MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

On the acceleration of galactic cosmic rays

Brian Reville (MPIK)

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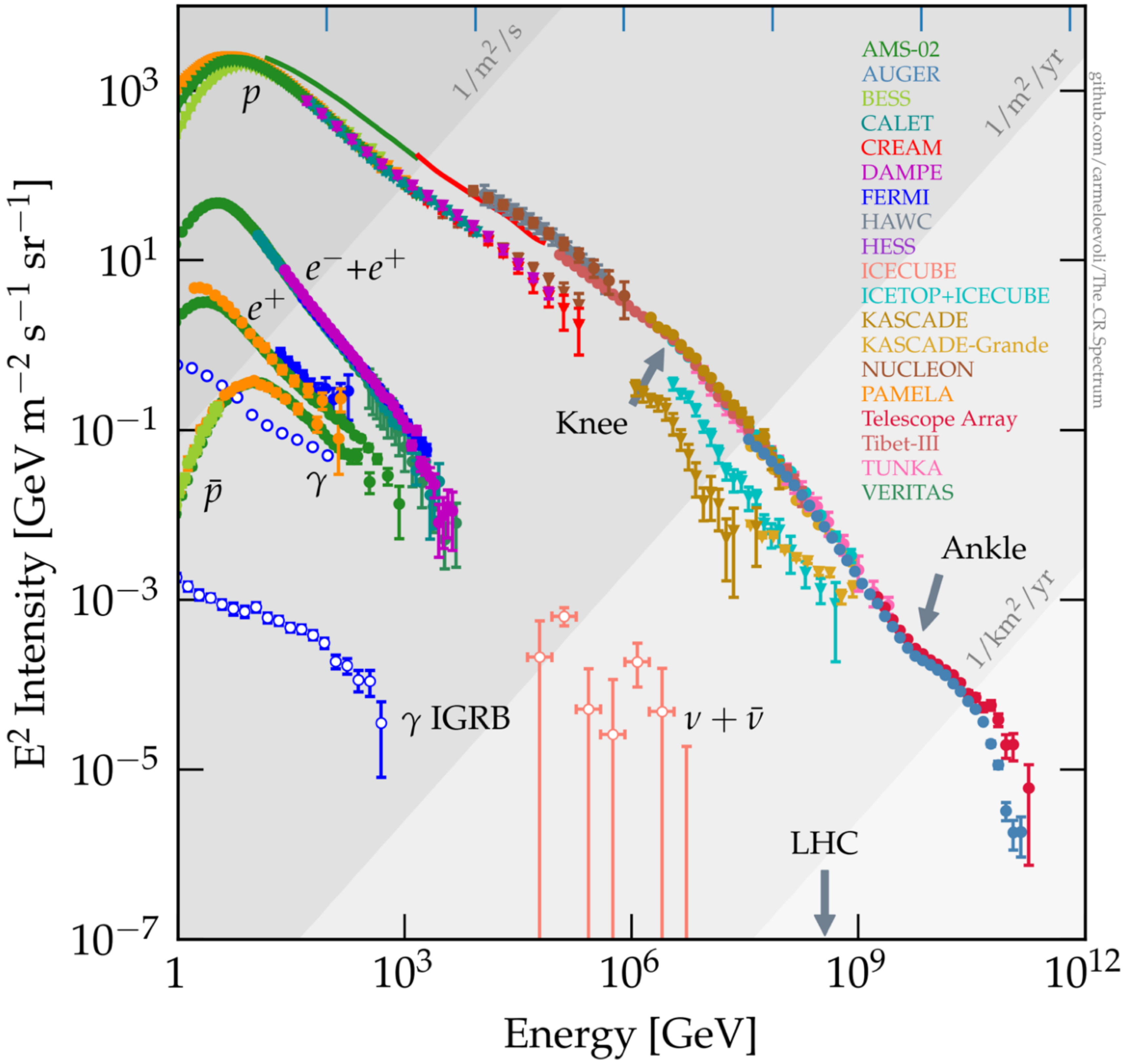
γ 2024

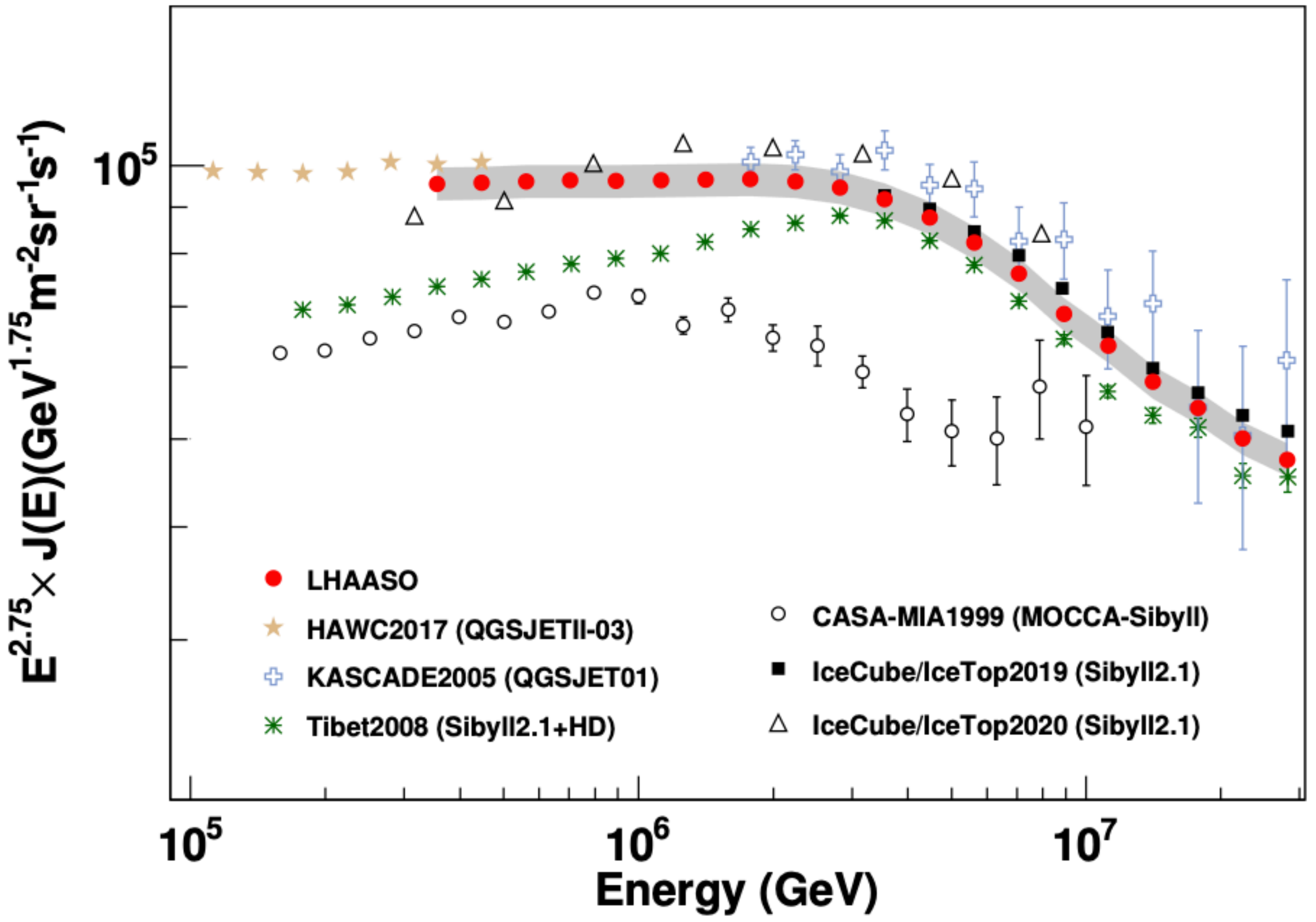
8th Heidelberg International Symposium on
High Energy Gamma Ray Astronomy
Milano, 2-6 September 2024

WHERE THERE'S SMOKE THERE'S FIRE....

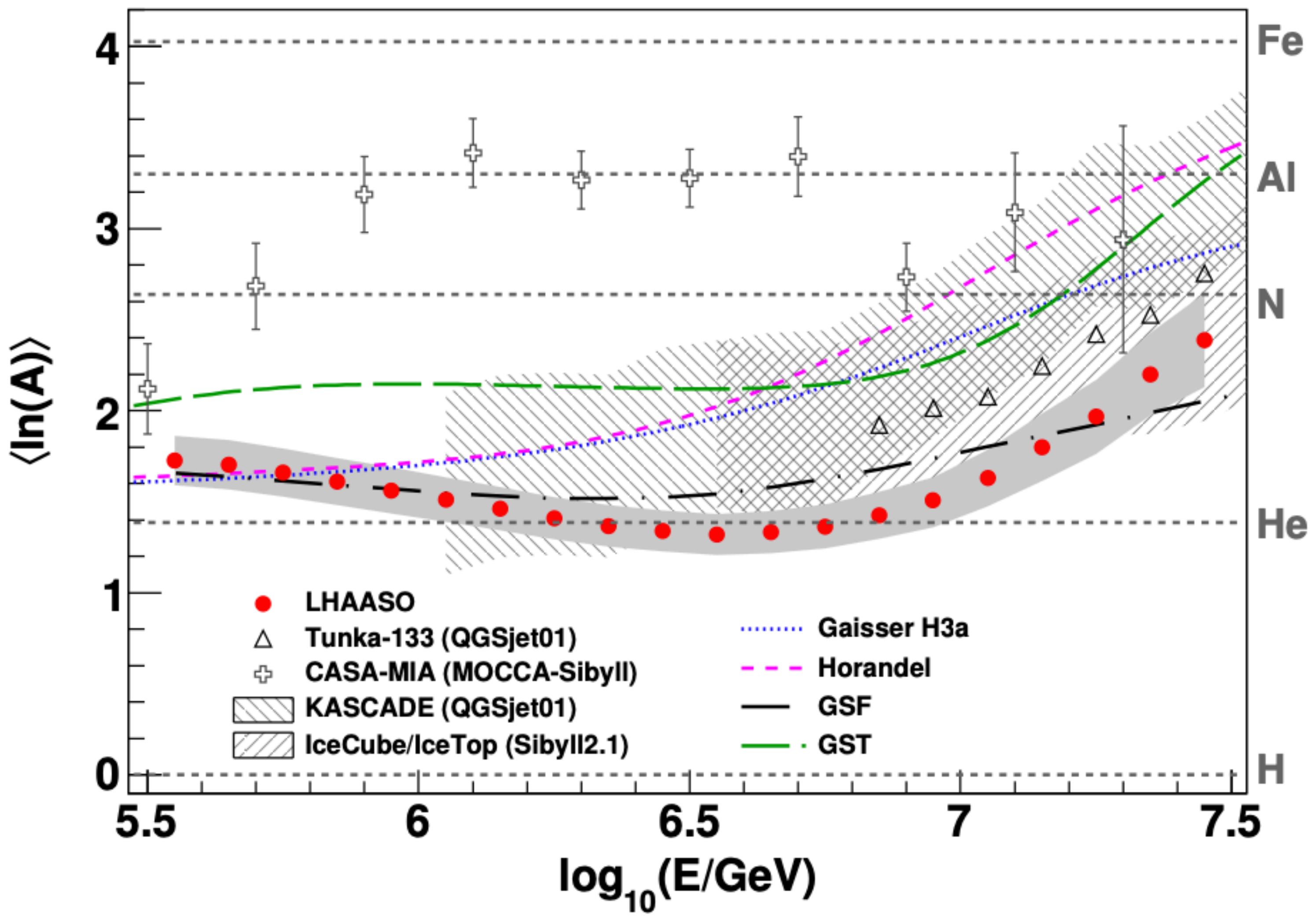
The spectrum of Cosmic rays measured at Earth



Credit: C. Evoli



LHAASO Coll., 2024
Zhen Cao's talk



Observations attacking the knee from multiple angles

GENERAL CR ACCELERATION CONSIDERATIONS

What distinguishes thermal and non-thermal phenomena?

Injection & feedback

What determines the shape of the non-thermal population?

Large dynamic range. Do GeV particles replicate physics of TeV, or PeV…?

What determines the maximum energy?

It is not guaranteed that a particle reaches maximum potential across source

Is maximum energy limited by time / geometry / losses / escape ?

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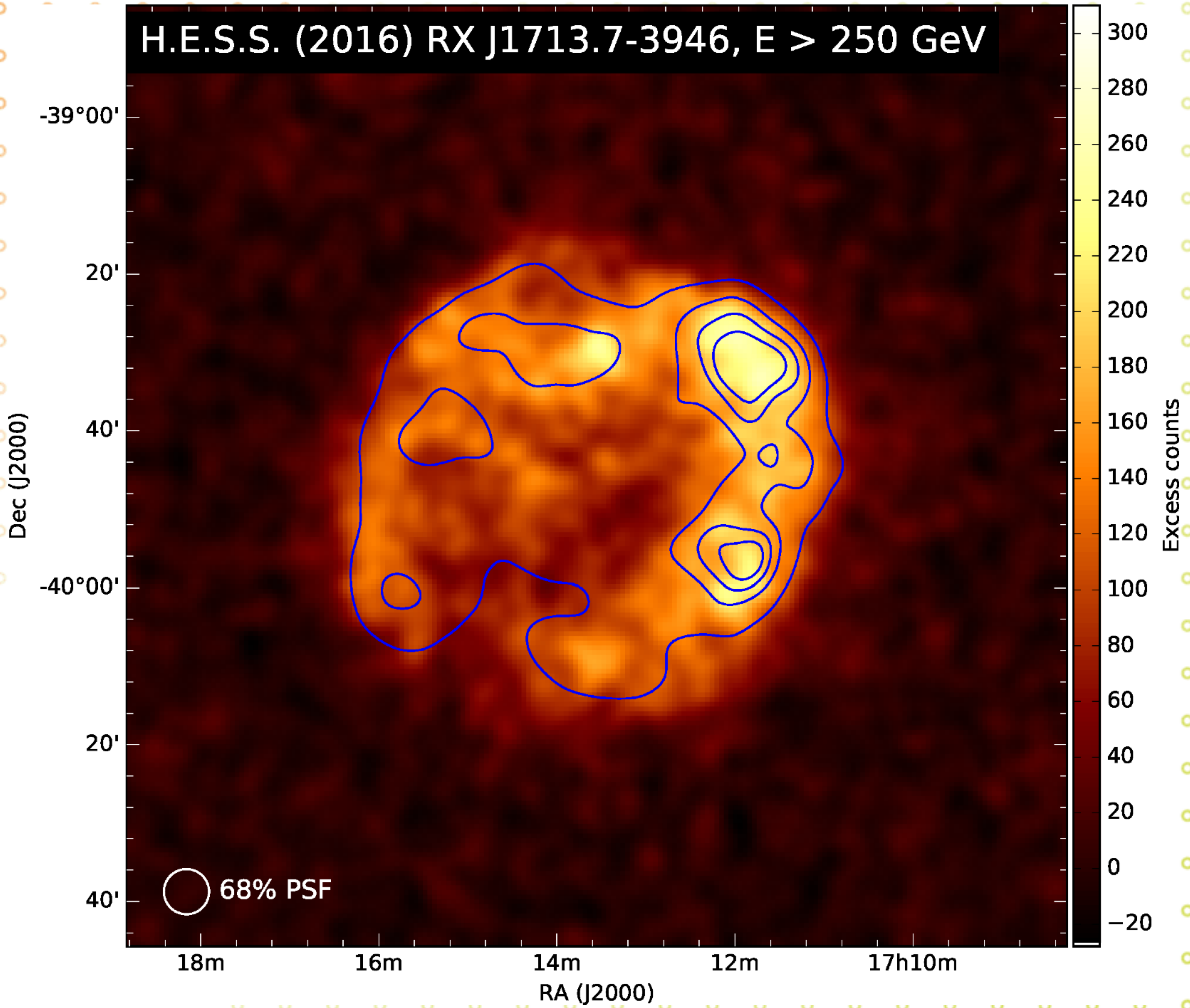
1. Particle Acceleration

2. Is magnetic field amplification still relevant?

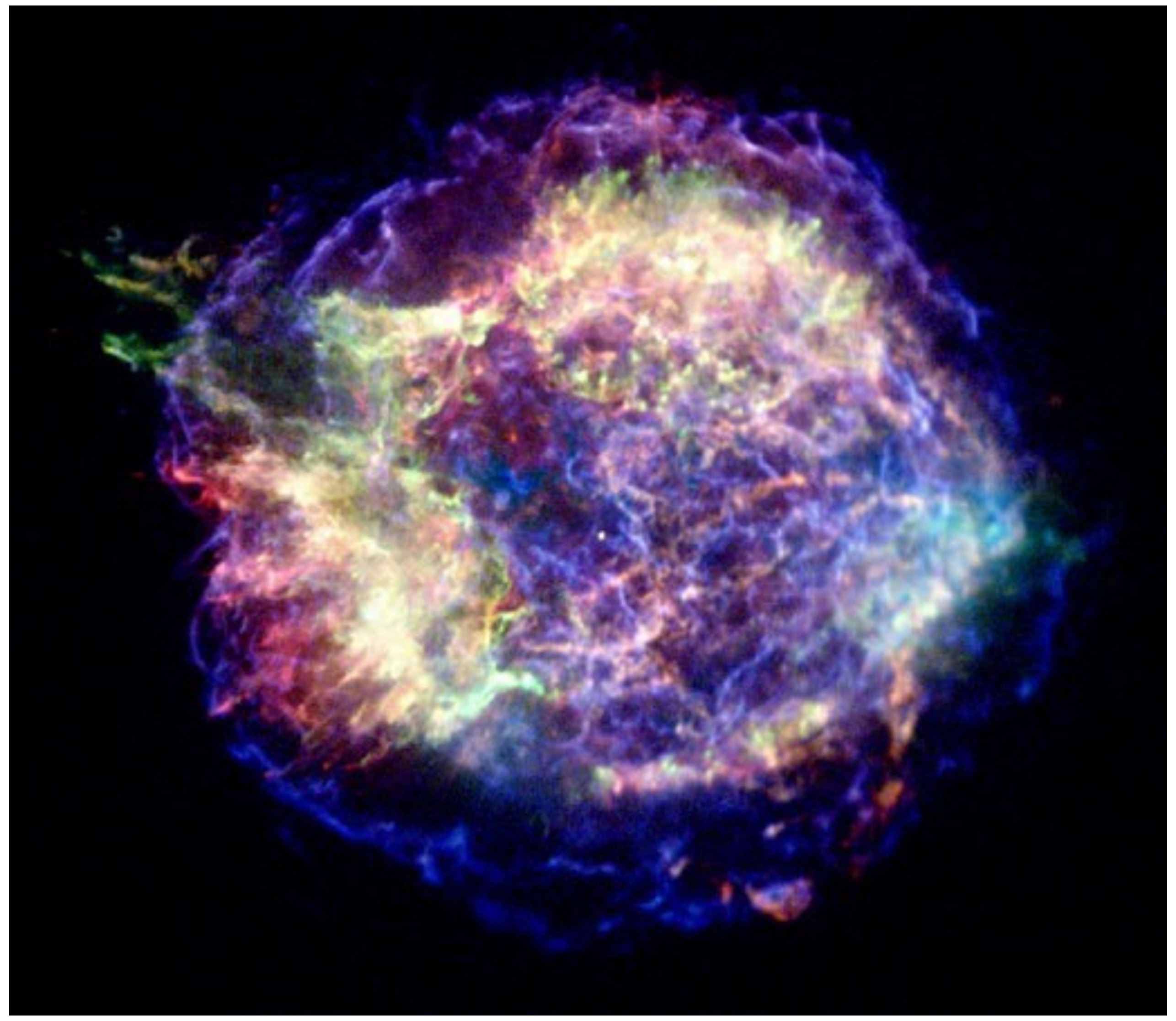
3. Some recent observational highlights

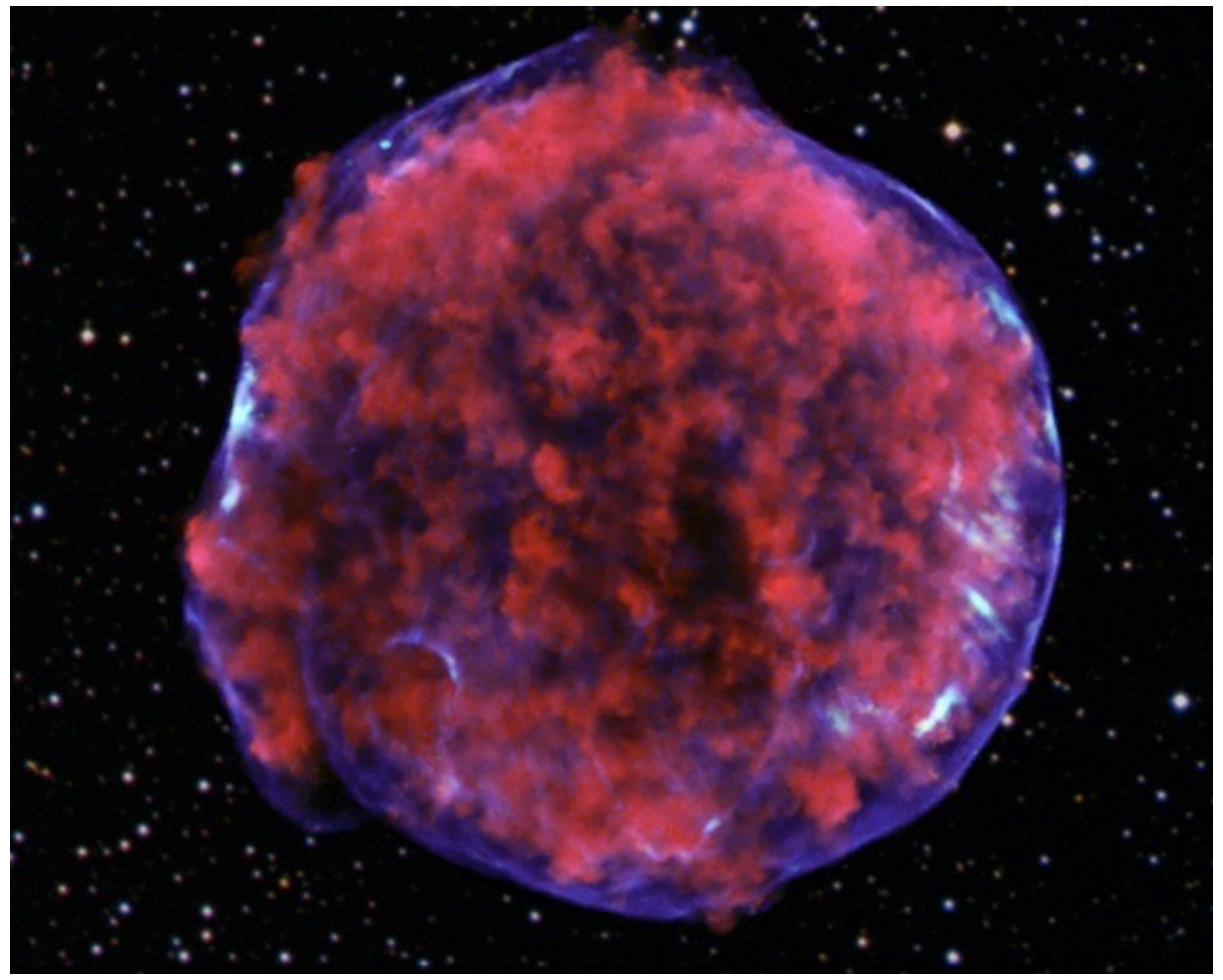
CAN WE SAY WE UNDERSTAND THIS?



(H.E.S.S. Collaboration 2018)

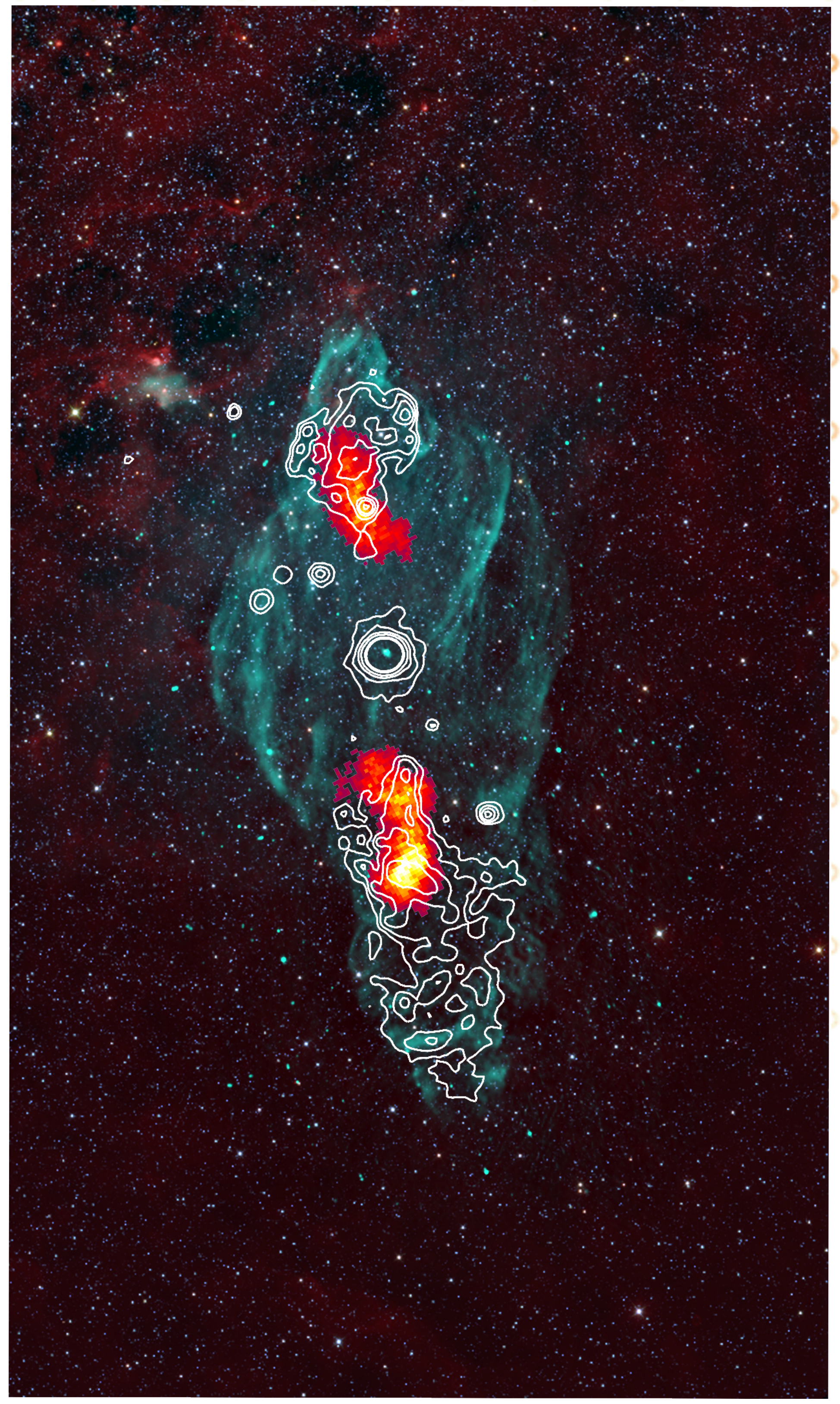
OR THESE….



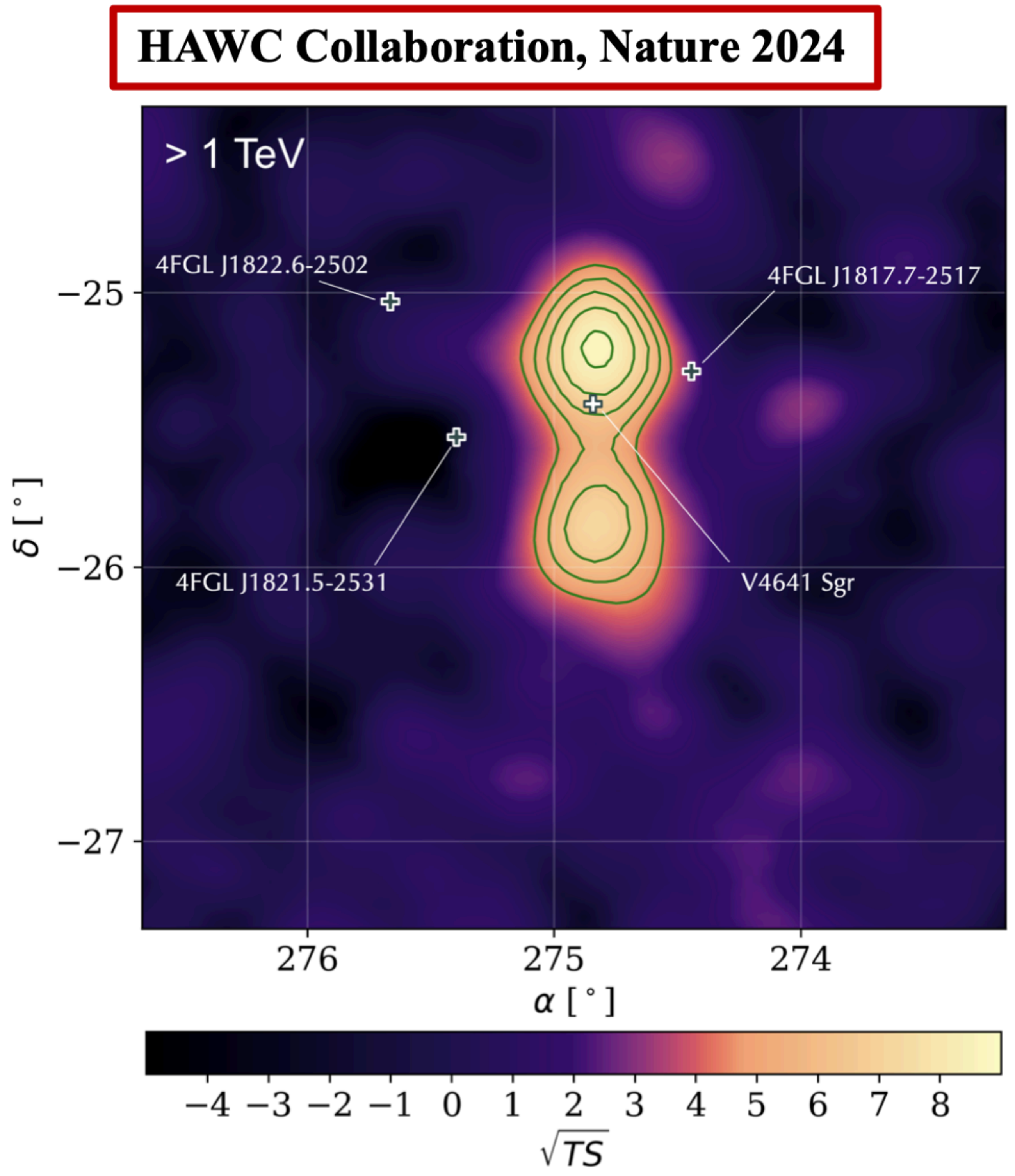


(H.E.S.S. Collaboration 2018)

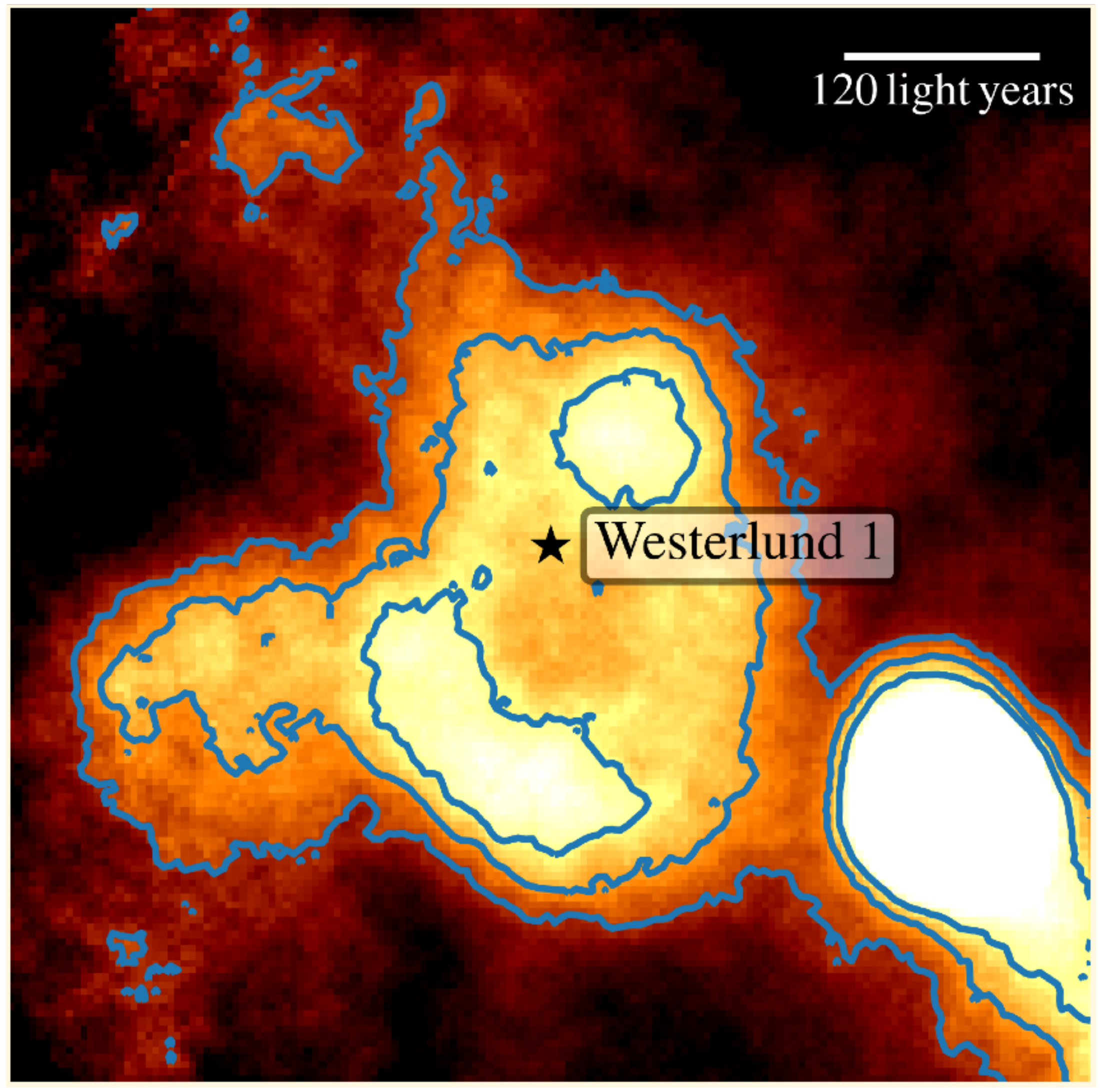
OR EVEN THESE….



SS 433
(HESS Coll. '24)

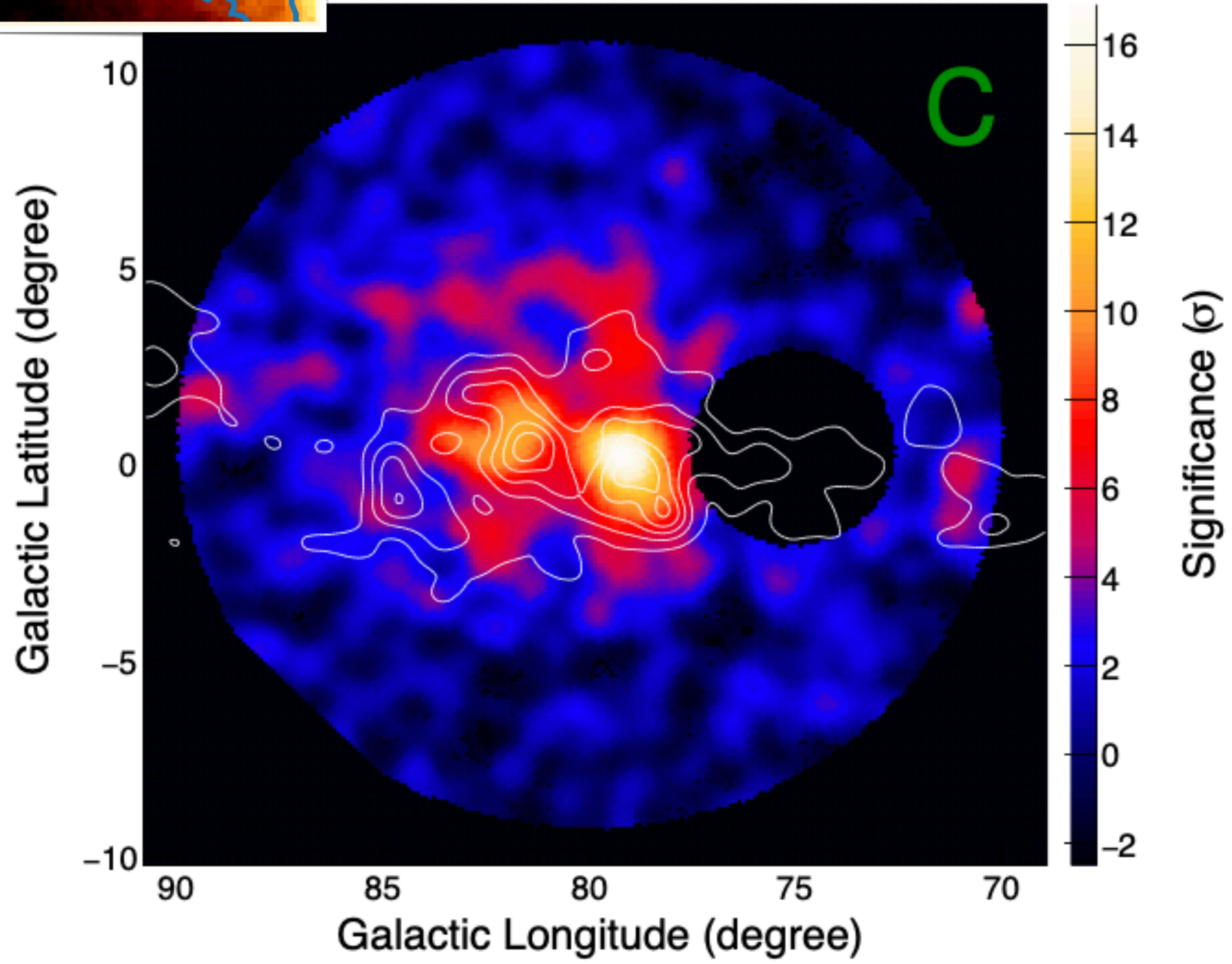


V4641 SGR. Sabrina's Talk



HESS J1646-458
(HESS Coll. '22)

Cygnus region
(LHAASO Coll. '24)
Ruizhi & Thibault's Talks



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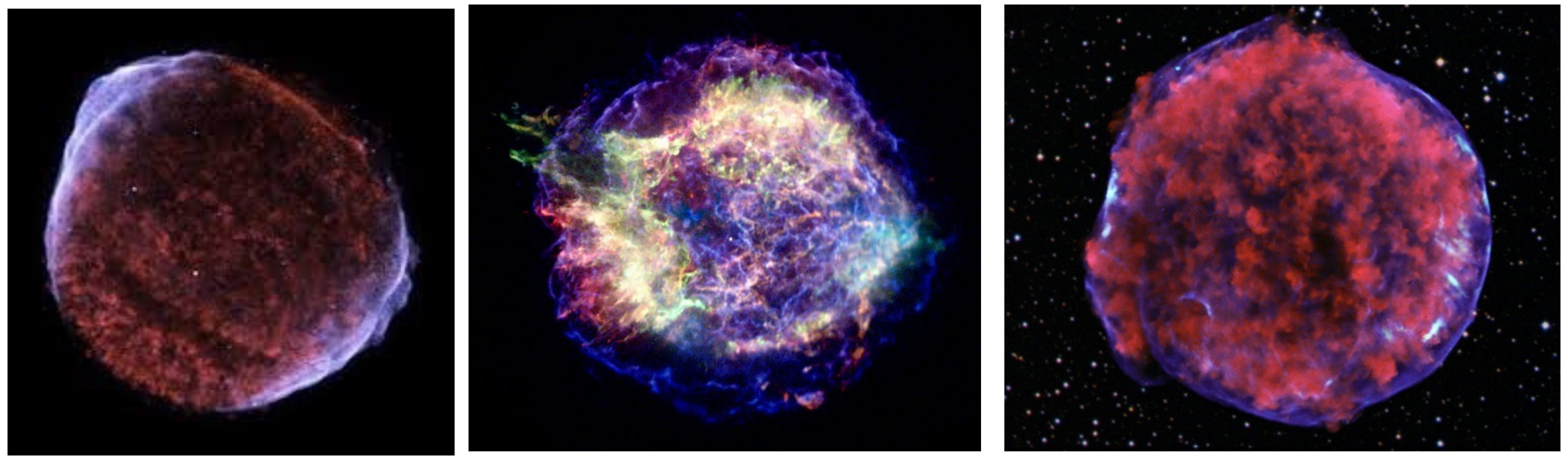
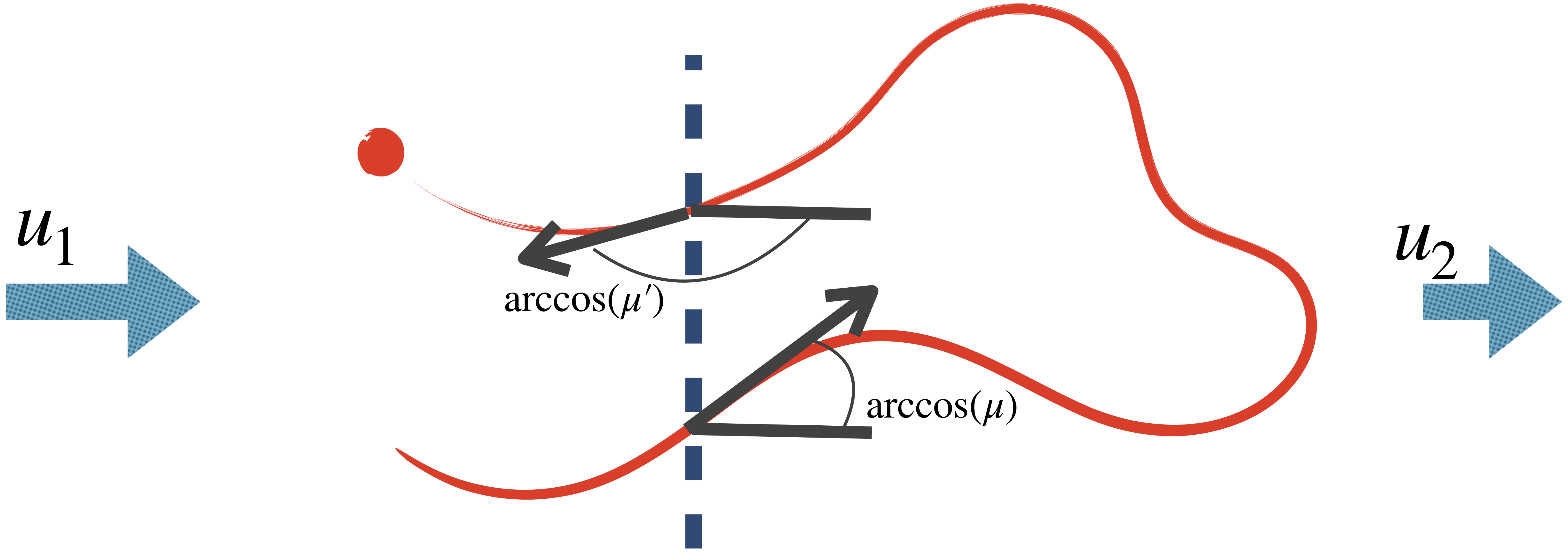
THE CASE FOR DSA IN SNRS



Credit:NASA

a) We see their non-thermal emission

b) Observations agree “nicely” with theory of diffusive shock acceleration



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

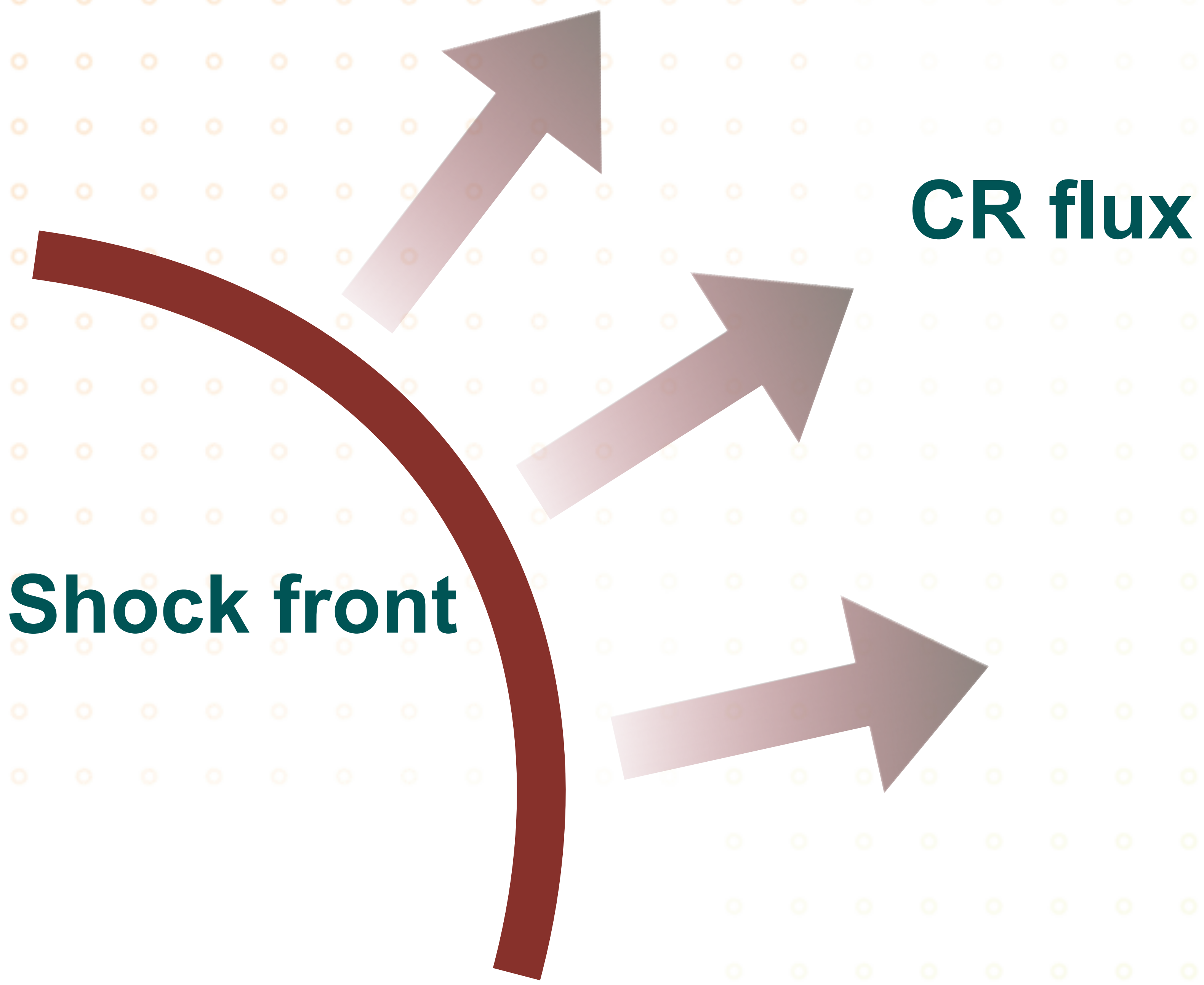
$$\frac{\partial \ln f_0}{\partial \ln p} = -\frac{3(u_1/u_2)}{(u_1/u_2)-1} \approx 4$$

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

So what’s the problem(s)?

OPEN ISSUES

Acceleration must be efficient (~10% of SNR's energy OVER ITS LIFETIME)



Pressure gradient ahead of shock does work on external medium

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

Feedback unavoidable:

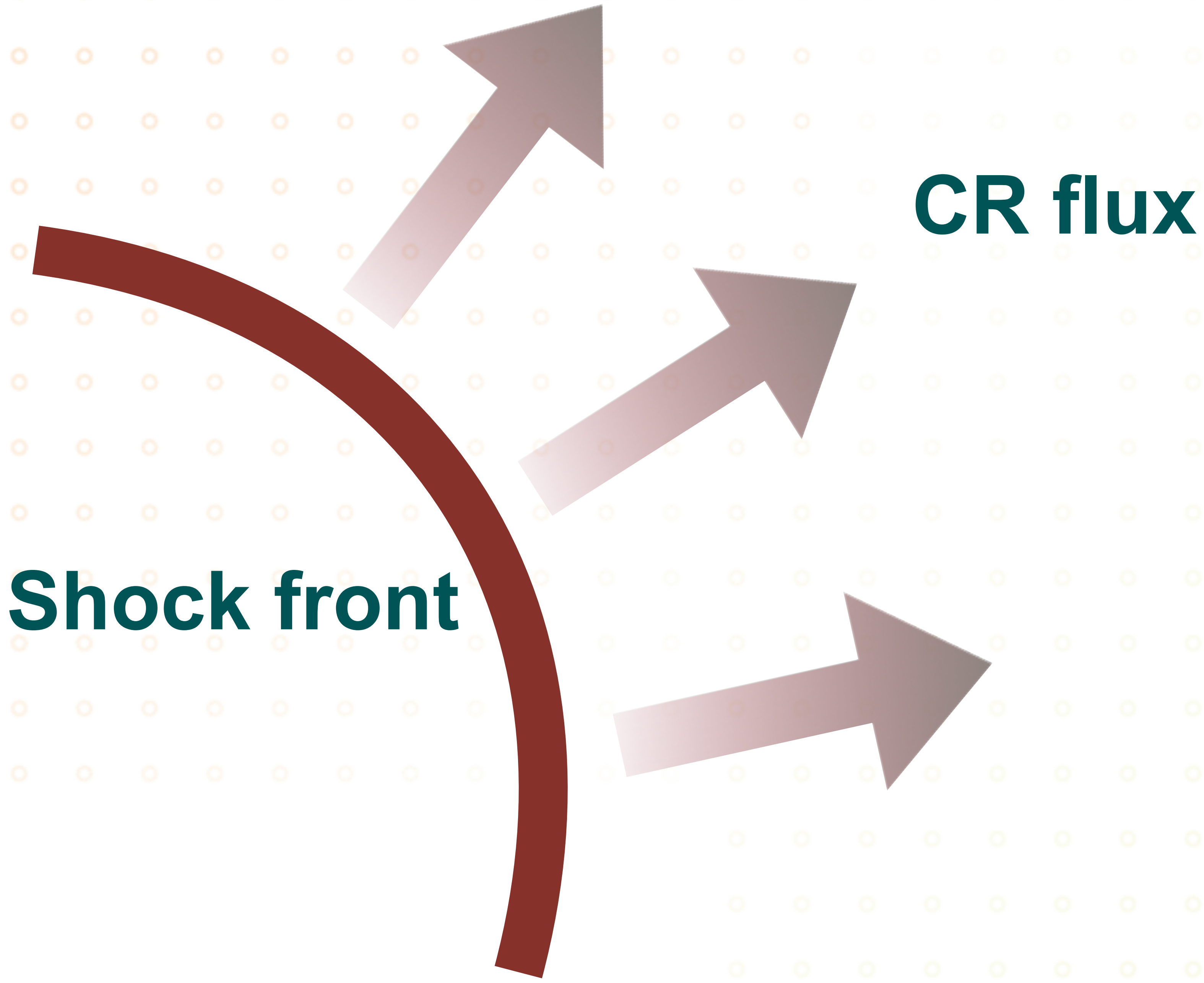
Hydrodynamic (Eichler 79, Blandford 80, Drury & Volk 81, Bell 86, Malkov 97 etc.)

Hydromagnetic: (Bell 78, McKenzie & Volk 82, Lucek & Bell 00, 01, Bell 04, 05 etc.)

Broadly supported by kinetic simulations (*caveat emptor*)

OPEN ISSUES

What are the essential ingredients of a “complete” model?



Consider for example Cassiopeia A:

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

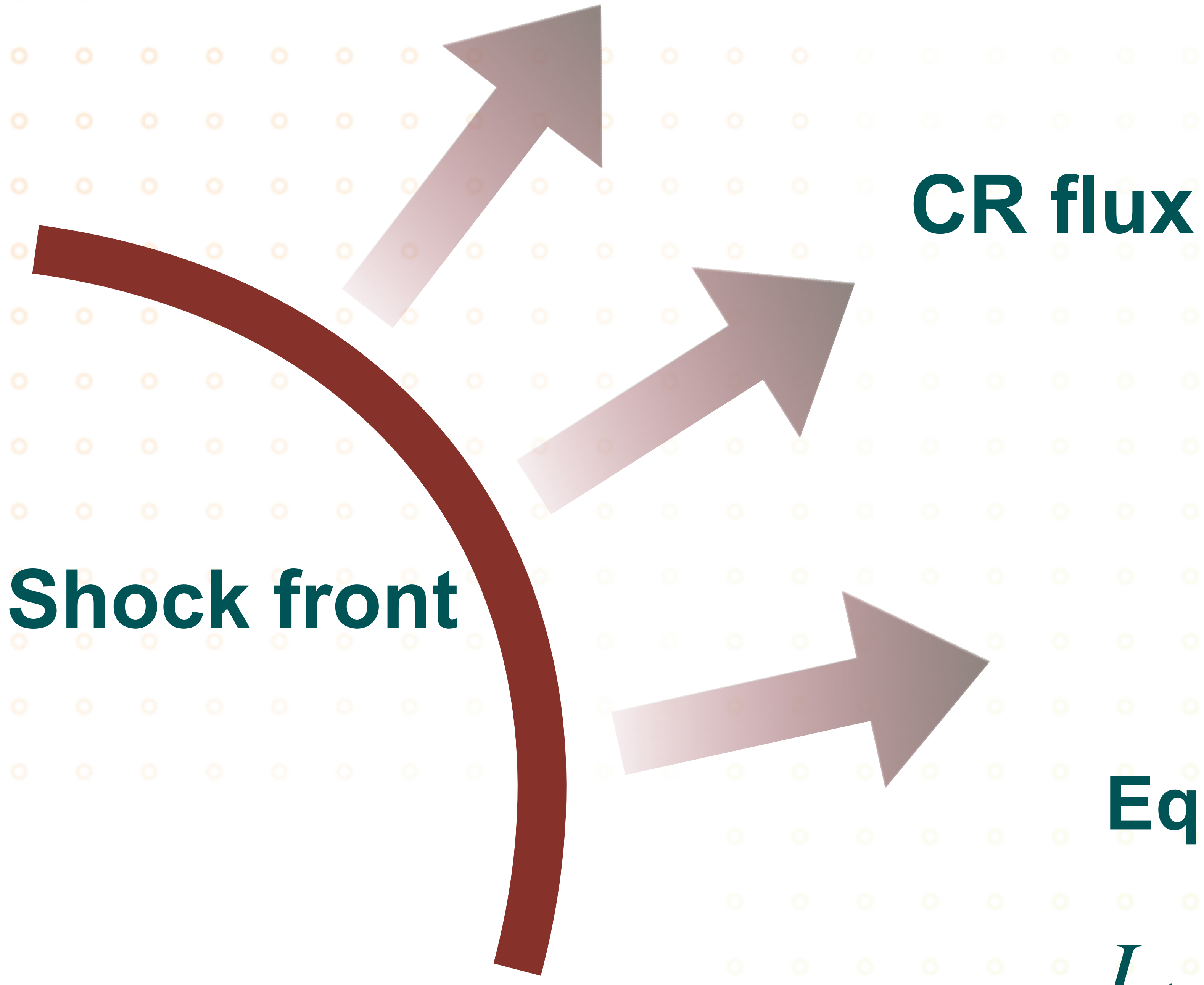
$r_g\ /\ (c/\omega_{\mathrm{pe}}) \approx 10^5$

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

It is INEVITABLE that intense microscale magnetic fluctuations are present in the shock vicinity.

OPEN ISSUES

What are the essential ingredients of a "complete" model?



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 $t_{\rm dyn} = \dfrac{R_{\rm sh}}{u_1}$

$L_1 \gtrsim 0.1 R_{\rm sh}$ **indep. of the scattering assumptions.**

Note, precursors are in principle visible at highest energies in resolvable sources.

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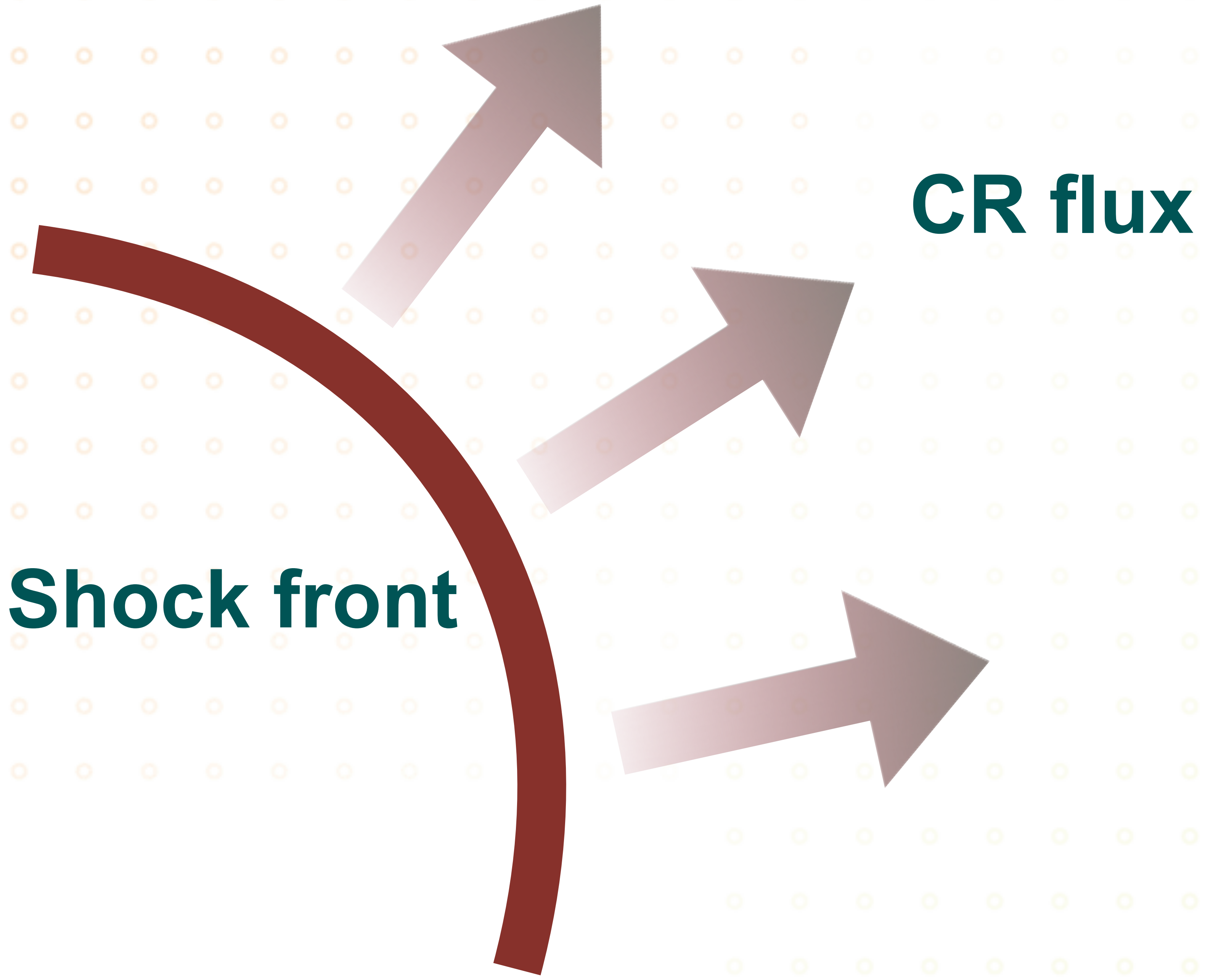
"CONVENTIONAL" "WISDOM"



Highest energy CRs are accelerated "early"

Why so ?

We need confinement.

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

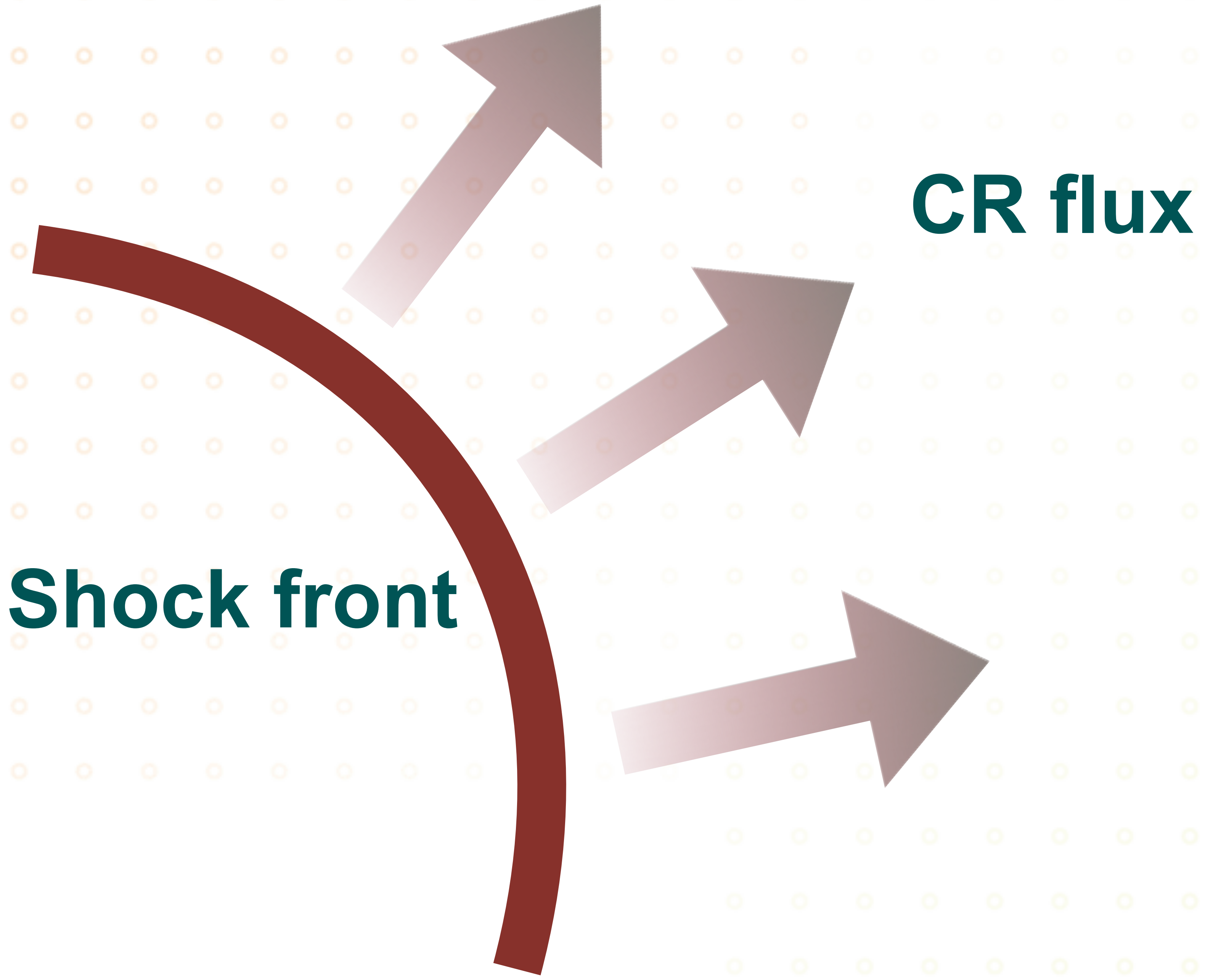
$$t_{\rm growth} \propto \frac{\sqrt{\rho}}{j_{\rm cr}} \propto \frac{\sqrt{\rho}}{\rho u_{\rm sh}^3}$$

Fast shocks in dense environments preferable

Favours CCSNR shocks in dense winds of RSG progenitor.

Maximum energies $\gtrsim$ PeV are predicted in favourable conditions.

“CONVENTIONAL” “WISDOM”



Highest energy CRs escape “early”

Why so ?

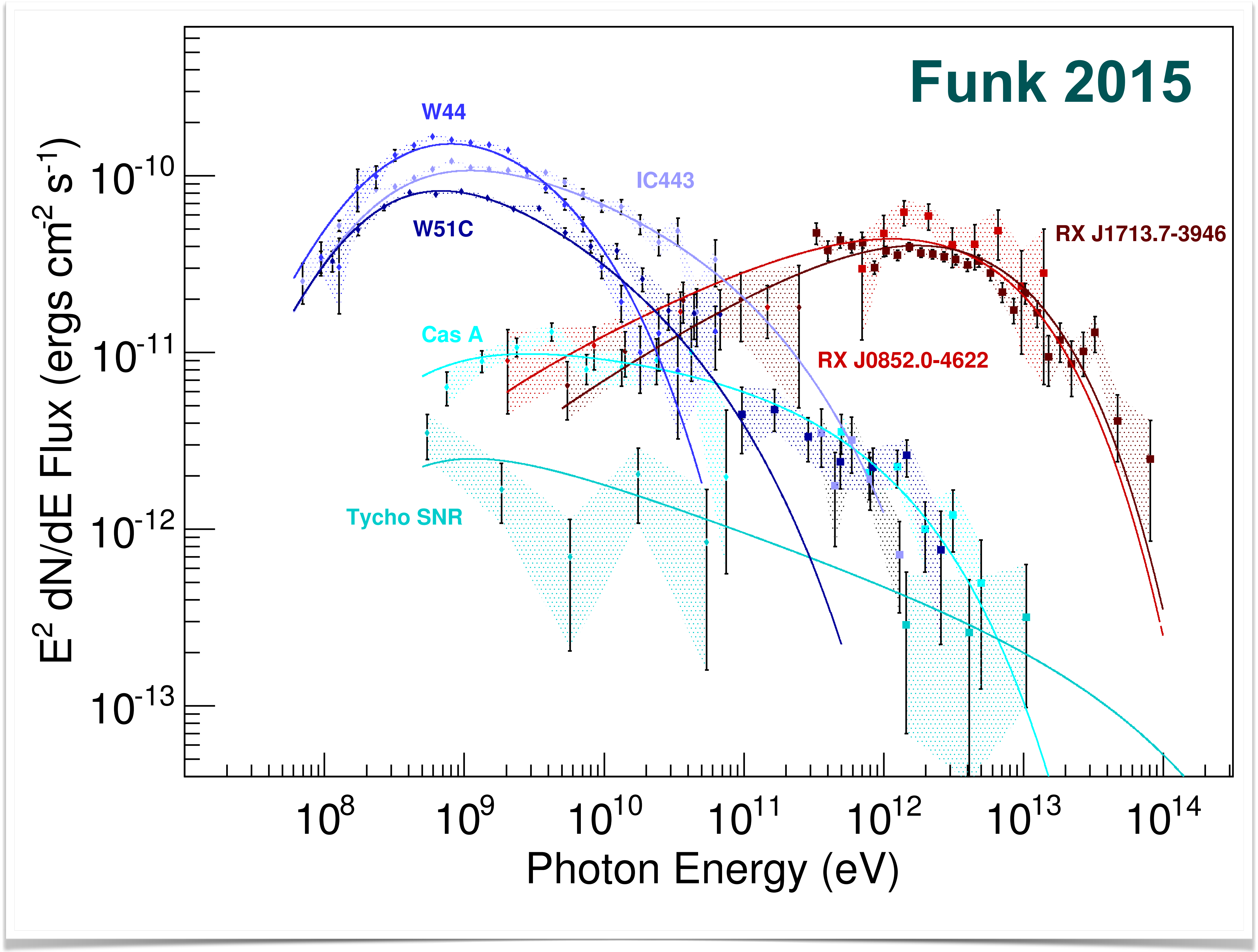
Particles at $E_{\max}$ not effectively scattered

If $v_r > 0$ escape to infinity.

But if $v_r < 0$ by same logic CRs propagate unimpeded toward centre of SNR.

Reality likely something in between. This has not been explored TMK.

THE LIMIT OF SUPERNOVA REMNANTS

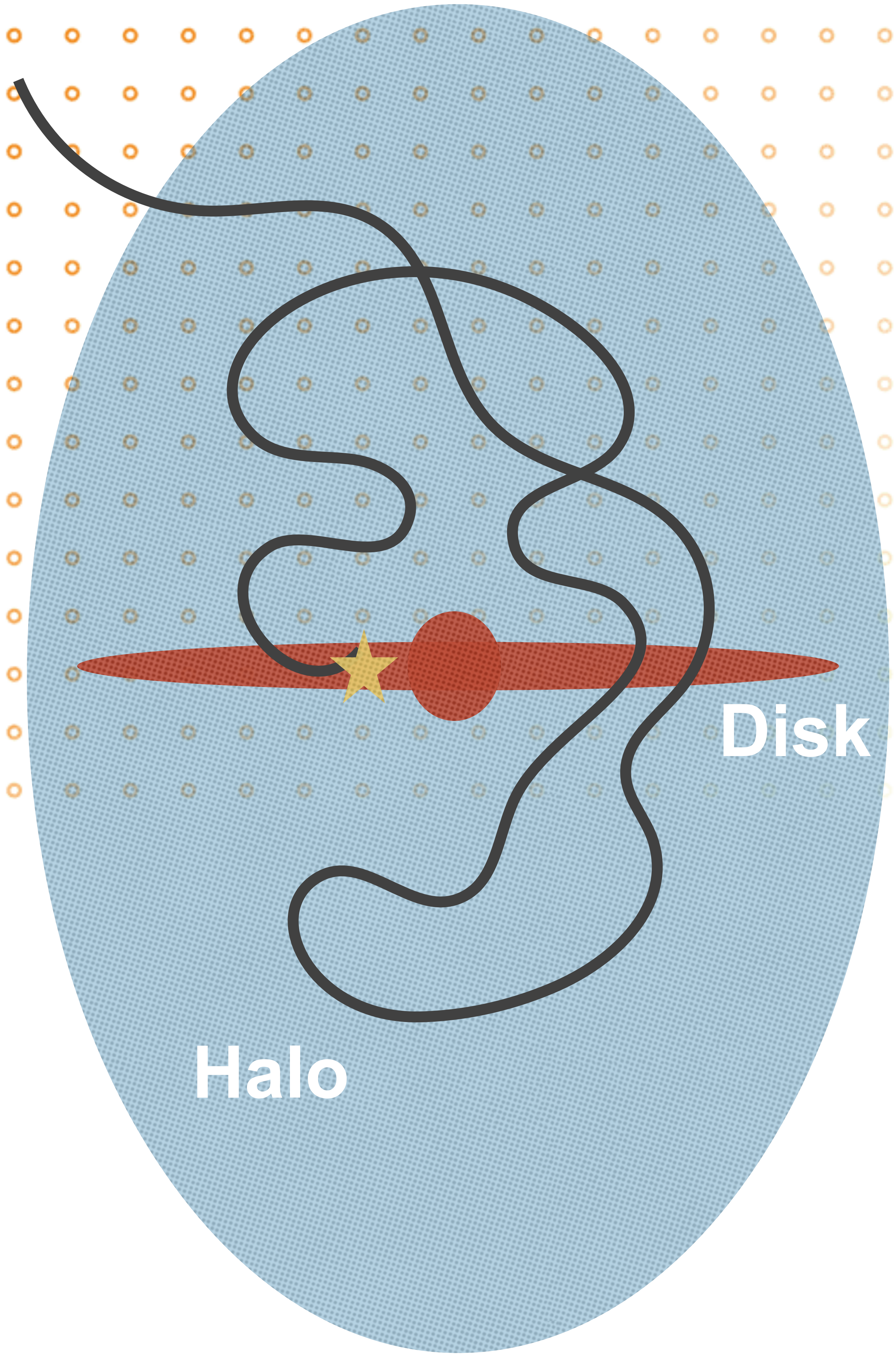


Acceleration of particles to PeV is hard (as it should be)

Are all detected supernovae past their prime?

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

SPECTRAL SIGNATURES



c.f. Sarah Recchia's talk on Monday.

Source spectrum $Q_{cr} \propto E^{-s}$

Particles escape following diffusion in the Halo $D_{cr} \propto E^{\delta}$

Spectrum at Earth $J \propto E^{-(s+\delta)}$

Naive application of MHD turbulence theory (Kraichnan or Kolmogorov) would indicate $\delta \sim 0.3 - 0.5$
See next talk (?)

Somehow we require $s \sim 2.2 - 2.4$,
steeper than the basic test-particle DSA theory

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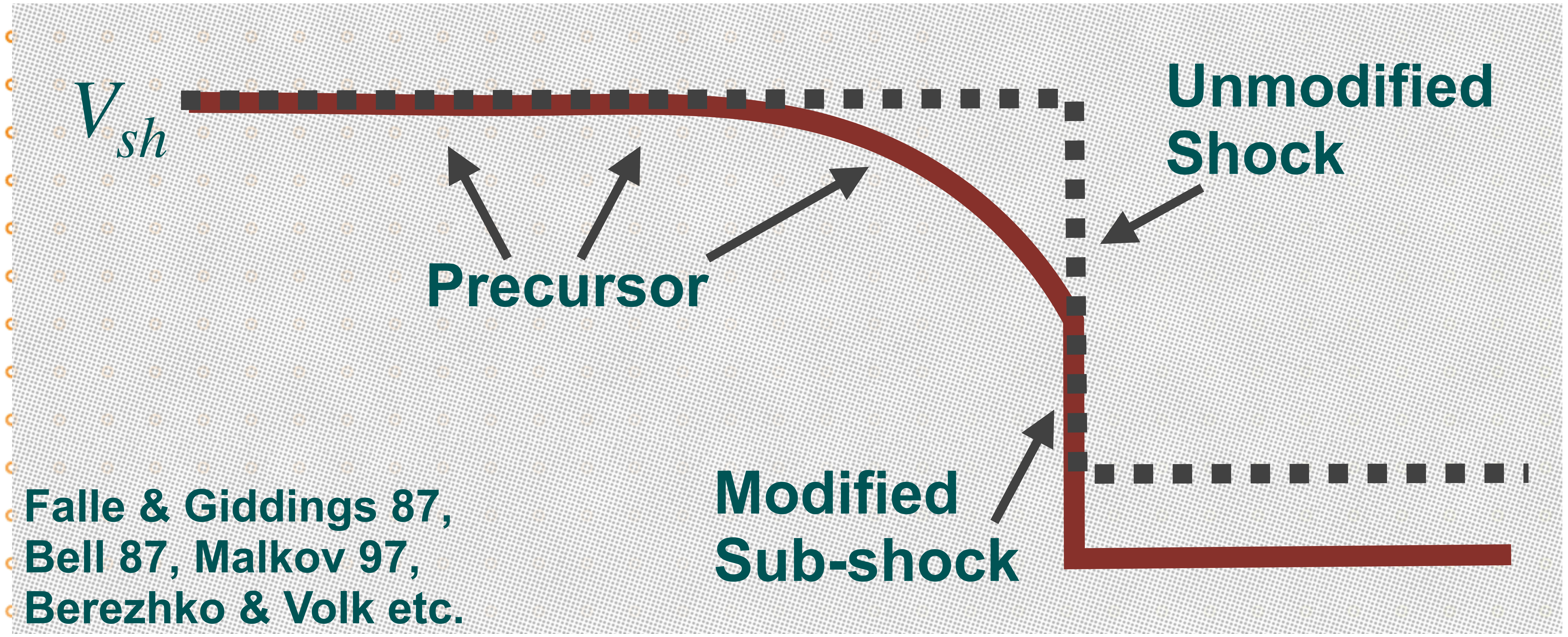
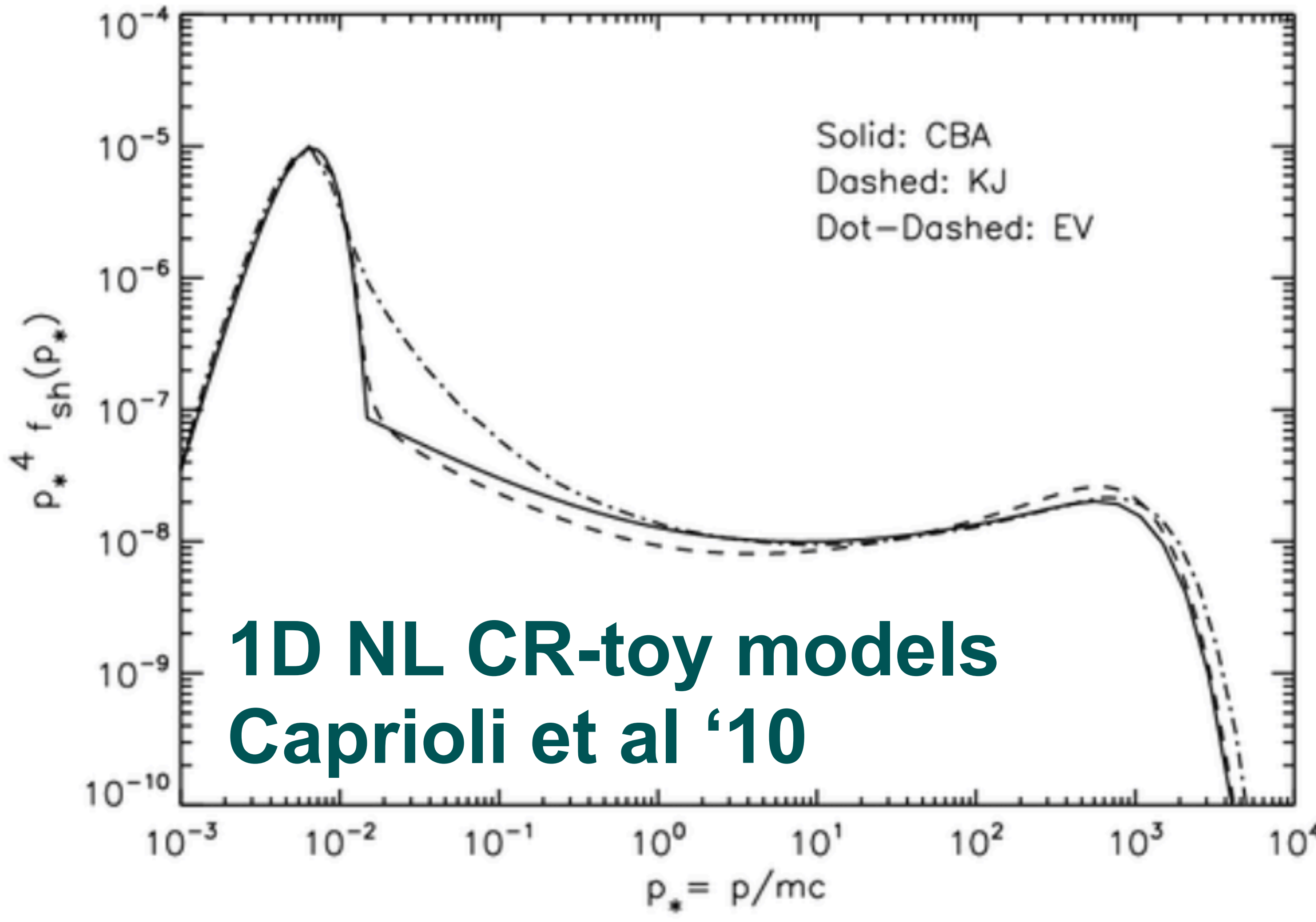
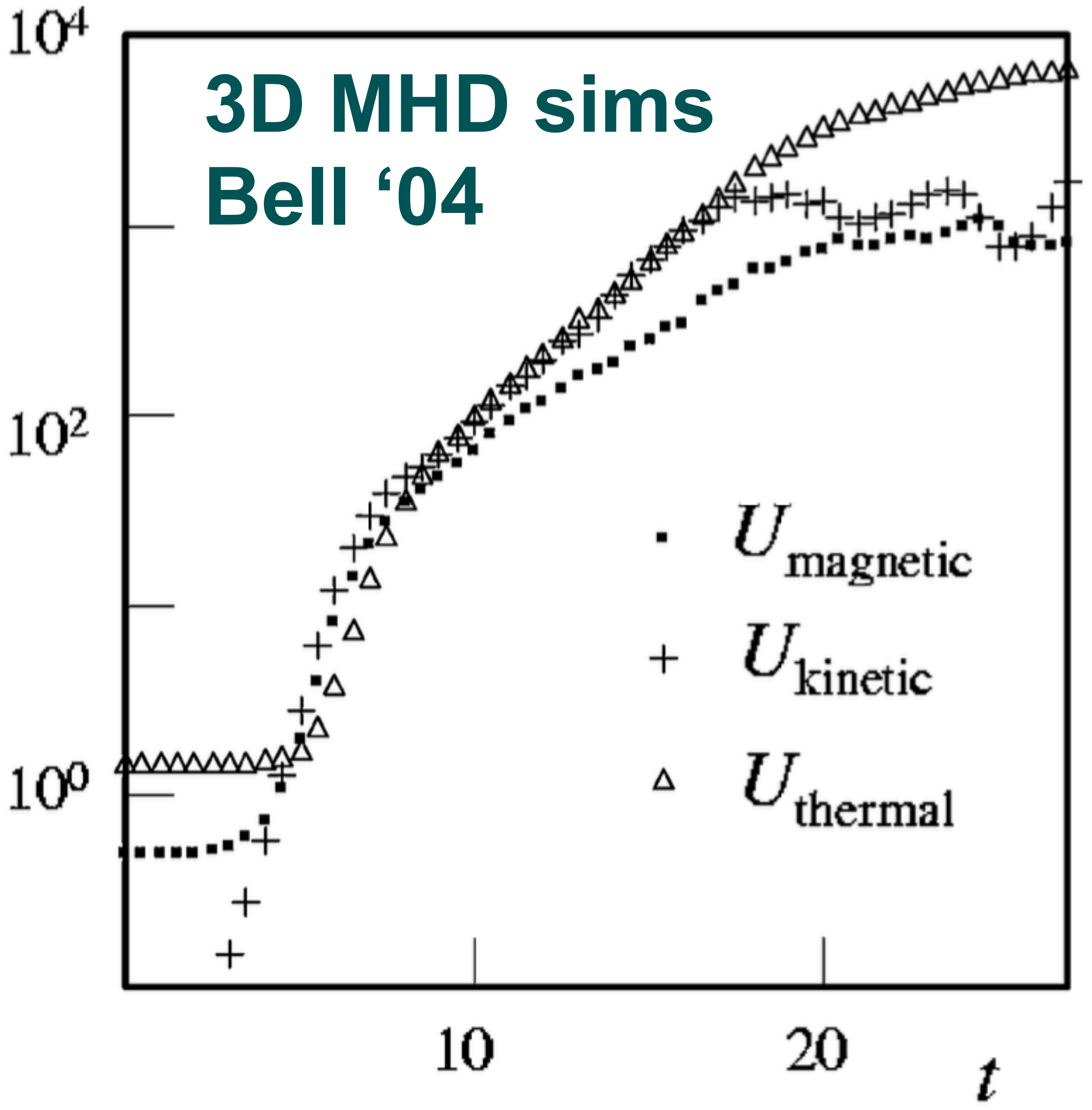
A HISTORICAL NOTE







Historical 1D linear models - Alfven waves are excited by streaming CRs
Predicts <u>hardening</u> of spectrum at high energies.

Post 2004 - CRs <u>dominate</u> plasma physics. Linear picture nots reliable.

Hierarchy of energy: Shock > CRs > Thermal > Magnetic field.

WAYS TO STEEPEN SOURCE (PROTON) SPECTRUM

A. Weak shocks (e.g. stellar cluster wind termination shocks Webb 82, Morlino 21)

B. Reduction in the relative motion of scattering centres
Virakashvili 08, Diesing 19

C. Enhanced escape downstream (trapping, non-diffusive behaviour)
Duffy 95, Bell 11

D. Energy losses upstream (e.g. in amplifying magnetic field)
Virakashvili 15, Bell 19, Pohl 21

E. Cut-off shallower than exponential

DSA has wiggle room to account for different spectra

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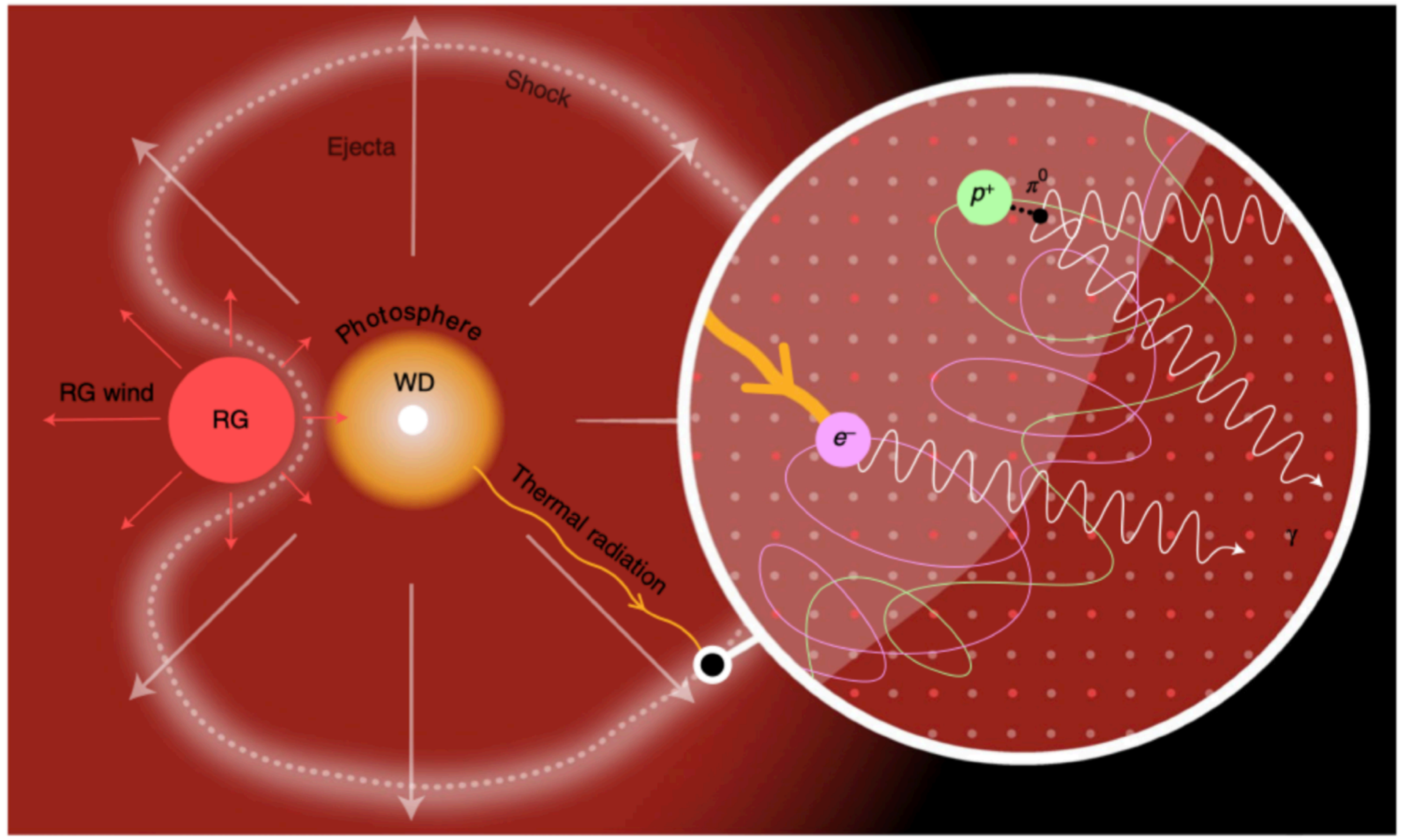
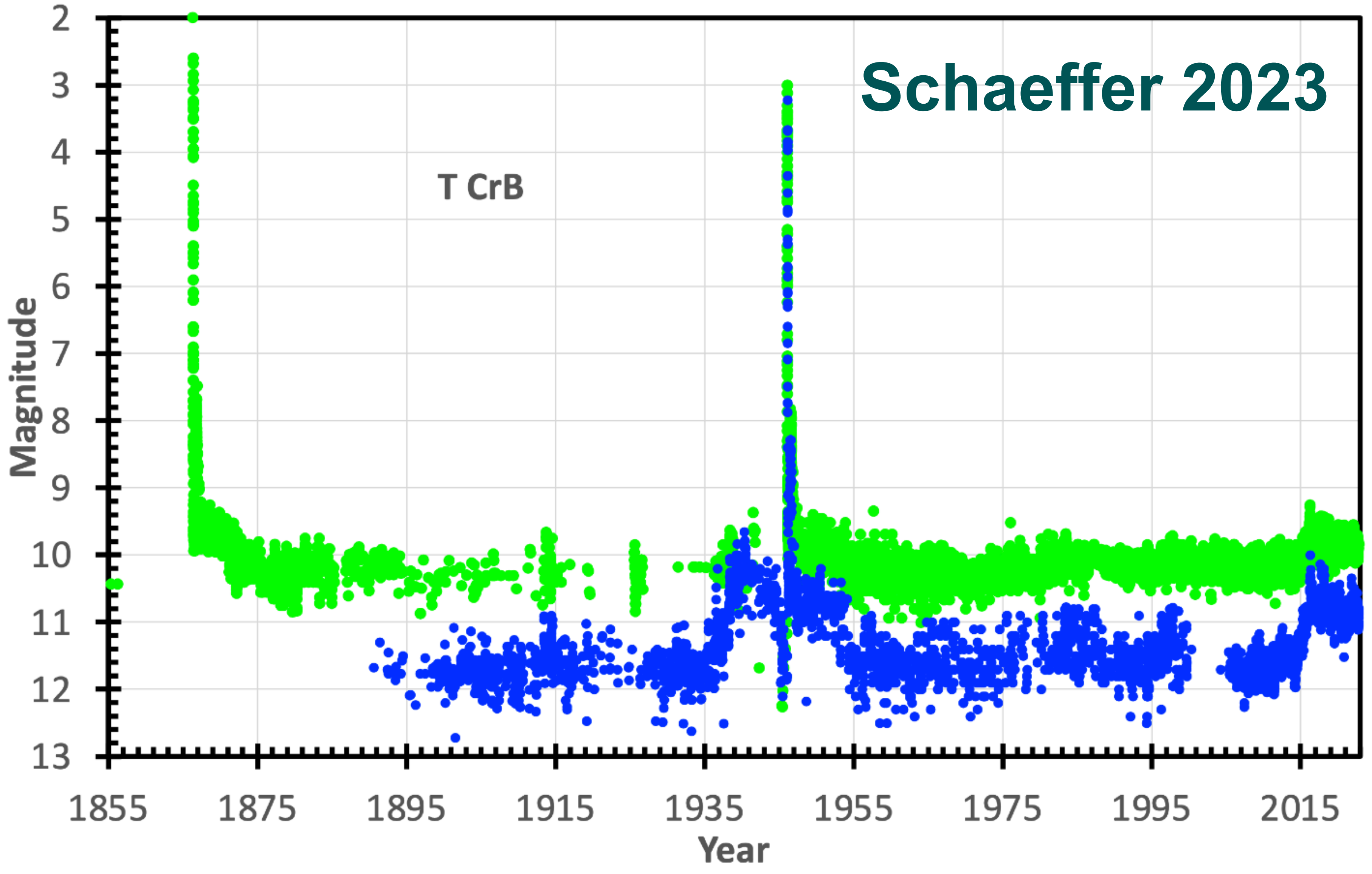
RECENT HIGHLIGHTS

First Nova explosion at VHE gamma rays
H.E.S.S. announced first detection of VHE signal *from this event on Aug10, 2021 (**ATel #14844**)*

How are the VHE gamma rays produced ?

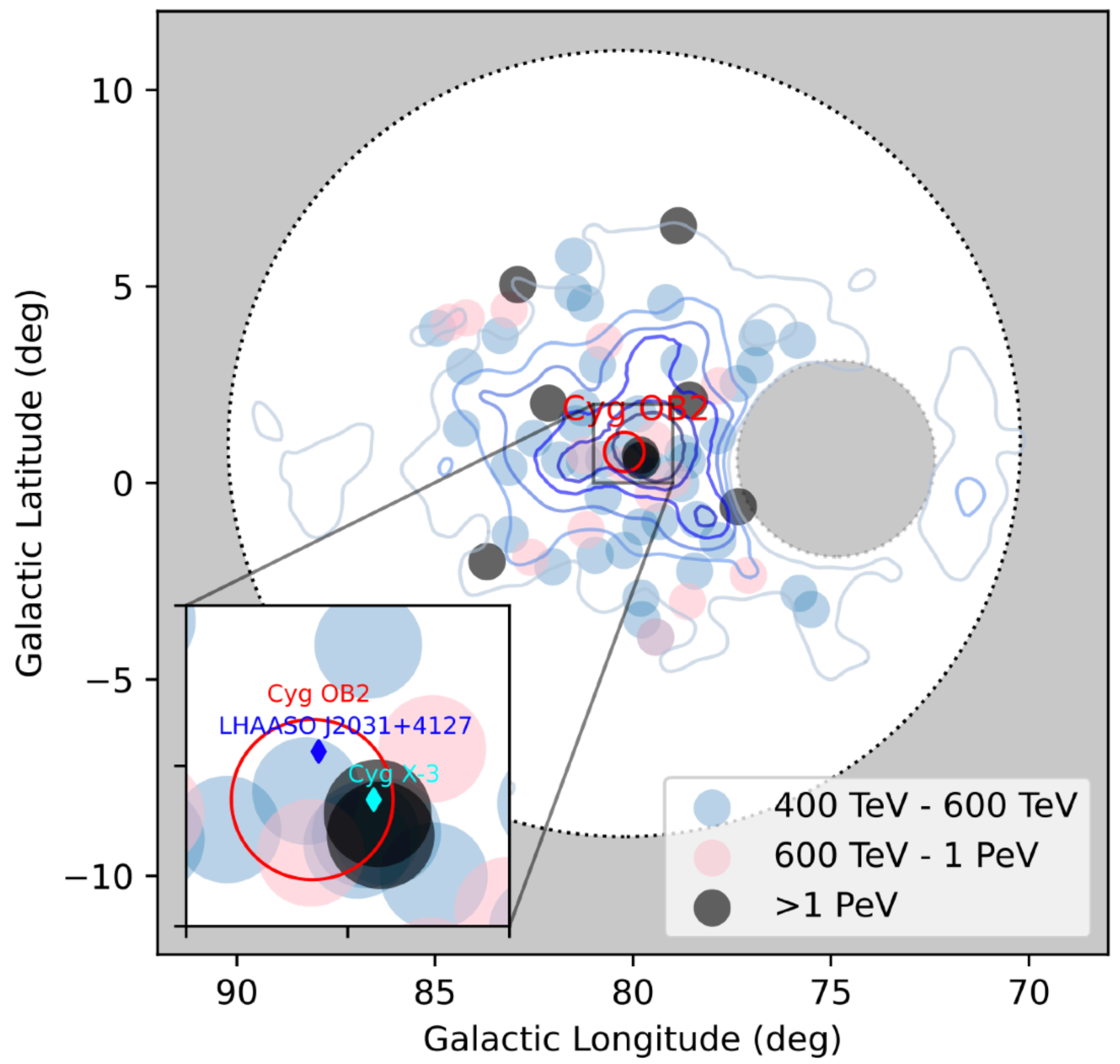




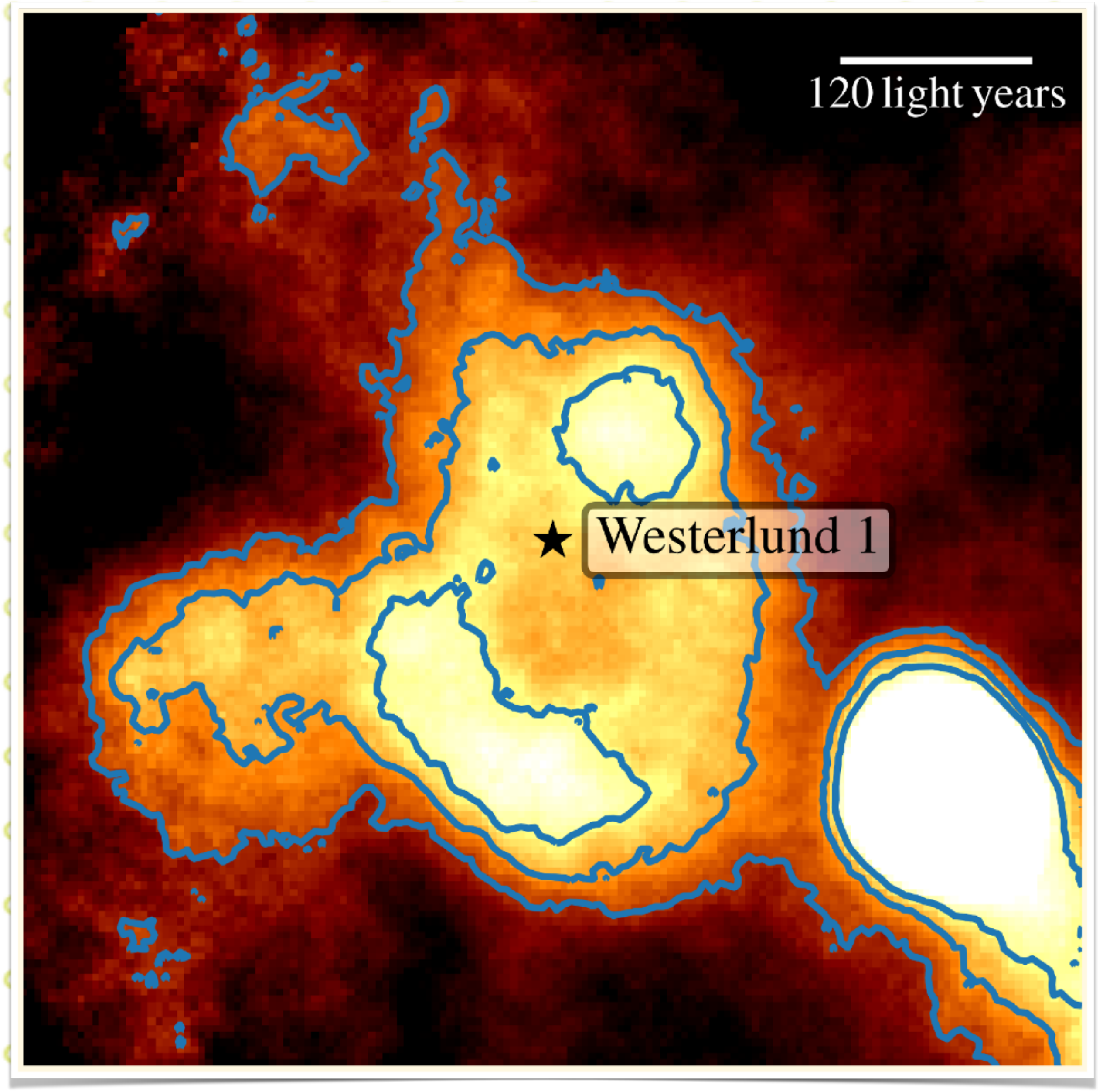
First scientific interpretations of the event: **David Paneque's talk**

Perfect laboratory for testing SNR theories in time dependent laboratory
Maximum energy predicted to be at most a few TeV, lets hope T CrB surprises us!!

RECENT HIGHLIGHTS



LHAASO Coll. 24, Ruizhi's talk



H.E.S.S. Coll. 22

Many interesting talks yesterday on γ-ray emission from stellar clusters & associations

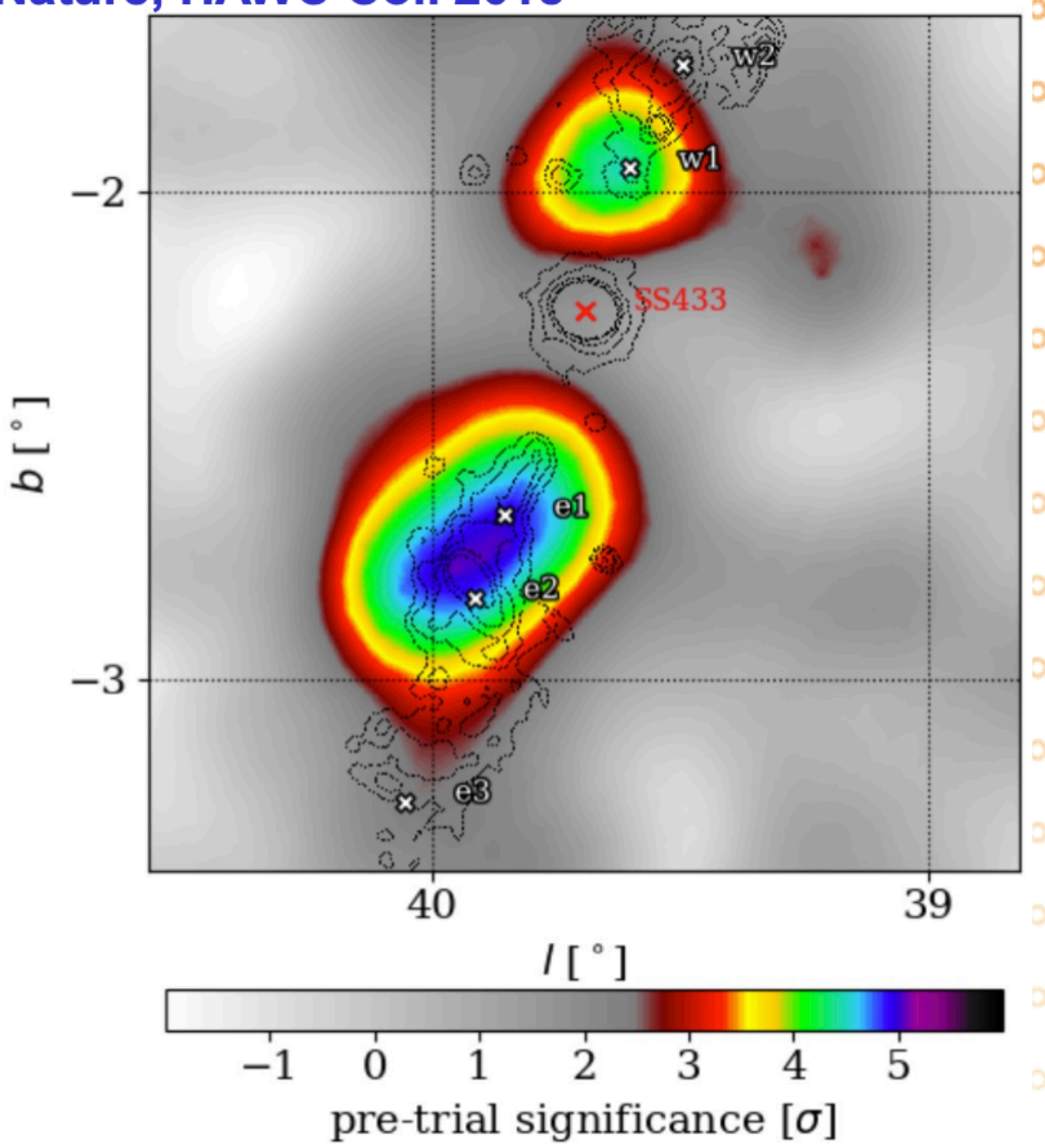
See Vieu 22, 23, 24a, 24b for detailed discussion on limits of sources and acceleration
Haerer et al. 23 for Wd1 and Thibaults talk yesterday for Cygnus region

Bottom line : the only plausible <u>>PeV proton accelerators</u> in these sources are SNRs.

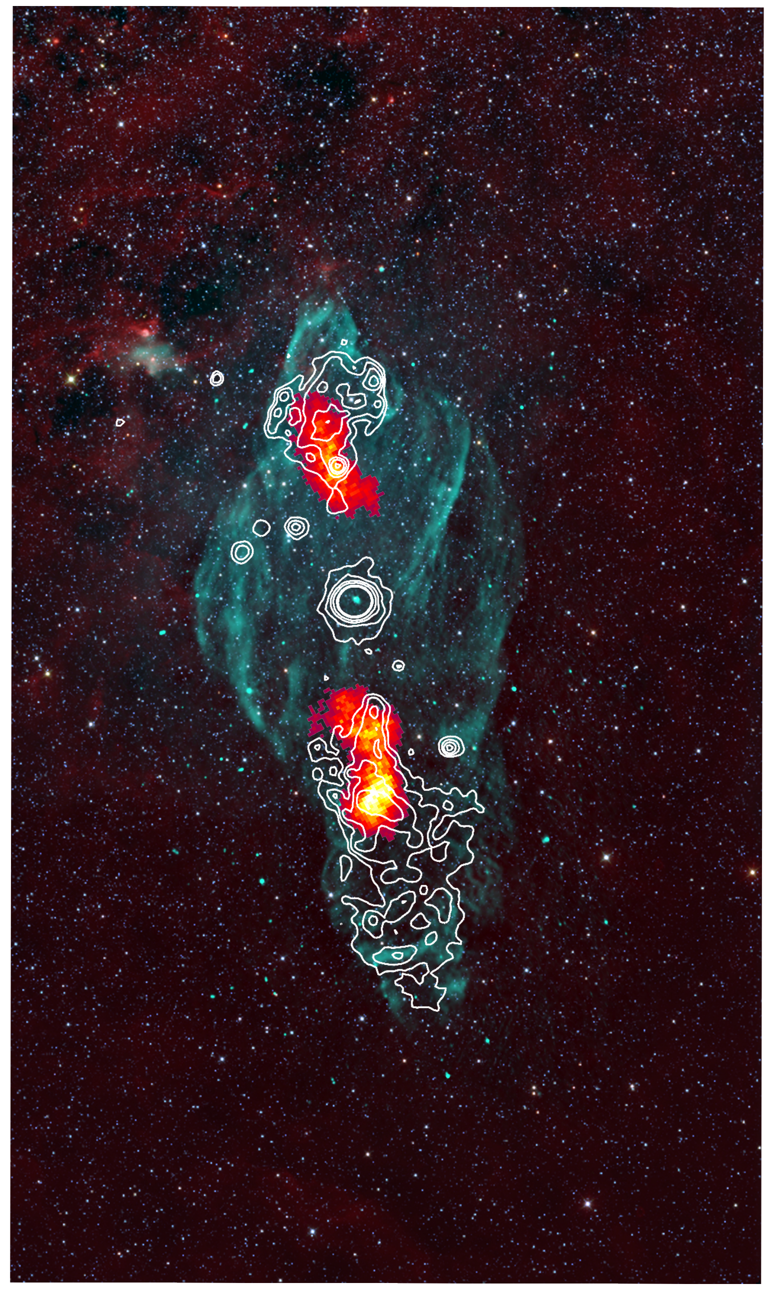
RECENT HIGHLIGHTS

SS 433

Nature, HAWC Coll 2018

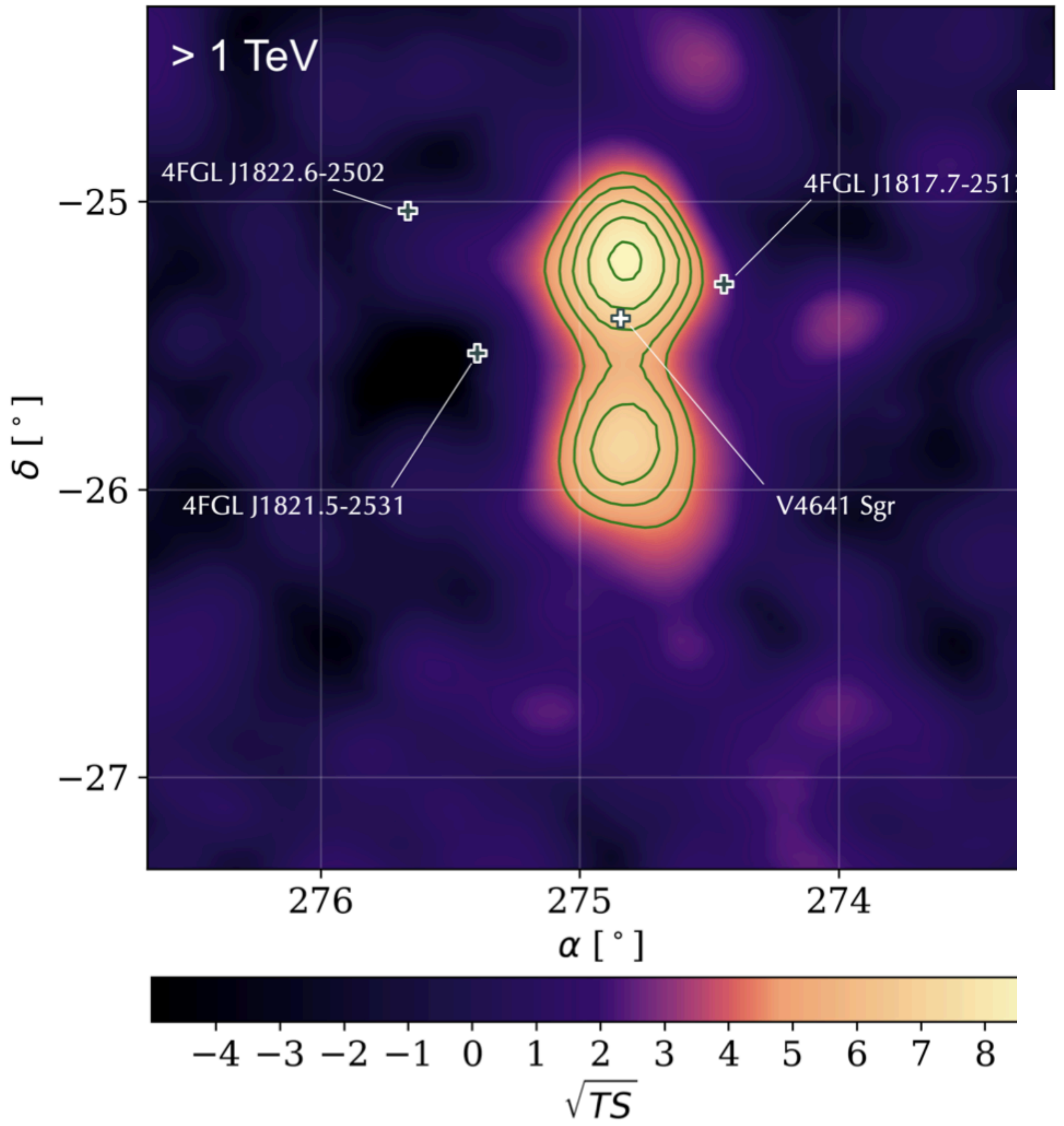


Sabrina's talk



HESS Coll. 24

HAWC Collaboration, Nature 2024



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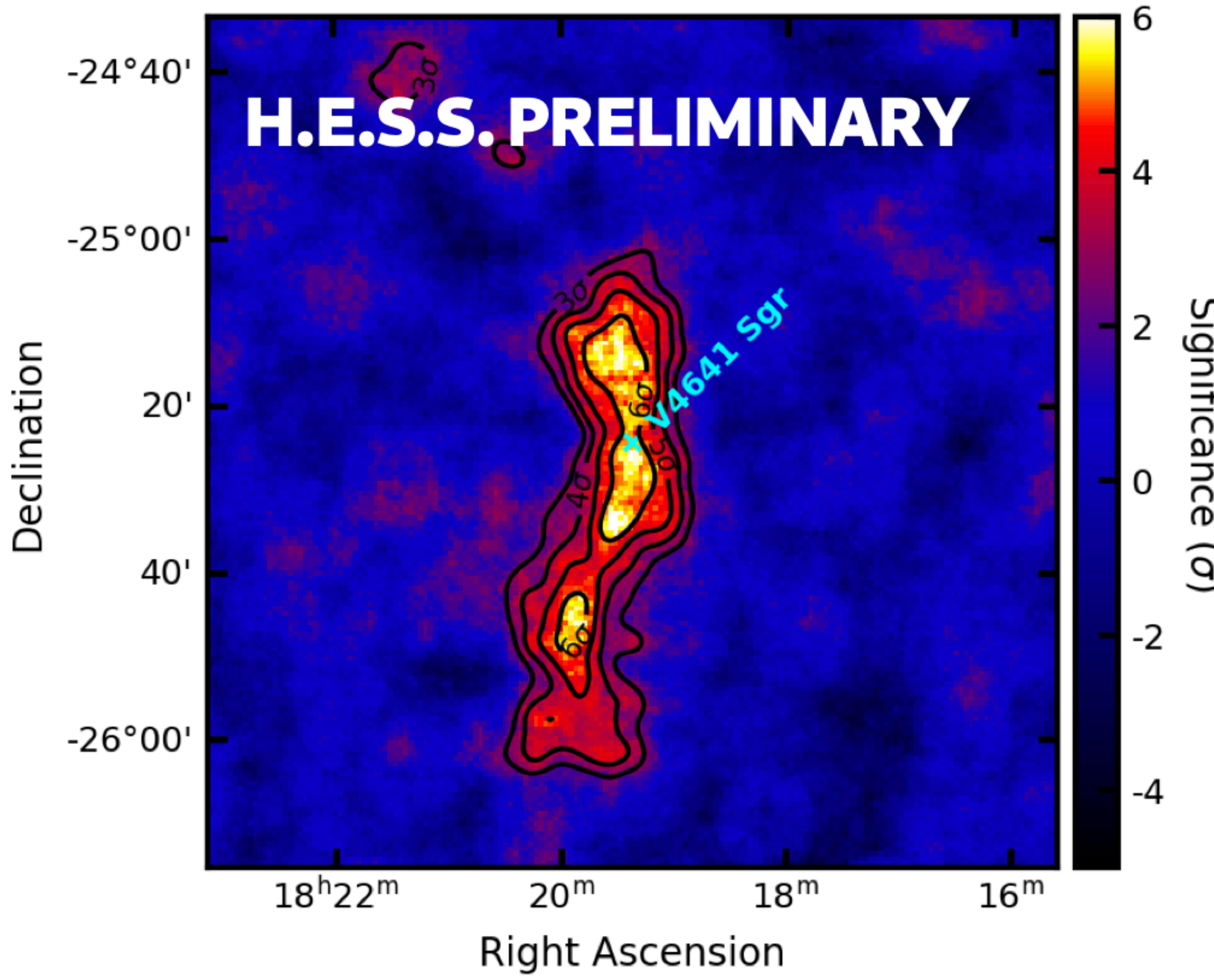

Laura's talk

Microquasars appear to be extremely effective (PeV?) accelerators (almost certainly at a shock in case of SS 433)
Emission appears to be IC dominated, but we KNOW these jets are heavy
Energetics should be sufficient to contribute to a second population above CR knee

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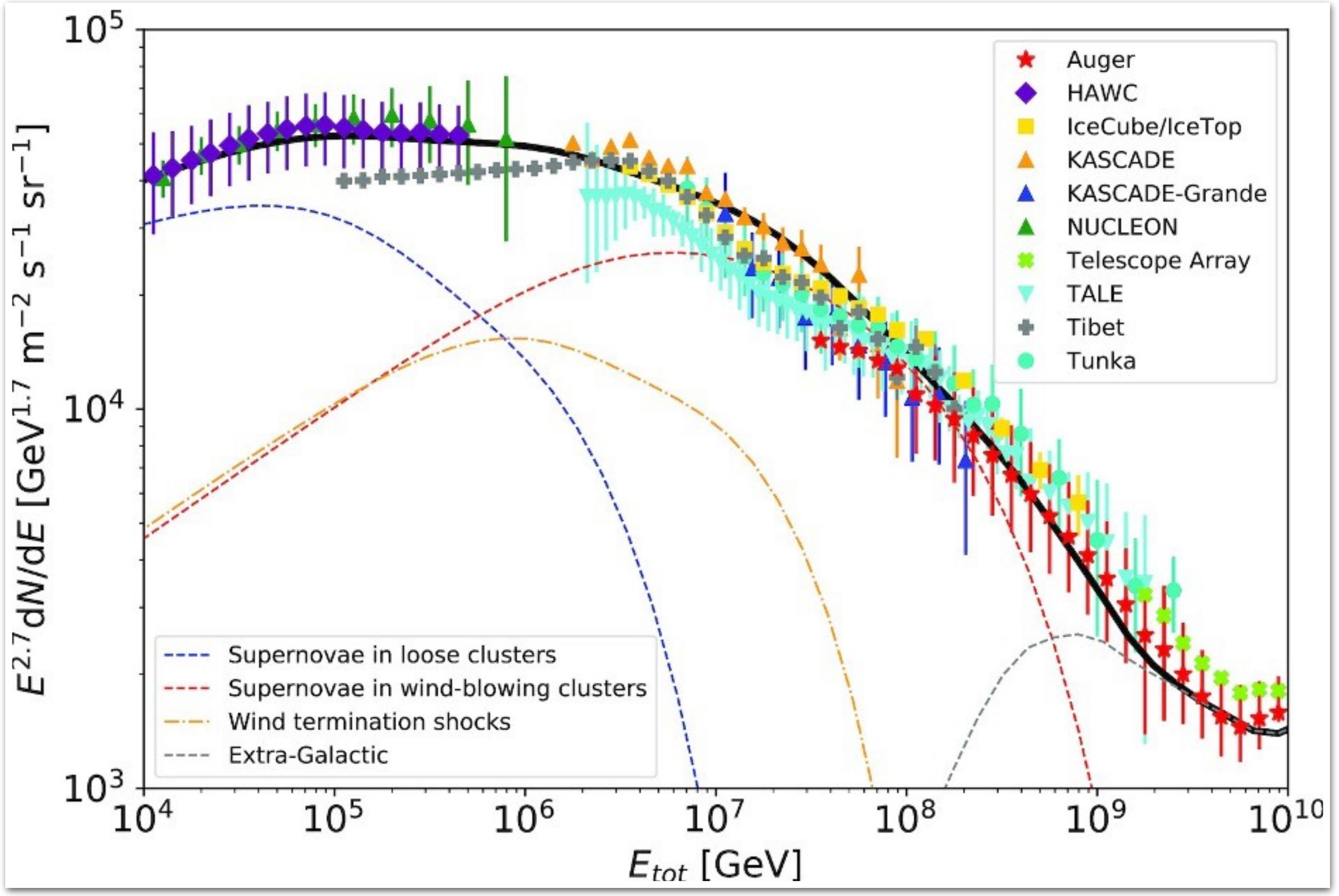
Summary

Vieu & BR, 2023



Galactic CR production best explained in shock acceleration scenarios

New twists appear thanks to new gamma-ray discoveries in VHE & UHE regimes

SNRs still set the standard. Model is of course not complete and new discoveries await us (T CrB)

Theoretical models have been greatly boosted by explosion in computing power, but new tools likely required

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

LHAASO, CTAO, SWGO ensure a bright gamma-ray future