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DARK

Unravelling the Nature of Collapsar Jets with Neutrinos

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TAUP

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CARLSBERGFONDET

Outline

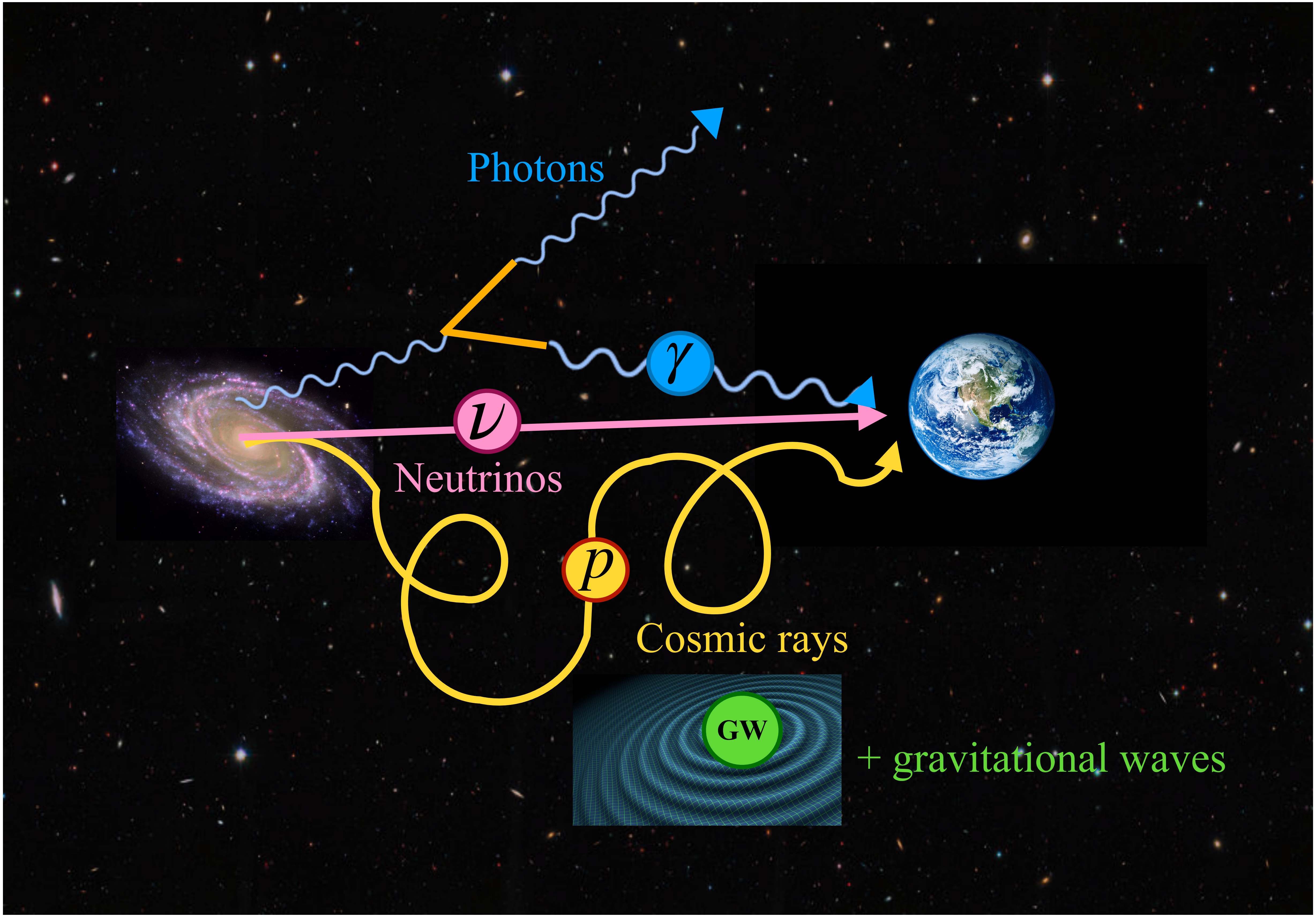
- Multi-Messenger astronomy era.
- High-energy neutrinos diffuse flux.
- Supernovae (SNe) Ib/c and gamma-ray bursts (GRBs).
- Optically thick collapsar jets as high-energy neutrino sources.
- Conclusions.

Based on:

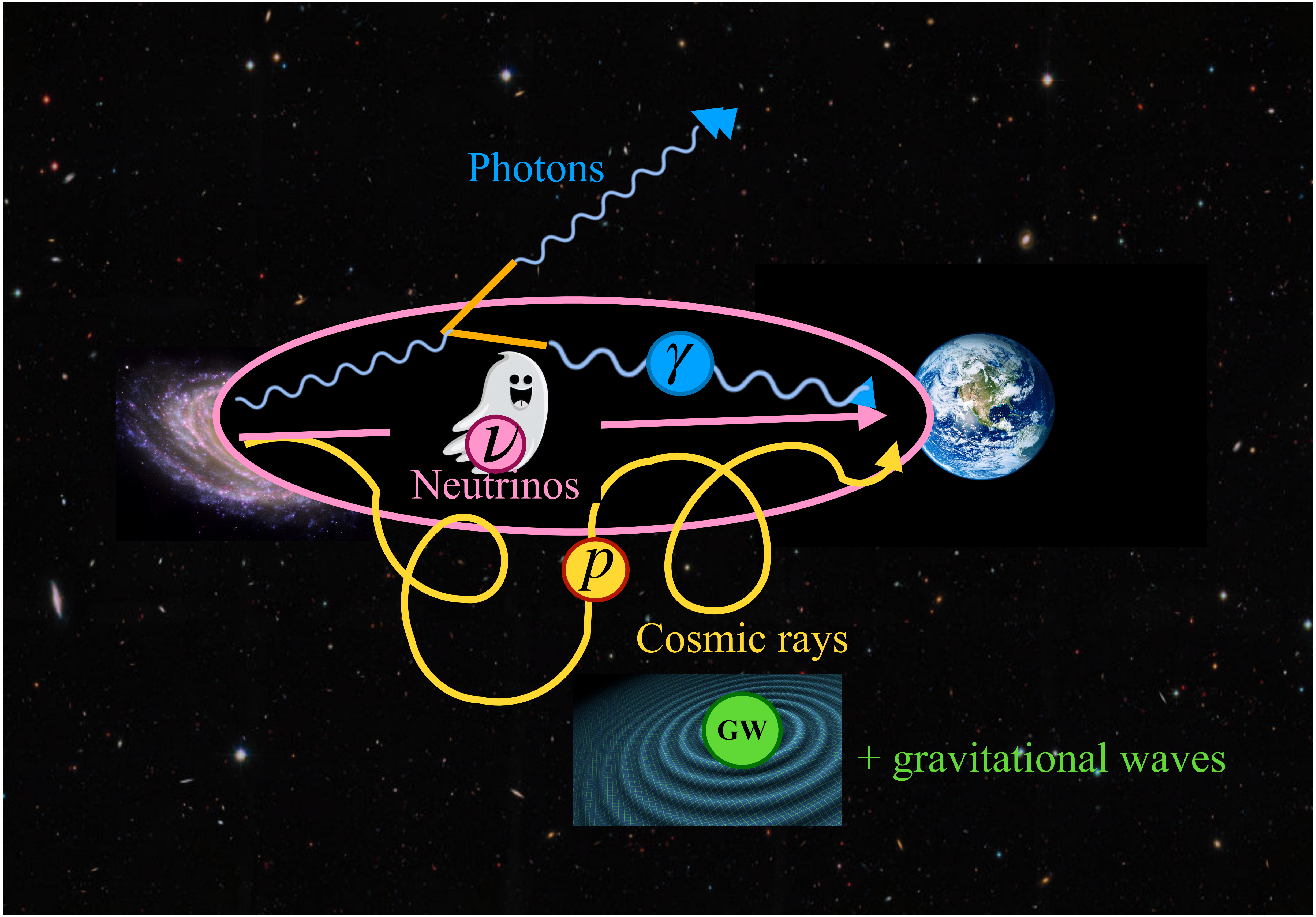
E. Guarini, I. Tamborra and O. Gottlieb, **PRD 107 (2023) 2**

E. Guarini, I. Tamborra, R. Margutti and E. Ramirez-Ruiz, **arXiv:2308.03840**

Multi-Messenger Astronomy



Ghostly Messengers from the Cosmos



Neutrino Production in Astrophysical Transients

- Astrophysical sources can accelerate protons and electrons, e.g. through **shocks** or **magnetic reconnection**.

- Electrons cool emitting photons, while protons mainly cool through photo-hadronic and hadronic interactions.

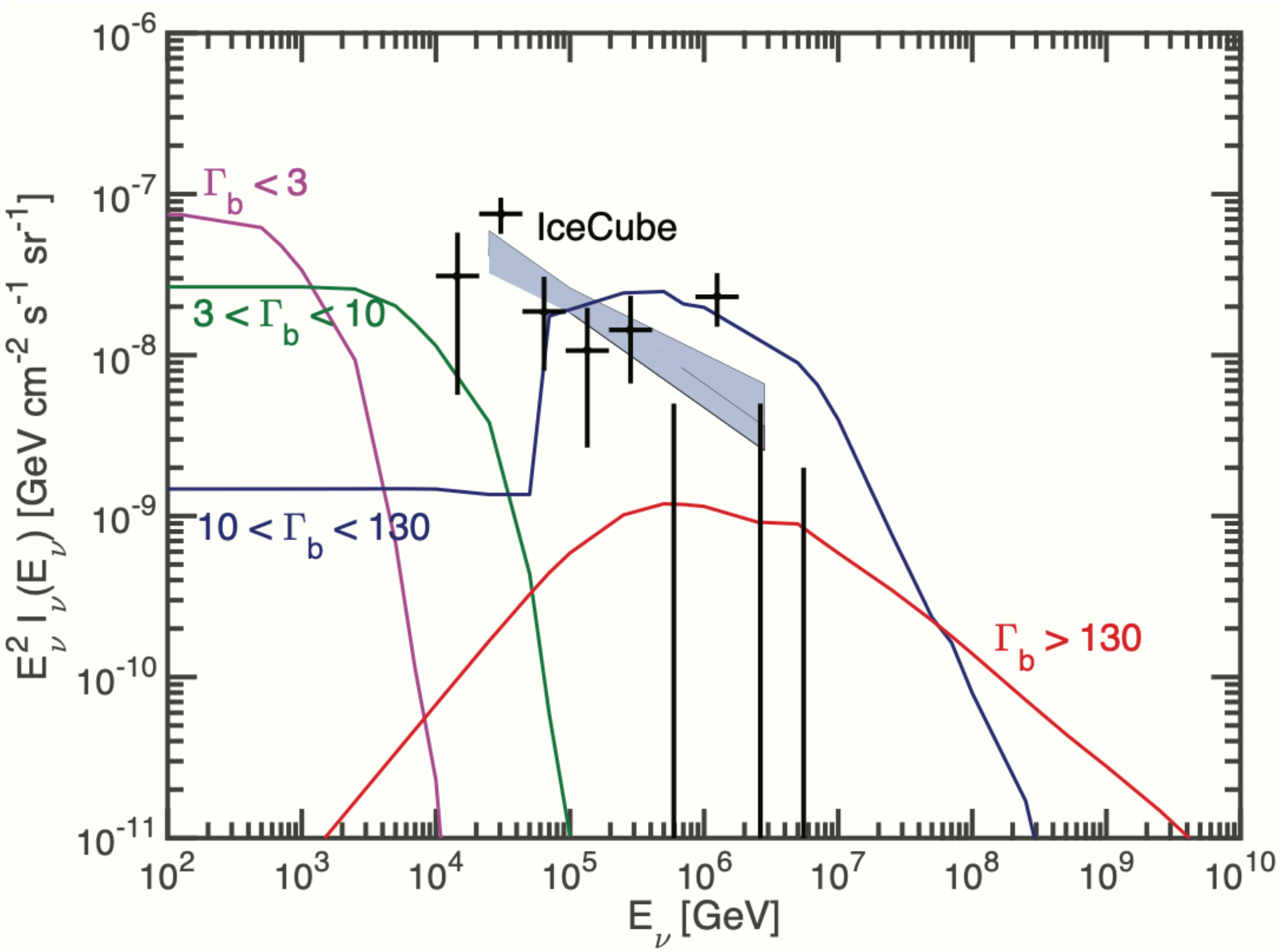
$$p + \gamma \longrightarrow \Delta^+ \longrightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

$$p + p \rightarrow \pi^+ : \pi^- : \pi^0$$

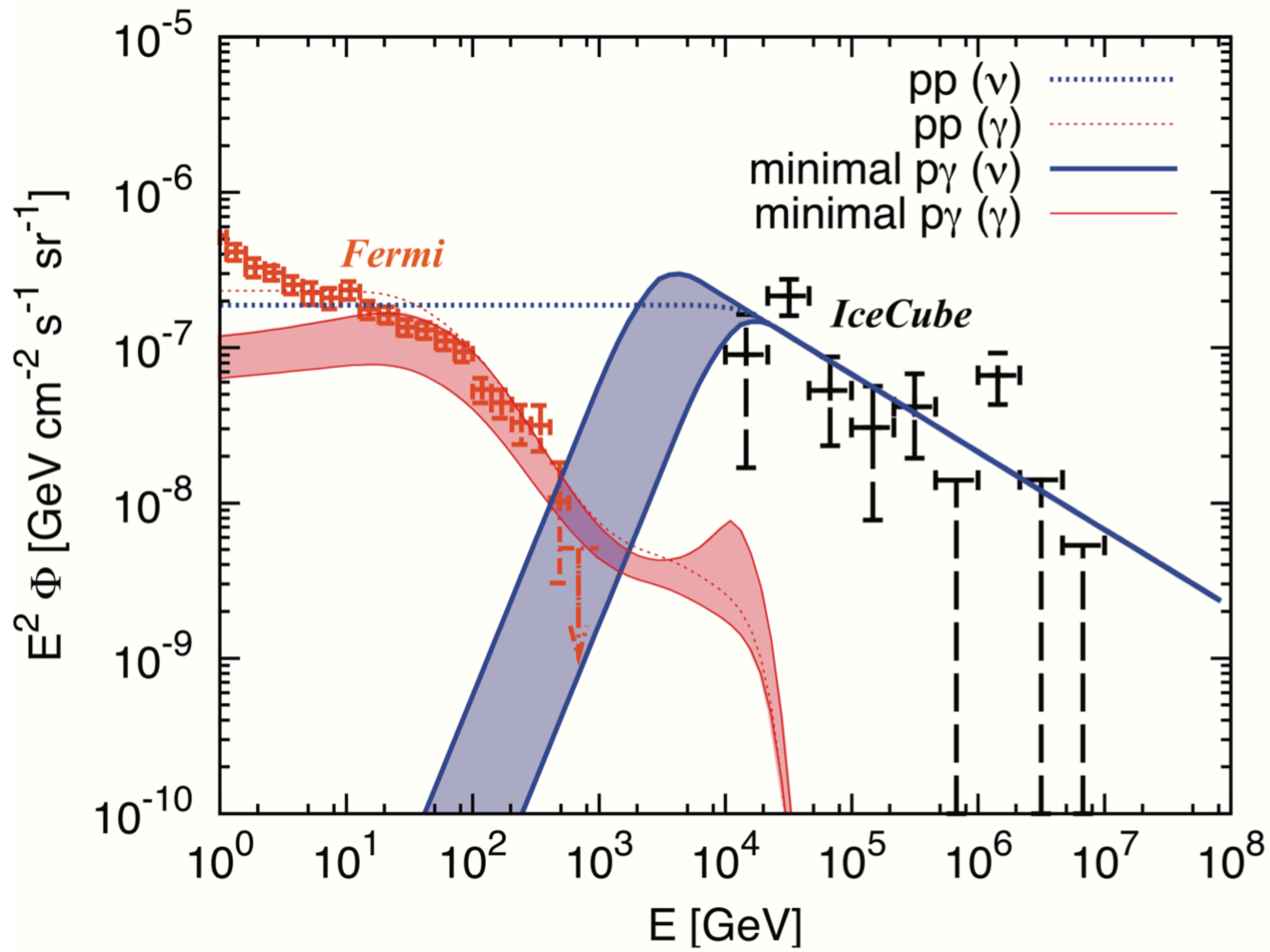
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$$

$$\pi^0 \longrightarrow 2\gamma$$

High-Energy Neutrino Diffuse Flux



Tamborra and Ando, PRD (2016)

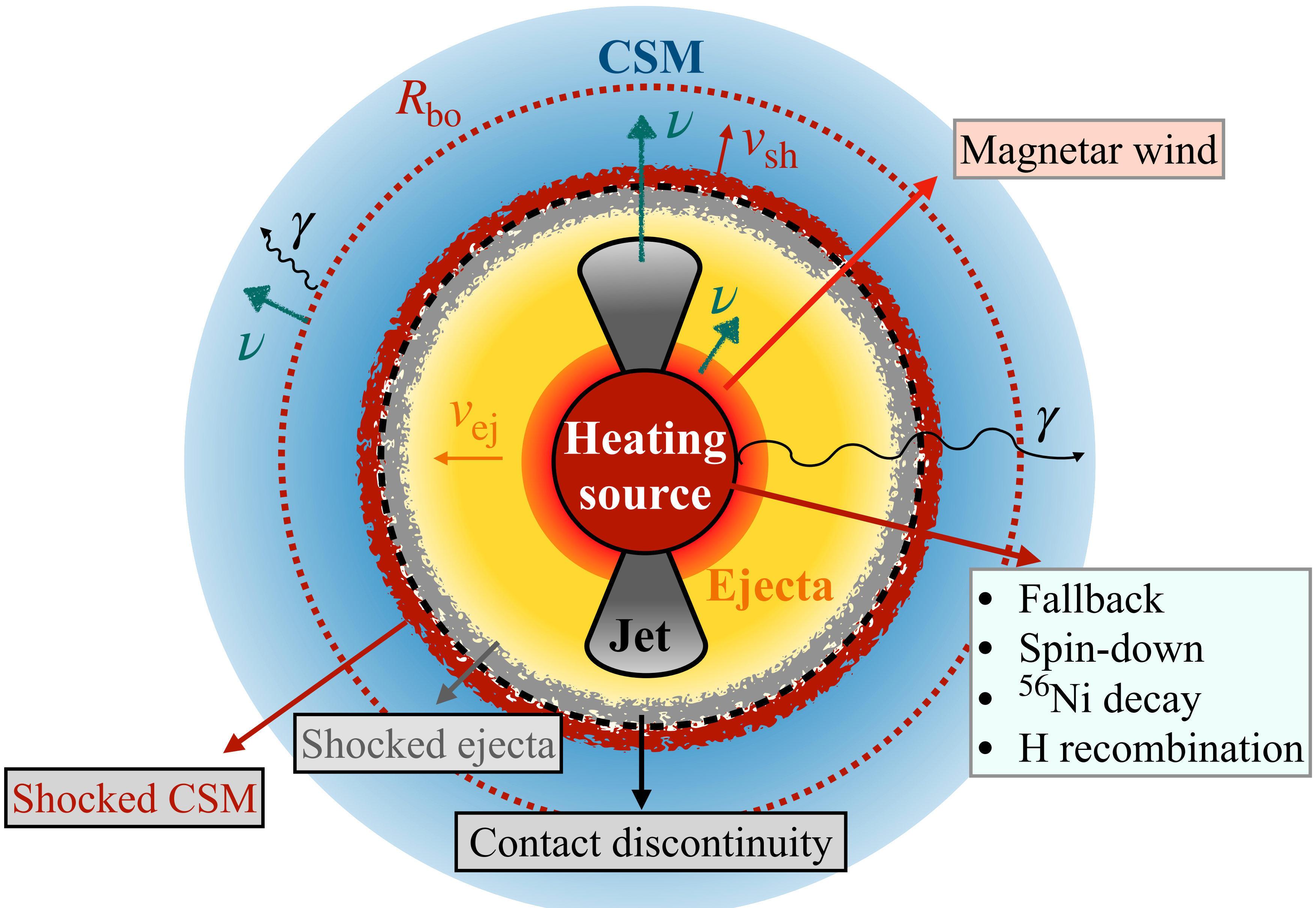


Murase, Guetta and Ahlers, PRL (2016)

- Sources opaque to gamma-rays have been suggested as main contributors to the high-energy neutrino flux observed at IceCube ($E_\nu \lesssim \mathcal{O}(10^5)$ GeV).
- Optically thick collapsar jets have been considered among the most promising opaque sources.

But are optically thick collapsar jets good candidates?

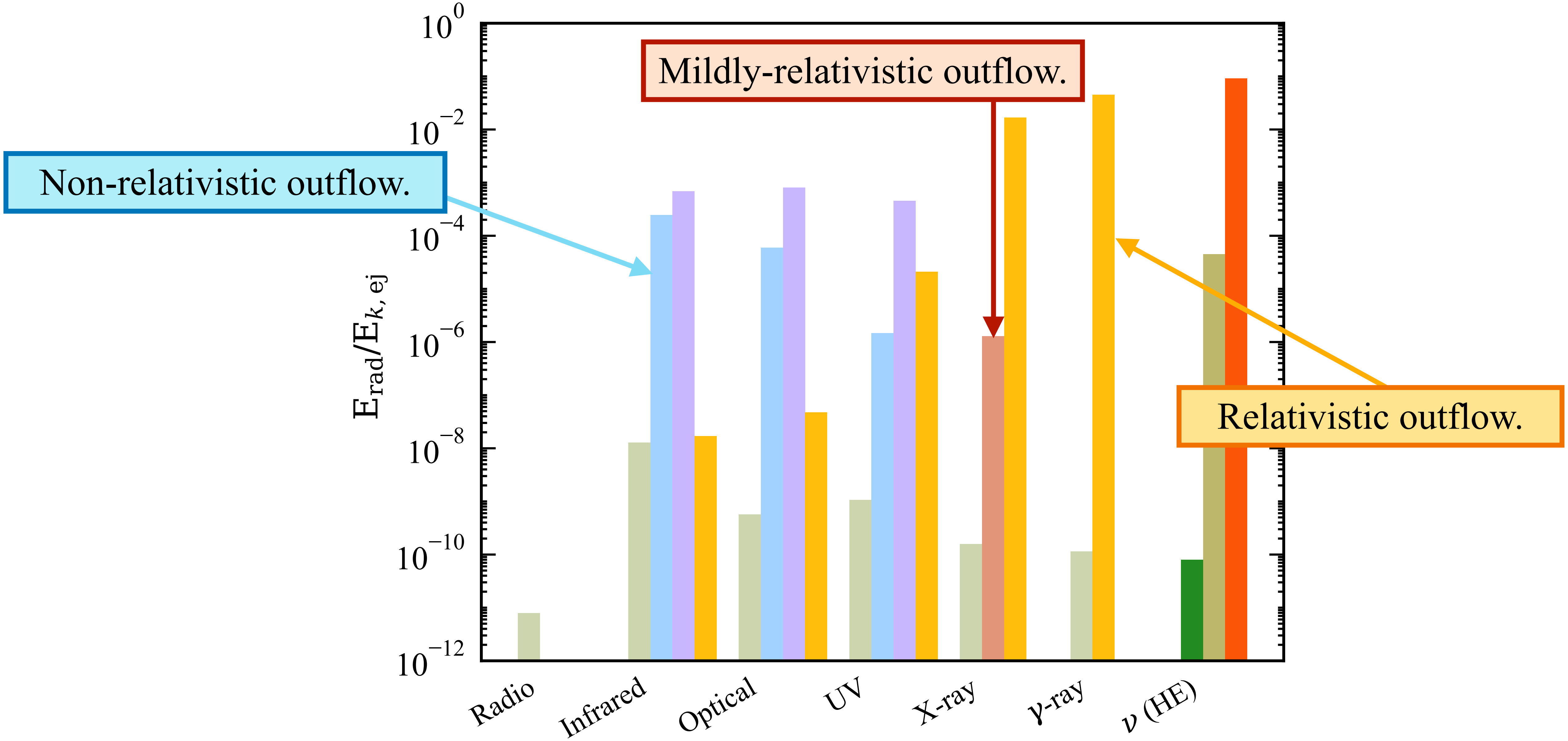
SNe Ib/c Broad Line and GRBs



Guarini, Tamborra, Margutti and Ramirez-Ruiz [arXiv:2308.03840] (2023)

- Believed to originate from the collapse of massive and hydrogen-depleted stars.
- Several processes can shape the observed light-curve.
- SNe Ib/c broad line (BL) may harbour jets as suggested by their mildly-relativistic ejecta.
- Some SNe Ib/c BL have been observationally associated with GRBs.

Multi-Messenger Emission of SNe Ib/c BL with Jet

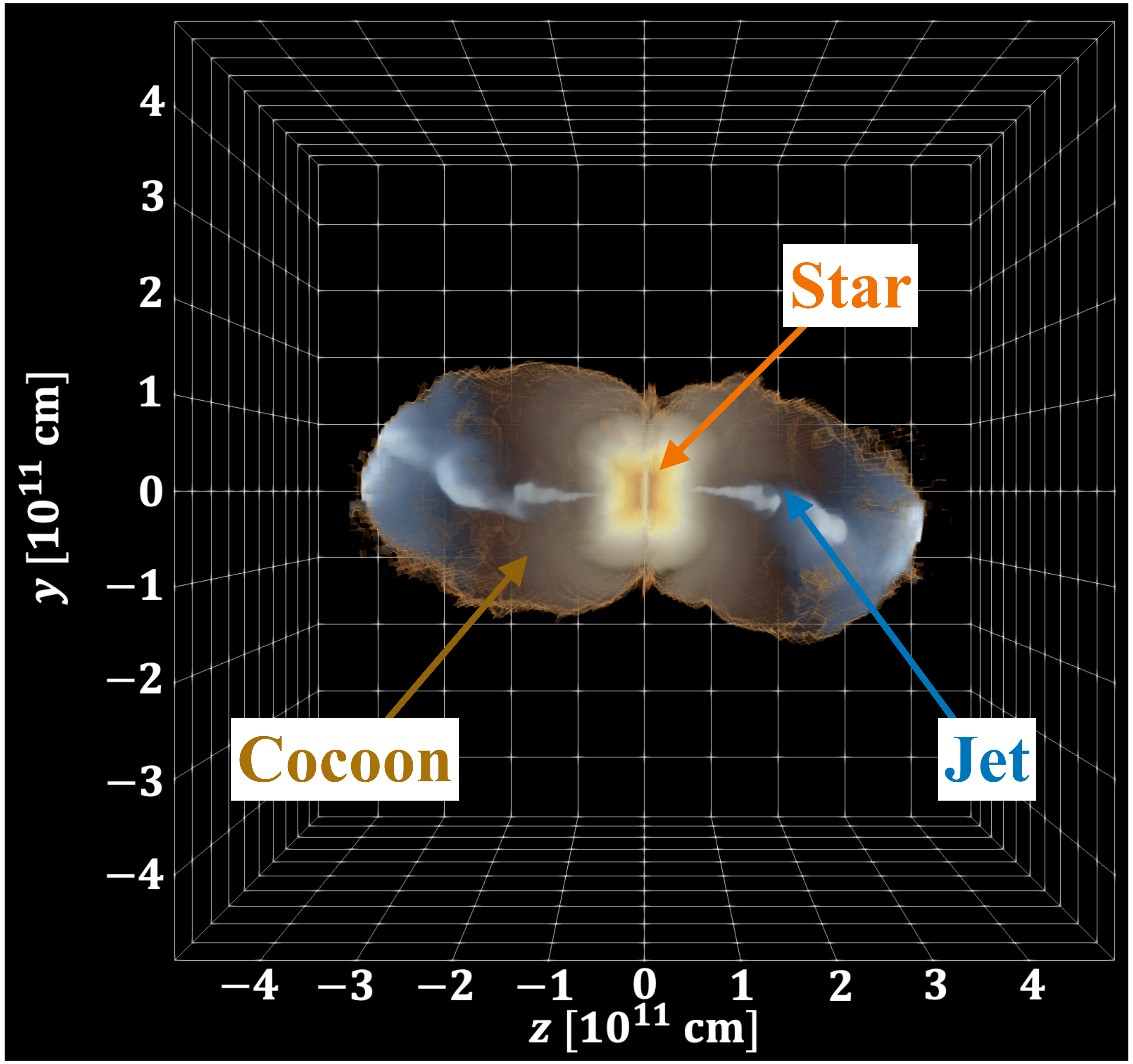


Guarini, Tamborra, Margutti and Ramirez-Ruiz [arXiv:2308.03840] (2023)

- The non-relativistic outflow emits the bulk of energy in the ultraviolet/optical/infrared bands.
- The mildly-relativistic component of the outflow emits a flash of X-rays.
- The relativistic jetted outflow emits radiation in the X-ray/gamma-ray bands.

See also: Villar et al., ApJ (2017)

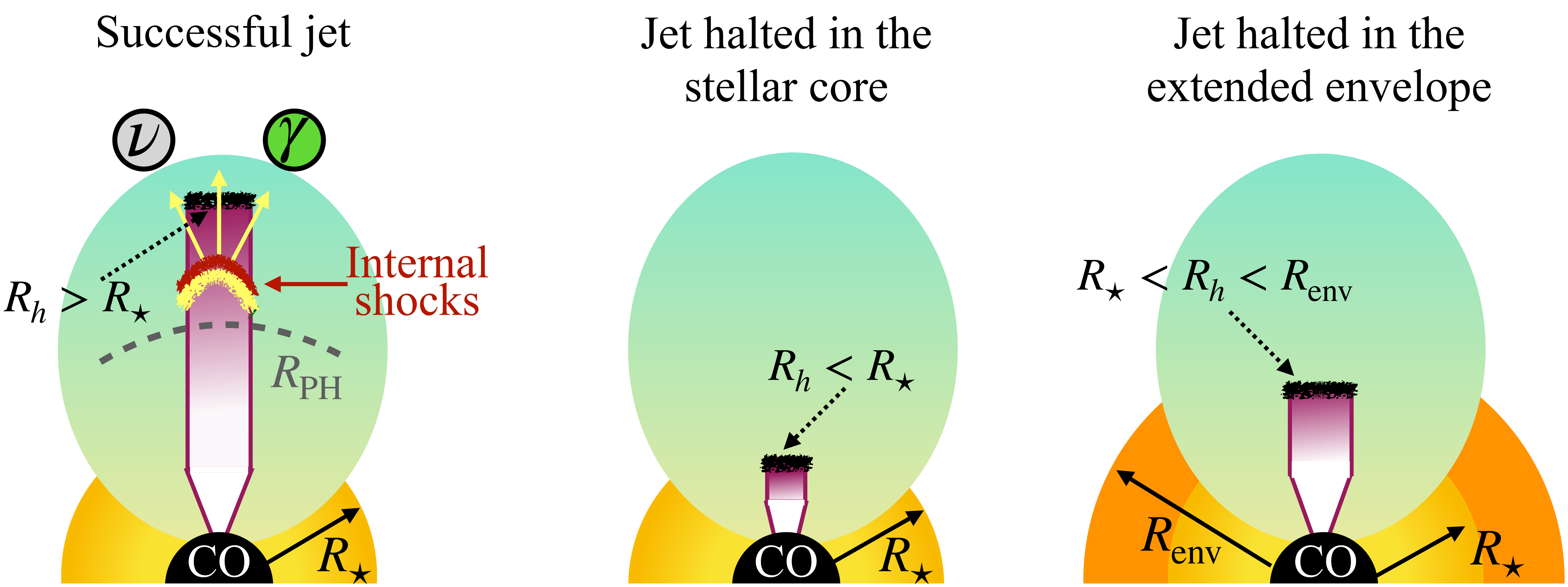
Jet Launching Mechanism



Guarini, Tamborra and Gottlieb, PRD (2022)

- The iron core of the dying massive star collapses into a black hole.
- An accretion disk forms due to fast rotation and energy is extracted, powering a relativistic jet.
- While the jet punches through the stellar mantle, it inflates a high-pressure region called cocoon.

Jet Propagation in the Progenitor Star

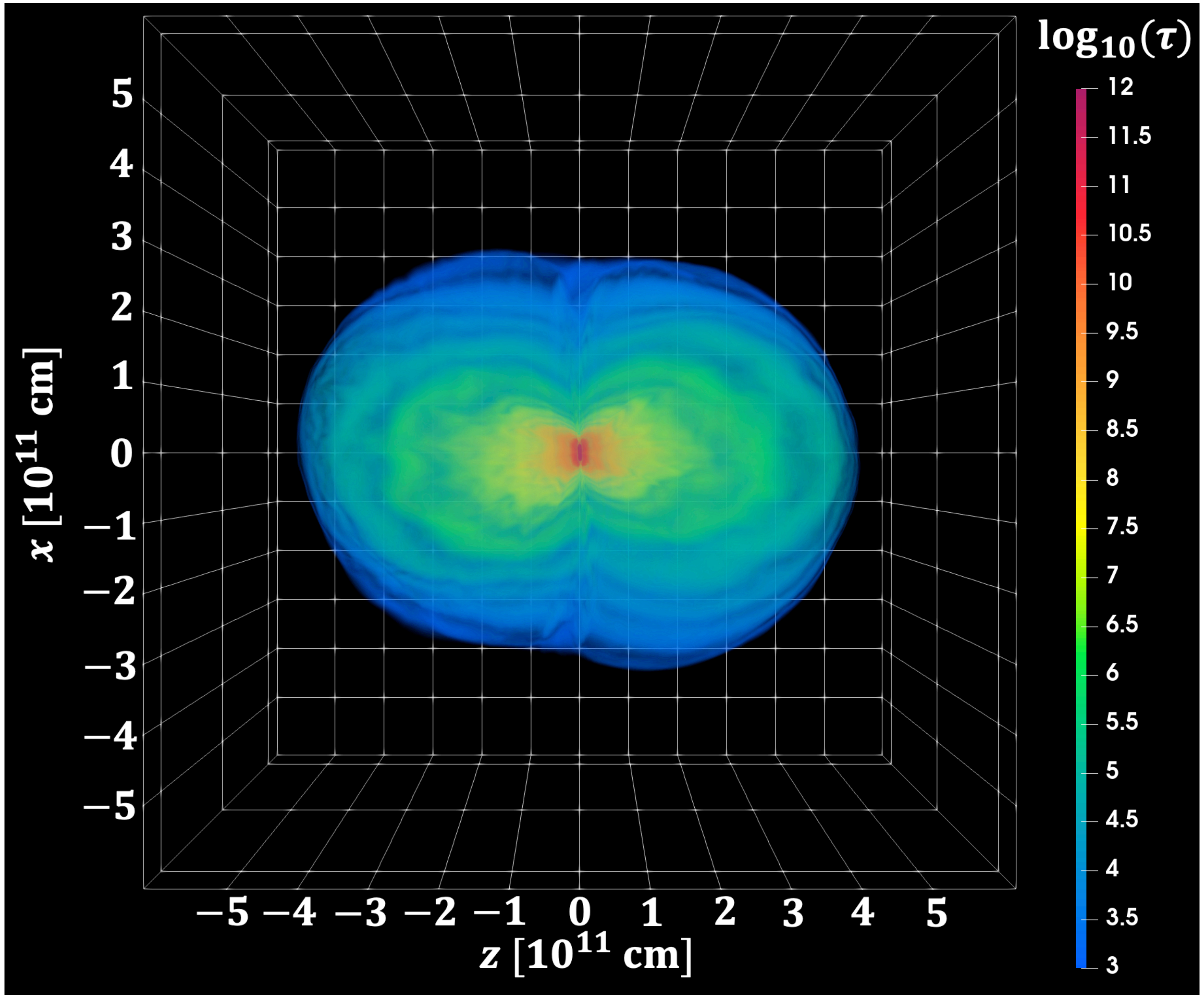


Guarini, Tamborra and Gottlieb, PRD (2023)

- The jet can either break out from the progenitor star (GRB) or it can be halted in it.
- The cocoon always breaks out from the star independently on the fate of the jet.
- Inhomogeneities in the jet cause internal shocks, as fast shells catch up with slower ones.

See also Gottlieb et al., PRD (2022)

Particle Acceleration in Collapsar Jets



Baryon density

$$\tau = \sigma_T n \frac{R}{\Gamma} \lesssim 1$$

Jet Lorentz factor

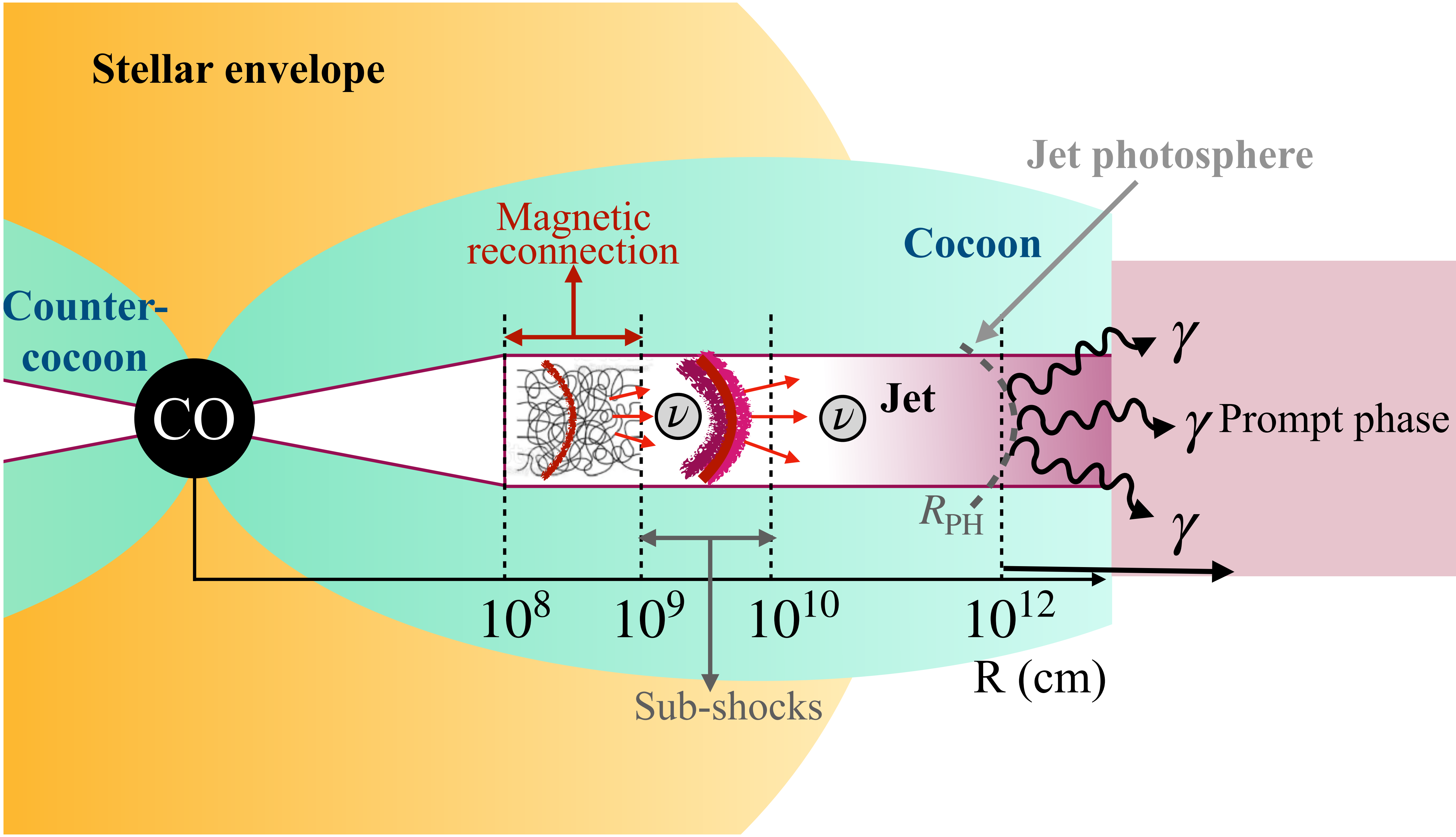
Condition for efficient particle acceleration at shocks

Guarini, Tamborra and Gottlieb, PRD (2022)

- The cocoon loads the jet with baryons ⟶ Jet density increases while Lorentz factor decreases.
- The jet optical depth increases and particle acceleration at internal shocks is prevented.

See also: Gottlieb and Globus, ApJ (2022); Gottlieb et al., ApJ (2022)

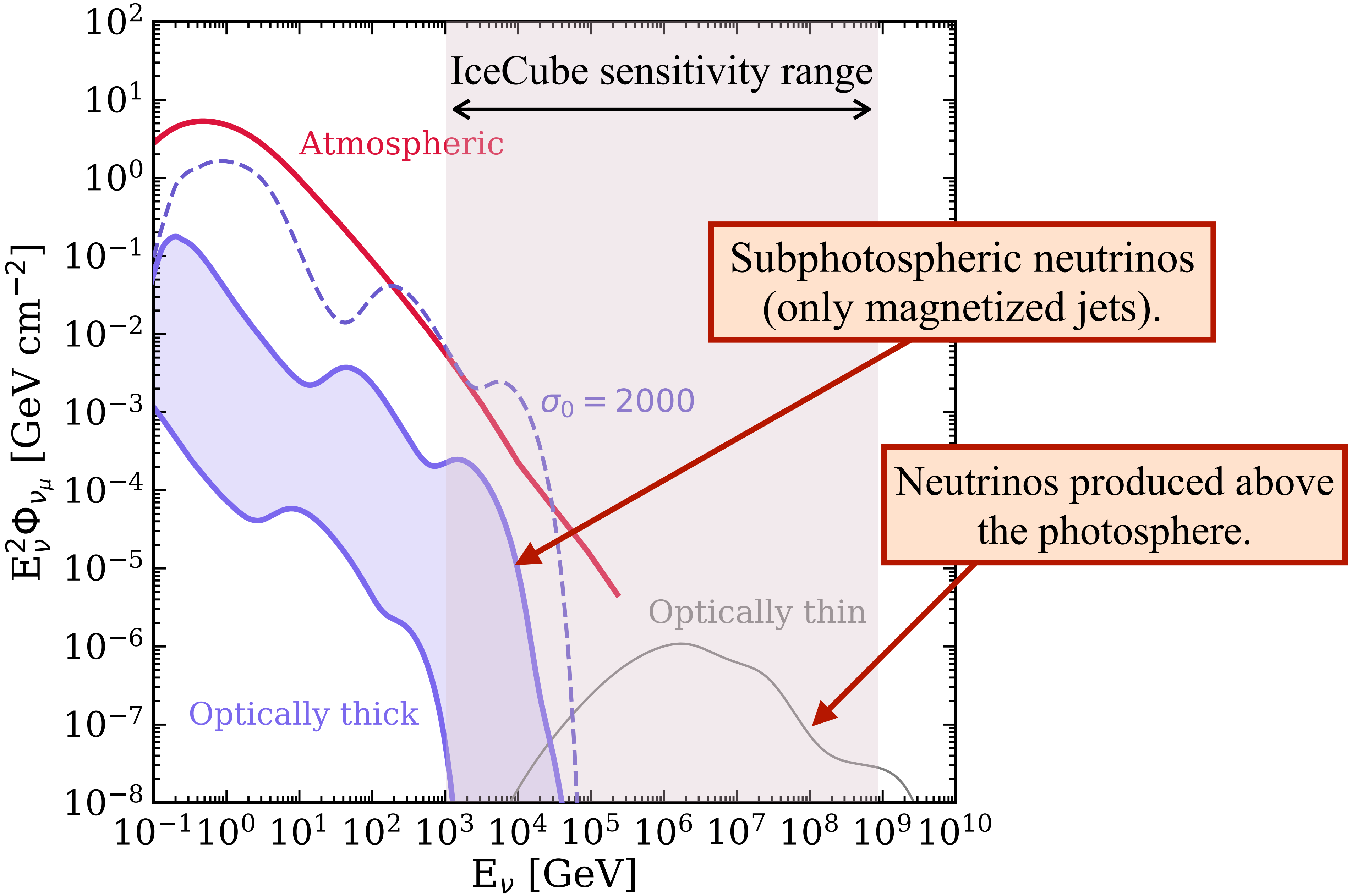
Subphotospheric Particle Acceleration



Guarini, Tamborra and Gottlieb, PRD (2022)

- If the jet is magnetized, particles can be accelerated at sub-shocks or through magnetic reconnection below the photosphere ($R \lesssim R_{PH}$).
- Particle acceleration may also occur above the jet photosphere ($R \gtrsim R_{PH}$).

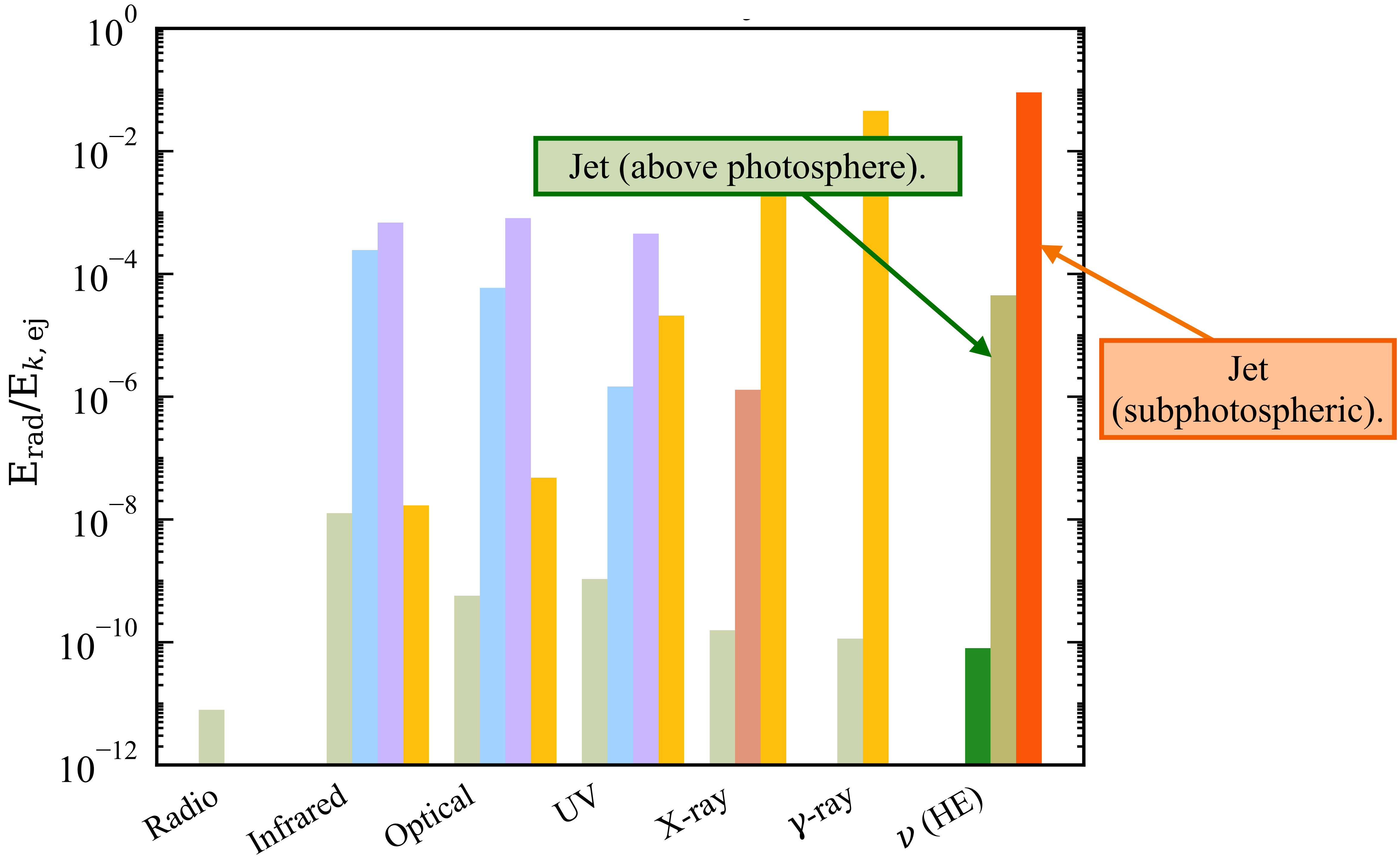
Subphotospheric Neutrino Signal



Guarini, Tamborra and Gottlieb, PRD (2022)

- Neutrino signal sensitive to jet magnetization.
- The signal lies below the energy range where IceCube is sensitive.
- Subphotospheric neutrinos from magnetized jets cannot contribute to the diffuse flux observed at IceCube.

Multi-Messenger Emission of SNe Ib/c BL with Jet



Guarini, Tamborra, Margutti and Ramirez-Ruiz [arXiv:2308.03840] (2023)

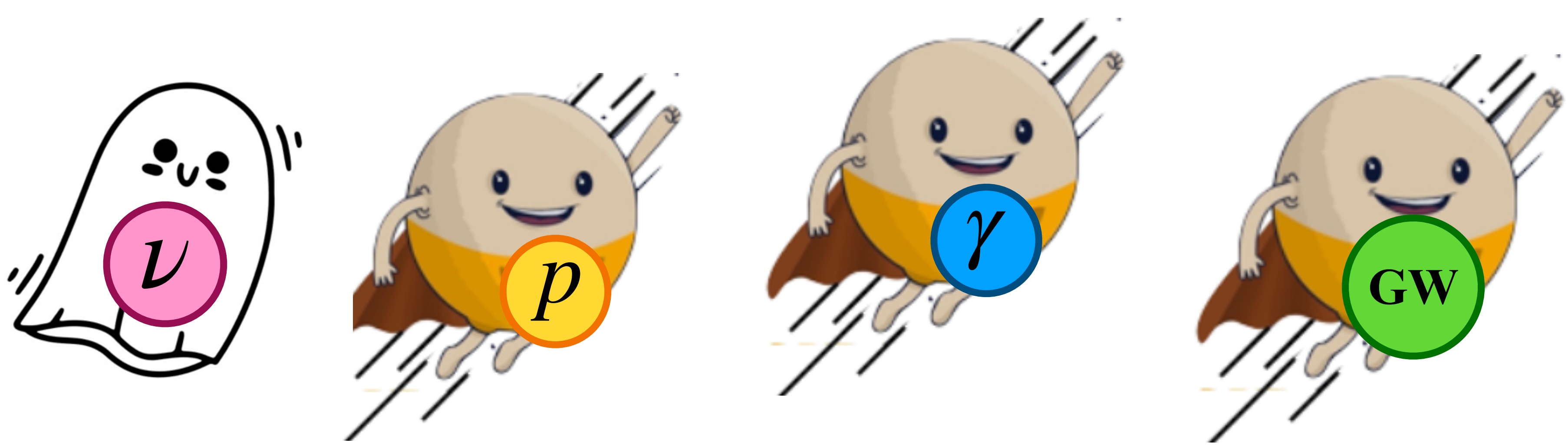
Subphotospheric neutrinos could be the only signature of unsuccessful jets in SNe Ib/c BL.

Conclusions

- Particle acceleration and neutrino production below the jet photosphere are favoured in magnetized jets.
- Optically thick magnetized jets cannot produce the bulk of the high-energy neutrino flux observed at IceCube.
- The subphotospheric neutrino signal is sensitive to the jet magnetization.

Neutrinos are unique probes of the transient sky.

The dream of multi-messenger astronomy is here!



Thanks for your attention!

Questions?