The recurrent nova RS Ophiuchi

and the Galactic CR connection

Brian Reville, MPI für Kernphysik, CDY seminar, 22.2.23

With special thanks to the H.E.S.S. RS Oph team:
E. Wilhelmi, D. Khangulyan, S. Steinmaßl, R. Konno, J.-P. Ernenwein,
T. Unbehaun, J. Mackey, S. Ohm, A. Mitchell
and the entire H.E.S.S. collaboration

Outline

- Summary of gamma-ray novae
- RS Ophiuchi - past & present
- Gamma-ray view of RS Oph

Stella Nova

Binary systems with a WD and star over-flowing its Roche-lobe

WD accretes matter onto its surface

Atmosphere is heated by WD, until thermonuclear runaway expels gas from WD surface

Typically observed as optical transients

Peak Optical luminosity can exceed the Eddington luminosity of the WD
$L \sim 10^{38}\,\mathrm{erg\,s^{-1}}$

Galactic nova rate ~50 per year

Credit: DESY, Science Communication Lab

Novae classes

Classical Novae

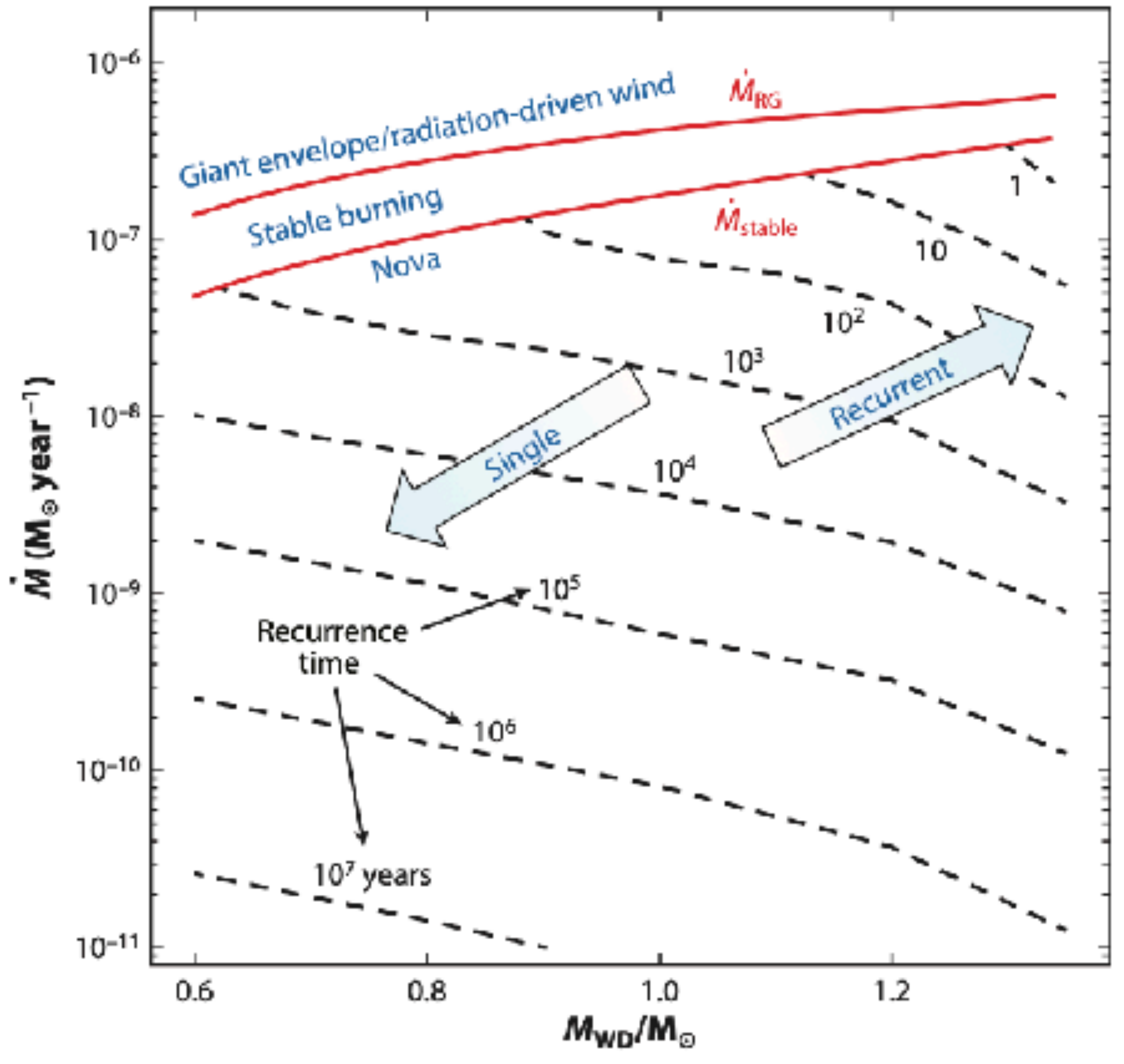
- **Main sequence companion**
- **Orbital periods of hours to days**
- **Orbital separation ~ 10^{10} cm**
- **Ejecta mass $10^{-5} - 10^{-4} M_\odot$**
- **Ejecta velocities 100s-1000s km/s**

It is thought that all novae are likely recurrent, though most recurring on astronomical timescales

Novae have been observed from **RS Oph** in: 1898, (1907?),1933, (1945?),1958, 1967, 1985, 2006, and **2021**

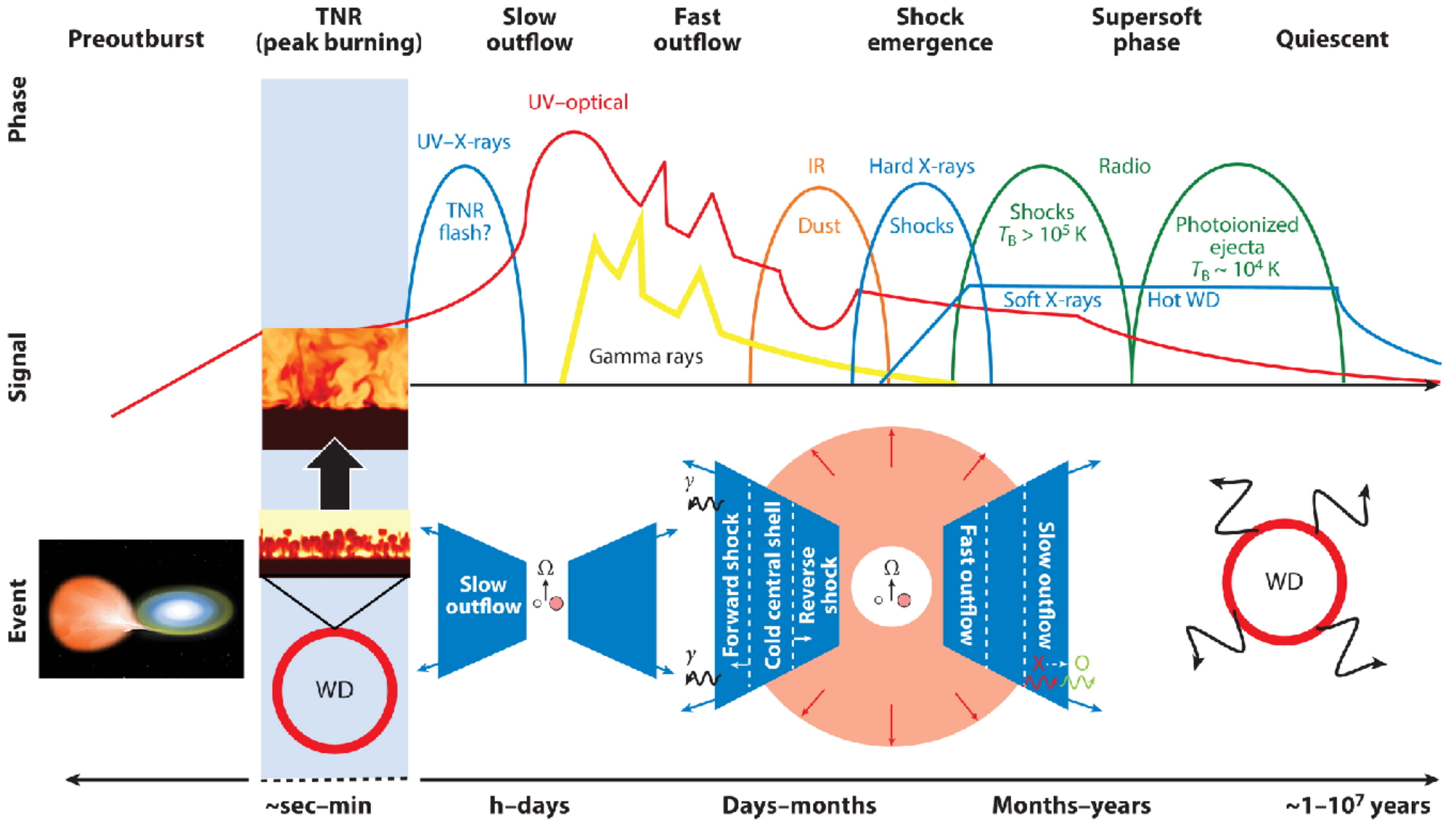
Embedded Novae

- **RG/AGB companion**
- **Orbital periods of ~100 days**
- **Orbital separation ~ 10^{12-14} cm**
- **Ejecta mass $10^{-7} - 10^{-6} M_\odot$**
- **Ejecta velocities 100s-1000s km/s**



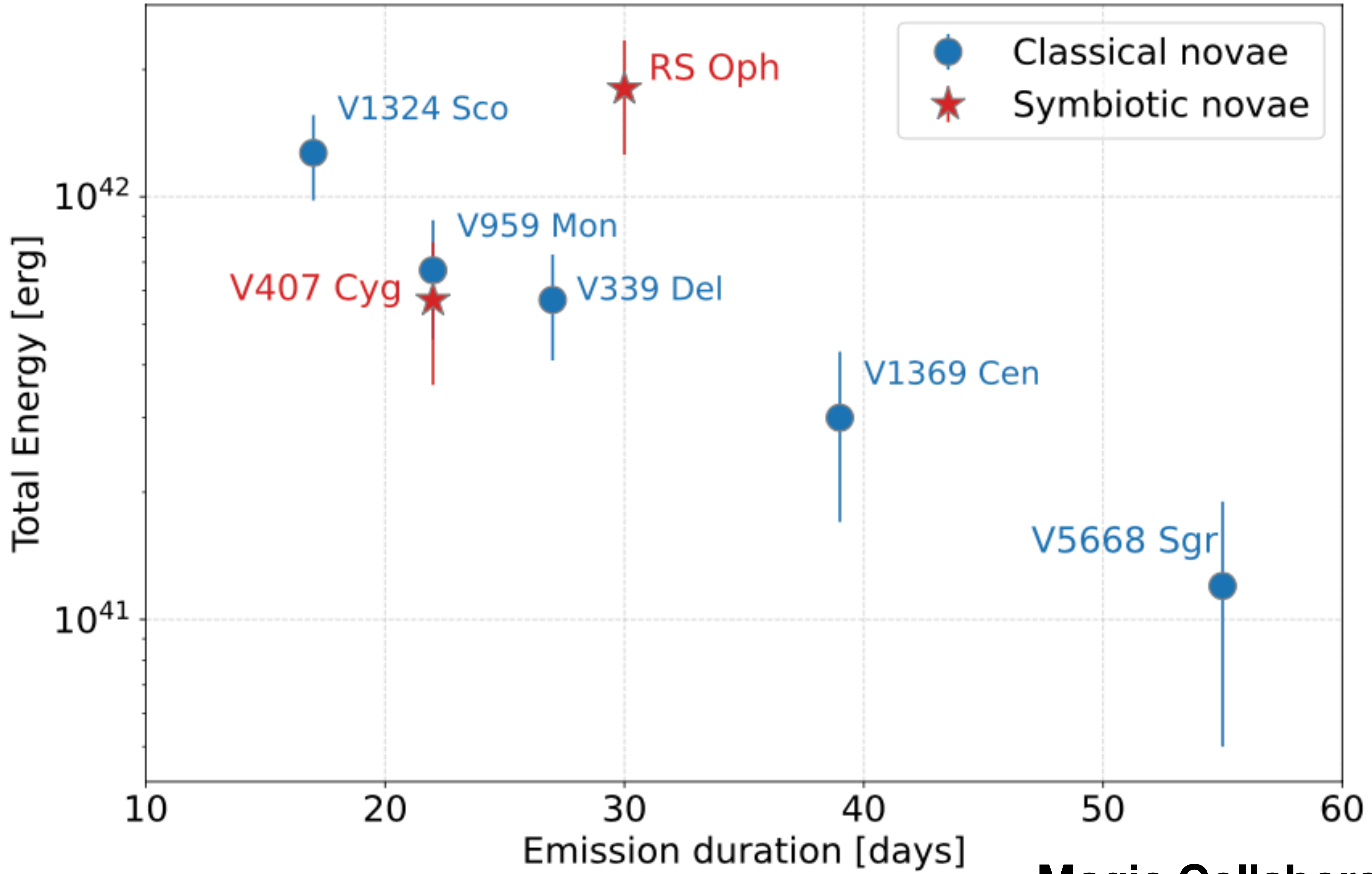
Chomiuk et al. 21

A multi-wavelength picture of novae



Chomiuk L, et al. 2021
Annu. Rev. Astron. Astrophys. 59:391–444

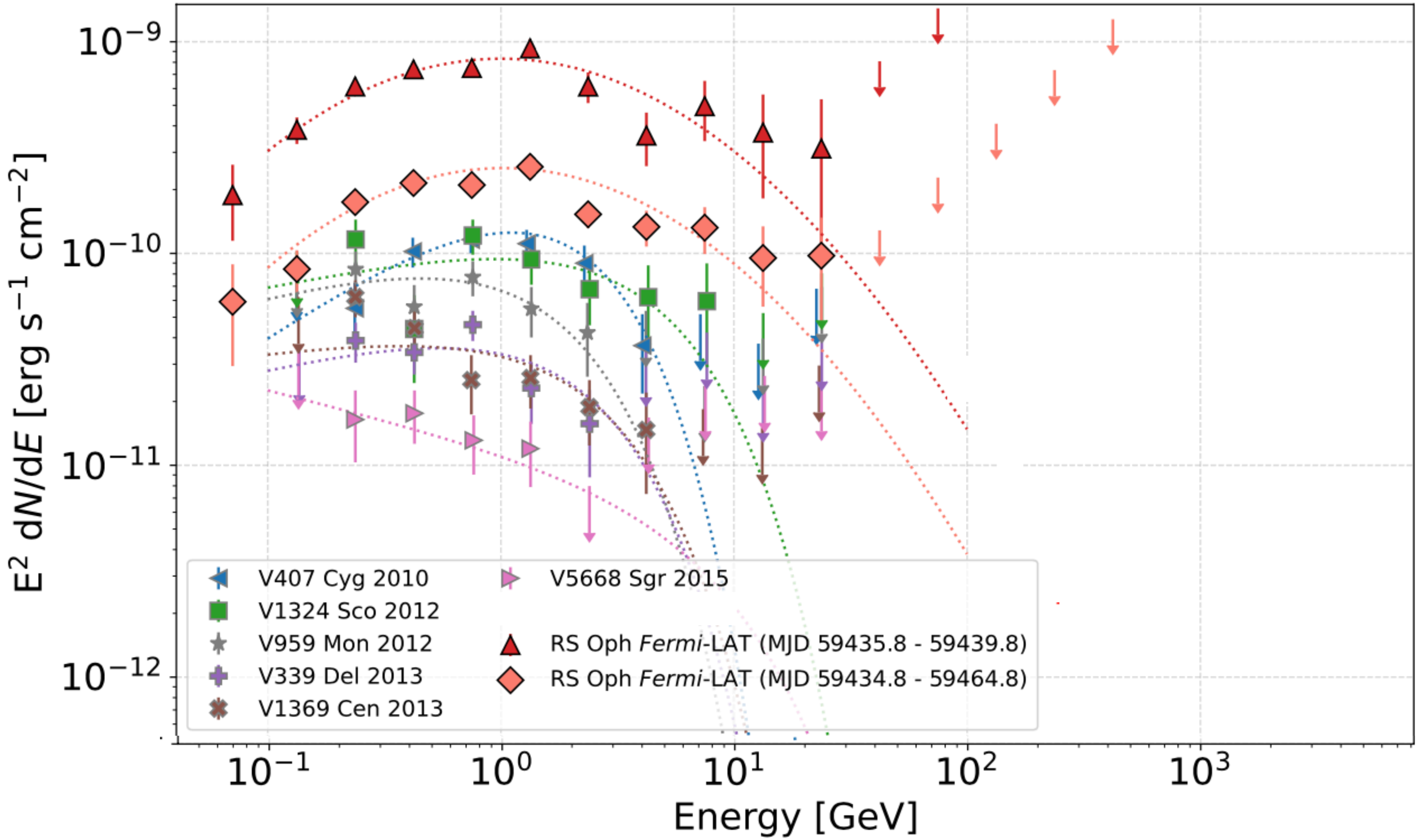
Gamma-ray detections of Novae



17 gamma-ray nova detections to date

Magic Collaboration 2022

Gamma-ray detections of Novae



Magic Collaboration 2022

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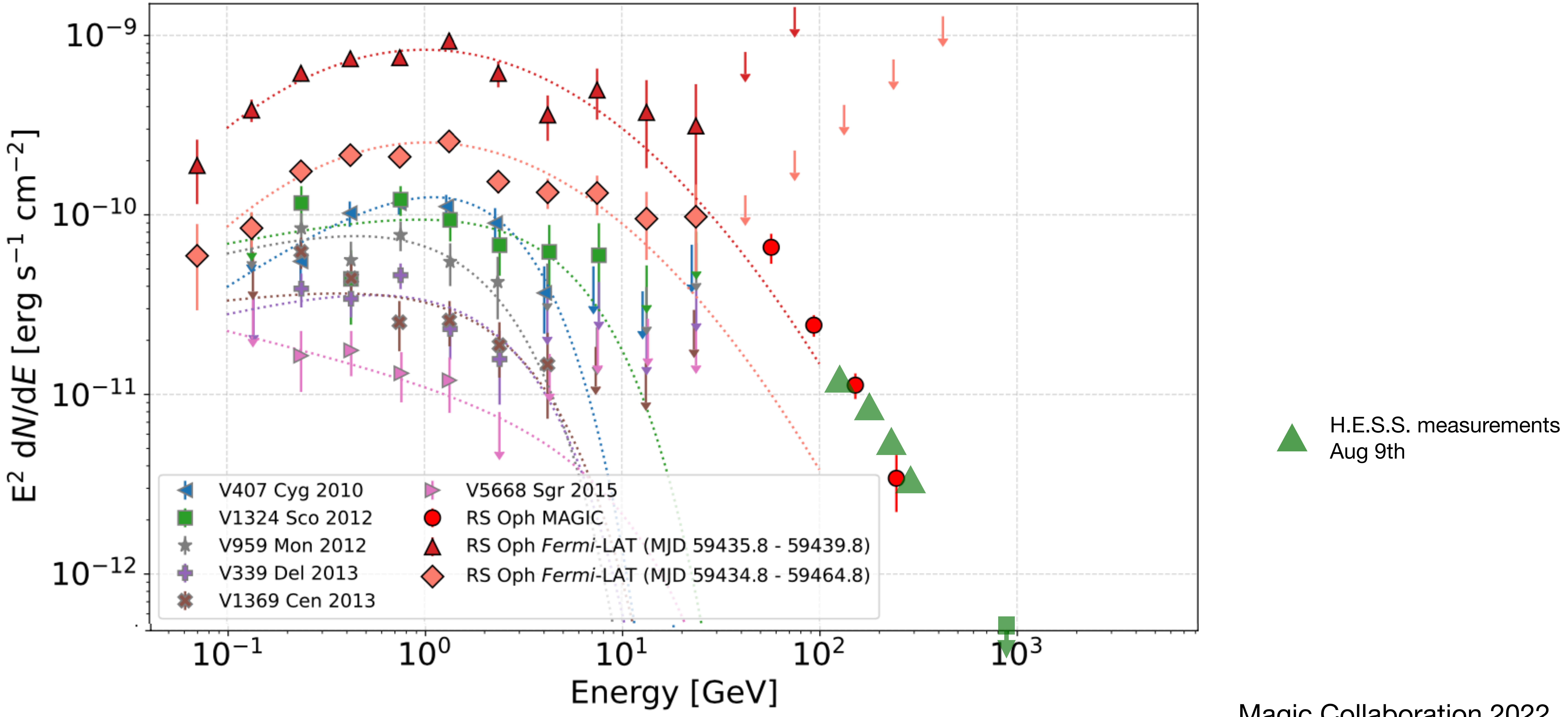


Magic Collaboration 2022

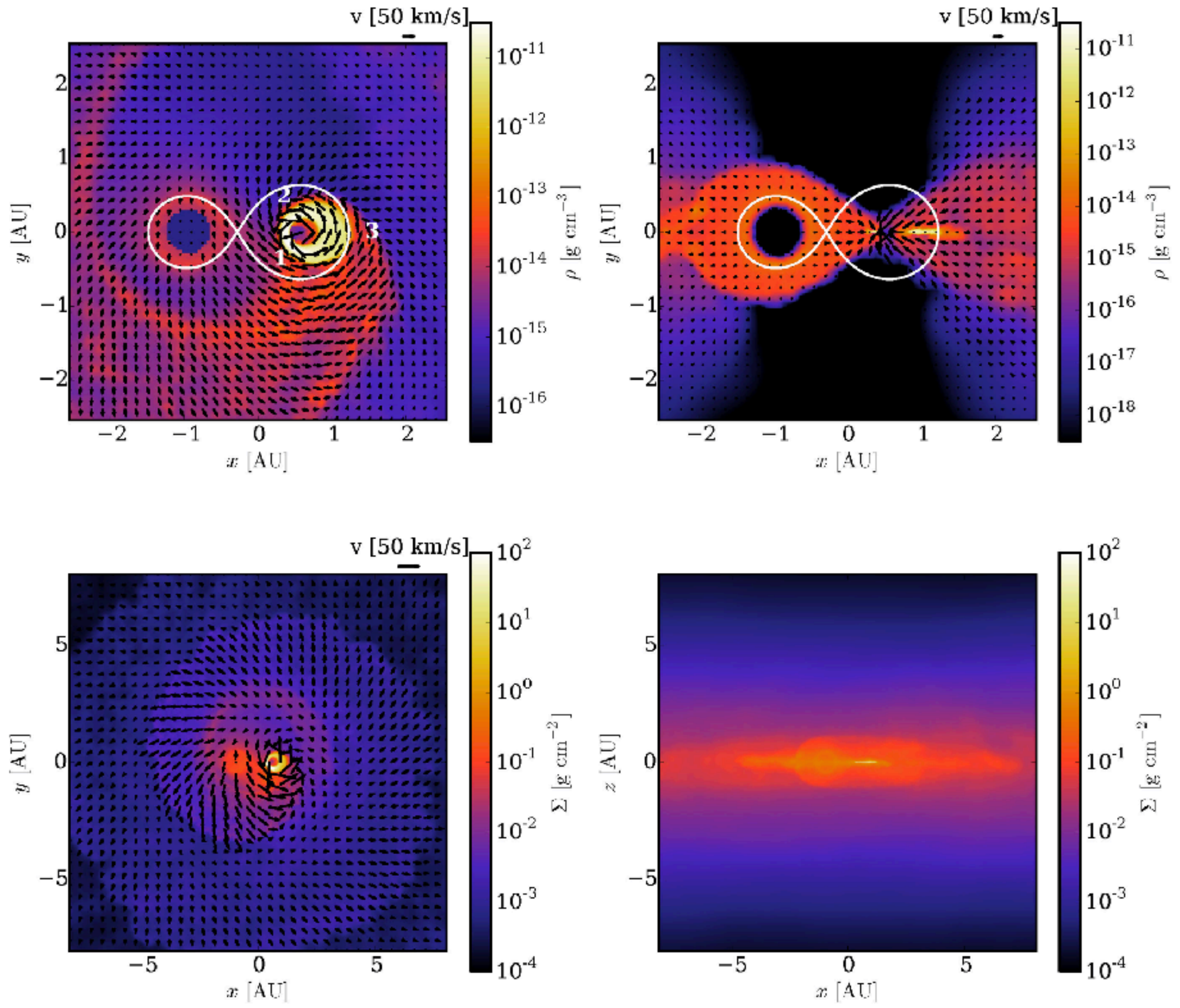
RS Ophiuchi

- Distance: $2.4^{+0.3}_{-0.2}$ kpc (Gaia eDR3) (this value remains highly uncertain)
- Orbital Period 453.6 days
- $M_{RG} \approx 0.8\ M_\odot, M_{WD} \lesssim 1.4 M_\odot$
- $\dot{M}_{RG} = 10^{-8} - 10^{-6}\ M_\odot\,\mathrm{yr}^{-1}$
- Asymptotic wind speed $v_{RG} \approx 30\ \mathrm{km\,s^{-1}}$

How might this structure influence the nova expansion?

3D SPH simulation by

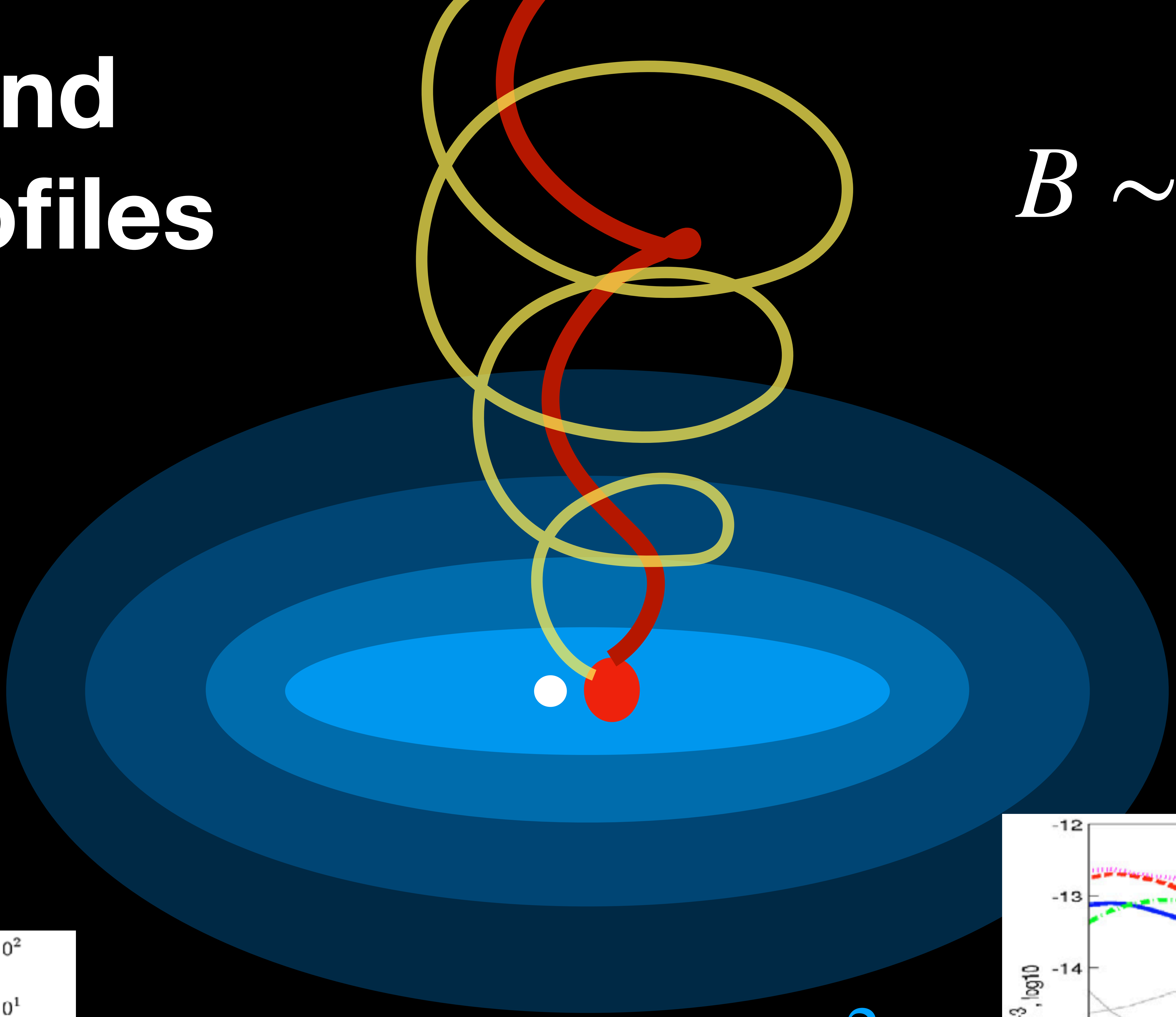
824 *R. A. Booth, S. Mohamed and Ph. Podsiadlowski* 2016



Density and Bfield profiles

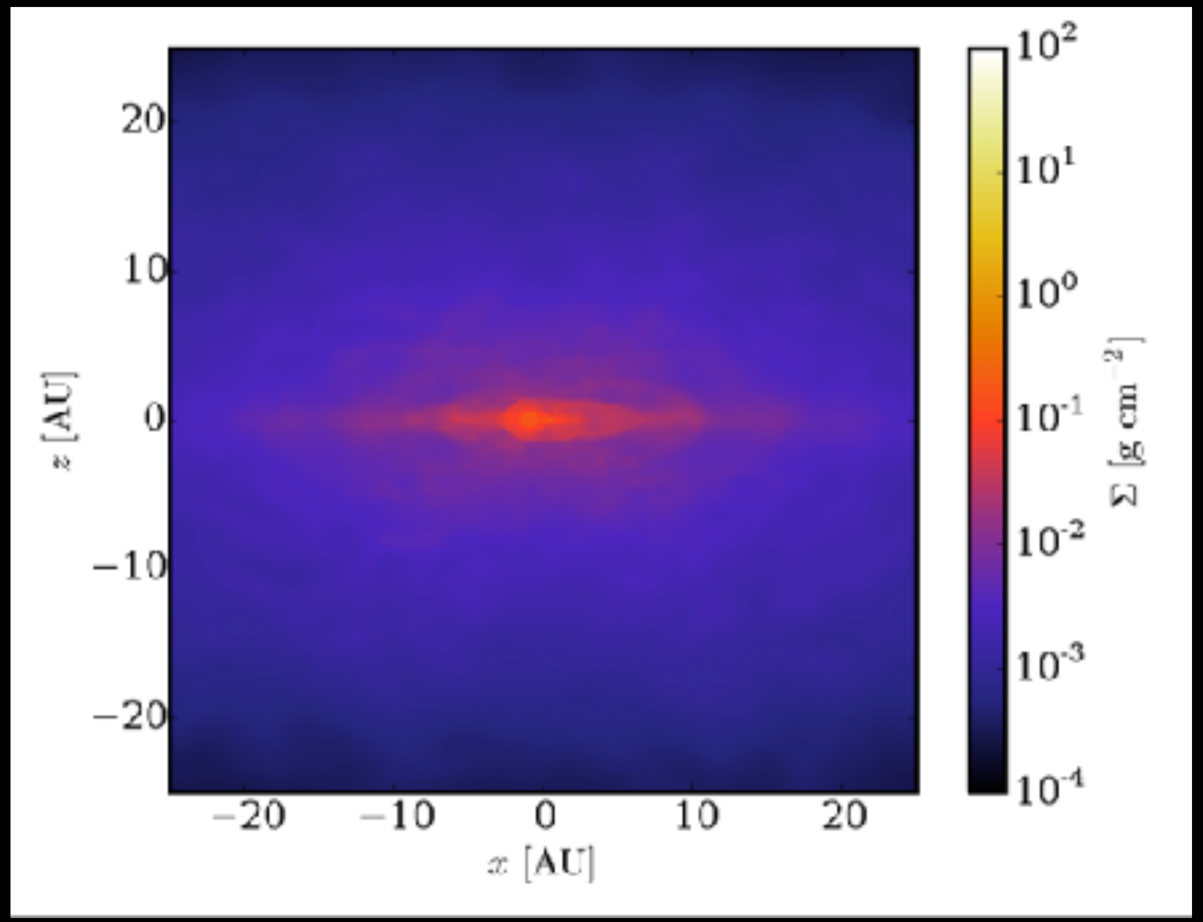
$$B \sim r^{-(2-1)} f(\theta)$$

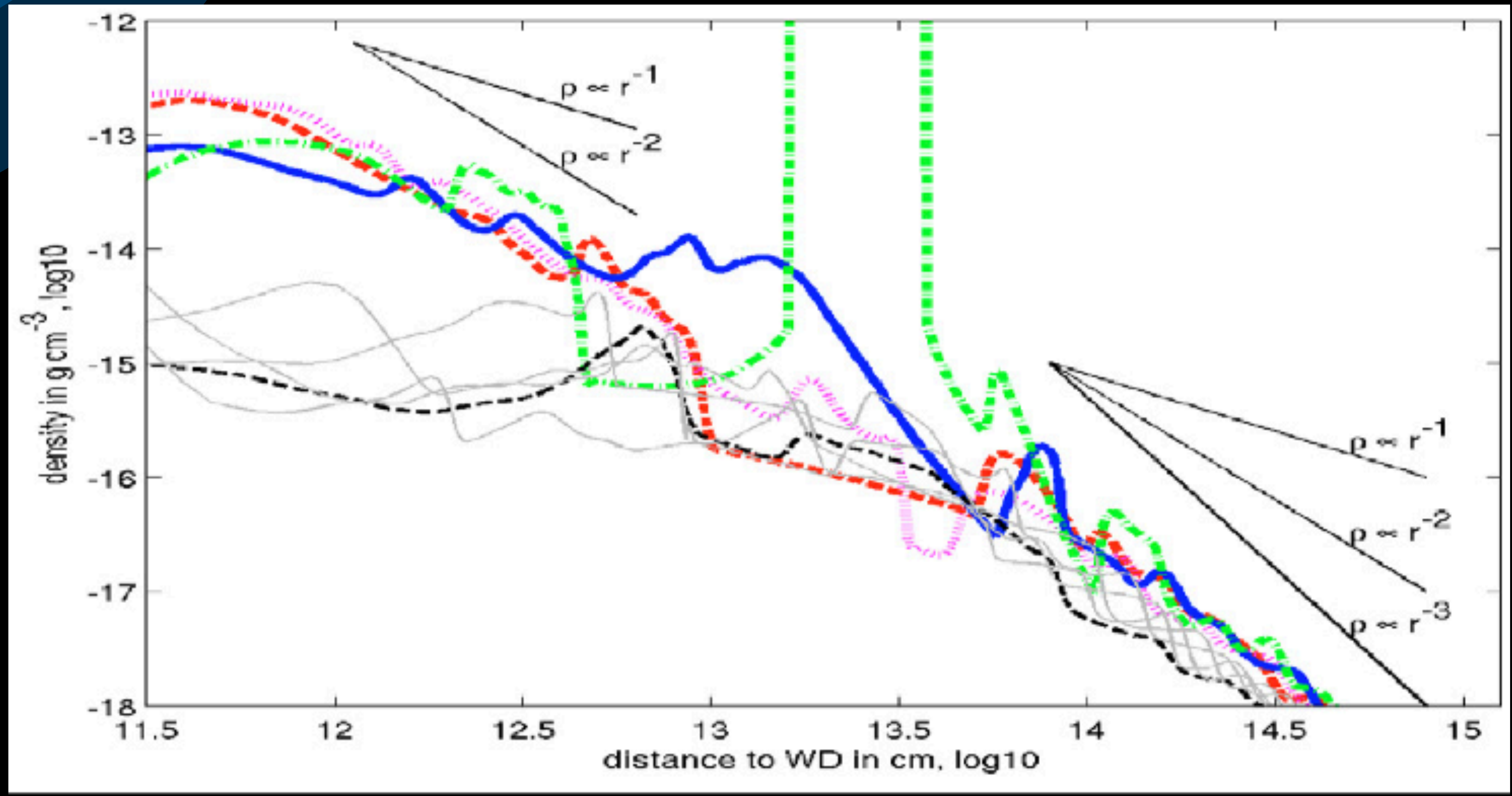
Parker steady wind solution
(For single star)



$$\rho \sim r^{-2}$$

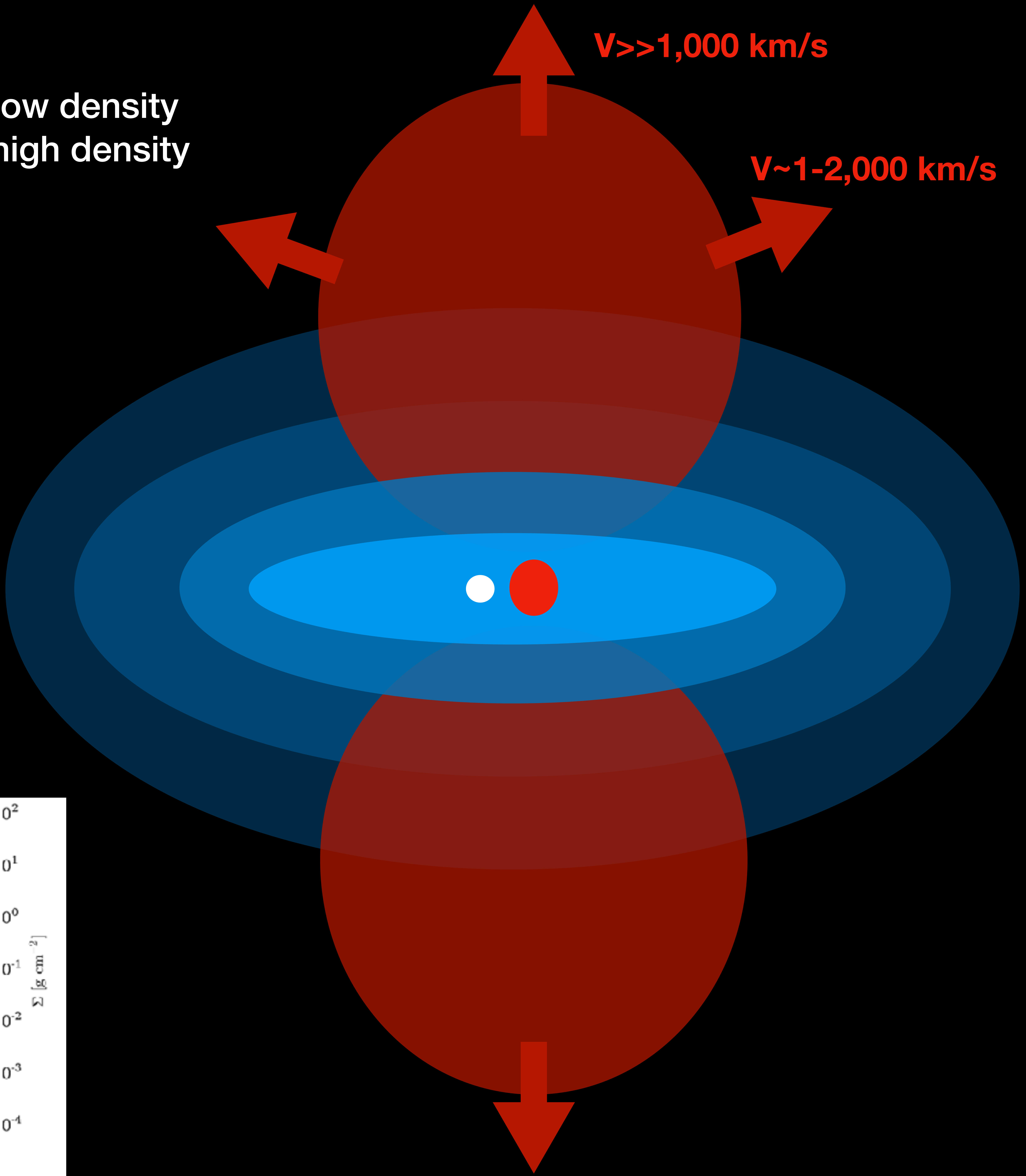
Booth et al 2016



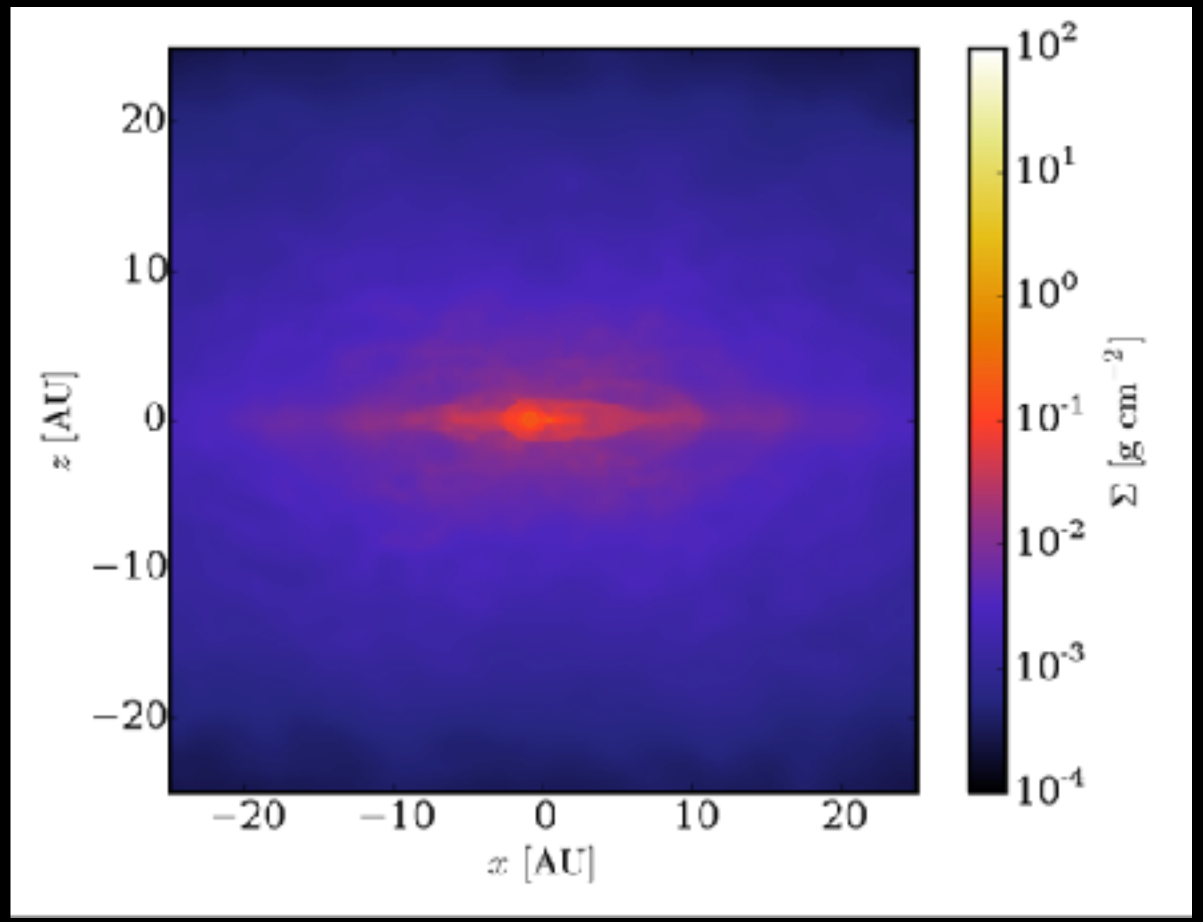


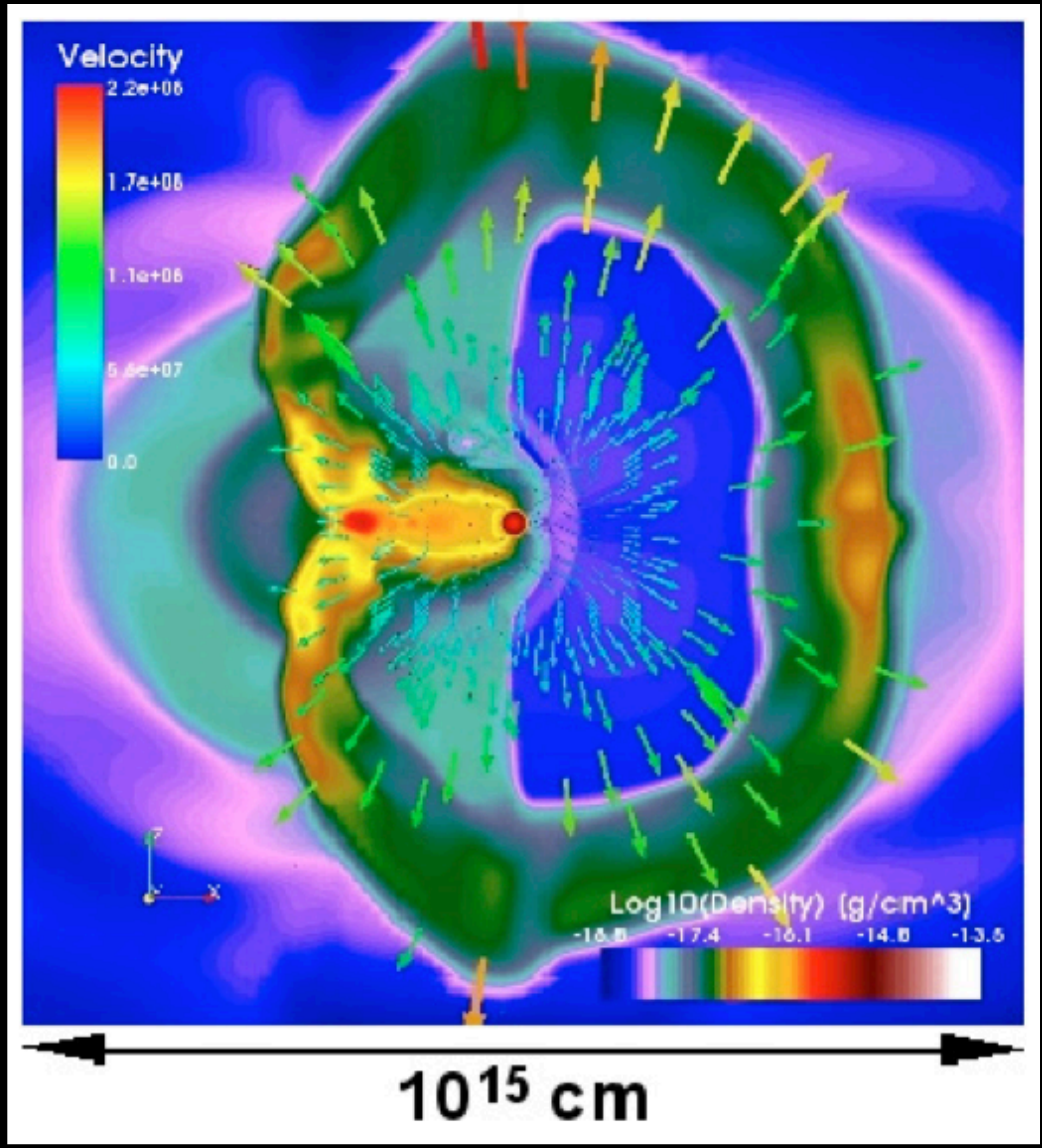
Walder et al 2008

Fast shock in low density
Slow shock in high density



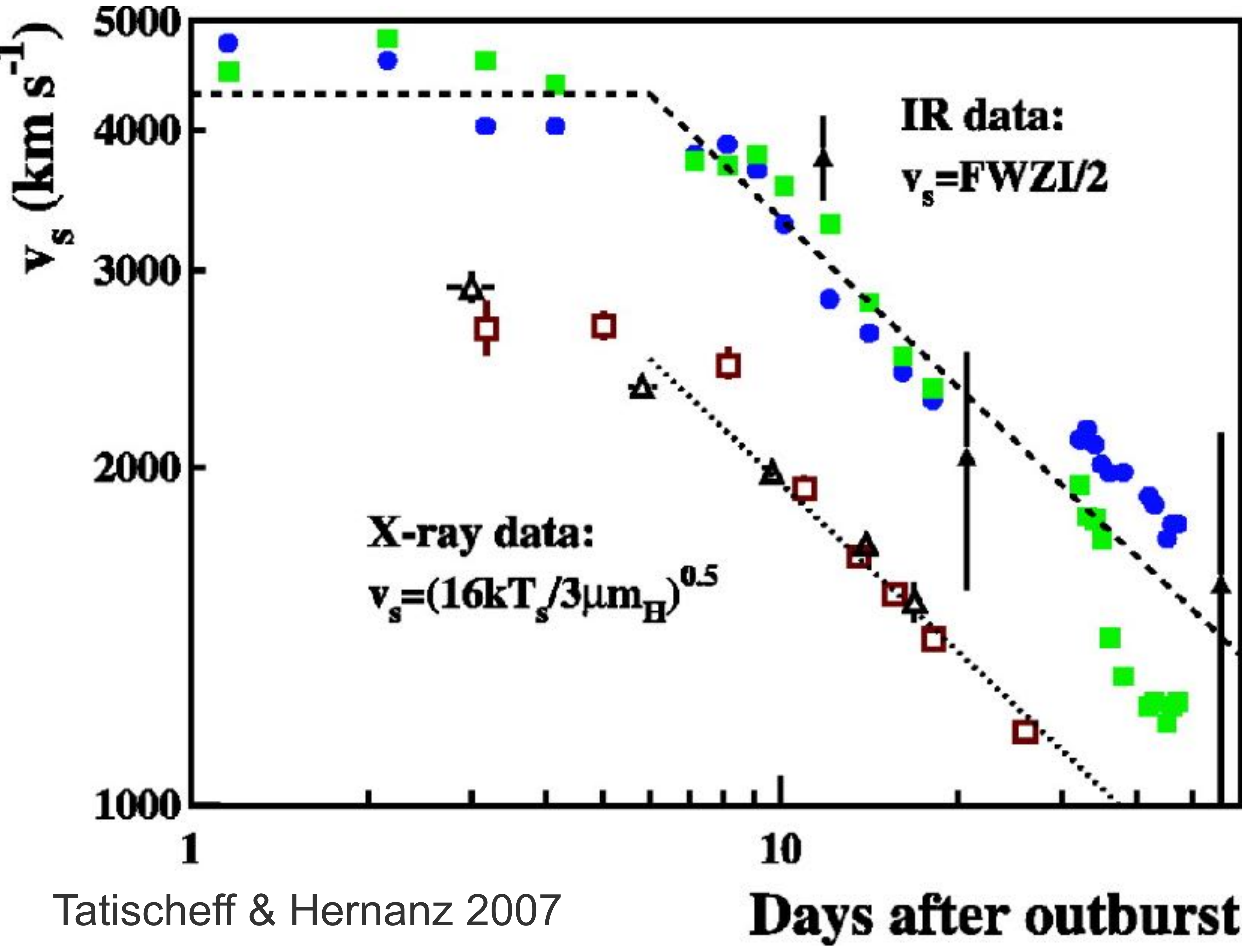
Booth et al 2016





Walder et al 2008

The shock in 2006



Tatischeff & Hernanz 2007

Observations close to $R_{\rm sh} \propto t^{1/2}$
For $\rho \propto r^{-s}$, spherical model:
s=1 non-radiative, or
s=2 radiative

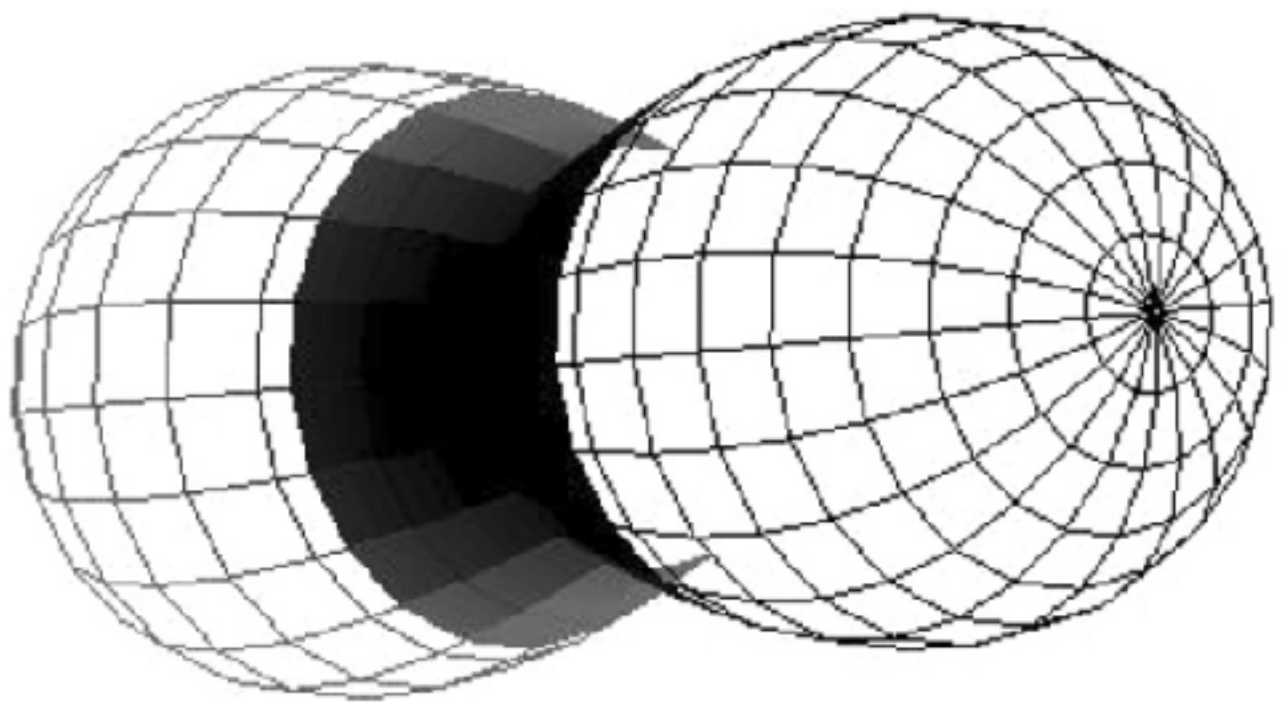


Figure 6. Dumbbell (outer) and hour glass (inner) structure that is used to replicate the RS Oph remnant.

Ribeiro et al. 09

A spherical shock expands at ≈ constant velocity, merging to a Sedov-Taylor solution after it sweeps up a mass comparable to the initial ejecta.

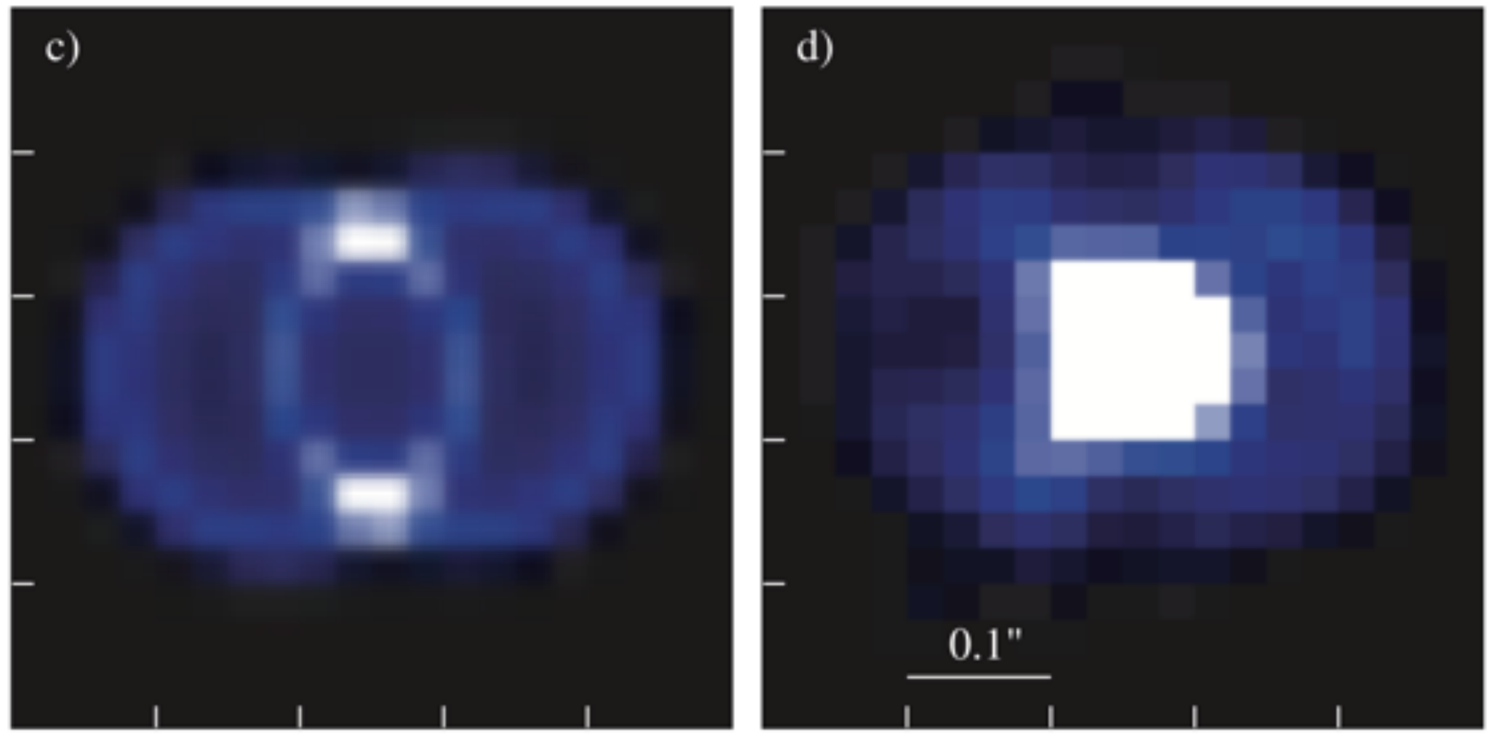
Thereafter, $E_{explosion} \approx \frac{1}{2} M_{\rm tot} \dot{R}_{\rm sh}^2, \quad M_{\rm tot} = \int_{Vol} \rho \; d^3x$

For shock expanding in density profile $\rho \propto r^{-s}$,
$R_{\rm sh} \propto t^{2/(5-s)}$

For radiative shocks $M_{\rm tot}\dot{R}_{\rm sh} \approx$ const -> $R_{\rm sh} \propto t^{1/(4-s)}$

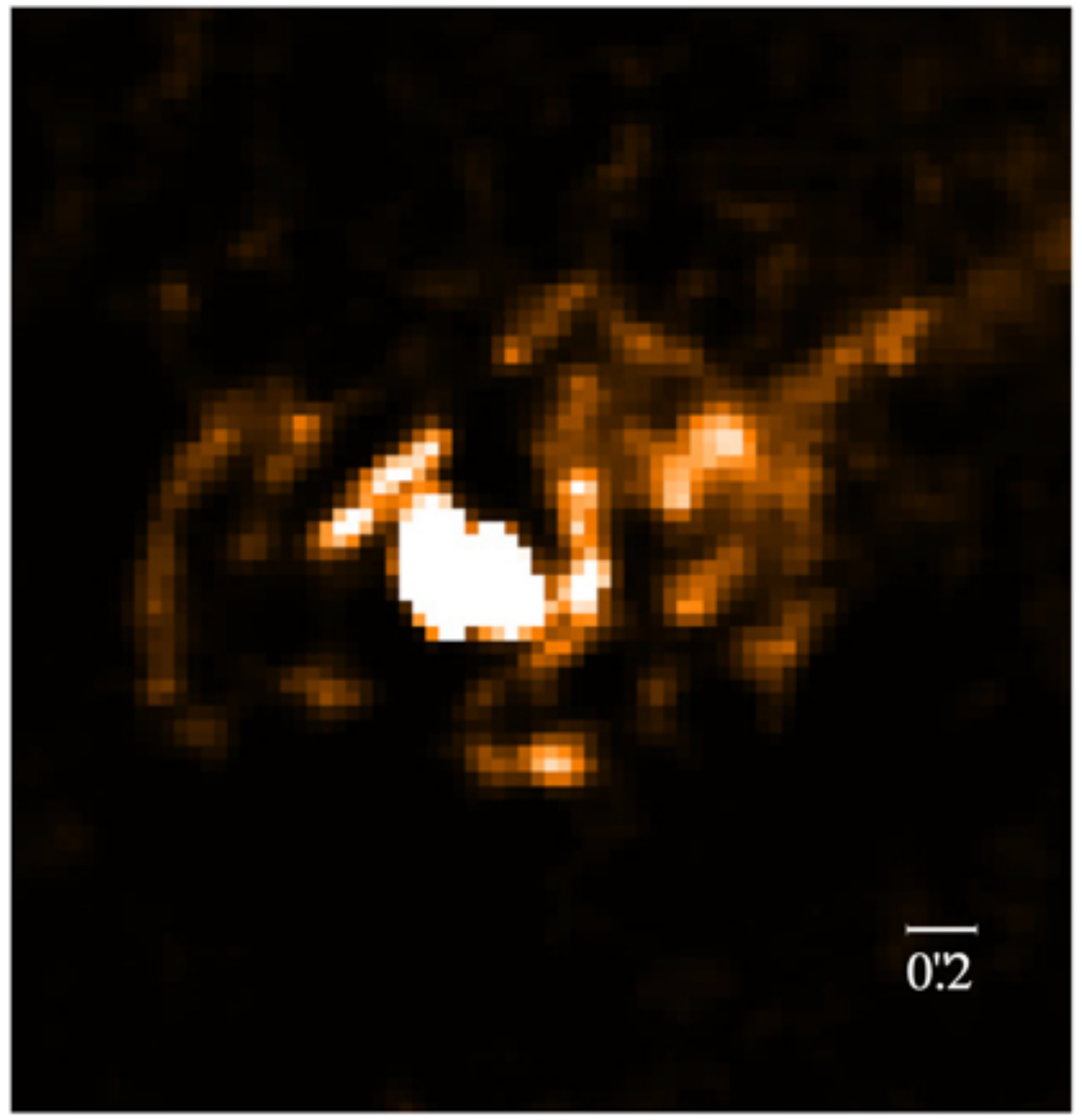
Aftermath of 2006 outburst

HST - 155 days



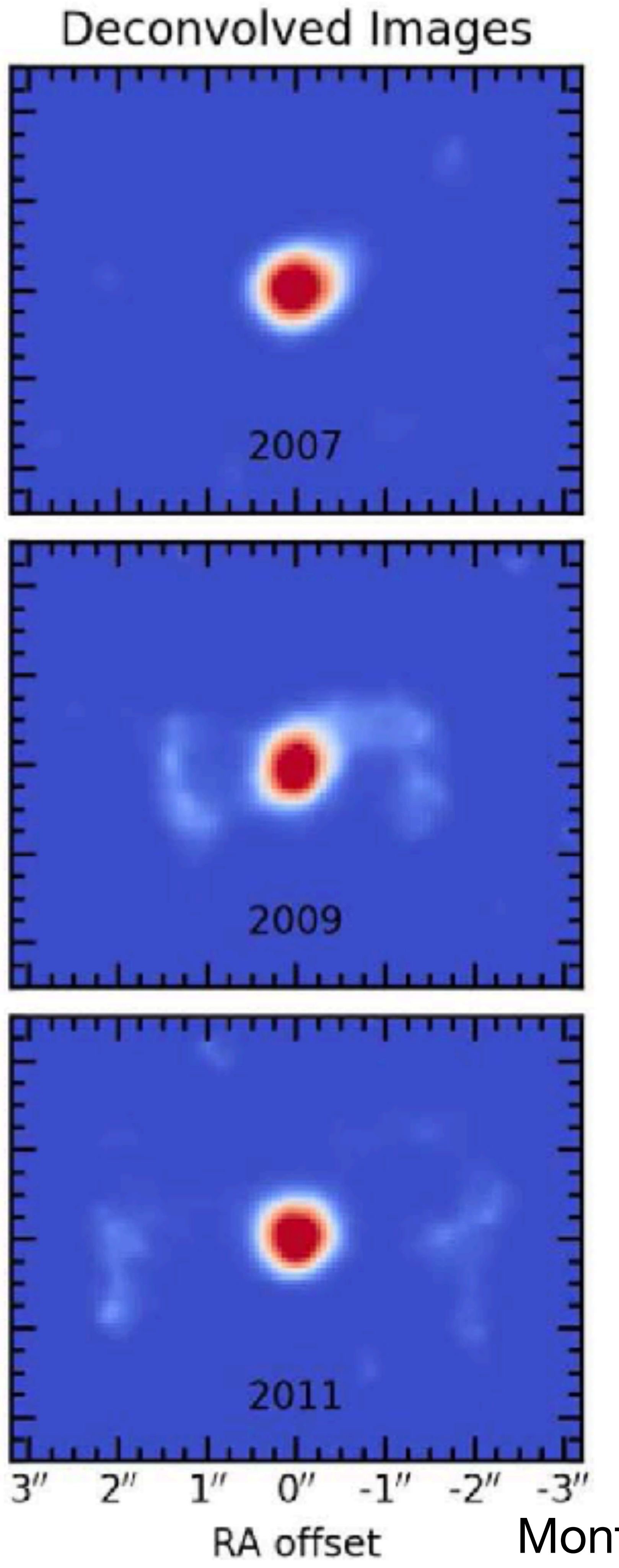
Bode et al. 07

HST - 449 days



Ribeiro et al. 09

Chandra- ~1800 days



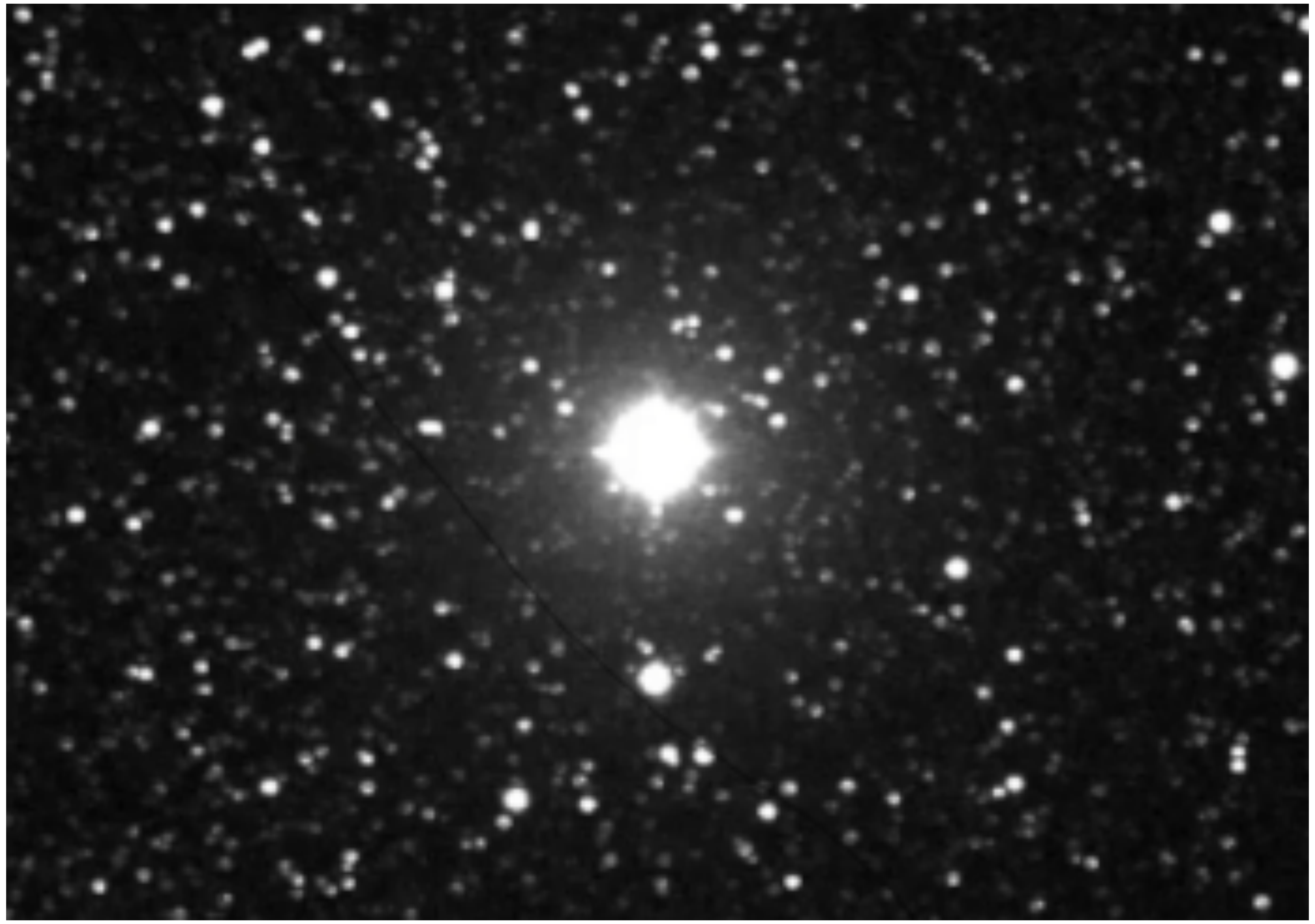
Montez et al. 22

Clear evidence of bipolar outflow

$v_{exp} > 1000 \text{ km s}^{-1}$

With minimal deceleration over several years

The 2021 outburst of RS Ophiuchi

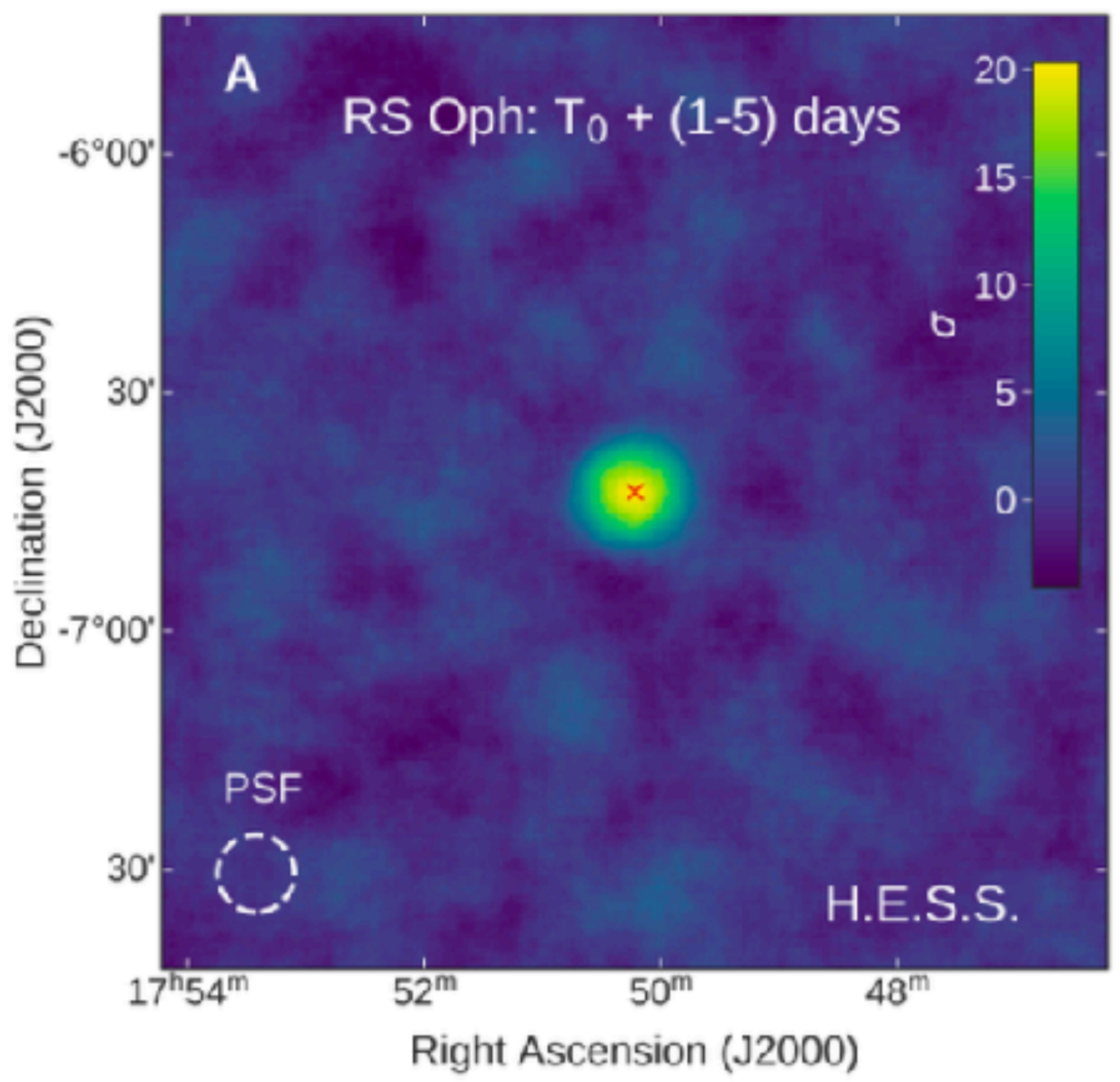


https://skyandtelescope.org/astronomy-news/recurrent-nova-rs-ophiuchi-just-blew-its-top/

On Aug 8, 2021 nova observed by a number of amateur astronomers*

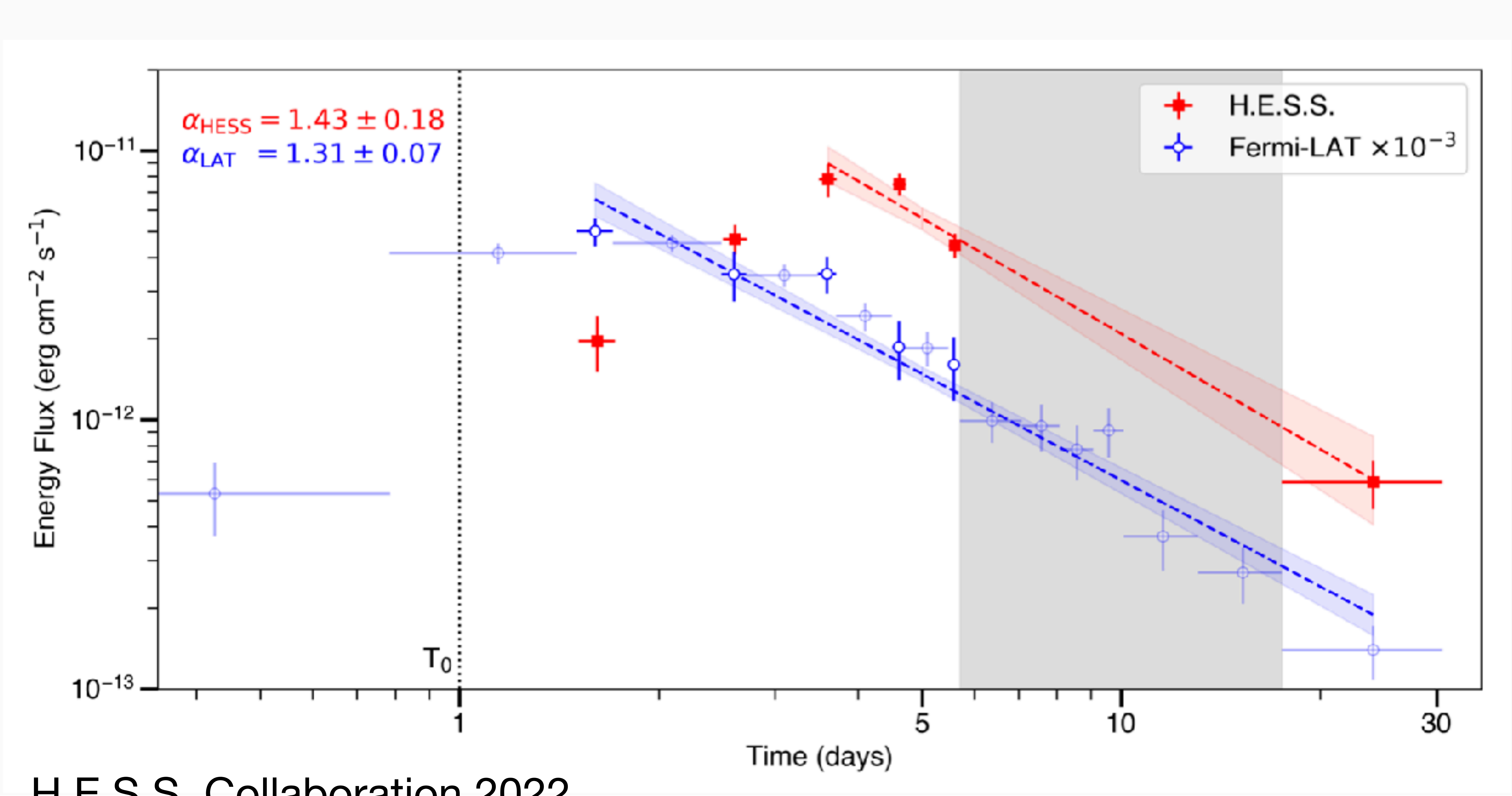
Observations were followed up by H.E.S.S, Magic, and CTA (LST1)

H.E.S.S. Collaboration 2022



*for some entertaining dialogue on competing claims for first observation, see comments in skyandtelescope.org link

Integrated flux at different energy bands



H.E.S.S. Collaboration 2022

$\text{Flux} \propto (t/T_0)^{-\alpha}$

T_0 = time of peak optical emission

Fermi Flux: 60 MeV - 500GeV
H.E.S.S. Flux : 250GeV-2.5 TeV

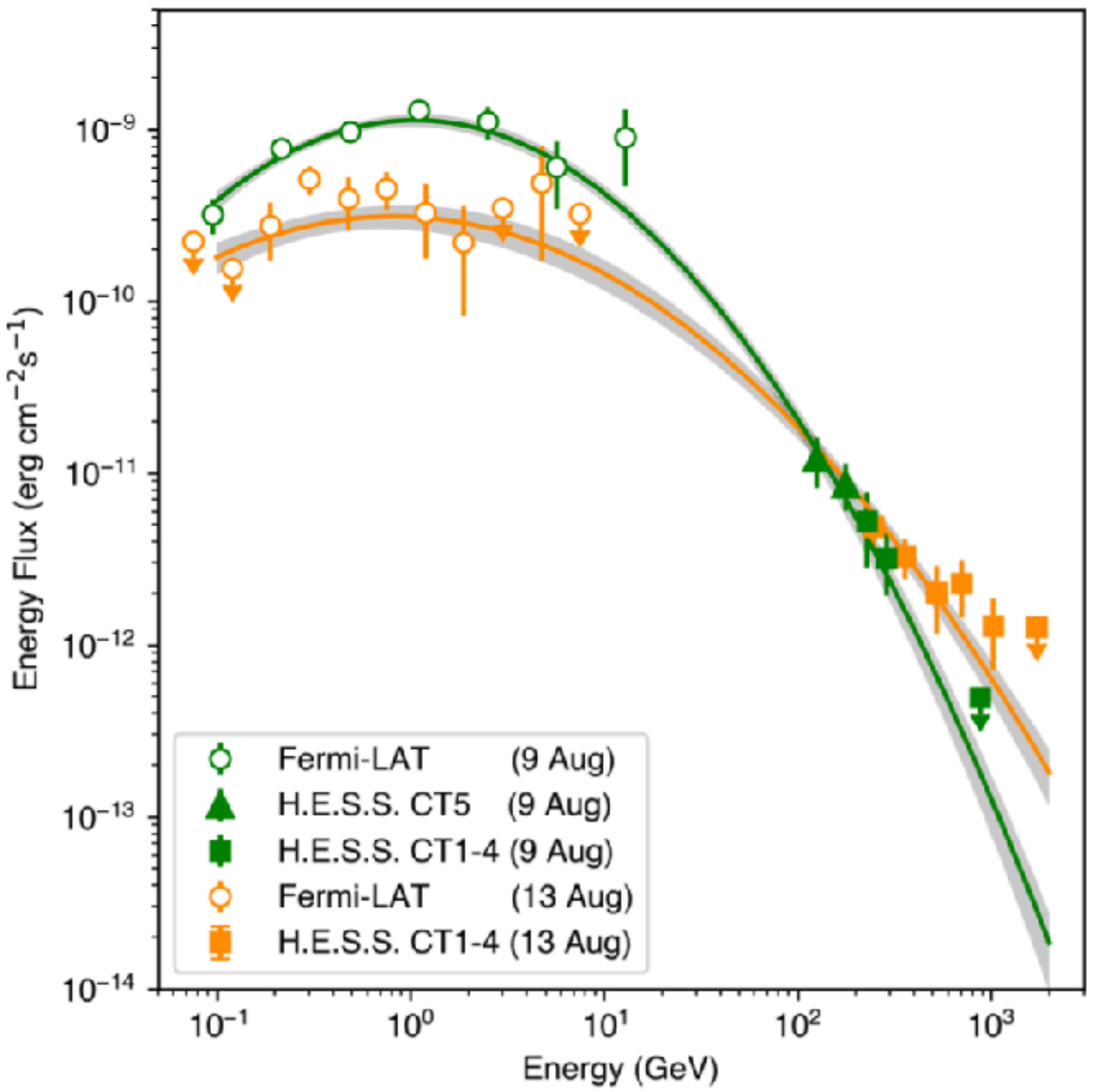
Fermi peak at ~$T_0 + 1$ days

H.E.S.S. peak ~$T_0 + 3$ days

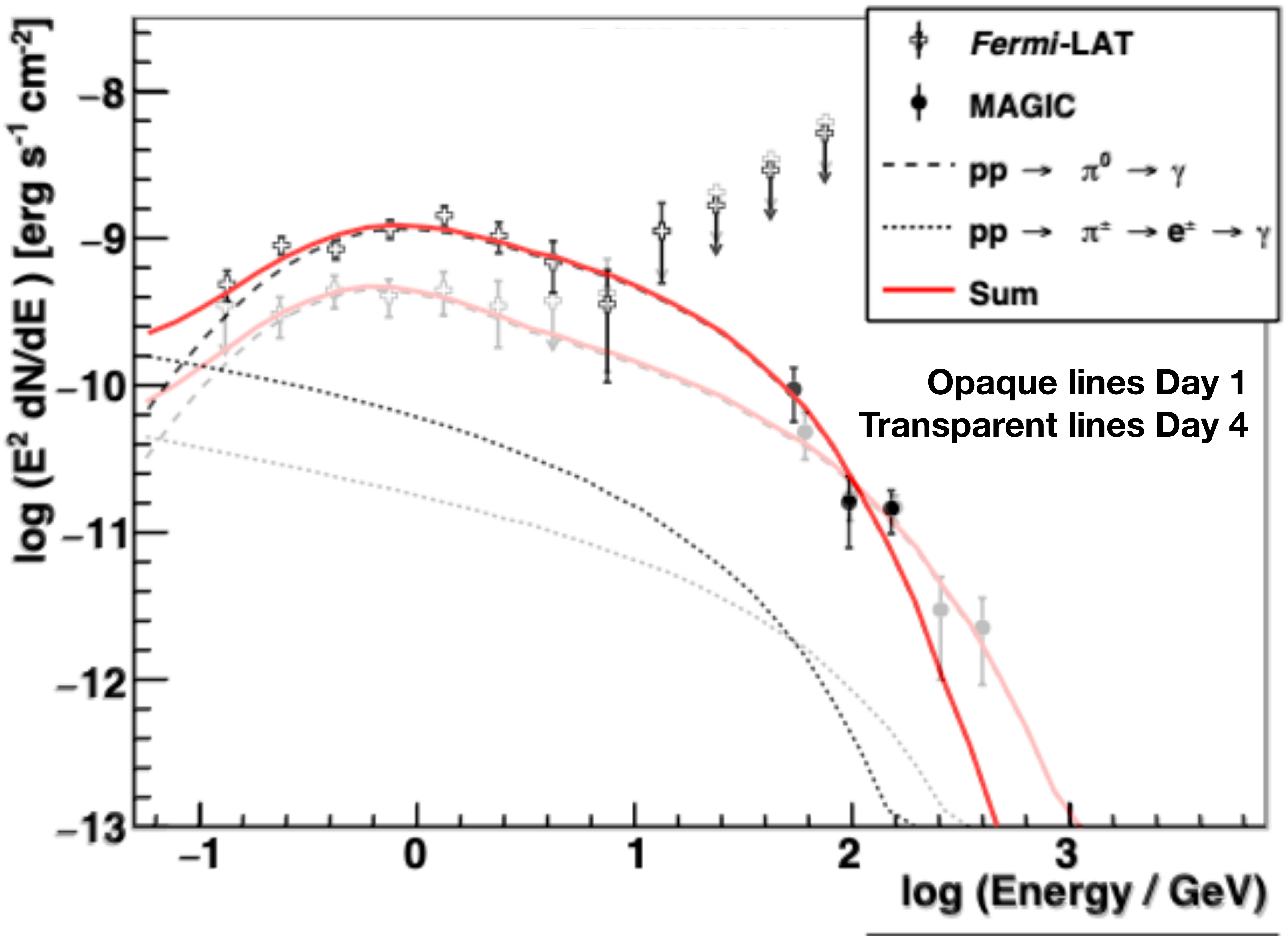
Decay timescales comparable

Emission detected for several weeks

Gamma-ray detection reveals >TeV acceleration



H.E.S.S. Collaboration 2022



Magic Collaboration 2022

Can we learn anything from this to test maximum energy for SNRs?

A digression into maximum energy

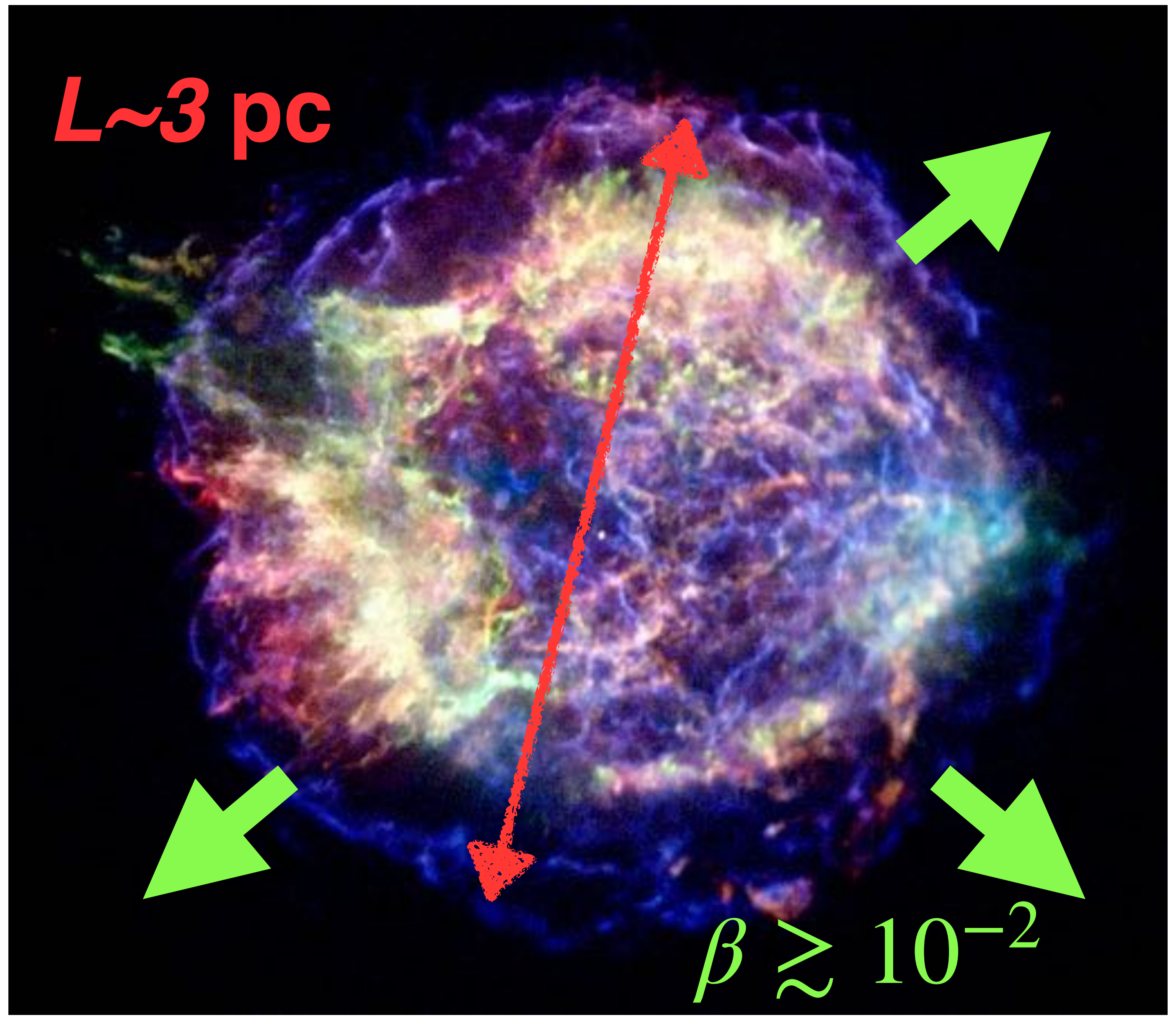
Hillas 1981: maximum potential difference sampled by a particle $\epsilon_{\rm Hillas} = q\int \boldsymbol{E}\cdot d\boldsymbol{s} \approx q\beta BL$

Alternatively following Lagage & Cesarsky '83, Heavens '84

<u>IF</u> we take the limit of magnetised transport ie. $D_{\rm Bohm} \approx \epsilon/ZeB$**.**

Equating acceleration time ($t_{\rm acc} \approx D/u_{\rm sh}^2$**) to shock age:**

$$\epsilon_{LC} \approx q\beta_{\rm sh}B\ (u_{\rm sh}t_{\rm age}) \approx \epsilon_{Hillas}$$

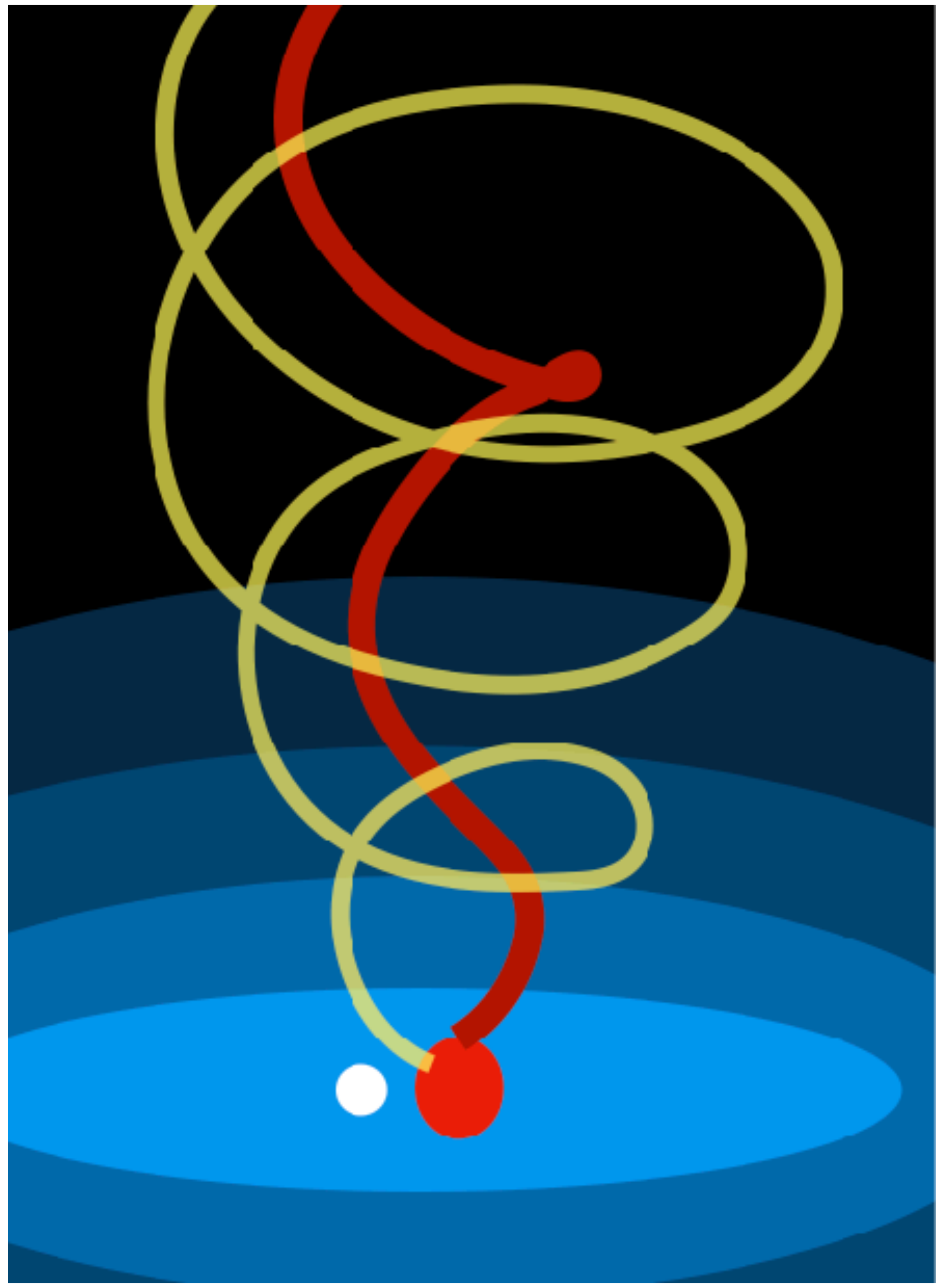


Numerically (taking some SNR parameters for now):

$$\epsilon_{\rm Hillas} \approx 100Z \left(\frac{u_{sh}}{5{,}000\ \mathrm{km/s}}\right)\left(\frac{B}{3\ \mu\mathrm{G}}\right)\left(\frac{R_{sh}}{1\ \mathrm{pc}}\right)\ \mathrm{TeV}$$

Though considerable uncertainty remains over what to choose for B. Can Nova observations help?

Magnetic field structure for RS Oph



If we assume in the polar region $B \propto r^{-2}$
(i.e. Parker wind solution near the axis)

$$\epsilon_{\rm Hillas} \approx 10Z \left(\frac{u_{sh}}{5{,}000\ \text{km/s}}\right)\left(\frac{B^*}{1\ \text{G}}\right)\left(\frac{R_{sh}}{1\ \text{au}}\right)^{-1}\ \text{TeV}$$

Adopting a 1Gauss field on surface of the RG star, at $R^* = 0.35$ au

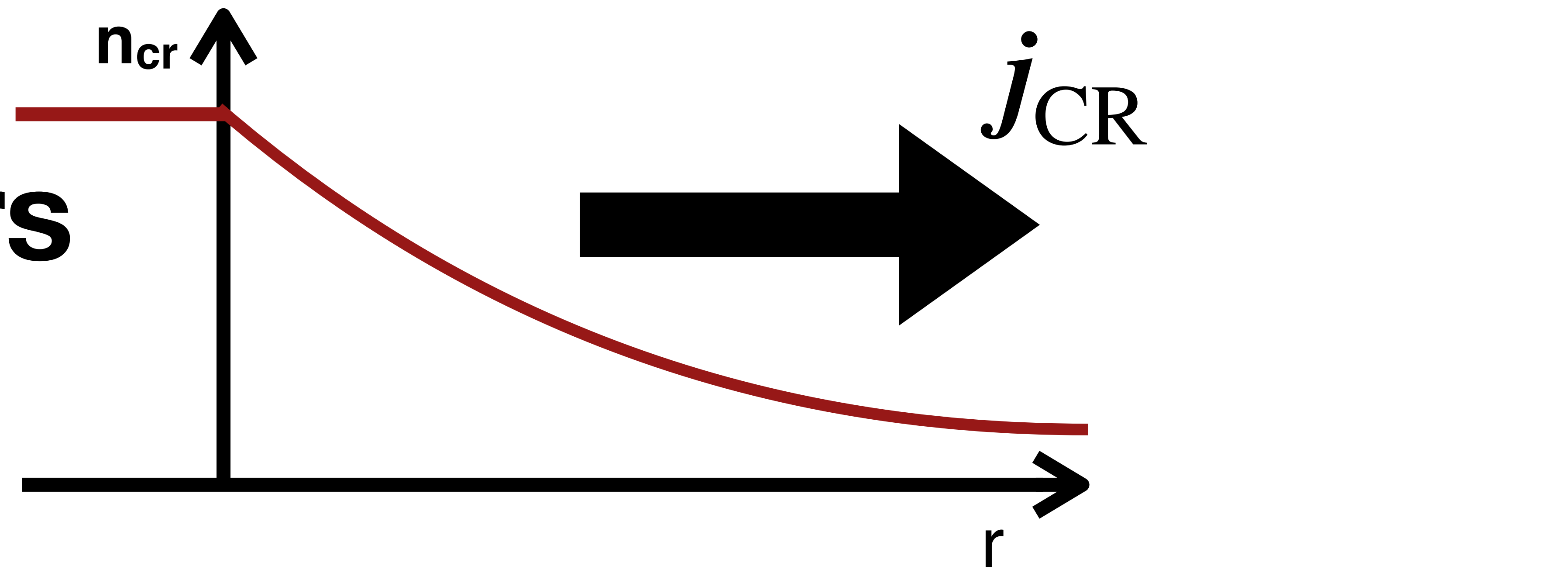
Should take care that wind is super Alfvénic at base of wind.

For 5,000 km/s, shock radius is already at 10 au at peak of HESS emission.

We need to consider some form of **magnetic field amplification**

A digression into magnetic field amplification

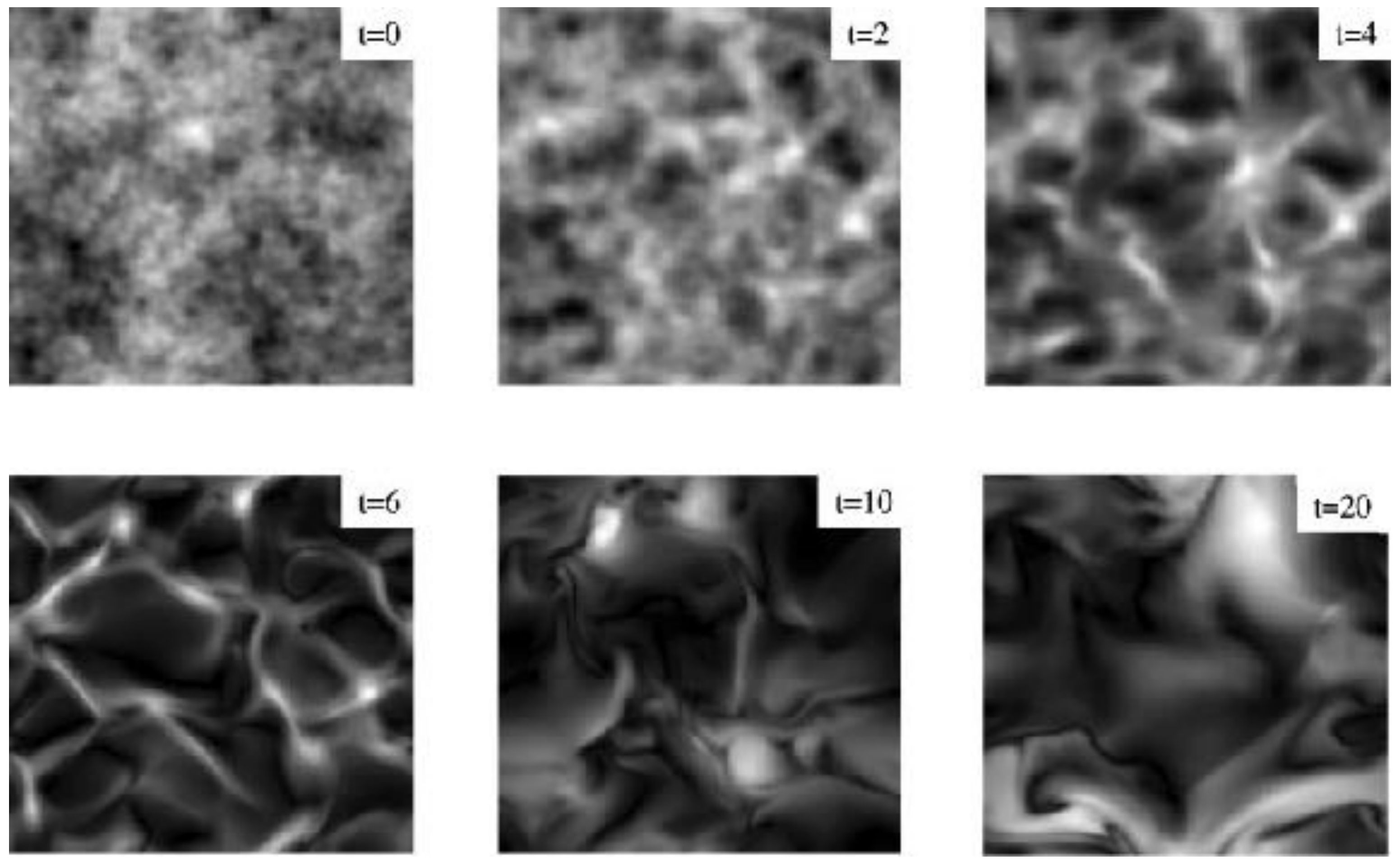
Shock precursors (Cosmic rays)



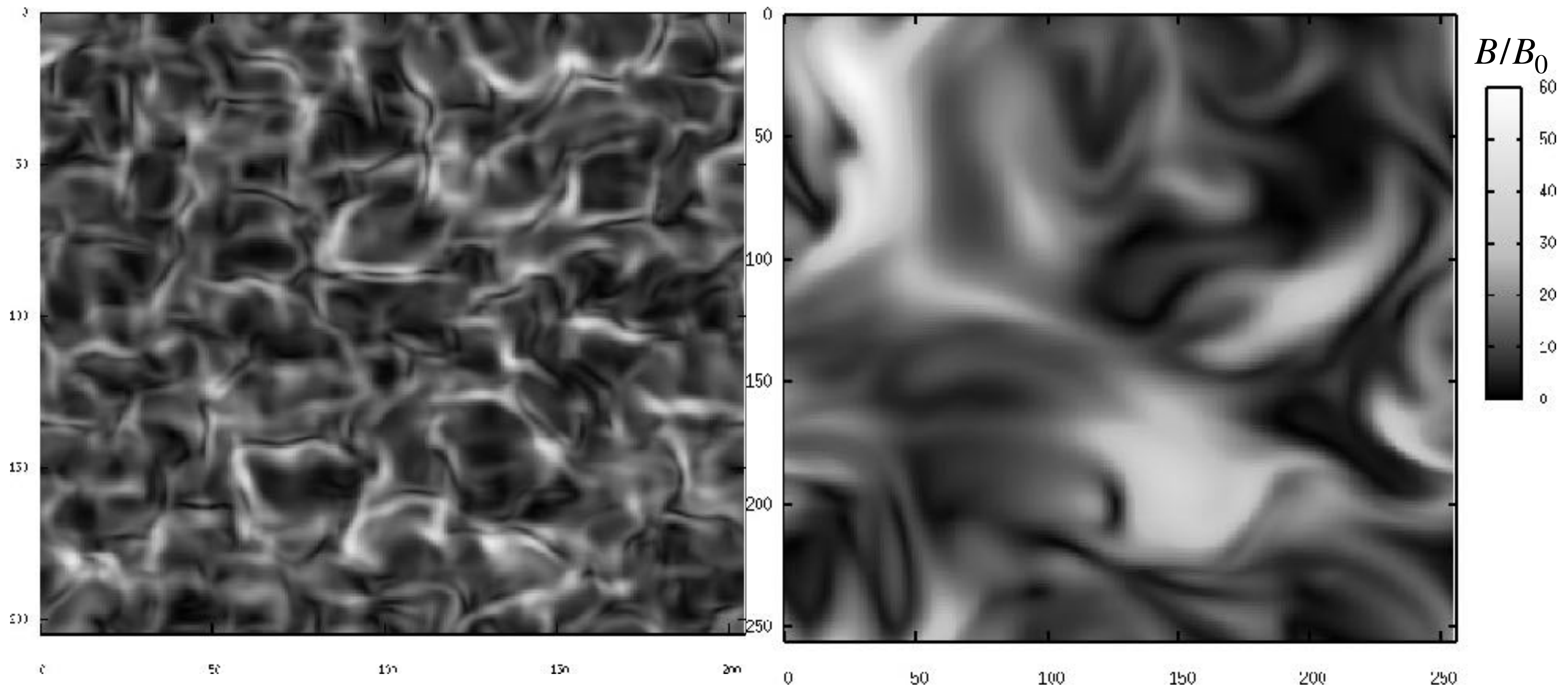
Ideal MHD: $E = -u \times B$

$\nabla \times \boldsymbol{B} = j_{MHD} + j_{CR}$

On scales << CR gyroradius, CRs are rigid, but return current is magnetised.



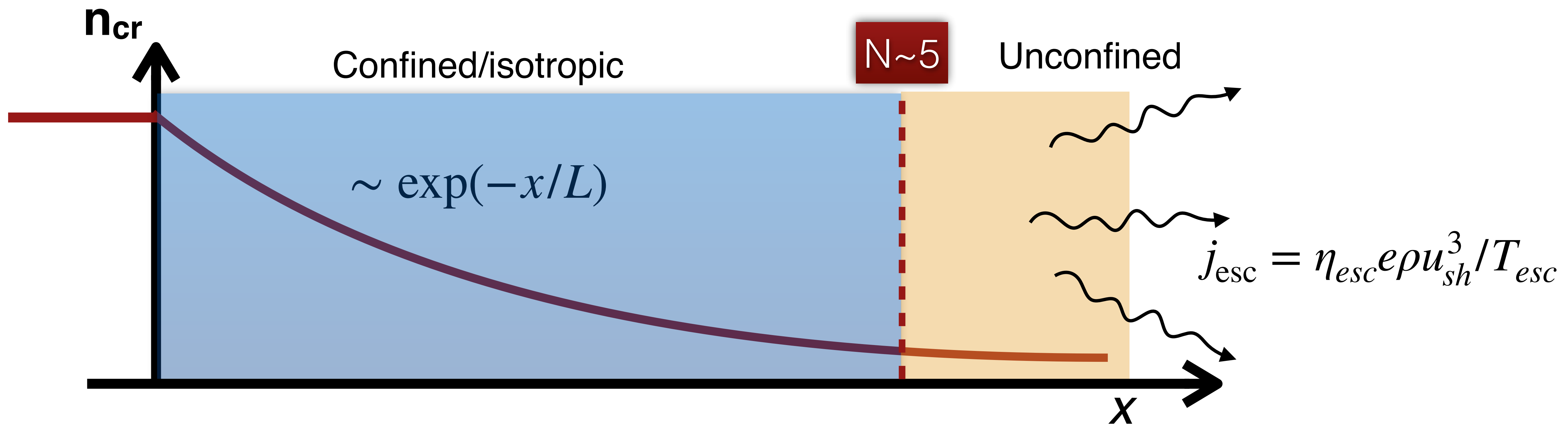
Bell 2004



Field grows initially on small (sub CR gyro scales)
in non-linear phase, field grows rapidly to scale of box

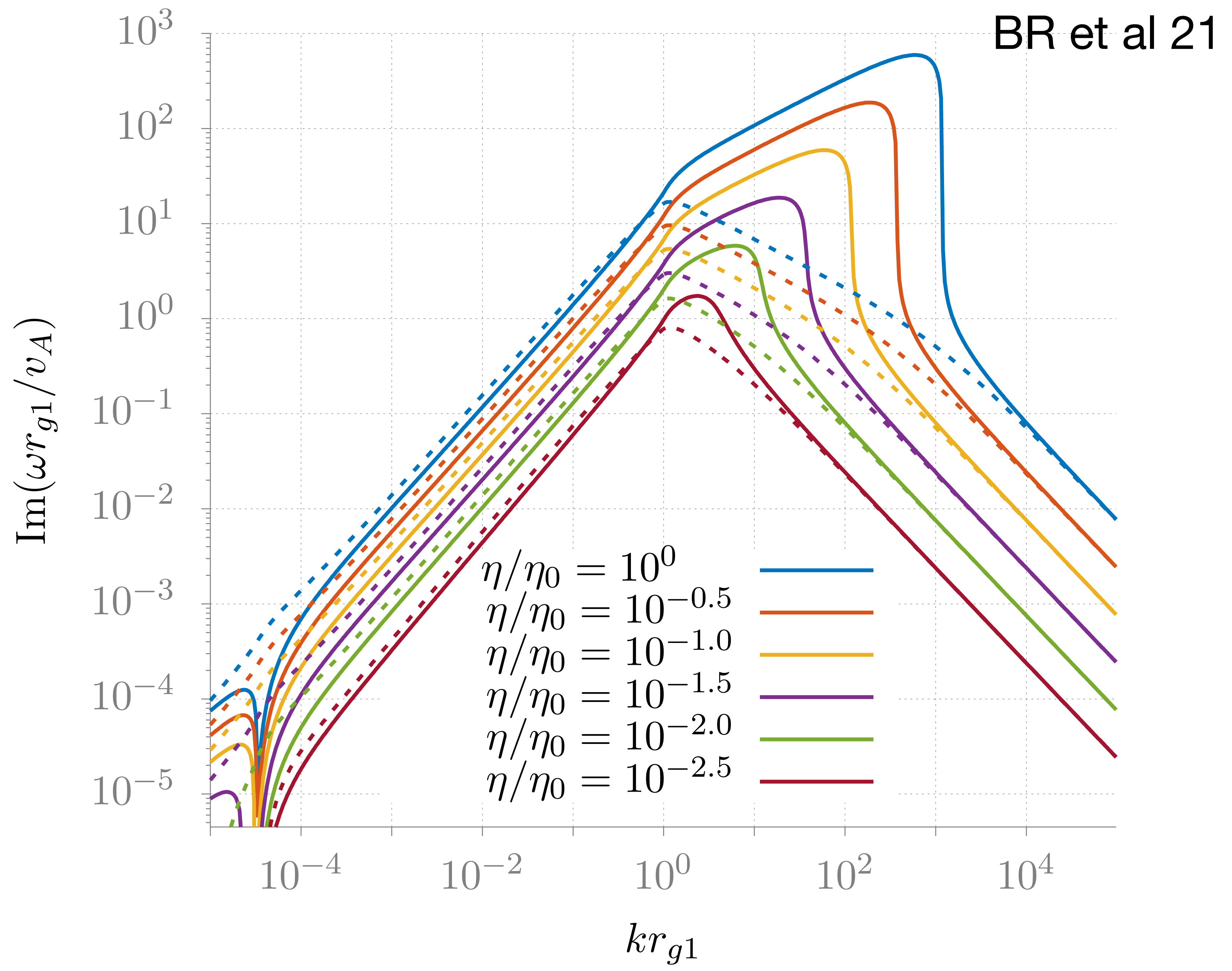
A self-consistent picture?

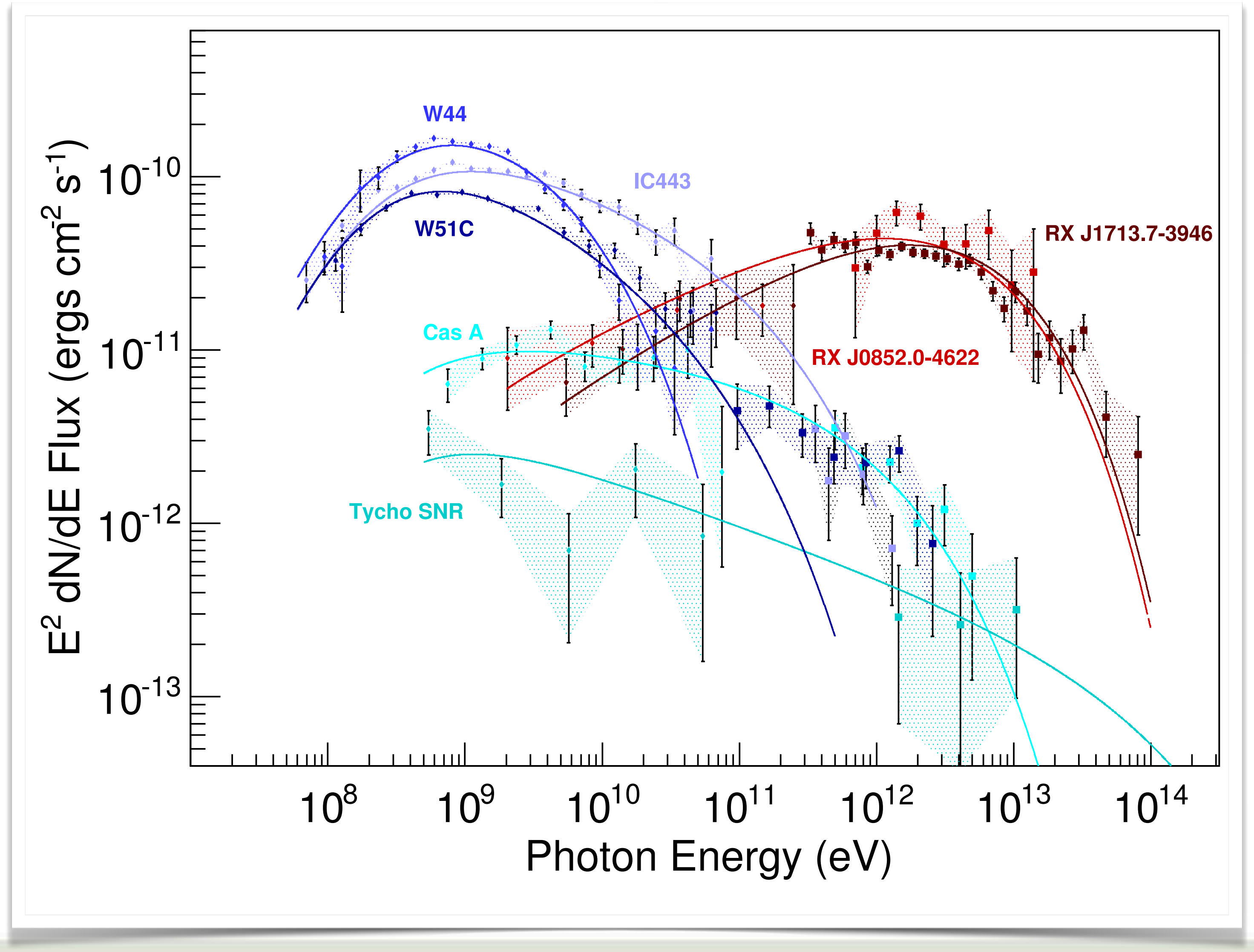
Need many exponential growth times to confine particles



$$\epsilon_{max} \approx 100\sqrt{n}\left(\frac{P_{cr}}{\rho u_{sh}^2}\right)\left(\frac{u_{sh}}{5{,}000\ \mathrm{km\ s^{-1}}}\right)^3\left(\frac{t_{snr}}{100\ \mathrm{yrs}}\right)\ \mathrm{TeV}$$

Zirakashvilli & Ptuskin 08
Bell et al.13





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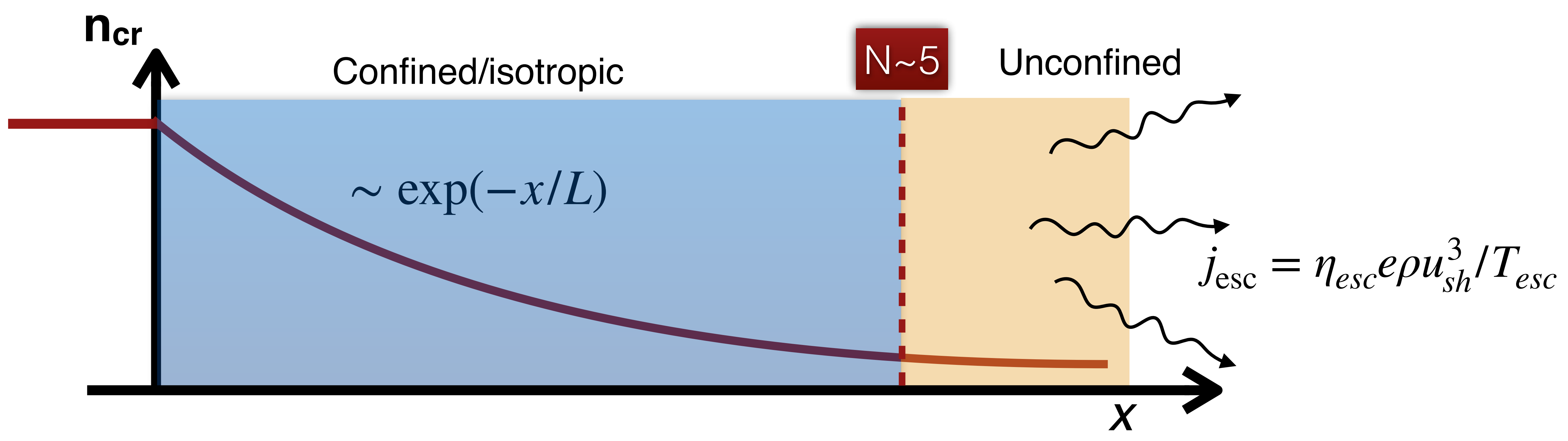
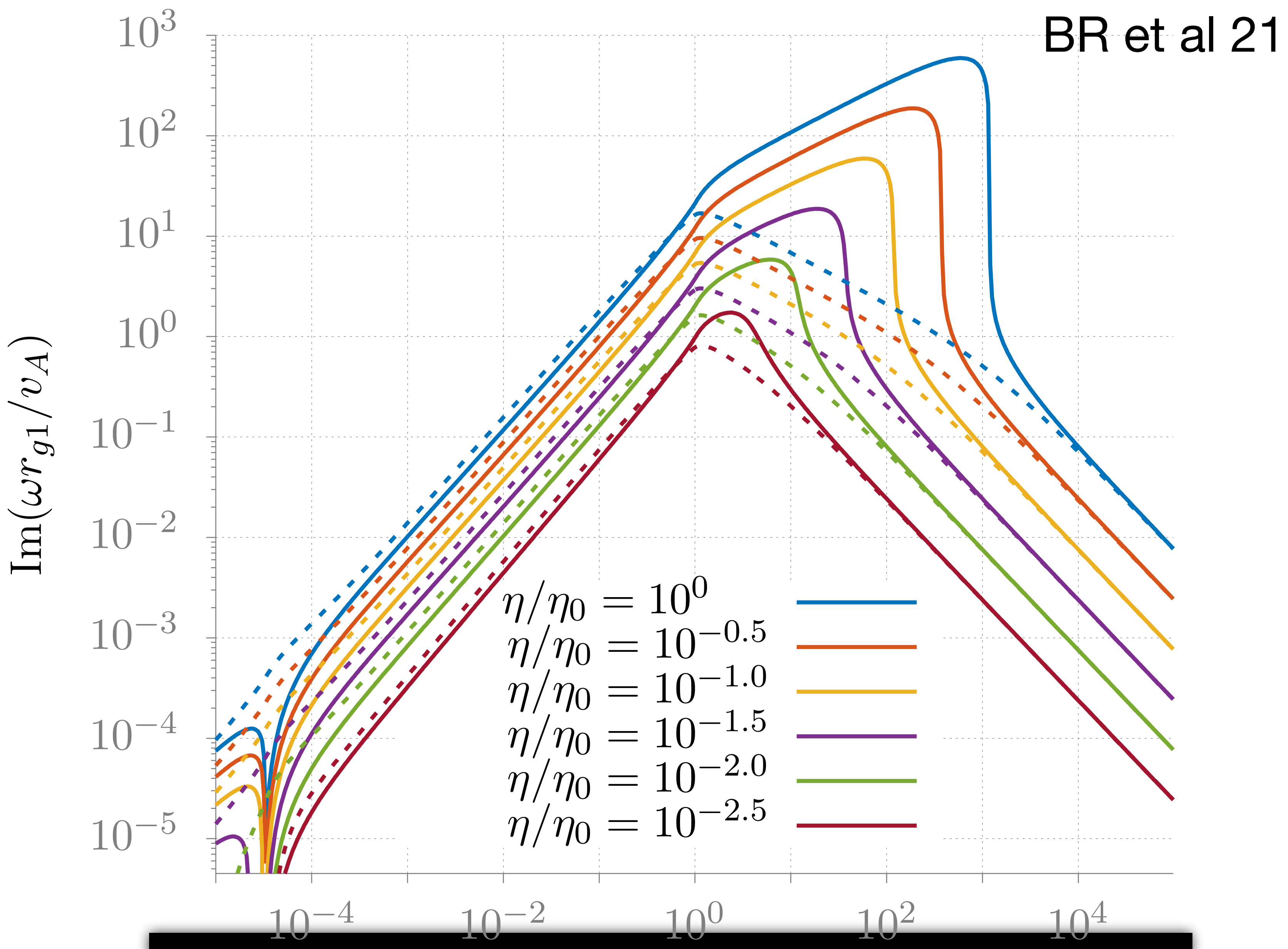


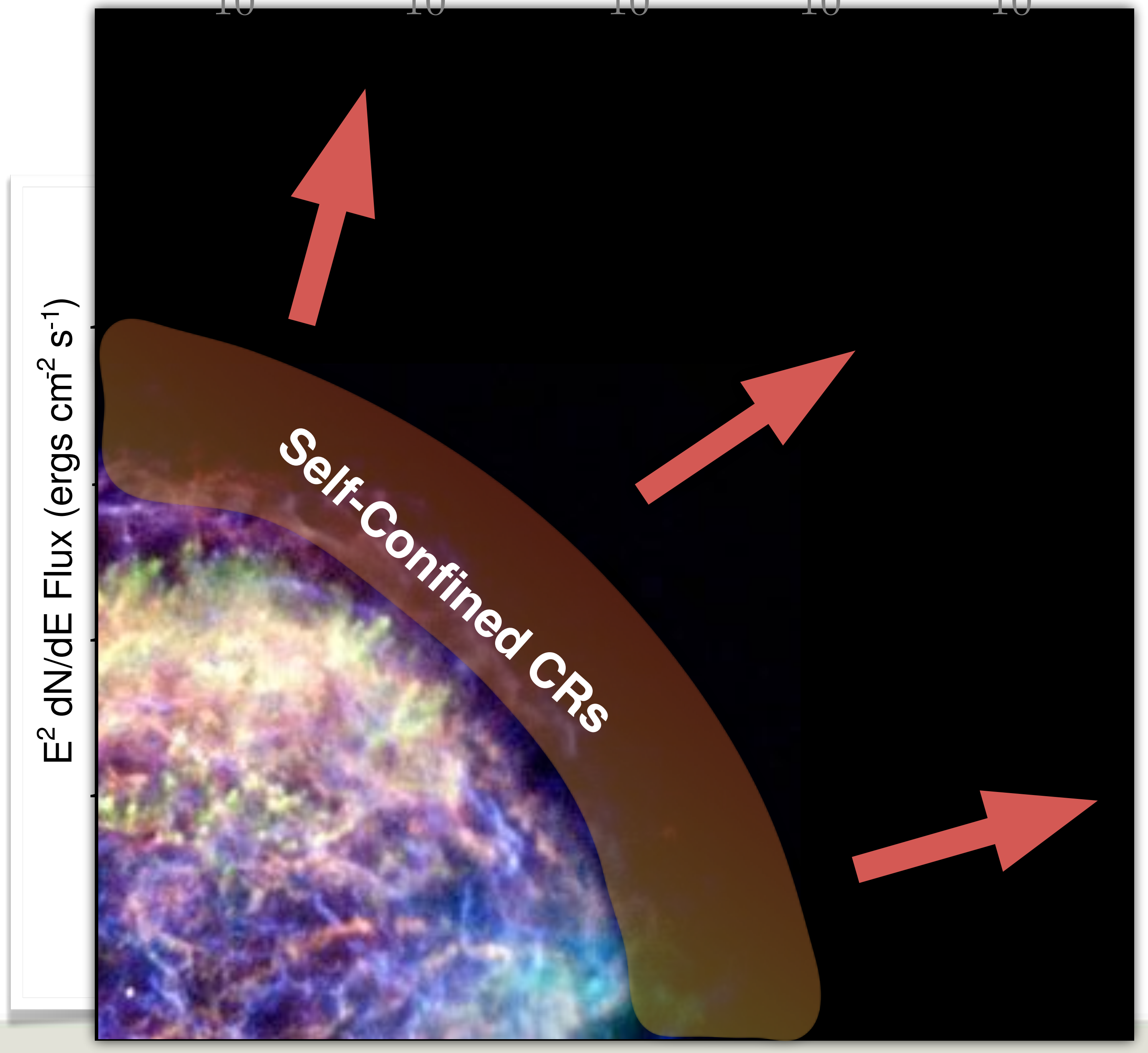
$$\epsilon_{max} \approx 100\sqrt{n}\left(\frac{P_{cr}}{\rho u_{sh}^2}\right)\left(\frac{u_{sh}}{5{,}000 \text{ km s}^{-1}}\right)^3\left(\frac{t_{snr}}{100 \text{ yrs}}\right) \text{TeV}$$

Zirakashvilli & Ptuskin 08
Bell et al.13

Shocks from CCSn (**or RS Oph**) expand into stellar winds: $4\pi r^2 \rho v_w = \dot{M}$

$$\epsilon_{max} \approx 0.8Z\left(\frac{\eta_{esc}}{0.03}\right)\left(\frac{u_{sh}}{10{,}000 \text{ km s}^{-1}}\right)^2\sqrt{\frac{\dot{M}/(10^{-5} M_\odot \text{yr}^{-1})}{v_w/(10 \text{ km/s})}} \text{ PeV}$$

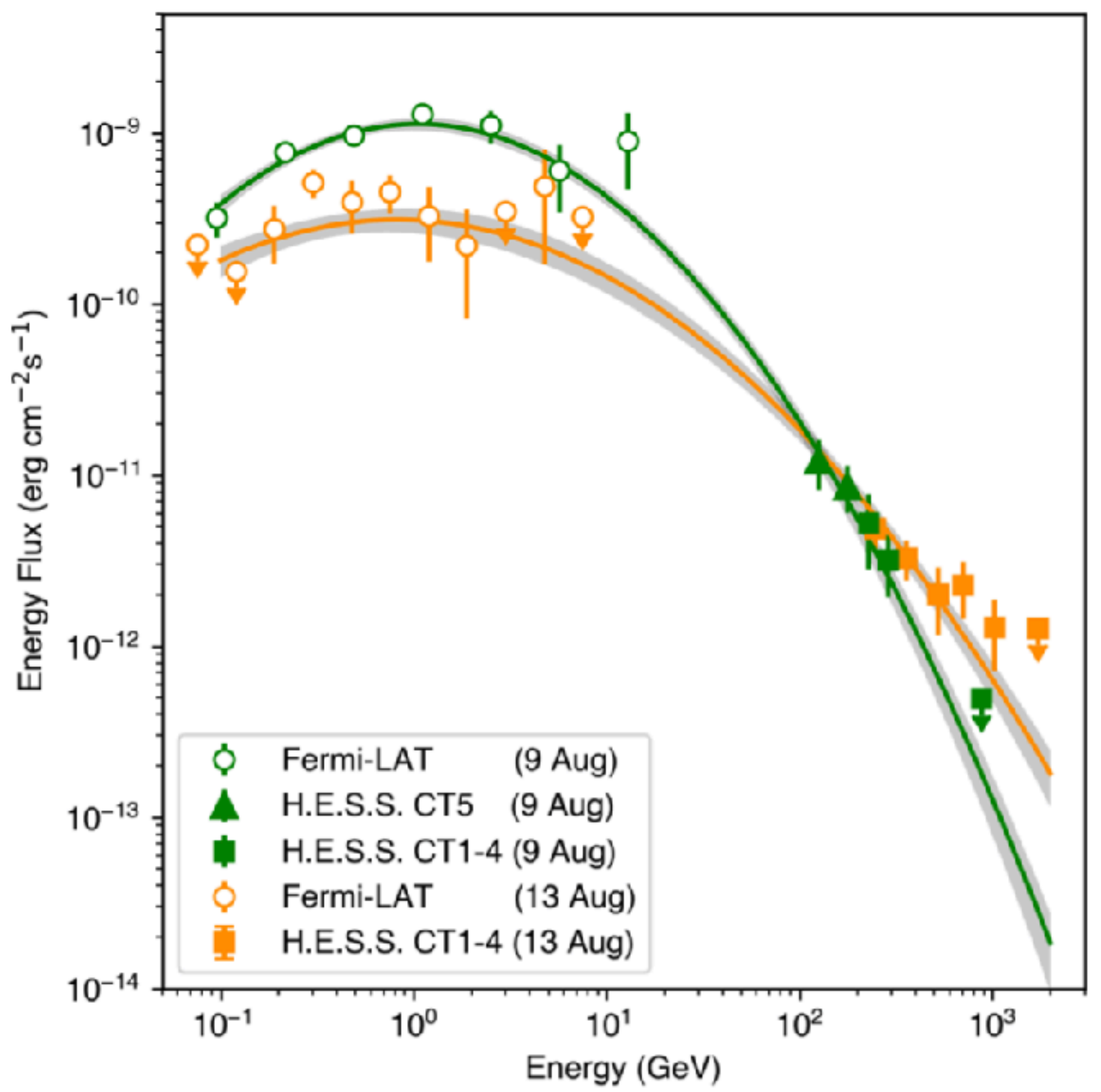




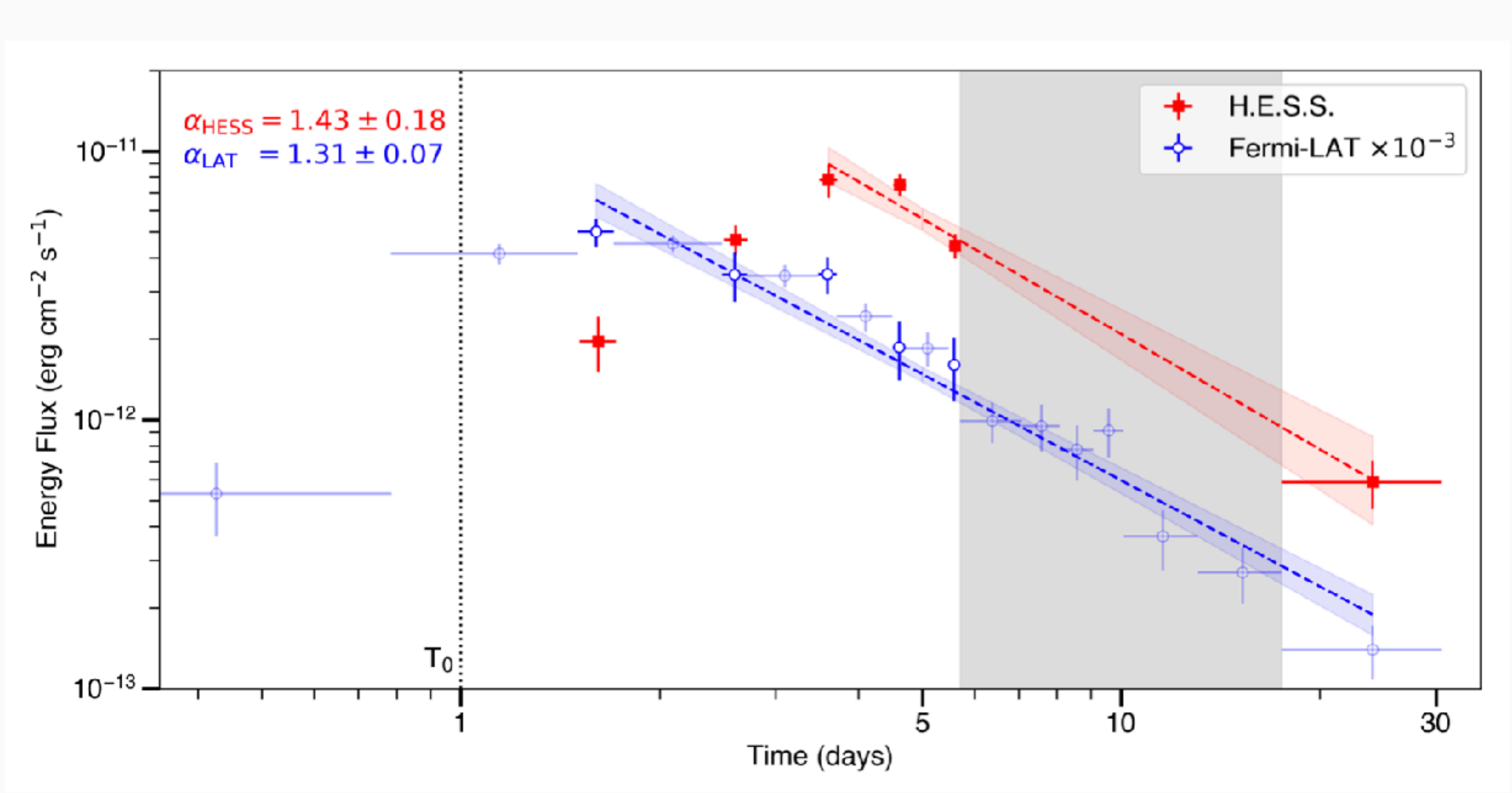
Implications for interpretation of RS Oph

$$\epsilon_{\max} \approx 5Z \left(\frac{\eta_{esc}}{0.01}\right) \left(\frac{u_{\rm sh}}{5{,}000\ \rm km\ s^{-1}}\right)^2 \sqrt{\frac{\dot{M}/(10^{-7} M_\odot {\rm yr}^{-1})}{v_w/(10\ \rm km/s)}}\ \rm TeV$$

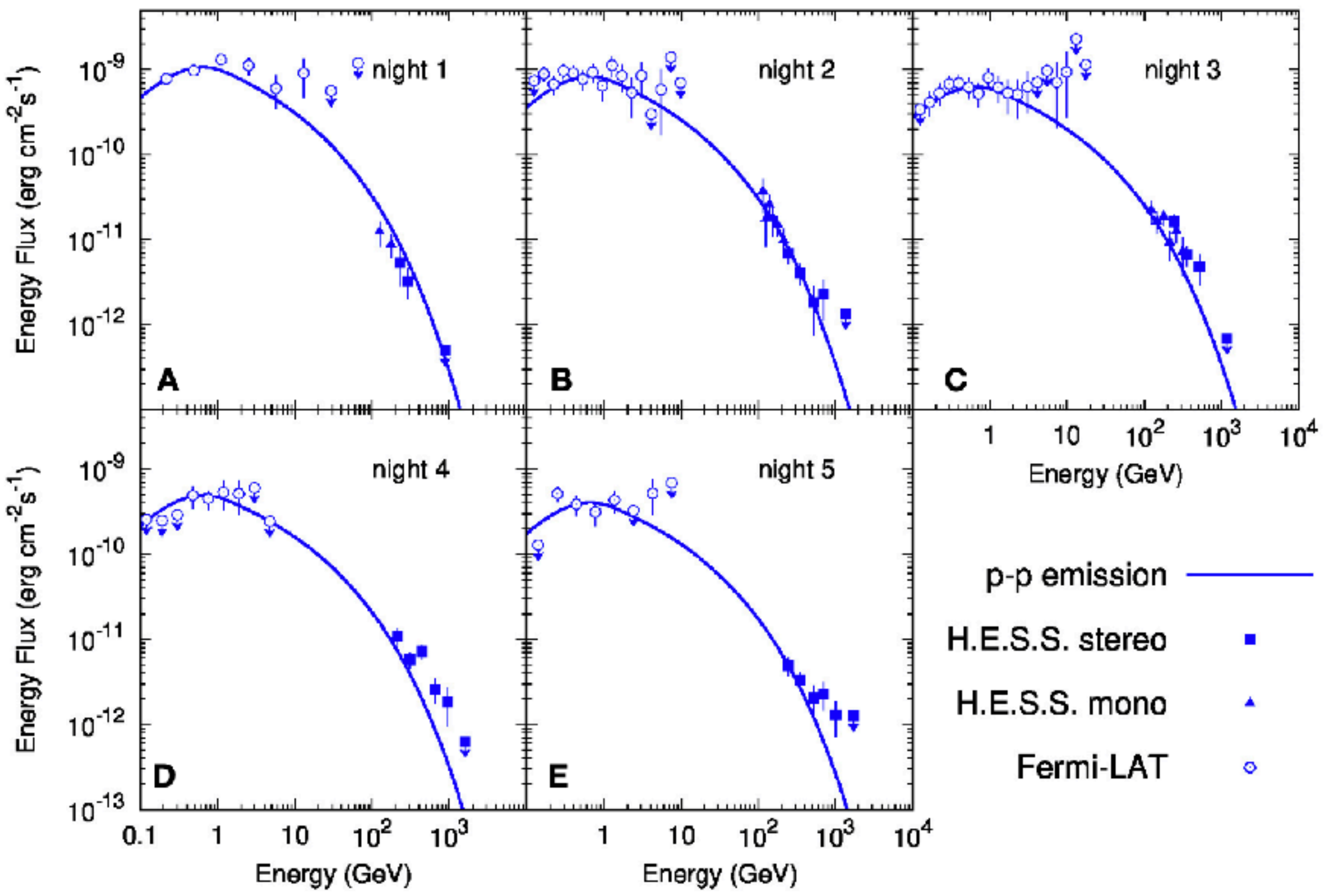
Gamma-rays detected up to ~ TeV consistent with the maximum particle energy prediction



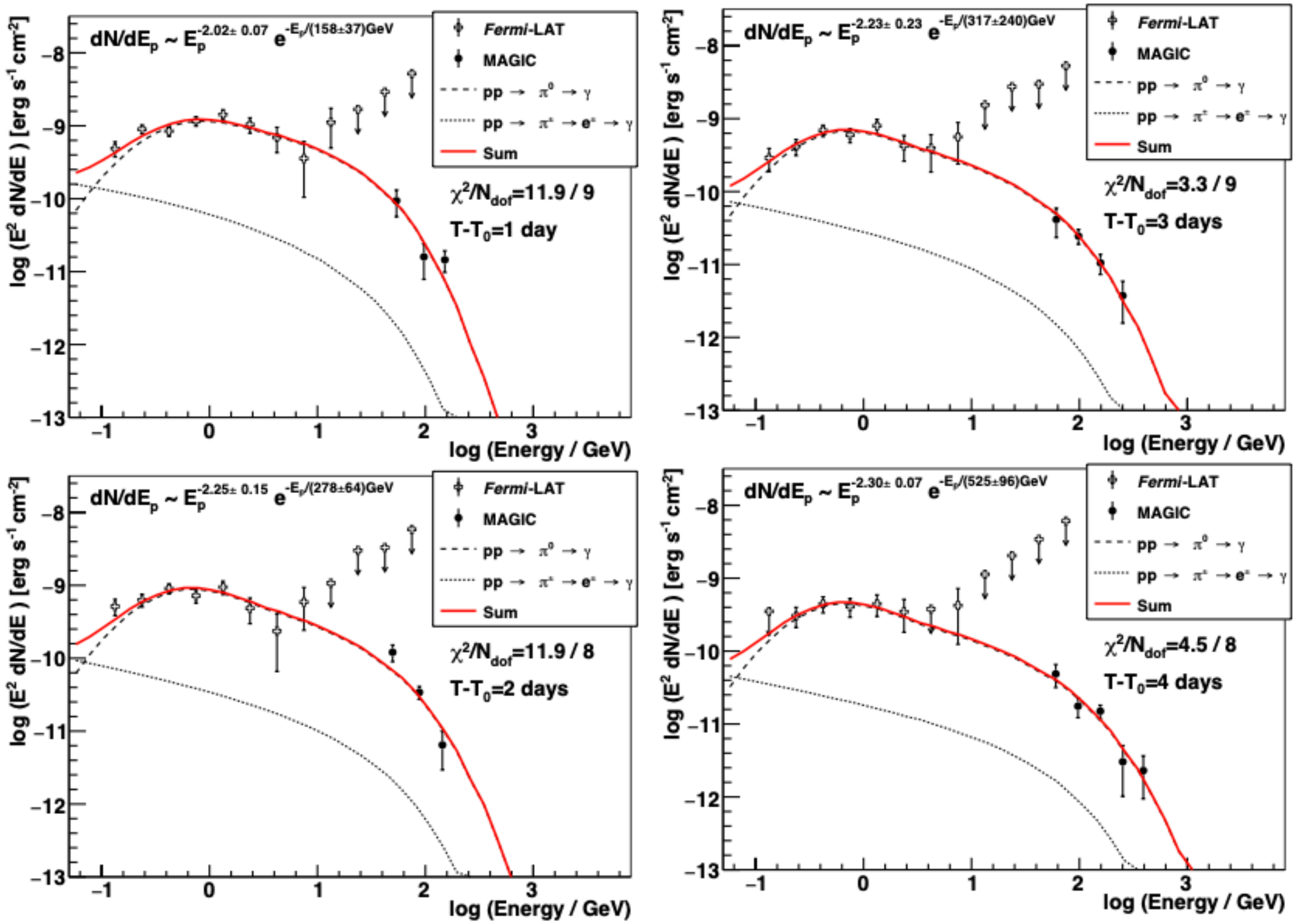
H.E.S.S. Collaboration 2022



Hadronic γ-rays from RS Oph

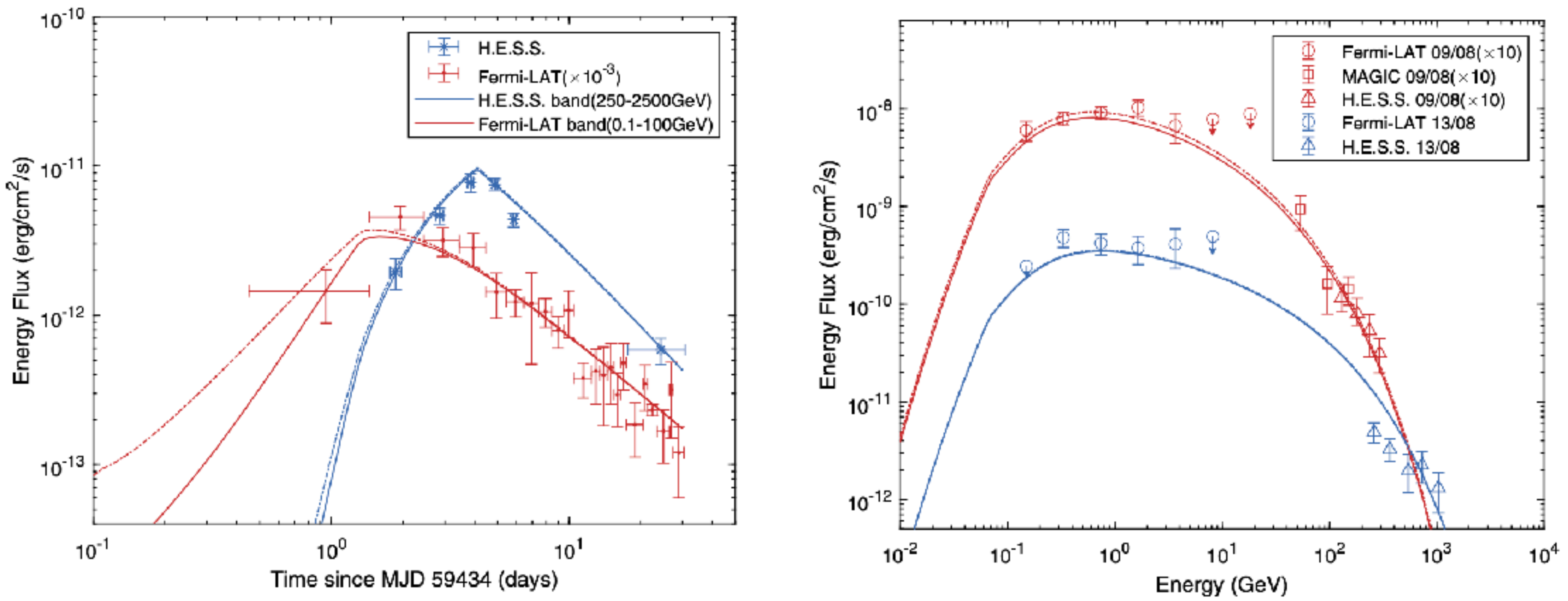


H.E.S.S. Collaboration 2022
Time dependent shock model with fixed injection shape
(Maximum energy has weak time dependence)

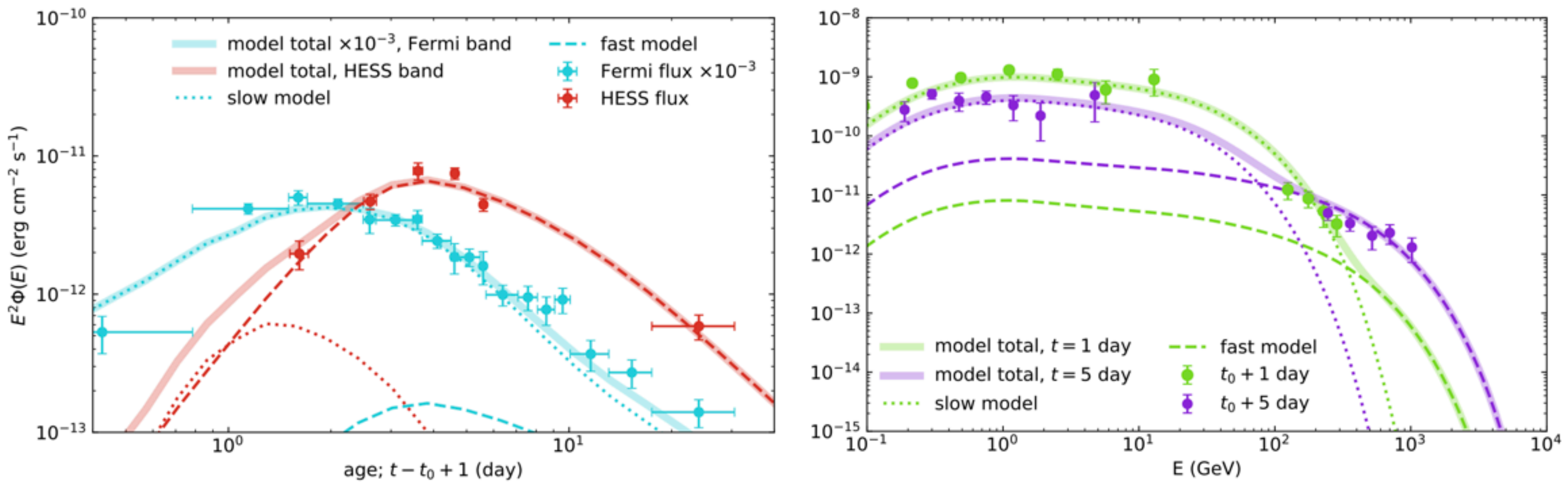


Magic Collaboration 2022
Fits hint at general trend - flux reduction, spectral softening and increasing maximum energy with time

Hadronic γ-rays from RS Oph continued



Zheng et al. PRD 2022
Single zone time dependent model



Diesing et al, arXiv.2211.02059
Multi-zone time dependent model

What next?

Detection by IACT instruments bring a unique perspective on nova

In the wake of the 2006 burst, numerous groups performed detailed 3D simulations of RS Oph like systems. A renewed effort is warranted.

If RS Oph is typical of embedded novae, **CTA** will have opportunities to observe many more sources, with improved sensitivity, energy range
(and hopefully with better visibility conditions than those that plagued the observations of HESS and MAGIC)

Despite the much larger rate of events, the total energy input from novae is dwarfed by that from supernovae. Nevertheless the larger rate provides opportunities to explore similar non-thermal processes to those occurring at/near the shocks of CCSne and their remnants

Conclusions

- New gamma-ray discoveries are changing how we think of the cosmic ray origin problem (CRs >> PeV still unclear. But see Vieu et al. 22, 23)
- The plasma physics of CRs and their self-generated fields are broadly consistent with observations (we're doing something right……maybe?)
- Additional theoretical work is needed on the multi-scale aspects, inspiration from simulations/observations are welcome.
- TeV novae are a fascinating new platform to test models of particle acceleration, magnetic field amplification, winds from binary stars
- Future observations will provide new insights, but much work remains to be done before we can say we understand the non-thermal physics of RS Oph

Thank you