TWO PATHS TOWARD TESTING SNRS AS GALACTIC PEVATRONS

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Background image: W49B
X-ray: NASA/CXC/MIT/L.Lopez et al
Infrared: Palomar
Radio: NSF/NRAO/VLA

OUTLINE

PART I.

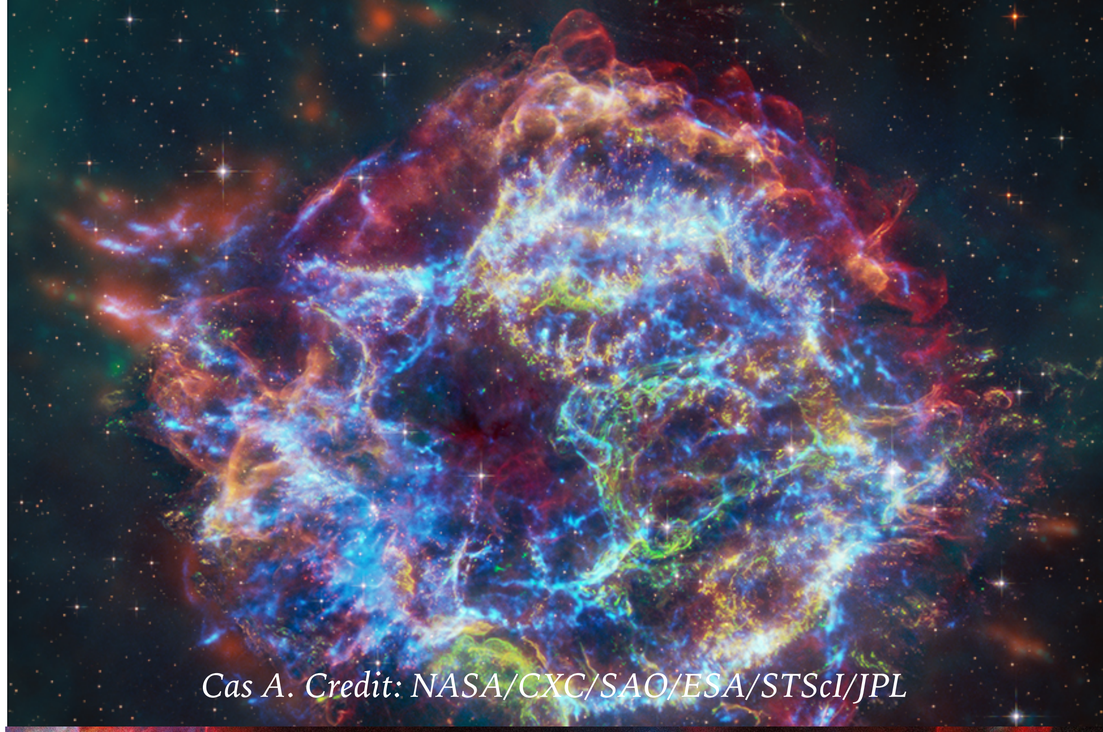
Are SNRs hadronic accelerators? And to what energies?

Prospects for neutrino detection in stacked samples of hadronic SNRs

PART II.

Can SNRs accelerate CRs to PeV energies? If so, how?

Simulations of SNR shocks and the Bell instability



Cas A. Credit: NASA/CXC/SAO/ESA/STScI/JPL

Veil Nebula, Cygnus Loop. Credit: ESA/Hubble & NASA

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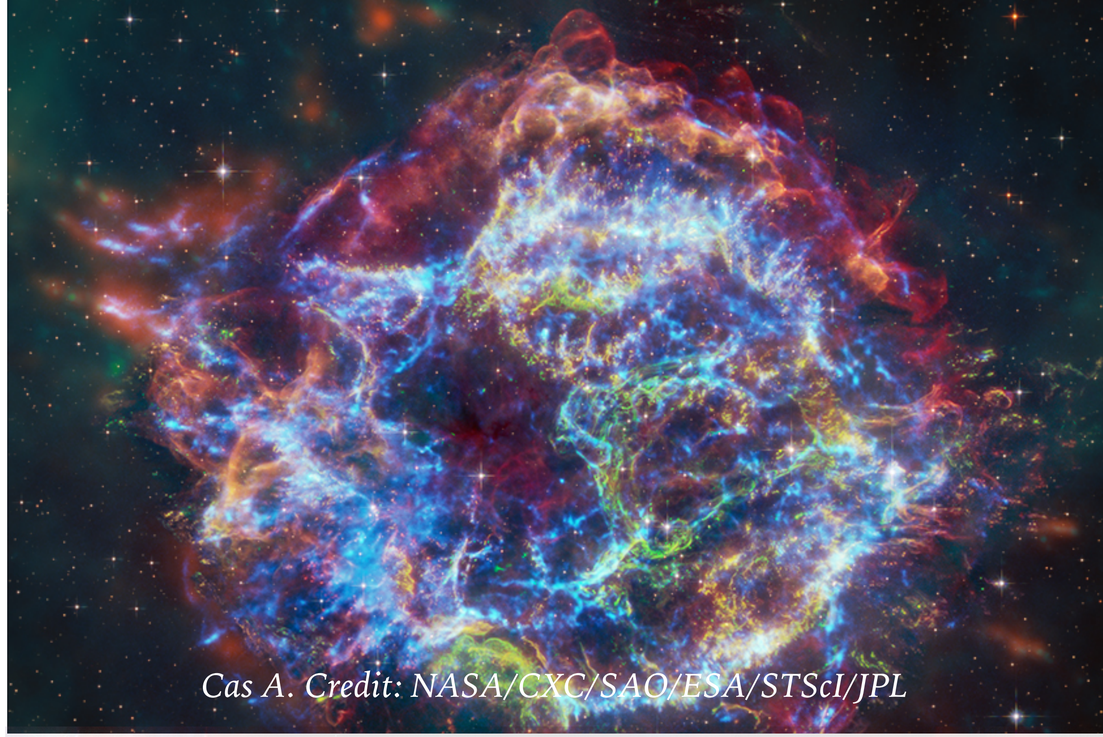
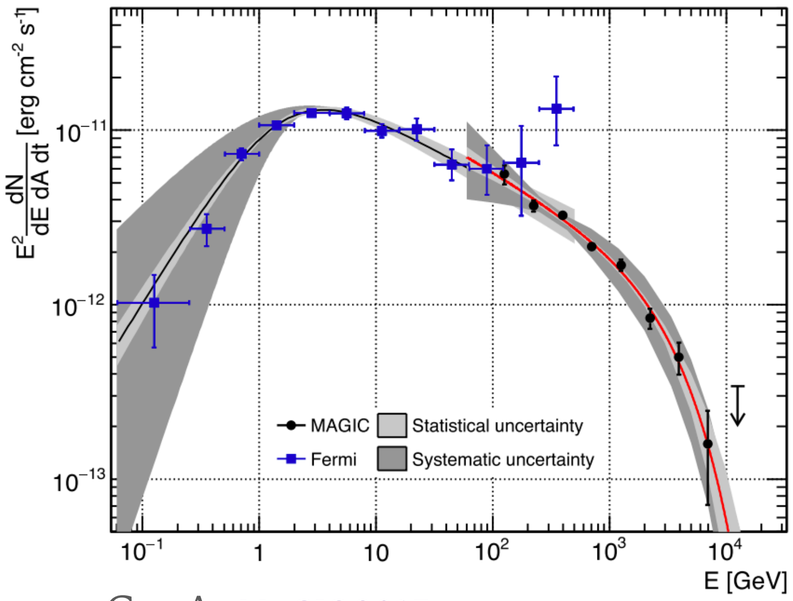


Cas A. Credit: NASA/CXC/SAO/ESA/STScI/JPL

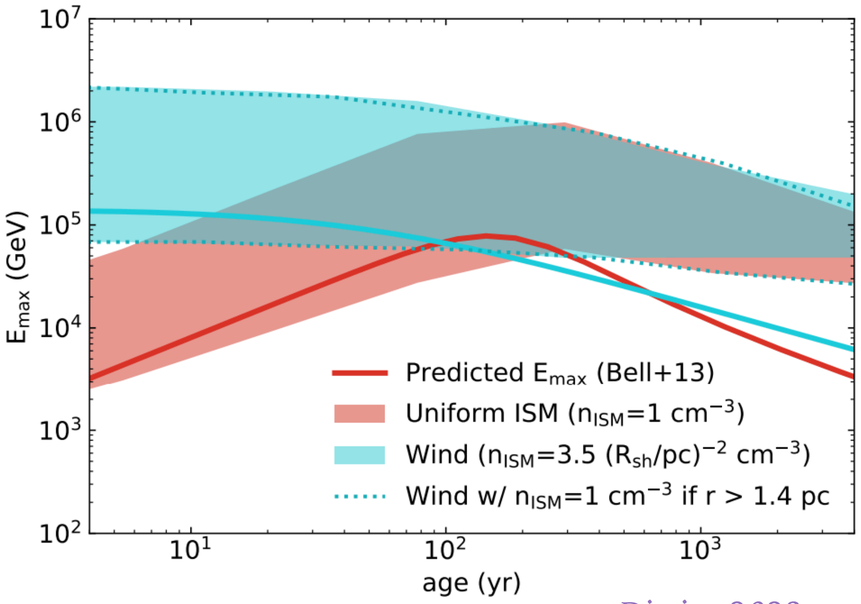
Veil Nebula, Cygnus Loop. Credit: R. Gendler & Hubble & NASA

SNR PEVATRONS

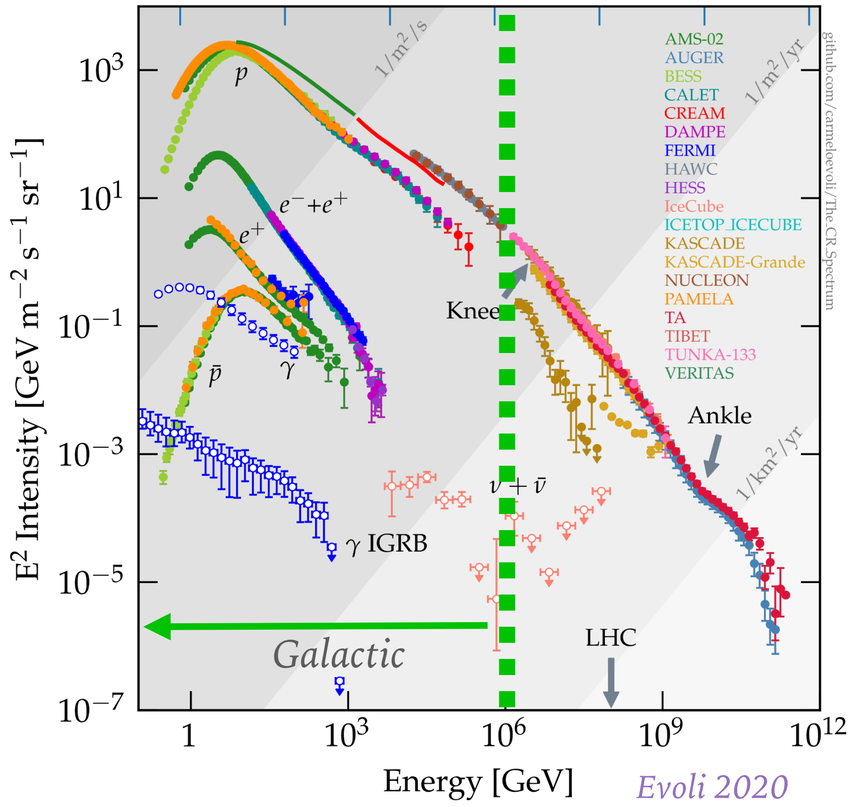
- The source of Galactic CRs up to the knee (~PeV) is still not known
  - SNRs theoretically have the right energetics and spectral slope from diffusive shock acceleration (+ propagation effects)
- Problems from observations (e.g., *Suzuki+2022*) and theory (e.g., *Bell+2013, Cristofari+2021*)



Cas A, *MAGIC 2017*

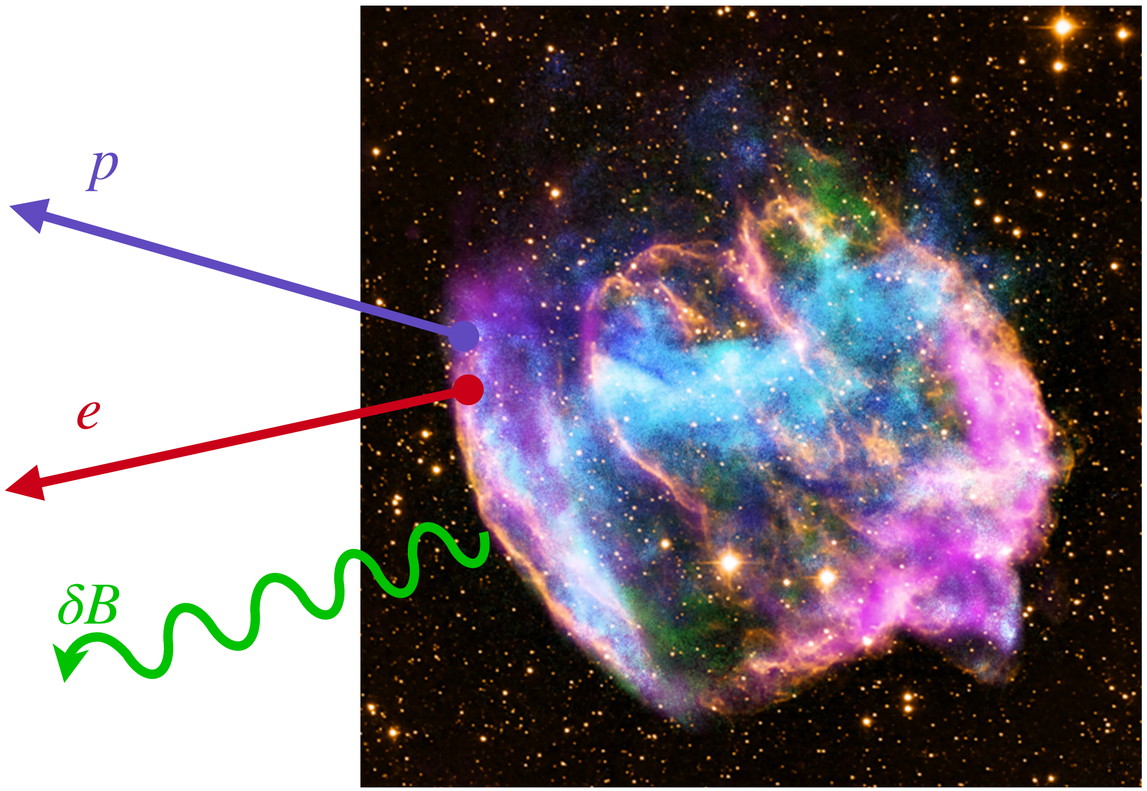


Diesing 2023



Evoli 2020

NEUTRINO WINDOW INTO HADRONIC SOURCES



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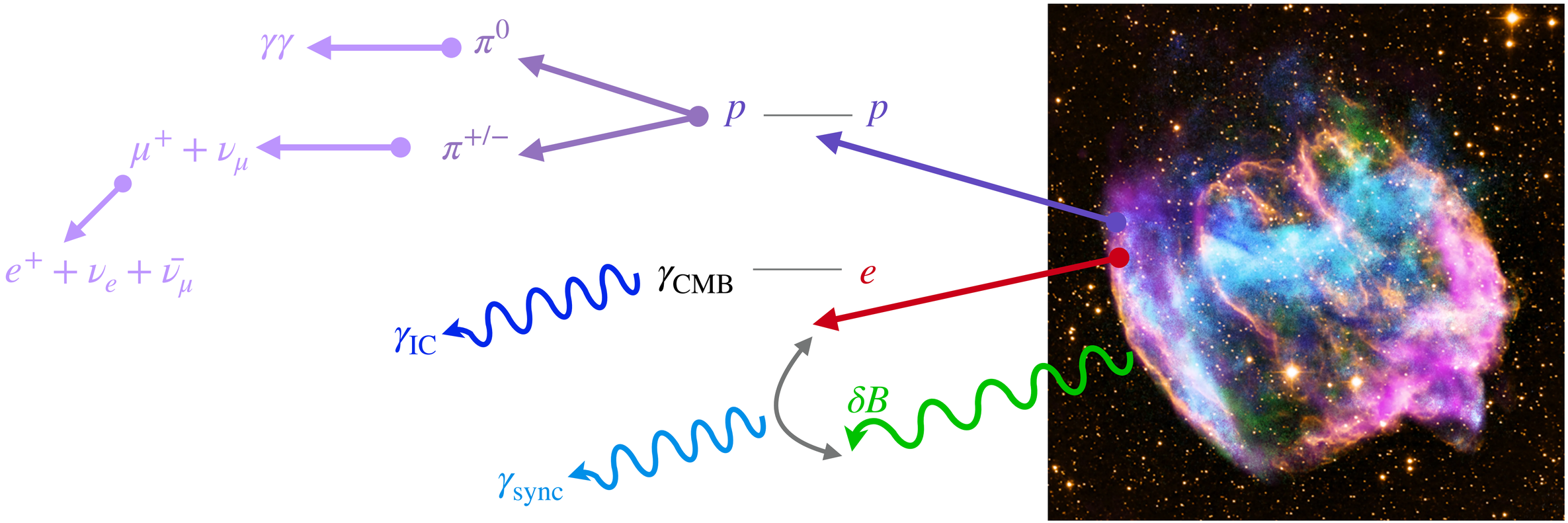

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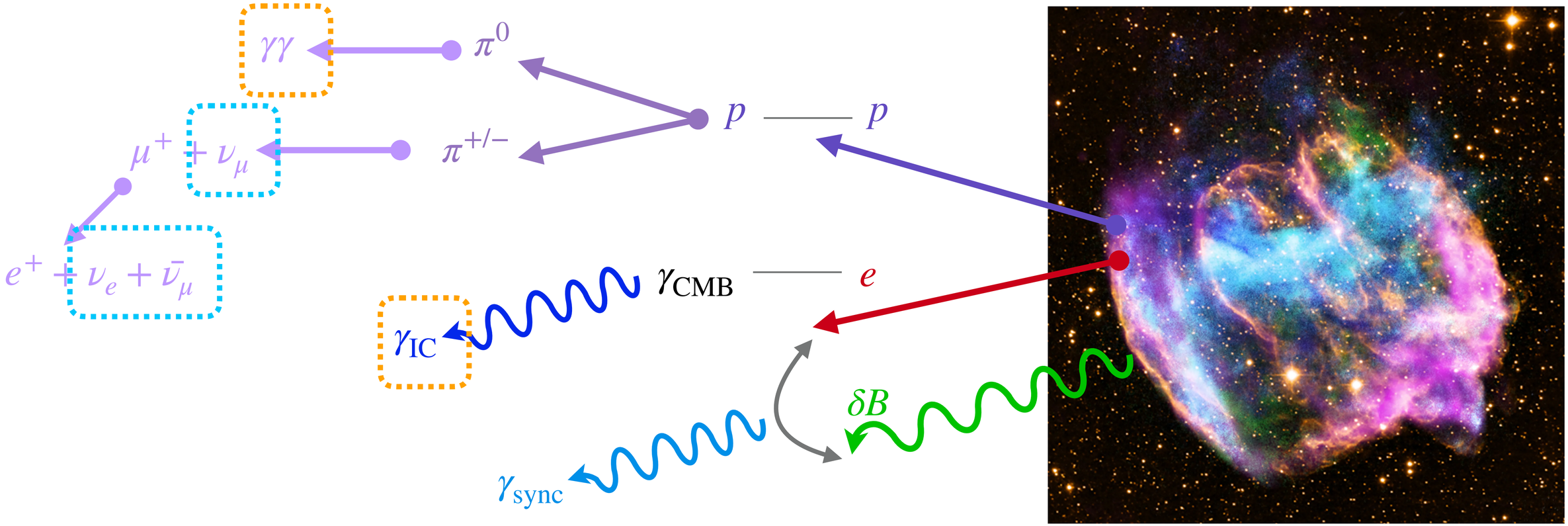
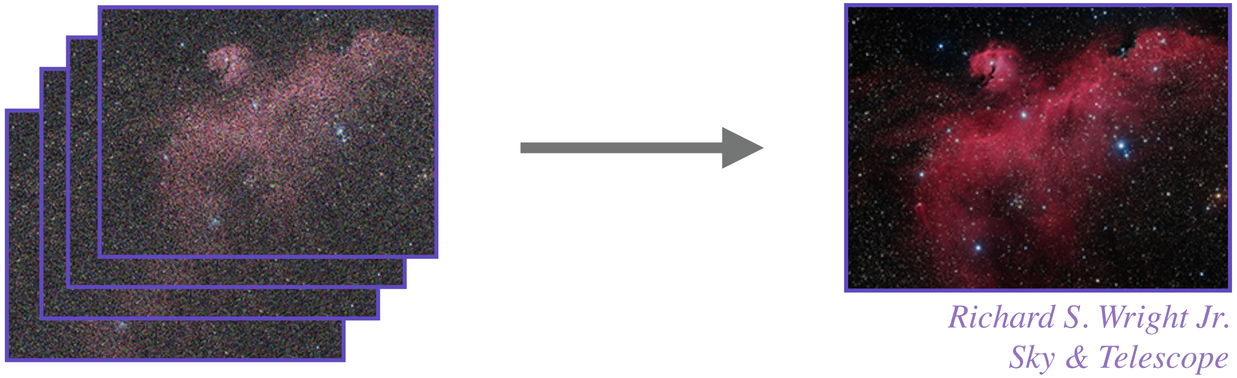


Gamma rays are ambiguous— could be from inverse Compton or from π^0 decay

Neutrinos are **unambiguous** hadronic byproducts. They also **retain pointing** (unlike cosmic rays).

DETECTING NEUTRINOS

Stacking analyses give us a chance at detecting (aggregate) faint signals, essentially: (summed signal)/(summed noise)



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Sky & Telescope

Leptonic sources increase noise without increasing neutrino signal

Aartsen+2017m, IceCube

Source Catalog	Number of Sources	*p*-value
Milagro Six	6	30%
HAWC Hotspots	10	31%
SNR with mol. clouds	10	25%
SNR with PWN	9	34%
SNR alone	4	42%

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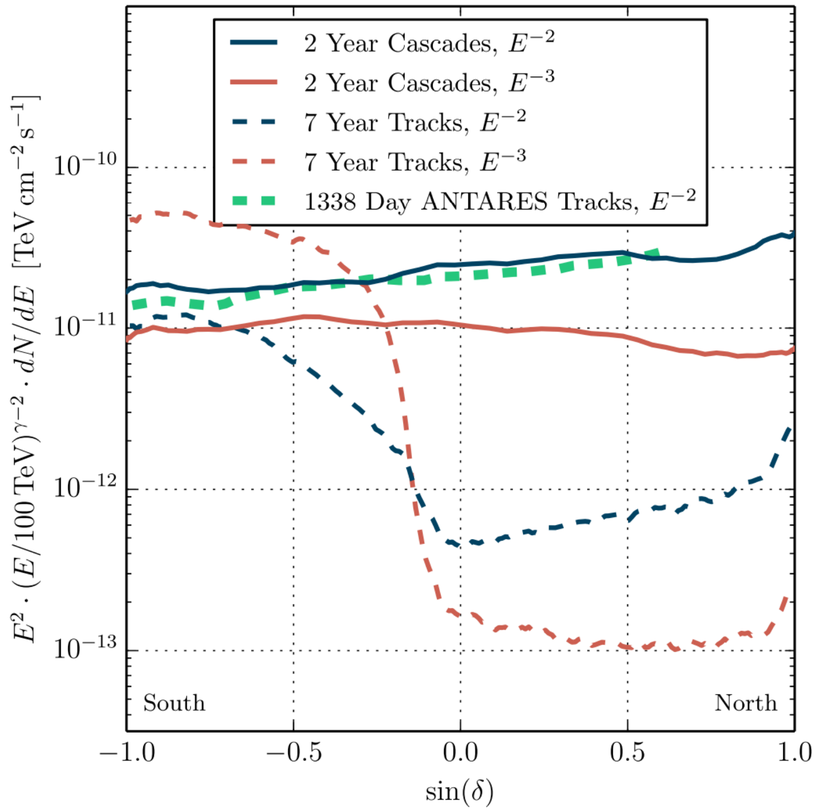

IceCube's sensitivity is a function of the source's **declination** and neutrino energy

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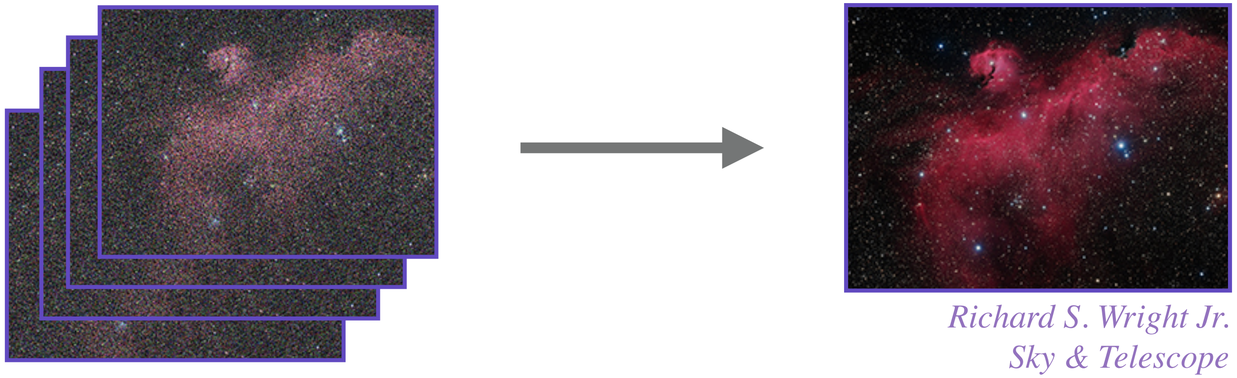

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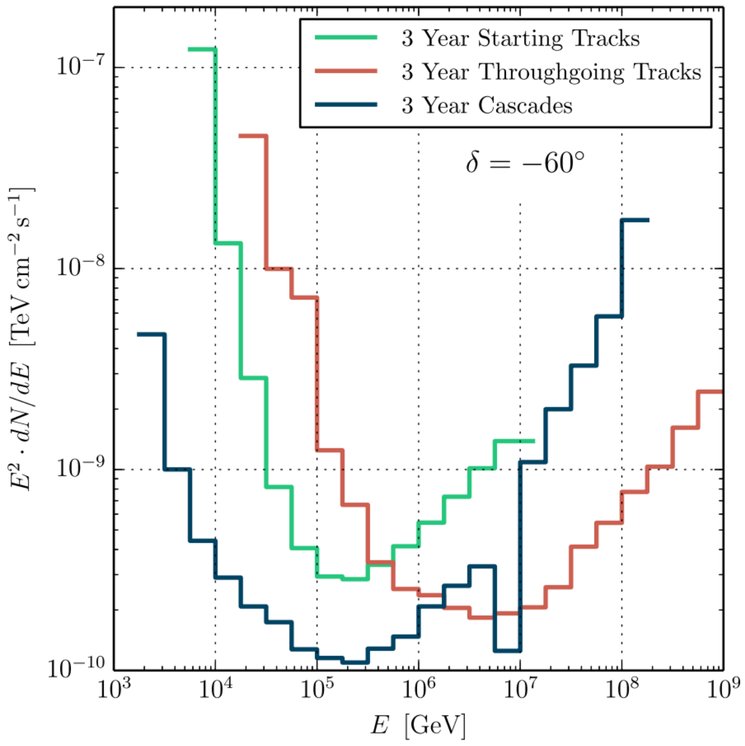

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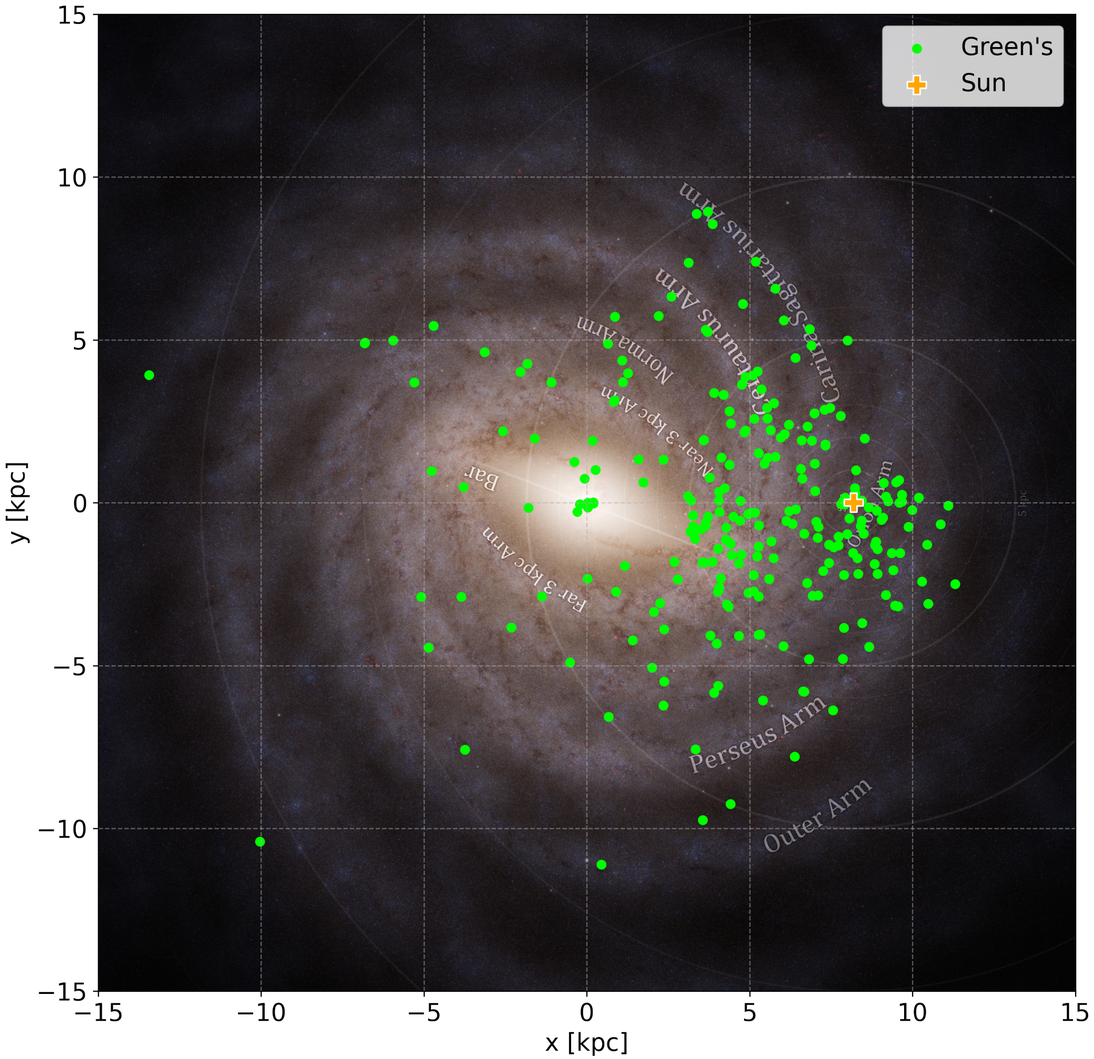
GALACTIC SNR CENSUS

Total known galactic SNRs: 310 (*Green 2025, Ferrand and Safi-Harb 2012*)



Background image: Gaia DR3,ESA/Gaia/DPAC, Stefan Payne-Wardenaar
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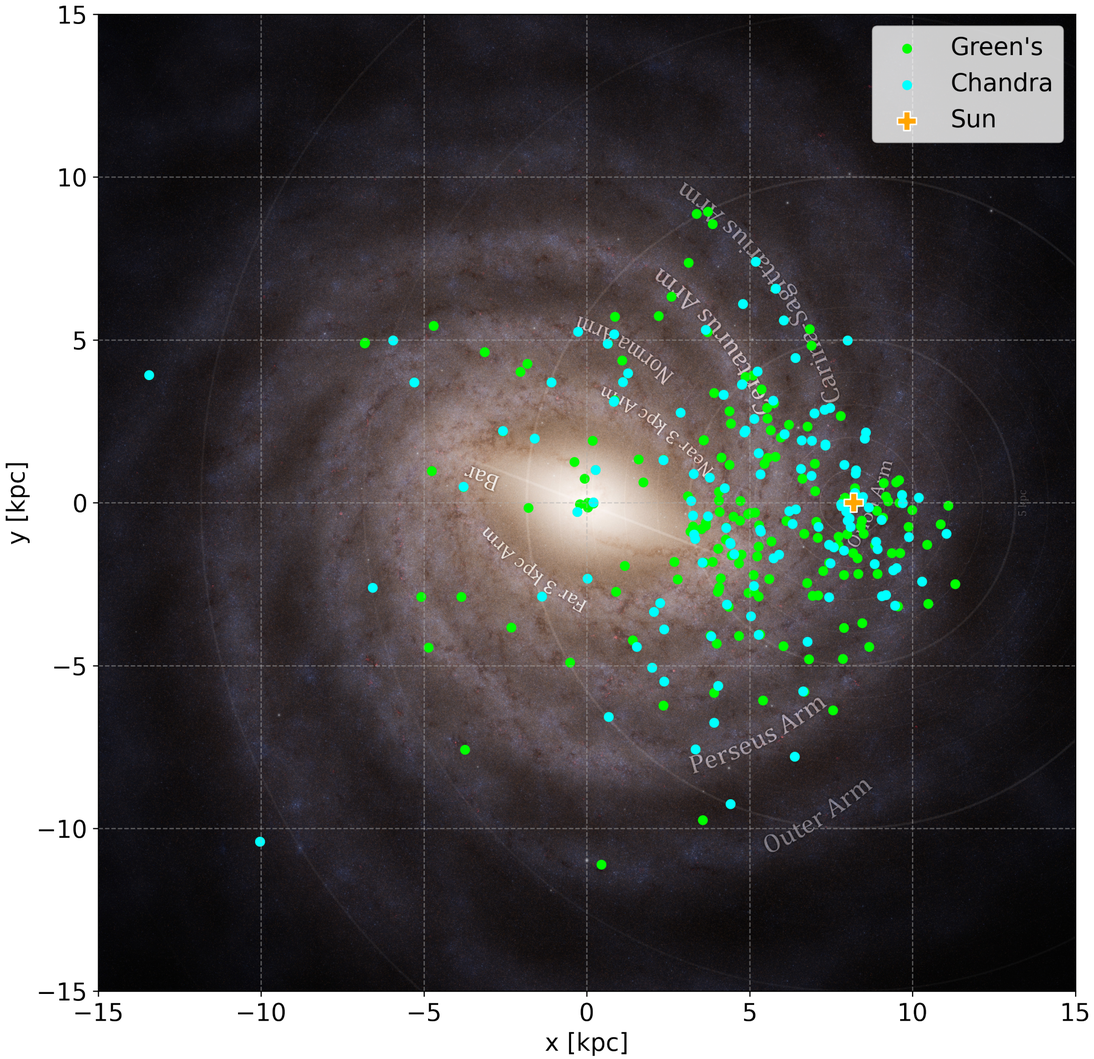

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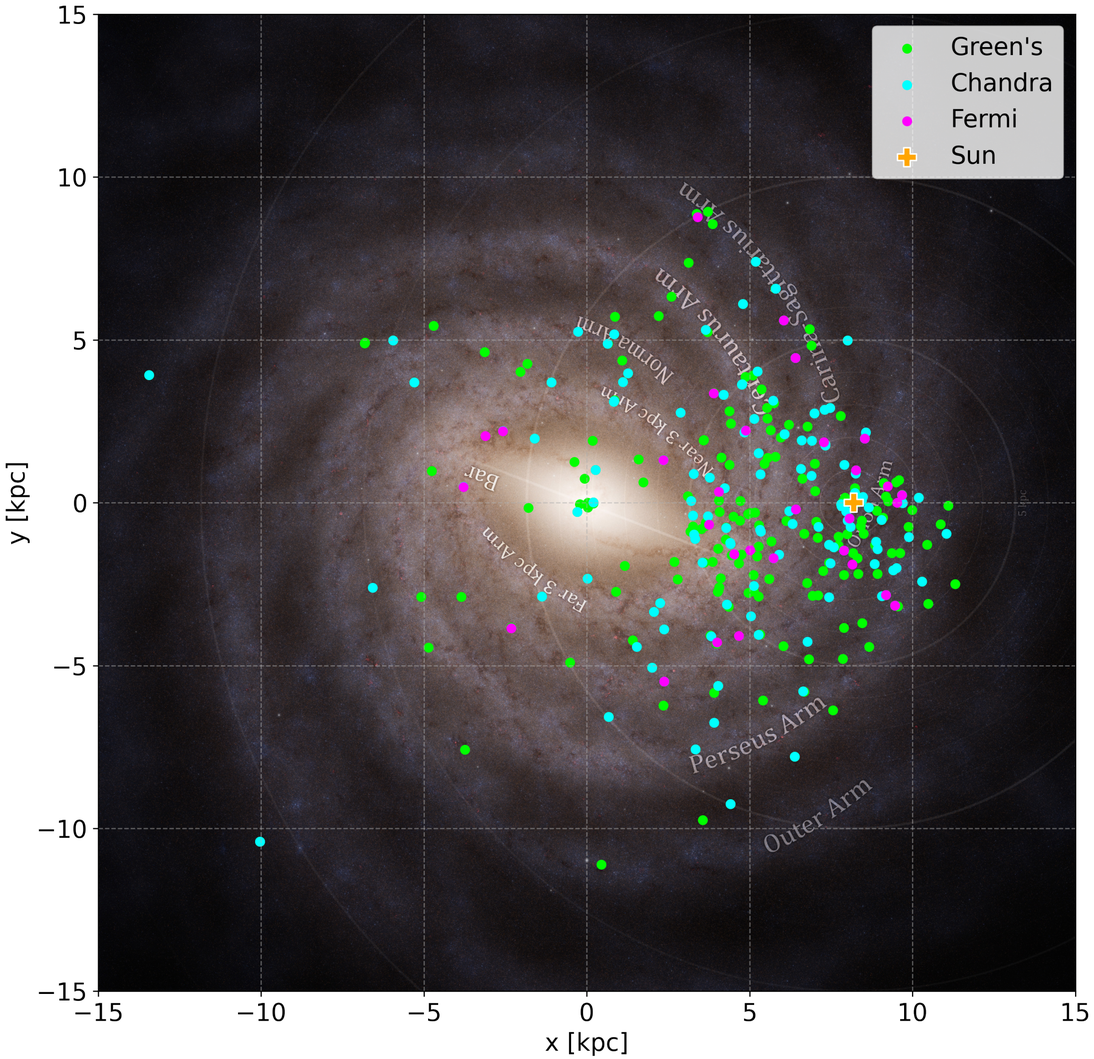

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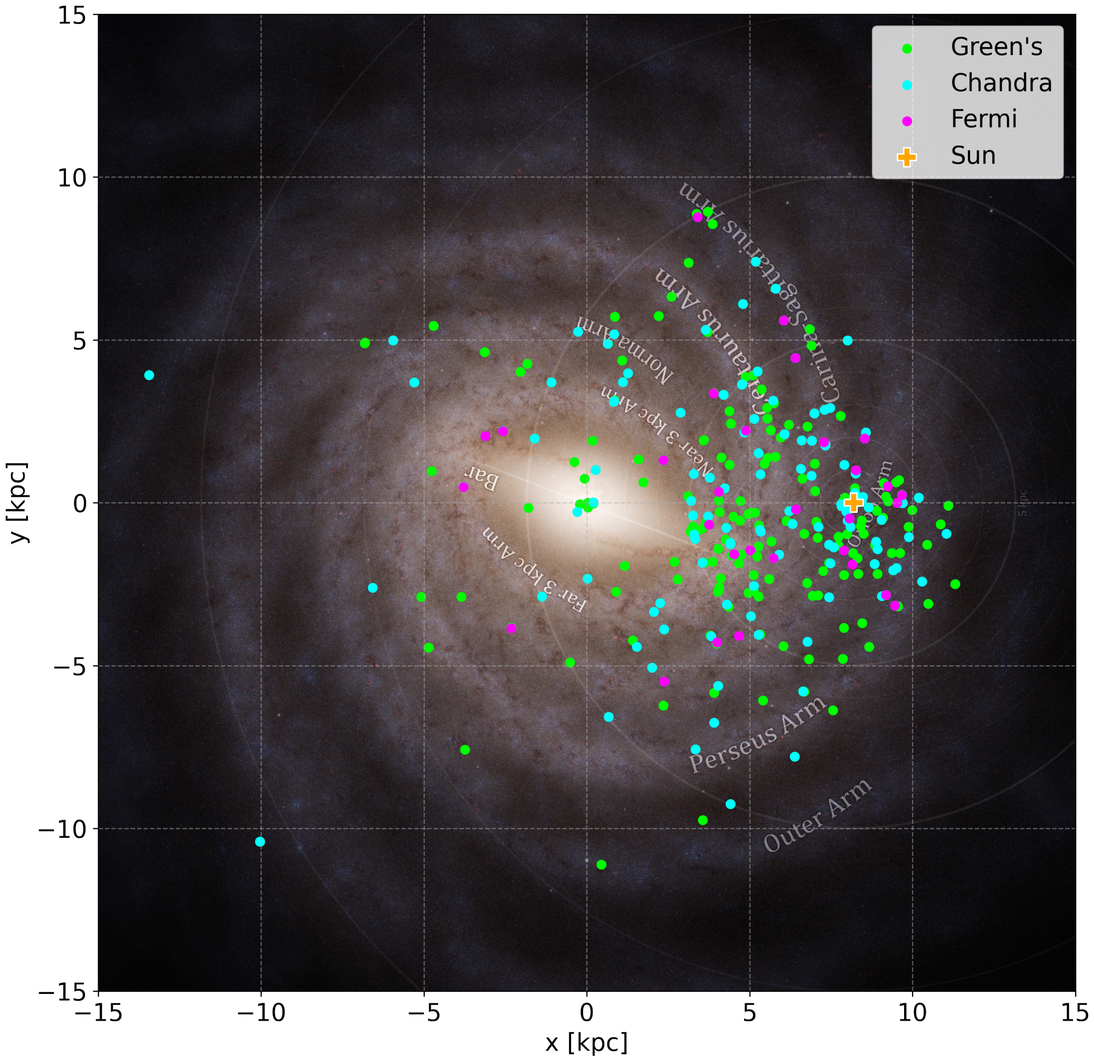
+Additional data from HESS, HAWC, VERITAS, MAGIC, and LHAASO

Sort into three catalogs

- **Tier 1:** Extremely likely to be hadronic
- **Tier 2:** Hadronic at low energies, inconclusive at TeV
- **Tier 3:** Possible sub-dominant hadronic component with relatively high flux



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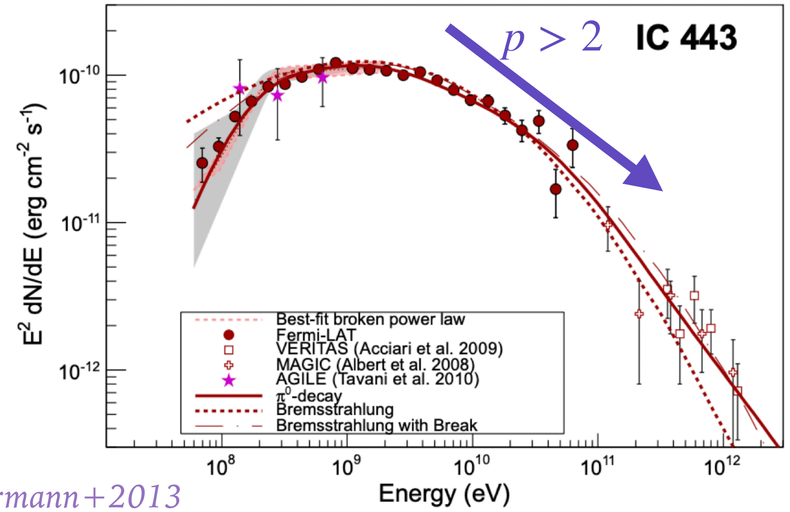
DISTINGUISHING HADRONIC VERSUS LEPTONIC SPECTRA

Diffusive Shock Acceleration (DSA) produces energy power laws:

$$\frac{dN}{dE} \propto E^{-p}, \text{ with } p = (r+2)/(r-1)$$

For strong shocks: $r \to 4$, and thus $p \approx 2$.
Corrections due to self-generated magnetic fields suggest $p \approx 2.2 - 2.4$ at strong shocks (*Haggerty+2020, Caprioli+2020*)



Ackermann+2013

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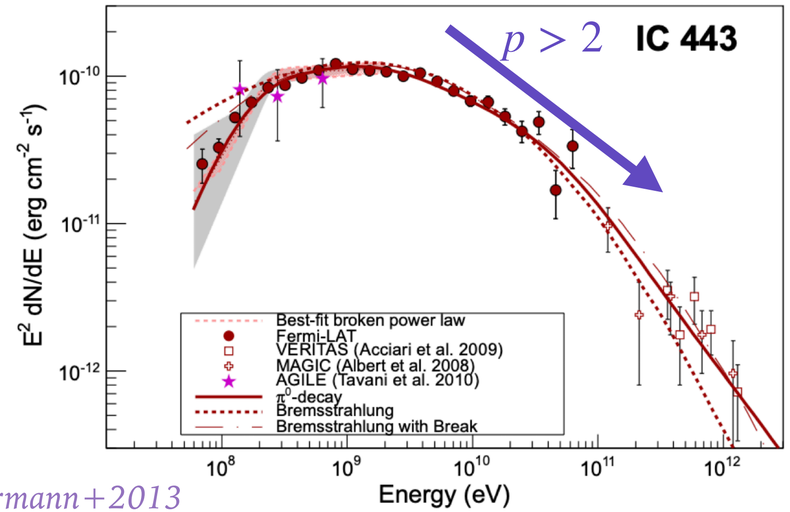
Inverse Compton (the dominant leptonic mechanism) produces:

$$\frac{dN}{dE} \propto E^{(-p-1)/2}, \text{ where } p \text{ is the electron spectral index.}$$

For a $p \approx 2$ electron spectrum, $\frac{dN}{dE} \propto E^{-1.5}$



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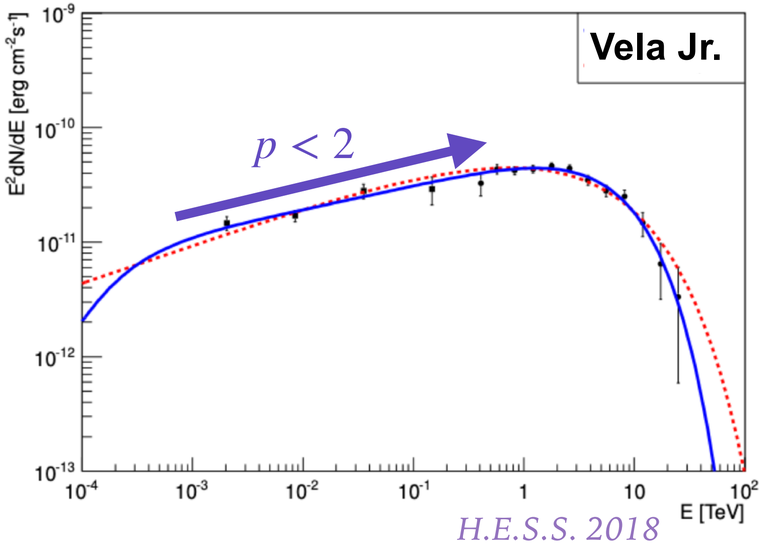

H.E.S.S. 2018

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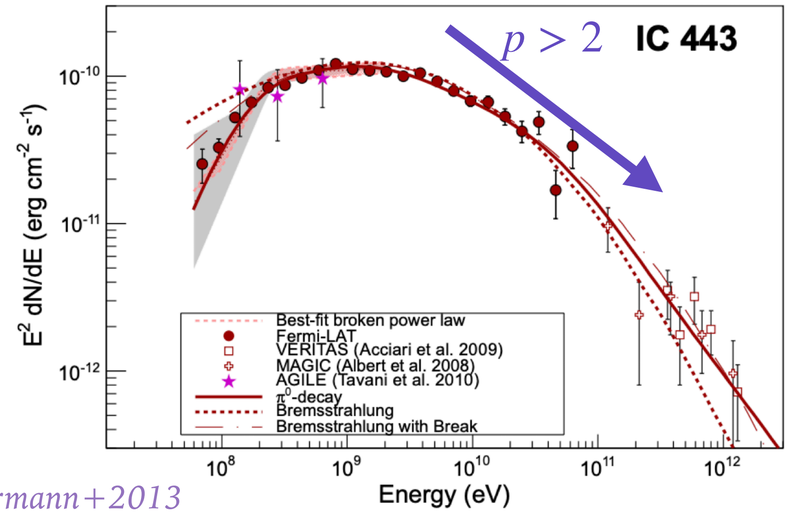
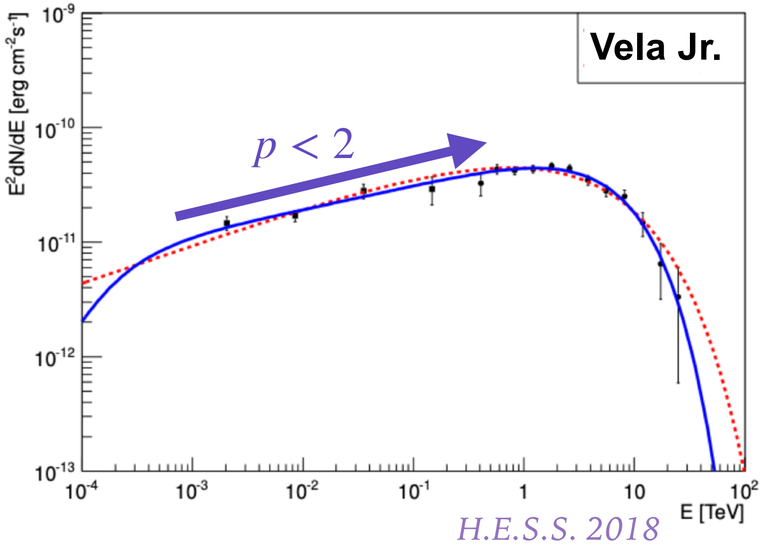


Ackermann+2013

Hadronic spectra are *soft*

Leptonic spectra are *hard*



H.E.S.S. 2018

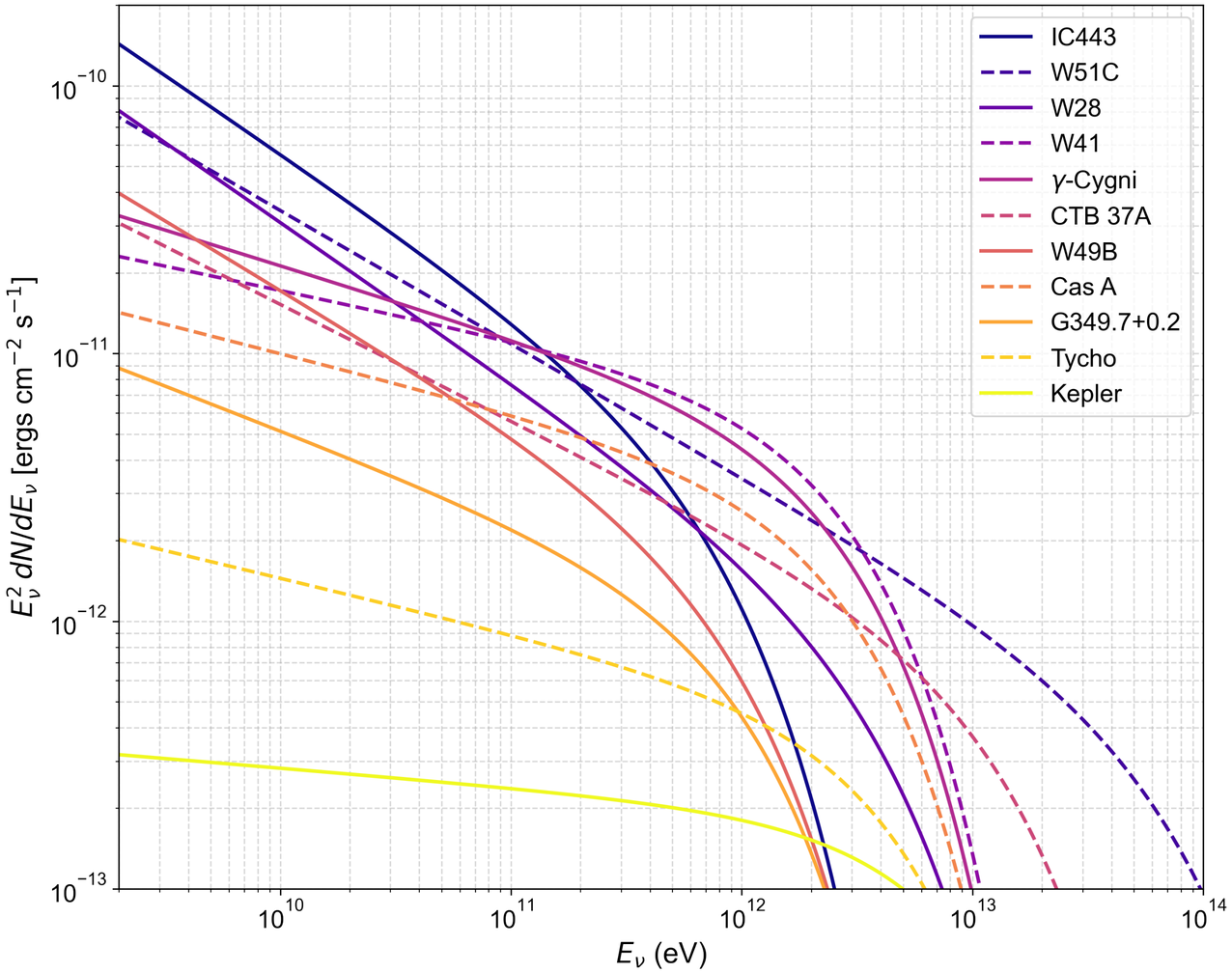
RESULTS

Tiers 1 & 2

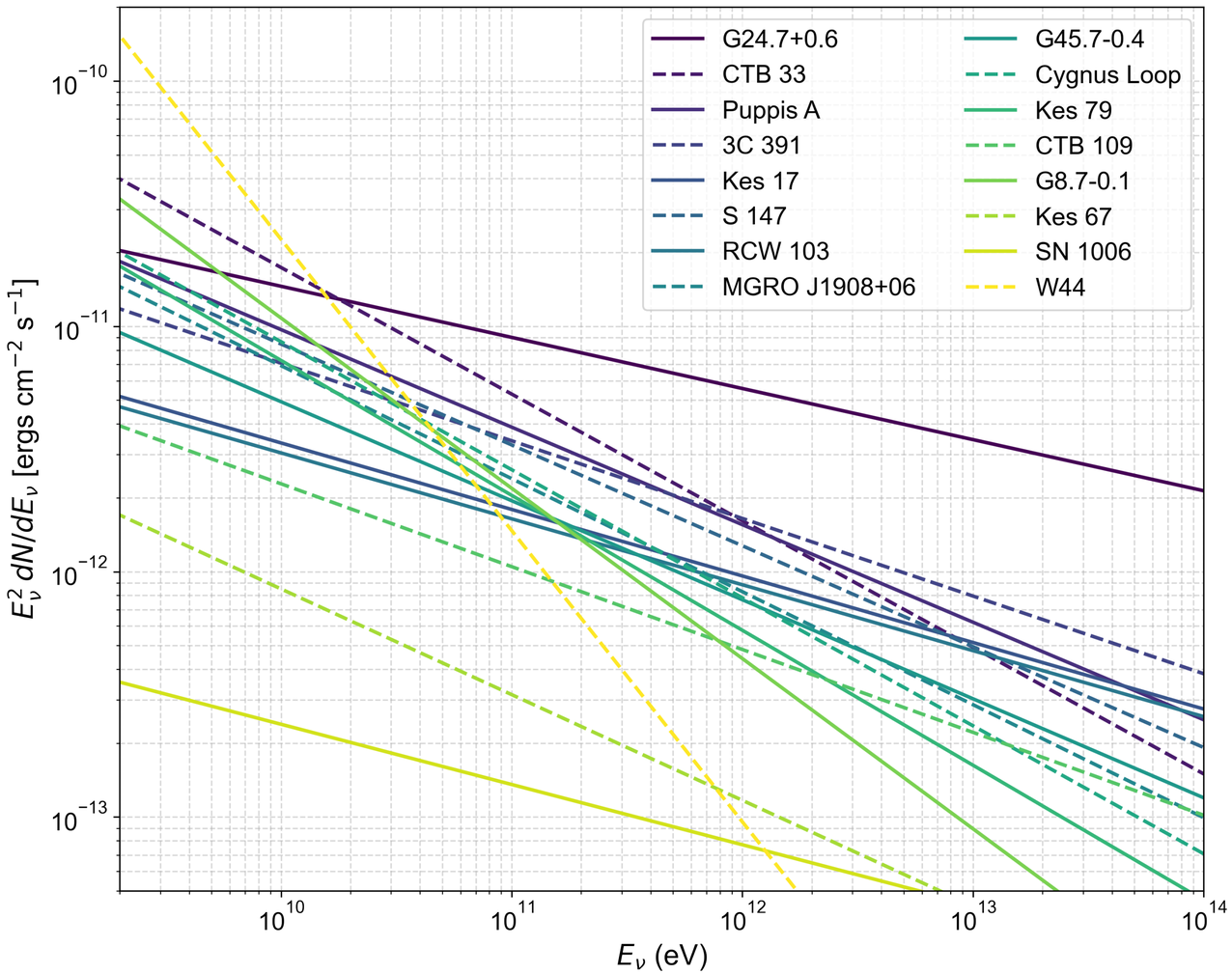
TIER 1 & 2 SELECTIONS

E. Simon, R. Diesing, D. Caprioli, S. Sclafani, in prep

Tier 1, assuming exponential cutoffs

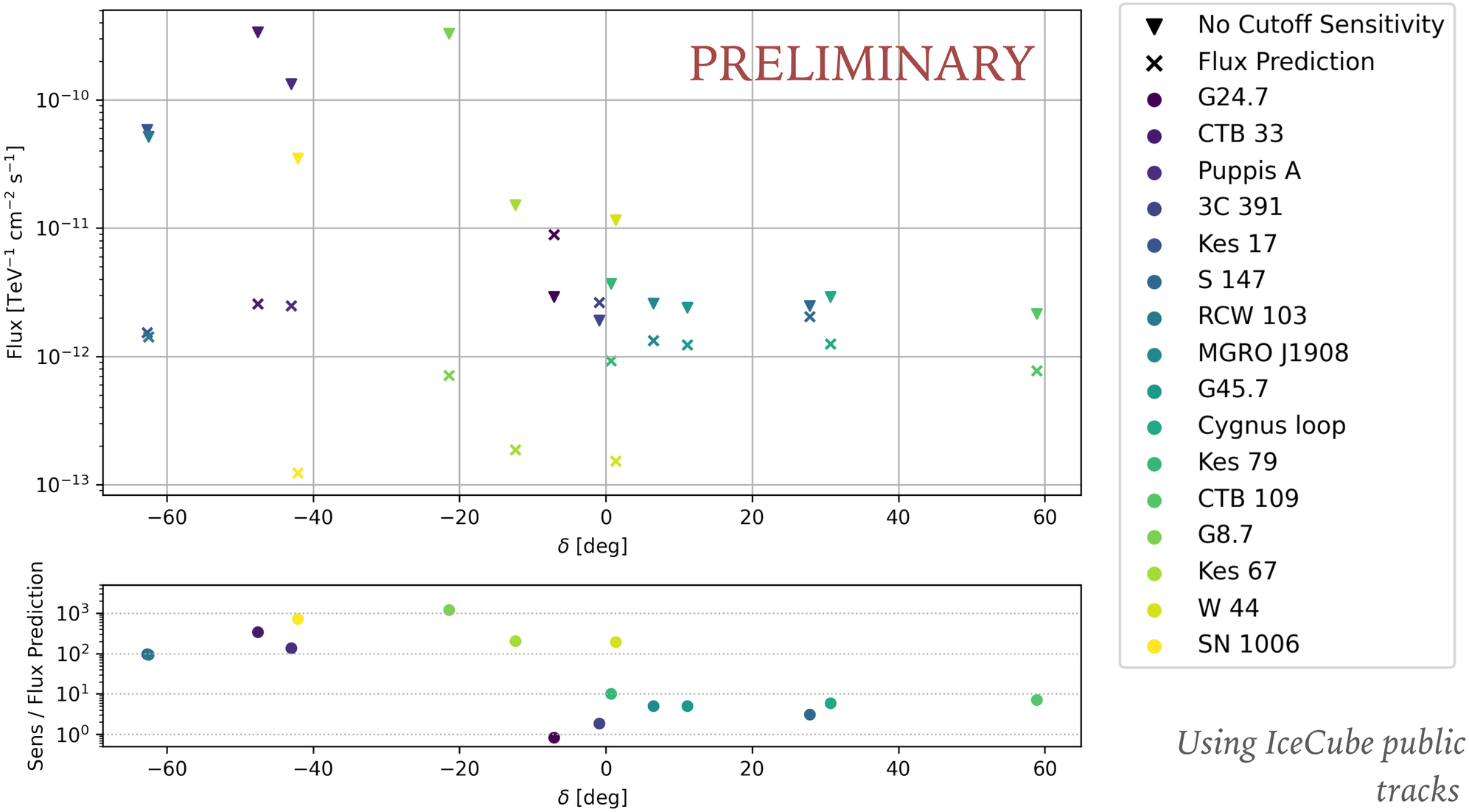


Tier 2, assuming no cutoff



INDIVIDUAL SOURCE SENSITIVITY

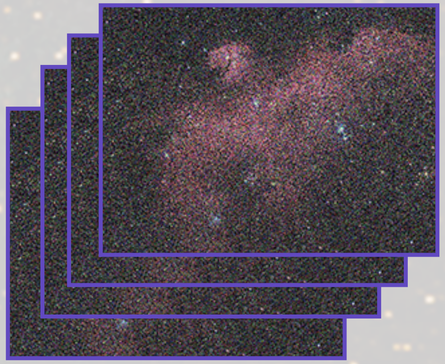
E. Simon, R. Diesing, D. Caprioli, S. Sclafani, in prep



Using IceCube public data, 10 year tracks

PART 1 CONCLUSIONS

- We used DSA-driven theory to create catalogs of the population of Galactic SNRs with $E_\gamma \gtrsim$ TeV are very likely to be hadronic for a future neutrino stacking analysis with IceCube
- Catalog may also be useful for other neutrino experiments
- A detection (or lack of one when we expect it) would provide a very strong constraint on SNRs as sources of Galactic cosmic rays
  - Do SNR neutrinos extend to ~200 TeV energies (implying ~PeV parent protons)?
  - Is the spectral index what we expect from DSA?
  - Can we infer whether Tiers 2 and 3 contain hadronic SNRs based on observed (or not observed) neutrinos?



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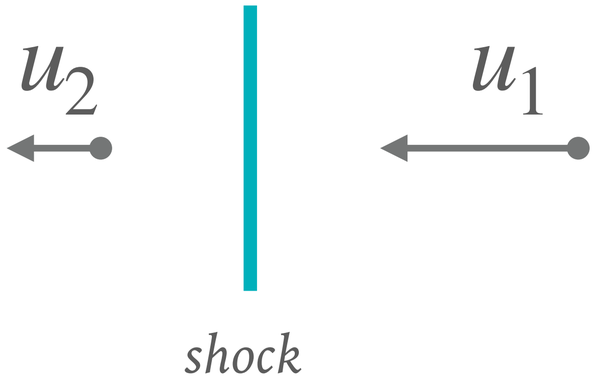
BELL INSTABILITY REVIEW

Bell+04, Bell+13



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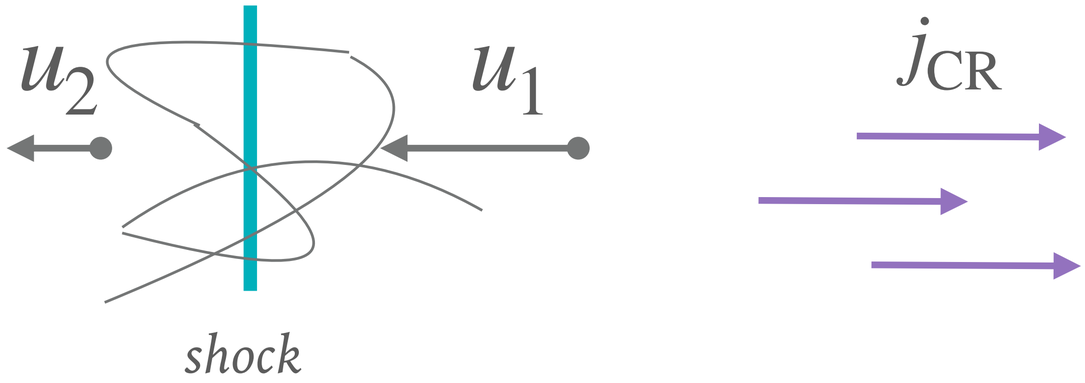

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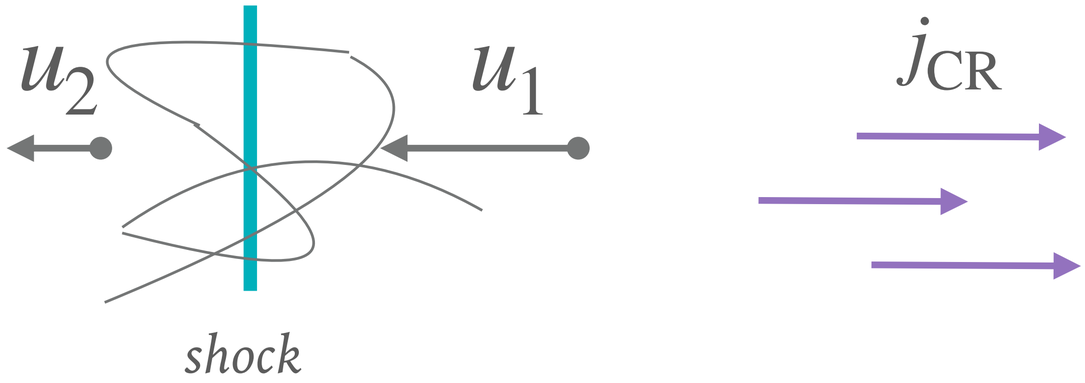

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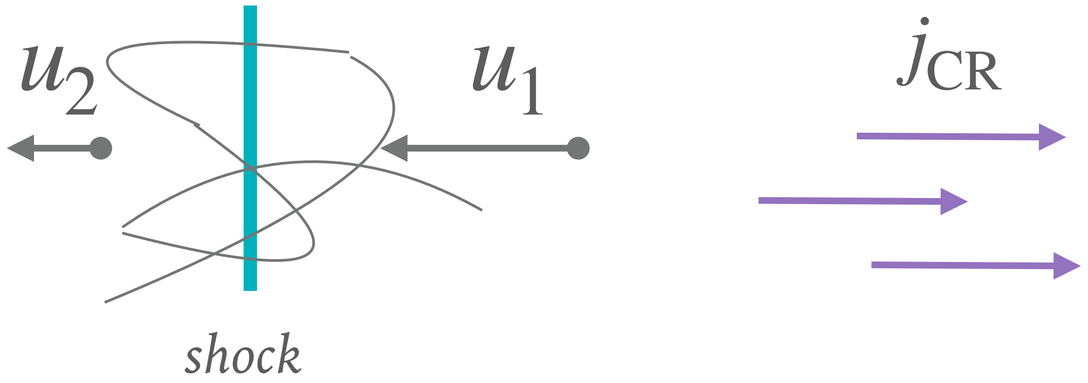

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Allows us to express the maximum energy in terms of the CR pressure and shock velocity:

$$E_{max} = 0.005 \frac{P_{CR}}{\rho u_{sh}^2} \rho u_{sh}^3 t \sqrt{\frac{\mu_0}{\rho}}$$

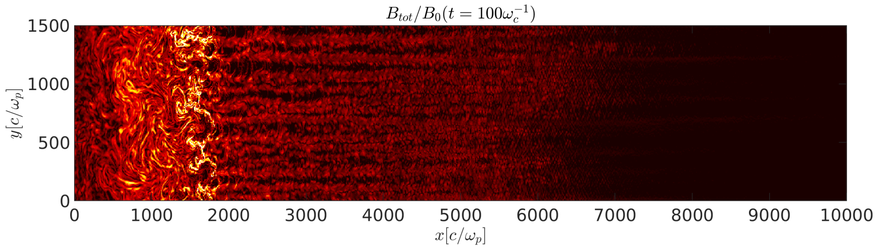
For typical SNR parameters,

$$E_{max} \sim 100 \text{ TeV}$$

We want to test this from first principles with kinetic simulations

HYBRID SIMULATIONS WITH THE FAUX-SHOCK SETUP

Traditional reflecting-wall (RW) style simulations have shrinking upstreams over time



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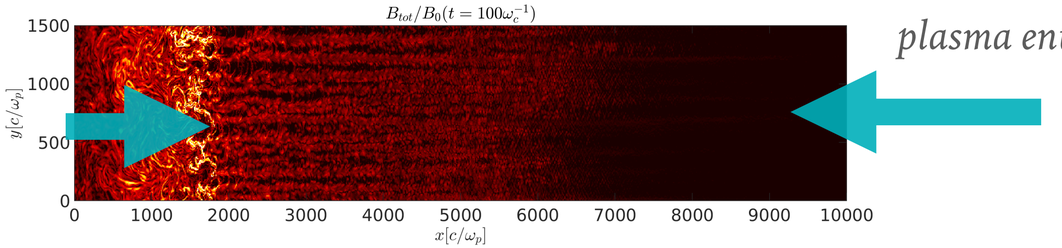
plasma reflects



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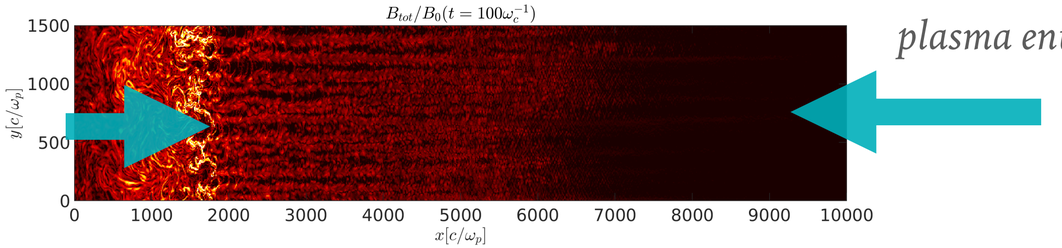

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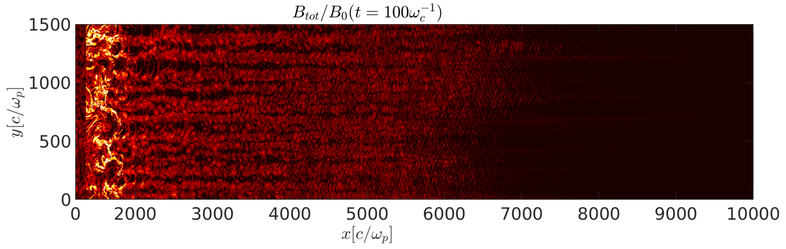
The faux-shock (FS) setup is in the shock frame and has a fixed upstream length (*arXiv:2507.14282*)



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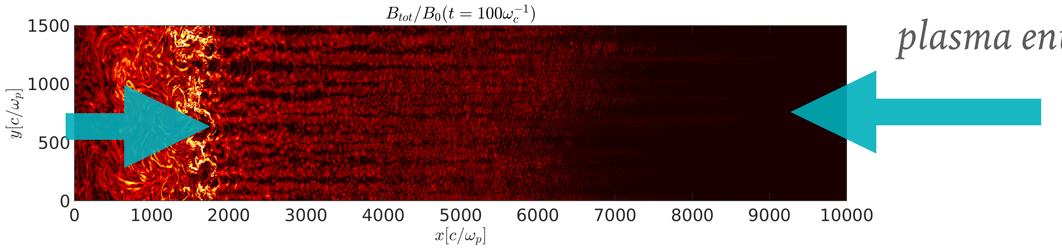

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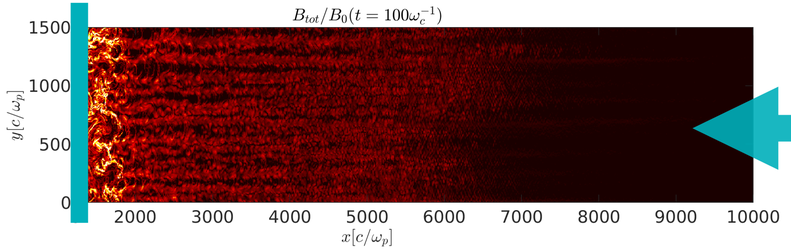

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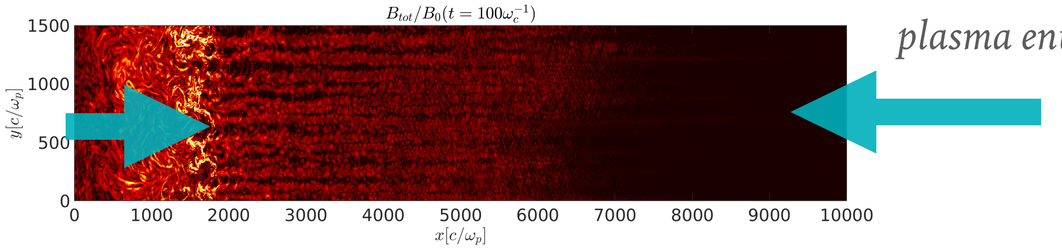

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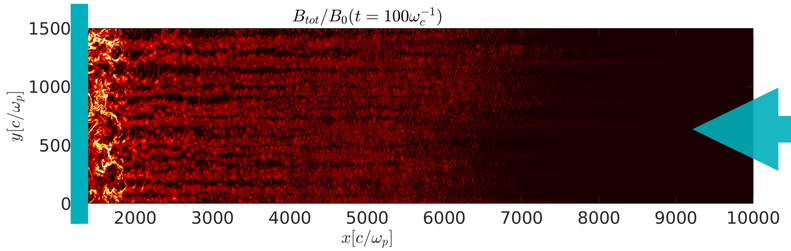

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We give up a self-consistent description of injection, and we get in return: high CR statistics and the ability to run large boxes for long times

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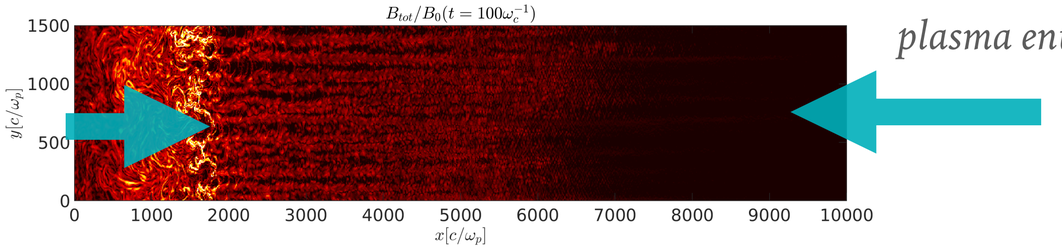

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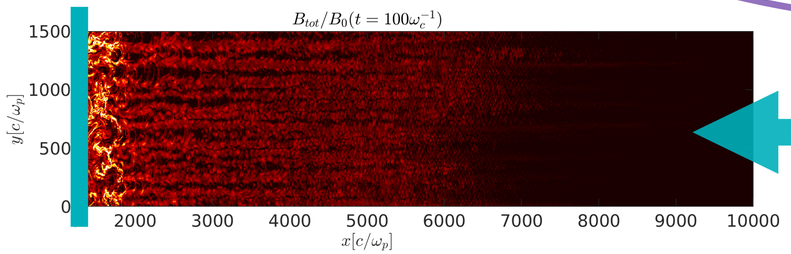
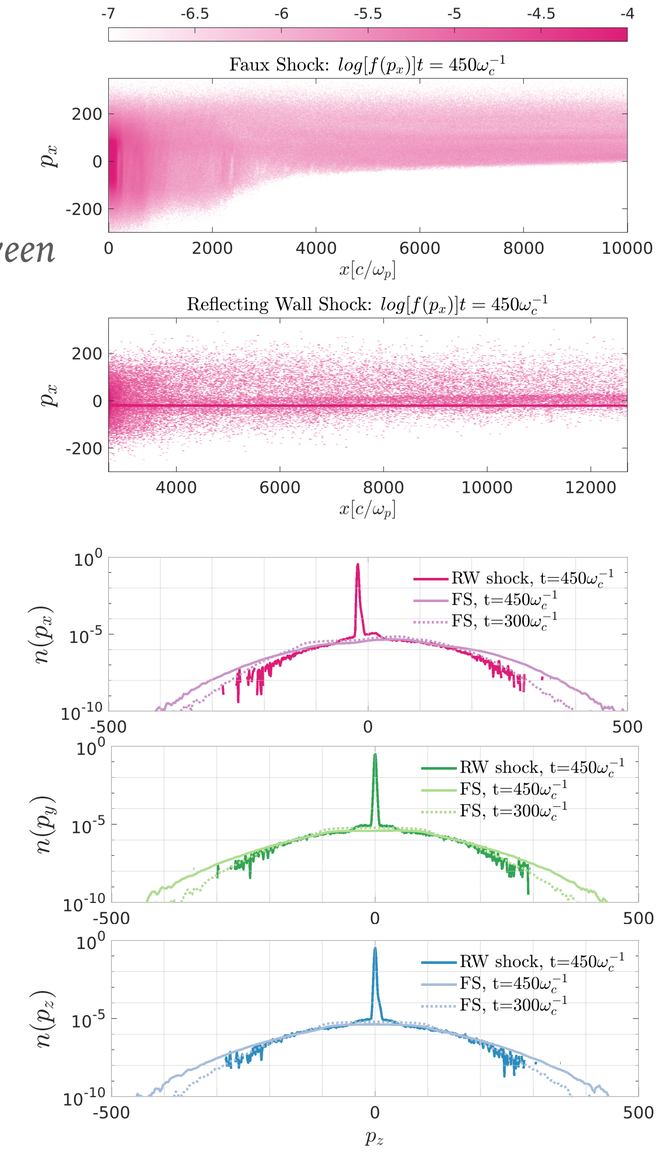


plasma enters

We give up a self-consistent description of injection, and we get in return: high CR statistics and the ability to run large boxes for long times

Great match between FS and RW simulations



HYBRID SIMULATIONS WITH THE FAUX-SHOCK SETUP

E. Simon, D. Caprioli, C. Haggerty, B. Reville, in prep

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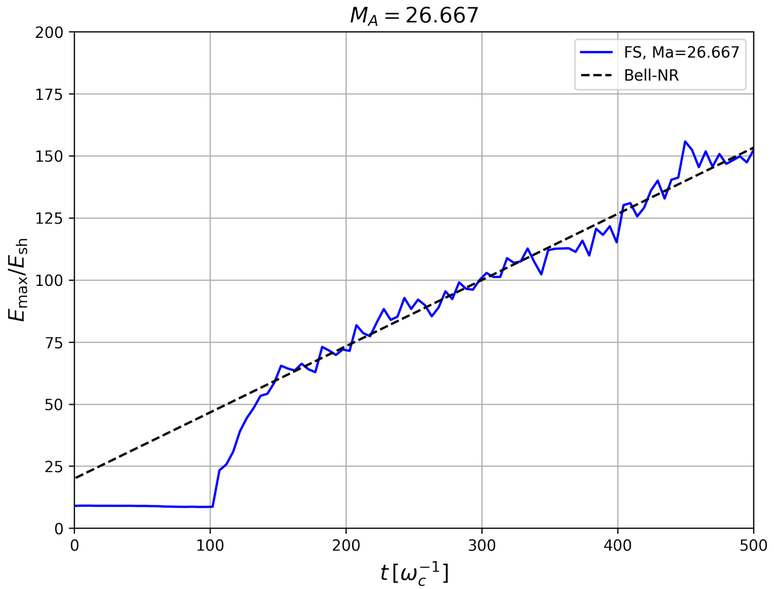

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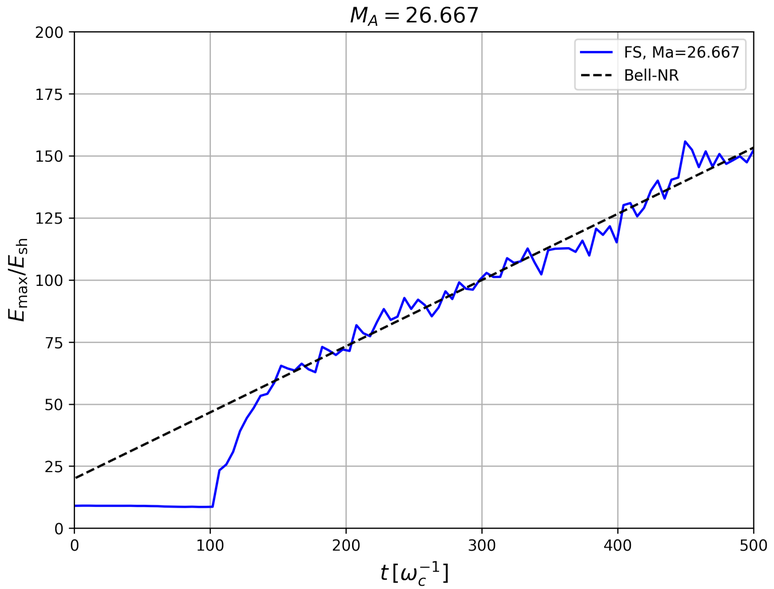

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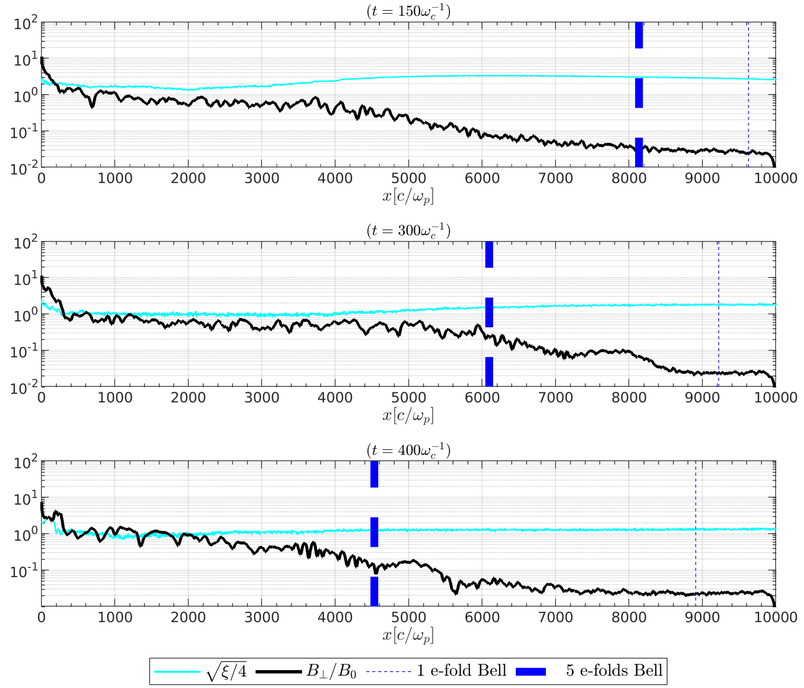

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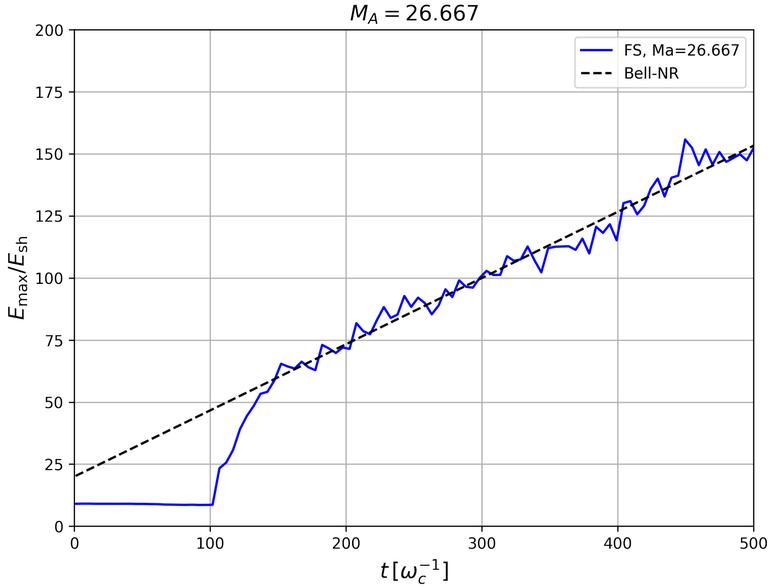

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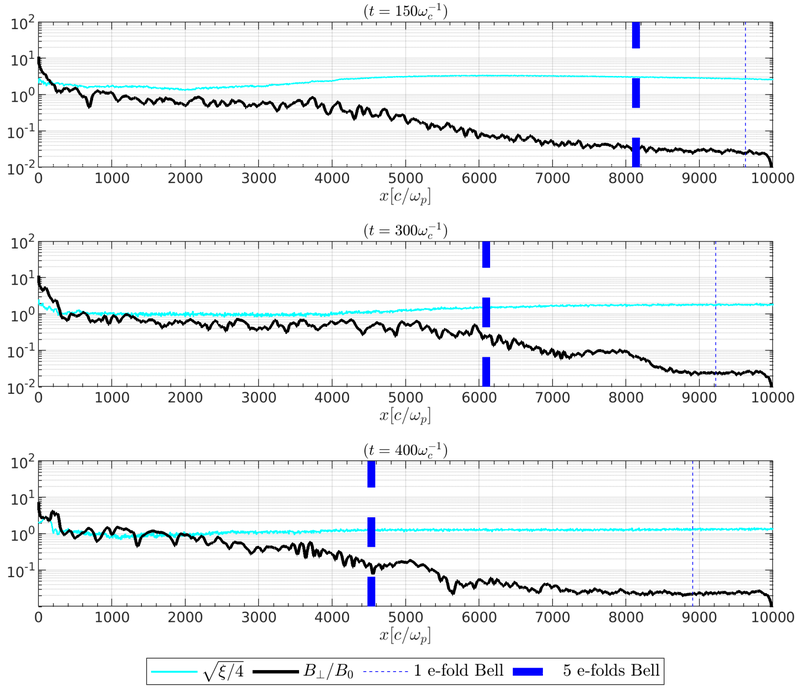
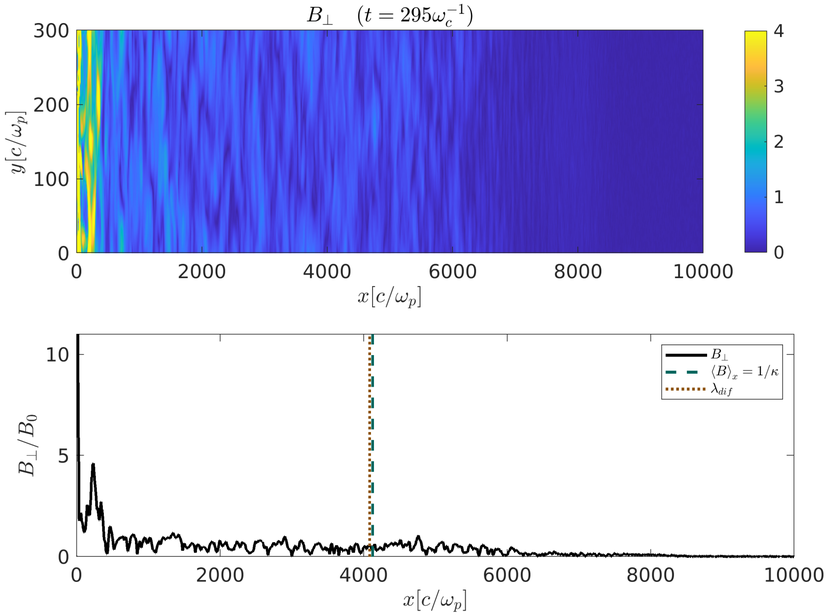


How does the diffusion coefficient compare to Bohm diffusion? *(Caprioli et al. 2014c)*



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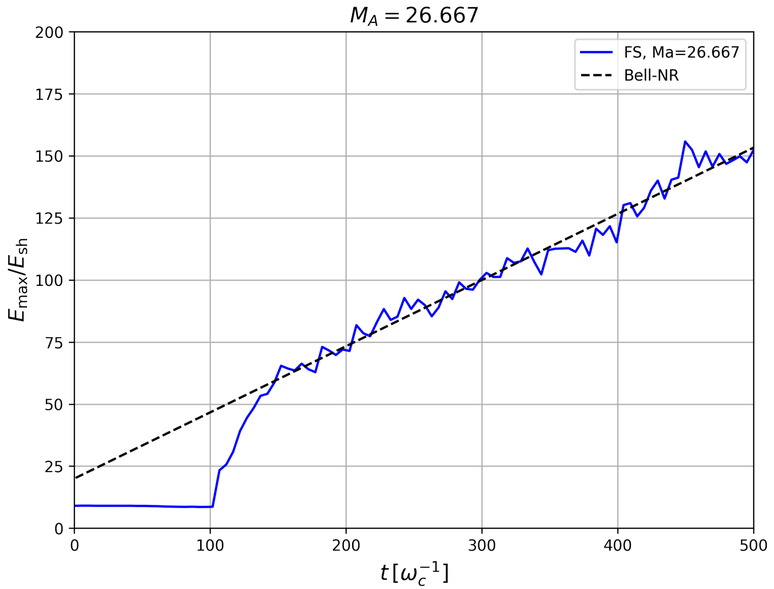

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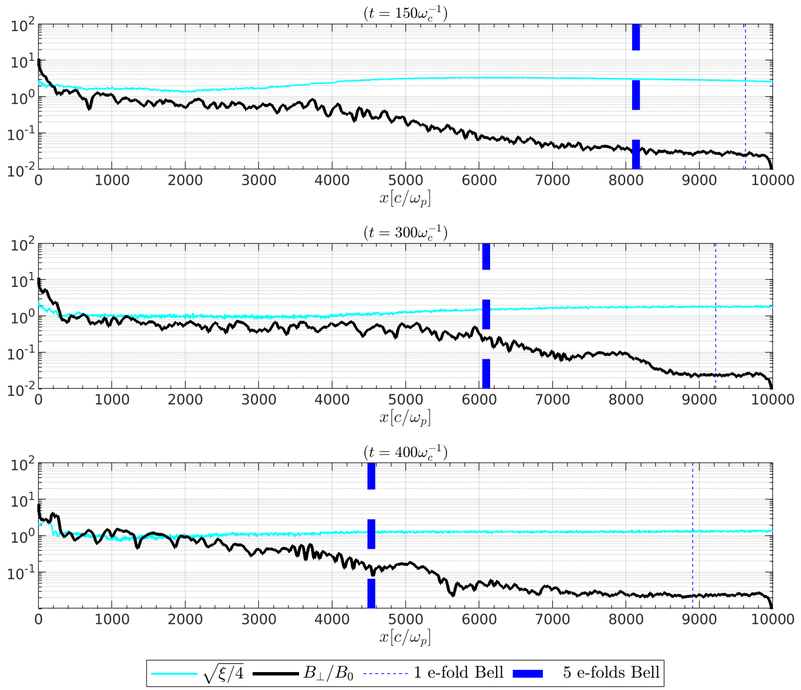

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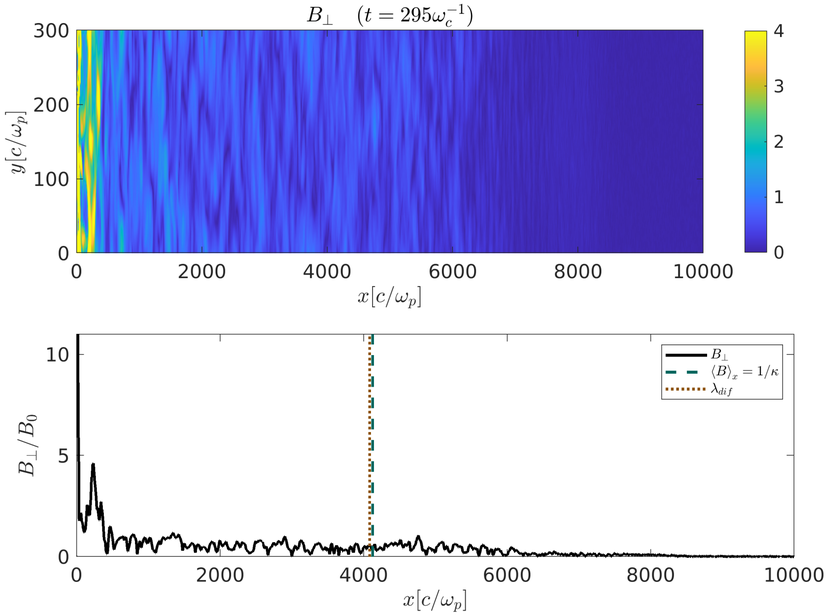
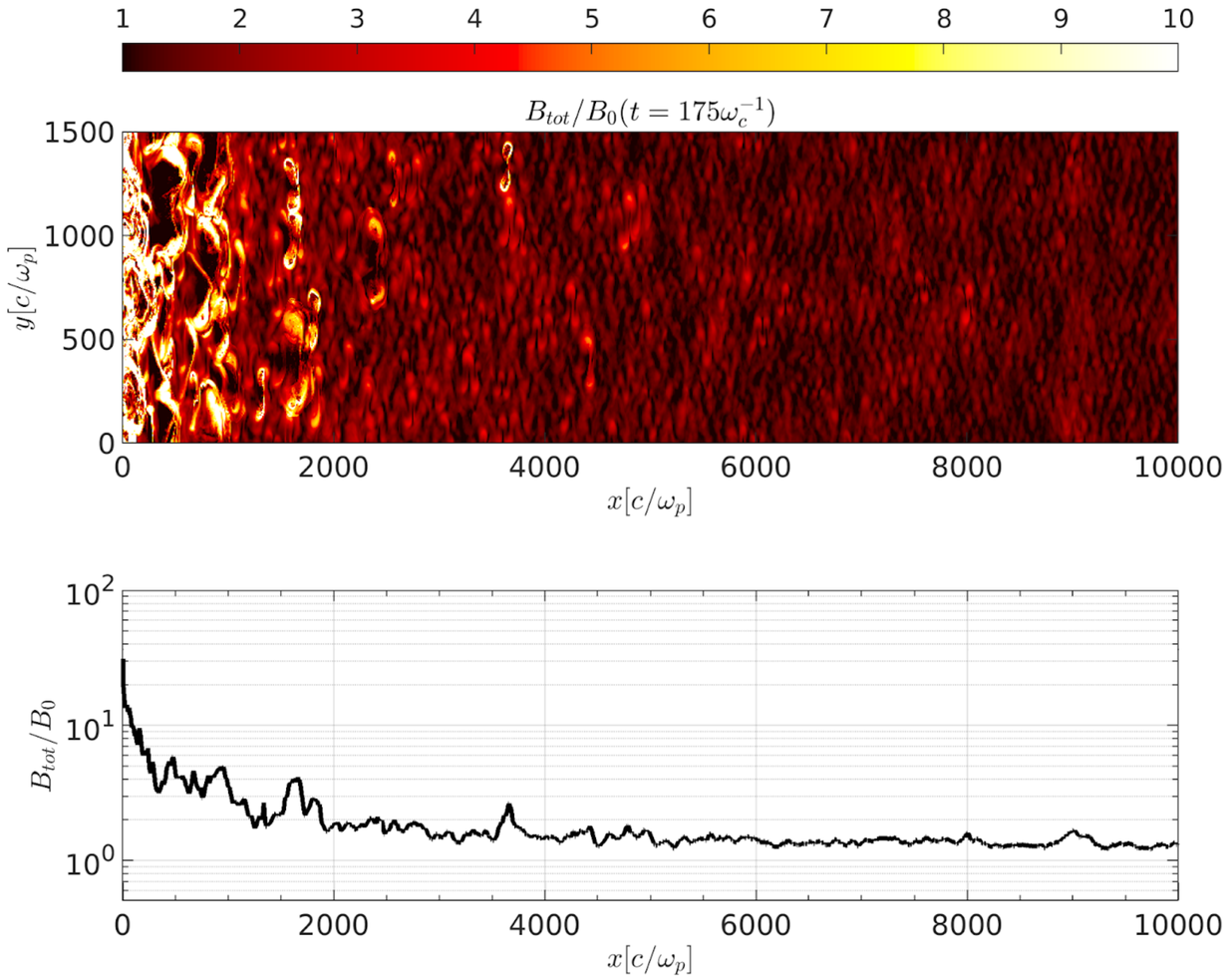


We see very good agreement between predictions and simulations for shocks with $M_A \lesssim 30$

HIGH MACH NUMBER SIMS WITH THE FAUX SHOCK



We see non-linear magnetic field structures arise that go beyond the amplification predicted by Bell, but only if the transverse box size is large enough

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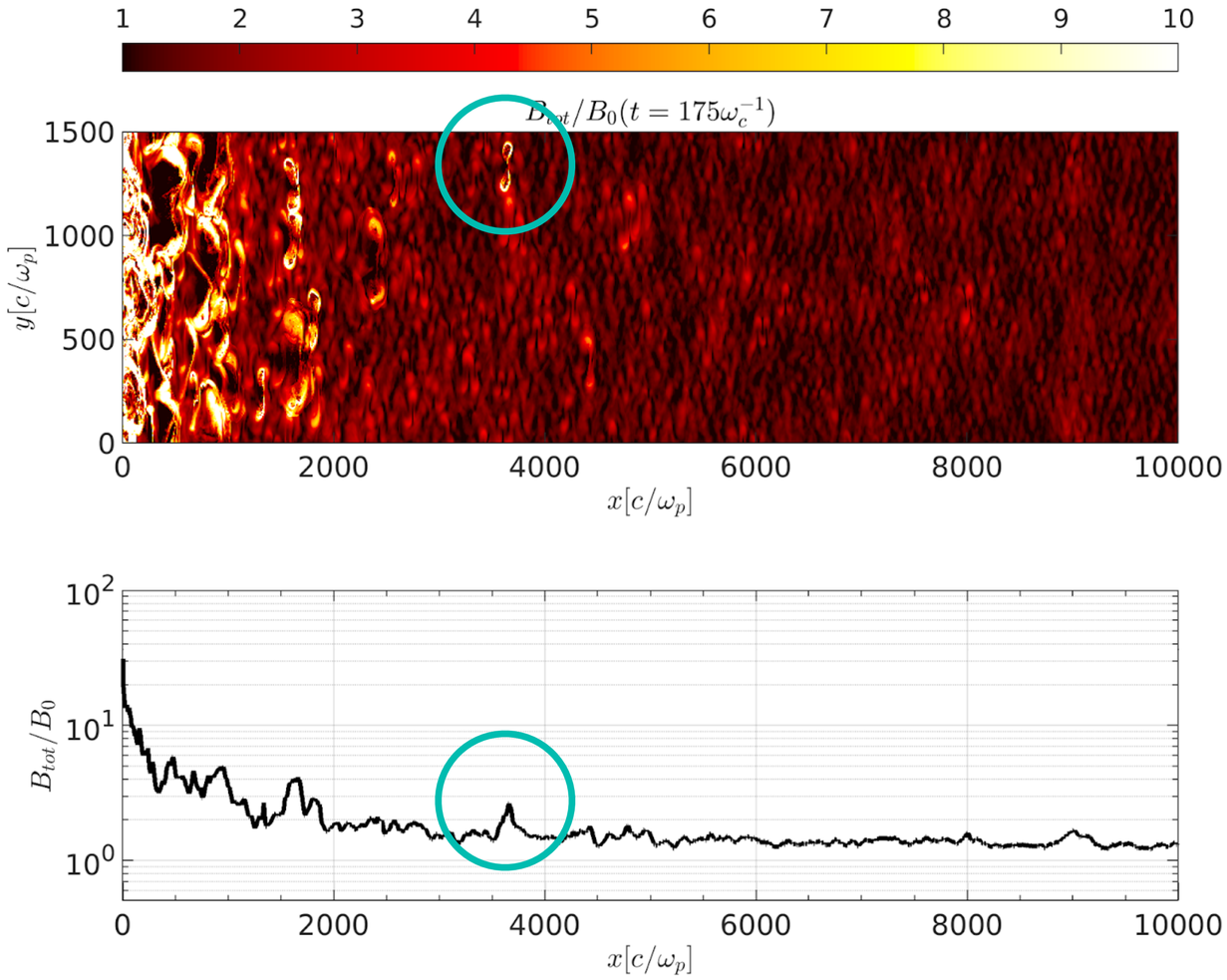

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Relevant literature: *Rogachevskii+2012, Beresnyak+2009, Bell+2025, Zekovic+2024*

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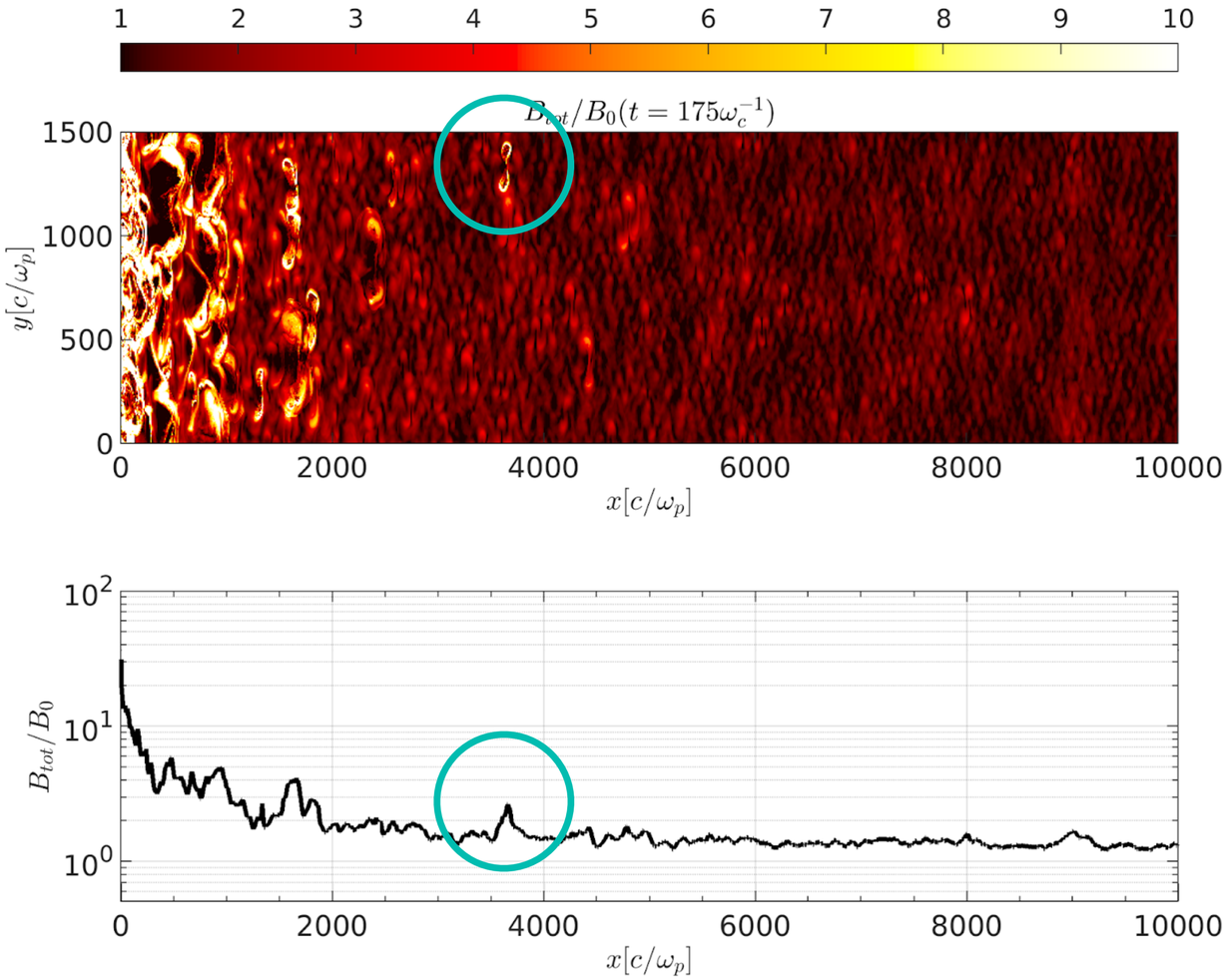

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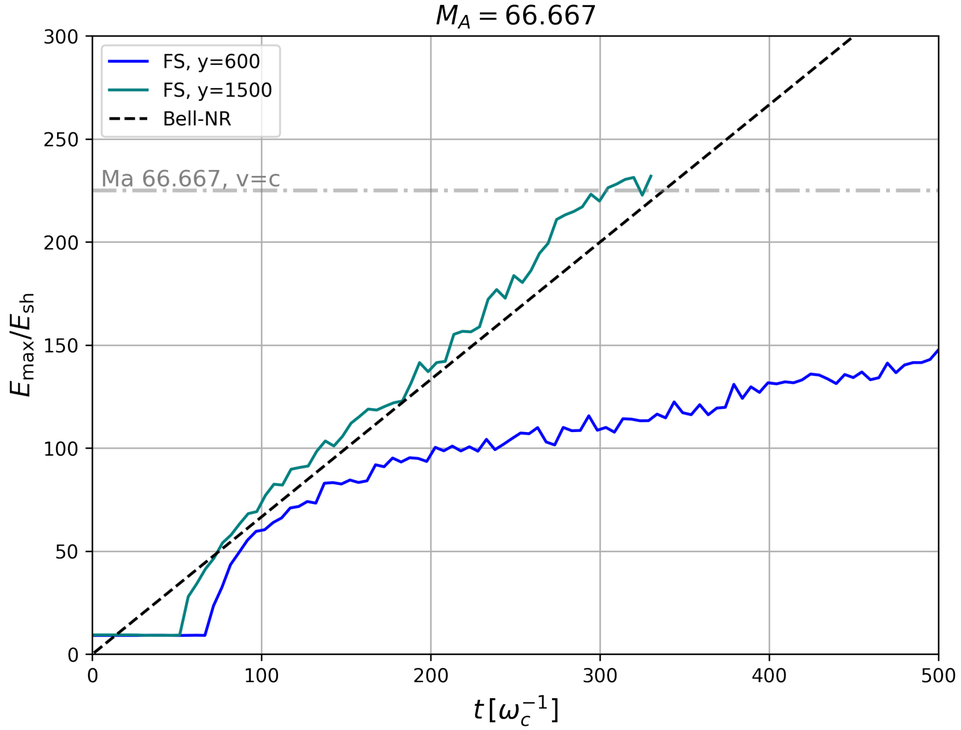

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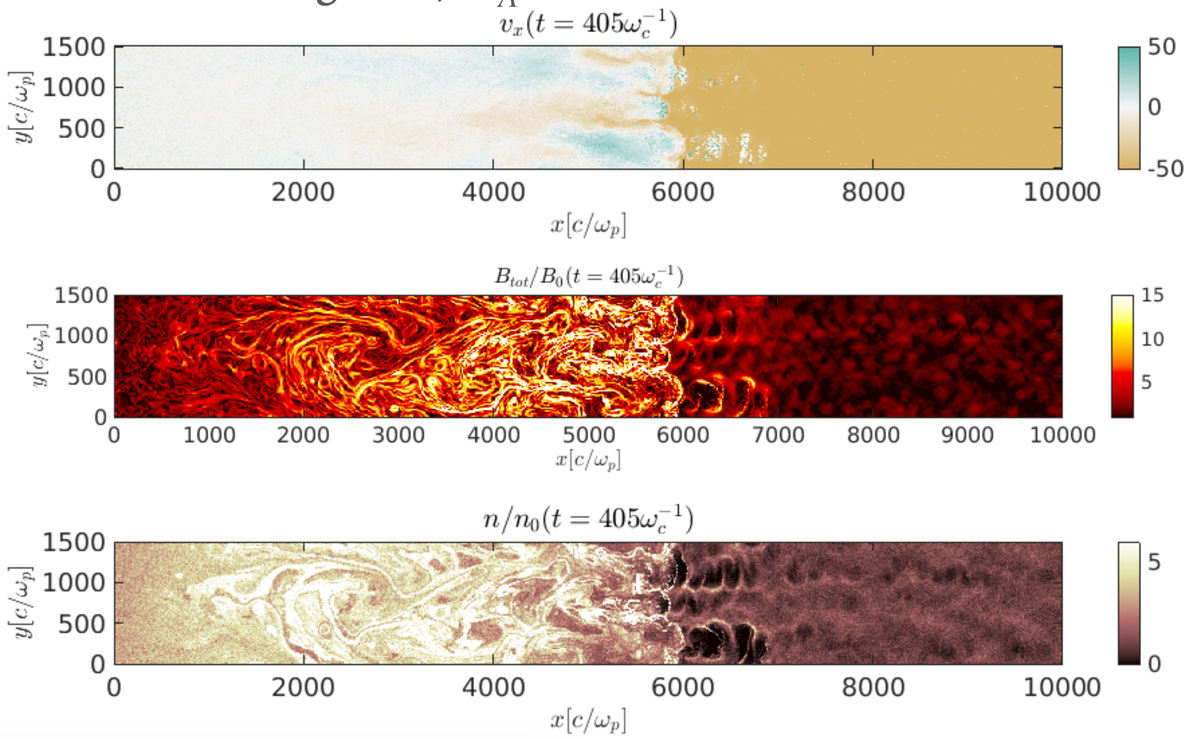
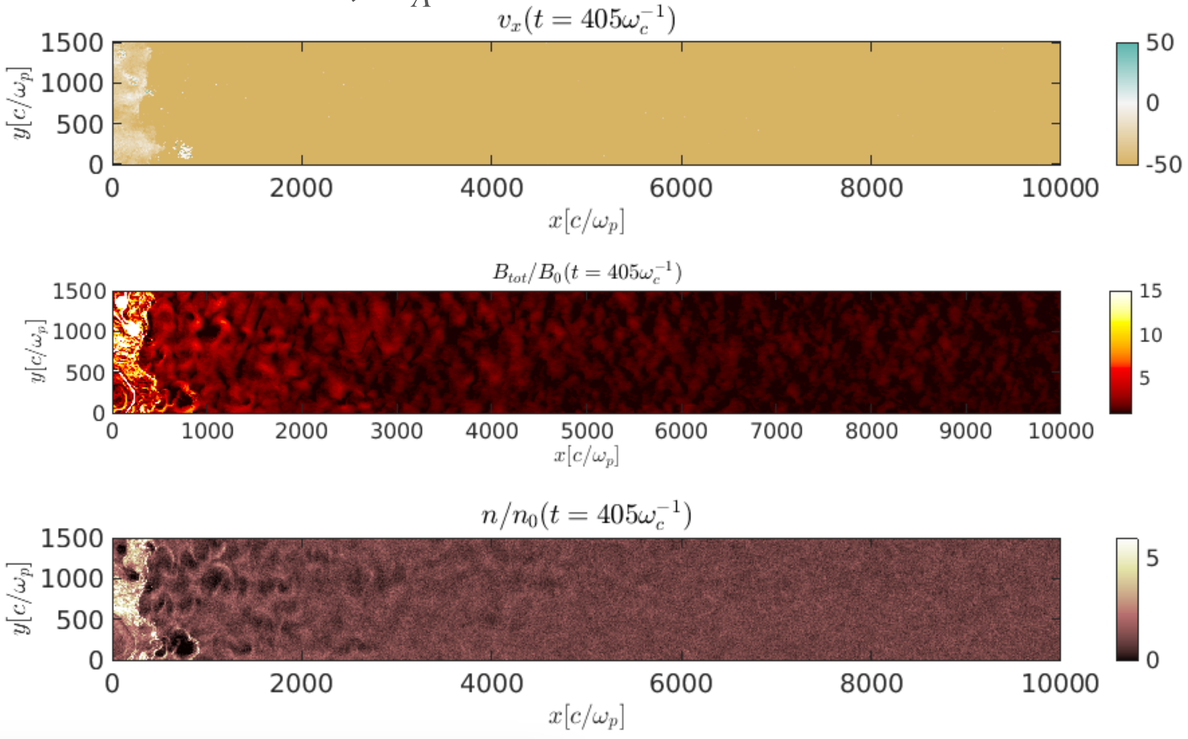
HIGH MACH NUMBER SIMS WITH REFLECTING WALL SHOCKS

Reflecting wall, $M_A = 66.667$



Faux shock, $M_A = 66.667$



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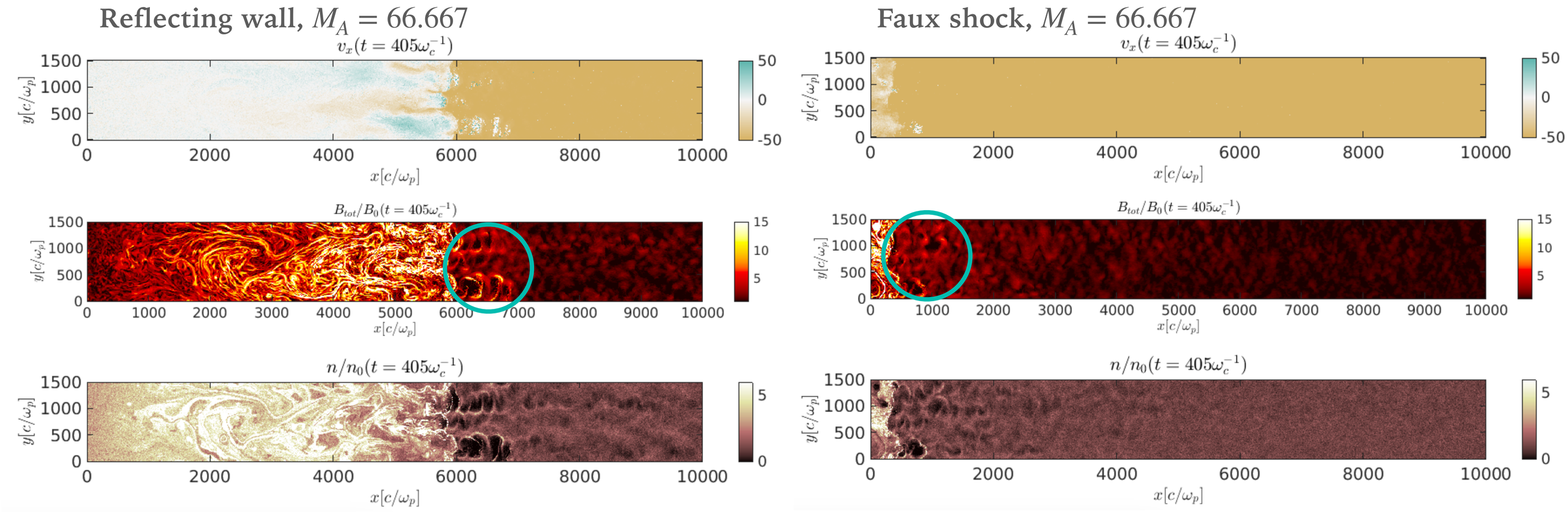


We see something similar in RW simulations

Big question: *does this affect particle acceleration, and can it accelerate particles faster than Bell?*

PART 2 CONCLUSIONS

- The Bell instability predicts that CRs can not be accelerated beyond ~100 TeV in typical SNRs
- Hybrid simulations with the faux shock setup show close agreement with
  - See close agreement with predictions from Bell+13 and Zacharegkas+24 for **low M_A shocks**
  - For higher M_A, we see non-linear structures forming with magnetic fields larger than those predicted from the Bell instability
    - Similar behavior with faux shock and reflecting wall style simulations
- Remains some possibility that there is physics beyond Bell at higher M_A shocks which might increase the rate of particle acceleration

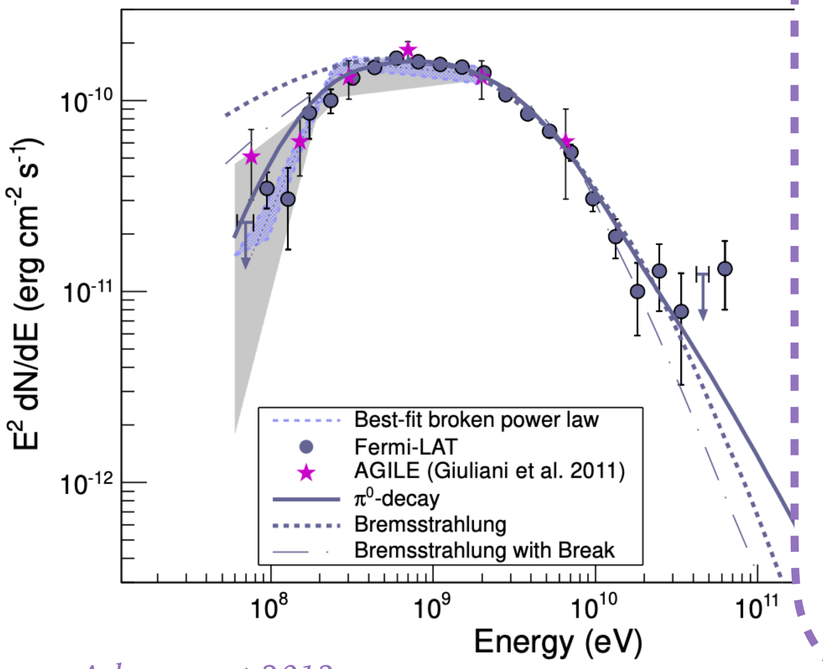
Thanks!

BACKUP

TIER TWO CATALOG: HADRONIC WITH CAVEATS

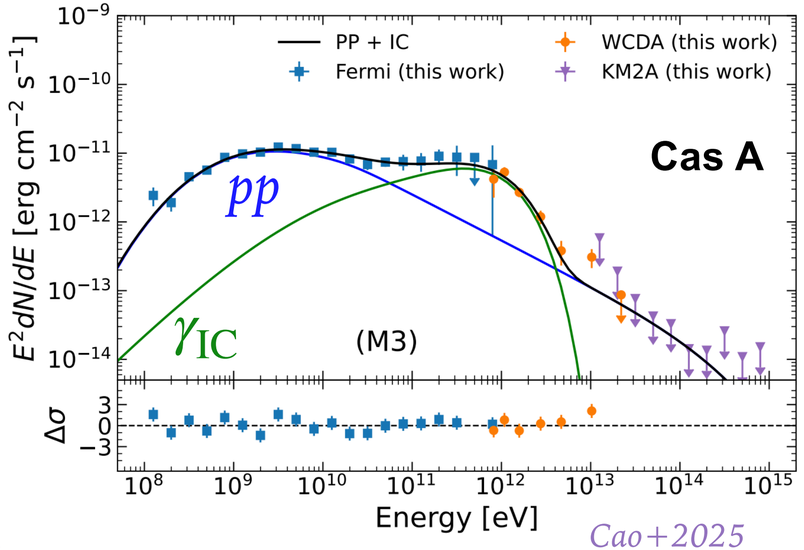
Sources which are at least partially hadronic but don't meet all of the criteria for Tier 1

sub-TeV observed emissio

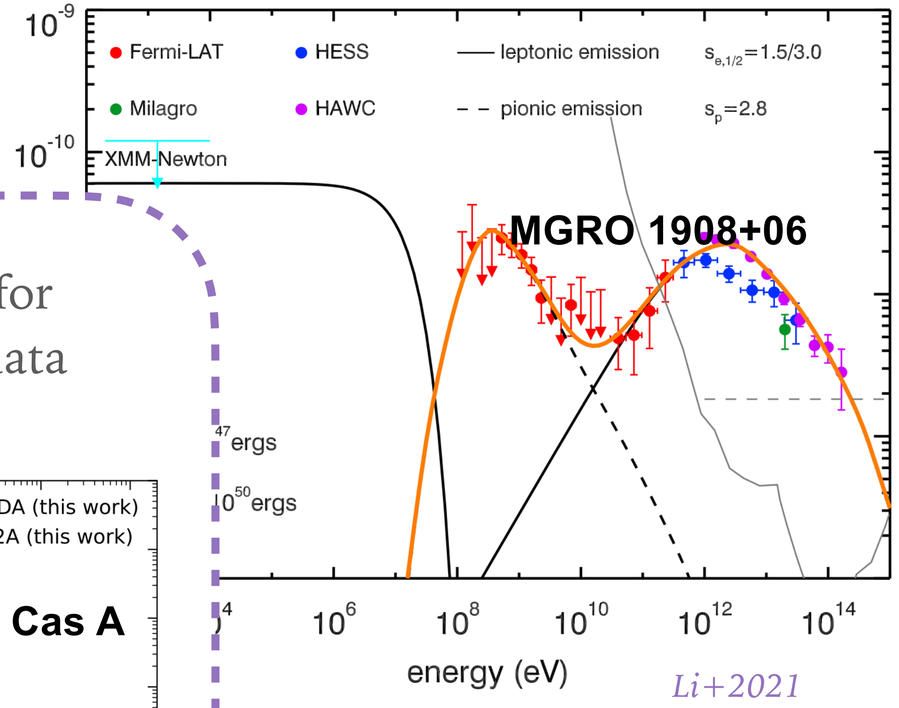


Ackermann+2013

Possibly seeing the same for Cas A (**Tier 1**) with new data from LHAASO?



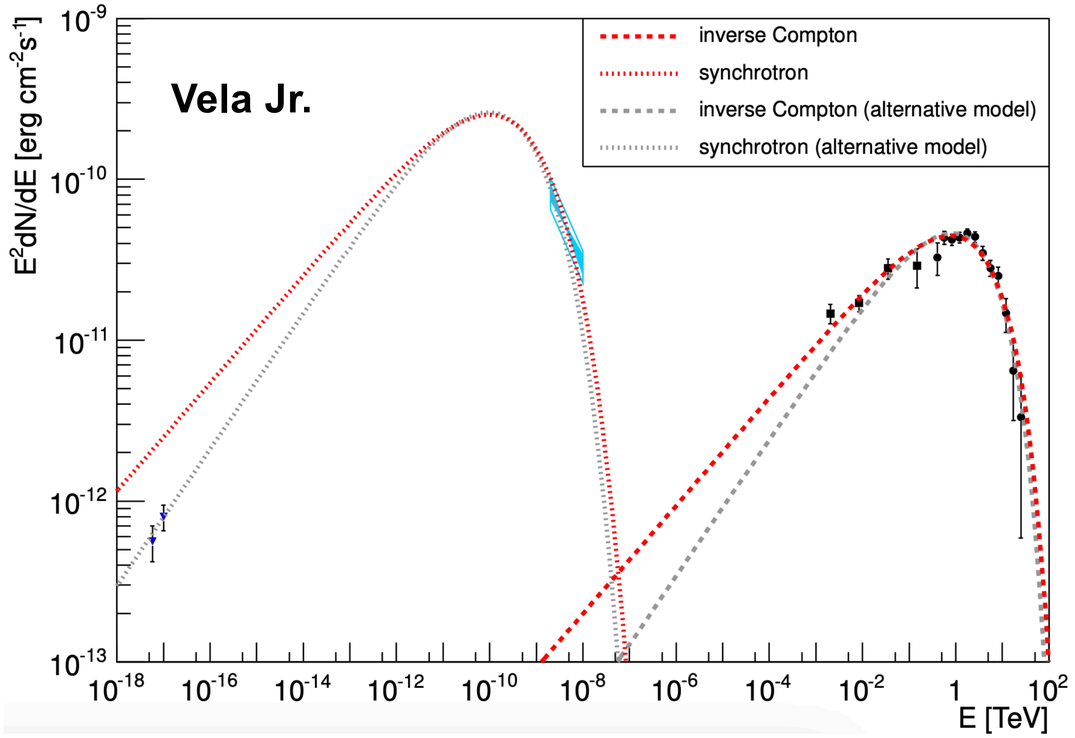
Cao+2025



Li+2021

on decay bump, but switches
o hard, leptonic spectrum at highest energies

TIER THREE CATALOG: LEPTONIC BUT LUMINOUS



H.E.S.S. Collaboration, 2018

Tier 3: Sources which are spectrally steep between GeV - TeV (leptonic-dominated), but have a differential GeV flux ≥ average GeV flux for Tier 1

- Under the most optimistic assumptions possible ($\frac{dN}{dE} \propto E^{-2}$), how much hadronic emission can be buried?

- Is it comparable to the sources in Tier 1?

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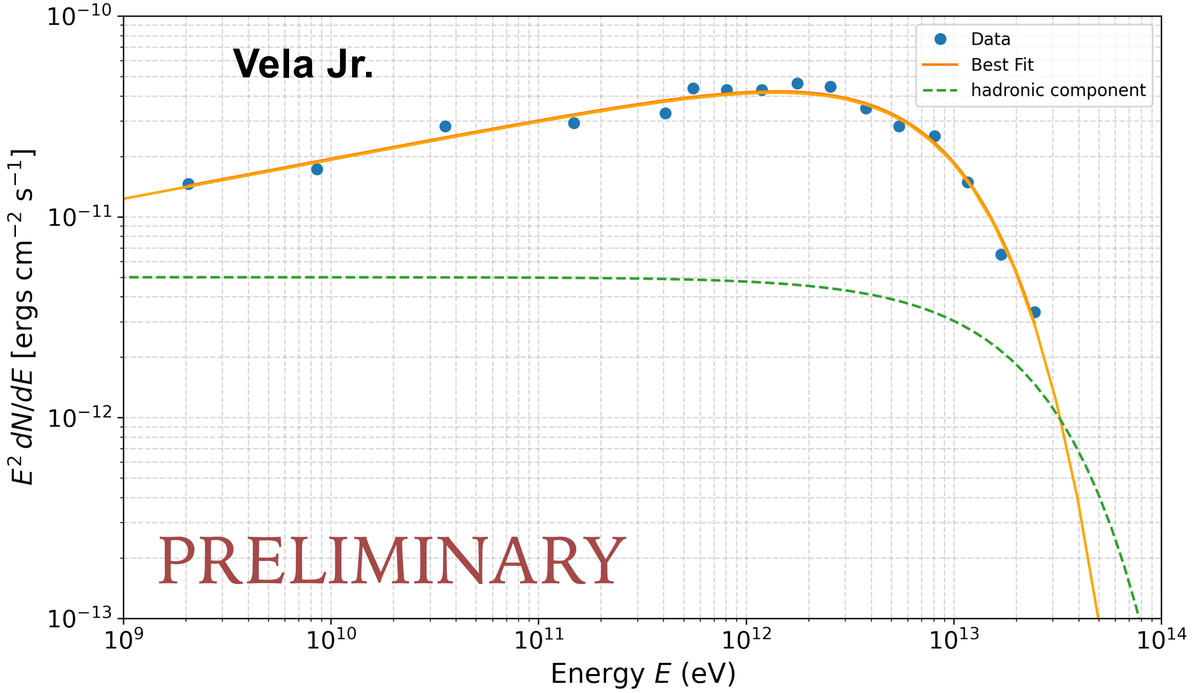

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Hadronic component can have quite a high “buried” contribution.

We then compare this *upper limit* to a realistic estimate based on the shock kinematics and observed SNR environment.