Acceleration of cosmic rays

Brian Reville

L. Härer, T. Vieu, J. Wang, J. Hinton, F. Aharonian, ZQ Huang, A. Shirin T
N. Schween, F. Schulze, C. Larkin, J. Kirk, L. Olivera Nieto

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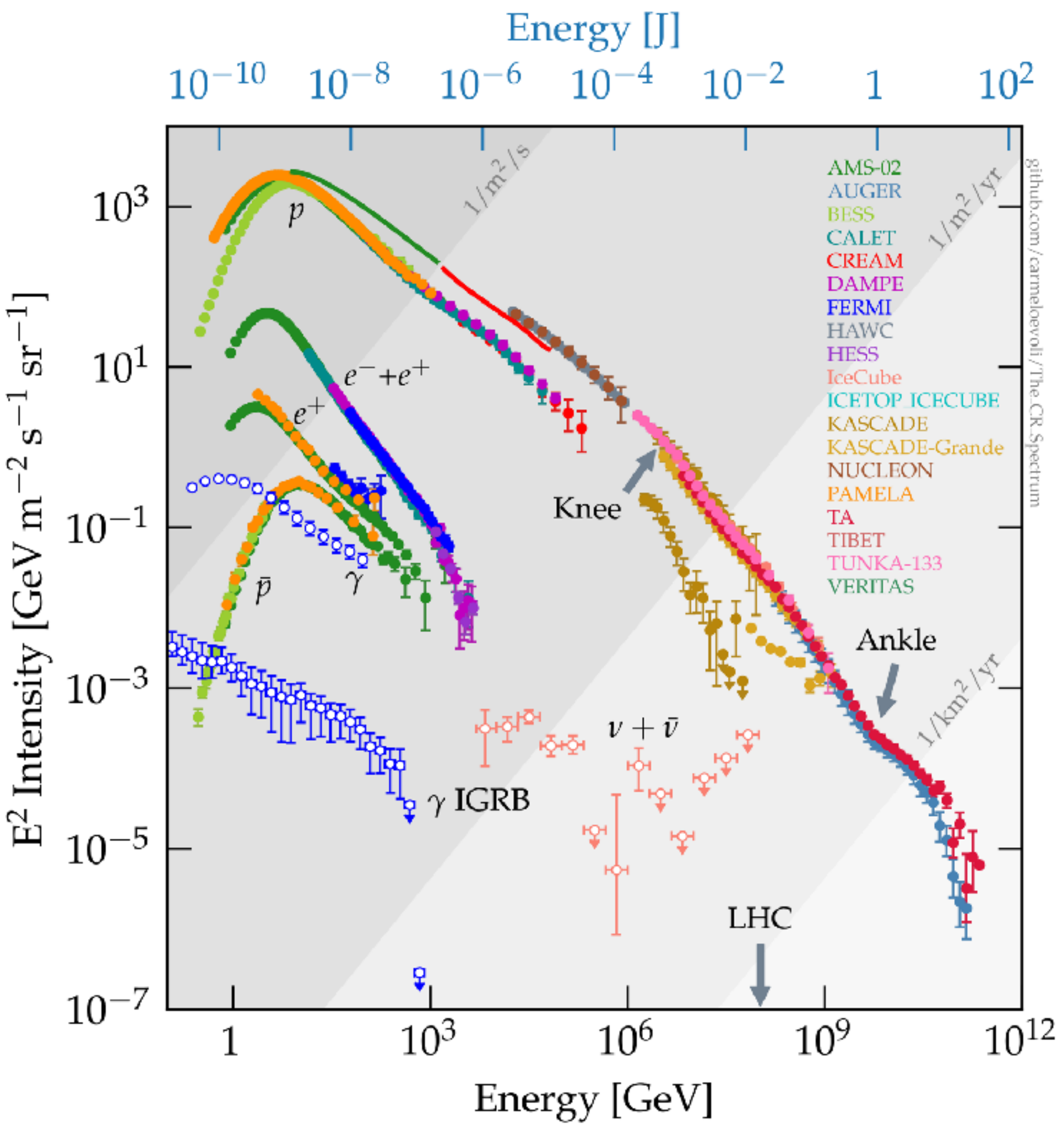
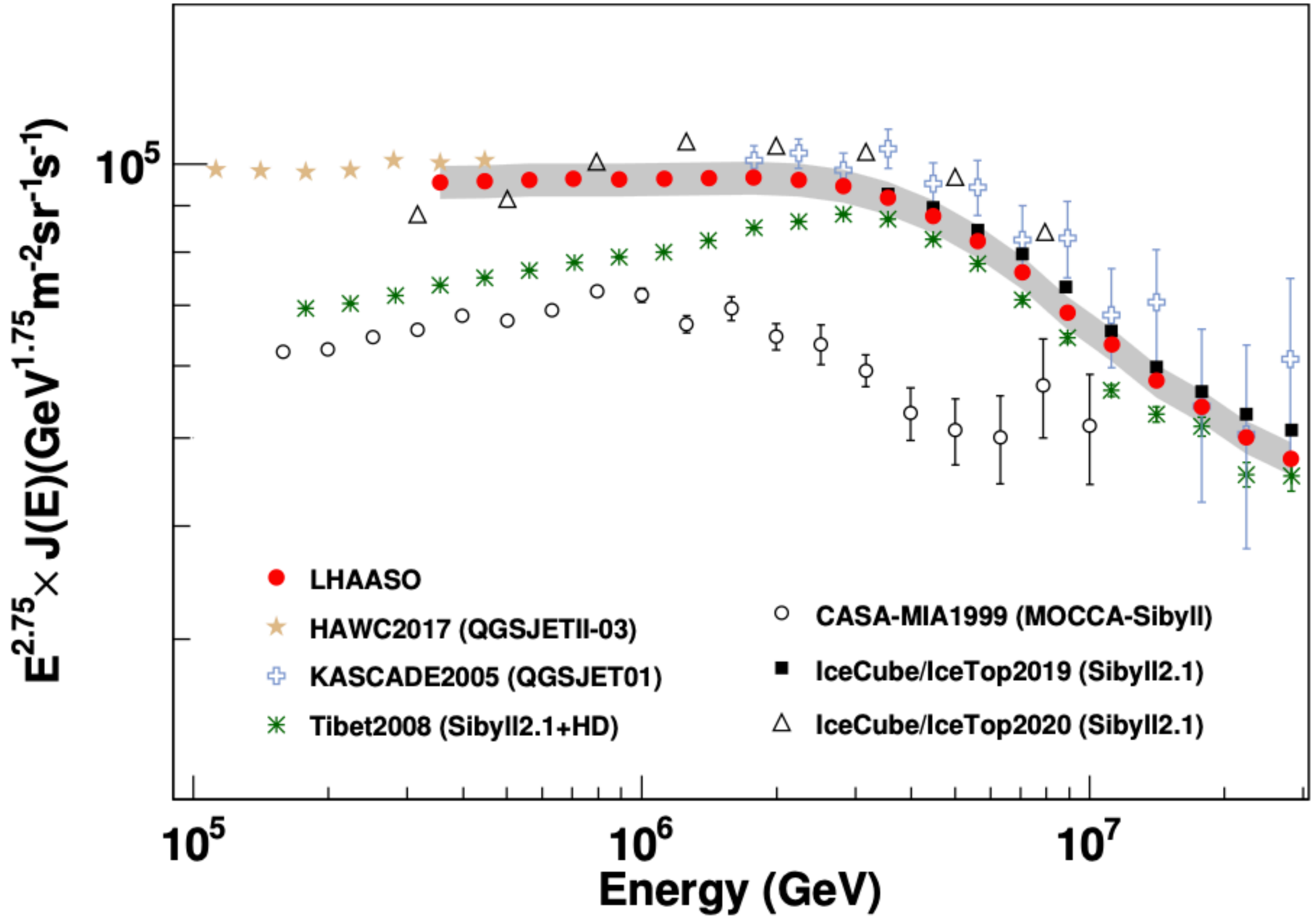
FÜR KERNPHYSIK

THE COSMIC RAY PUZZLE



Credit: C. Evoli

LHAASO Coll. 24



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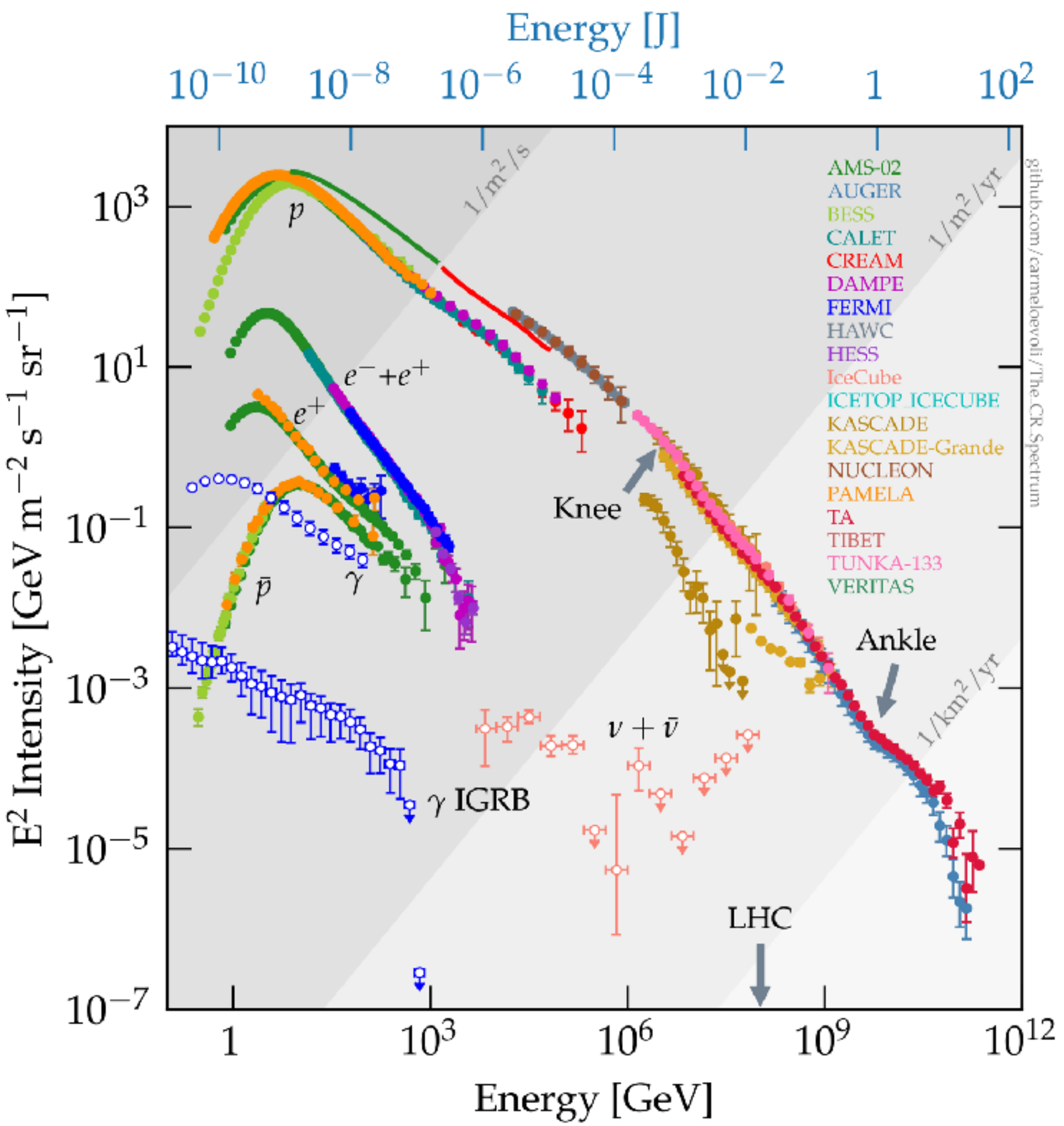

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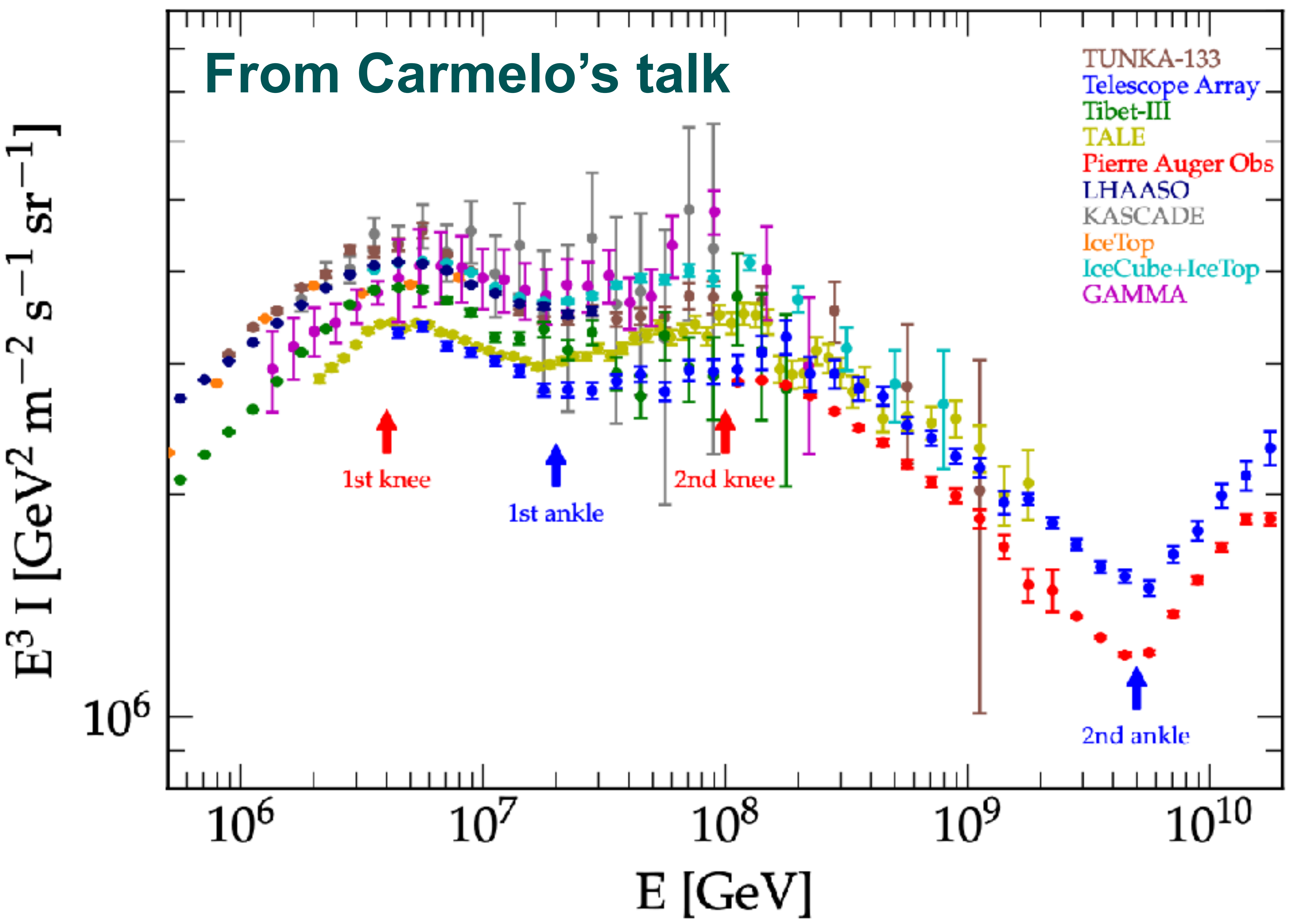

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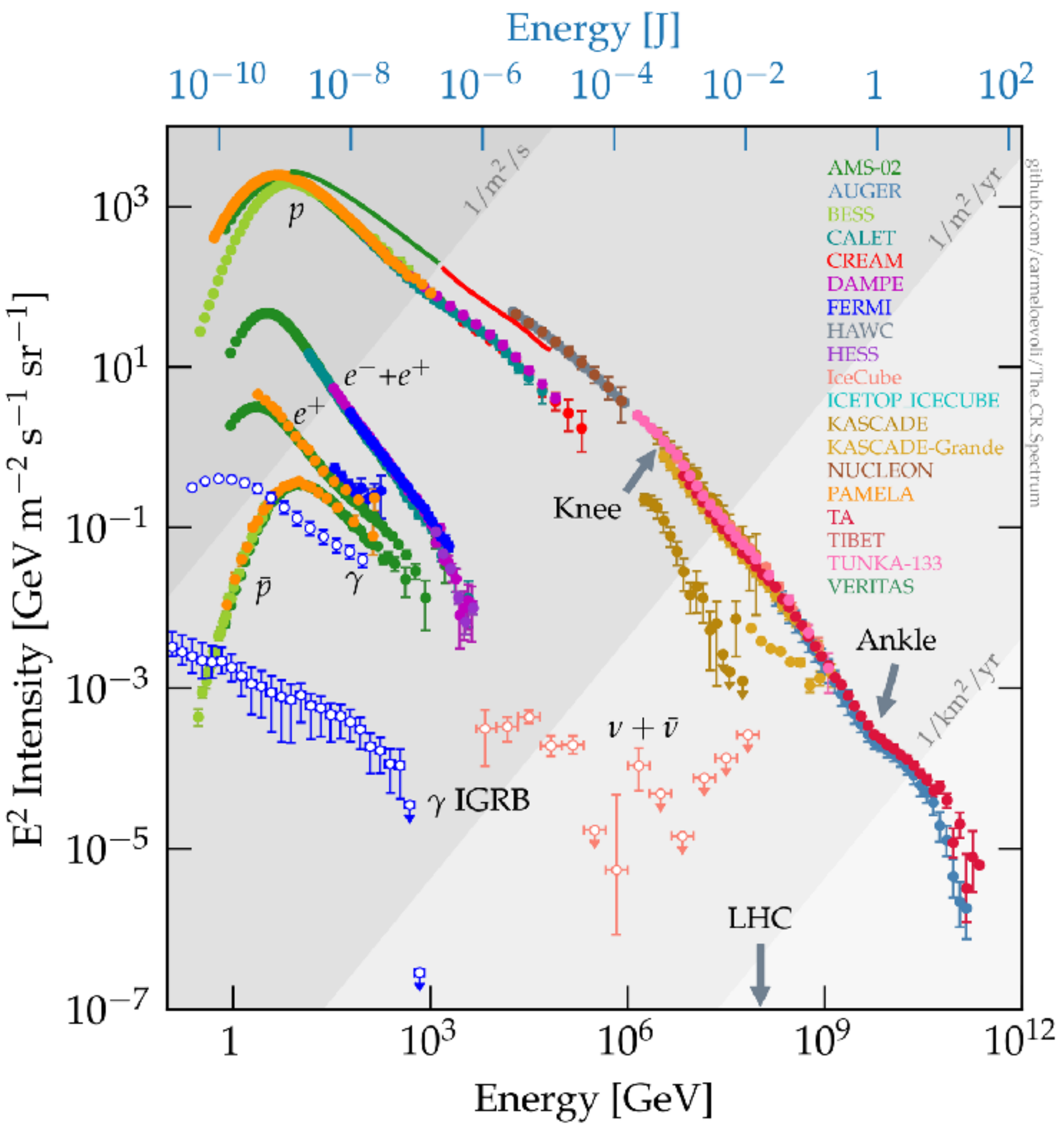

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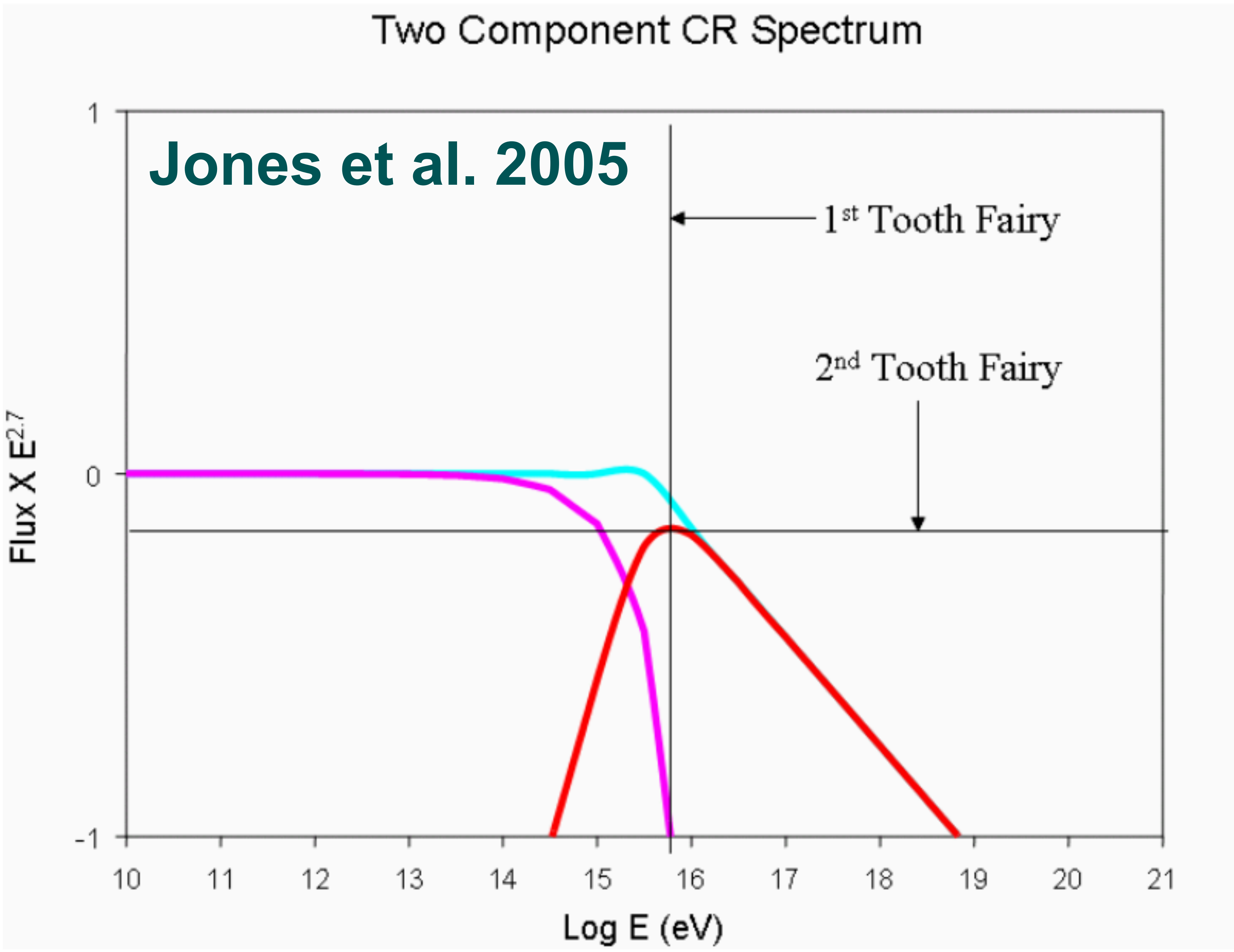

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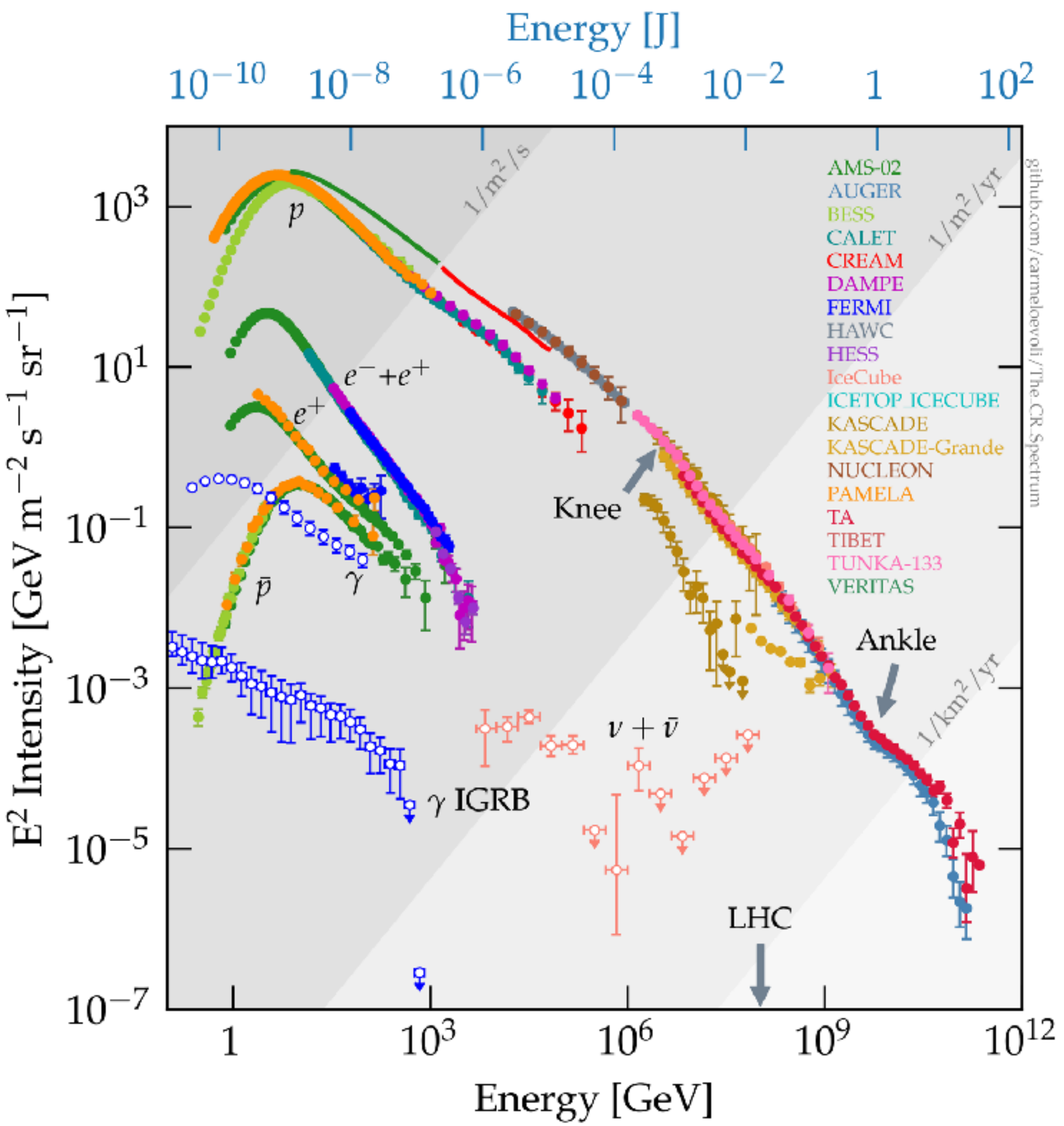

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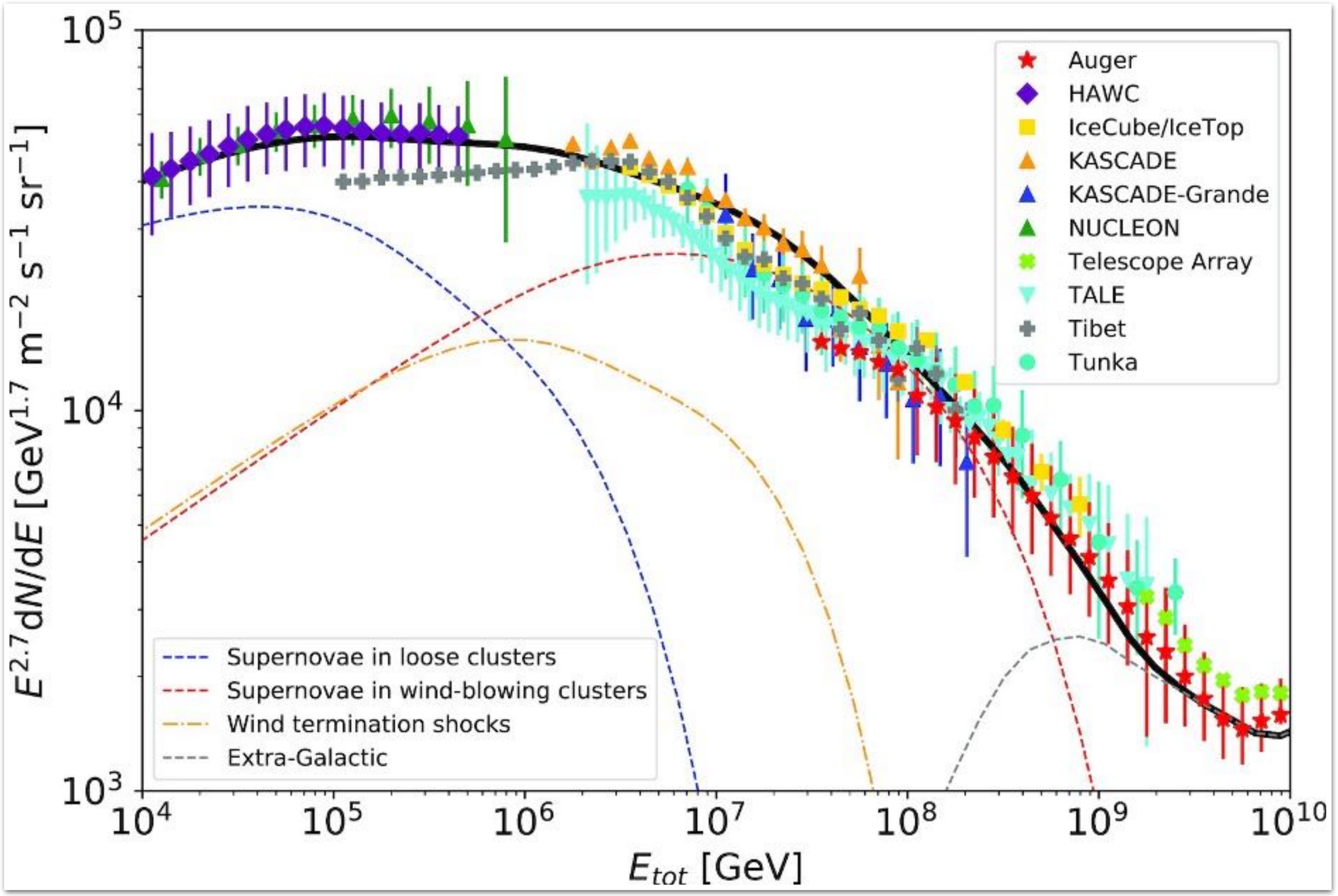

Vieu & BR, 2023

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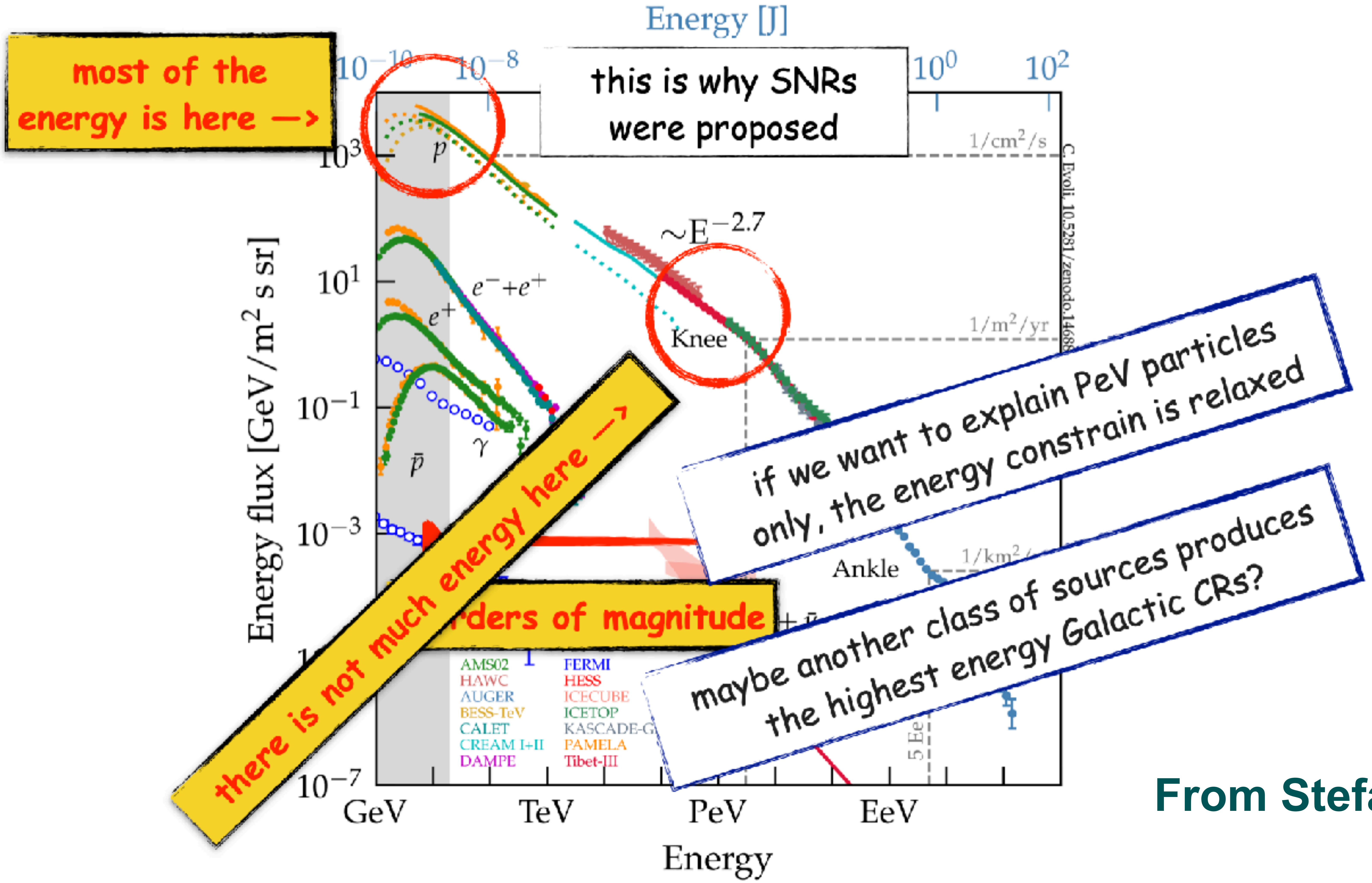
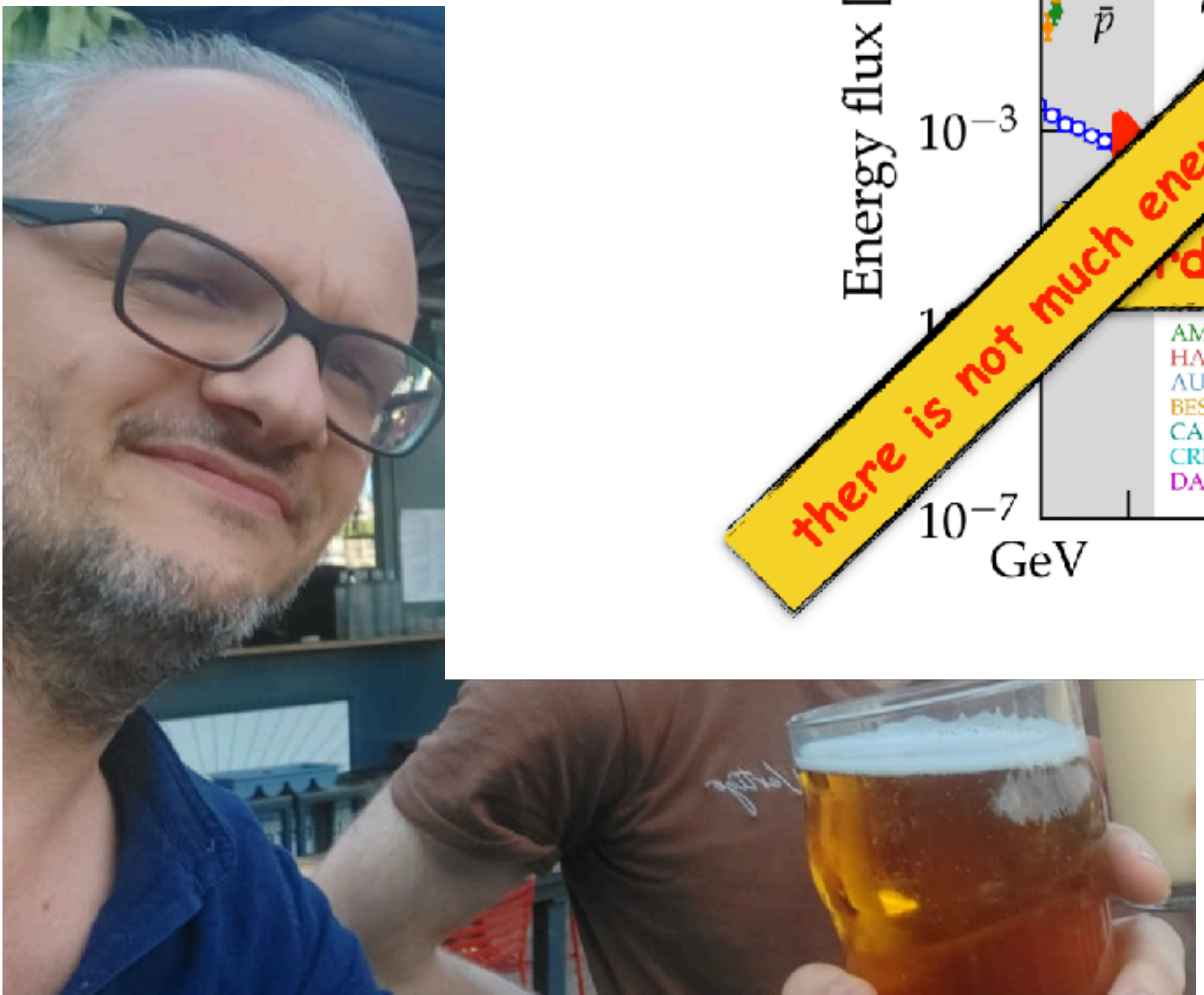
BEARS REPEATING





From Stefano’s talk

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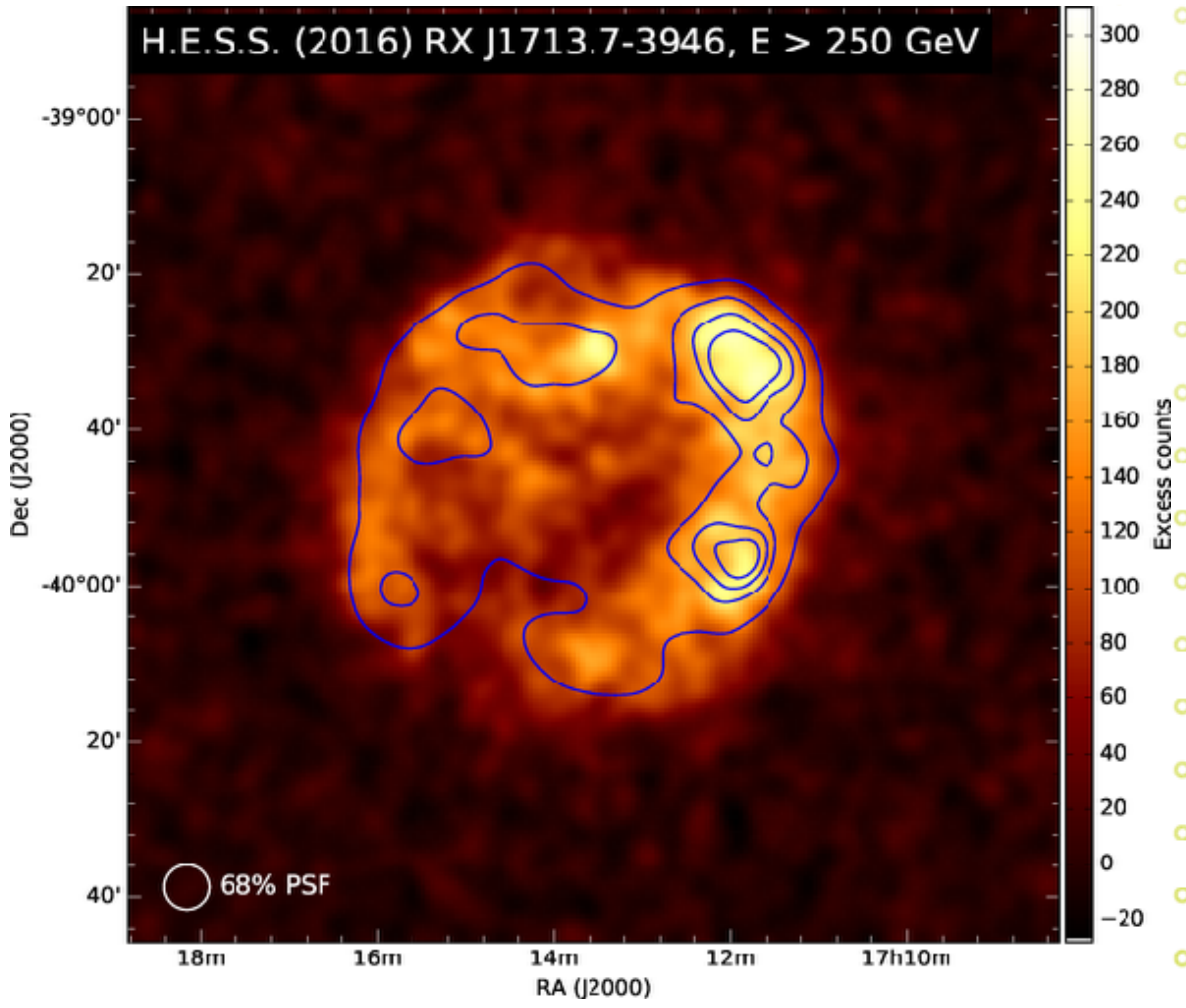

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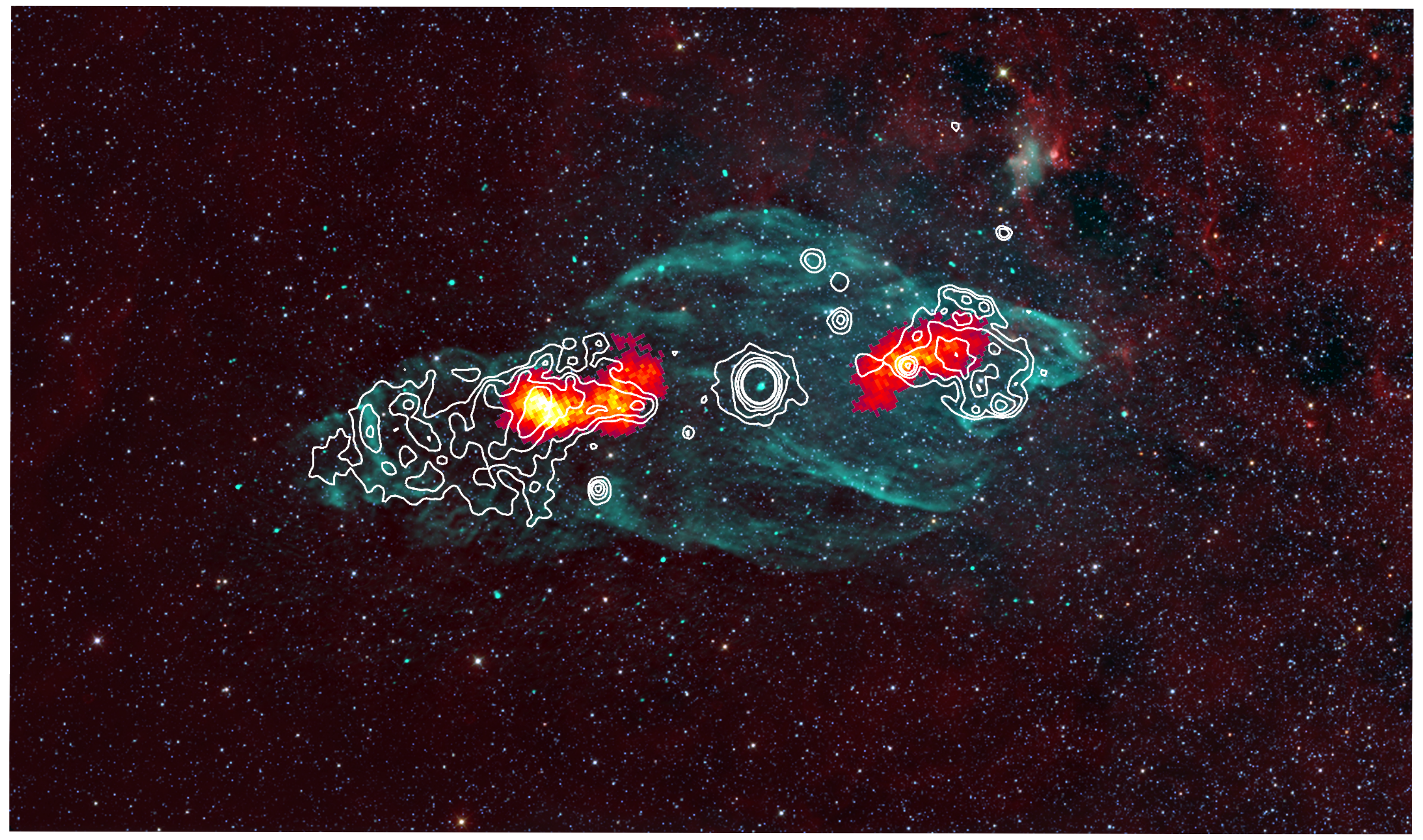
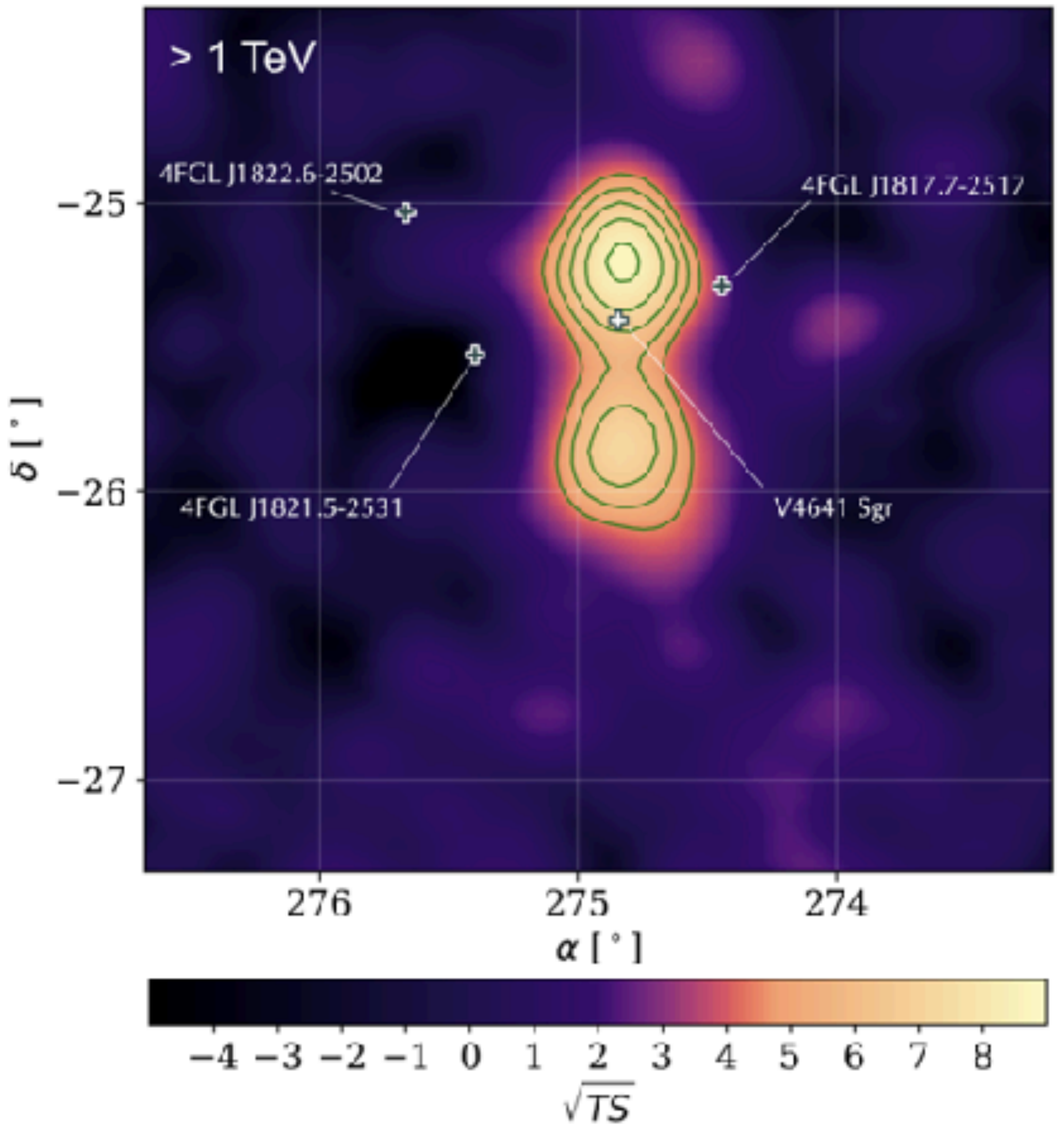
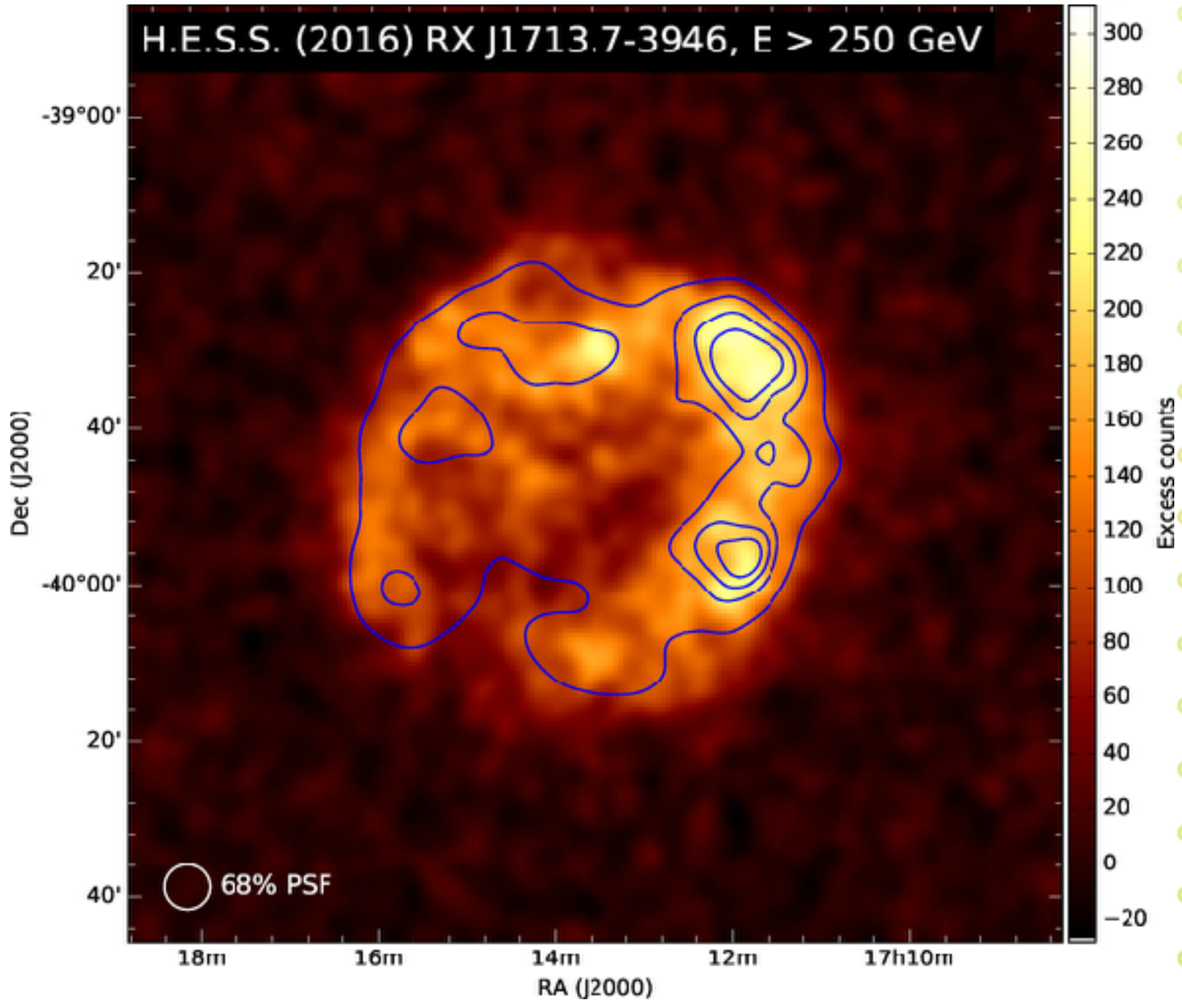


SS 433
(HESS Coll. '24)

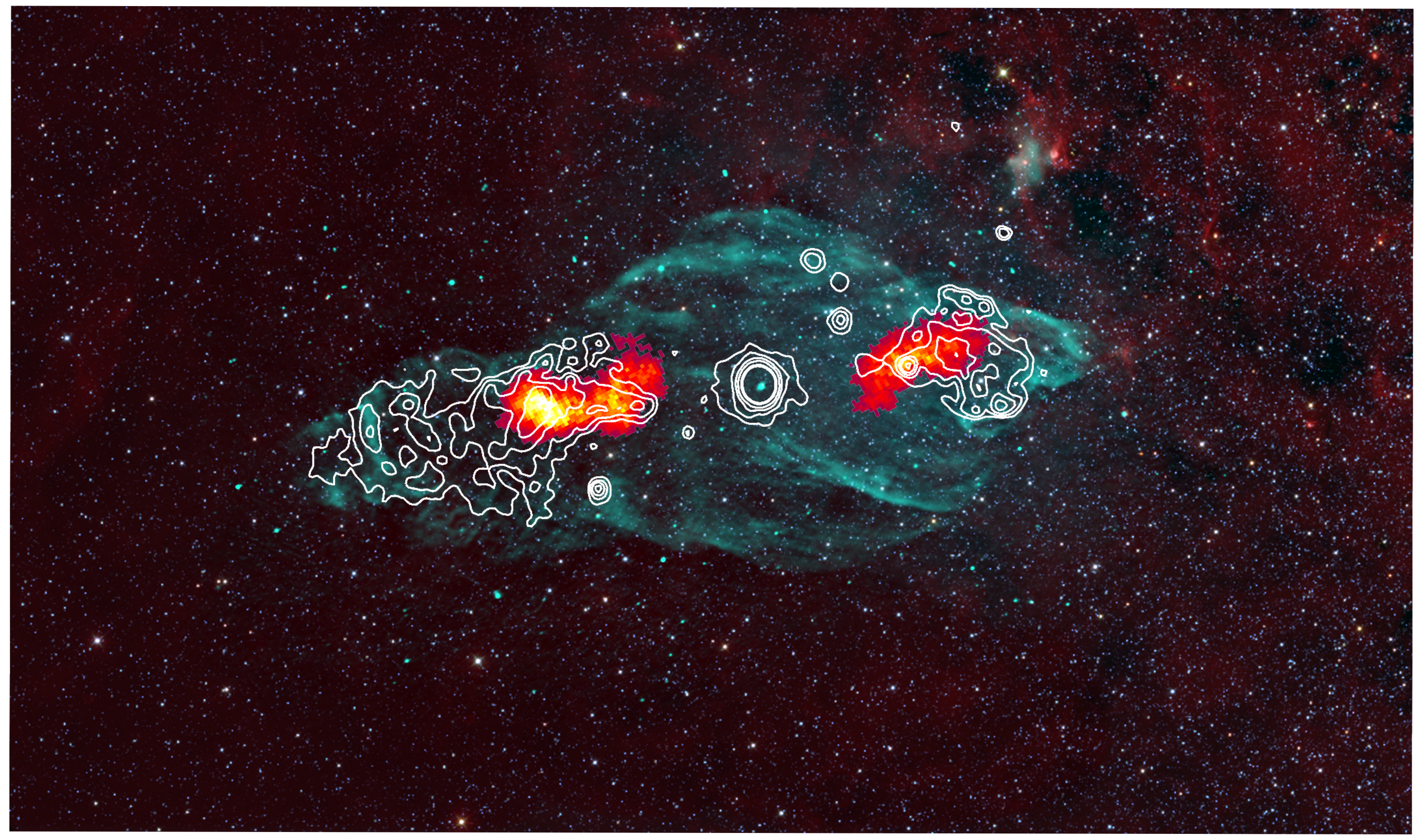
HAWC Collaboration, Nature 2024

V4641 SGR





Kong 2025



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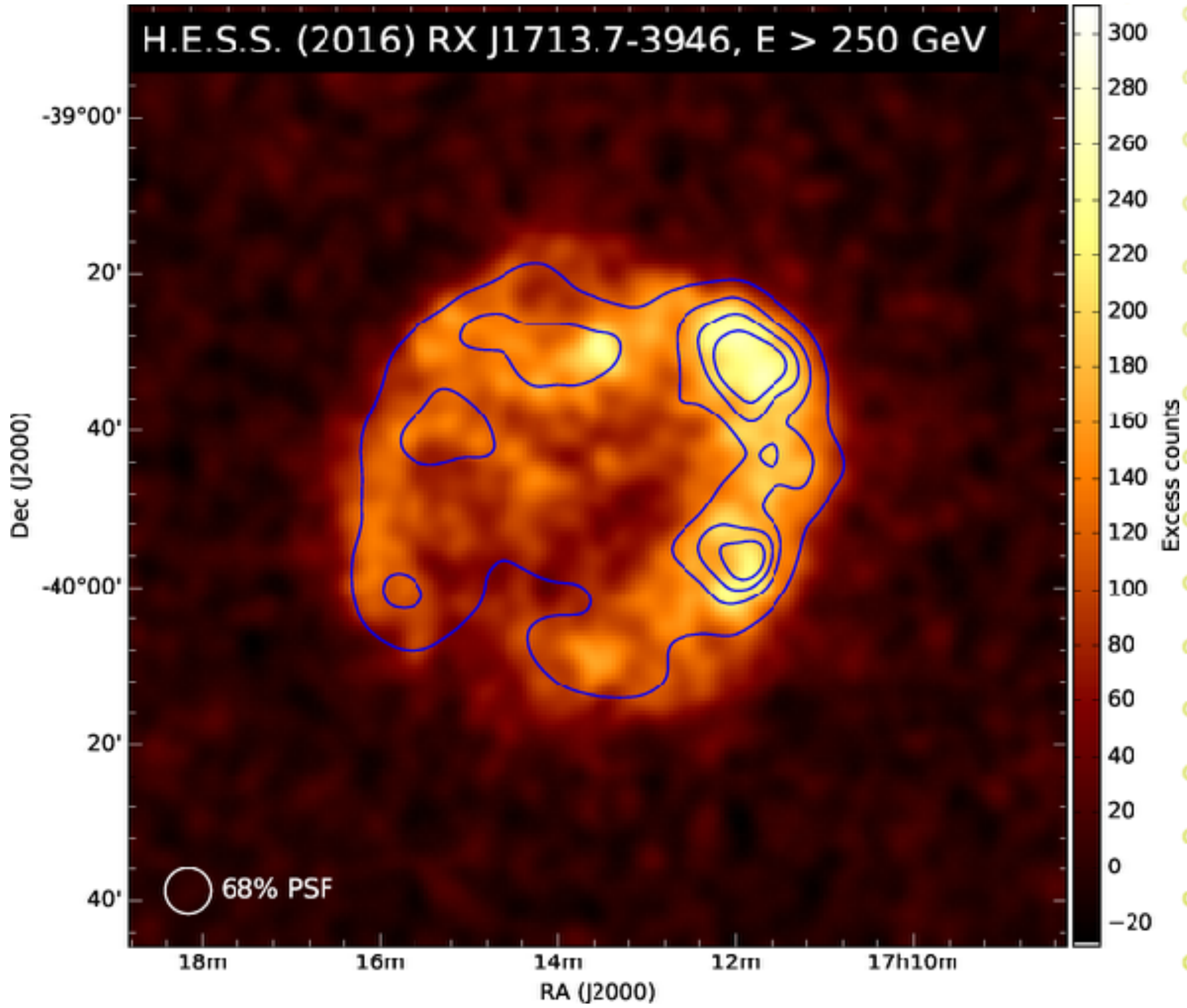
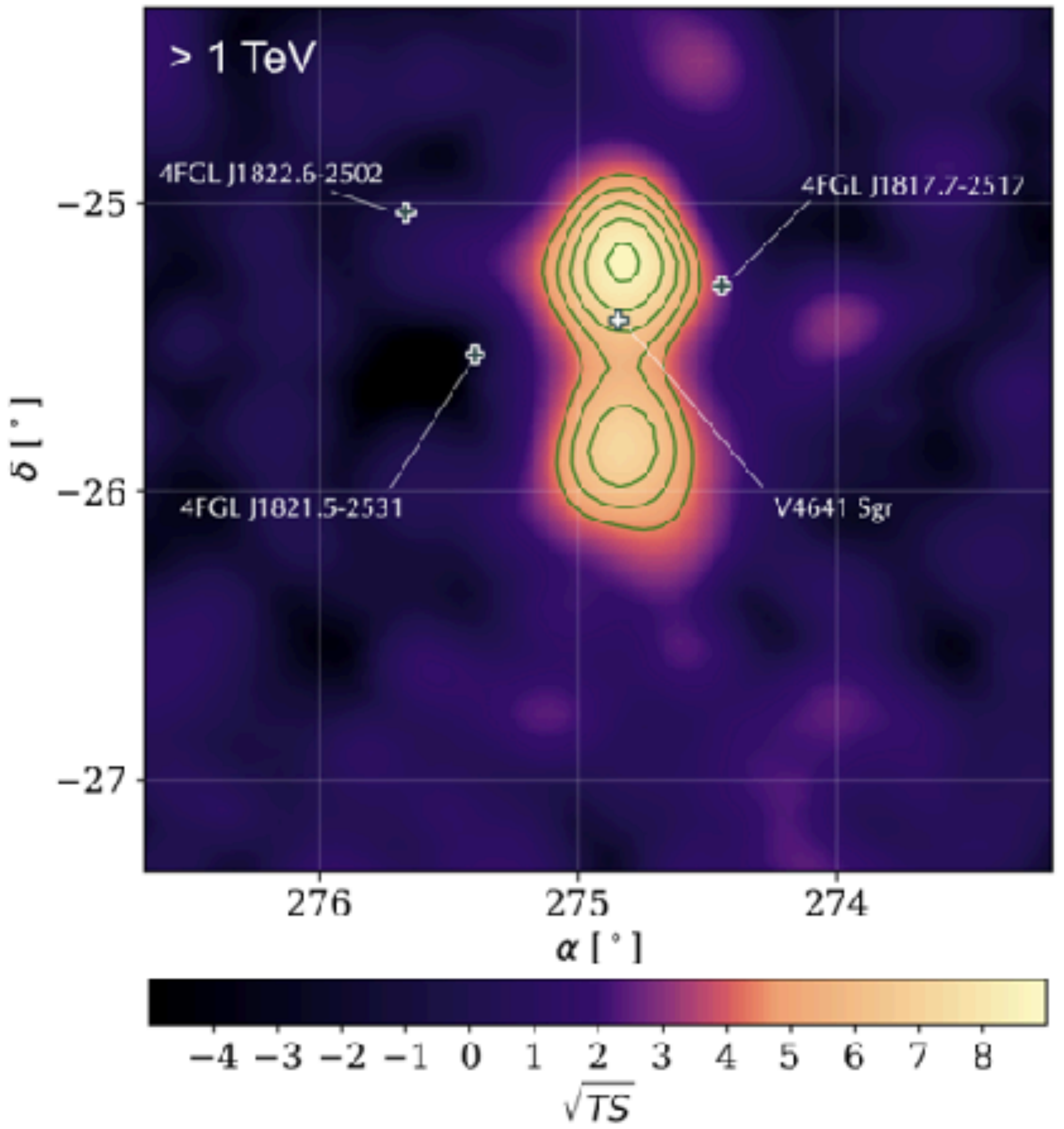


HAWC Collaboration, Nature 2024 V4641 SGR



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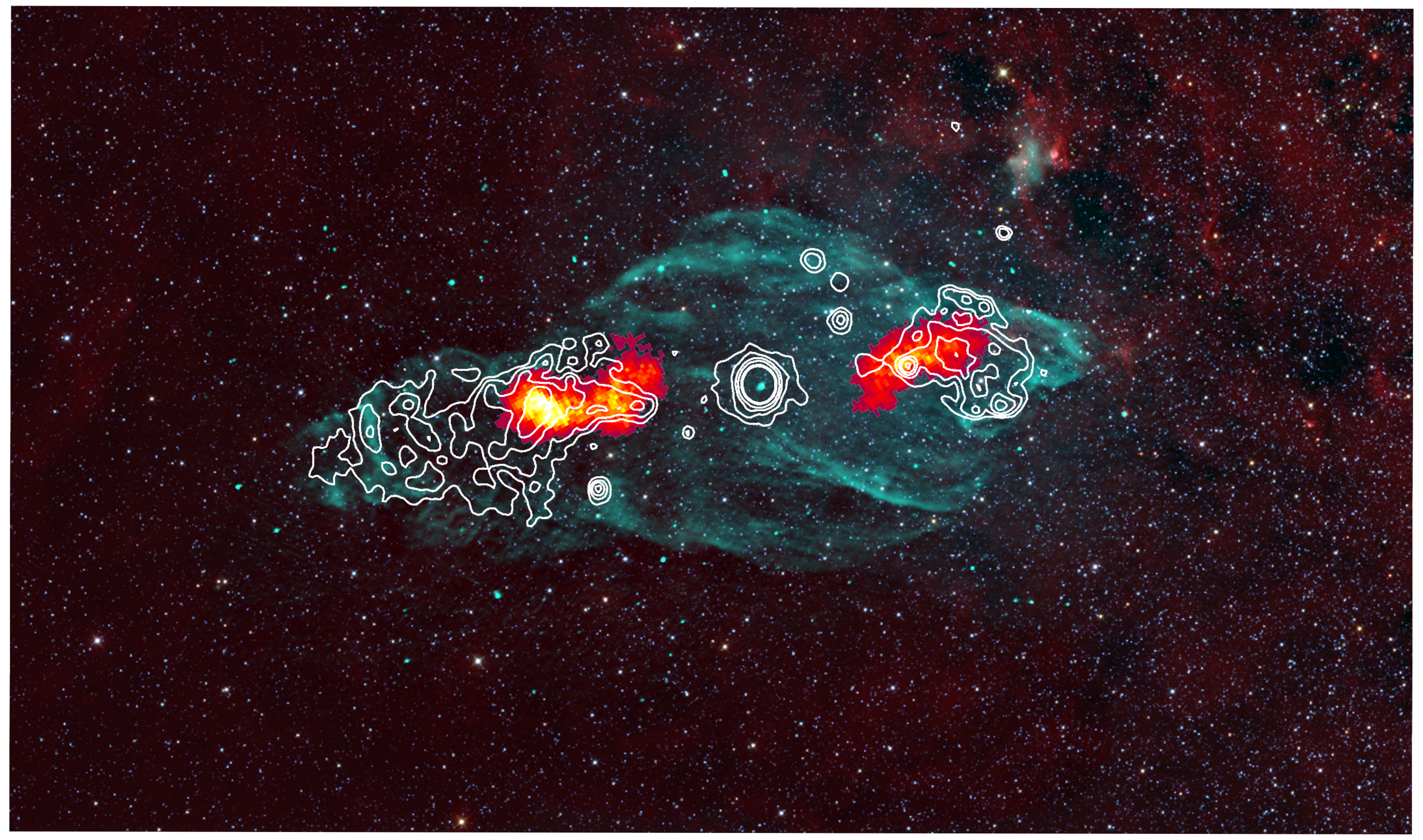

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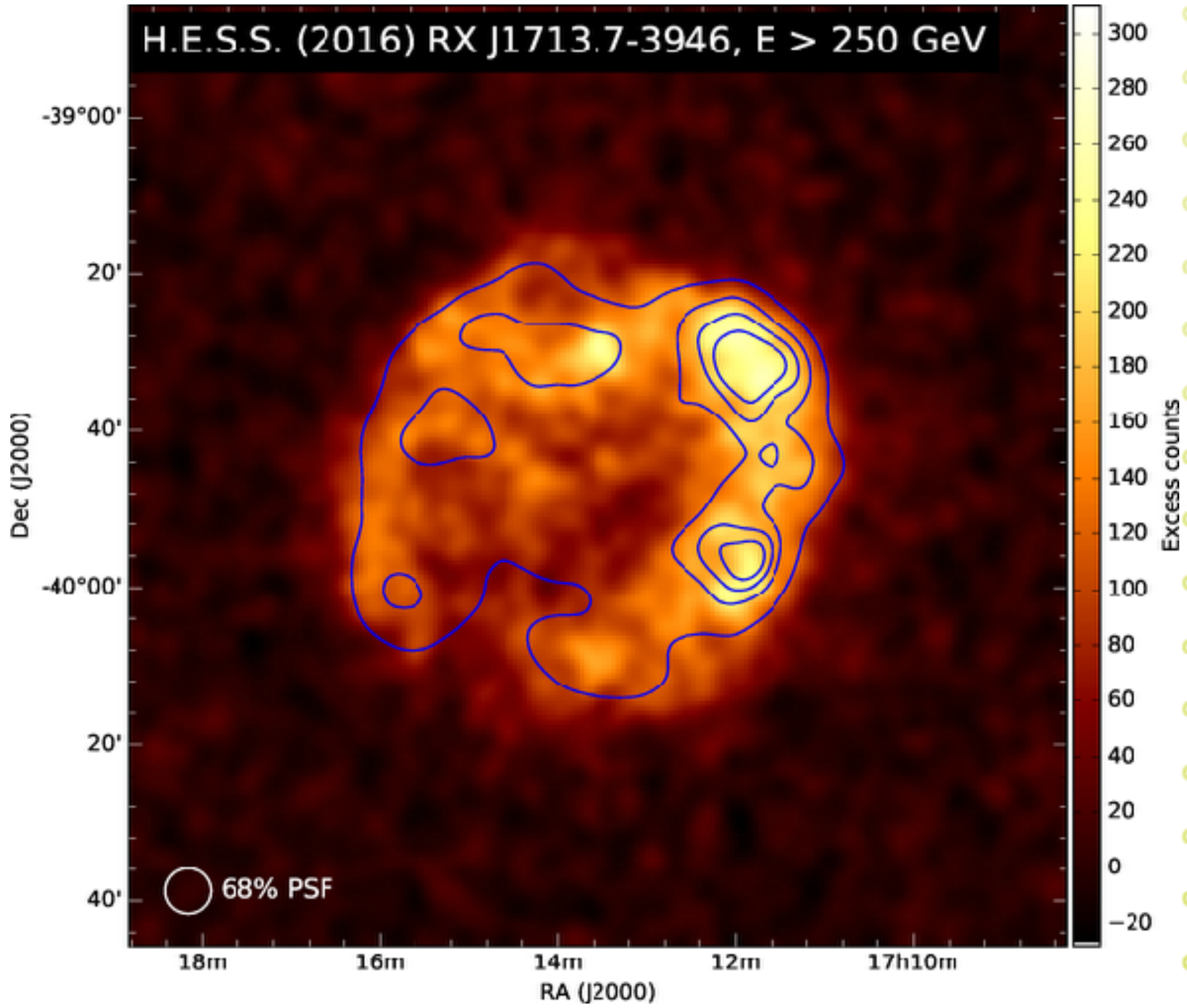
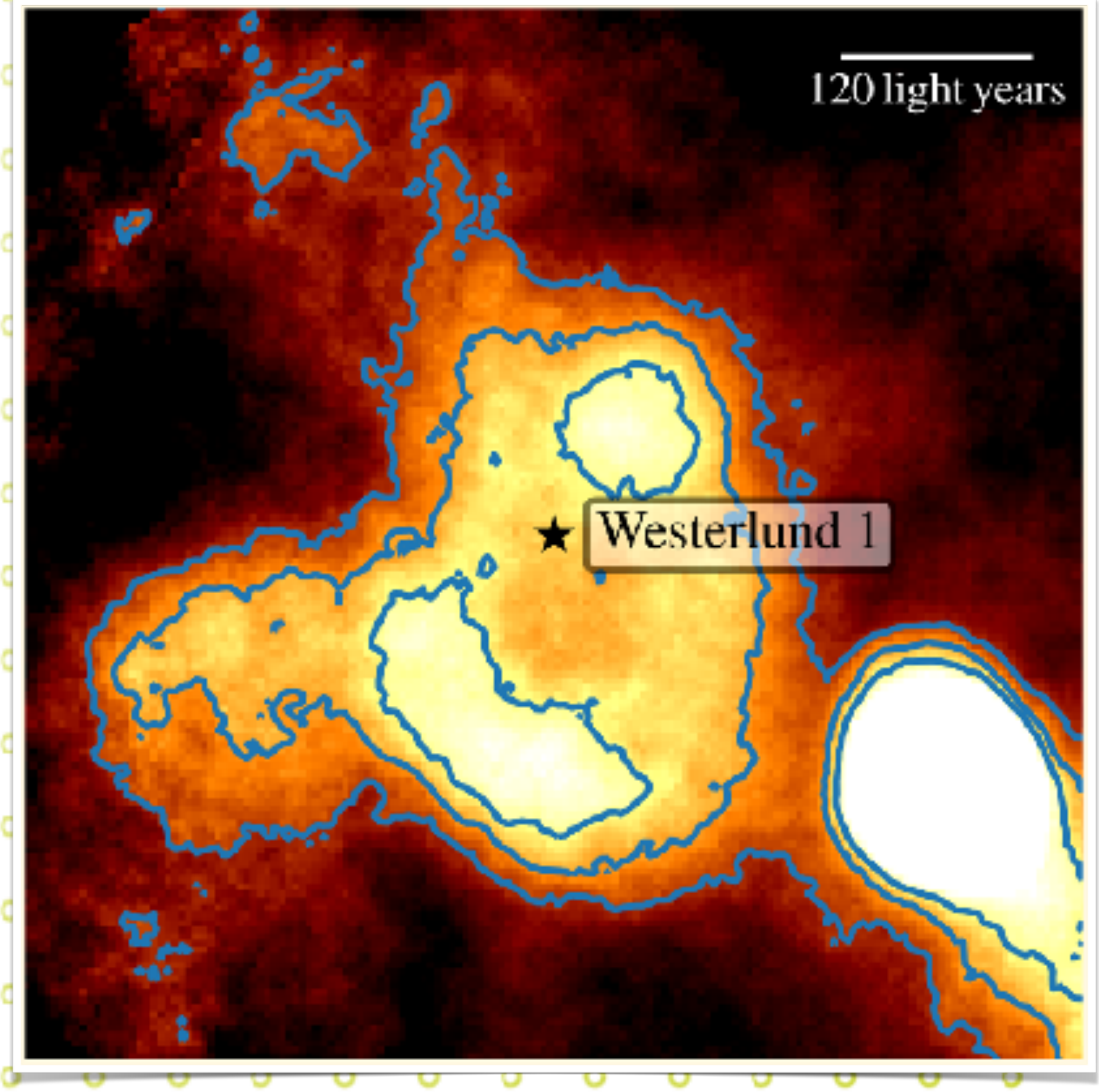
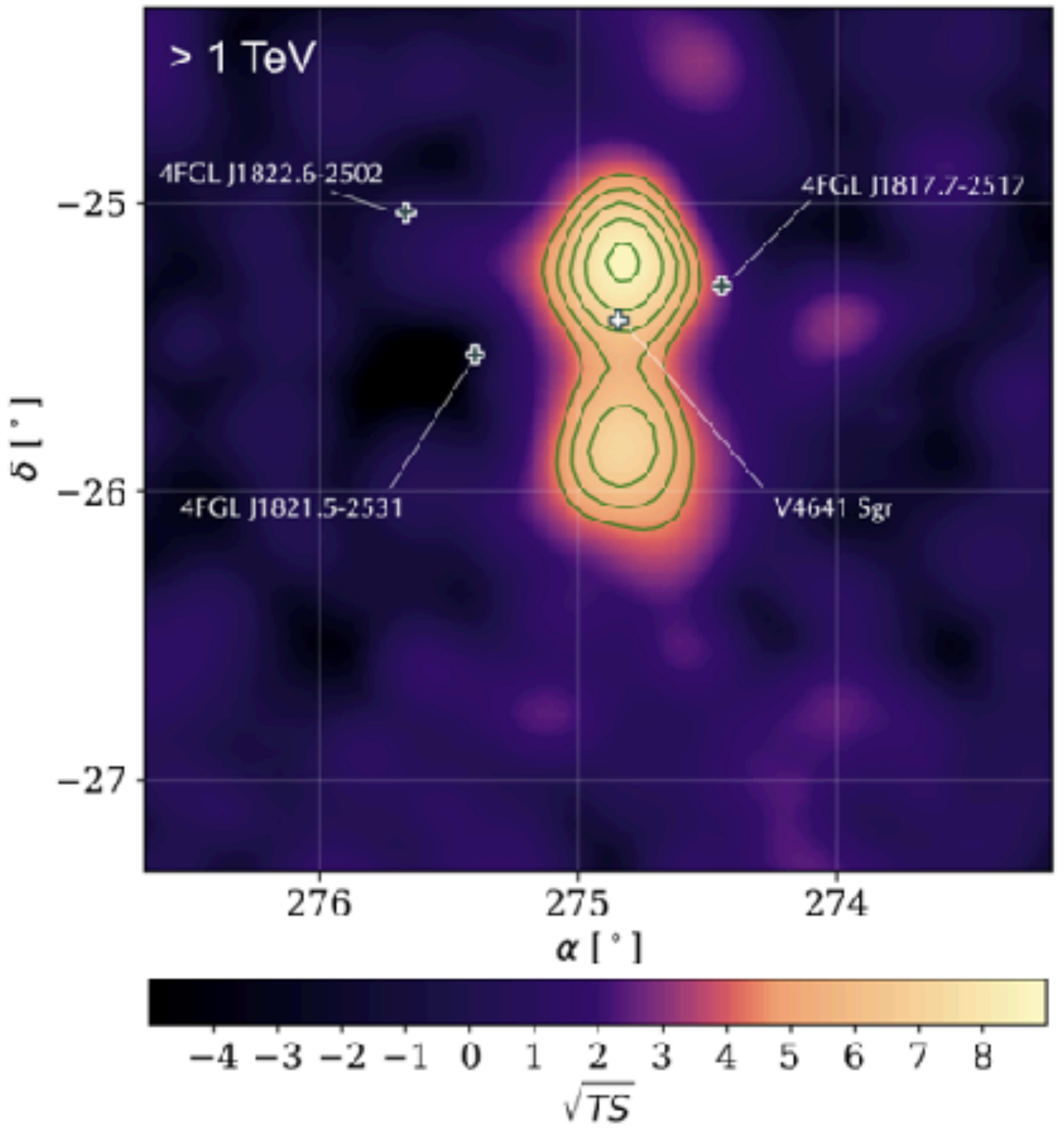


HESS J1646-458
(HESS Coll. ’22)

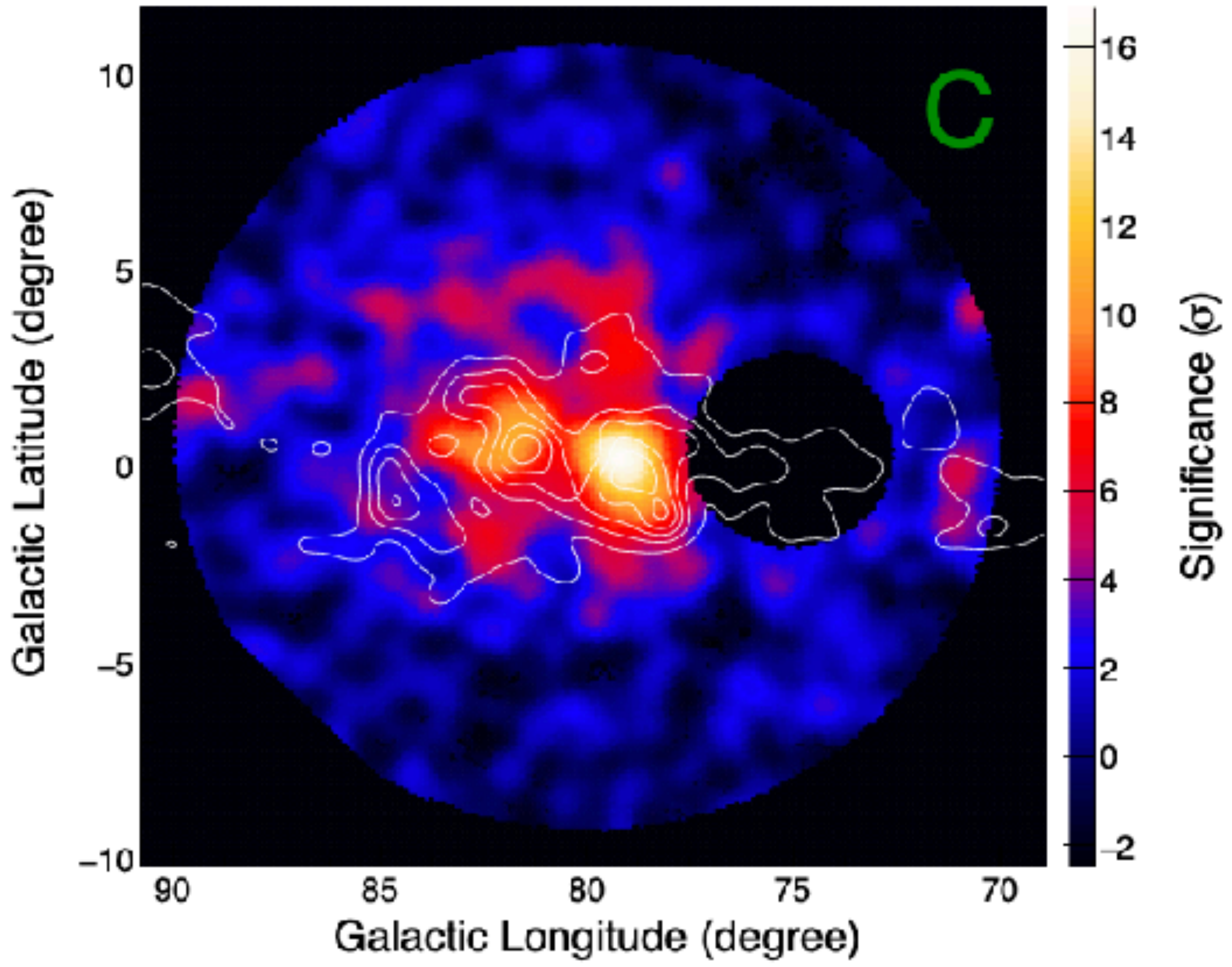


HAWC Collaboration, Nature 2024

V4641 SGR

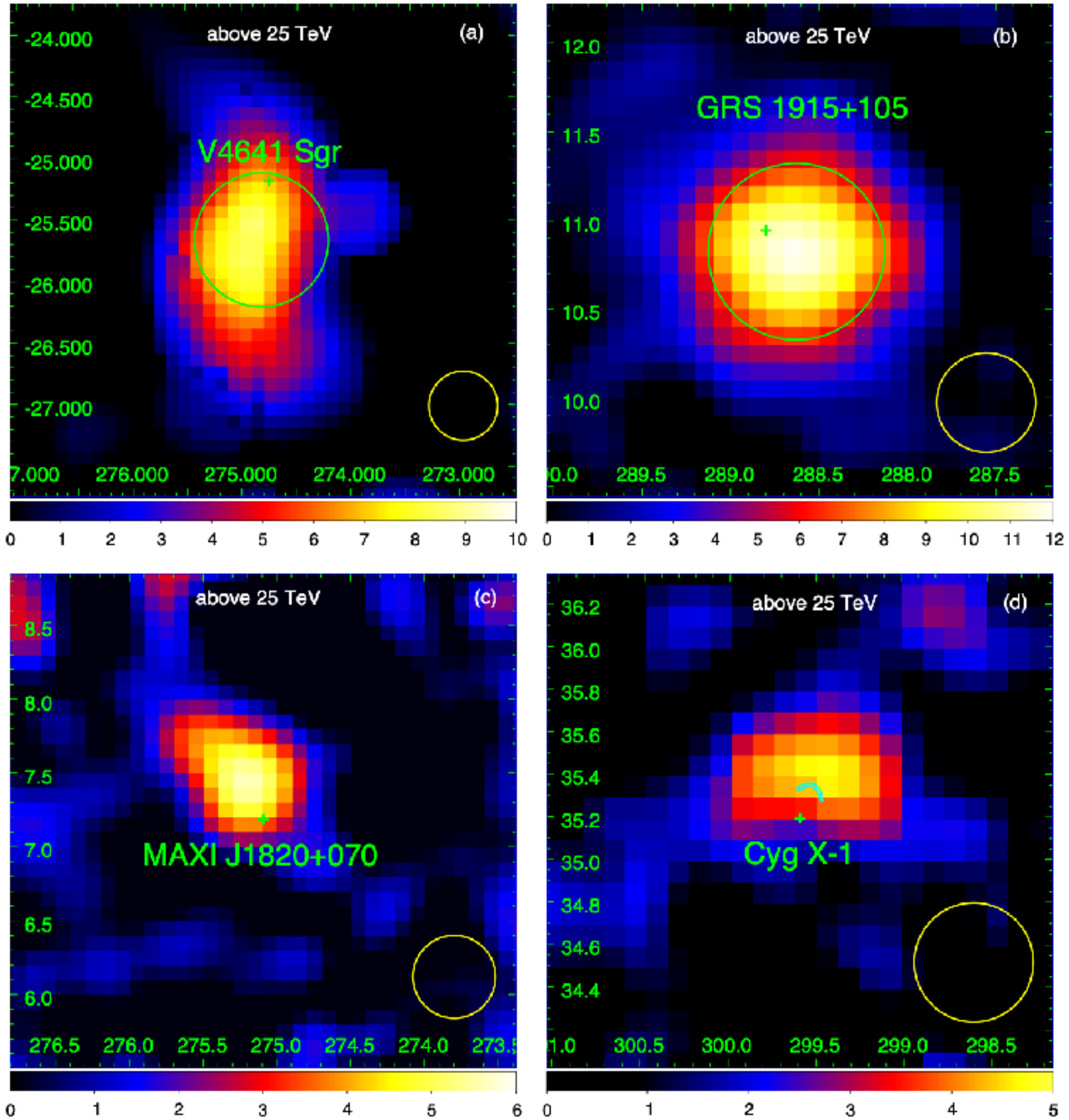


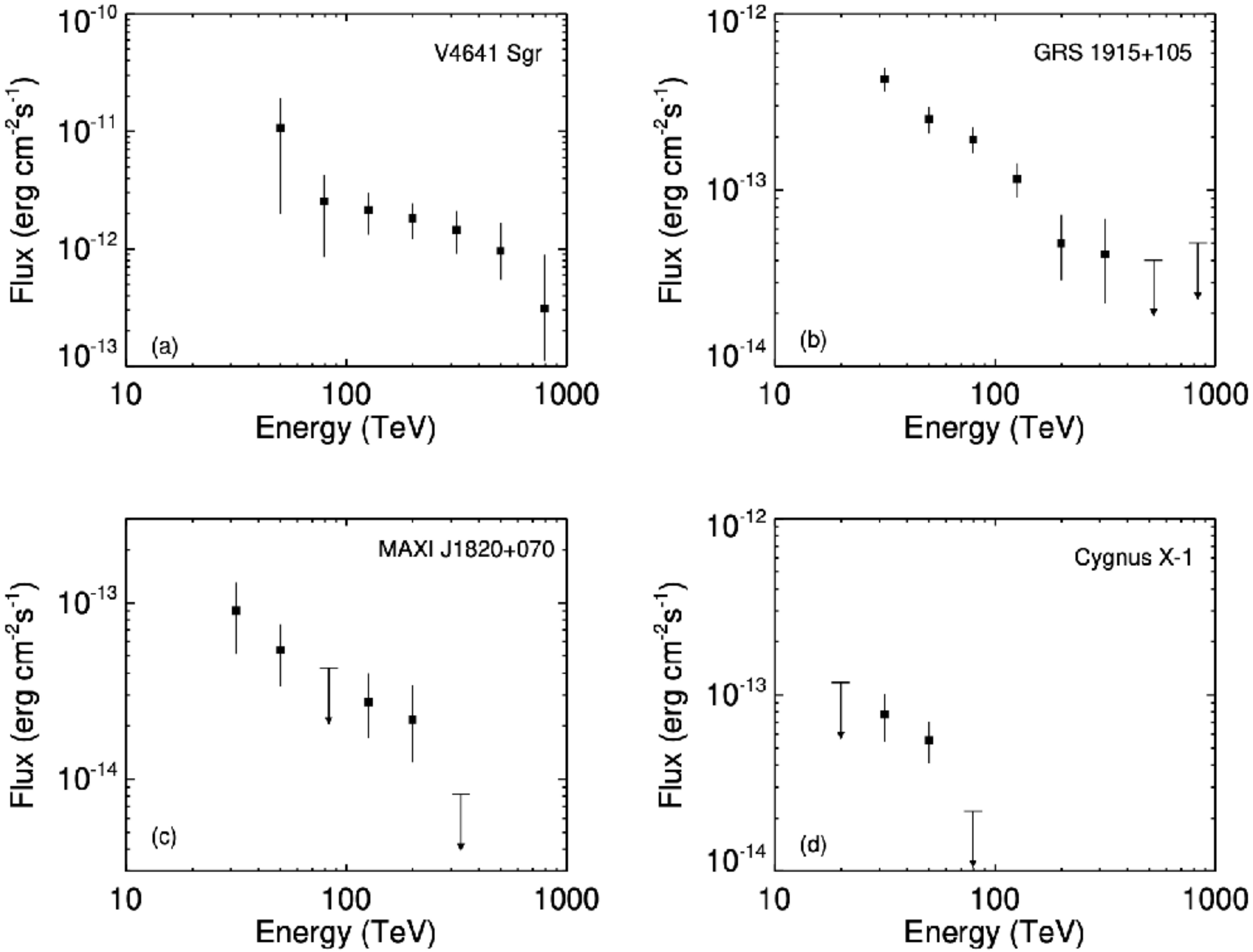
Cygnus region
(LHAASO Coll. ’24)



Kong 2025

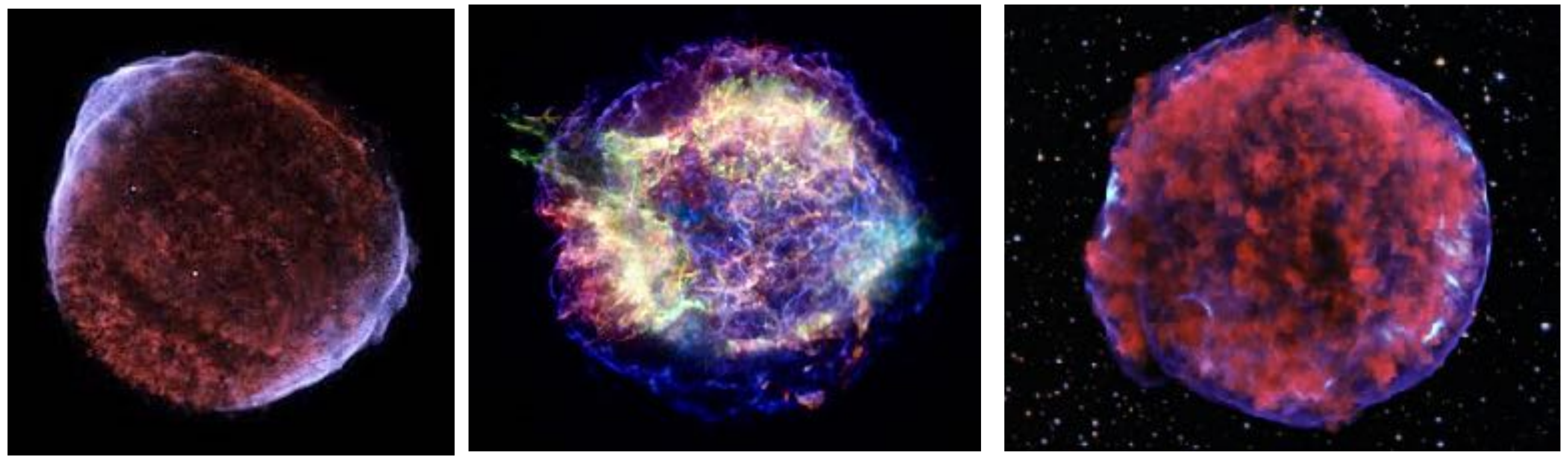
LHAASO VIEW OF MICROQUASARS





LHAASO Collab (arXiv 2024)

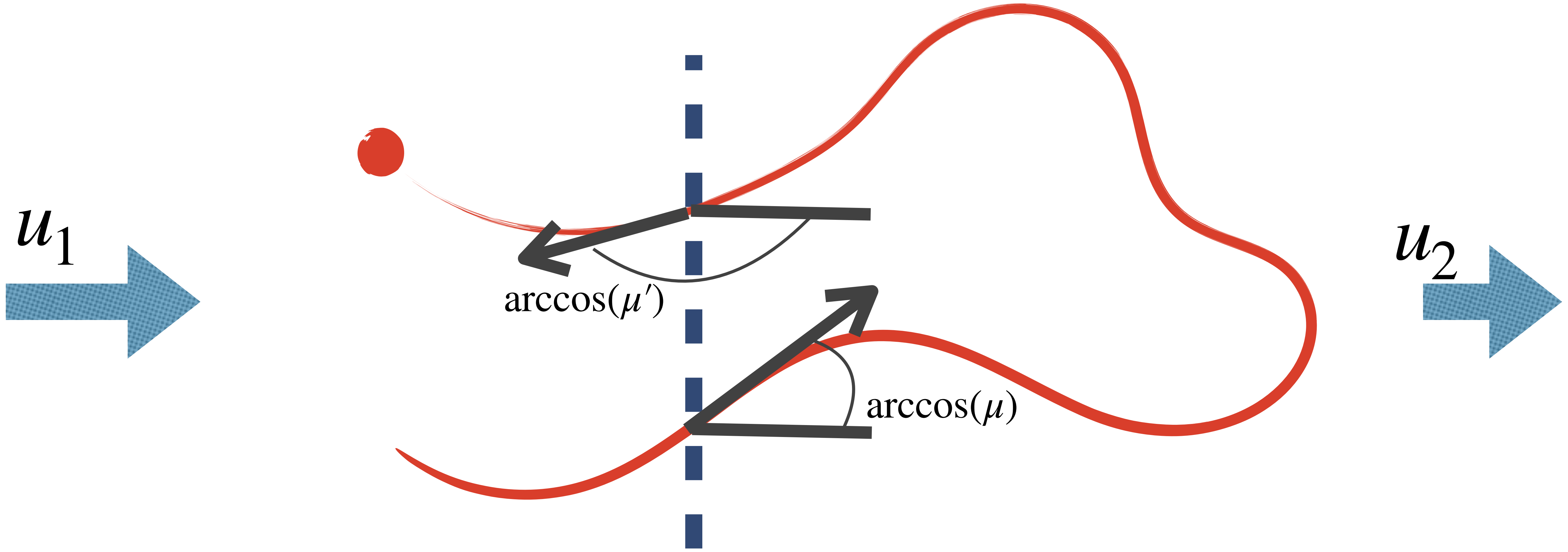
THE CASE FOR DSA IN SNRS



Credit:NASA

a) We see their non-thermal emission

b) Observations often agree with diffusive shock acceleration predictions



c) $L_{\rm cr} \approx$ 10% of SNR power input to Galaxy

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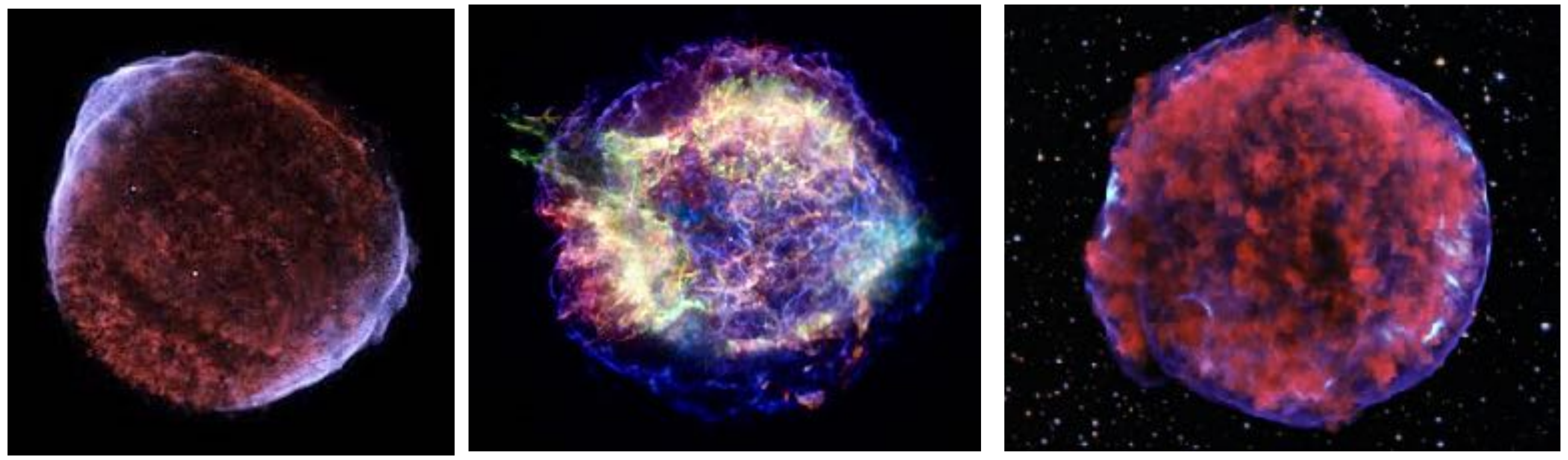

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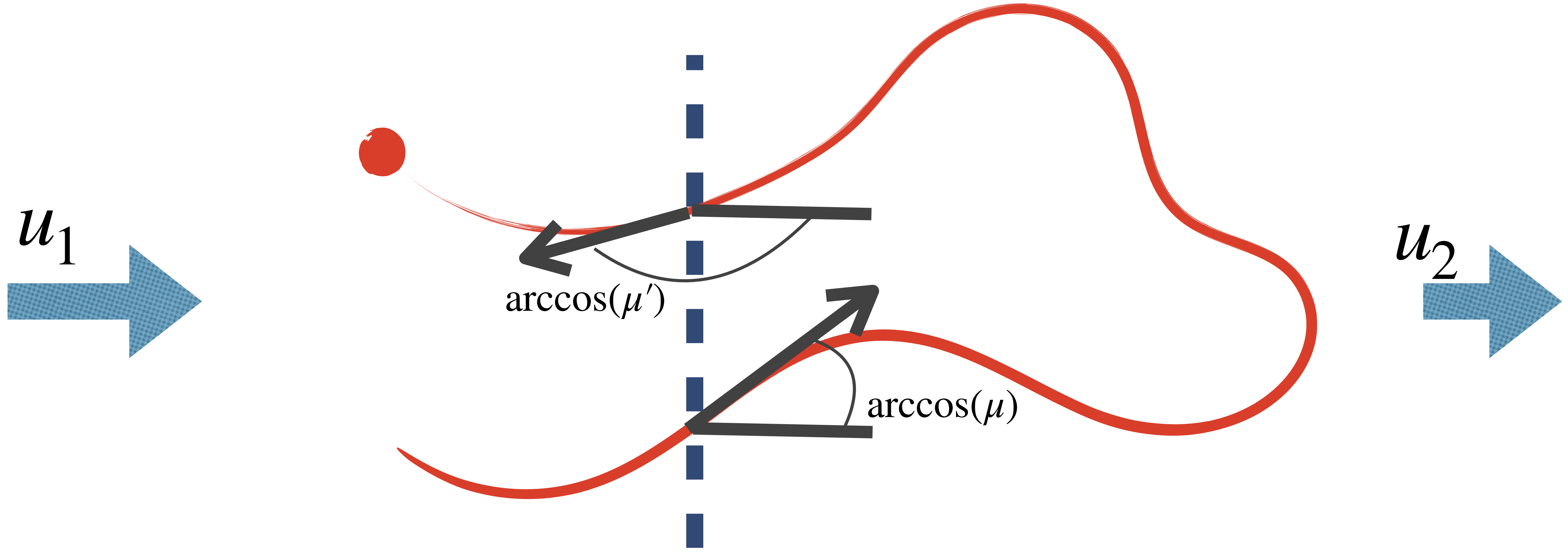

Scattering on MHD fluctuations
—> Isotropic distribution
—> No intrinsic momentum scale
—> Power laws (Bell 78, etc.)

$$\frac{\partial \ln f_0}{\partial \ln p} = -\frac{3(u_1/u_2)}{(u_1/u_2) - 1} \approx 4$$

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See Pasquale's slides for derivation

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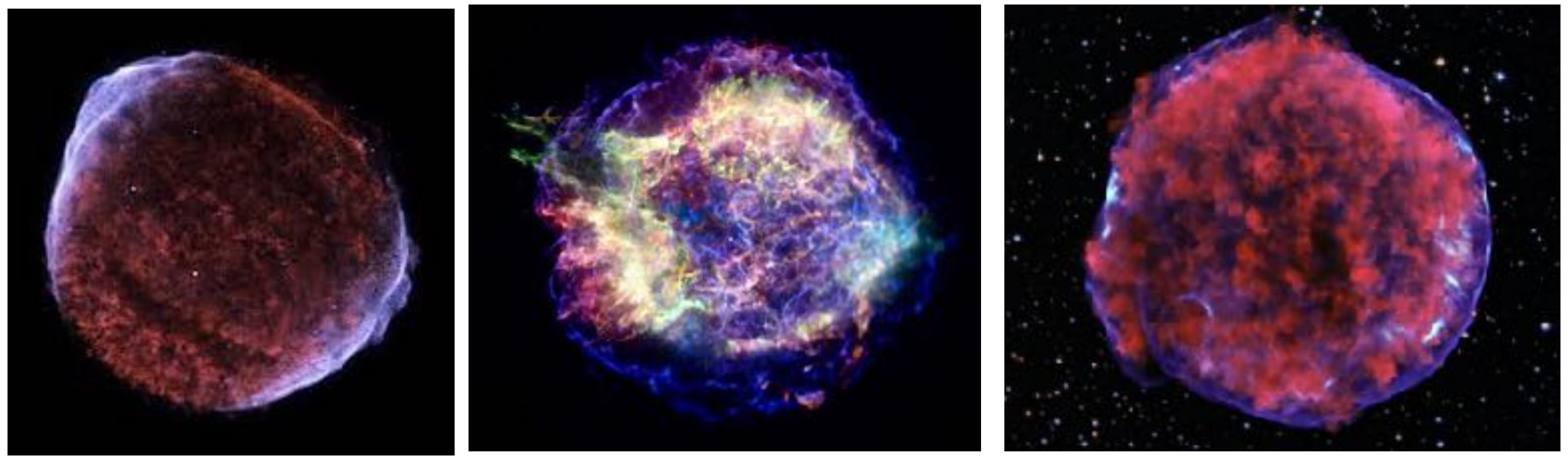

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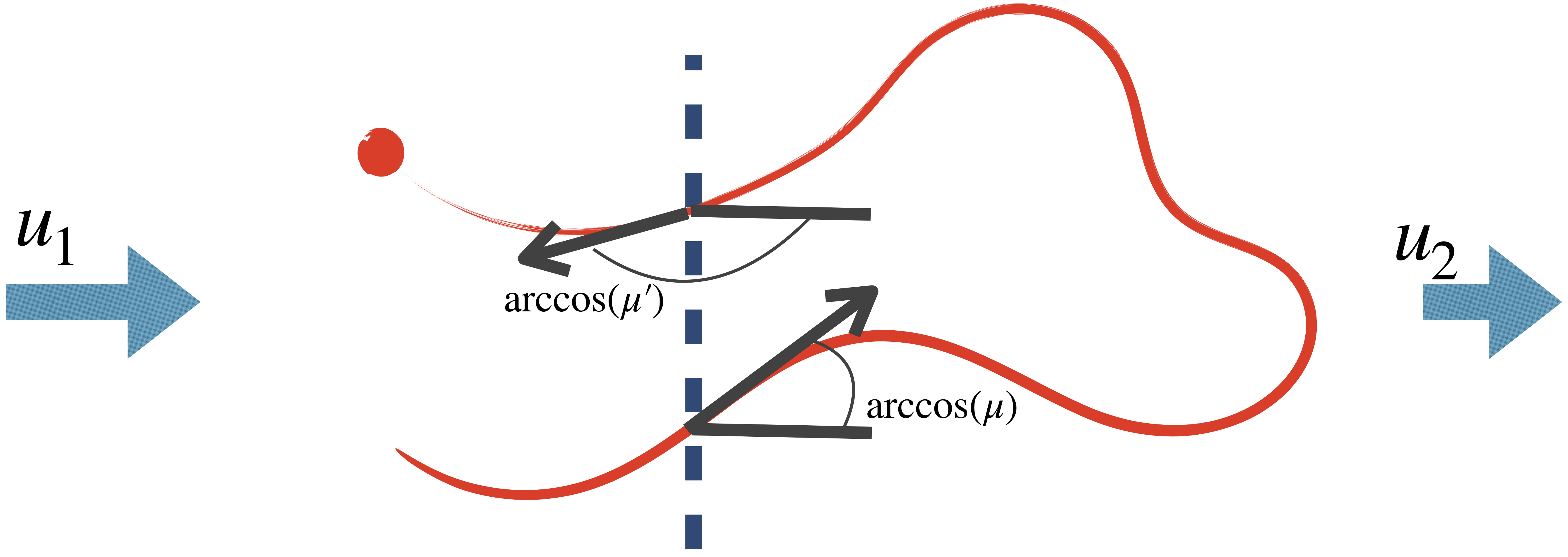

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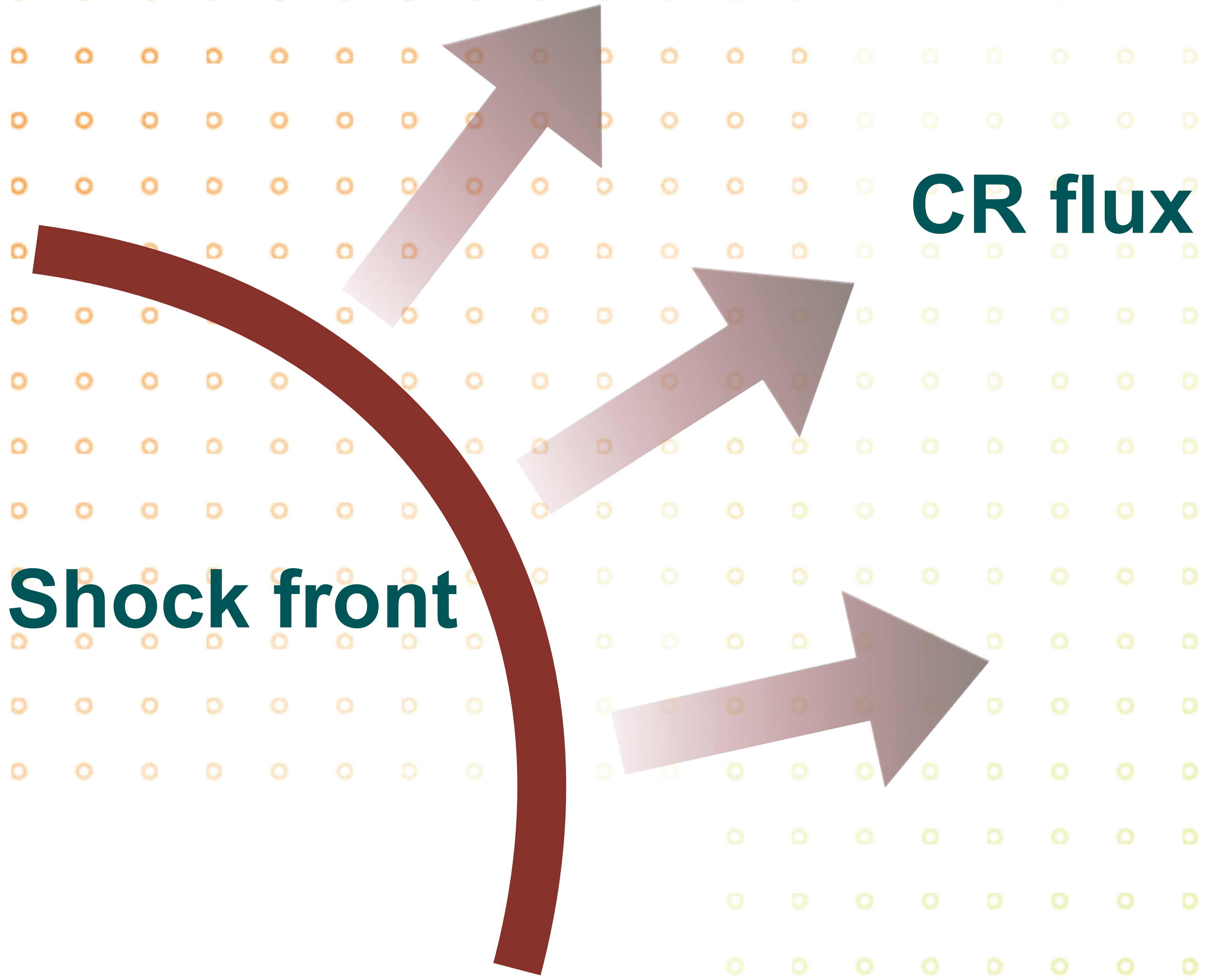
So what's the problem(s)?

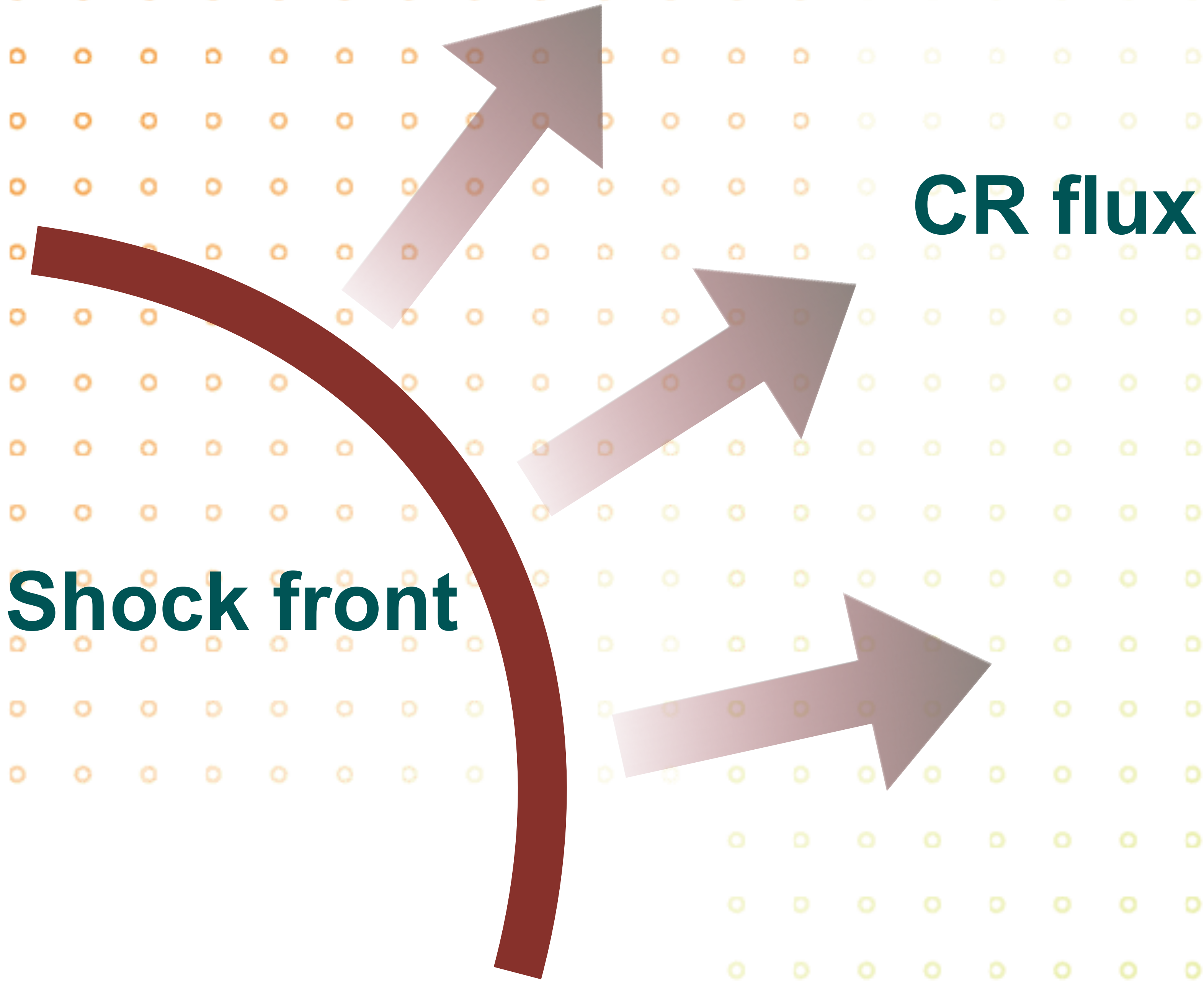
OPEN ISSUES



Pressure gradient ahead of shock does work on external medium

- **Decelerates incoming flow (relative to shock)**
- **Amplifies magnetic fields**

OPEN ISSUES



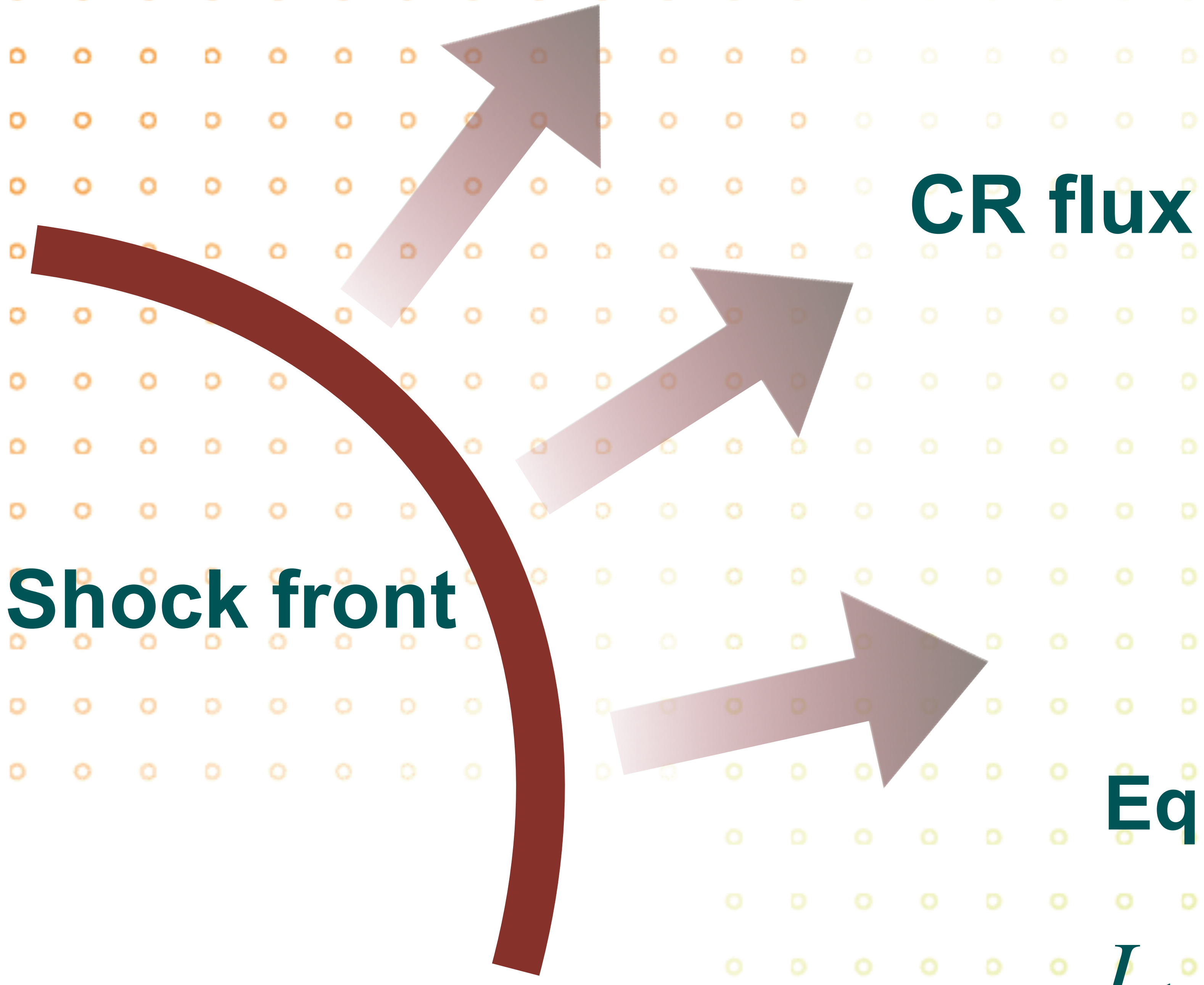
Consider for example Cassiopeia A:

$V_{\mathrm{sh}} \approx 5{,}000\ \mathrm{km\ s^{-1}}$
$B_{ext} \approx 3 - 5\ \mu\mathrm{G}$
$\rho_{\mathrm{ext}} \approx 10^{-25-24}\ \mathrm{g\ cm^{-3}}$

$r_g\ /\ (c/\omega_{\mathrm{pe}}) \approx 10^5$

Laminar shock transition in such a scenario is impossible
But this is a purely academic point.
Such scenarios do not exist.

OPEN ISSUES



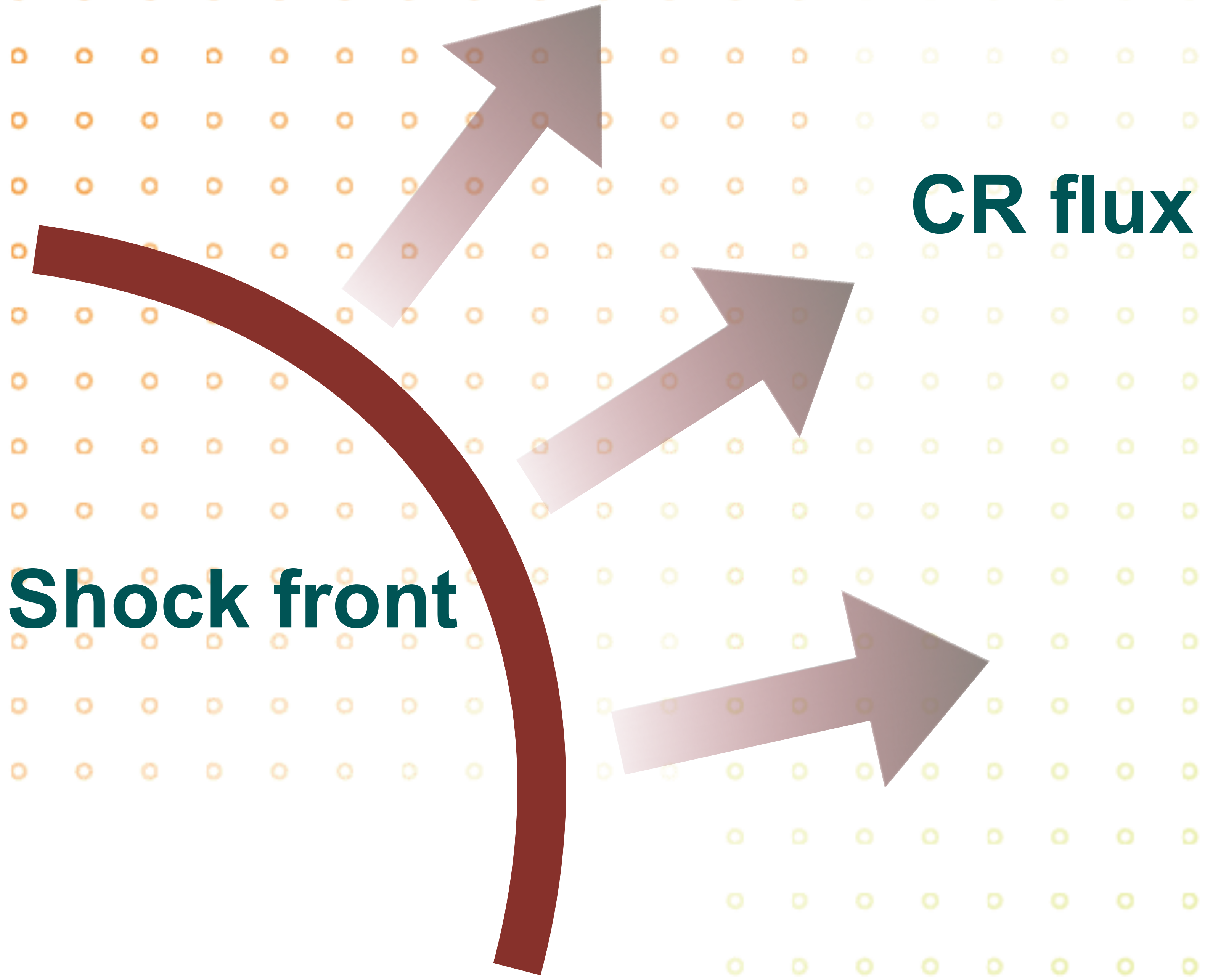
Acceleration time for DSA

$$t_{\rm acc} = \underbrace{\frac{3v}{4\Delta u}}_{\text{Fractional energy change per cycle}} \underbrace{\left(4\frac{L_1}{v} + 4\frac{L_2}{v}\right)}_{\text{Cycle time}}$$

Equate to dynamic time $t_{\rm dyn} = \dfrac{R_{\rm sh}}{u_1}$

$L_1 \sim R_{\rm sh}/4$ **indep. of the scattering assumptions.**

CONFINEMENT ISSUES



Highest energy CRs are accelerated “early”

Why so ?

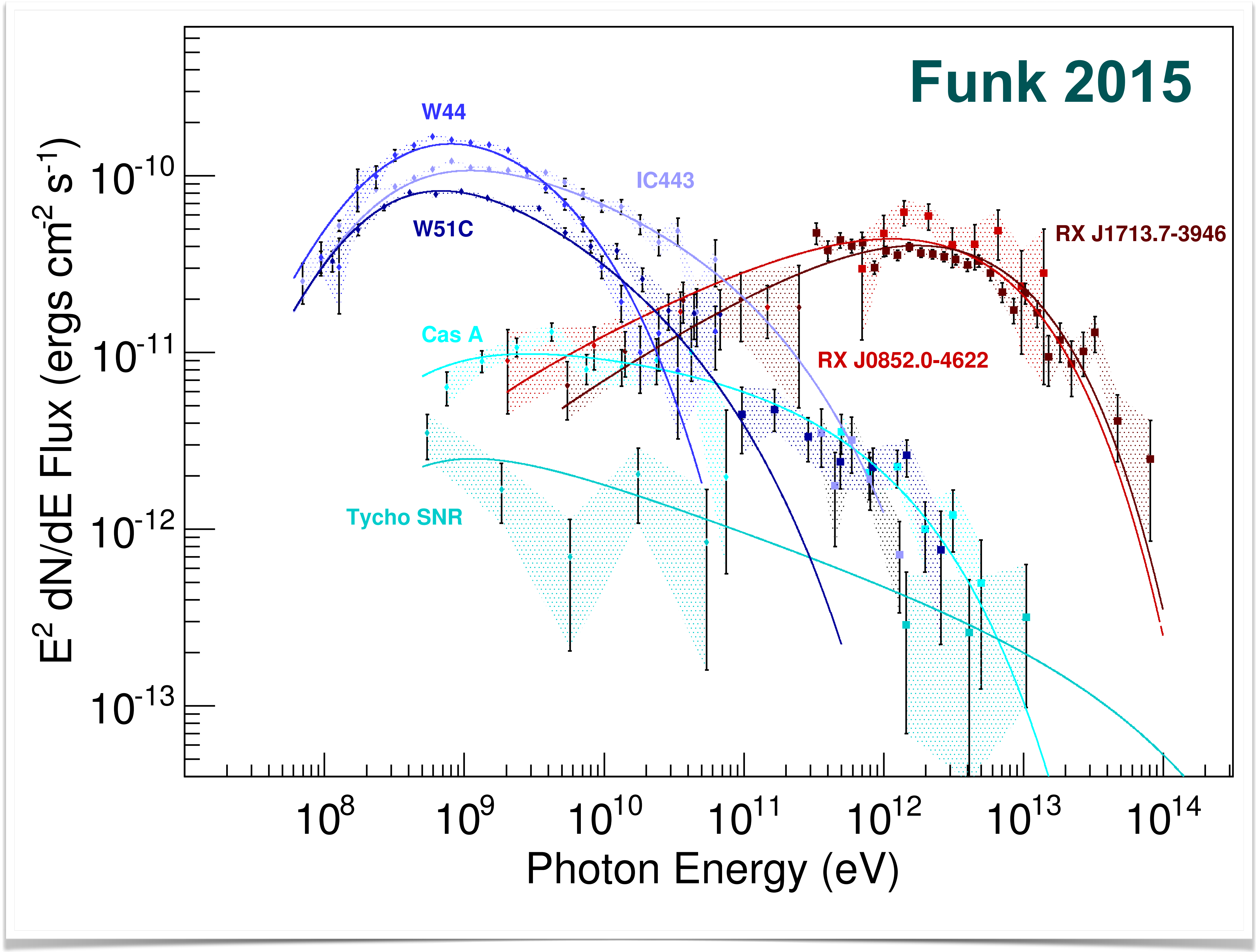
We need <u>confinement.</u>

Ability to grow scattering fields (a la Bell 2004):

$$t_{\mathrm{growth}} \propto \frac{\text{Inertia}}{\text{Driving}} \propto \frac{\sqrt{\rho}}{j_{\mathrm{cr}}} \propto \frac{\sqrt{\rho}}{\rho u_{\mathrm{sh}}^{3}}$$

Fast shocks in dense environments preferable

THE LIMIT OF SUPERNOVA REMNANTS



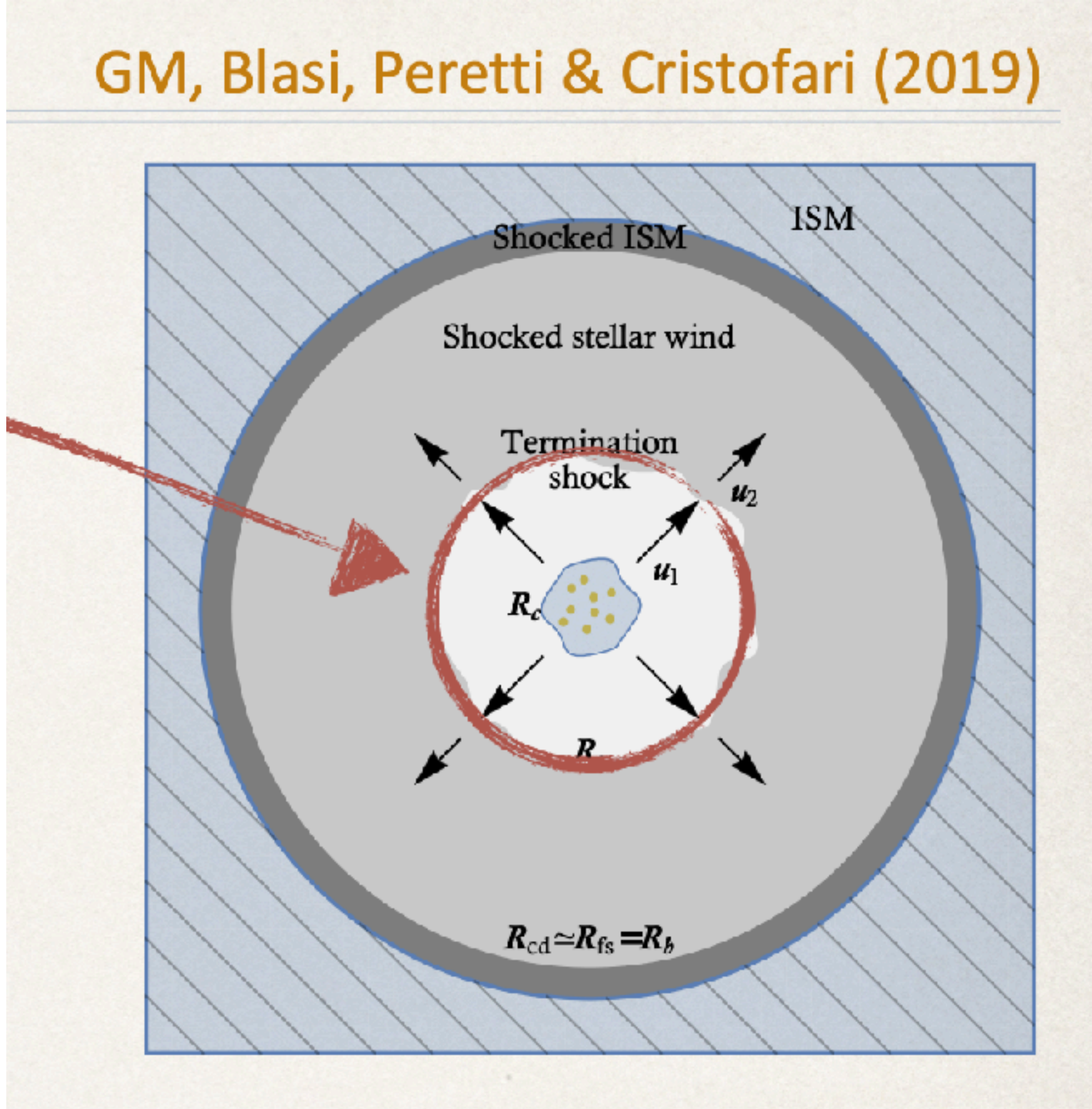
Acceleration of particles to PeV is hard (as it should be)

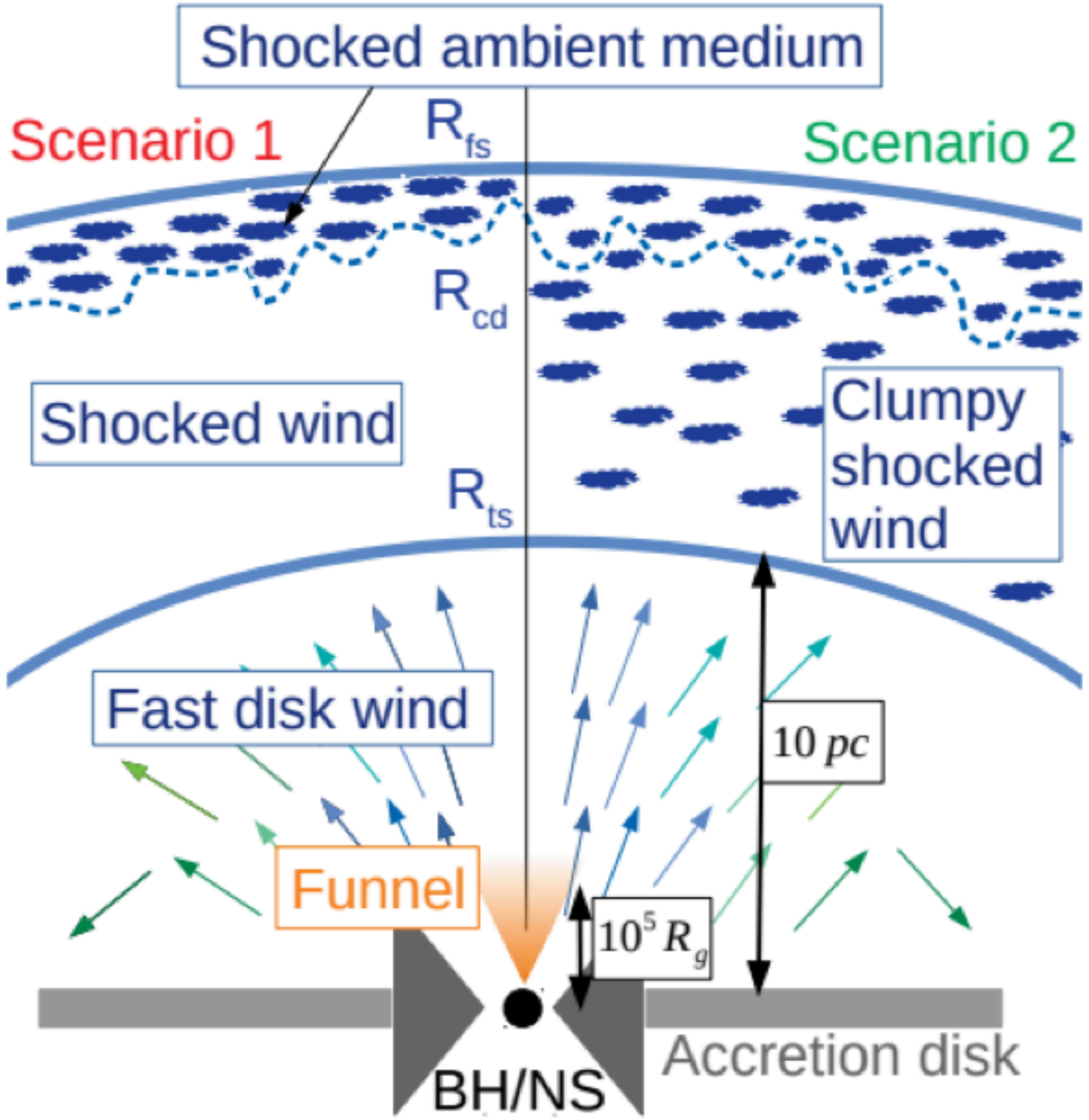
Are all detected supernovae past their prime?

LHAASO sensitivity at >100TeV could reveal former glory? (See Xiao Zhang's talk)

Do SNRs still hold unexpected surprises? Do we hold other sources to same standards?

DSA IN "NEW" SCENARIOS



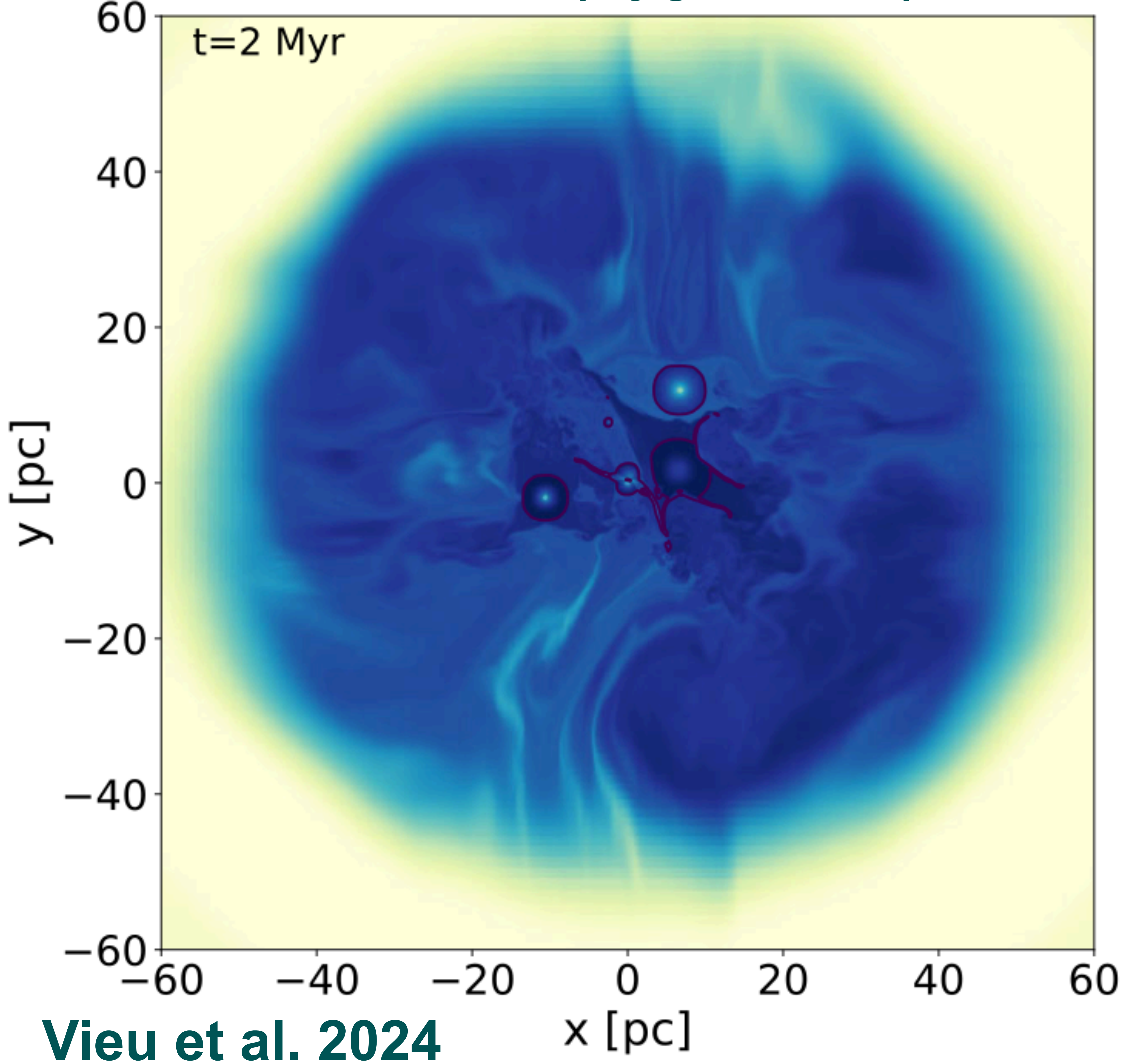


Giovanni's talk **Enrico's talk**

WTSs (should they exist) are ideal sites for DSA. But magnetic field topology important!!

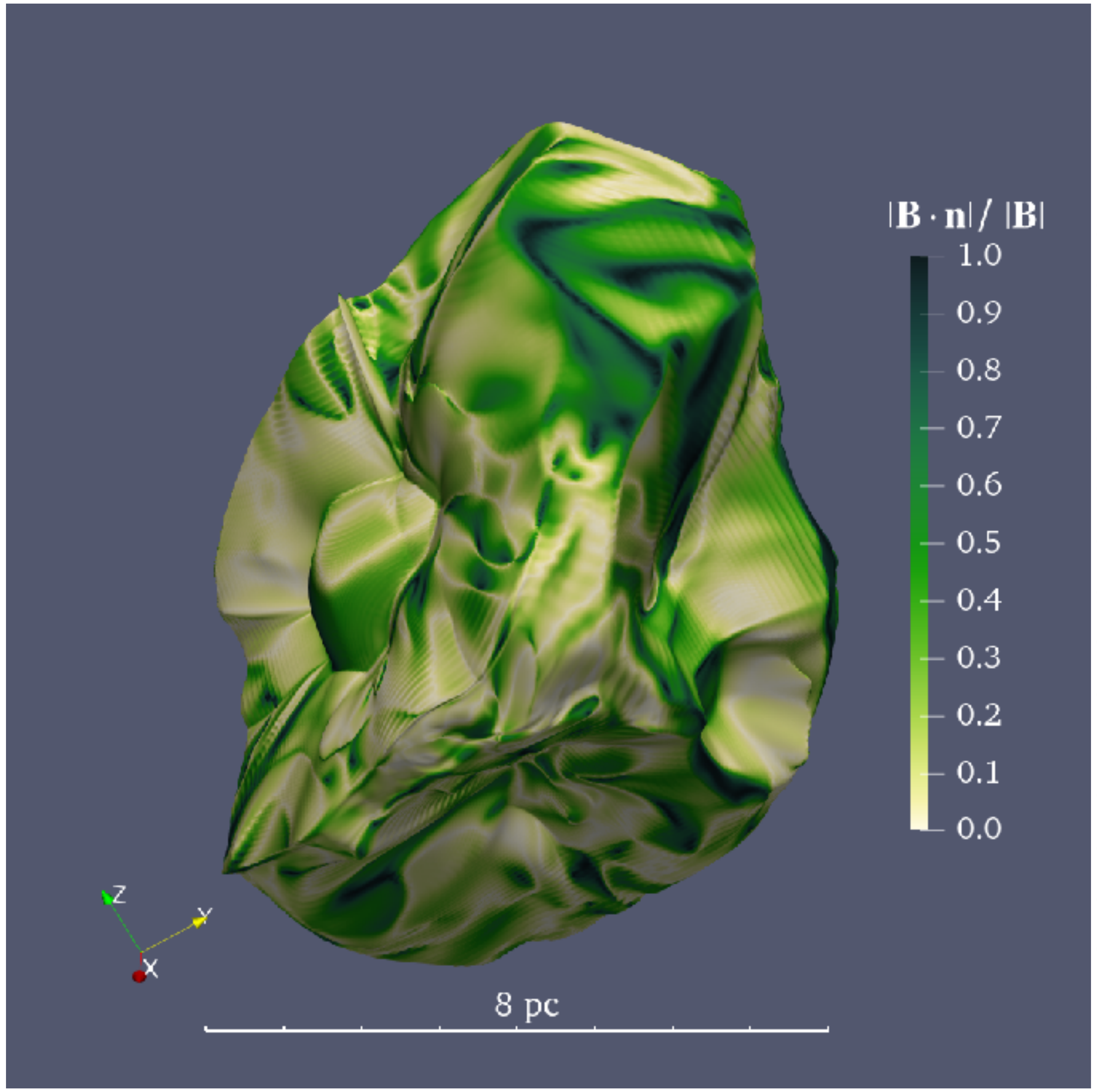
STUDYING THE GLOBAL PICTURE OF YMSCS

Loose Cluster (Cygnus like)



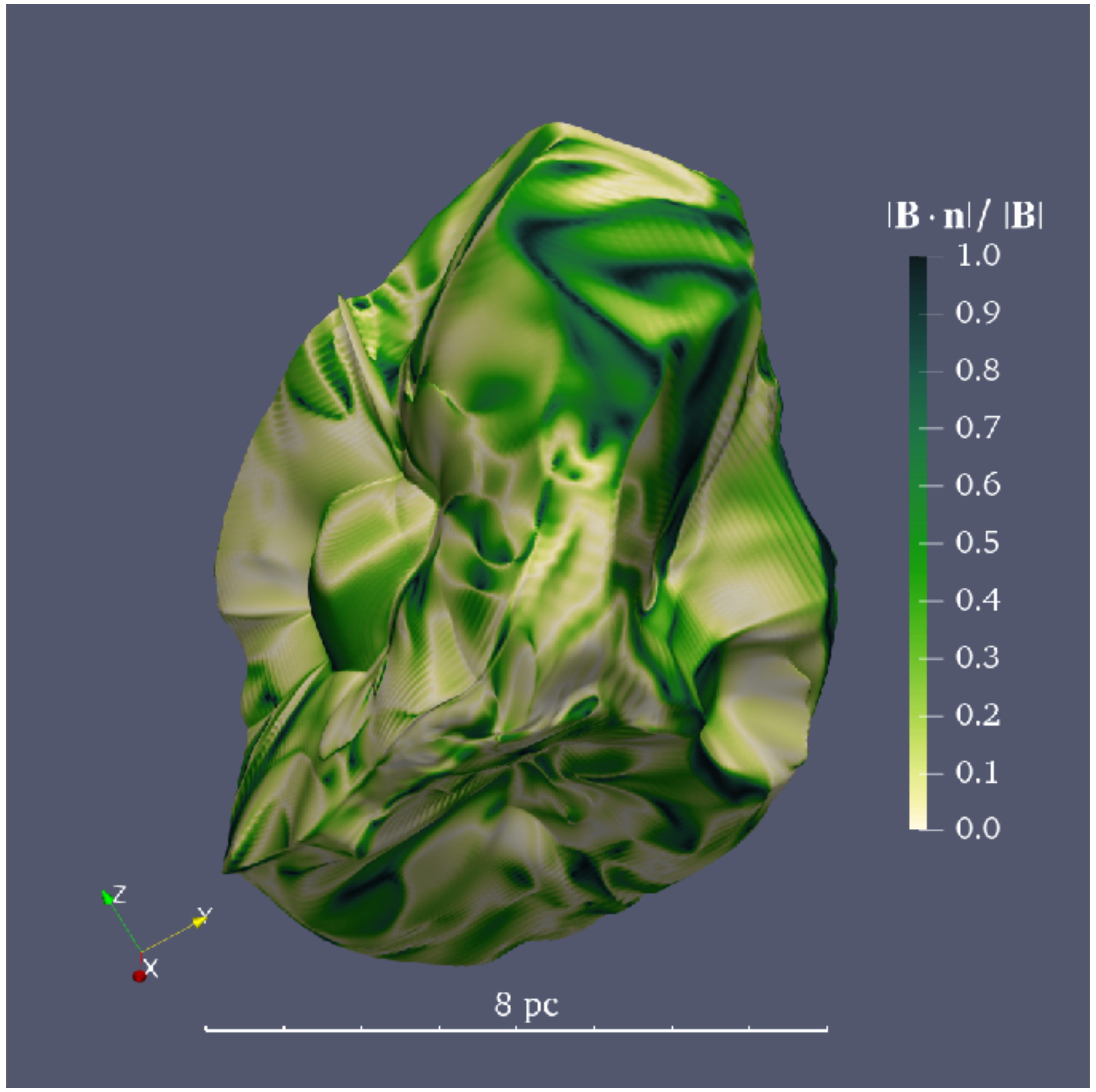
Vieu et al. 2024

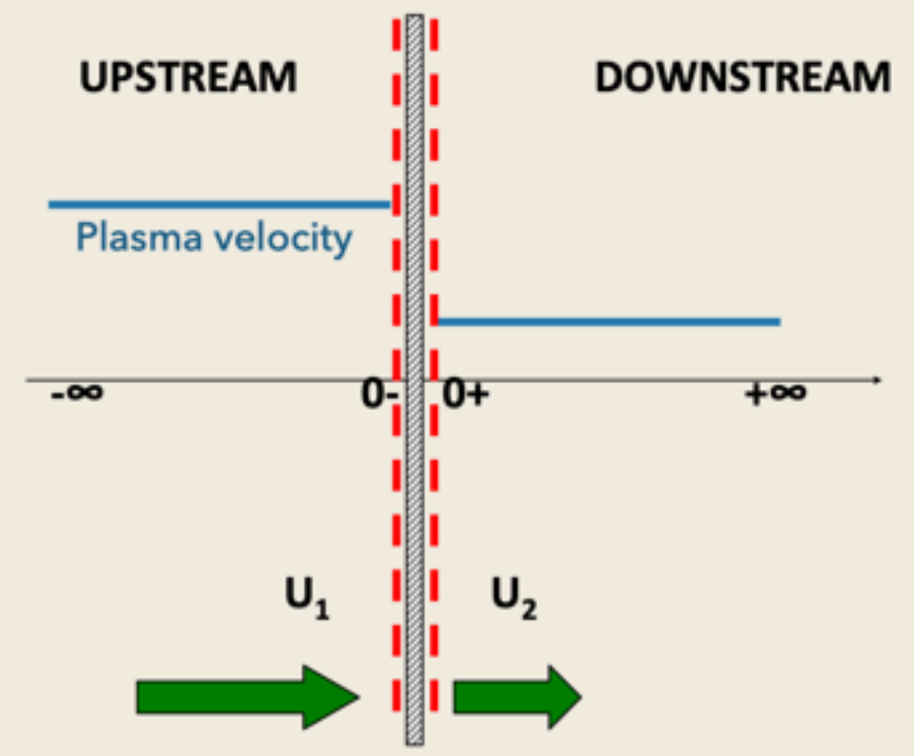
Compact Cluster (Wd1 like)
Isosurface of WTS



Haerer et al. (under review)

BEYOND PARALLEL SHOCKS?





$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x}\left[D\frac{\partial f}{\partial x}\right] - u\frac{\partial f}{\partial x} + \frac{1}{3}\frac{du}{dx}p\frac{\partial f}{\partial p} + Q(x,p,t)$$

DIFFUSION ADVECTION COMPRESSION INJECTION

From Pasquale's talk

For shocks with $\langle B \rangle \nparallel n$ the transport equation can lead to wrong results. Why?

Gyrotropy breaks down at shock transition due to sharp change in field direction ($B_\perp u_\parallel = \text{const}$)

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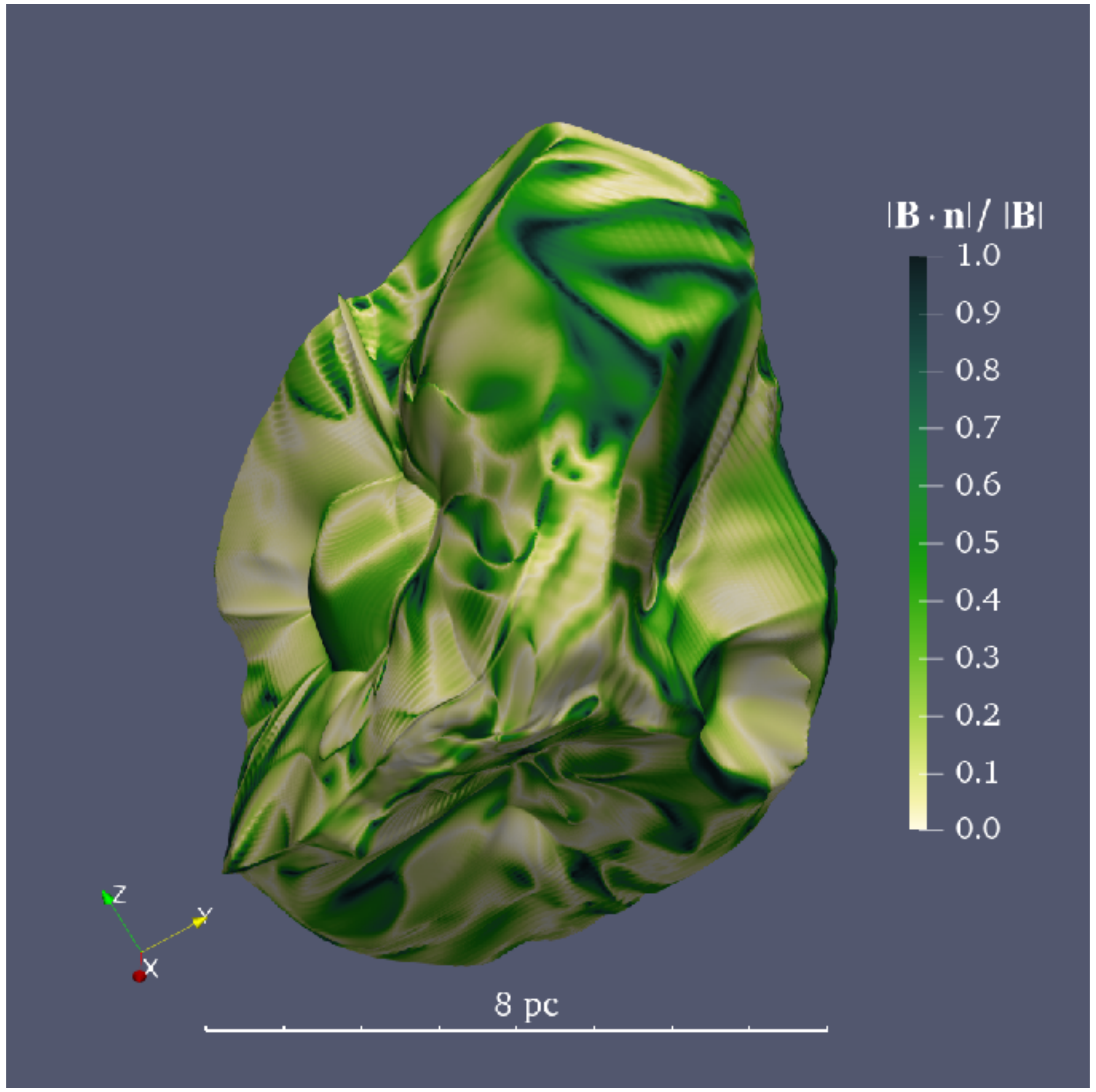

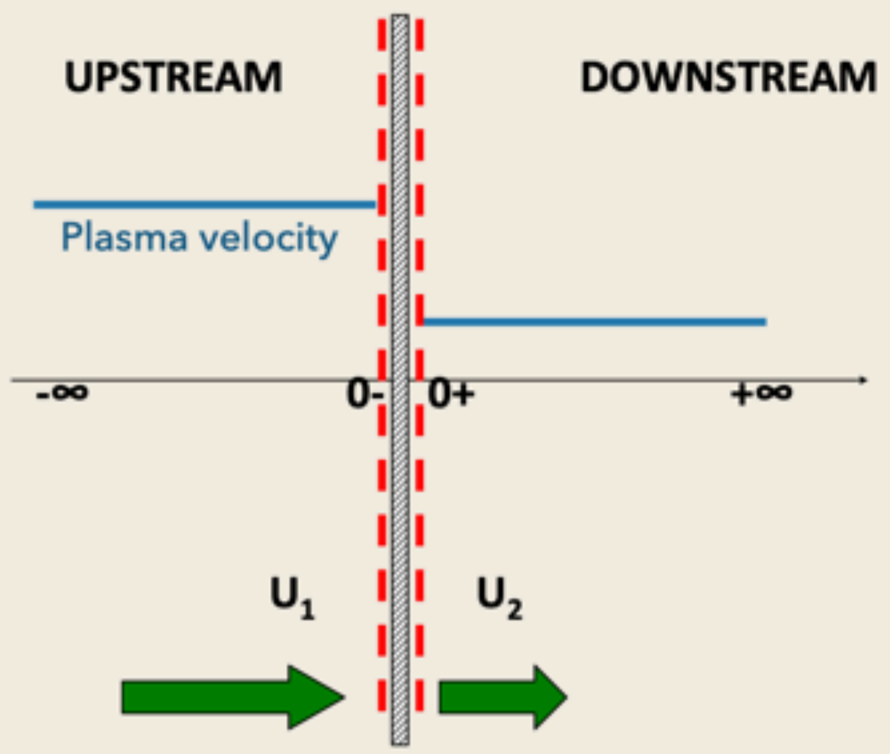

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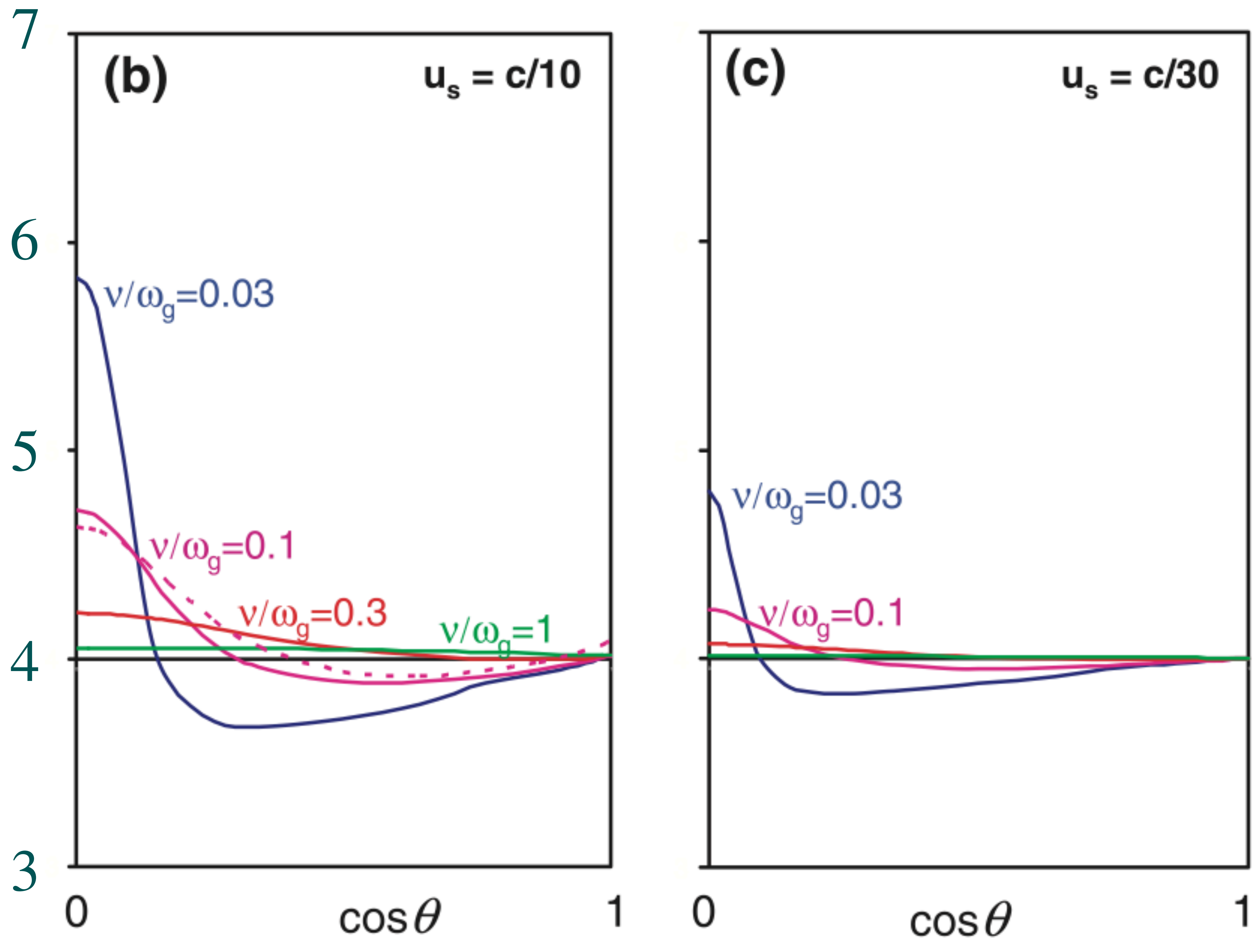
We revisit DSA at an oblique shock solving the full angle dependent Vlasov-Fokker-Planck equation with the open-source code* sapphire++

* sapphirepp.org

BEYOND PARALLEL SHOCKS?



Bell, Schure, BR 2011

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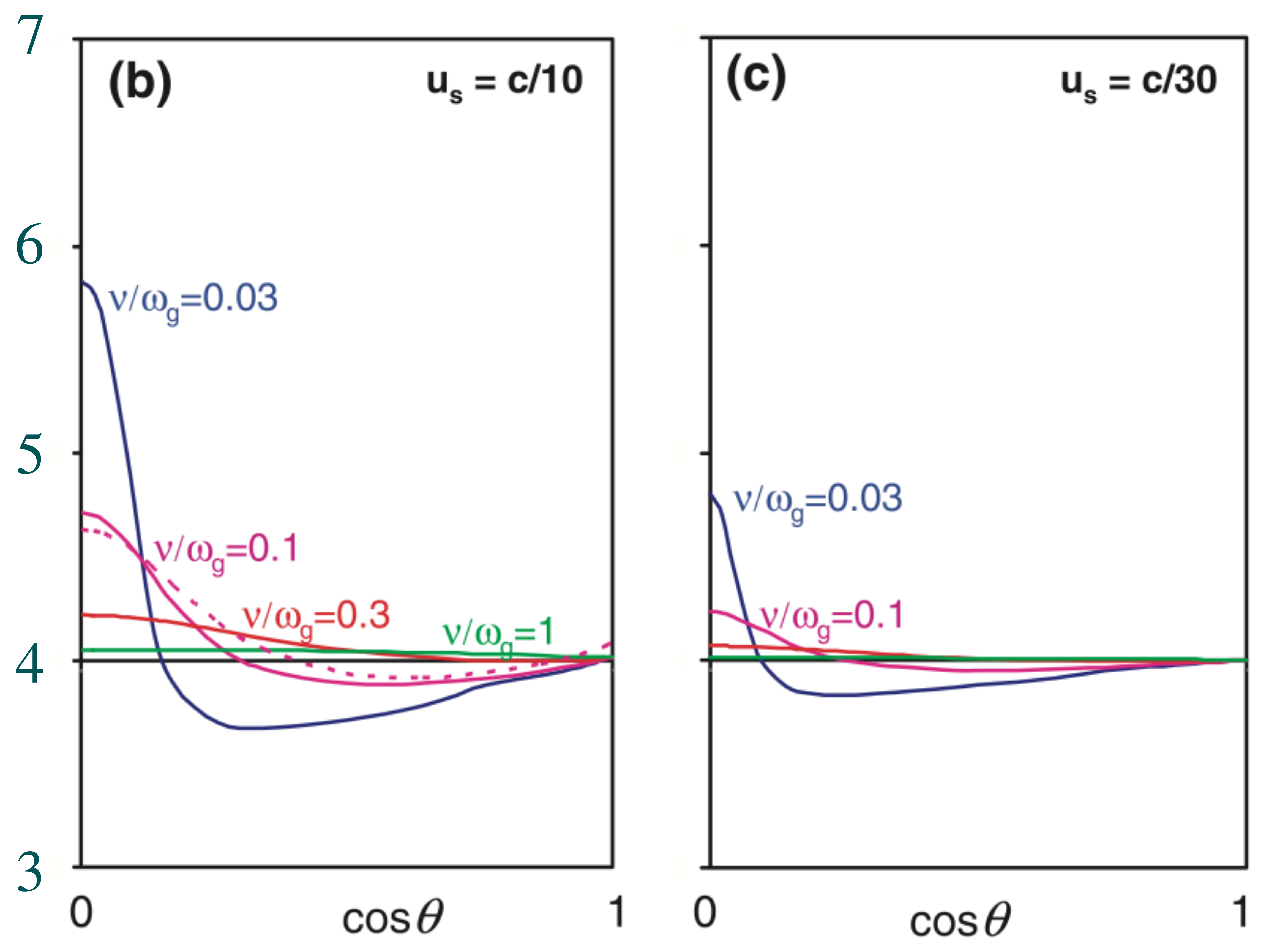
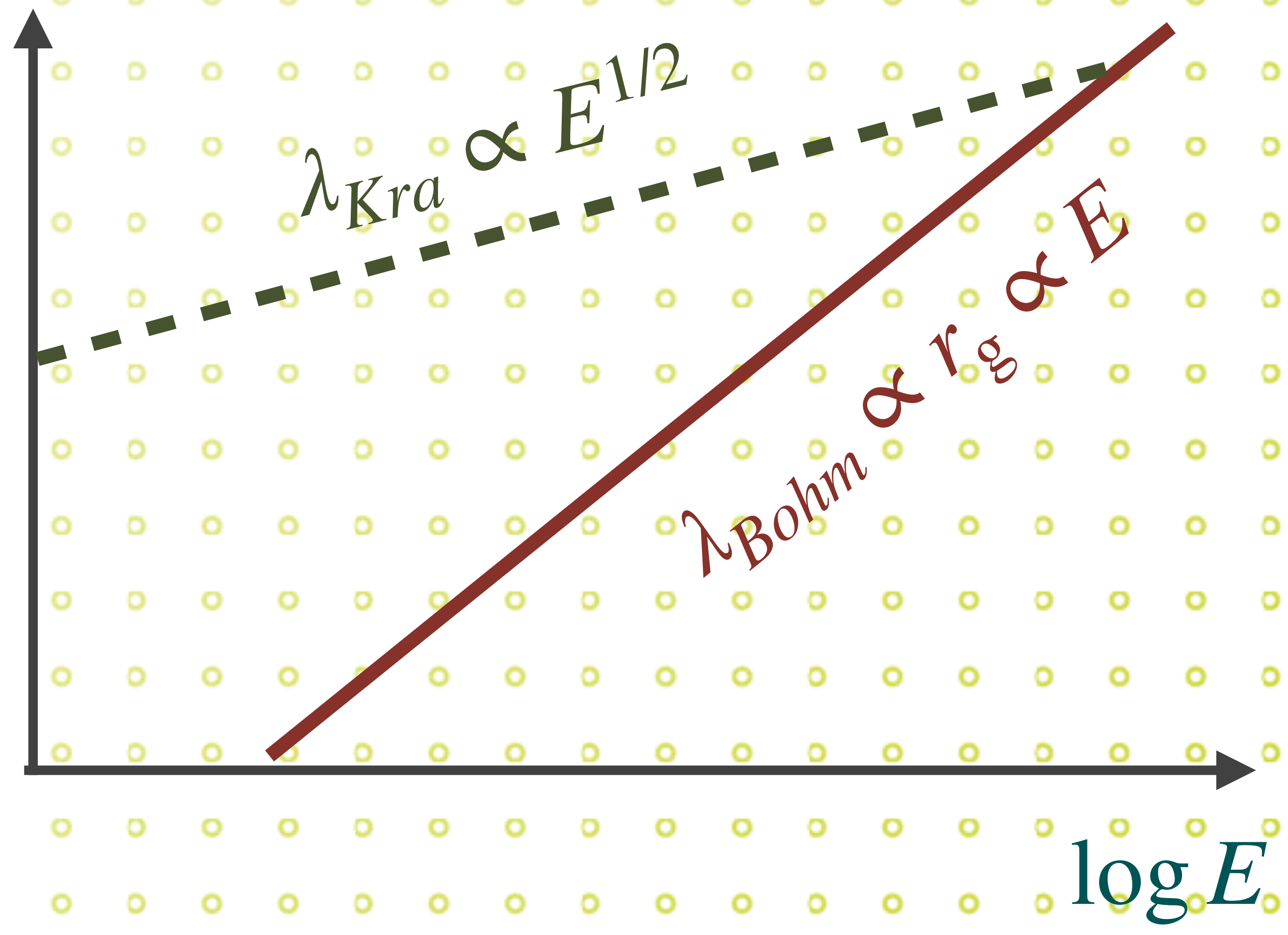


Bell, Schure, BR 2011

What happens if we assume Kraichnan scaling $\lambda_{\rm mfp} \propto r_{\rm g}^{0.5}$ for a 60° ($\cos\theta = 0.5$) shock?



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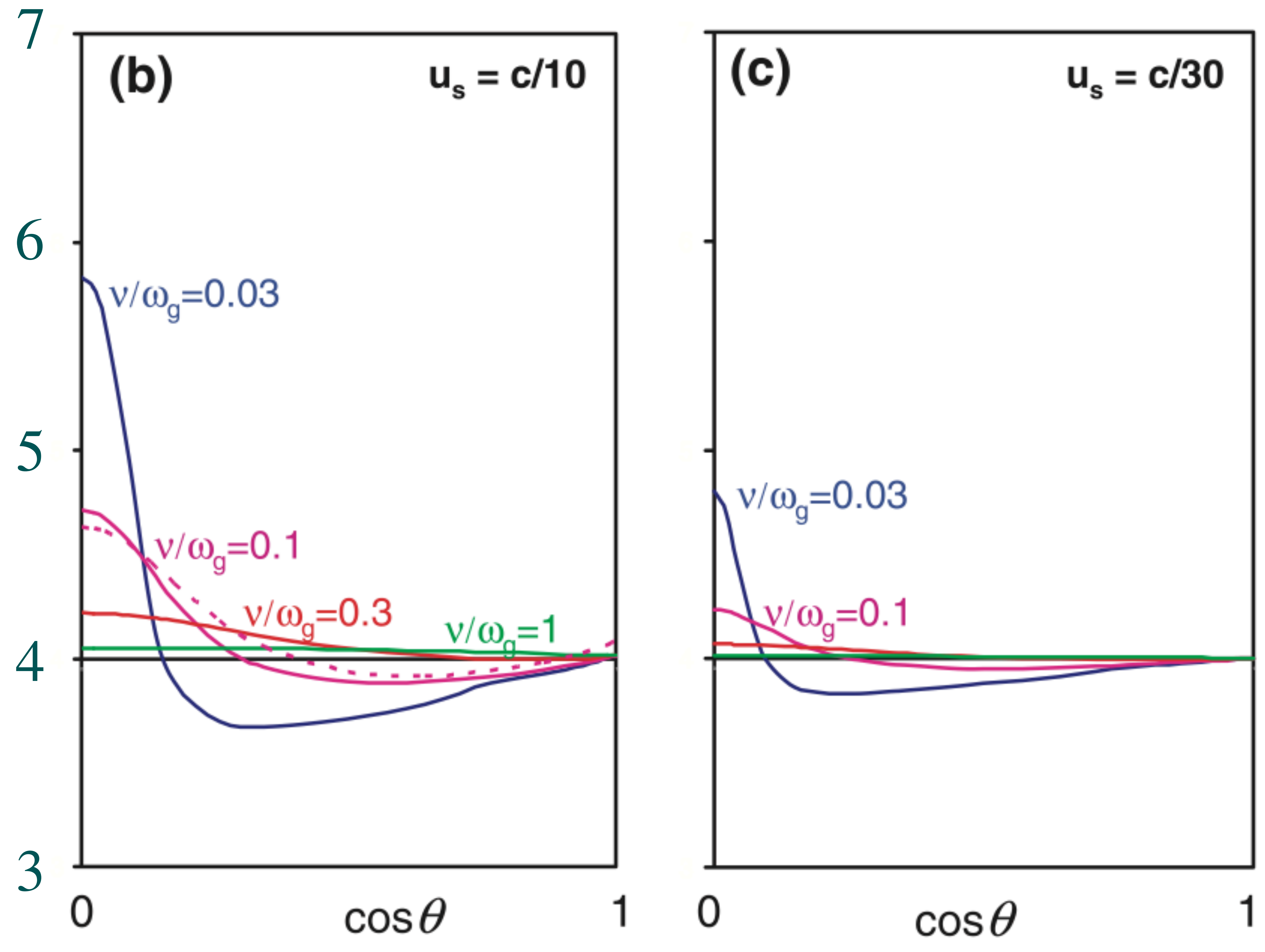

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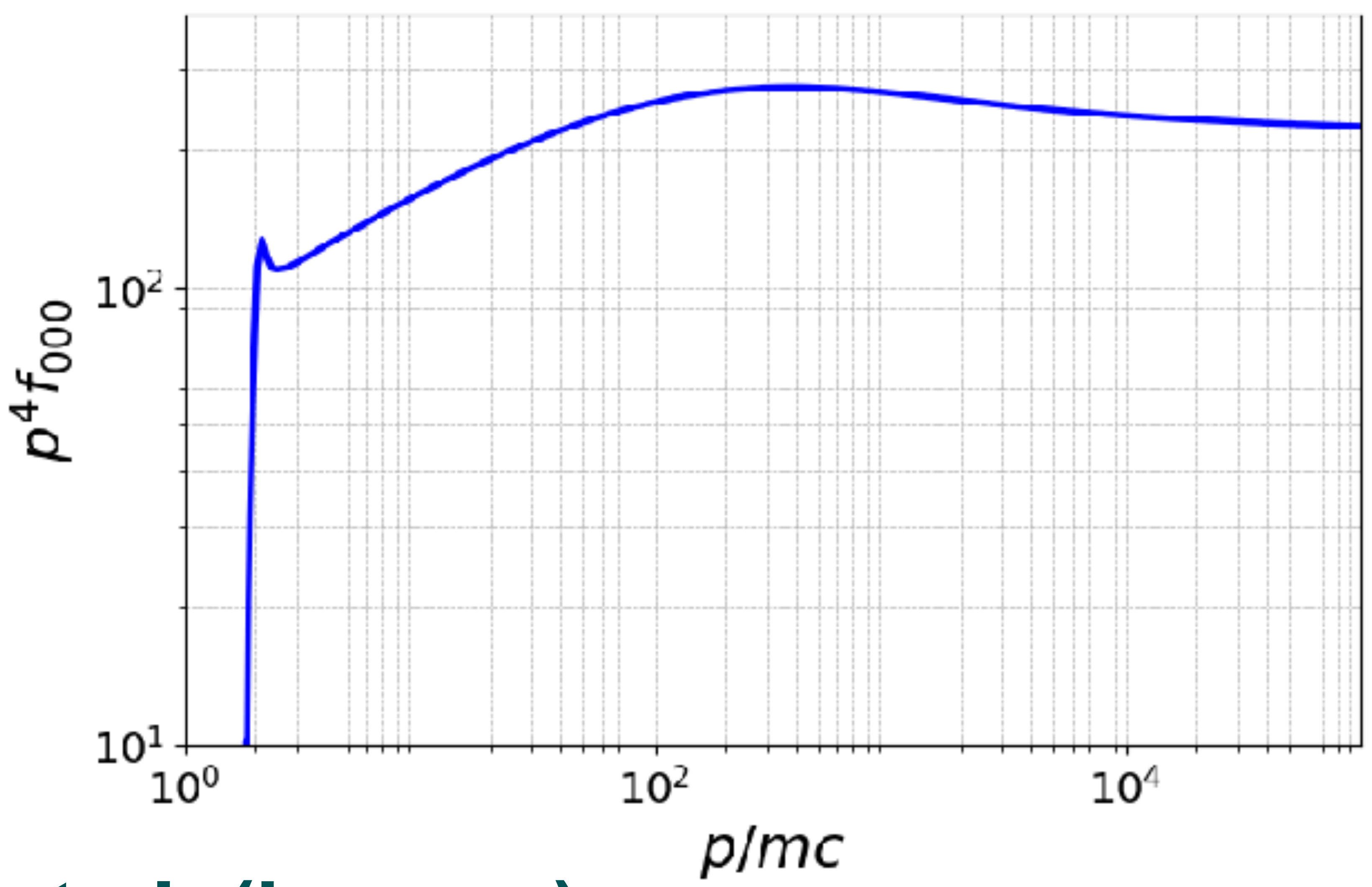

Asma Shirin T et al. (in prep)

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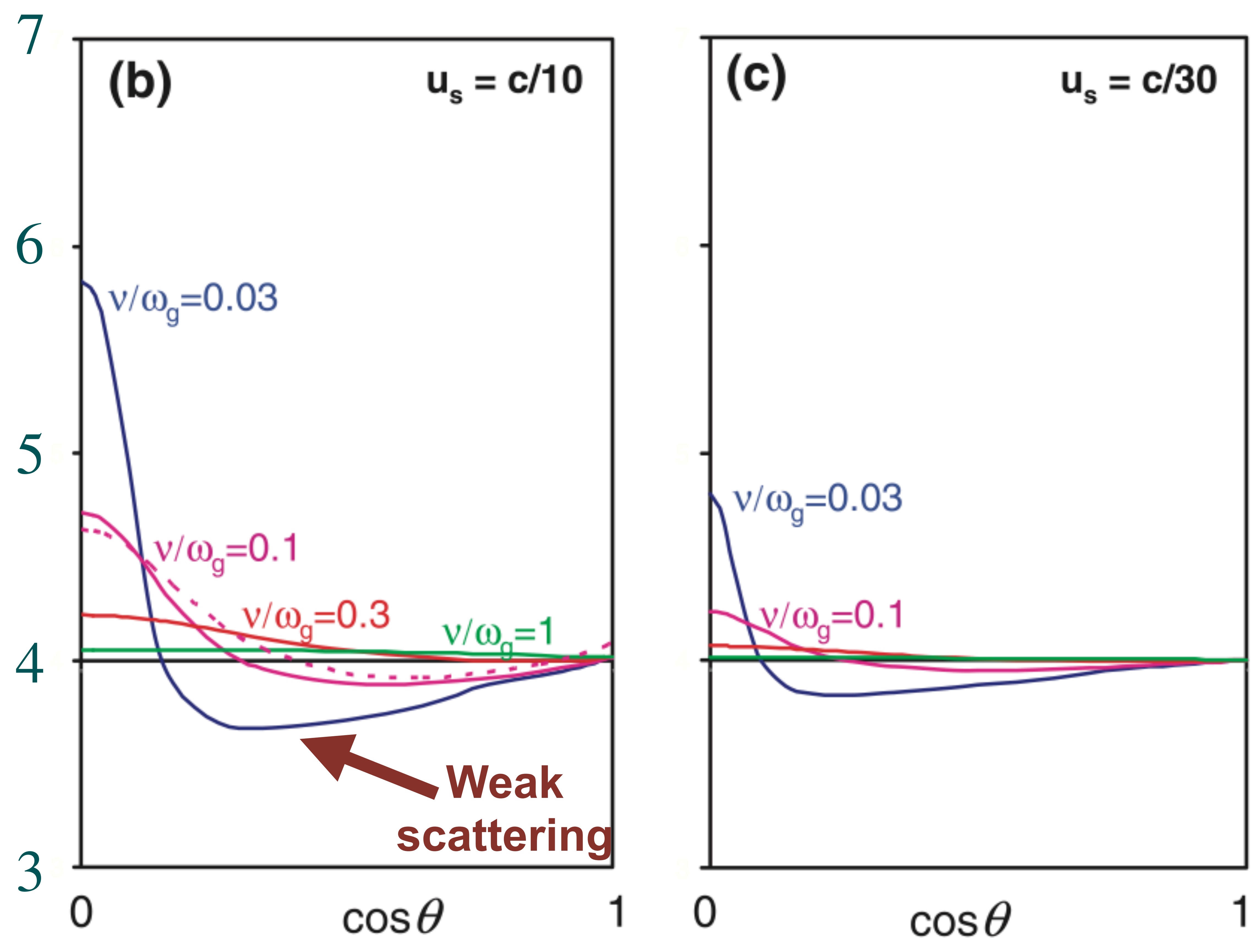

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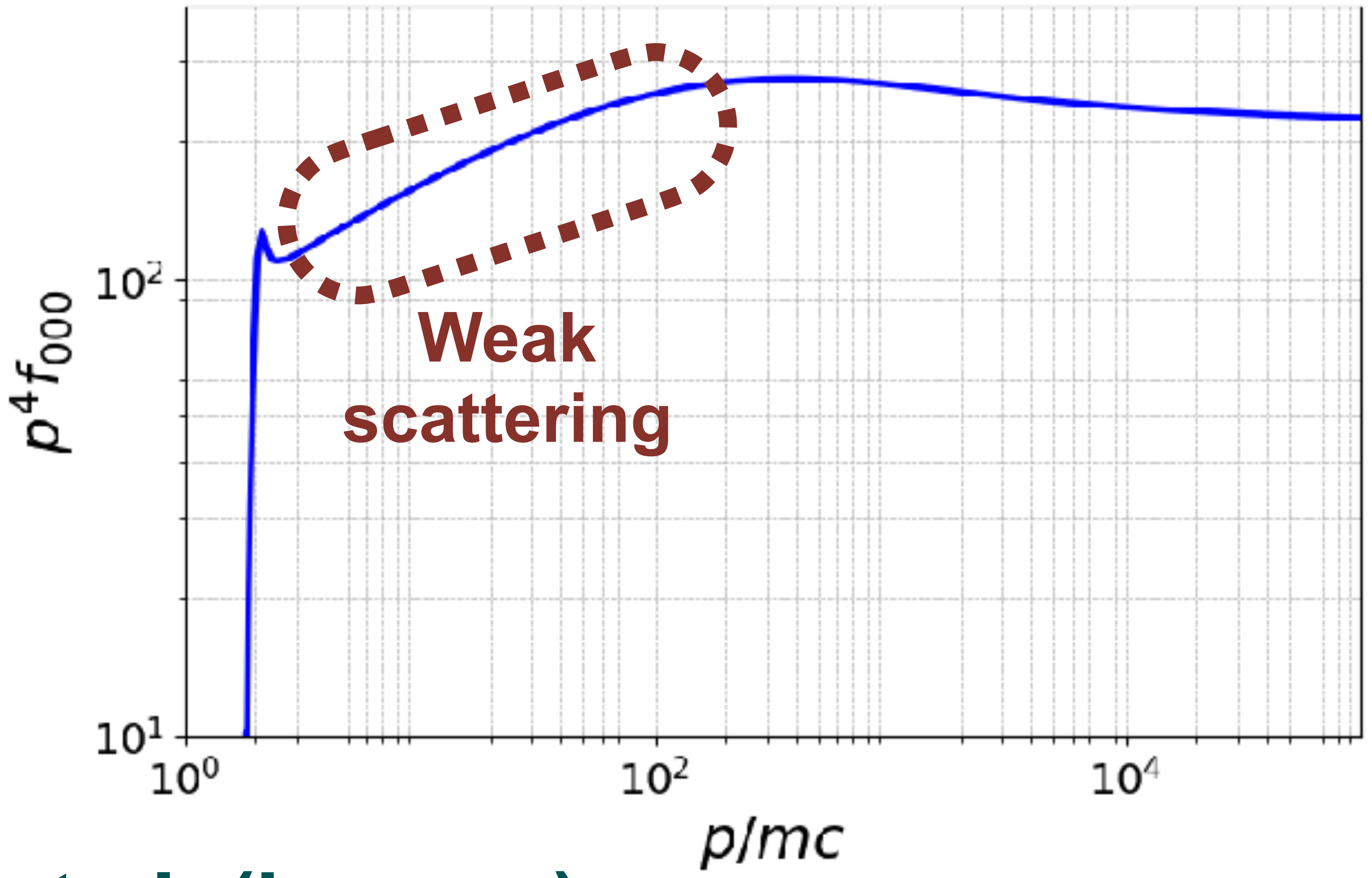

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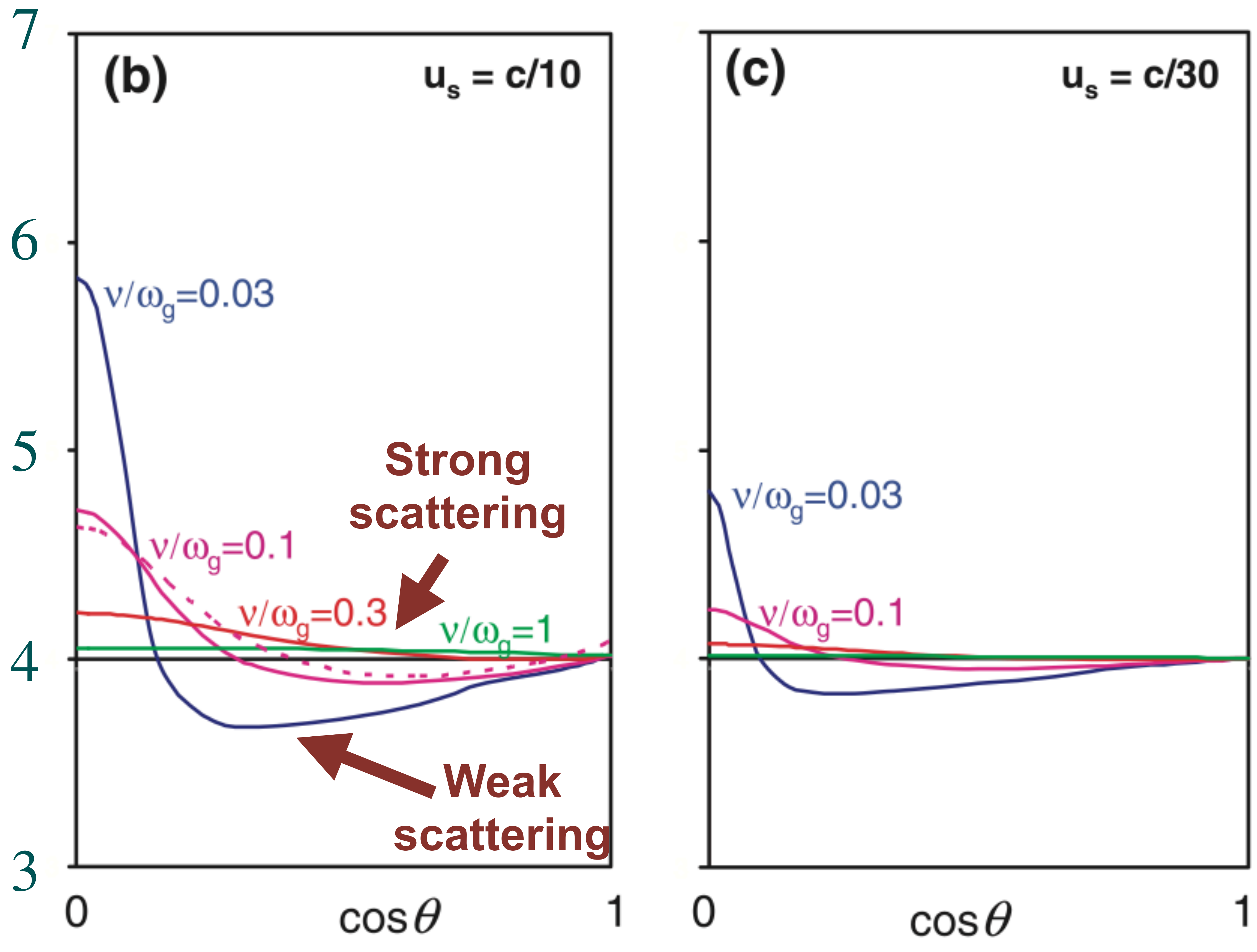

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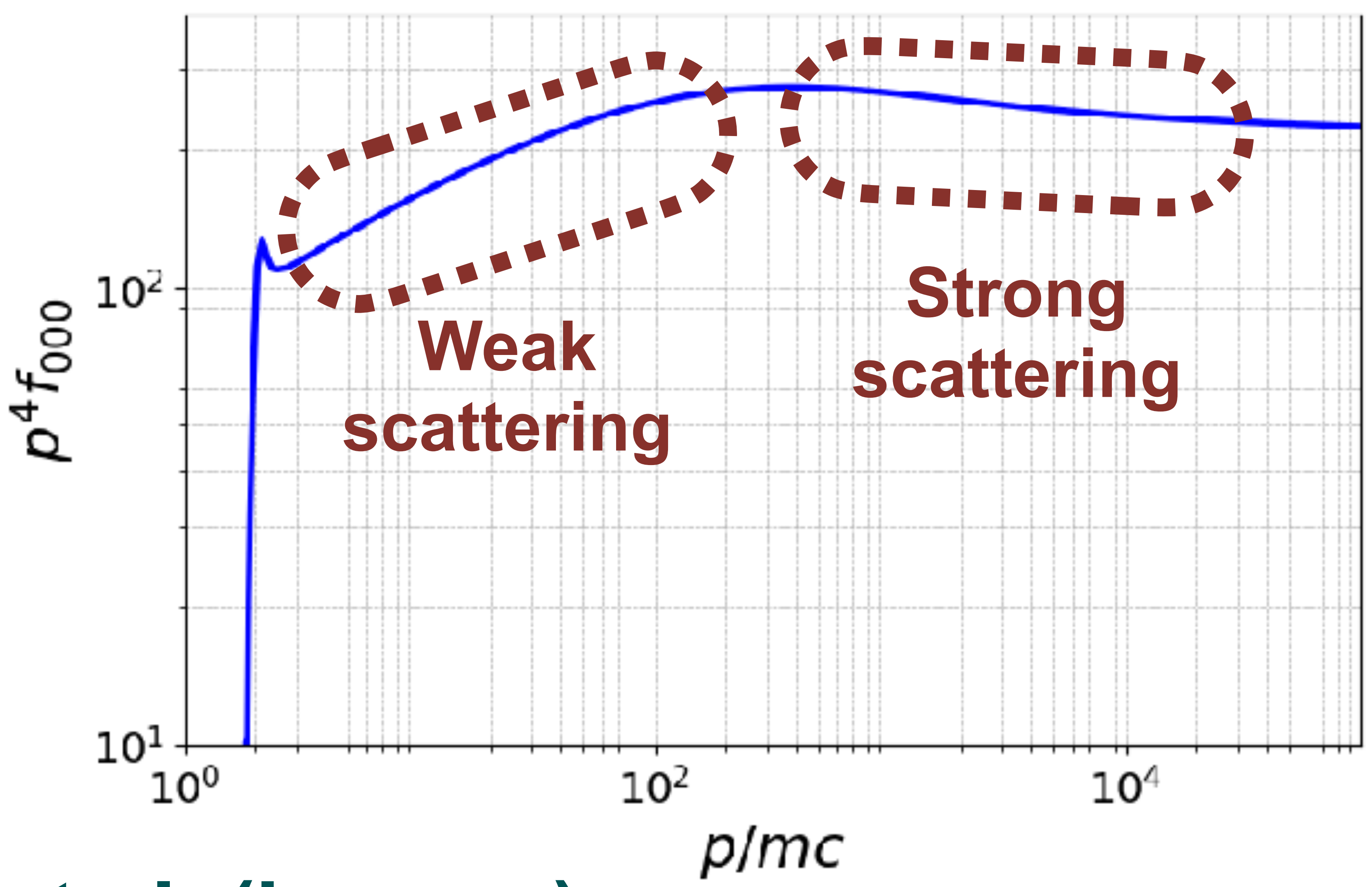

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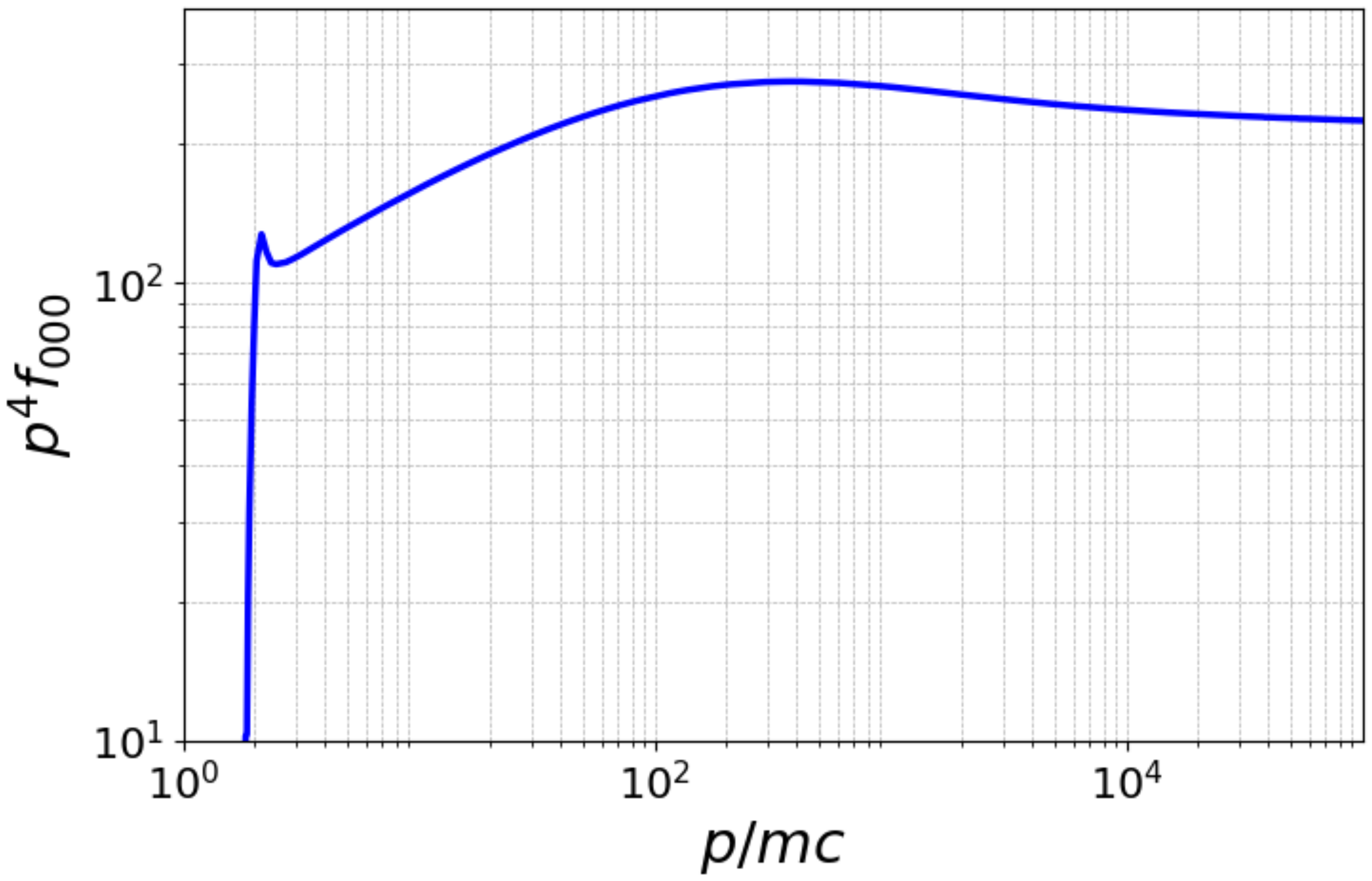
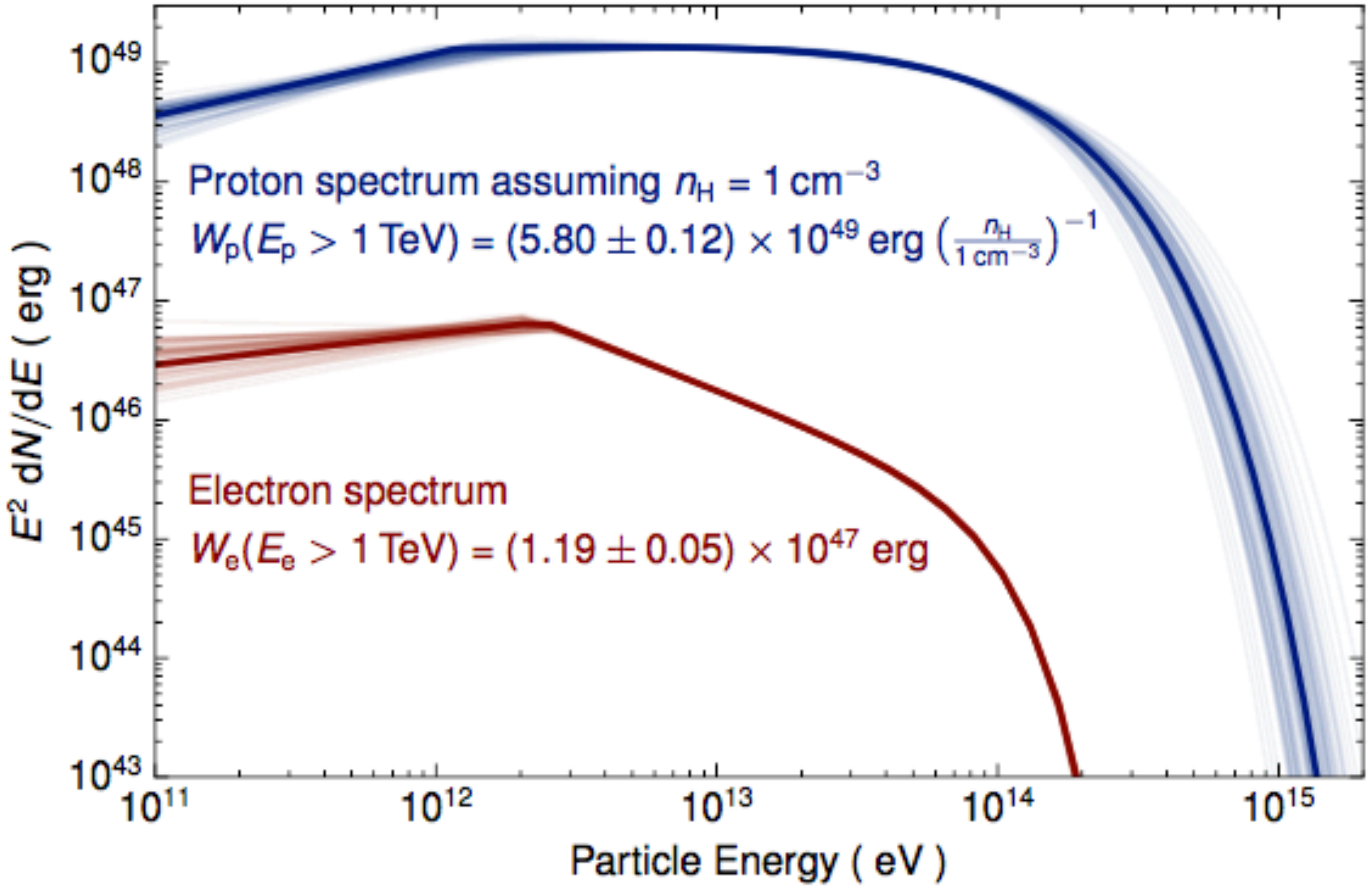


H.E.S.S. Coll. 2016
RXJ 1713



Curved spectra are expected for oblique shocks, <u>even in test particle limit.</u>
Since shocks can (probably) accelerate at all angles, but with variable efficiencies, broader implications still unclear

Summary

Galactic CR production best explained in shock acceleration scenarios.

New players in the game thanks to new gamma-ray discoveries in VHE & UHE regimes

Many questions remain on highest energies, and escape from sources, transport in the near environment, escape etc.

DSA still holds many surprises. Curved spectra possible even in test-particle limit (opens prospects for improved probing?).

LHAASO discoveries have made a profound impaction the field.