High-energy Neutrino Emission from Interaction-powered Supernovae

Tetyana Pitik

Niels Bohr Institute & DARK
INFN, Università di Perugia

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CARLSBERG FOUNDATION

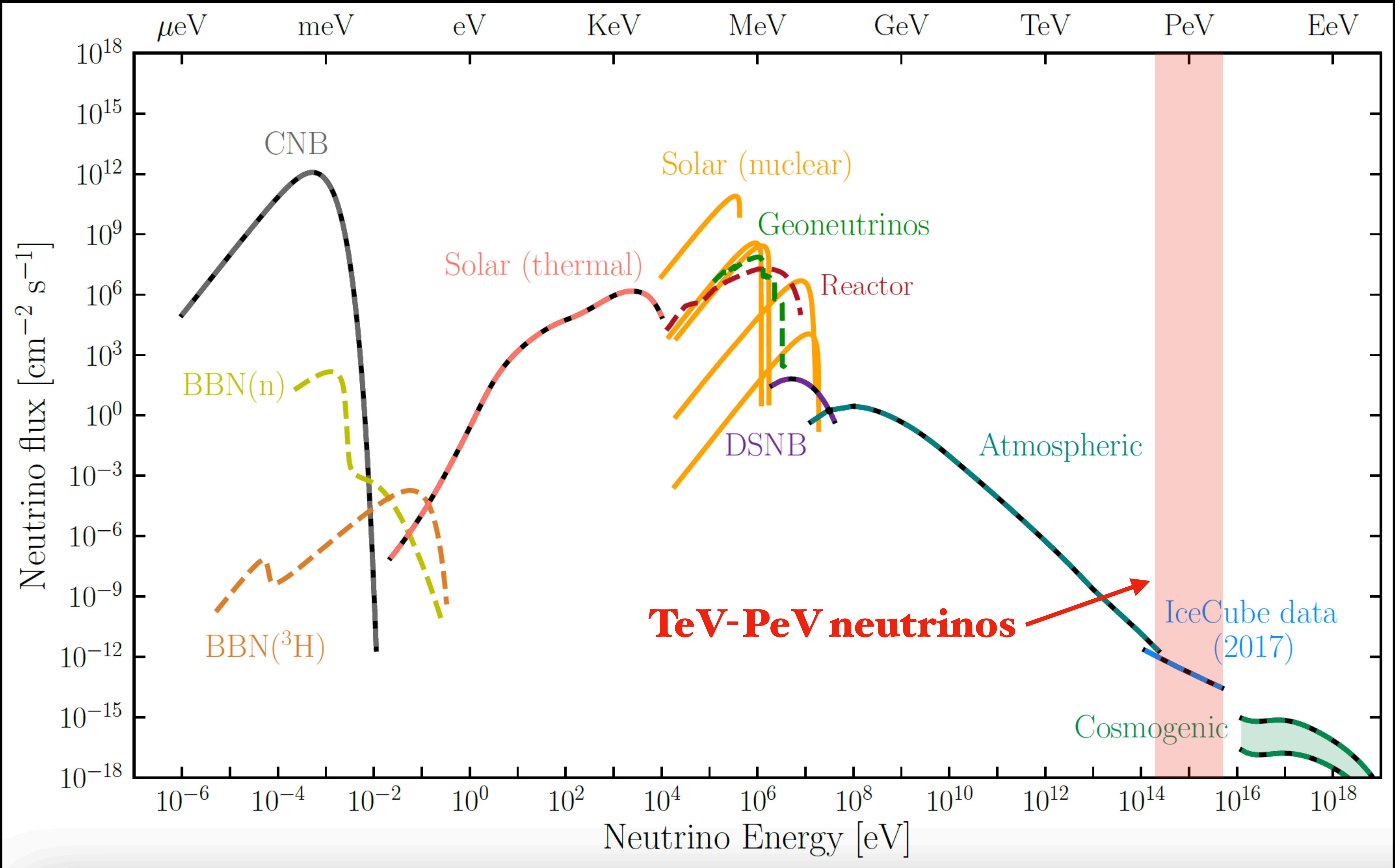
OUTLINE

- H-rich (superluminous) supernovae
- High-energy neutrinos from interaction-powered supernovae

This talk is based on:

T.Pitik, I.Tamborra, M.Lincetto, A. Franckowiak (MNRAS 524 (2023) 3)

Grand unified neutrino spectrum



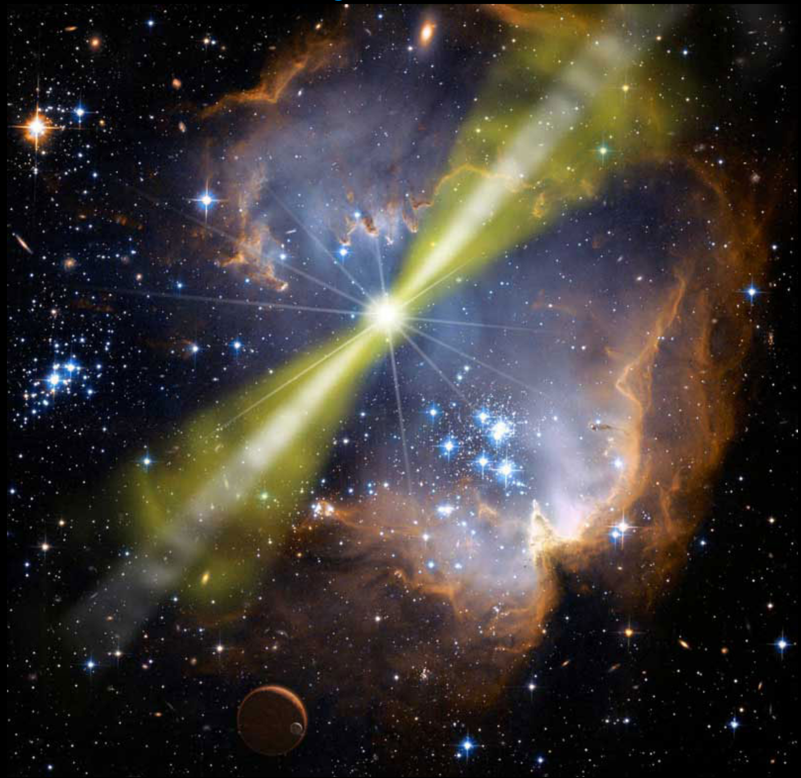
Adapted from E. Vitagliano, I. Tamborra, G. Raffelt Rev. Mod. Phys. 92 (2020)

Many candidate sources (steady and transient)

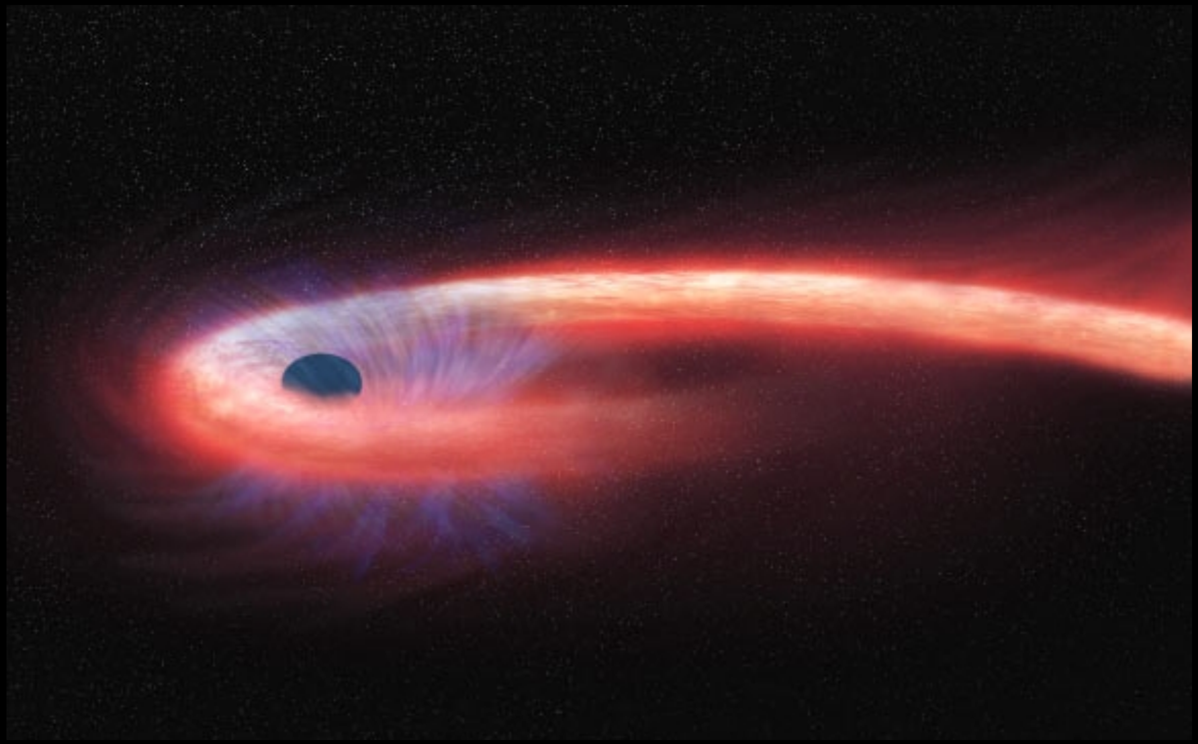
Starburst galaxies

Active Galactic Nuclei

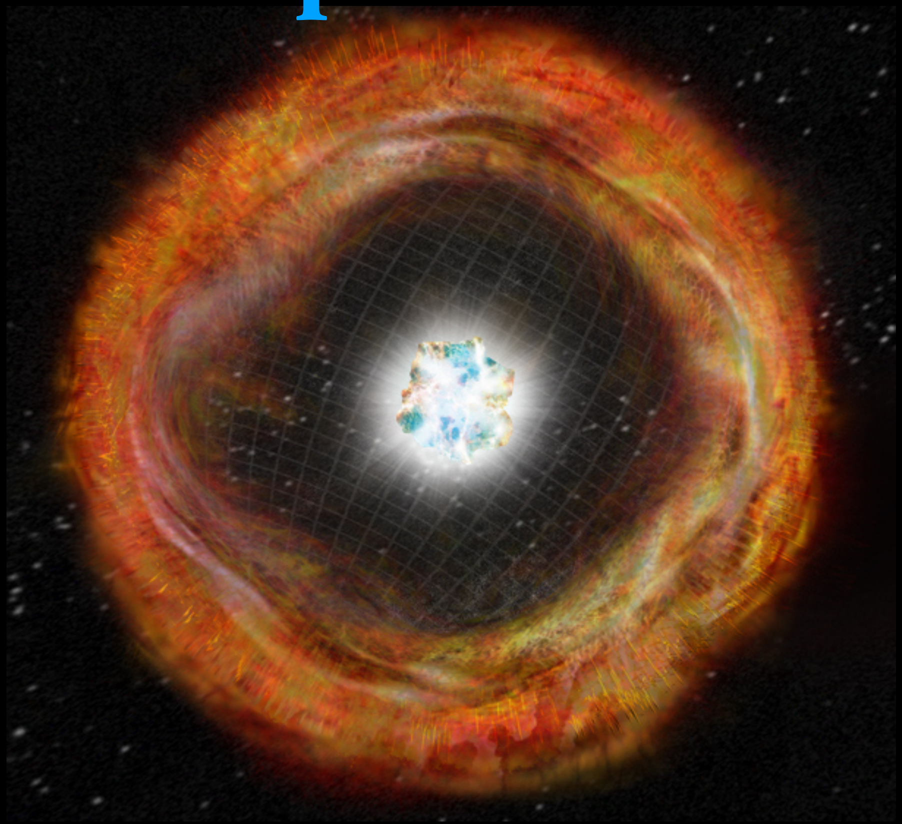
γ-ray bursts



Tidal Disruption Events



Supernovae



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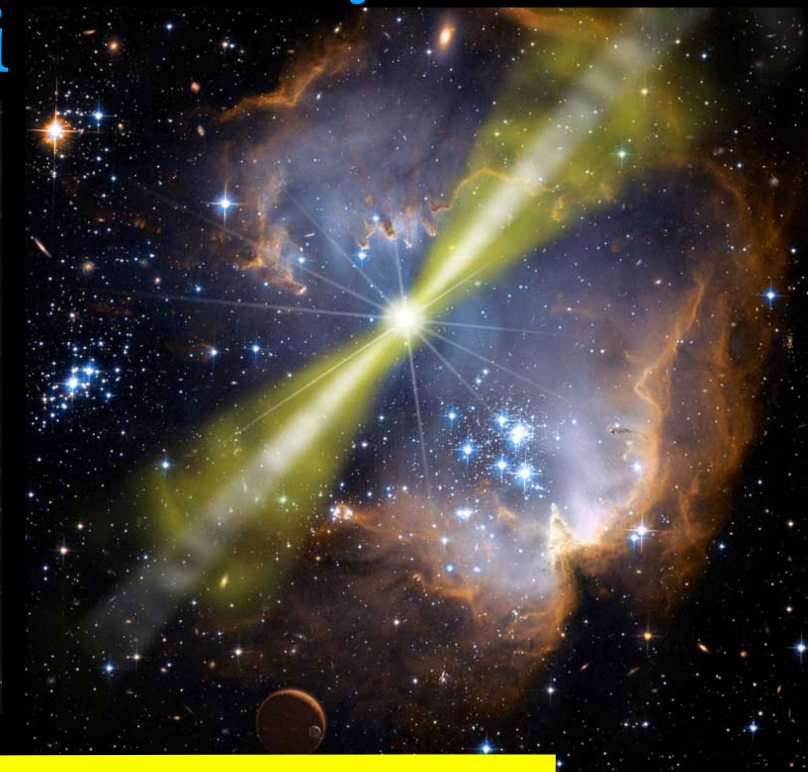

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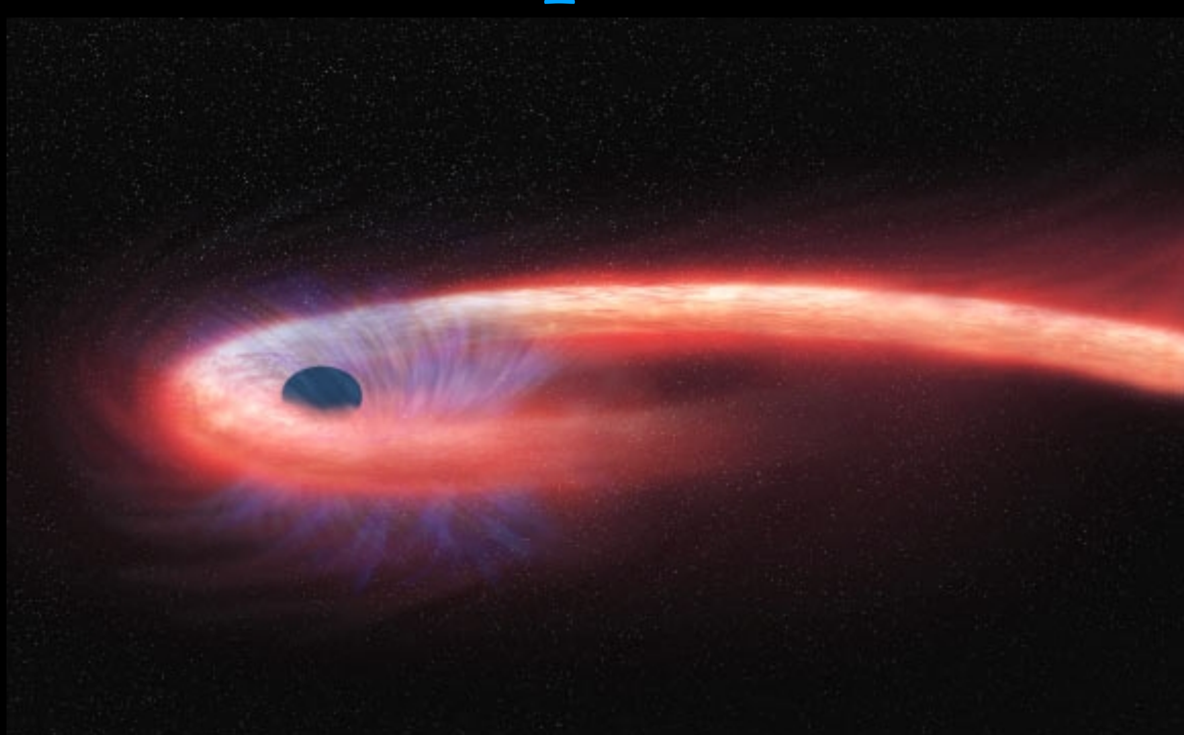

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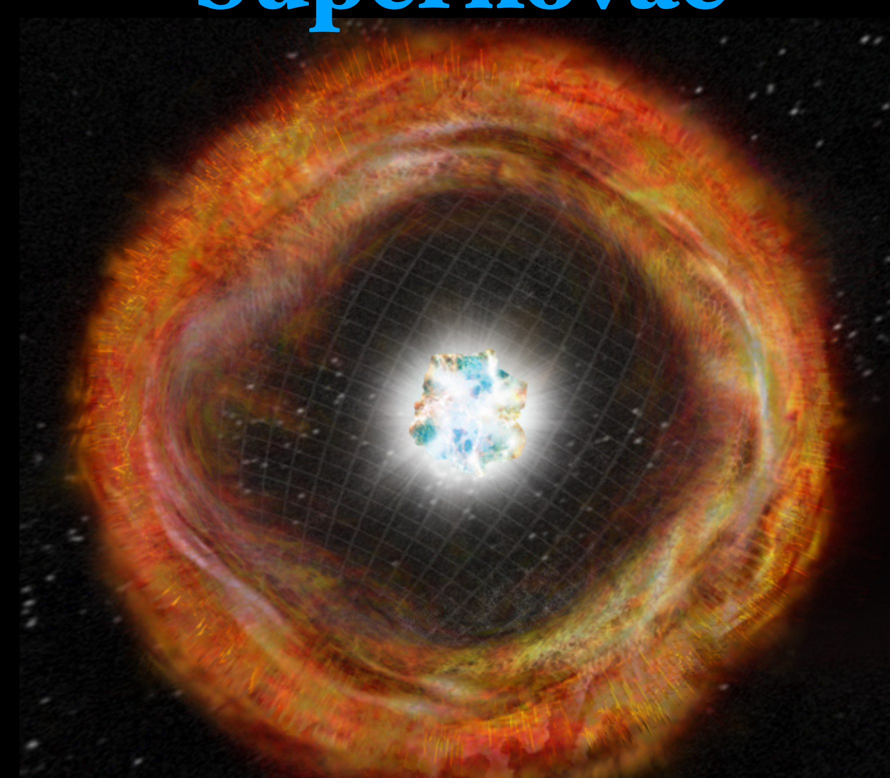
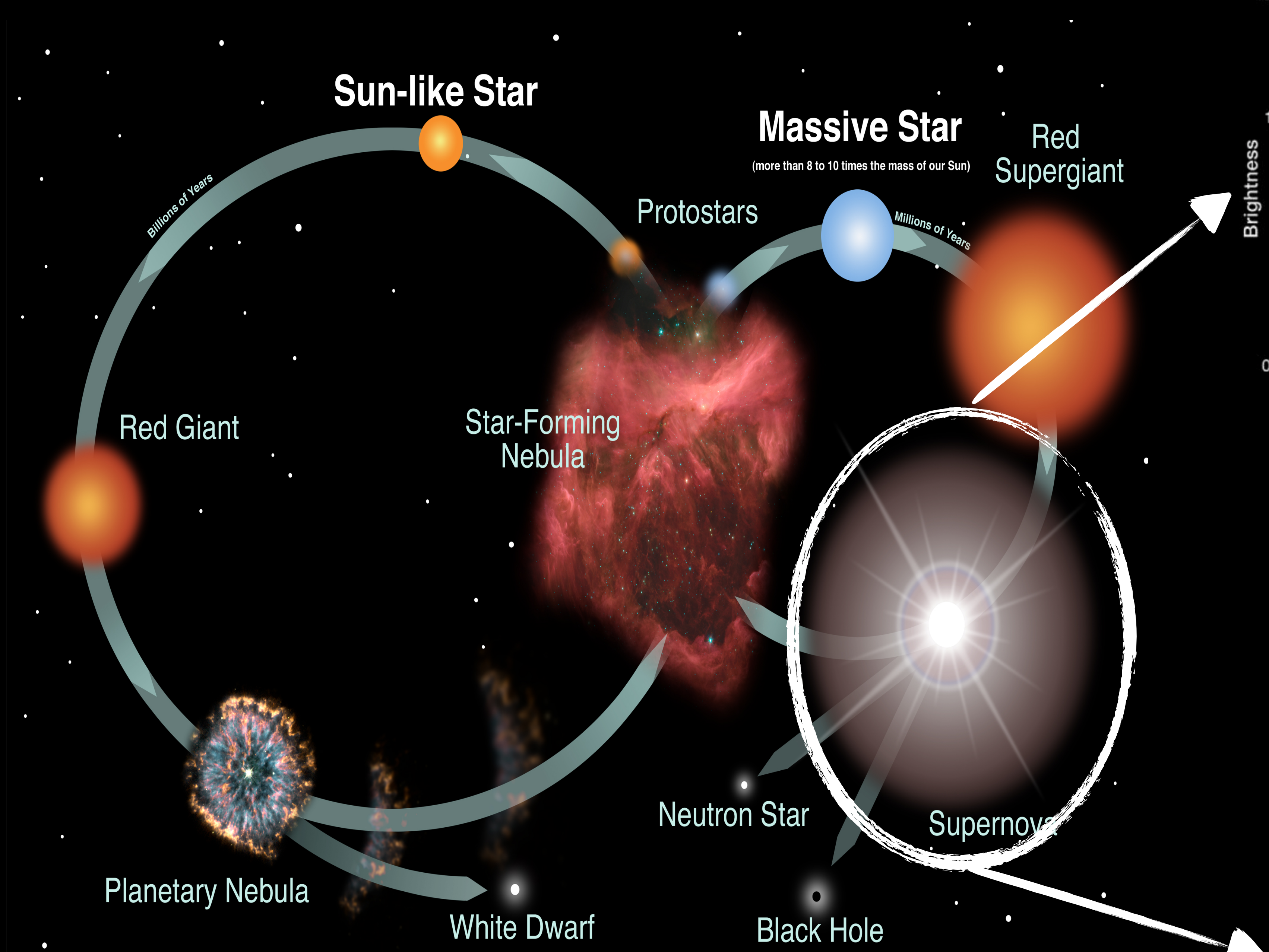
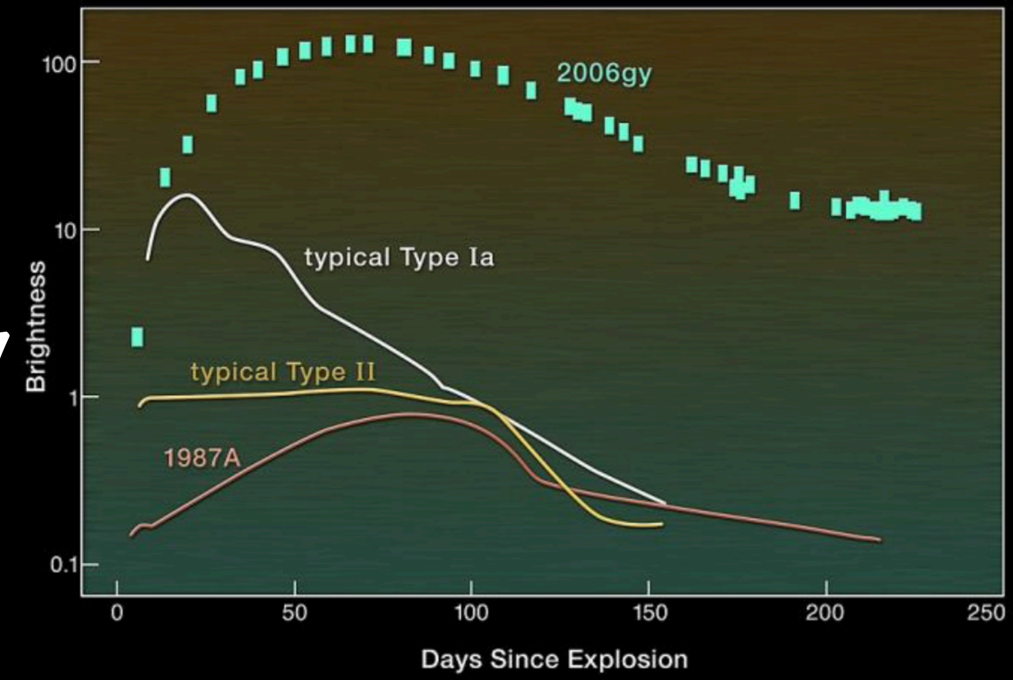


H-rich (superluminous) supernovae

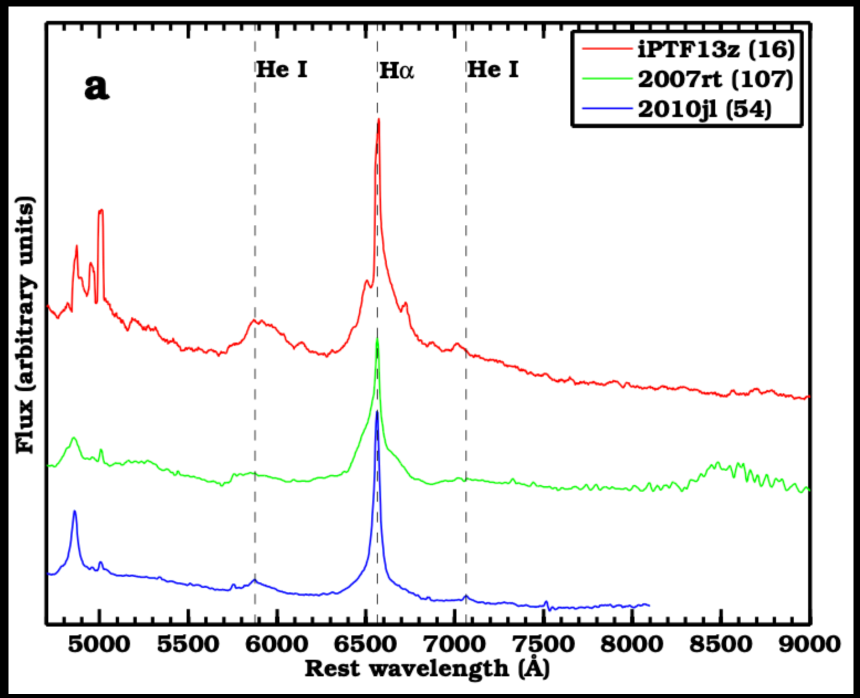
What is a H-rich (superluminous) supernova?



- ~ 10 – 100 **times brighter than typical SNe**



- **show strong narrow H line in the spectra**



Power source of superluminous supernovae

Three power source candidates:

Power source of superluminous supernovae

Three power source candidates:

Radioactive ^{56}Ni decay

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

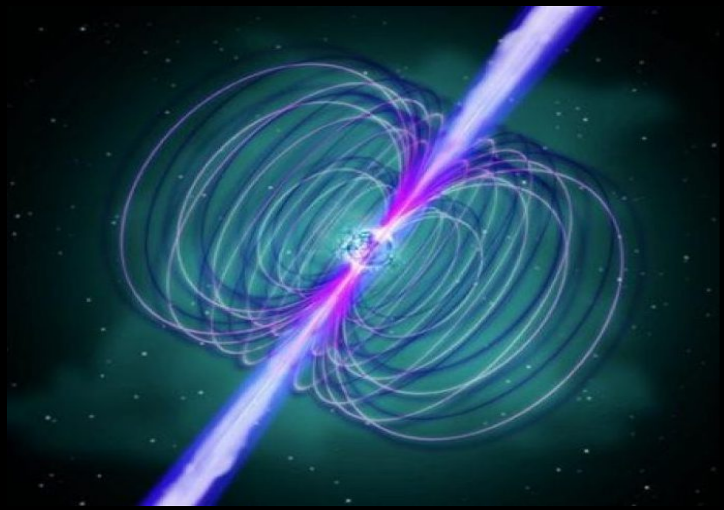
$$^{56}_{27}\mathrm{Co} \rightarrow {}^{56}_{26}\mathrm{Fe} + e^+ + \nu_e + \gamma$$

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

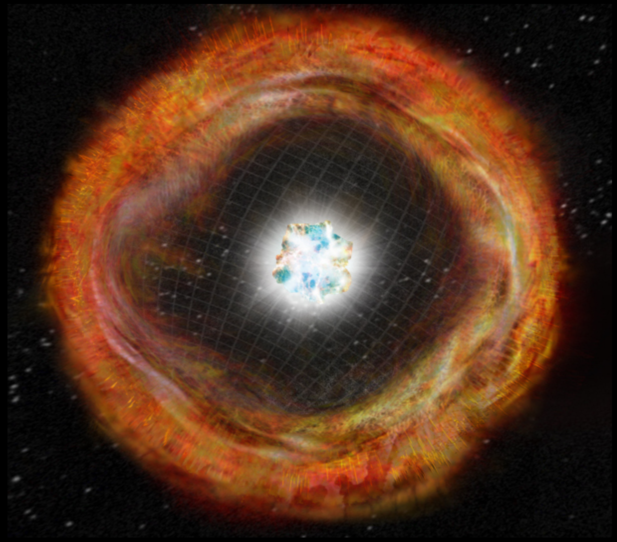


energy input from ms magnetar spindown

good candidate for SLSN I and SLSN II

still missing the smoking gun

Strong CSM interaction



energy input from dissipation of ejecta kinetic energy in the dense CSM

good candidate for SNe and SLSNe IIn

modeling the emission is complicated because of various unknown parameters

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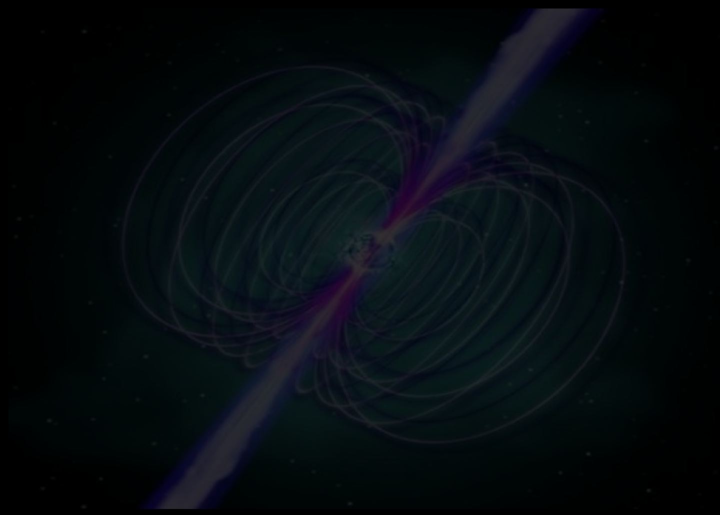

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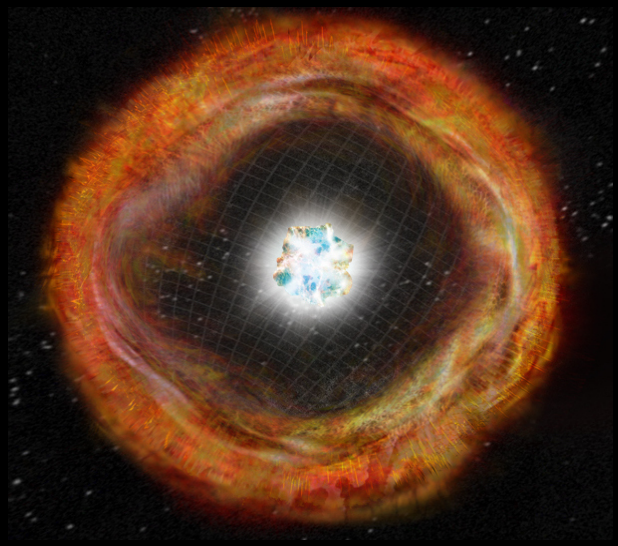

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High-energy neutrinos from interaction-powered supernovae

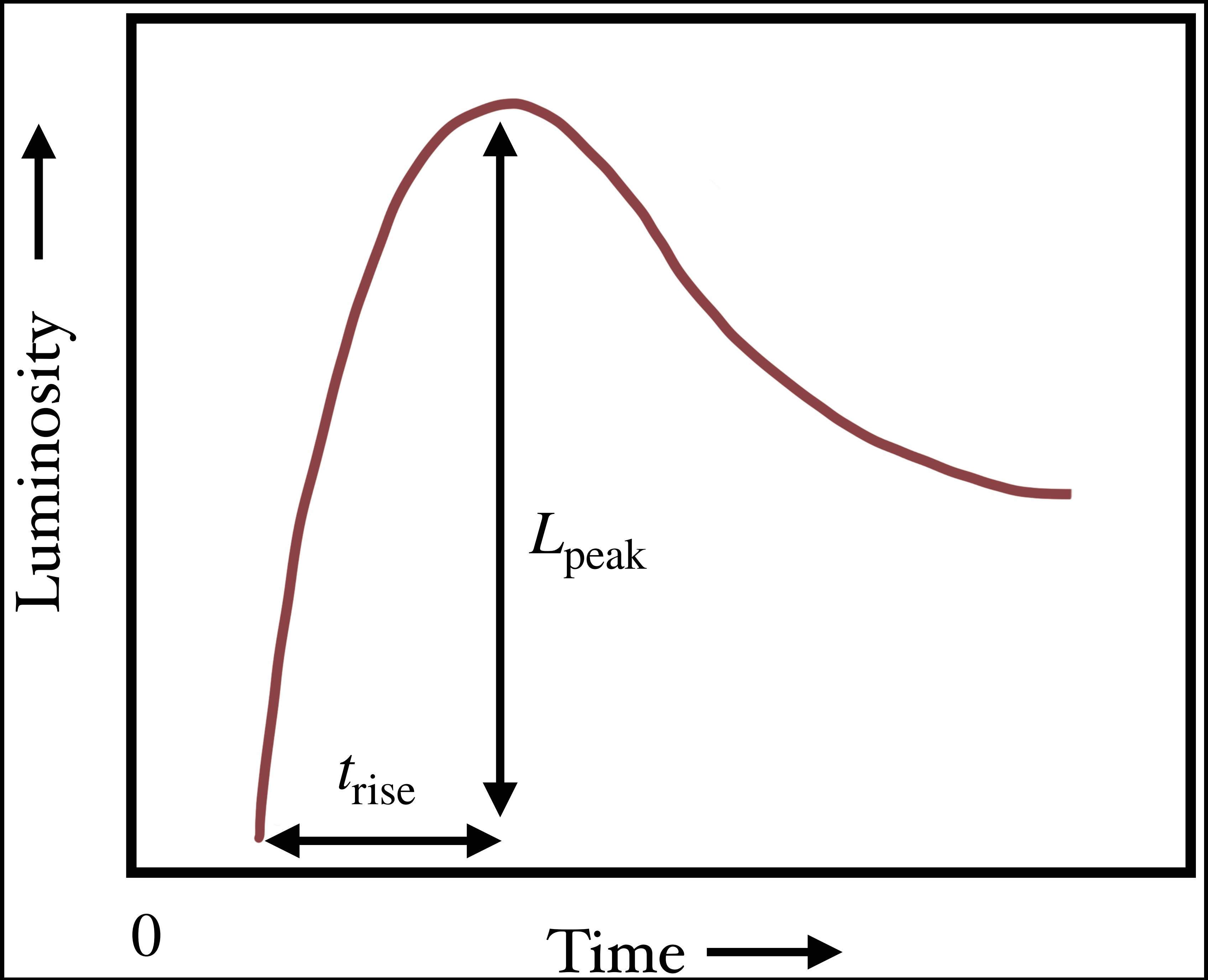
Interaction-powered supernovae parameters

Physical parameters which determine the observed properties :

- **Ejecta mass** $\longrightarrow$ $M_{\rm ej} \in (1 - 70)\, M_\odot$
- **Kinetic energy of the ejecta** $\longrightarrow$ $E_{\rm k} \in (10^{50} - 10^{53})$ erg
- **Structure of the star's envelope and star radius** $\longrightarrow$ $R_\star = 10^{13}$cm
- **CSM mass** $\longrightarrow$ $M_{\rm CSM} \in (1 - 70)\, M_\odot$
- **CSM composition** $\longrightarrow$ **solar composition for the CSM**
- **CSM radial distribution** $\longrightarrow$ **constant density and wind-like profile**
- **CSM geometry** $\longrightarrow$ **spherical with** $R_{\rm CSM} \in (5 \times 10^{15} - 10^{17})$ cm

* **Not surprising that the class of interacting SNe is so extremely diverse**

Lightcurve properties of interest in the study

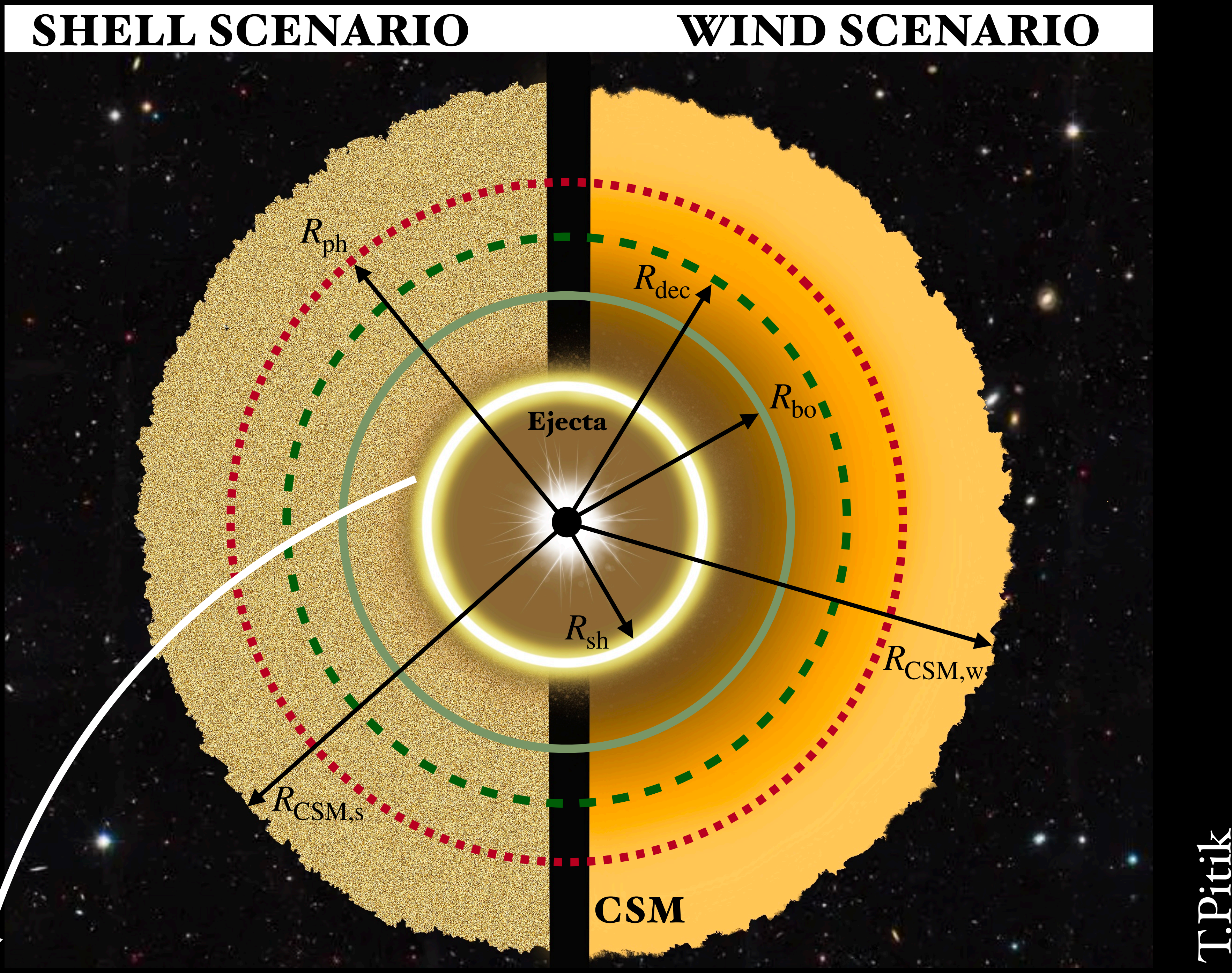


we want to see if there is a connection between t_{rise}, L_{peak} and the efficiency in producing high-energy neutrinos

Analytical treatment for L_{peak} and t_{rise}

$$L_{\text{peak}} = \frac{dE_k}{dt}\bigg|_{R_{\text{bo}}} = \frac{9}{8}\pi R_{\text{bo}}^2 v_{\text{sh}}^3(R_{\text{bo}})\rho_{\text{CSM}}(R_{\text{bo}})$$

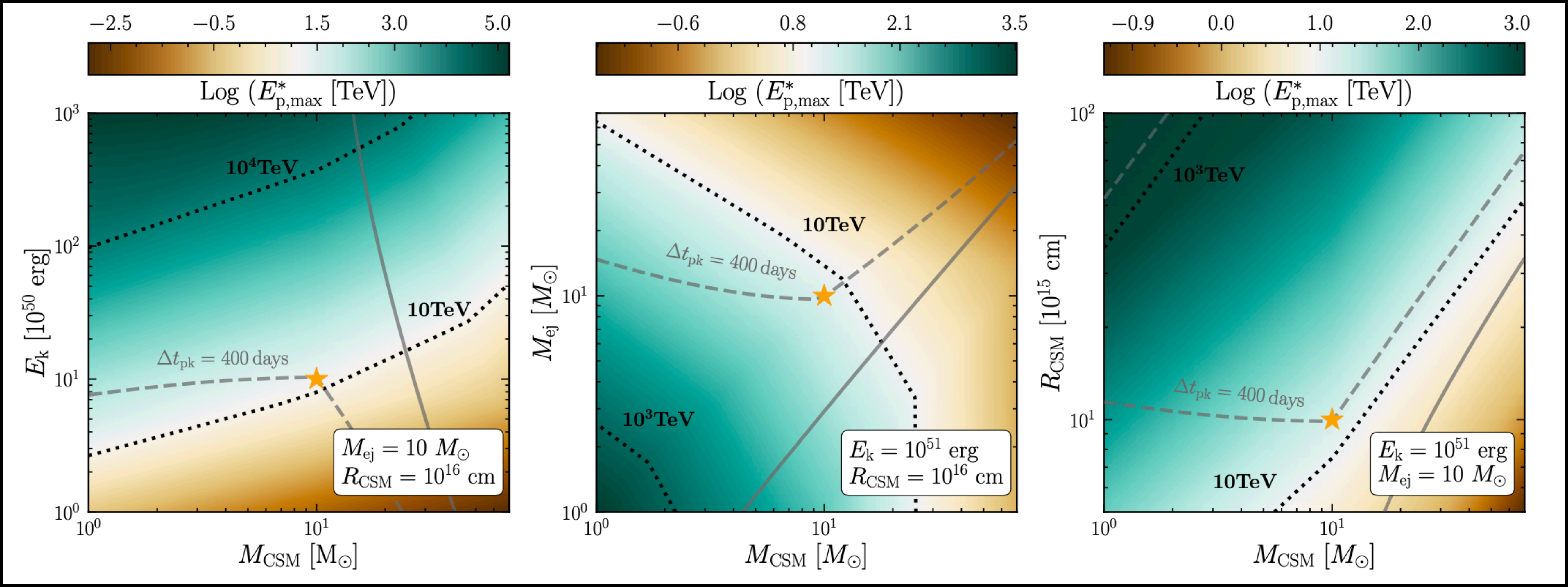
$$t_{\text{rise}} \approx \int_{R_{\text{bo}}}^{R_{\text{ph}}} \frac{d(R - R_{\text{bo}})^2}{D(R)}$$



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

$E^*_{p,max}$ dependence on SN parameters

$\Delta t_{pk} = t|_{E^*_{p,max}} - t_{peak}$ = time of maximum $E_{p,max}$ with respect to L_{peak}



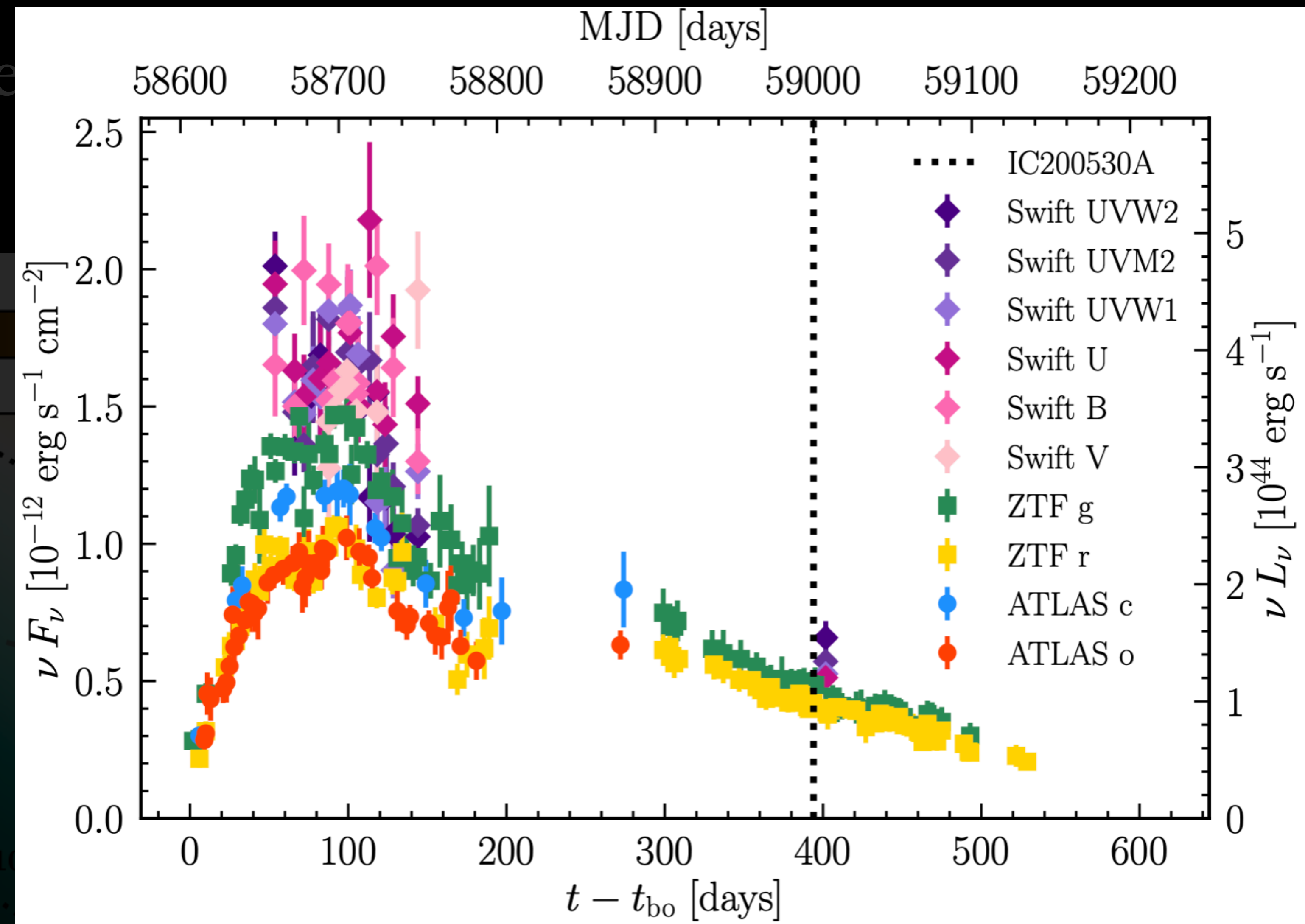
tipically $\Delta t_{pk} \gtrsim \mathcal{O}(100\,\text{days})$

for $E_k \lesssim 10^{52}$ erg, $M_{ej} \lesssim 10 M_\odot$, $M_{CSM} \lesssim 20 M_\odot$, $R_{CSM} \lesssim$ few $\times 10^{16}$ cm

$E^{*}_{\mathrm{p,max}}$ dependence on SN parameters

$\Delta t_{\mathrm{pk}} = t|_{E^{*}_{\mathrm{p,max}}} - t_{\mathrm{peak}}$ = time

IC200530A with $E_\nu \simeq 80\,\mathrm{TeV}$ from candidate SLSN candidate AT2019fdr



T.Pitik et al *ApJ* 929 (2022)

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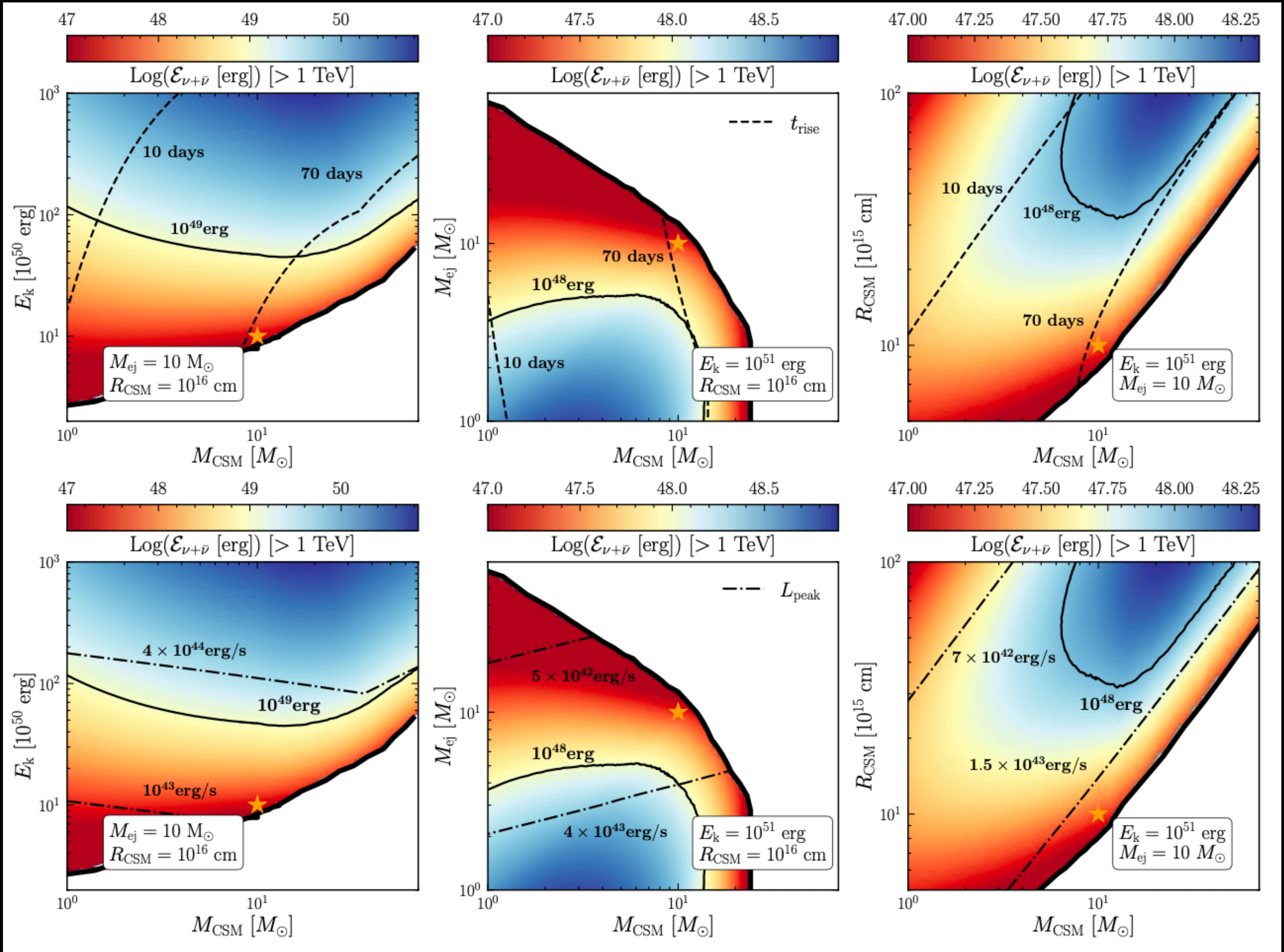
for $E_{\mathrm{k}} \lesssim 10^{52}$ erg, $M_{\mathrm{ej}} \lesssim 10 M_\odot$, $M_{\mathrm{CSM}} \lesssim 20 M_\odot$, $R_{\mathrm{CSM}} \lesssim \mathrm{few} \times 10^{16}$ cm

Neutrino energetics as a function of SN parameters: wind scenario



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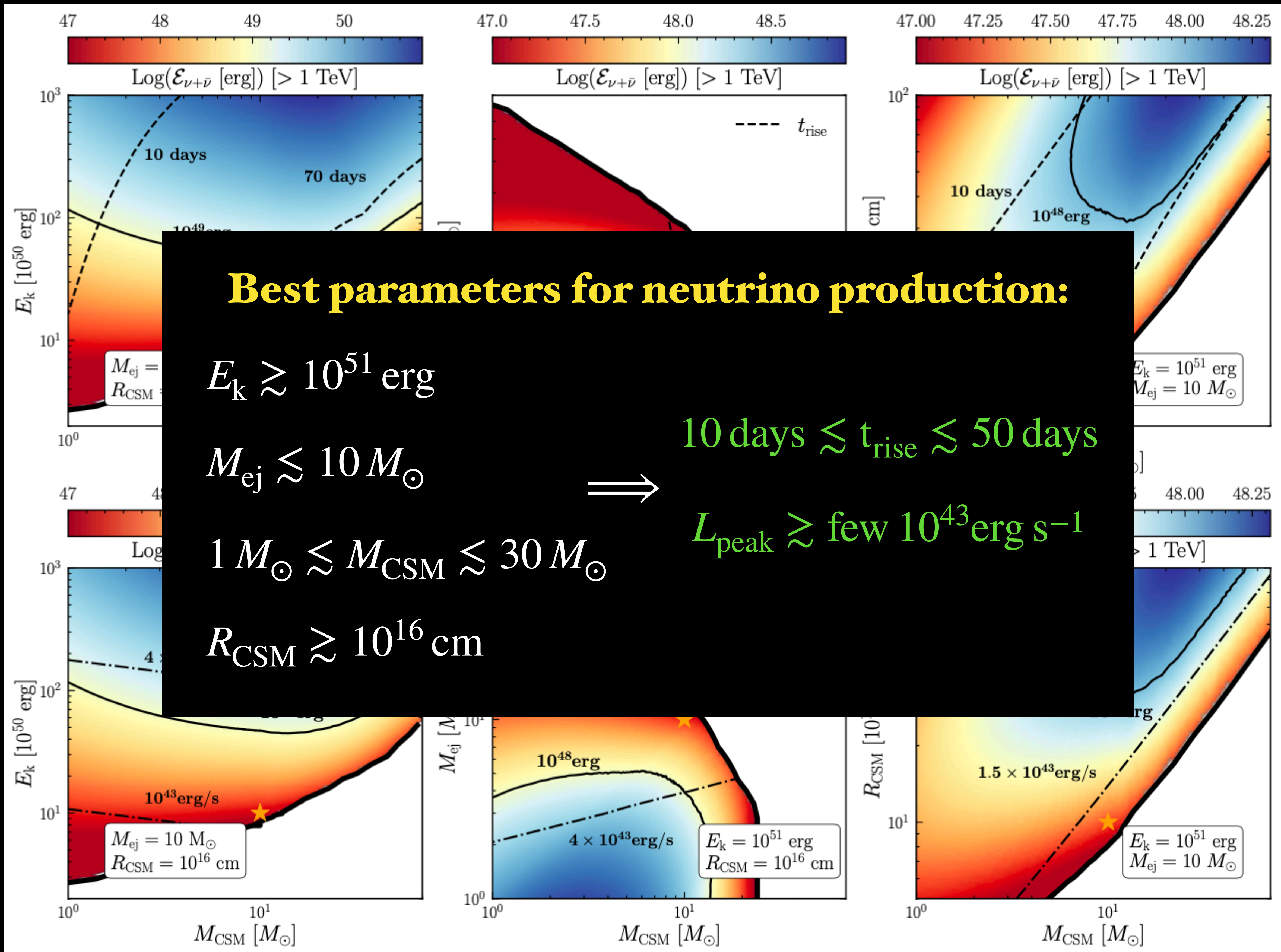


Best parameters for neutrino production:

$E_{\rm k} \gtrsim 10^{51}$ erg

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

$1\, M_\odot \lesssim M_{\rm CSM} \lesssim 30\, M_\odot$

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

$\Longrightarrow$

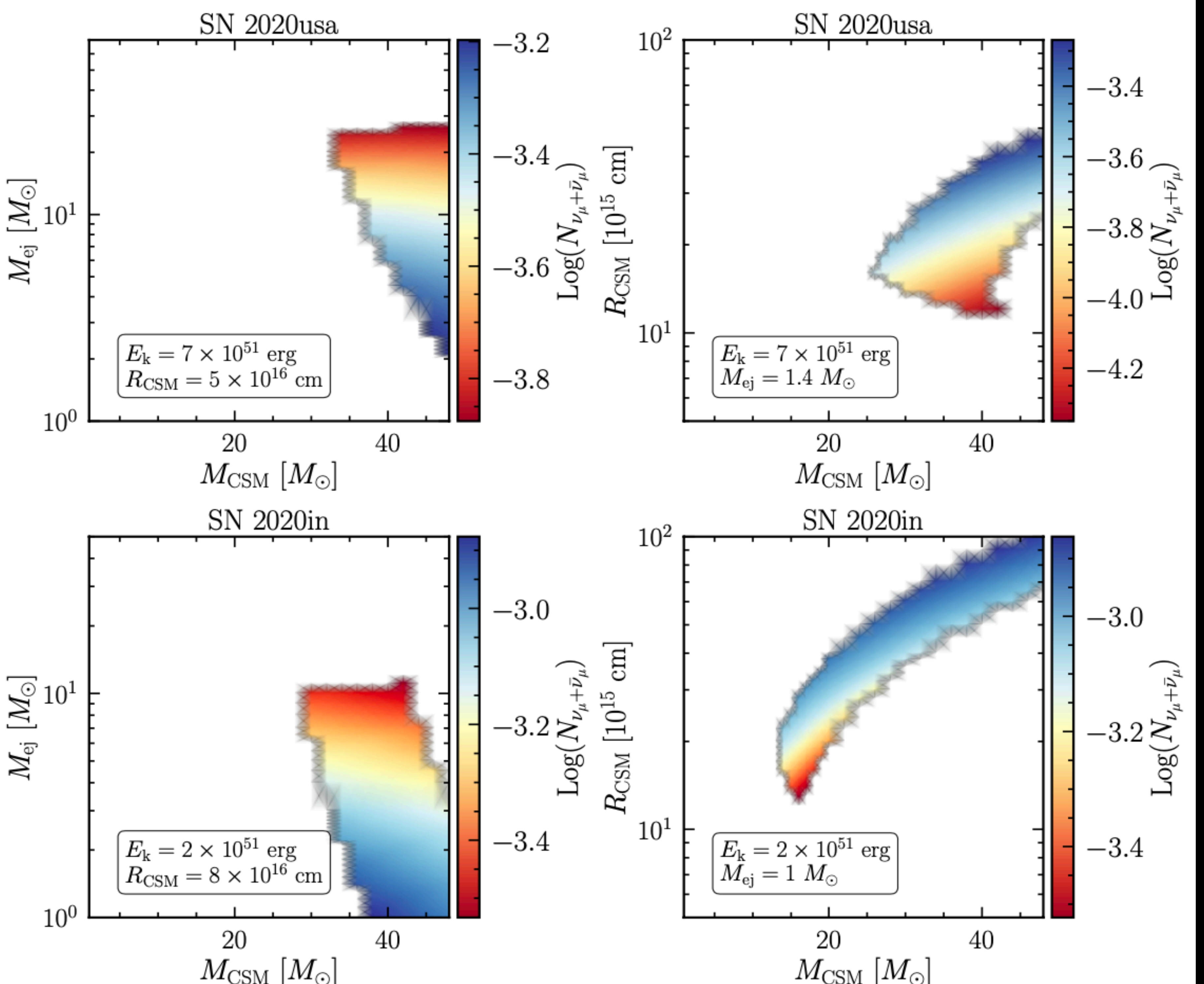
10 days $\lesssim t_{\rm rise} \lesssim$ 50 days

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

Two of the brightest SLSNe detected by the ZTF

- $t_{\rm rise} \in [1, 1.5] \times t_{\rm rise,obs}$
- $L_{\rm peak} \geq L_{\rm peak,obs}$
- $E_{\rm k} \geq E_{\rm rad,obs}$
- $t(R_{\rm ph}) - t(R_{\rm bo}) \geq t_{\rm dur,obs}$

	Redshift	$t_{\rm rise,obs}$ [days]	$L_{\rm peak,obs}$ [erg s^{-1}]	$E_{\rm rad,obs}$ [erg]	$t_{\rm dur,obs}$ [days]	Declination [deg]
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

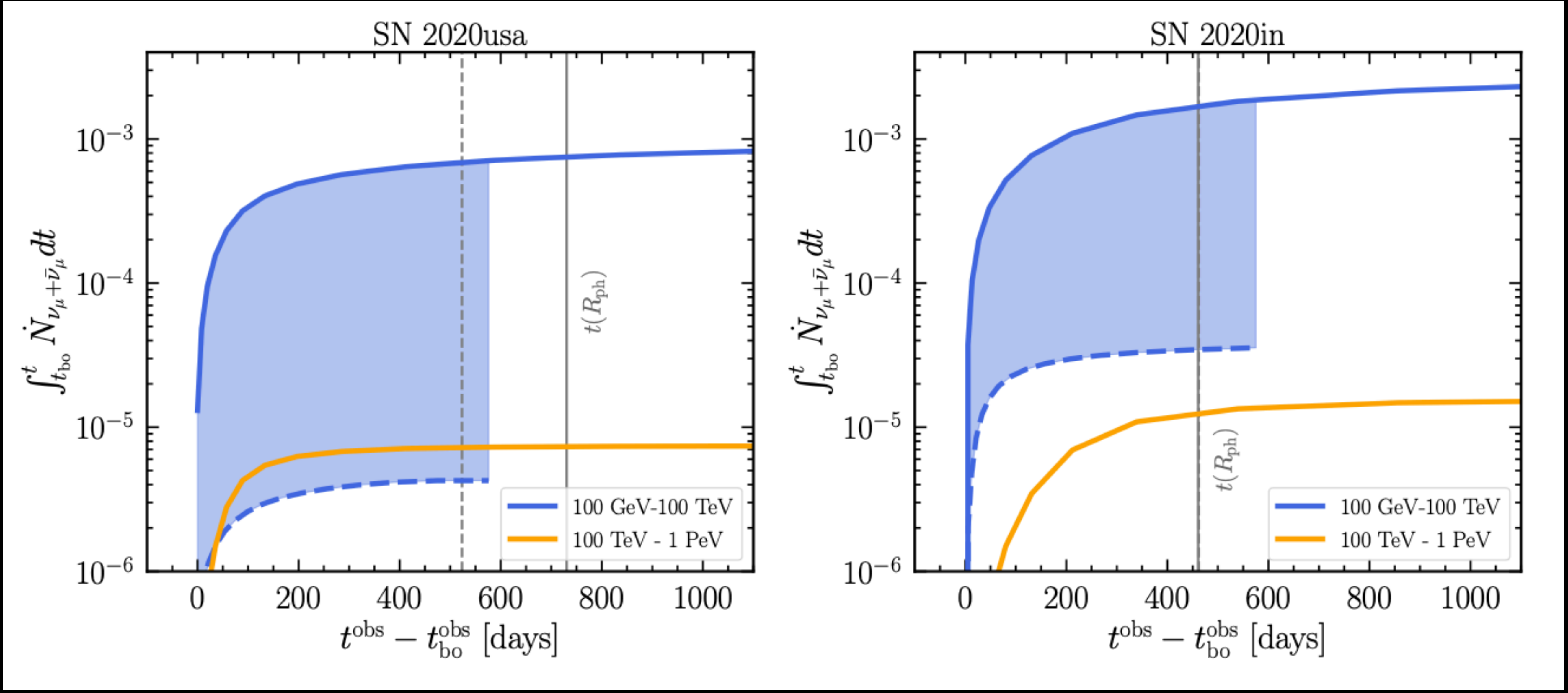


Cumulative number of neutrinos

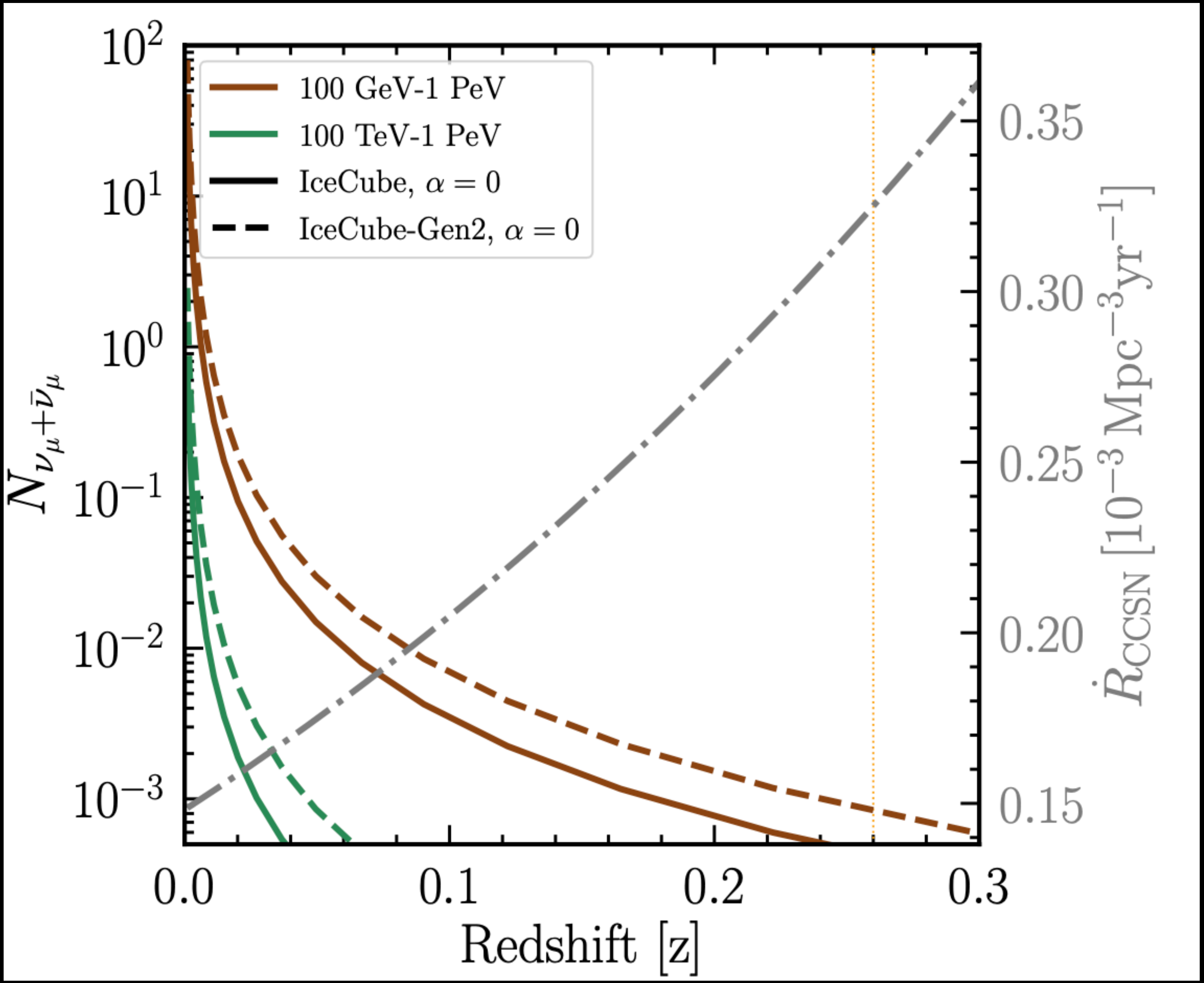
$t_{\rm rise} \in [1,1.5] \times t_{\rm rise,obs}$

$t(R_{\rm ph}) - t(R_{\rm bo}) \geq t_{\rm dur,obs}$

$L_{\rm peak} \in [1,1.5] \times \frac{L_{\rm peak,obs}}{\varepsilon_{\rm rad}}$ $E_{\rm rad} \in [1,1.5] \times \frac{E_{\rm rad,obs}}{\varepsilon_{\rm rad}}$



Expected number of neutrinos as a function of z



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

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

Multiwavelength emission can yield a source-by-source prediction

The temporal window can be optimized to reduce the background

Take home message

High-energy neutrinos from interaction-powered SNe

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

$L_{\rm peak} \gtrsim (10^{43} - 10^{44}) \mathrm{erg\,s^{-1}}$
$t_{\rm tise} \gtrsim (10 - 50)$ days

→ **necessary but not sufficient** → **Multiwavelenght observations are crucial**

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

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

➡ **In a stacked search, one should use source by source neutrino predictions**

➡ **A detection would confirm the mechanism powering SNe IIn , and constrain the SNe parameters**

Thank you for your attention !!!