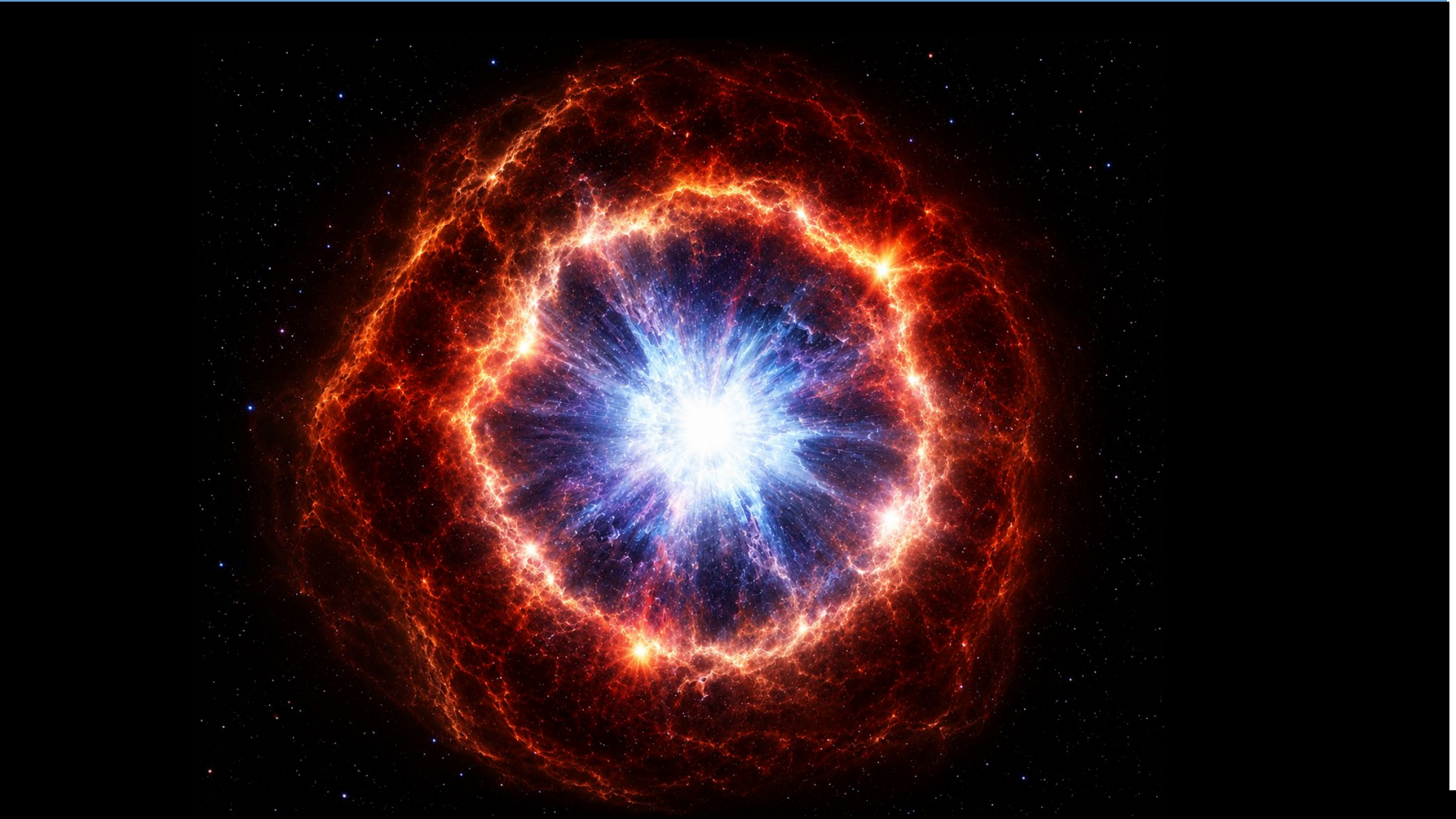

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Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Comunidad de Madrid

Ivan Franko National University of Lviv

Interacting SNe as cosmic-ray factories:
simulations and observations

Iurii Sushch

with Robert Brose, Jonathan Mackey, Maria Arias and others

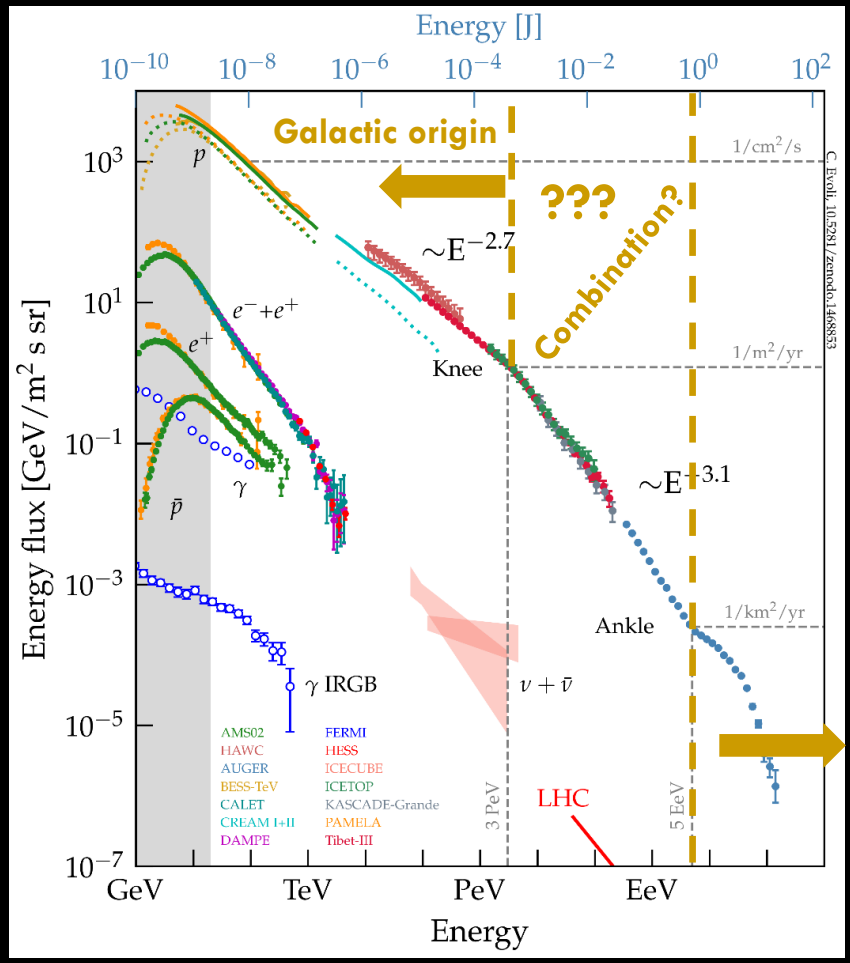
Galactic cosmic rays

- Featureless $\sim E^{-2.7}$ spectrum up to the 'knee' at 3 PeV

- CRs with energies below the 'knee' are of Galactic origin

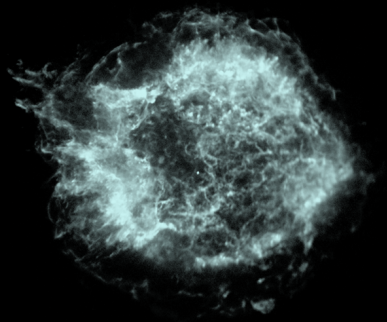
- Protons need to be accelerated to at least PeV energies with a smooth spectrum

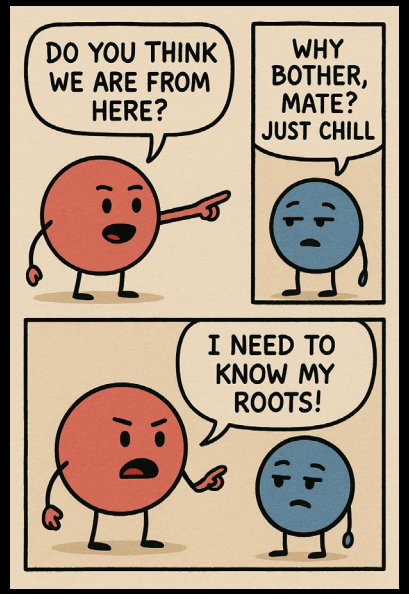
- Need to be accelerated beyond 10 PeV to cover for a smooth transition to extragalactic CRs

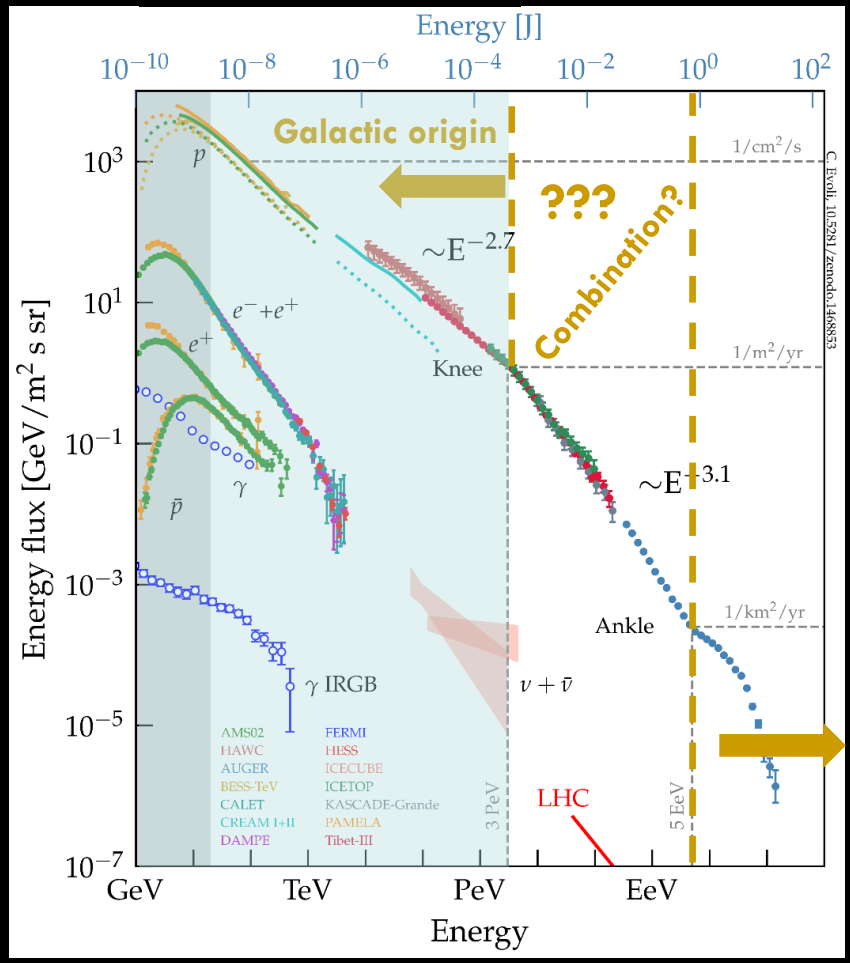


Evoli, 2018

Supernova remnant paradigm







Pro arguments:

- Enough energy to explain the CR energy density
- Effective acceleration at the shock [gamma-rays]
- Same type of sources ensuring smooth spectrum

Evoli, 2018

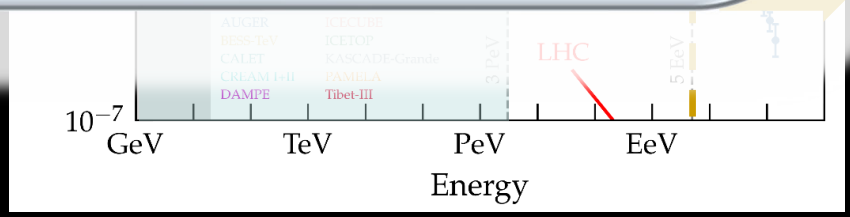
Supernova remnant paradigm

But can they reach the “knee”?

Pro argumen

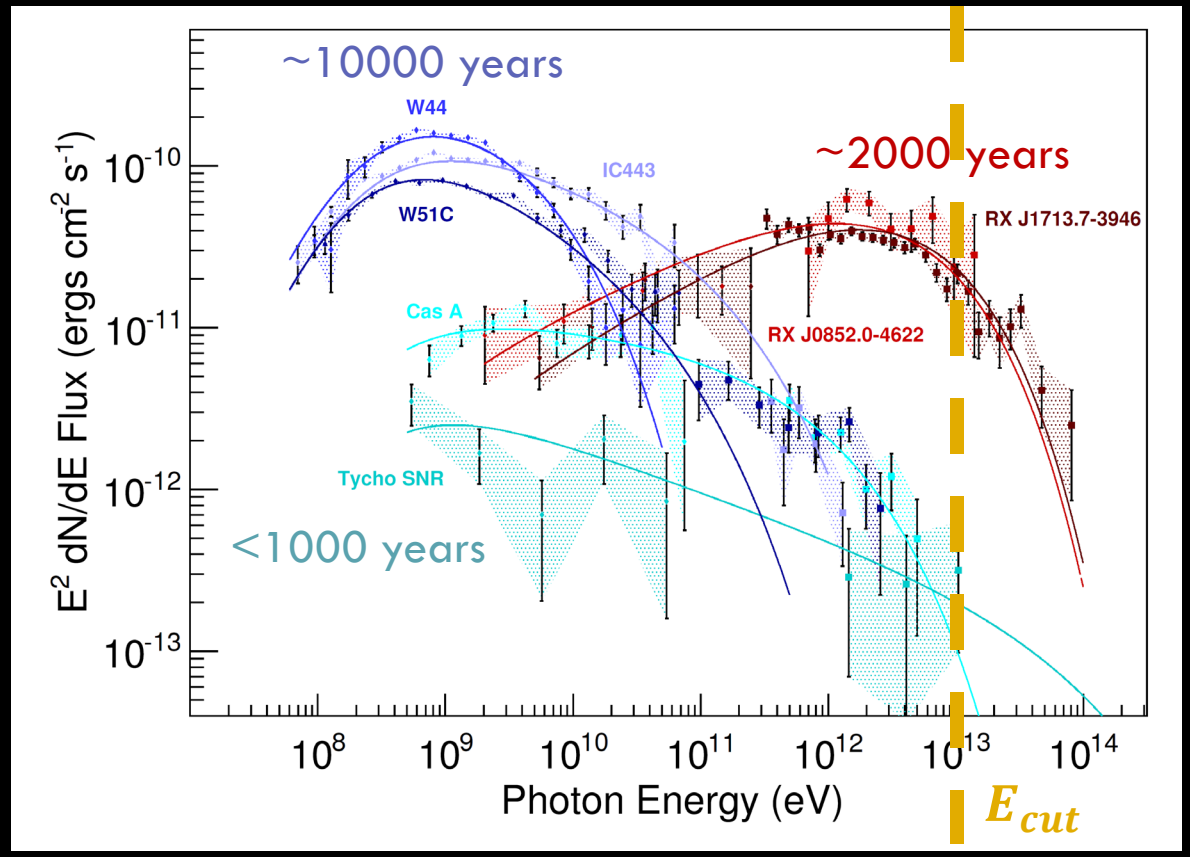
- Enough ene
- Effective accel
- Same type of sources ensuring smooth spectrum

Evoli, 2018



Exragalactic origin

Lack of observation evidence [gamma-rays]



At most reaching ~10 TeV for the cut-off in the gamma-ray spectrum that corresponds to ~100 TeV in maximum energy of protons.

Funk 2015

Maximum energy reachable in SNRs

Hillas criterion or geometrical limit – particles must be contained within the acceleration site, i.e. gyroradius should be smaller than the size of the site

$$E_{max} \sim \frac{B}{1\,mG}\,\frac{v_{sh}}{1000\,km/s}\,\frac{r_{sh}}{1\,pc}\,PeV$$

We need at least $100\ \mu G$ for typical values of shock velocities and sizes, while the intergalactic magnetic field is of order of $\sim 1\ \mu G$

Theoretical perspective

- Magnetic field is amplified through generation of turbulence by accelerated particles
- High ambient densities required to drive turbulence efficiently
- High velocity – young age
- Best case: very young core-collapse SNe with high mass-loss in their progenitors

Theo

- M
  ac
- Hi
- Hi
- Be
  pr

No gamma-ray detection of SNR younger than 330 years (Cas A)

No gamma-ray detections of SNe
(See **Andrea Simongini** talk)

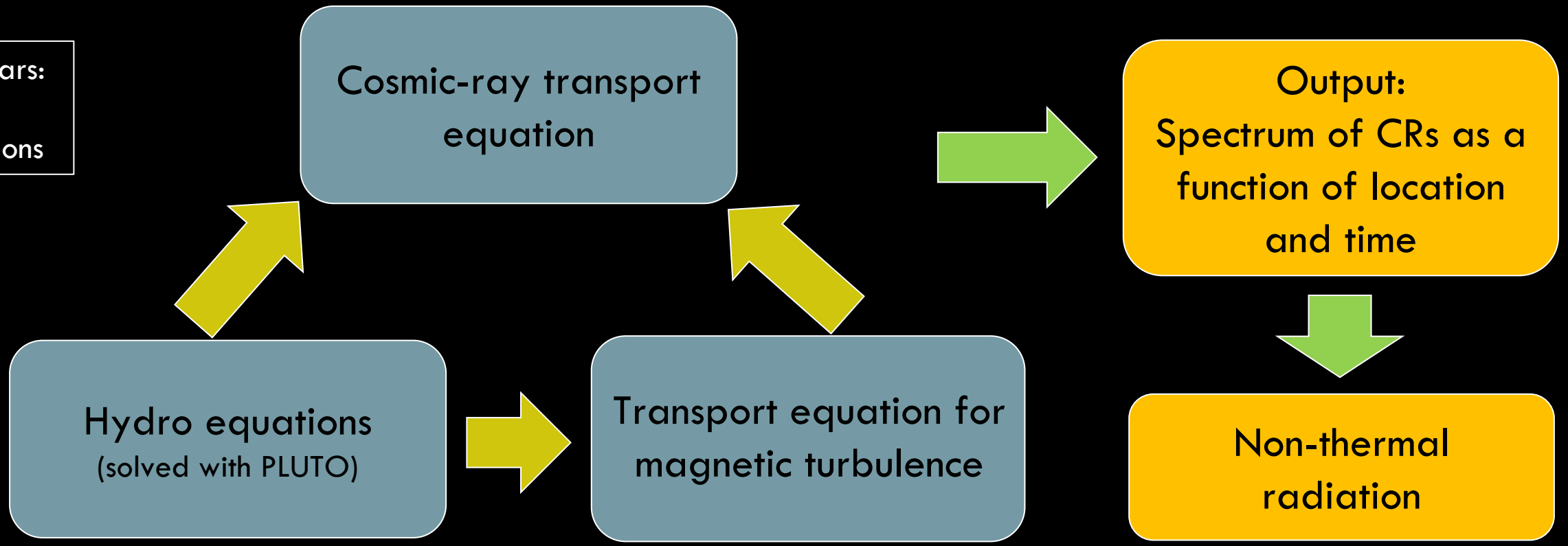
eir

Current main developers: IS, Robert Brose, Ludovica Crosato Menegazzi, Martin Pohl

RATPaC

Radiation Acceleration Transport Parallel Code

In last 5 years:
13 papers
>170 citations



Best case – very young core collapse SNRs

Model	$\dot{M}[M_\odot/\mathrm{yr}]$	V_w [km/s]
LBV	10^{-2}	100
RSG	$8.3 \cdot 10^{-5}$	15

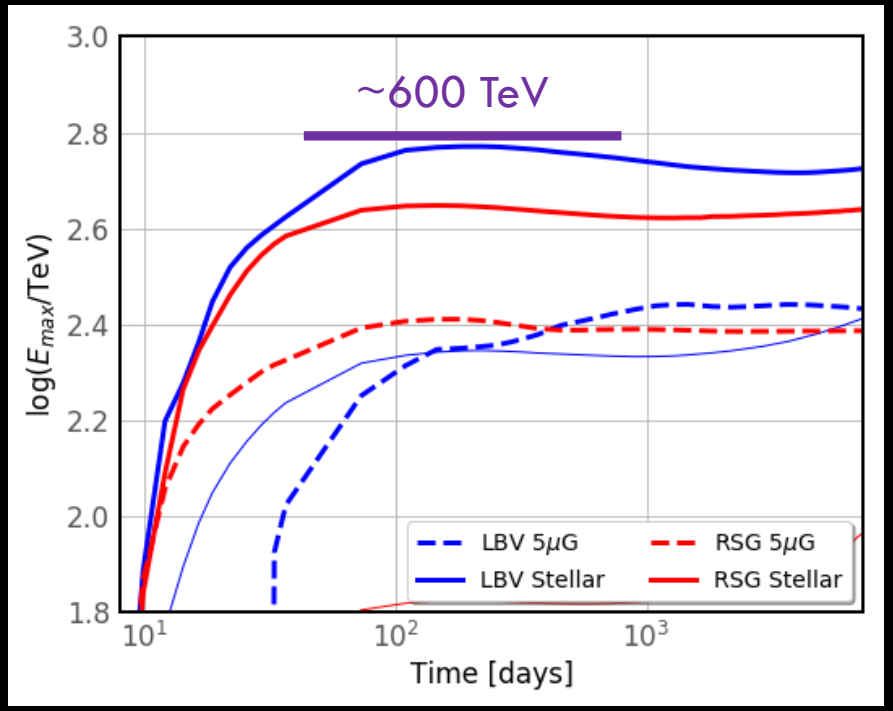
on the high end of the parameter space

$$\rho = \frac{\dot{M}}{4\pi v_w r^2}$$

$$B \sim B_* \frac{R_*}{r}$$

- Maximum energy limited by the available time to grow turbulence and by cascading of turbulence
- Saturates below 1 PeV for most optimistic cases

Type IIn – Luminous Blue Variable (LBV)
Type IIP – Red Supergiant (RSG)
Up to 20 years after explosion

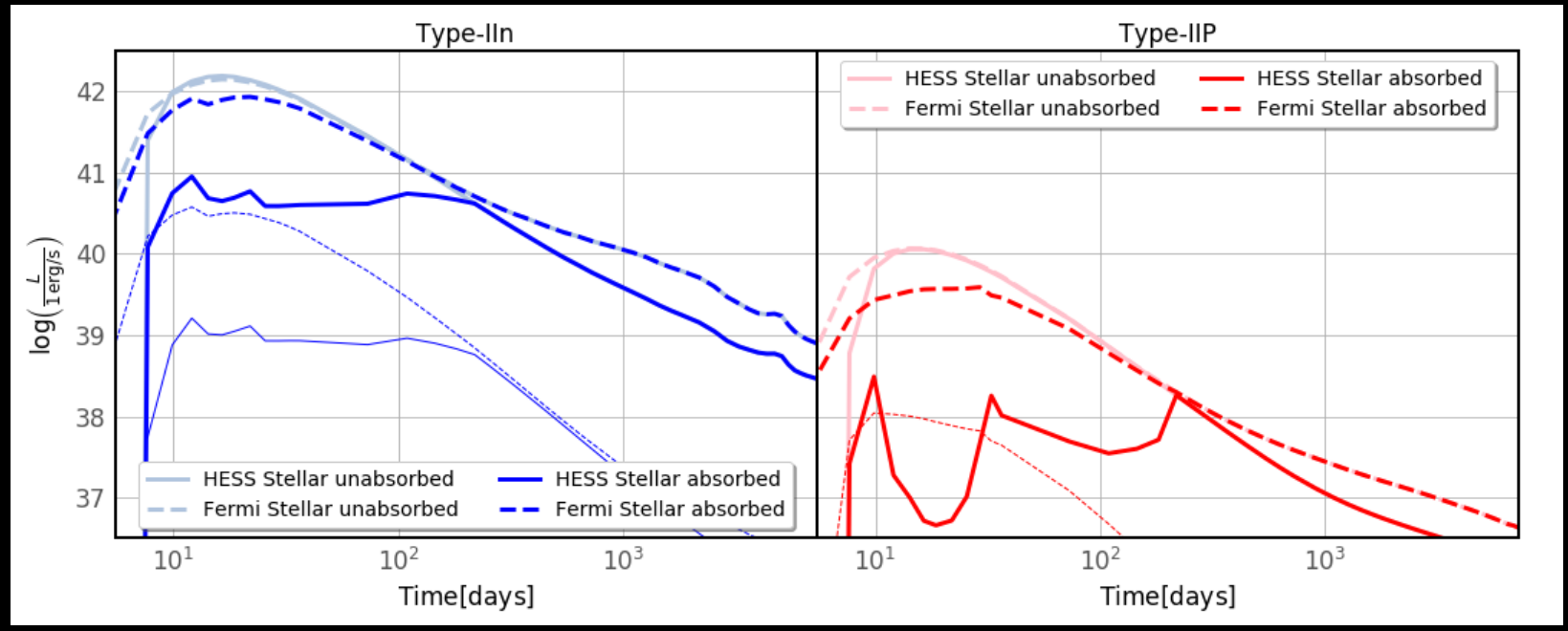


Brose, IS, Mackey, 2022

Problematic to detect in gamma-rays

H.E.S.S.: 1-10 TeV
Fermi: 1-300 GeV

- Absorption is the highest exactly where the intrinsic luminosity peaks
- Absorption is more effective in the H.E.S.S. energy range
- After about 1 year absorption is negligible

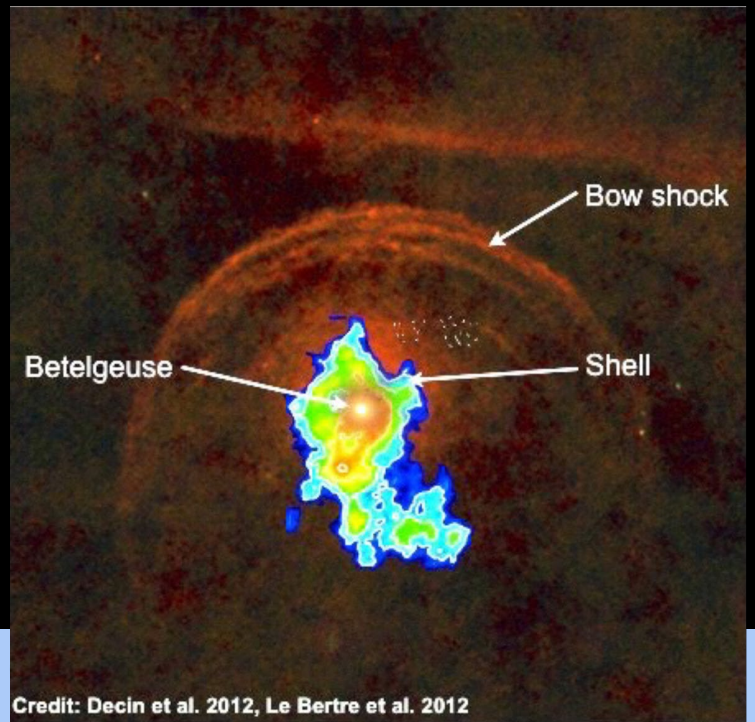


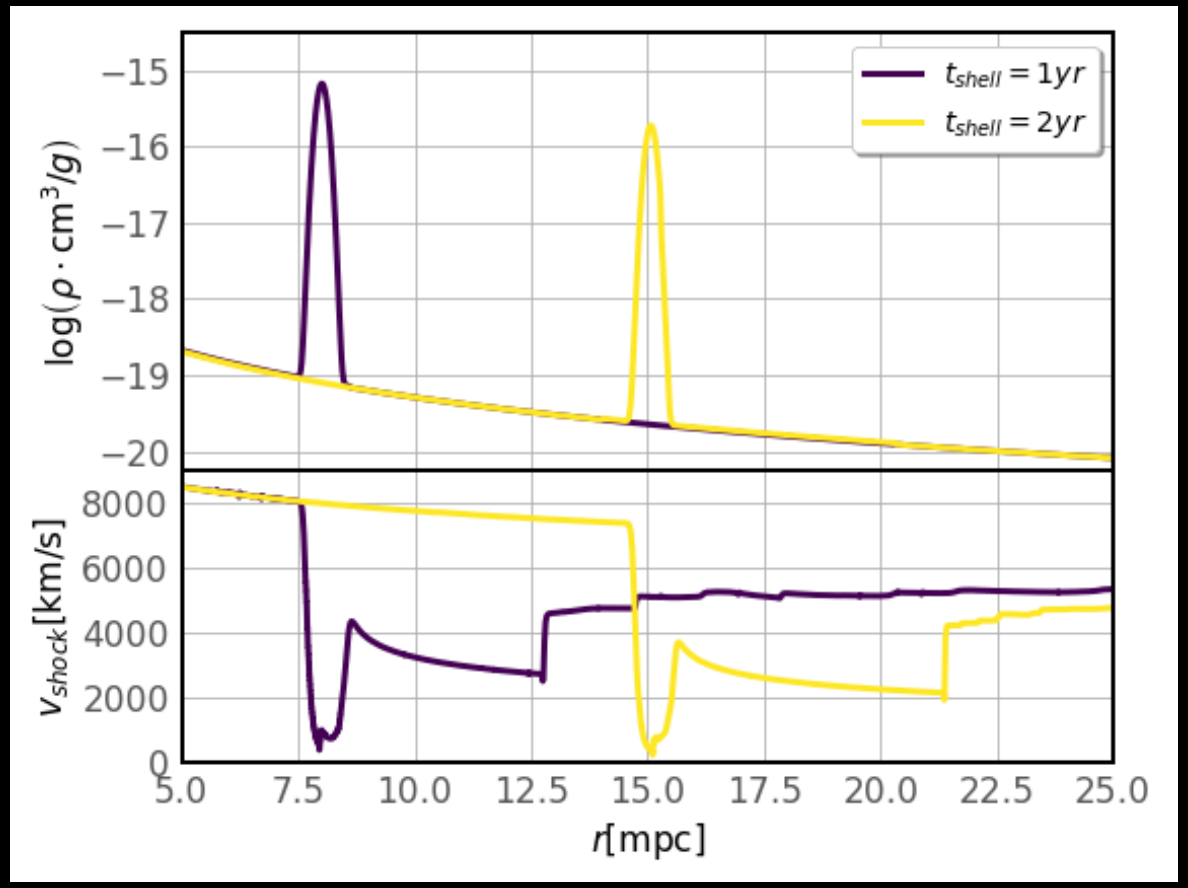
Brose, IS, Mackey, 2022

Can dense shells help?

Interaction with a dense shell formed in the circumstellar medium:

- short episodes of high mass loss in LBV
- photoionised shells with high compression ratio in RSG

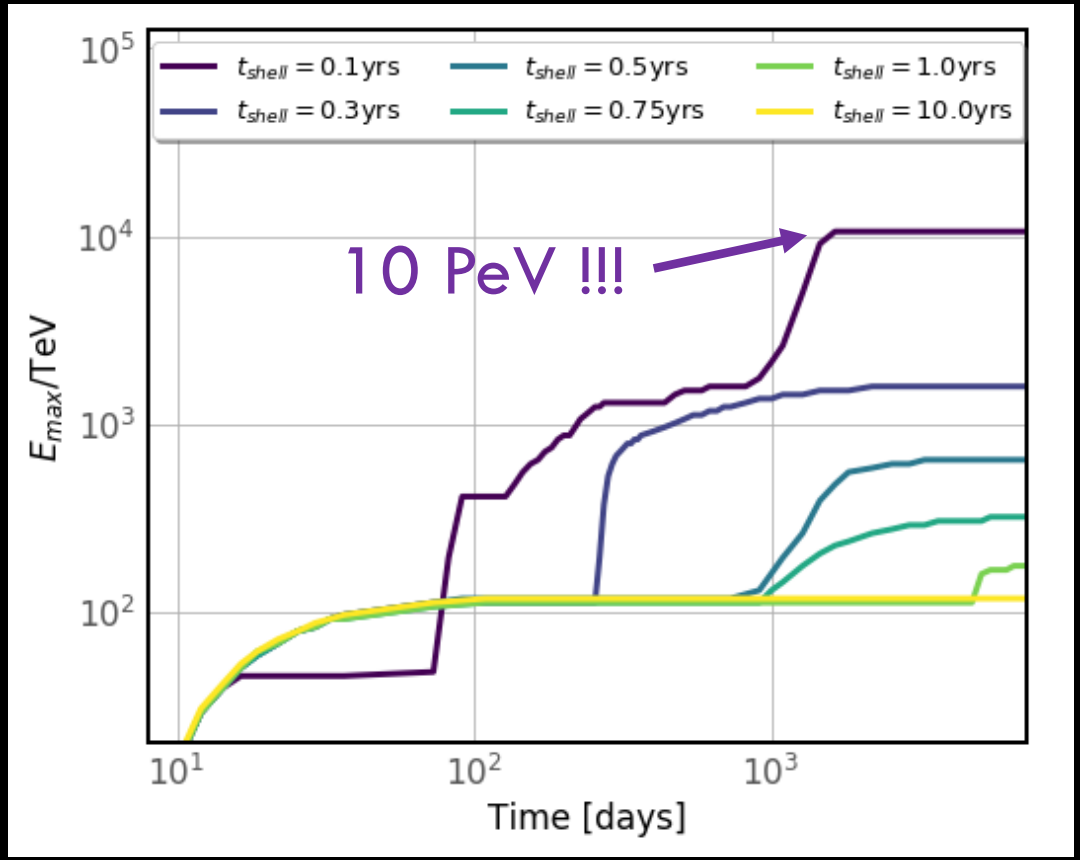




Brose, IS, Mackey, 2025

Can dense shells help?

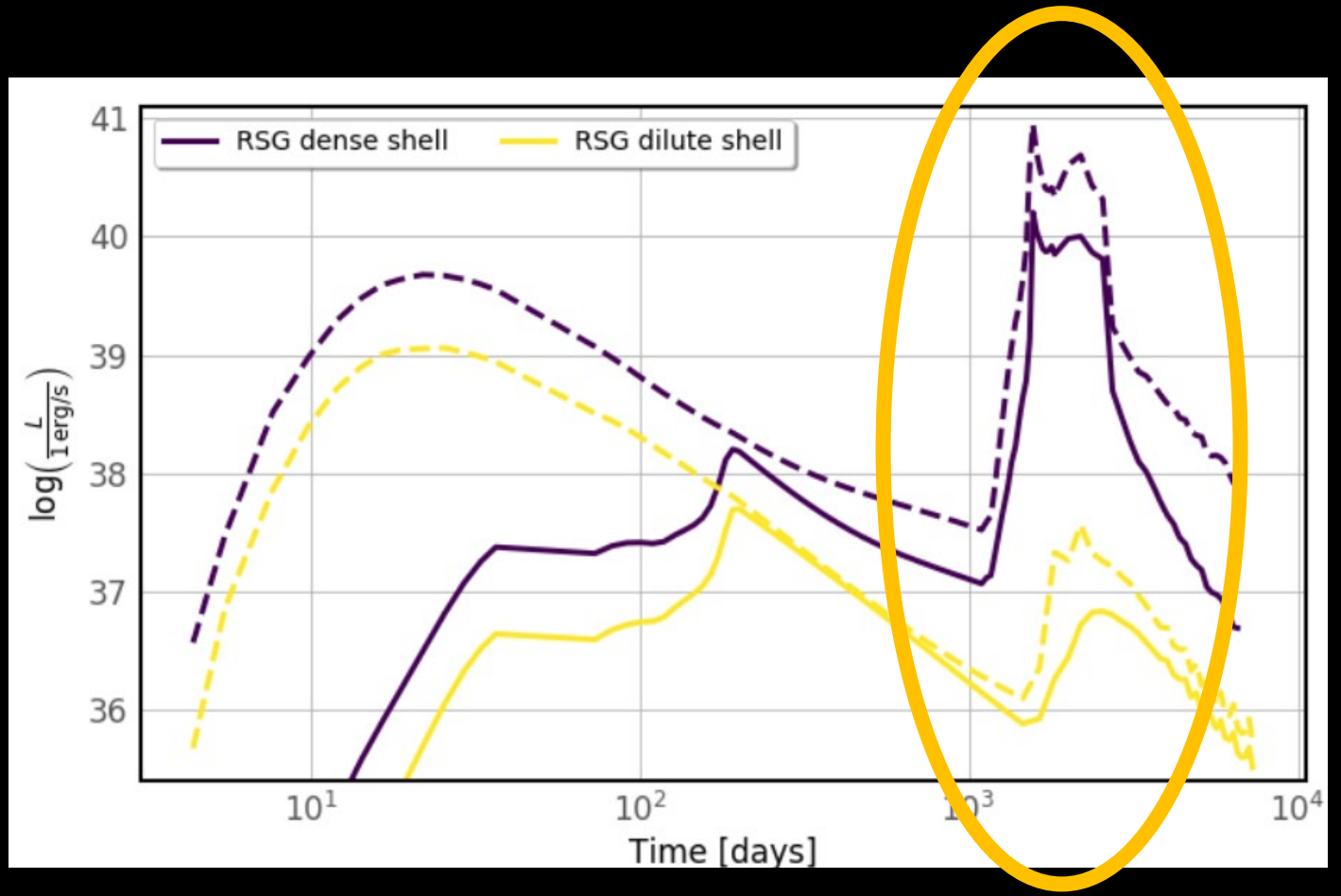
- Shock slows down increasing the precursor length scale and providing additional time for turbulence to grow
- Once passed the shell the shock accelerates again and travels through the medium with pre-amplified field



Brose, IS, Mackey, 2025

Can dense shells help?

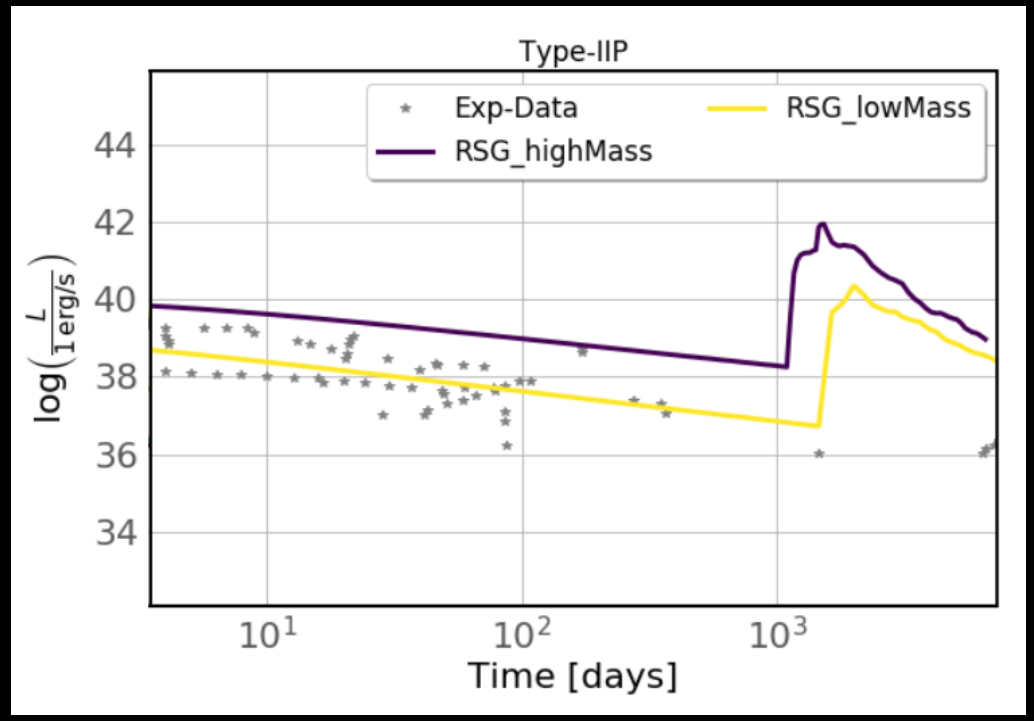
Enhanced gamma-ray luminosities where gamma-gamma absorption is not important anymore



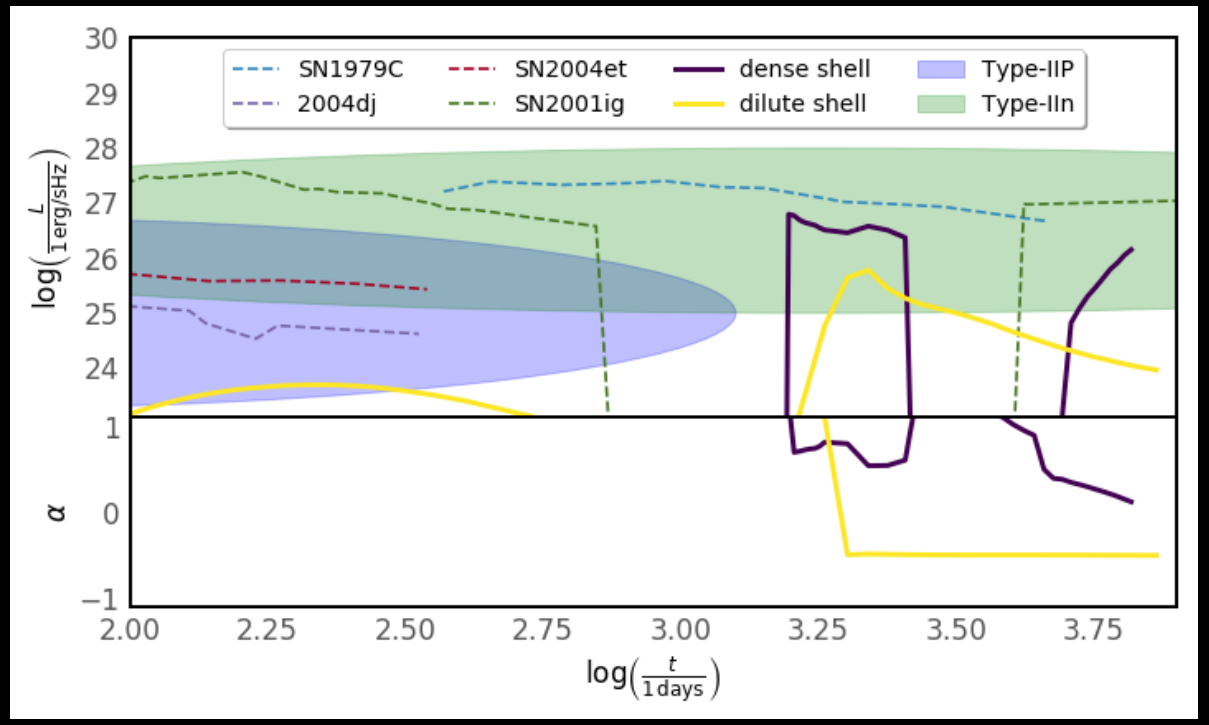
Brose, IS, Mackey, Arias 2026

Multiwavelength

Figure: X-ray luminosity



Figure(top): Radio luminosity at 4GHz.
Figure(right): Radio spectral-index 4GHz



Brose, IS, Mackey, Arias 2026

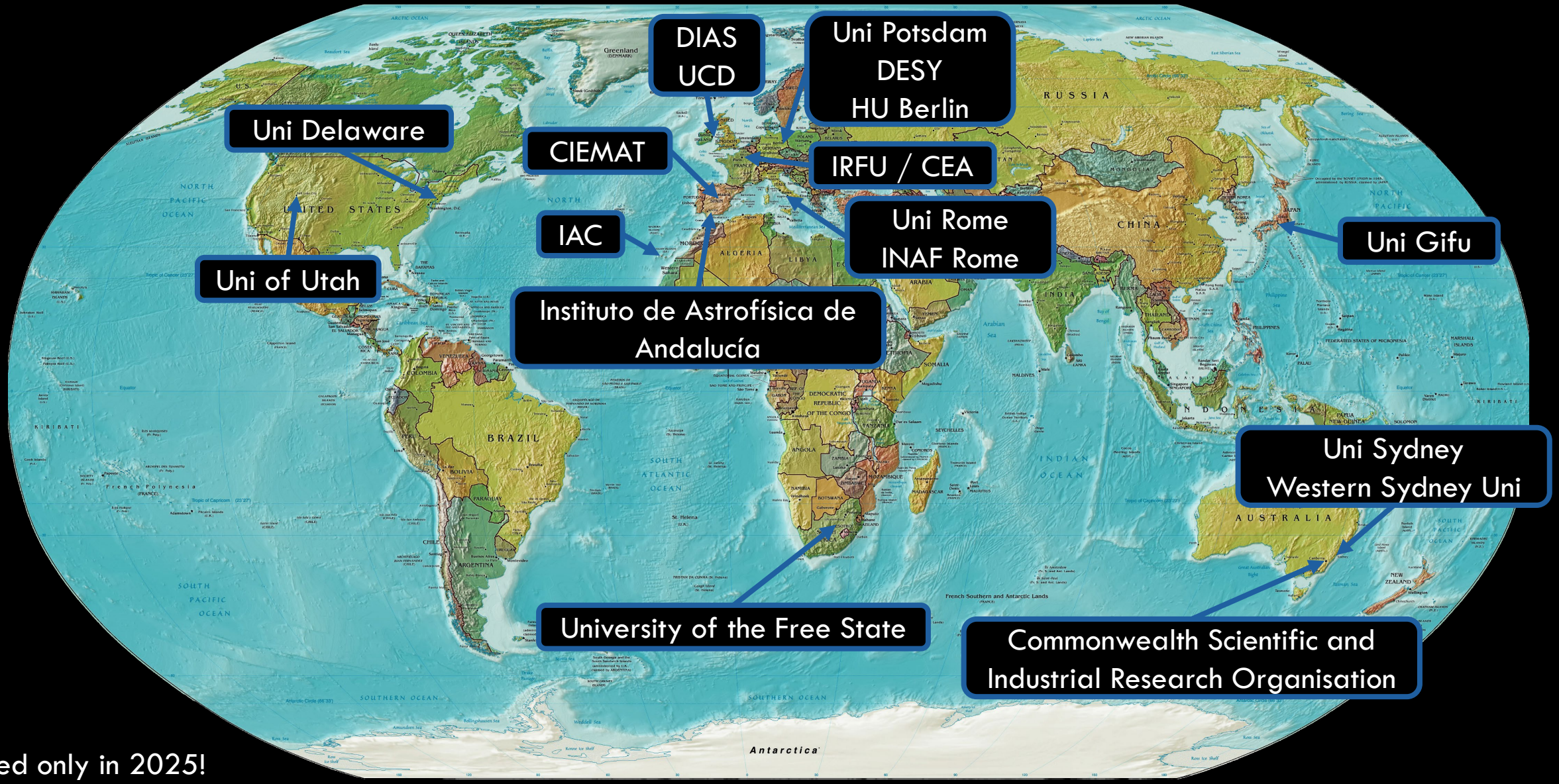
The RISE Project

Rebrightening of Interacting Supernova Emission

Key Idea:

- Monitor nearby SNe regularly
- Distances ≤ 15 Mpc
- Use radio and possibly millimeter observations
  → Short observation times
  → Less absorption in millimeter
  → Higher cadence
- Follow-up with gamma-ray, optical, (millimeter, more radio) and x-ray instruments
  → More contested wavebands
- Experts from many fields are required!

The RISE Collaboration



Started only in 2025!

The RISE “facilities”

First RISE Detections with ATCA!

Event	Type	Host	D (Mpc)	RA	Dec	Outcome
SN 2005af	IIP	NGC4945	4.2	13:05:19.3	-49:33:30	N
SN 2007it	II	NGC5530	12.2	14:18:25.6	-43:22:54	N
SN 2011ja	IIP	NGC 4945	4	13:05:11.119	-49:31:27	Y [14]
SN 2019ejj	II	ESO 430-G20	11	08:07:08.760	-28:03:11.66	N [15]
SN 2019fcn	II	ESO 430-G20	11	08:07:08.054	-28:03:22.90	N [15]
SN 2022aau	II	NGC 1672	15	04:45:41.754	-03:26:37.9	N [16]
SN 2024ggi	II	NGC 3621	7	11:19:37	-32:58:42	Y [17]

Overlapping with known x-ray binary

Table: Southern Radio and Millimeter targets (ATCA)

2.5 detections out of 7 targets!

SN 2007it

- no previous detection at radio
- (re-)brightening 18 years after explosion

RNAAS RESEARCH NOTES OF THE AAS

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SN 2007it on the RISE—A Radio Detection of an Interacting Supernova 18 yr Post-explosion

F. Acero, R. Z. E. Alsaberi, M. Arias, J. Borowska-Naguszewska, R. Brose, C. Burger-Scheidlin, P. G. Edwards, Q. Feng, M. D. Filipović, T. Laskar, S. Lazarević, J. Mackey, A. Nucara, K. Rose, S. Ryder, F. Schüssler, A. Simongini, Z. J. Smeaton, I. Sushch, S. Zhu, and The RISE Collaboration

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Research Notes of the AAS, Volume 10, Number 5

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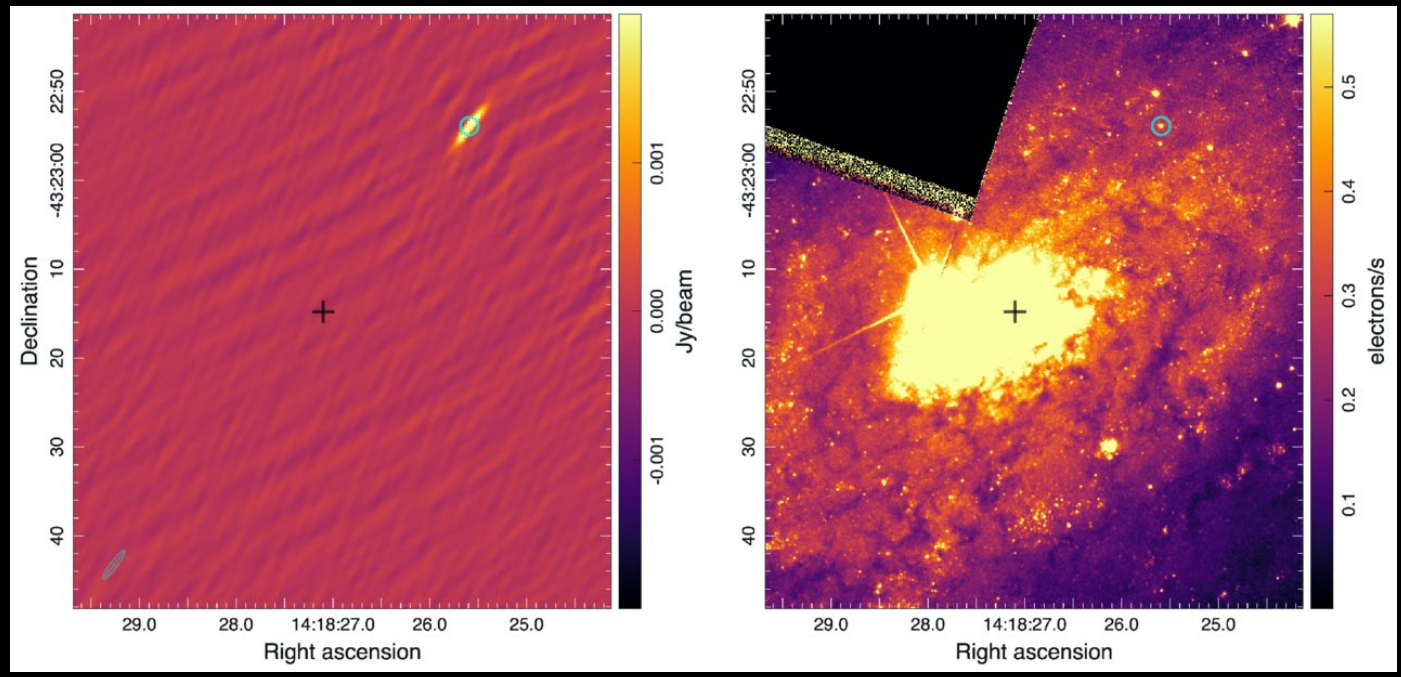
DOI 10.3847/2515-5172/ae6702



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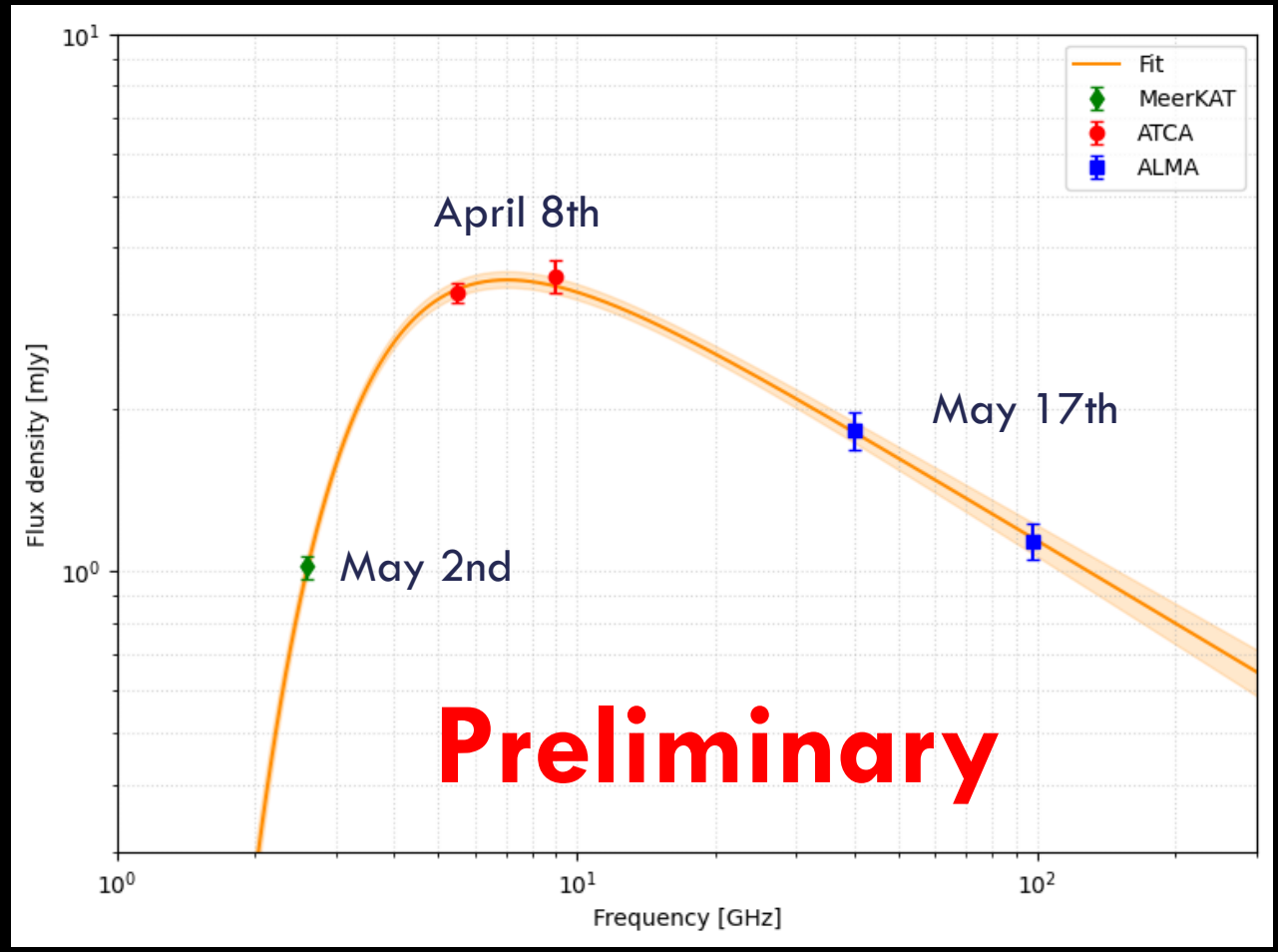

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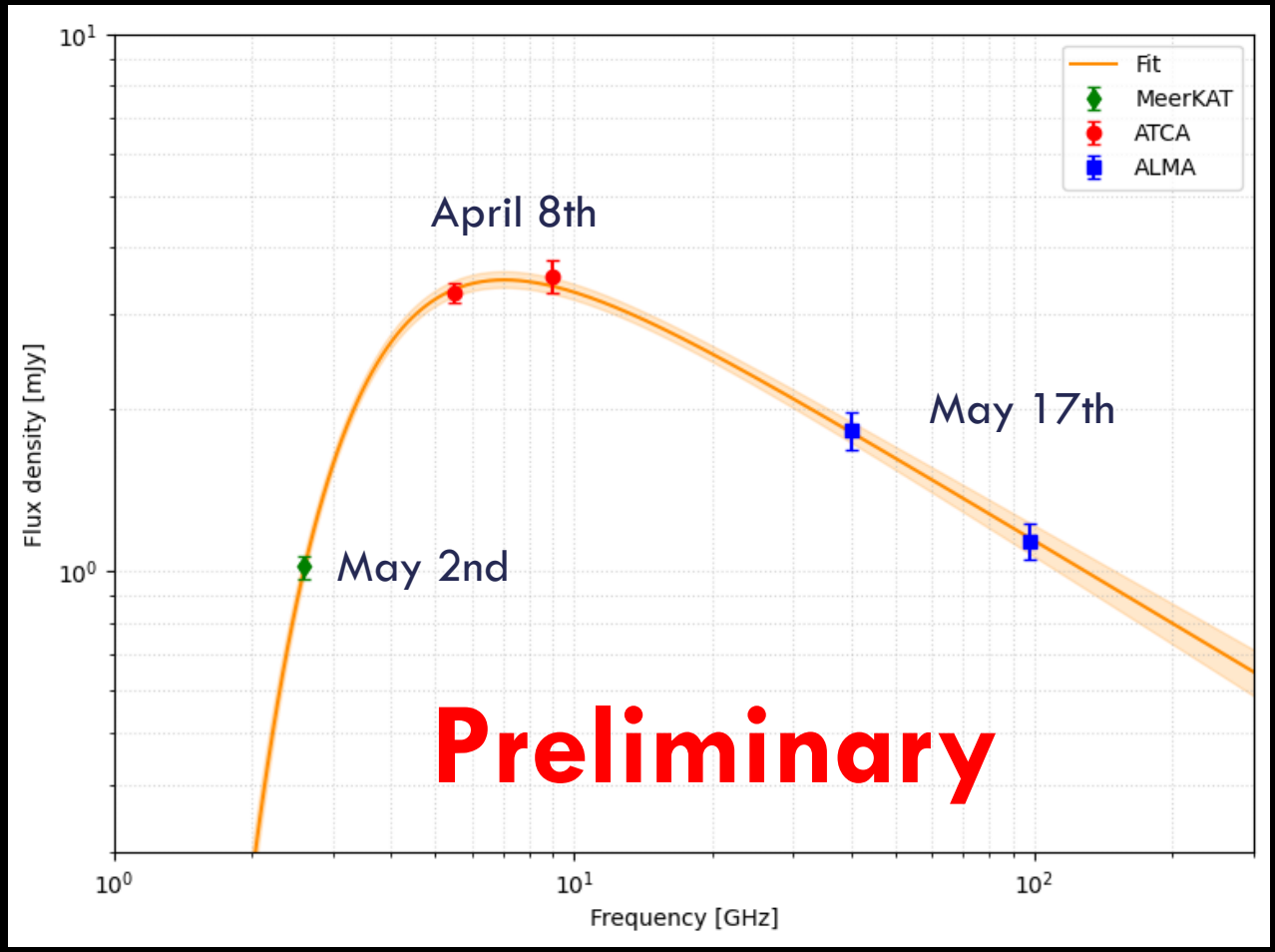
- power-law spectral index 0.5 – corresponds to electron spectral index of 2, expected in DSA.



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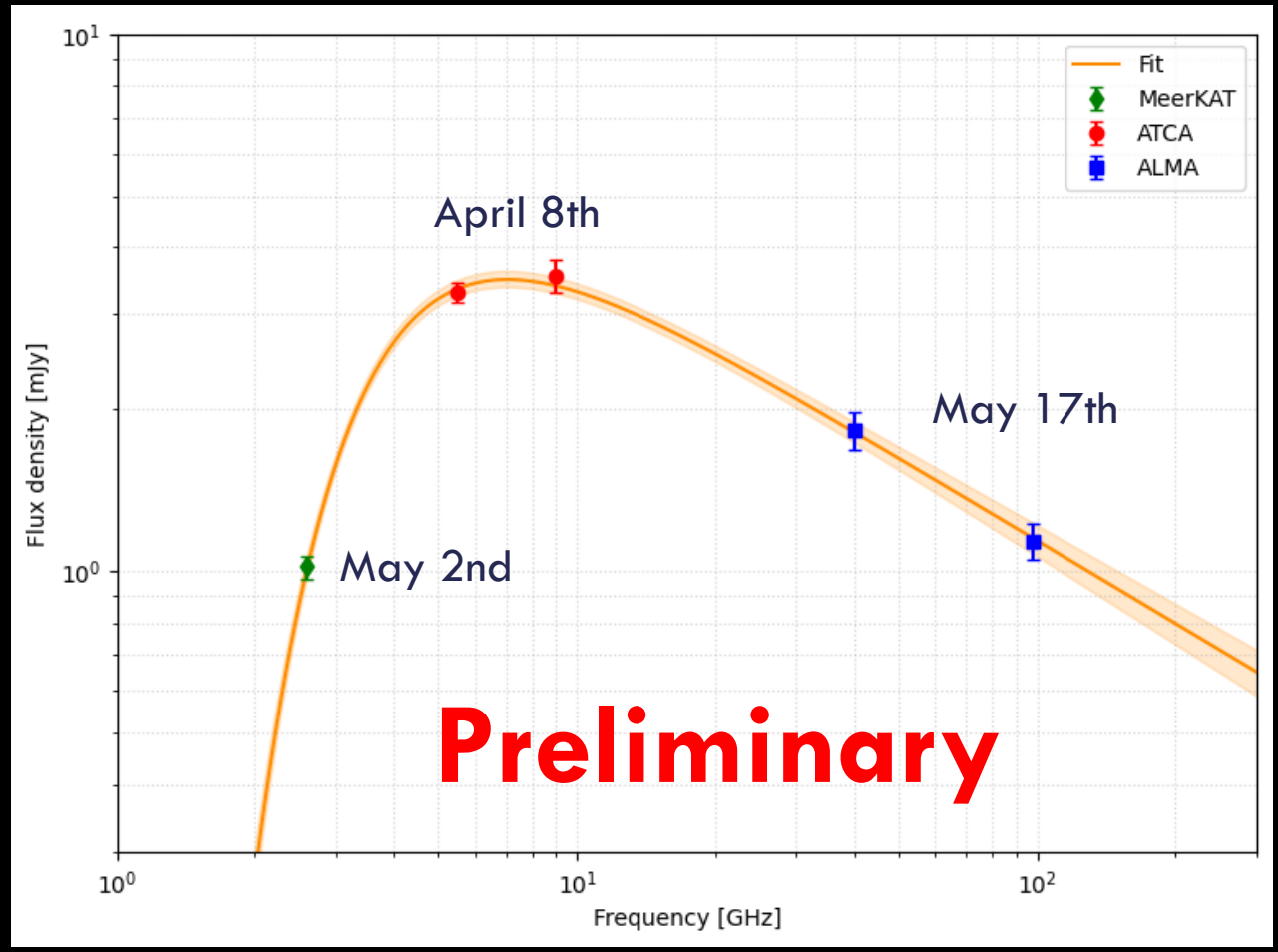
- detections with MeerKAT and ALMA (following DDT proposals)
- free-free absorbed synchrotron radiation
- power-law spectral index 0.5 – corresponds to electron spectral index of 2, expected in DSA.
- approved follow-up observations by XMM-Newton, SALT, H.E.S.S., LBA, ATCA



The LOGO problem

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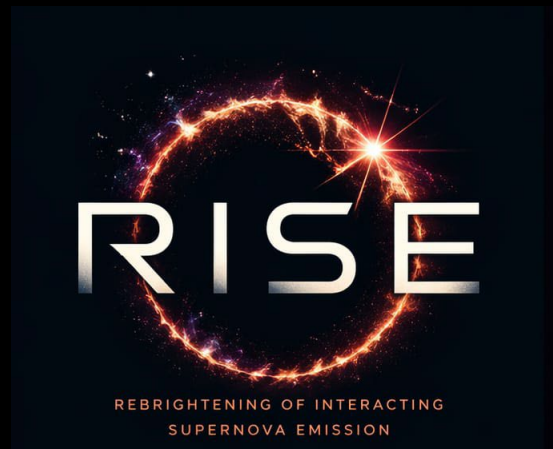

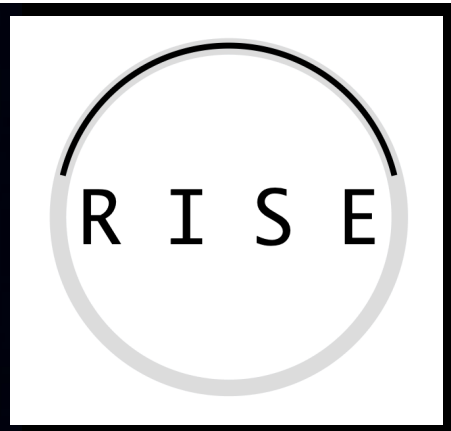

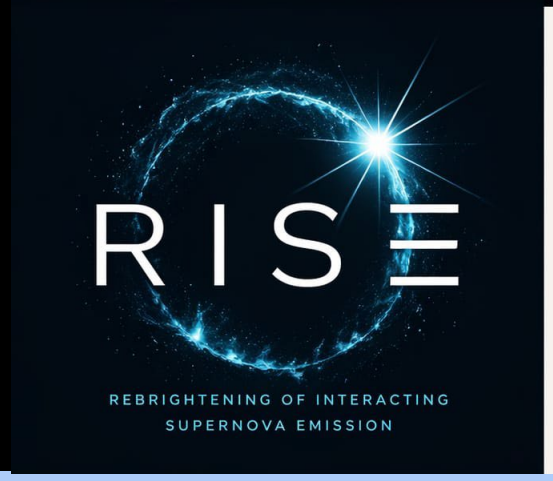

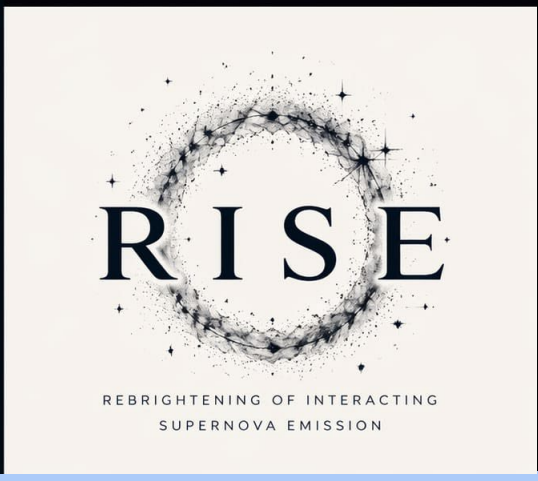


UTR-2 after occupation
Photo: Stas Kozliuk

School in Kharkiv region
Photo: nakypilo.ua


Publishing house Konvi
Photo: chytomo.com

- Over 4,000 educational institutions damaged or destroyed
- A total of 1,443 buildings and laboratories belonging to 177 scientific institutions have been damaged or destroyed
- Many astronomical facilities damaged, destroyed or annexed (Crimea) including the important low-frequency radio array UTR-2
- At least 35 publishing houses suffered direct material losses with over 10 million books destroyed


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Maybe it's about time to change policies and stop promoting war?

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