High-energy Neutrino Emission from Interaction-Powered Supernovae

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Neutrino Frontiers

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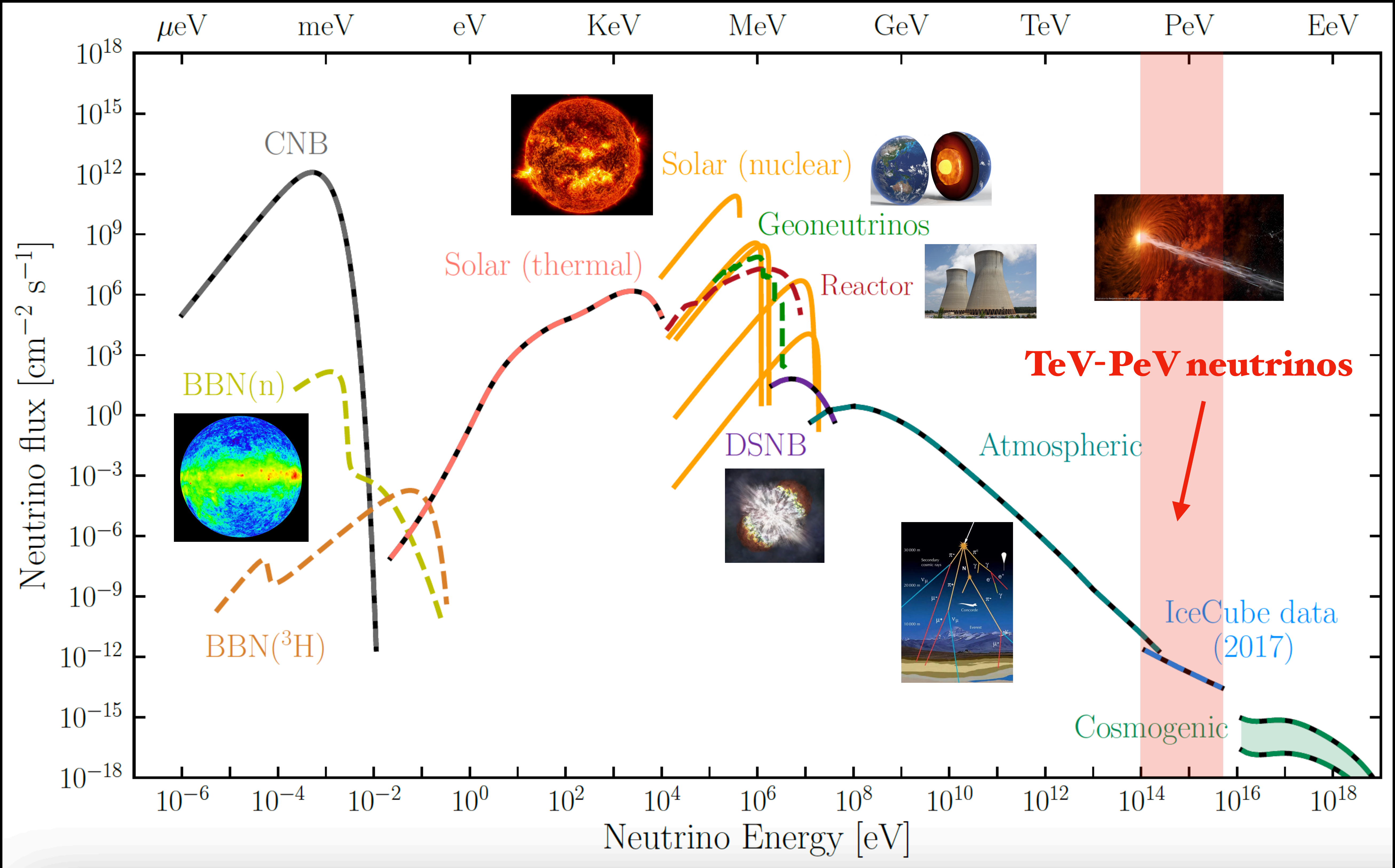
N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries

PHYSICS FRONTIER CENTER

NSF

Grand unified neutrino spectrum

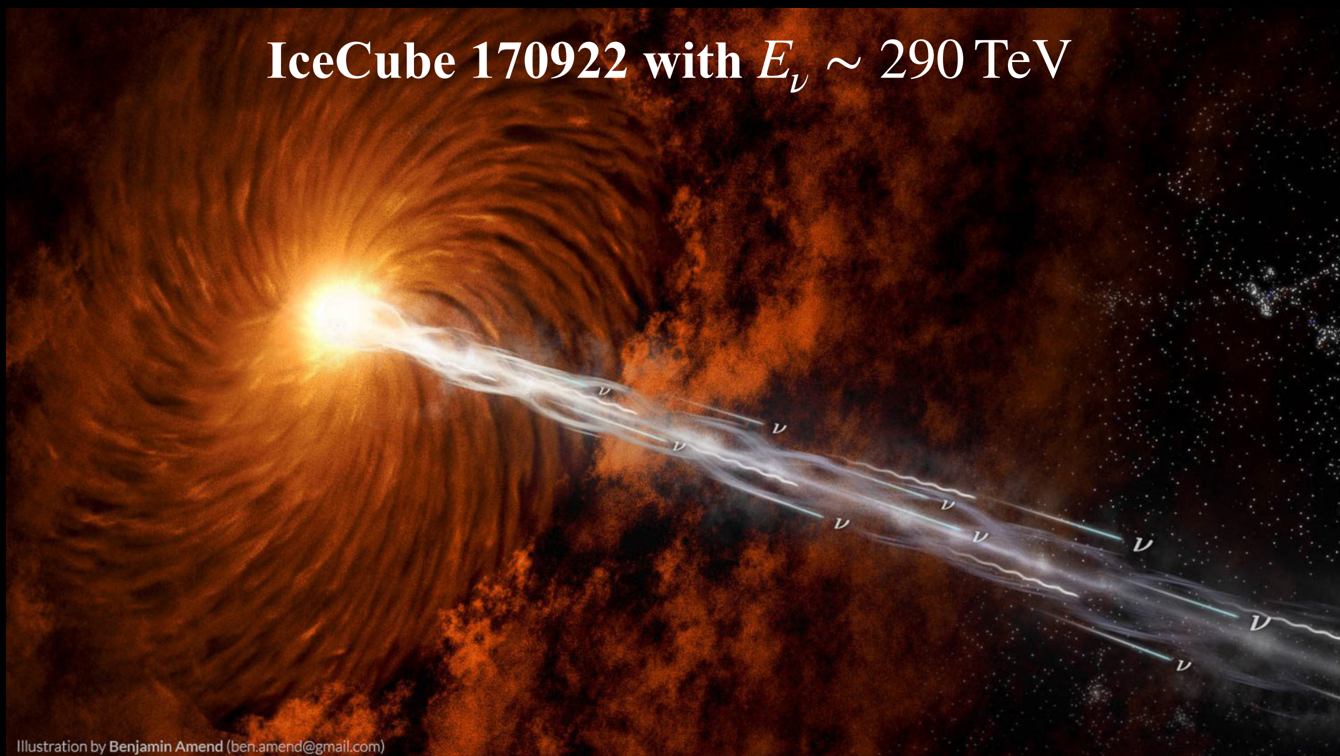


Adapted from E.Vitagliano, I.Tamborra, G.Raffelt Rev.Mod.Phys. 92 (2020)

Detected neutrino sources

Flaring blazar TXS 0506+056 2017

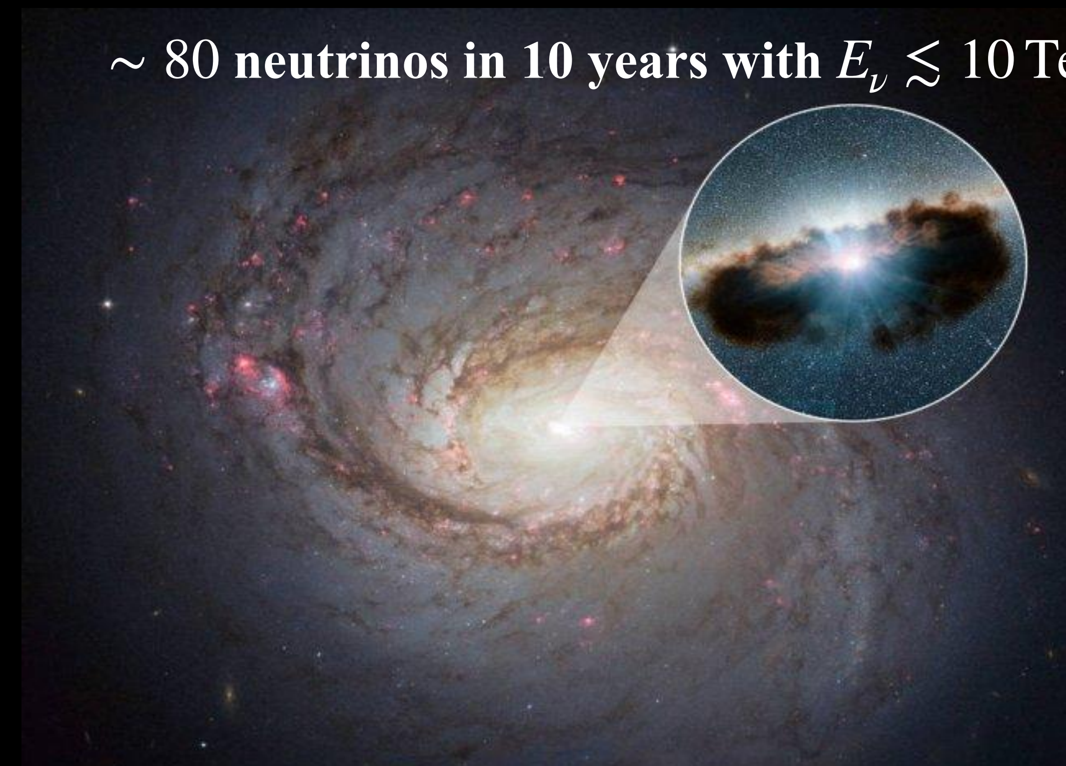
IceCube 170922 with $E_\nu \sim 290$ TeV



Science 361.6398 (2018)

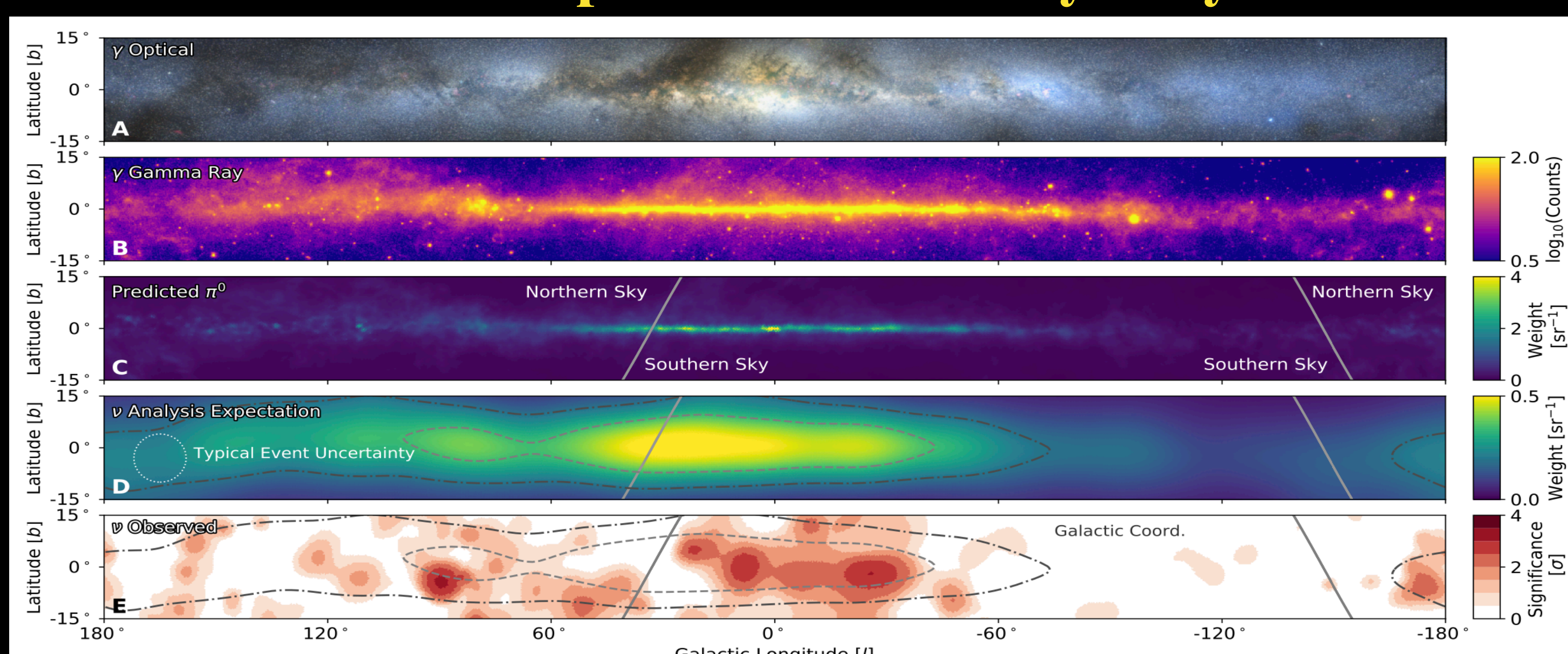
Active galaxy NGC 1068 2022

~ 80 neutrinos in 10 years with $E_\nu \lesssim 10$ TeV



Science 378.6619 (2022)

Galactic plane of the Milky Way 2023



Science 380 6652 (2023)

Many candidate sources

Steady sources:

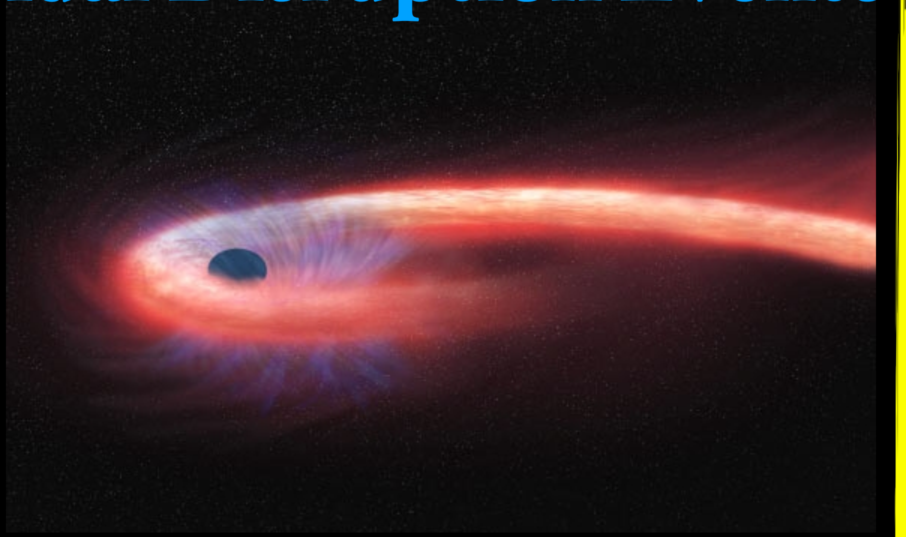
Starburst galaxies

Active Galactic Nuclei

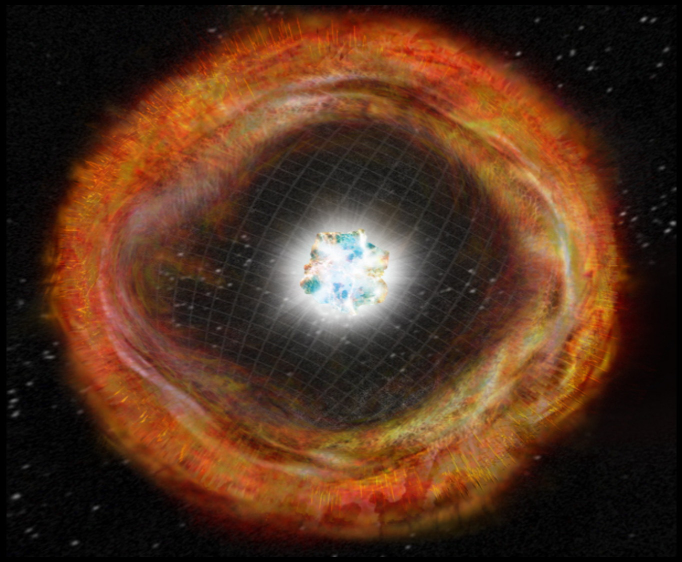
Galaxy Clusters

Transient sources:

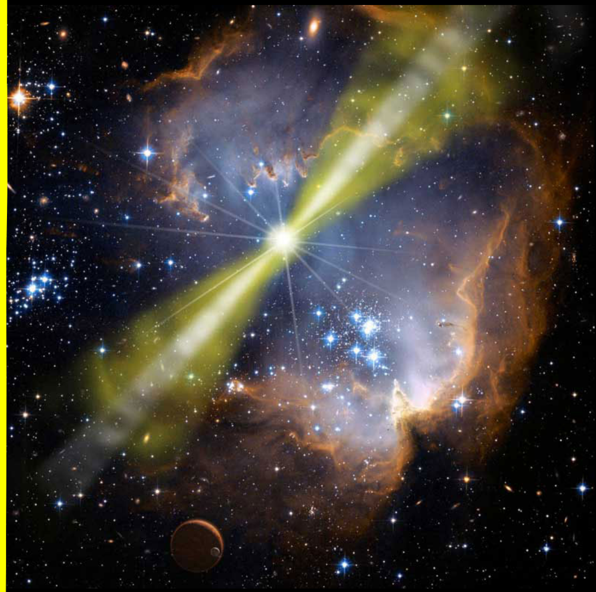
Tidal Disruption Events



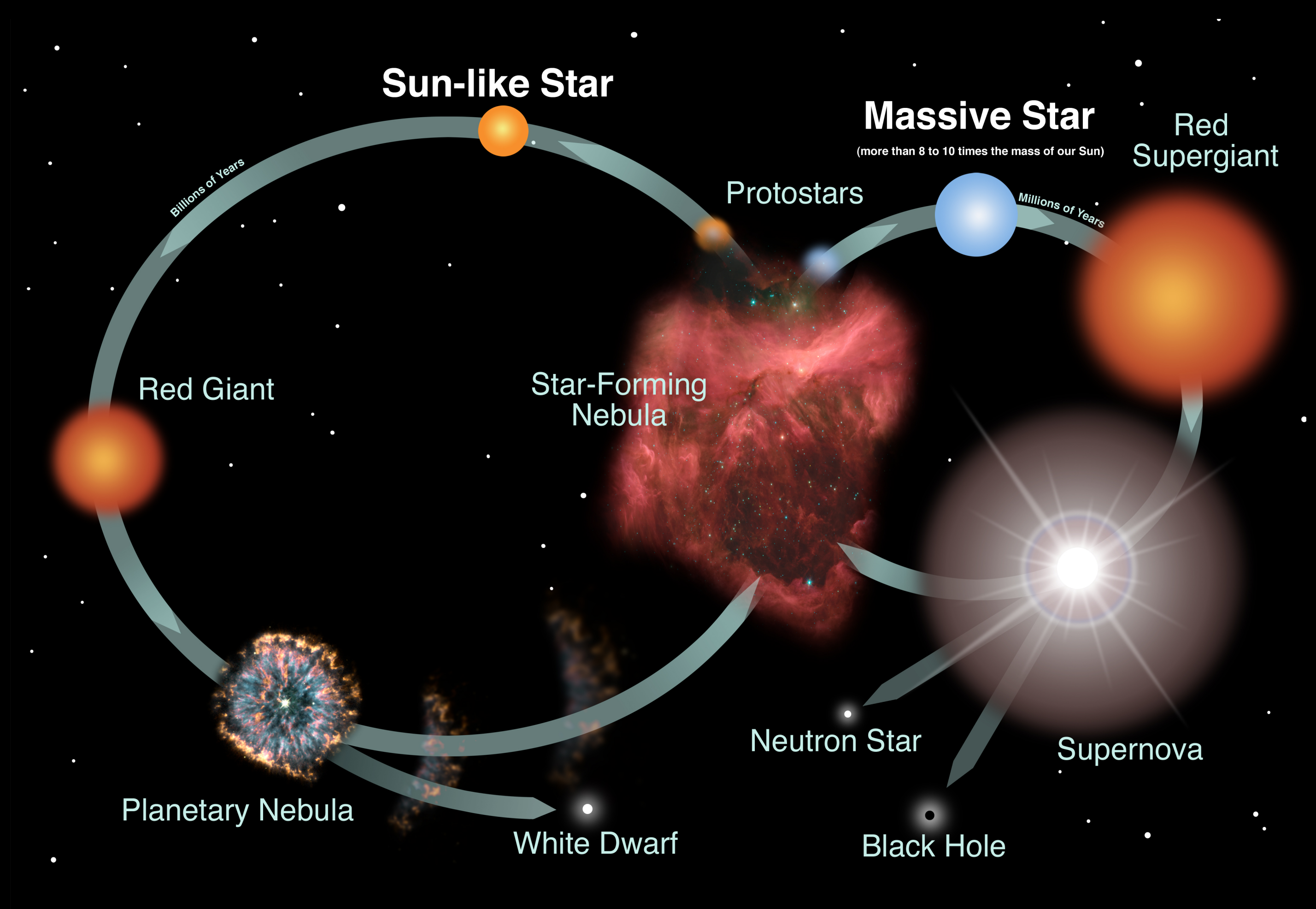
Interaction-powered Supernovae

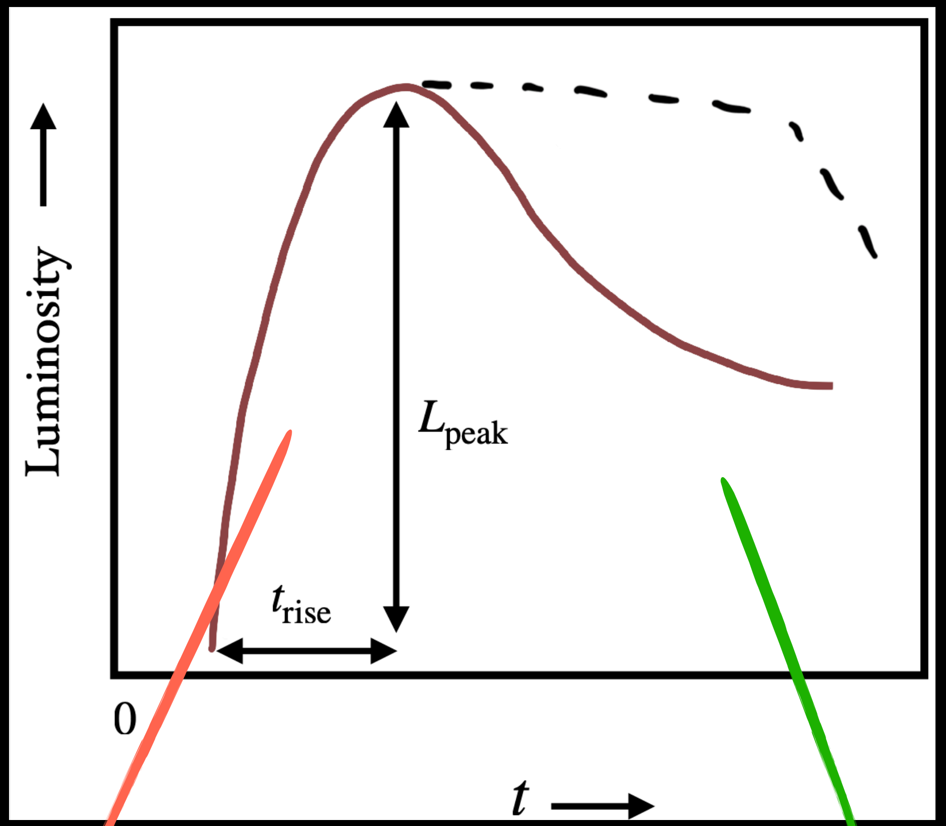


γ-ray bursts



Standard core-collapse supernovae





Cooling of shock-heated ejecta

^{56}Ni radioactive heating

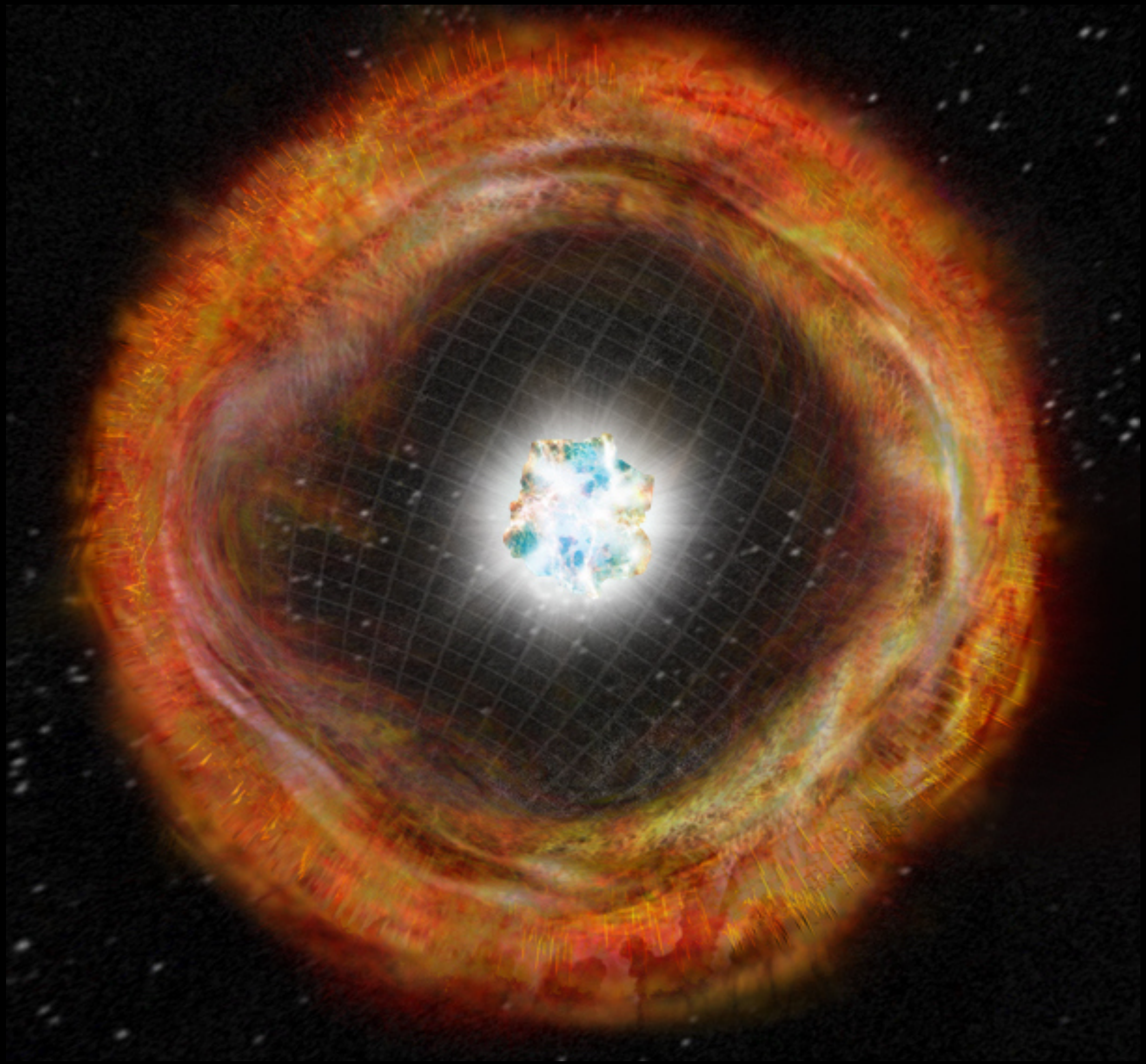
The radiated energy is ~ 1 % of the total ejecta energy

What if the SN explodes inside a circumstellar medium instead of "empty" space?

Interacting supernovae

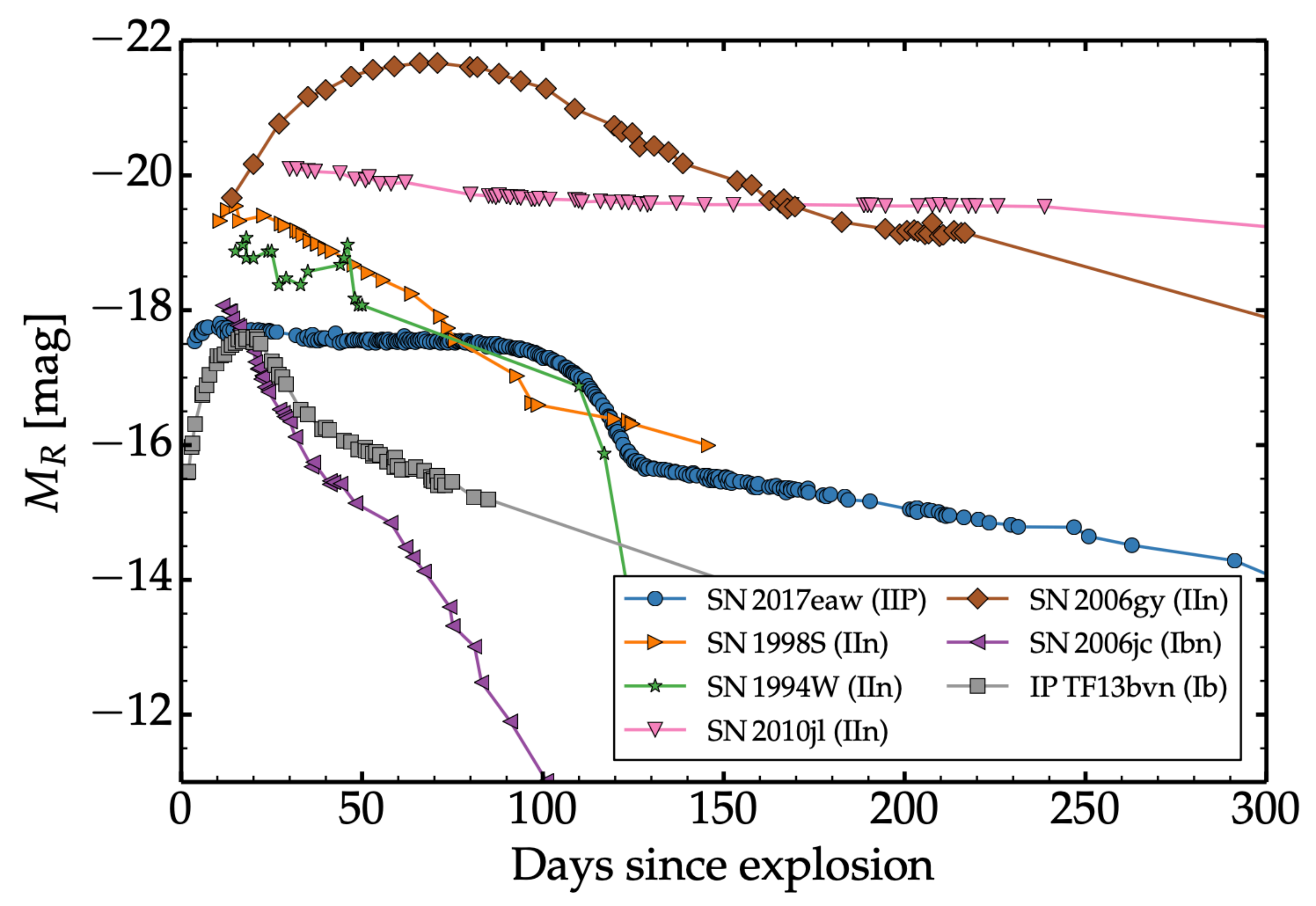
Ejecta are decelerated by the circumstellar medium (CSM)

extraction of kinetic energy → conversion into radiative energy



Interaction-powered supernovae

If the dissipated energy is $\sim 10 - 100$ larger than the standard SNe radiation the lightcurve can be considered completely powered by interaction



Dessart 2024

Power source of superluminous supernovae

Three power source candidates:

Radioactive ^{56}Ni decay

$$^{56}_{28}\mathrm{Ni} \rightarrow {}^{56}_{27}\mathrm{Co} + e^{+} + \nu_e + \gamma$$

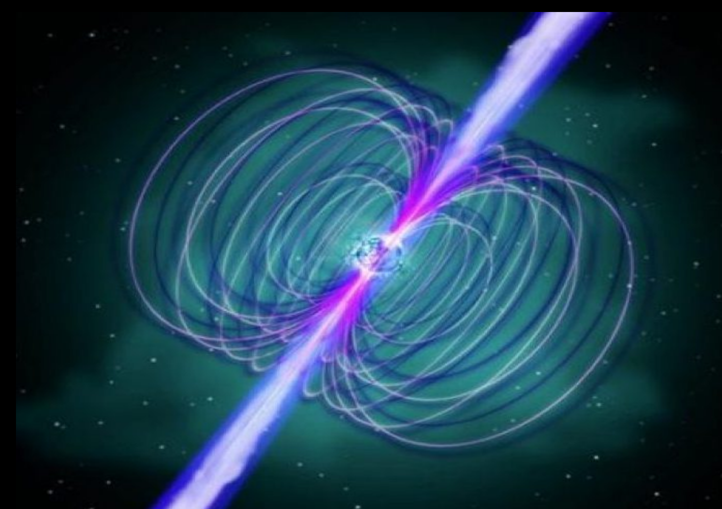
$$^{56}_{27}\mathrm{Co} \rightarrow {}^{56}_{26}\mathrm{Fe} + e^{+} + \nu_e + \gamma$$

1-10 $M_{\odot}$ of ^{56}Ni are required to explain the bright peaks

achievable only in pair-instability SNe

several observations are inconsistent with this model. Can only be adopted for few SLSN I

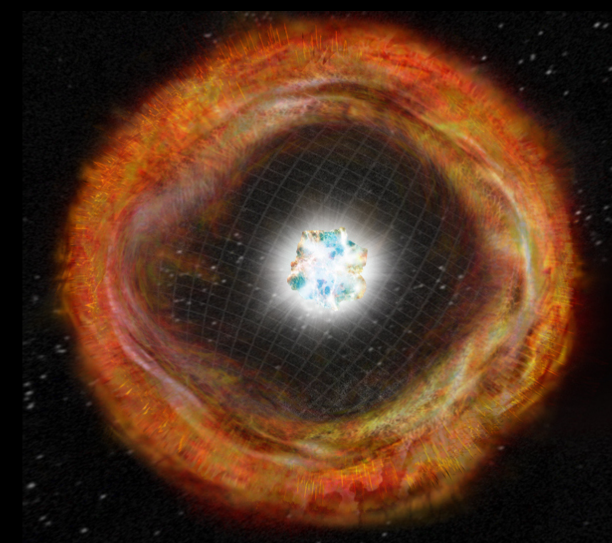
Magnetar spindown



energy input from ms magnetar spindown

good candidate for SLSN I and SLSN II

Strong CSM interaction

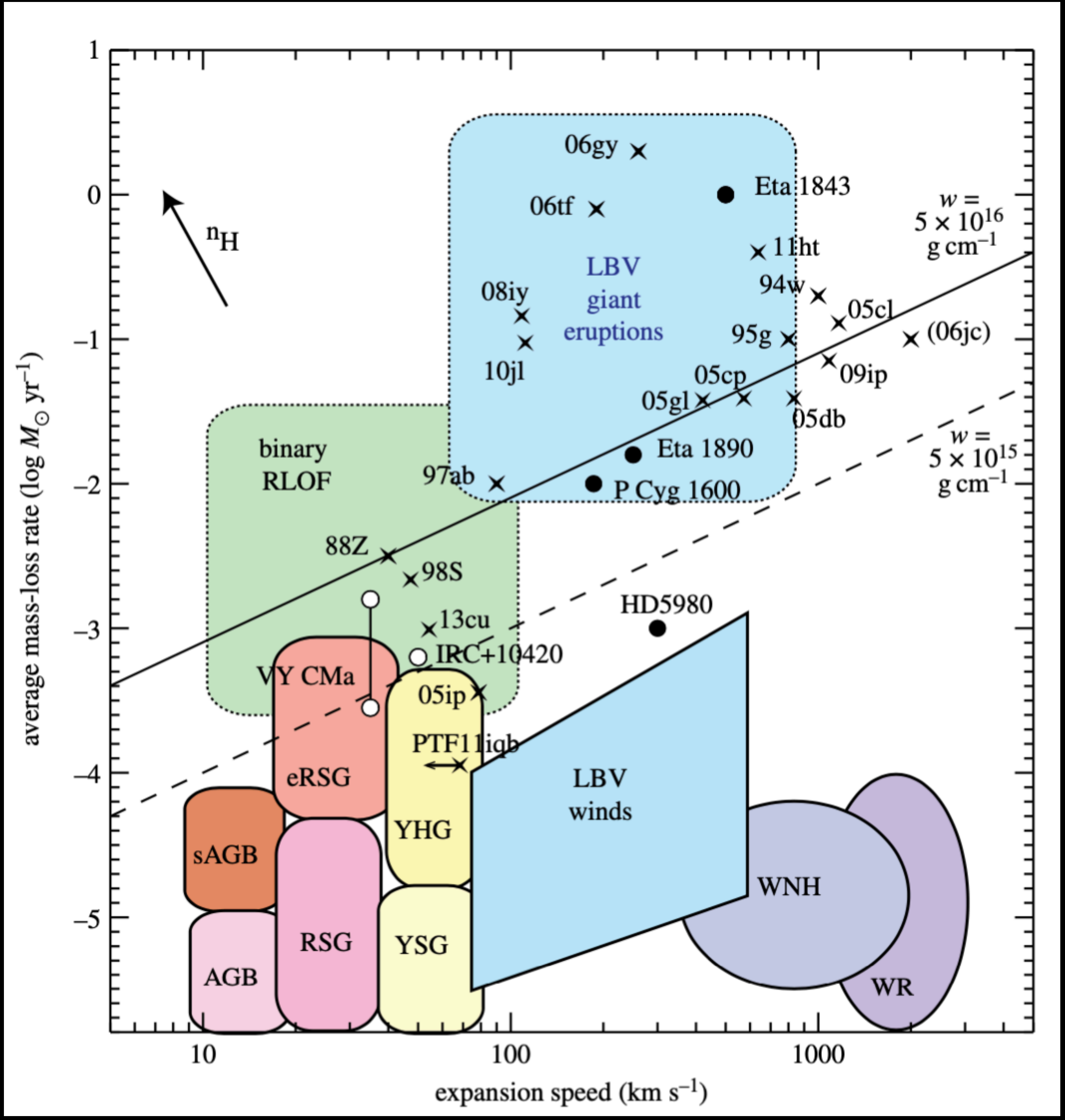


energy input from shock interaction with circumstellar medium

good candidate for Type IIn SN and SLSN, with strong narrow lines in the spectra

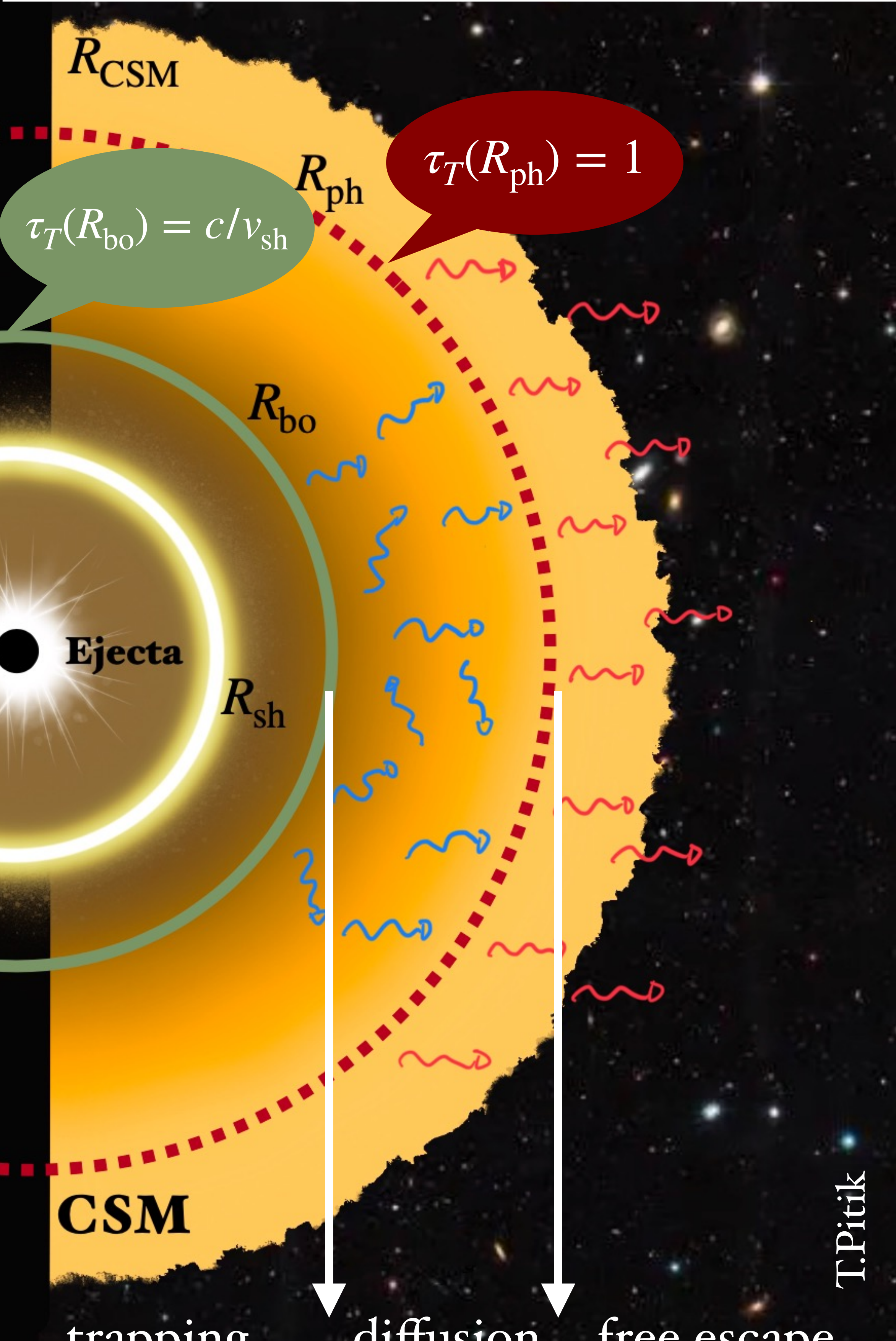
Origin of the circumstellar medium

Steady winds or short-lived episodes of mass loss

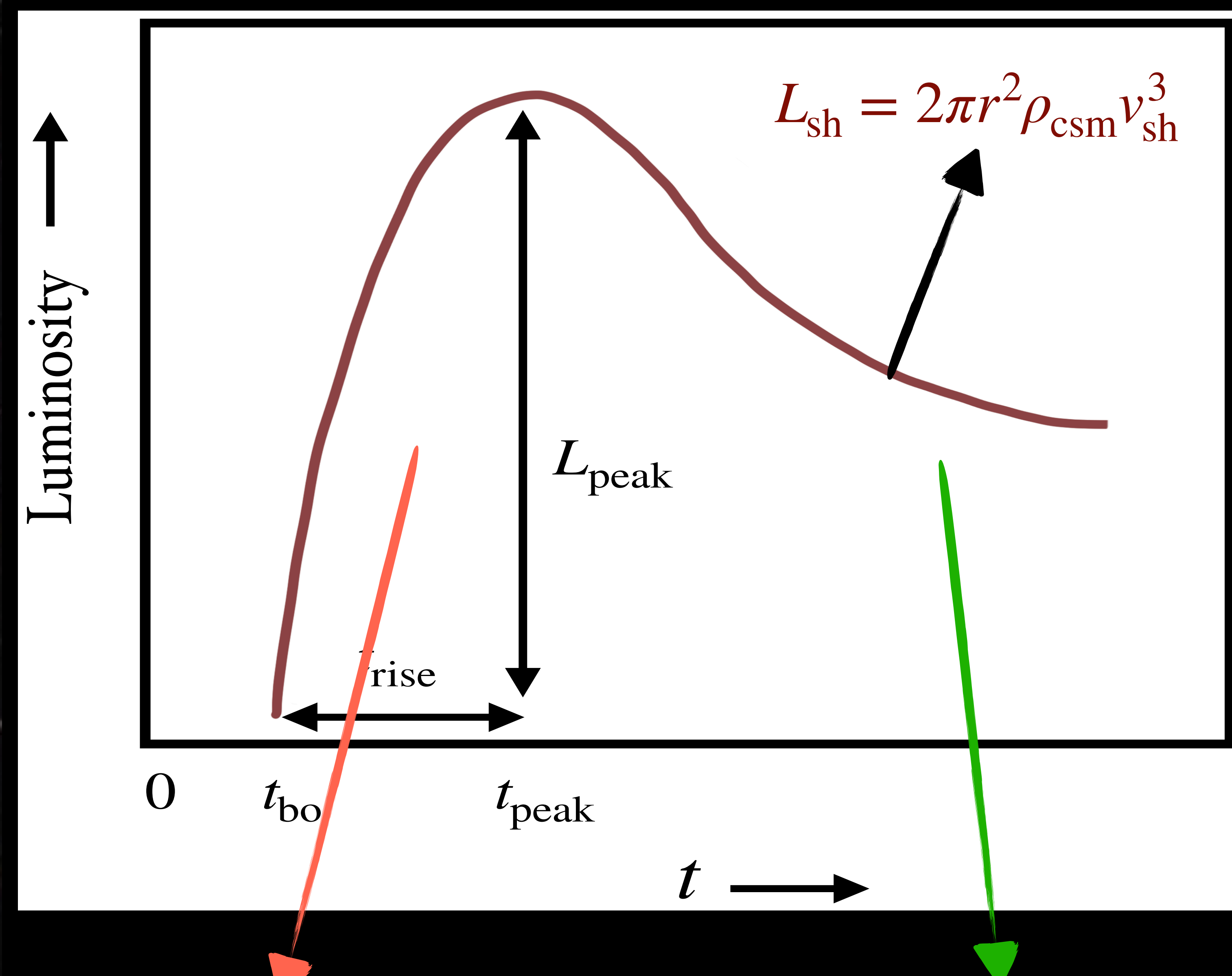


The progenitor and the precise mechanism of mass ejection prior to explosion remain an open question

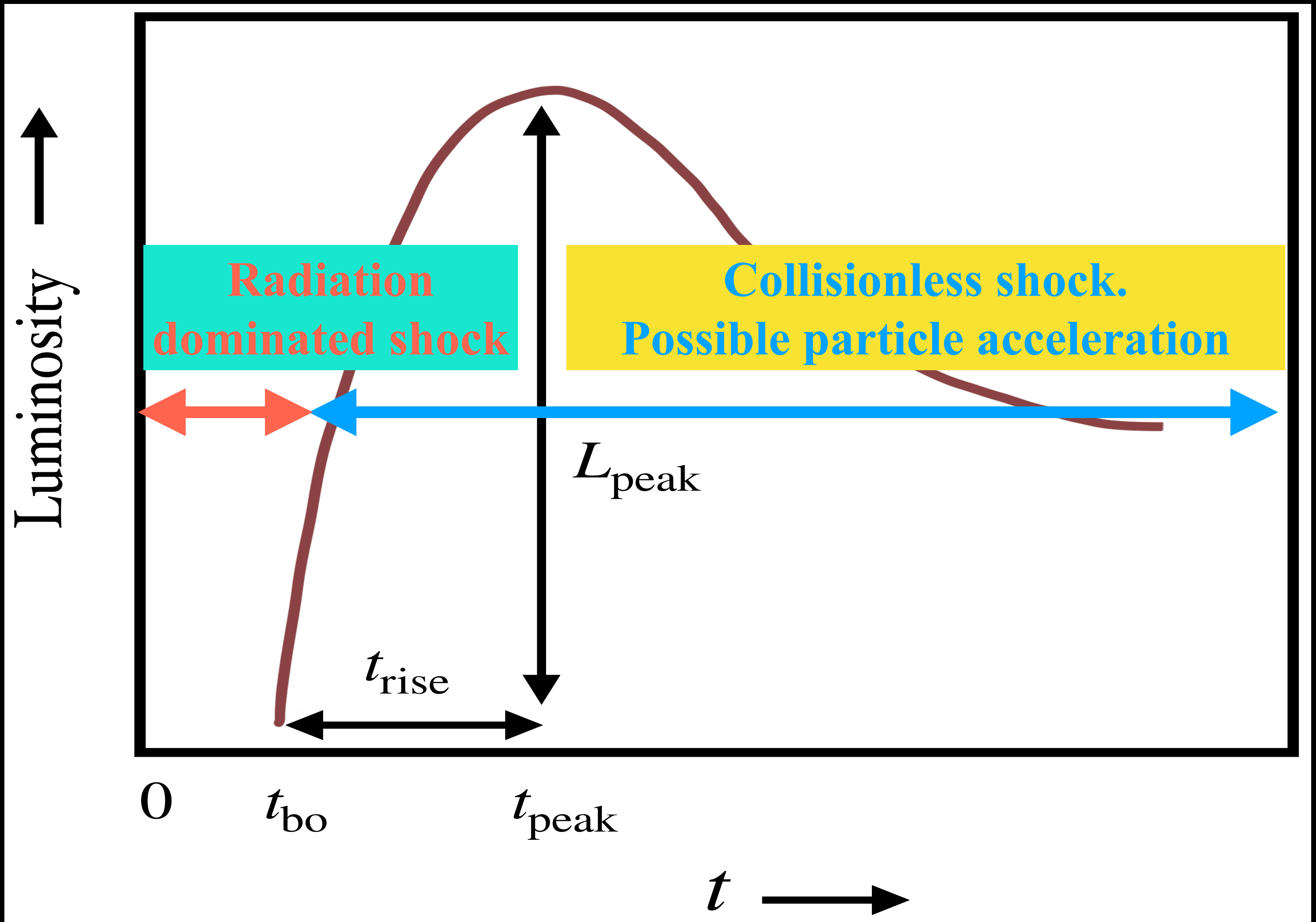
Bolometric ligthcurve from interaction-powered SNe



keV photons are reprocessed into UV-Optical band for $R_{bo} < R < R_{ph} \implies L_{optical} \sim L_{bolometric}$ for dense CSM



Multimessenger emission



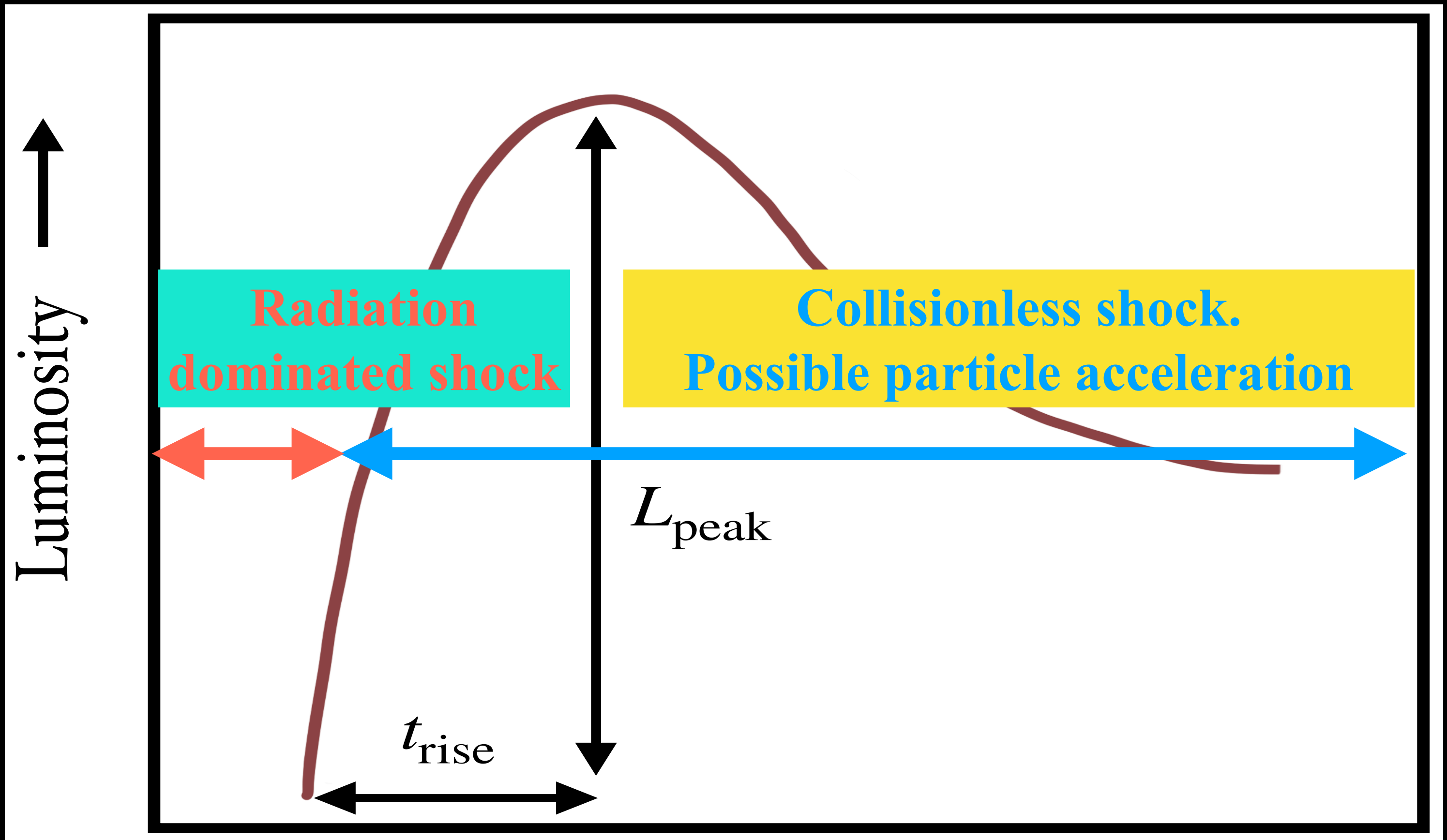
- Thermal X-rays from shocked plasma reprocessed into UV-Optical
- Non-thermal X-rays and radio from synchrotron of accelerated e^-
- γ-rays from e^- IC and π^0 decay
- **Neutrinos** from hadronic interaction of accelerated protons

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

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

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

Multimessenger emission



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Is there a connection between neutrino emission and photometric properties like $L_{\rm peak}$ and $t_{\rm rise}$?

- **Neutrinos** from hadronic interaction of accelerated protons

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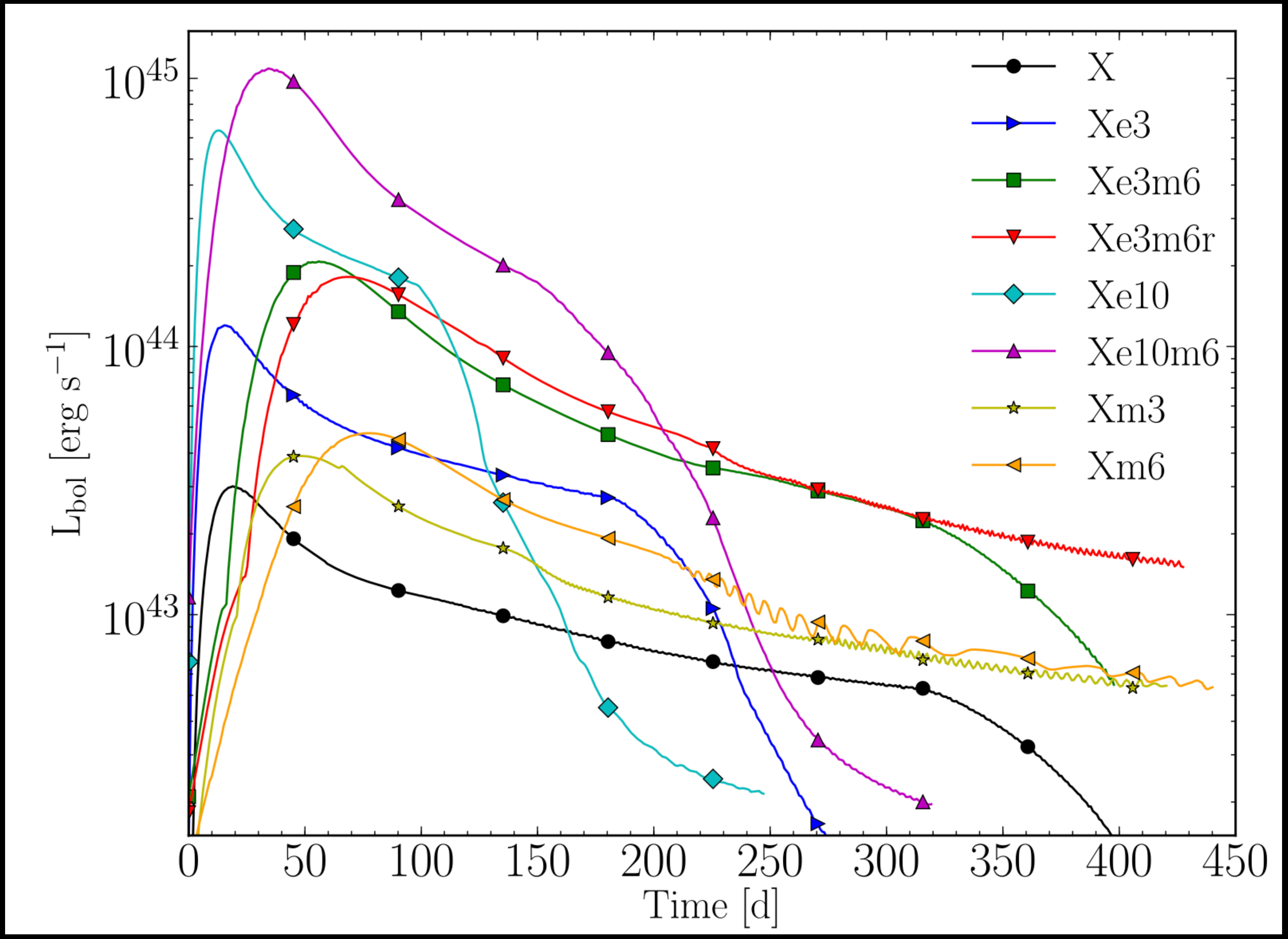
Bolometric ligthcurve properties

Physical parameters that determine the observations:

- ➡ **Ejecta mass**
- ➡ **Kinetic energy of the ejecta**
- ➡ **Ejecta density profile**
- ➡ **CSM mass**
- ➡ **CSM composition**
- ➡ **CSM radial distribution**
- ➡ **CSM geometry**



Dessart et al. 2015

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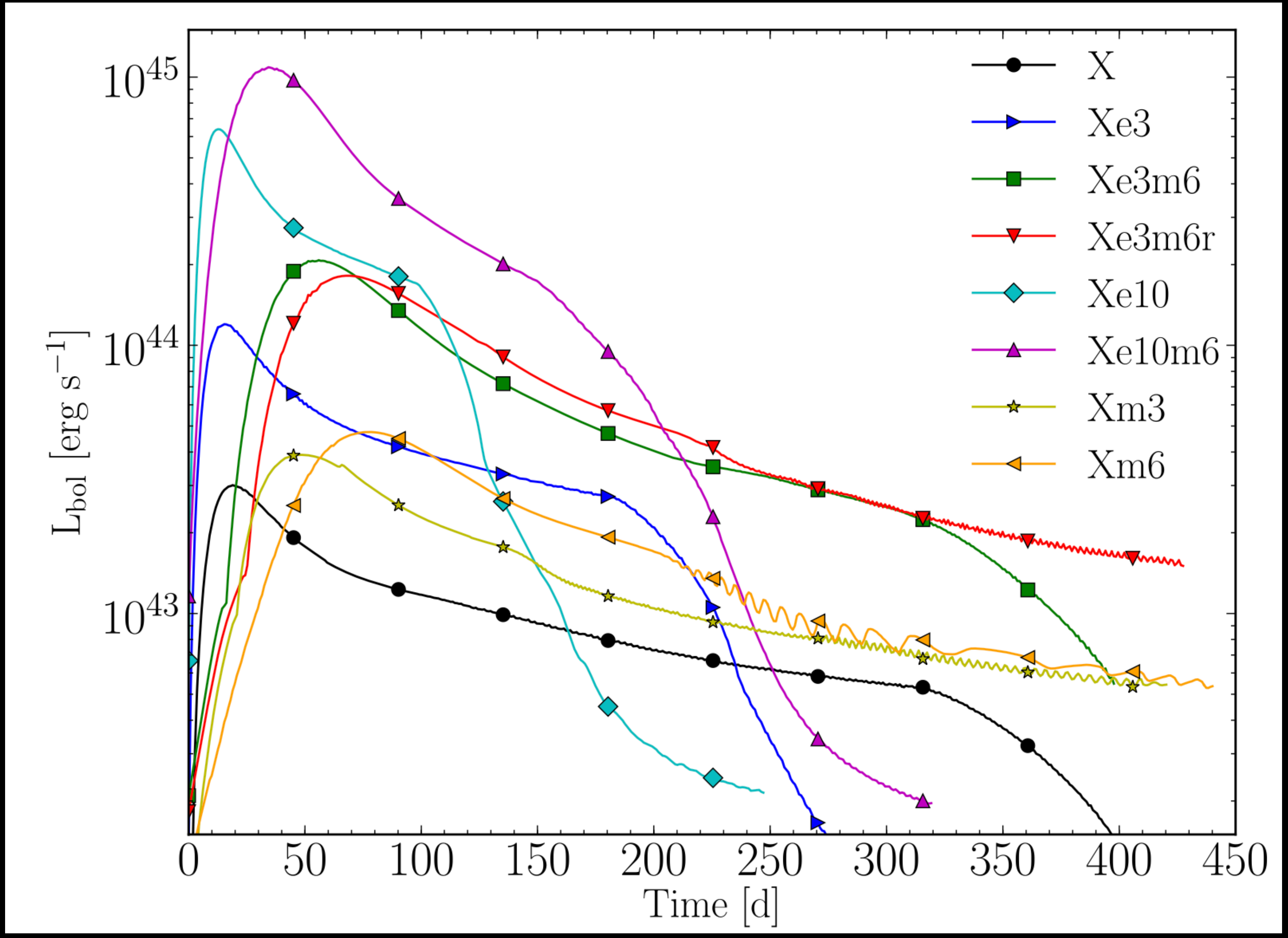
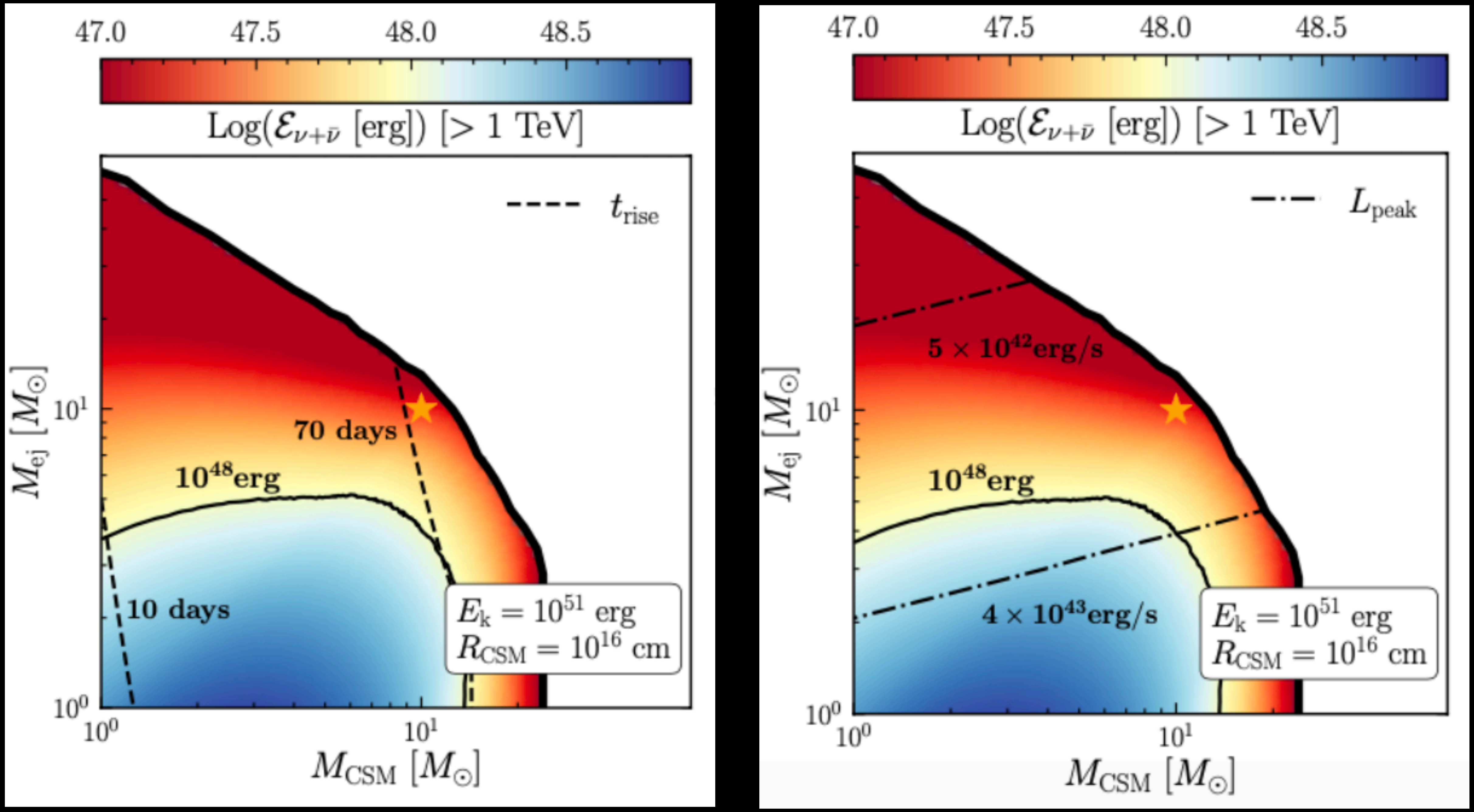


Dessart et al. 2015

Neutrino energetics as a function of SN parameters



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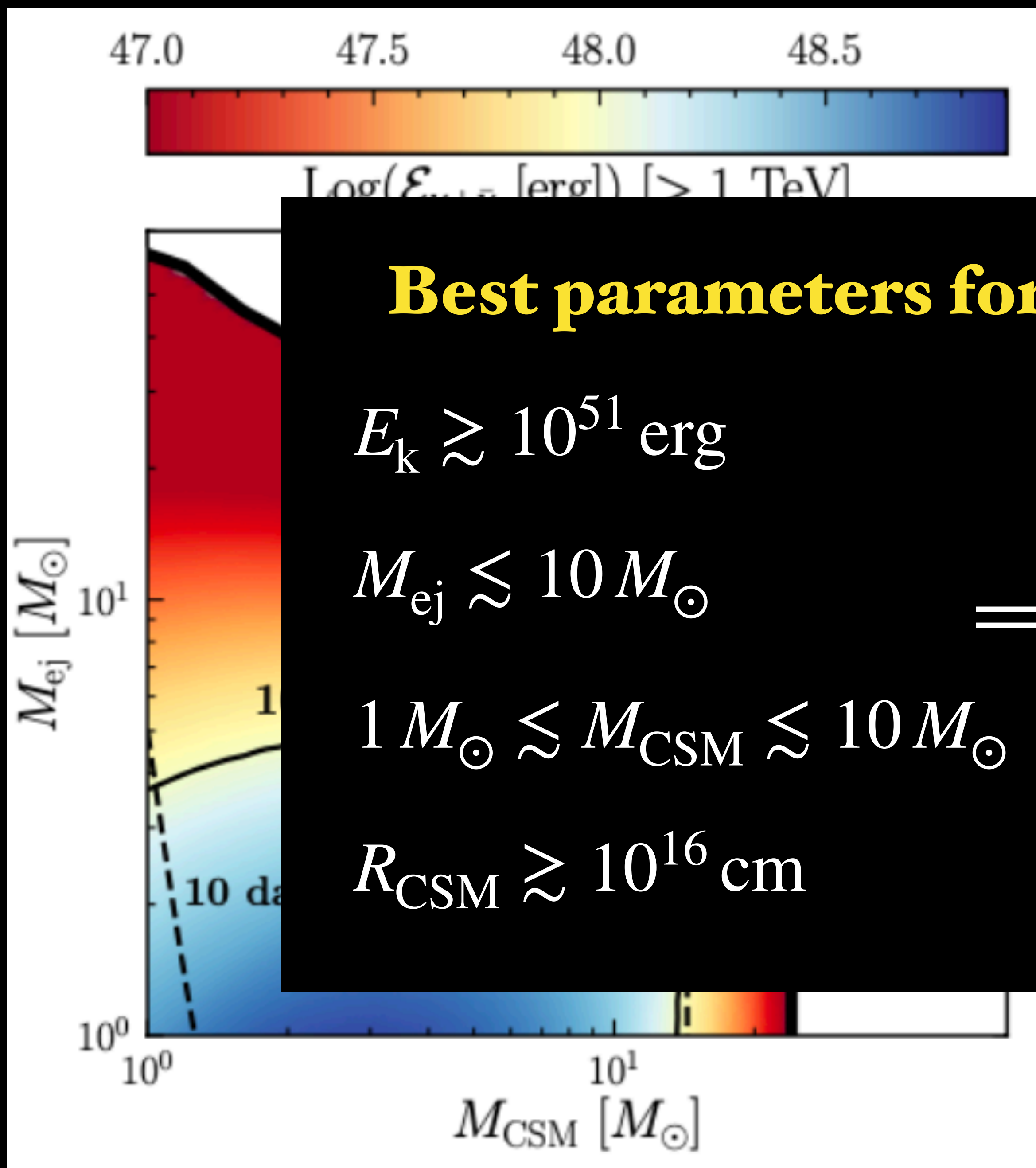
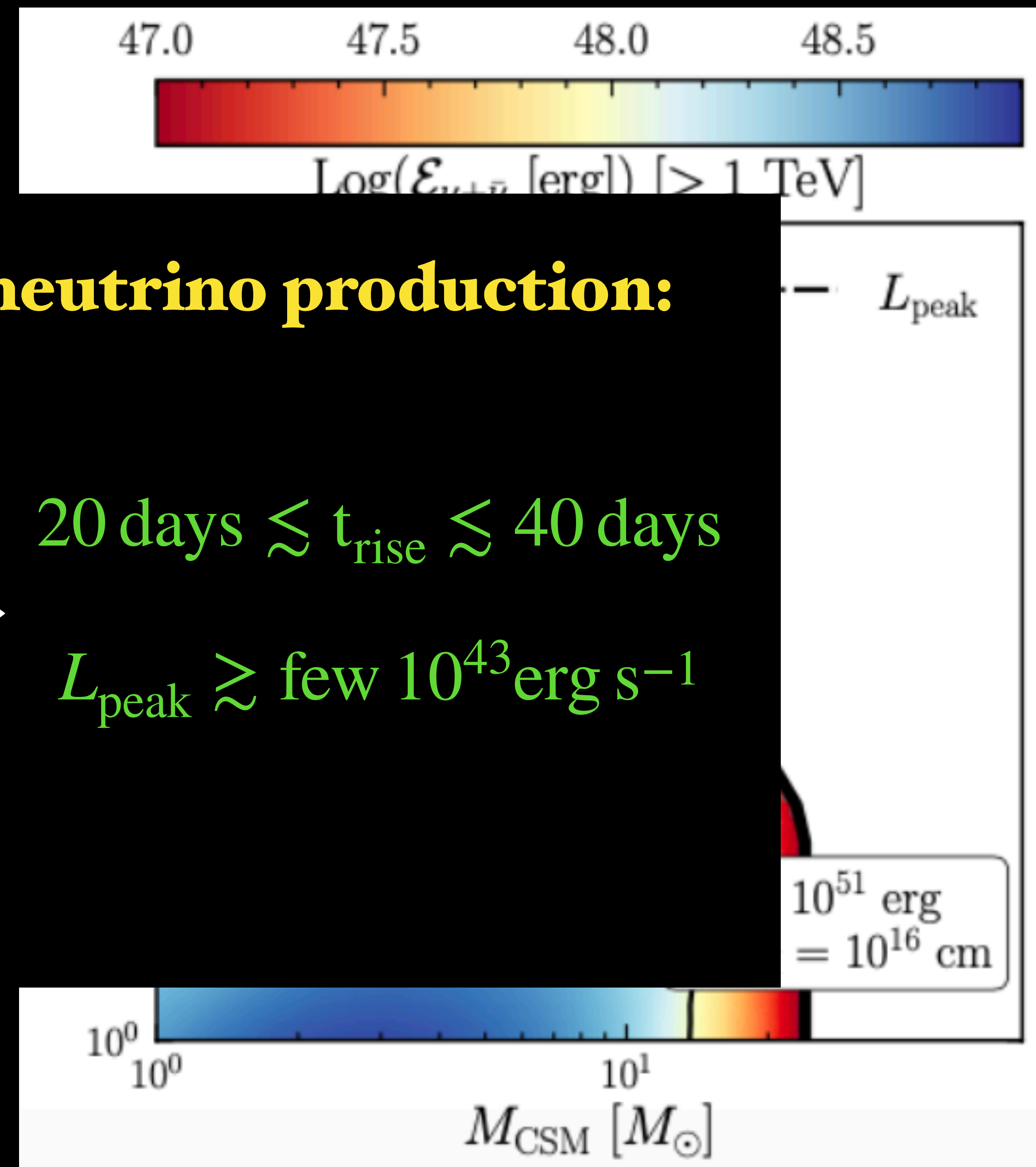
Neutrino energetics as a function of SN parameters: wind scenario





Best parameters for neutrino production:

$E_k \gtrsim 10^{51}$ erg

$M_{ej} \lesssim 10\, M_\odot$

$1\, M_\odot \lesssim M_{CSM} \lesssim 10\, M_\odot$

$R_{CSM} \gtrsim 10^{16}$ cm

$\Longrightarrow$

20 days $\lesssim t_{rise} \lesssim$ 40 days

$L_{peak} \gtrsim$ few 10^{43} erg s^{-1}

necessary but not sufficient → **Spectroscopic and multiwavelength observations are needed**

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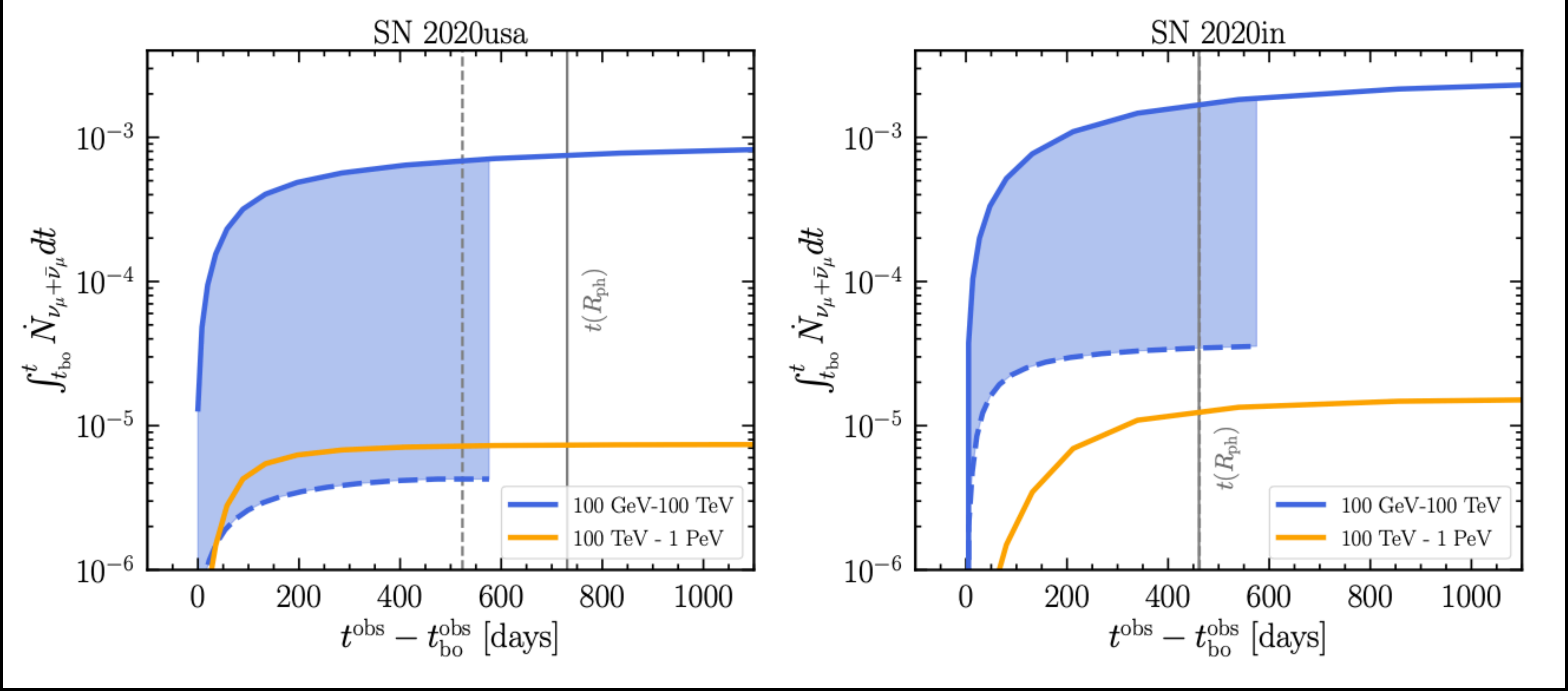
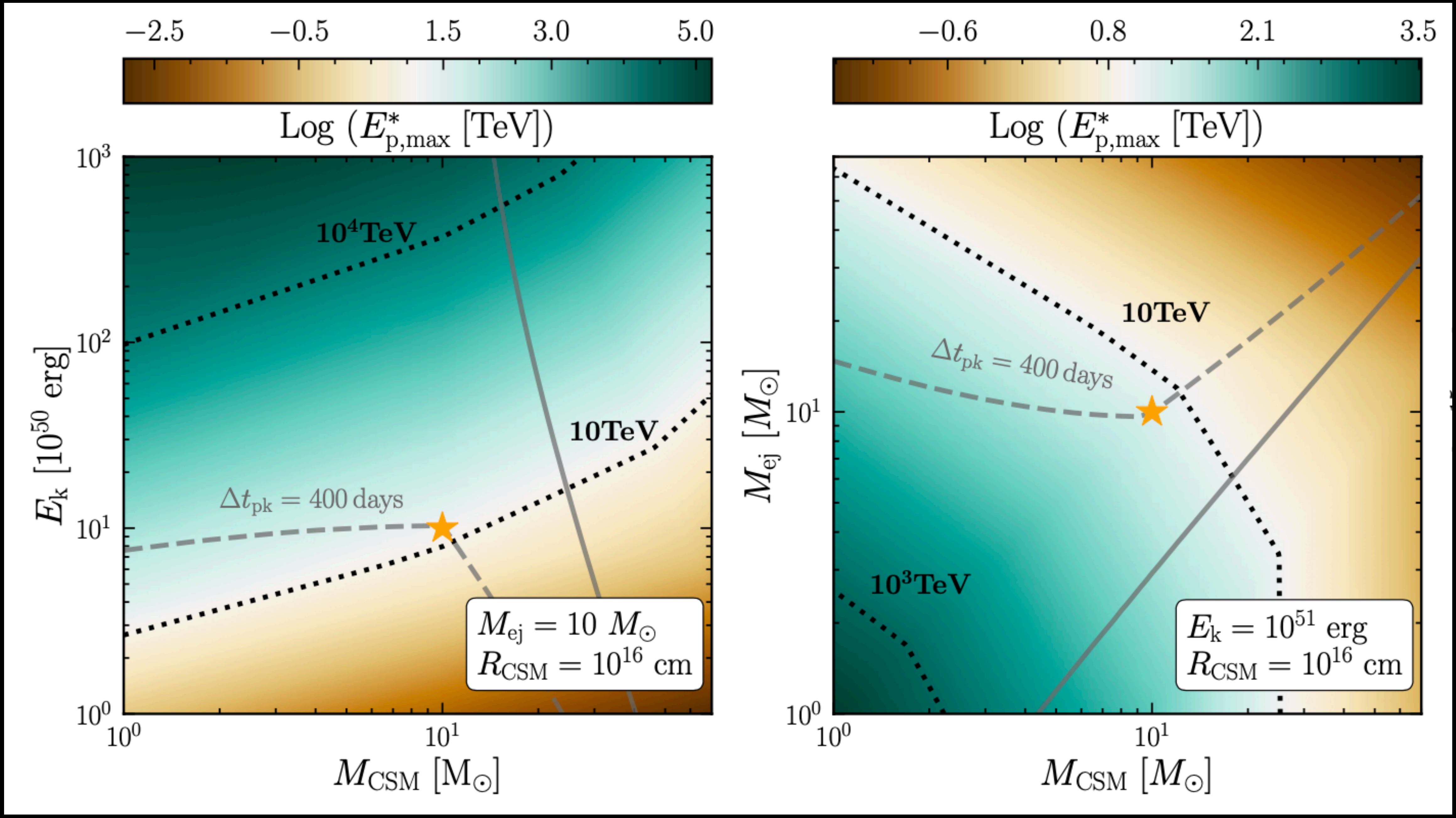
Two of the brightest SLSNe detected by the ZTF

	Redshift	$t_{\text{rise, obs}}$ (d)	$L_{\text{peak, obs}}$ (erg s^{-1})	$E_{\text{rad, obs}}$ (erg)	$t_{\text{dur, obs}}$ (d)	Declination (°)
SN 2020usa	0.26	65	8×10^{43}	1.3×10^{51}	350	−2.3
SN 2020in	0.11	42	3×10^{43}	3.3×10^{50}	413	20.2

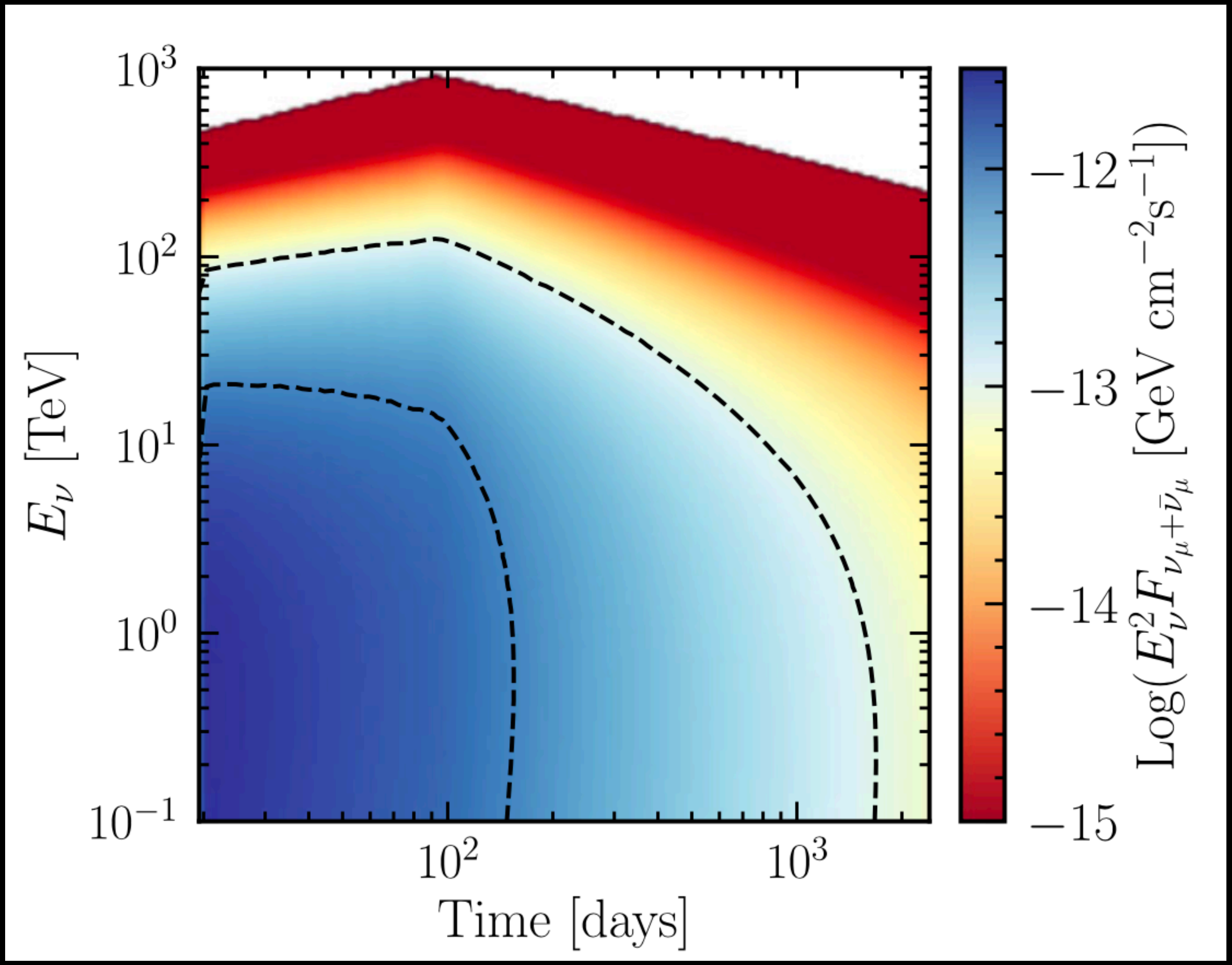


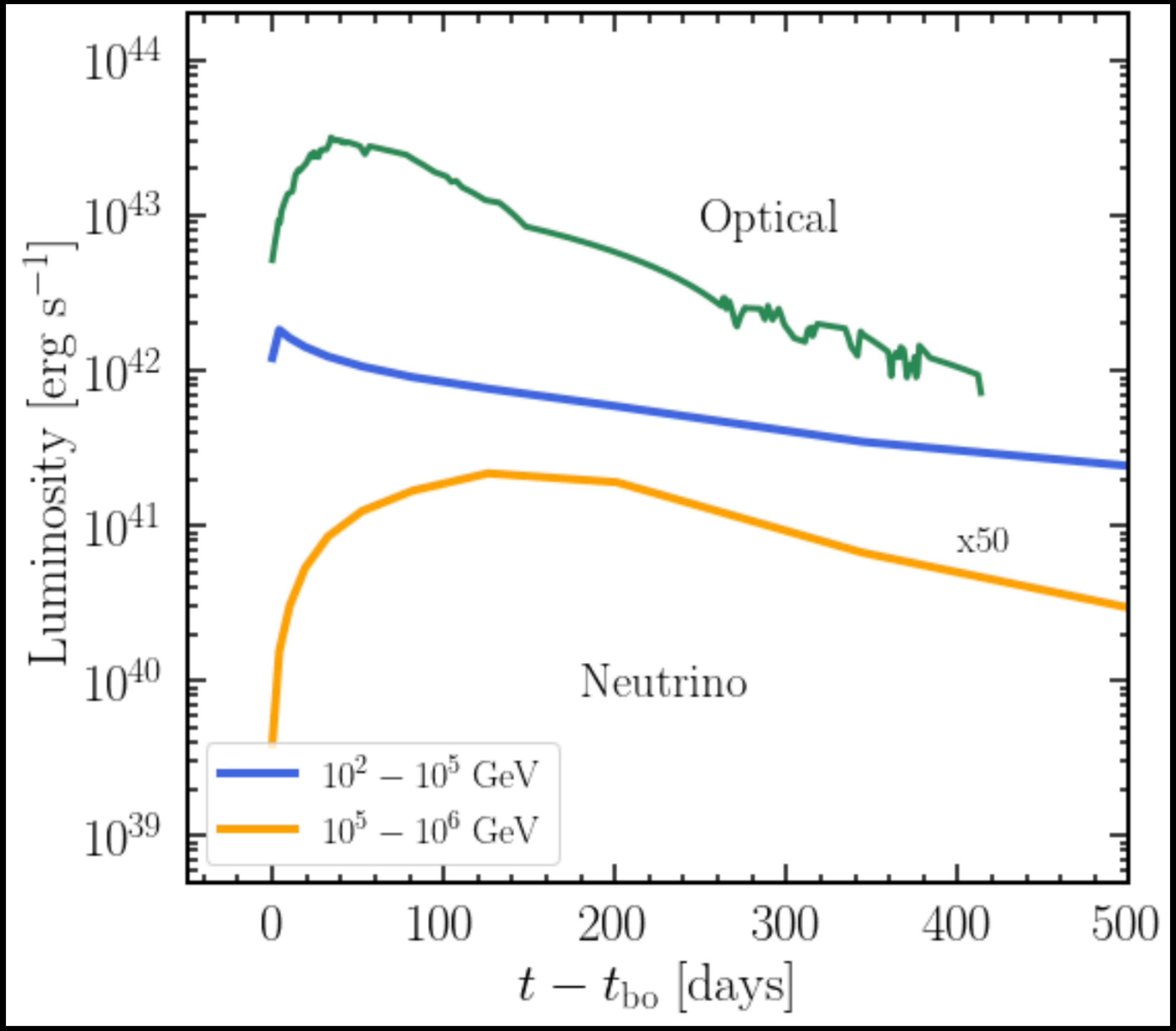
Maximum particle energy in radiative shocks



Peak of neutrino emission

SN2020usa, the brightest in ZTF catalog





The peak of high-energy neutrinos is $\sim \mathcal{O}(100\,\text{days})$ after the optical peak

➡ **the temporal window can be optimized to reduce the background**

Follow-up strategy for neutrino searches

The search for neutrinos from a source class is most sensitive when a stacking of all sources is applied

The stacking requires a weighting of the sources relative to each other

Previous searches:

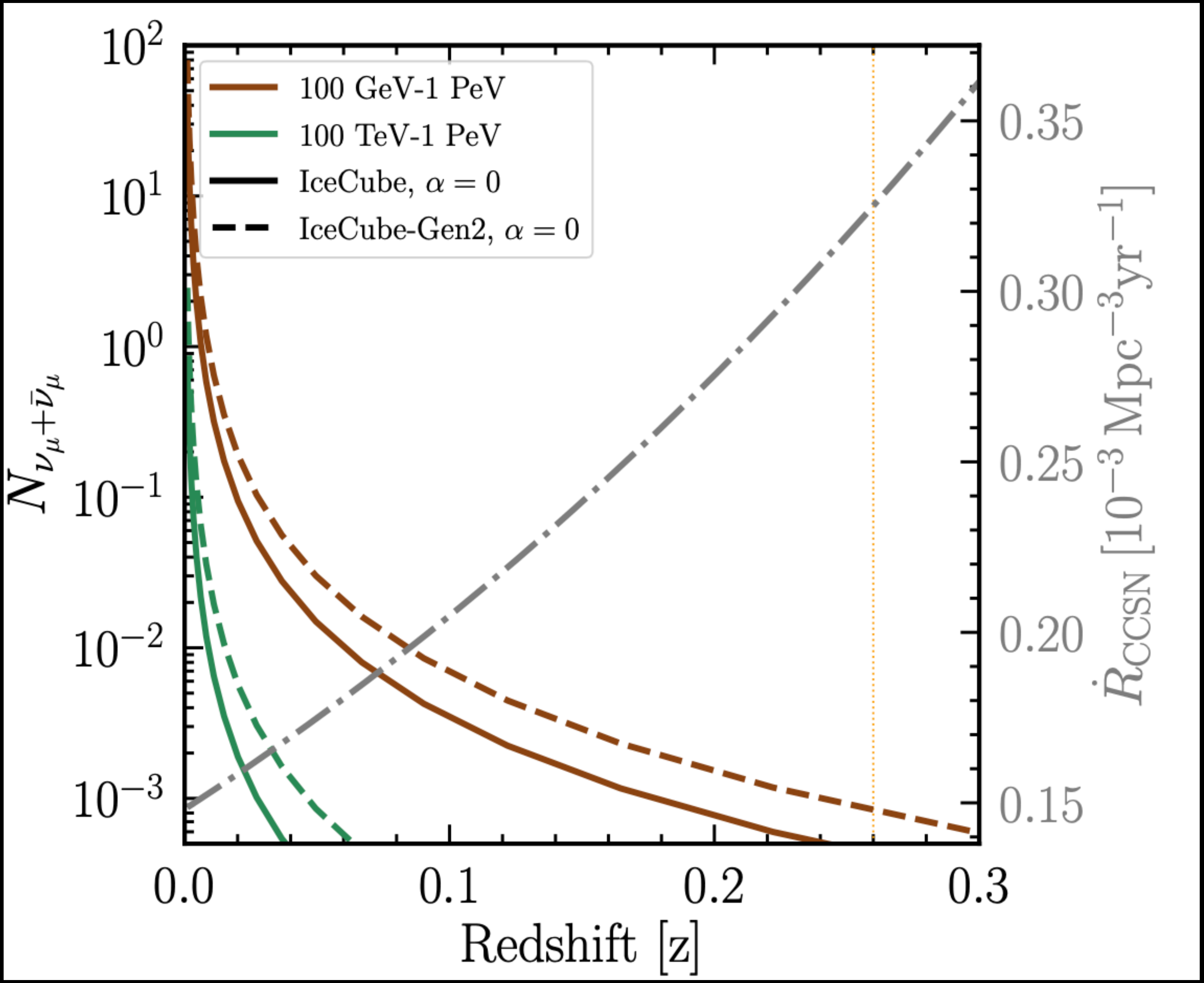
1. **assumed that all SNe are standard candles**
2. **used the optical peak flux as a weight**

Our work shows that neither of these methods is justified

The degeneracy in the parameters can be eliminated with complementary multiwavelength and spectroscopic observations

The temporal window for neutrino searches can be optimized to reduce the background

Expected neutrinos per SN as a function of redshift



$N_{\nu_\mu+\bar{\nu}_\mu} \gtrsim 10$ for $d_{\rm L} \lesssim 9\,(13)$ Mpc for IceCube (IceCube-Gen2)

Summary

High-energy neutrinos from interaction-powered SNe

➡ **Are efficiently produced in SNe events with:**

$L_{\rm peak} \gtrsim (10^{43} - 10^{44}) {\rm erg\, s^{-1}}$
$t_{\rm tise} \gtrsim (10 - 40)$ days
→ **necessary but not sufficient** → **Spectroscopic and multiwavelenght observations are needed**

➡ **The neutrino peak is delayed with respect to the optical peak by** $\mathcal{O}(100\ {\rm days})$

➡ **Point sources can be observable with high significance only for** $d_{\rm L} \lesssim 10$ Mpc

➡ **A detection would confirm the mechanism powering luminous SNe and help constrain the SN parameters**

➡ **Neutrino observations would probe the physics of particle acceleration in radiative shocks**

Thank you for the attention !!!