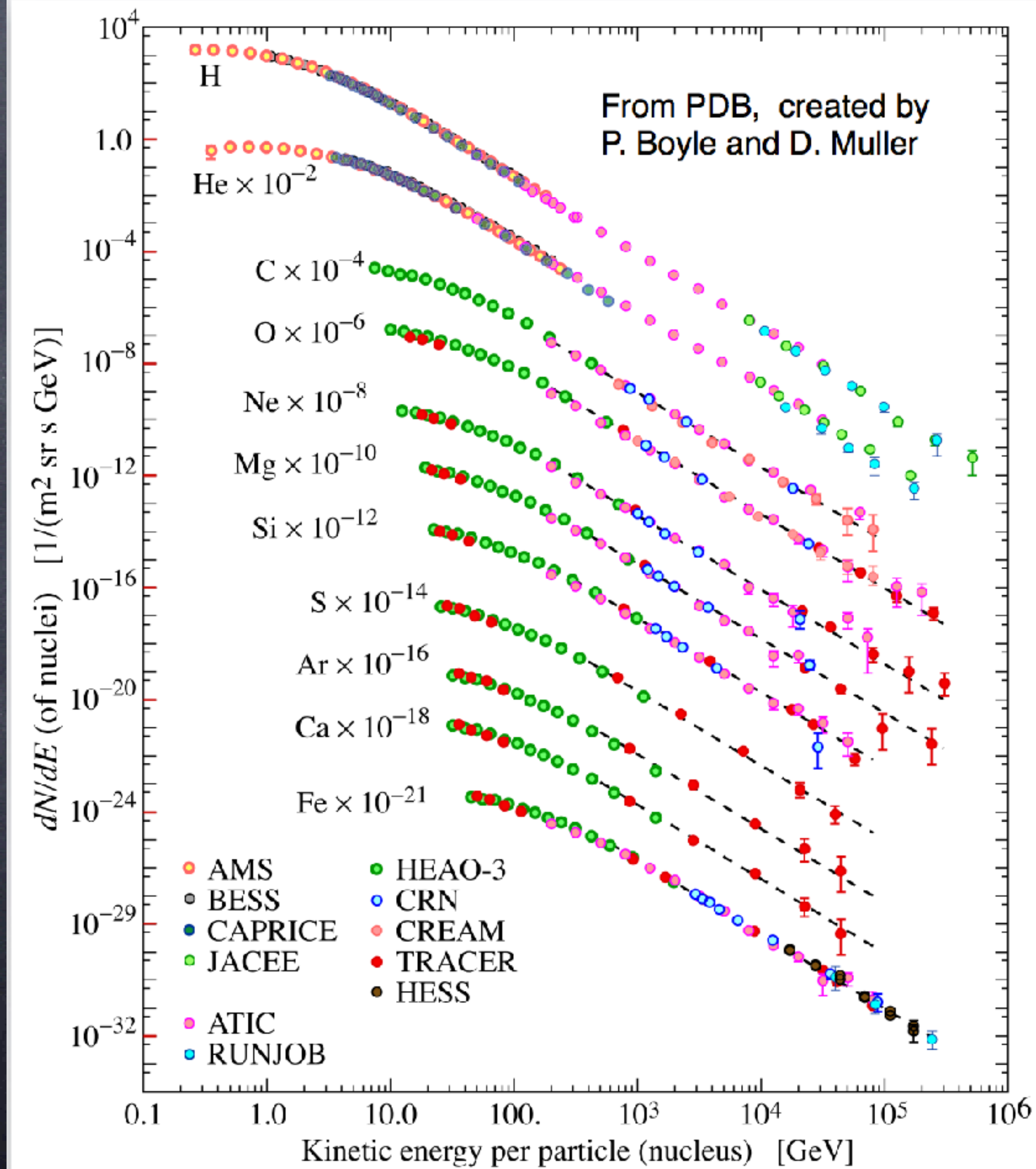
Spectra result from balance between acceleration and collisional losses: heavy ions should have steeper spectra!

$$\frac{dN}{dE} \propto E^{-(1+\tau_a/\tau_L)}$$

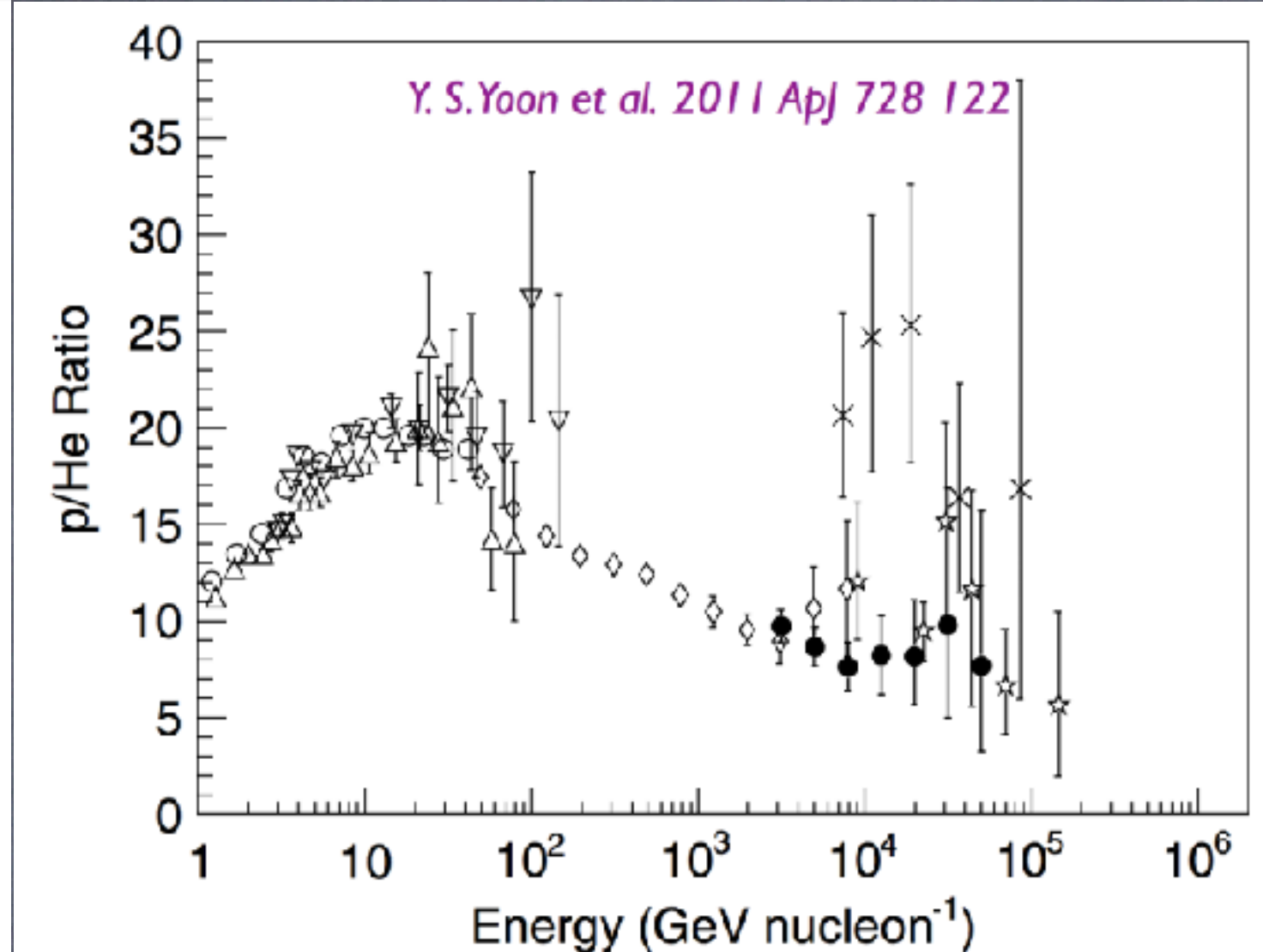
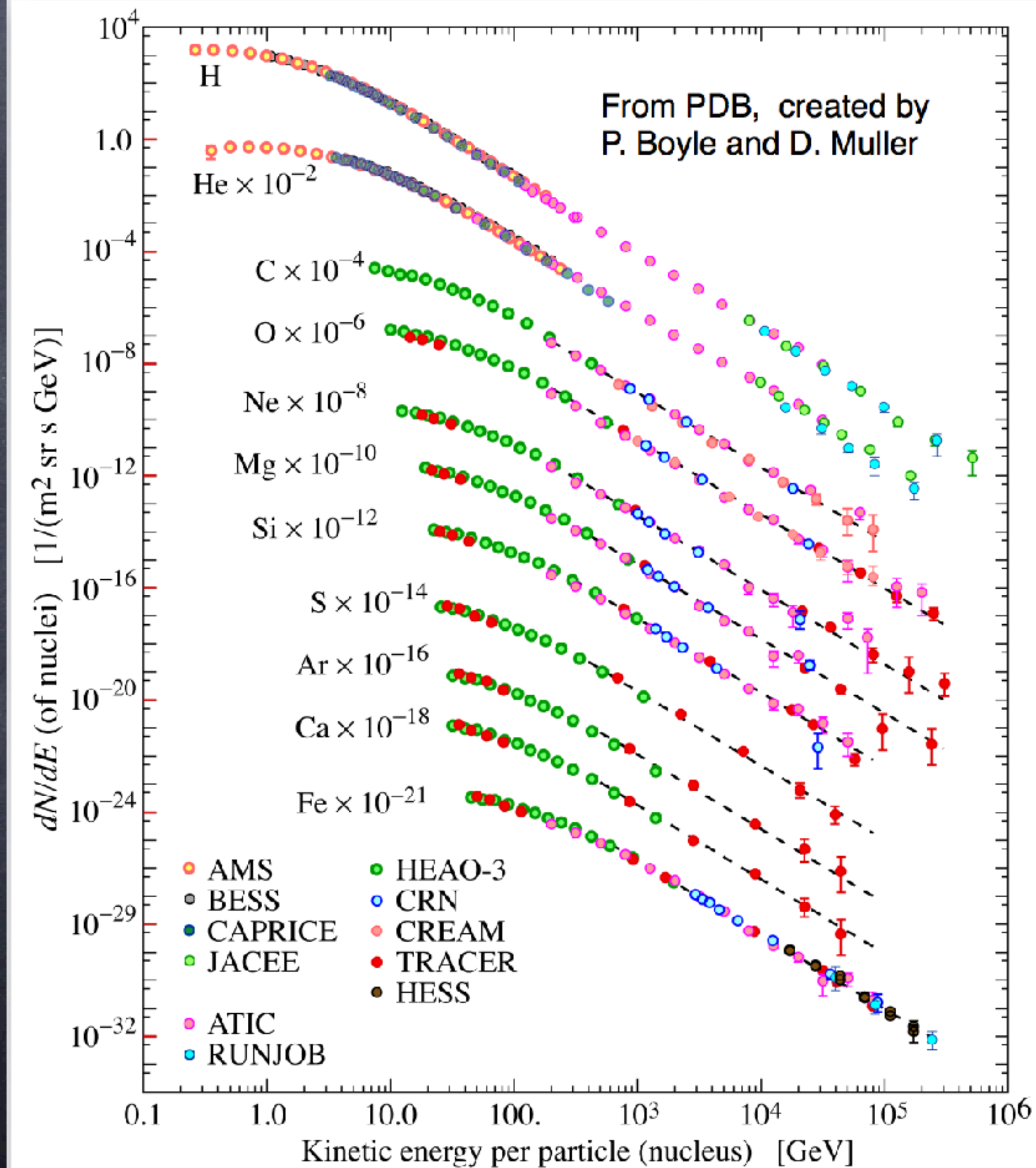
Abundances in Cosmic Rays and Solar Energetic Particles



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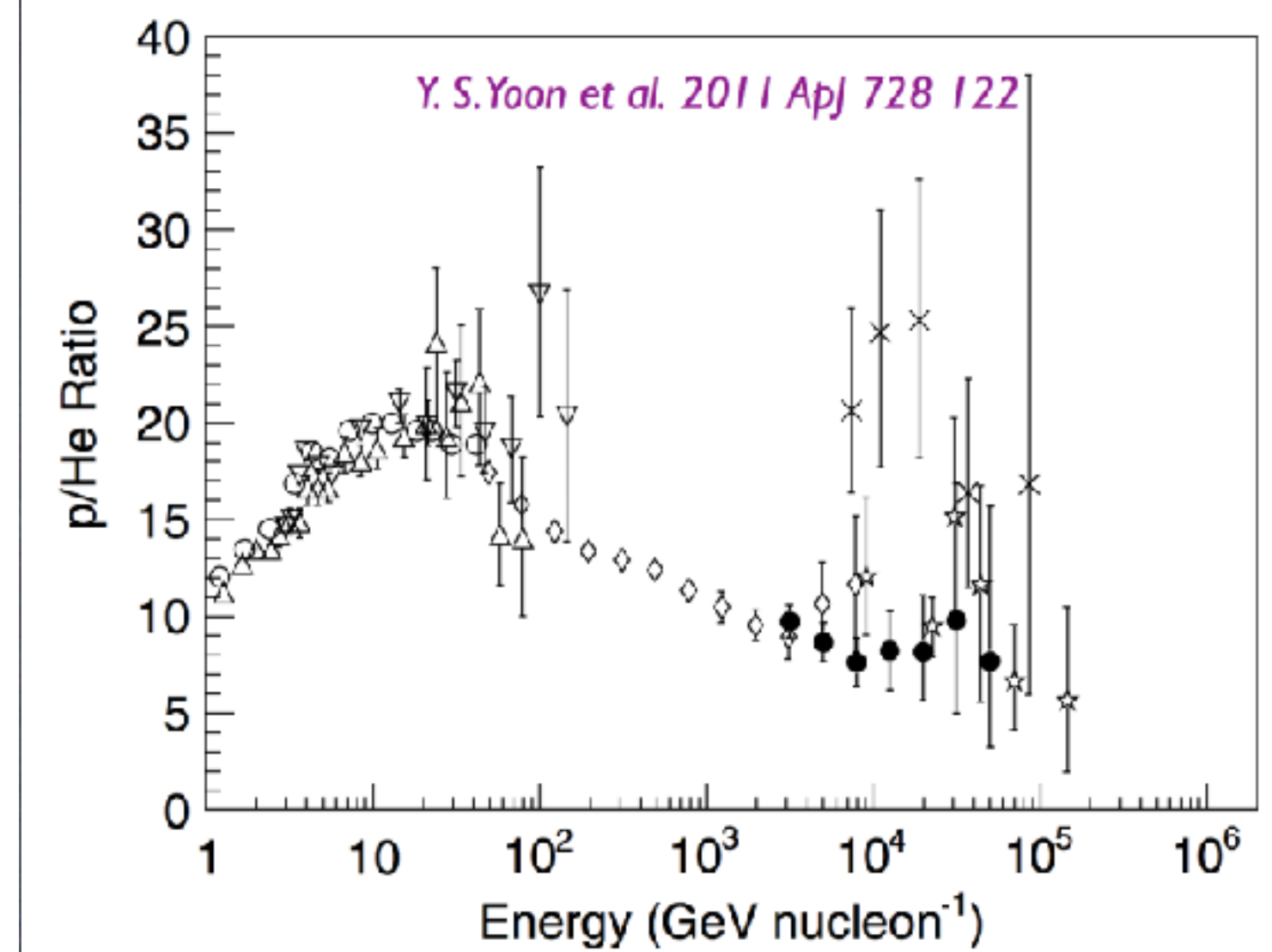
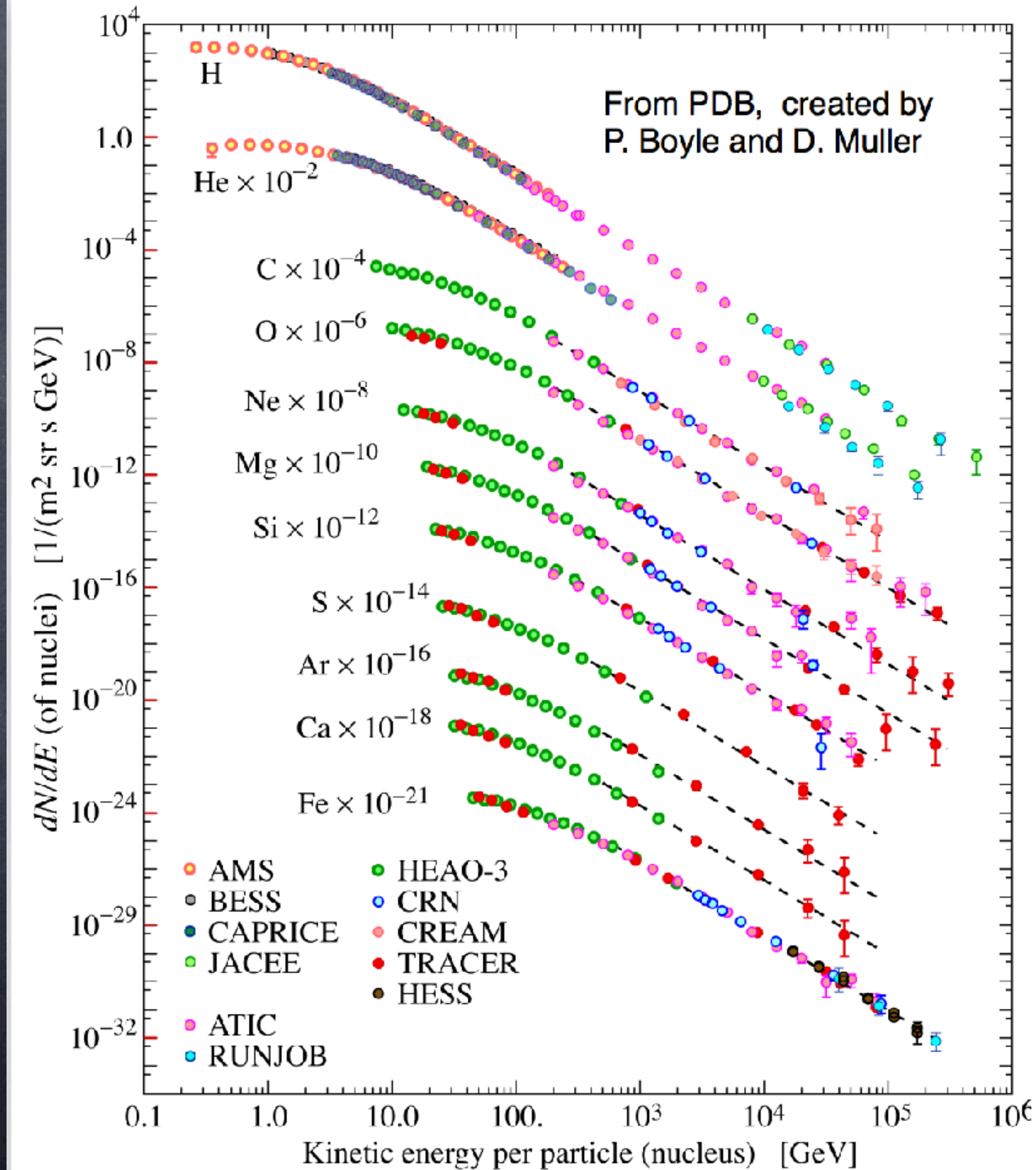


Abundances in Cosmic Rays and Solar Energetic Particles

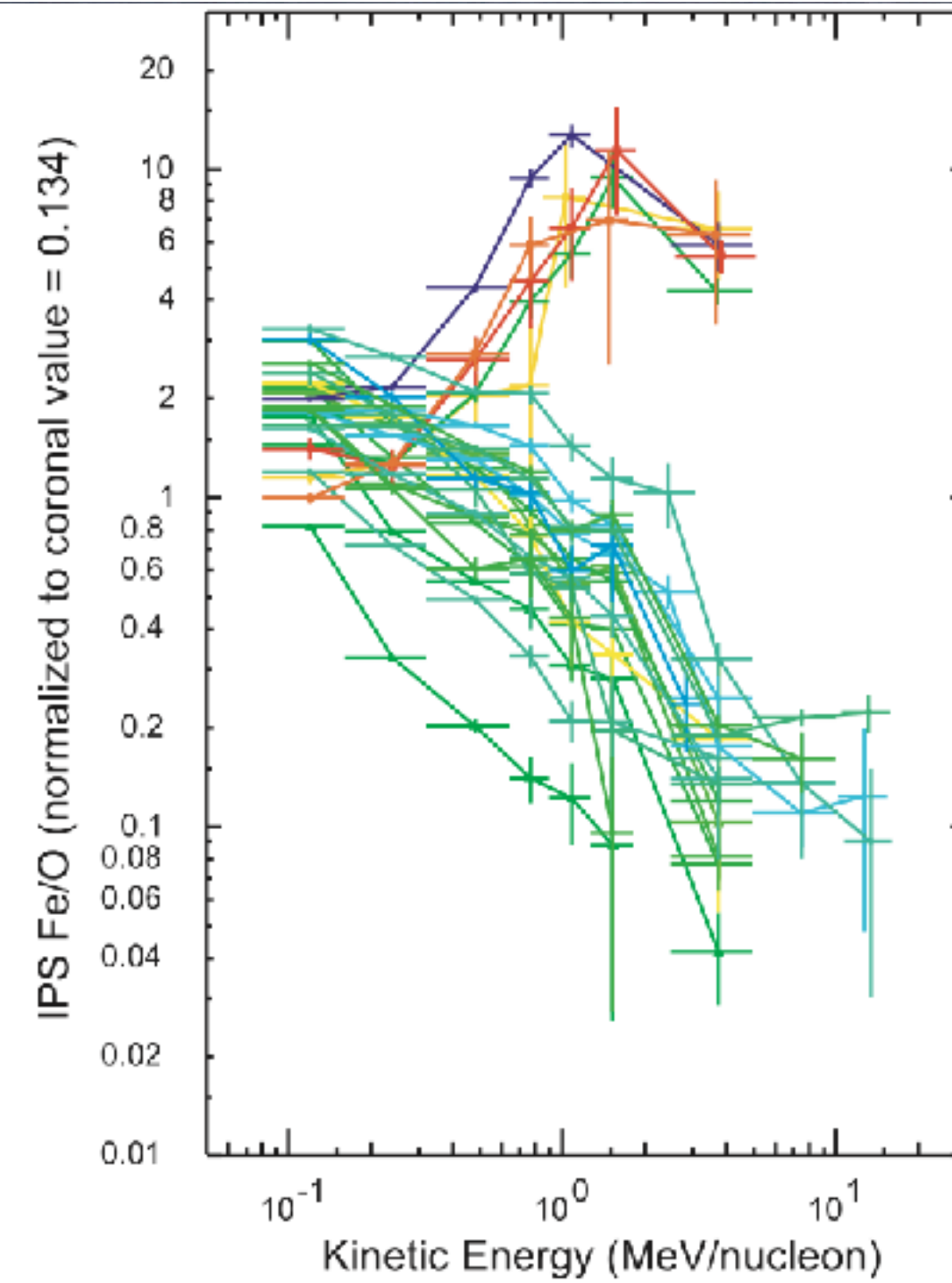


☉ Different slopes

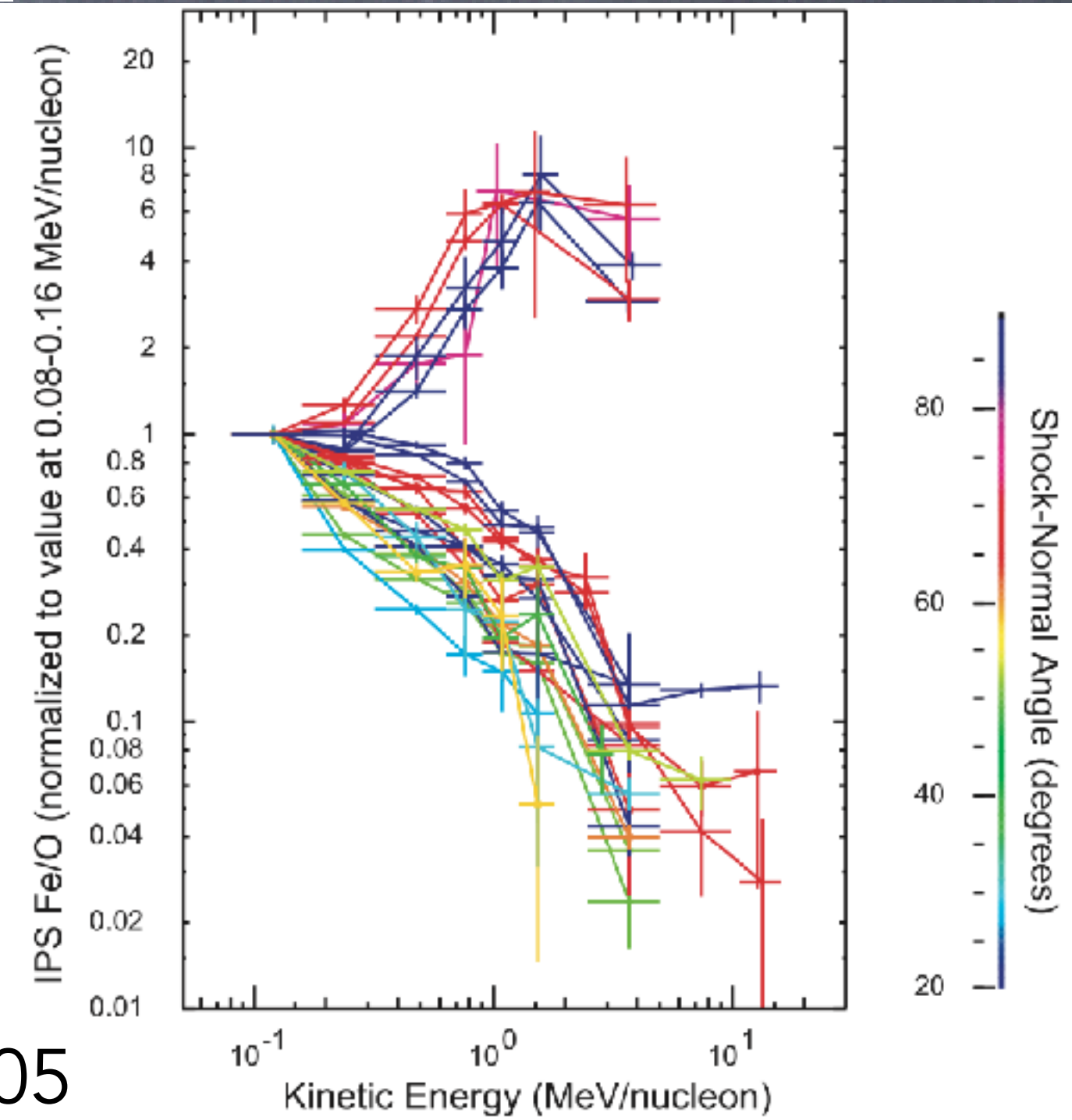
Abundances in Cosmic Rays and Solar Energetic Particles



- Different slopes
- SEP abundances depend on shock inclination and presence of seeds



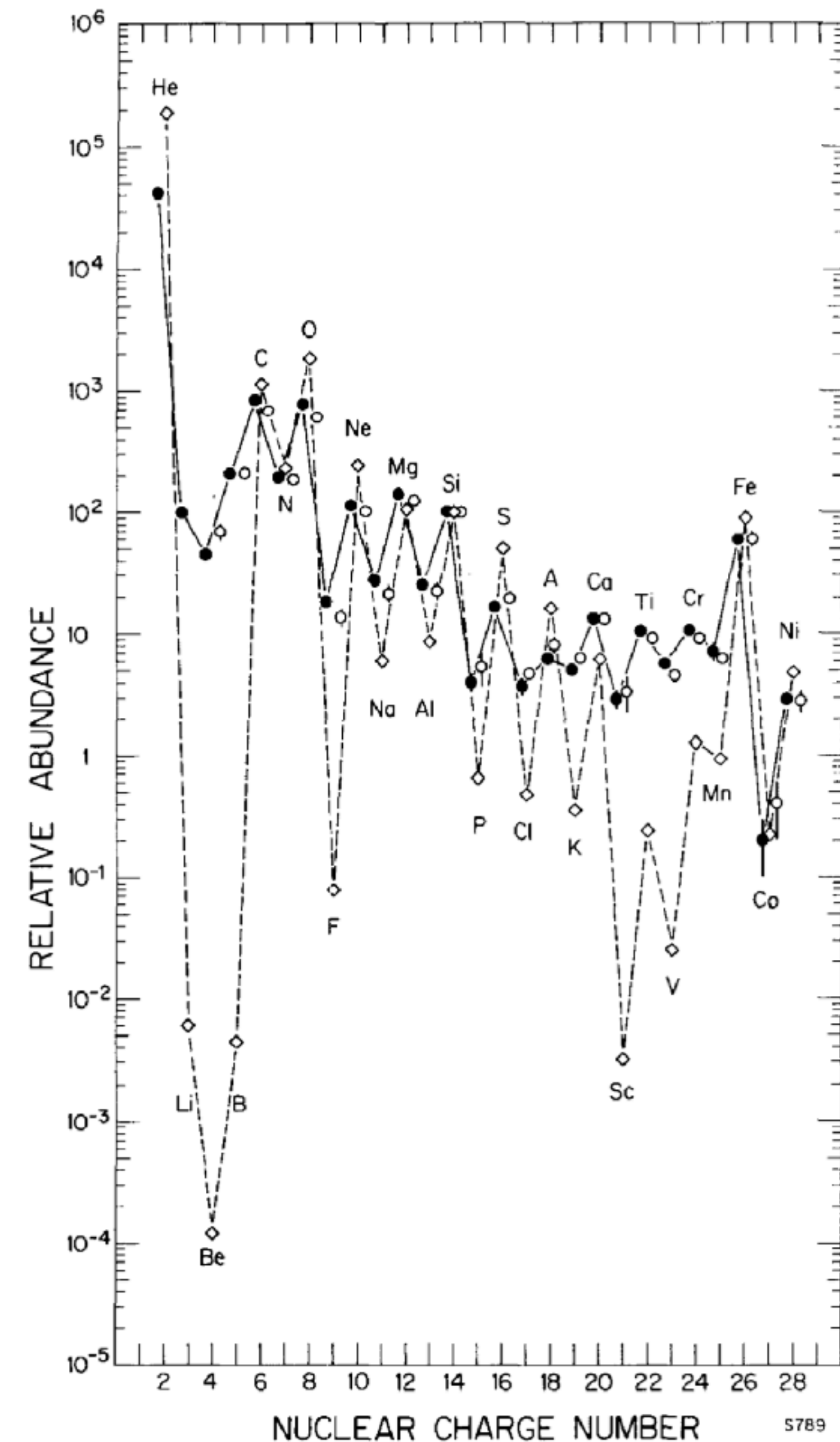
Tylka+05



Chemical Composition of Galactic CRs - I



- Similar to **solar** at low energies
(Simpson 1983);
- Largest **anomalies** (Li, Be, B, sub-Fe elements) explained by **spallation** during propagation



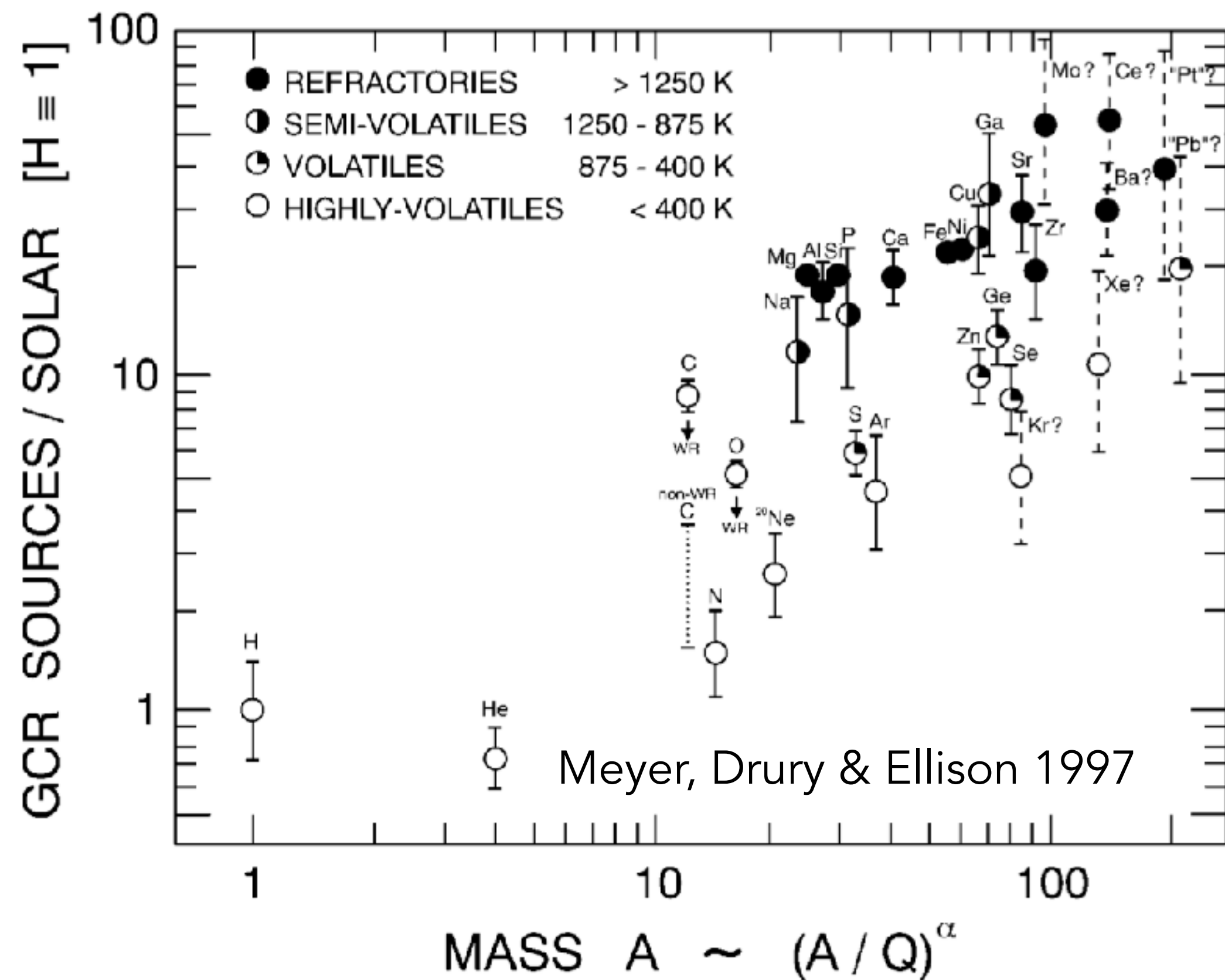
Chemical Composition of Galactic CRs - II



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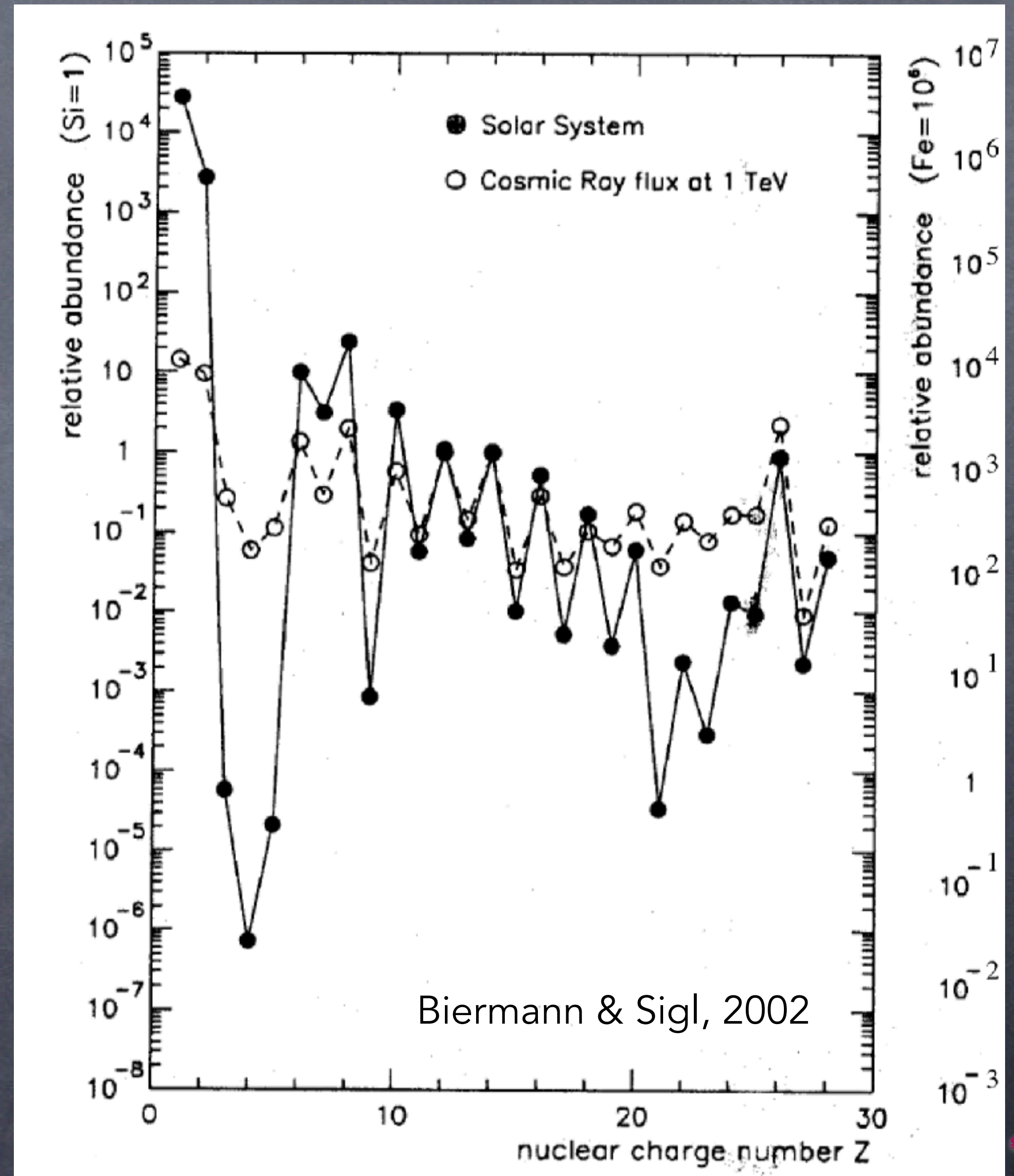
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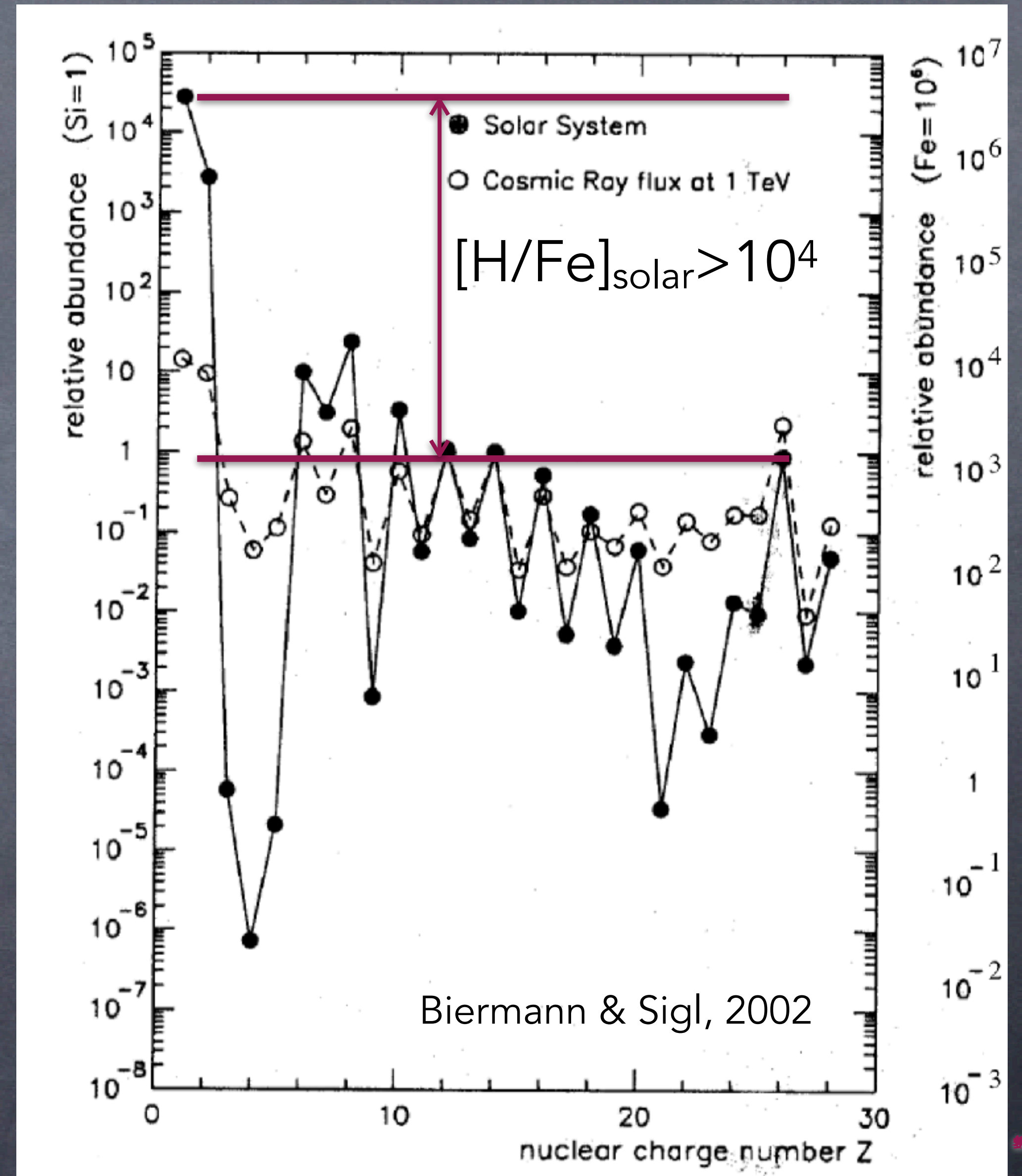
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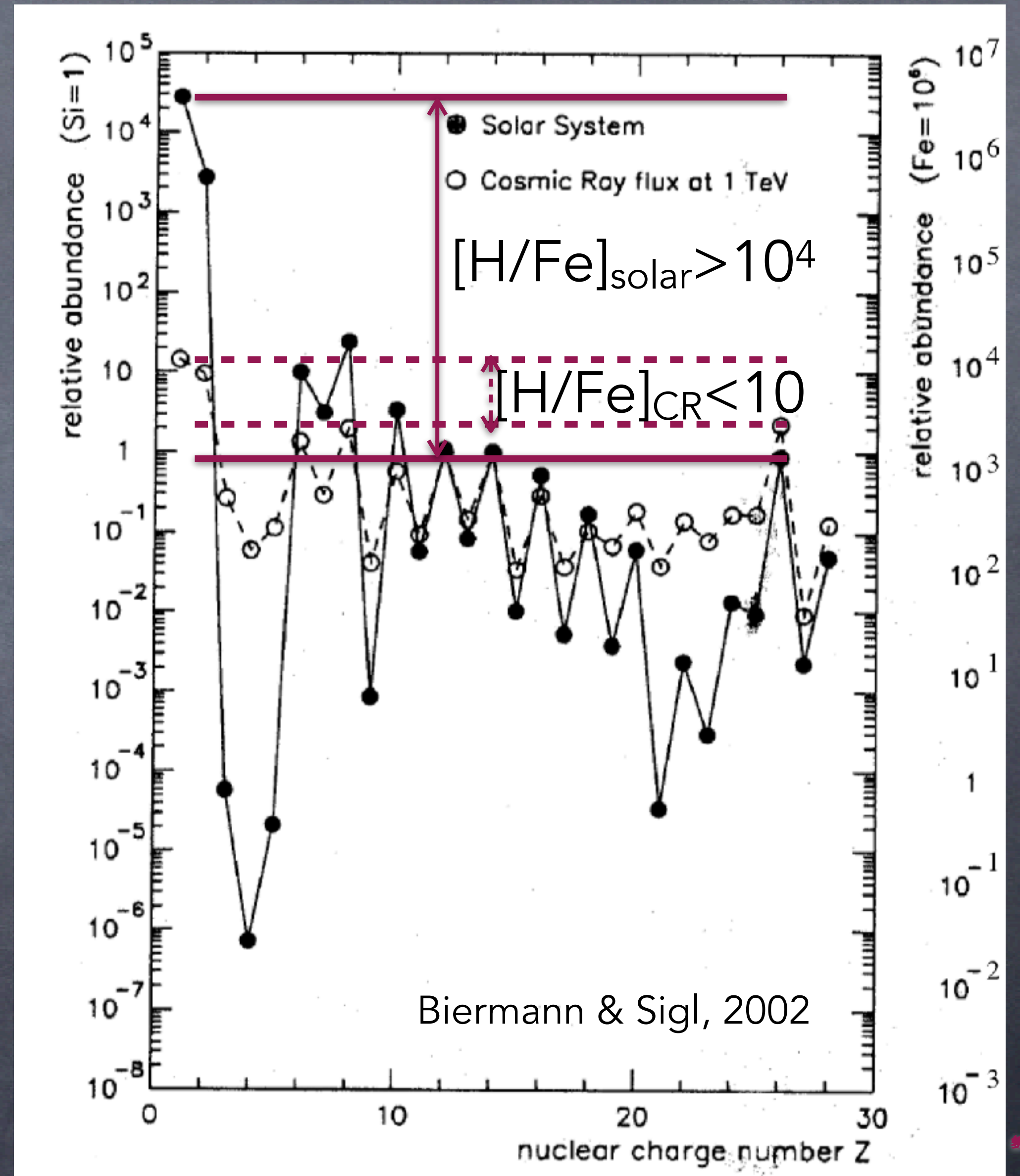
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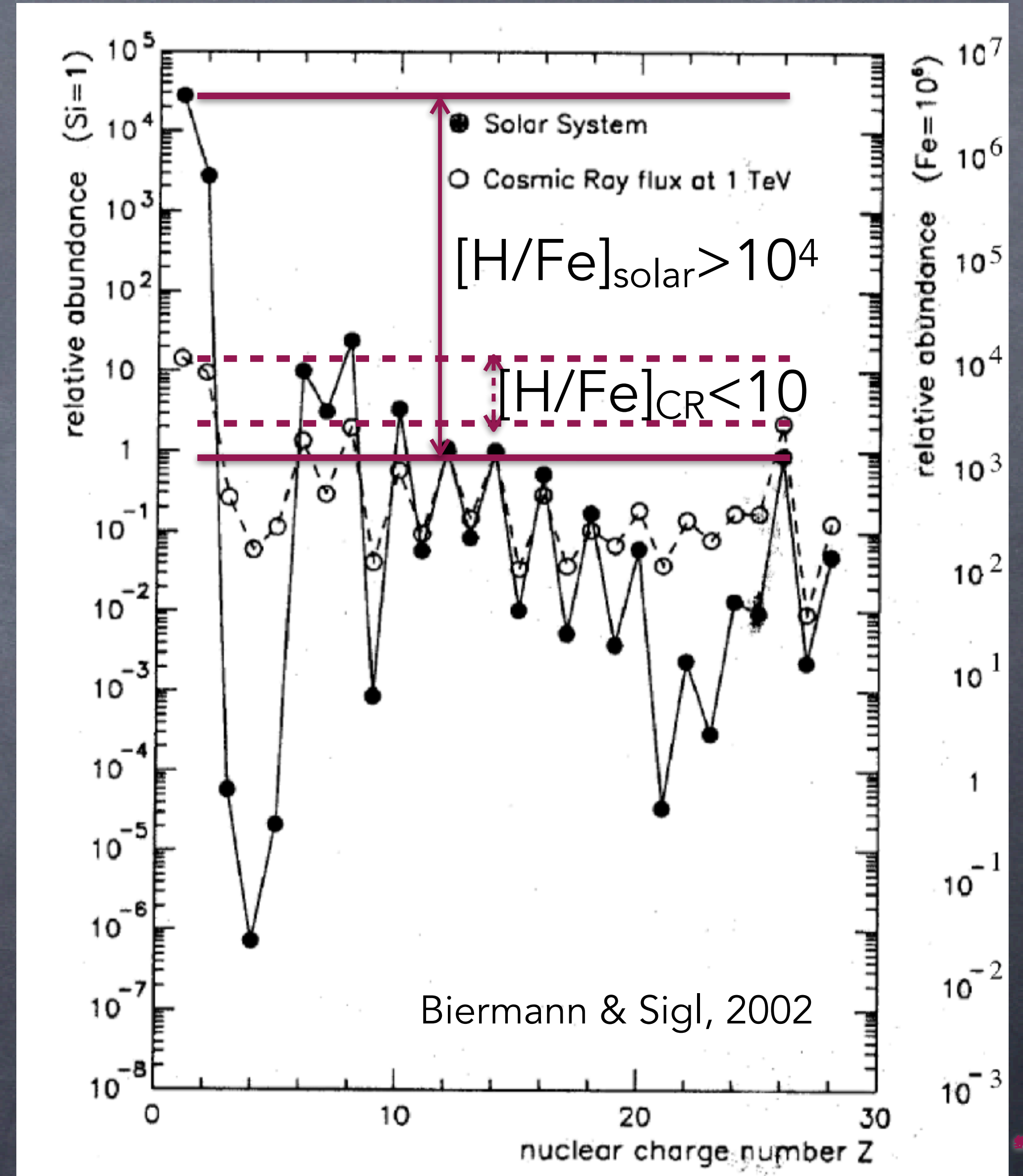
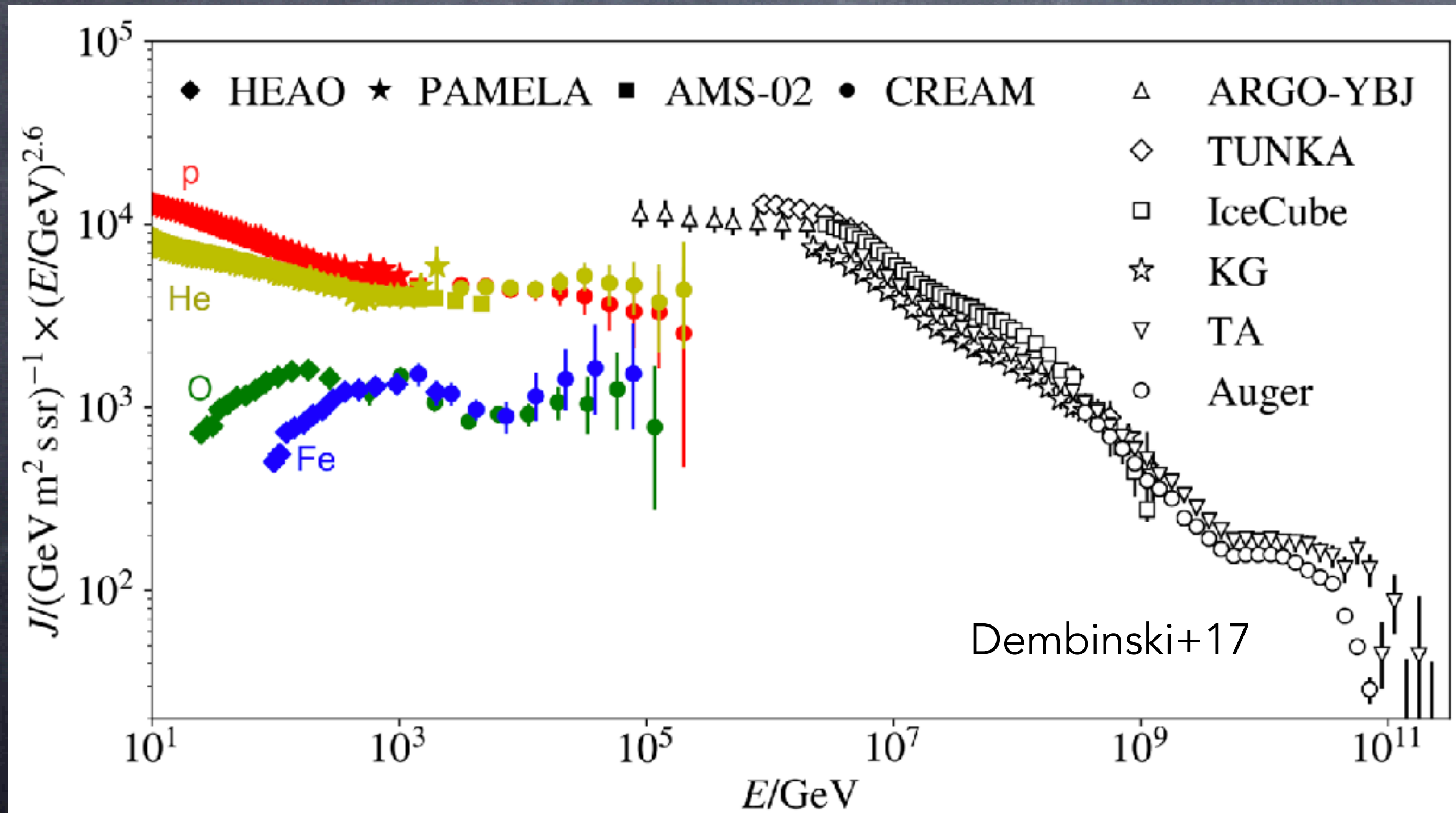
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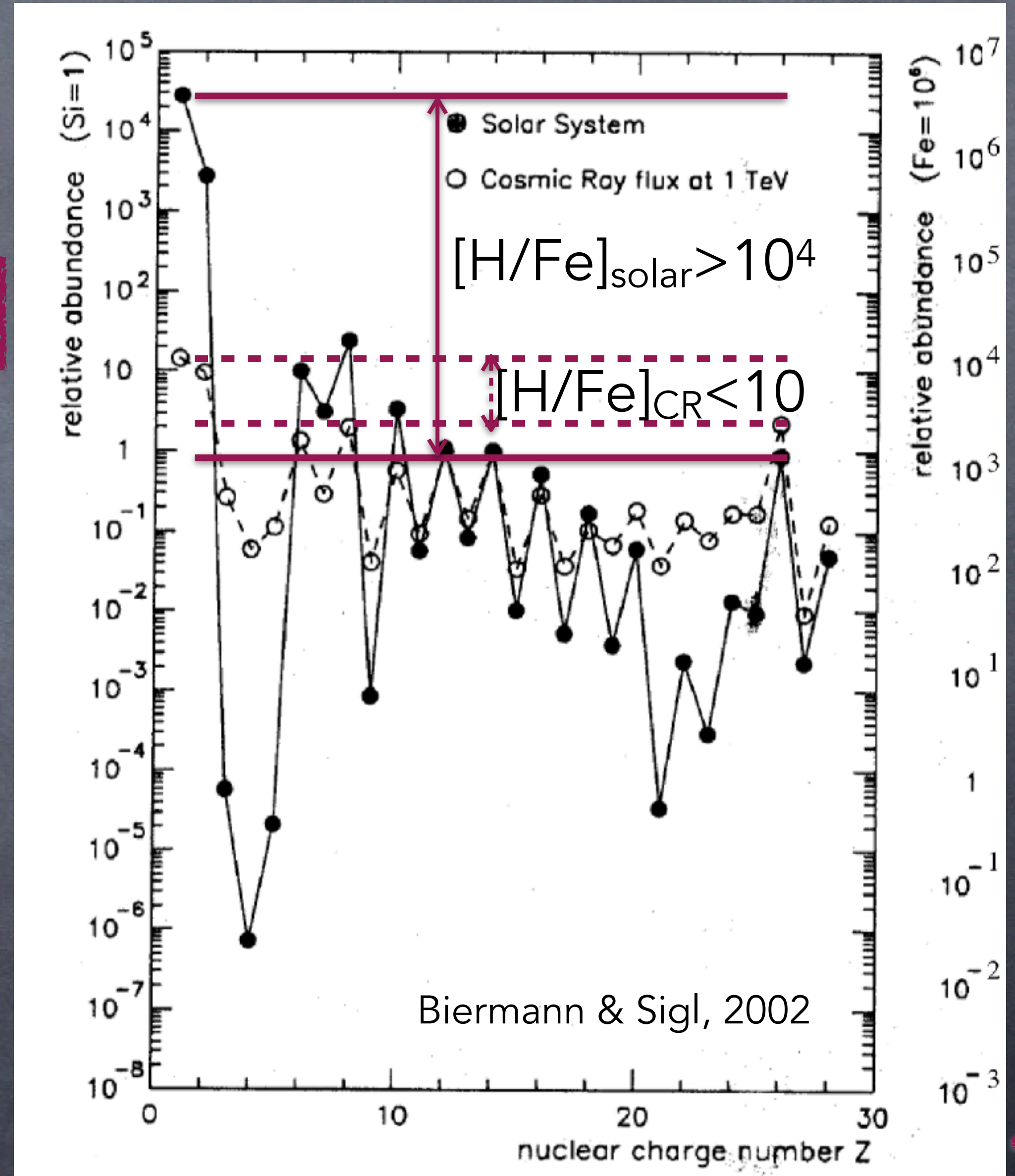
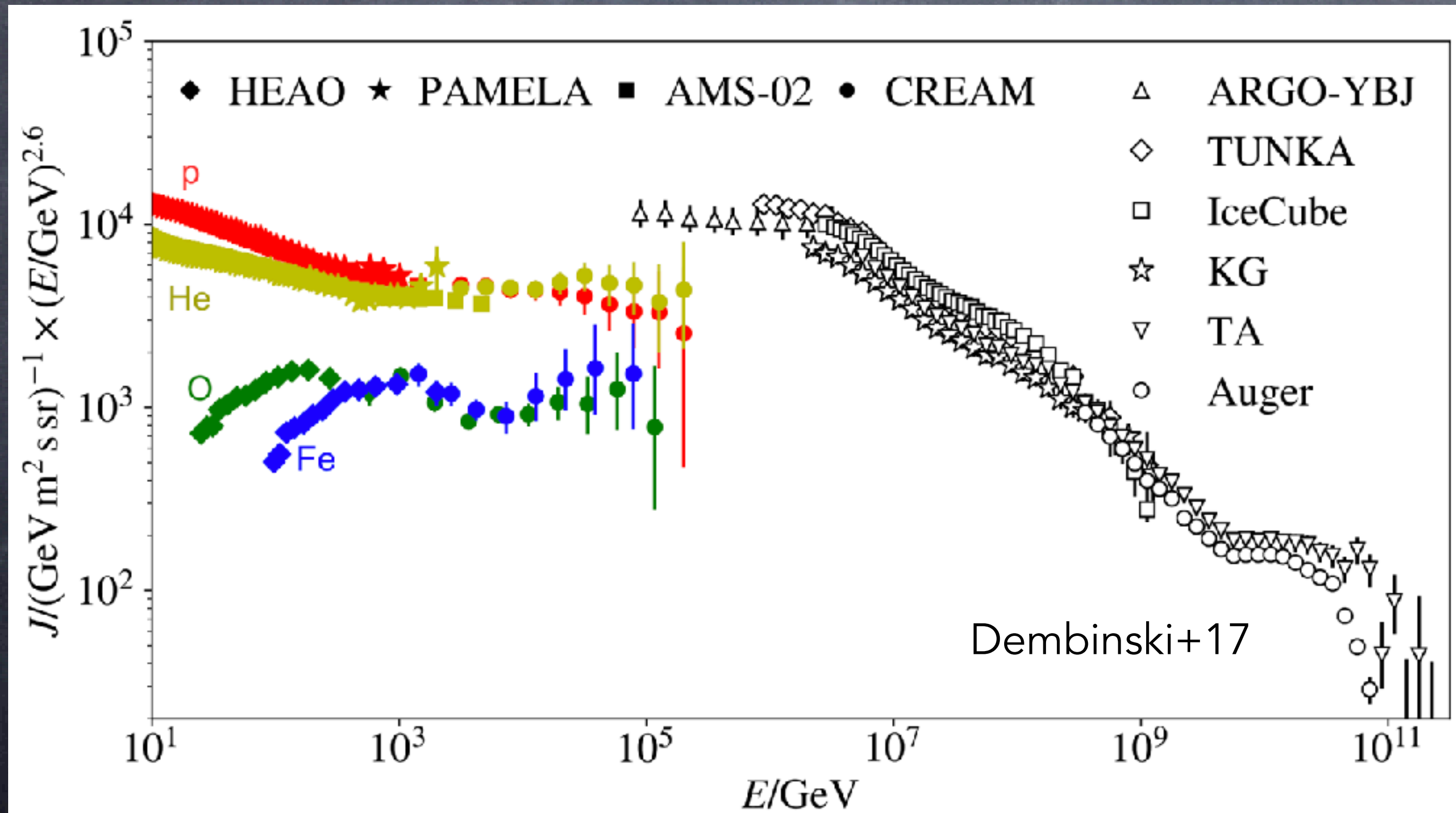


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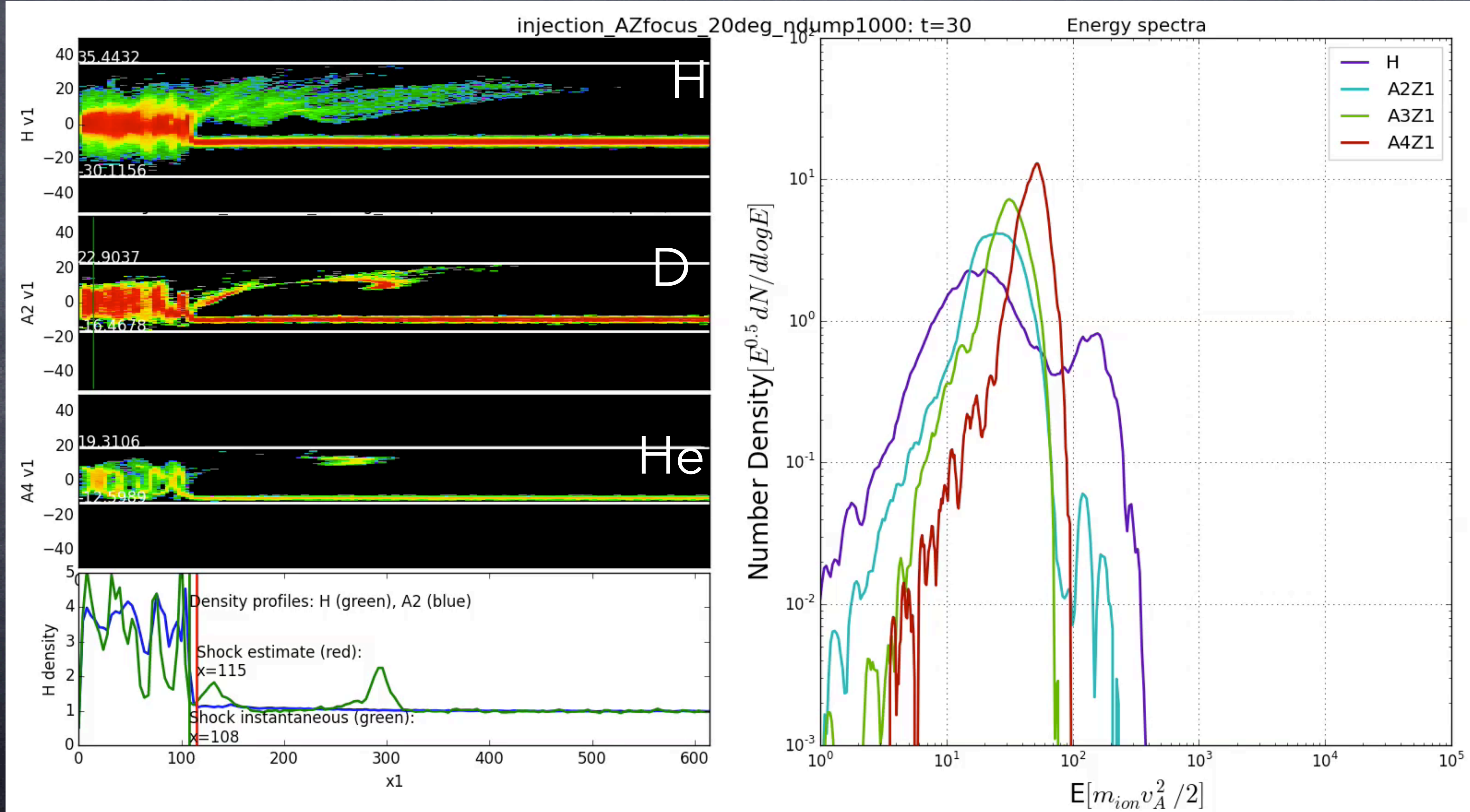
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Heavy nuclei must be **injected more** efficiently than H!



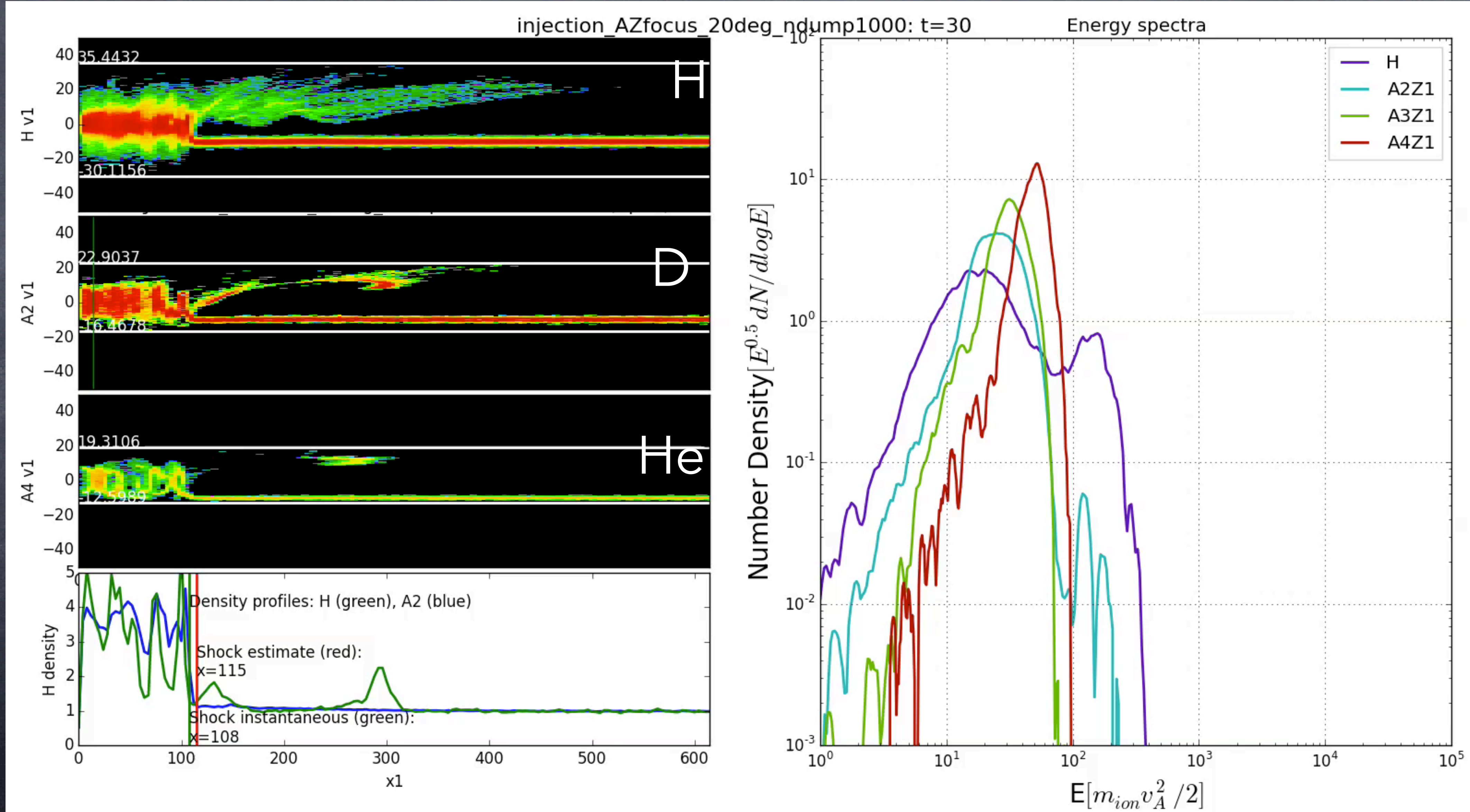
Hybrid Simulations

- M=10, parallel shock, with **singly-ionized** nuclei (DC, Yi, Spitkovsky 2017)



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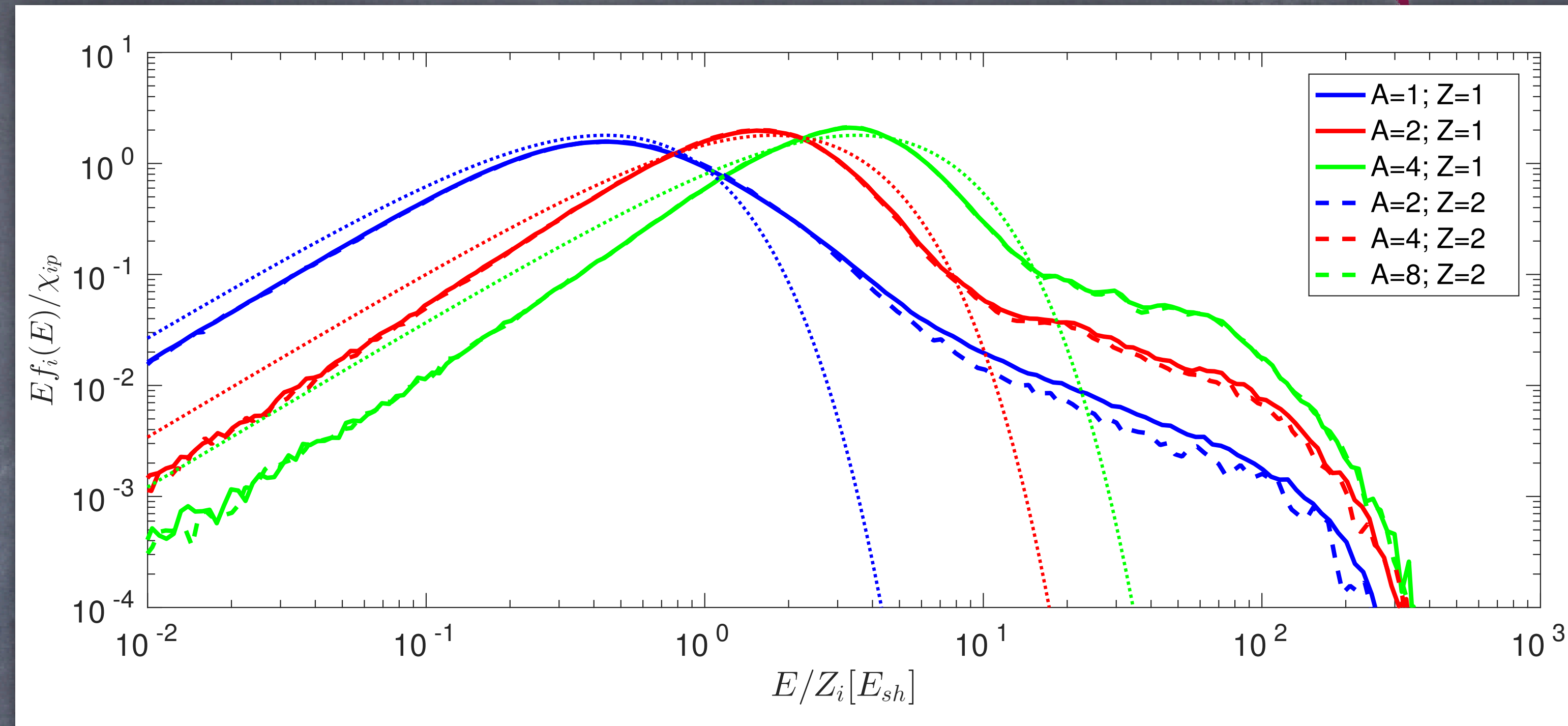
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Hybrid Simulations with Heavy Ions



- Quasi-parallel shock, $M=20$
Ion DSA when proton DSA!

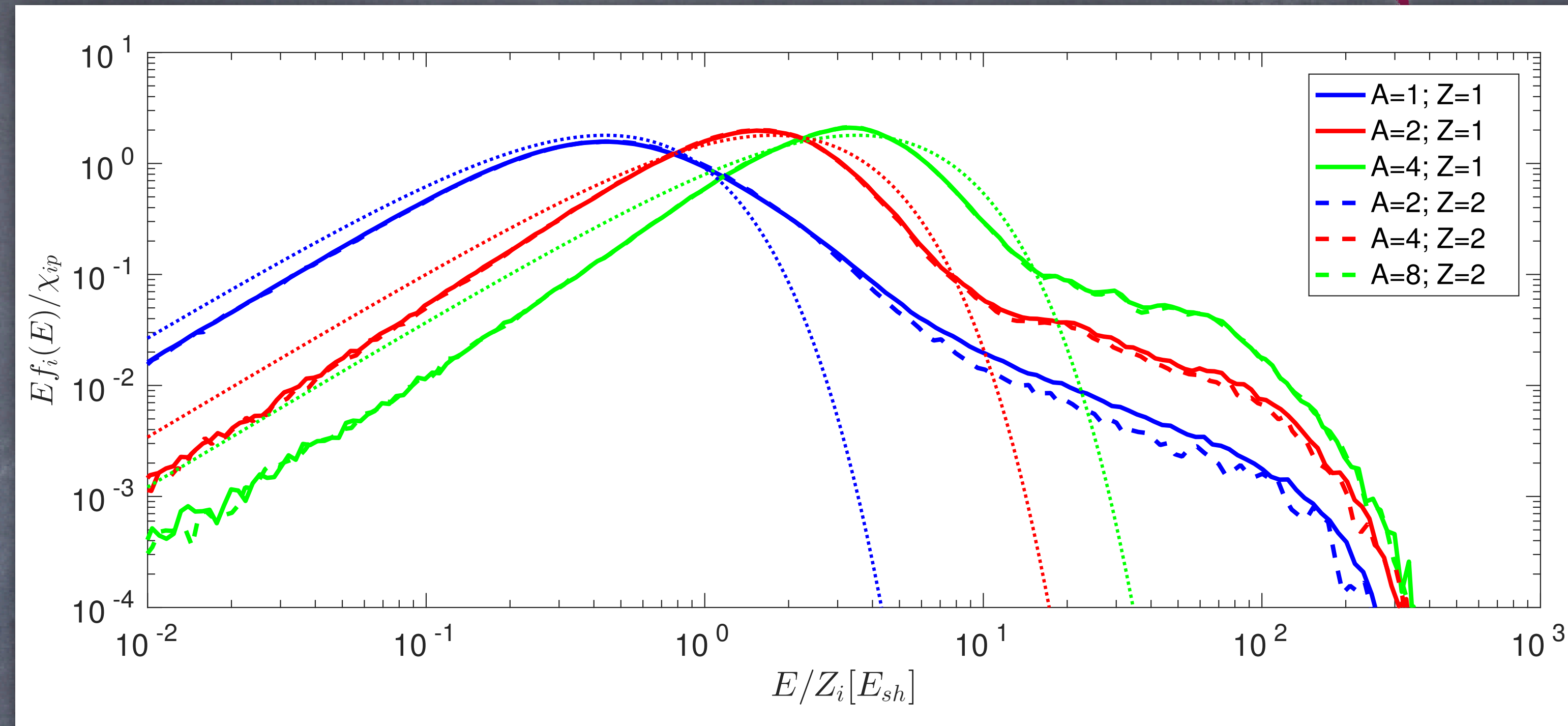


DC, Yi & Spitkovsky, 2017

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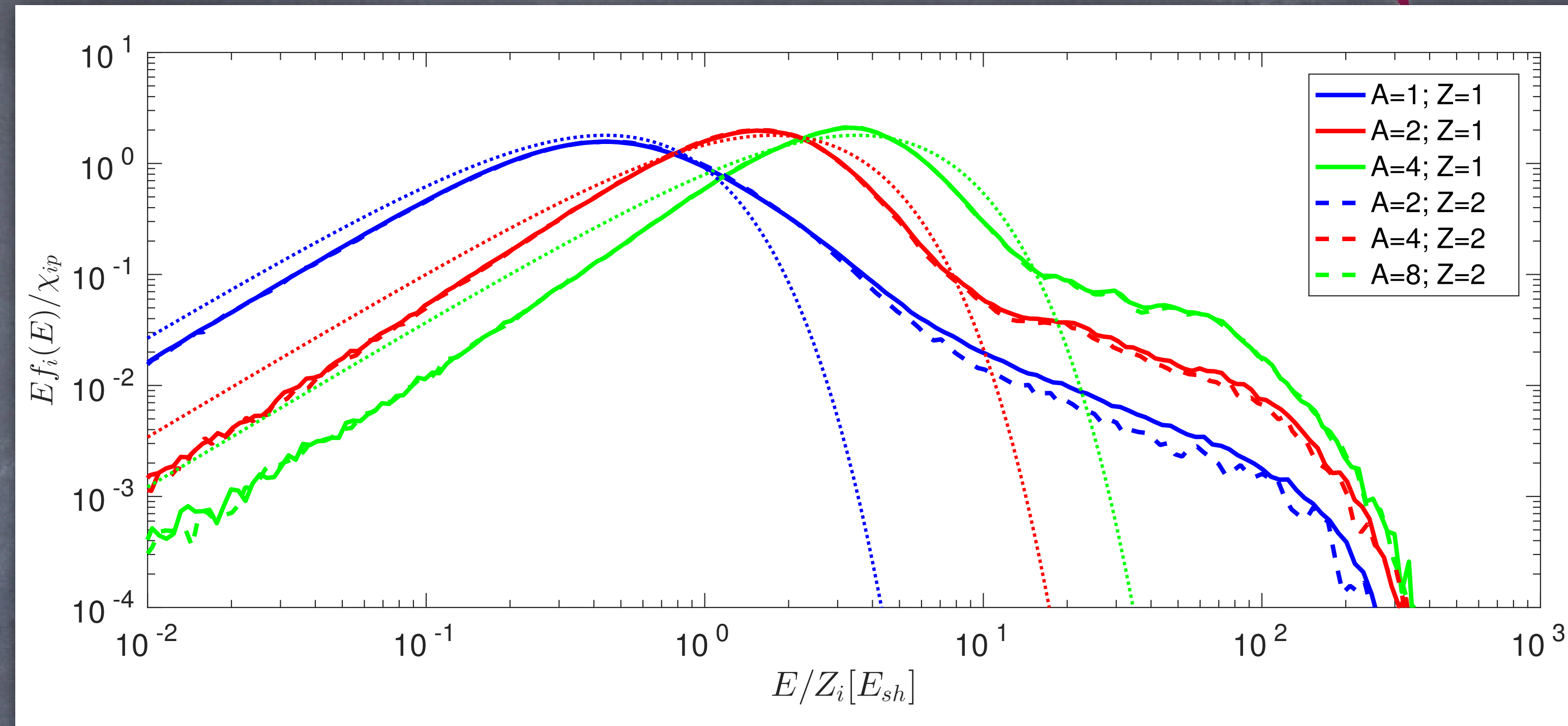
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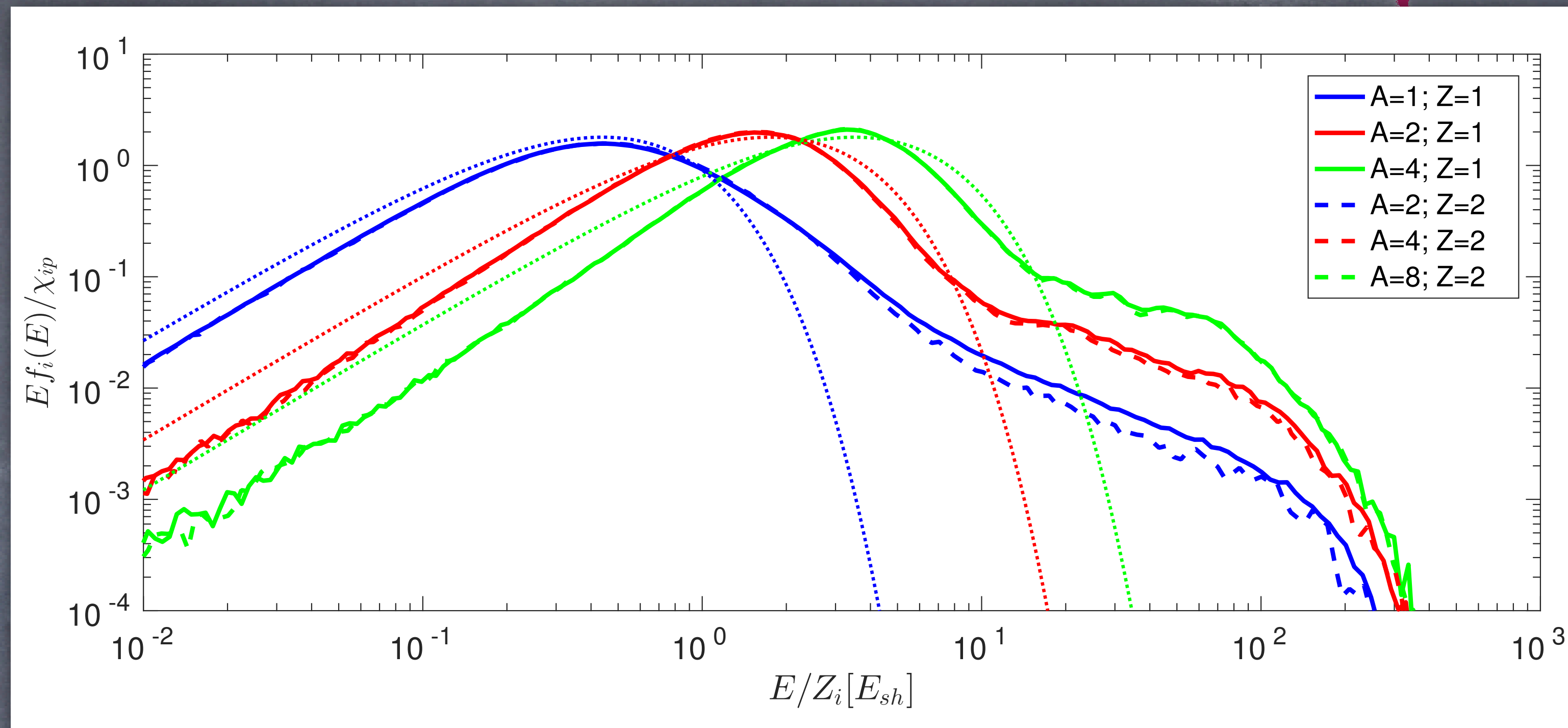
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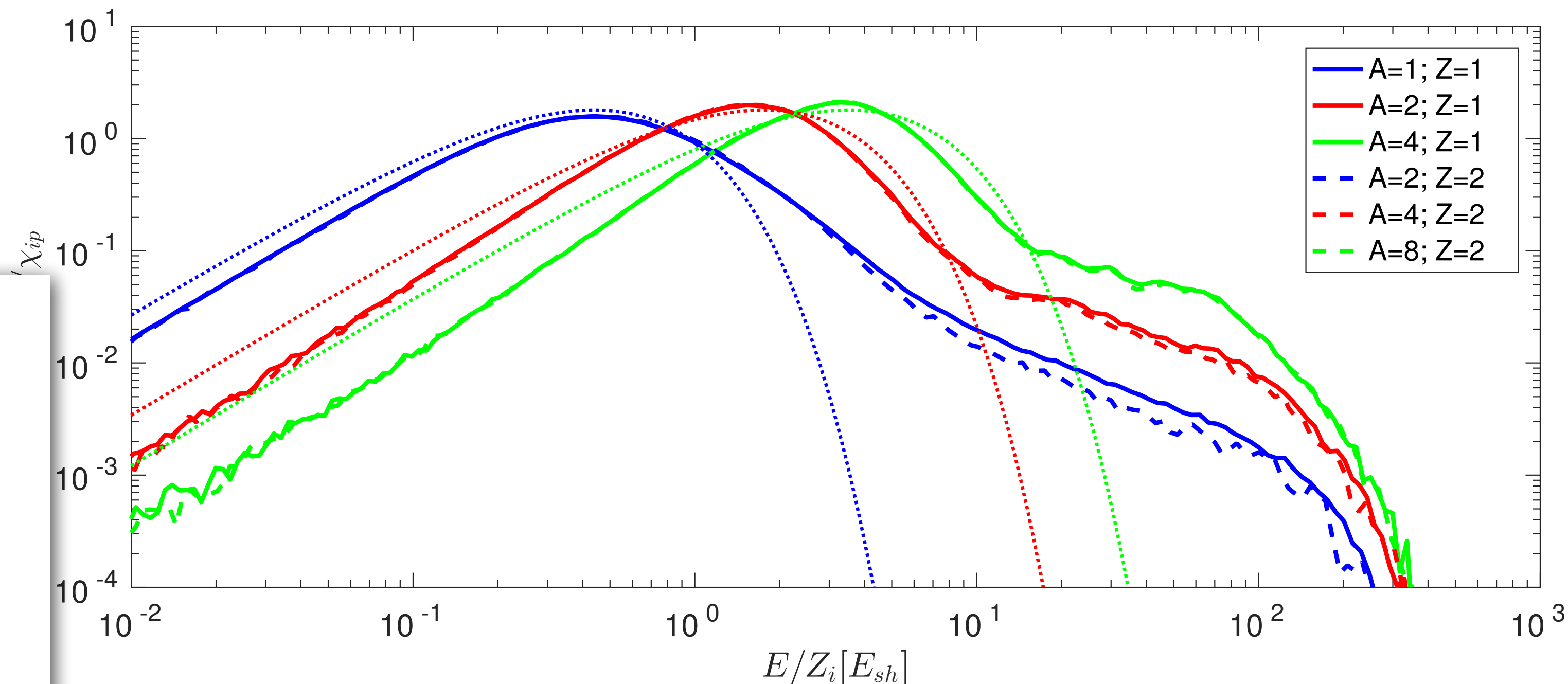
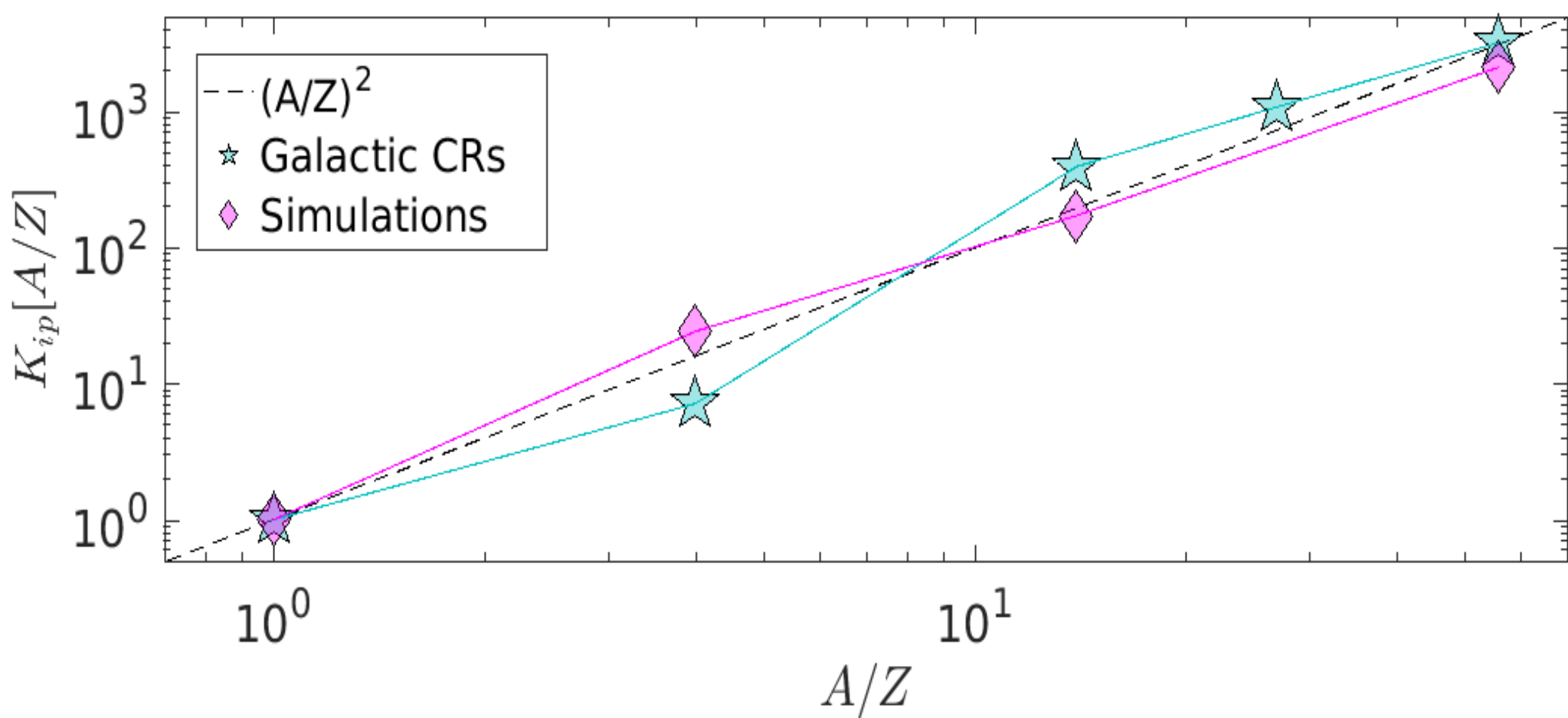
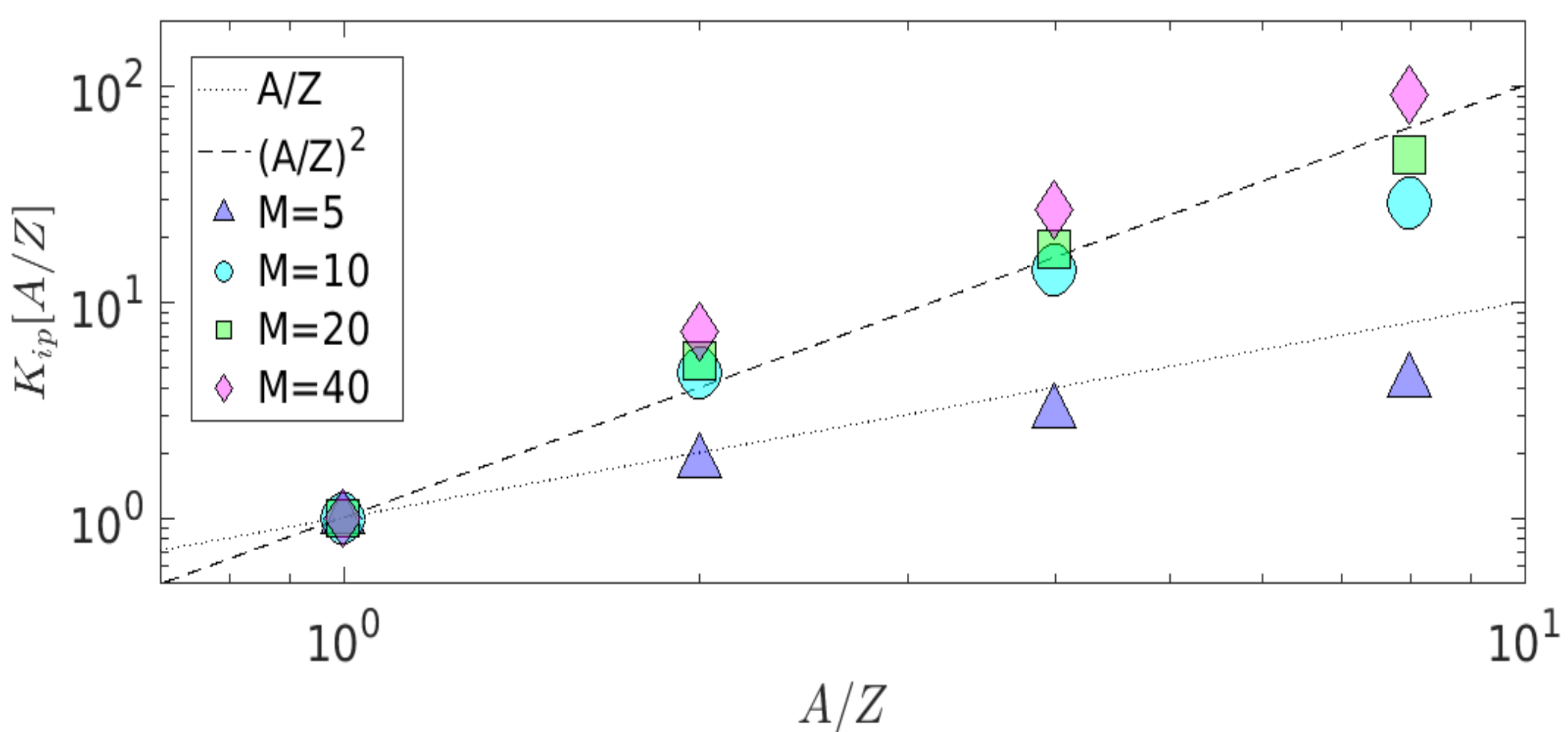
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DC, Yi & Spitkovsky, 2017

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- Explains CR chemical enhancements!

Helium is *not* test-particle!



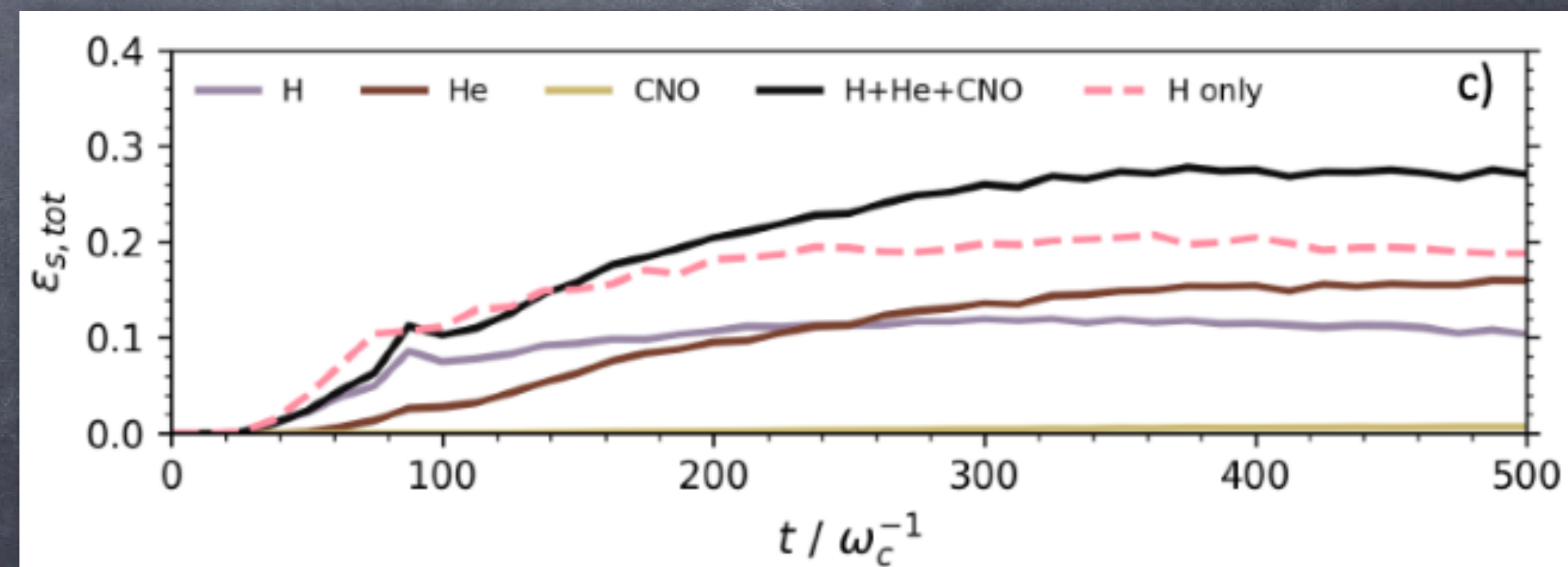
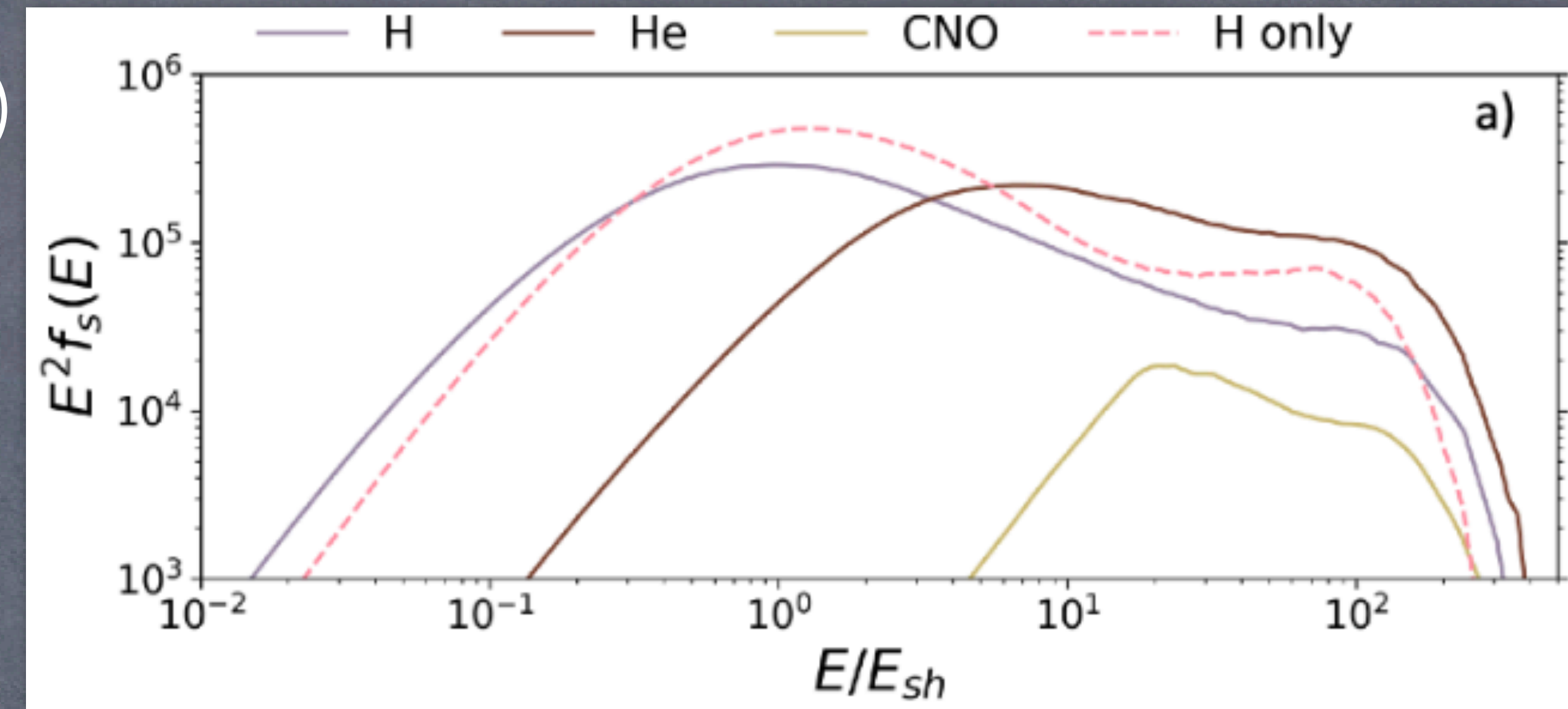
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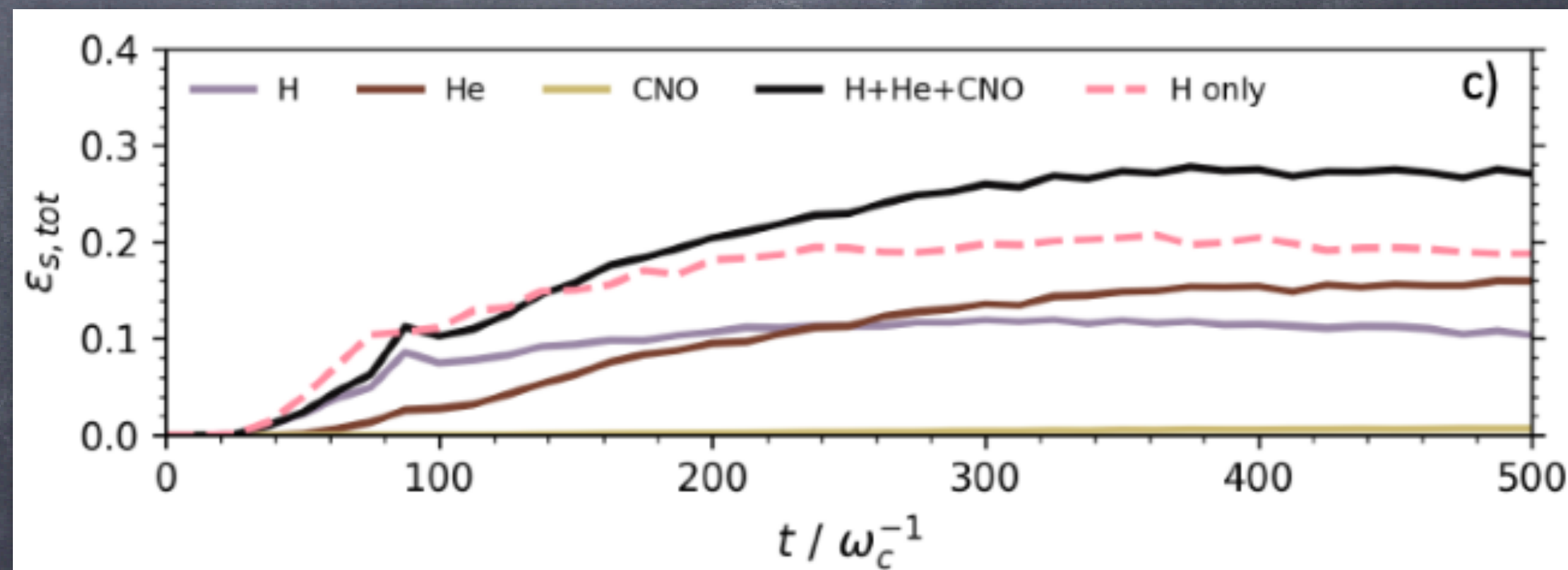
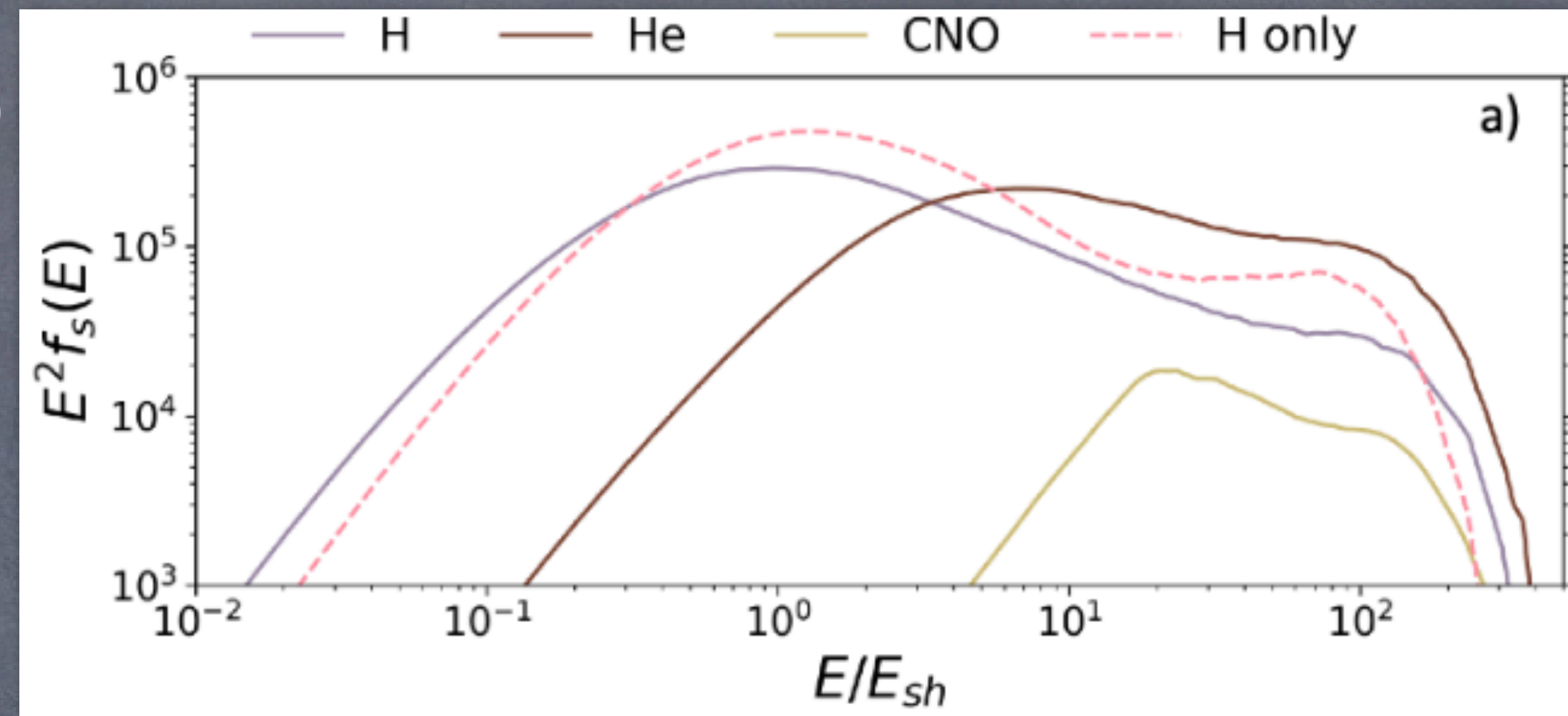
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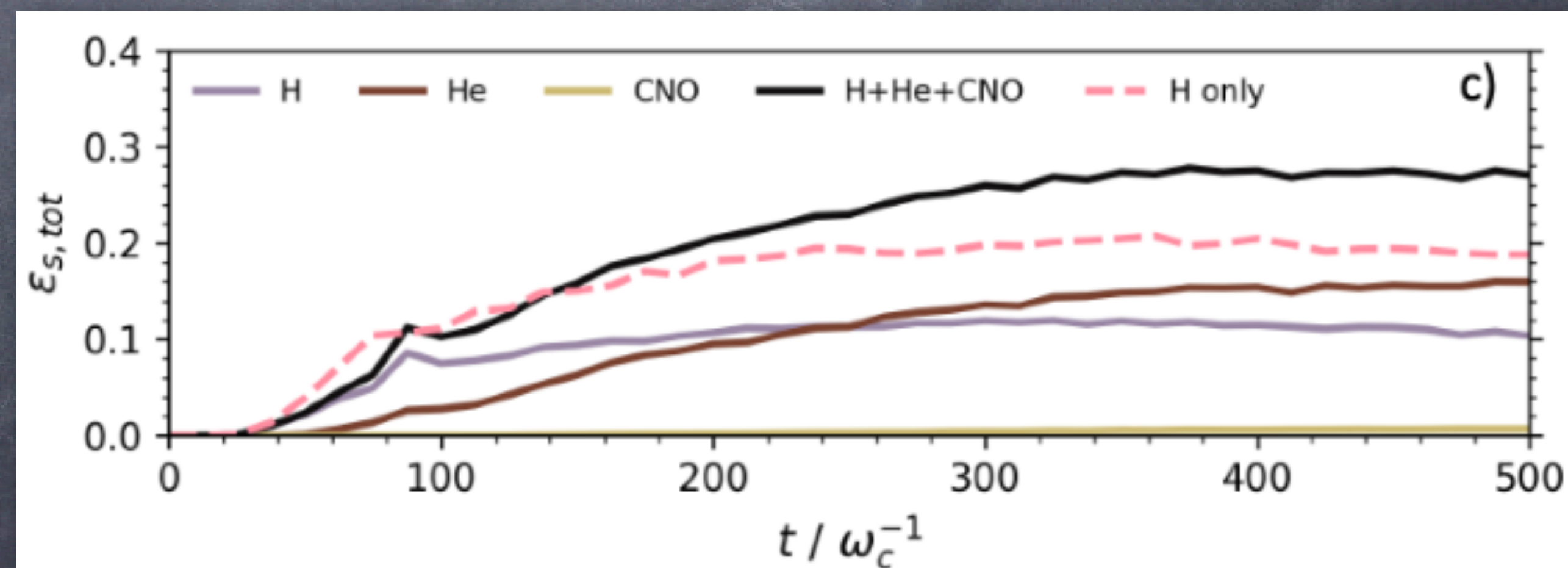
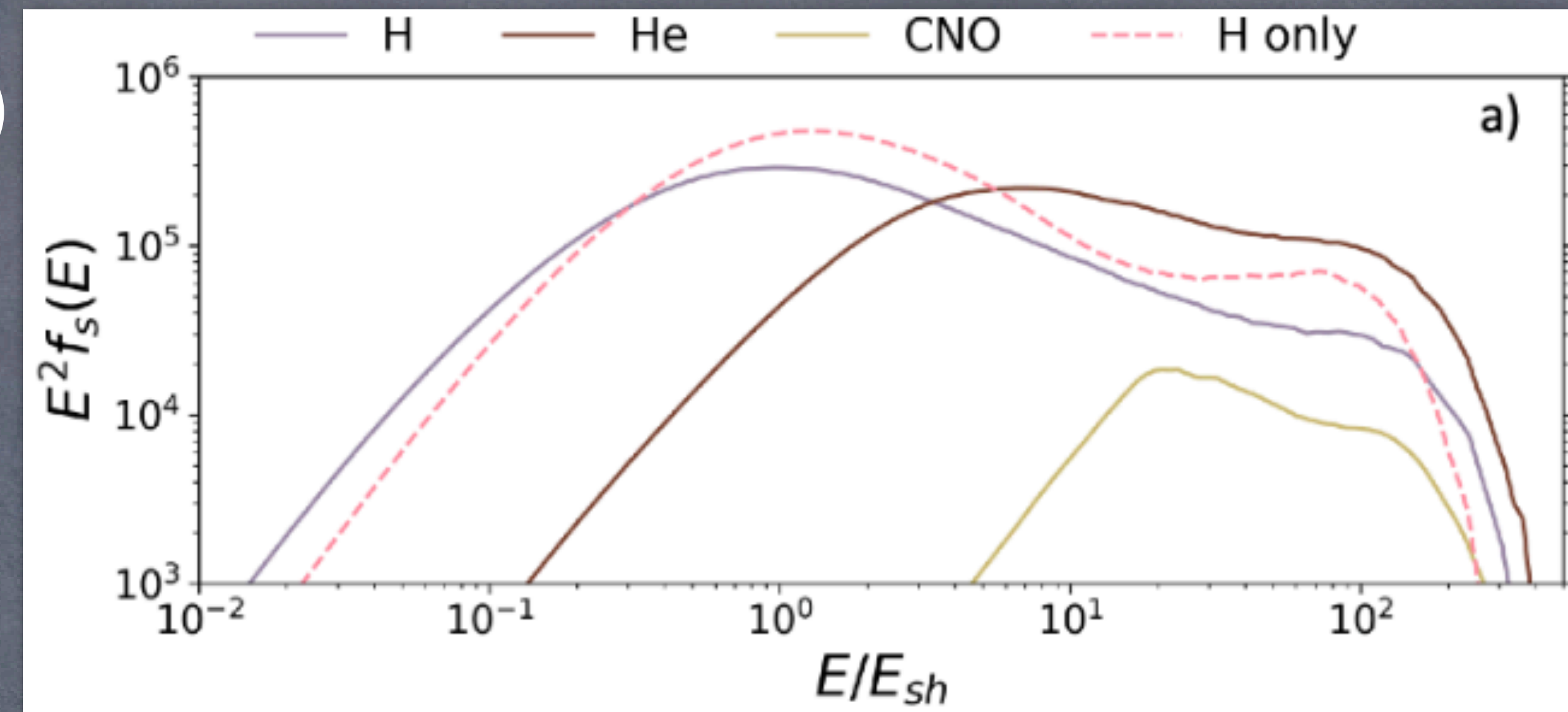
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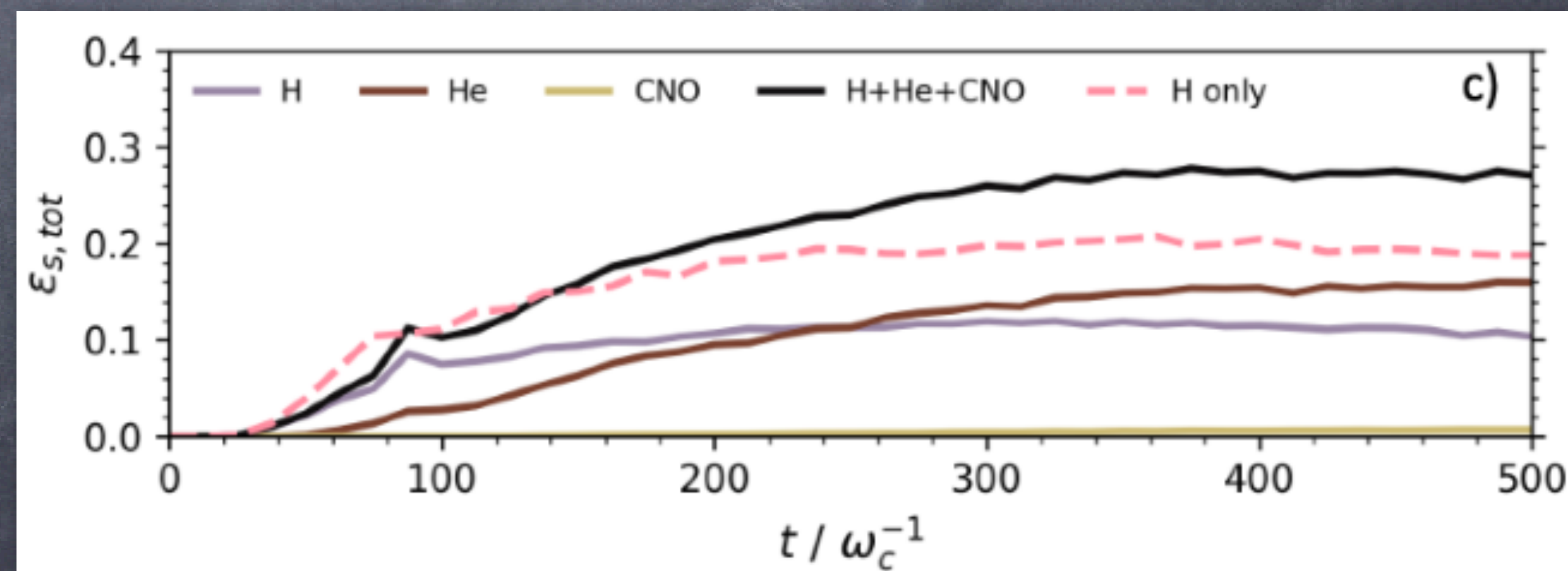
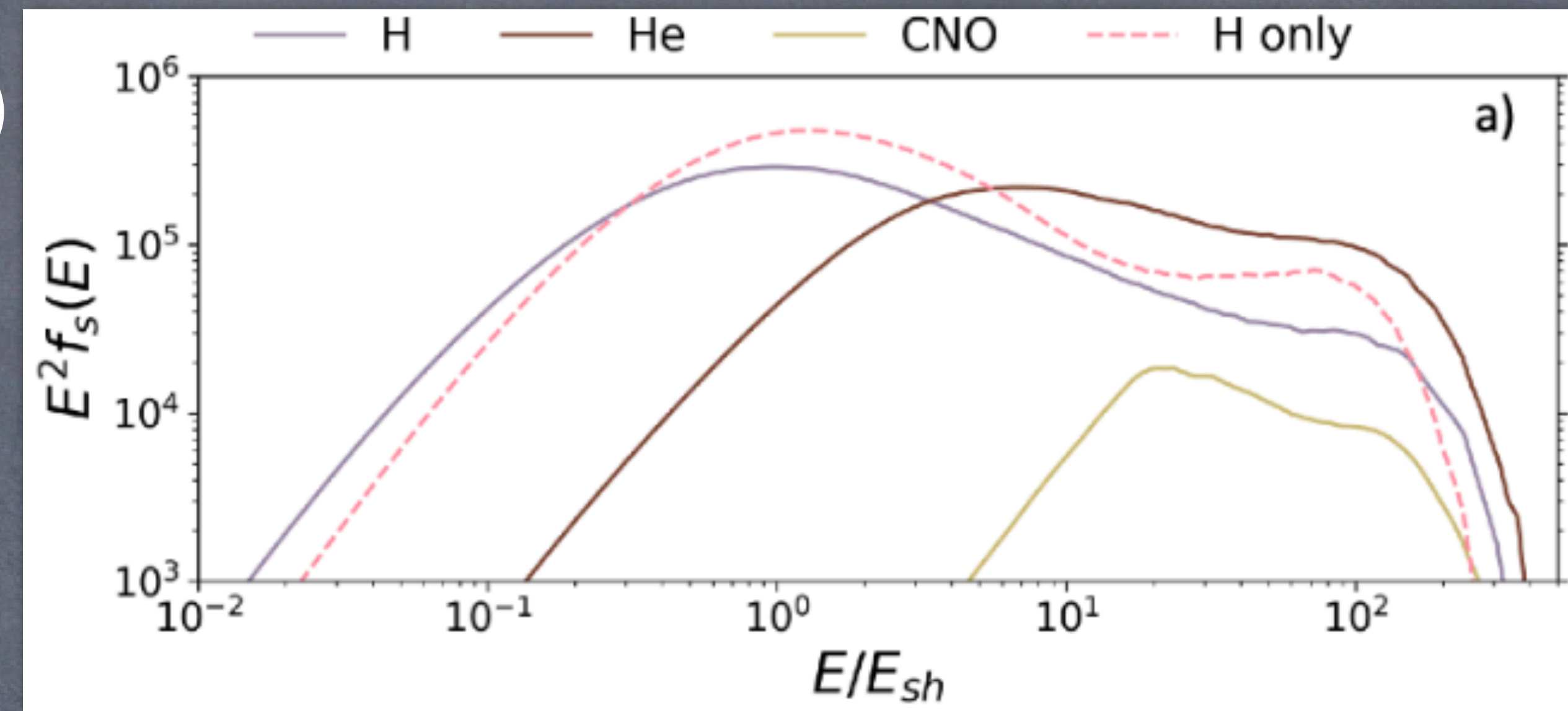
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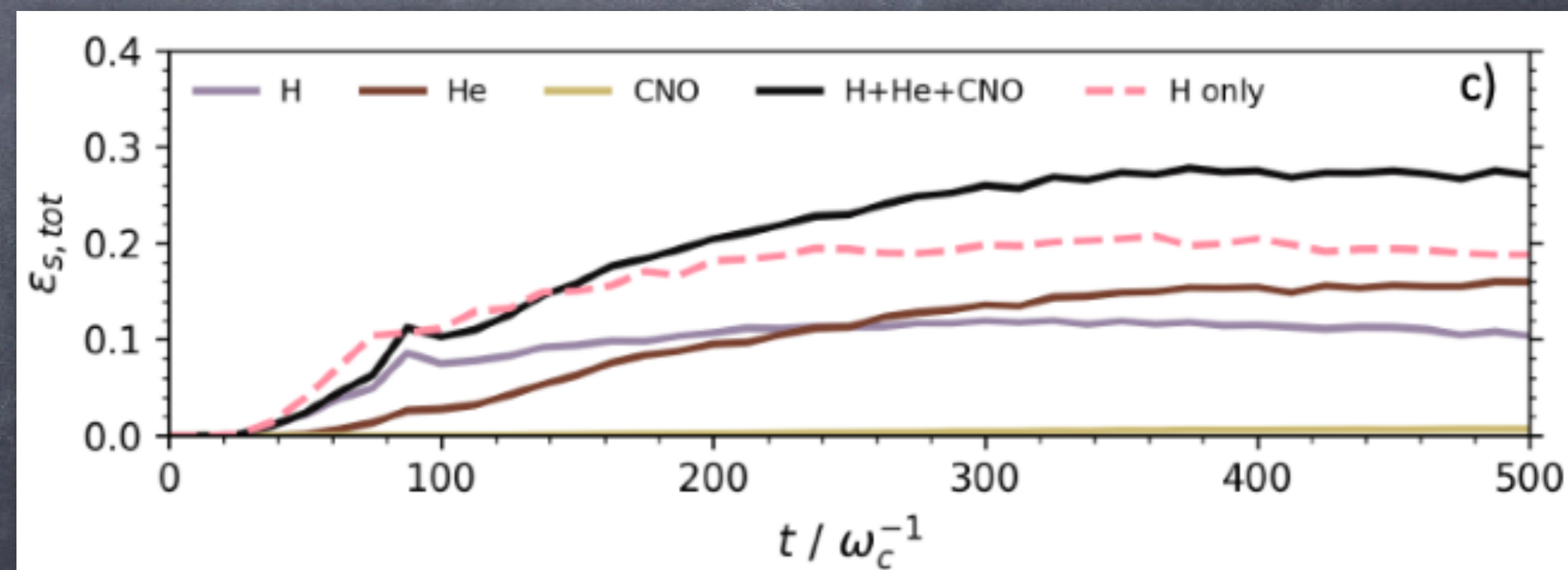
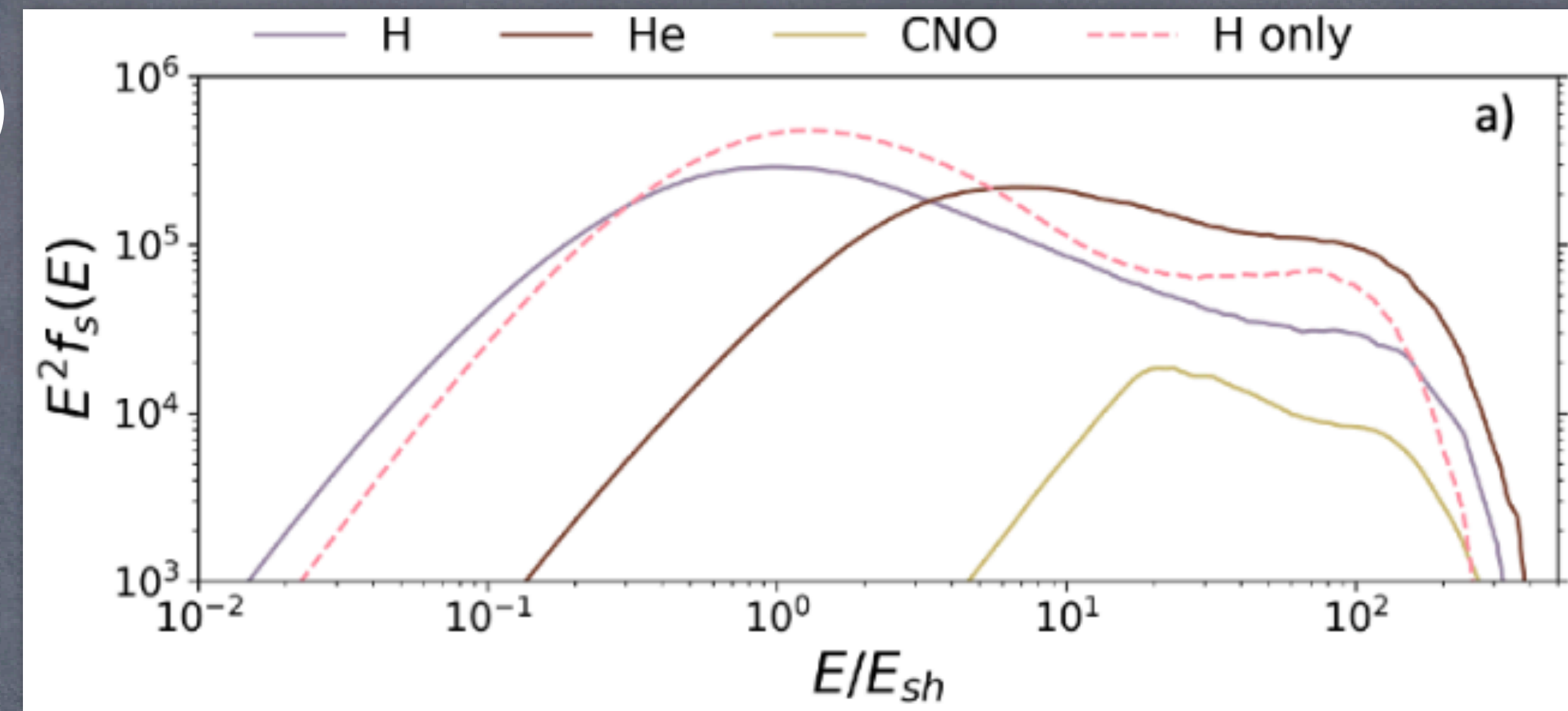
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- **Nuclei acceleration**
 - Efficient when protons are accelerated (**requires turbulence!**)
 - For strong shocks, **enhancement** $\propto (A/Z)^2$, for $M_s \lesssim 5$, **enhancement** $\propto A/Z$