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

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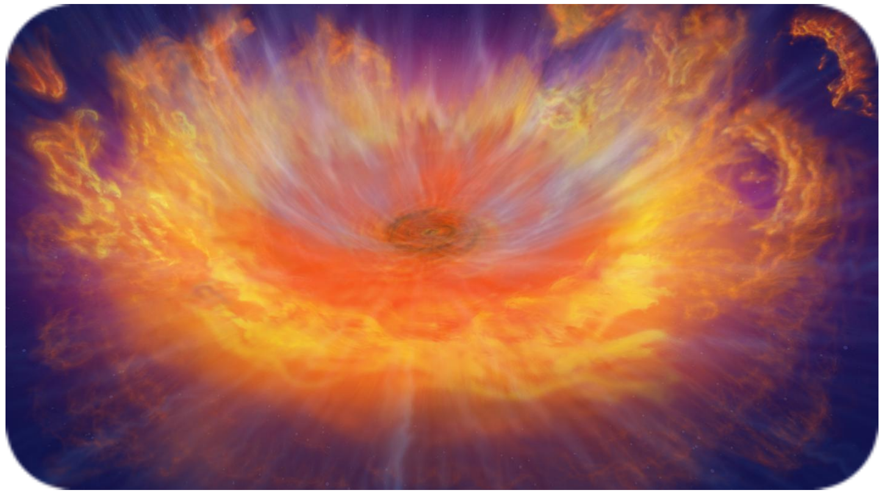
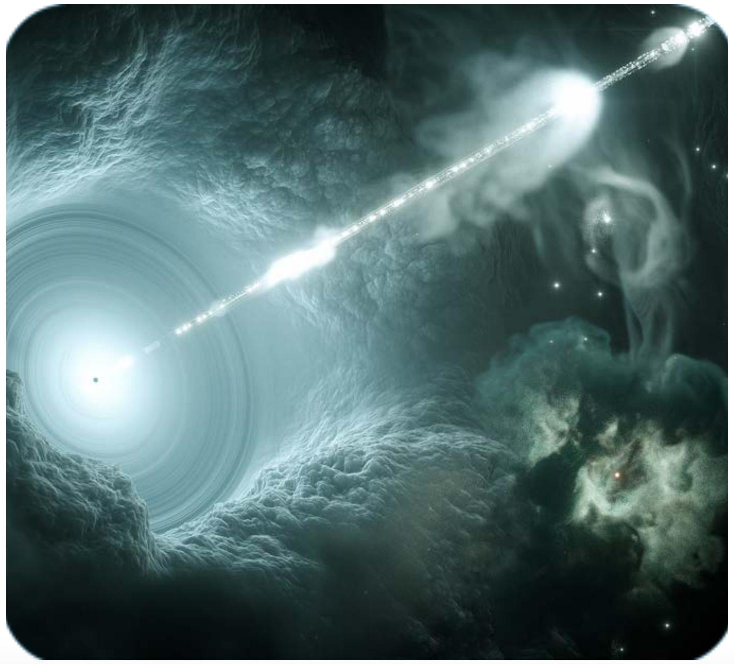
UHECR 2018

GW170817 → **First multi-messenger observation : GW + EM**

What about UHECR and Neutrinos ?



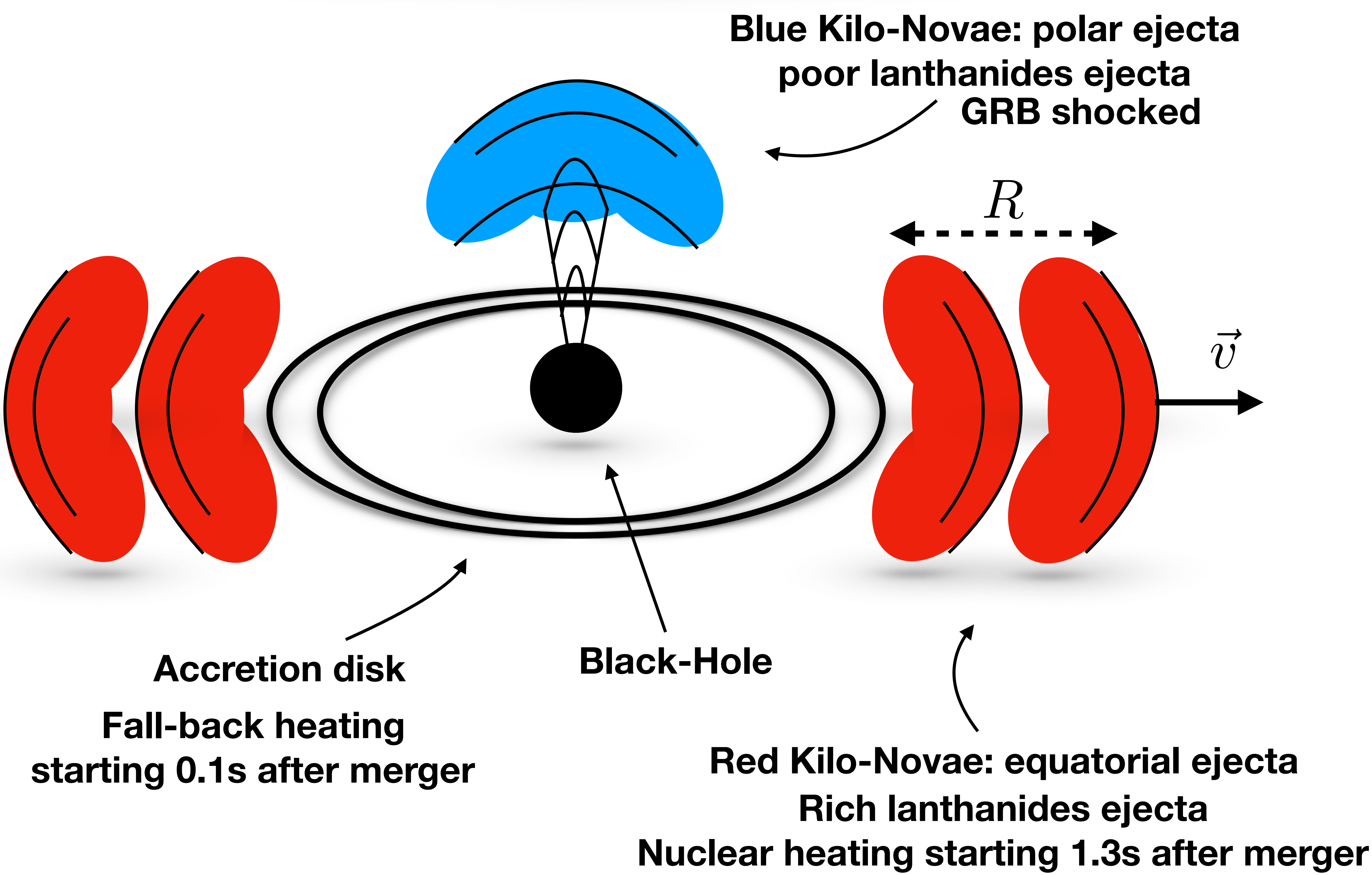
TXS 0506+056 → **No GW**

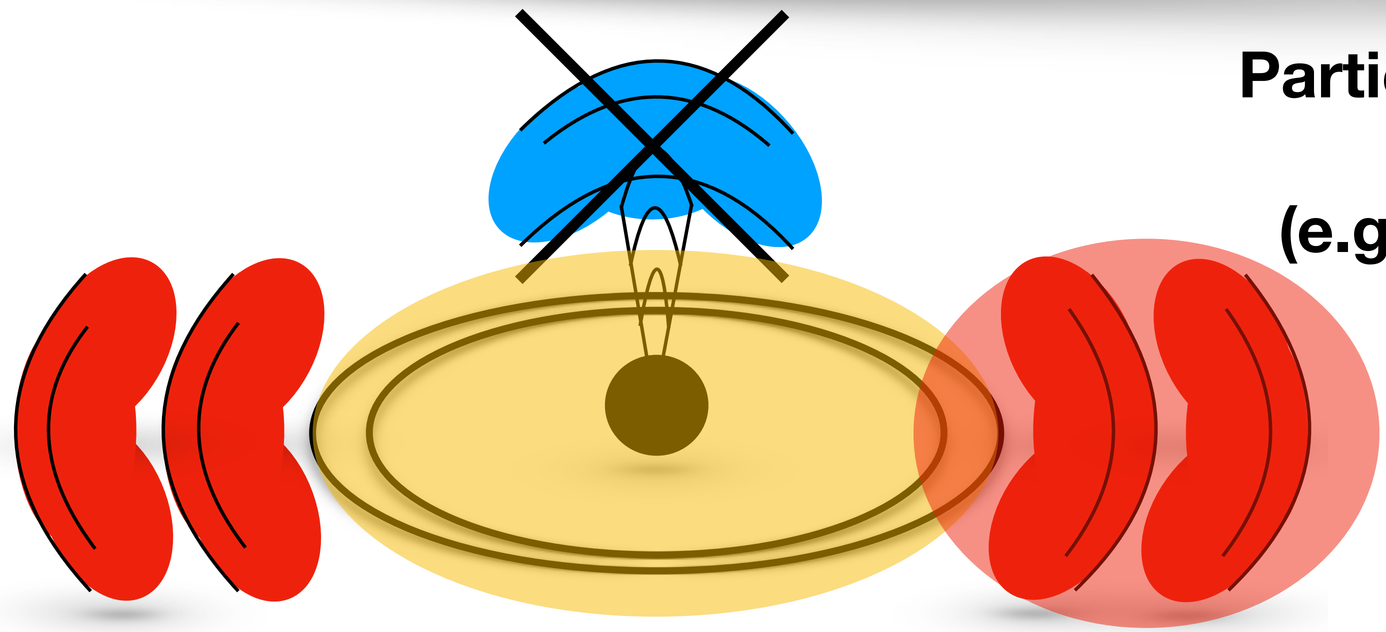


All multi-messenger : GW + neutrinos + EM + UHCR

Possible ?
Which distance ?

Neutron star merger structure





2 zones model

Particle accelerations and escape via blue side = similar to GRB studies (e.g., Zhang et al. 2016, Baerwald et al. 2016, Kimura et al. 2018…)

Alternative scenario: acceleration in wind / corona / disk

Examples of possible processes at play for acceleration

Particle acceleration in accretion flow *Kimura et al. 2015*

Electric field acceleration *Levinson 2000*

Magnetic reconnection *Riquelme et al. 2012, Hoshino 2013, 2015*

Stochastic acceleration *Lynn et al. 2014*

We assume UHECR acceleration and focus on interactions in the Kilonova

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)

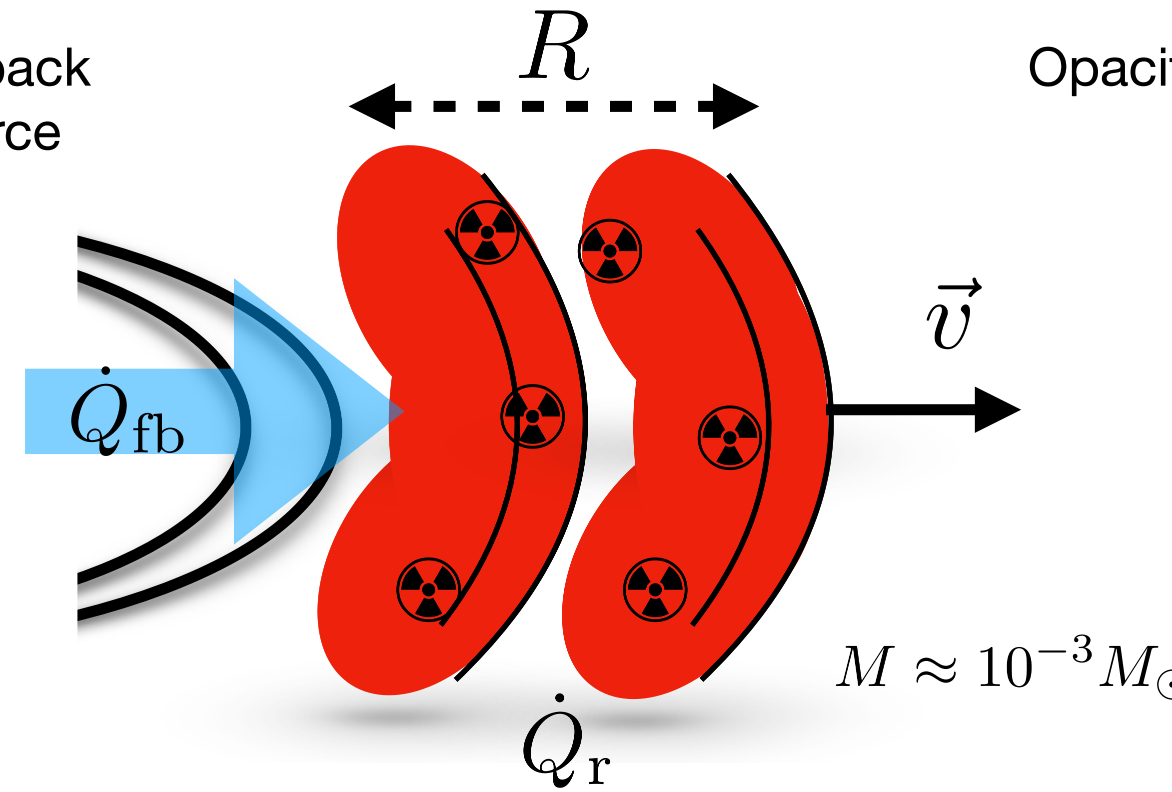
Metzger et al. 2011

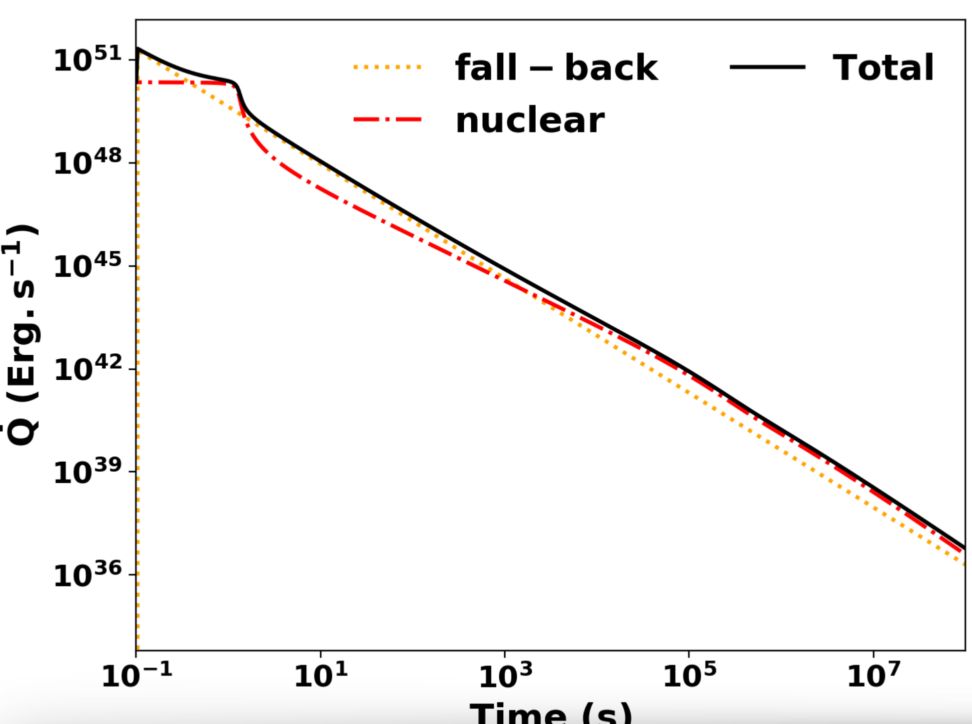
Fall-back

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

Mass accretion rate

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





Nuclear reaction

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

Nuclear mass energy

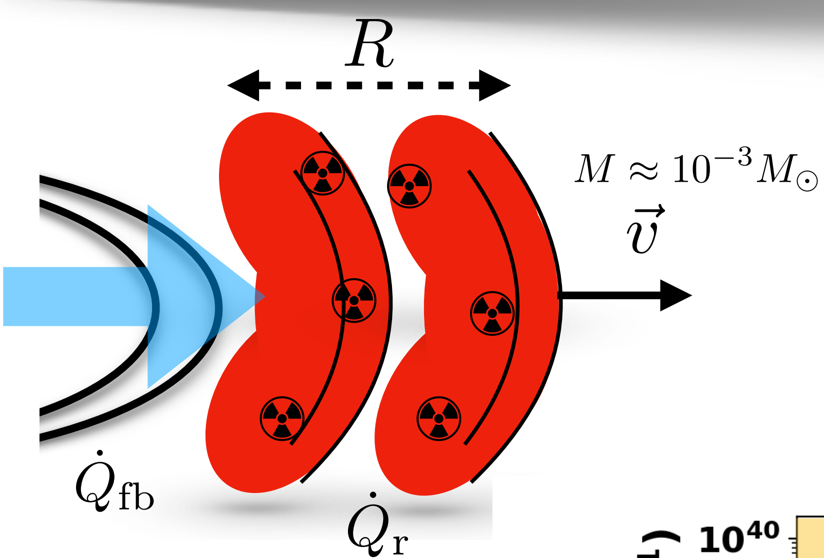
Mass fraction of lanthanides

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

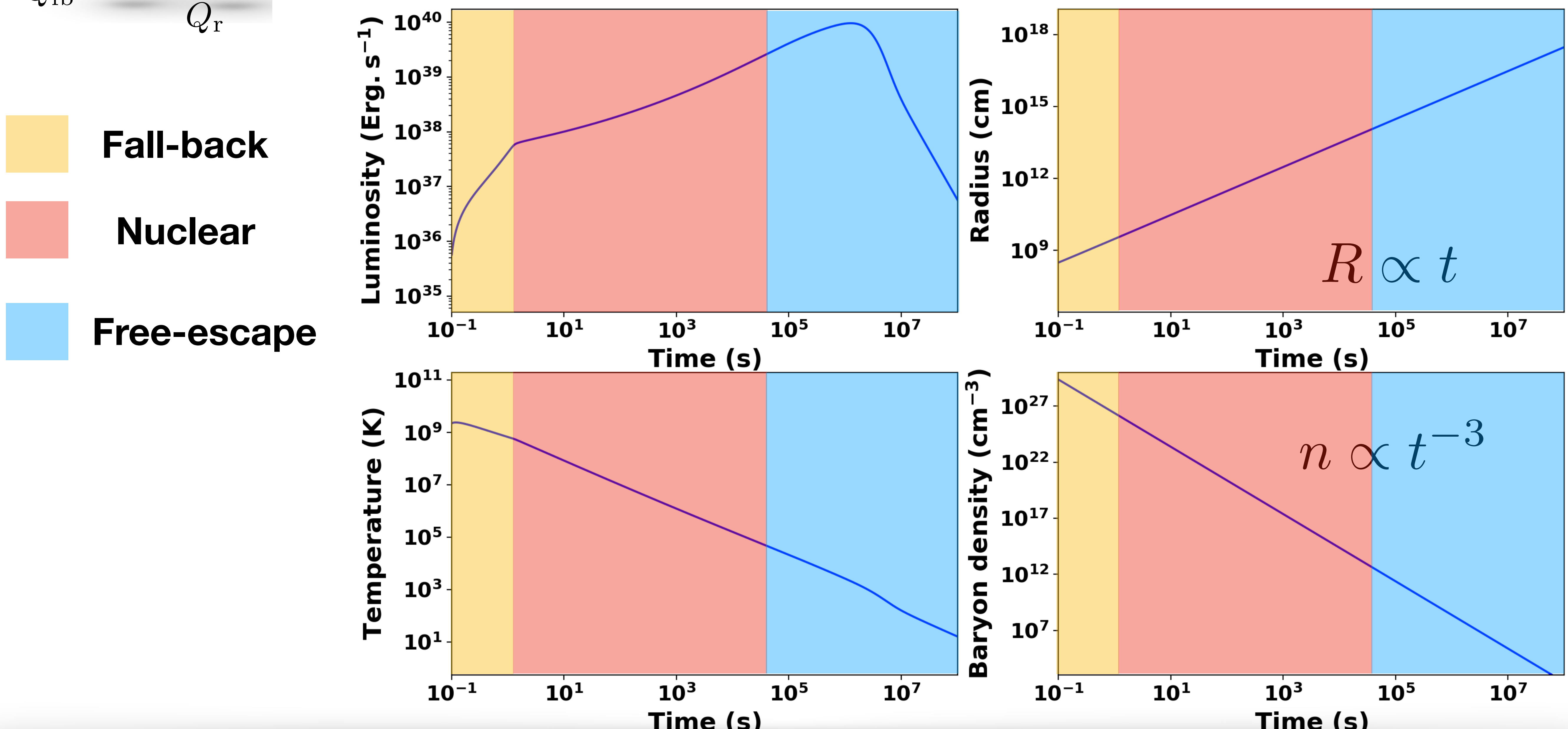
$$t_0 = 1.3 \text{ and } \sigma = 0.11$$

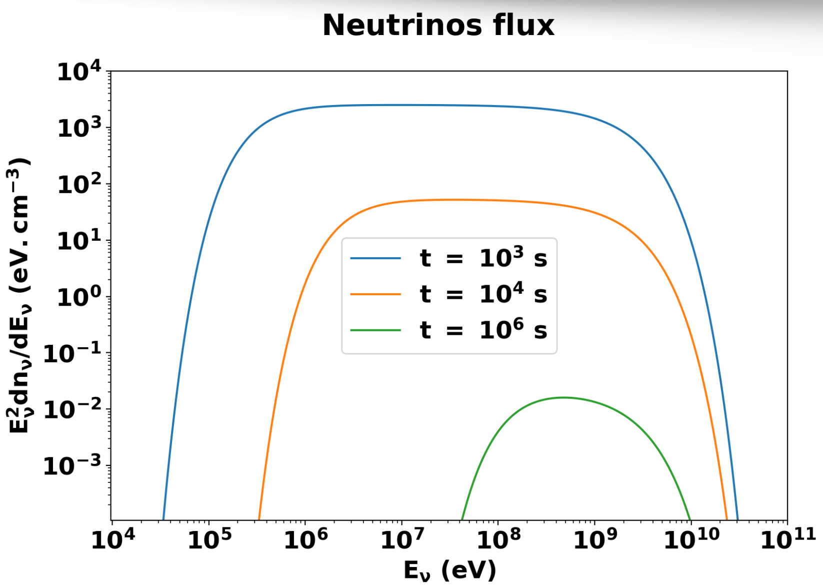
Thermal efficiency

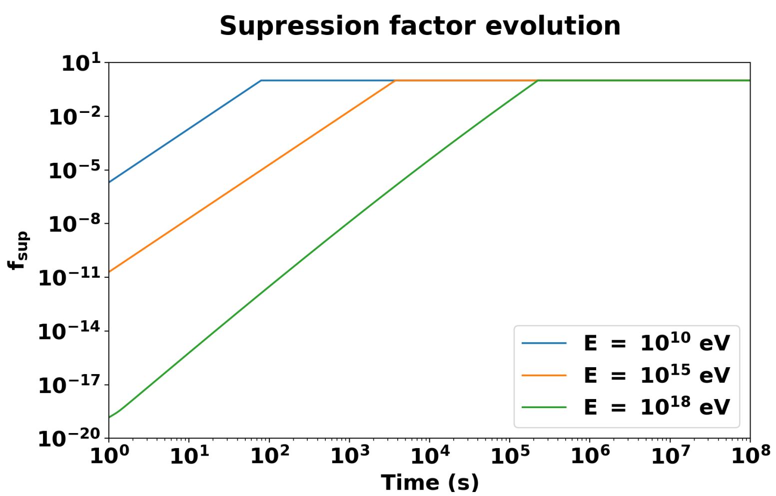
Barnes et al. 2016, M. R. Drout et al, 2017

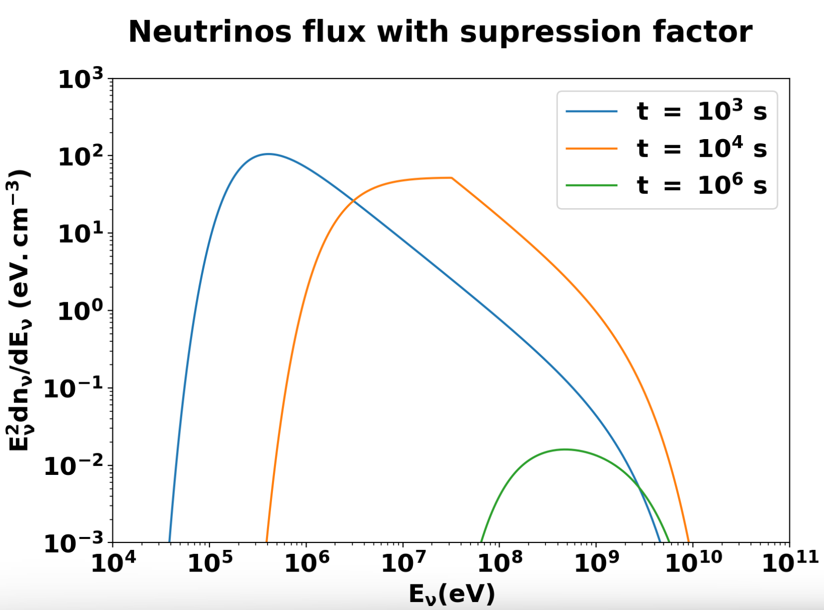


$$\frac{d\mathcal{E}}{dt} = -\frac{\mathcal{E}}{R}\frac{dR}{dt} - \frac{\mathcal{E}}{t_{\rm esc}} + \dot{Q}_{\rm r} + \dot{Q}_{\rm fb}$$









Monte-Carlo propagation code

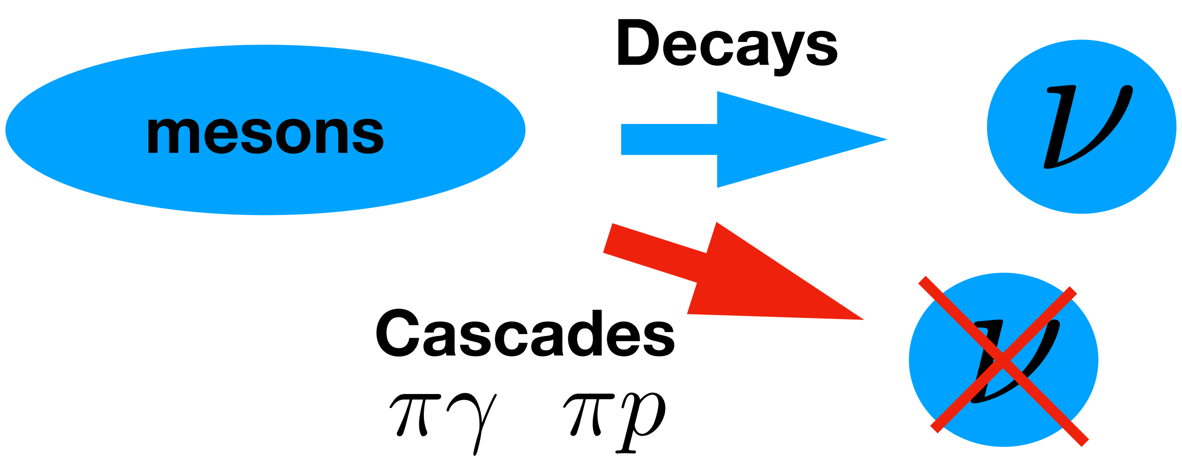
Kotera et al. 2009, Guépin et al. 2017

EPOS/SOPHIA tables interactions

Cooling processes

Synchrotron, Inverse Compton

mesons cascades

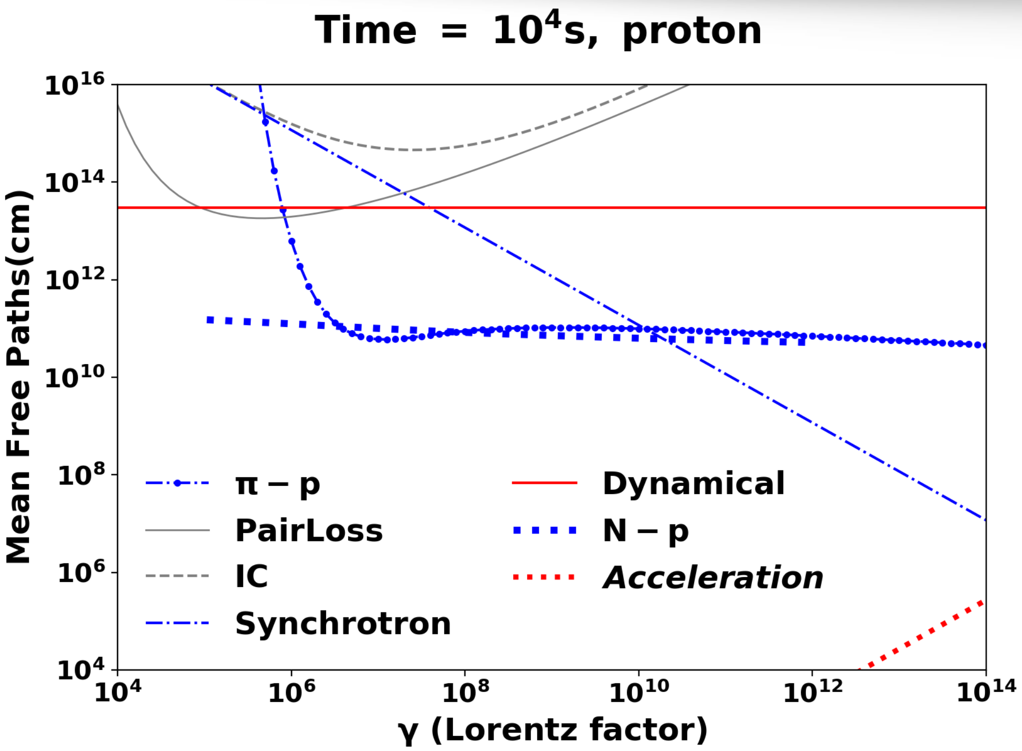


Neutrinos flux suppression

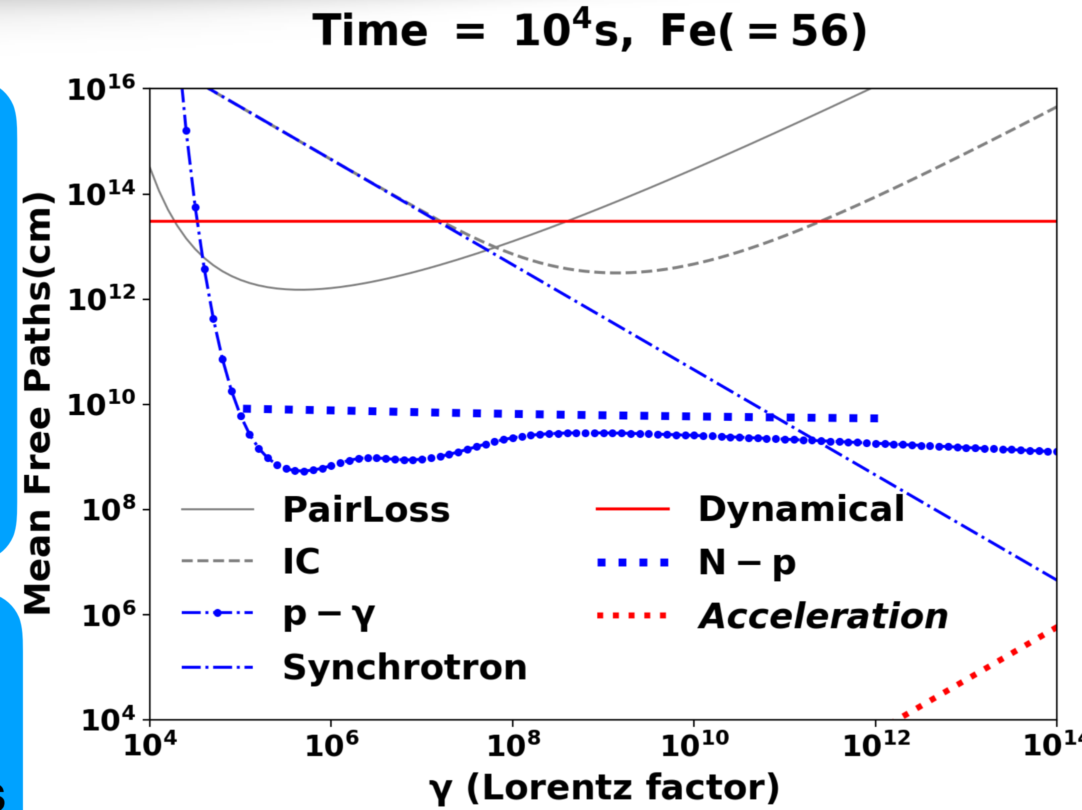
$$f_{\mathrm{sup}} = \min\left[1, \left(\left(\frac{t_{\pi,p}}{\gamma_\pi \tau_\pi}\right)^{-1} + \left(\frac{t_{\pi,\gamma}}{\gamma_\pi \tau_\pi}\right)^{-1} + \left(\frac{t_{\mathrm{sync}}}{\gamma_\pi \tau_\pi}\right)^{-1}\right)^{-1}\right]$$

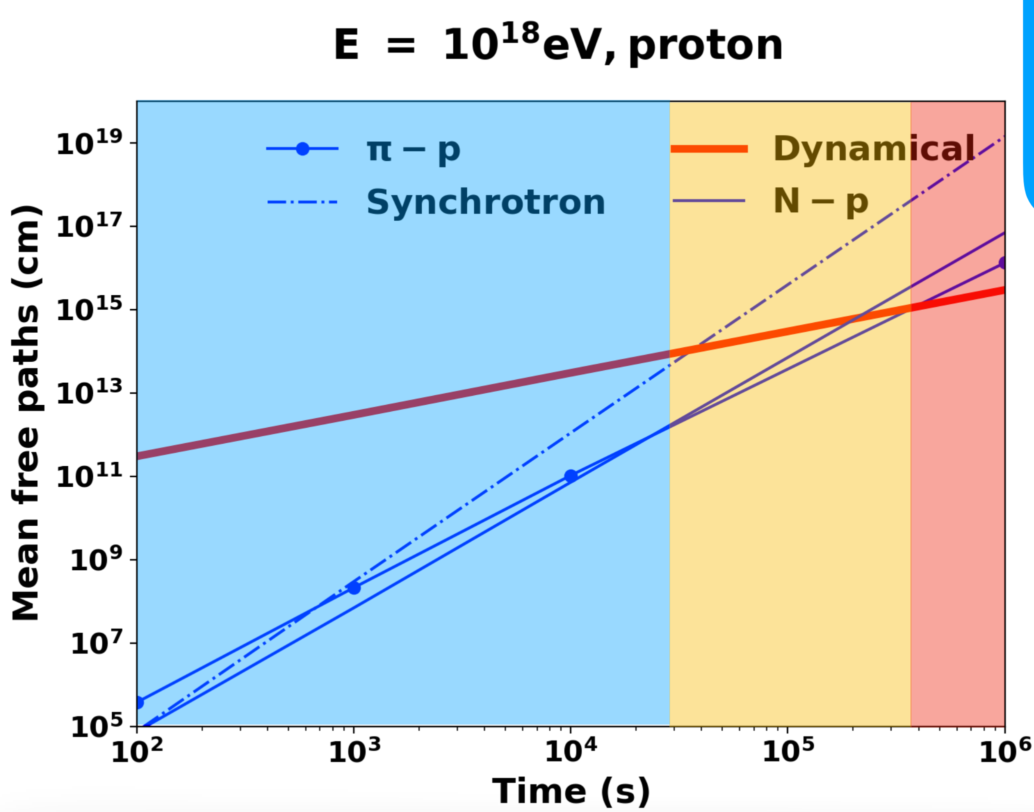
pion-proton interactions | photomeson interactions | synchrotron cooling

Fang et al. 2016



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





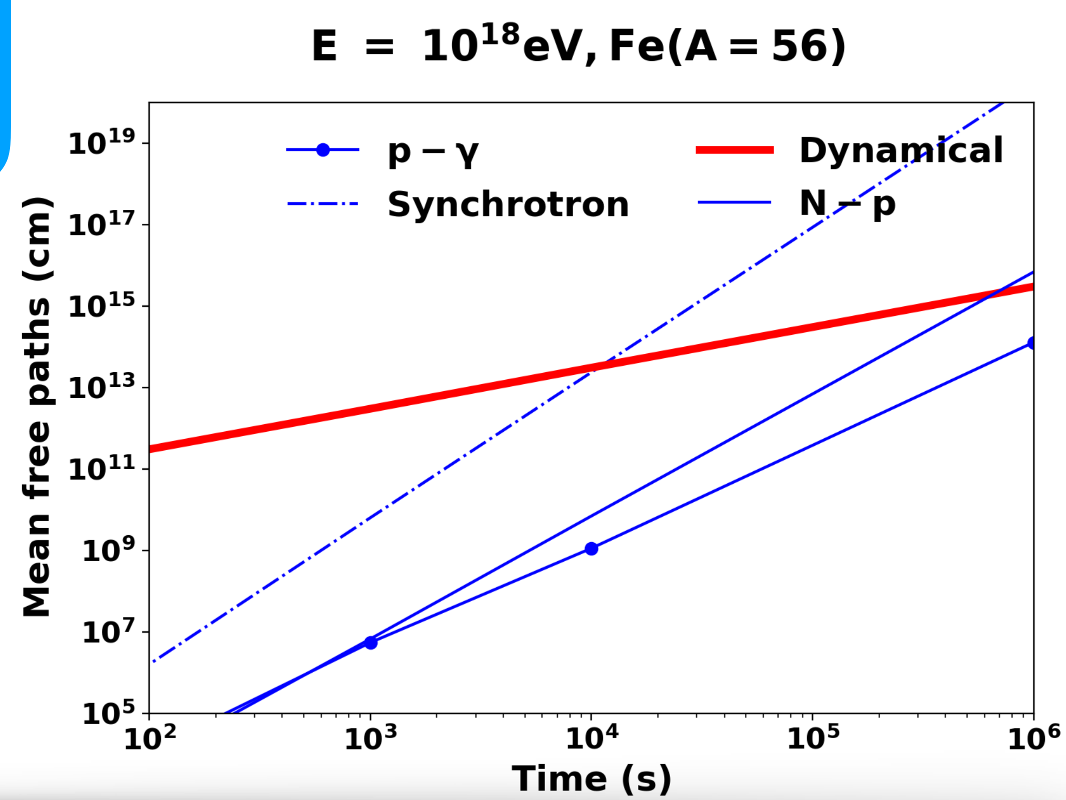
Neutrino production efficiency : interactions efficiencies (👍) mesons cascades (suppression factor 👎)

Ideal neutrino production time

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

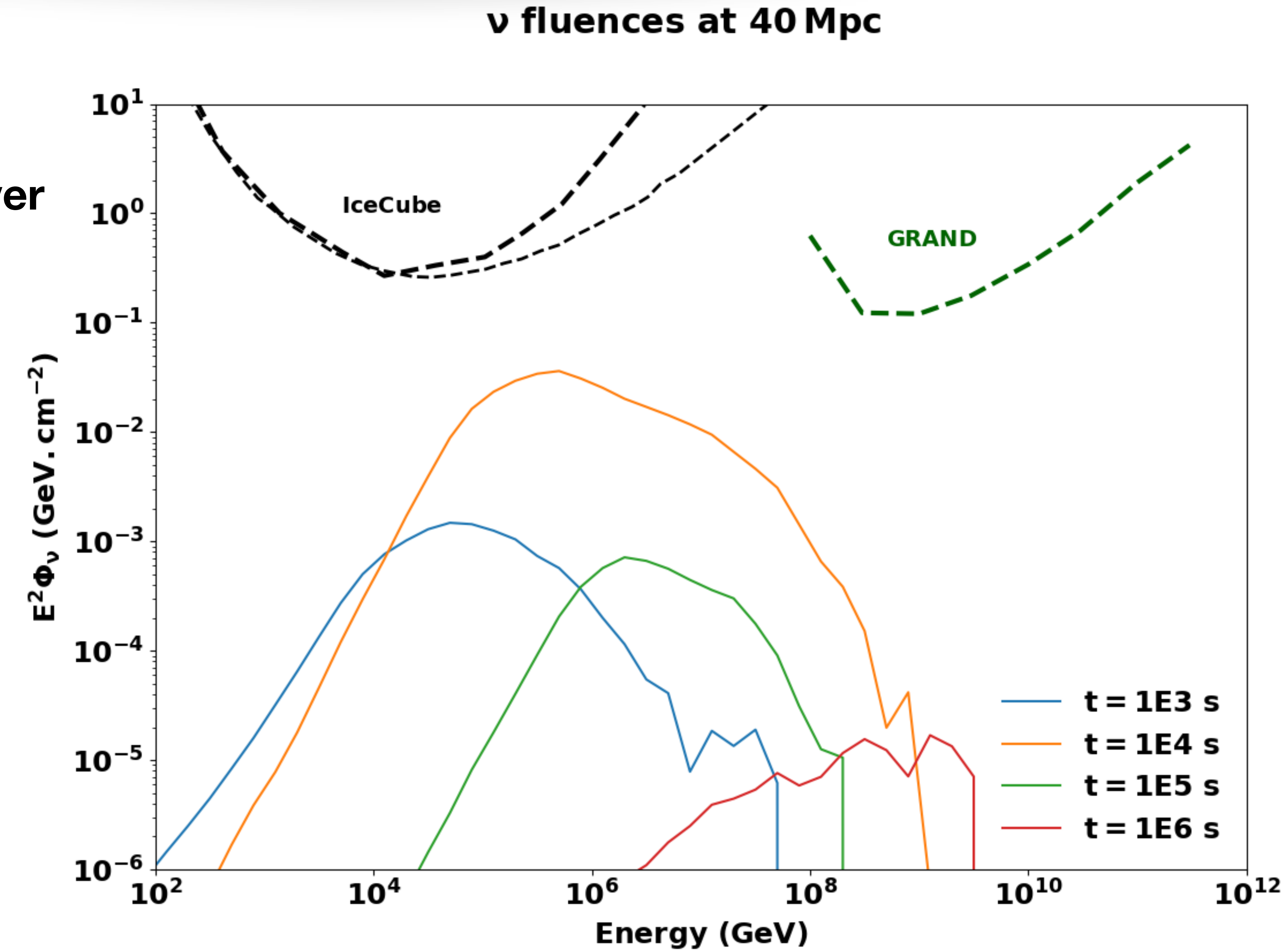
proton-proton dominant

Photomeson dominant



Case of GW170817
distance to the observer
≈ 40 Mpc

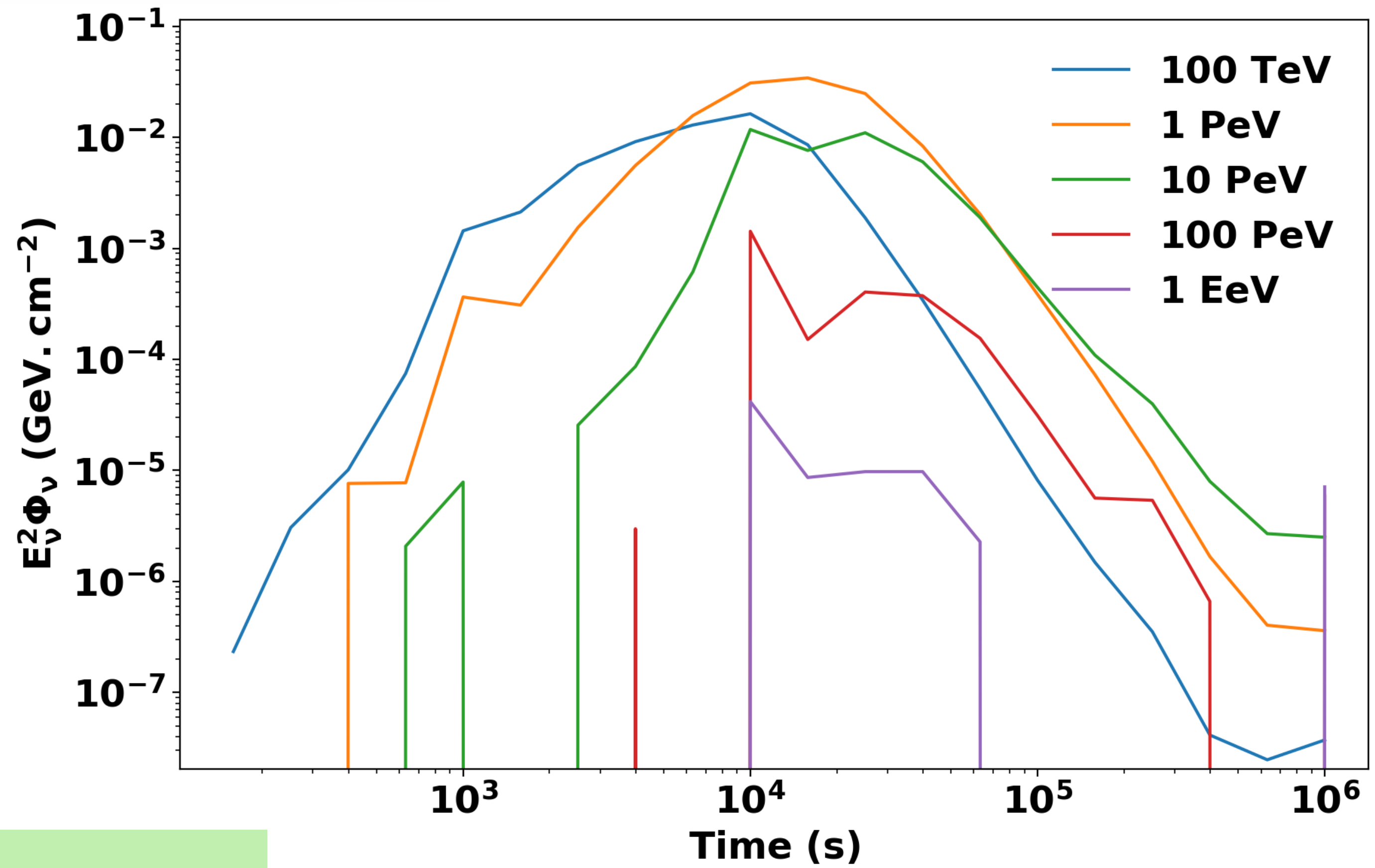
Ideal neutrino
production time
$\approx 10^4$ s



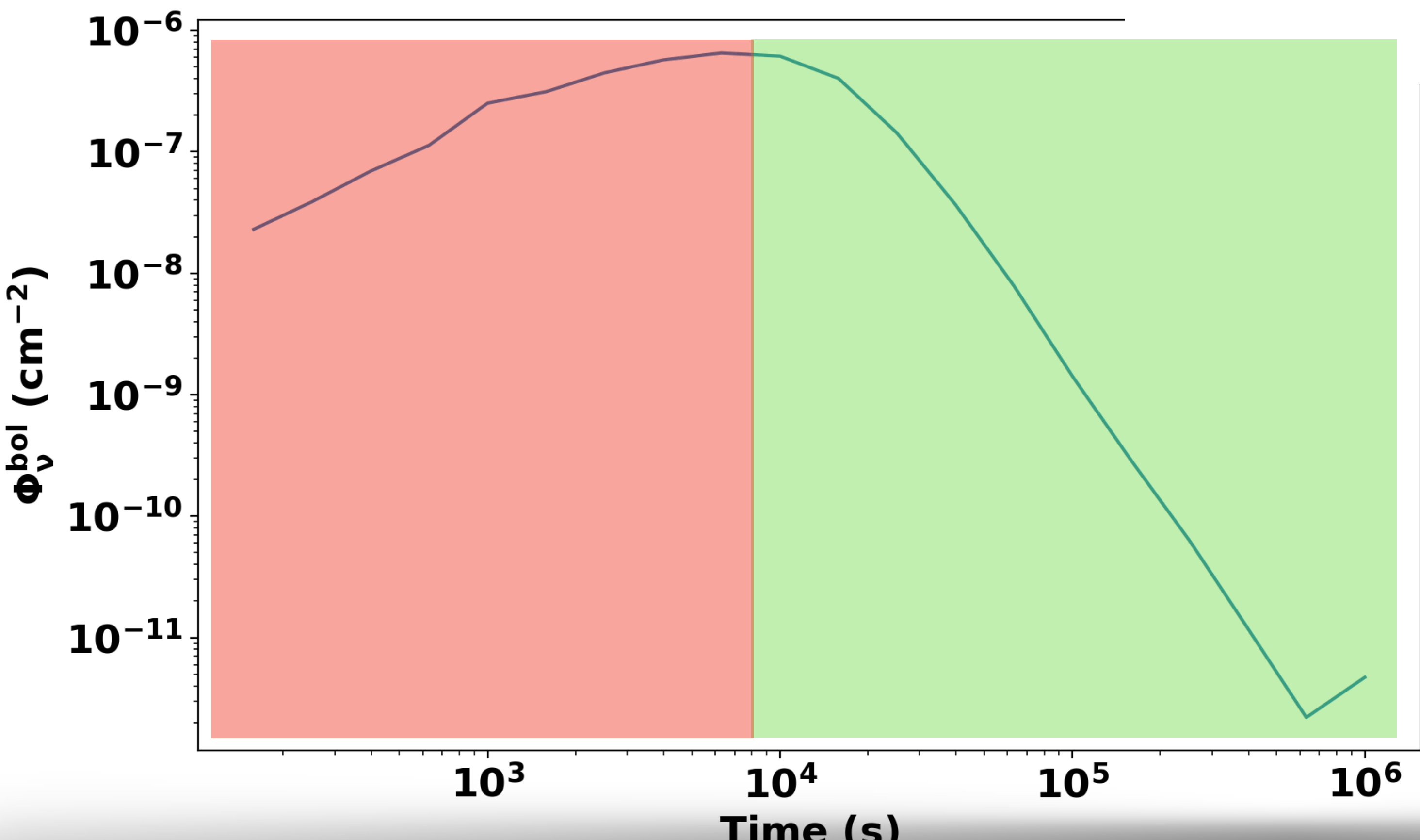
Higher emission
around PeV energies

Higher neutrinos luminosity
at
$\approx 10^4$ s

ν ligthcurve



Bolometric ν lightcurve

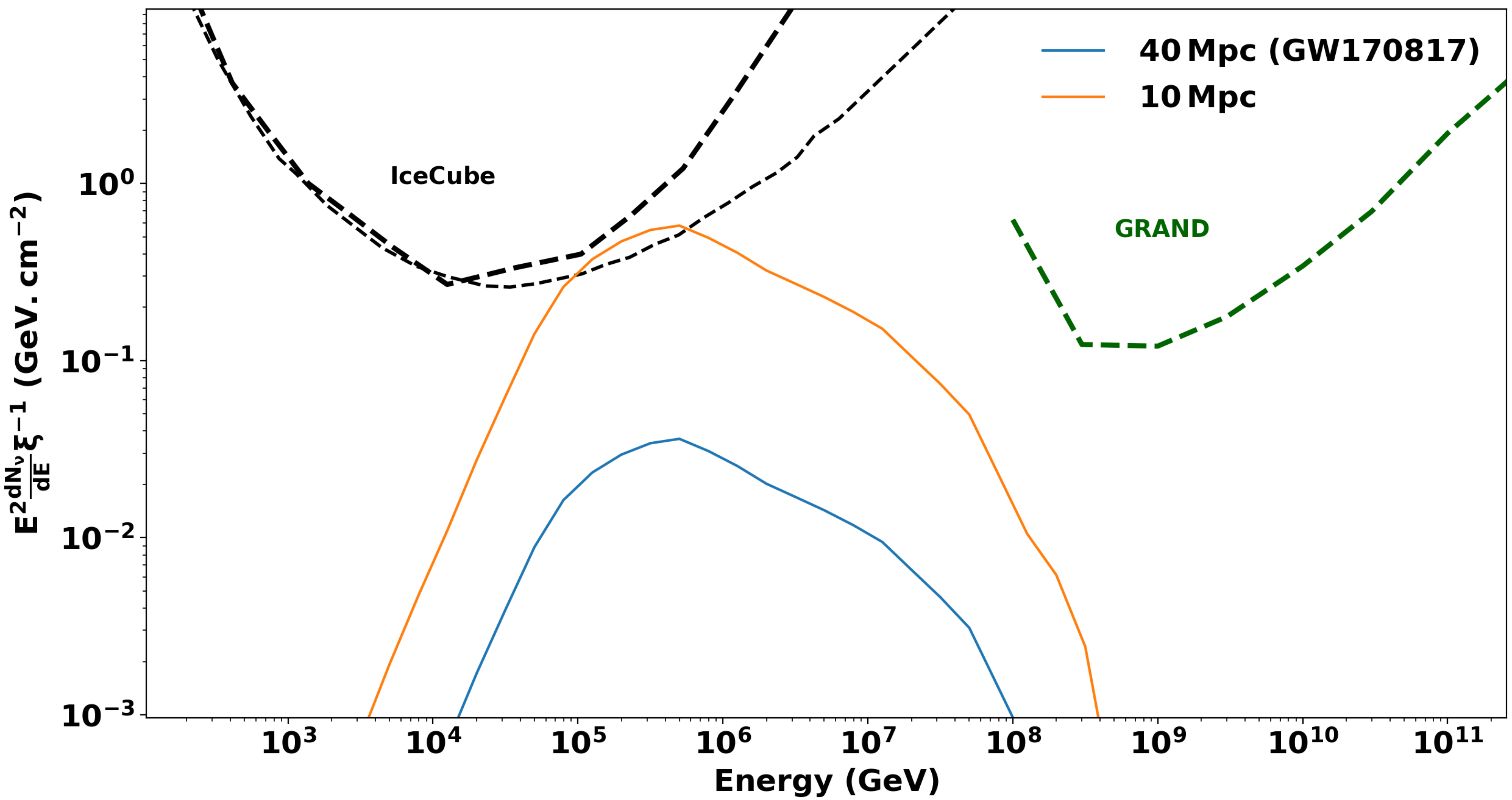


meson cascades

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

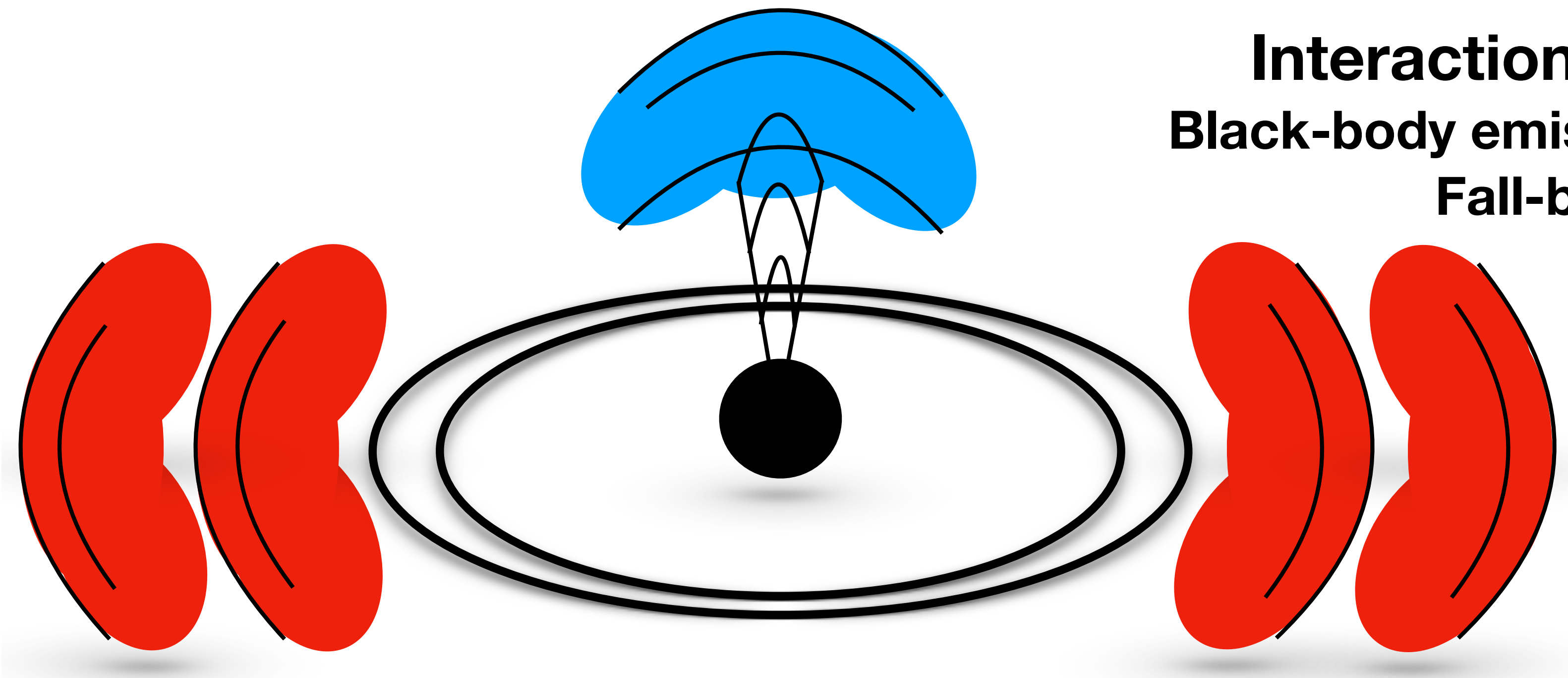
Red Kilo-novae -> equatorial plane

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

Particle acceleration of UHECR particles

Outflows coming from the wind /corona / 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