The Niels Bohr International Academy

DARK

Lessons on Astrophysical Transients from Neutrinos

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Ostuni
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CARLSBERGFONDET

Outline

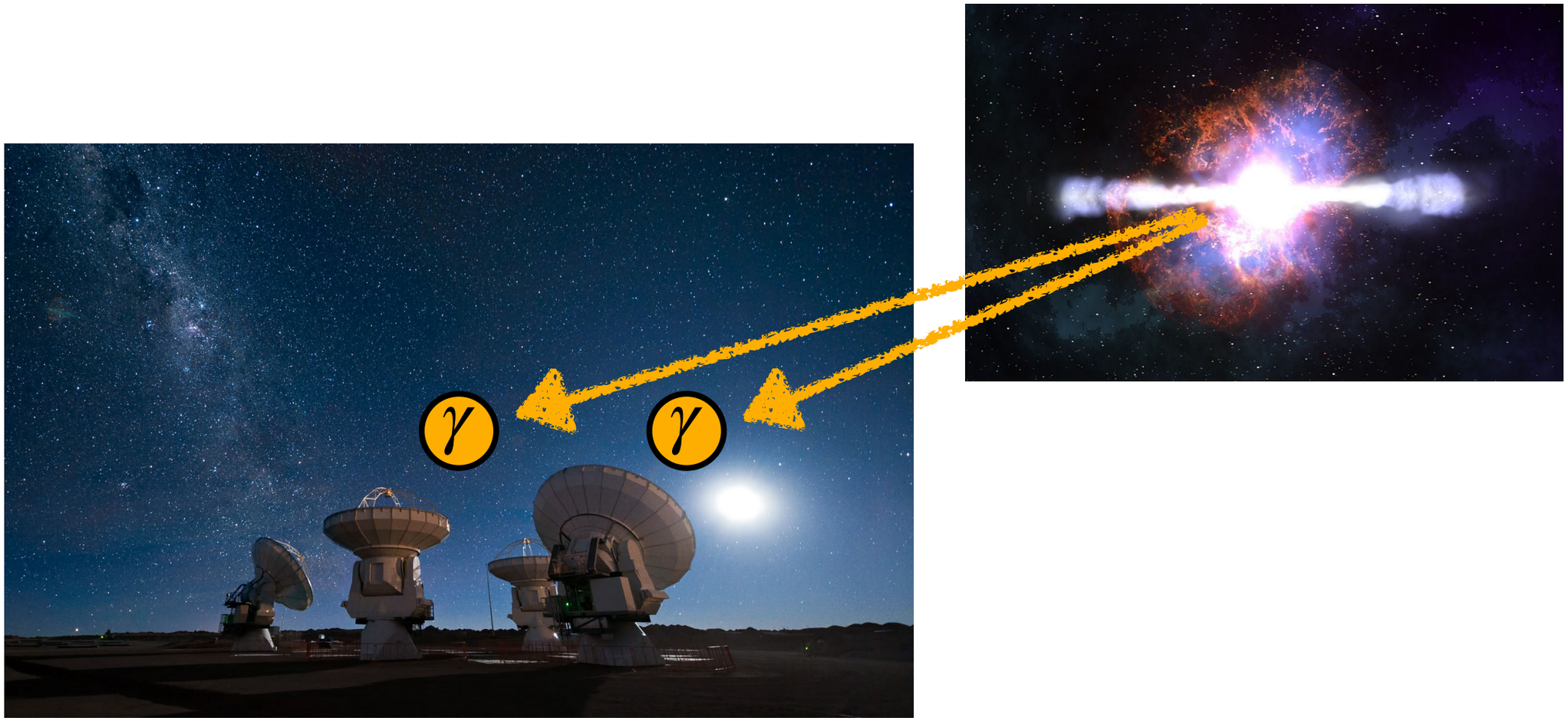
- The multi-messenger astrophysics era.
- Neutrino production in astrophysical transients.
- The optical jump of GRB afterglows.
- Luminous Fast Blue Optical Transients (LFBOTs).
- Conclusions and outlook.

Based on:

E. Guarini, I. Tamborra, D. Bégué, T. Pitik and J. Greiner, **JCAP 06 (2022) 06, 034 [arXiv:2112.07690]**

E. Guarini, I. Tamborra and R. Margutti, **ApJ 935 (2022)157** [**arXiv:2205.12282]**

Looking at the Universe through Photon Lenses



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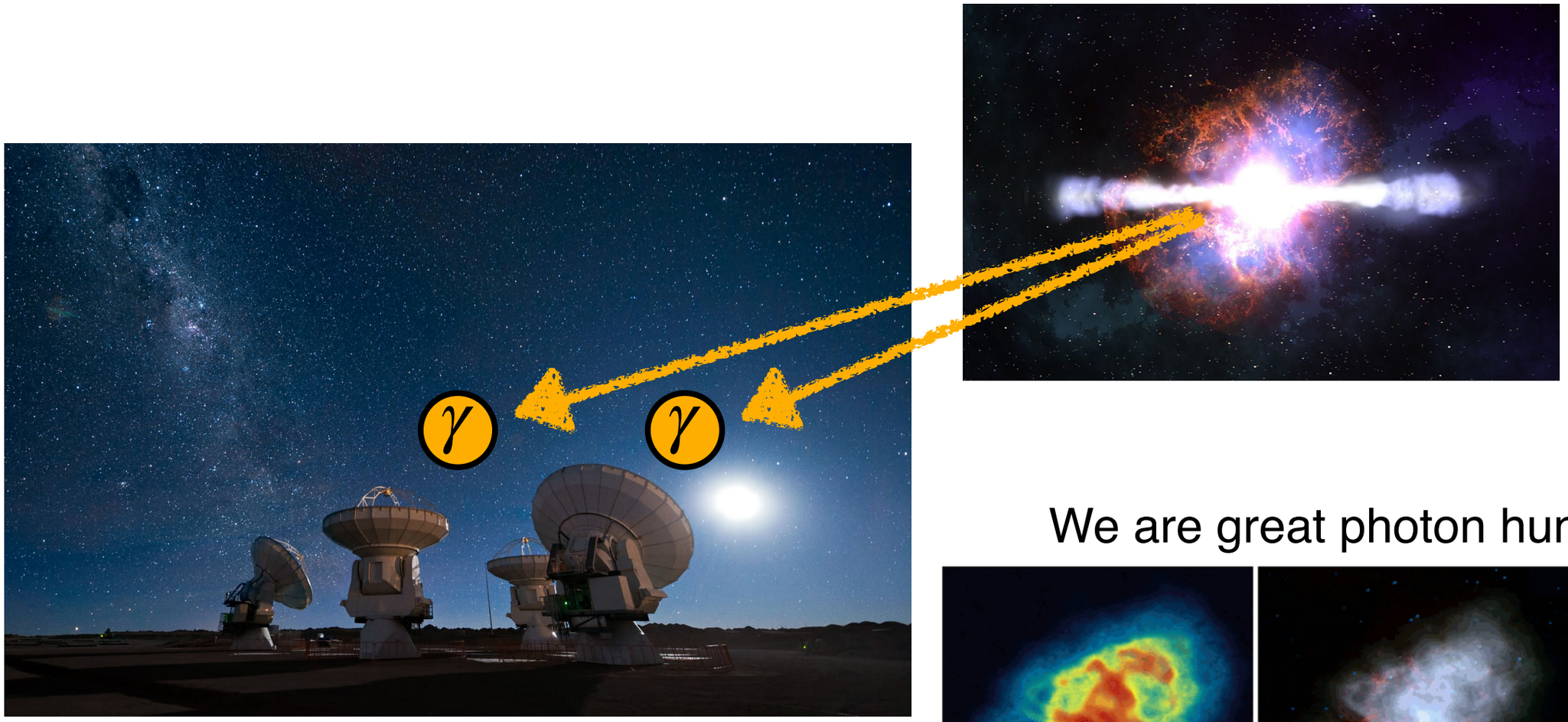
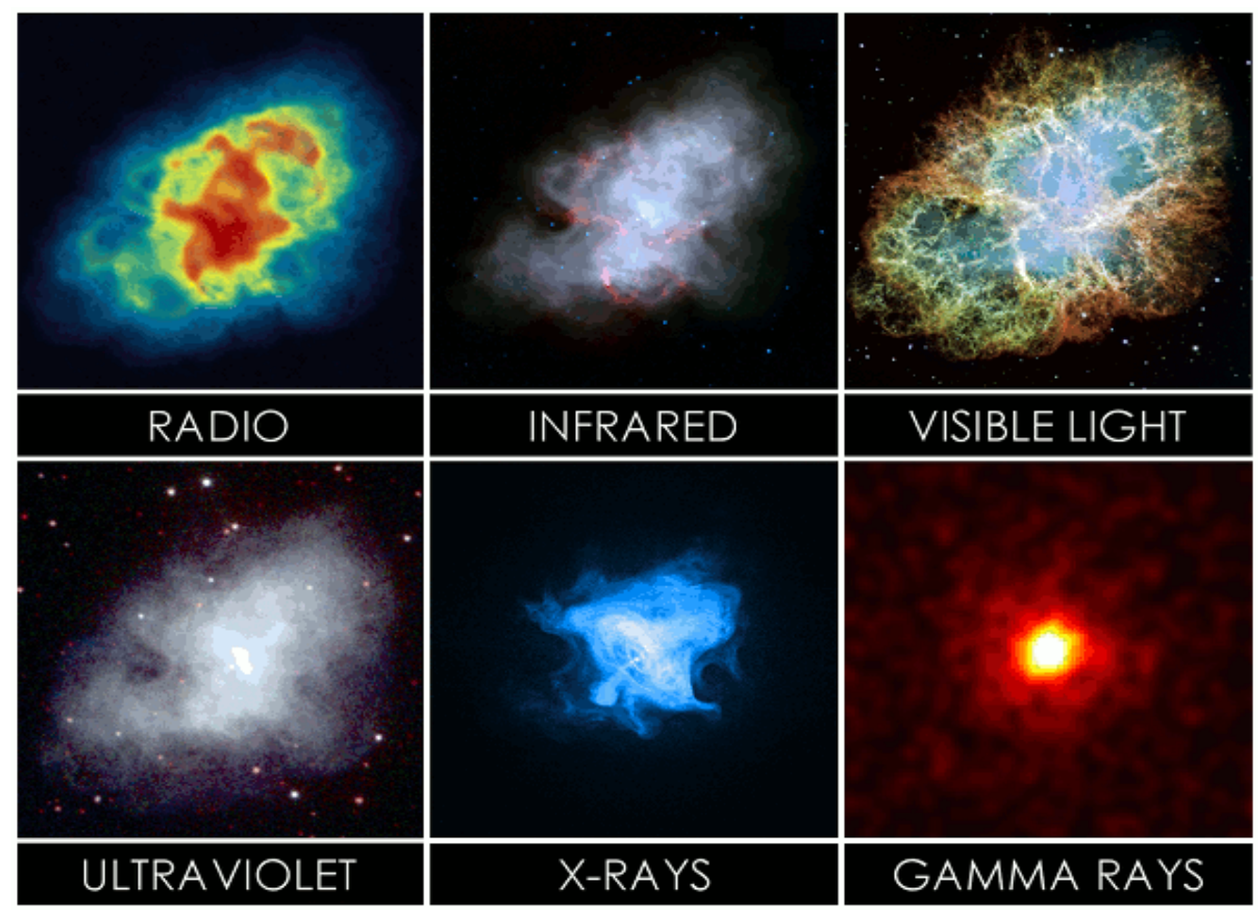


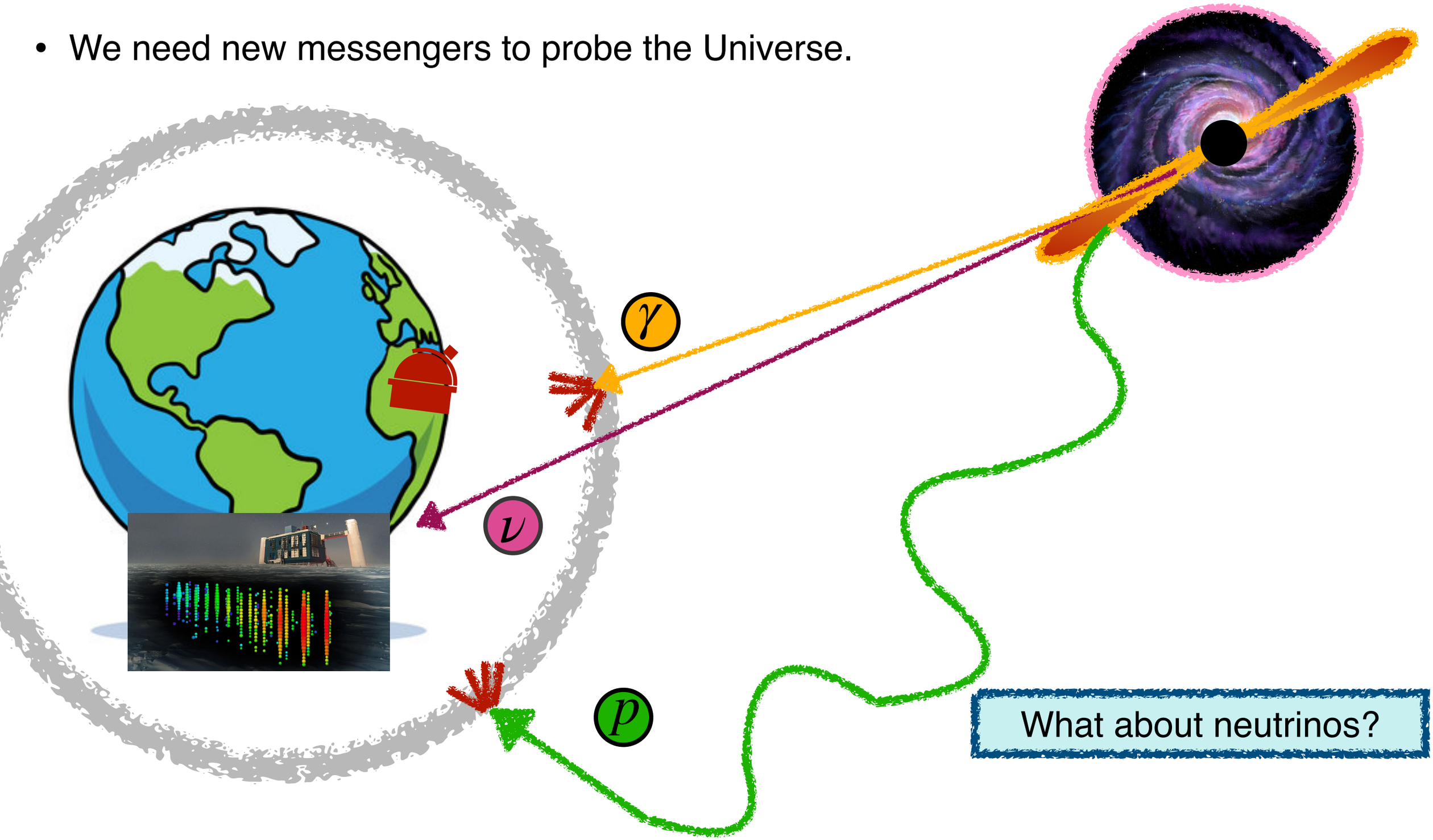
We are great photon hunters!



What if we could change our glasses?

Looking at the Universe through Neutrino Lenses

- Photons are absorbed on their way to Earth: not enough information.
- We need new messengers to probe the Universe.



Neutrino Production in Astrophysical Transients

- Shocks are common in astrophysics.
- Protons and electrons can be accelerated at the shocks.
- Electrons cool emitting photons, while protons mainly cool through photo-hadronic and hadronic interactions.

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

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

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

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

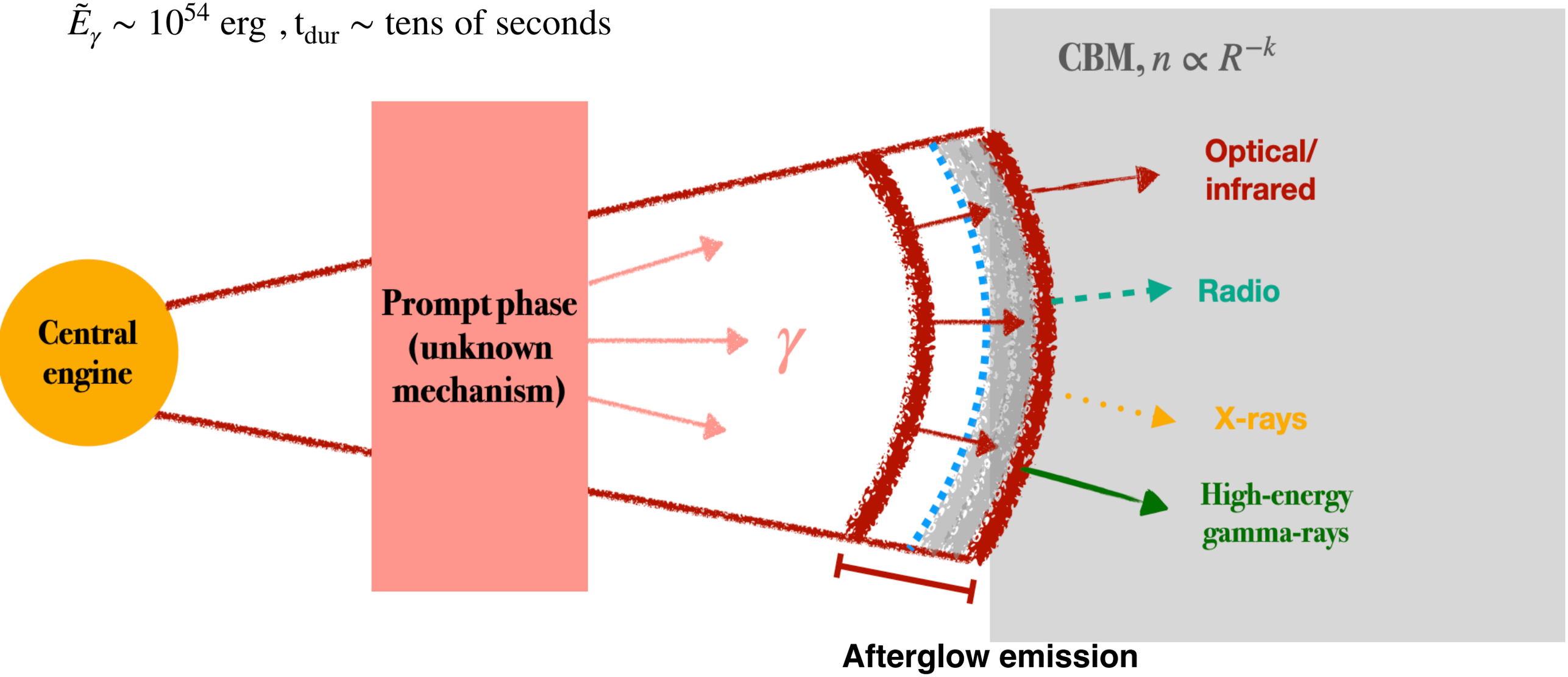
How could we use neutrinos?

Let us look at two examples!

Example 1:
Optical Jumps in Gamma-ray Burst Afterglows

GRBs: The Standard Fireball Model

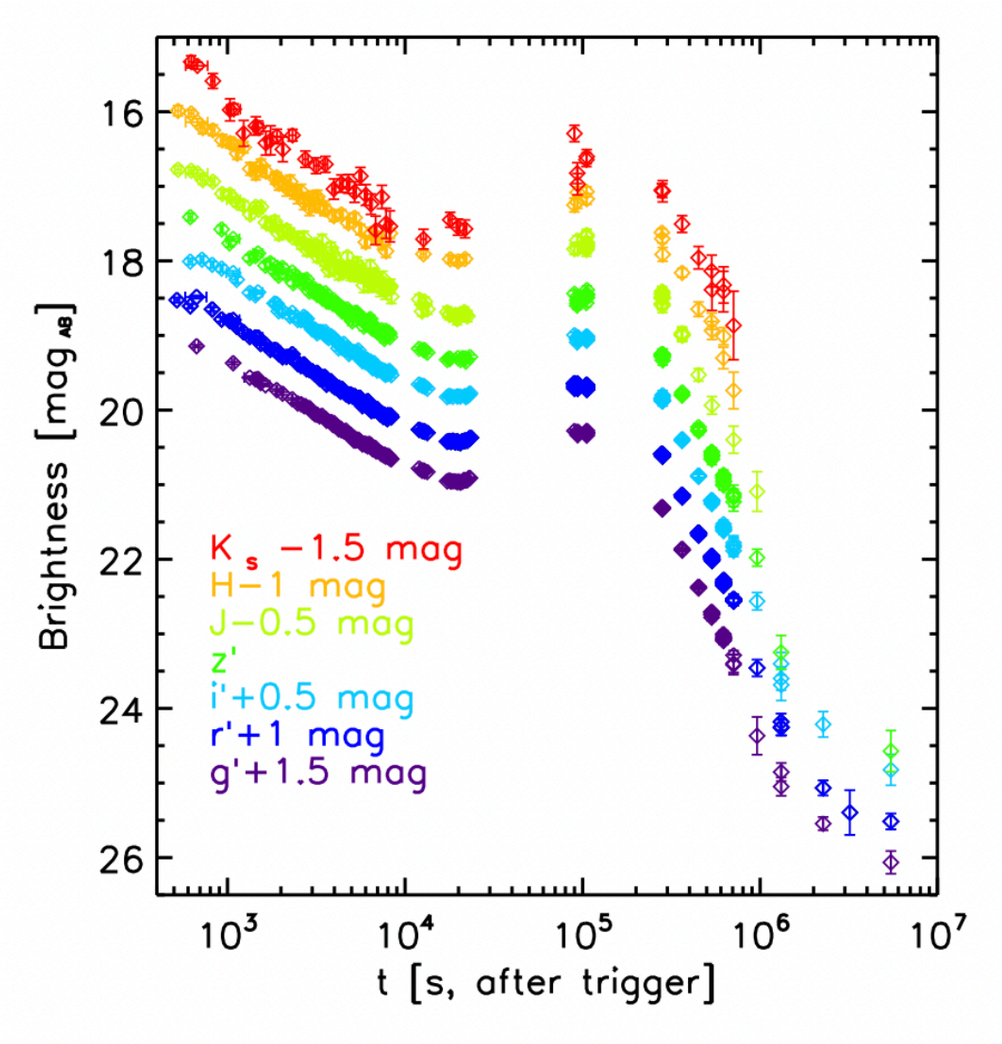
$\tilde{E}_\gamma \sim 10^{54}$ erg , $t_{dur} \sim$ tens of seconds



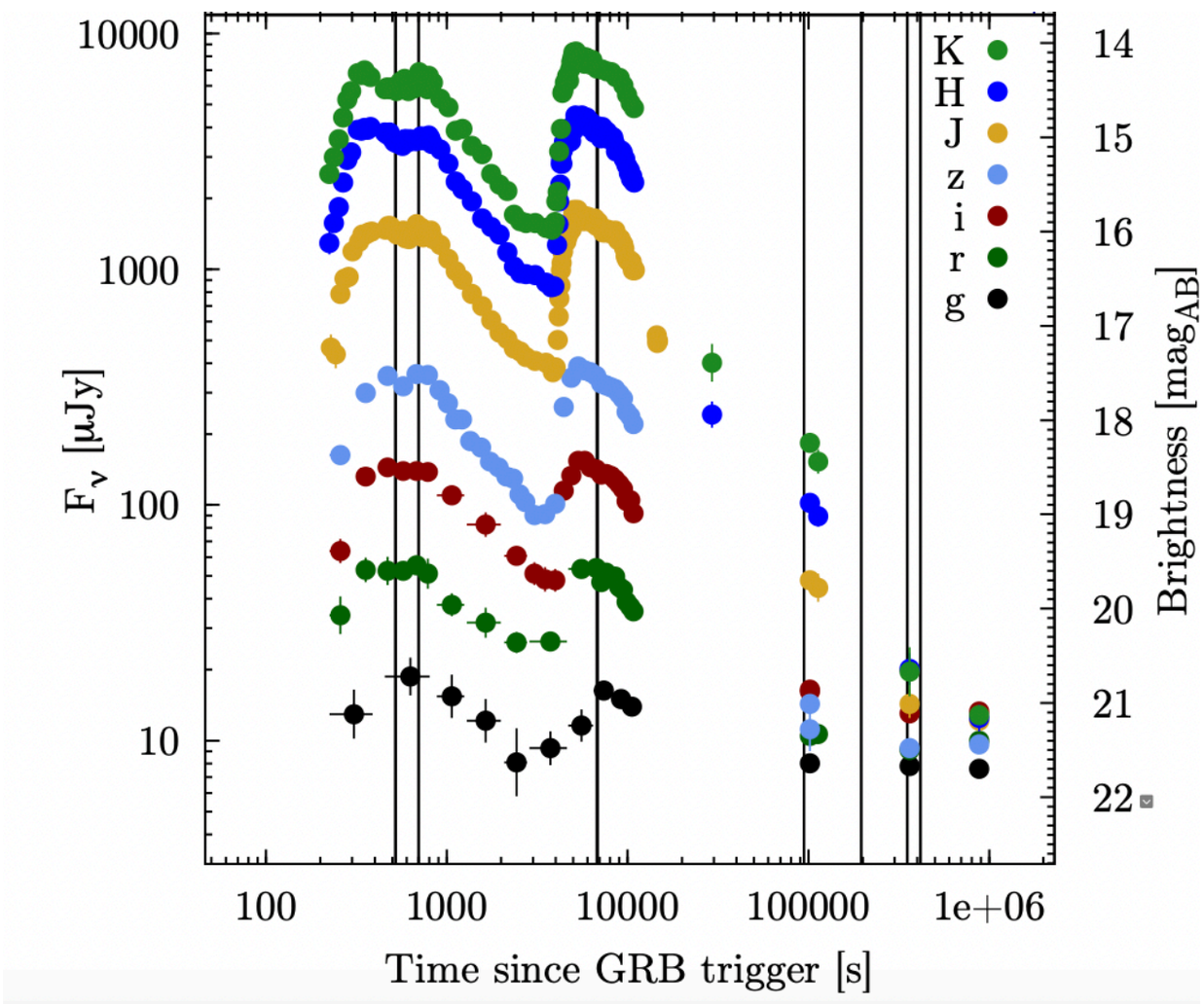
- Delayed emission observed up to several days after the trigger of the burst
- Observed in the optical/infrared, radio , X-ray and TeV band
- The afterglow emission results from the interaction between the ejecta and the circumburst medium (CBM).

Afterglow: Optical Jump

- Sudden re-brightening observed up to a few hours after the prompt emission.
- Observed in the optical/X-ray band (usually brighter in optical).
- The standard fireball model does not account for an optical jump.

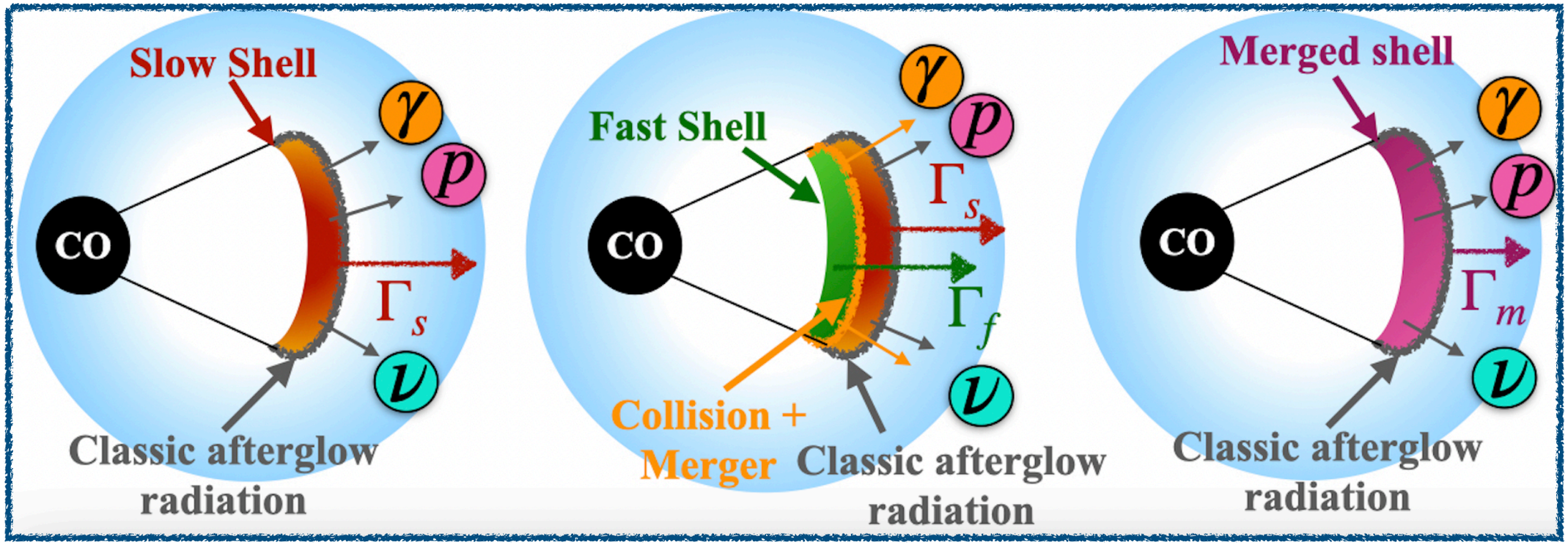


Nardini et al., Astron. Astrophys. (2013)



Greiner et al., A&A (2013)

Merger of Two Relativistic Shells



①

Slow shell propagates with Γ_s and generates classic afterglow radiation.

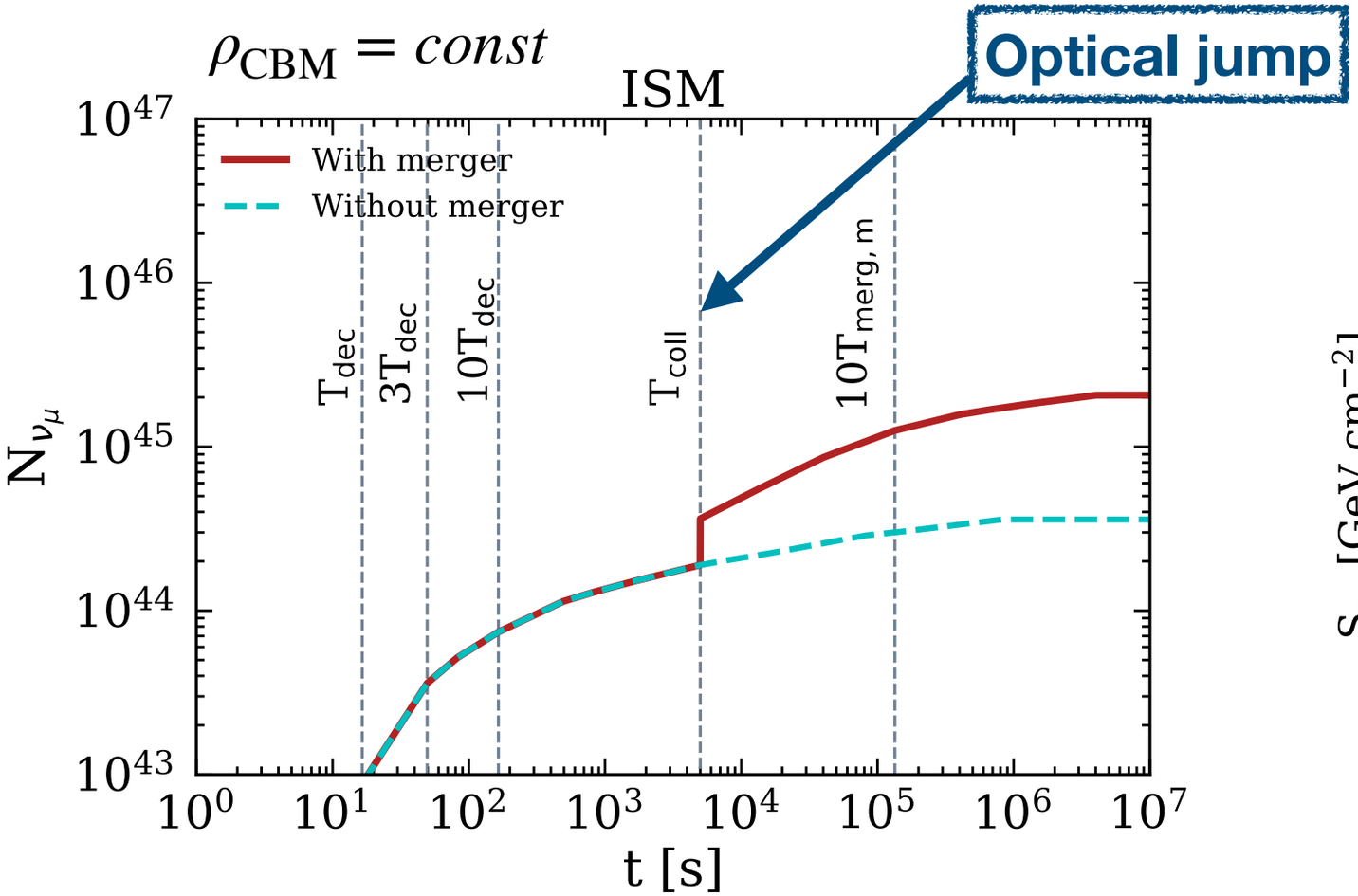
②

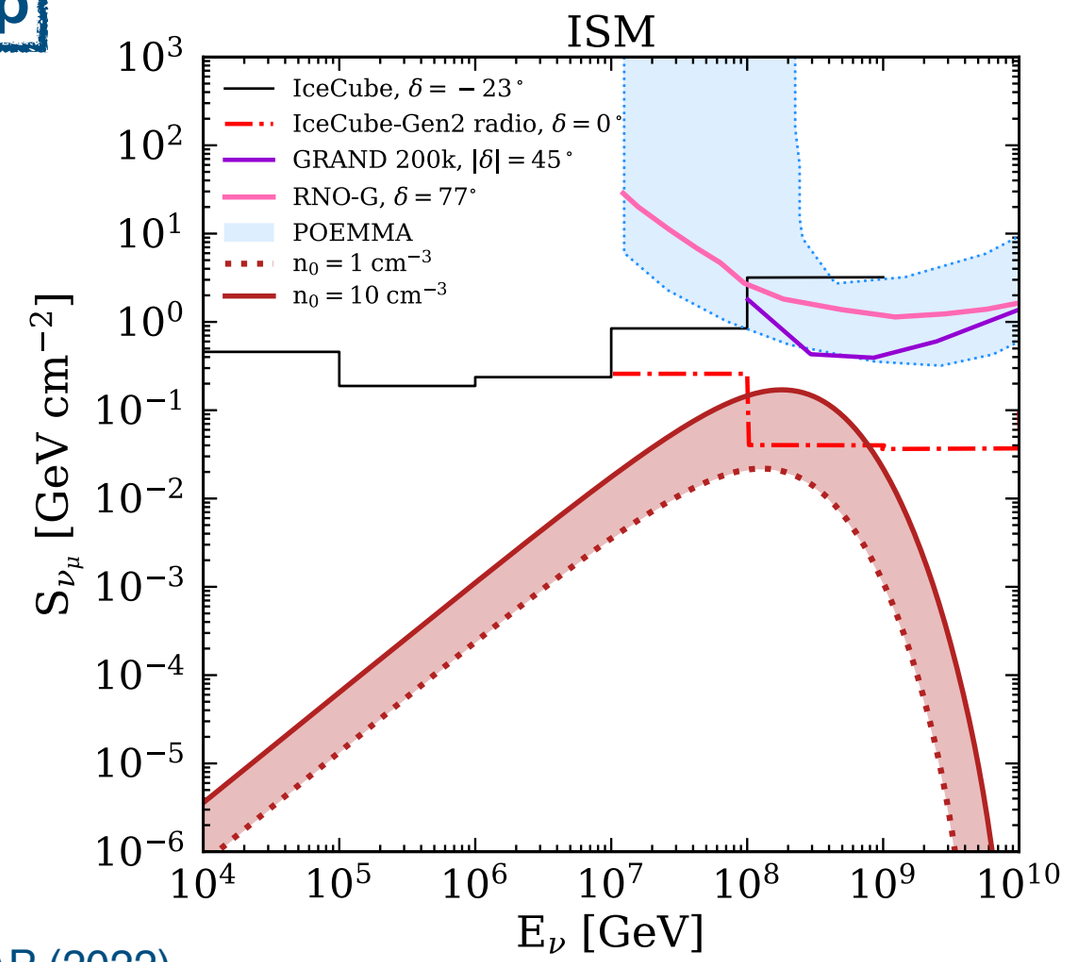
- *Fast* shell emitted with Γ_f.
- Fast and slow shells collide and merge into a single shell.
- Afterglow radiation from the slow shell + radiation from the merger.

③

Merged shell propagates with Γ_m and generates classic afterglow radiation.

Neutrino Event Rate





Guarini et al., JCAP (2022)

- An optical jump in the total light-curve corresponds to a jump in the neutrino event rate.
- ISM scenario: total number of neutrinos increases by a factor ~ 6 .
- Upcoming radio telescopes will be sensitive to GRB afterglows up to $d_L \sim 10 - 40$ Mpc.

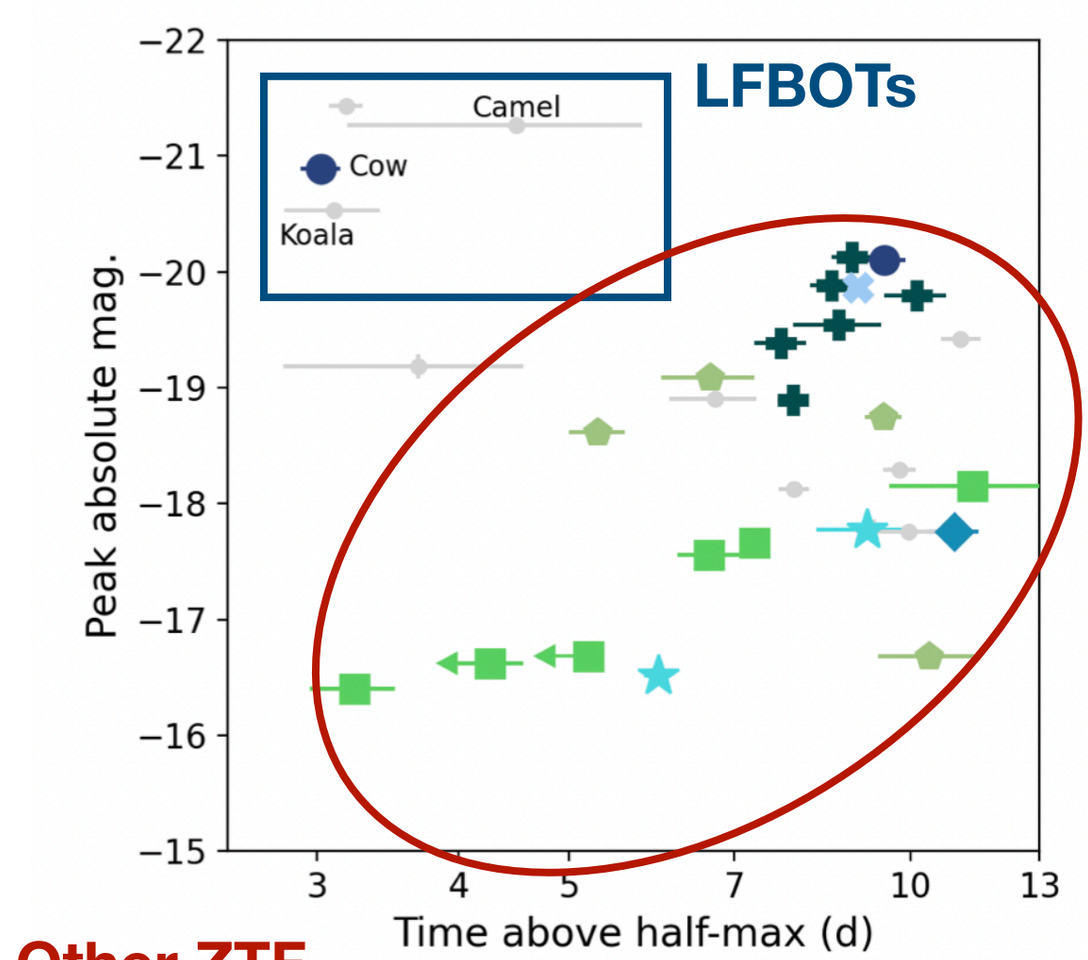
Take Home Messages on GRB Optical Jumps

- Optical jumps leave a signature in the neutrino signal, the neutrino number increases up to an order of magnitude.
- Future neutrino facilities, e.g. IceCube-Gen2 Radio, can potentially detect neutrinos from GRB afterglows with optical jumps.
- Neutrinos could be used to constrain the properties of the CBM where the GRB occurred.
- Neutrinos could probe the mechanism powering the optical jump.

Example 2:
Luminous Fast Blue Optical Transients (LFBOTs)

LFBOTs: What We Know So Far

- Supernova-like transients.
- Optical rise times: ~2 days.
- Optical peak luminosities: $L_{\rm peak} \gtrsim 10^{44}$ erg s^{-1}.
- Observed in the optical, X-ray and radio bands.



Other ZTF fast transients

Ho et al. , 2021 (arXiv:2105.08811)

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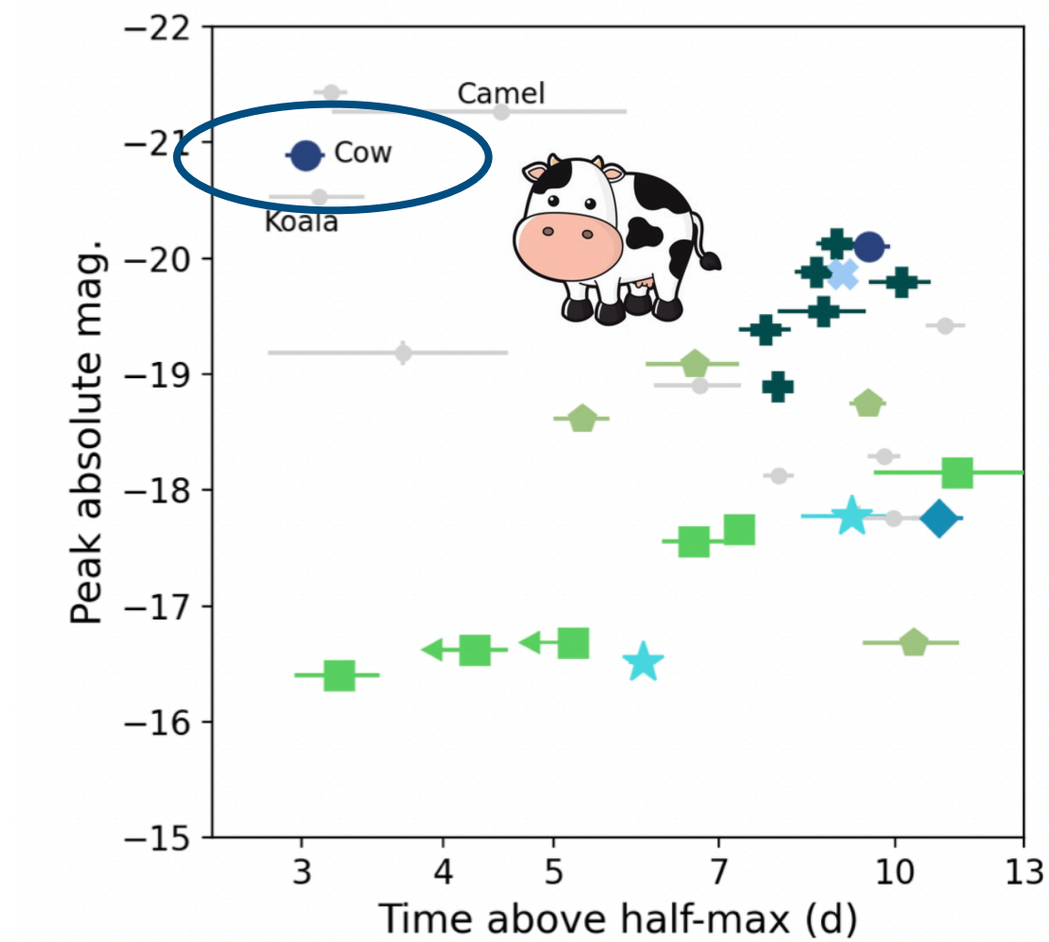

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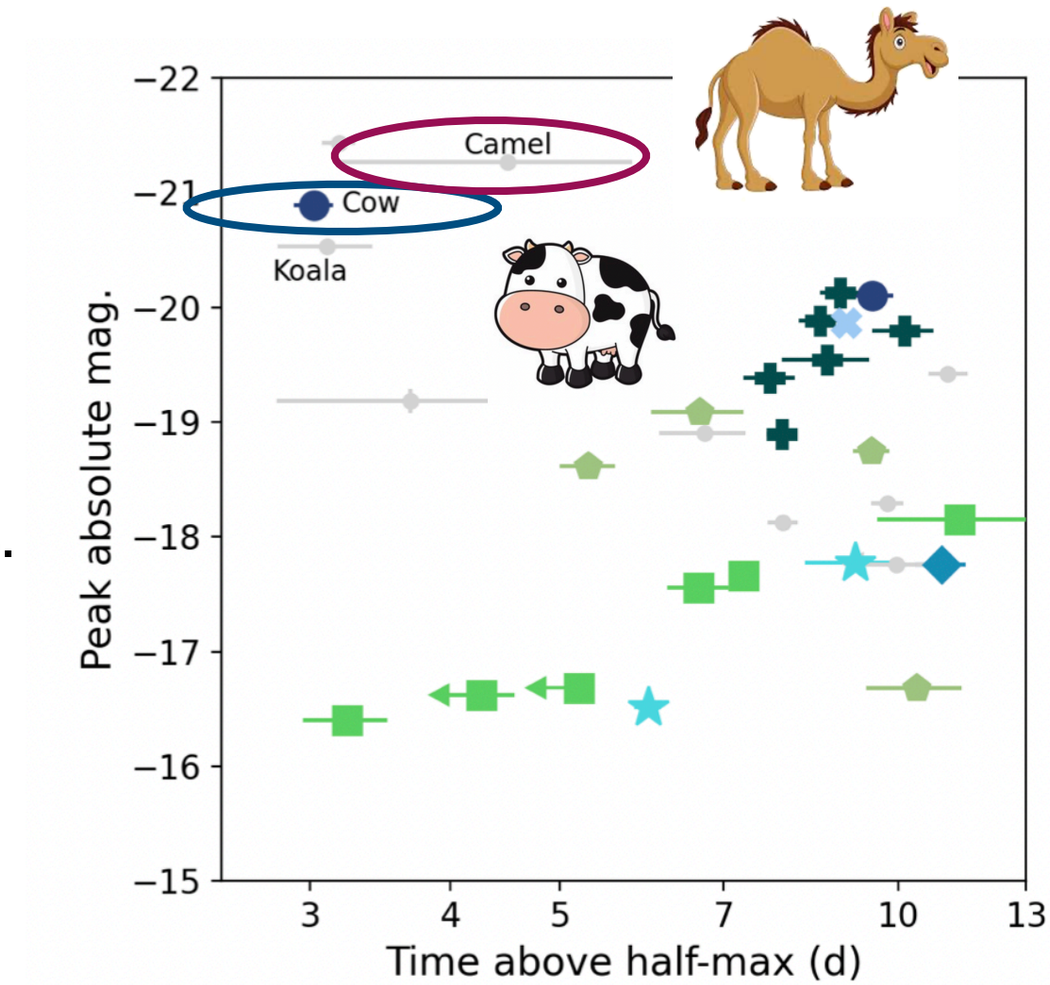

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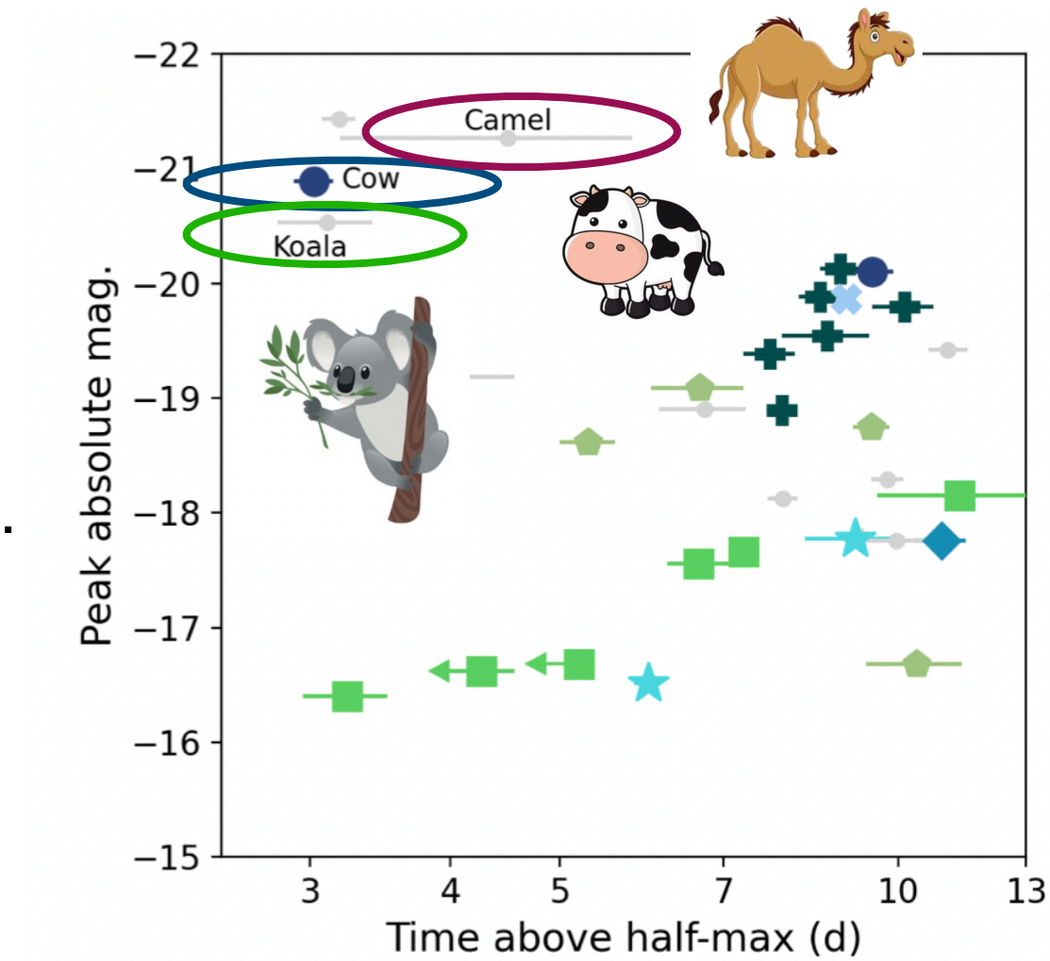

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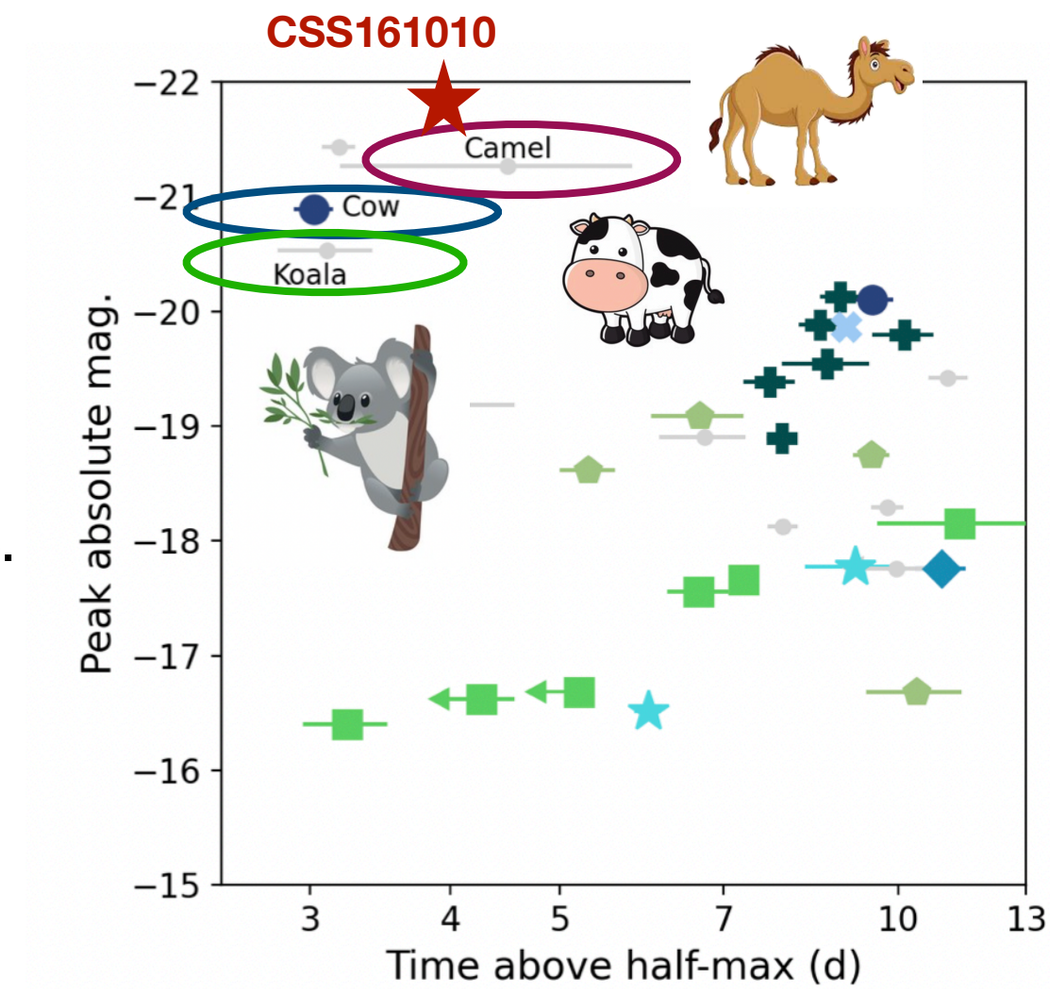
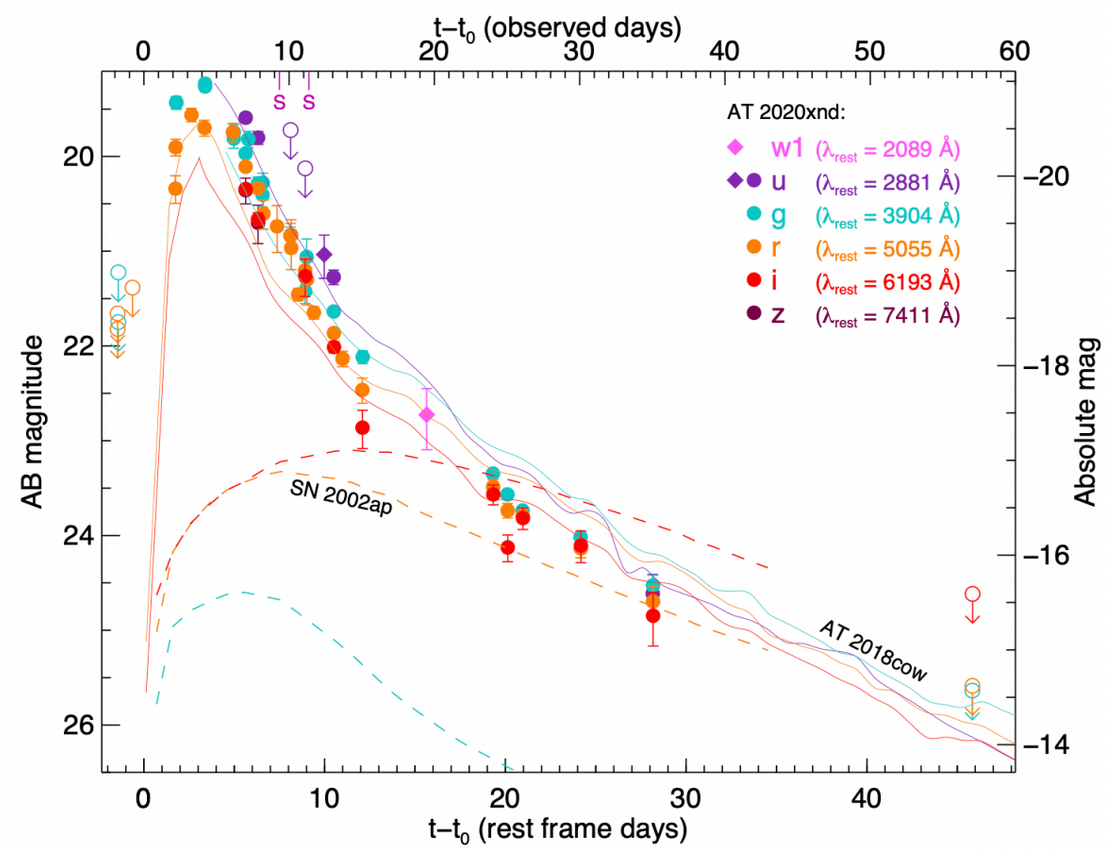


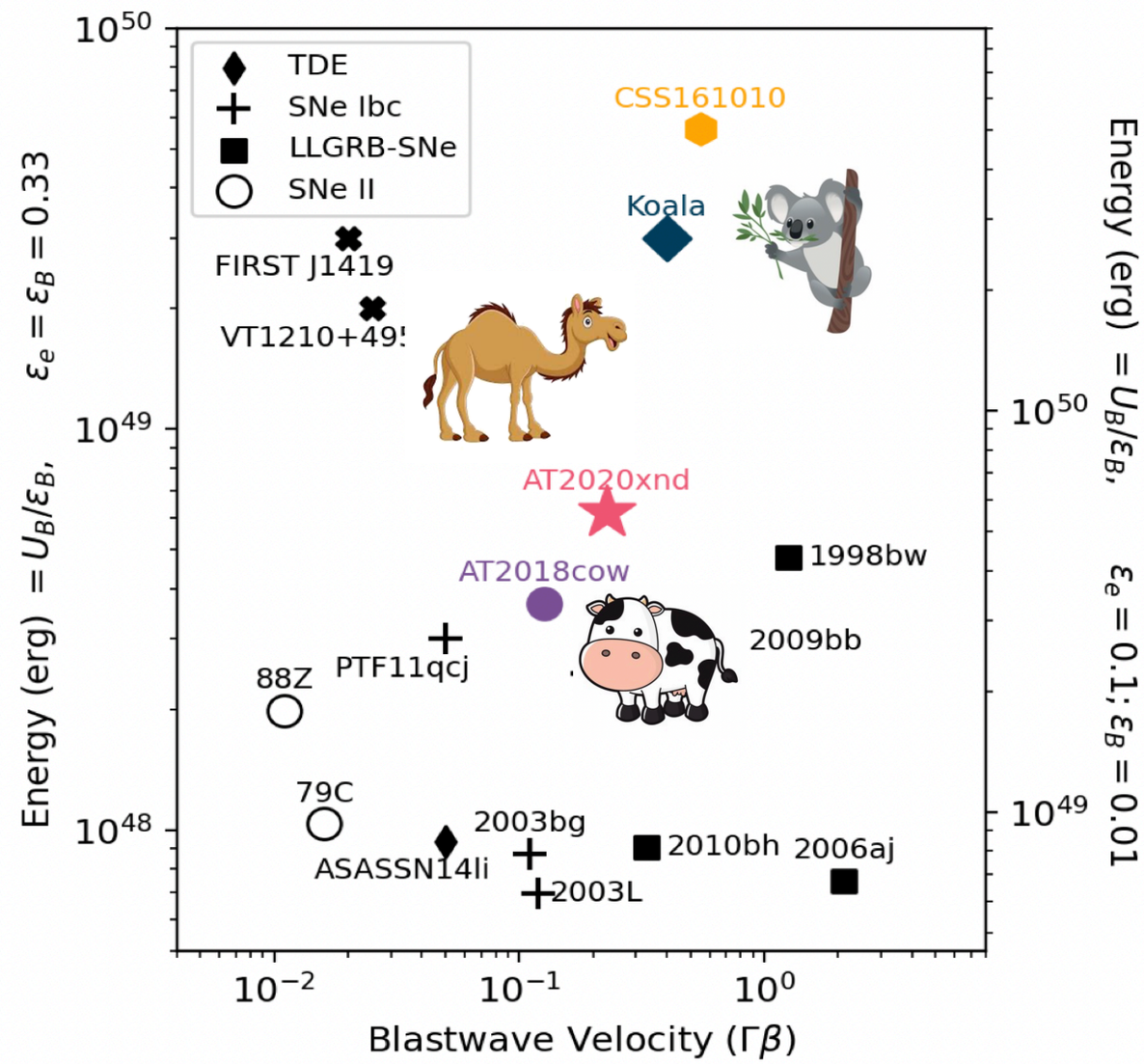
Ho et al. , 2021 (arXiv:2105.08811)

LFBOTs: What We Still Don't Know

- The radio emission is consistent with synchrotron radiation from ejecta-CSM interaction ($v_{\rm ej} \gtrsim 0.1c$).
- The origin of the ejecta is still unknown.
- What powers the optical and X-ray radiation?



Perley et al., Mon. Not. Roy. Astron. Soc. (2021)



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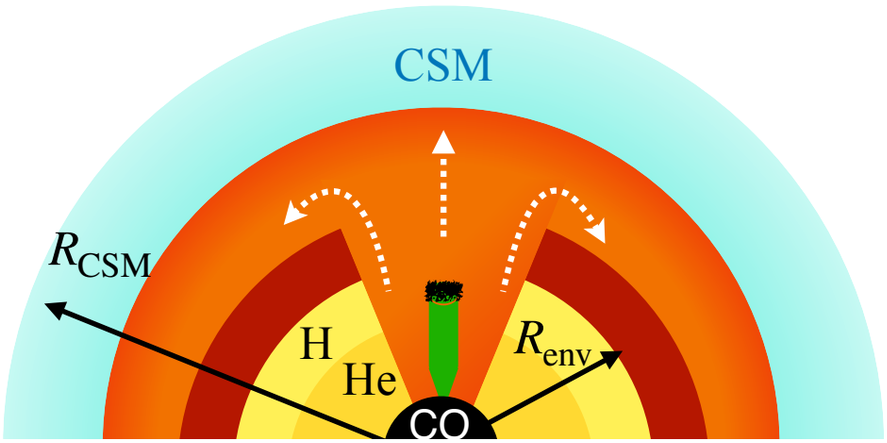
Main Ingredients

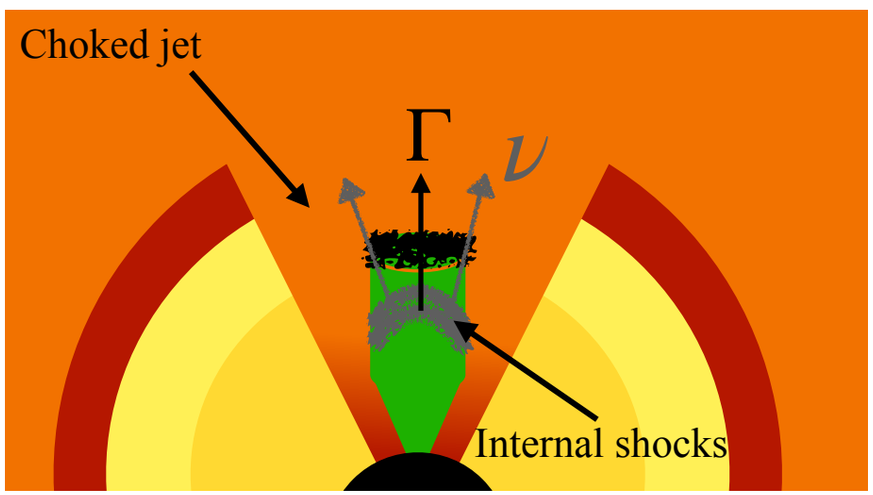
- Hydrogen (H) in the spectrum.
- Asymmetry required.
- No $\gamma-$rays observed from LFBOTs.

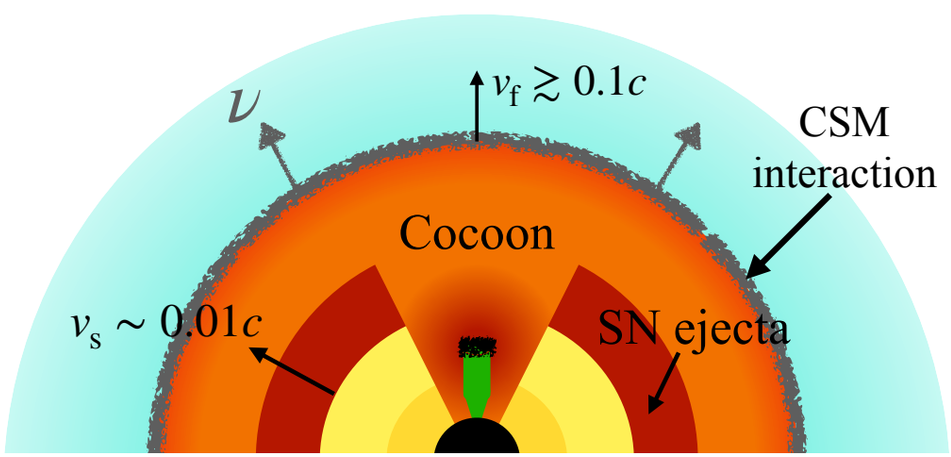
Theoretical Models

See Gottlieb, Tchekhovskoy and Margutti, Mon. Not. Roy. Astron. Soc. (2022); Metzger, Astrophys. J. (2022)

Cocoon model







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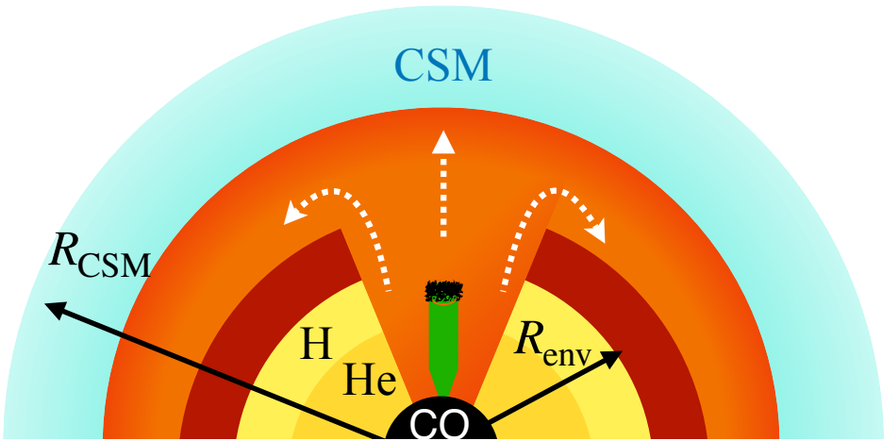
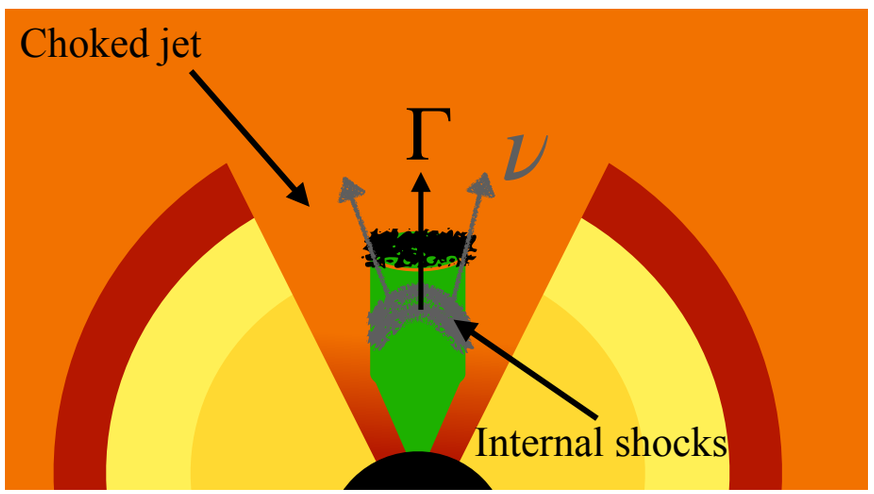
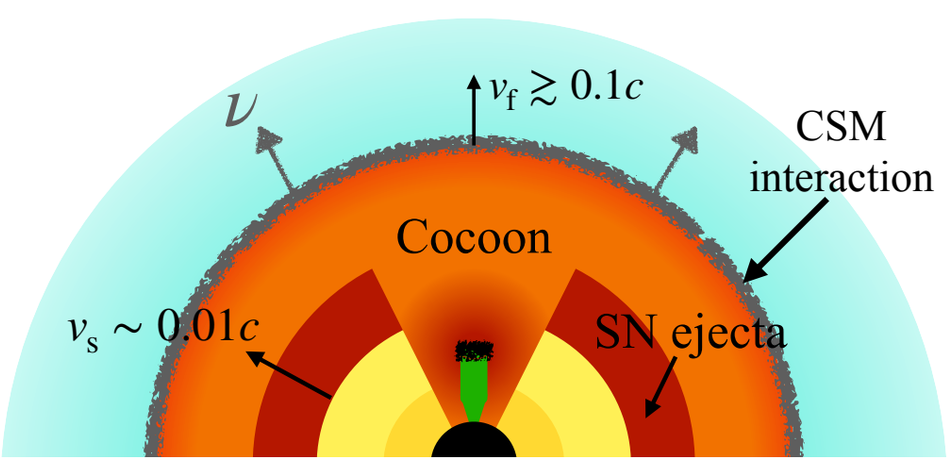
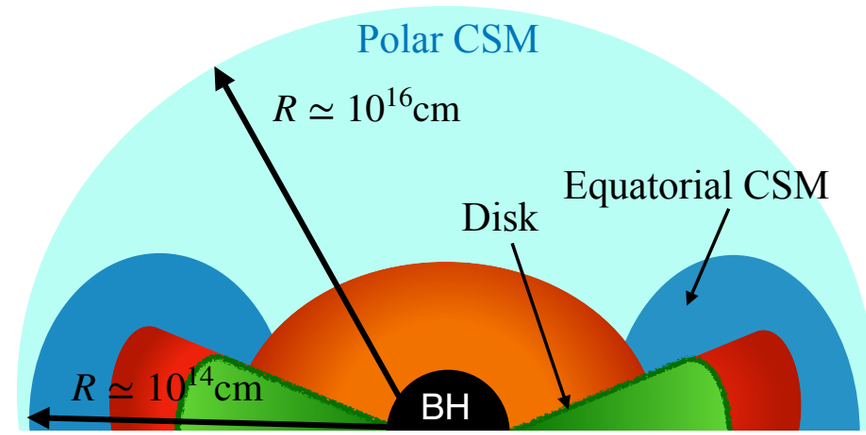
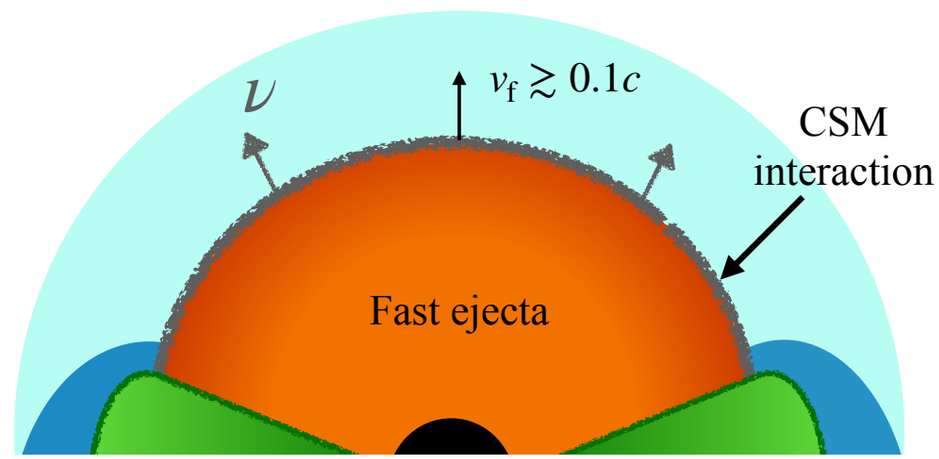


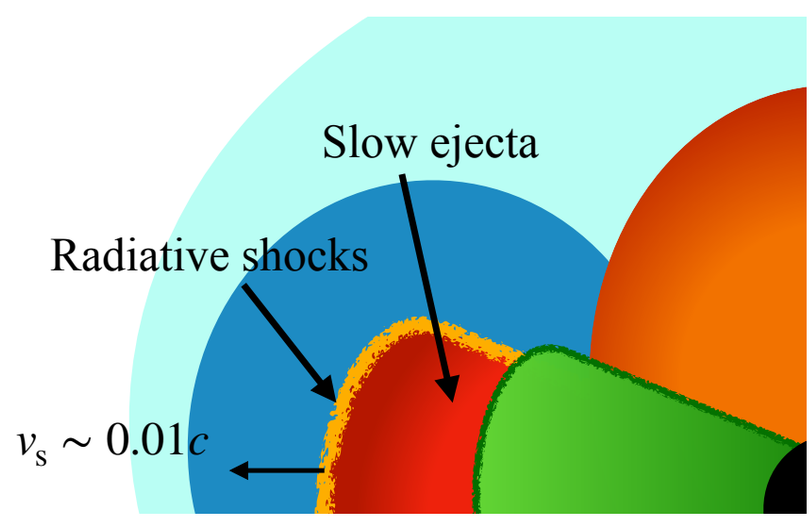




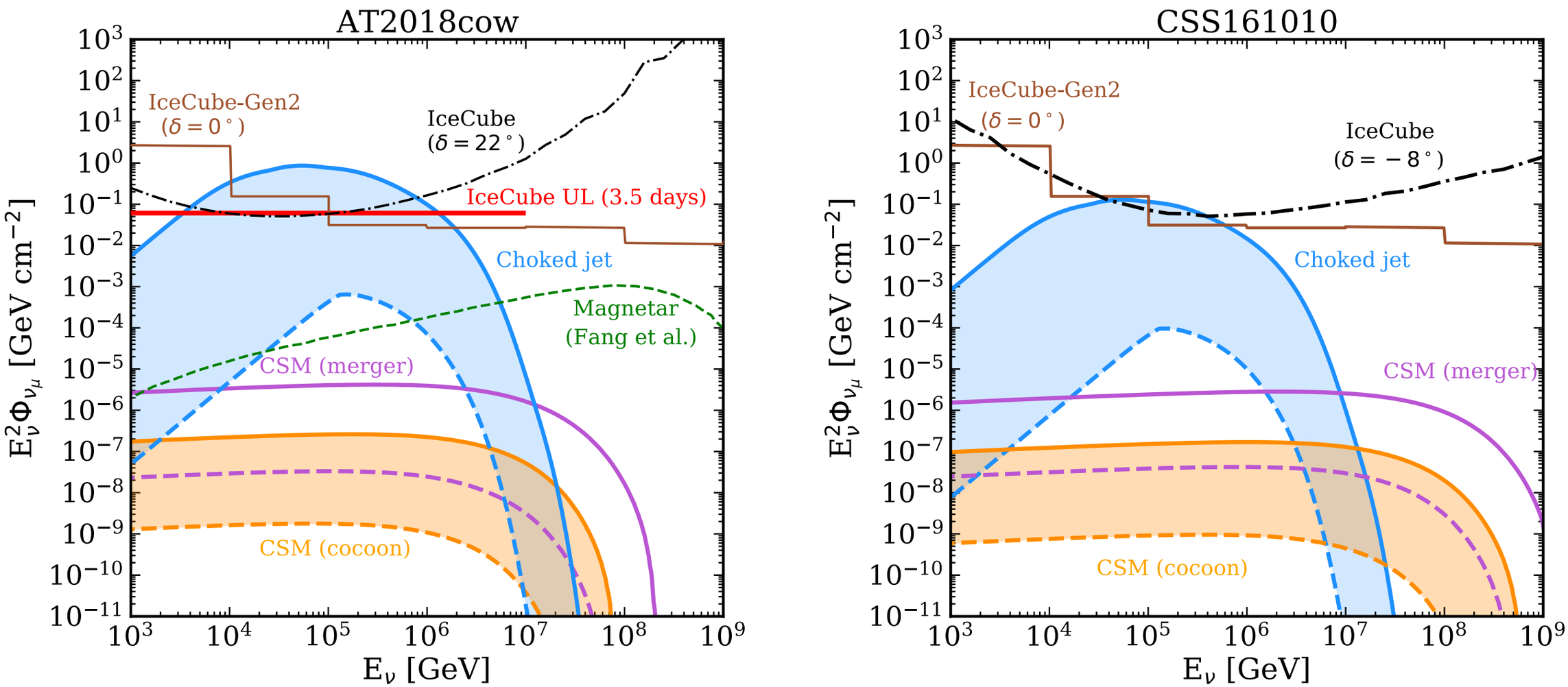
Merger model







Neutrino Signal from Nearby LFBOTs



Guarini, Tamborra and Margutti, ApJ (2022)

- Largest contribution from the choked jet.
- The flux from a choked jet is direction dependent.
- The flux from CSM interaction is isotropic.

Take Home Messages on LFBOTs

- Neutrinos carry signatures on the mechanism powering LFBOTs.
- Existing IceCube neutrino data in the direction of AT2018cow restrict the allowed parameter space for a choked jet.

Conclusions

- Photon and neutrino fluxes are larger when a jump occurs in GRBs.
- Neutrinos can disentangle the mechanism powering LFBOTs sources.
- Upcoming neutrino facilities such as IceCube-Gen2 radio, GRAND200k, RNO-G and POEMMA and existing neutrino telescopes such as IceCube will be able to detect the signal from future nearby GRBs and/or LFBOTs.

Neutrinos are unique probes of the transient sky.

Exciting times ahead for multi-messenger astrophysics!

Thanks for your attention!

Questions?

Bakcup slides

The Standard Fireball Model (III)

CBM density profile $n \propto R^{-k}$

k=0: ISM

$n = n_0 = const$

k=2: wind

$n = AR^{-2},\ A = 3.02 \times 10^{35} A_\star\ \mathrm{cm}^{-1}$

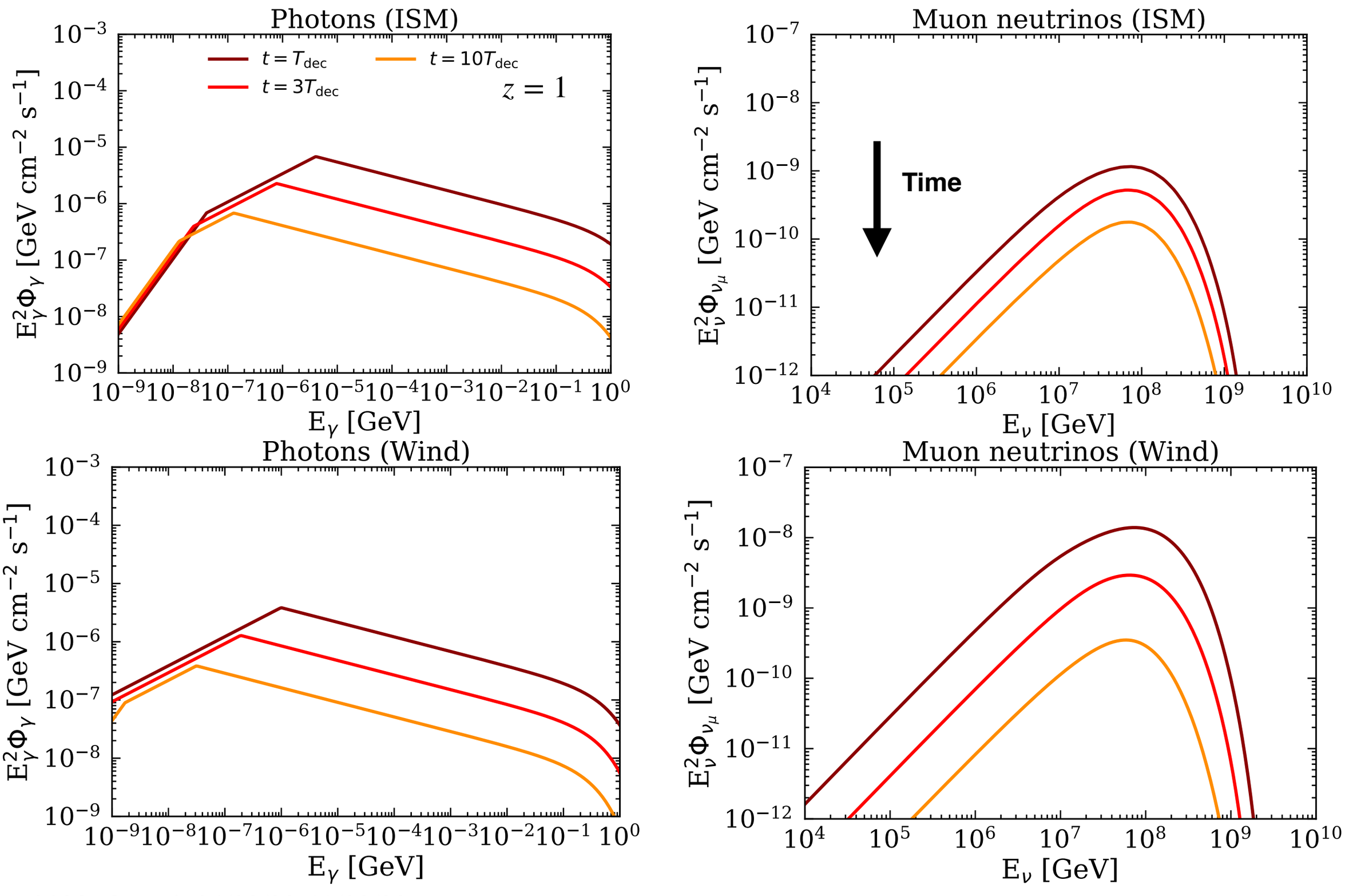
$$T_{\rm dec} = \left[\frac{3\tilde{E}_{k,{\rm iso}(1+z)^3}}{64\pi n_0 m_p c^5 \Gamma_0^8}\right]^{1/3}$$

$$T_{\rm dec} = \frac{\tilde{E}_{k,{\rm iso}(1+z)}}{16\pi A m_p c^3 \Gamma_0^4}$$

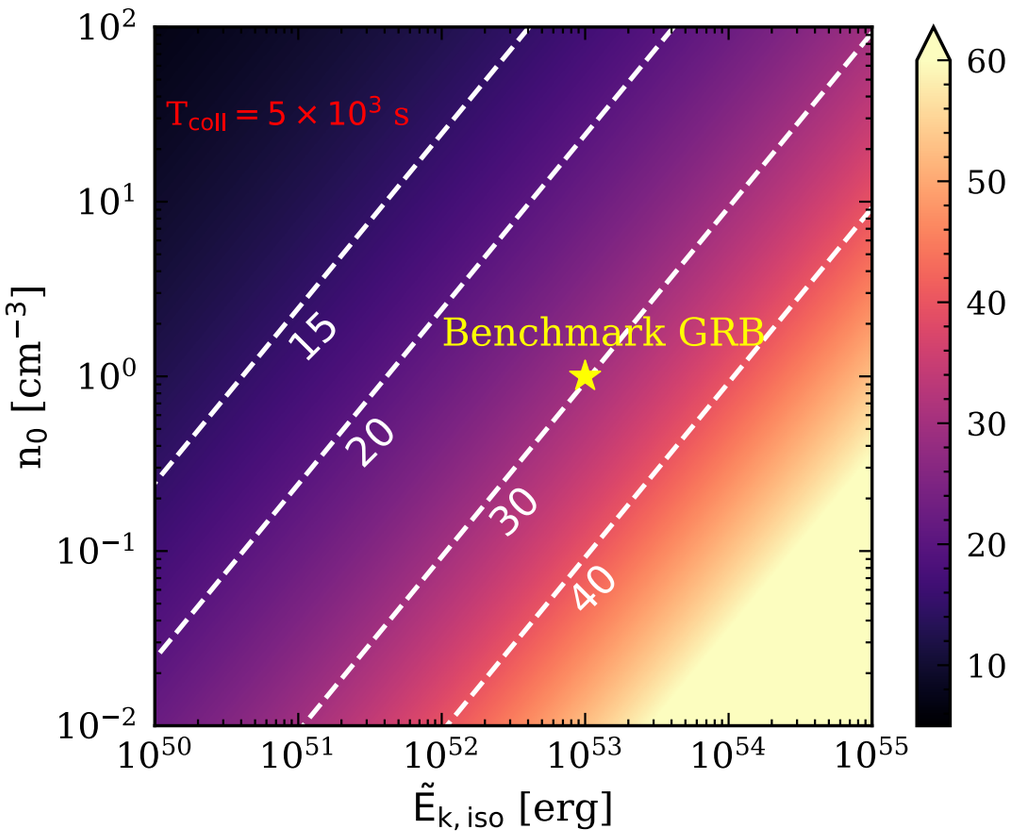
$$\Gamma = \Gamma_0 \left(\frac{T_{\rm dec}}{4t}\right)^{1/4}$$

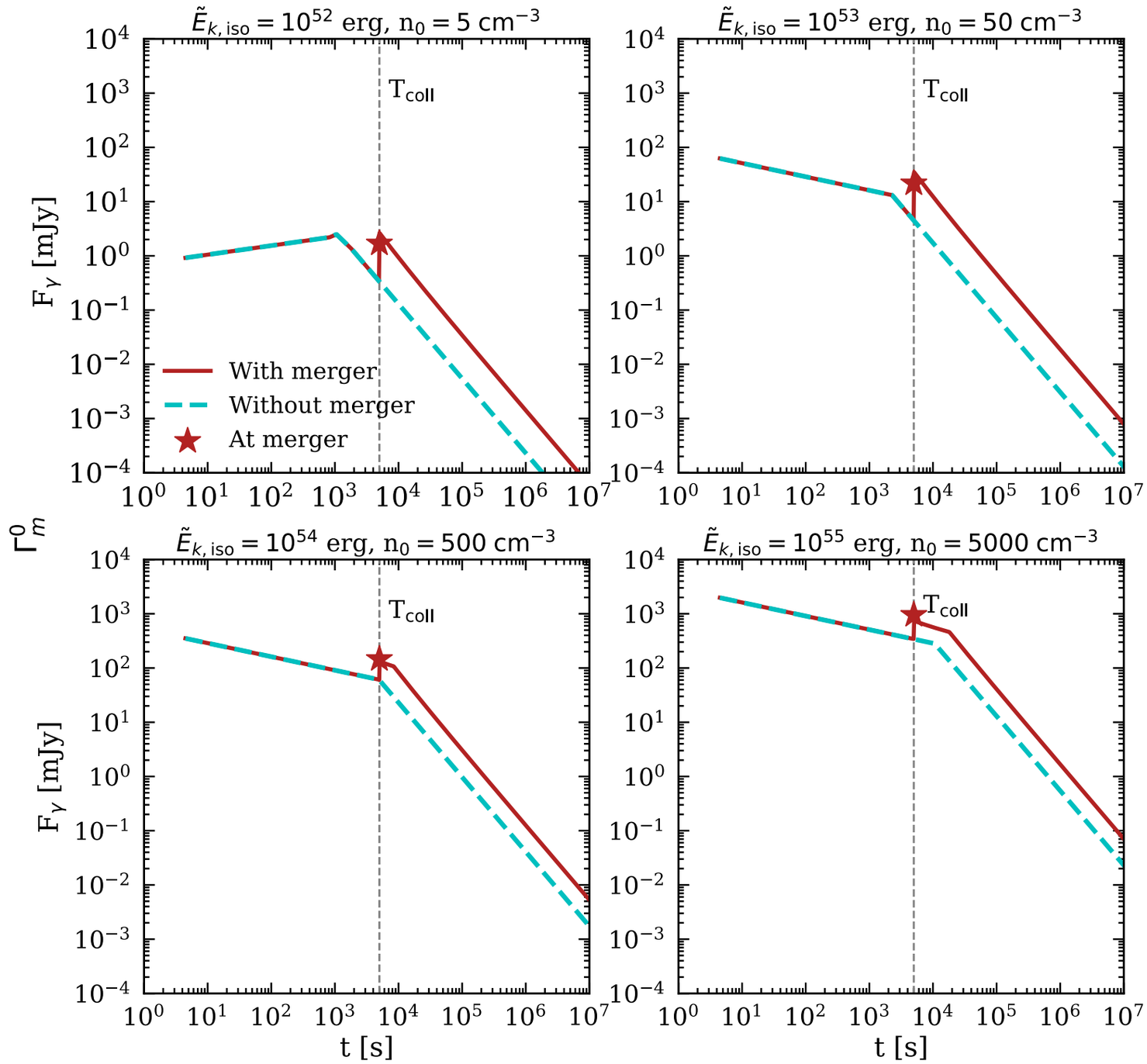
$$t'_{\rm dyn} \simeq \frac{R}{8\Gamma c}$$

Classic Afterglow - Neutrino and Photon Energy fluxes



Degeneracies of the problem





Scaling relations for the merged shell

$$R_{\mathrm{dec},m}^{\mathrm{ISM}} \simeq \left(\frac{3\tilde{E}_{k,m}}{8\pi n_0 m_p c^2 {\Gamma_m^0}^2} + R_{\mathrm{coll}}^3 \right)^{1/3}$$

$$R_{\mathrm{dec},m}^{\mathrm{wind}} \simeq \frac{\tilde{E}_{k,m}}{4\pi A m_p c^2 {\Gamma_m^0}^2} + R_{\mathrm{coll}}$$

The initial energy of the merged shell is:

$$\tilde{E}_{\mathrm{tot},m} \simeq \frac{4}{3}\tilde{W}_m + \Gamma_m^0 m_m c^2$$

Merged shell

From the conservation of energy and momentum we get the initial Lorentz factor of the merged shell and the internal energy released at the collision.

Initial Lorentz factor

$$\Gamma_m^0 \simeq \sqrt{\frac{m_f\Gamma_f + m_{\rm eff}\Gamma}{m_f/\Gamma_f + m_{\rm eff}\Gamma}}$$

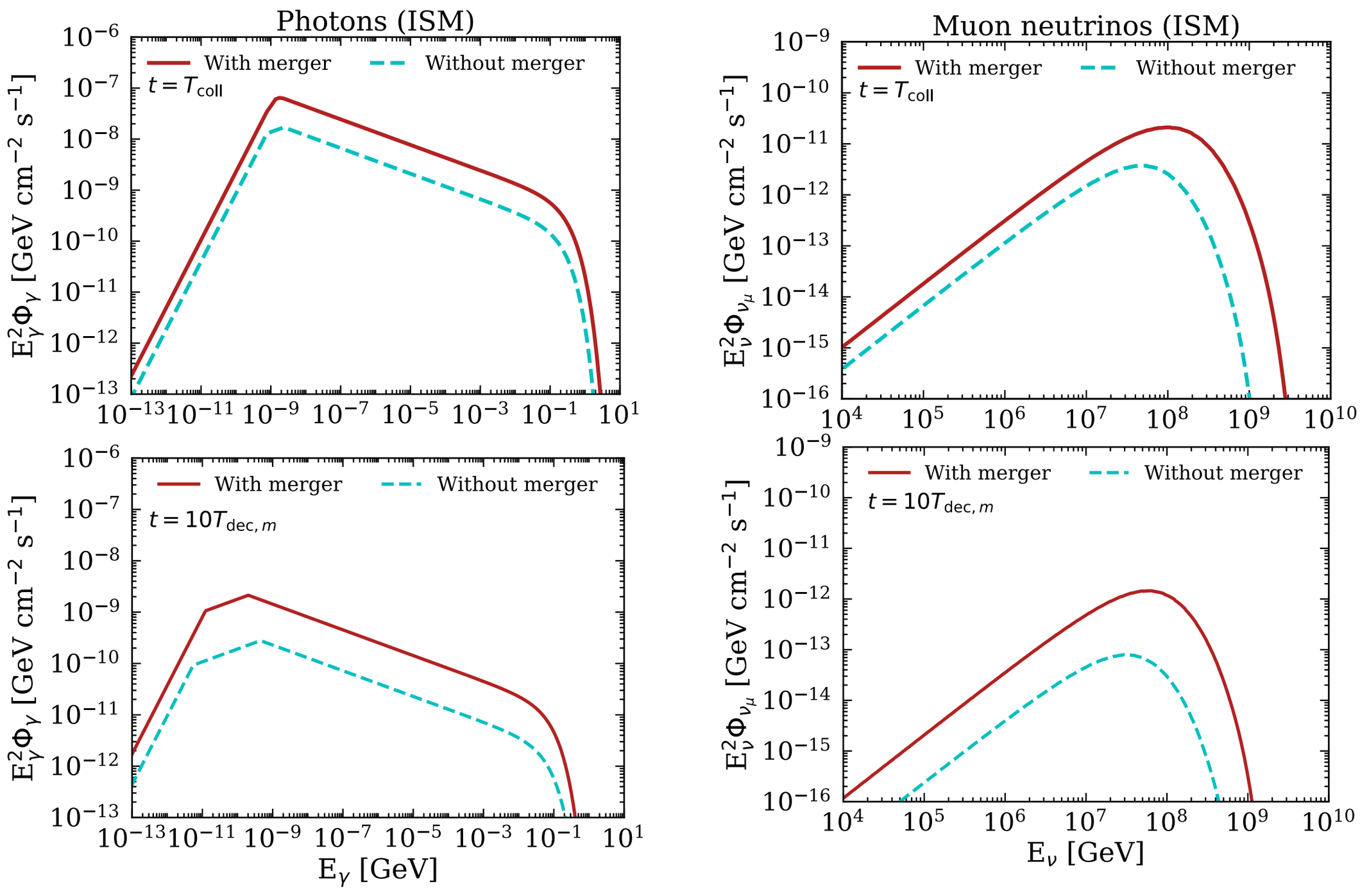
Internal energy

$$\tilde{W}_m = \frac{1}{\hat{\gamma}}[(m_f\Gamma_f + m\Gamma)c^2 - (m+m_f)\Gamma_m^0 c^2] + \Gamma W'$$

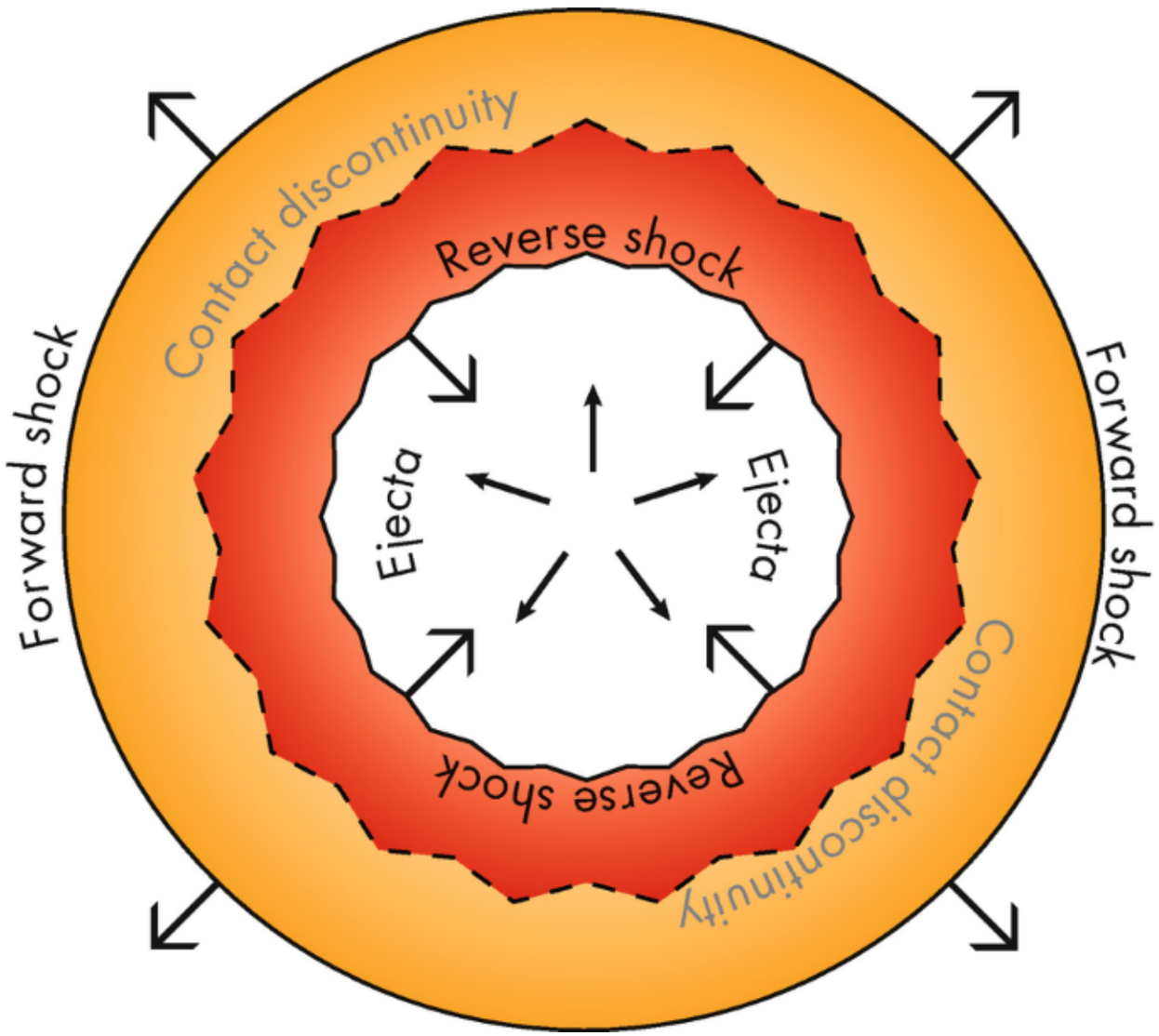
After a transitory phase, the merged shell propagates in the CBM and it is decelerated to the BM solution ⟶

- Classic afterglow radiation from the merged shell
- Same scaling relations for the Lorentz factor and the radius as the slow shell

Afterglow with Jump - Neutrino and Photon Energy Fluxes



Forward-Reverse Shock system



Conservation of energy, momentum and number of particles needed: Two shocks

LFBOTs: Theoretical Constraints

Boundary conditions in the jet head

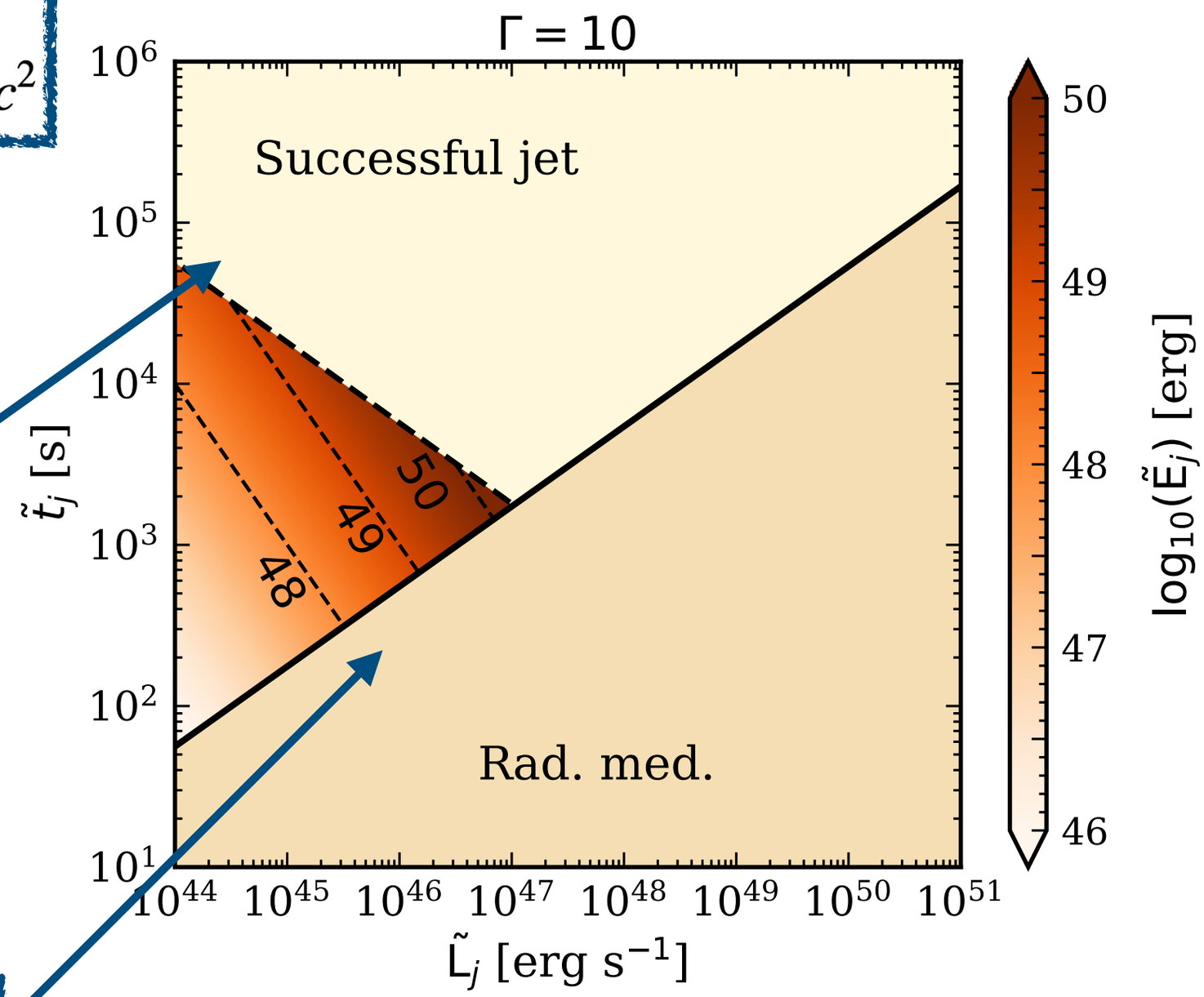
$$e_{\rm sh,env} = (4\Gamma_h + 3)(\Gamma_h - 1)\rho_{\rm env}(R_h)c^2 \ ,$$
$$e_{\rm sh,j} = (4\Gamma_{\rm rel} + 3)(\Gamma_{\rm rel} - 1)n'_j(R_h)m_p c^2$$

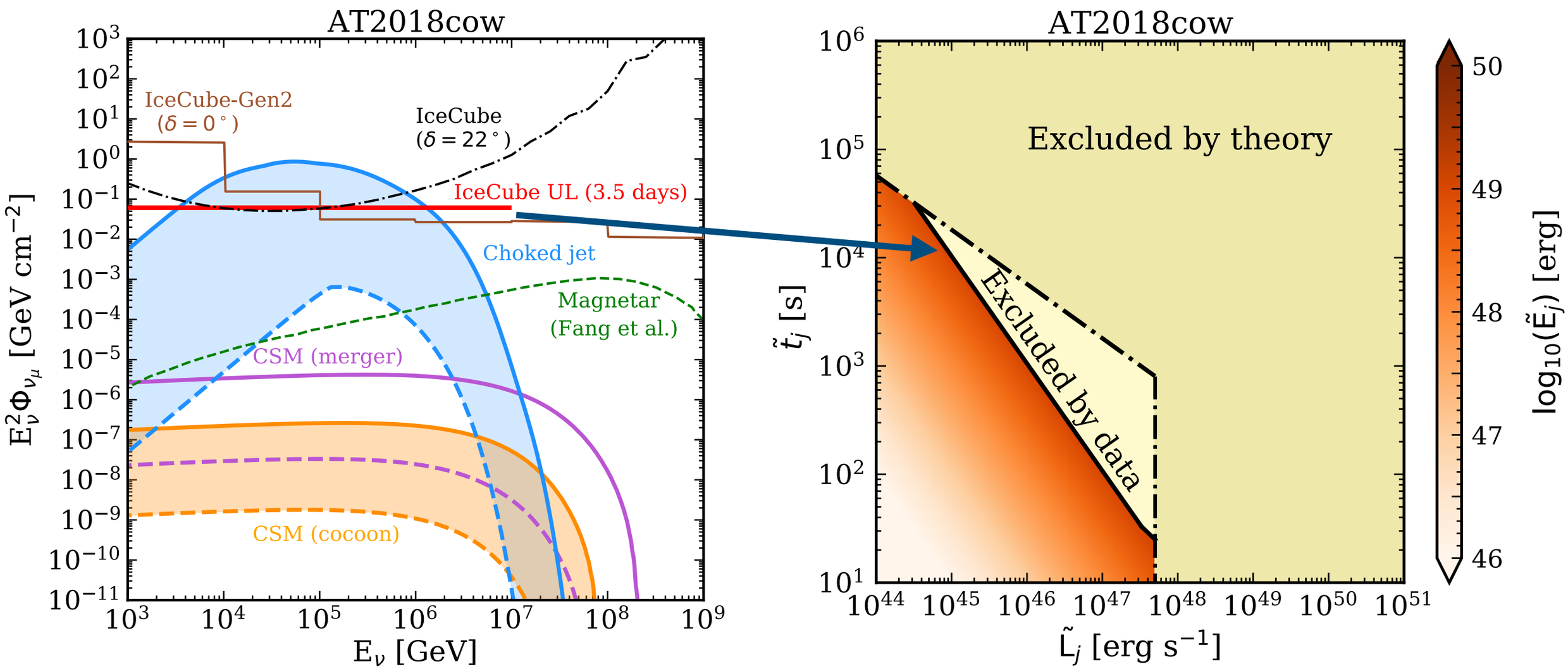
$$R_h \simeq \left[\frac{4\tilde{t}_j^2 \tilde{L}_j}{(4\Gamma_h + 3)\pi c \rho_{\rm env,0} R_{\rm env}^2 \theta_j^2}\right]^{1/2}$$

Jet chocked if $R_h < R_{\rm env}$ at the end of the jet lifetime

Collisionless shocks condition:

$$n'_p \sigma_T R_{\rm IS}/\Gamma \lesssim \min[\Gamma_{\rm r}^2, 0.1 C^{-1}\Gamma_{\rm r}^3]$$





Guarini, Tamborra and Margutti, ApJ (2022)

LFBOTs: Detection Perspectives