Neutrino signatures from magnetar remnants of BNS mergers: coincident detection prospects with GWs

Mainak Mukhopadhyay
Pennsylvania State University

TeV Particle Astrophysics (TeVPA)
Chicago
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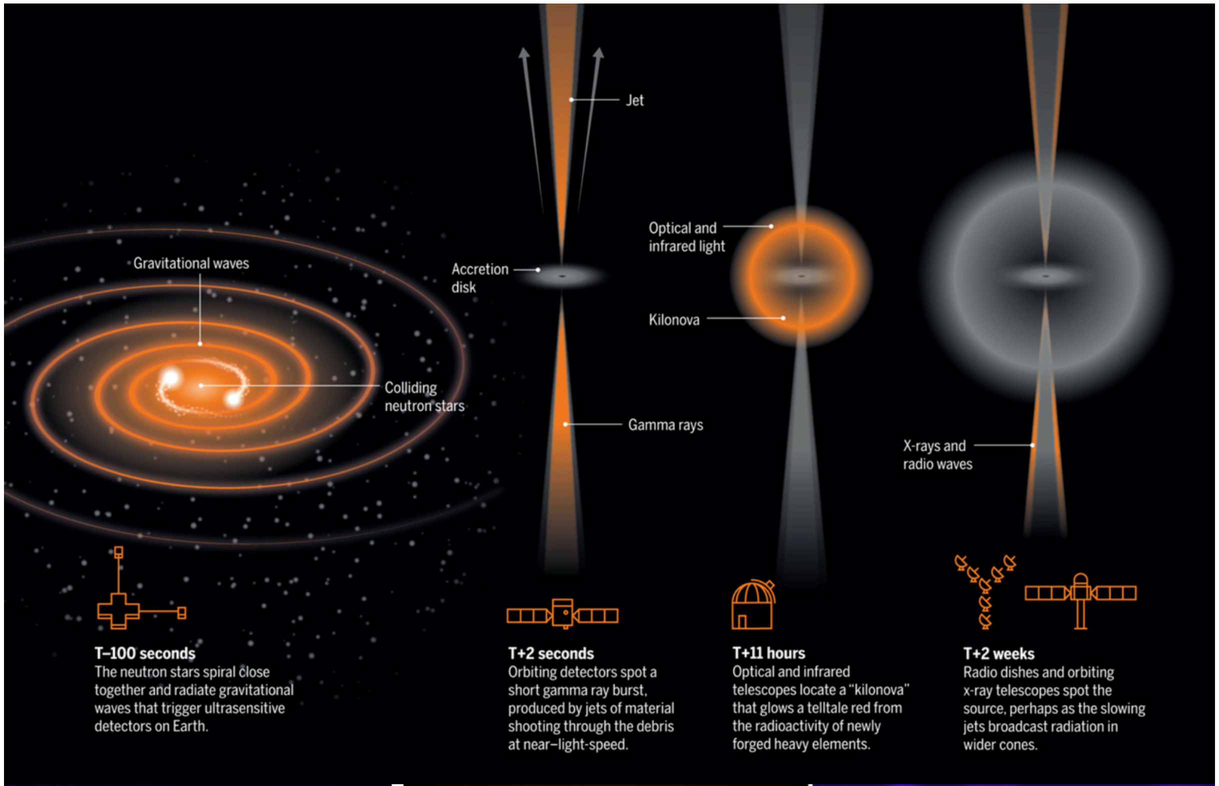
GW170817

~ 40 Mpc (NGC 4993)



T–100 seconds
The neutron stars spiral close together and radiate gravitational waves that trigger ultrasensitive detectors on Earth.

T+2 seconds
Orbiting detectors spot a short gamma ray burst, produced by jets of material shooting through the debris at near–light-speed.

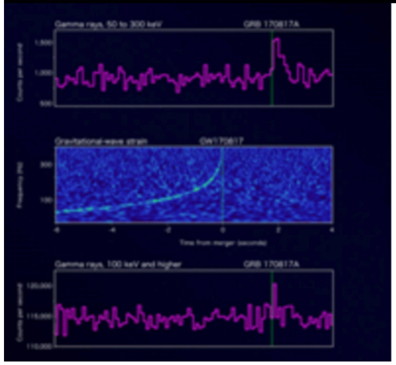
T+11 hours
Optical and infrared telescopes locate a "kilonova" that glows a telltale red from the radioactivity of newly forged heavy elements.

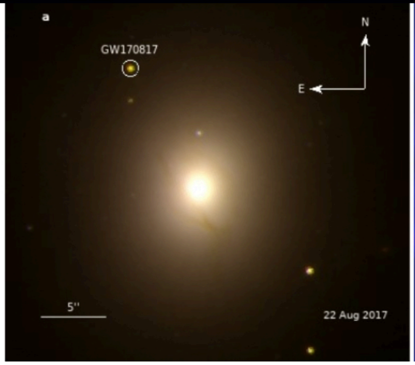
T+2 weeks
Radio dishes and orbiting x-ray telescopes spot the source, perhaps as the slowing jets broadcast radiation in wider cones.

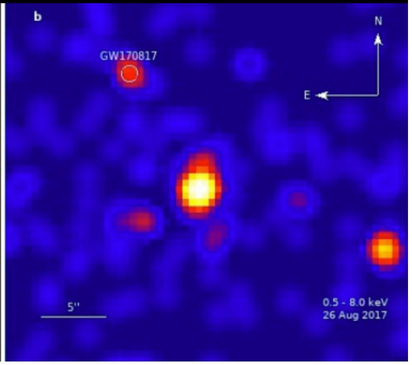
No neutrinos :(

Gamma rays (Fermi+Integral)

GW (Adv. LIGO+Virgo)







X-rays (Chandra)

Optical (HST)

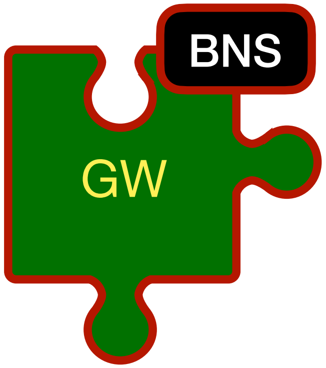
Image credits: https://ahead.iaps.inaf.it
Abbott et al. 2017, ApJ 848, L13
Troja, Piro, van Earthen et al., 2017, Nature, 551, 71

BNS mergers: particle accelerators and multi-messenger zoo

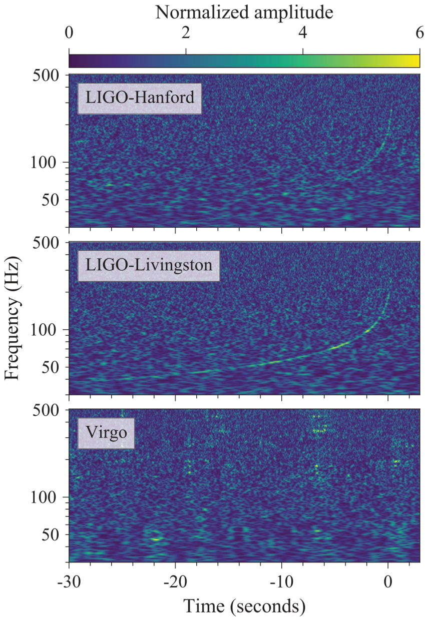
BNS

Batista et al., Front. Astron. Space Sci. 6 (2019), 23
Kimura+, PRD (2018), Fang & Metzger (2017)
Mukhopadhyay et al. (2024)
LIGO Collab (2017)

BNS mergers: particle accelerators and multi-messenger zoo


BNS

GW



Observed

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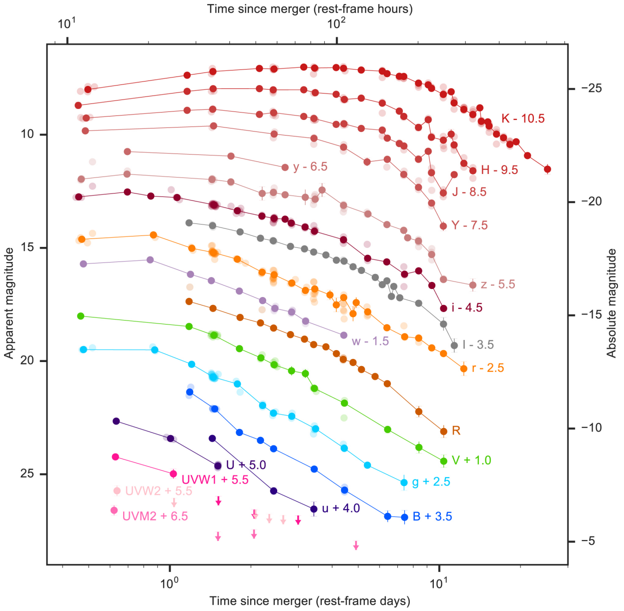
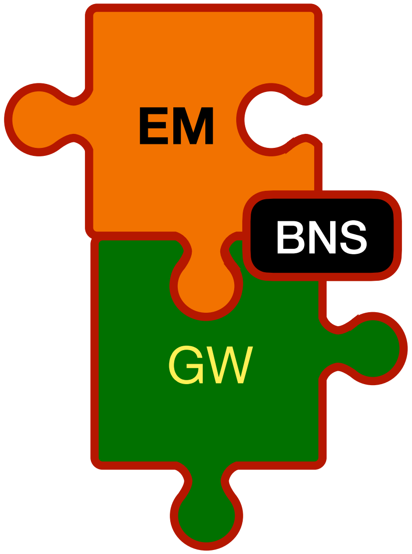
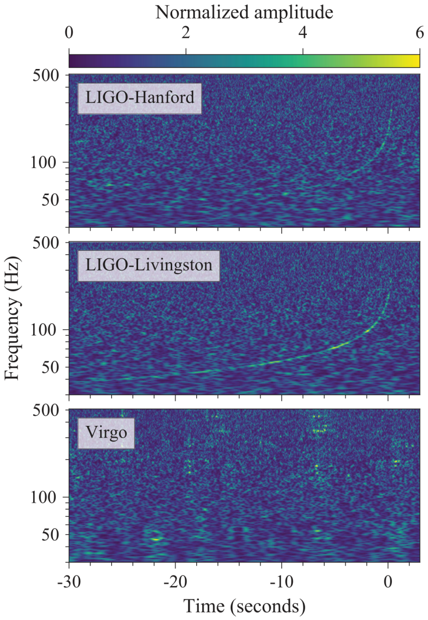


Kilonova emission
Afterglow emission
Short GRB





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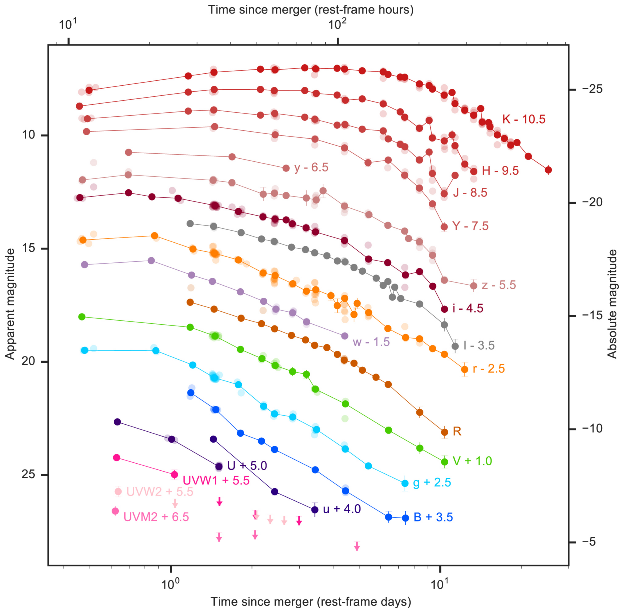

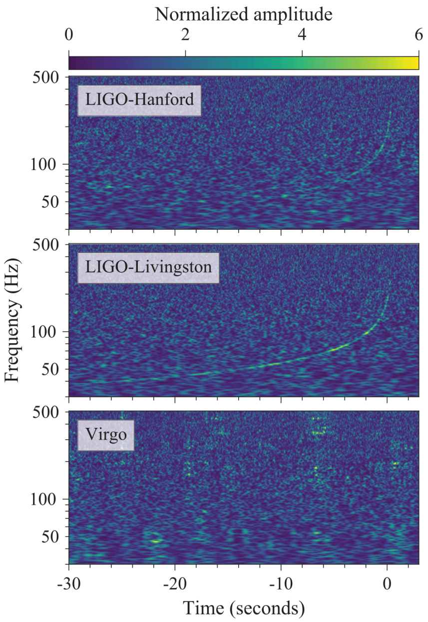

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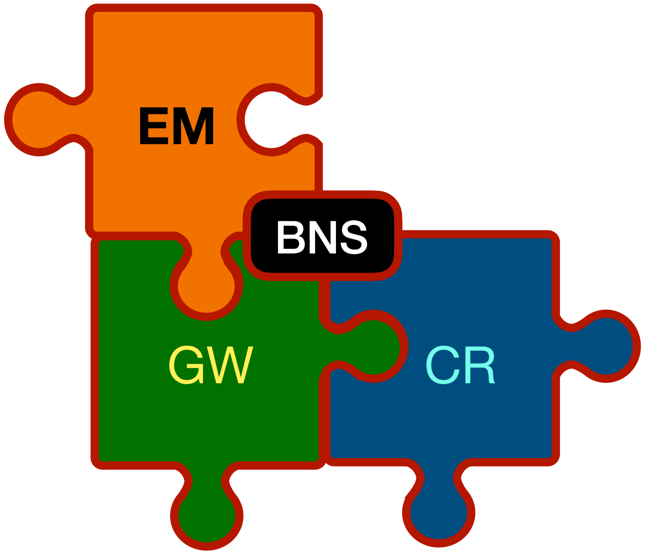

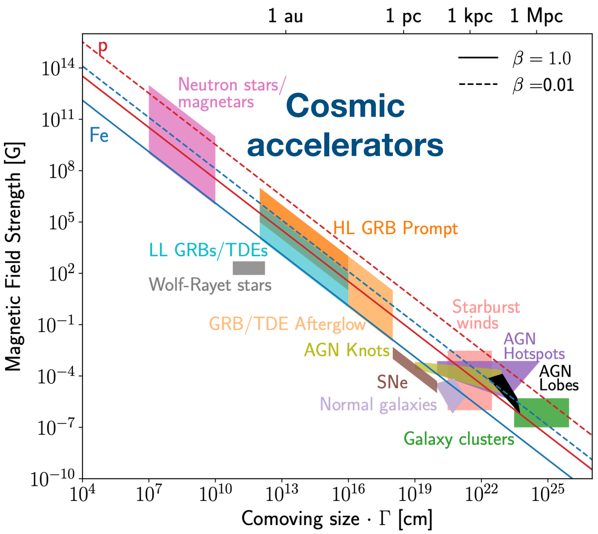

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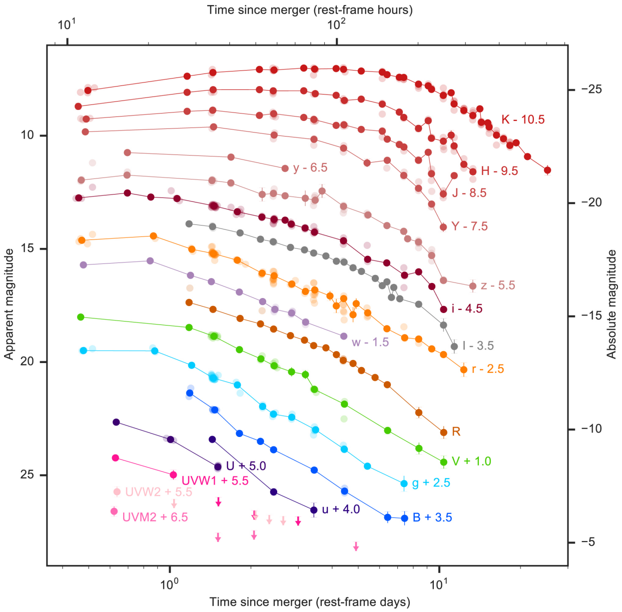

Kilonova emission
Afterglow emission
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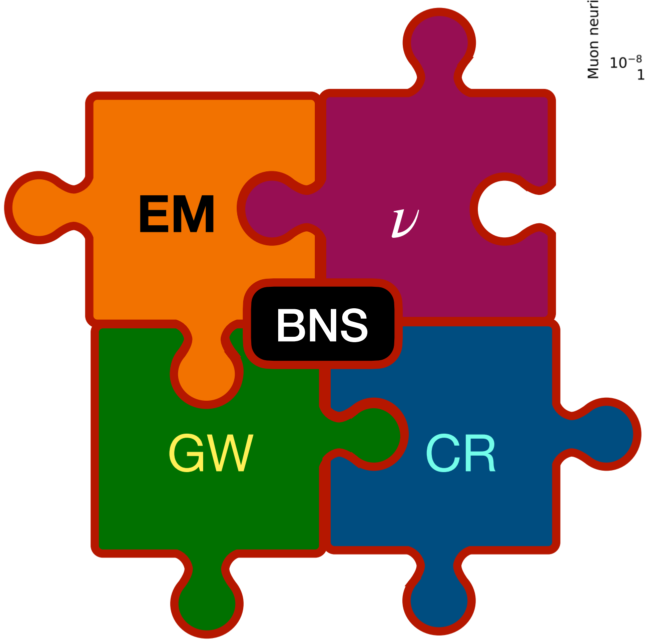

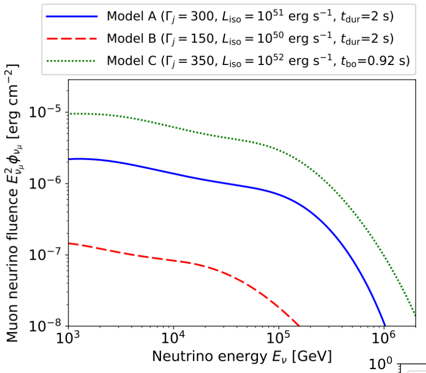

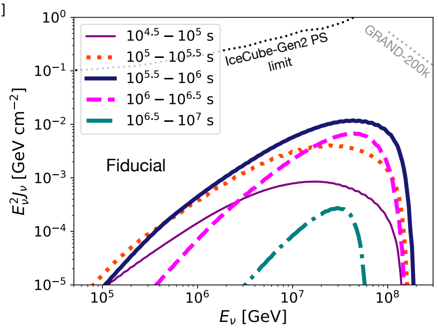

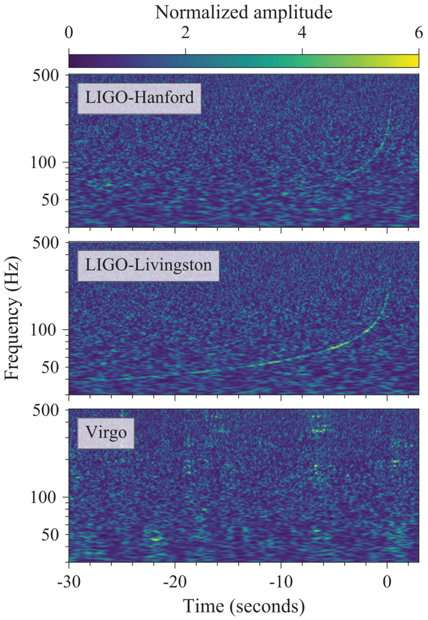

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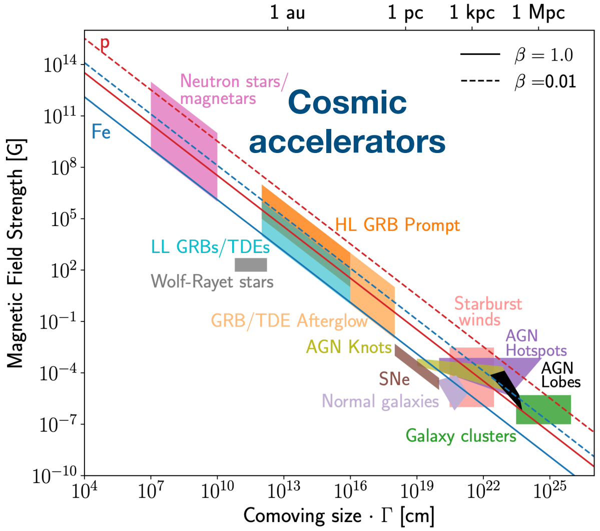

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Kimura+, PRD (2018), Fang & Metzger (2017)
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LIGO Collab (2017)

Based on

High-energy neutrino signatures from pulsar remnants of binary neutron-star mergers: coincident detection prospects with gravitational waves
MM, S.S. Kimura, B.D. Metzger
Submitted to ApJ *(arXiv: 2407.04767)*

Electromagnetic signatures from pulsar remnants of binary neutron-star mergers
MM, S.S. Kimura
(in preparation)

Gravitational wave triggered high energy neutrino searches from BNS mergers: prospects for next generation detectors
MM, S. S. Kimura, K. Murase
Phys. Rev. D 109, 4, 043053 (2024) *(arXiv: 2310.16875)*

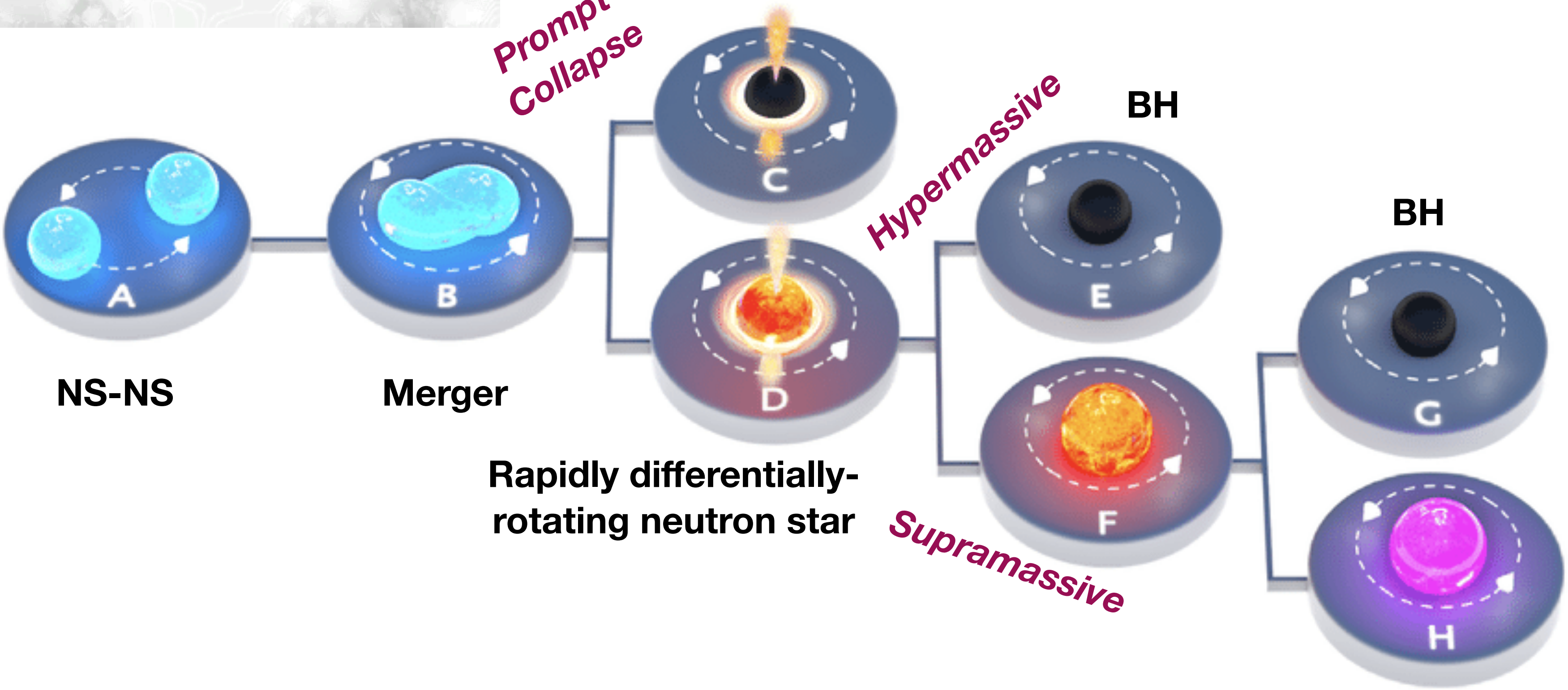
Ultrahigh energy neutrino searches using next-generation gravitational wave detectors at radio neutrino detectors: GRAND, IceCube-Gen2 Radio, and RNO-G
MM, K. Kotera, S. Wissel, K. Murase, S.S. Kimura
Accepted in Phys. Rev. D *(arXiv: 2406.19440)*

Fate of NS-NS mergers

SWIFT NEUTRON STAR
COLLISION V. 2

ANIMATION: DANA BERRY
310-441-1735
PRODUCED BY ERICA DREZEK

Fate decided by EOS, Mass, Spin, ….



BH-Torus,Jet

Prompt Collapse

BH

Hypermassive

BH

NS-NS

Merger

Rapidly differentially-rotating neutron star

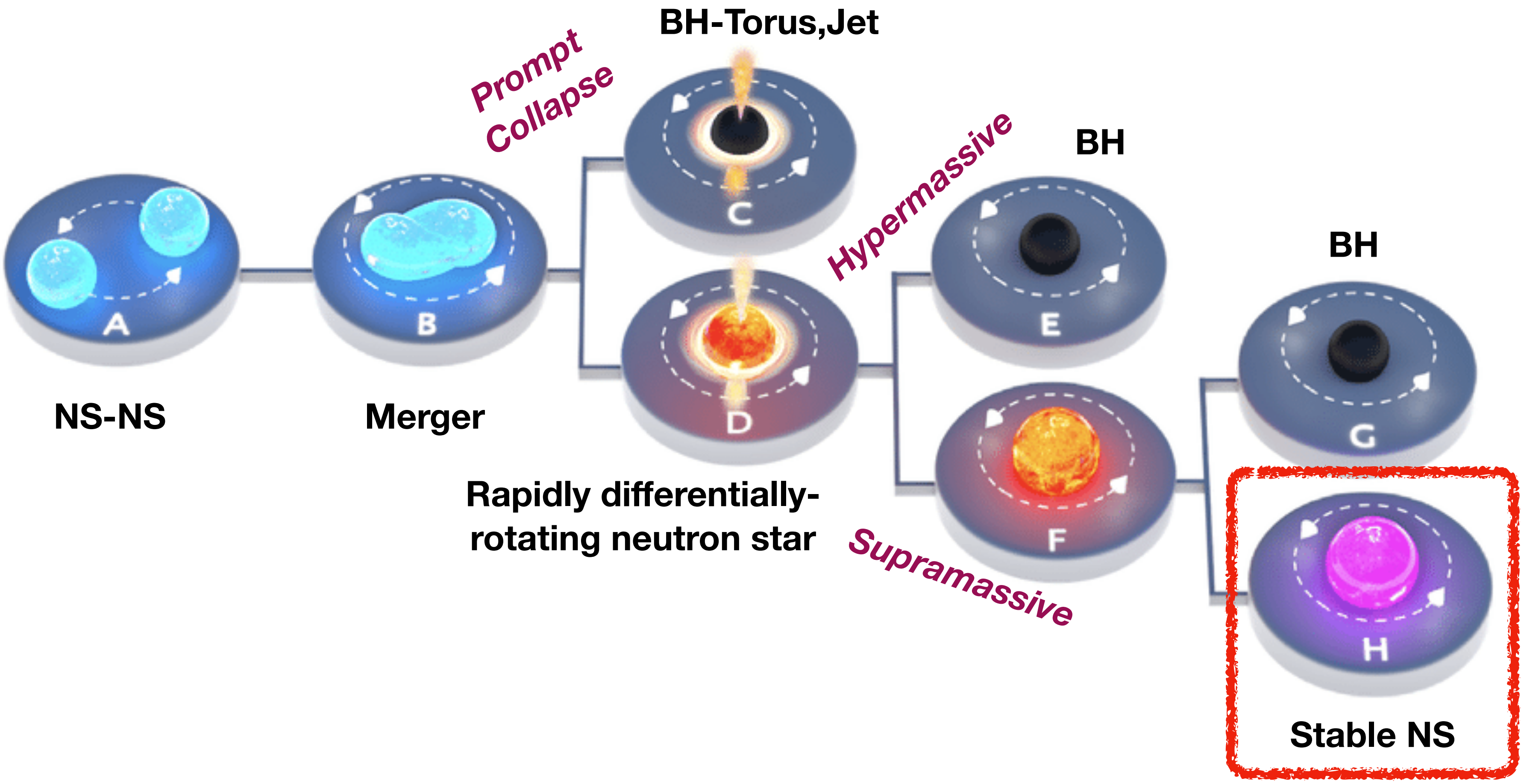
Supramassive

Stable NS

Piro, Giacomazzo, Perna arXiv:1704.08697

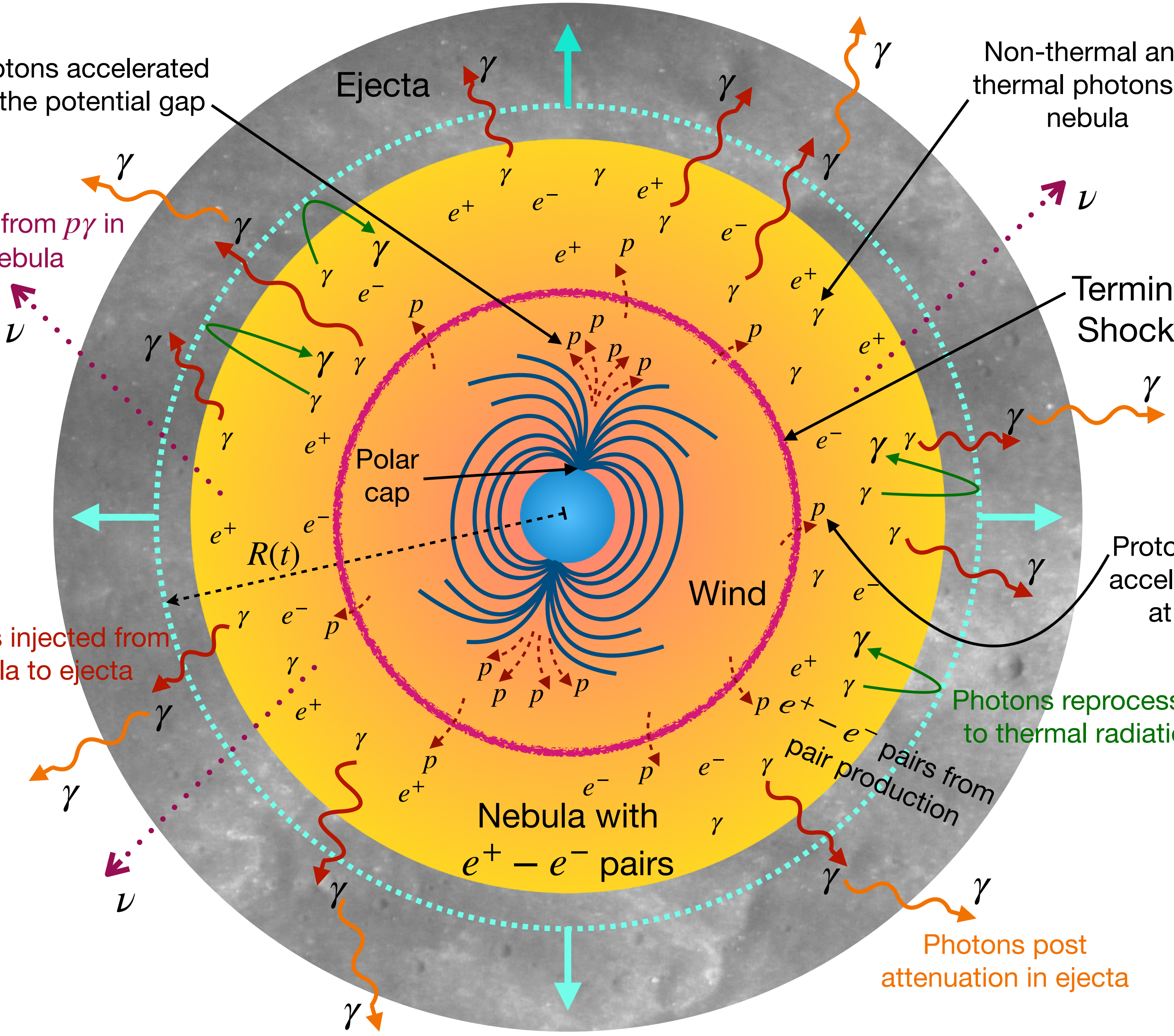
Fate of NS-NS mergers

Fate decided by EOS, Mass, Spin, ….



Piro, Giacomazzo, Perna arXiv:1704.08697

Model



Protons accelerated at the potential gap

Non-thermal and thermal photons in nebula

Neutrinos from $p\gamma$ in the nebula

Termination Shock (TS)

Protons re-accelerated at TS

Photons injected from nebula to ejecta

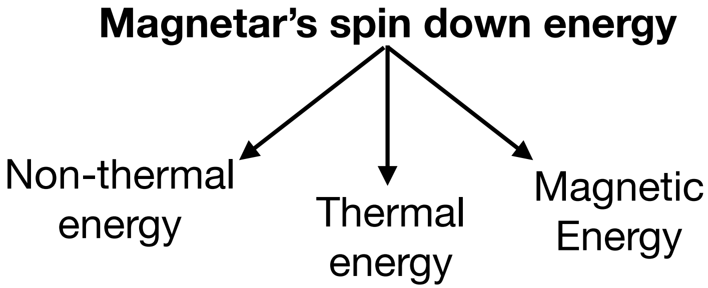
Photons reprocessed to thermal radiation

$e^+ - e^-$ pairs from pair production

Photons post attenuation in ejecta

Nebula with $e^+ - e^-$ pairs

Model: Evolution of thermal, non-thermal, and magnetic energies



Magnetar's spin down energy

Non-thermal energy

Thermal energy

Magnetic Energy

Metzger, B. D., & Piro, A. L. 2014, MNRAS, 439, 3916
Fang, K. & Metzger, B.D. 2017, ApJ 849, 153

Model: Evolution of thermal, non-thermal, and magnetic energies

Magnetar’s spin down energy

Non-thermal energy

Thermal energy

Magnetic Energy

Spin-down luminosity

Photon diffusion from nebula to ejecta

Non-thermal energy

$$\frac{dE_{\rm nth}}{dt} = L_{\rm sd} - \frac{E_{\rm nth}}{R}\frac{dR}{dt} - \frac{E_{\rm nth}}{t_{\rm diff}^{\rm neb}}$$

PdV work by the nebula

Model: Evolution of thermal, non-thermal, and magnetic energies

Magnetar's spin down energy

Non-thermal energy

Thermal energy

Magnetic Energy

Non-thermal energy

$$\frac{dE_{\rm nth}}{dt} = L_{\rm sd} - \frac{E_{\rm nth}}{R}\frac{dR}{dt} - \frac{E_{\rm nth}}{t_{\rm diff}^{\rm neb}}$$

Fraction of non-thermal photons that escape

Heating rate due to decay of r-process elements in the ejecta

Thermal energy

$$\frac{dE_{\rm th}}{dt} = \left(1 - \mathscr{A}\right)\frac{E_{\rm nth}}{t_{\rm diff}^{\rm neb}} - \frac{E_{\rm th}}{R}\frac{dR}{dt} - \frac{E_{\rm th}}{t_{\rm diff}^{\rm ej}} + Q_{\rm rp}^{\rm heat}$$

Photon diffusion through ejecta

Model: Evolution of thermal, non-thermal, and magnetic energies

Magnetar's spin down energy

Non-thermal energy

Thermal energy

Magnetic Energy

Non-thermal energy

$$\frac{dE_{\rm nth}}{dt} = L_{\rm sd} - \frac{E_{\rm nth}}{R}\frac{dR}{dt} - \frac{E_{\rm nth}}{t_{\rm diff}^{\rm neb}}$$

Thermal energy

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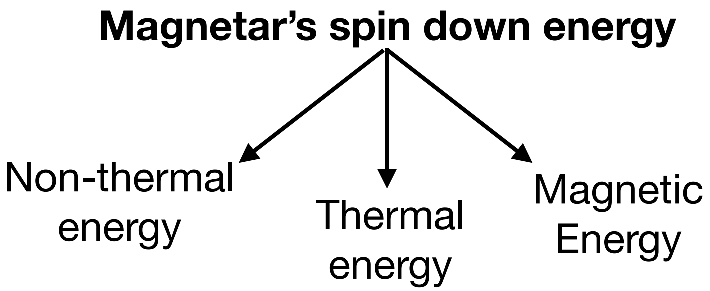
Magnetic field strength amplification parameter

$\epsilon_{\rm B} \sim 10^{-4}$

Magnetic energy

$$\frac{dE_B}{dt} = \varepsilon_B L_{\rm sd} - \frac{E_B}{R}\frac{dR}{dt}$$

Model: Evolution of thermal, non-thermal, and magnetic energies



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Non-thermal energy

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Thermal energy

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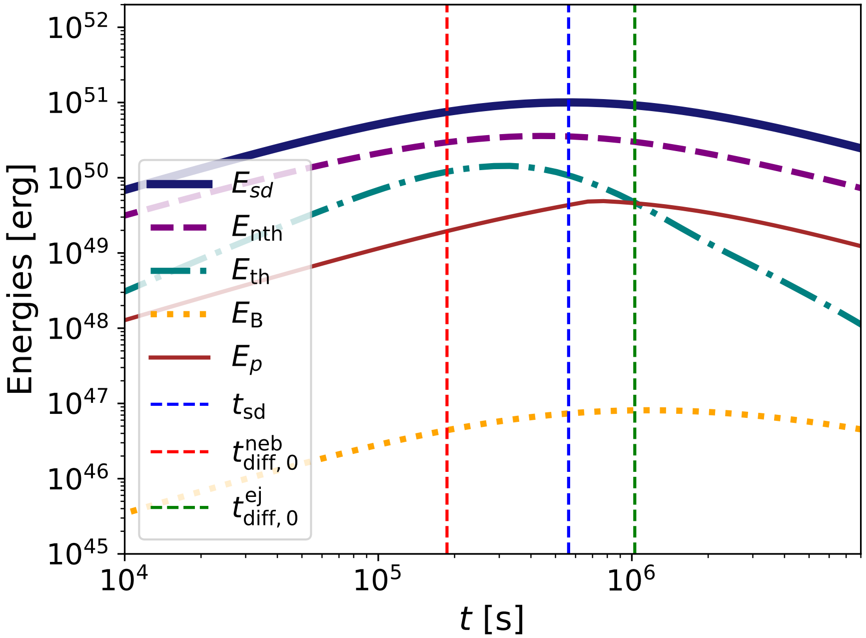
Magnetic energy

$$\frac{dE_B}{dt} = \varepsilon_B L_{\rm sd} - \frac{E_B}{R}\frac{dR}{dt}$$

Work done on the ejecta

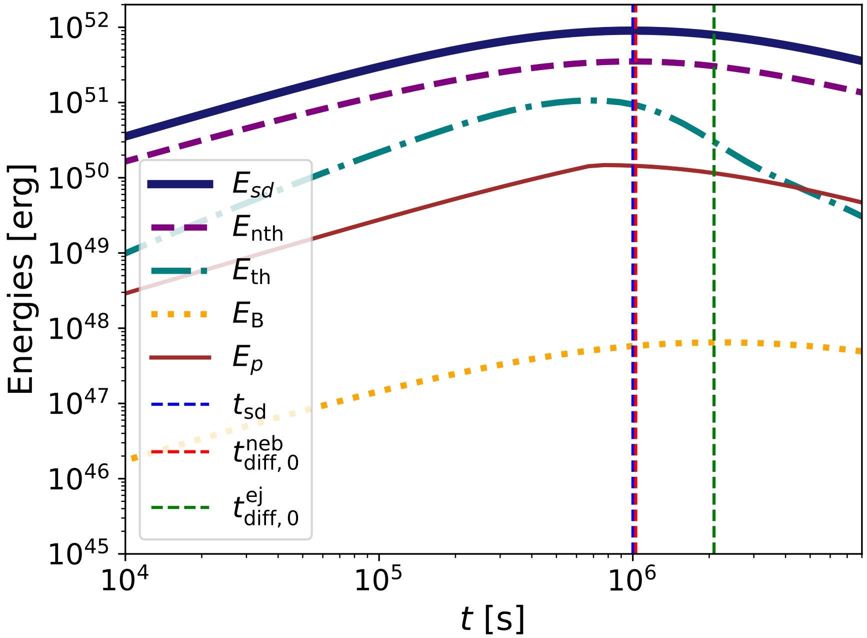
$$\frac{d}{dt}E_{\rm kin} = \frac{d}{dt}\left[M_{\rm ej}c^2(\Gamma_{\rm ej} - 1)\right] = \frac{v}{R}\left(E_{\rm nth} + E_{\rm th} + E_B\right)$$

Model: Evolution of thermal, non-thermal, and magnetic energies



Fiducial:

$B_d = 10^{14}$ G, $P_i = 0.003$ s, $M_{\rm ej} = 0.03\ M_{\odot}$, $\beta_{\rm ej} = 0.03$



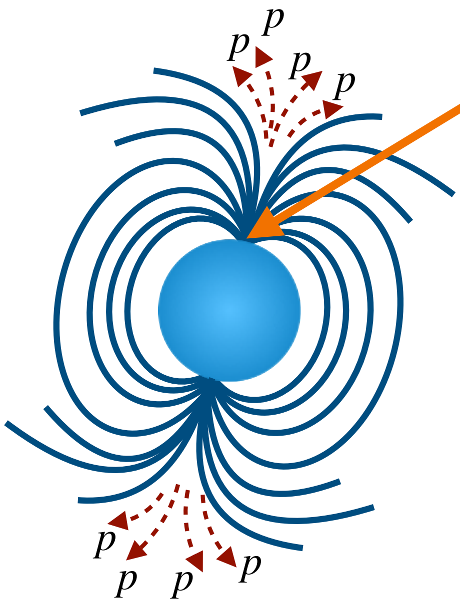
Optimistic:

$B_d = 2.5 \times 10^{13}$ G, $P_i = 0.001$ s, $M_{\rm ej} = 0.1\ M_{\odot}$, $\beta_{\rm ej} = 0.1$

$$L_{\rm sd} = \alpha \frac{\mu^2 \Omega^4}{c^3} = 7.13 \times 10^{45}\ {\rm erg\ s^{-1}} \left(\frac{B_d}{10^{14}\ {\rm G}}\right)^2 \left(\frac{P_i}{0.003\ {\rm s}}\right)^{-4} \left(1 + \frac{t}{t_{\rm sd}}\right)^{-2}$$

$$t_{\rm sd} = 5.63 \times 10^5\ {\rm s} \left(\frac{B_d}{10^{14}\ {\rm G}}\right)^{-2} \left(\frac{P_i}{0.003\ {\rm s}}\right)^2$$

Cosmic ray (CR) proton acceleration: injection spectra



CR protons extracted from the magnetar surface: Goldreich-Julian (GJ) number density of charges

$$n_{\rm GJ} = -\frac{\mathbf{\Omega}\cdot\mathbf{B}}{2\pi Zec}$$

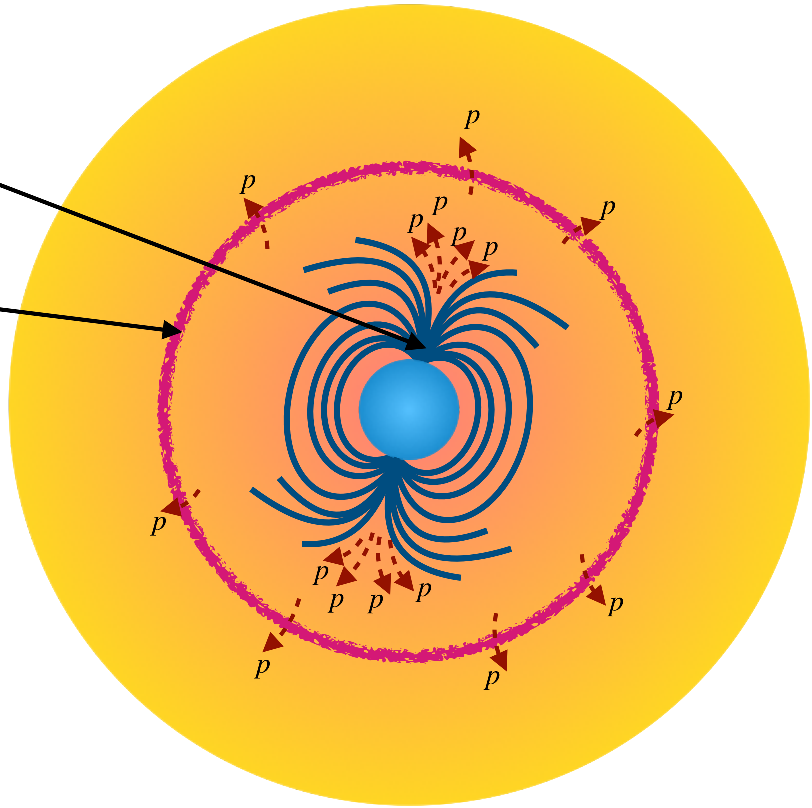
$$\dot{N}_p = n_{\rm GJ} 2A_{\rm pc}c = \frac{4\pi^2}{Ze}\frac{R_*^3}{c}\frac{B_0}{P^2}$$

Acceleration sites:

Polar cap

\+

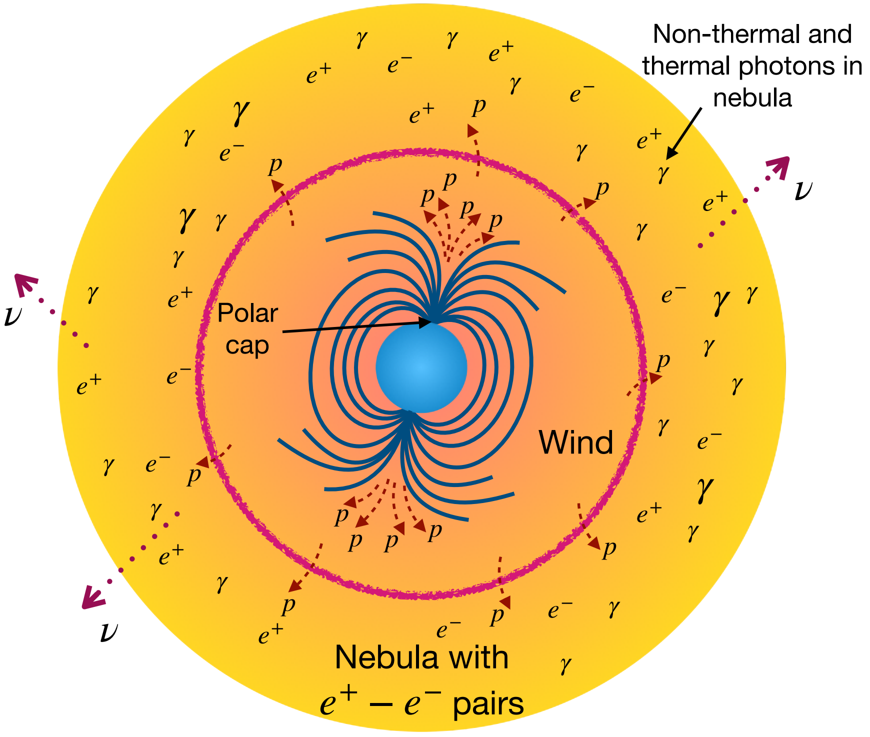
Termination shock (TS)



$$\frac{d\dot{N}_{p,\rm inj}}{d\varepsilon'_p} = \dot{N}_p^{\rm norm} Q_p^{\rm inj}(\varepsilon'_p) = \dot{N}_p^{\rm norm}\,\delta\left(\varepsilon'_p - \varepsilon_p^{\prime\rm cutoff,pc}\right)$$

$$\varepsilon_p^{\prime\rm cutoff} = \max\left[\varepsilon_p^{\prime\rm cutoff,pc}, \varepsilon_p^{\prime\rm cutoff,TS}\right]$$

Cosmic ray (CR) proton acceleration



Compute steady state CR spectrum by solving the transport equation

This along with the photon field spectrum gives the neutrino fluences

$e^+ - e^-$ spectra

$$\frac{dN}{d\gamma_e} \sim \begin{cases} \gamma_e^{-1.5}, \, \gamma_e \leq \gamma_{e,\mathrm{br}} \\ \gamma_e^{-2.5}, \, \gamma_e > \gamma_{e,\mathrm{br}} \, , \end{cases}$$

Electron break Lorentz factor

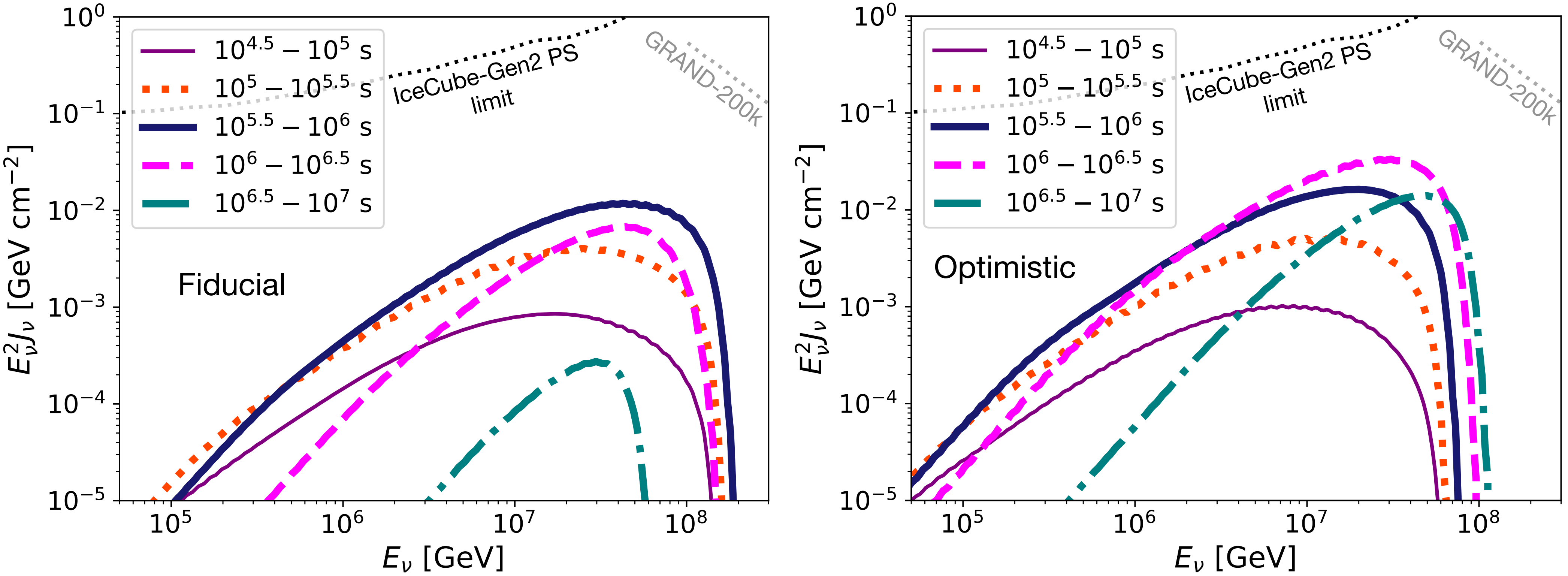
$$\gamma_{e,\mathrm{br}} = 10^3$$

Transport Equation

Synchrotron, inverse Compton, Breit-Wheeler processes

EM cascades

The money plot: Neutrino fluences (takeaway)



$d_L = 40$ Mpc

Peak fluence: $\sim 1 \times 10^{-2}$ GeV cm^{-2}

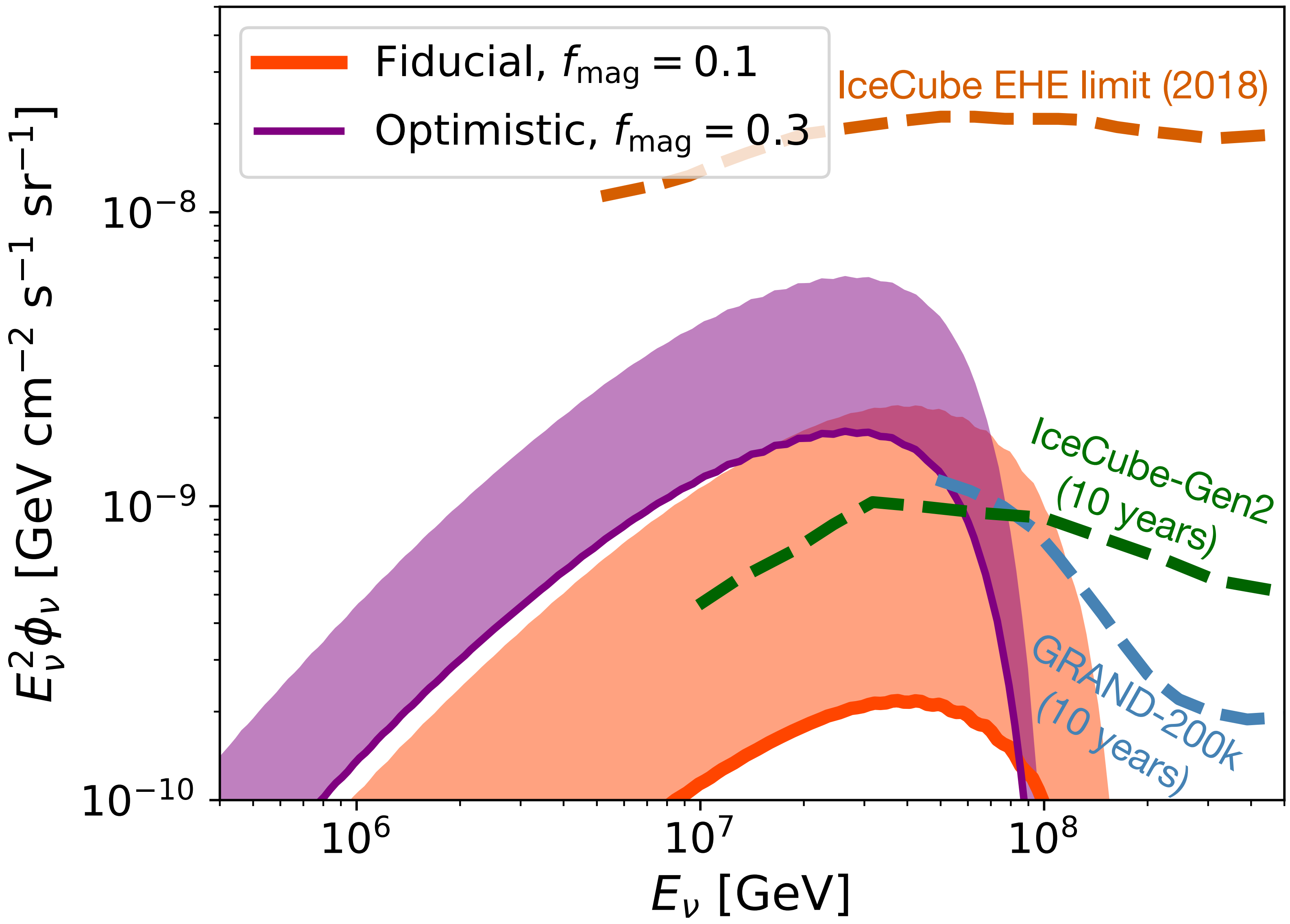
Peak fluence: $\sim 4 \times 10^{-2}$ GeV cm^{-2}

Neutrino energy: $\sim 10^7$ GeV $- 10^8$ GeV

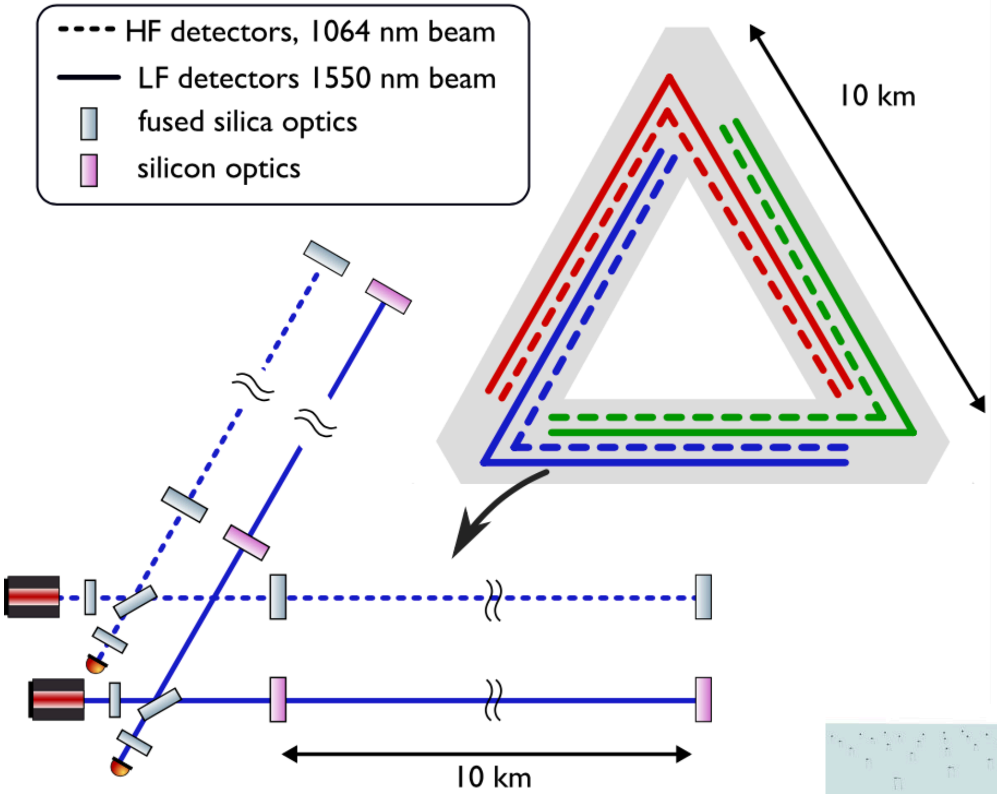
Peak fluence $\sim 10^{5.5}$ s $- 10^6$ s post-merger

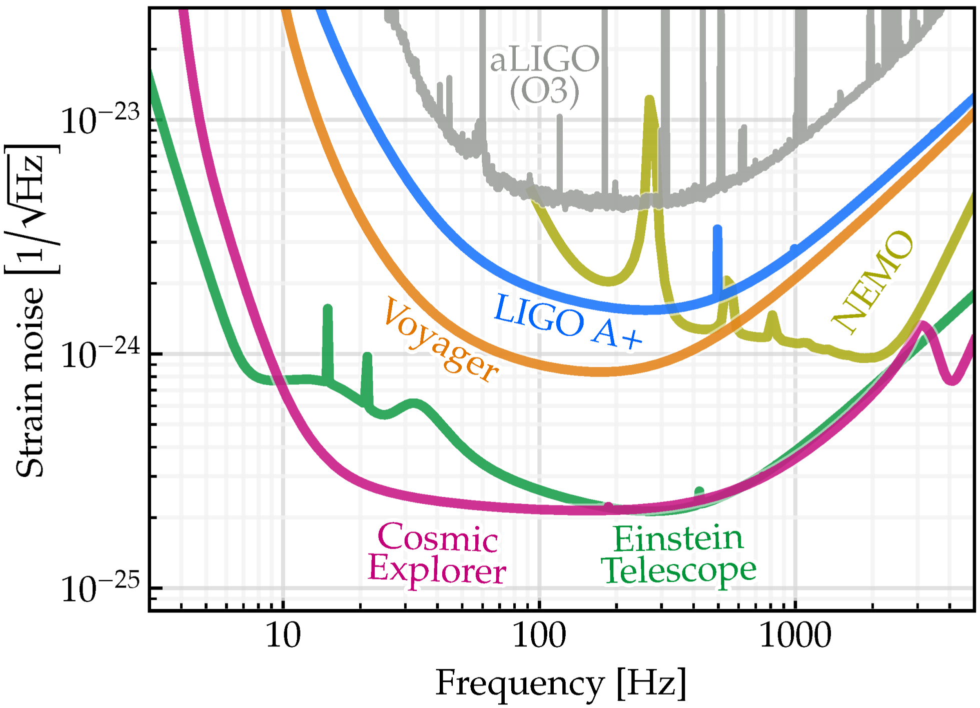
Peak fluence $\sim 10^6$ s $- 10^{6.5}$ s post-merger

Diffuse neutrino flux



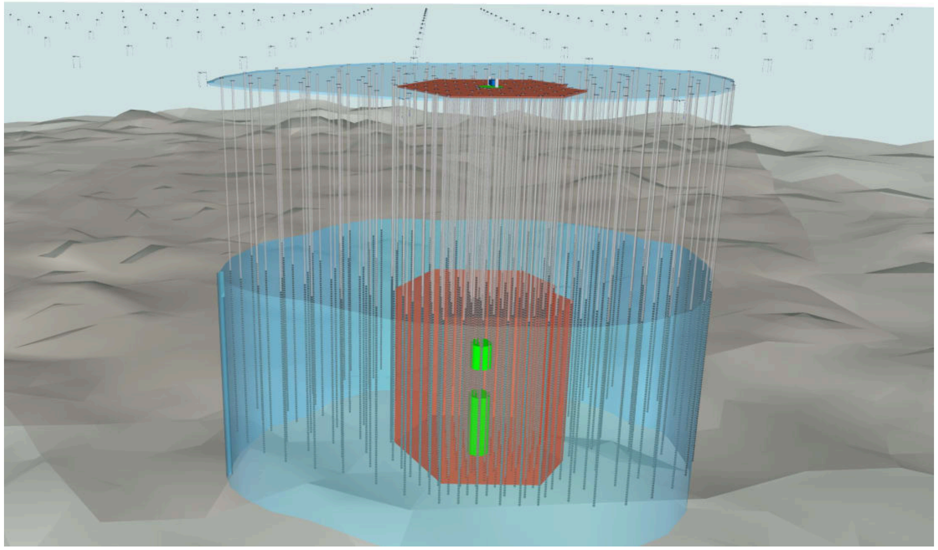
Next-generation GW and neutrino detectors





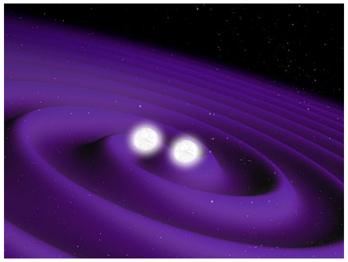
Einstein Telescope (ET)

IceCube-Gen2



Evans et al., (2021)

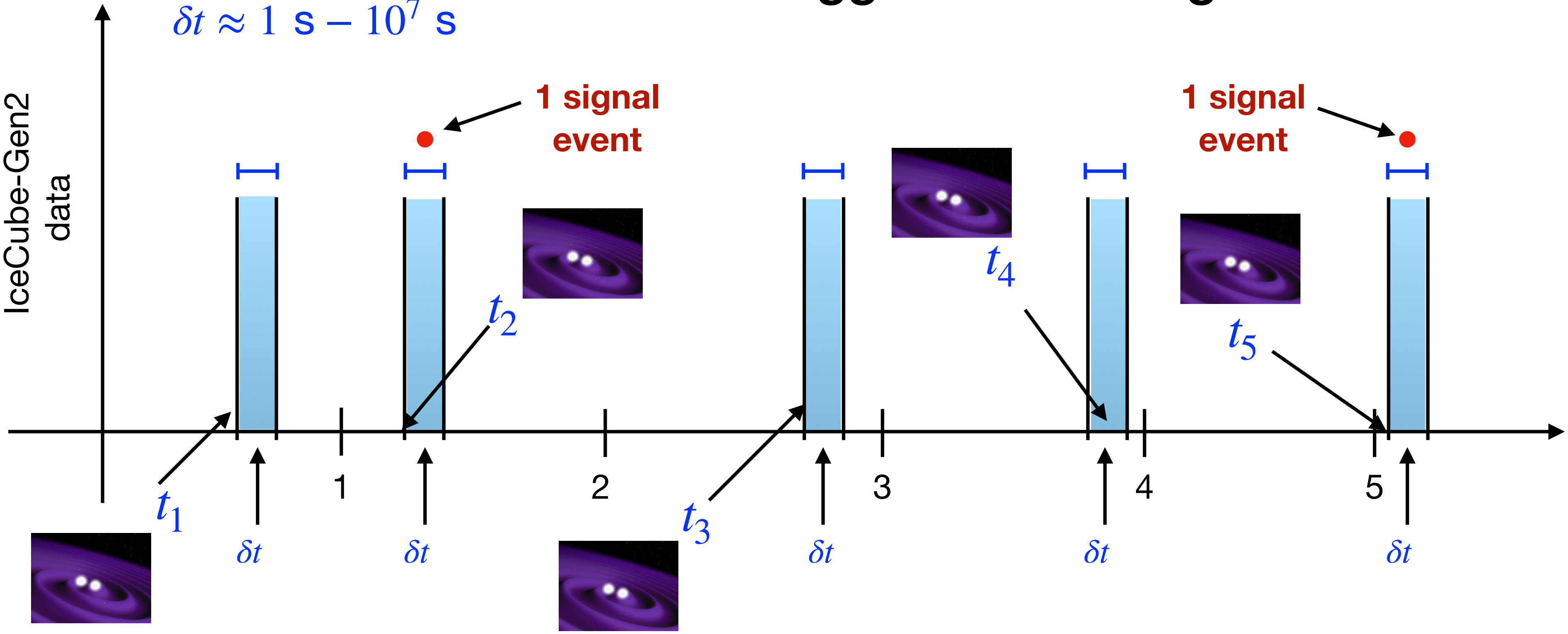
Detection strategy: triggered stacking search



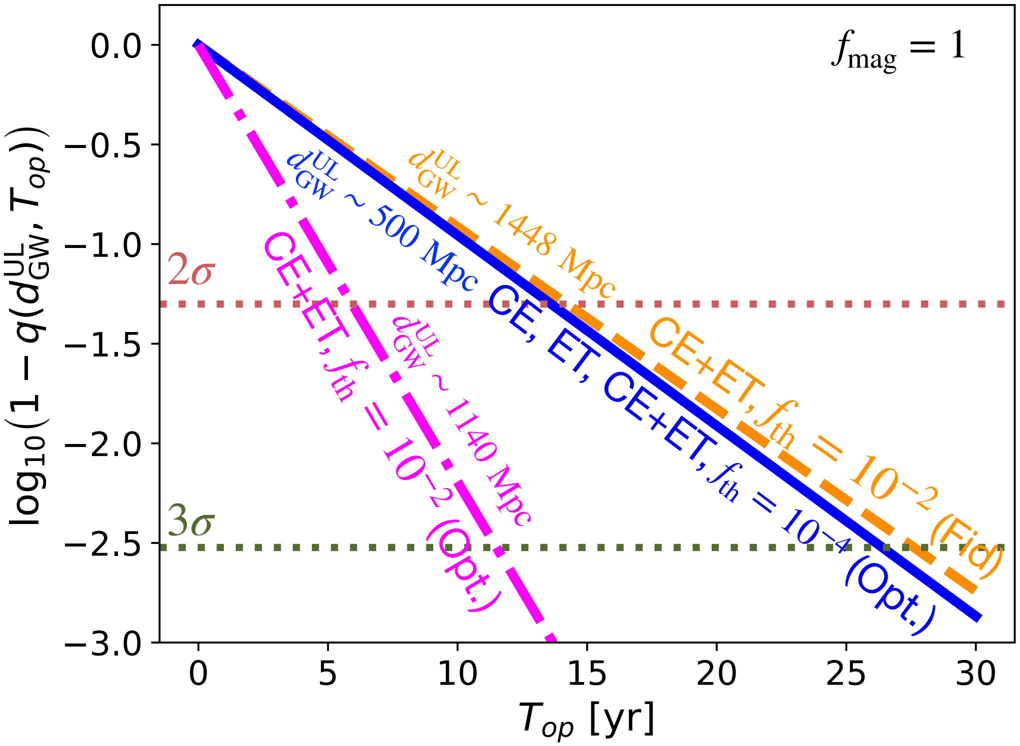
→ **Trigger from next-gen GW detectors** → **Neutrinos in IceCube-Gen 2**

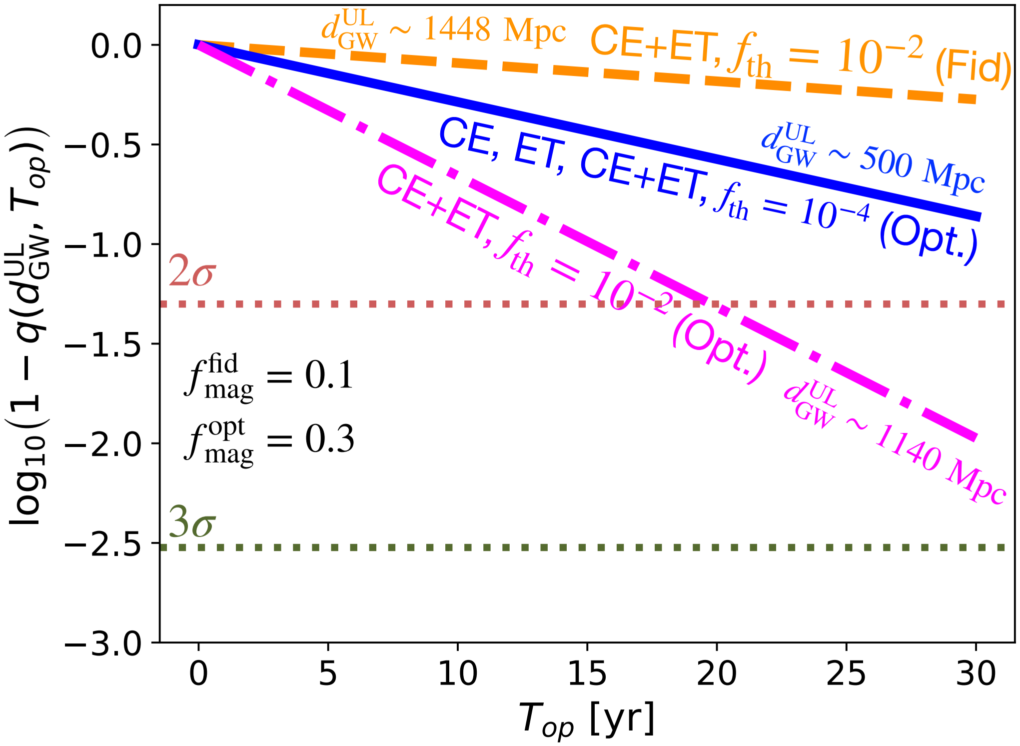
Triggered-stacking searches

$\delta t \approx 1 \text{ s} - 10^7 \text{ s}$

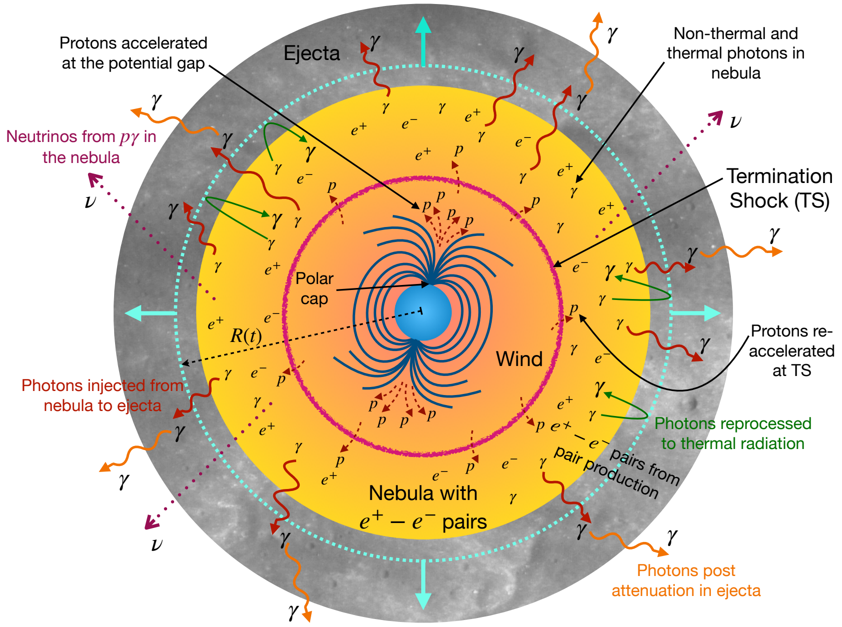


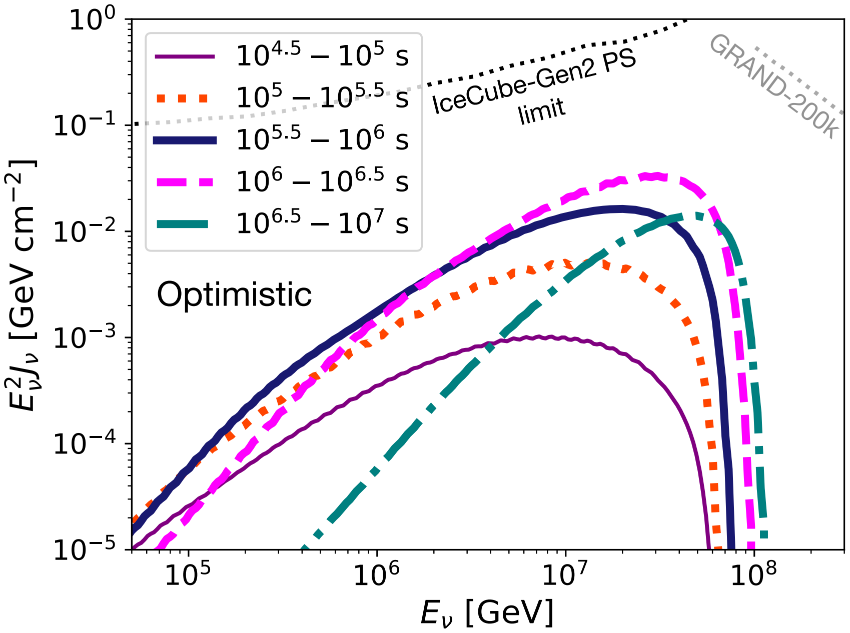
Results: Magnetar remnants from BNS mergers

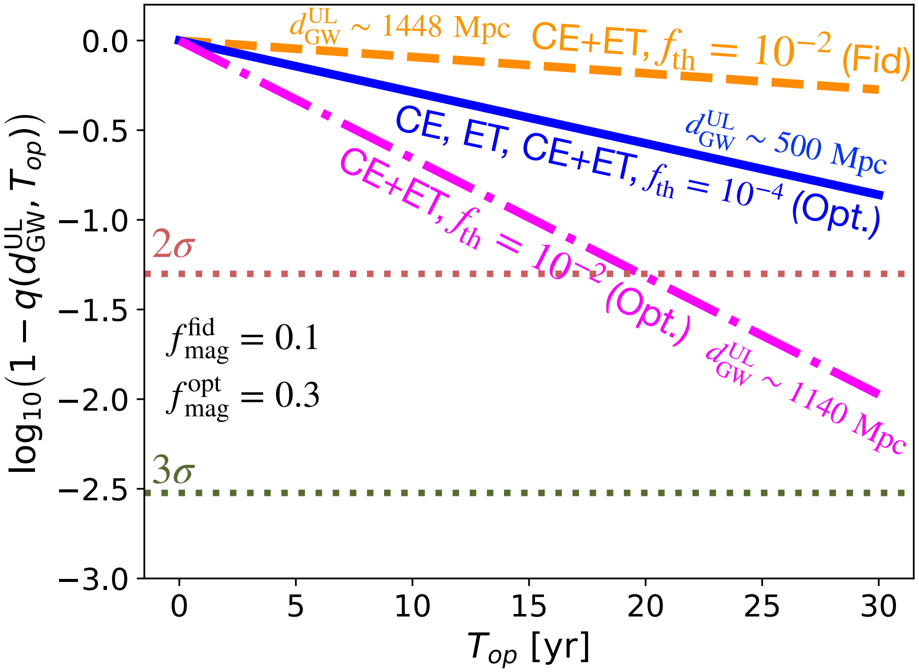




Takeaways







Thank You!

Backup

Cosmic ray (CR) proton acceleration: injection spectra

$$\frac{d\dot{N}_{p,\mathrm{inj}}}{d\varepsilon'_p} = \dot{N}_p^{\mathrm{norm}} Q_p^{\mathrm{inj}}(\varepsilon'_p) = \dot{N}_p^{\mathrm{norm}} \delta\left(\varepsilon'_p - \varepsilon_p^{\prime\mathrm{cutoff,pc}}\right)$$

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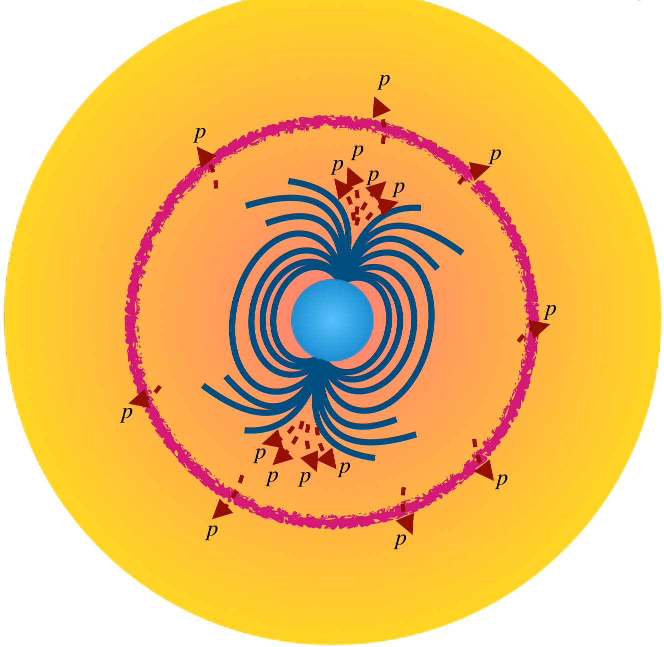
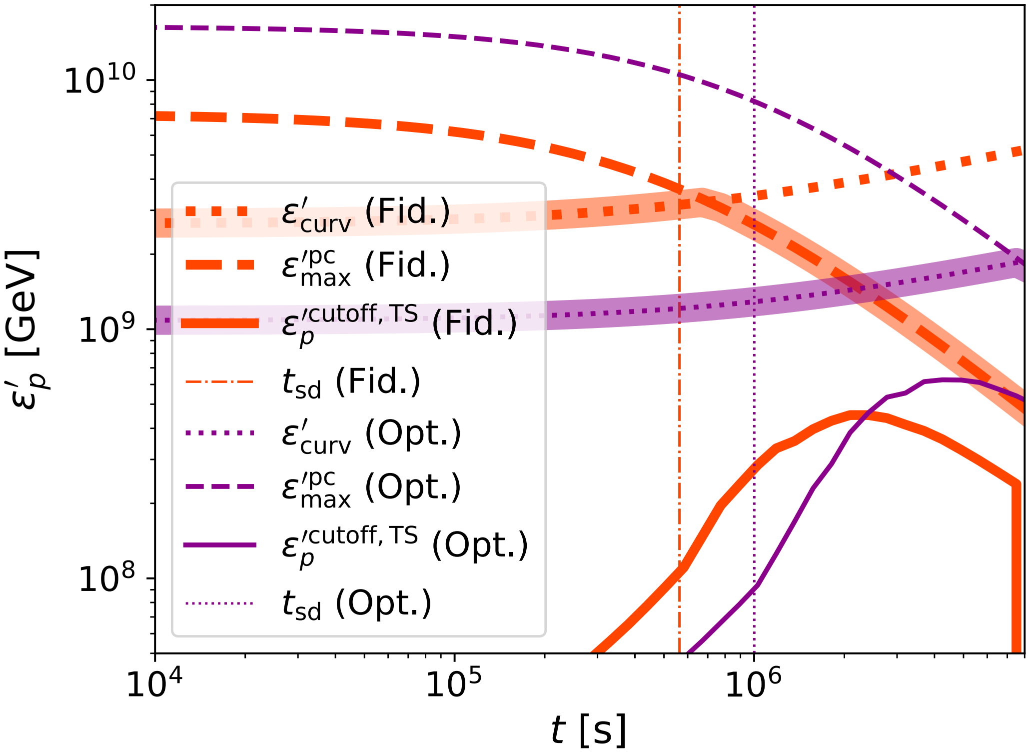
Acceleration sites:

Polar cap

+

Termination shock (TS)





Cosmic ray (CR) proton acceleration: injection spectra

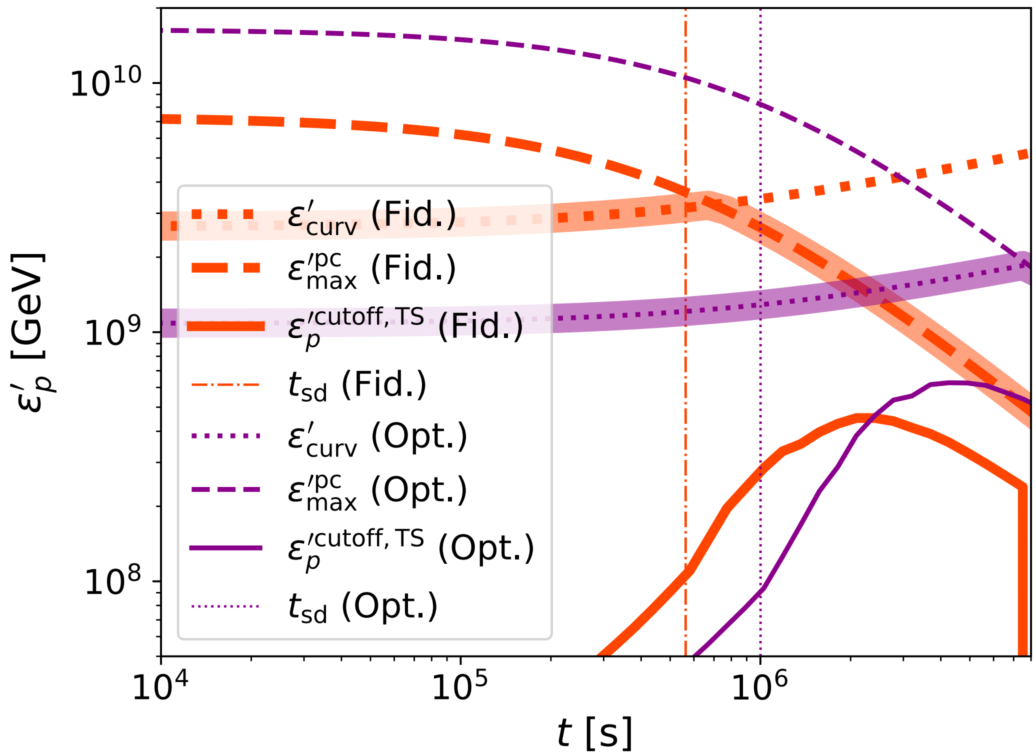
$$\frac{d\dot{N}_{p,\mathrm{inj}}}{d\varepsilon'_p} = \dot{N}_p^{\mathrm{norm}} Q_p^{\mathrm{inj}}(\varepsilon'_p) = \dot{N}_p^{\mathrm{norm}} \delta\left(\varepsilon'_p - \varepsilon_p^{\prime\mathrm{cutoff,pc}}\right)$$

$$\varepsilon_p^{\prime\mathrm{cutoff}} = \max\left[\varepsilon_p^{\prime\mathrm{cutoff,pc}}, \varepsilon_p^{\prime\mathrm{cutoff,TS}}\right]$$

$$\varepsilon_p^{\prime\mathrm{cutoff,pc}} = \min\left[\varepsilon_{\mathrm{max}}^{\prime\mathrm{pc}}, \varepsilon'_{\mathrm{curv}}\right]$$

$$\varepsilon_{\mathrm{max}}^{\prime\mathrm{pc}} = 4\eta_{\mathrm{gap}}(Ze)B_d\left(\frac{\pi R_*}{cP}\right)^2 R_*$$

$$\varepsilon'_{\mathrm{curv}} = \gamma_p m_p c^2 = \left[\frac{3m_p^4 c^8 B_d R_{\mathrm{curv}}^2}{2e}\right]^{1/4}$$



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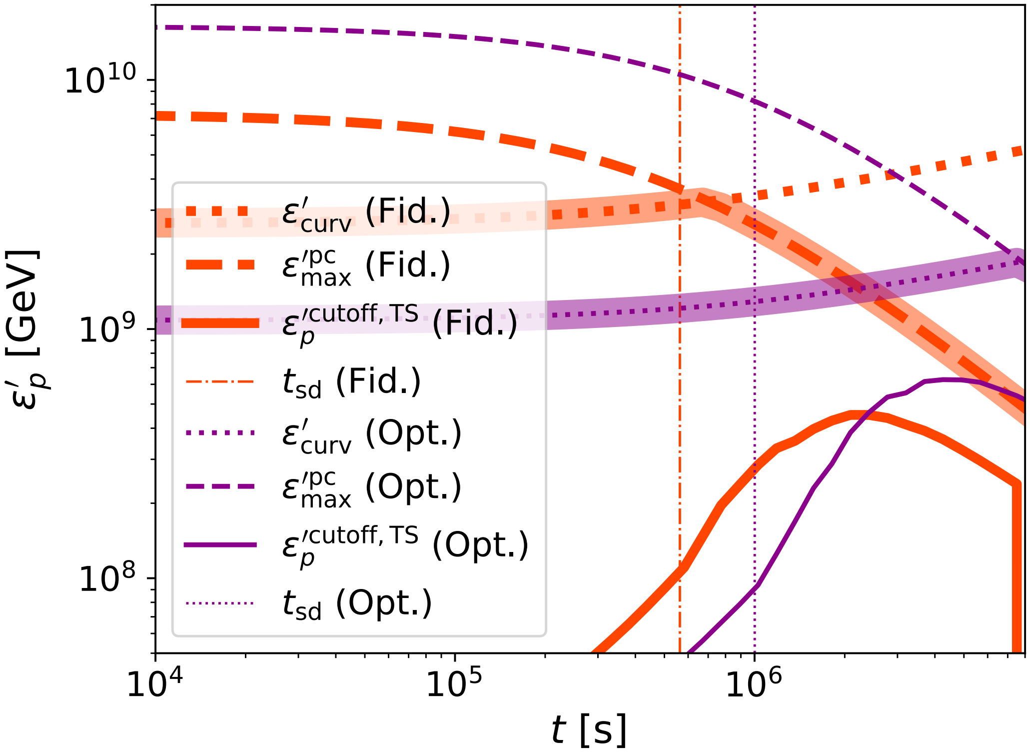
$$t_{\mathrm{acc}}'^{-1} = t_{\mathrm{loss}}'^{-1}$$

$$t'_{\mathrm{acc}} = \eta_{\mathrm{acc}} \varepsilon'_p / \left(ZecB'_{\mathrm{neb}}\right)$$

$$t_{\mathrm{loss}}'^{-1} = t_{\mathrm{esc}}'^{-1} + t_{\mathrm{cool}}'^{-1}$$

$$t'_{\mathrm{esc}} = \max\left[R(t)^2 / D_c(\varepsilon'_p), R(t)/c\right]$$

$$t_{\mathrm{cool}}'^{-1} = t_{pp}'^{-1} + t_{\mathrm{p}\gamma}'^{-1} + t_{\mathrm{sync}}'^{-1} + t_{\mathrm{BH}}'^{-1} + t_{\mathrm{dyn}}'^{-1}$$



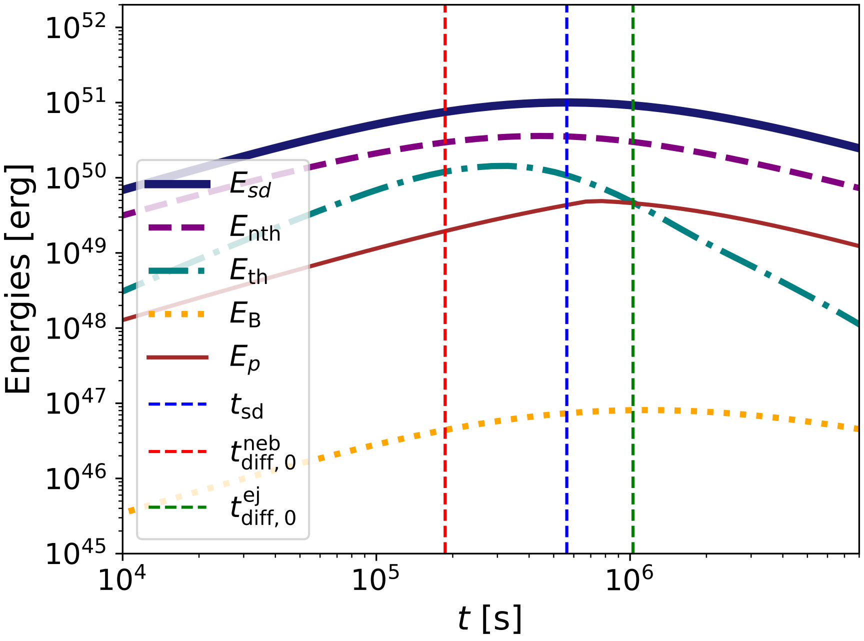
Cosmic ray (CR) proton acceleration

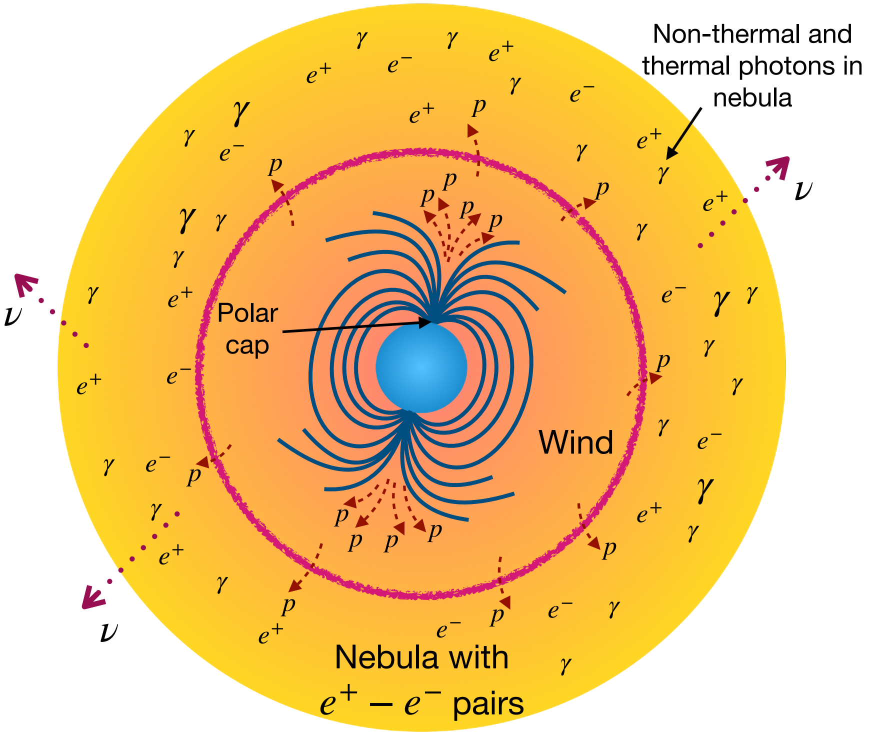
Compute steady state CE spectrum
by solving the transport equation

$$\frac{d}{d\varepsilon'_p}\left(-\frac{\varepsilon'_p}{t'_{\rm cool}}\frac{dN_p}{d\varepsilon'_p}\right) = \frac{d\dot{N}_{p,\rm inj}}{d\varepsilon'_p} - \frac{1}{t'_{\rm esc}}\frac{dN_p}{d\varepsilon'_p}$$

$$\frac{dN_p}{d\varepsilon'_p} = \frac{t'_{\rm cool}}{\varepsilon'_p}\int_{\varepsilon'_p}^{\infty} d\tilde{\varepsilon}_p \dot{N}_{p,\rm inj}(\tilde{\varepsilon}_p)\,\exp\Big(-\mathscr{G}(\varepsilon'_p,\tilde{\varepsilon}_p)\Big)$$

$$\mathscr{G}(\varepsilon_1,\varepsilon_2) = \int_{\varepsilon_1}^{\varepsilon_2}\frac{t'_{\rm cool}}{t'_{\rm esc}}\frac{d\tilde{\varepsilon}_p}{\tilde{\varepsilon}_p}$$





$$E_p = \dot{N}_{p,\rm inj}\varepsilon_p^{\prime\rm cutoff,pc}t$$

Cosmic ray (CR) proton acceleration

Compute steady state CE spectrum
by solving the transport equation

↓

This along with the photon field spectrum
gives the neutrino fluences

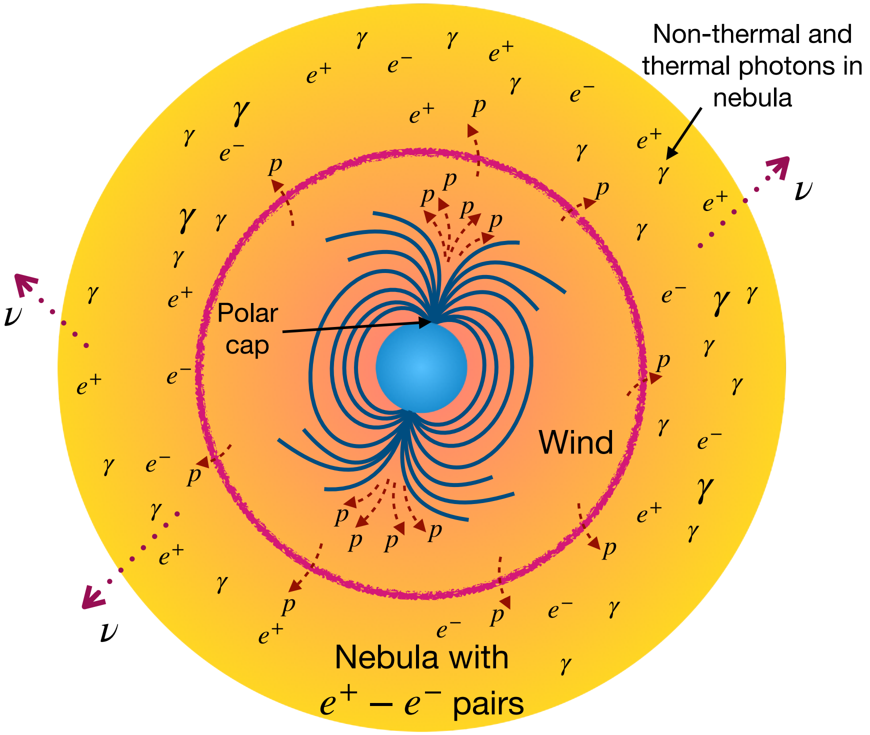
$e^+ - e^-$ spectra

$$\frac{dN}{d\gamma_e} \sim \begin{cases} \gamma_e^{-1.5}, \ \gamma_e \leq \gamma_{e,\mathrm{br}} \\ \gamma_e^{-2.5}, \ \gamma_e > \gamma_{e,\mathrm{br}}\,, \end{cases}$$

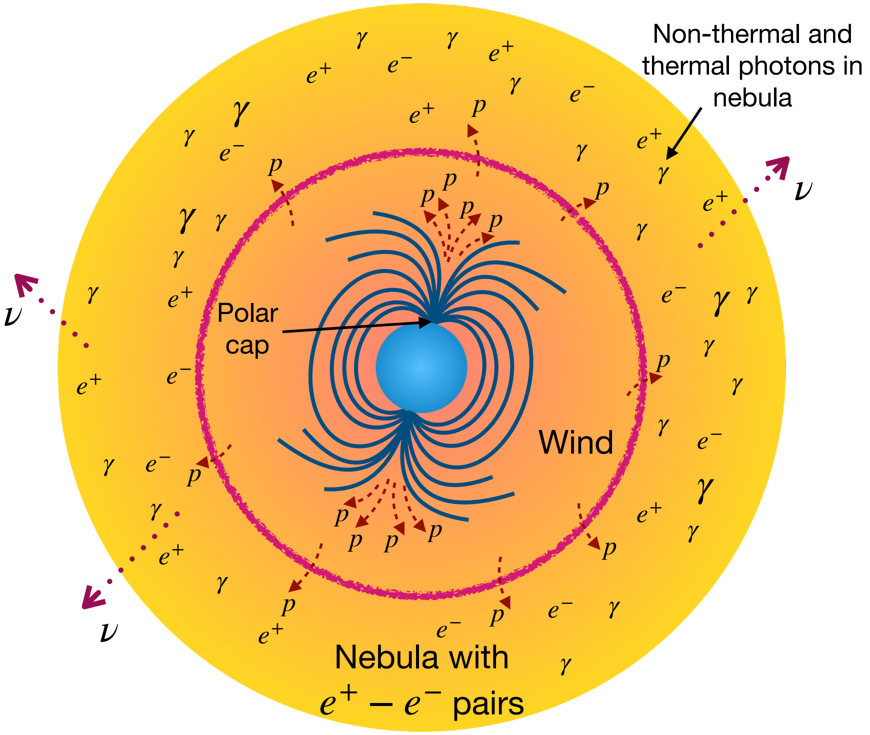
Electron break Lorentz factor

For galactic PWNe:
$\gamma_{e,\mathrm{br}} \sim 10^5 - 10^6$

Pair injection at upstream of TS ->
decreased wind velocity and hence
lower $\gamma_{e,\mathrm{br}}$. We choose $\gamma_{e,\mathrm{br}} = 10^3$



Cosmic ray (CR) proton acceleration



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Transport Equation

Electron break Lorentz factor

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Pair injection at upstream of TS -> decreased wind velocity and hence lower $\gamma_{e,\rm br}$. We choose $\gamma_{e,\rm br} = 10^3$

Synchrotron, inverse Compton, Breit-Wheeler processes

EM cascades

Details about r-process heating rate

$$Q_{\rm rp}^{\rm heat} = f_{\rm therm} f_{\rm diff} \dot{E}_{\rm rp} M_{\rm ej}$$

Fraction of photons that have thermalized (non-trivial)

Fraction of thermalized photons that diffuse from ejecta to the nebula

$$f_{\rm therm} = \begin{cases} 0.7, \ t \le t_{{\rm tr},\gamma} \\ 0.2, \ t > t_{{\rm tr},\gamma} \end{cases}$$

$$f_{\rm diff} = \frac{t_{\rm dyn}}{t_{\rm diff}^{\rm ej}}$$

$$t_{\rm diff}^{\rm neb} \approx \frac{R}{c}(1 + \tau_{\rm diff}^{\rm neb})$$

$$t_{\rm dyn} = \frac{R}{\Gamma_{\rm ej} v}$$

$$\tau_{\rm diff}^{\rm neb} = \frac{n'_{\pm}\sigma_T R}{\Gamma_{\rm ej}} = \left(\frac{4YL_{\rm sd}\sigma_T}{\pi m_e c^3 R \Gamma_{\rm ej}^2}\right)^{1/2}$$

Time at which ejecta becomes transparent to gamma-rays

$$t_{{\rm tr},\gamma} \approx \left(\kappa_\gamma M_{\rm ej}/(4\pi v^2)\right)^{1/2} \approx 0.4 \ {\rm day} \left(\frac{\kappa_\gamma}{0.05 \ {\rm cm^2 g^{-1}}}\right)^{1/2} \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{1/2} \left(\frac{\beta_{\rm ej}}{0.3}\right)^{-1}$$

Rate of energy generated from r-process nuclei decay

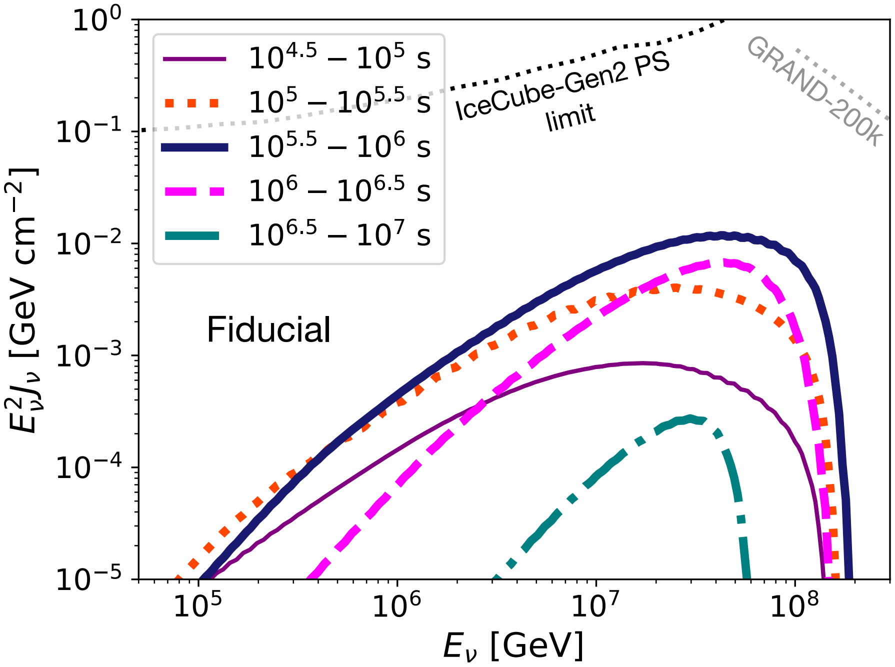
$$\dot{E}_{\rm rp} = \dot{E}_{0,{\rm rp}} \left(\frac{t}{t_{0,{\rm rp}}}\right)^{-1.3}$$

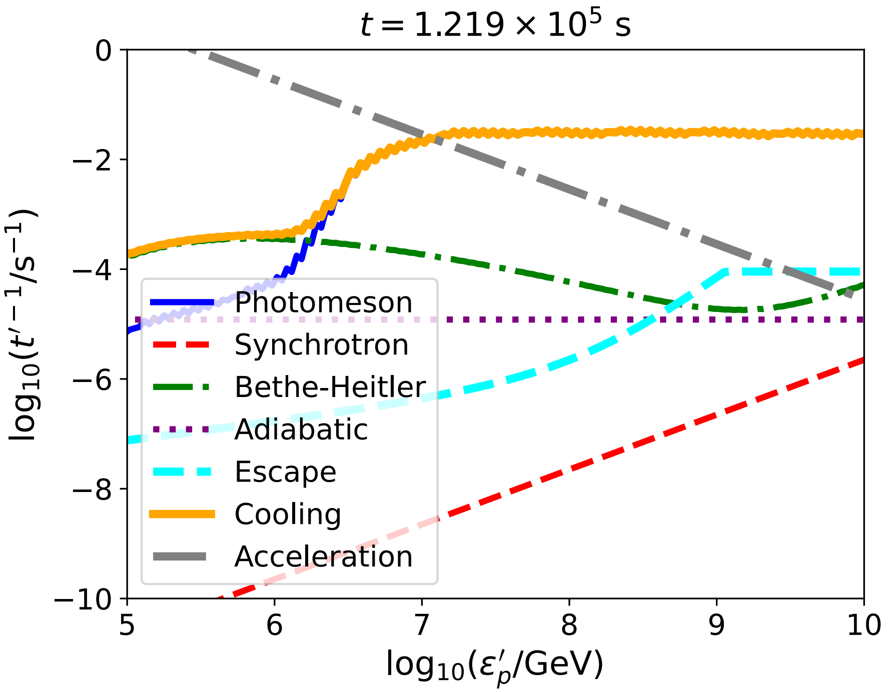
$$\dot{E}_{0,{\rm rp}} = 1.6 \times 10^{11} \ {\rm erg \ s^{-1} g^{-1}}$$

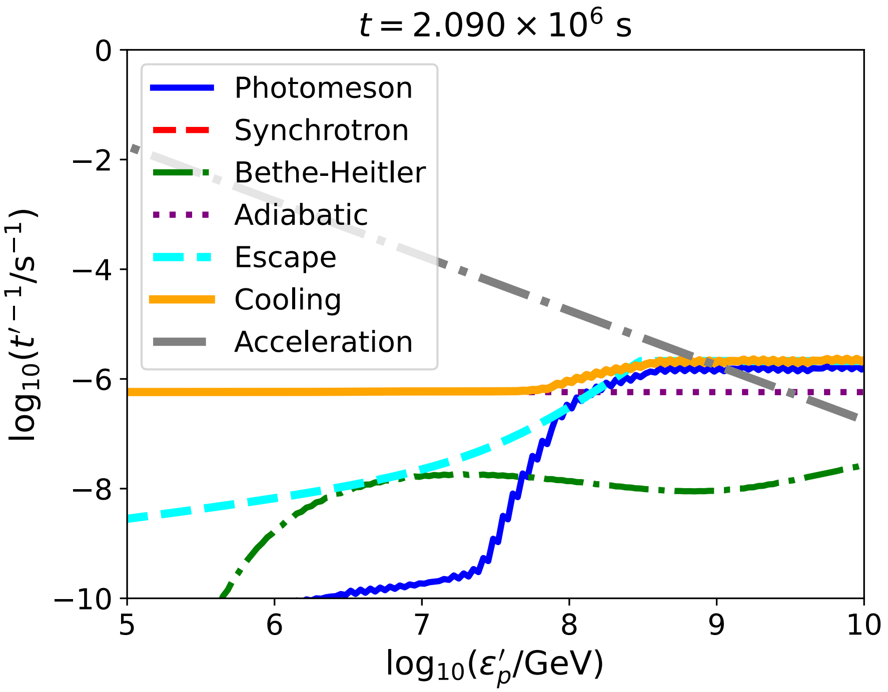
$$t_{0,{\rm rp}} = 10^4 {\rm s}$$

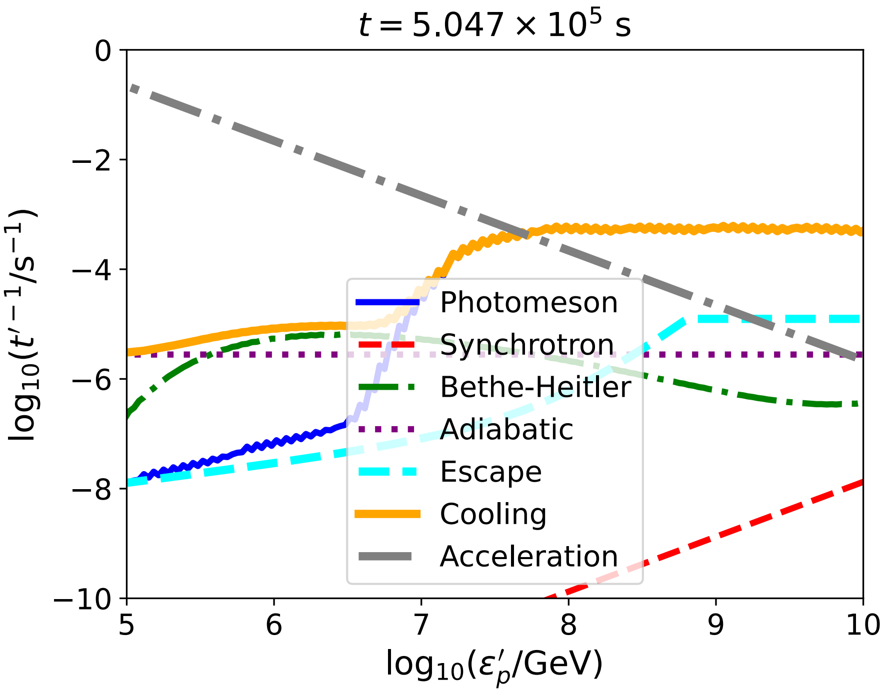
Hotokezaka et al. (2016)

Neutrino fluences: timescales

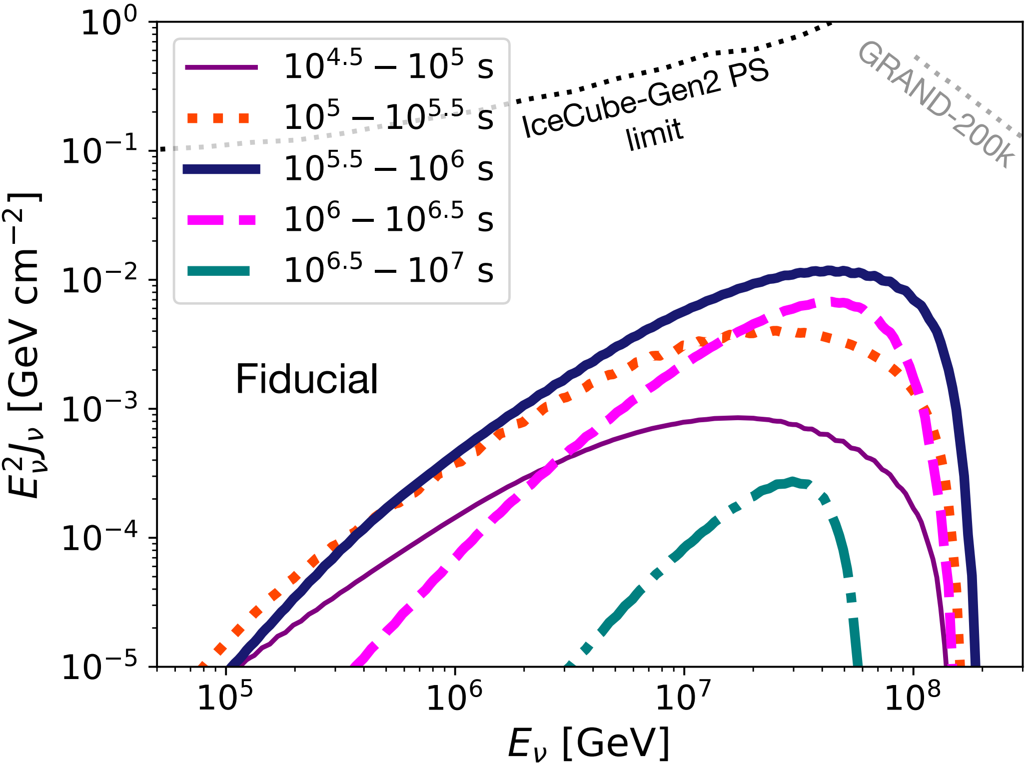


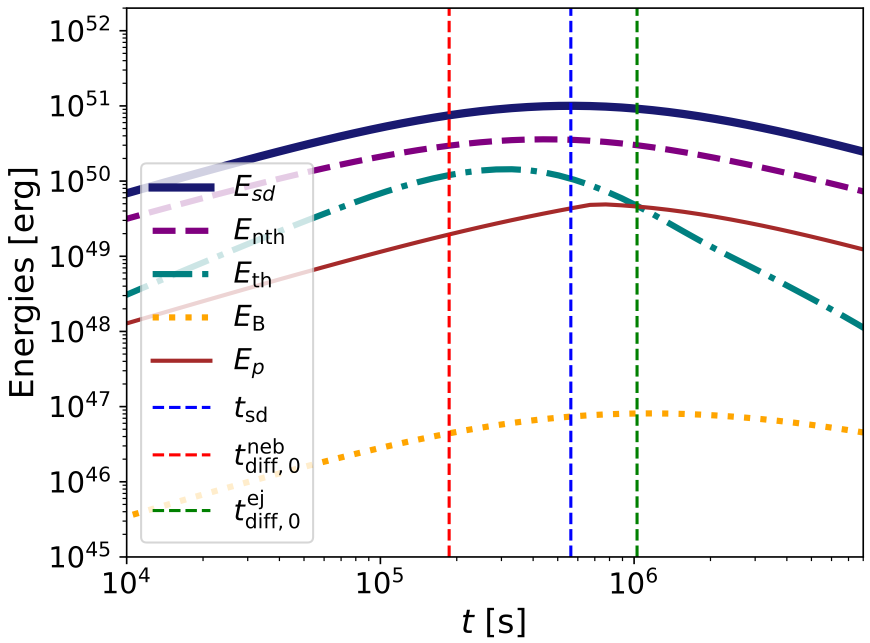


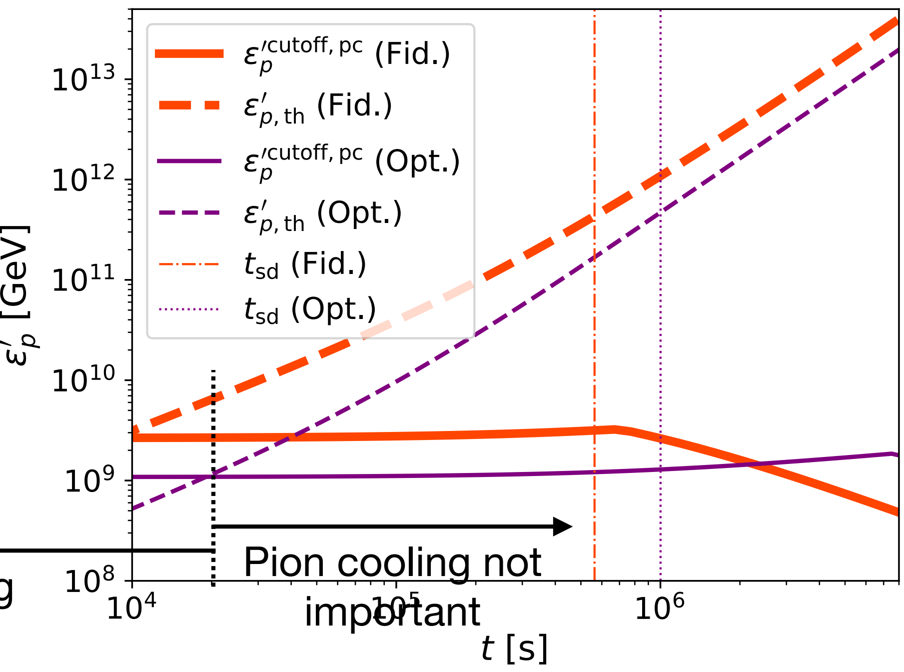




Neutrino fluences: importance of pion cooling







Pion cooling important

Pion cooling not important

Backgrounds