Probing astrophysical transients with high-energy neutrinos

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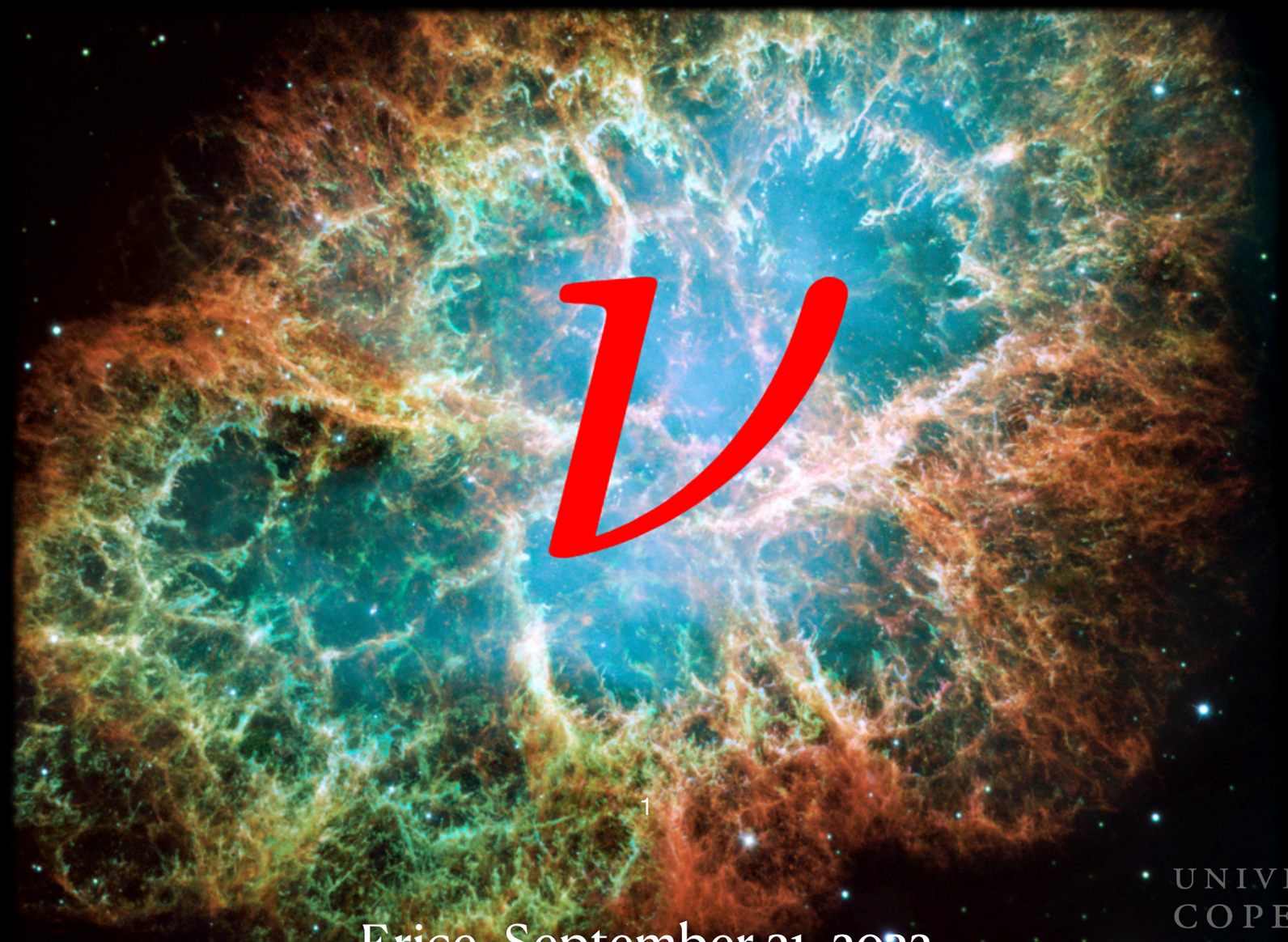
Niels Bohr Institute & DARK



Erice, September 21, 2022

INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS

UNIVERSITY OF COPENHAGEN

CARLSBERG FOUNDATION

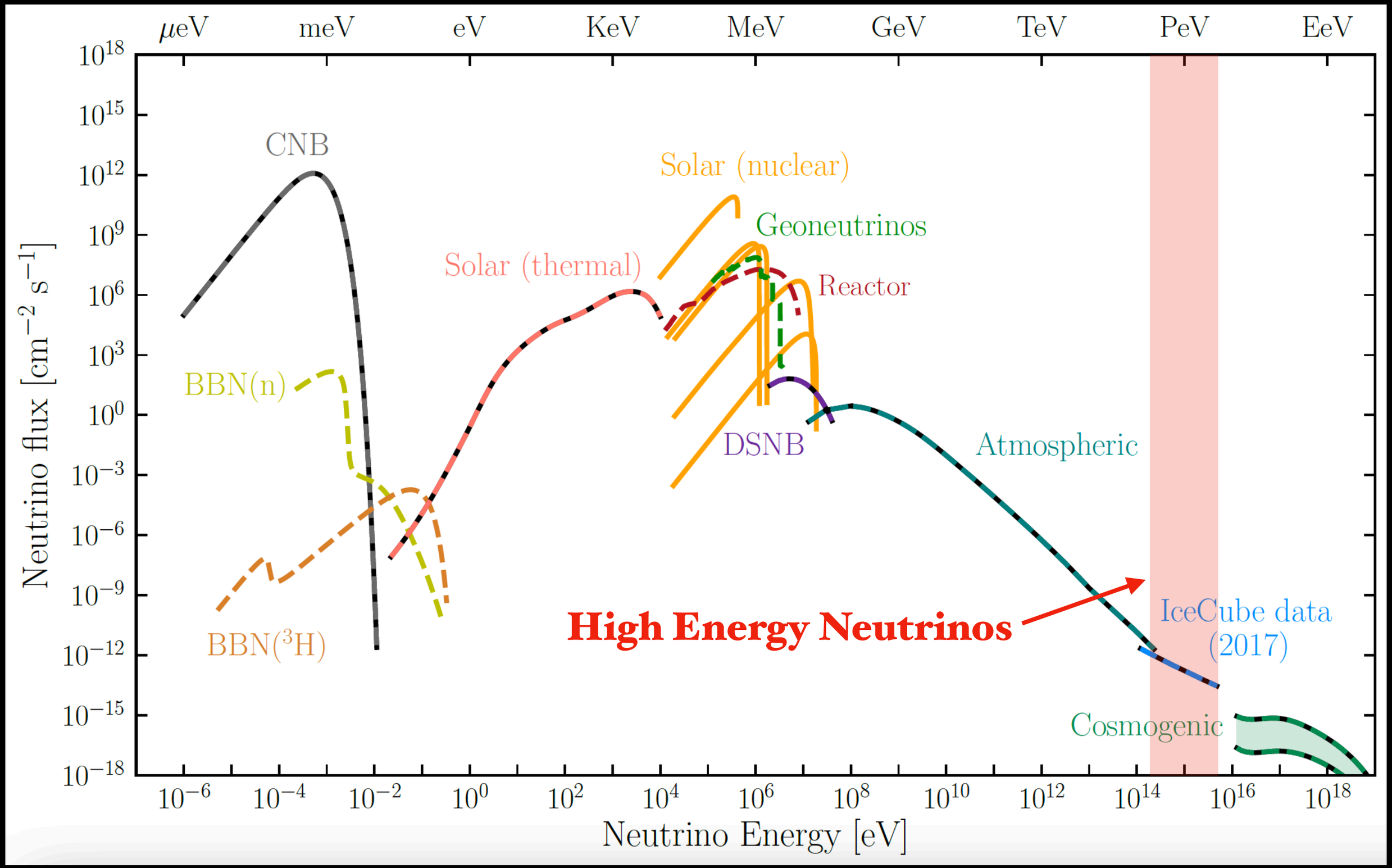
OUTLINE

- **High-energy neutrinos in astrophysical sources**
- **High-energy neutrinos from prompt γ-ray bursts**
- **High-energy neutrinos from γ-ray burst afterglow optical bumps**
- **High-energy neutrinos from super-luminous supernovae**

This talk is based on:

T.Pitik, I.Tamborra, M.Petropoulu 2021 *JCAP* 05 (2021)
T.Pitik, I.Tamborra,C.Agus,K.Auchettl *ApJ* 929 163 (2022)
E.Guarini,I.Tamborra,D.Begue,**T.Pitik**, J.Greiner *JCAP* 06 (2022)

Grand unified neutrino spectrum



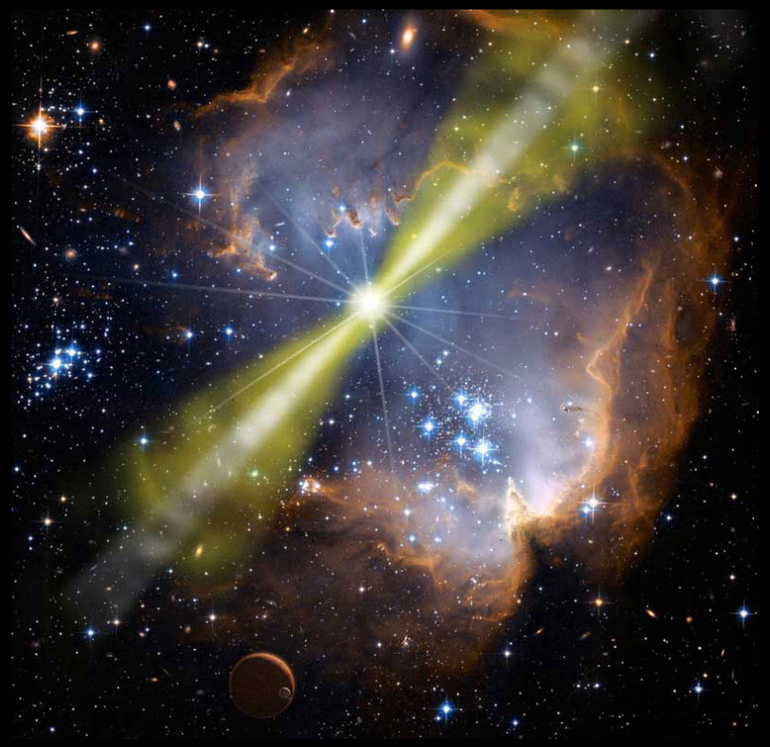
Adapted from E.Vitagliano, I.Tamborra, G.Raffelt Rev.Mod.Phys. 92 (2020)

Many candidate sources

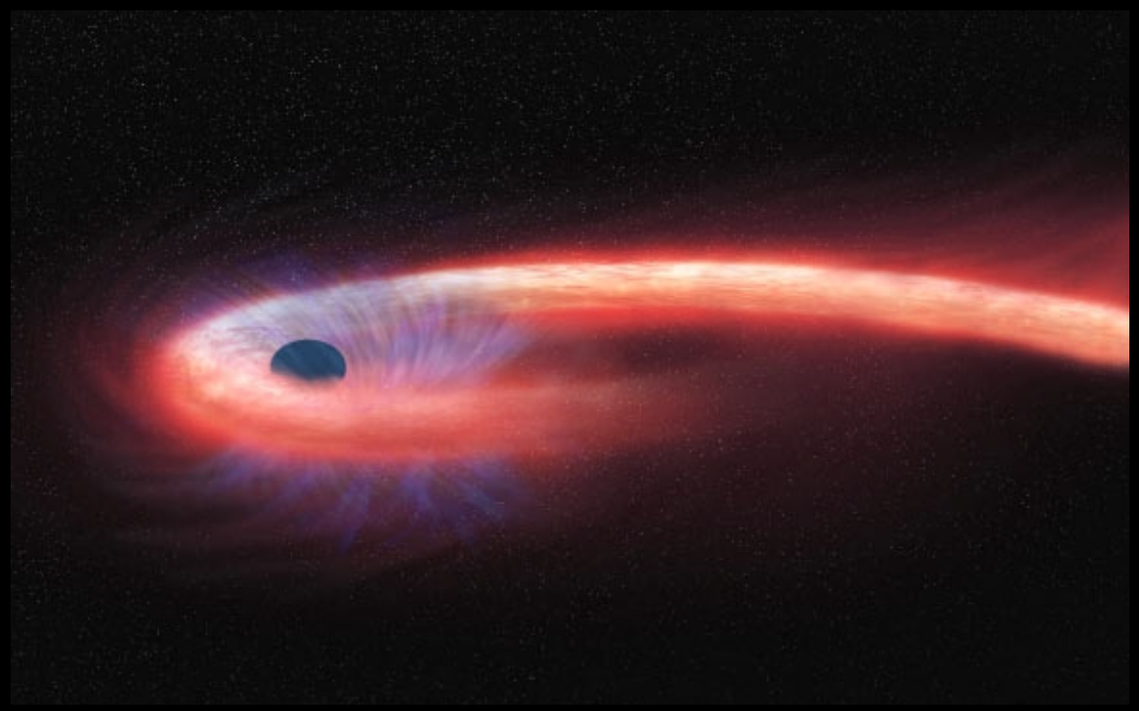
Starburst galaxies

Active Galactic Nuclei

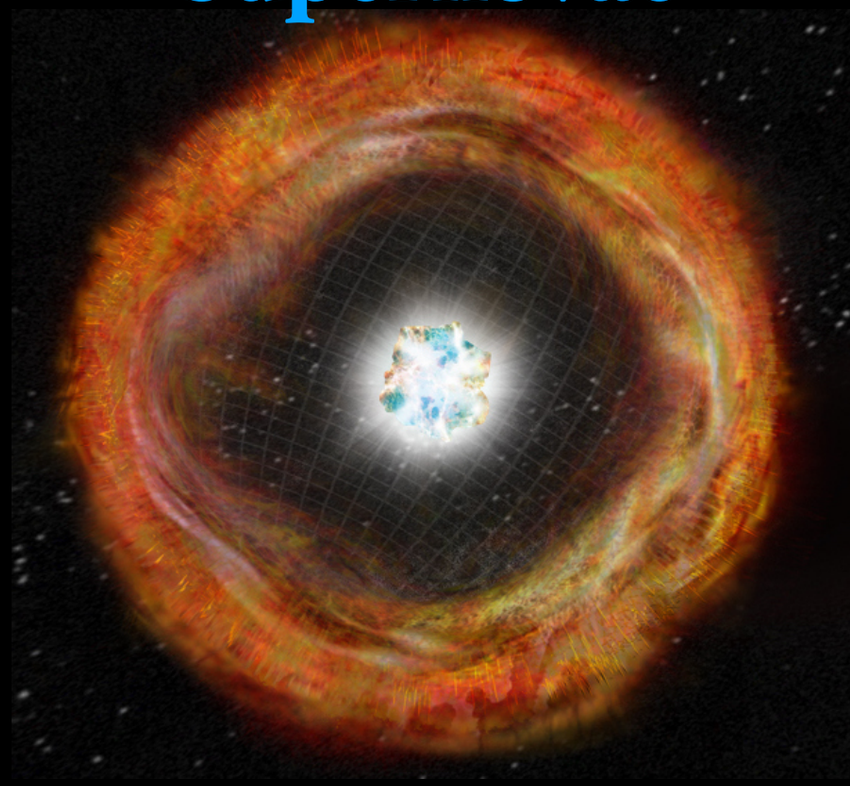
γ-ray bursts



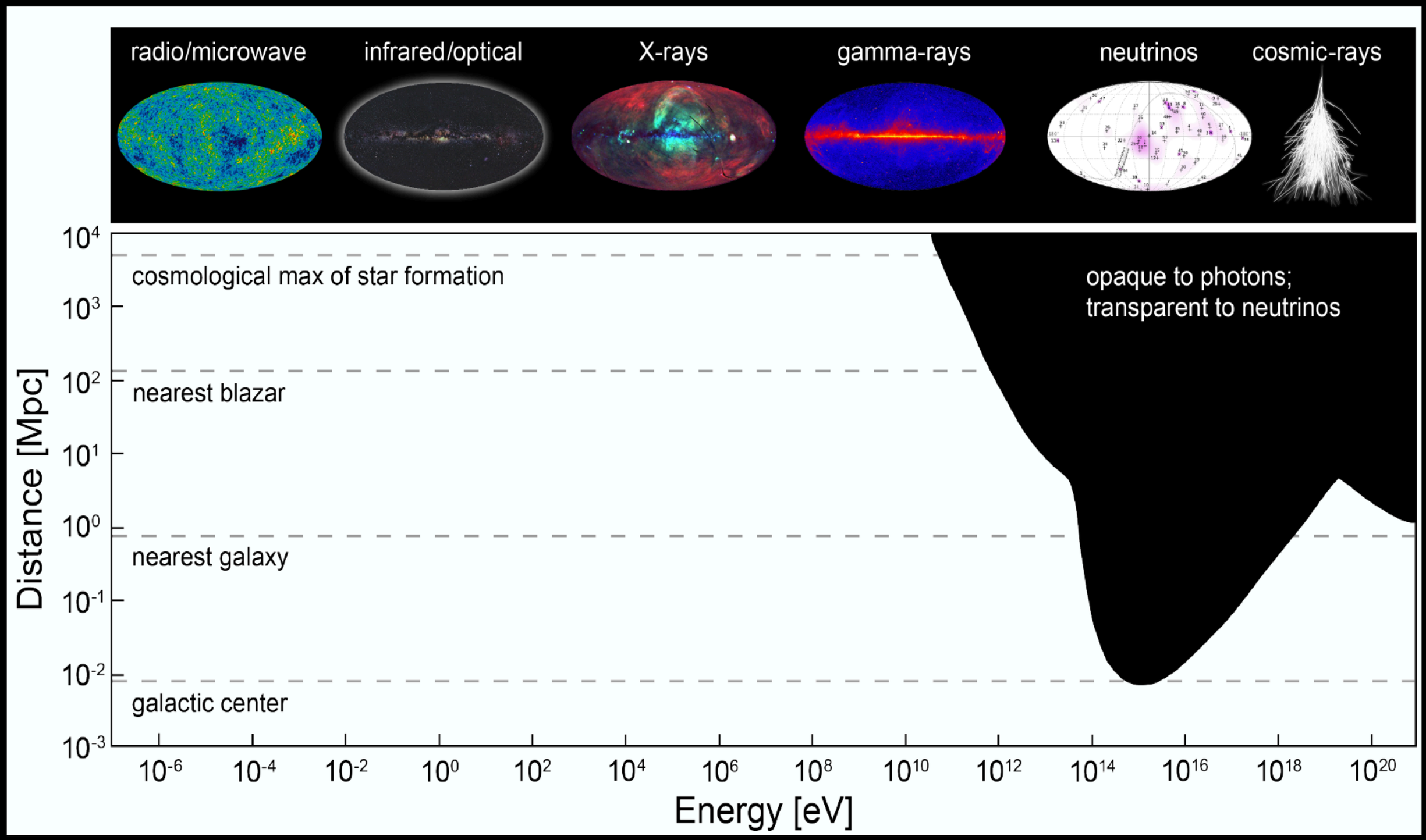
Tidal Disruption Events



Supernovae



What makes high-energy neutrinos so exciting?

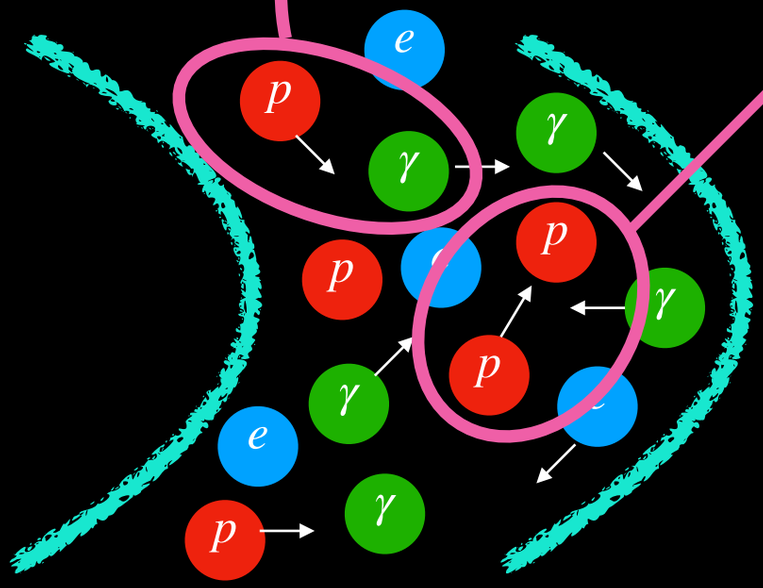


6 out of 29 decades in energy (from radio waves to UHECRs) can only be covered by neutrino astronomy

How are high energy neutrinos produced?

photo-hadronic: $p + \gamma \longrightarrow X + \text{many}(\pi^0 + \pi^+ + \pi^-)$

hadronic: $p + p \longrightarrow X + \text{many}(\pi^0 + \pi^+ + \pi^-)$



shock acceleration region

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu \longrightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$$

$$\pi^0 \longrightarrow \gamma + \gamma$$

What can we learn by using high-energy neutrinos?

- They are the smoking gun of cosmic ray accelerators

- They can probe fundamental physics

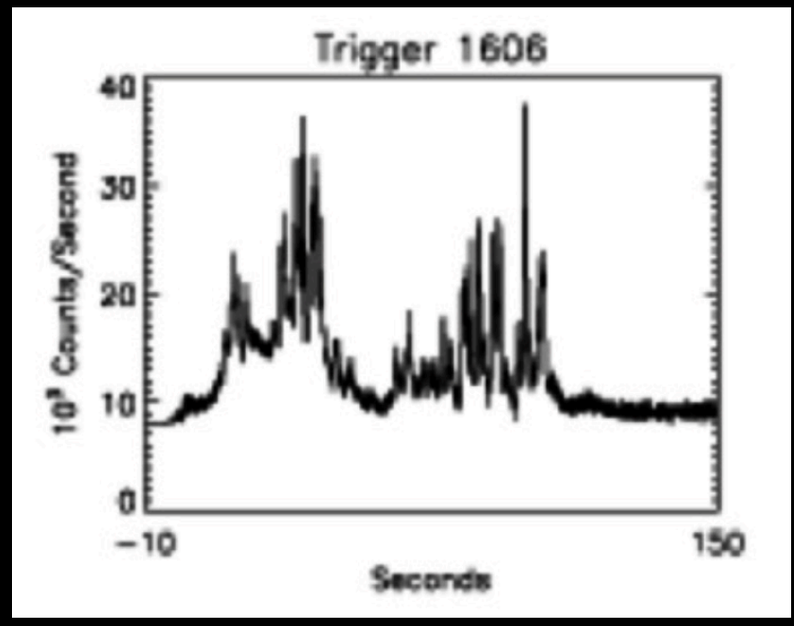
- They can constrain the physics within extreme astrophysical sources (AGNs, GRBs, TDEs, SNe, etc)

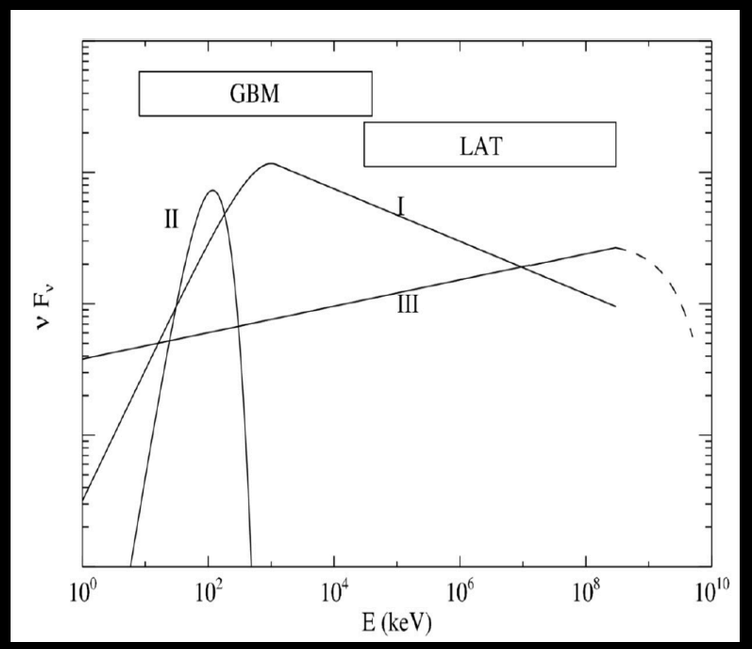
my focus

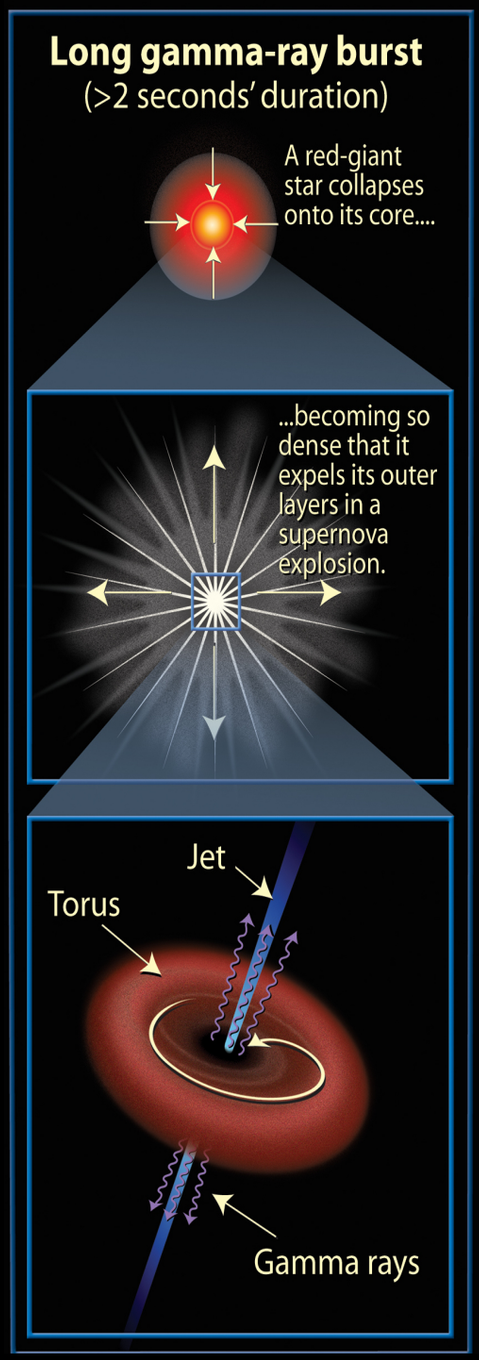
Long Gamma Ray Bursts

The most powerful and intense explosive events in the Universe

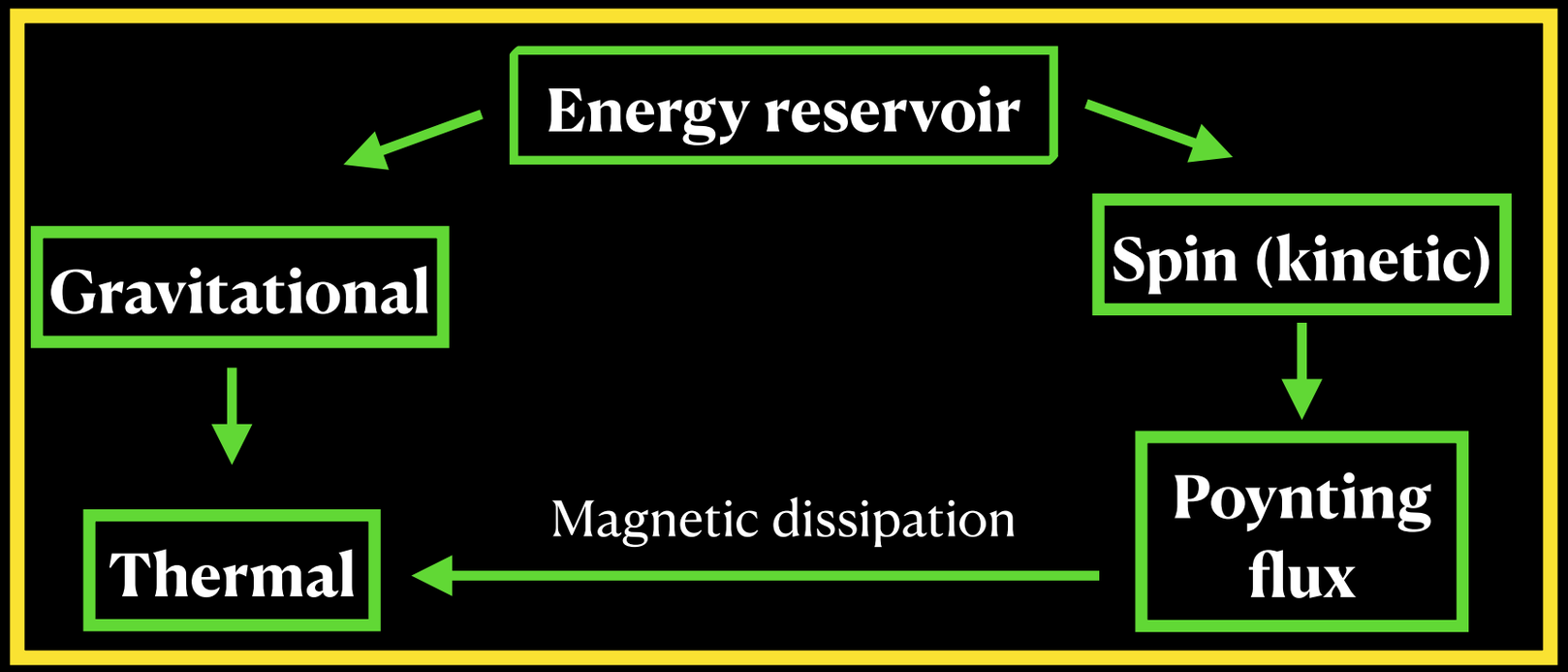
- **Flashes of γ-rays ($1 - 10^4$ keV) lasting for $\mathcal{O}$(10) s**
- **Energetics: $E_\gamma \sim 10^{50} - 10^{52}$ erg**
- **Spectra: mainly non-thermal**
- **Lightcurves: extremely irregular ($t_{\rm min} \simeq 1 - 10^4$ ms)**
- **Progenitors: collapsing massive stars**
- **Two possible central engines: hyper-accreting BHs or rapidly spinning magnetars**



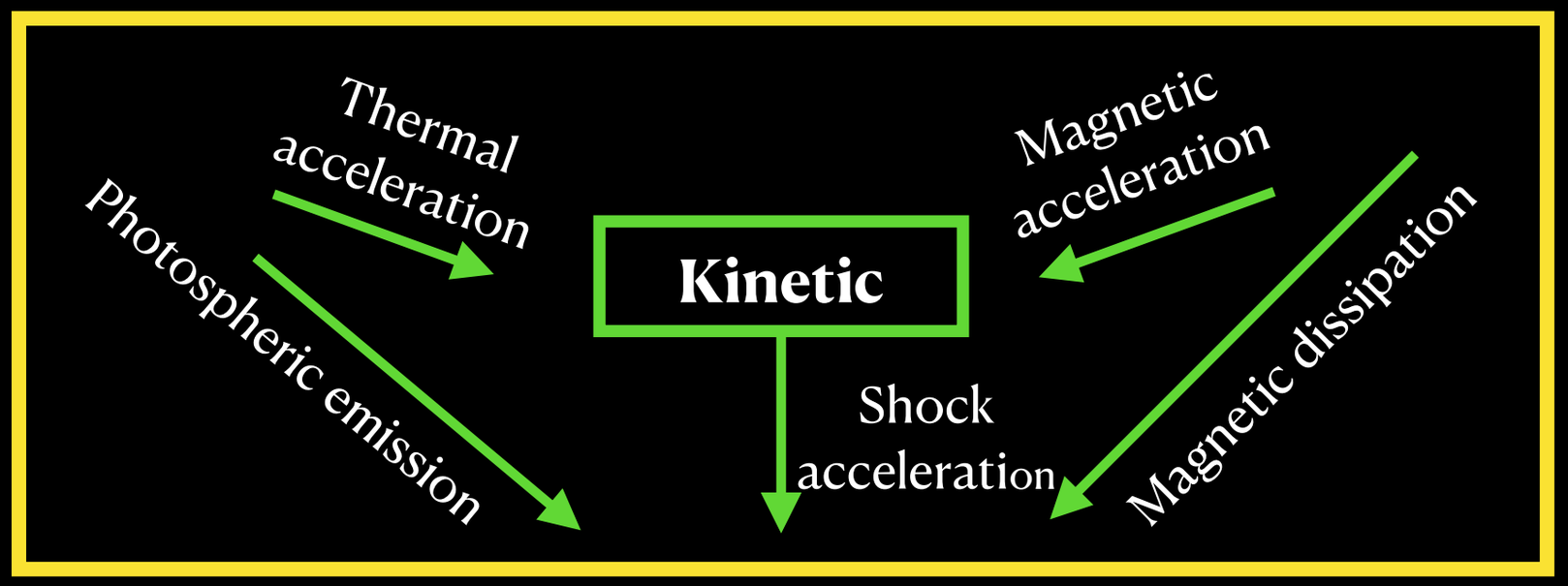




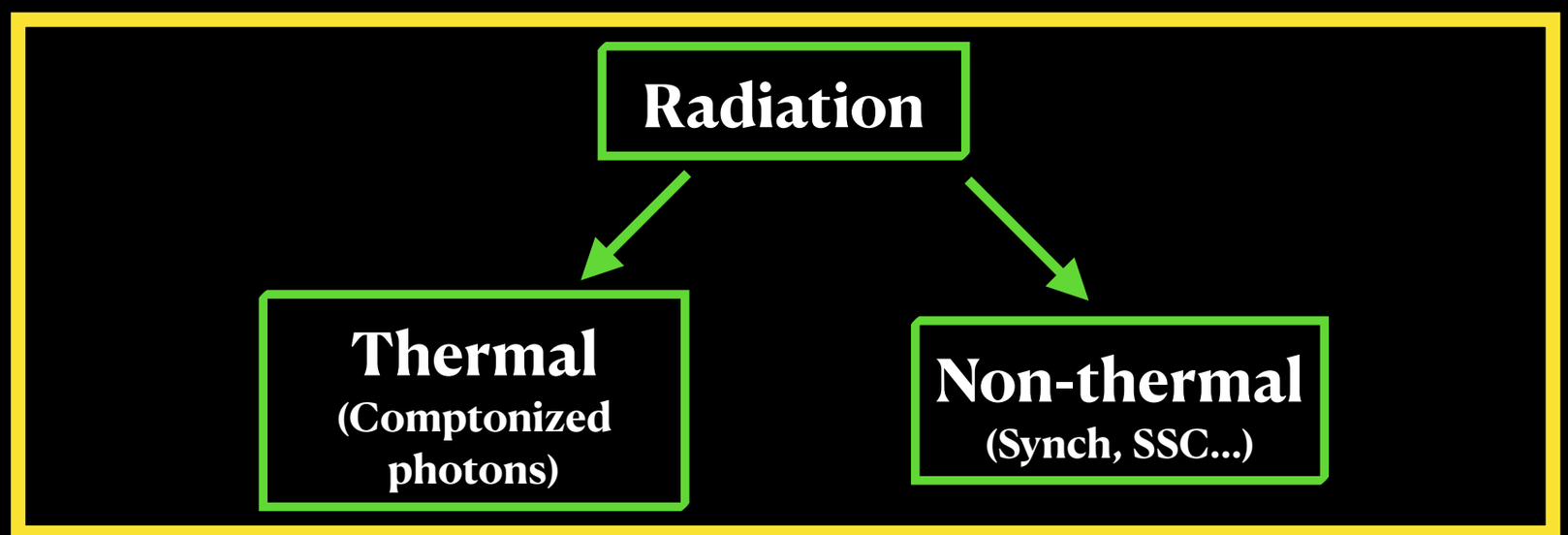
Open questions:



What is the GRB jet composition ?



What is the energy dissipation mechanism ?

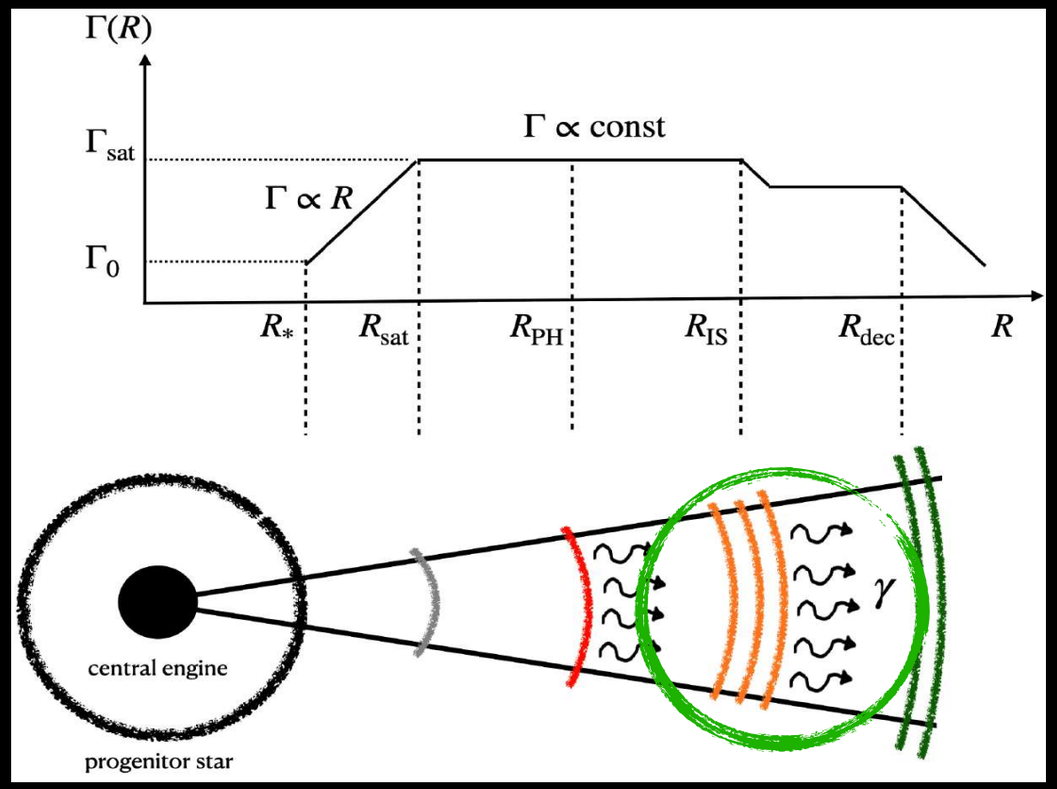


What is the radiation mechanism ?

GRB spectra alone are not sufficient

Can we diagnose the jet mechanism by using neutrinos?

Matter and Poynting flux dominated jets

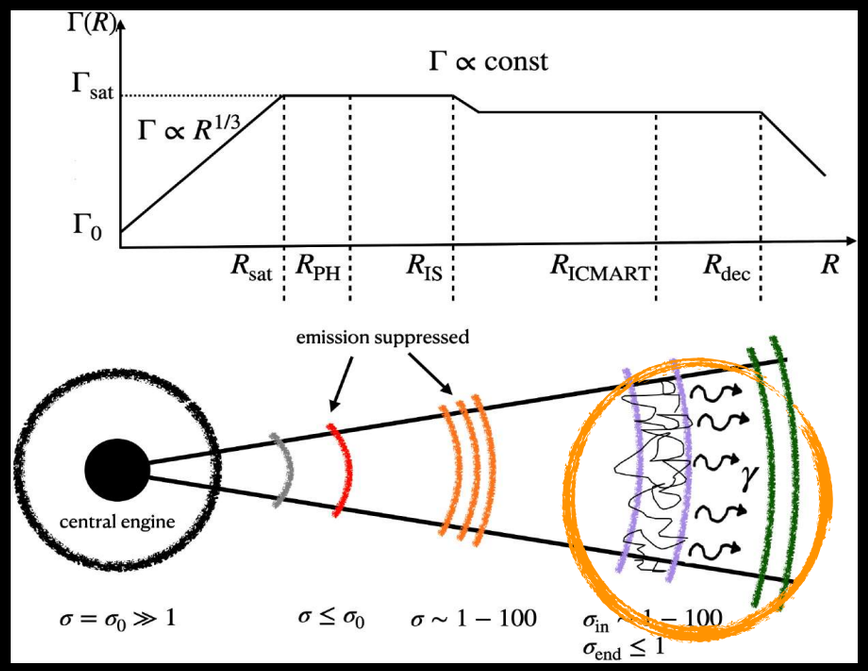


1. **Internal shock model**
2. **Dissipative photosphere + Internal Shocks**
3. **3 component model**

Proton synchrotron model

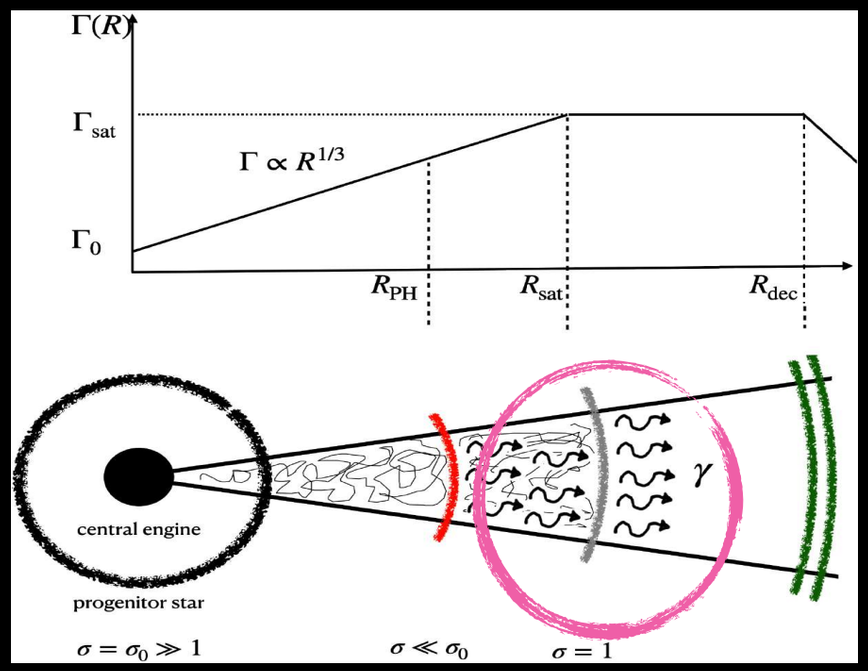
Piran et al 1993

ICMART model

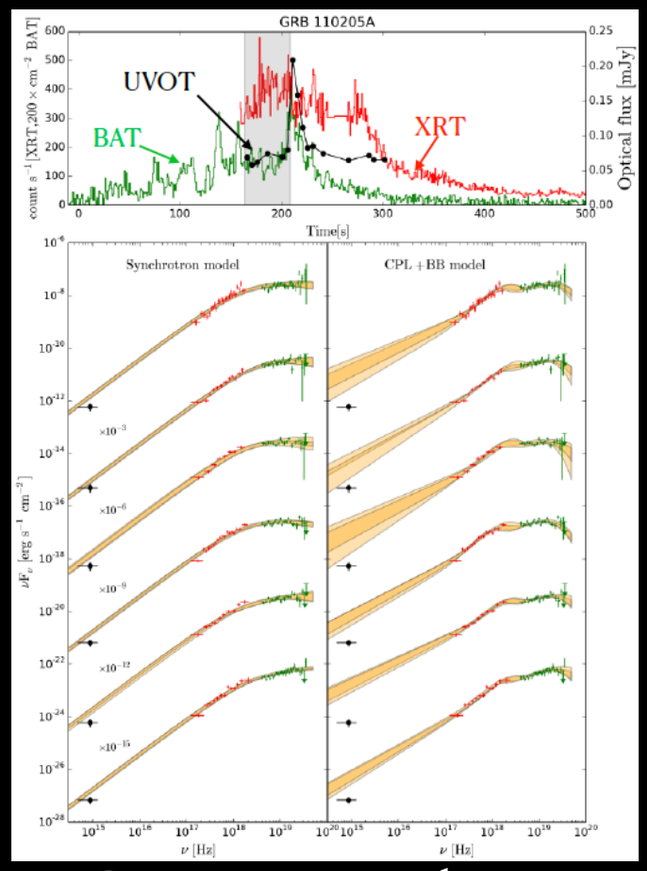


Zhang et al 2010

Magnetized jet with gradual dissipation

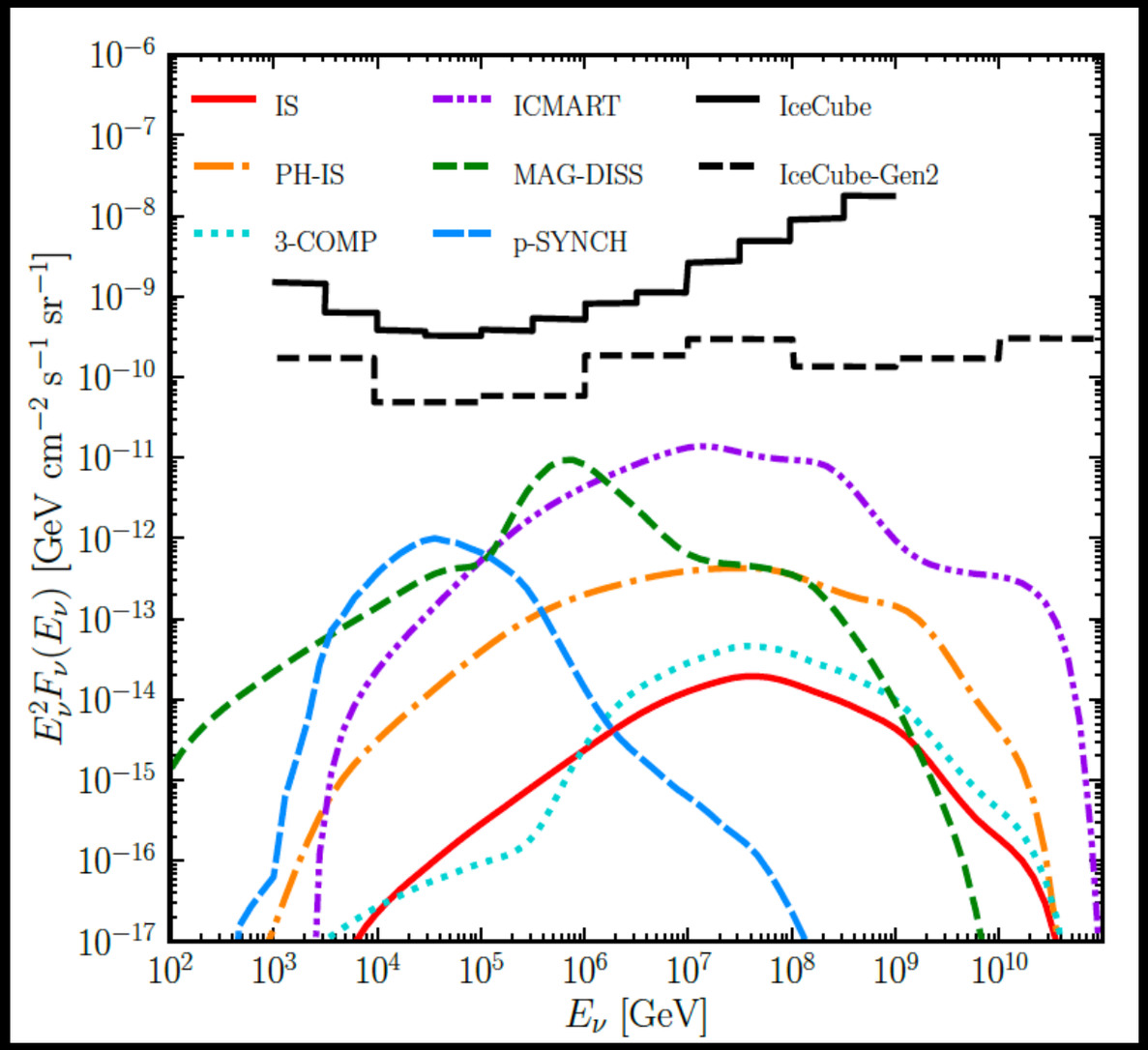


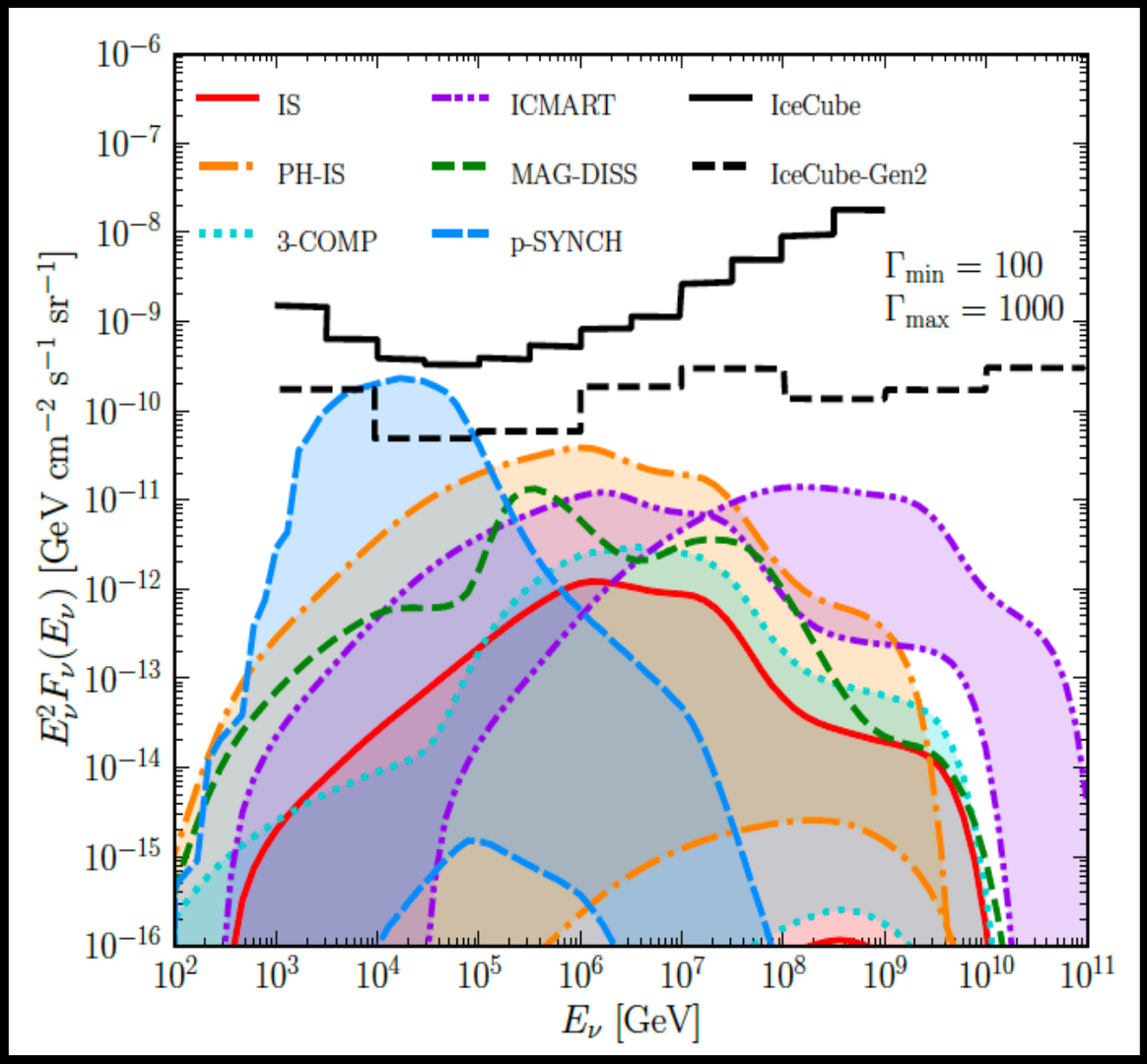
Drenkhahn 2002



Oganesyan et al 2019

Results

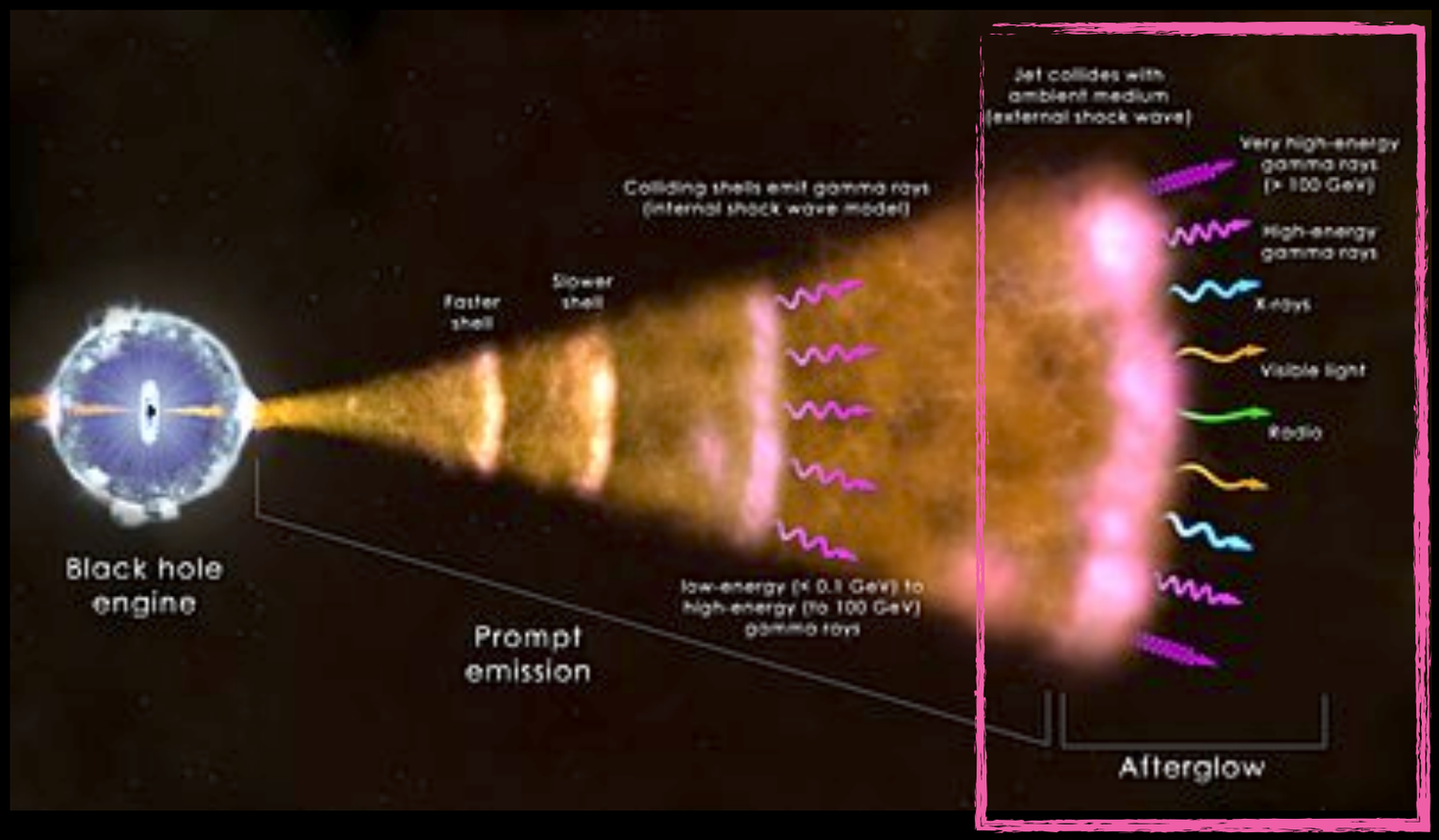


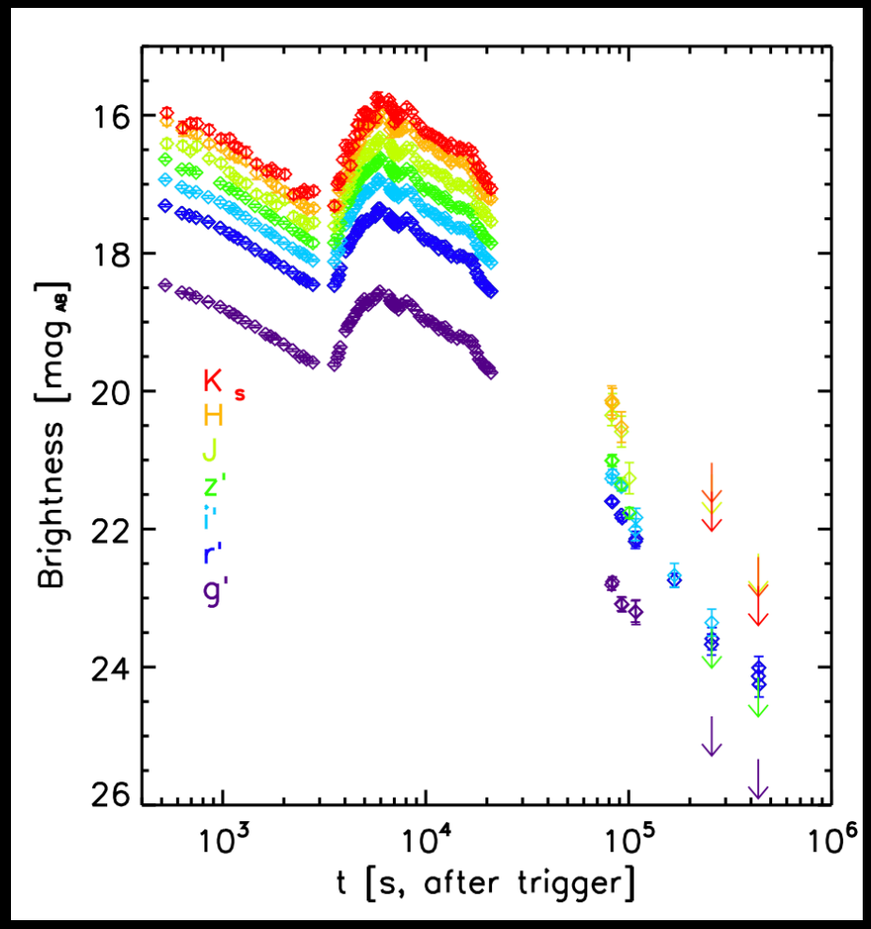


Different GRB scenarios lead to very different neutrino energy distributions

T.Pitik, I.Tamborra, M.Petropoulu 2021 *JCAP* 05 (2021)

Optical bumps in γ-ray burst afterglows





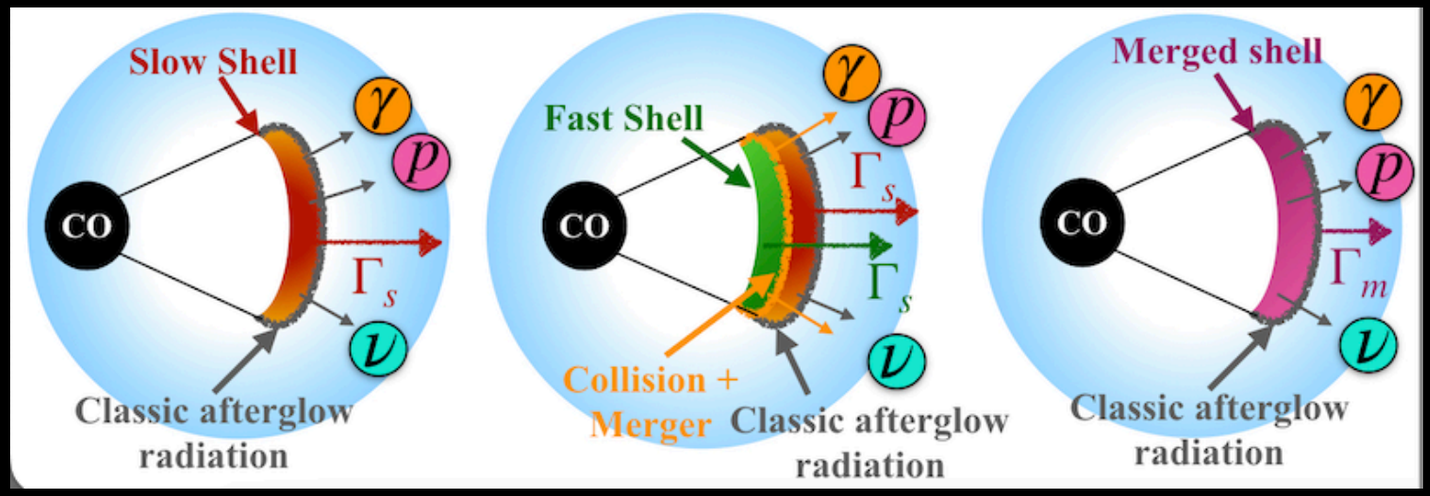
M.Nardini et al 2011 *A&A* 531 (2011)

Possible interpretations of the late rebrigtening:

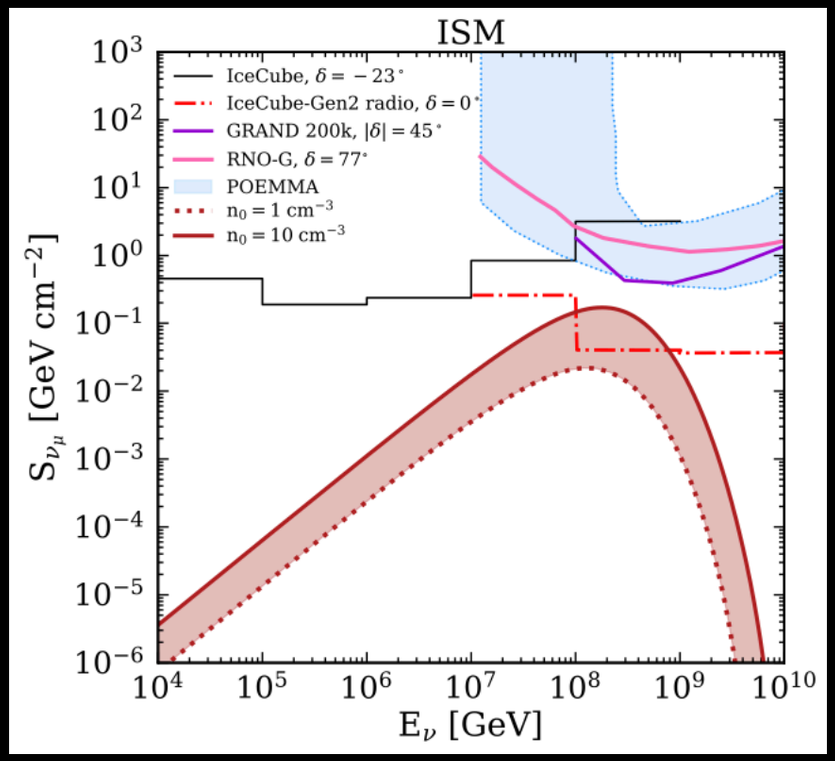
- Inhomogeneities in the circumburst medium
- Late central engine activity
- **Late energy injection: ultra-relativistic shell collision** — our focus
- Complex geometric structure of the jet

Can neutrinos reveal the mechanism behind optical bumps?

1 **Modeling of the shell collision**



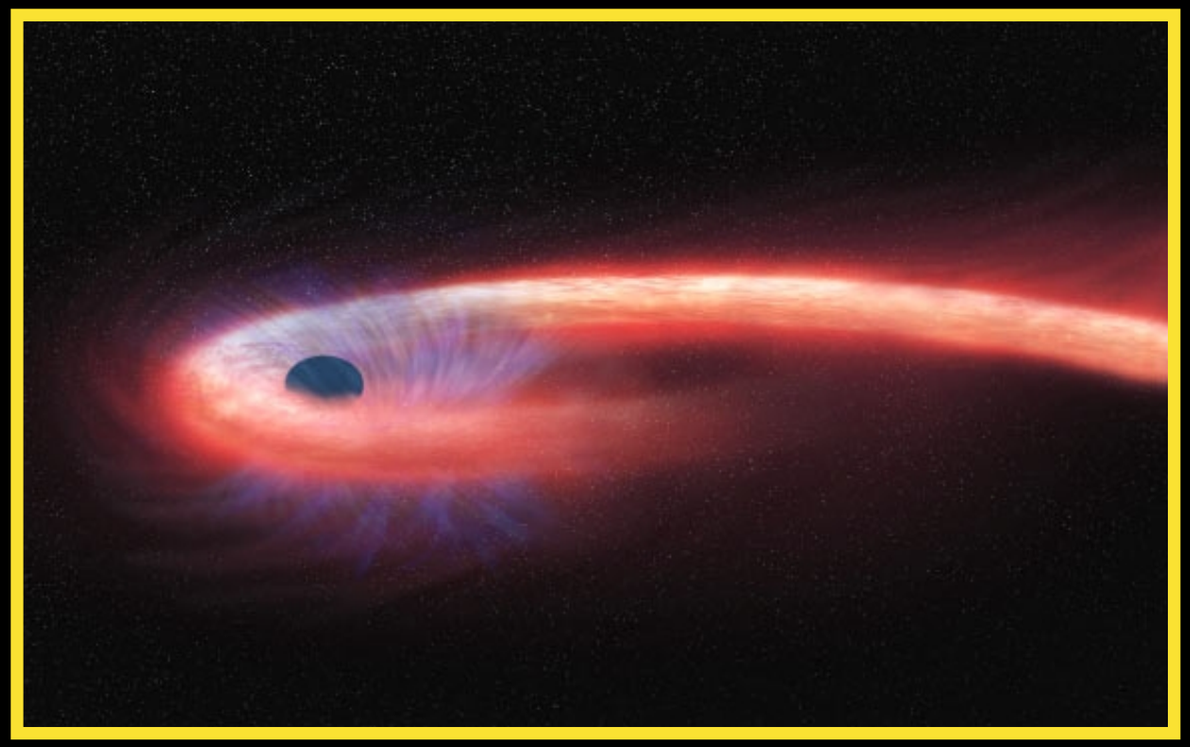
2 **Optical bumps can be probed through neutrinos for sources at $\sim \mathcal{O}(10)$ Mpc**



E.Guarini,I.Tamborra,D.Begue,T.Pitik, J.Greiner *JCAP* 06 (2022)

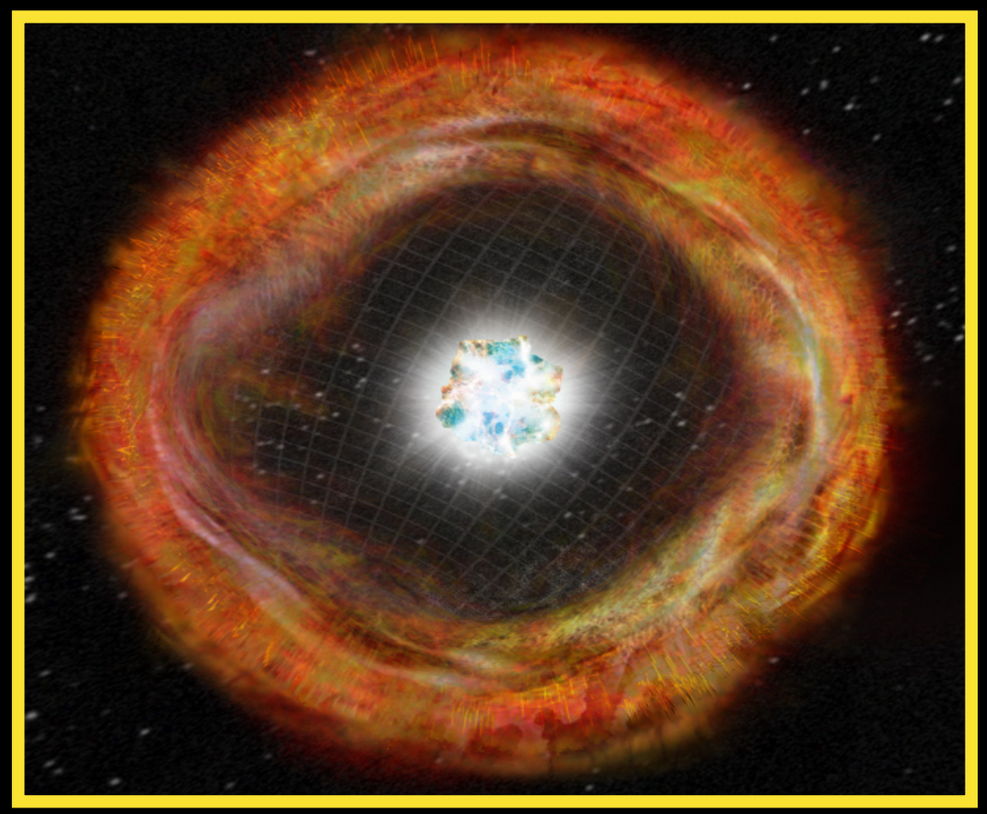
Controversial classification of transient AT2019fdr (with likely neutrino association)

Tidal Disruption Event



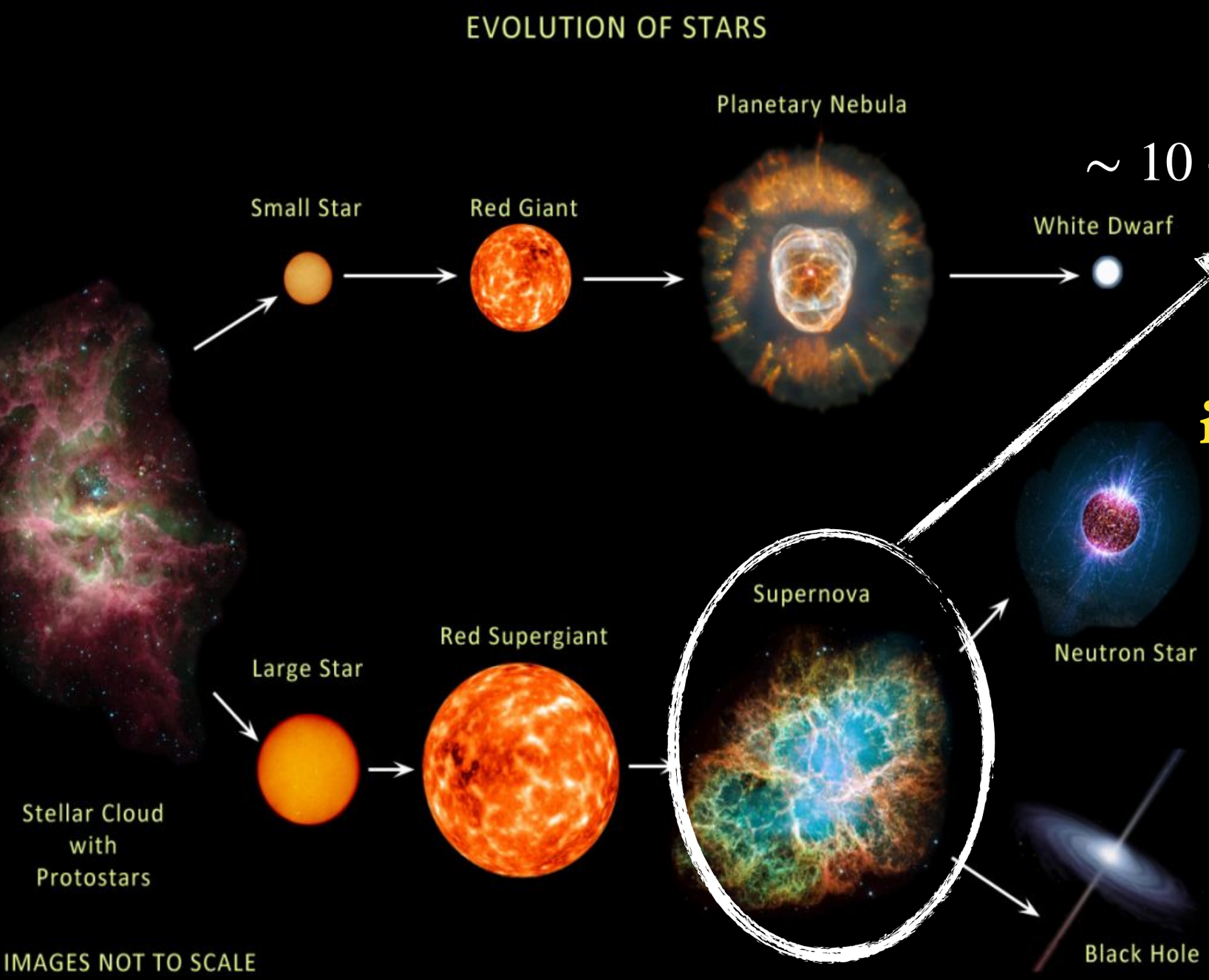
VS

Hydrogen-rich Superluminous Supernova



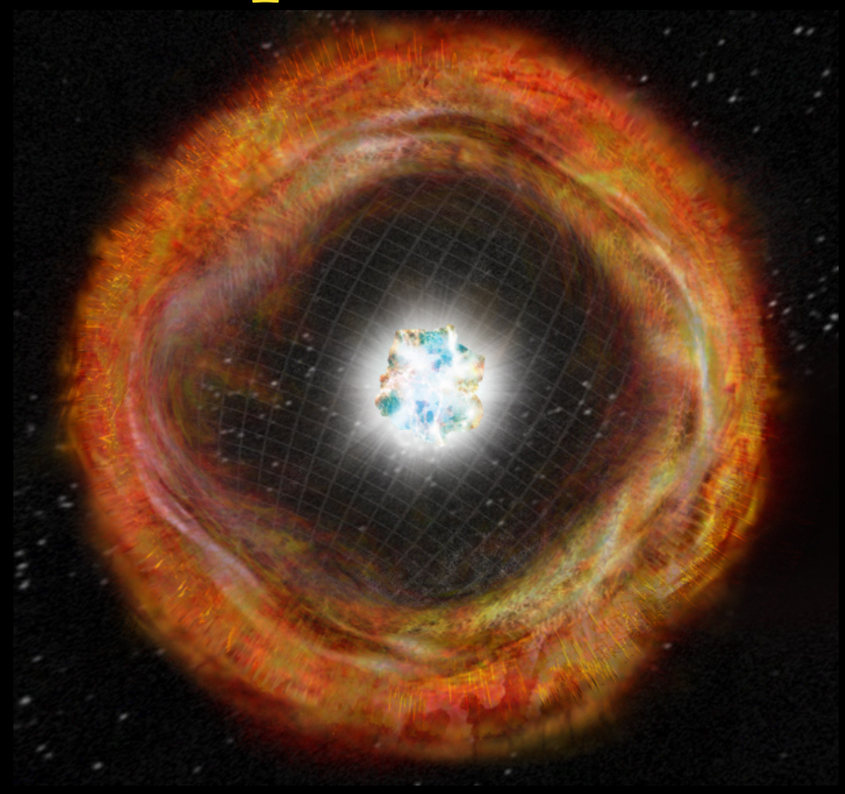
CAN WE USE NEUTRINOS TO DISENTANGLE THE TWO SCENARIOS?

What is a hydrogen-rich superluminous supernova?



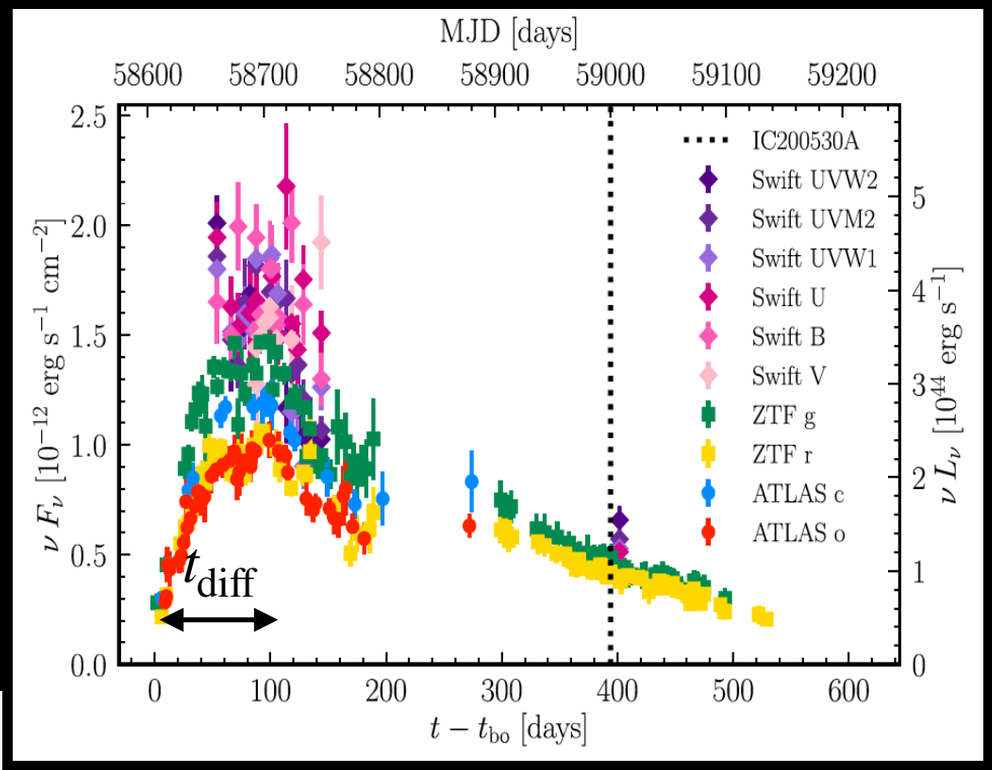
$\sim 10 - 100$ **times brighter than typical SNe**

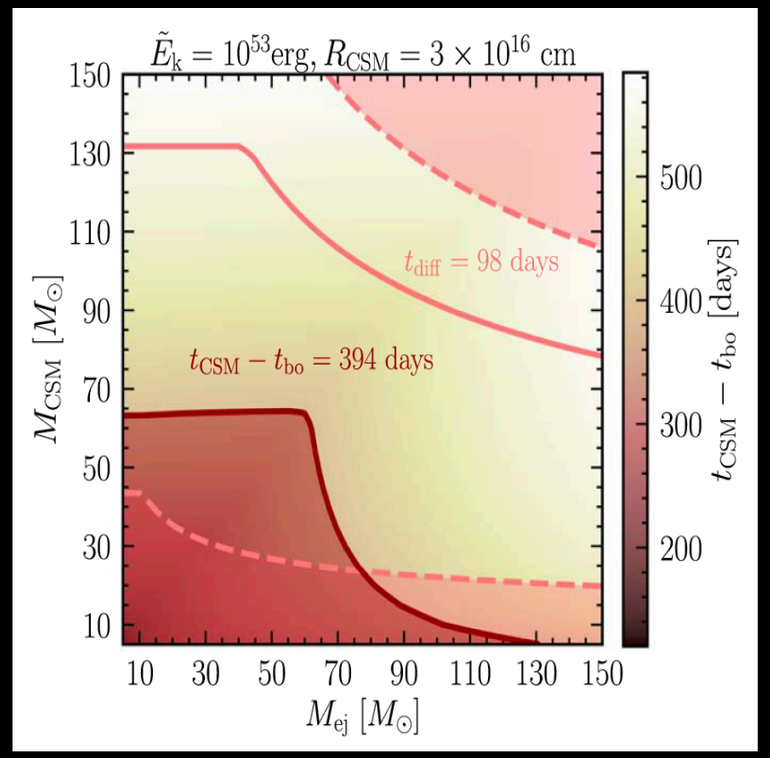
interaction-powered supernova

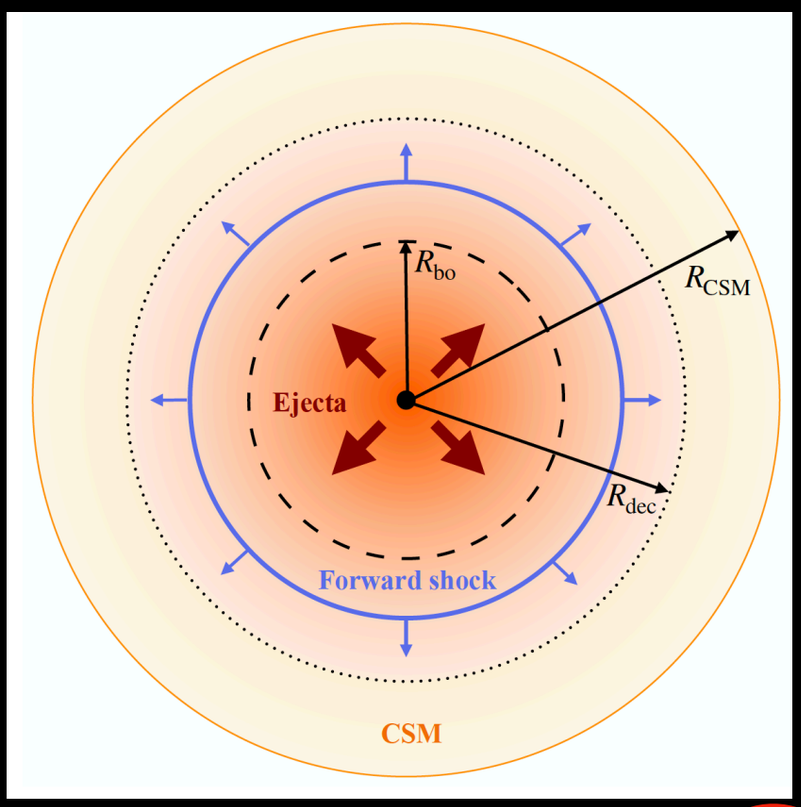


Neutrino production

1 We consider the parameter space compatible with the light curve of AT2019fdr







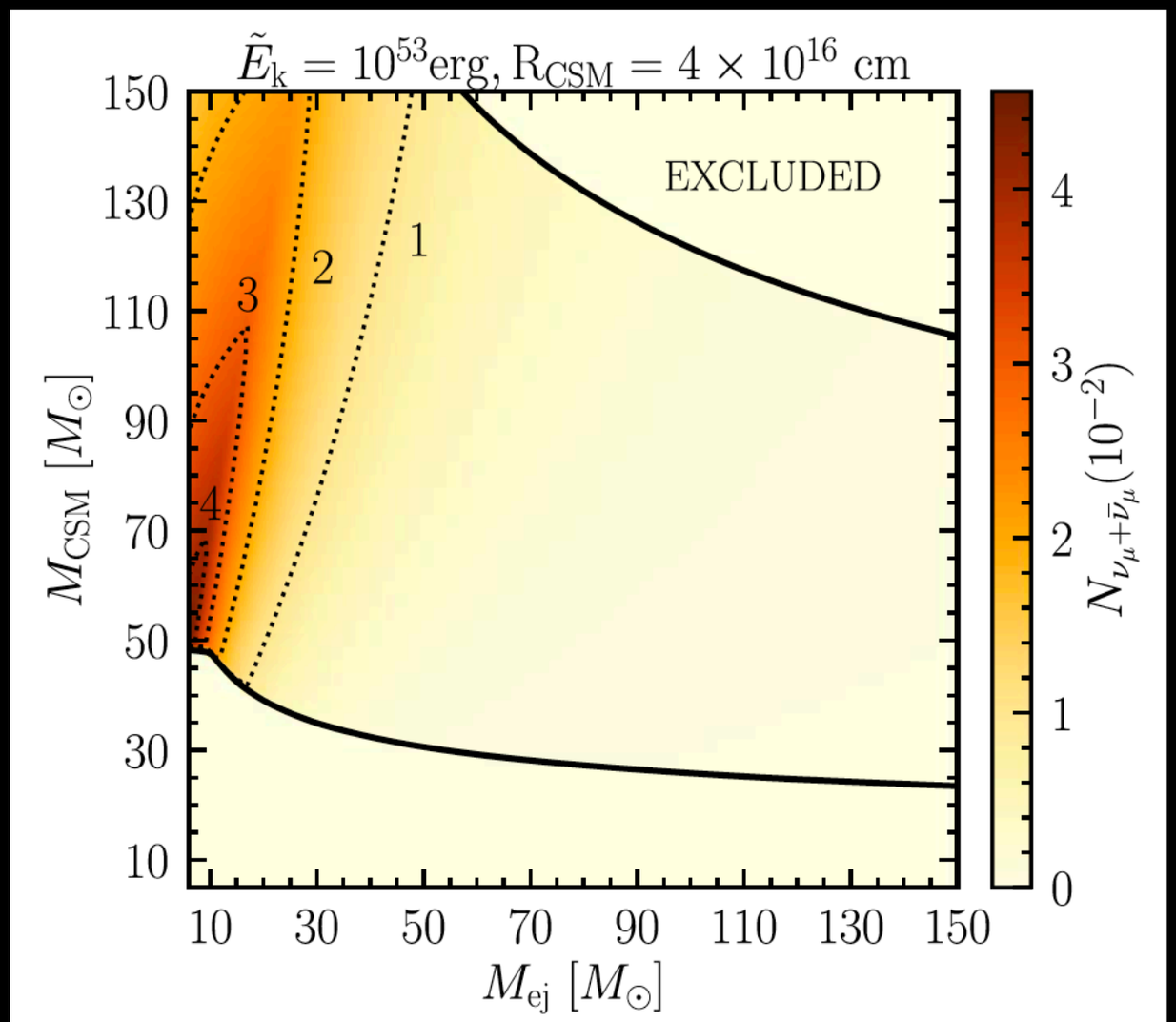
2 $\forall\, E_k, M_{ej}, M_{CSM}, R_{CSM}$ **we solve he evolution equation for relativistic protons:**

$$\frac{\partial N_{\rm p}(\gamma, R)}{\partial R} - \frac{\partial}{\partial \gamma}\left[\frac{\gamma}{R} N_{\rm p}(\gamma, R)\right] + \frac{N_{\rm p}(\gamma, R)}{v_{\rm sh} t_{pp}(R)} = Q_{\rm p}(\gamma, R)$$

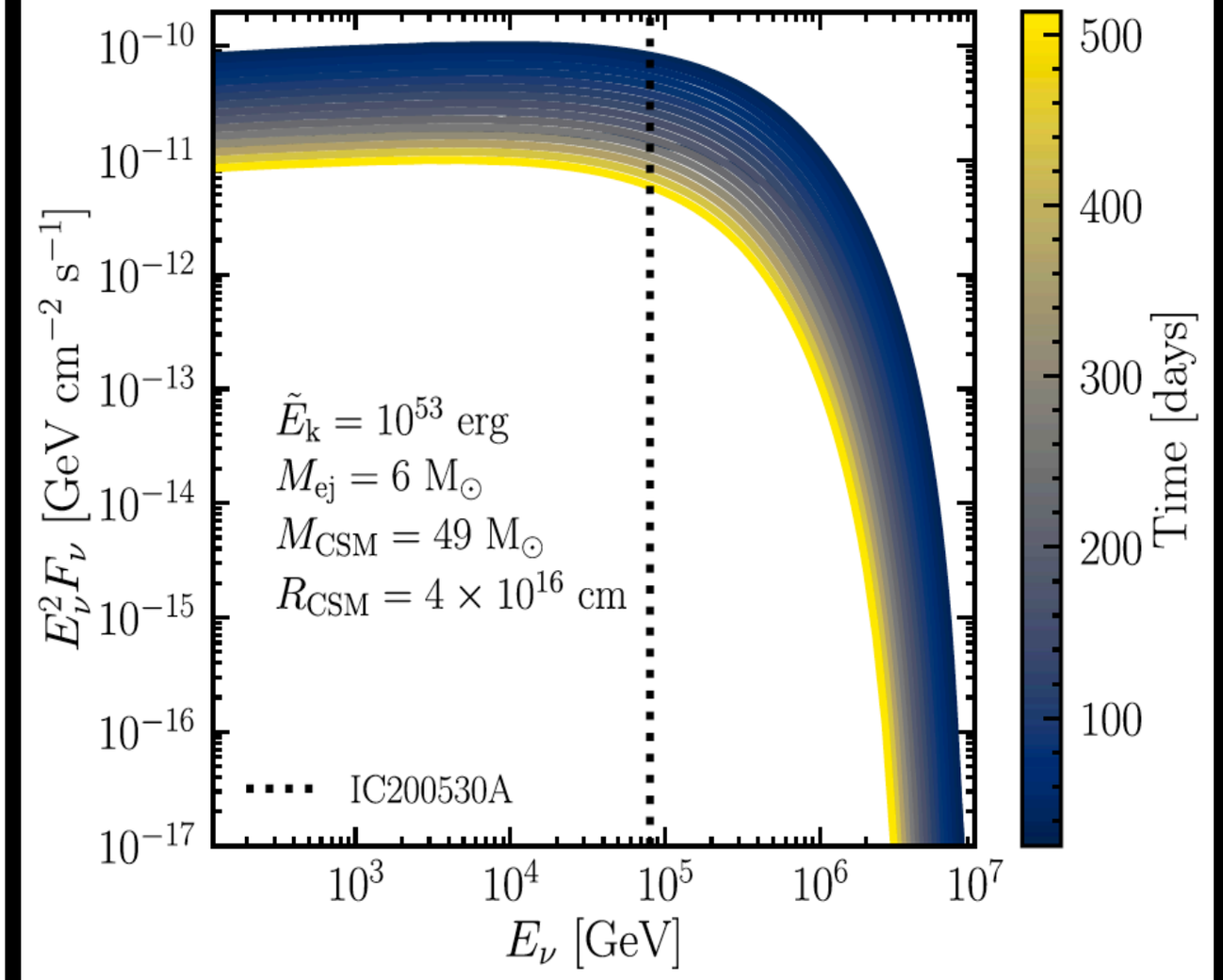
$$p + p \longrightarrow \text{many}(\pi^0 + \pi^+ + \pi^-) \longrightarrow \text{many}(\nu_e + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu)$$

Results

Total number of neutrinos



Flux of the most optimistic scenario



The SLSN scenario is compatible with neutrino observation

T.Pitik, I.Tamborra,C.Agus,K.Auchettl 2022 *ApJ* 929 163

Conclusions

High energy neutrinos can:

➡ probe the source powering mechanism

➡ constrain the source properties

➡ unveil the nature of the source

Thank you !