Ultrahigh energy cosmic-rays and neutrinos from neutron-star mergers

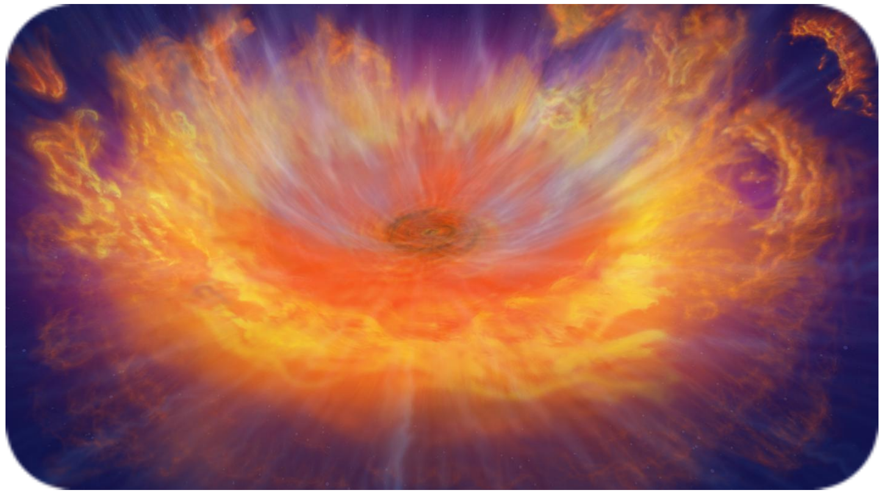
Valentin Decoene,
Claire Guépin, Ke Fang, Kumiko Kotera, Brian D. Metzger

PNHE 2018

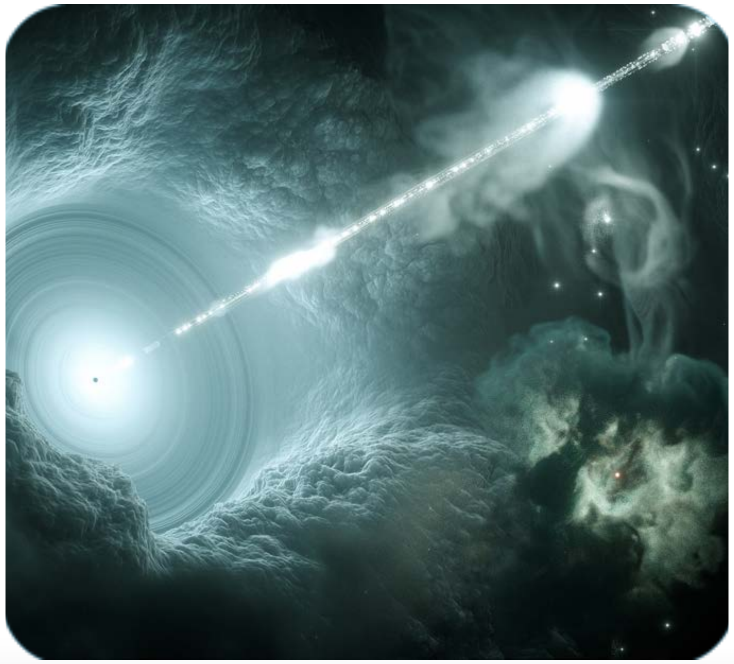
SORBONNE UNIVERSITÉ

GW170817 → First multi-messenger observation : GW + EM

What about UHECR and Neutrinos ?



TXS 0506+056 → No GW

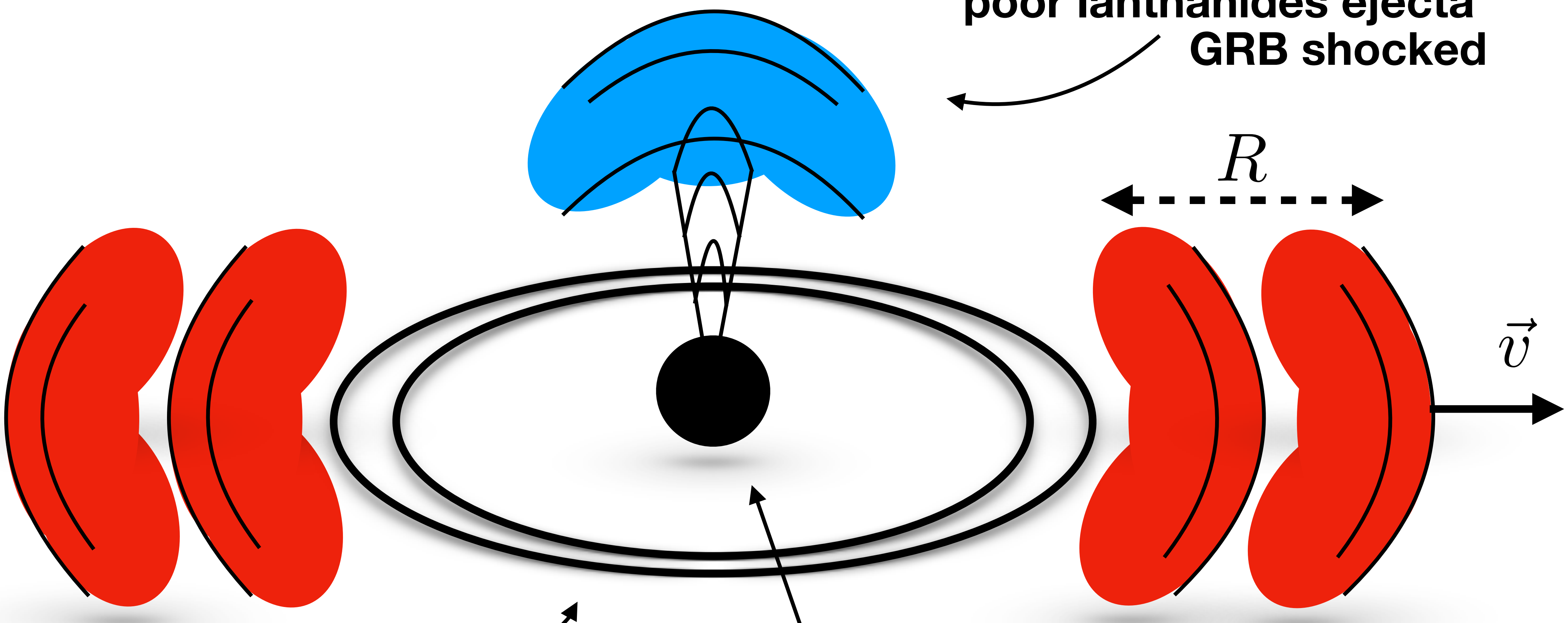


All multi-messenger : GW + neutrinos + EM + UHCR

Possible ?
Which distance ?

Neutron star merger structure

Blue Kilo-Novae: polar ejecta
poor lanthanides ejecta
GRB shocked

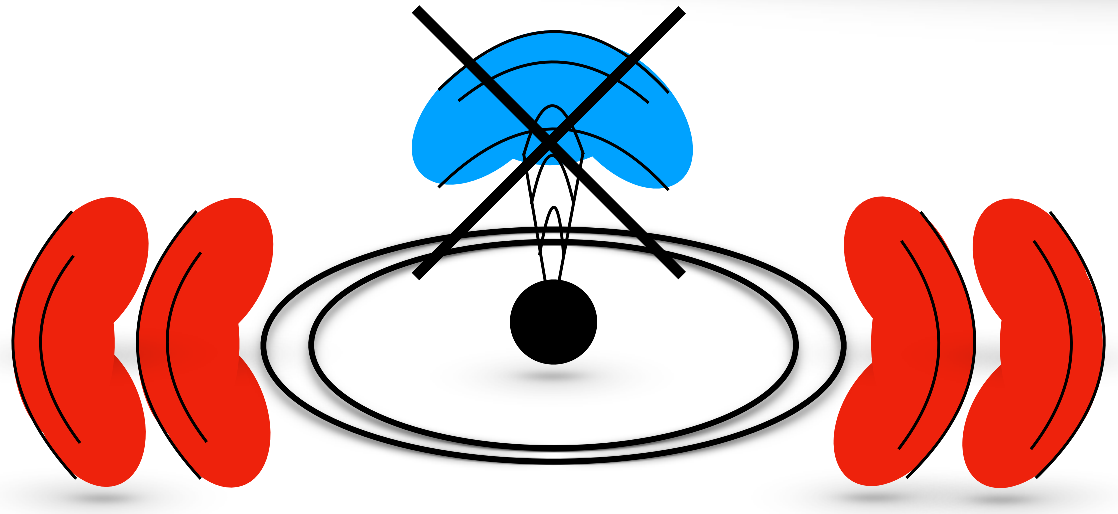


Accretion disk

Black-Hole

Fall-back heating
starting 0.1s after merger

Red Kilo-Novae: equatorial ejecta
Rich lanthanides ejecta
Nuclear heating starting 1.3s after merger



Particle accelerations and escape via blue side = similar to GRB studies (e.g., Zhang et al. 2016, Baerwald et al. 2016, …)

Alternative scenario: acceleration in wind

$$B_{\rm disk} = 10^{15}\ {\rm G}$$ *Siegel et al. 2017*

$$R_{\rm disk} = 10^{5}\ {\rm cm}$$

Successful acceleration : $t_{\rm acc} < t_{\rm dyn}$

$$t_{\rm acc} = 1.6 \times 10^{-11}\ {\rm s}\ E_{18}\, \eta_{0.1}\, B_{15}^{-1} Z_1^{-1} \quad < \quad t_{\rm dyn} = 3.3 \times 10^{-6}\ {\rm s}\ R_5$$

acceleration efficiency ($\eta_{0.1}$)

charge number (Z_1)

$$\longrightarrow \quad E_{\rm max} \approx 10^{22}\ {\rm eV}\ \eta_{0.1}^{-1} R_5 Z_1 B_{15}$$

Thermodynamical equilibrium

$$\frac{d\mathcal{E}}{dt} = -\frac{\mathcal{E}}{R}\frac{dR}{dt} - \frac{\mathcal{E}}{t_{\rm esc}} + \dot{Q}_{\rm r} + \dot{Q}_{\rm fb}$$

Mechanical losses | Radiative losses | Radioactive source | Fall-back source

$$t_{\rm esc} \approx (\tau + 1)\frac{R}{c} = \left(\frac{3M\kappa}{4\pi R^2} + 1\right)\frac{R}{c}$$

Opacity (lanthanides)

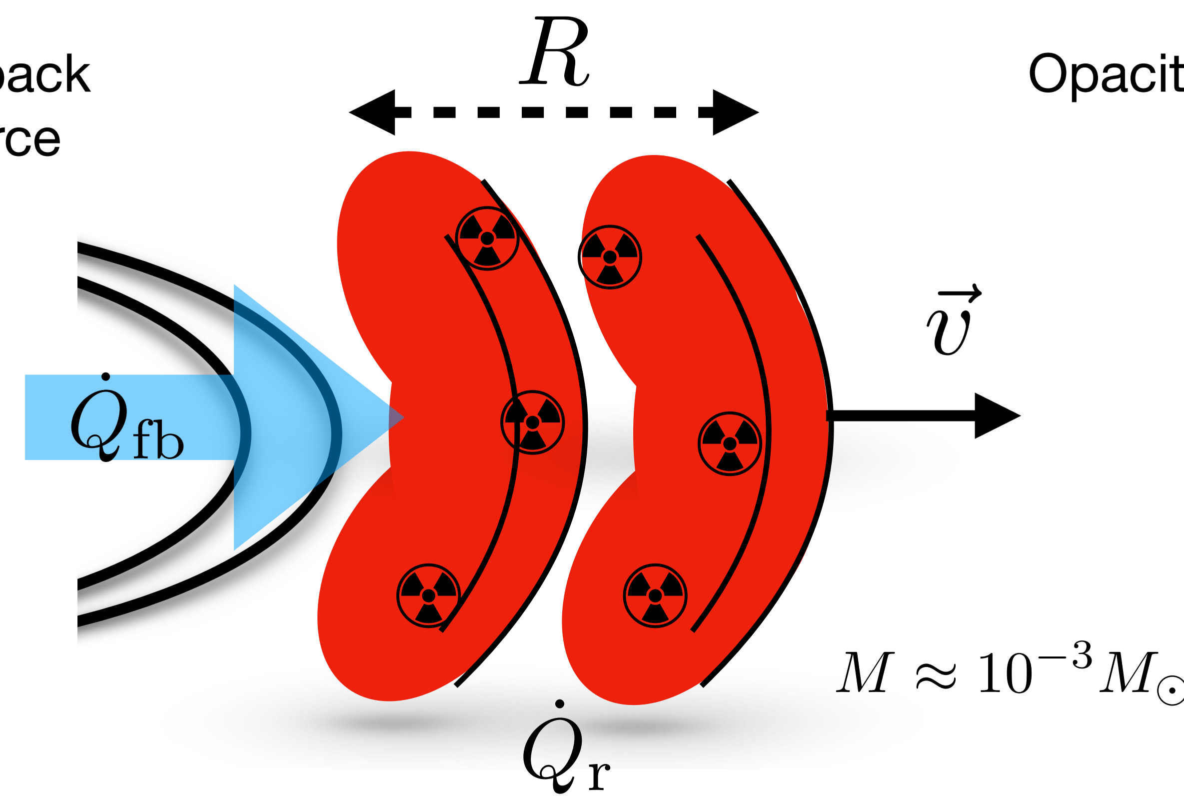
Metzger et al. 2011

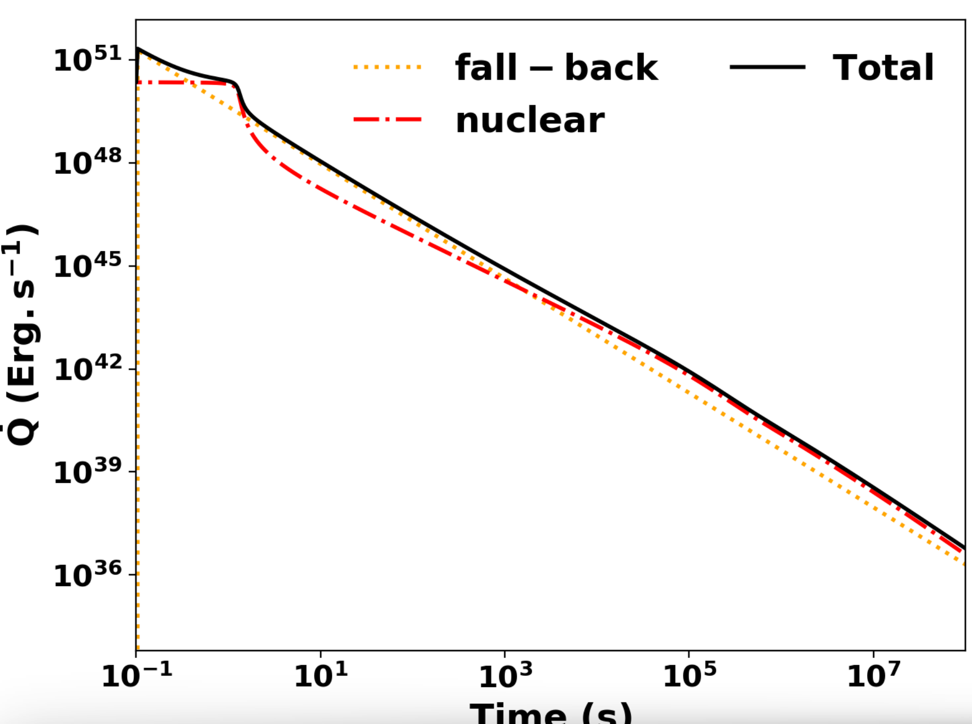
Fall-back

Mass accretion rate

$$\dot{Q}_{\rm fb} = \epsilon_{\rm fb}\dot{M}_{\rm fb}c^2$$

$$= 2\times 10^{51}\ {\rm Erg.s^{-1}}\ \epsilon_{\rm fb,0.1}\dot{M}_{\rm fb,-3}(0.1{\rm s})\,t_{0.1}^{-5/3}$$





Nuclear reaction

Nuclear mass energy

$$\dot{Q}_{\rm r} = M\,X_{\rm r}\,\dot{e}_{\rm r}(t)$$

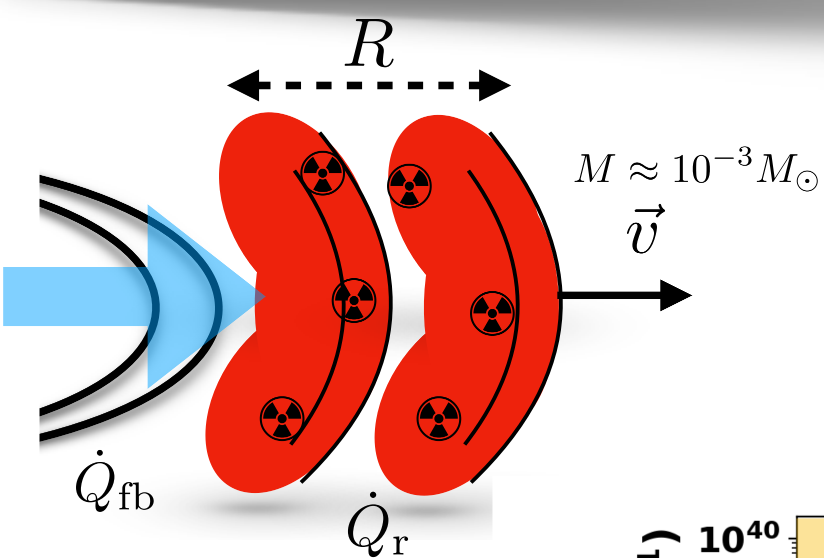
Mass fraction of lanthanides

$$\dot{e}_{\rm r}(t) = 4\times 10^{18}\ {\rm Erg.s^{-1}.g^{-1}}\ \epsilon_{\rm th}(t)\,f(t;t_0,\sigma)$$

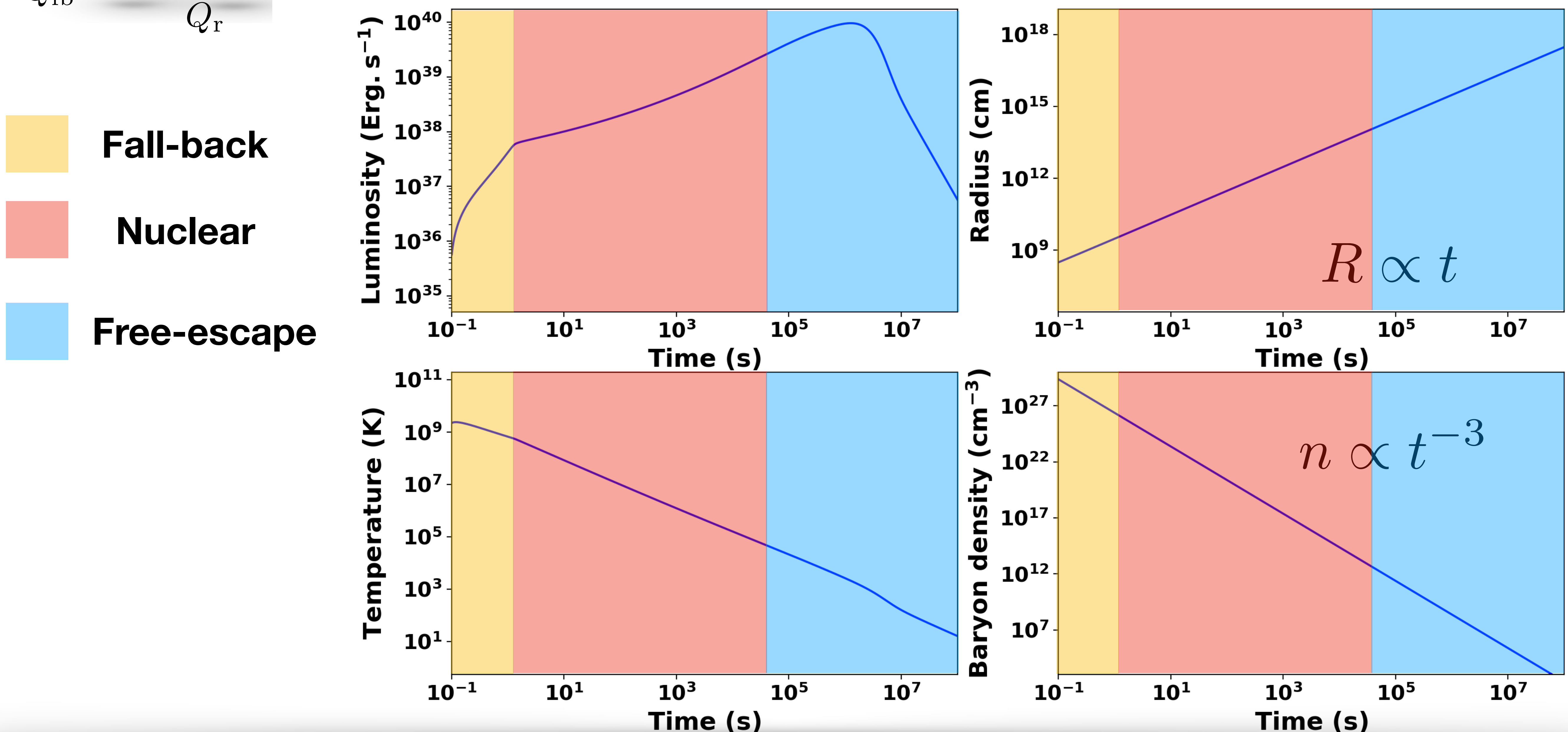
$$t_0 = 1.3 \text{ and } \sigma = 0.11$$

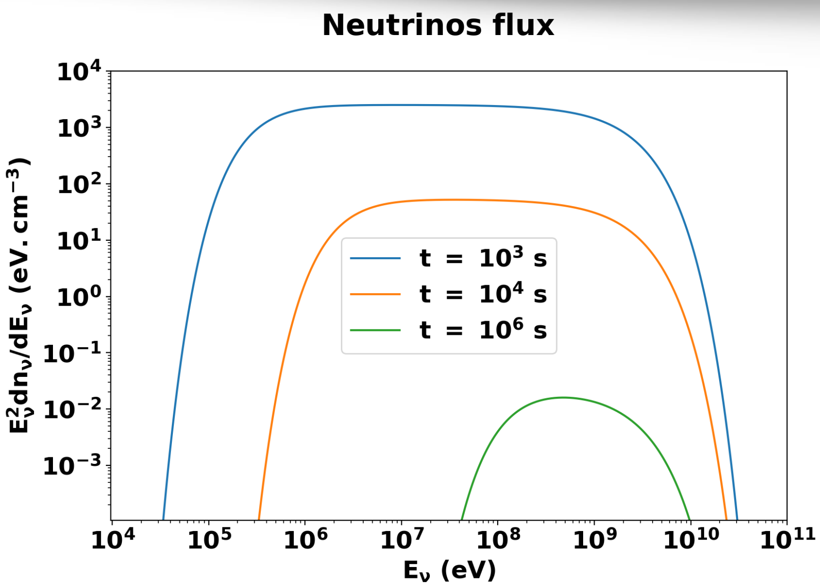
Thermal efficiency

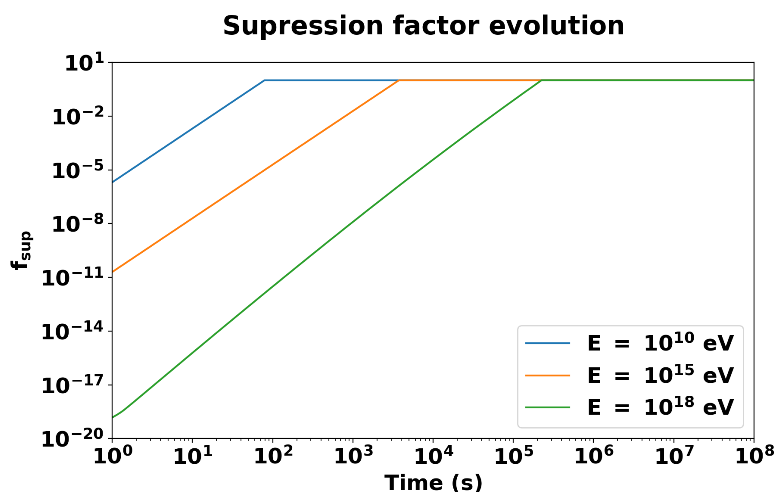
Barnes et al. 2016, M. R. Drout et al, 2017

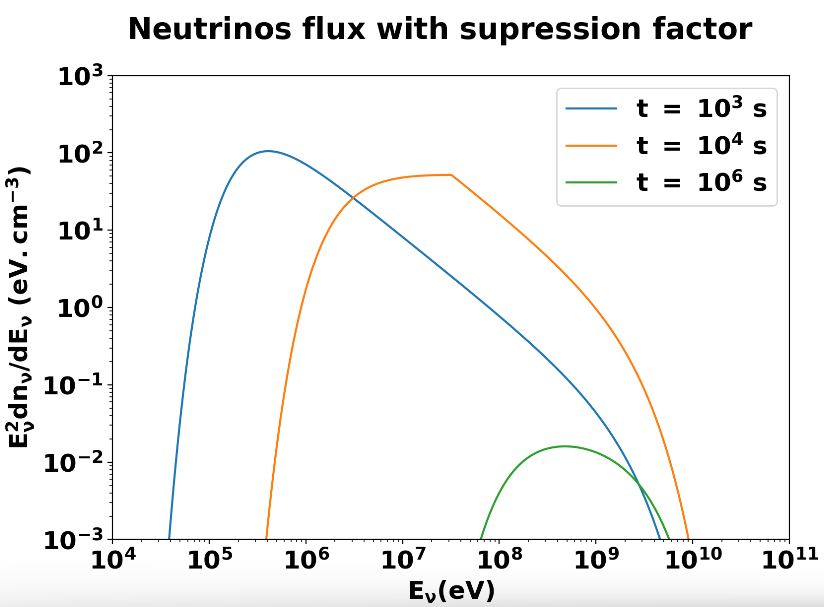


$$\frac{d\mathcal{E}}{dt} = -\frac{\mathcal{E}}{R}\frac{dR}{dt} - \frac{\mathcal{E}}{t_{\rm esc}} + \dot{Q}_{\rm r} + \dot{Q}_{\rm fb}$$









Monte-Carlo propagation code

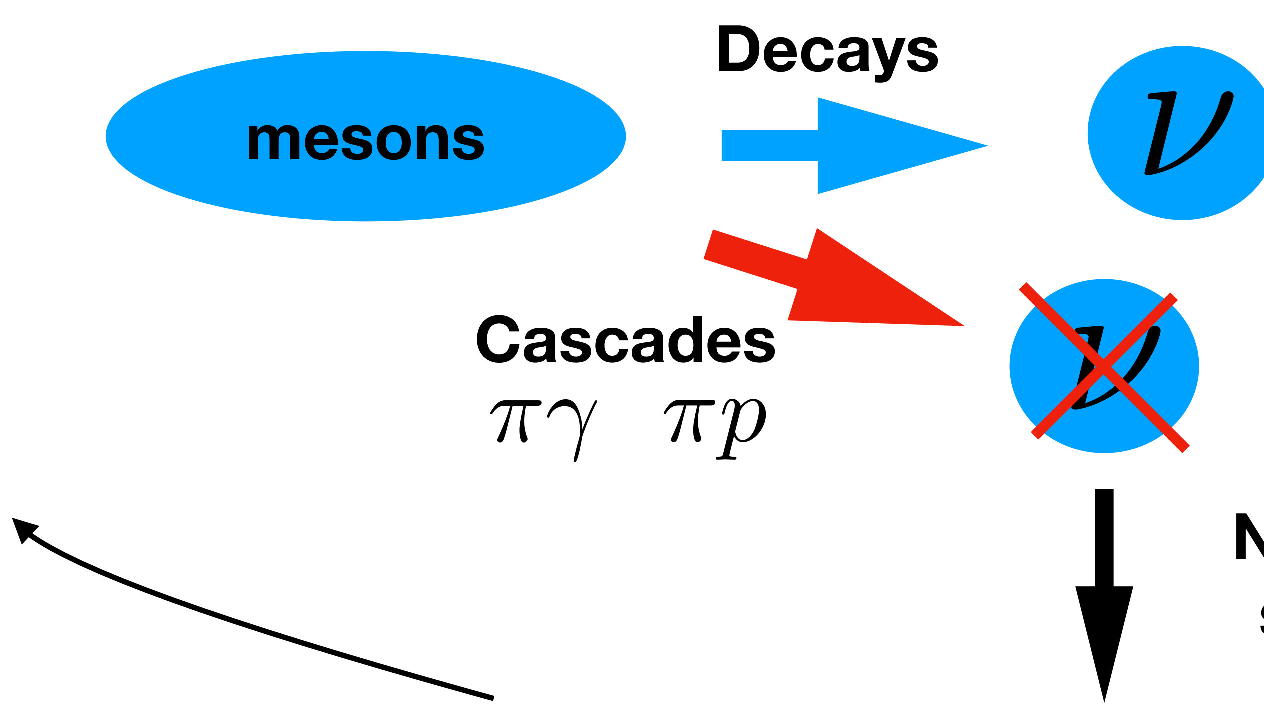
Kotera et al. 2009, Guépin et al. 2017

EPOS/SOPHIA tables interactions

Cooling processes

Synchrotron, Inverse Compton

mesons cascades



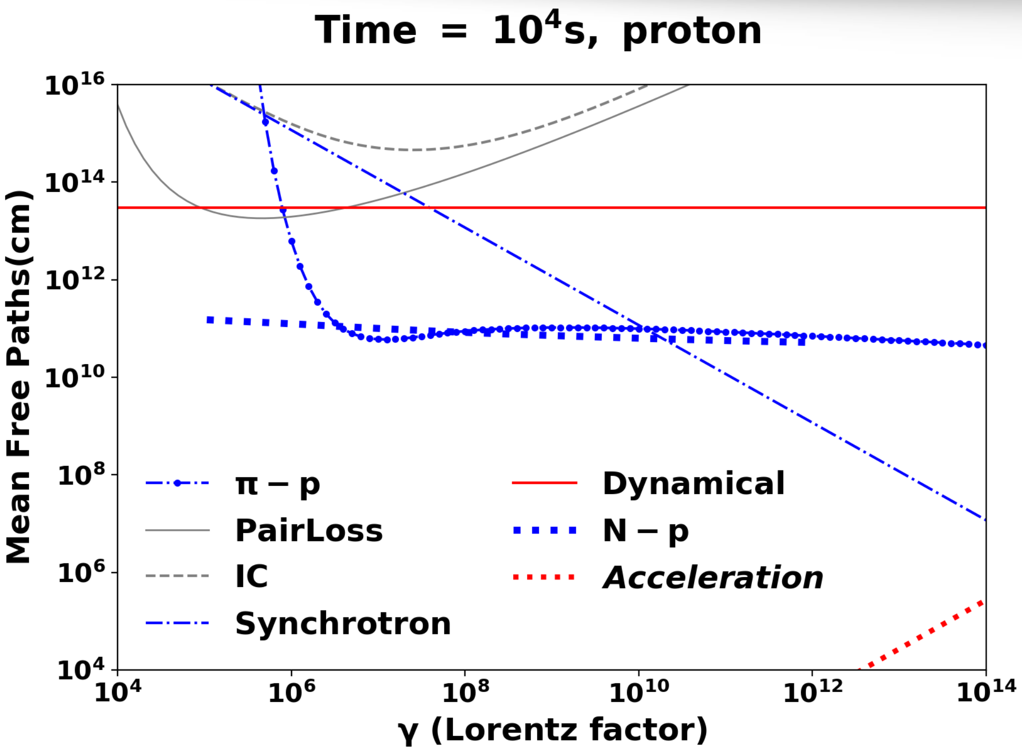
Neutrinos flux suppression

$$f_{\rm sup} = \min\left[1, \left(\left(\frac{t_{\pi,p}}{\gamma_\pi \tau_\pi}\right)^{-1} + \left(\frac{t_{\pi,\gamma}}{\gamma_\pi \tau_\pi}\right)^{-1} + \left(\frac{t_{\rm sync}}{\gamma_\pi \tau_\pi}\right)^{-1}\right)^{-1}\right]$$

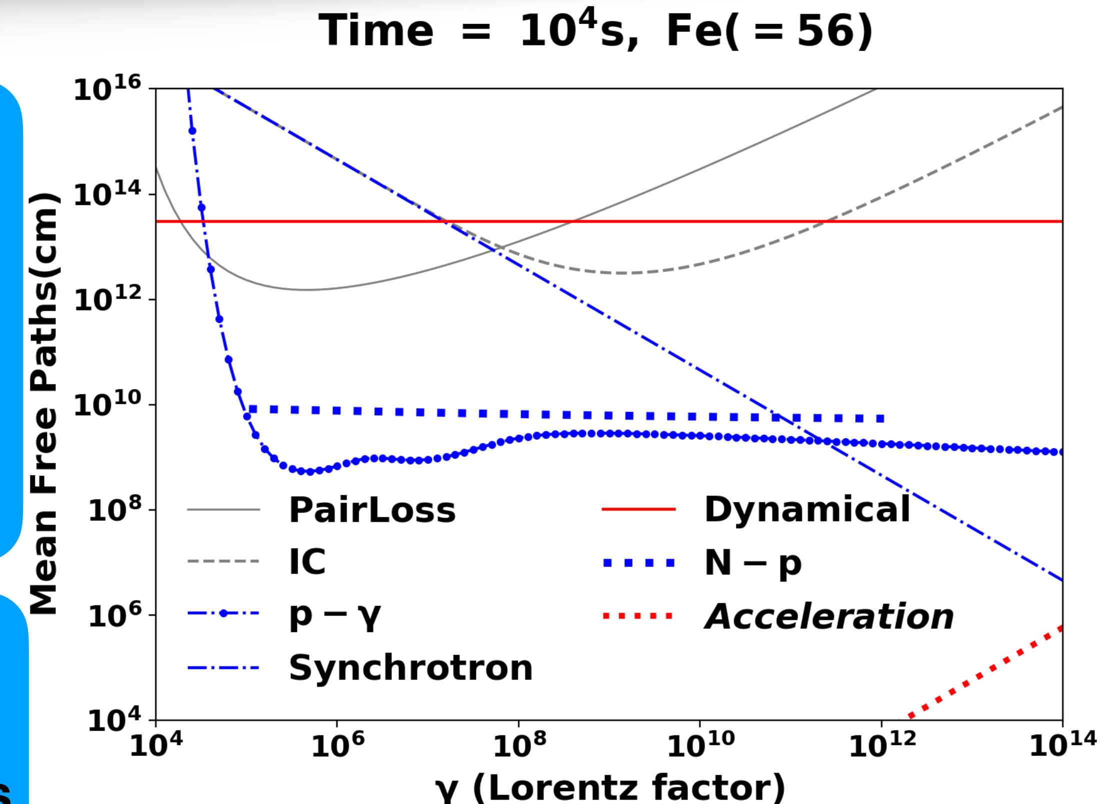
pion-proton interactions | photomeson interactions | synchrotron cooling

Fang et al. 2016

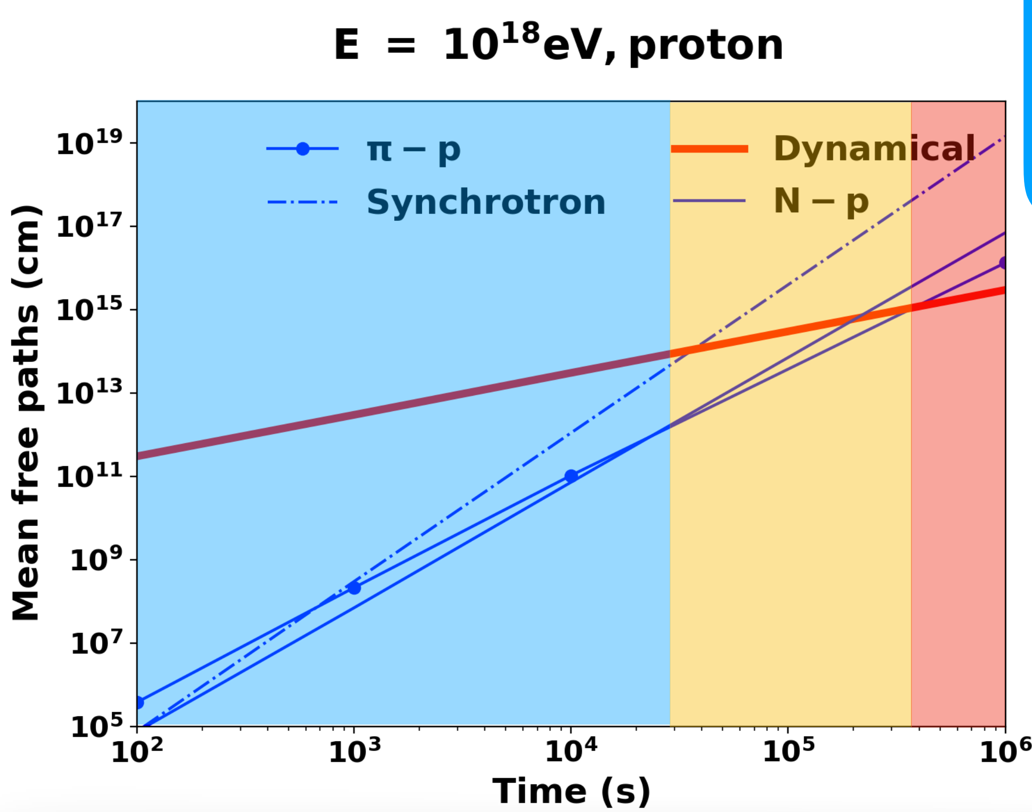
Interaction background



UHECR production efficiency : competition between background density (escape rate 👍) dynamical expansion (lower energy 👎)



Neutrino production efficiency : interactions efficiencies (👍) mesons cascades (suppression factor 👎)

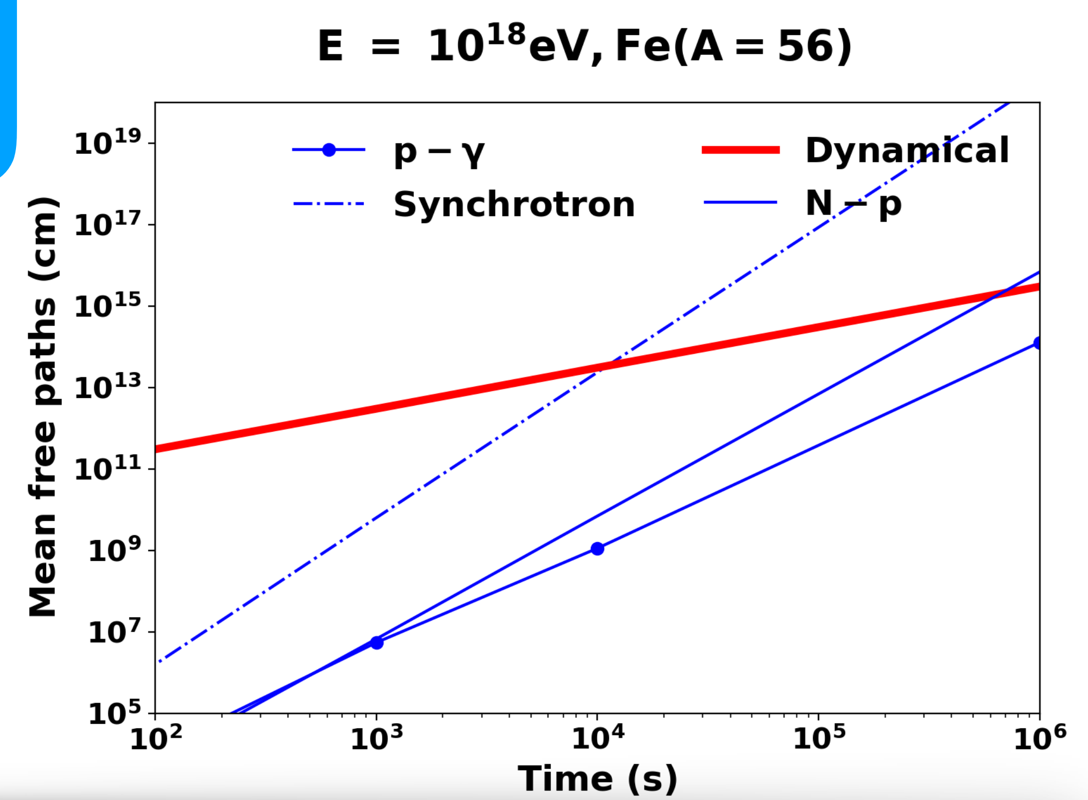


Ideal neutrino production time

$$\approx 10^4 \text{ s}$$

proton-proton dominant

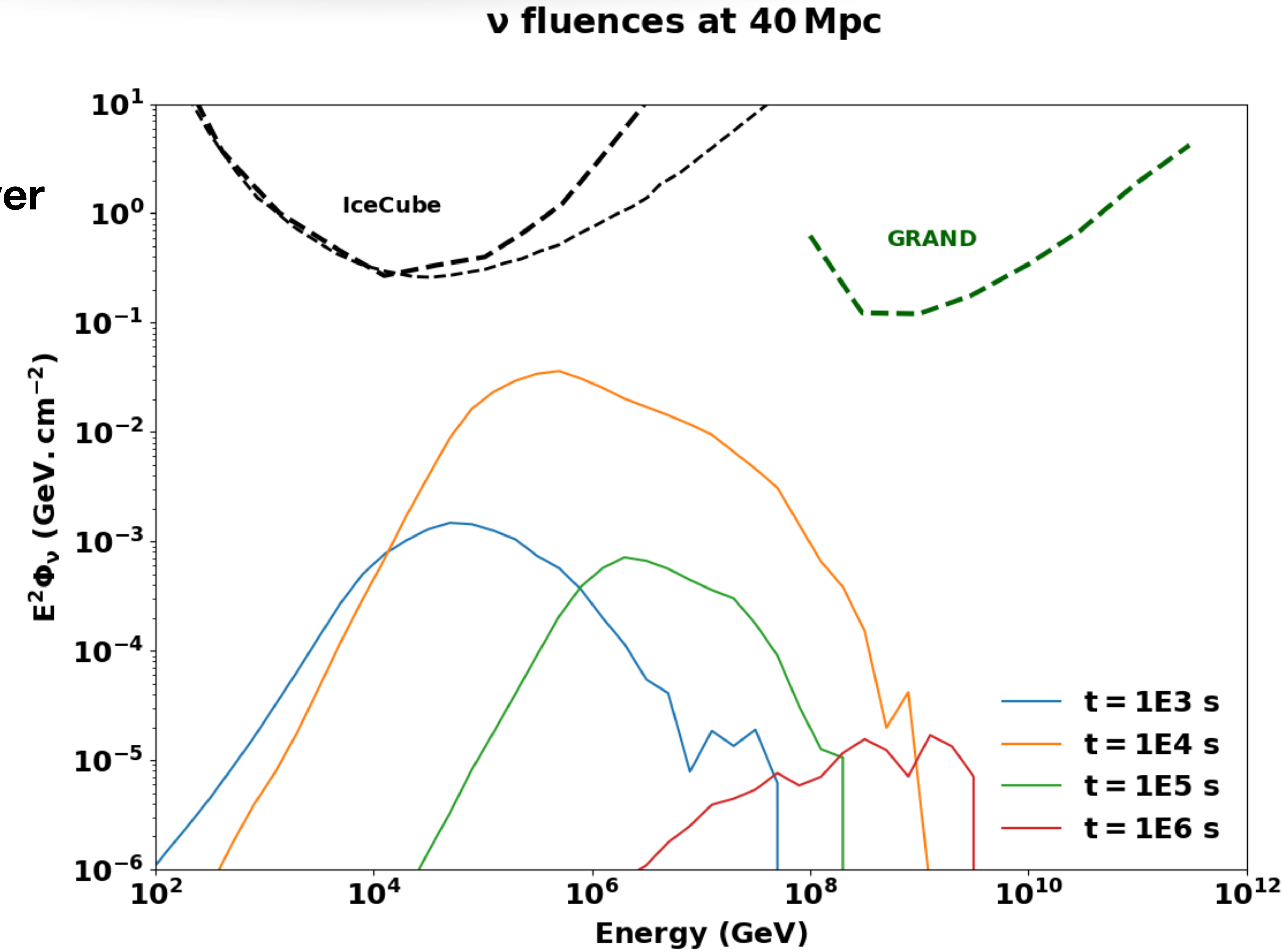
Photomeson dominant



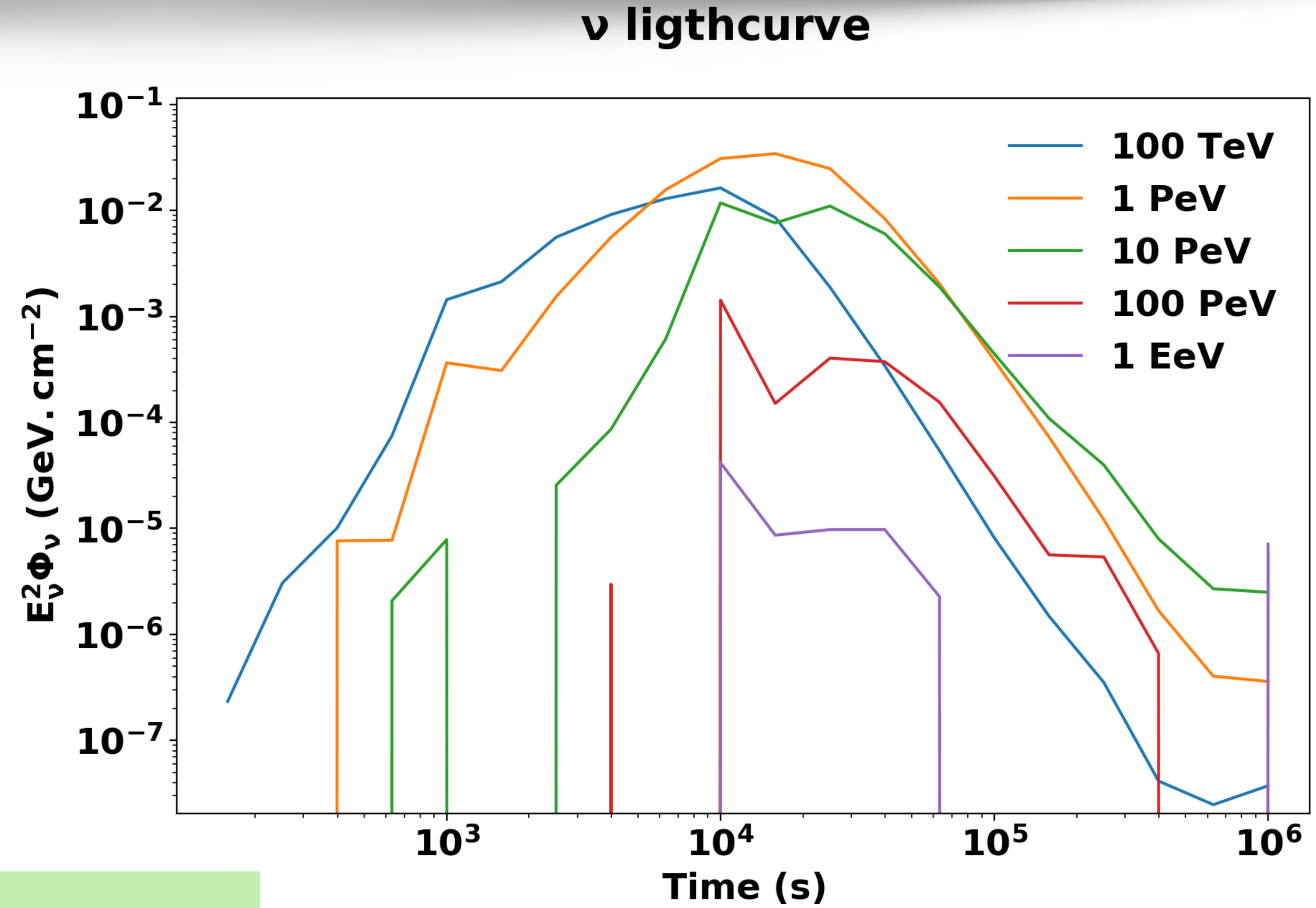
Case of GW170817 distance to the observer ≈ 40 Mpc

Ideal neutrino production time

$\approx 10^4$ s

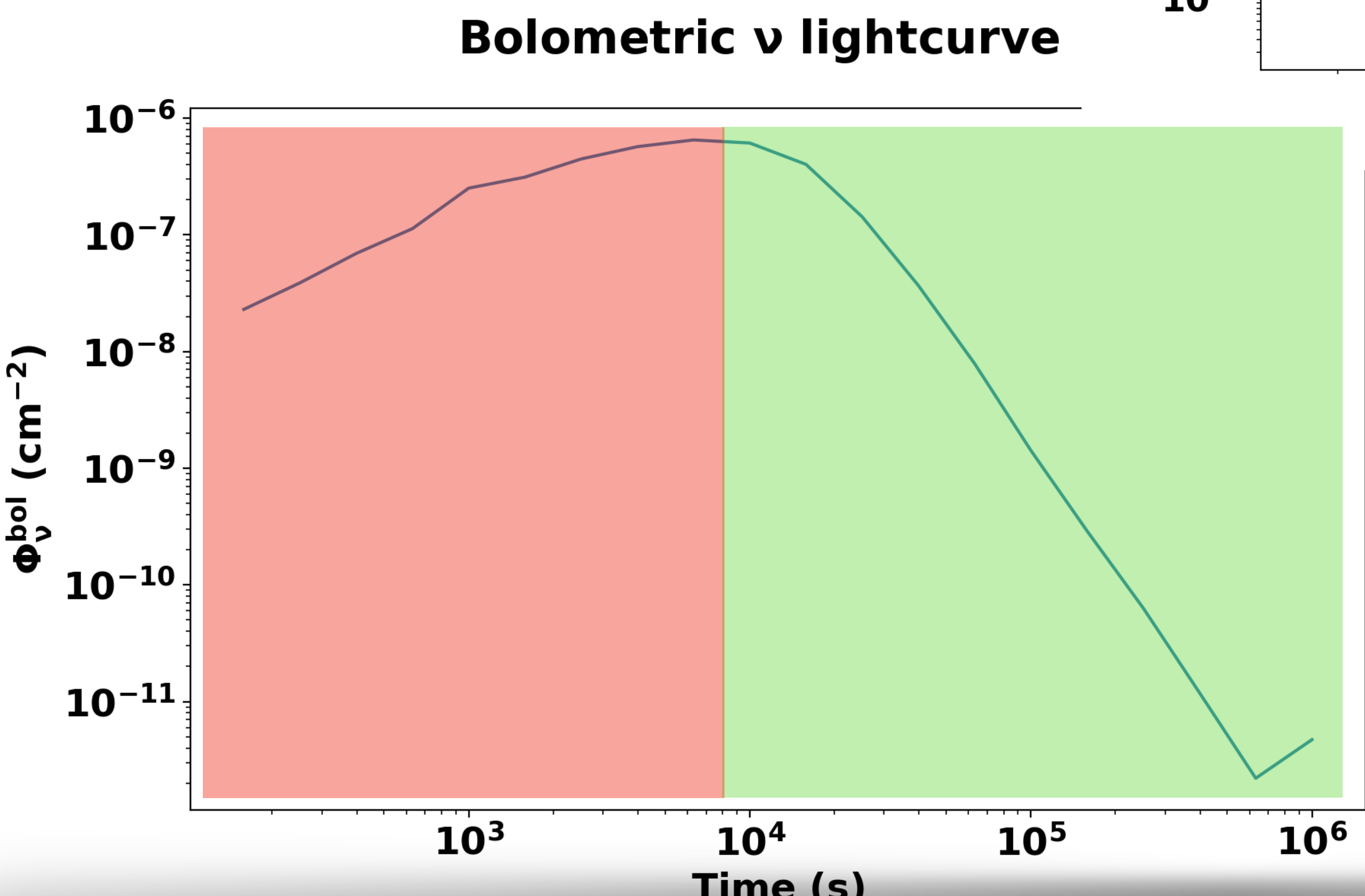


Higher emission around PeV energies



Higher neutrinos luminosity at

$\approx 10^4$ s

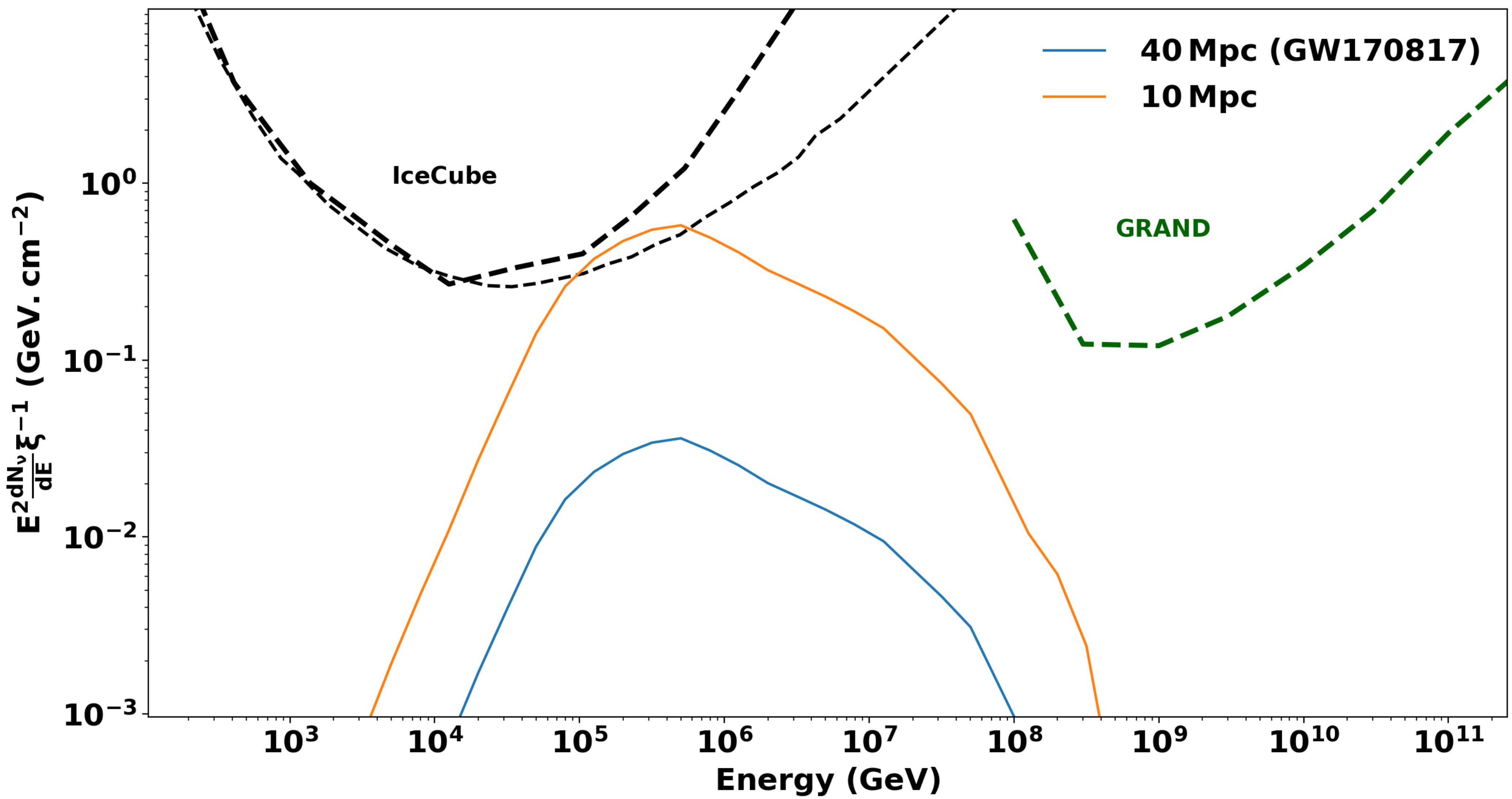


meson cascades

background dilution

Competition between interactions efficiency and meson cascades

All flavor ν fluence at 10^4s



Aartsen et al. 2015, Fang et al. 2017

NS merger rate at 10 Mpc

$$r = 1.540^{+3.200}_{-1.220}\, 10^{-2}\ \mathrm{yr}^{-1}$$

Abbott et al. 2017c

→ **1 every 66 years**

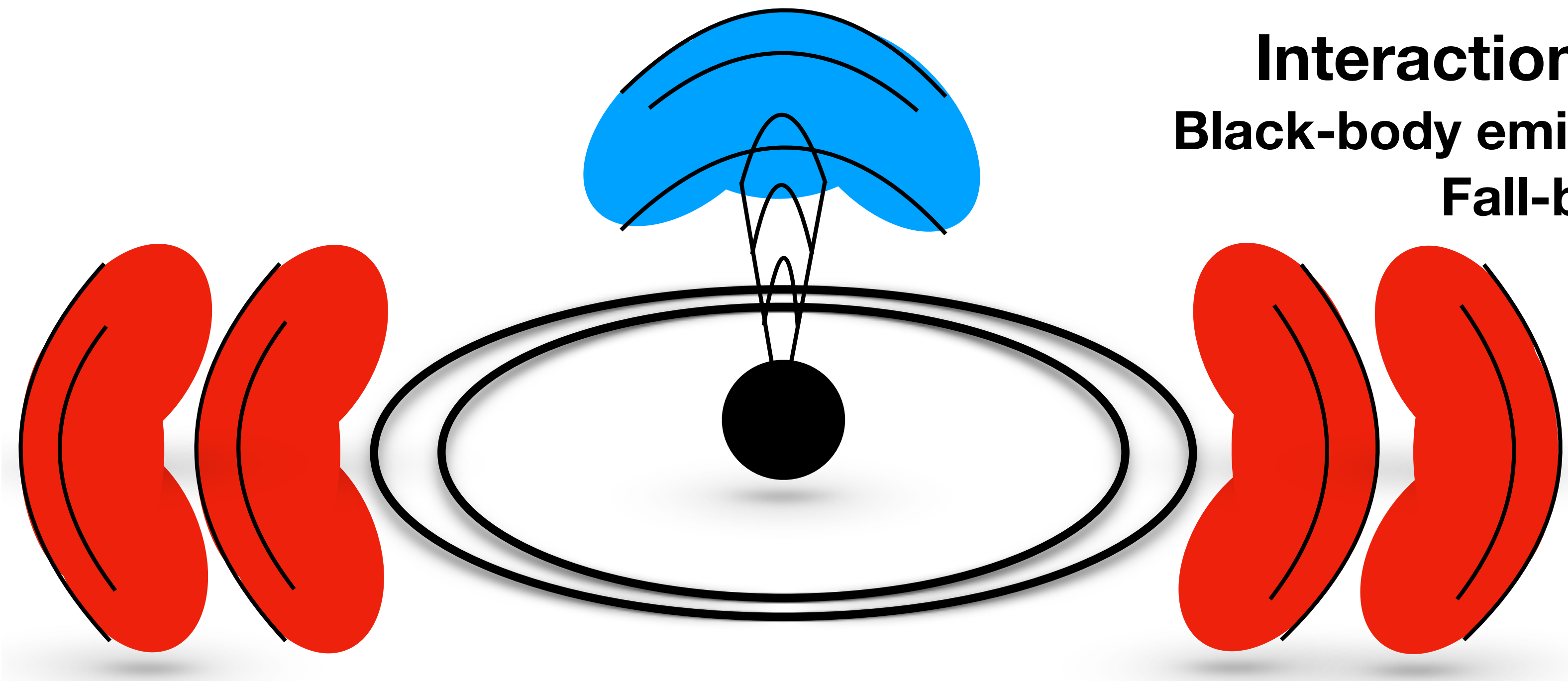
Summary

Neutrons star merger model for the ejecta

Red Kilo-novae -> equatorial plane
Rich lanthanides ejecta -> heavy r-process

Interactions background model

Black-body emission from nuclear reactions
Fall-back from the disk



Particle interactions and propagations

Mean free paths inside the ejecta
Numerical propagation

Disk acceleration of UHECR particles

Outflows coming from the disk
Targeting the equatorial ejecta

Neutrinos fluence

Observable around a few hours with IceCube at 10 Mpc

Neutrinos lightcurves

Neutrinos follow-up of the KN evolution