# Neutrinos from Choked Jets Accompanied by Type-II Supernovae

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# Observations on Diffuse Gamma-Ray and Neutrinos

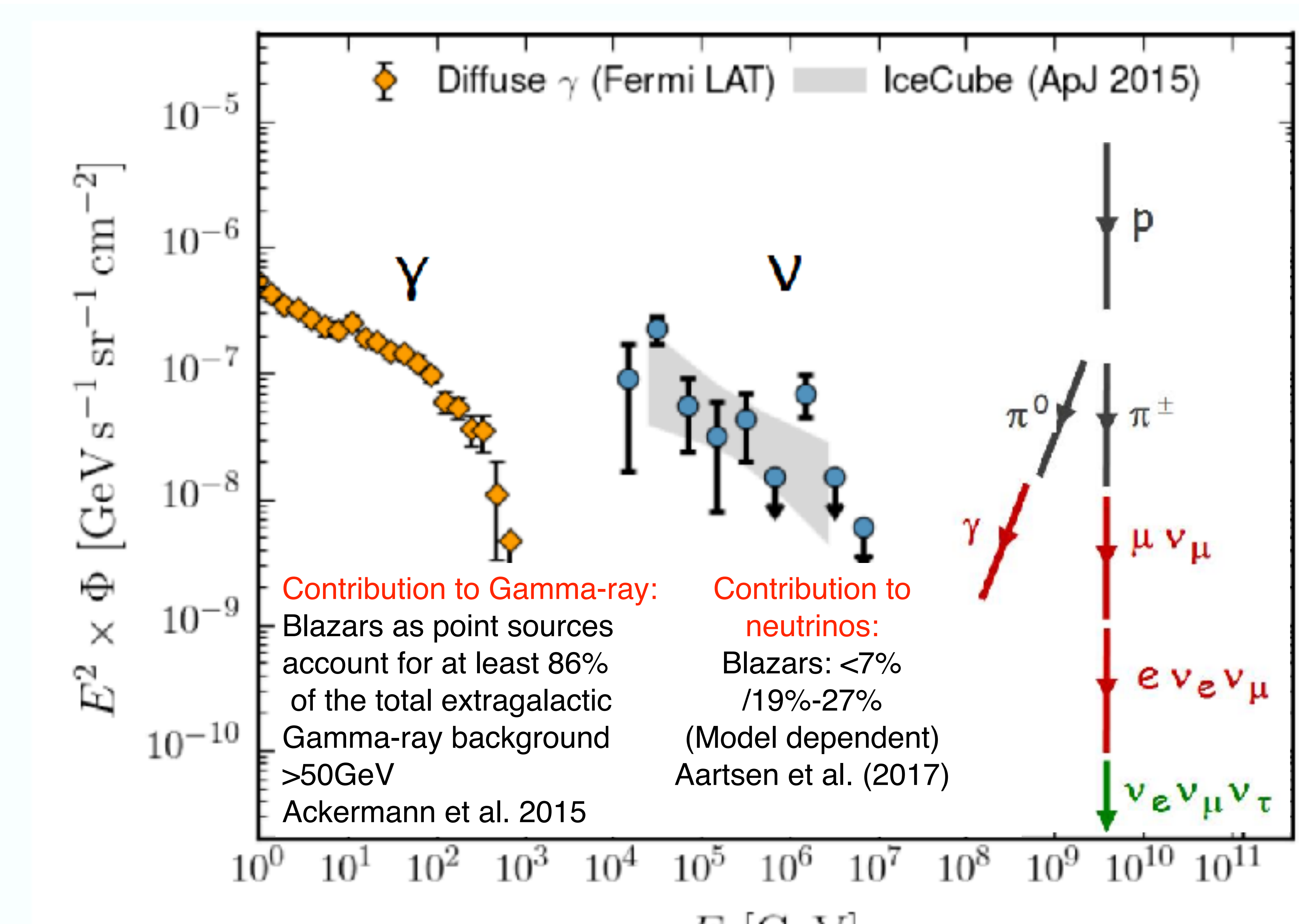



Fig. adapted from L. Mohrmann

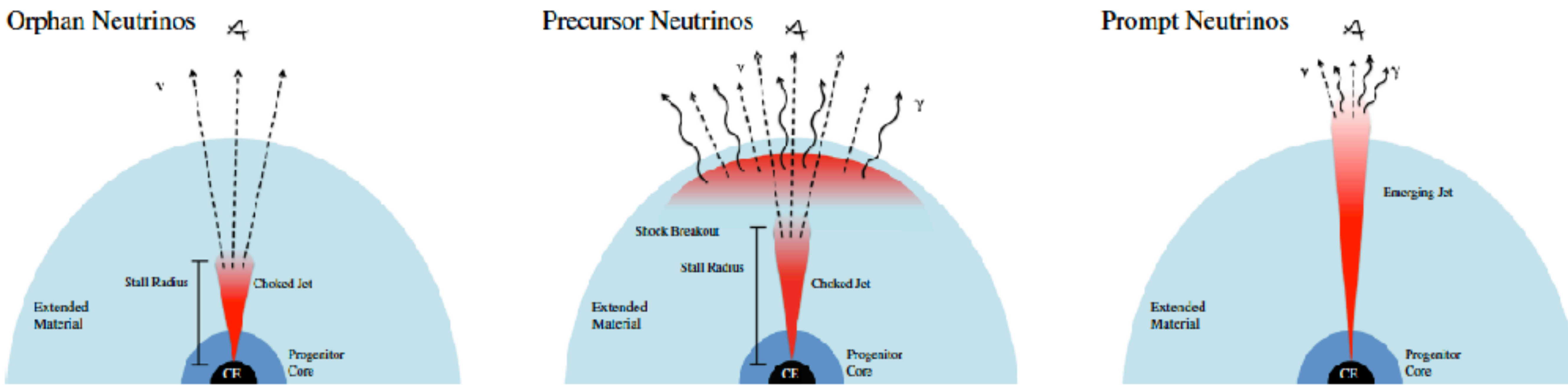
# Possible solutions

1. The neutrino sources themselves are opaque to gamma rays (Hidden source) :

- choked jets in TDEs of supermassive black holes ( Wang & Liu 2016; …)
- choked jets in core-collapse massive stars (Meszaros & Waxman 2001; Razzaque et al.2004; Murase & Ioka 2013; Xiao & Dai 2014; Senno et al. 2016; …)
- AGN cores (Stecker 2005; Murase et al. 2016; …)
- Starburst Galaxies (Chang et al. 2016; …)

2. The neutrino sources are distant (Chang et al. 2016;…)

# Jets in Core-Collapse Massive Stars




Jet-driven SNe

Low luminosity GRBs (Shock breakout)

High luminosity GRBs & Low luminosity GRBs

Senno et al. 2016

Local HL GRB rate: $0.8^{+0.1}_{-0.1}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

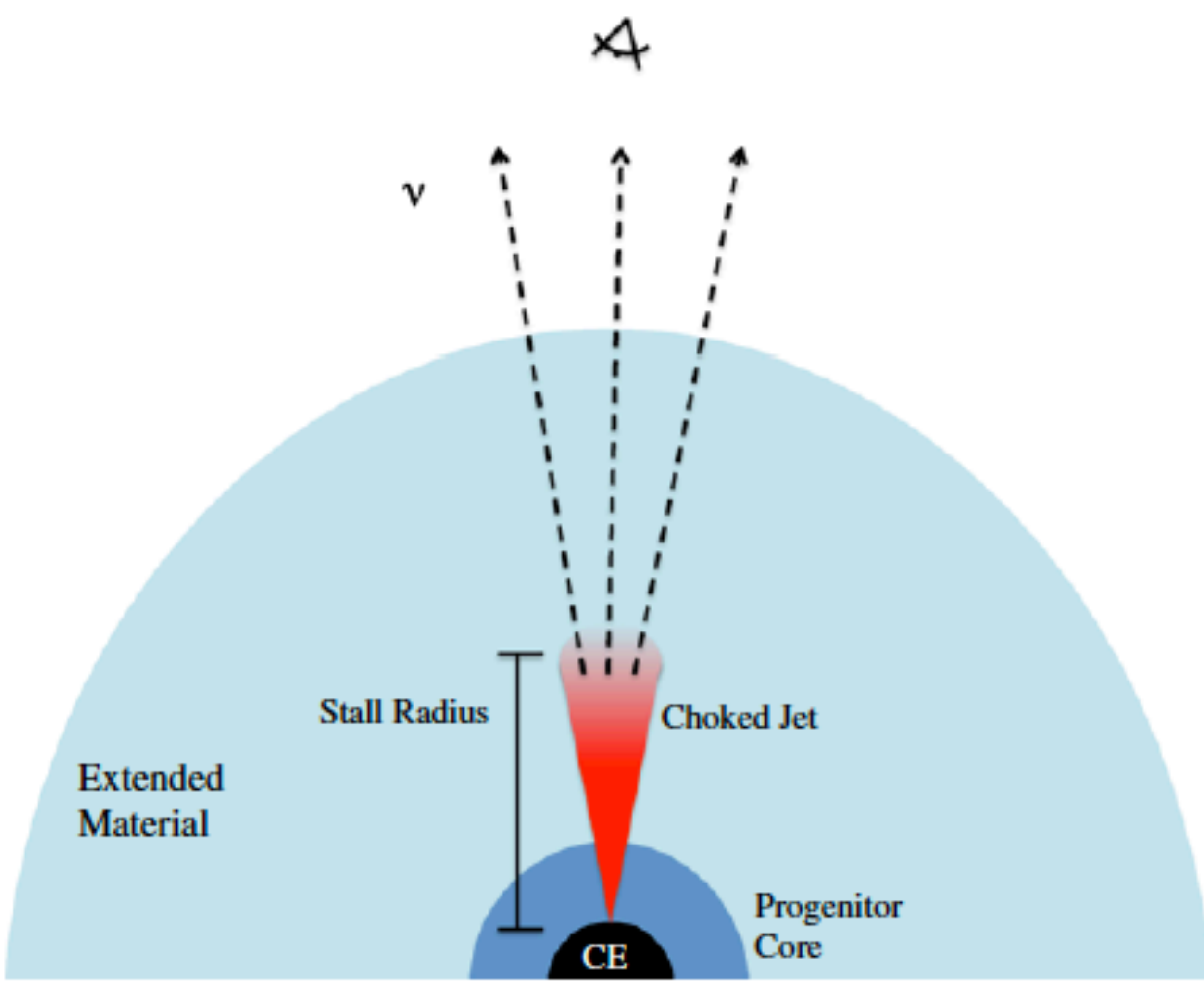
Local LL GRB rate: $164^{+98}_{-65}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

Local SNII rate: $10^5\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

# Choked Jets in Red Supergiant Stars

Condition 1:The jet life time is shorter than the time of jet crossing the extended material/ a thick stellar envelope.

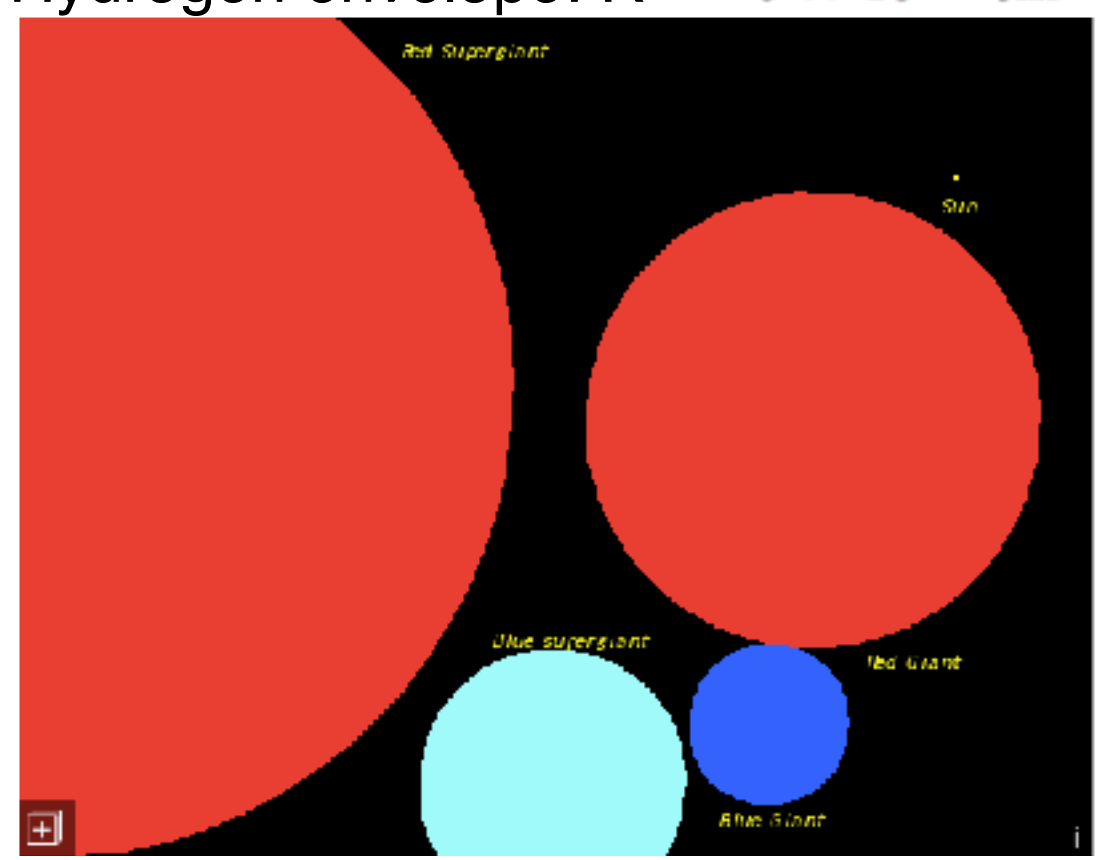
$$t < t_{\rm cros} \qquad t_{\rm cros} = 1.1 \times 10^5 \ {\rm s} \ R_{13.5}^2 L_{\rm iso,48}^{-1/2} \rho_{\rm H,-7}^{1/2}$$



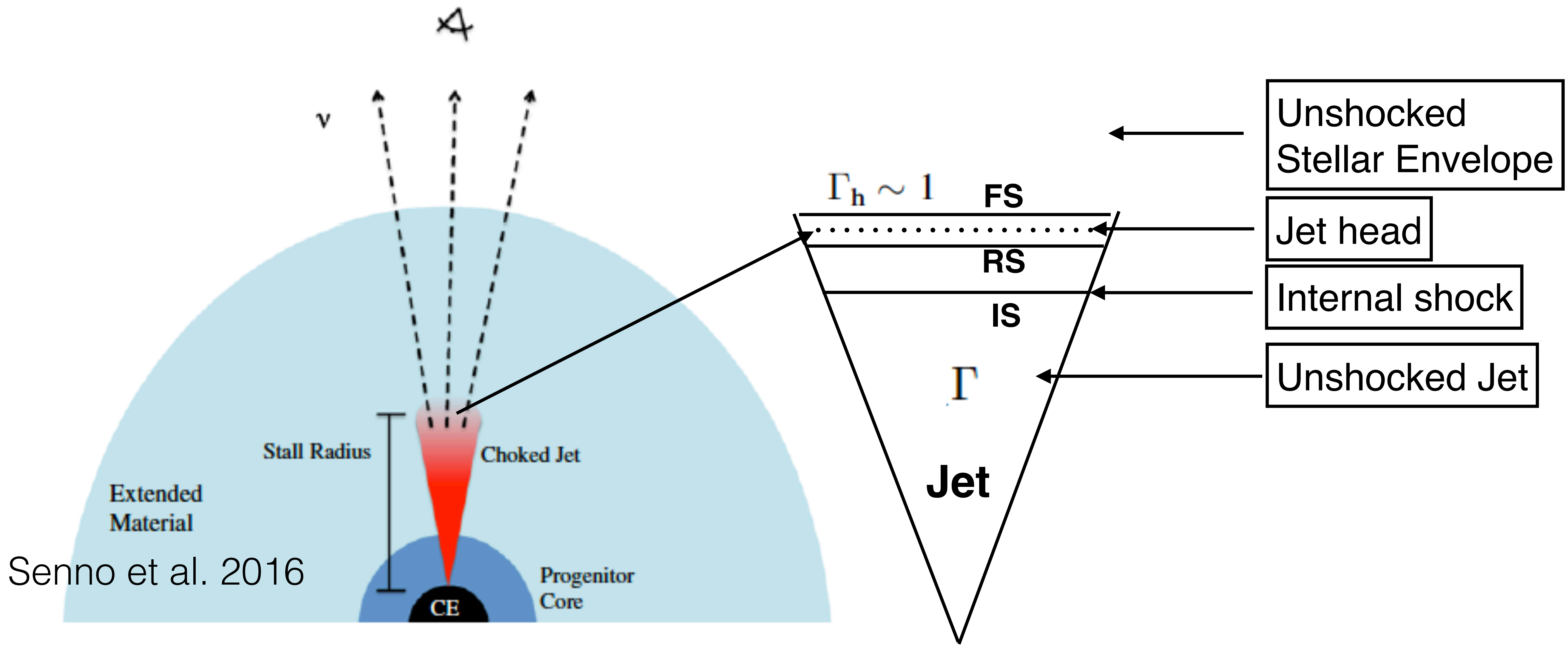

Senno et al. 2016

Red Supergiant Stars

Hydrogen envelope: R $\tilde{\sim} \ 3 \times 10^{13} \ {\rm cm}$



# Sketch of Jet Head and Internal Shock in the Choked Jet




## Assumptions:

1. Protons are accelerated in the internal shock.
2. Thermal photons emitted by the jet head propagate back to the internal shock (pp collision is ignored).

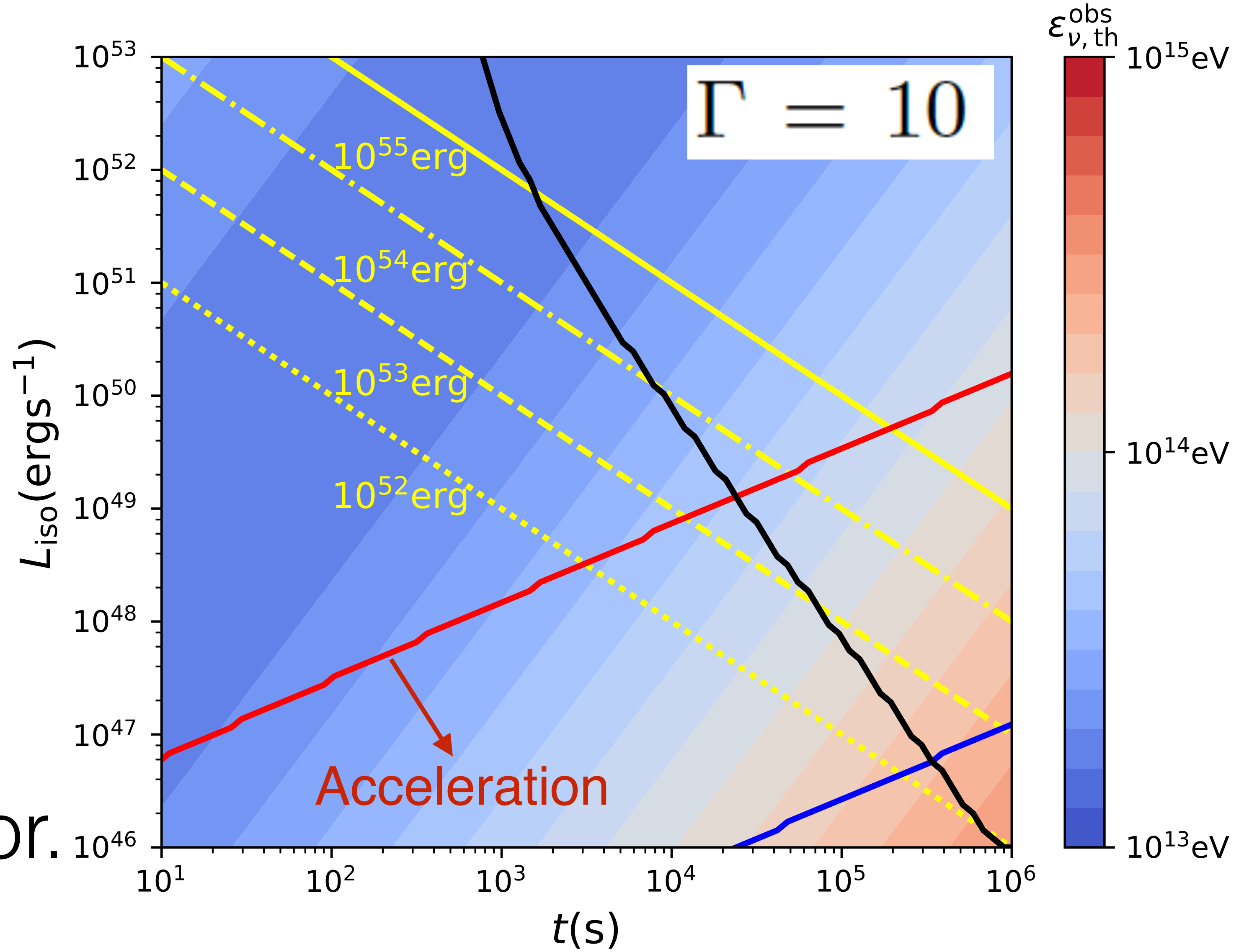
# Condition 2: Collisionless Internal Shock

The comoving size of the upstream flow $l_u = \frac{R_{IS}/\Gamma}{\Gamma_{rel}}$ is much smaller than the mean free path of the photons $l_{dec} = 1/(n_u \sigma_T)$

i.e., $l_u < l_{dec}$

$$\tau = 0.13\,\Gamma_1{}^3 L_{iso,48}^{3/4} t_4{}^{1/2} \rho_{H,\ 7}^{1/4} < \min[\Gamma_{rel}^2,\ 0.1 C^{-1} \Gamma_{rel}^3].$$

Lower luminosity,
longer jet lifetime,
and higher bulk Lorentz factor.



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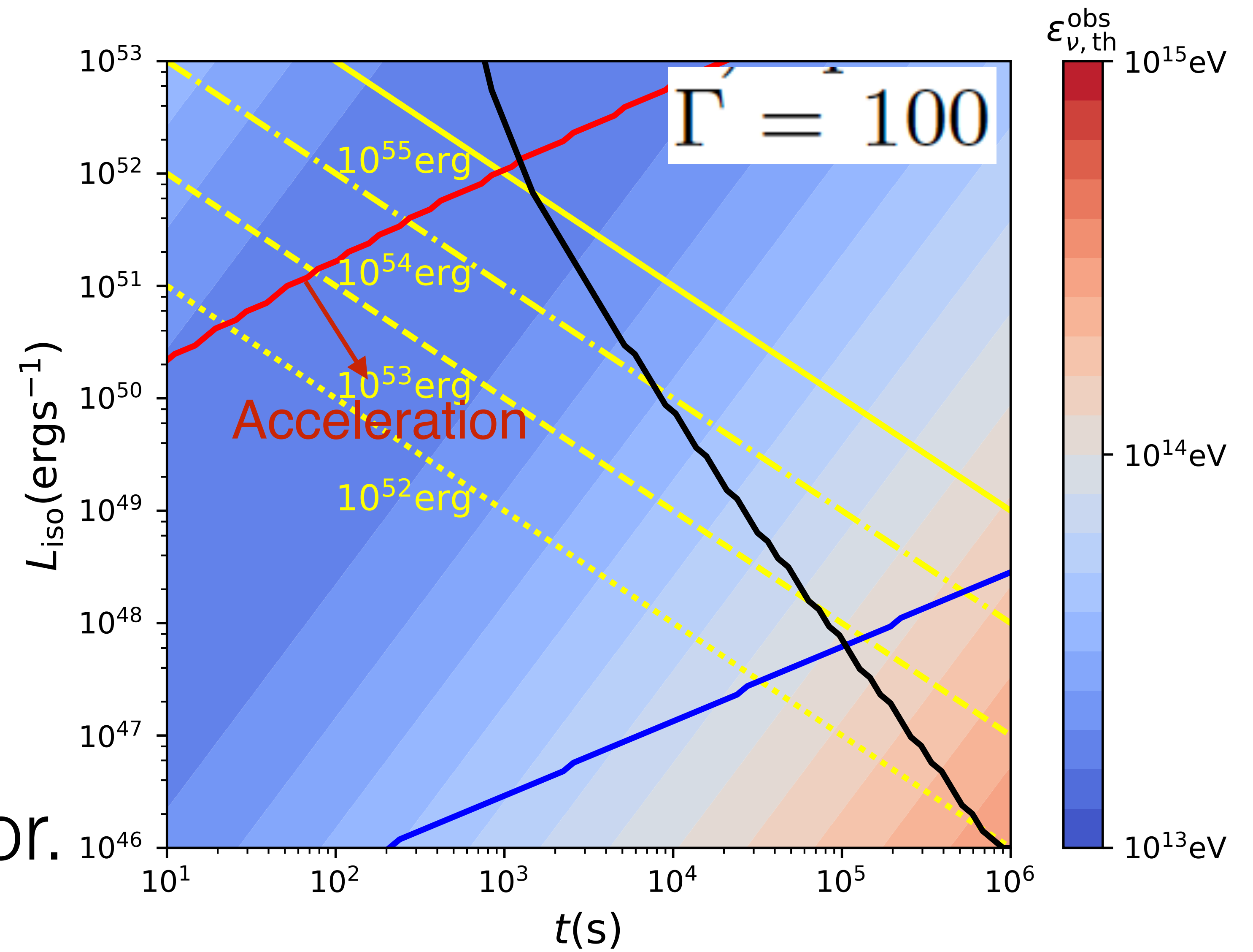


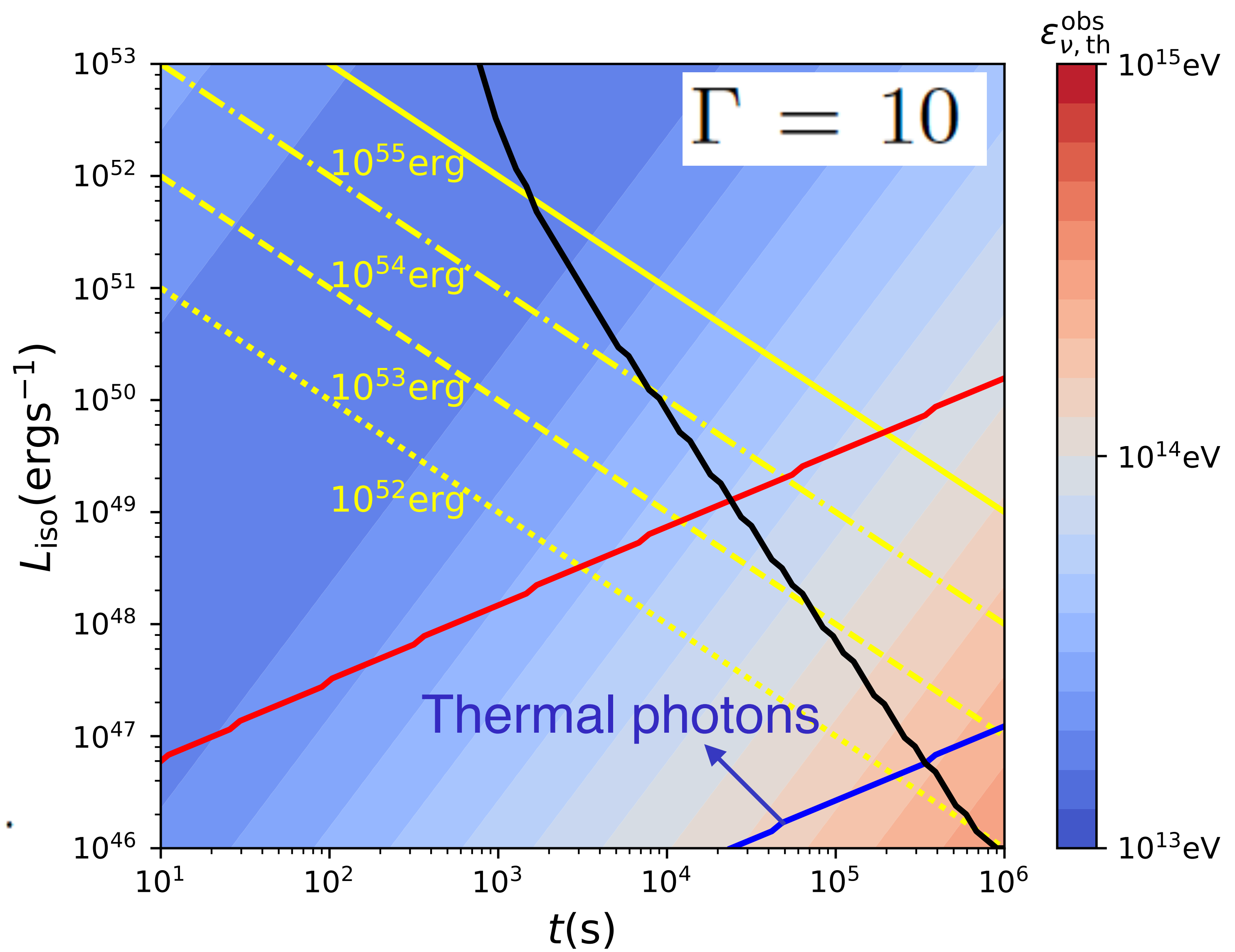
# Condition 3: Optical Thick Jet Head

Thermal photons are produced and escaping to the internal shock with a fraction of $f_{\rm esc} = 1/\tau_{\rm h}$

$$\tau_{\rm h} > 1$$

$$k_{\rm B} T_{\rm h} = 99\ {\rm eV}\ \epsilon_{{\rm c},-1}^{1/4} L_{{\rm iso},48}^{1/8} t_4^{-1/4} \rho_{{\rm H},-7}^{1/8} f_{\rm c}$$

$$\epsilon_{\gamma,{\rm IS}} = \bar{\Gamma}(2.8 k_{\rm B} T_{\rm h})$$
$$= 2.8 \times 10^3\ {\rm eV}\ \epsilon_{{\rm e},-1}^{1/4} L_{{\rm iso},48}^{1/8} t_4^{-1/4} \rho_{{\rm H},-7}^{1/8} f_{\rm c}.$$



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Thermal photons are produced and escaping to the internal shock with a fraction of $f_{esc} = 1/\tau_h$

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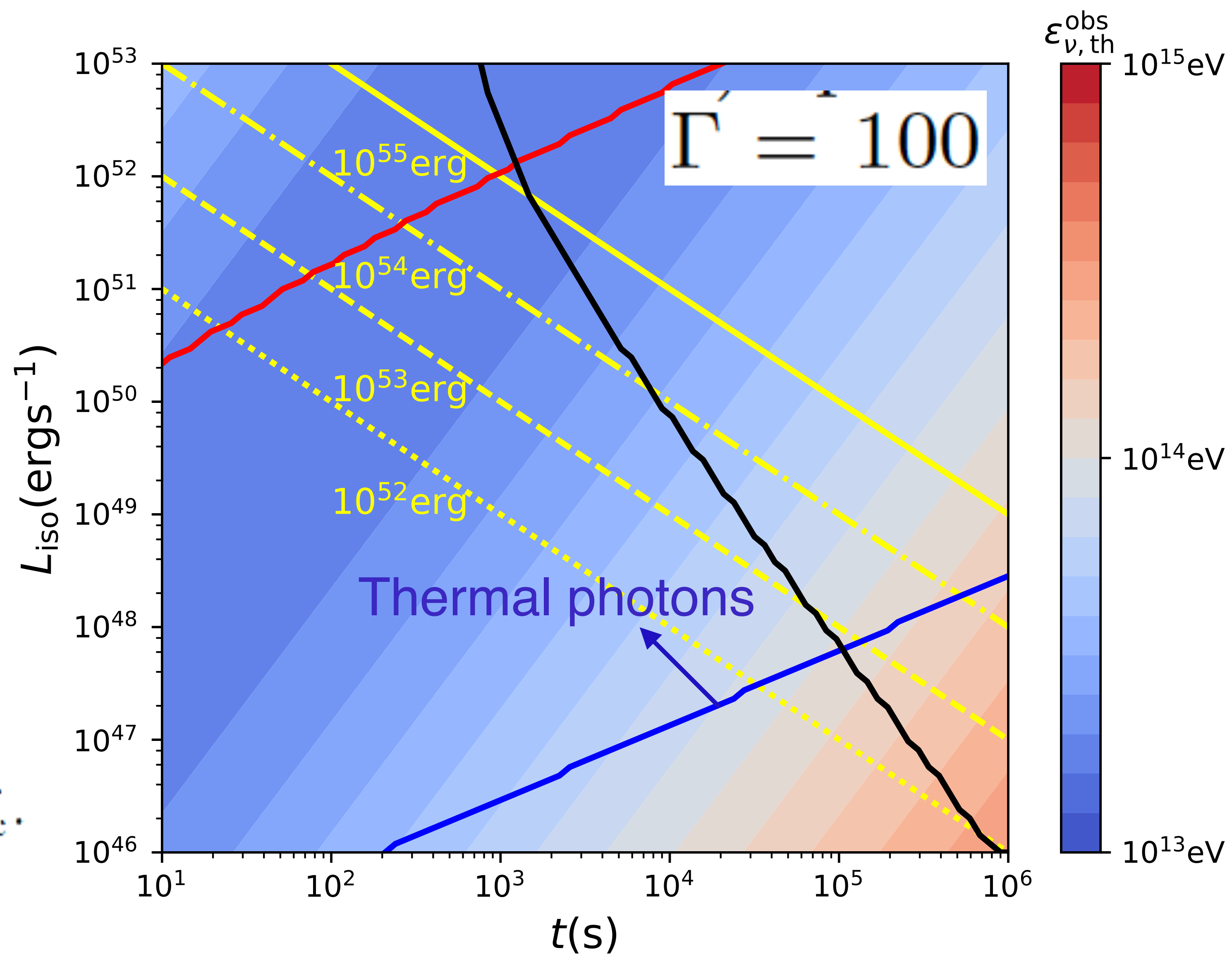
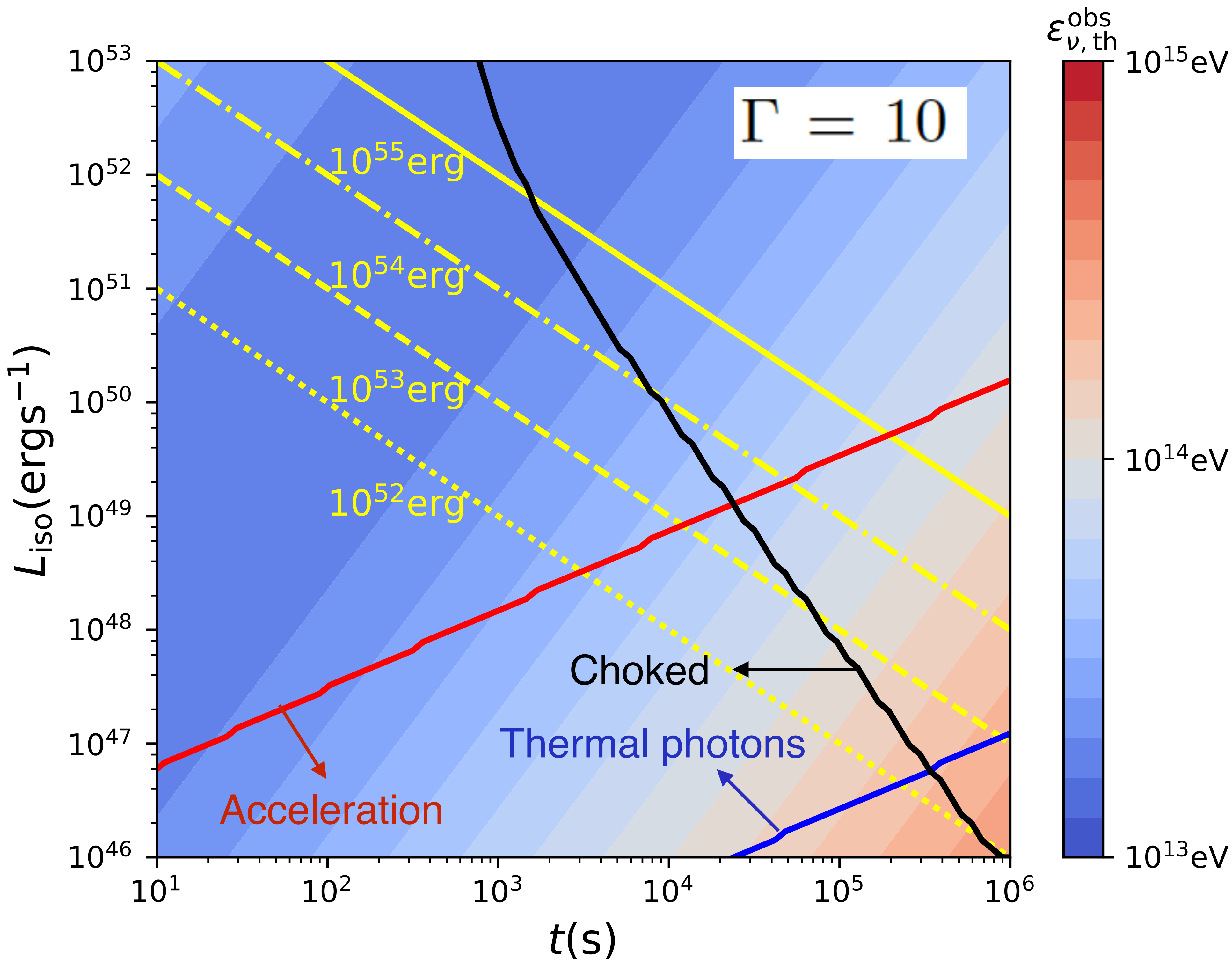
$$\epsilon_{\gamma,IS} = \bar{\Gamma}(2.8 k_B T_h) = 2.8 \times 10^3 \text{ eV } \epsilon_{e,-1}^{1/4} \bar{\Gamma}_2 L_{iso,48}^{1/8} t_4^{-1/4} \rho_{H,-7}^{1/8} f_c .$$



# Constraints on the Jet life time and the Luminosity



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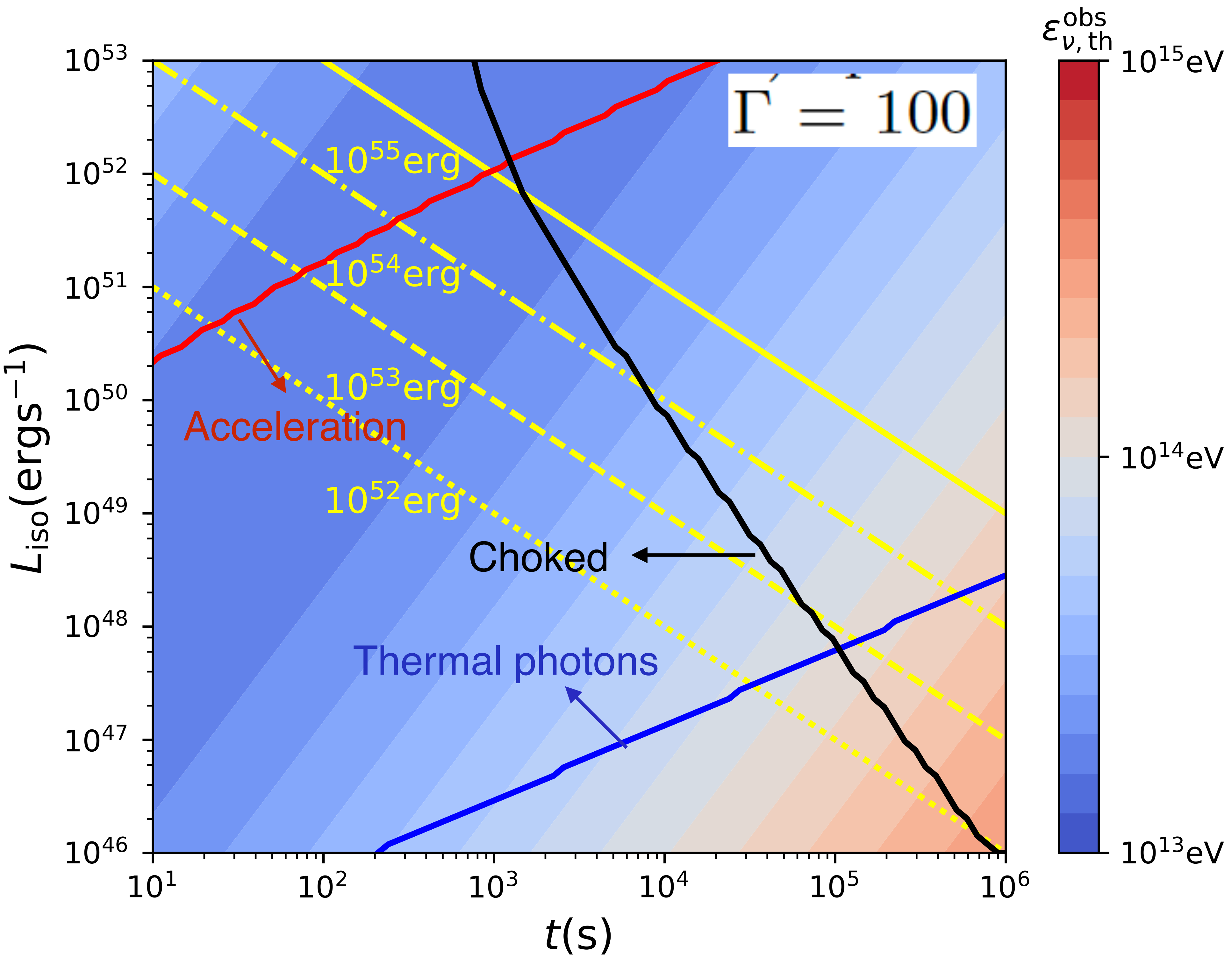
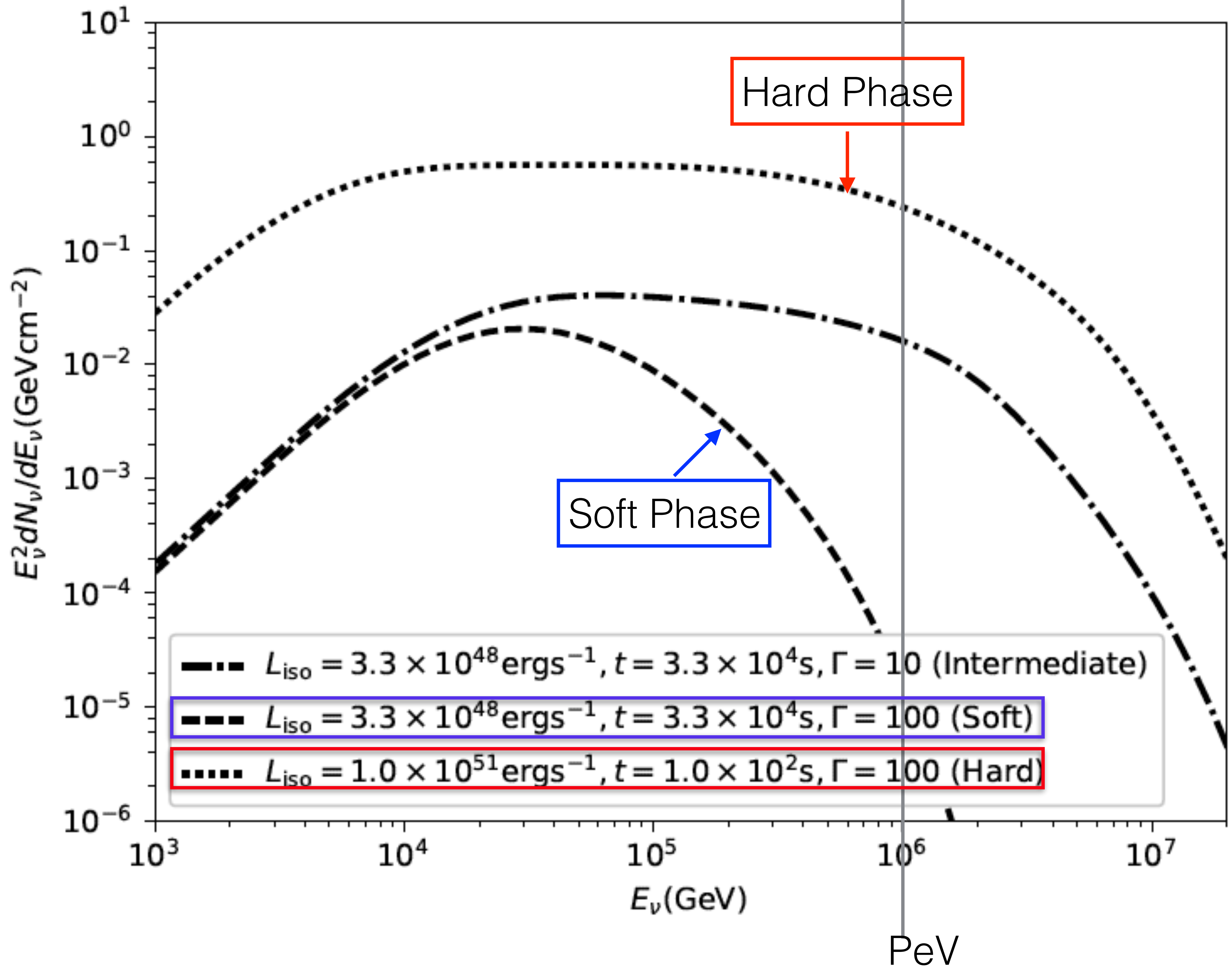
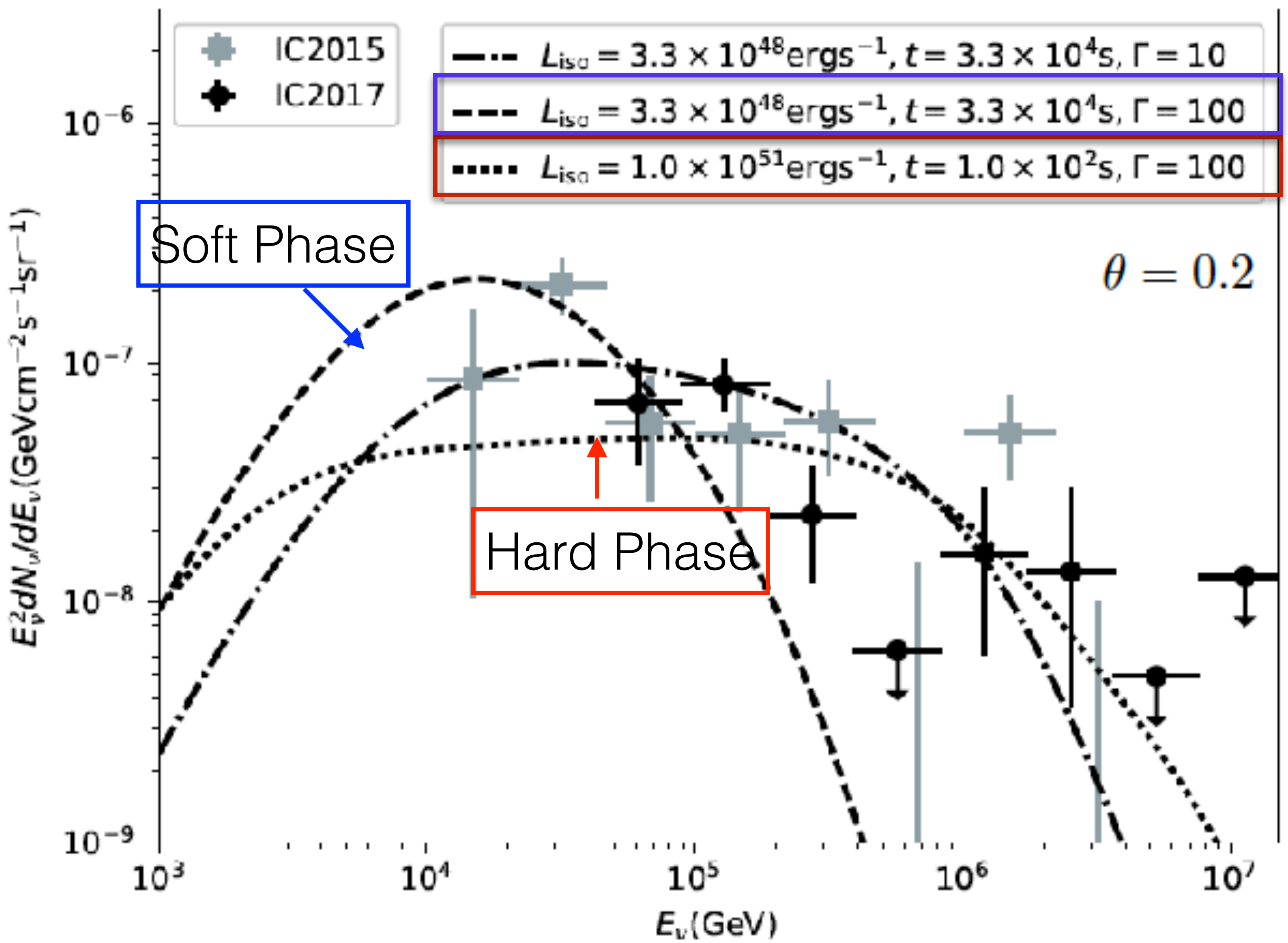


# Neutrino Spectra from Individual Sources at 1 Gpc




He+, 2018,ApJ,856,119H

# Diffuse Neutrino Spectra: One-component Spectra




We assume the source rate is in proportion to the star formation rate

$$\rho_{\rm sf} = 0.015 \frac{(1+z)^{2.7}}{1+[(1+z)/2.9]^{5.6}} M_\odot \mathrm{yr}^{-1} \mathrm{Mpc}^{-3}$$

$$R_{\rm cj} = A_{\rm cj} \rho_{\rm sf}$$

Madau & Dickinson (2014)

The constrained local source rate: 1%-20% of the typical SNII rate



He+, 2018,ApJ,856,119H

# Muon Neutrino Multiplets
# Predicted by the Choked Jet Model

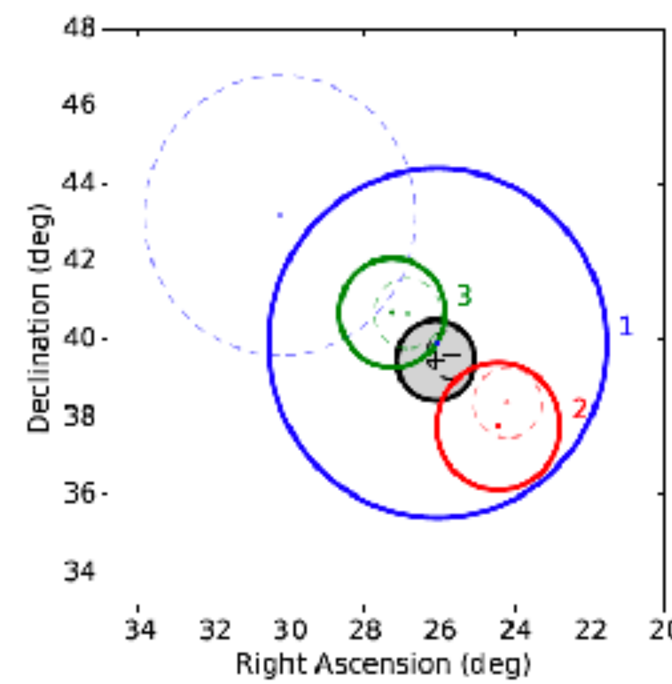
| | $L_{iso}$ ergs$^{-1}$ | $t$ s | $\Gamma$ | $A_{cj}$ $M_{\odot}^{-1}$ | $R_{cj}(z=0)$ Gpc$^{-3}$yr$^{-1}$ | $N_S(N_{\nu_\mu}>1)$ yr$^{-1}$ | $N_S(N_{\nu_\mu}>2)$ yr$^{-1}$ | $N_S(N_{\nu_\mu}>3)$ yr$^{-1}$ |
|---|---|---|---|---|---|---|---|---|
| Soft Phase | $3.3\times10^{48}$ | $3.3\times10^{4}$ | 100 | $1.4\times10^{-3}$ | $2.1\times10^{4}$ | 2.0 | 0.77 | 0.42 |
| Intermediate Phase | $3.3\times10^{48}$ | $3.3\times10^{4}$ | 10 | $3.0\times10^{-4}$ | $4.5\times10^{3}$ | 2.1 | 0.78 | 0.42 |
| Hard Phase | $1.0\times10^{51}$ | $1.0\times10^{2}$ | 100 | $1.0\times10^{-4}$ | $1.5\times10^{3}$ | 2.5 | 0.81 | 0.45 |

He+, 2018,ApJ,856,119H

- We predict that 4 multiplets within ~100 s to ~10,000 s can be found in 10 years operation of IceCube.

- On February 17, 2016, the IceCube real-time neutrino search identified, for the first time, a triplet arriving within 100 s of one another. No likely electromagnetic counterpart was detected. the probability to detect at least one triplet from atmospheric backgrounds is 32%.

- Wider time window might introduce more atmospheric neutrinos.




The IceCube Collaboration, 2017

# The limited distance to detect muon neutrinos from Choked Jets accompanied by SNe

- Newly Born Jet-driven SNII (asymmetry explosion)

| E_SN=1e51erg (L_jet=1e48erg/s, T_jet=1e3s, Gamma=100) | Singlet | Doublet | Triplet |
|---|---|---|---|
| **Distance** | 0.25 Gpc | 0.18 Gpc | 0.14 Gpc |
| **Redshift** | z~0.056 | z~0.041 | z~0.032 |

| E_SN=1e52erg (L_jet=1e49erg/s, T_jet=1e3s, Gamma=100) | Singlet | Doublet | Triplet |
|---|---|---|---|
| **Distance** | 0.93 Gpc | 0.65 Gpc | 0.53 Gpc |
| **Redshift** | z~0.19 | z~0.14 | z~0.11 |

# Follow-up Observations

**AMON ICECUBE_GOLD EVENTS Alerts** https://gcn.gsfc.nasa.gov/amon.html

**AMON ICECUBE_GOLD and _BRONZE EVENTS**

| EVENT | | | | OBSERVATION | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RunNum_EventNum | Rev | Date | Time UT | NoticeType | RA [deg] | Dec [deg] | Error90 [arcmin] | Error50 [arcmin] | Energy | Signalness | FAR [#/yr] | Comments |
| 133331_47828126 | 2 | 19/11/19 | 01:01:29.38 | GOLD | 230.0999 | +3.1699 | 220.19 | 154.19 | 1.7648e+02 | 4.4999e-01 | 1.5417 | IceCube Gold event. The position error is statistical only, there is no systematic added. |

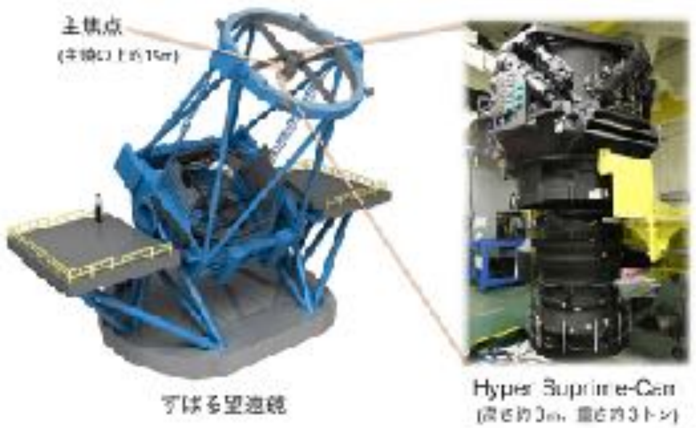
SWOM/GWAC-F60 A/B
SWOM/GWAC
SWOM

Xinglong-2.16
GMG-2.4
……

Large Synoptic Survey Telescope(LSST) 3.5° FOV

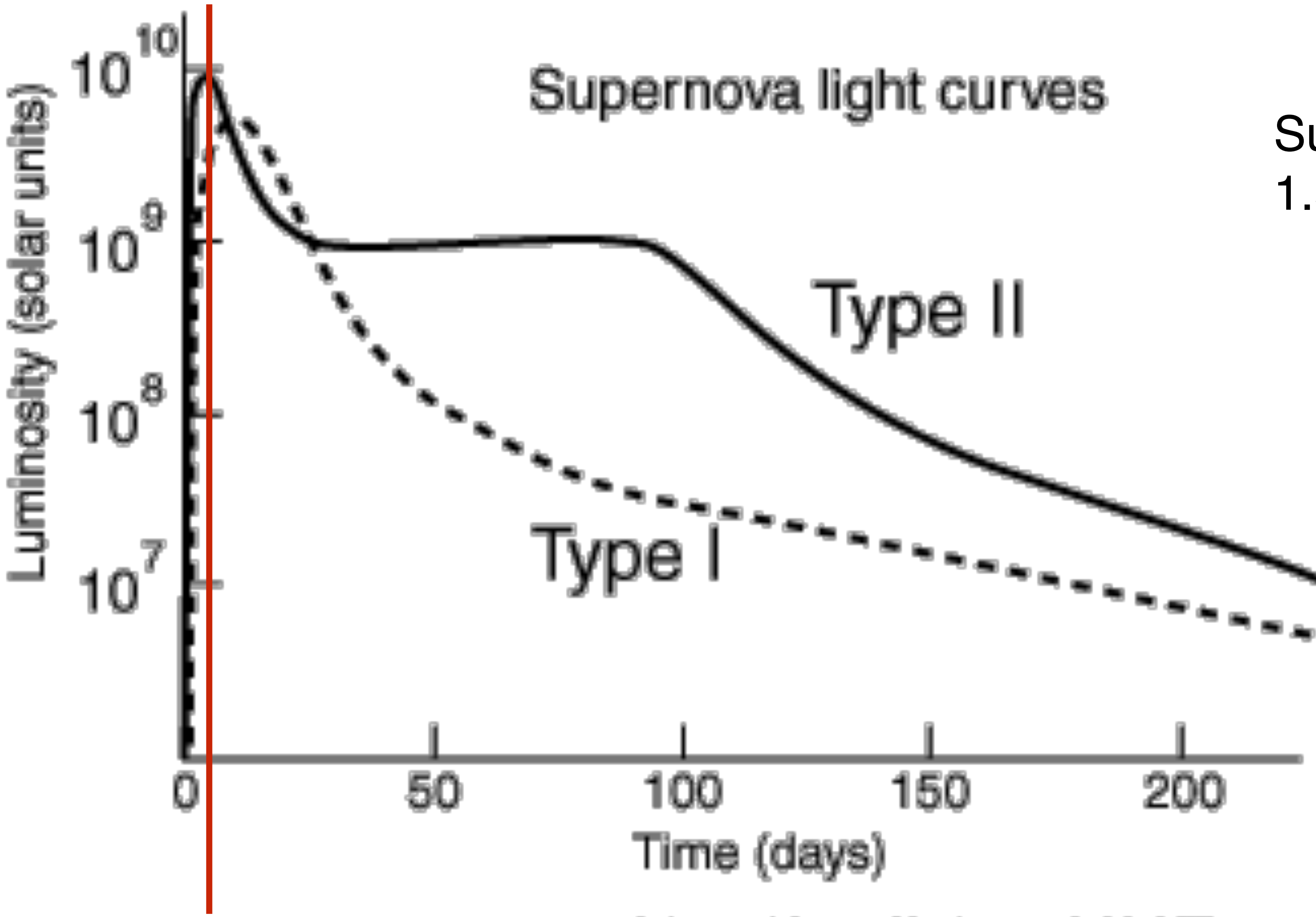
Pan-STARRS1(PS1) 3.3 degree FOV

Subaru Hyper-Suprime-Cam (HSC): 1.5 degree FOV



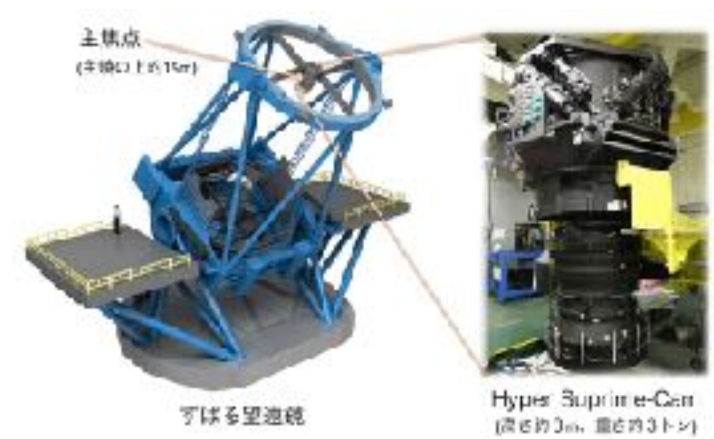
# Follow-up Observations

- The time delay between neutrinos and SN explosion: A few hours.




Adapted from Chaisson & McMillan

Subaru Hyper-Suprime-Cam (HSC):
1.5 degree FOV



# Summary

- 1. The choked jet neutrinos from SNII can explain the neutrino flux observed by IceCube under the constraint of the diffuse GeV gamma-ray background.

- 2. We propose to search for SNII following single neutrinos/multiplets observed by IceCube.

Thank you!