Particle acceleration at supernova remnants

Pierre Cristofari
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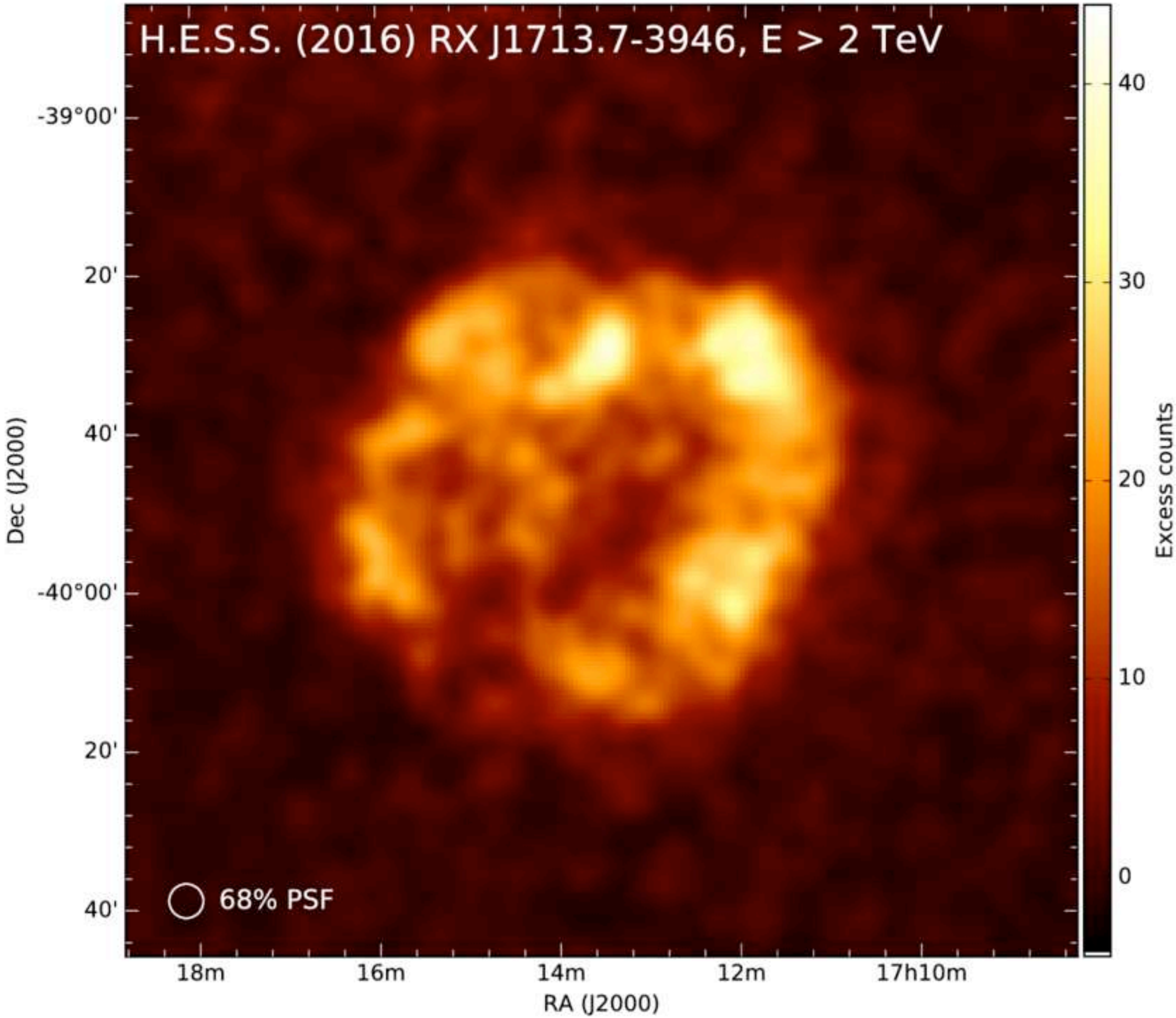
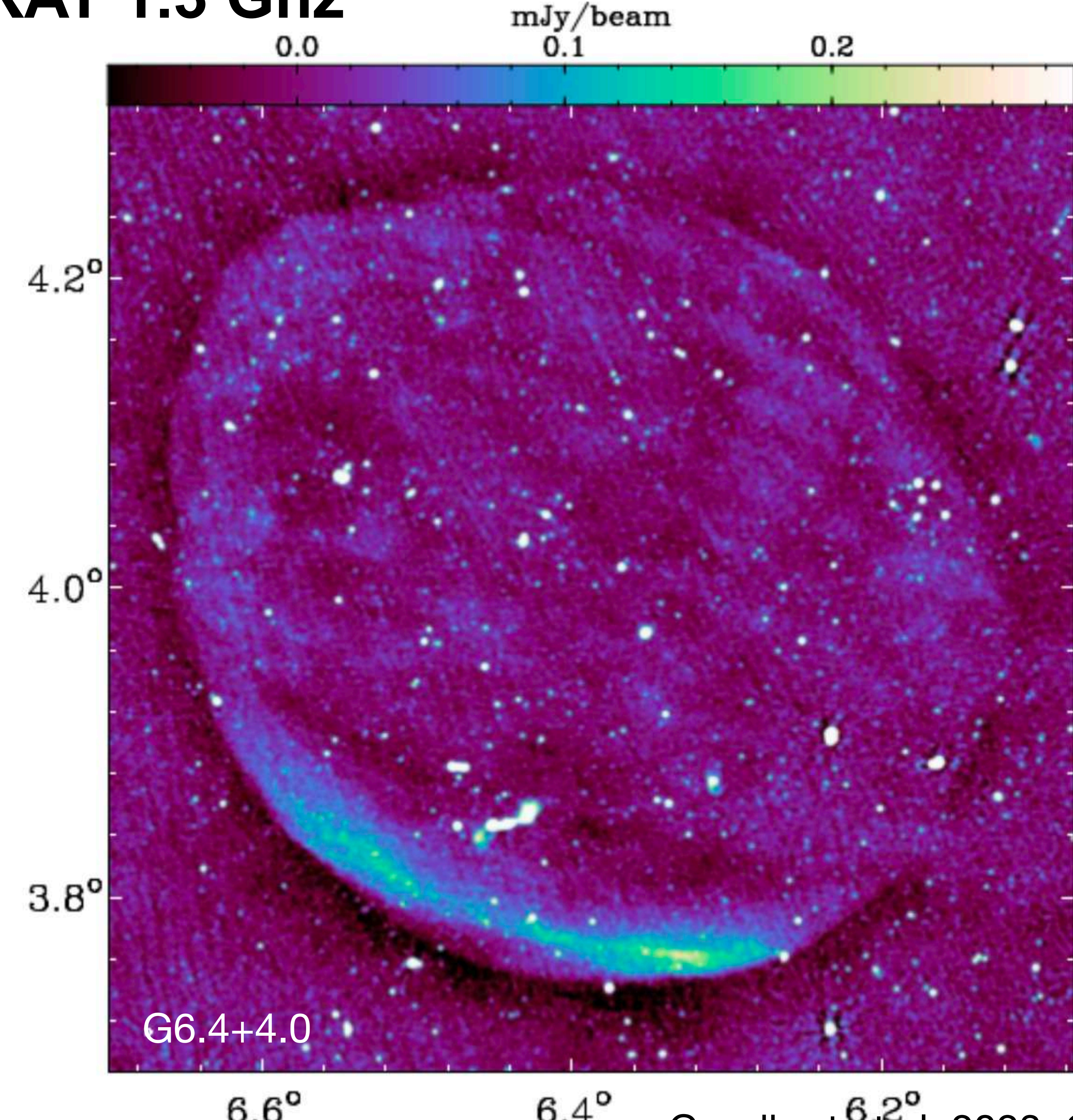
Journées théories
APC Nov. 2024

Observatoire de Paris | PSL


H.E.S.S. (2016) RX J1713.7-3946, E > 2 TeV
-39°00'
20'
40'
-40°00'
20'
40'
Dec (J2000)
18m
16m
14m
12m
17h10m
RA (J2000)
68% PSF
Excess counts
40
30
20
10
0

MeerKAT 1.3 Ghz



Goedhart et al. 2023, Cotton et al. 2023

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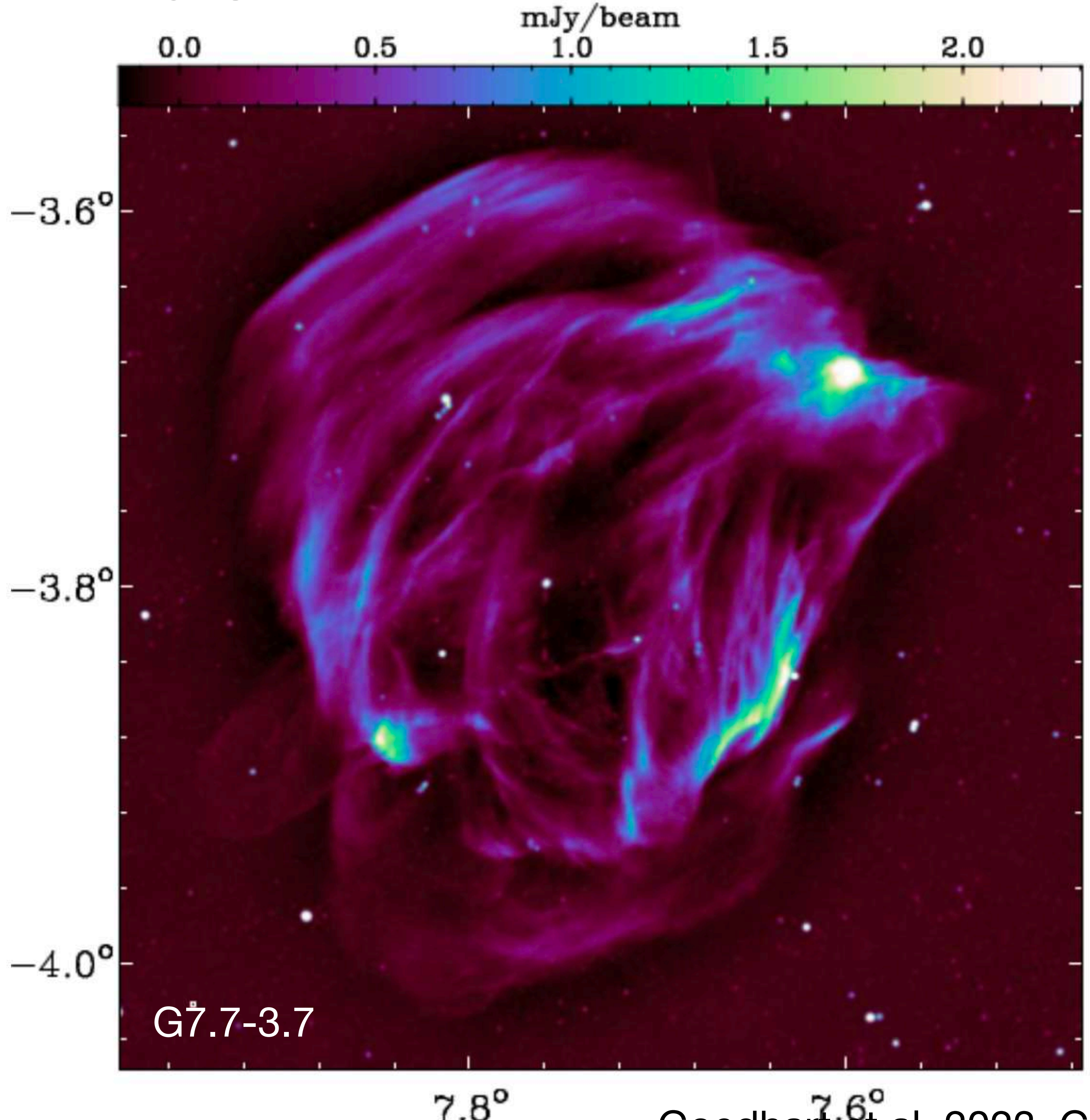

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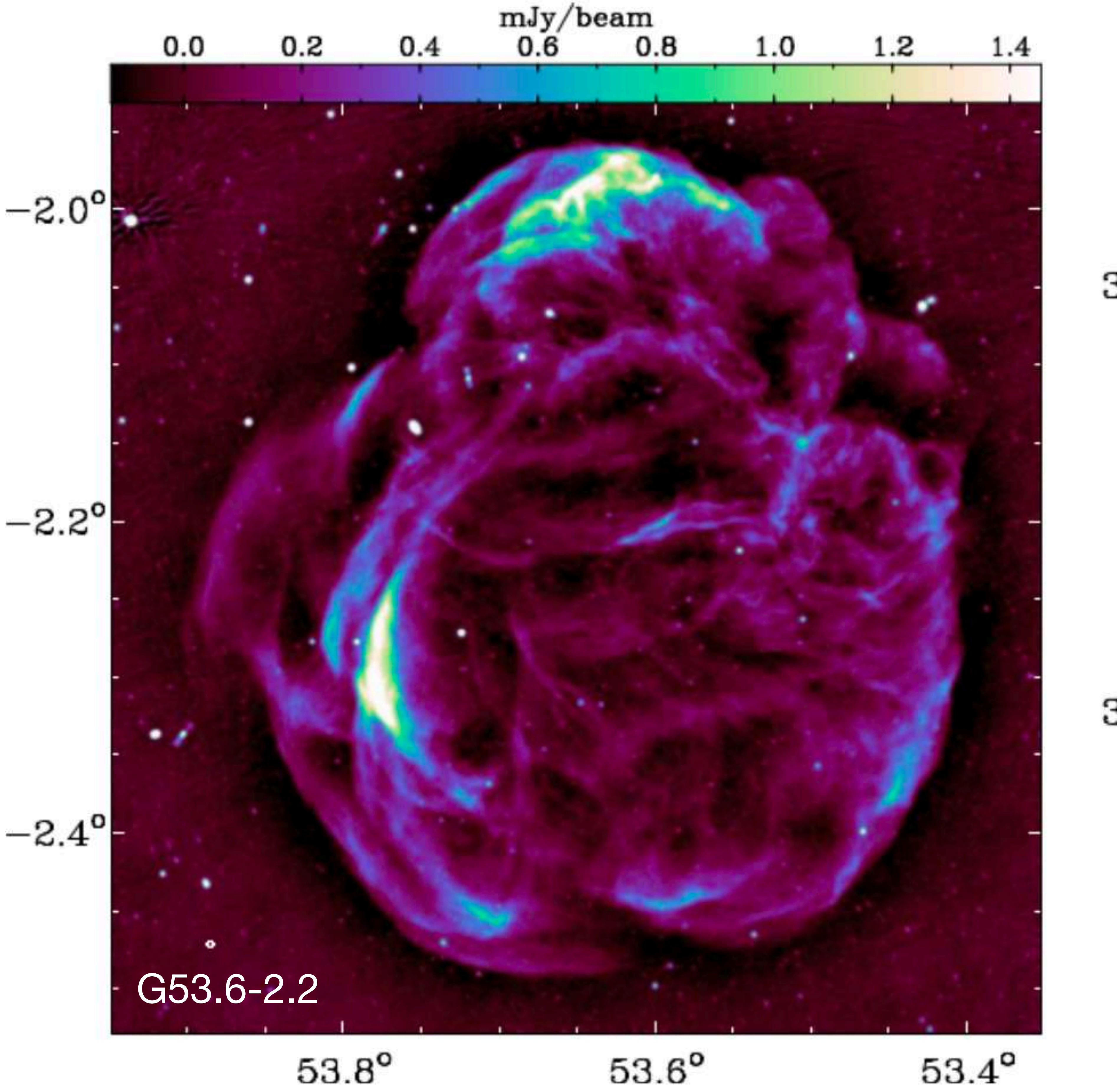

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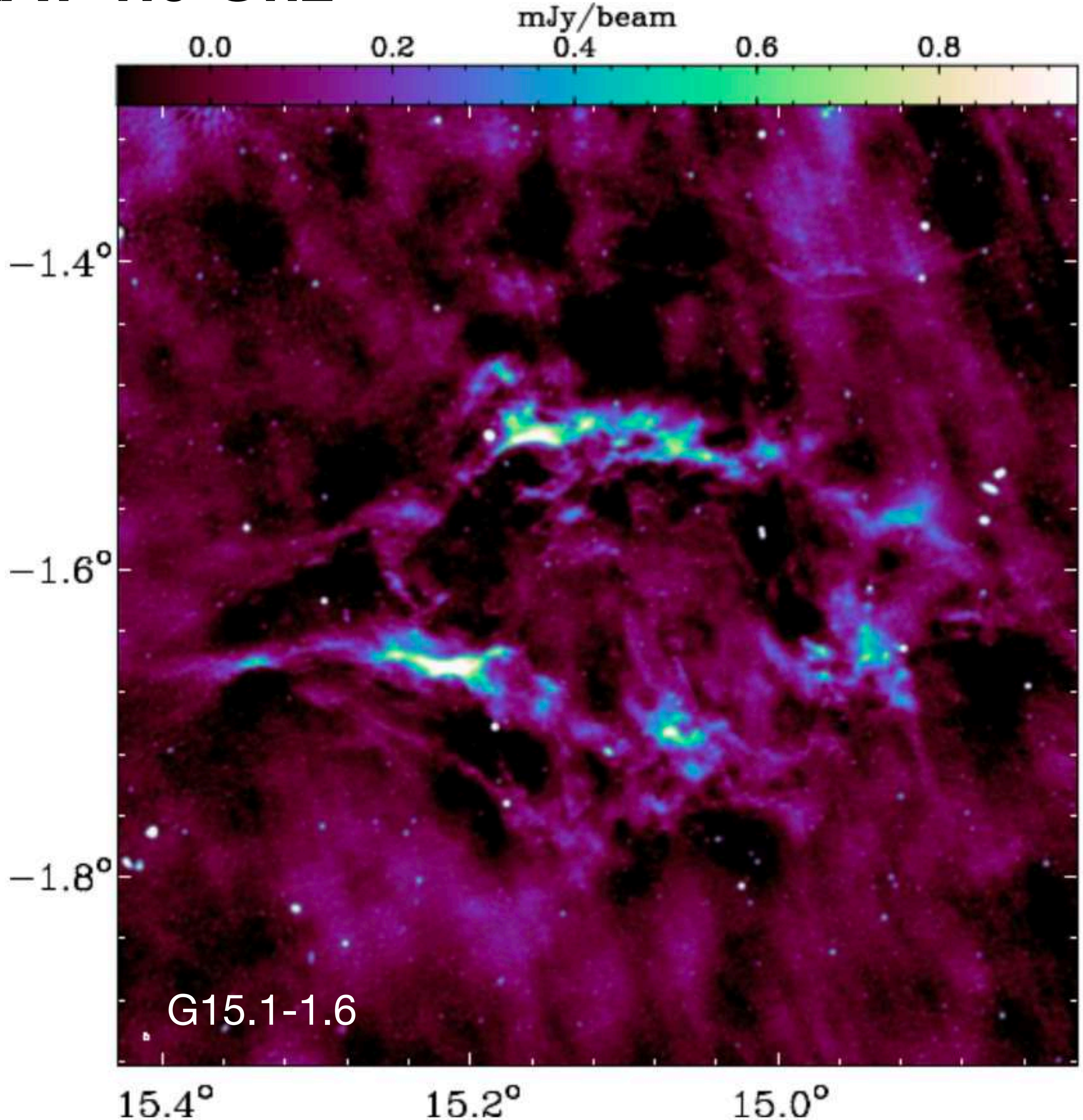

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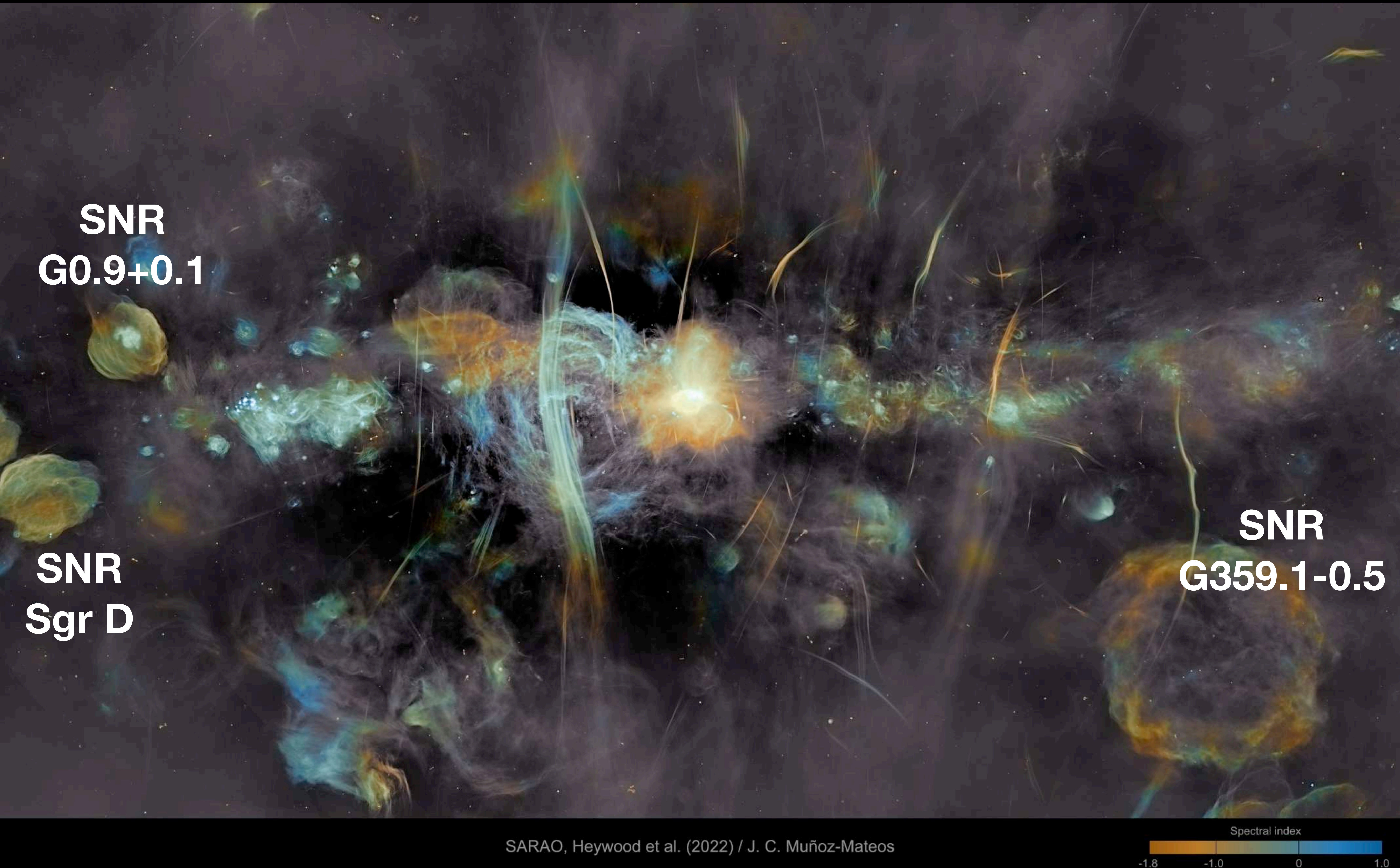
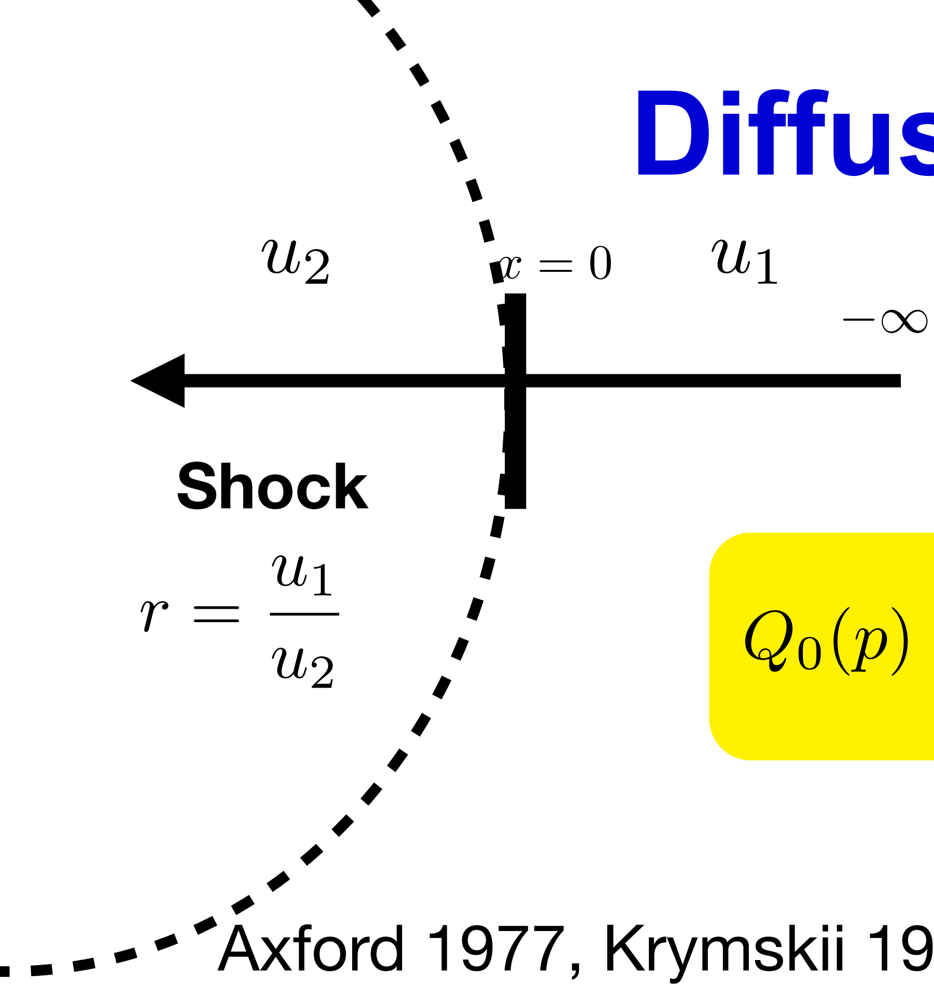


MeerKAT 2022

Diffusive shock acceleration (DSA)



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

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$$f_0(p) = s\frac{\eta n_1}{4\pi p_{\rm inj}^3}\left(\frac{p}{p_{\rm inj}}\right)^{-s}$$

$$\mathcal{M} \gg 1 \qquad s = \frac{3r}{r-1} \to 4$$

Axford 1977, Krymskii 1977, Bell 1978, Blandford 1987

The 1D test-particle theory at strong colisionless shocks is well known

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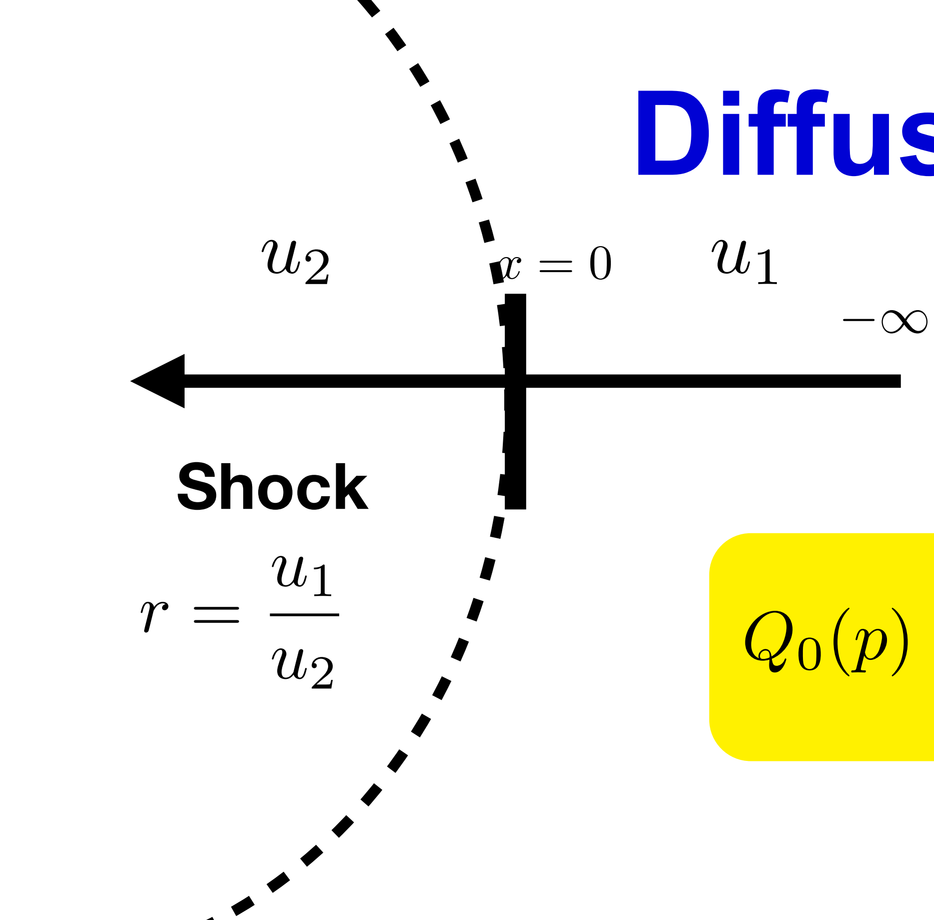

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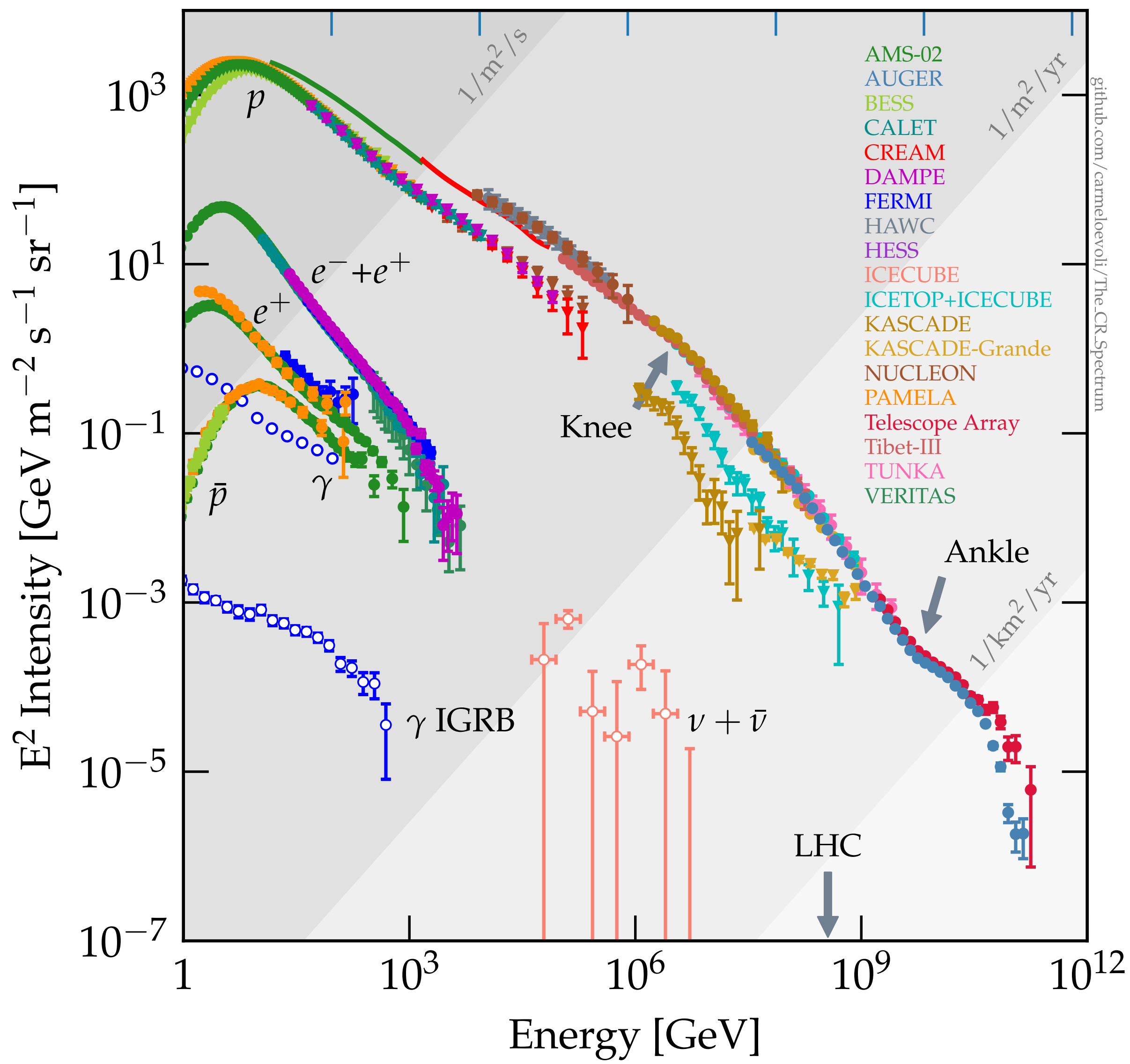
Reviews: Drury 2012, Blasi 2013, Schure 2014, Gabici 2019, Ferrand 2020

The contribution of supernova remnants to protons below the knee



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★Sustain the total CR power ✓

★Inject a spectrum that can account for proton spectrum ~✓

★Reach the knee (be pevatrons) ?

Evoli 2021

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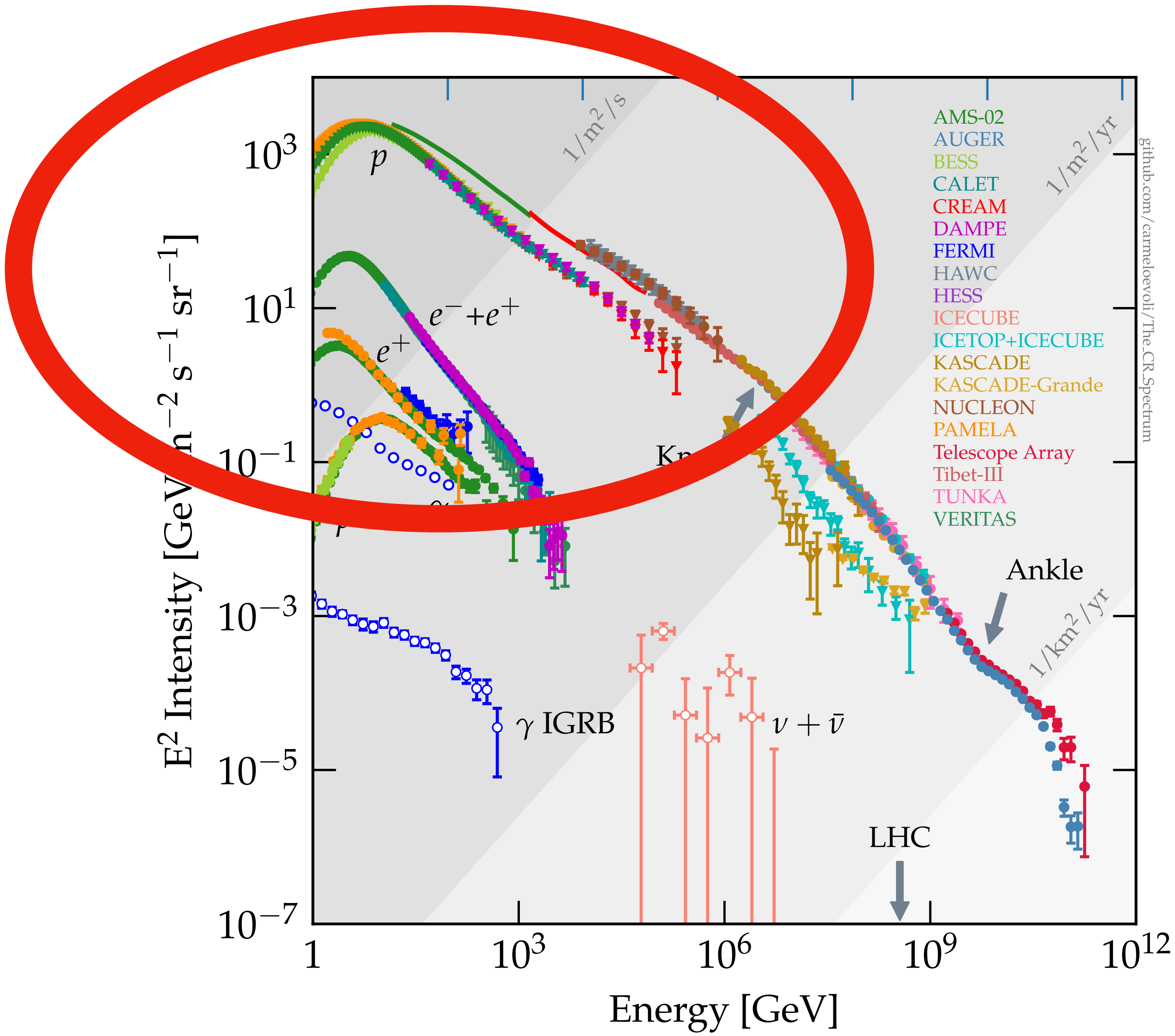

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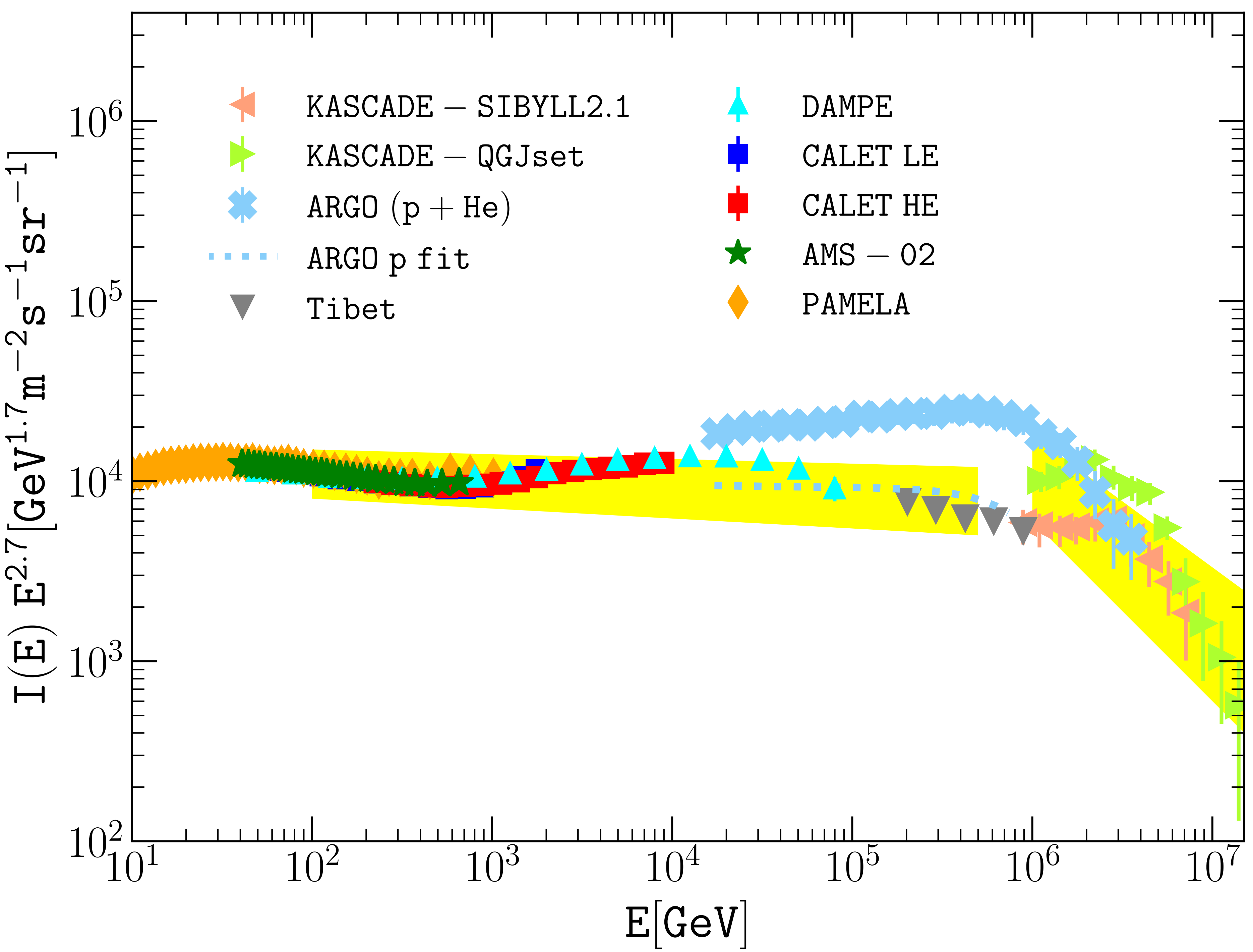

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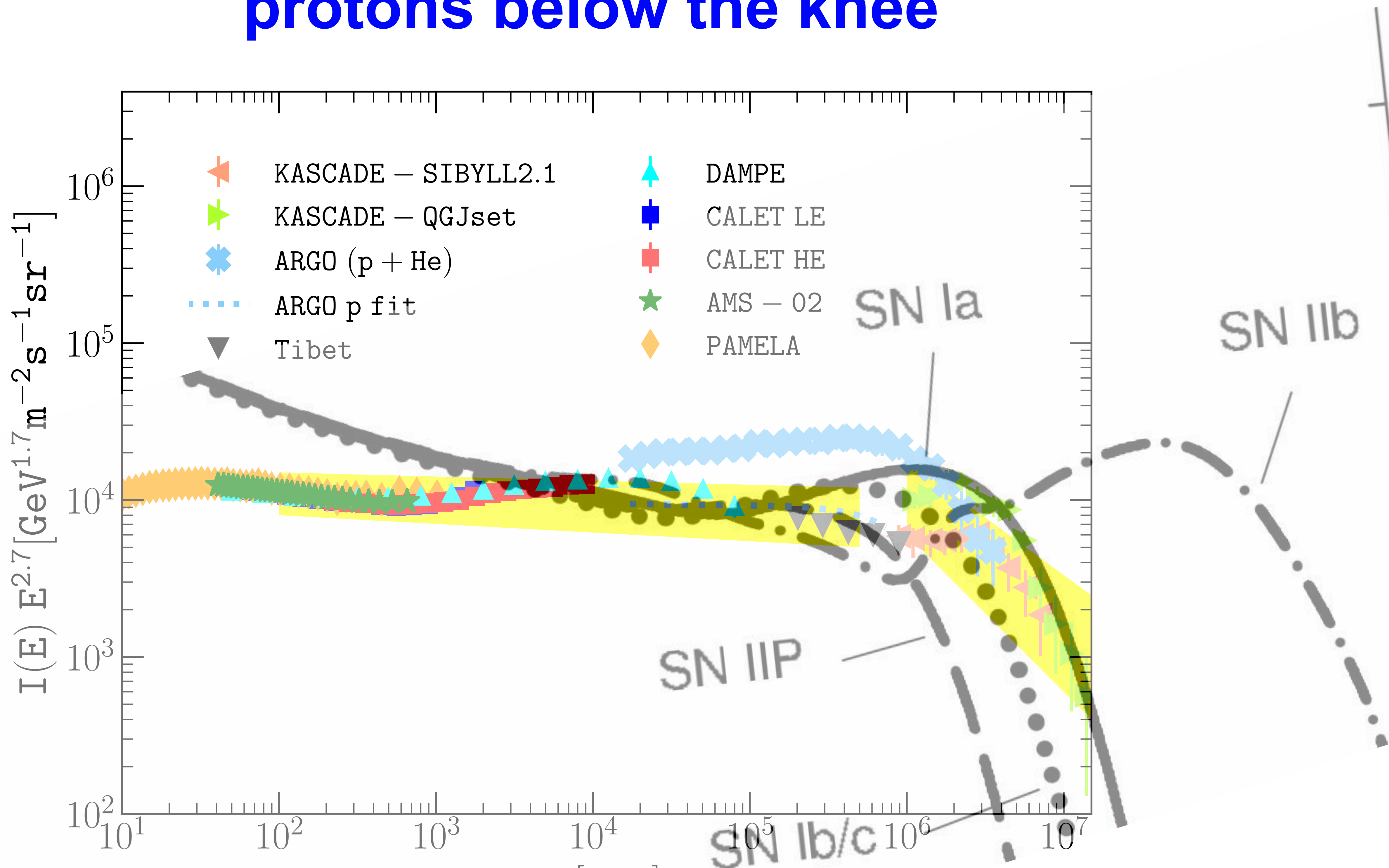

Ptuskin, Zirakashvili & Seo 2010

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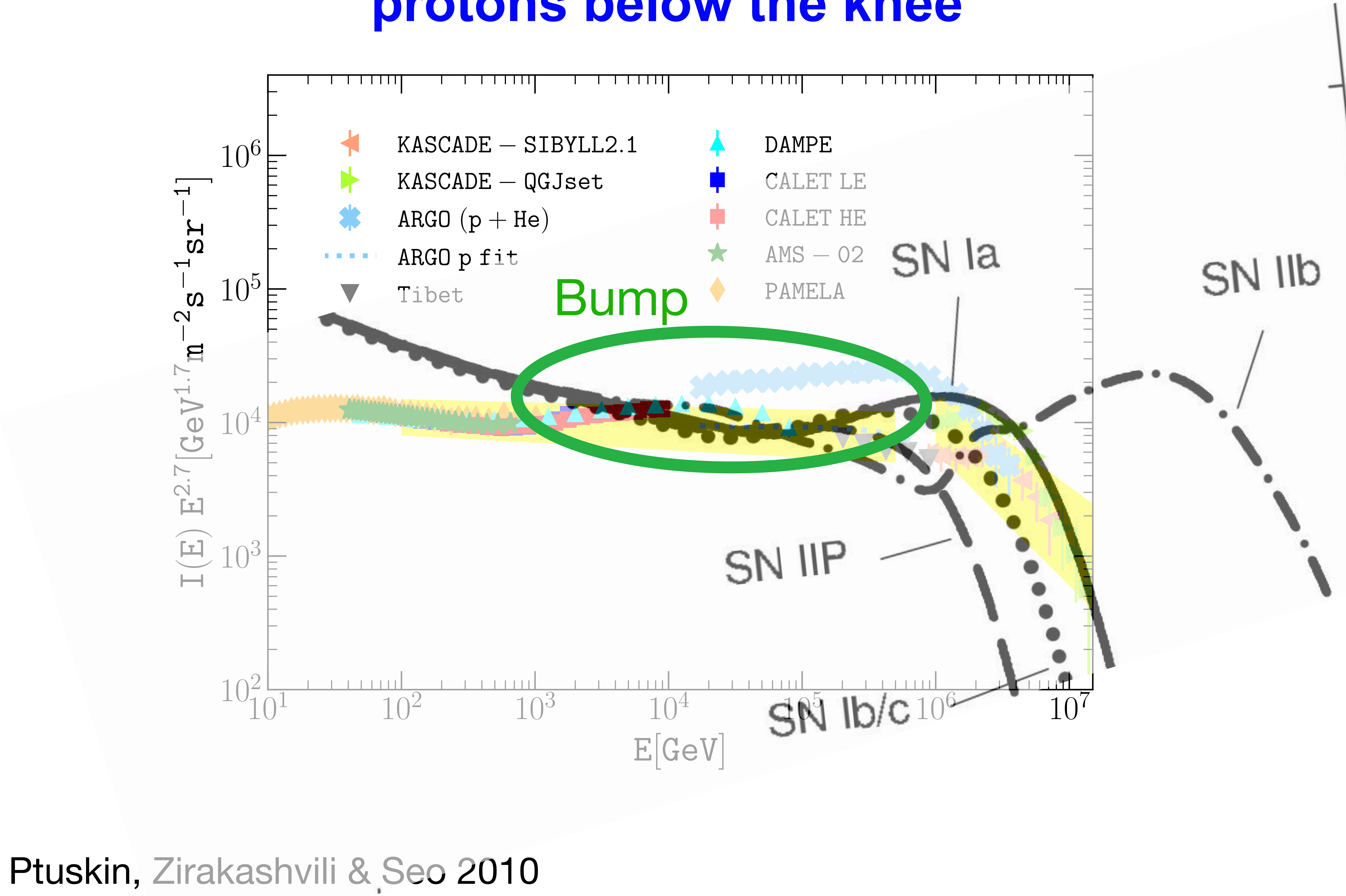

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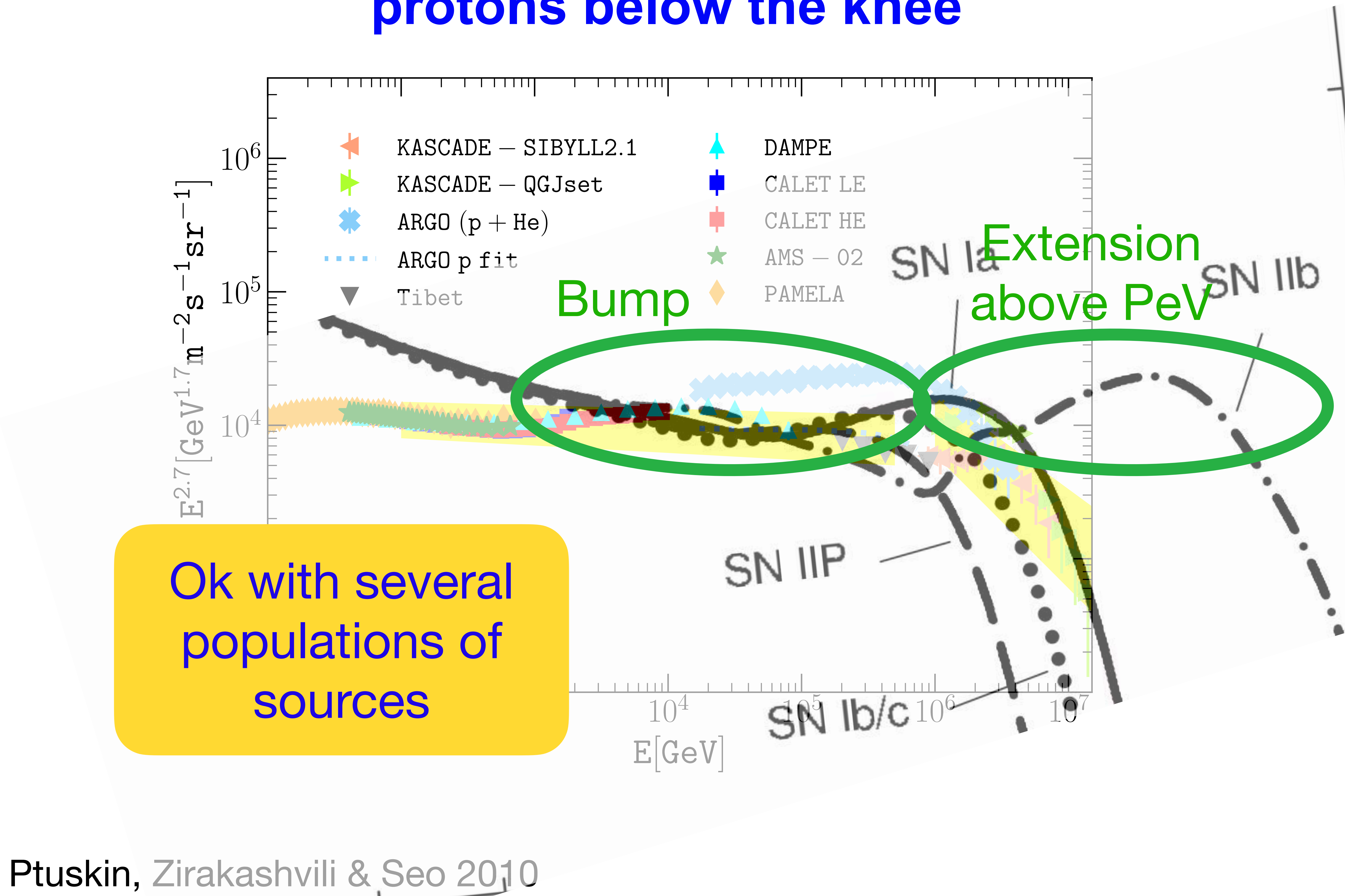

Ok with several populations of sources

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The case of supernova remnants

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Hillas criterion

$$E_{\rm max} \approx \xi \left(\frac{R_{\rm sh}}{\rm pc}\right) \left(\frac{u_{\rm sh}}{1000{\rm km/s}}\right) \left(\frac{B}{\mu\ {\rm G}}\right) {\rm TeV}$$

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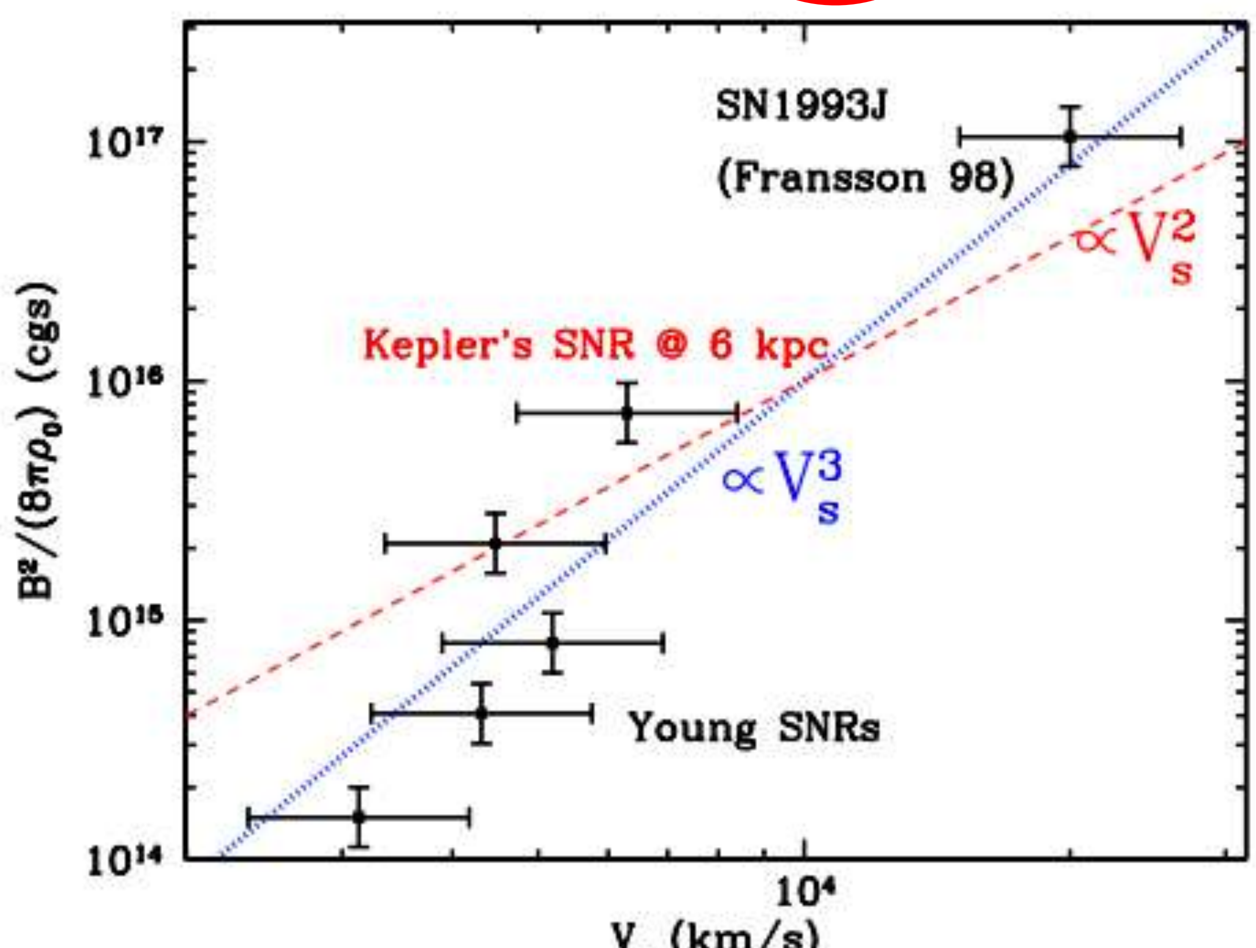

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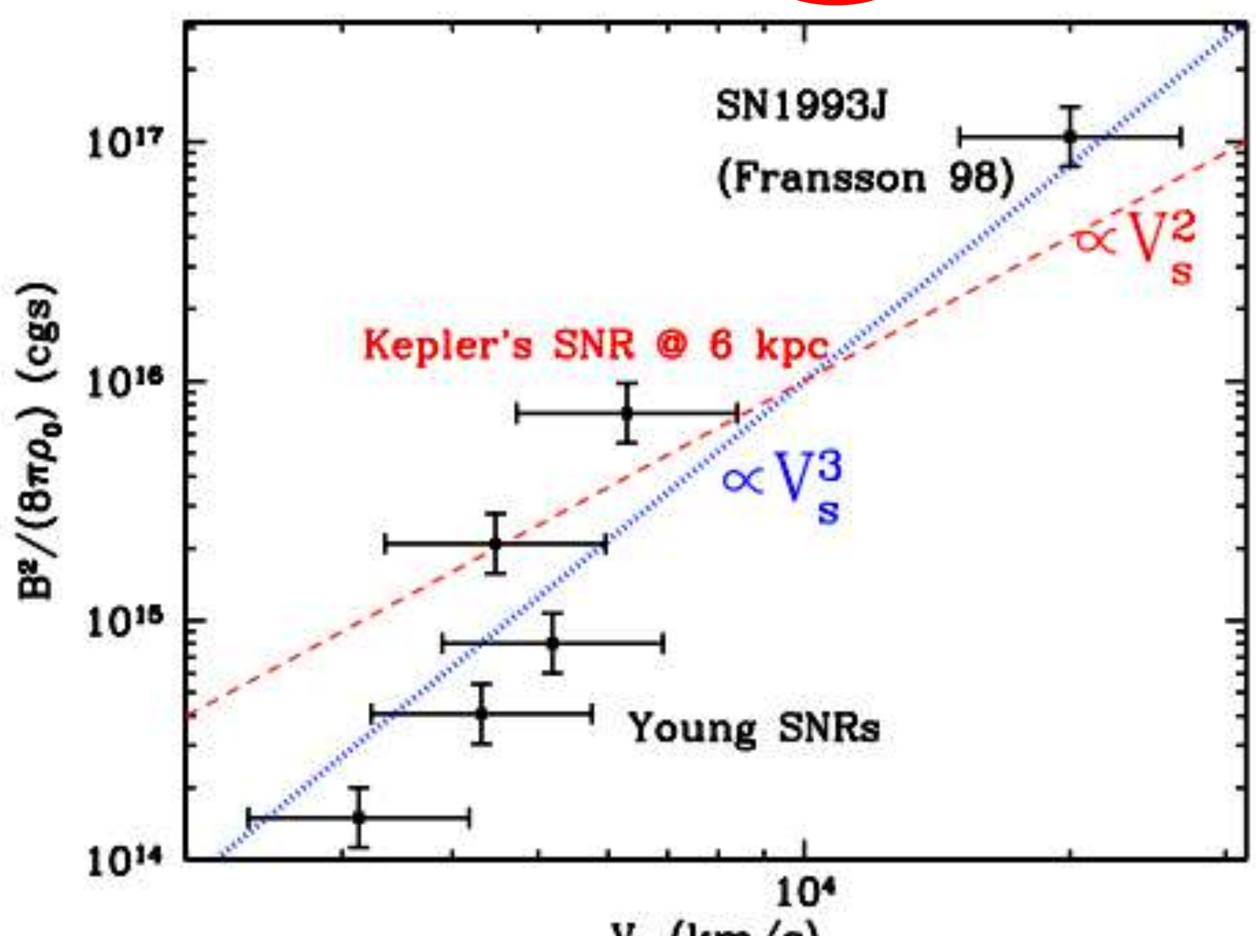
Growth of the non-resonant streaming instability

$$p_{\max}(t) \approx \frac{r_{\rm sh}(t)}{10}\frac{\xi e\sqrt{4\pi\rho(t)}}{\Lambda}\left(\frac{u_{\rm sh}(t)}{c}\right)^2$$



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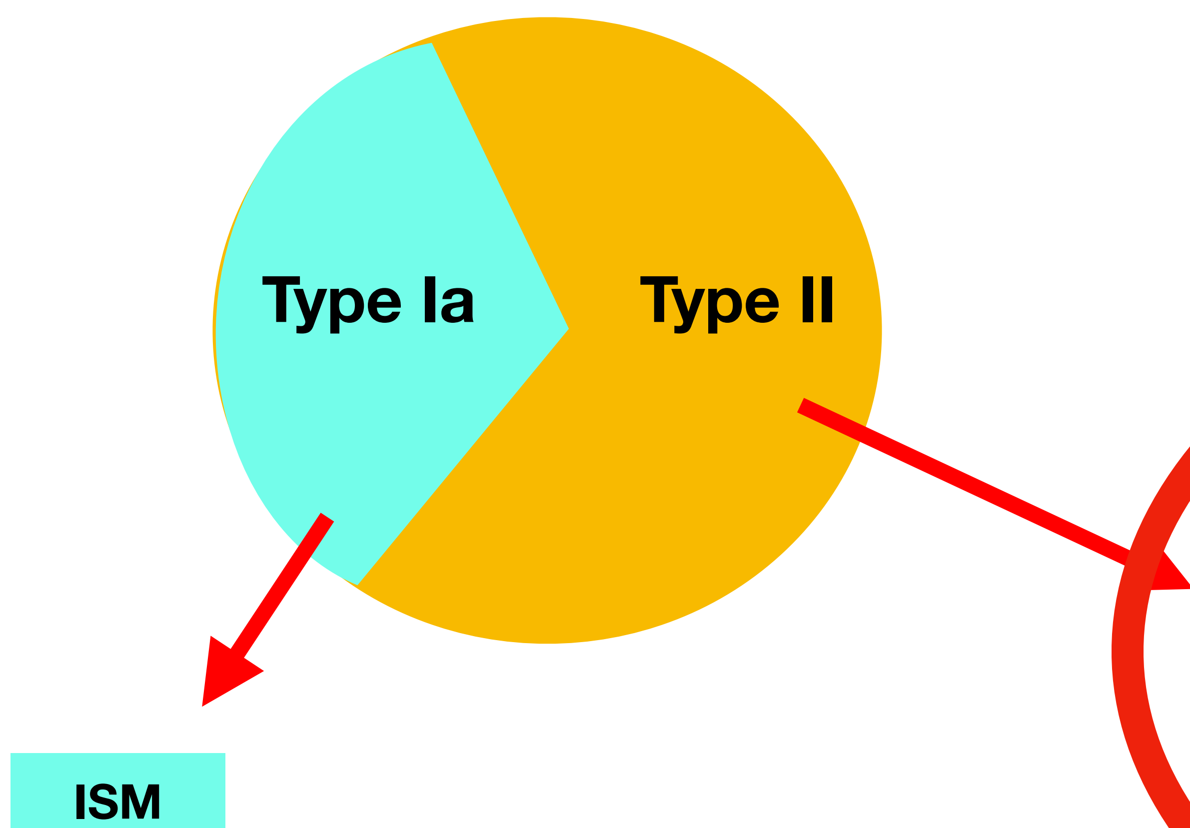
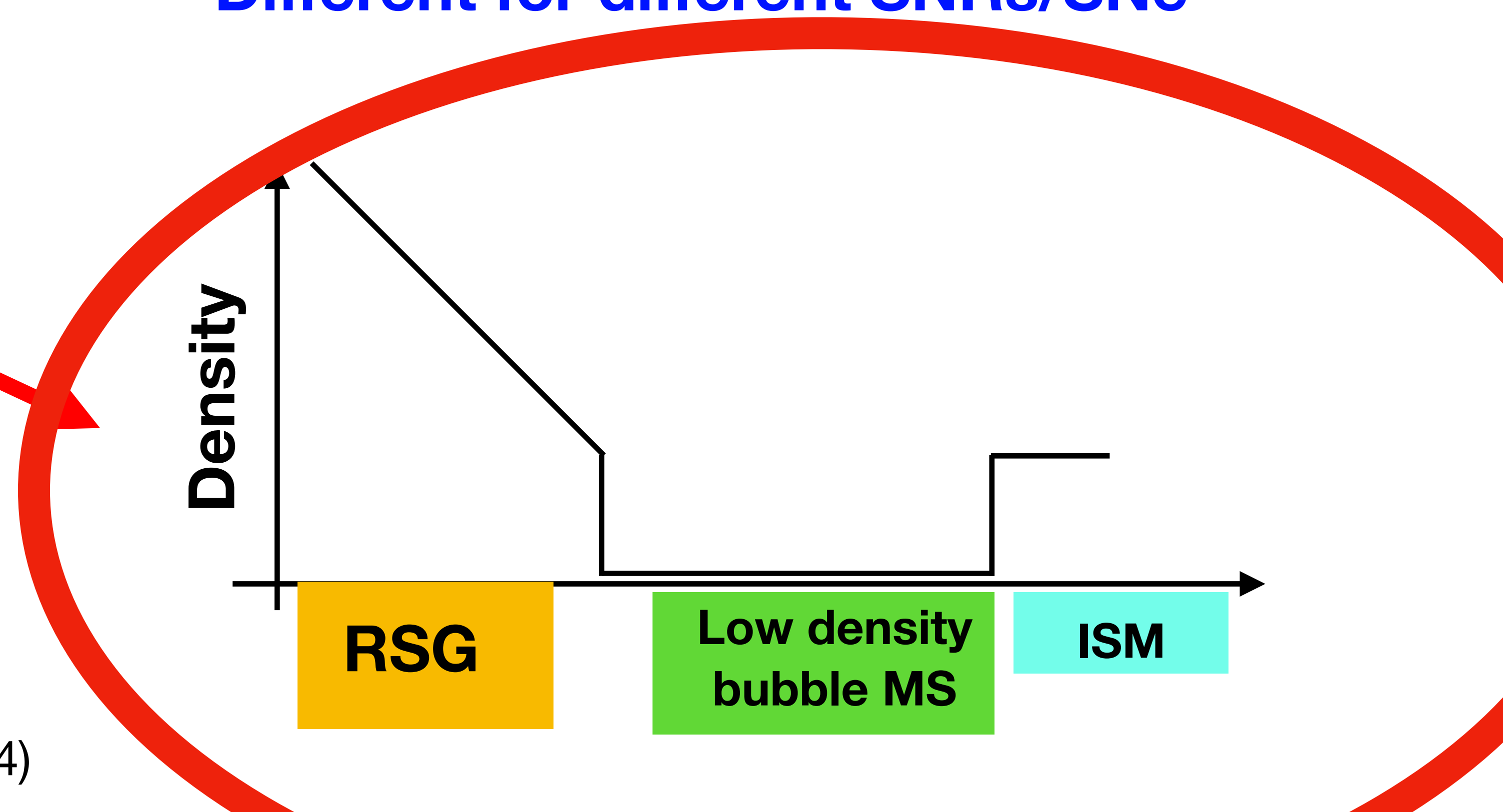
Different for different SNRs/SNe





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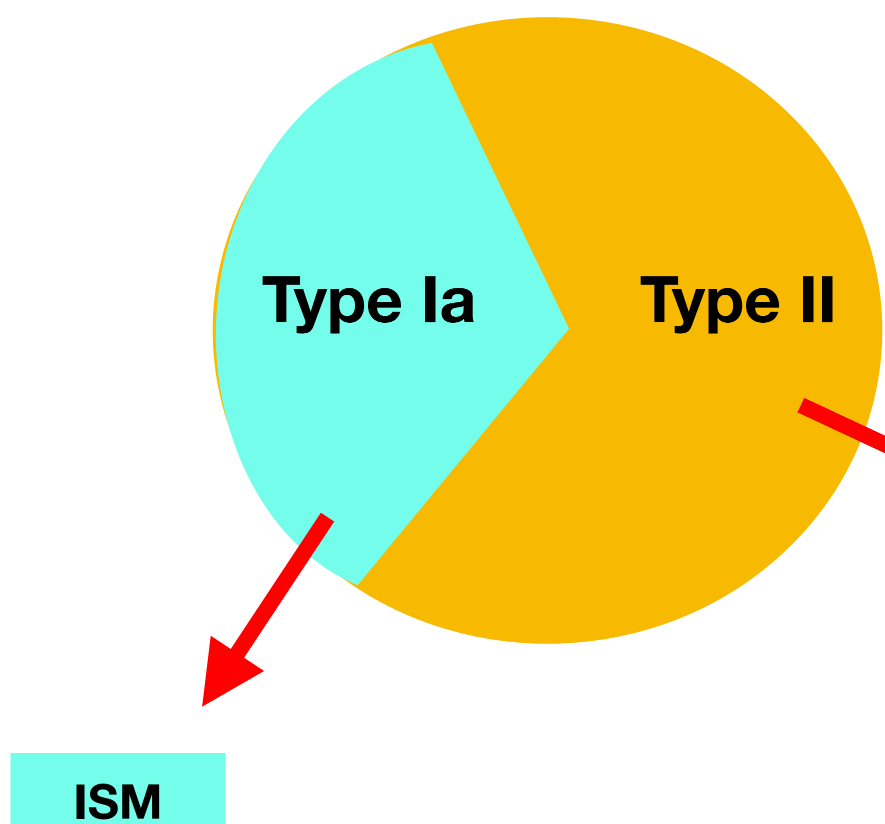

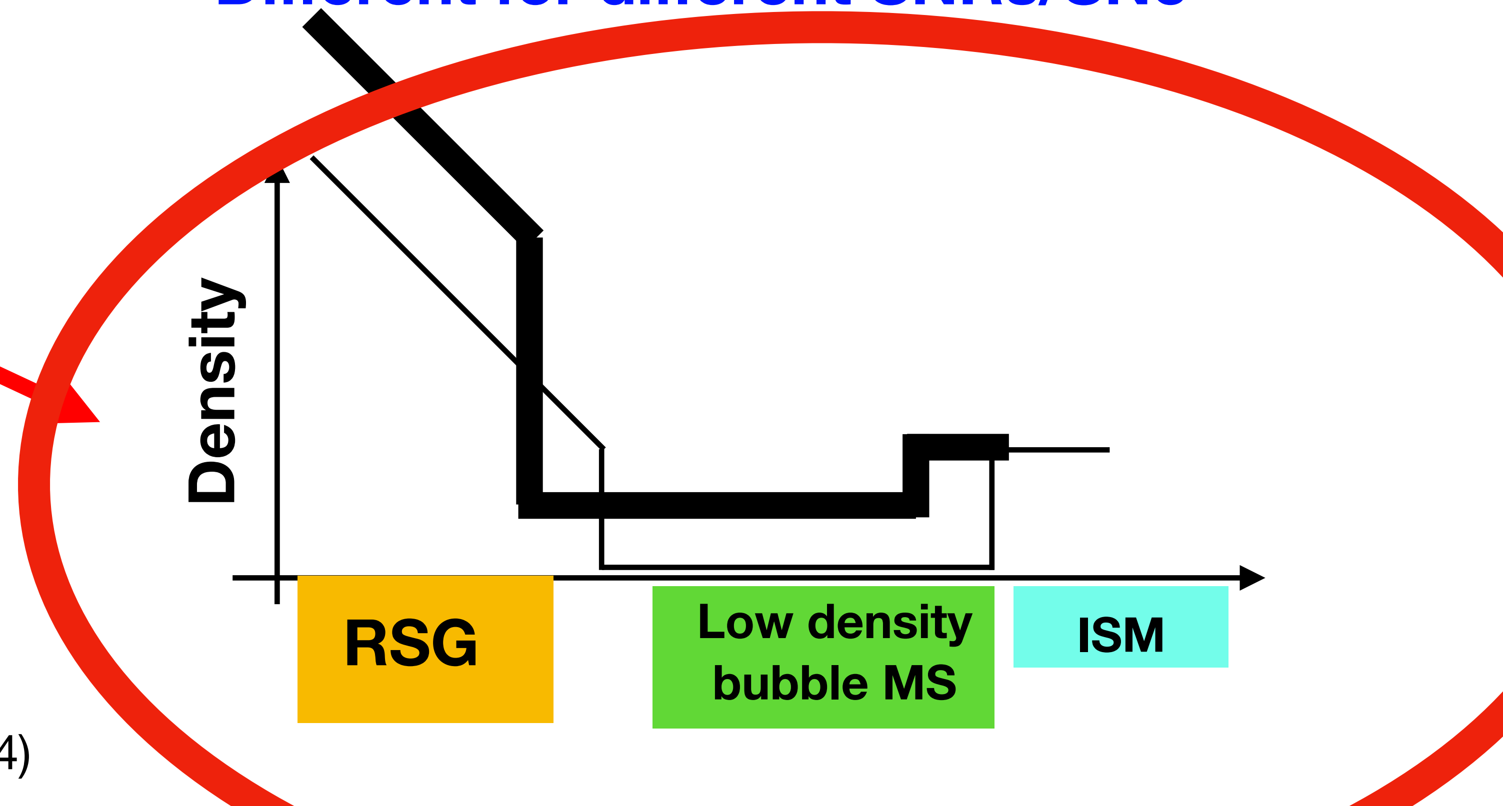

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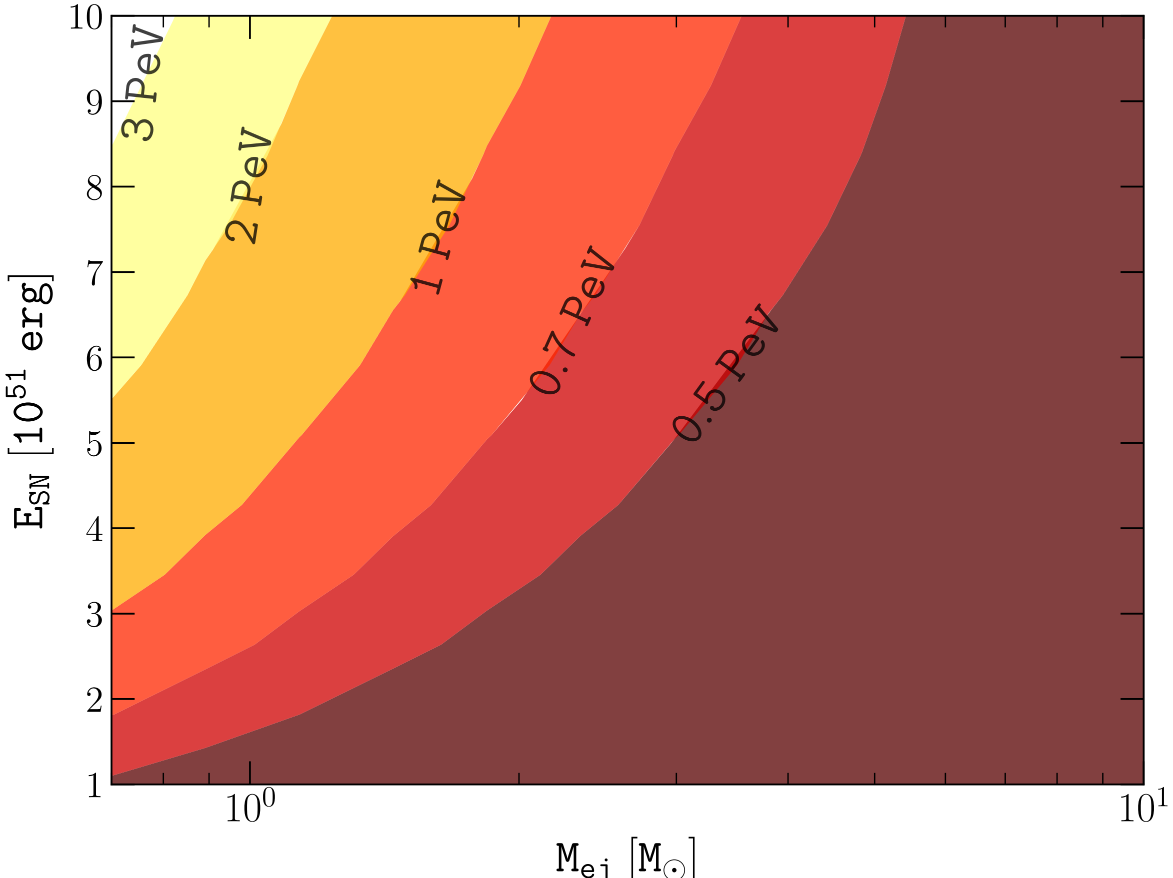
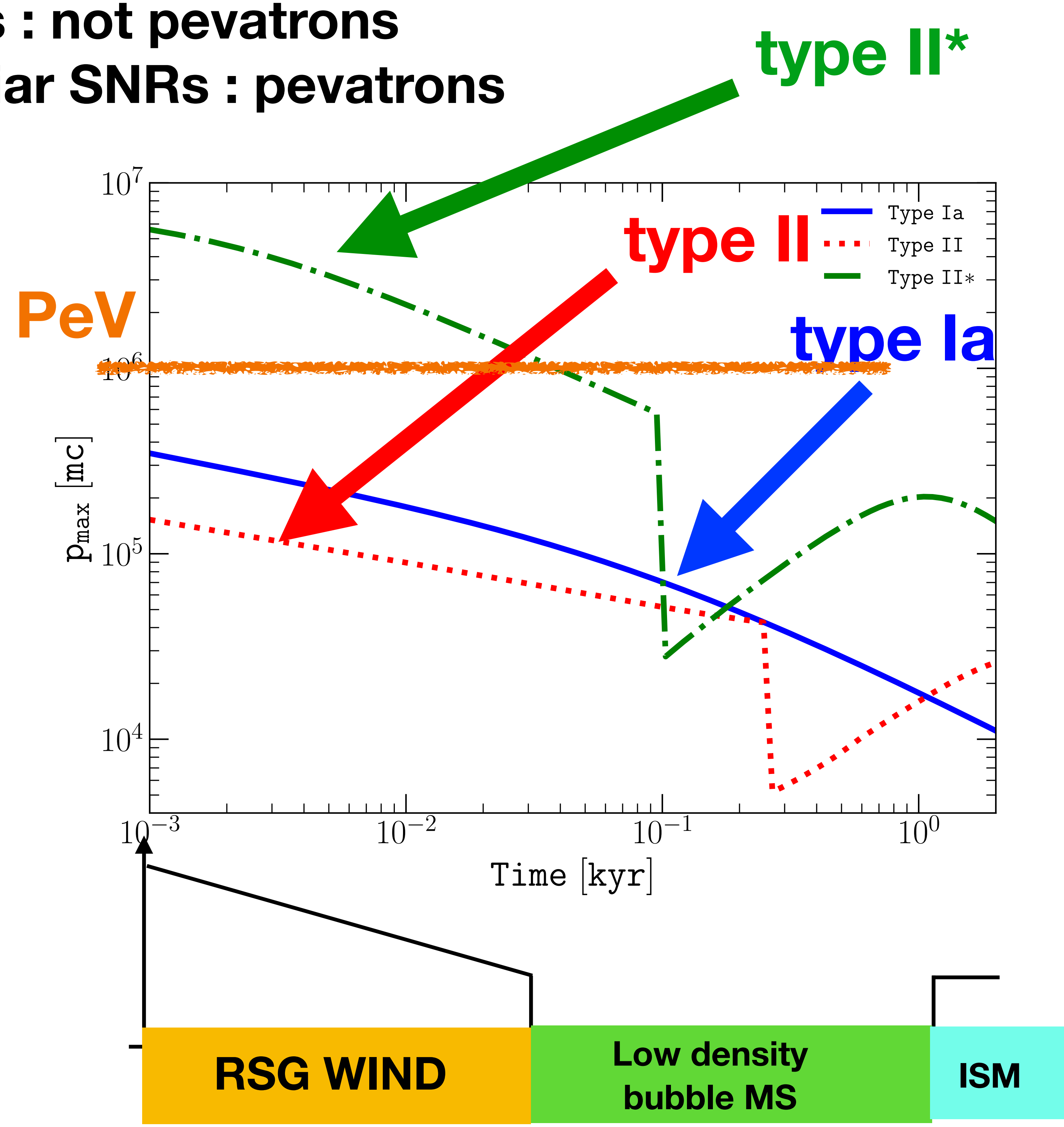
Typical SNRs : not pevatrons
Young and peculiar SNRs : pevatrons



$$\dot{M}_{\rm RSG} = 10^{-4} M_\odot/{\rm yr}$$
$$\xi = 0.1$$

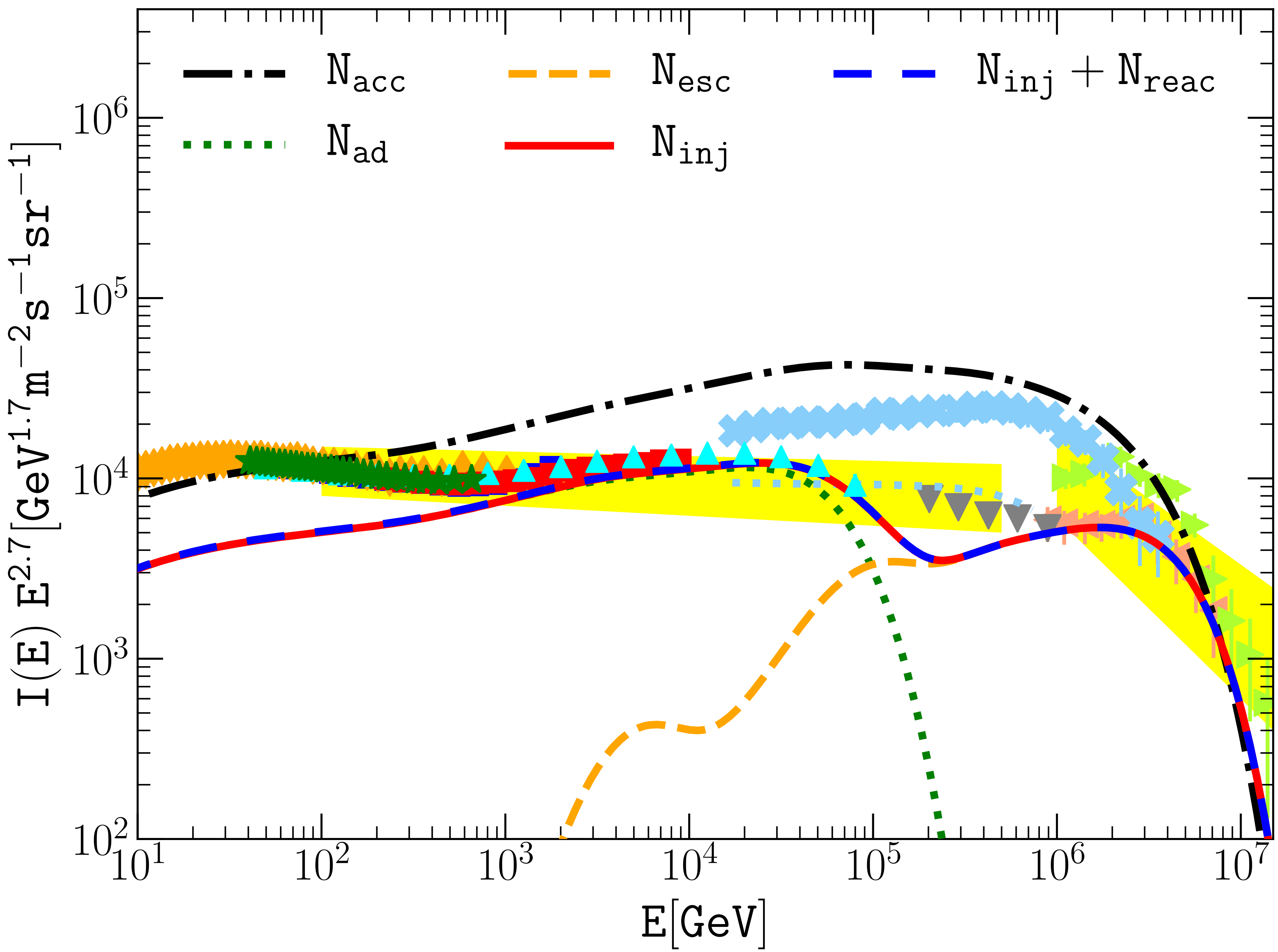


Bell (2004), Bell et al. (2013), Schure et al. (2014), Ptuskin et al. (2010), Cardillo et al. (2016) PC, Blasi & Amato (2020)

The low rate of SNR pevatrons ~ 1-5 % of SNe

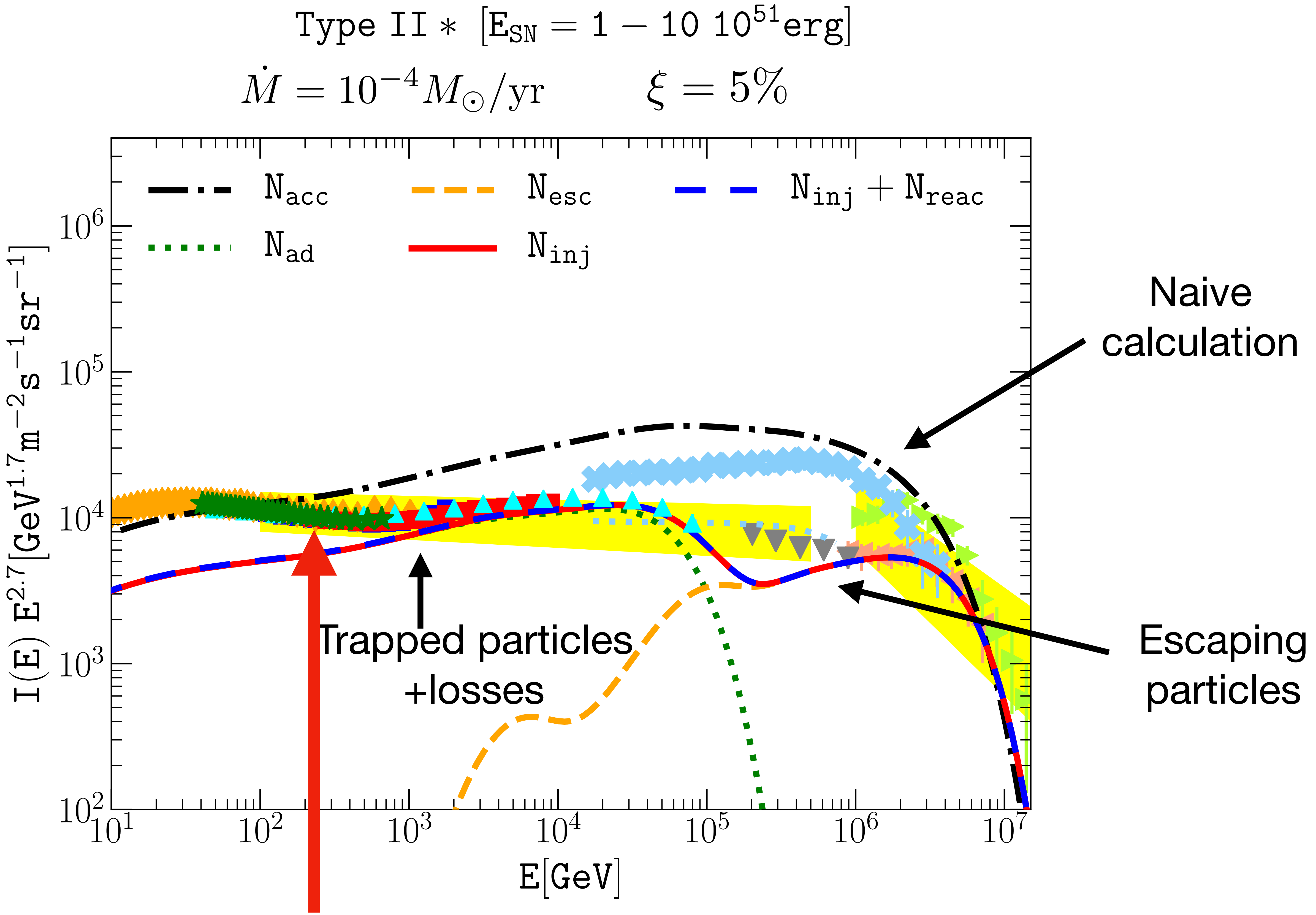
Type II * $[E_{SN} = 1 - 10\ 10^{51}\text{erg}]$

$\dot{M} = 10^{-4} M_{\odot}/\text{yr} \qquad \xi = 5\%$



PC, Blasi, Amato 2020

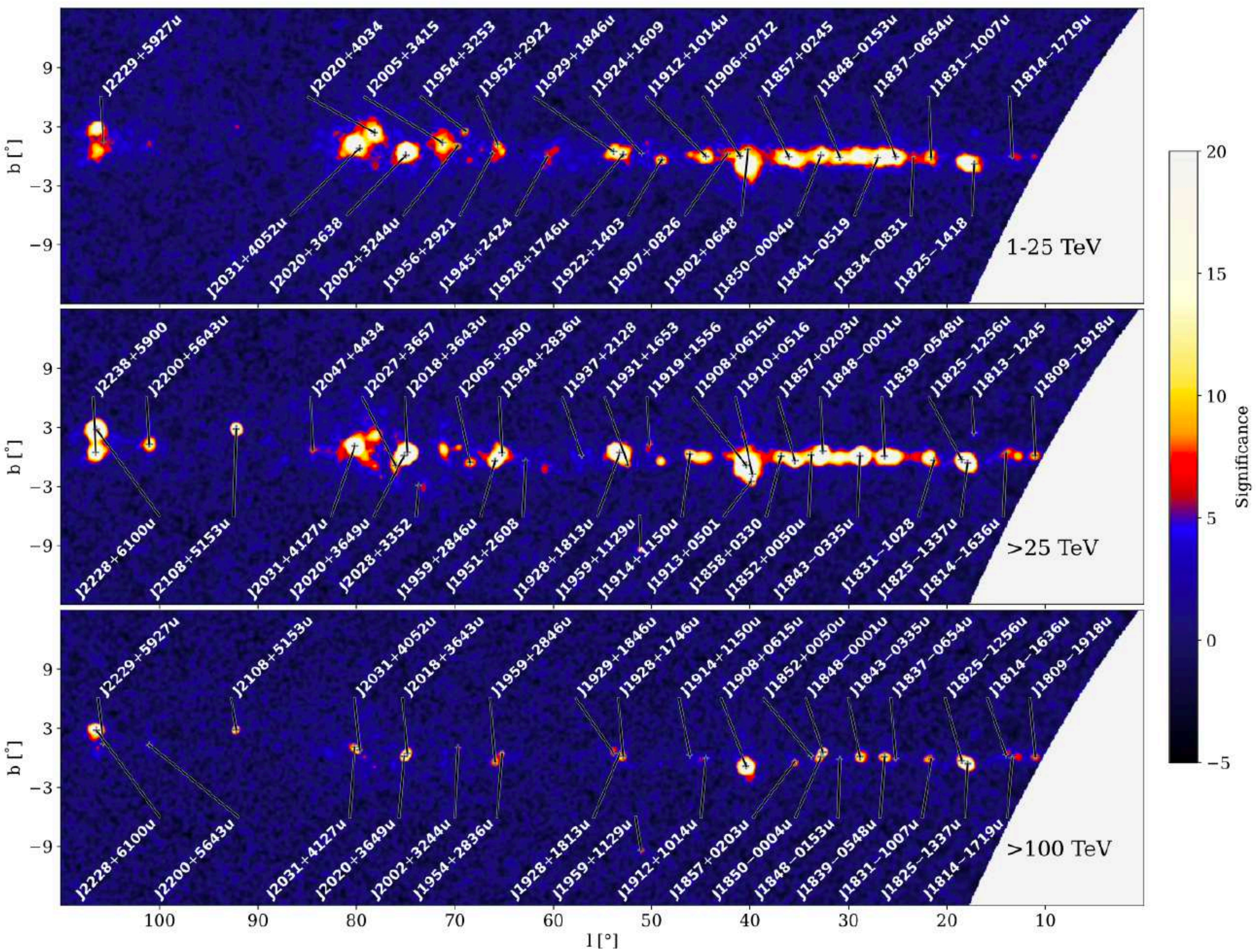
Proton spectrum with only one object?



Major problem: no room for other SNRs/ other accelerators

PC, Blasi, Amato 2020

LHAASO catalog and SNRs



90 sources, 43 above 100 TeV, almost no *direct* association with a SNR shock

Cao et al. 2024

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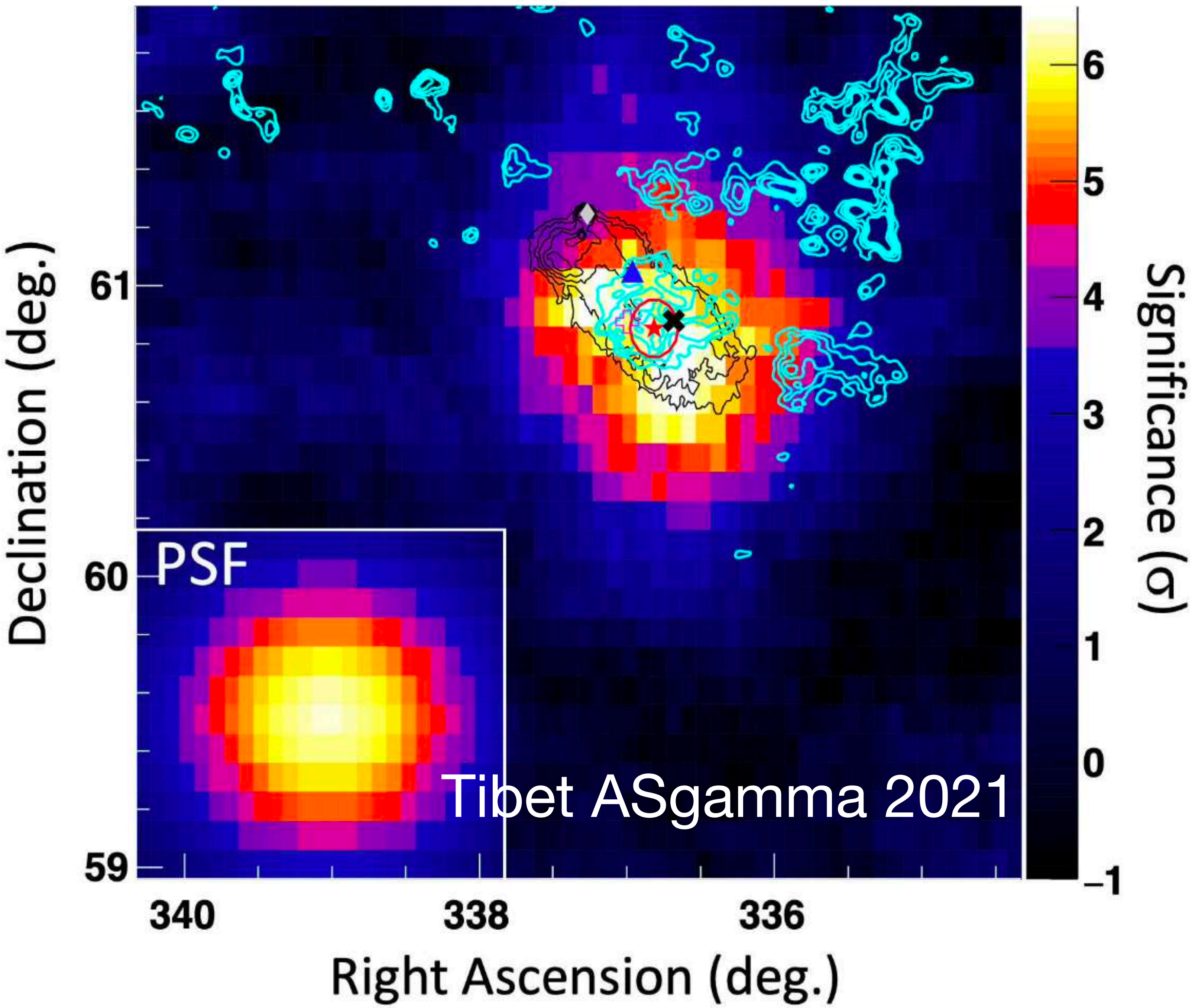

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The case of G106.3+2.7?

Very complex region, role SNR unclear

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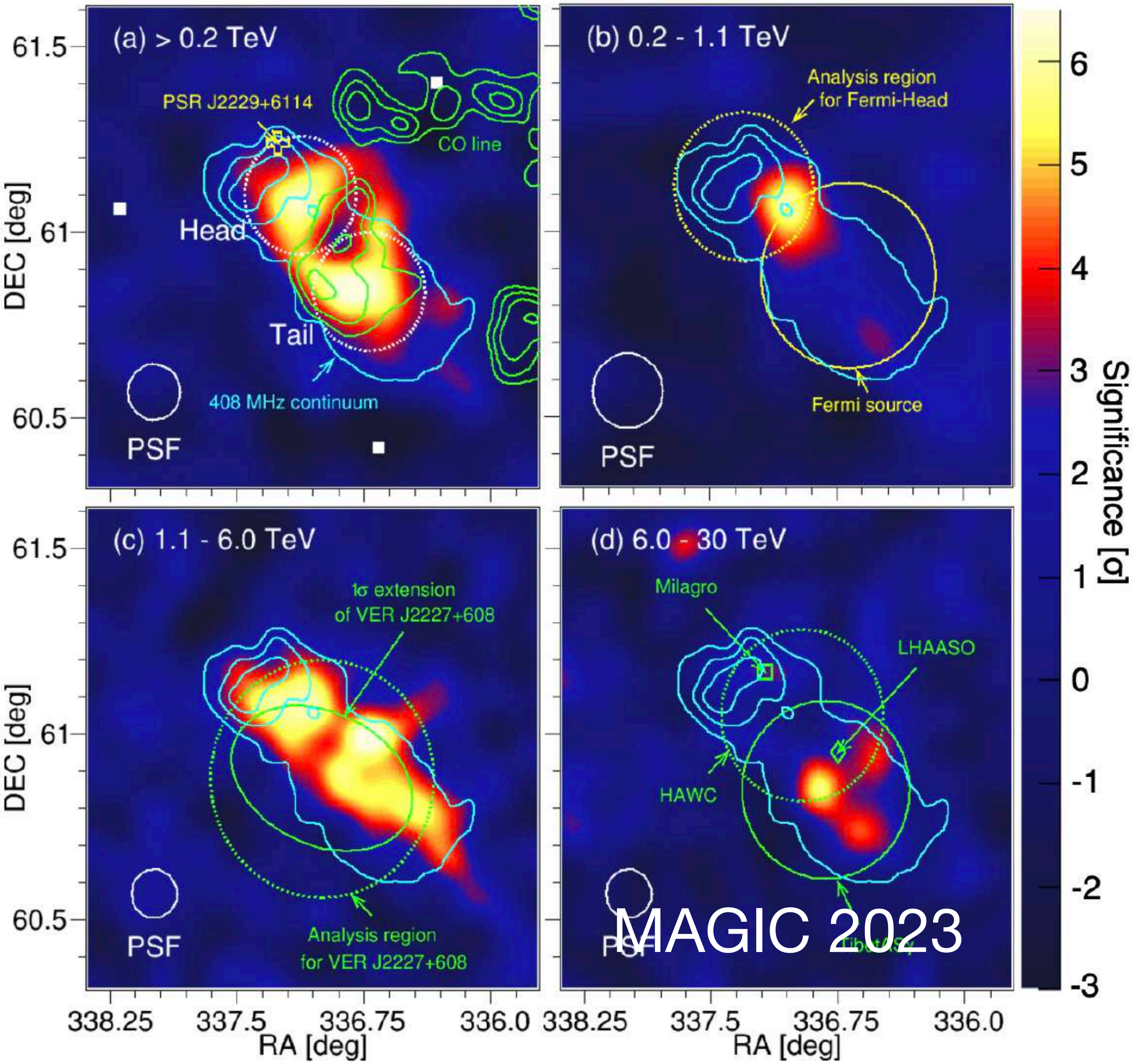

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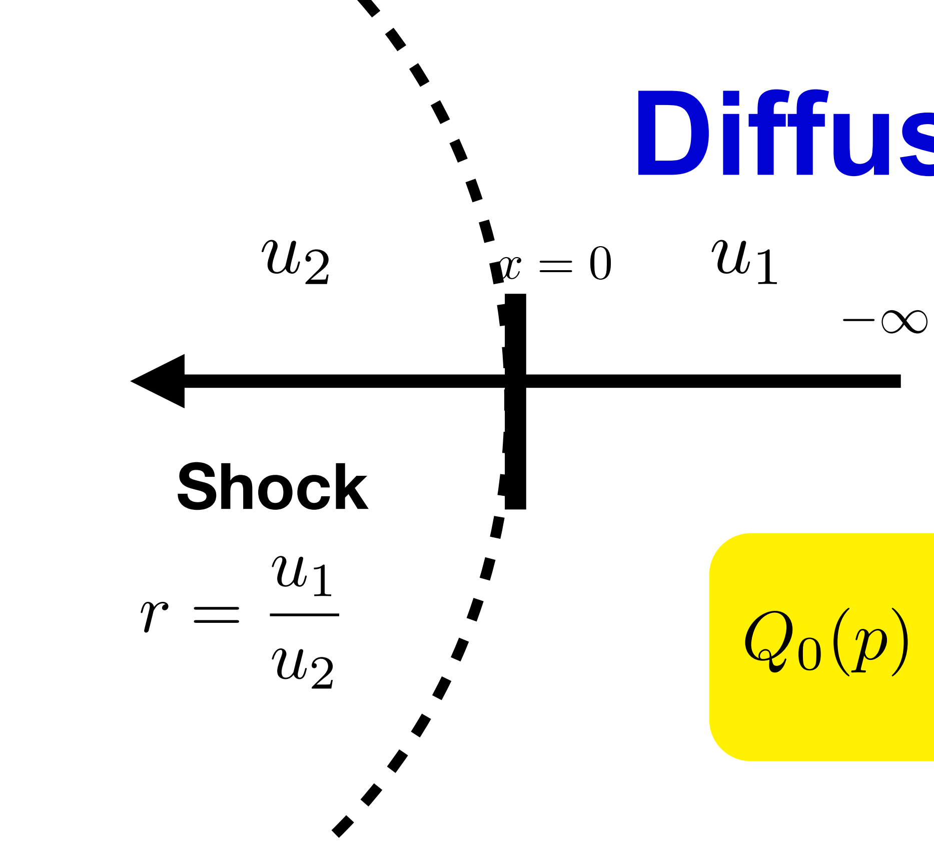

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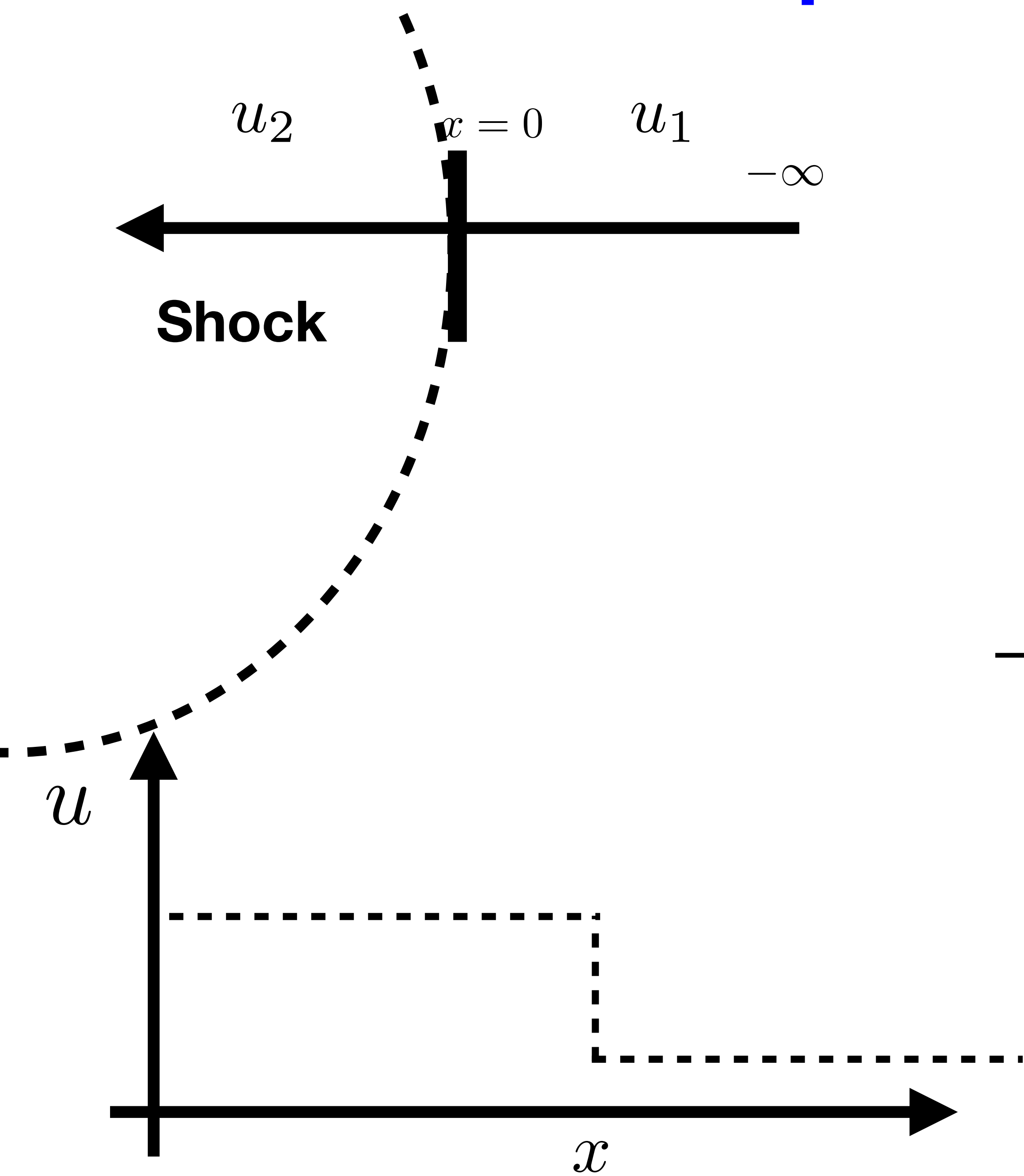

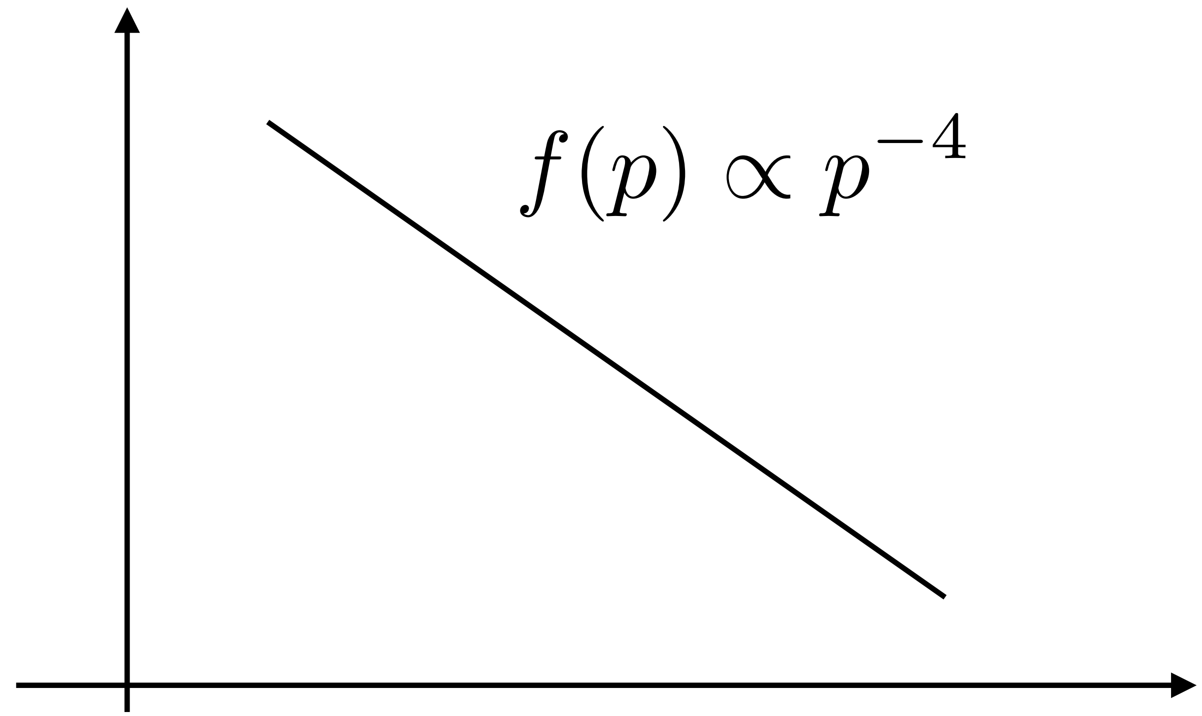

Drury& Völk (1980,1981), Bell (1987)
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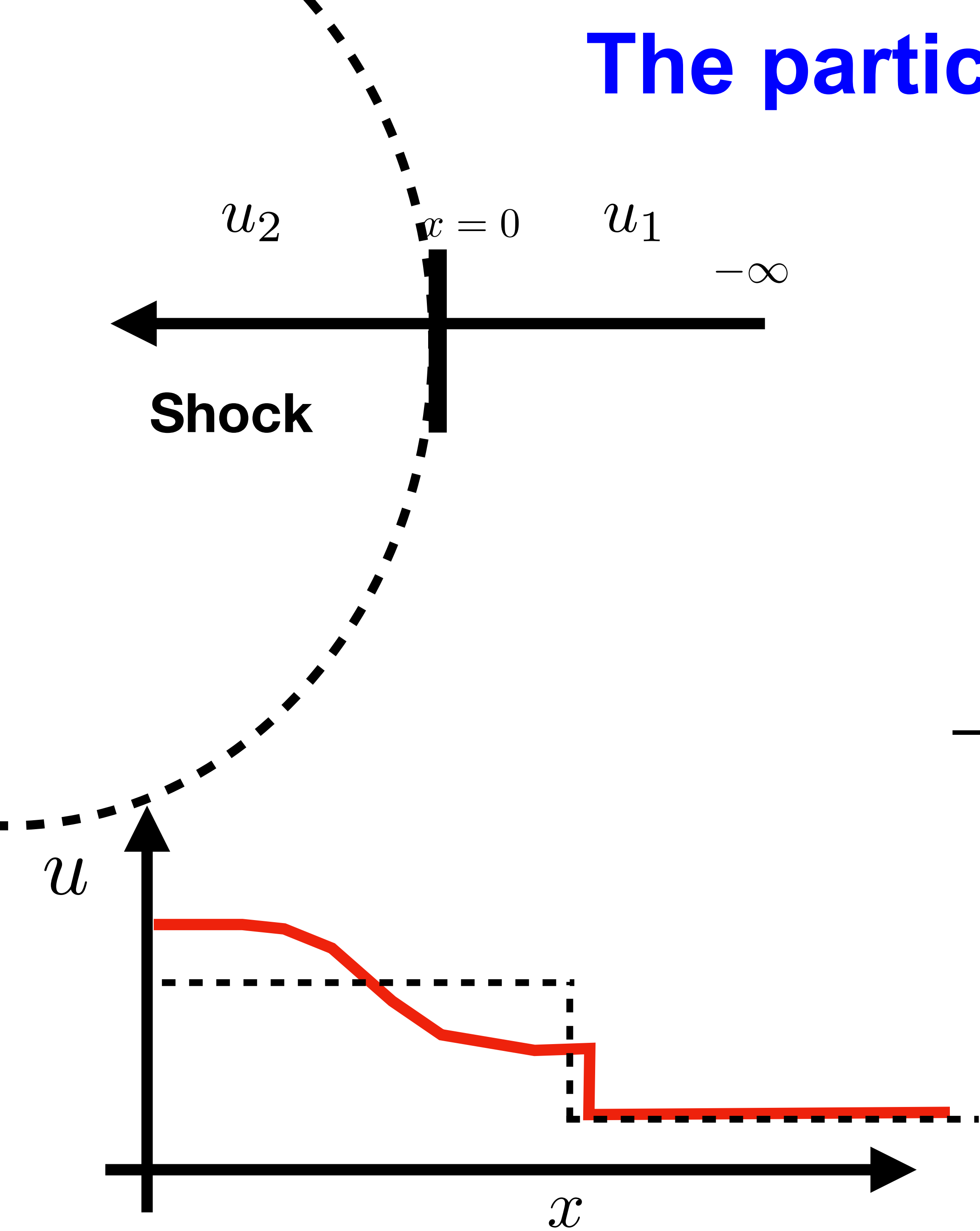

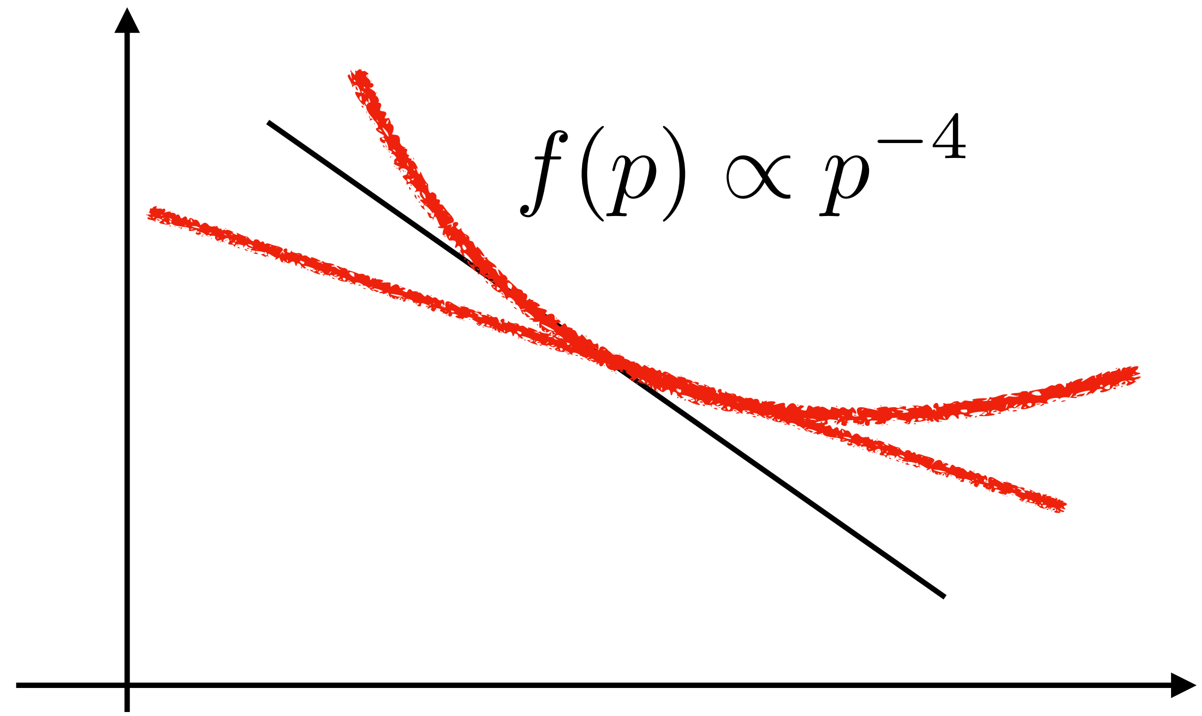

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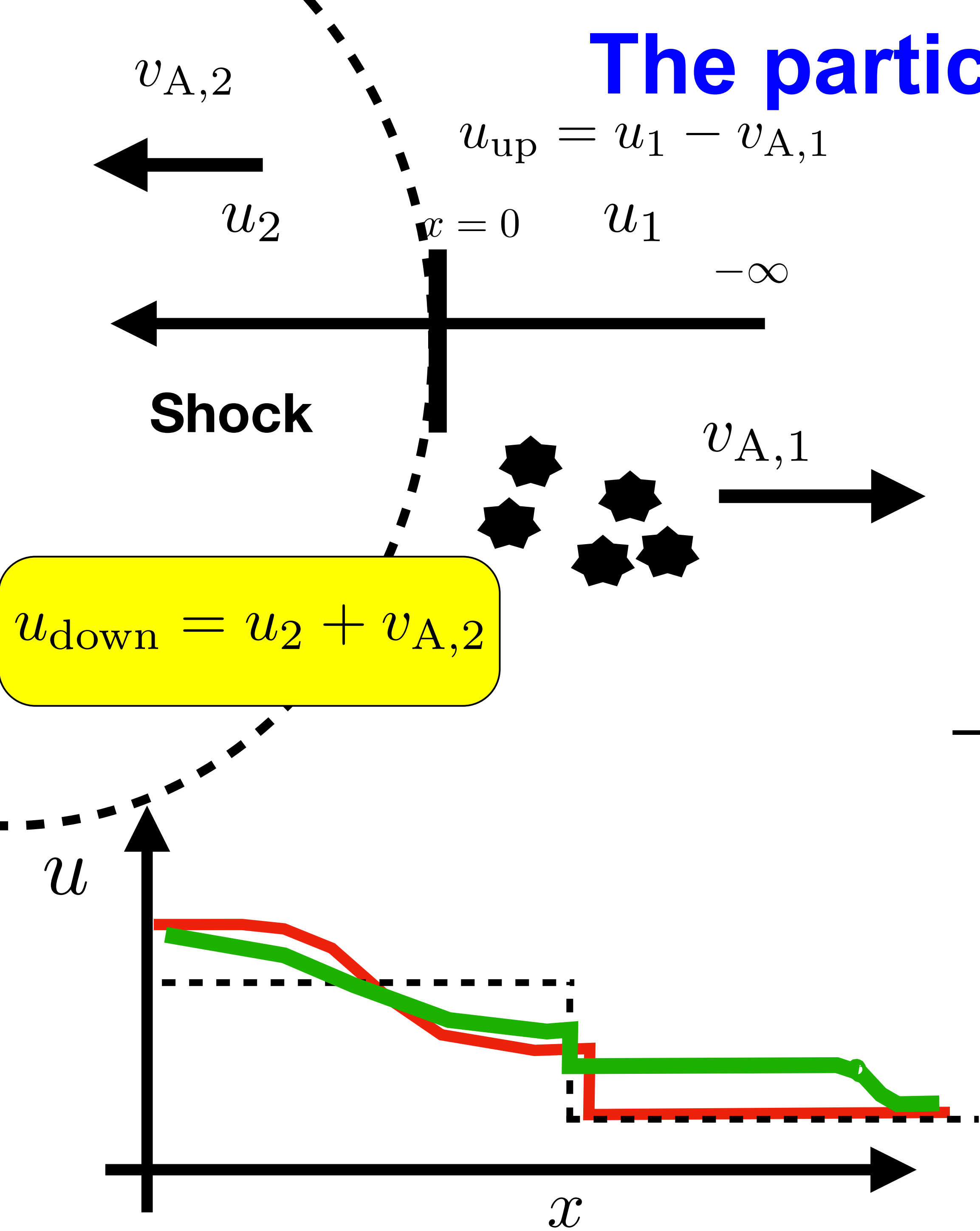

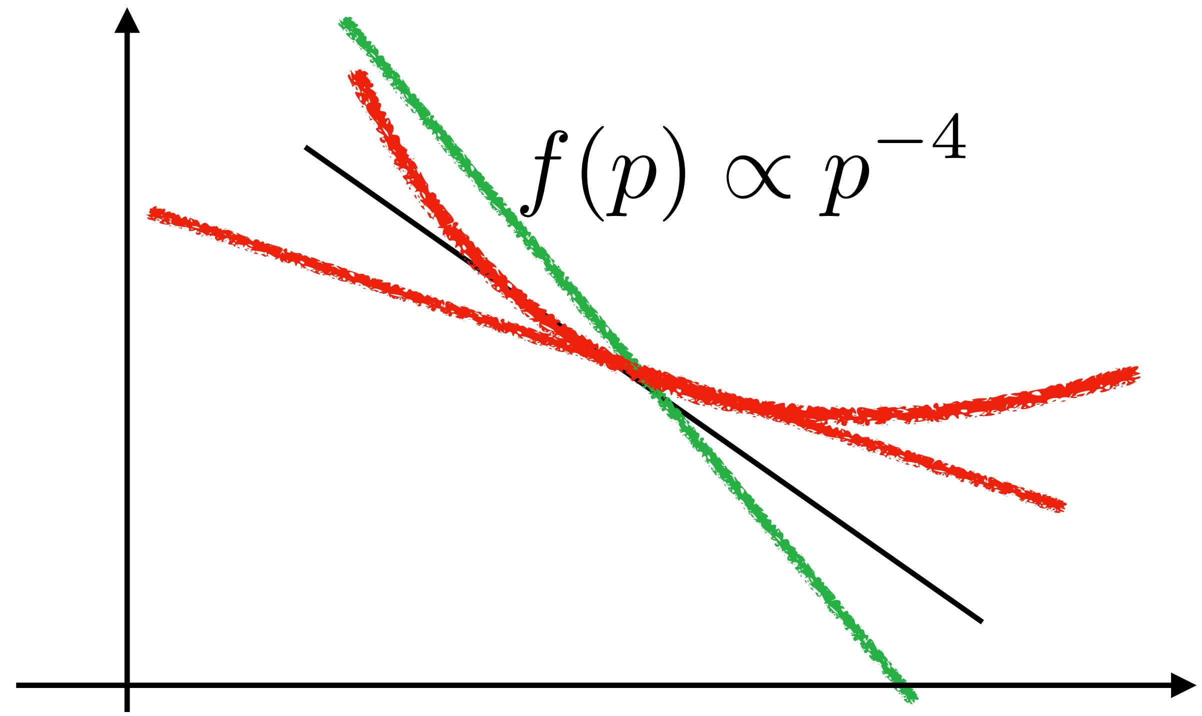

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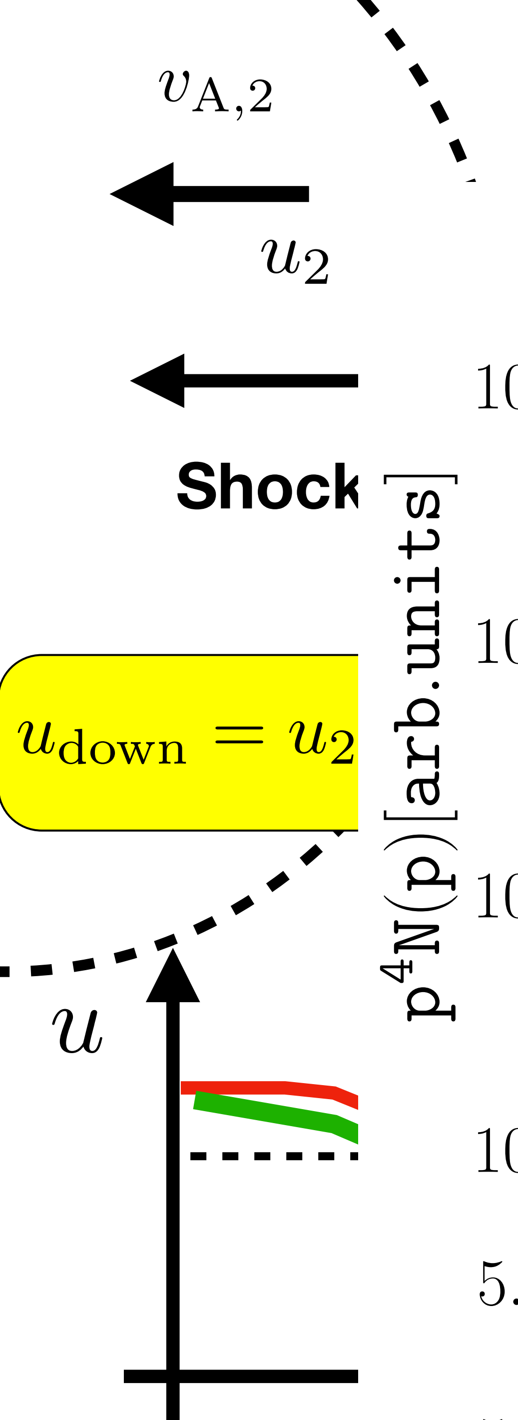

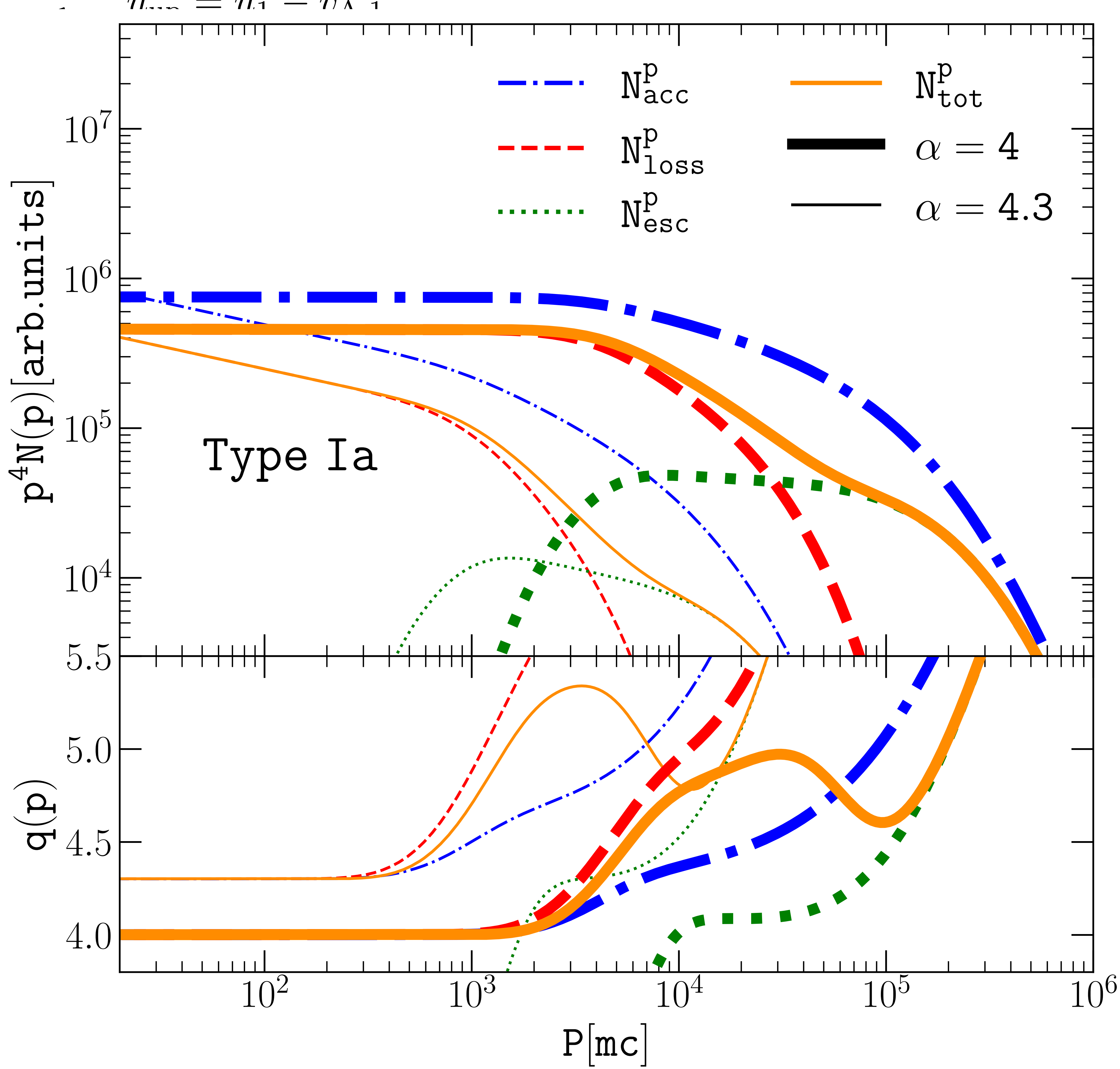

Jones & Ellisc
(19

5) Kang & Jones
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Drury (1983), ubmitted 2022)

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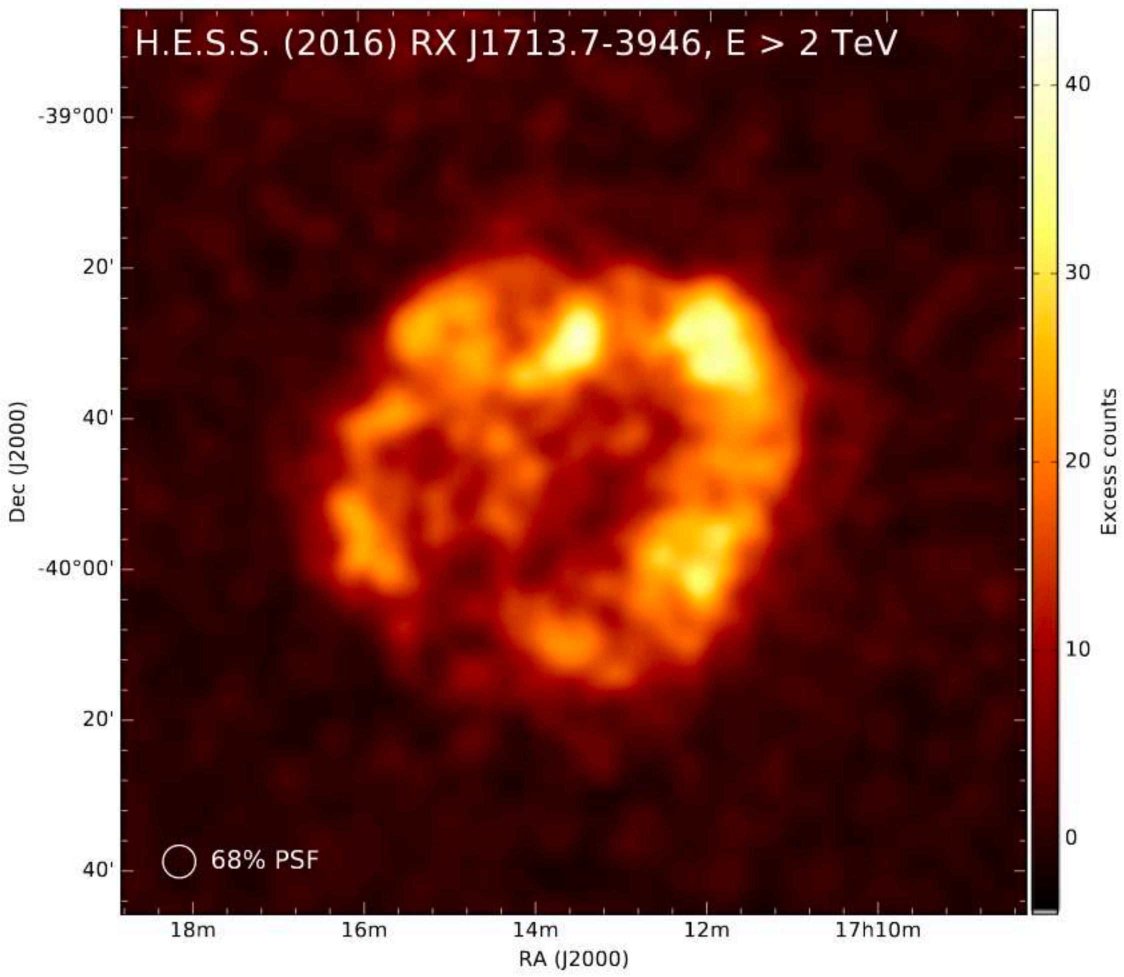

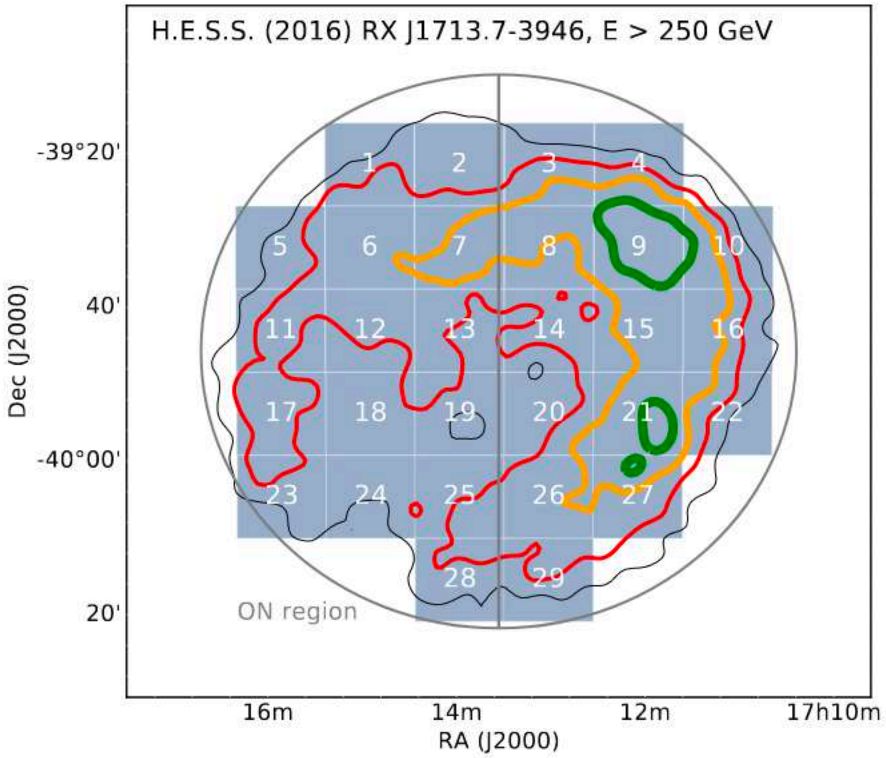

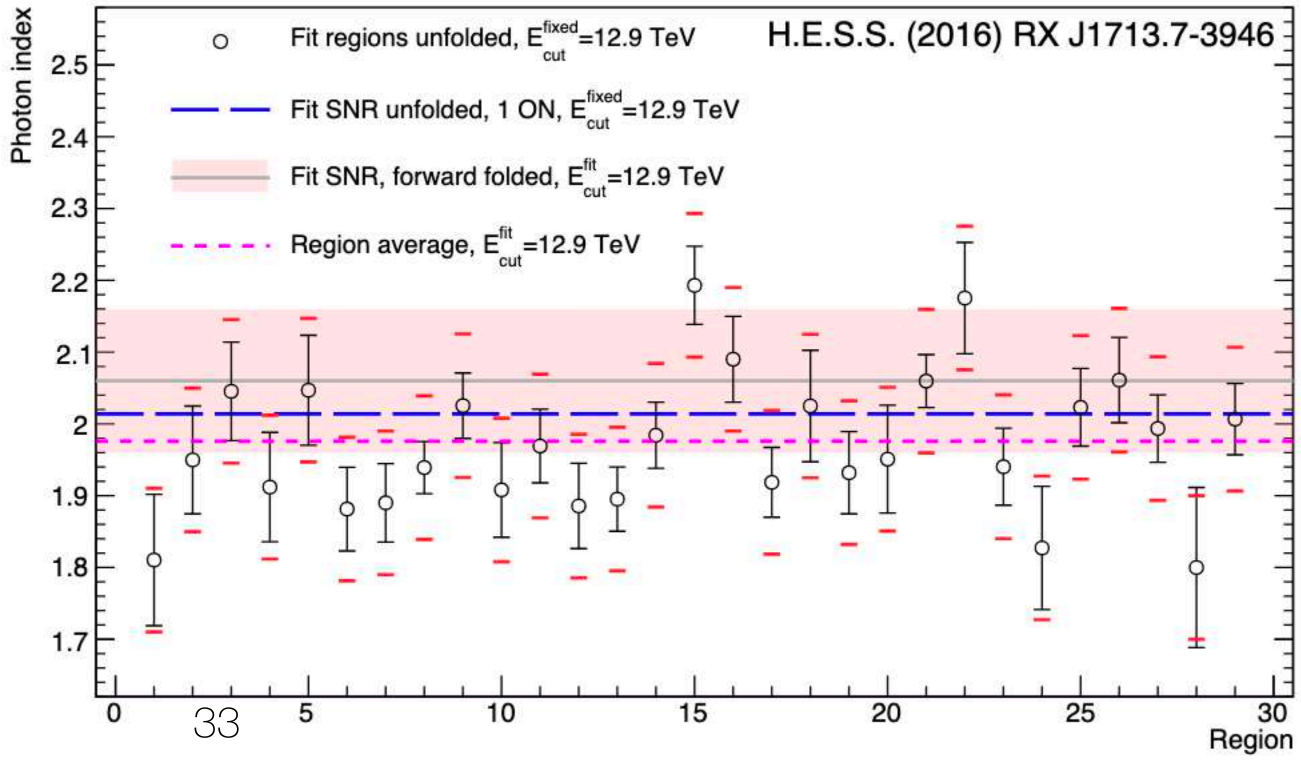

HESS C

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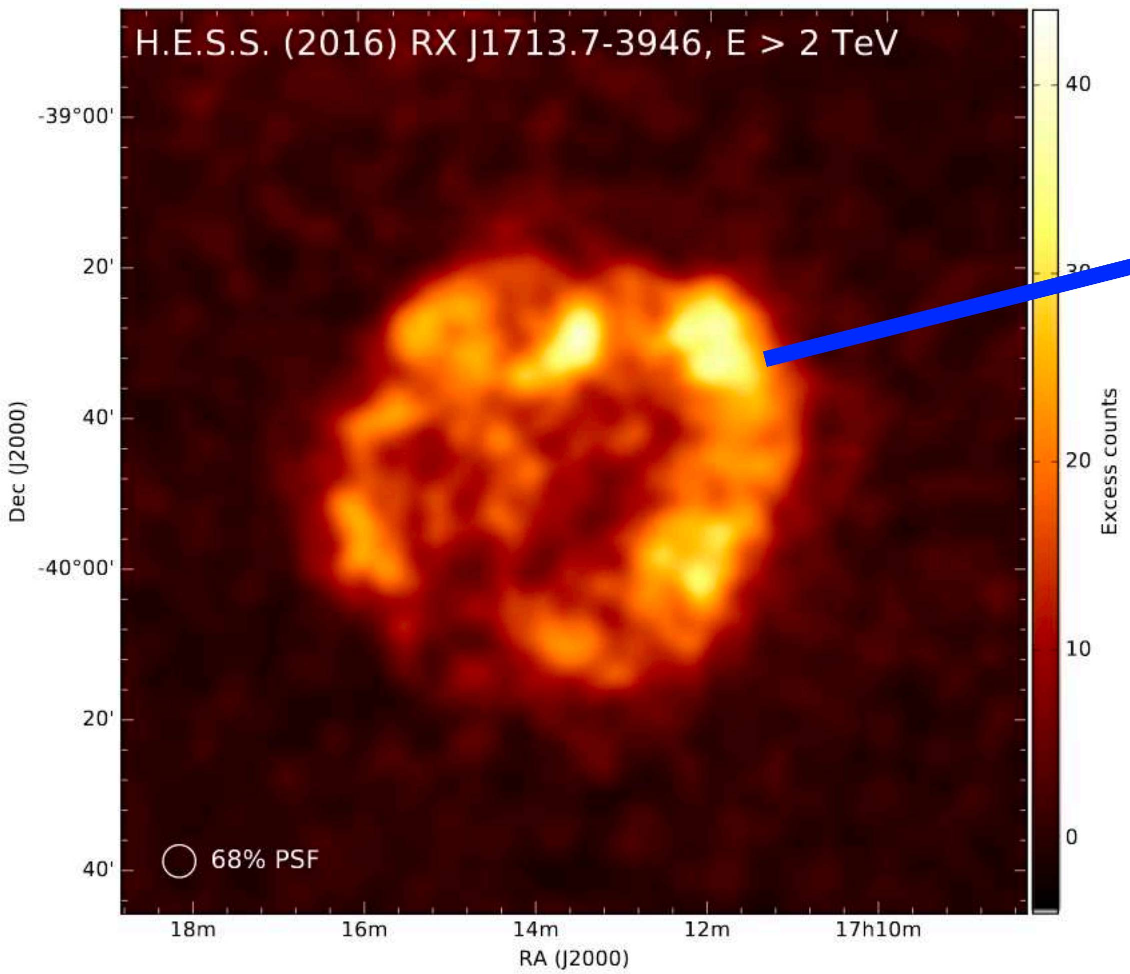
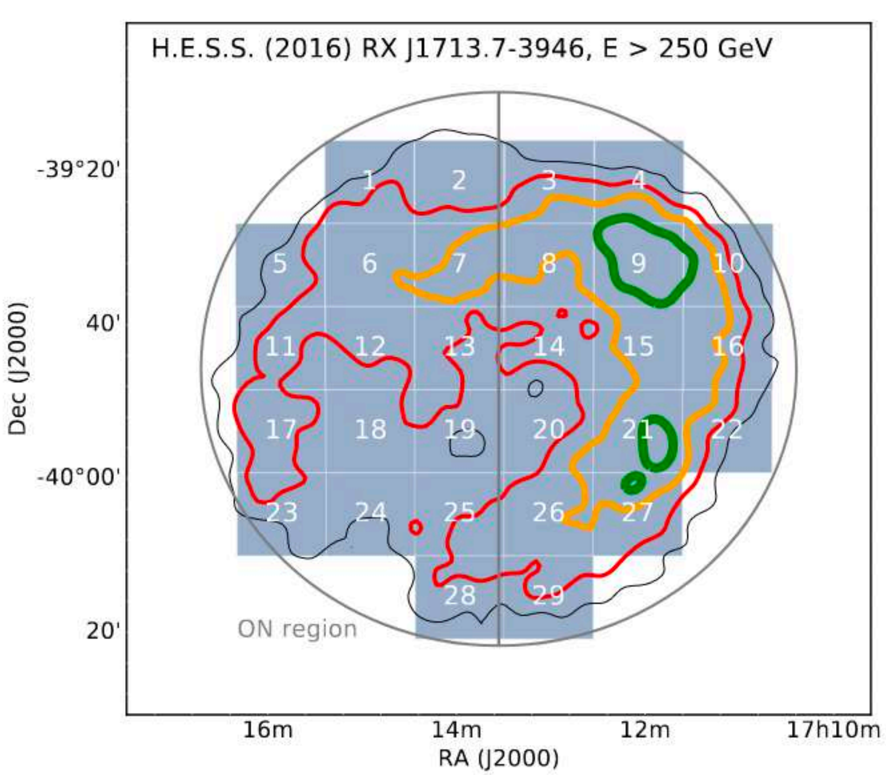
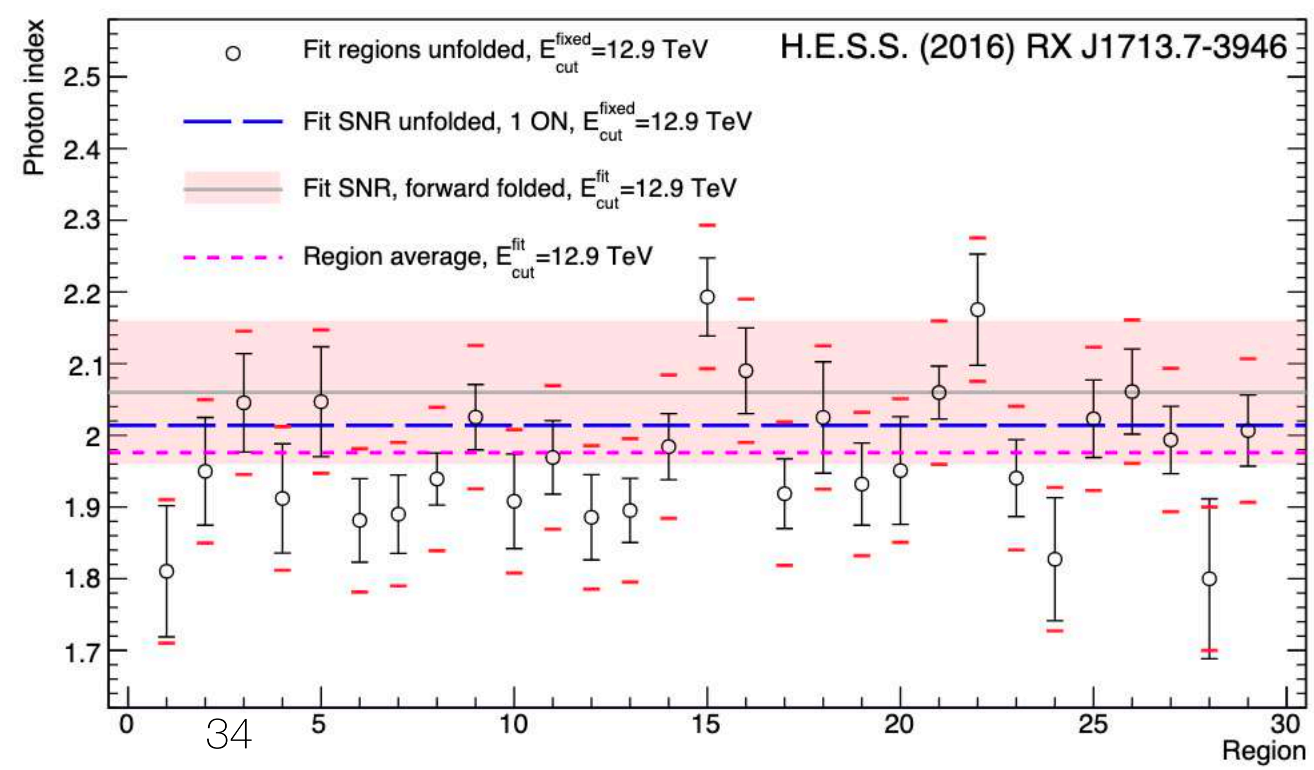


Particles at the shock?





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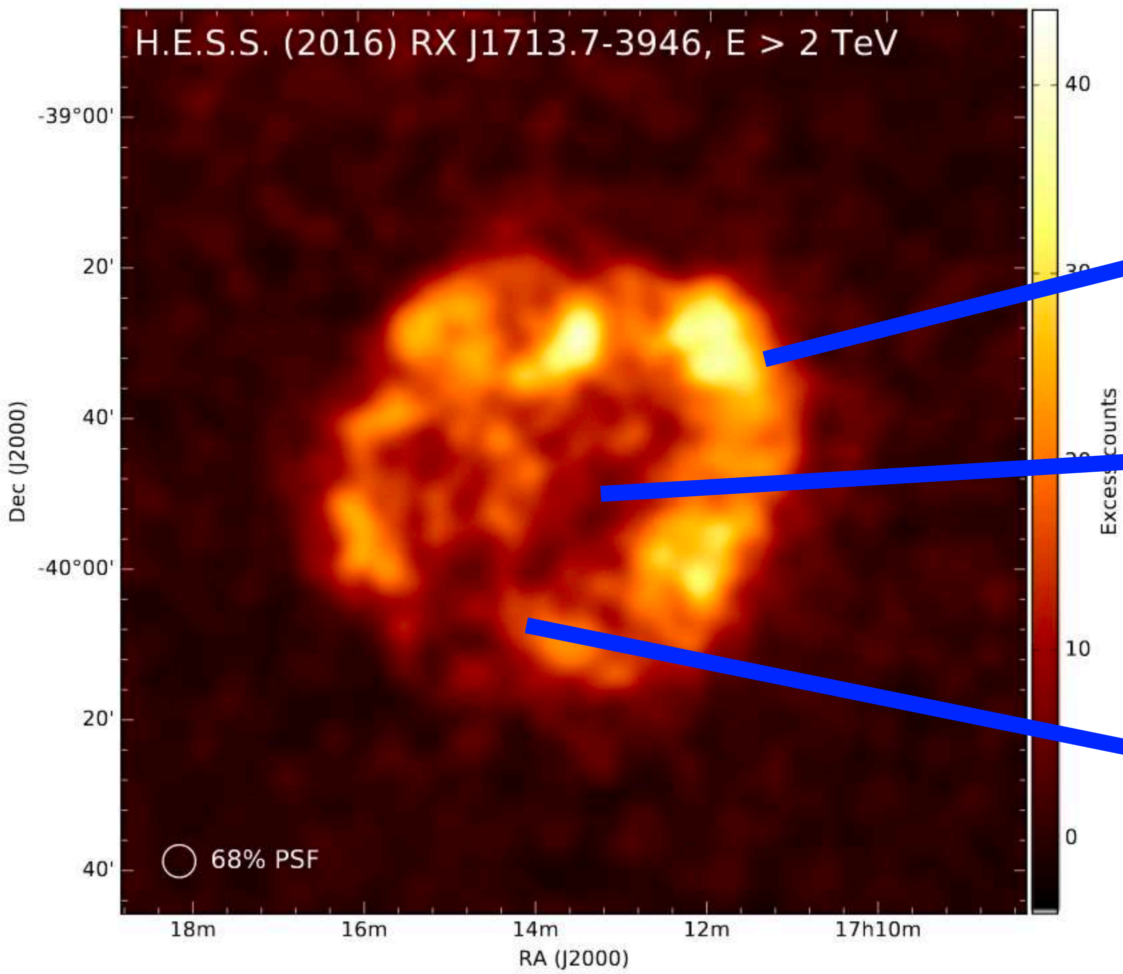

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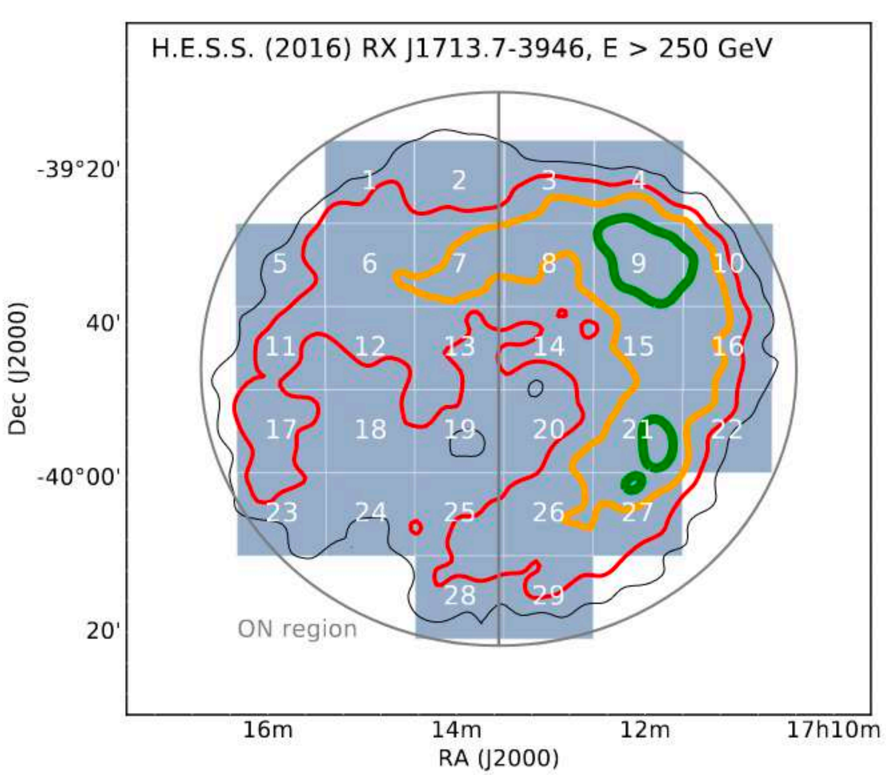
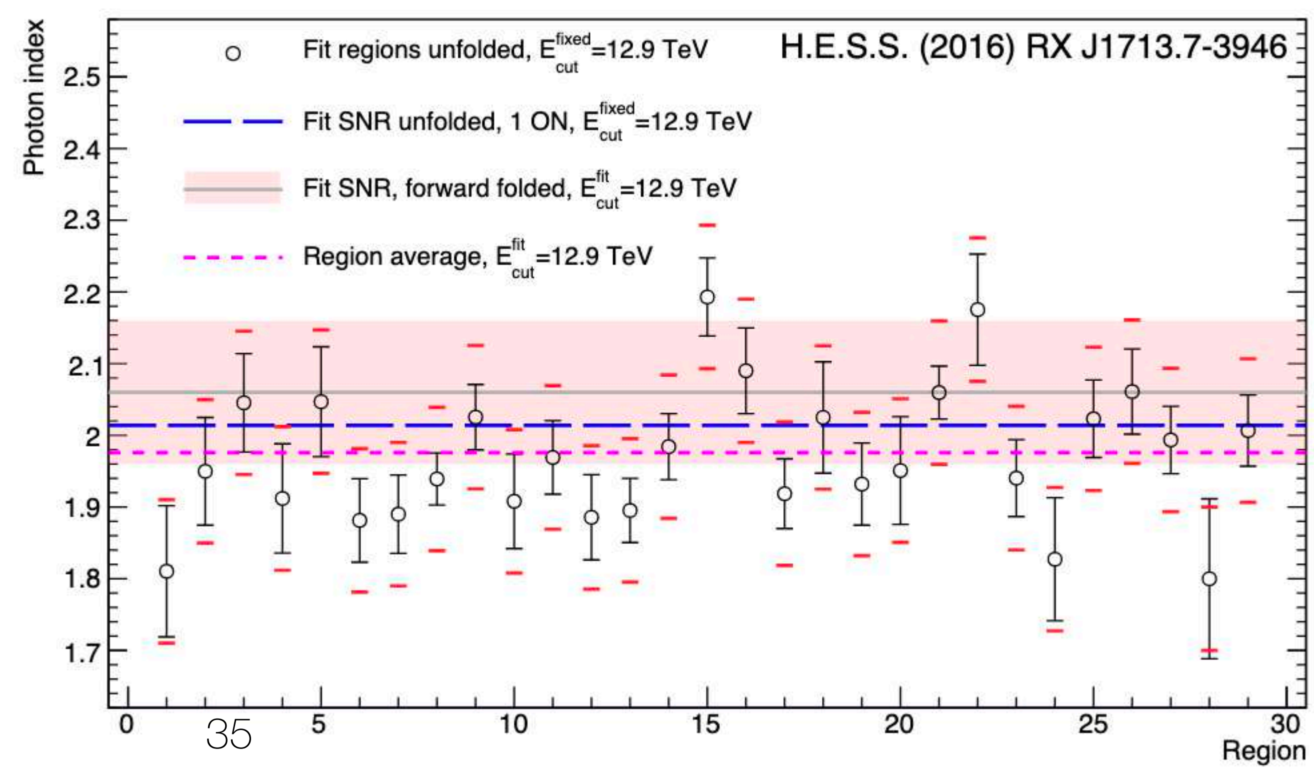
Inside the SNR? losses?

Accelerated/reaccelerated





HESS C

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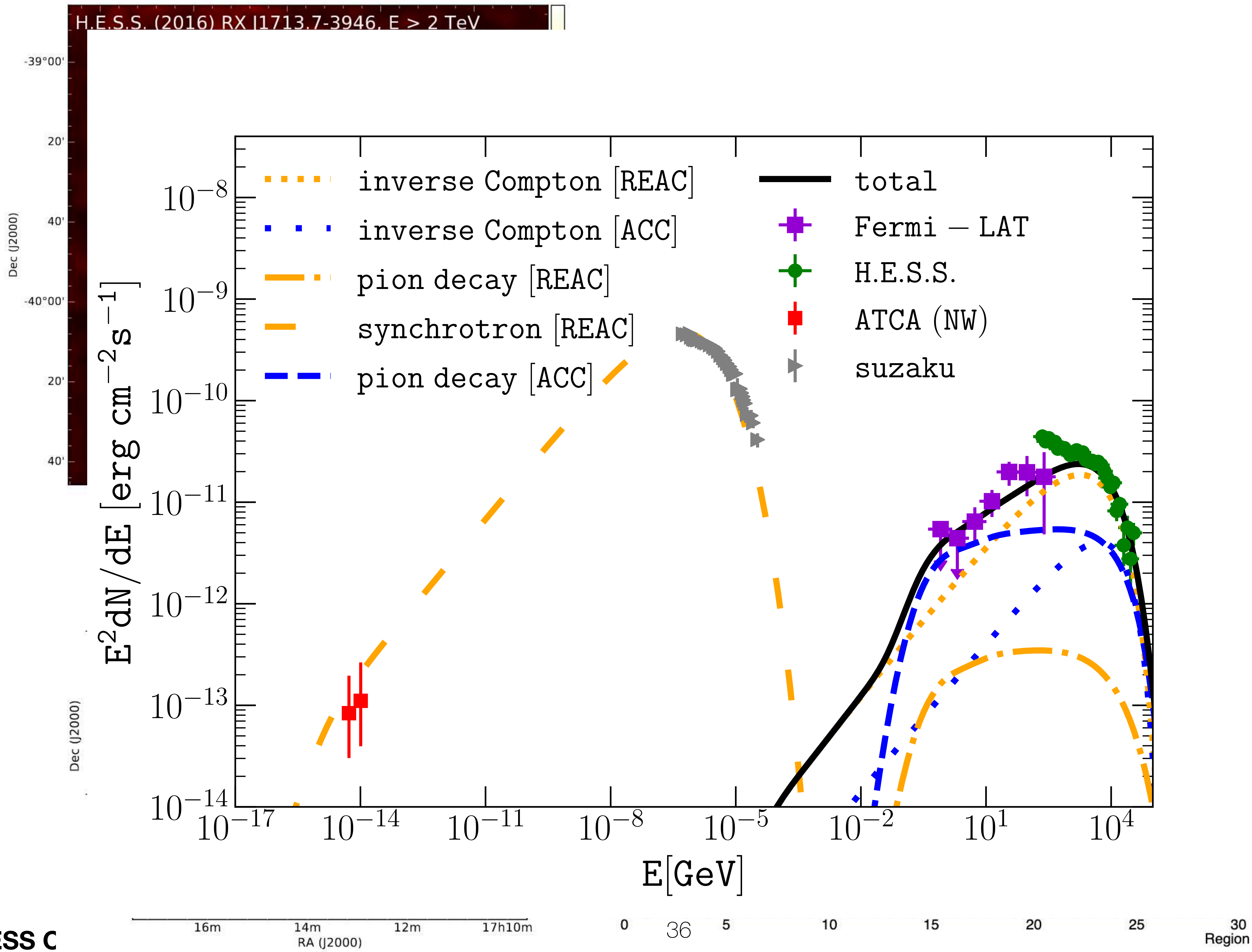

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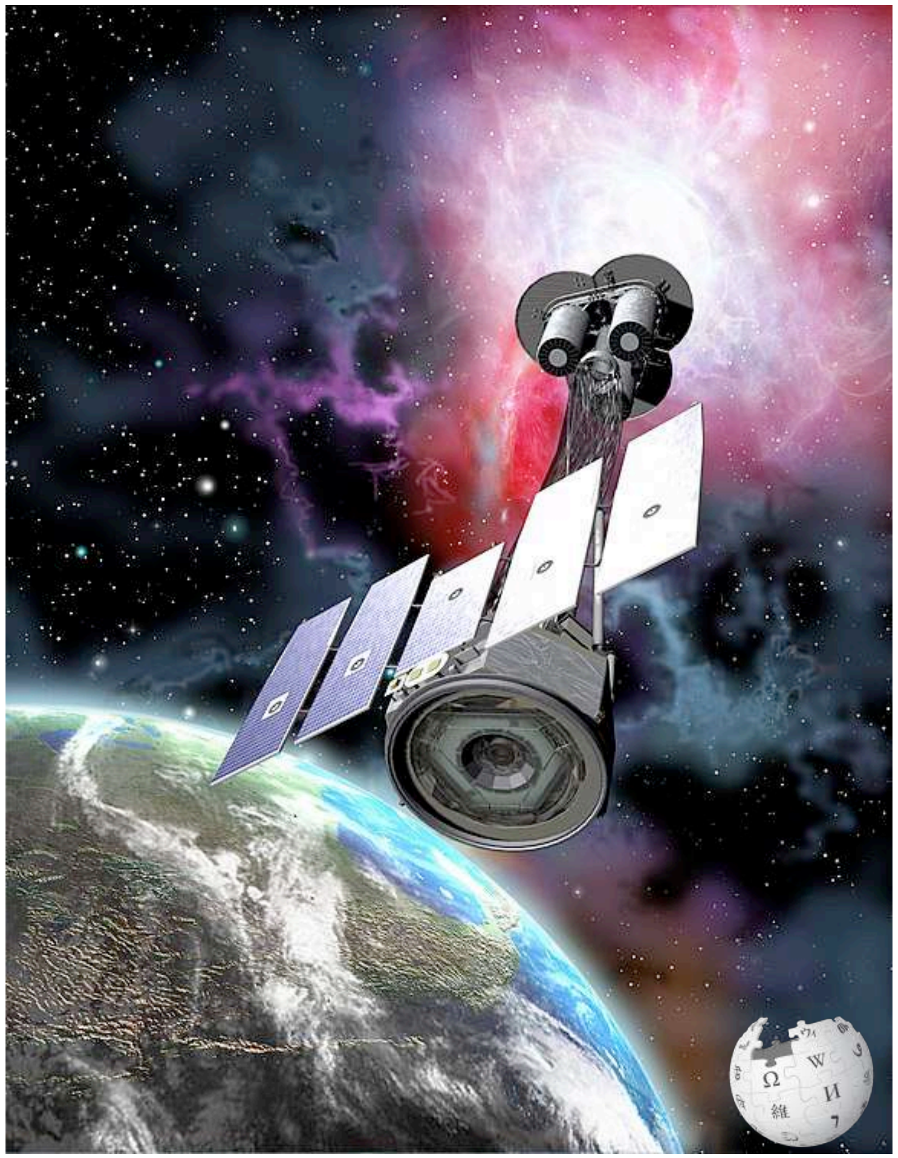
HESS C

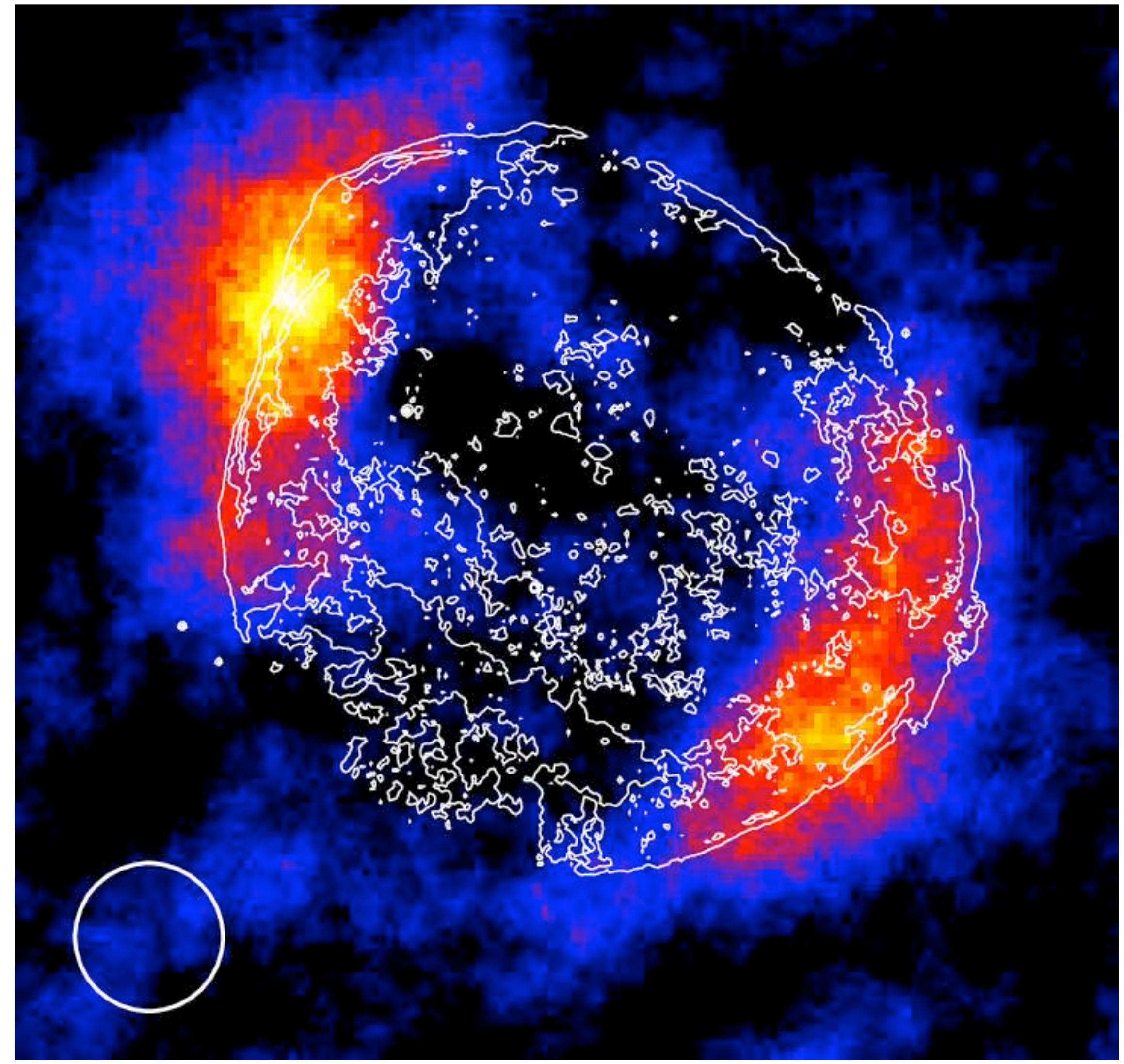
Magnetic structures and turbulence in SN 1006 revealed with imaging X-ray polarimetry

Ping Zhou [1], Dmitry Prokhorov [2], Riccardo Ferrazzoli [3], Yi-Jung Yang [4,5] Patrick Slane [6]

+ long list of co-authors



Imaging X-ray Polarimetry Explorer (IXPE)



SN 1006 H.E.S.S.

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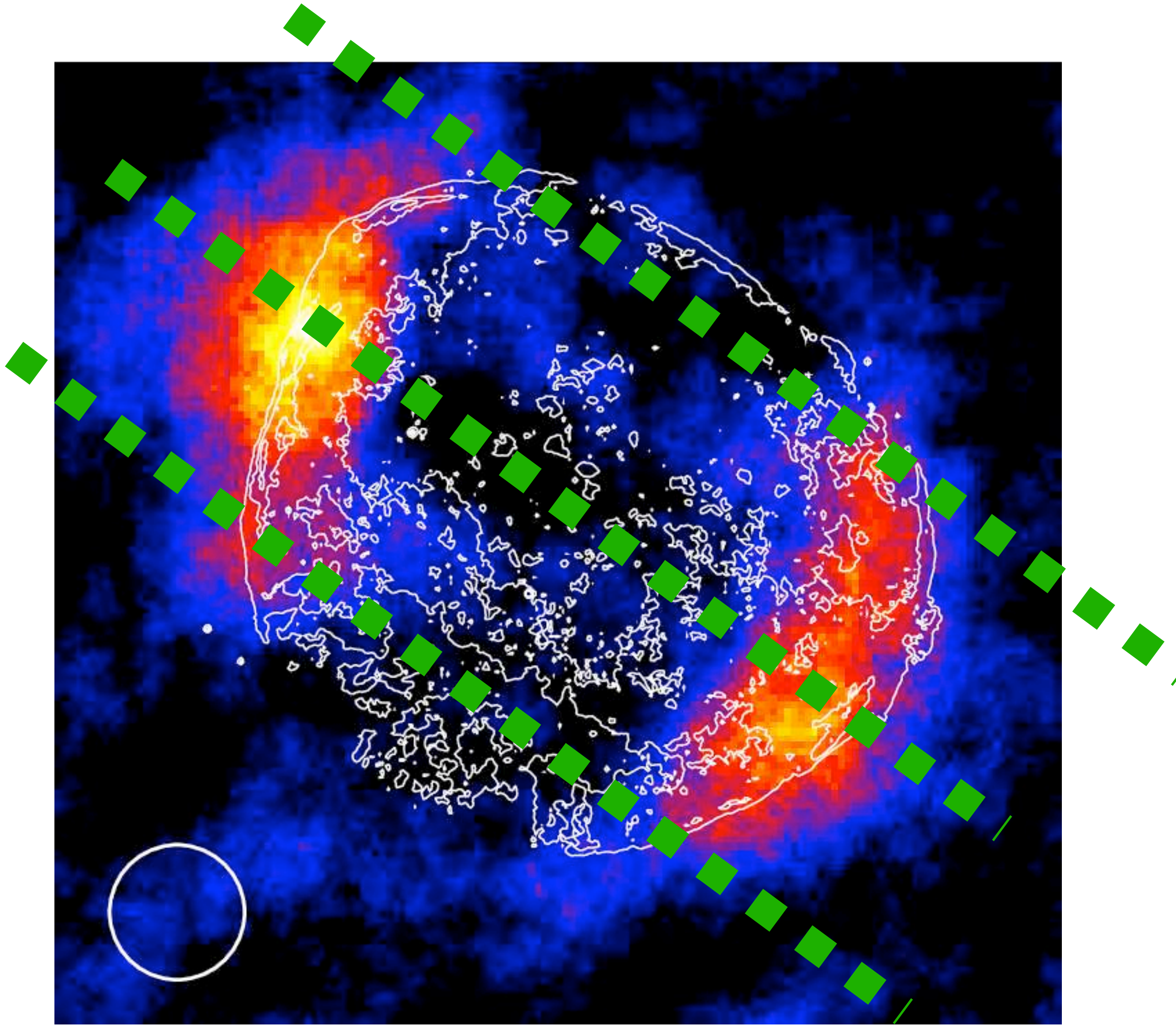

SN 1006 H.E.S.S.

Caprioli et al. 2018, Giuffrida et al. 2022

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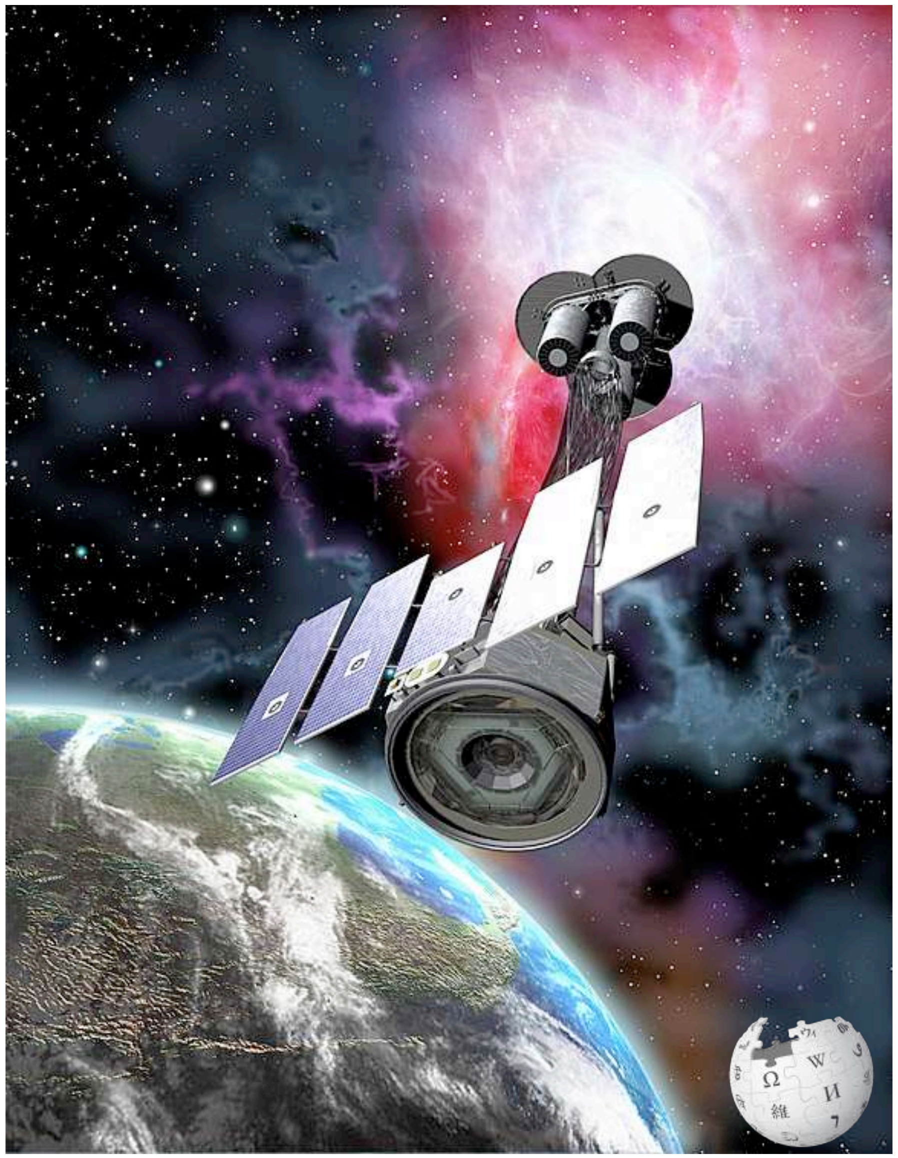

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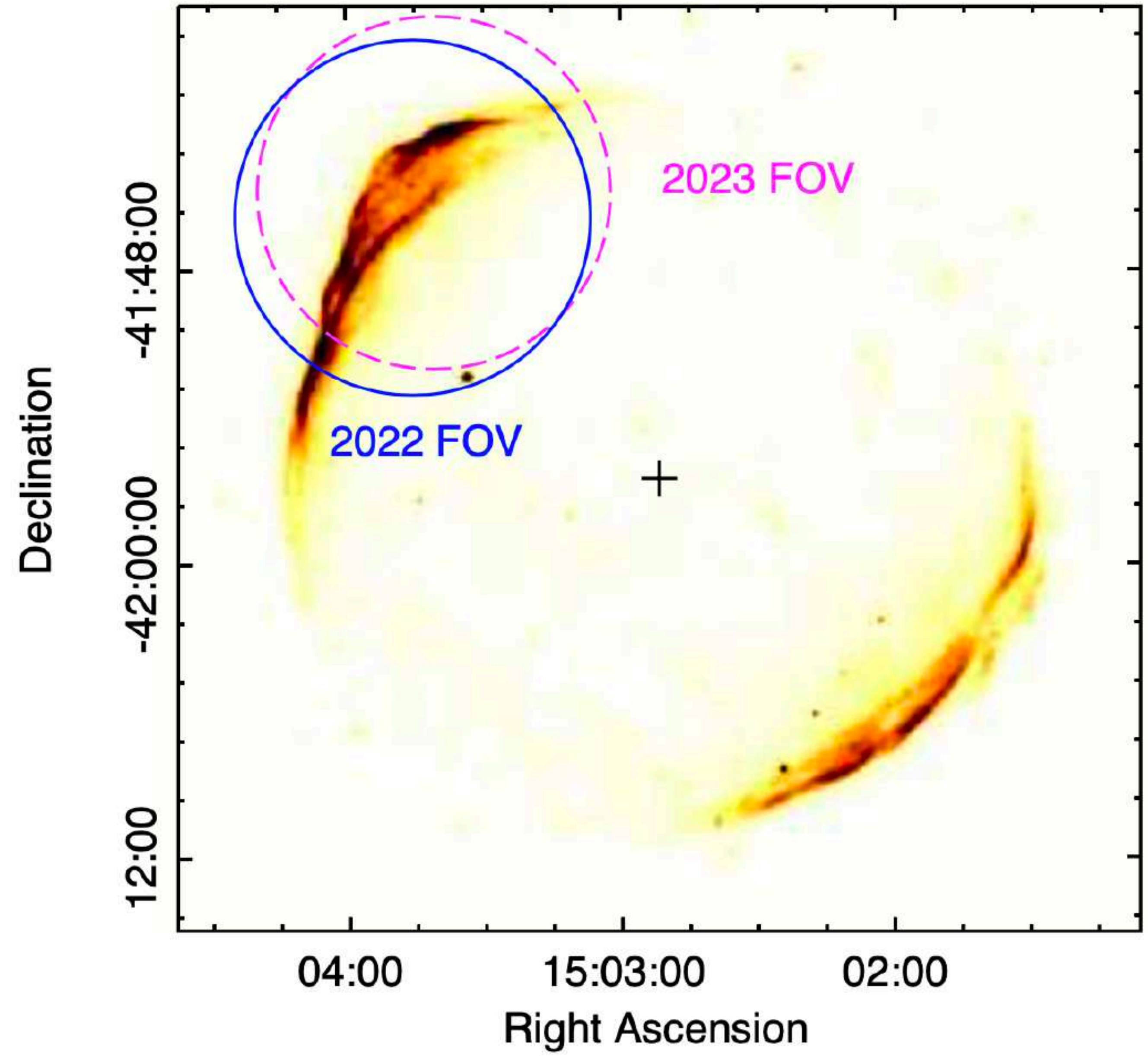

Magnetic structures and turbulence in SN 1006 revealed with imaging X-ray polarimetry

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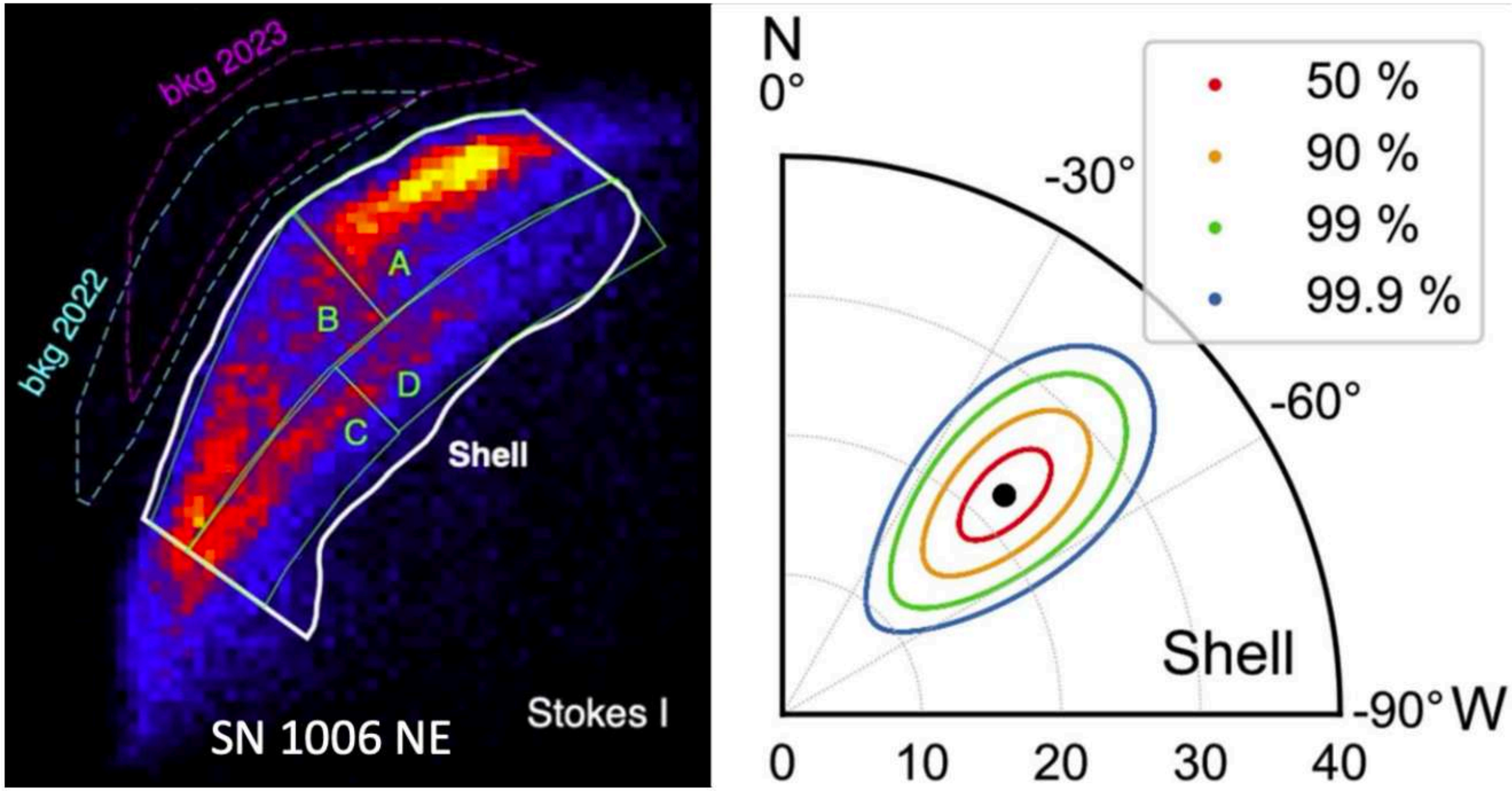

We report the X-ray polarization distribution **in the northeastern shell of SN1006 from a 1 Ms observation** **with the Imaging X-ray Polarimetry Explorer (IXPE)**. We found an average polarization degree of 22.4 ± 3.5% and an average polarization angle of −45.4 ± 4.5° (measured on the plane of the sky from north to east). The X-ray polarization angle distribution **reveals that the magnetic fields immediately behind the shock in the northeastern shell of SN 1006 are nearly parallel to the shock normal or radially distributed, similar to that in the radio observations, and consistent with the quasi-parallel CR acceleration scenario.**

The X-ray polarization degree of SN 1006 .. **favoring that CR-induced instabilities set the turbulence in SN 1006 and CR acceleration is environment-dependent**.

Review

Probing Magnetic Fields in Young Supernova Remnants with IXPE

Patrick Slane [1,*], Riccardo Ferrazzoli [2], Ping Zhou [3] and Jacco Vink [4]

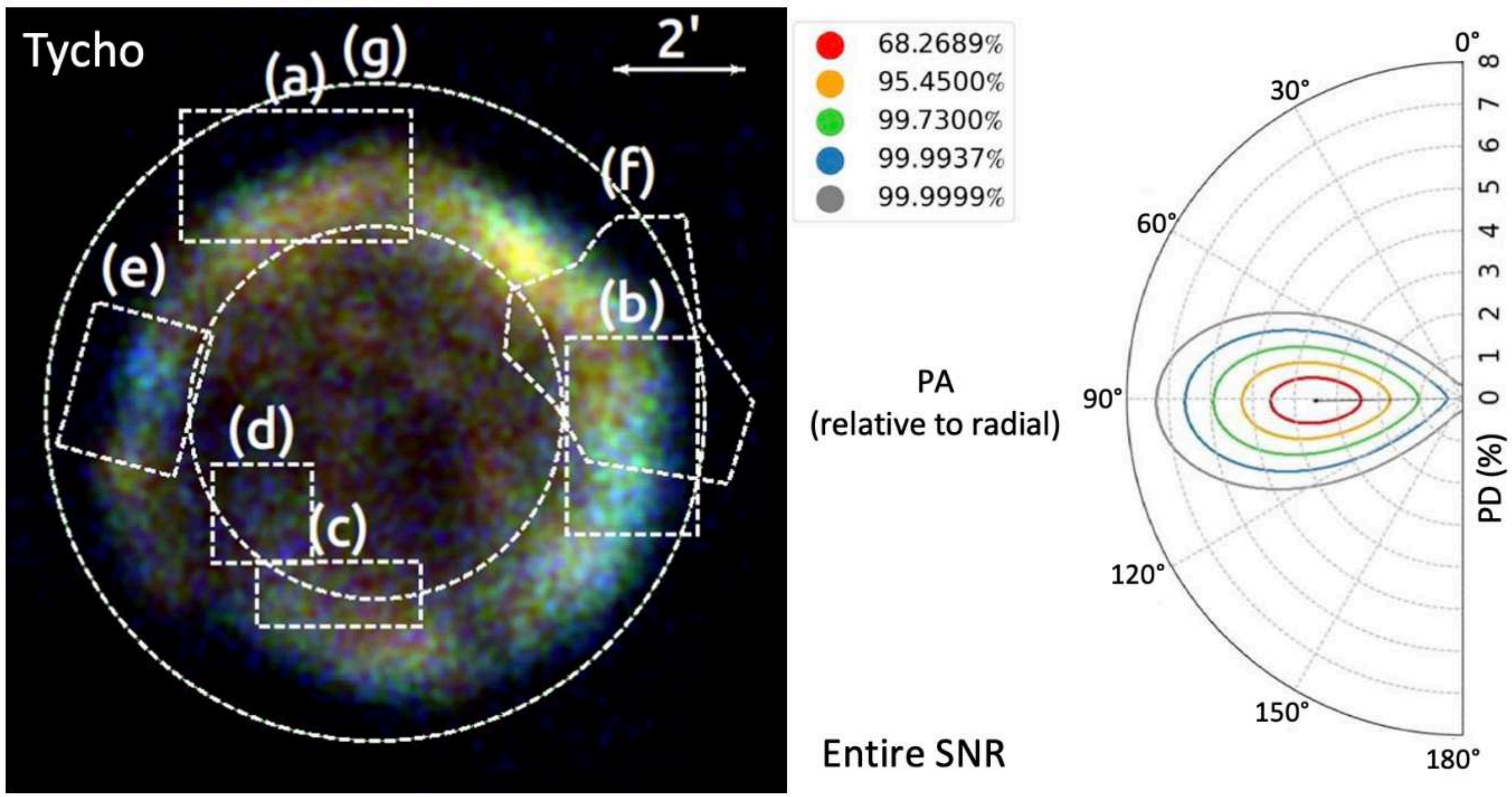

Figure 2. **Left**: IXPE image of Tycho. Labels identify specific regions investigated in [38]—the northeast knot (a); the western (b) and southern (c) nonthermal stripes and the nonthermal arc region (d); and regions in which strong polarization is detected (e,f). **Right**: Polar plot for entire SNR (region g). The polarization degree is indicated on the radial axis and the polarization angle is shown, with 0° corresponding to the radial direction; an angle of 90° indicates a radial magnetic field direction. The contours show significance levels.

Slane et al. 2024

Review

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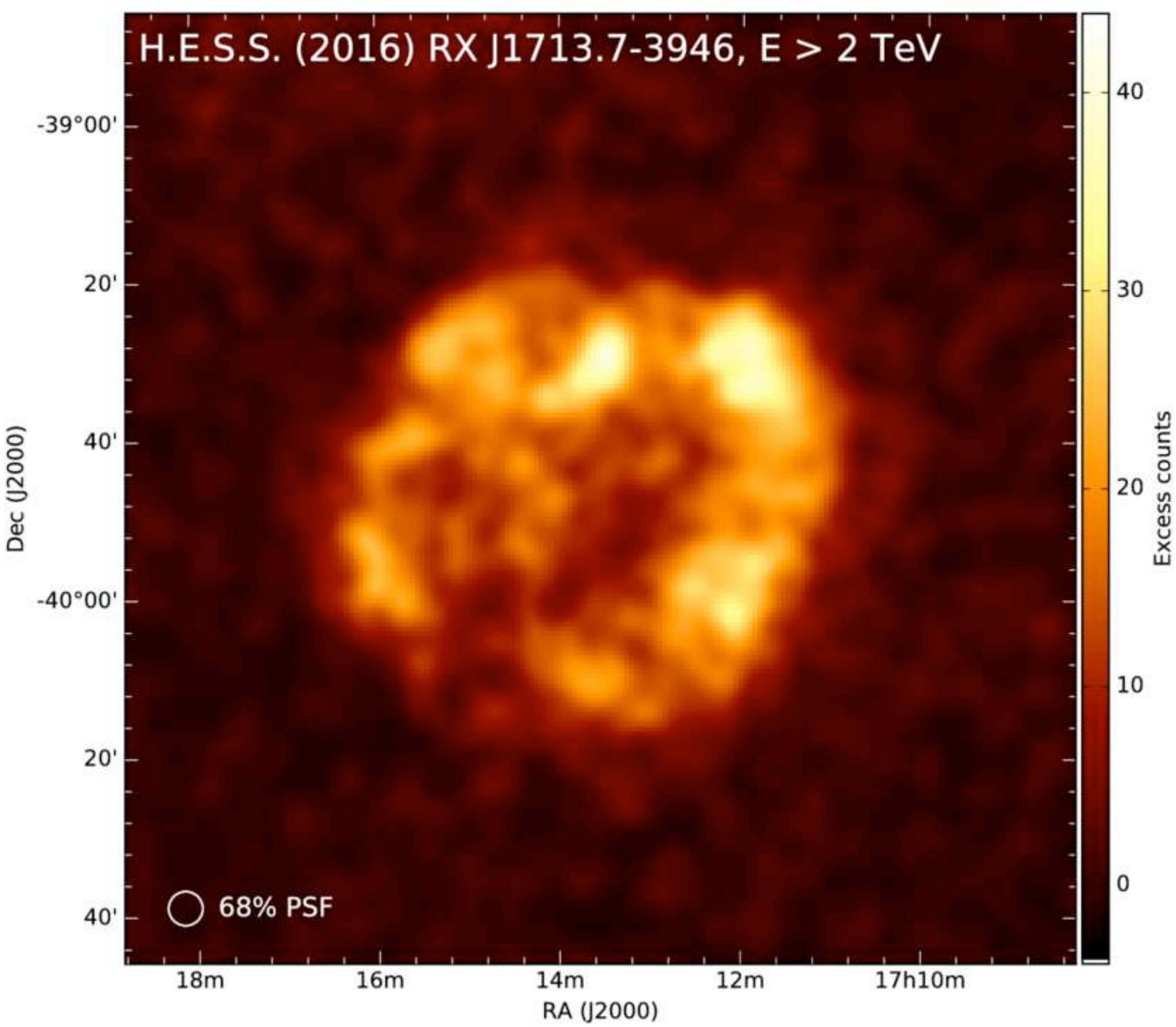

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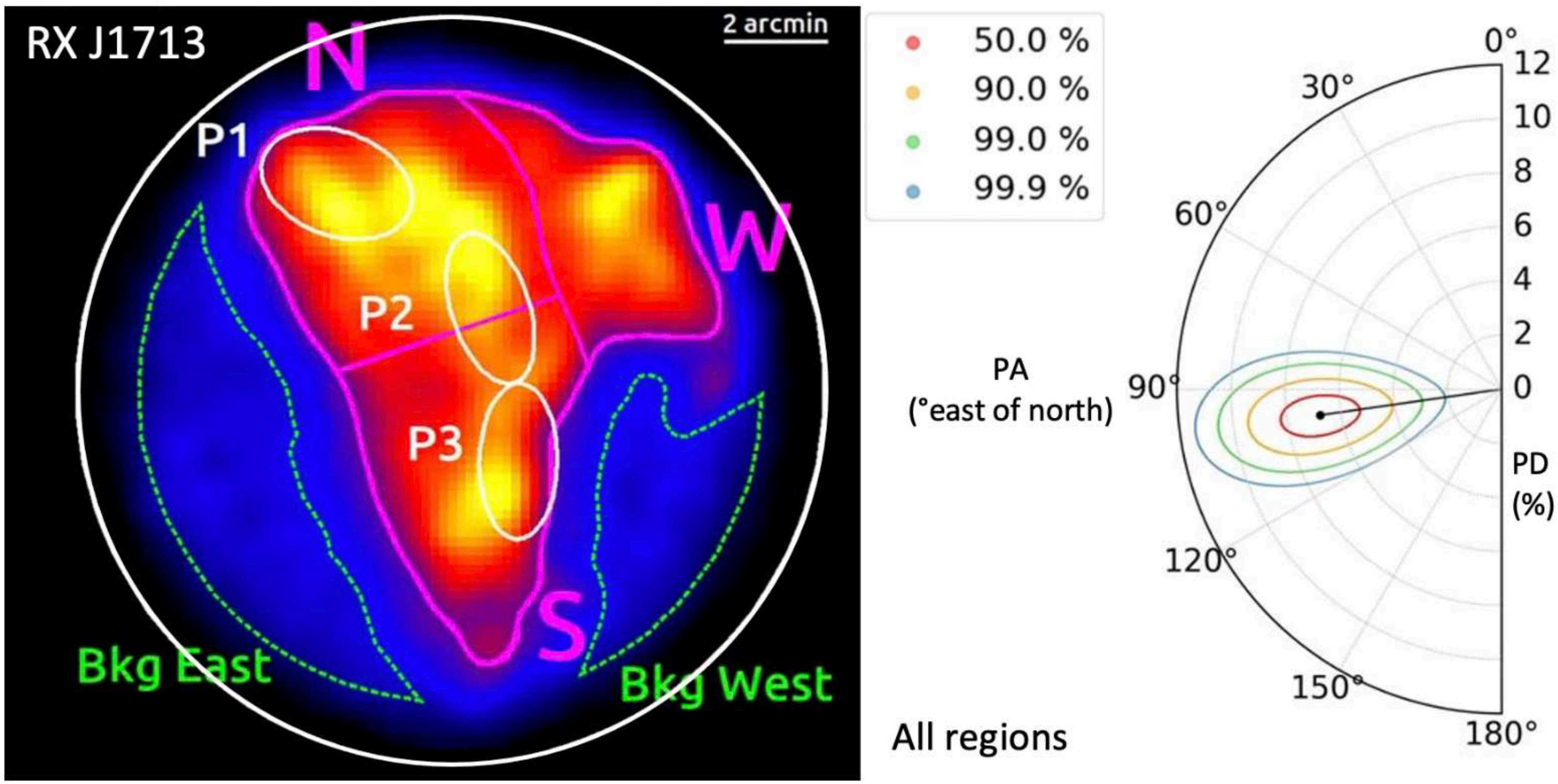


Figure 4. Left: IXPE image of the NW limb of RX J1713.7−3946. Labels identify north, west, and south (N, W, S) regions of the extended emission structure and discrete regions P1–P3 that show evidence for higher polarization—all were investigated in [52]. **Right**: Polar plot for entire limb region, composed of N + W + S. The polarization angle is measured from north to east, with an angle of ∼100° corresponding to the radial direction from the center of RX J1713.7−3946 and, thus, to a magnetic field that is tangential to the shock surface. The contours show significance levels.

Review

Probing Magnetic Fields in Young Supernova Remnants with IXPE

Patrick Slane [1,*], Riccardo Ferrazzoli [2], Ping Zhou [3] and Jacco Vink [4]

	Polarization Degree (%) [a] Rim	SNR	Peak	V_{shock} (km s^{-1})	n_0 (cm^{-3})	Bohm Factor (η)	B^b_{low} (μG)
Cas A	4.5 ± 1.0	2.5 ± 0.5	∼15	∼5800	0.9 ± 0.3	∼1–6	25–40
Tycho	12 ± 2	9 ± 2	23 ± 4	∼4600	∼0.1–0.2	∼1–5	30–40
SN 1006 (NE)	22.4 ± 3.5	...	31 ± 8	∼5000	∼ 0.05–0.08	∼6–10	18–26
RX J1713 (W)	13.0 ± 3.5	...	46 ± 10	1400–2900	∼0.01–0.2	∼1.4	∼10

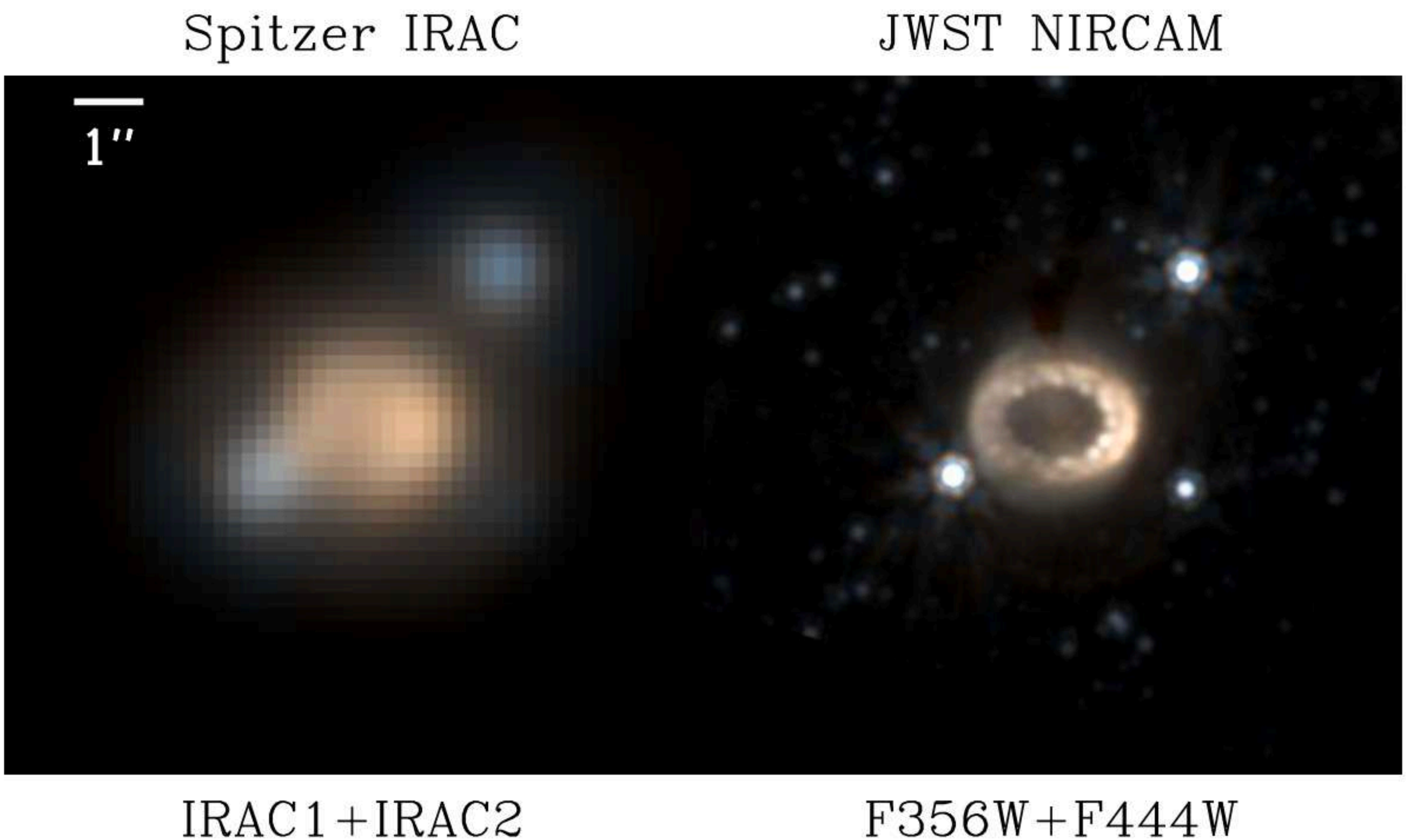
(a) X-ray polarization degree for SNR rim, entire SNR, and peak value within SNR. (b) Lower limit to post-shock magnetic field based on rim width, e.g., [20].

« the polarization degree is quite small, indicating high levels of turbulence in the immediate post-shock regions, as expected from models for diffusive shock acceleration with magnetic field amplification. »

Ability to study small (sub) regions, orientation of the magnetic fields

JWST NIRcam observations of SN1987A

Decomposition of overlapping emission from Equatorial ring, forward shock (CSM), reverse shock (SN ejecta)



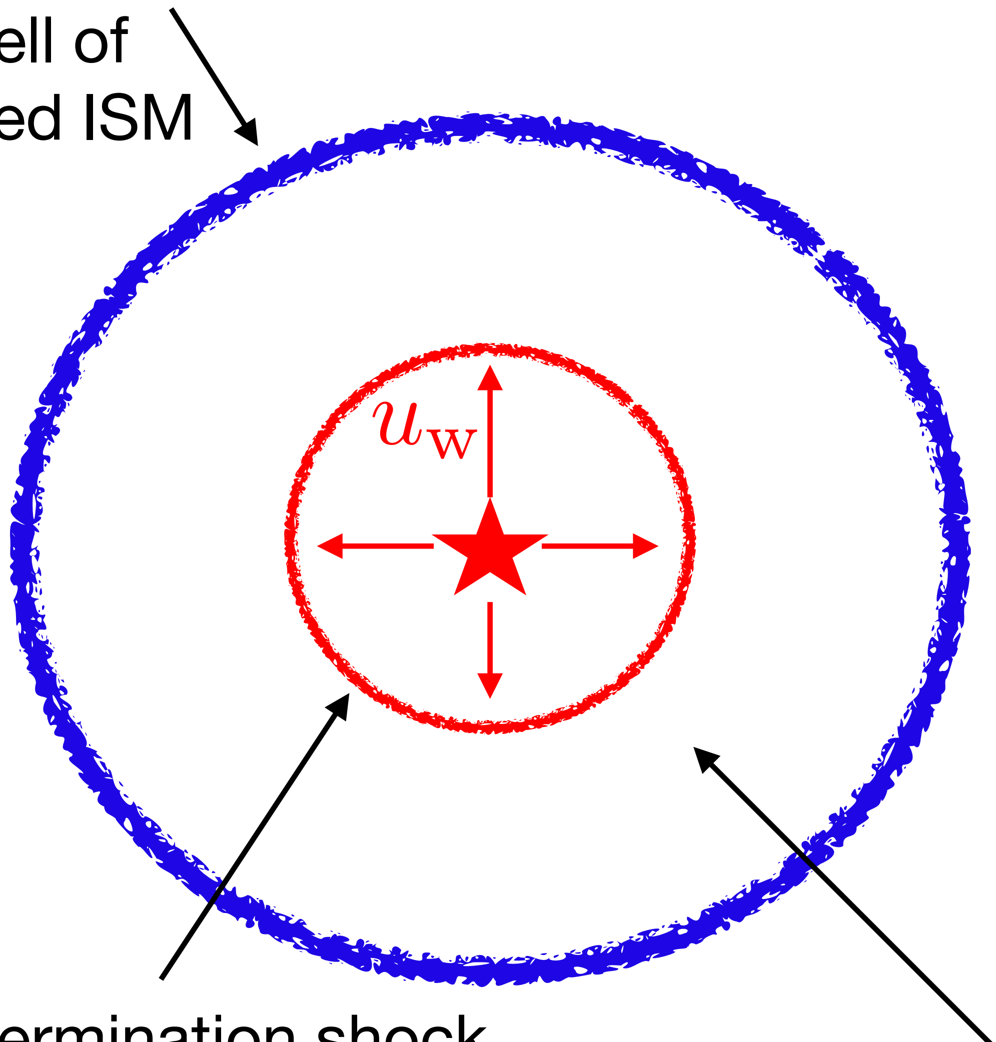
Arendt et al. 2020

Arendt et al. 2023

Diversity of SNe and complexity of SNR environment ⟷ **Stellar clusters and interstellar bubbles**

Diversity of SNe and complexity of SNR environment ⟷ Stellar clusters and interstellar bubbles

Cassé & Paul 1980,1982; Volk& Forman 1982, Cesarsky & Montmerle 1983; Webb et al. 1985, Bykov et al. 2001 ++, Parizot et al. 2004, Ferrand & Marcowith 2010, Morlino et al. 2021, Vieu et al. 2022



Castor et al. 1975, Weaver et al. 1977, MacCray&Kafatos 1987, MacLow&McCray 1988, Koo&McKee 1992

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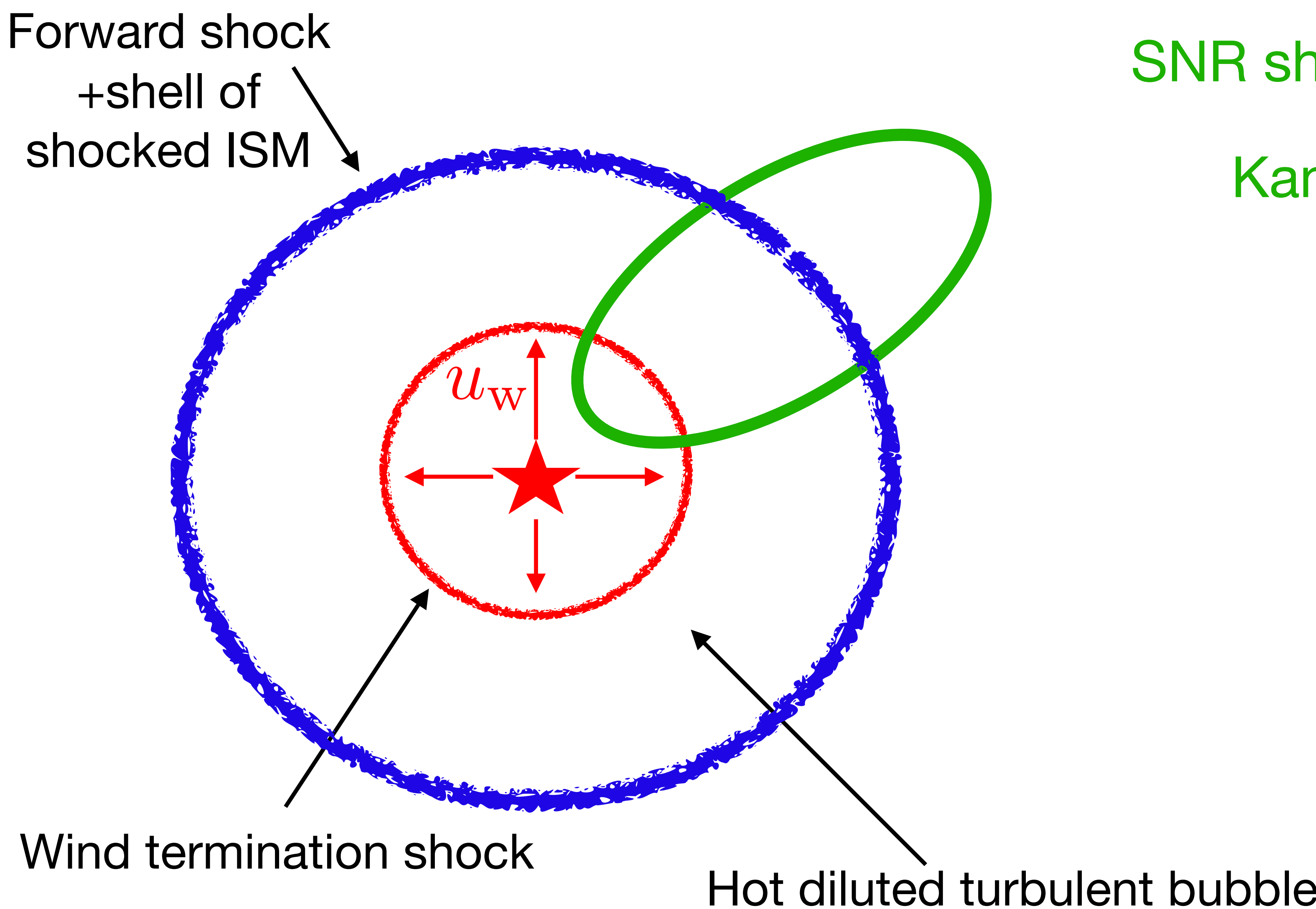
SNR shock and wind Termination shock interaction
Kamijima et Ohira 2024



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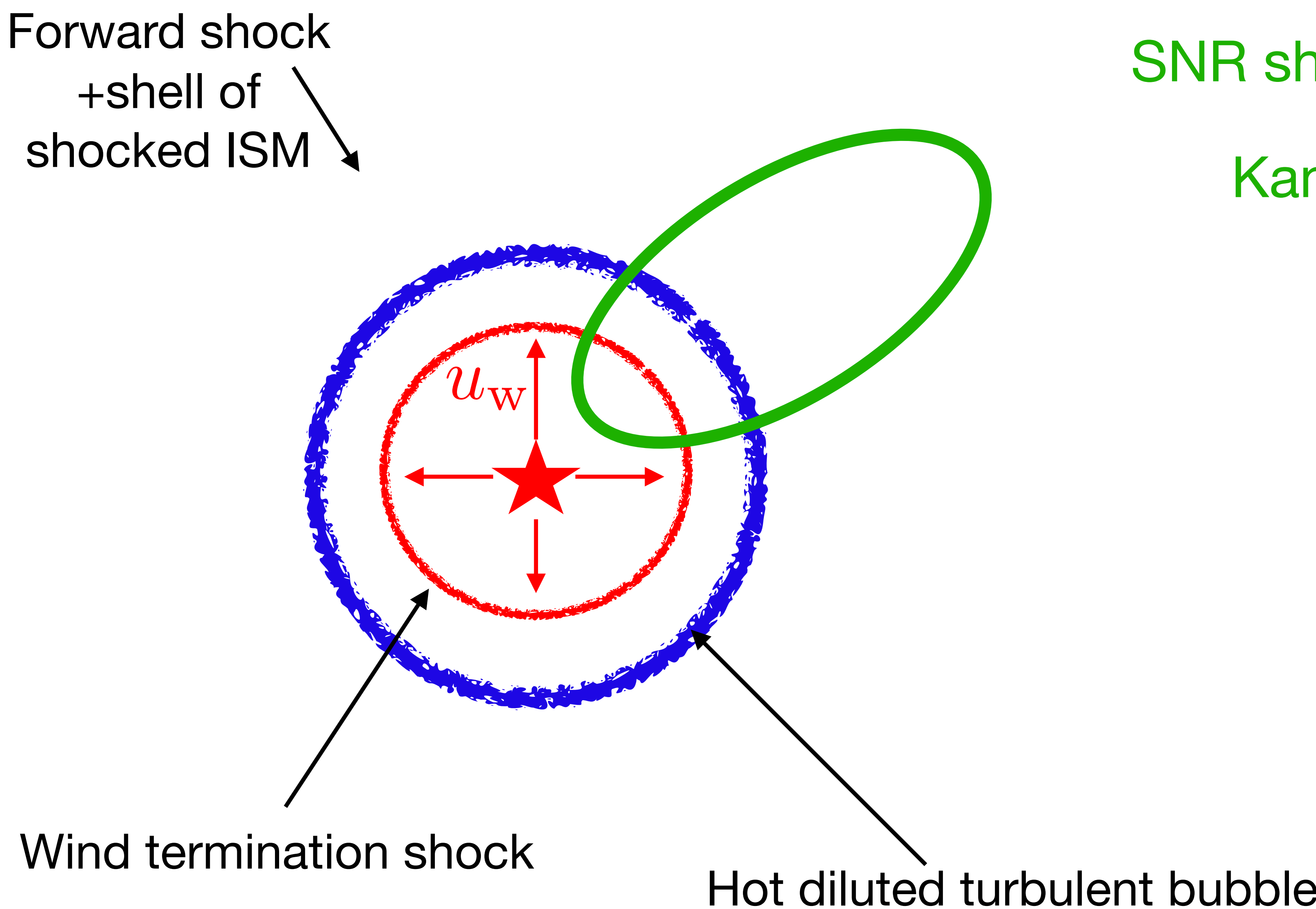

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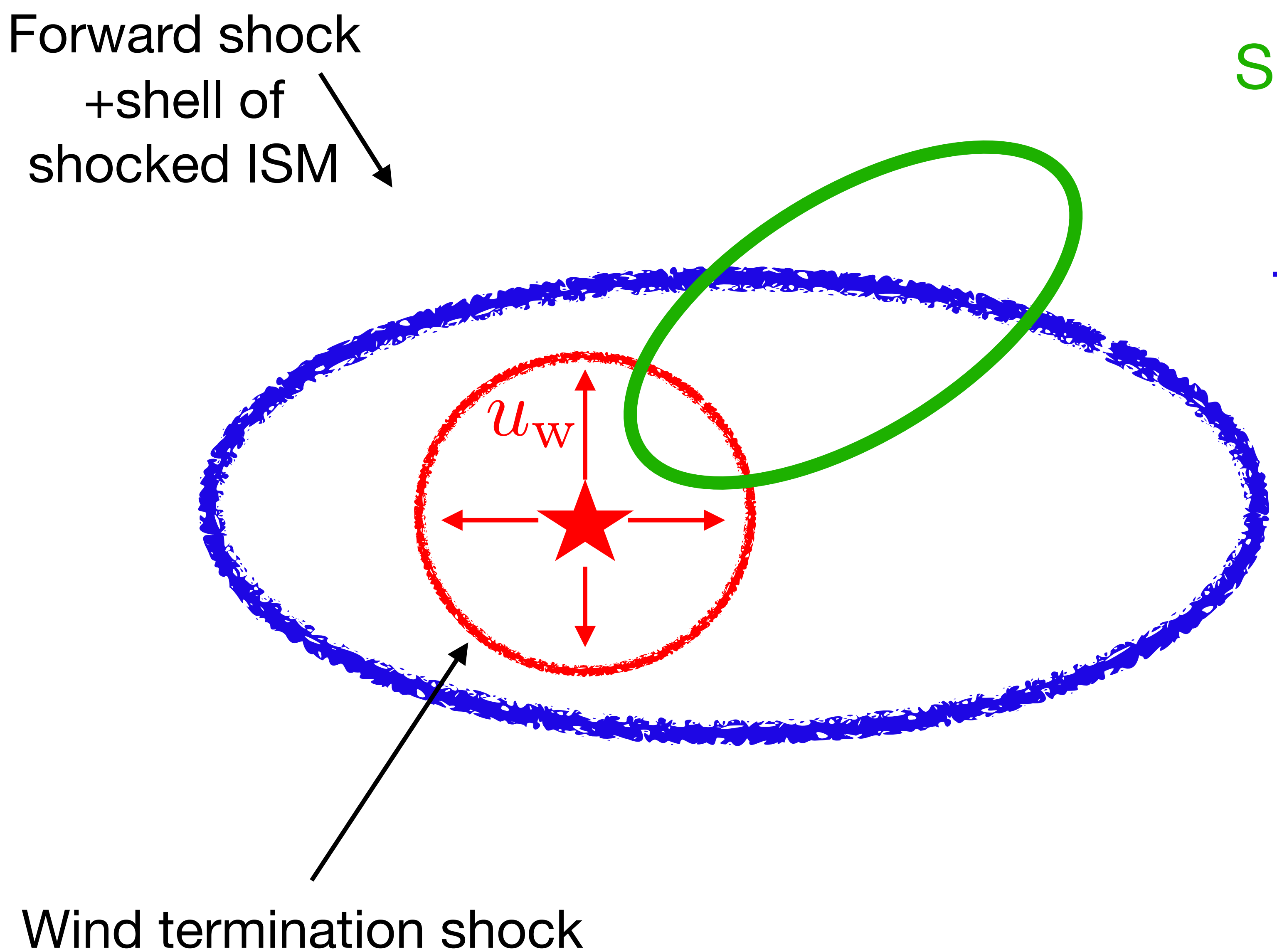

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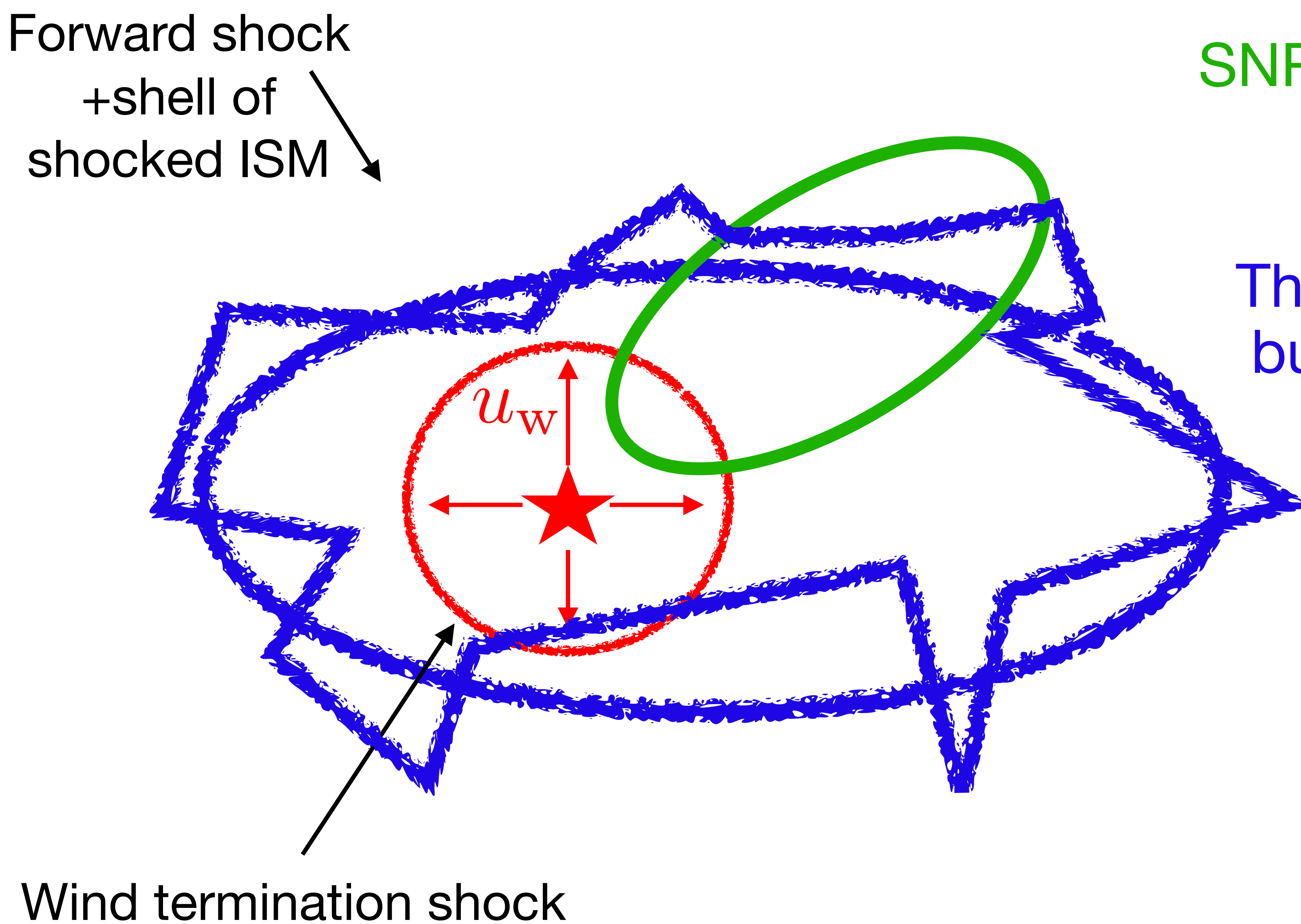

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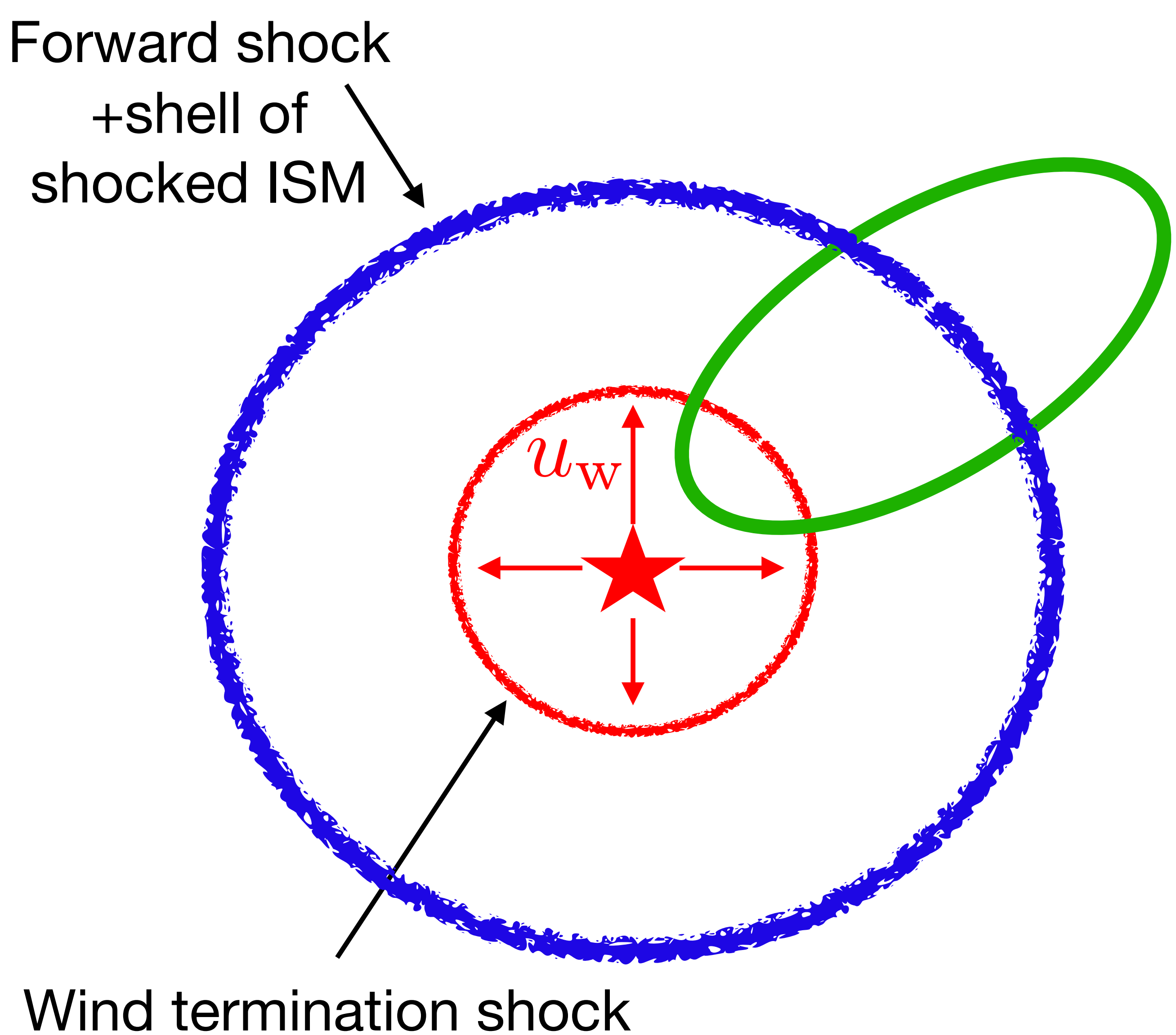

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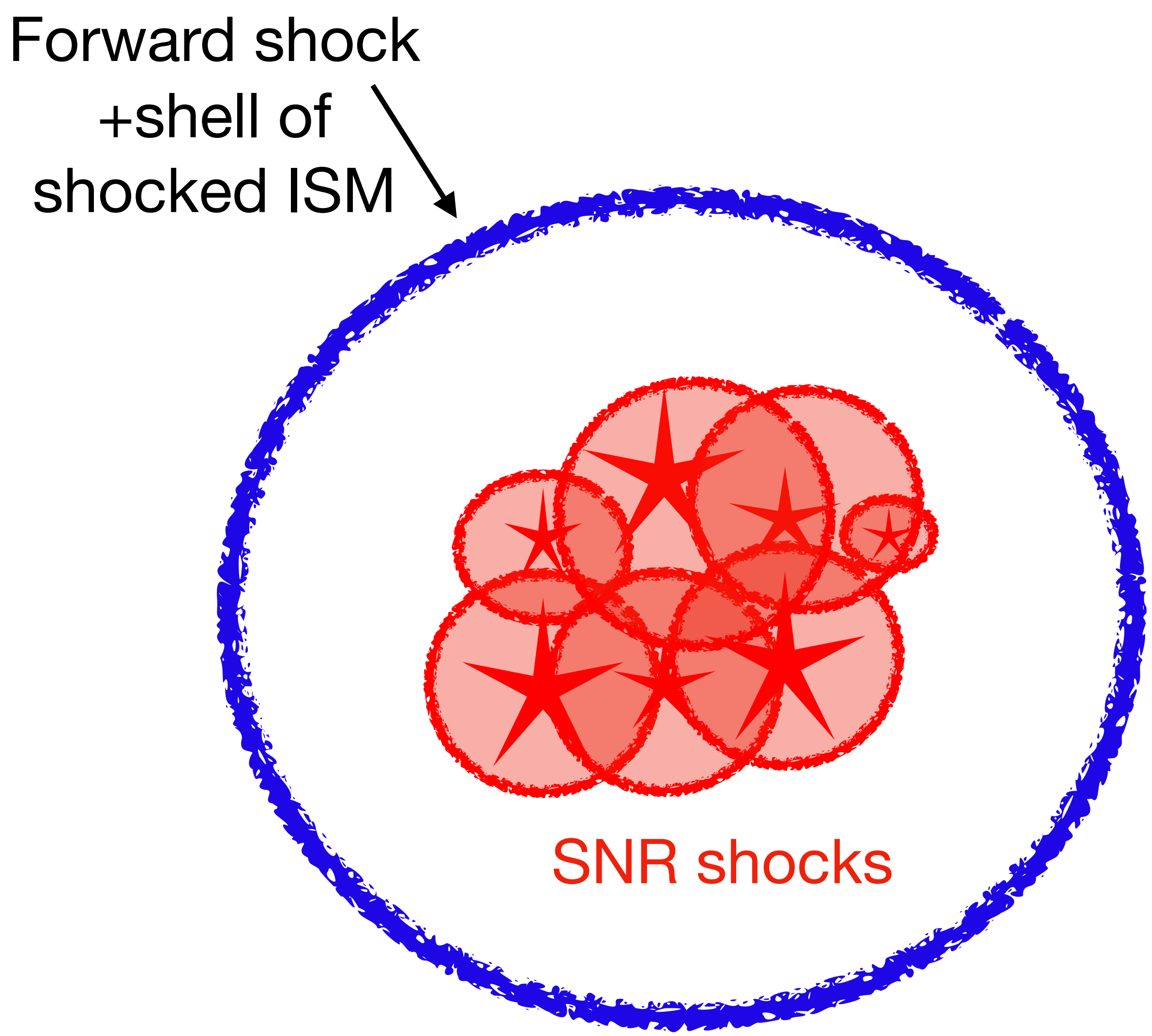

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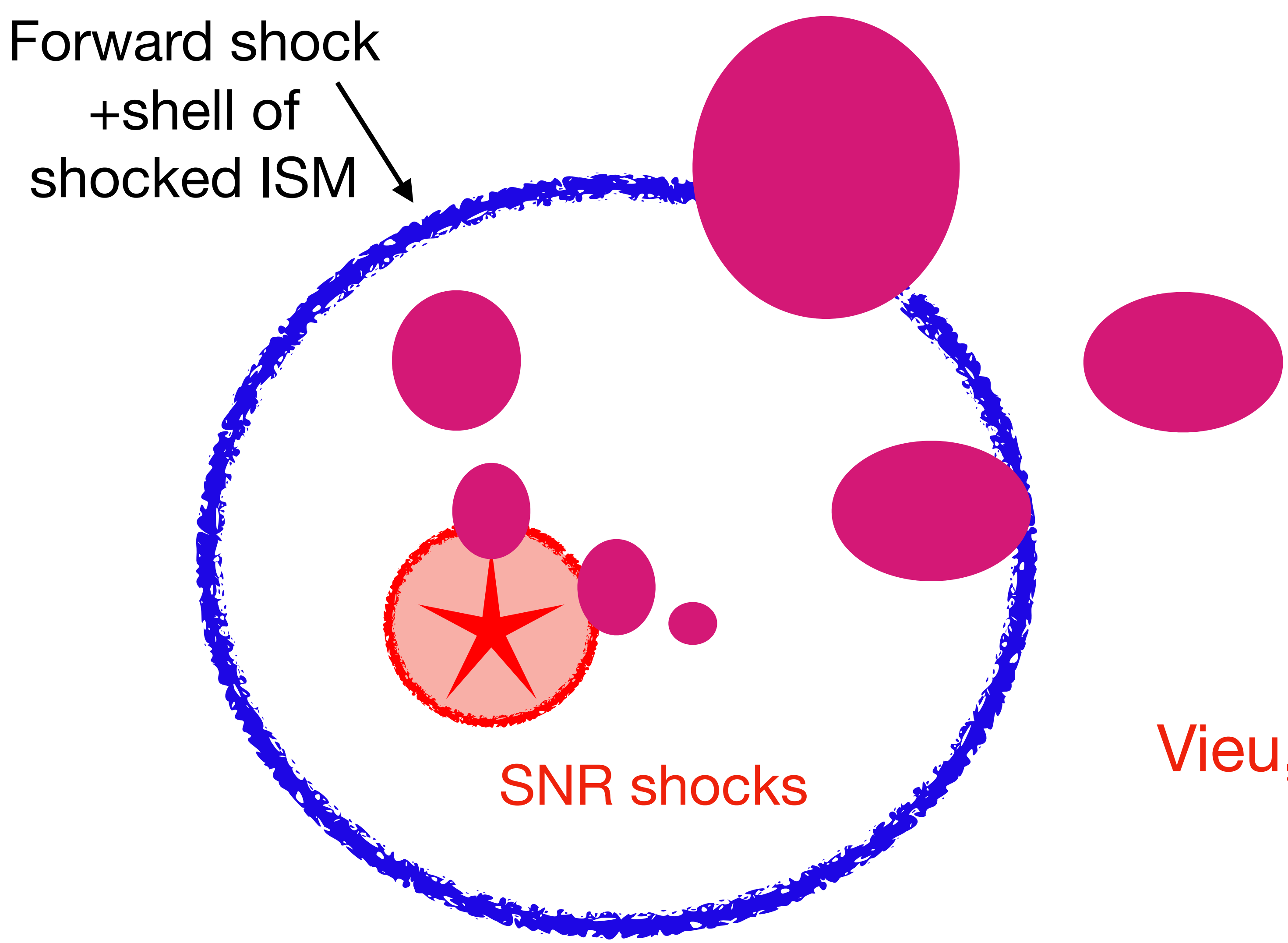

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Shock-clouds interactions, clumpiness of CSM
Gabici& Aharonian 2014, Inoue et al. 2021, Bamba et al. 2023

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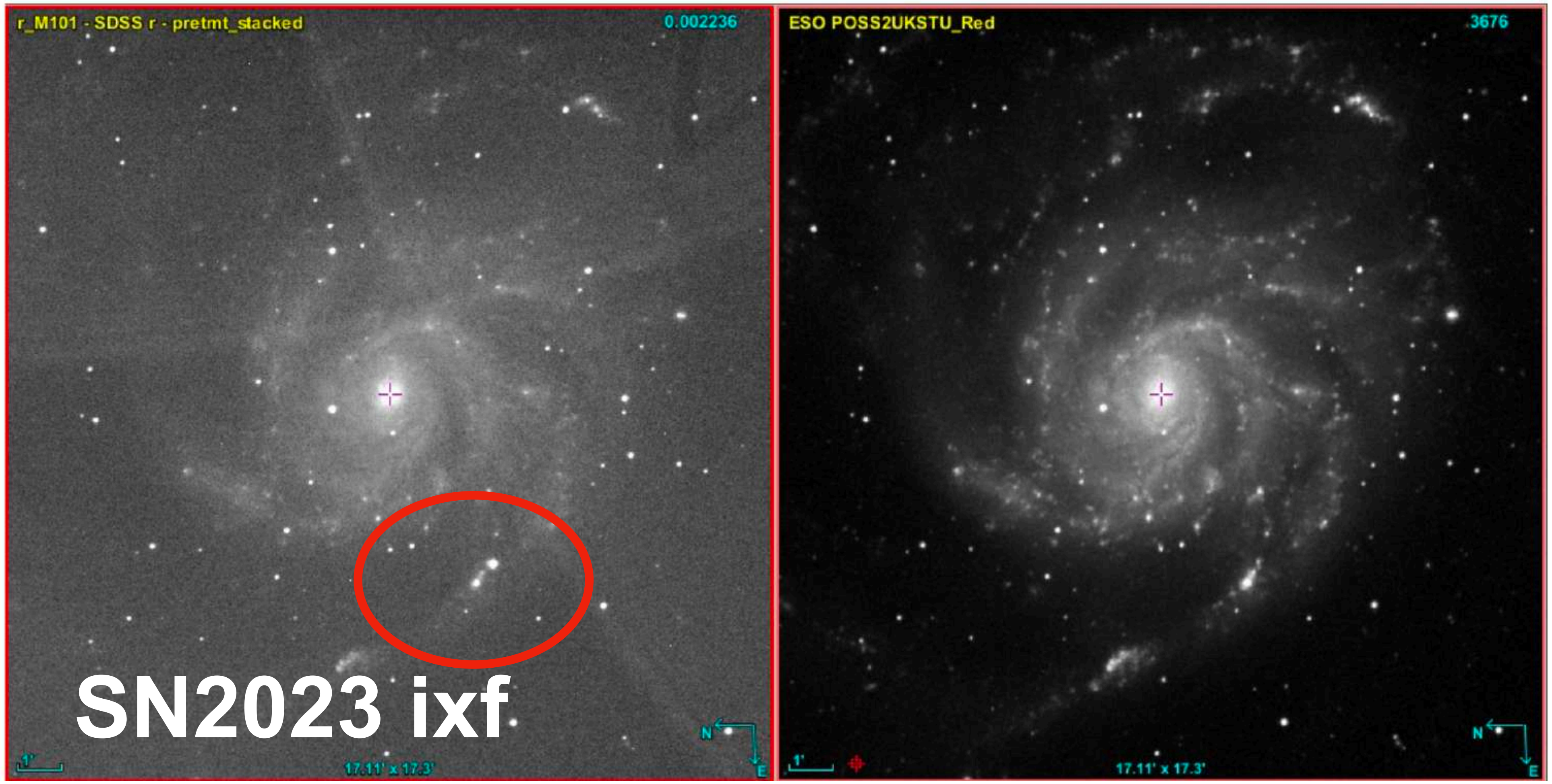
VHE emission from young extragalactic SNRs



So far no detection in GeV/ TeV for any extraGalactic CCSNe

Goal: model particle acceleration + gamma-ray emission for typical CCSNe (detectability with CTAO)

Issues:

- diversity of CCSNe (types)
- environments
- variation of mass-loss rate of the winds in the years before the explosion
- clumps
- types of shocks (radiative, radiation mediated, colisionless)
- our « limited » understanding of particle acceleration at SNR shocks

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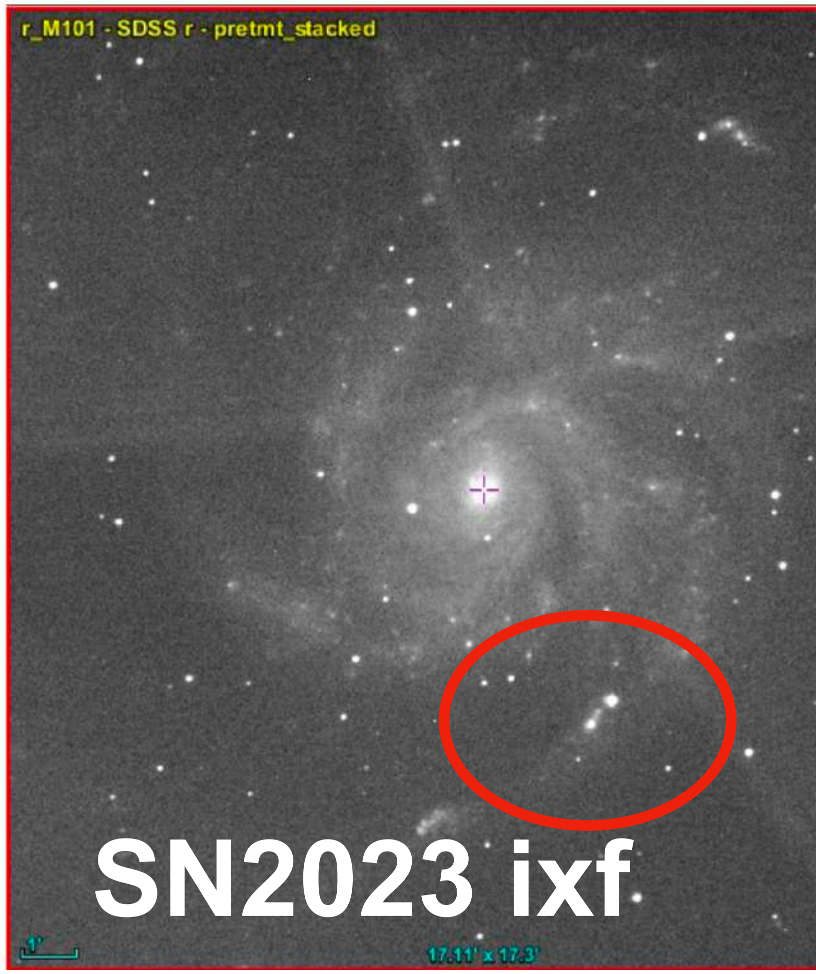

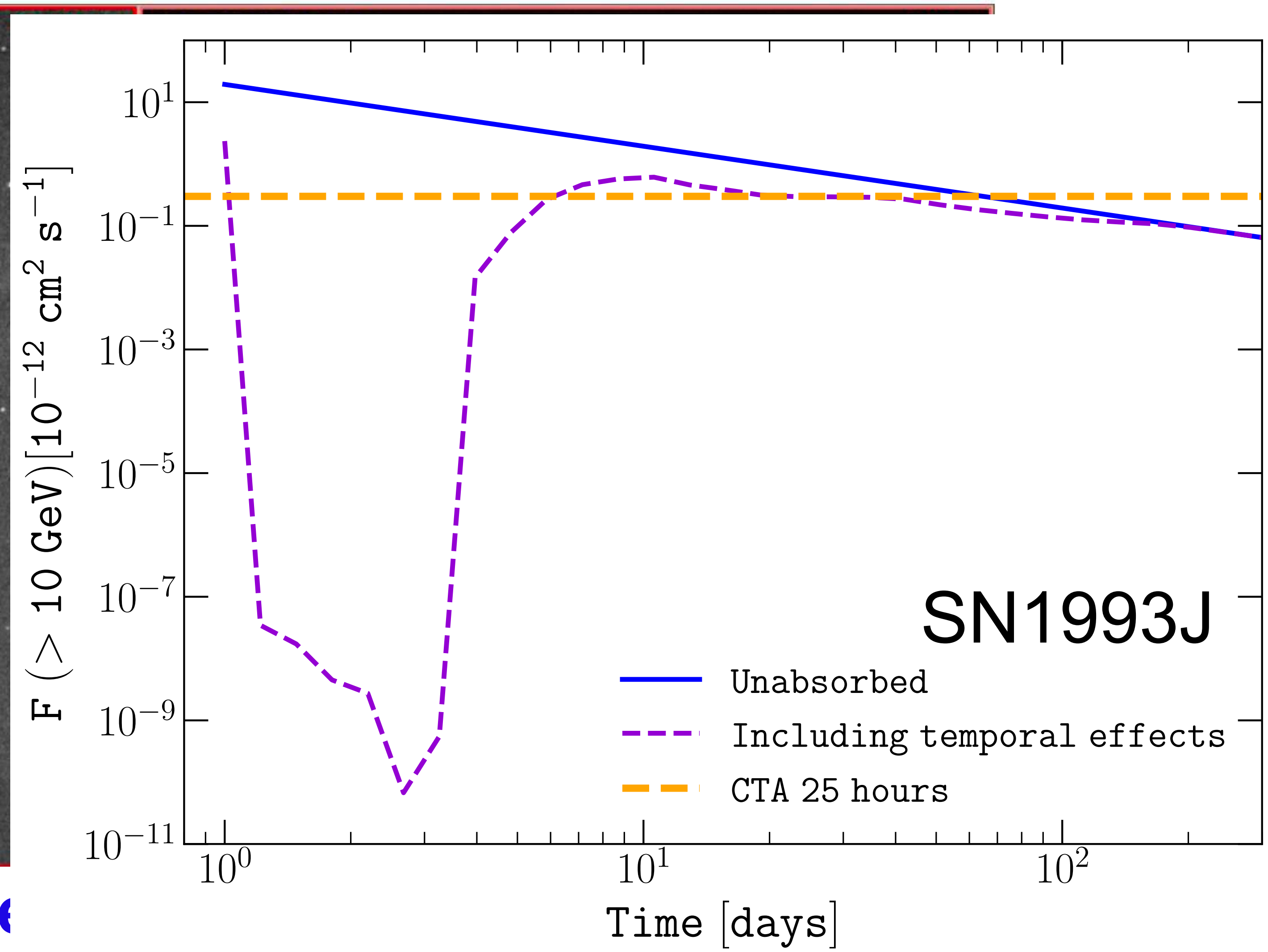

So far no detection in Ge

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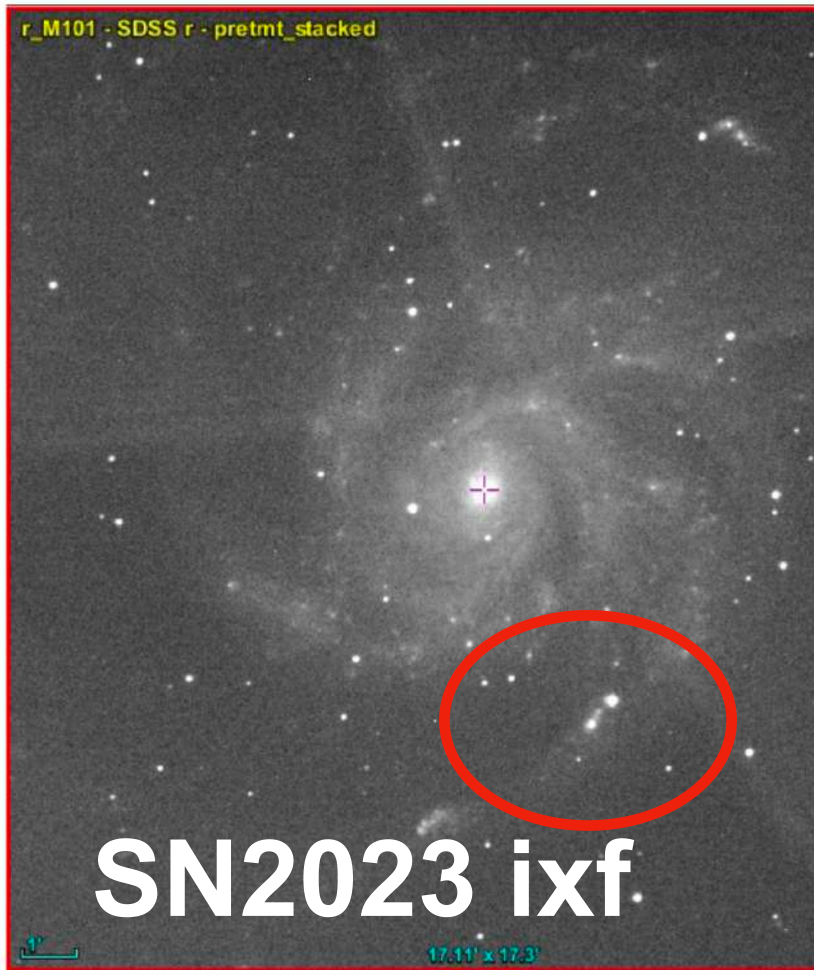

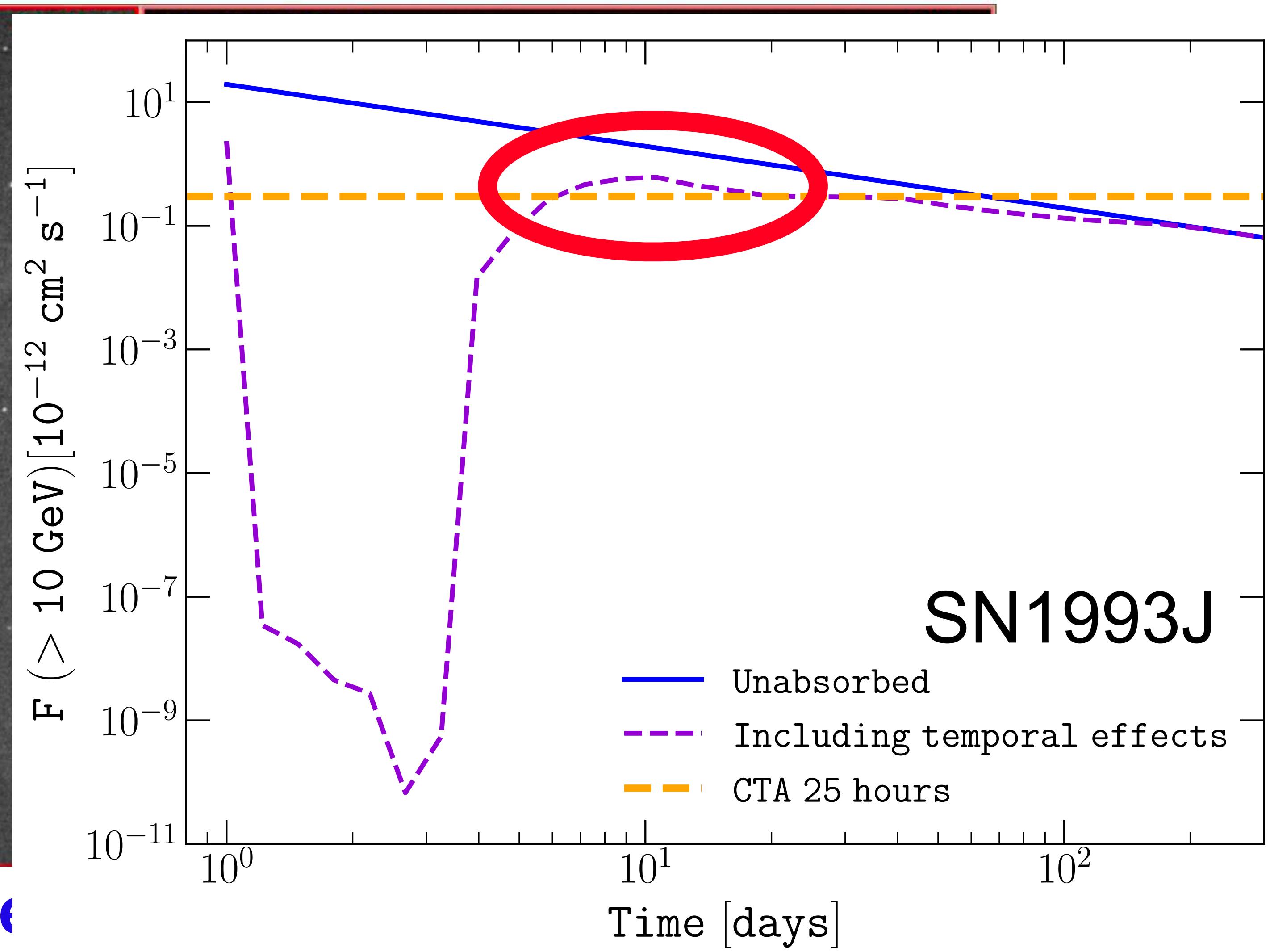

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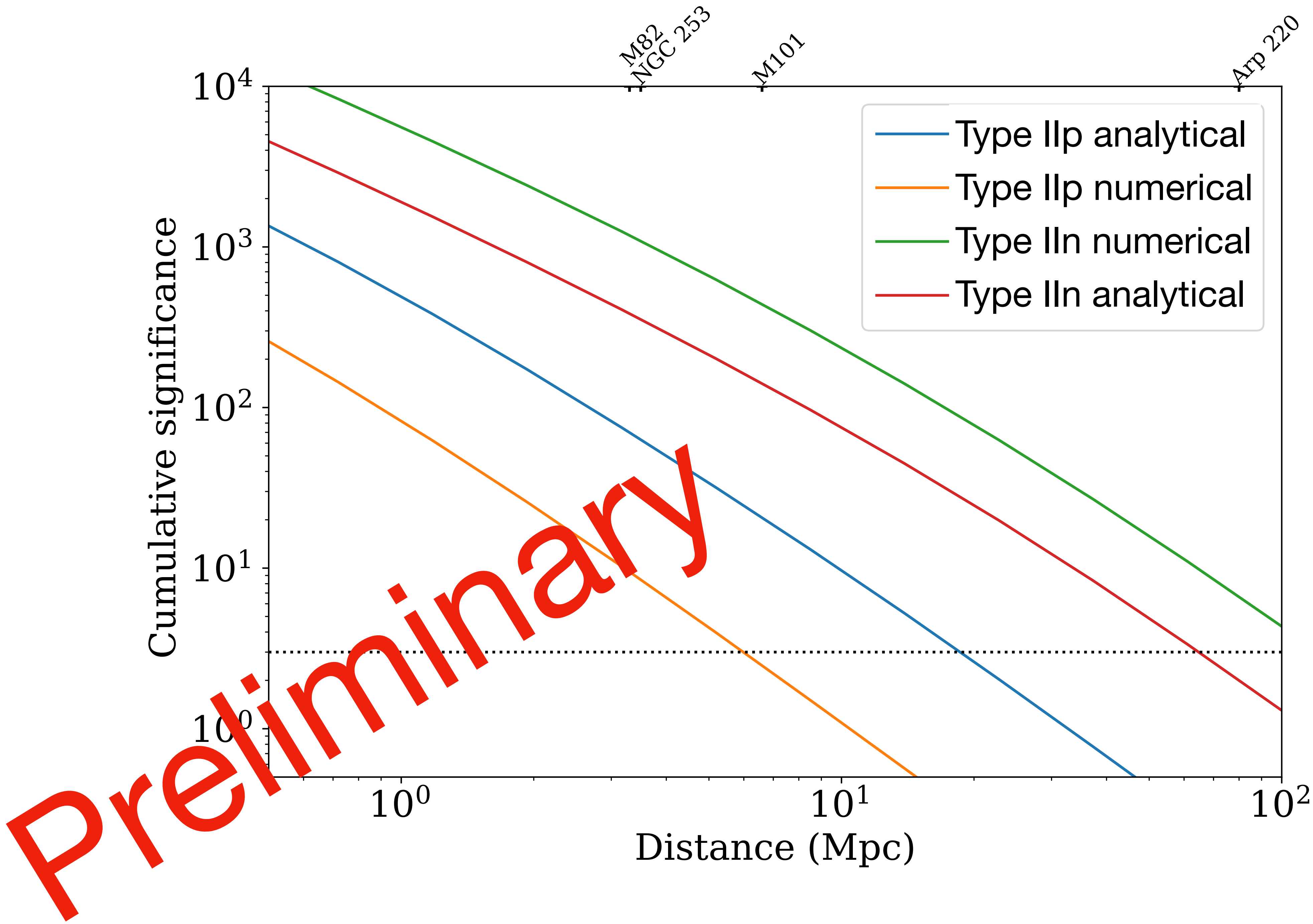
Detectability with the Cherenkov Telescope Array Observatory (CTAO) 50 hours



Summary: Particle acceleration at supernova remnants

LHAASO: almost zero, or zero SNR pevatron
MeerKAT, SKA: incredible resolution
JWST: (incredible resolution) emission from CSM, SN ejecta, 1987A
IXPE: structure of magnetic fields at SNR shocks (parallel/oblique)
Various theoretical works taking into account the SNR environment (clumps/clouds, massive star bubbles, etc.)

CTAO