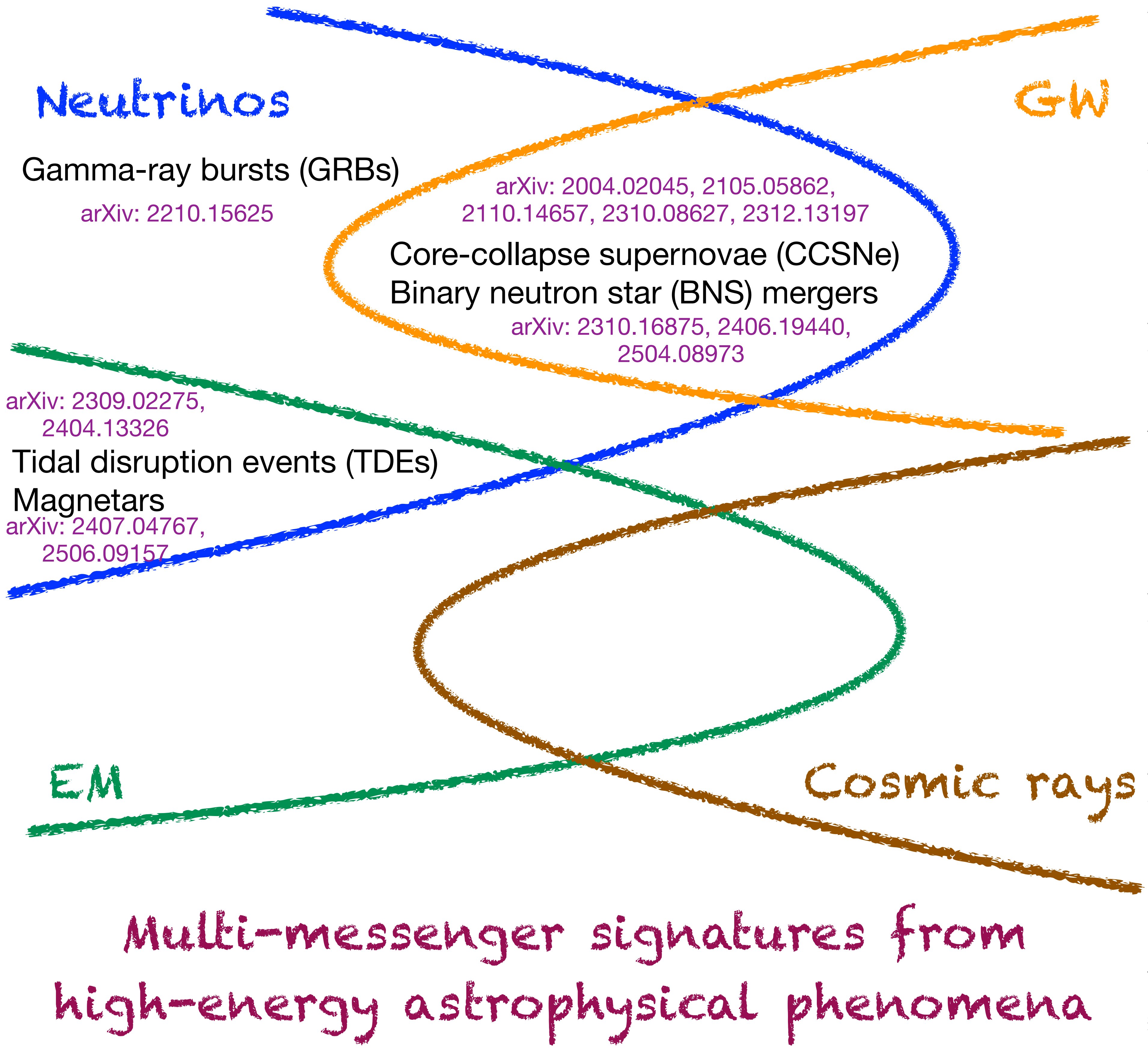
Multi-messenger signatures from magnetar remnants of BNS mergers

Mainak Mukhopadhyay
Pennsylvania State University

IAP-HEU Group Seminar
KIT, Karlsruhe
June 26, 2025

PennState

Research overview



IceCube likelihood analysis pipeline: Correlations with Type Ia/ Type II supernovae
Upcoming JWST searches

Astrophysical probes of dark matter (DM):
DM cooling in AGNs, CR boosted DM
arXiv:2408.08947
DM induced neutron star implosions

Quantum fields in time- and space-dependent backgrounds: particle production and back reaction
Applications to early universe cosmology: formation and annihilation of vortices, domain walls, cosmic strings
arXiv:1907.03762, 2004.07249, 2009.11480, 2110.08277, 2303.03415, 2406.13301, 2503.03808

Connections to LISA and NANOGrav results?

Prologue

New physics, understanding the fundamentals,….

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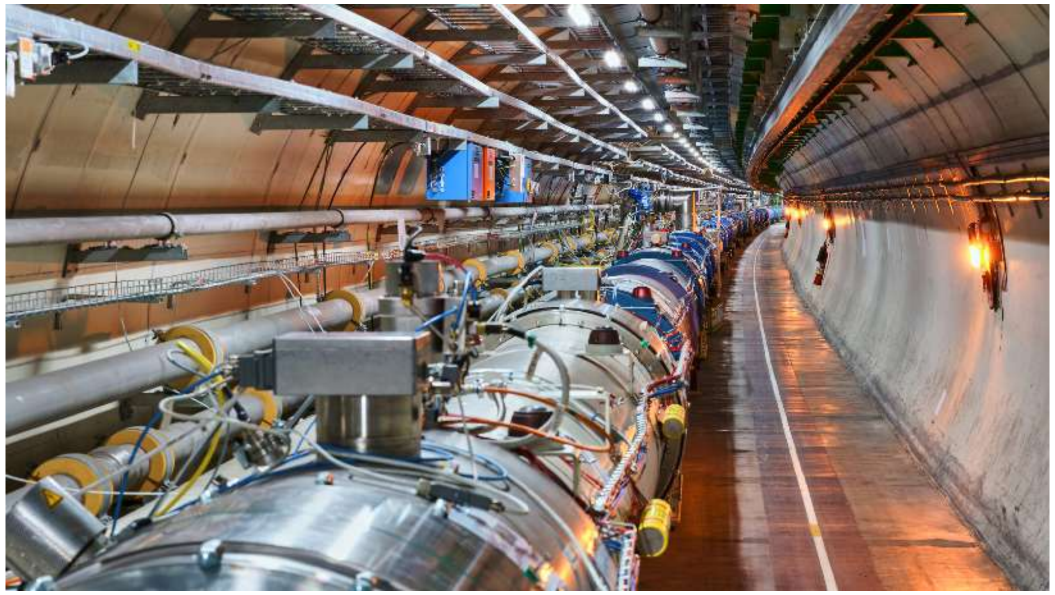
New physics, understanding the fundamentals,….

Man-made Accelerators

LHC



Tevatron

Image credits: Wikipedia

Prologue

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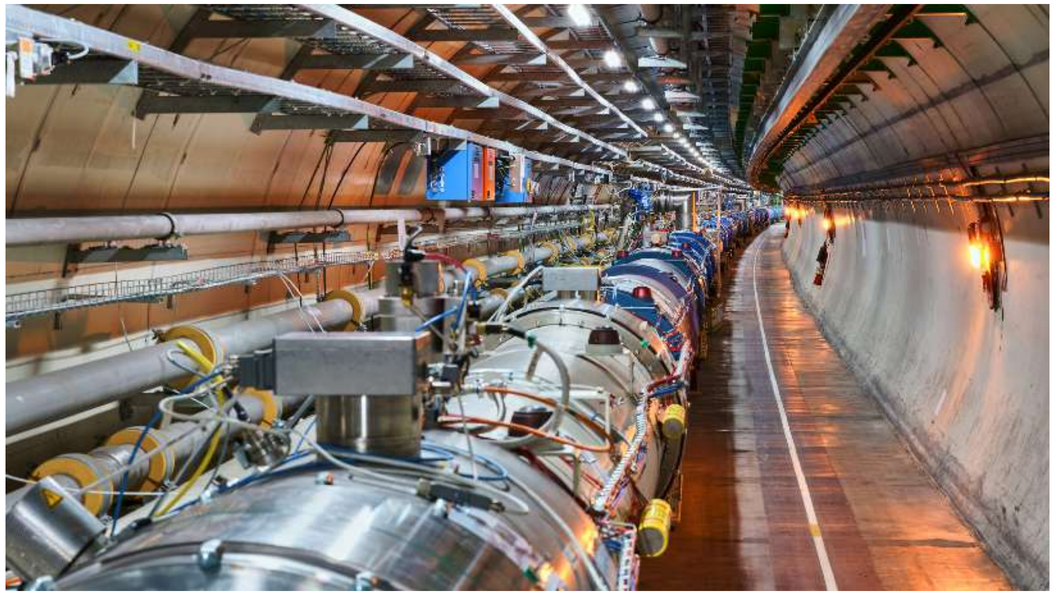
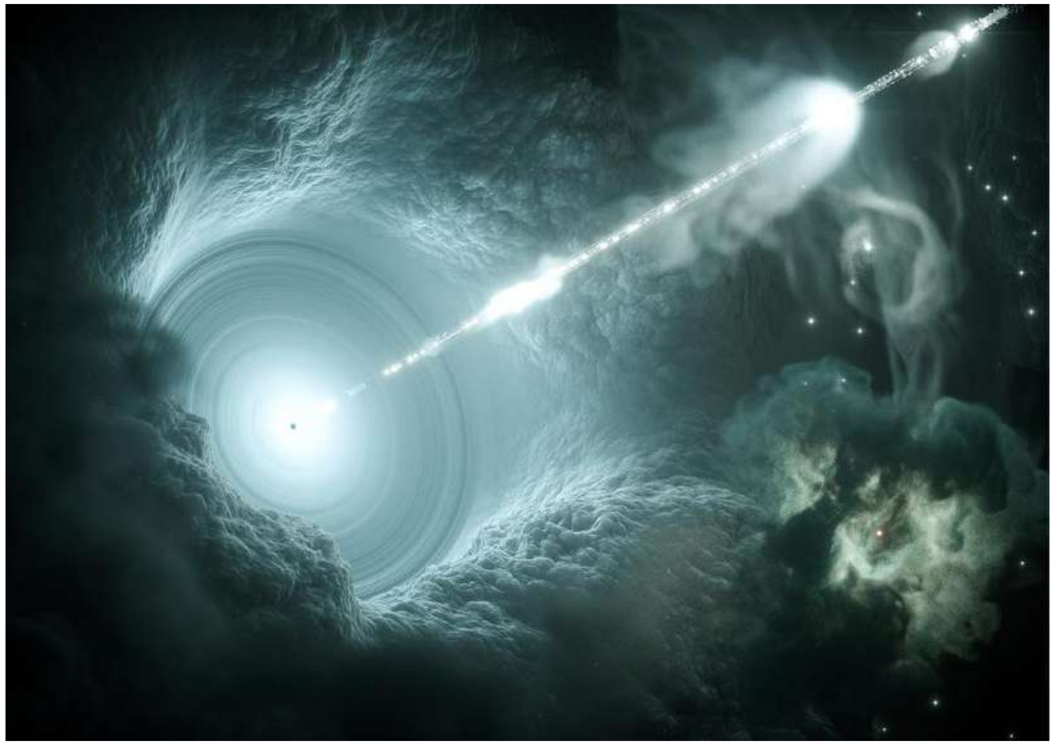


Tevatron

Cosmic Accelerators



High-energy astrophysical phenomena

Image credits: Wikipedia
Science Comm., DESY, Zeuthen

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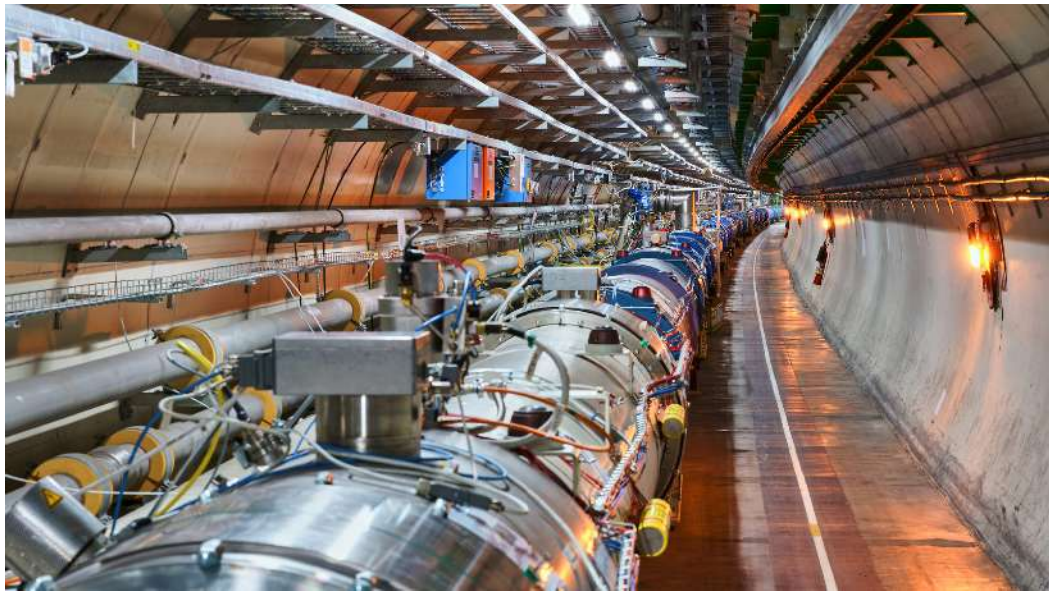

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The multi-messenger paradigm

Compact object mergers, TDEs, CCSNe,….

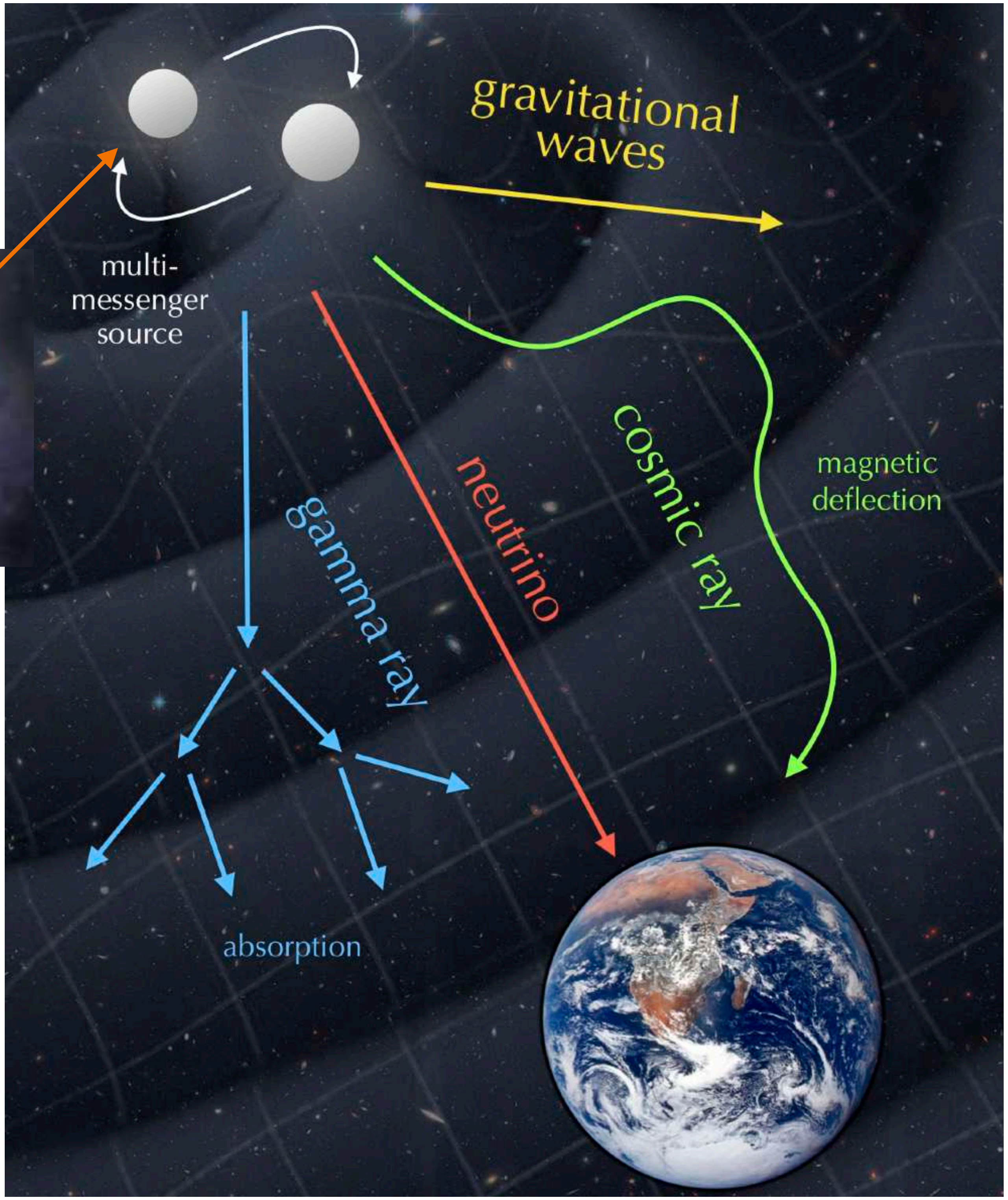

Image credits: NBI
IceCube Collab.+ Science 2022
IceCube Collab.+ Science, 380, 2023

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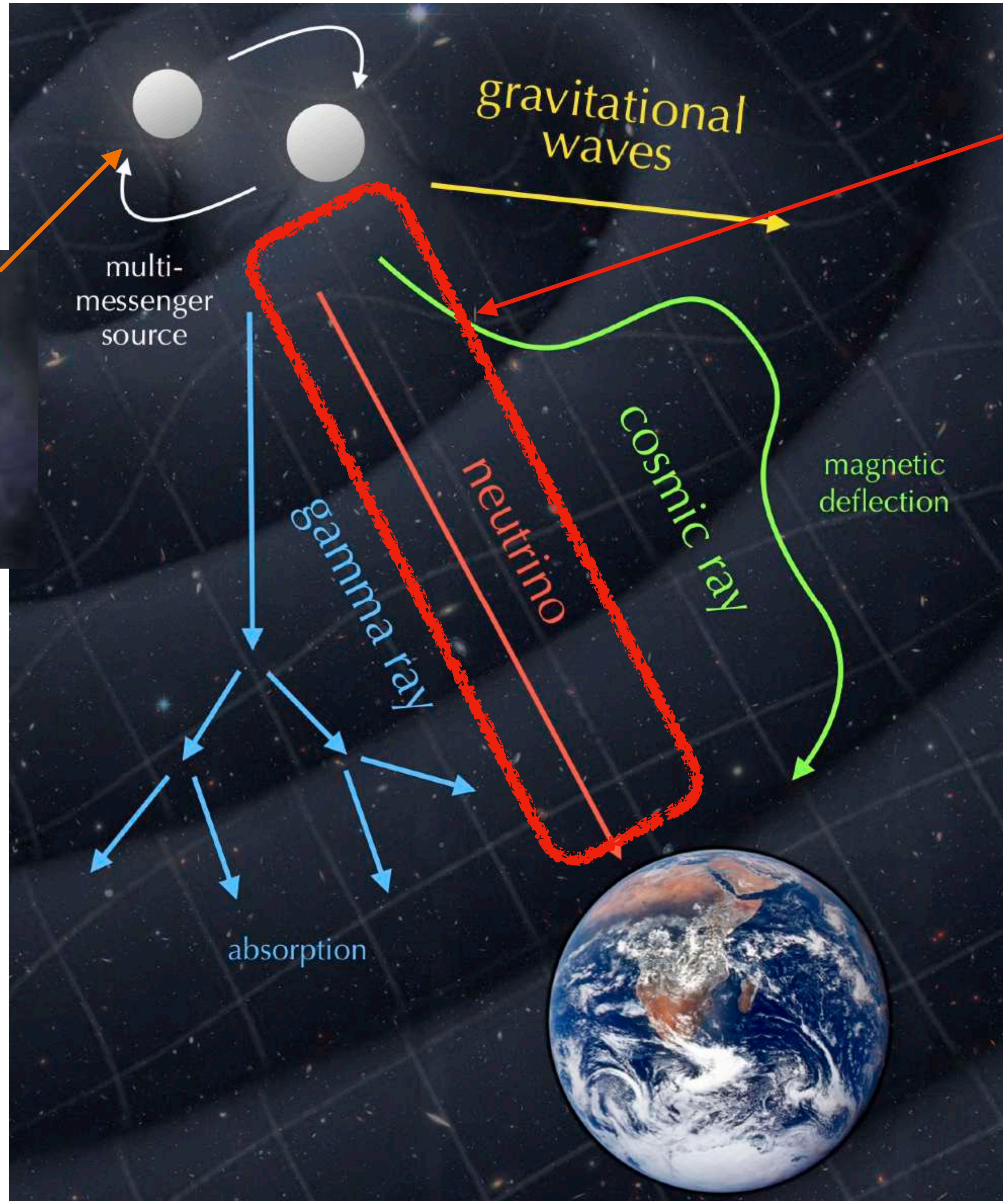

High-energy neutrinos

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IceCube Collab.+ Science 2022
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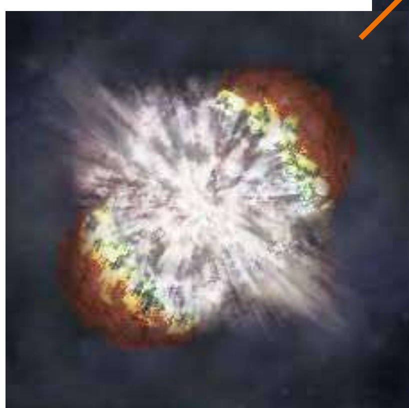
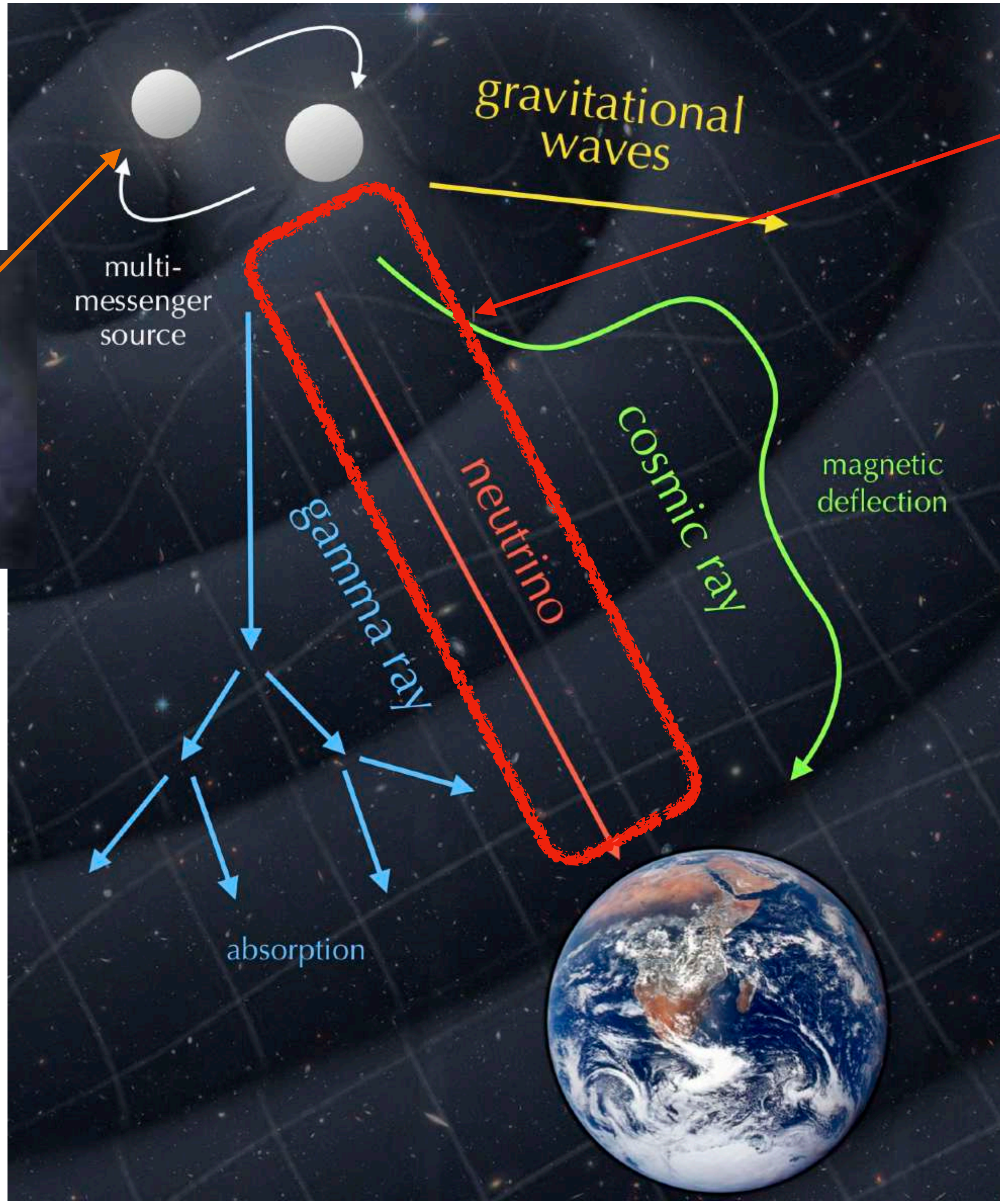
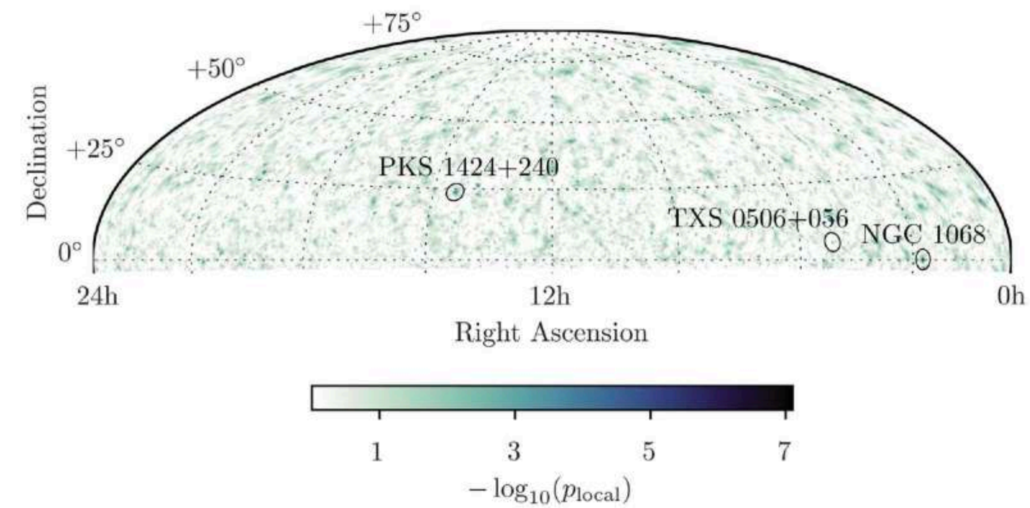
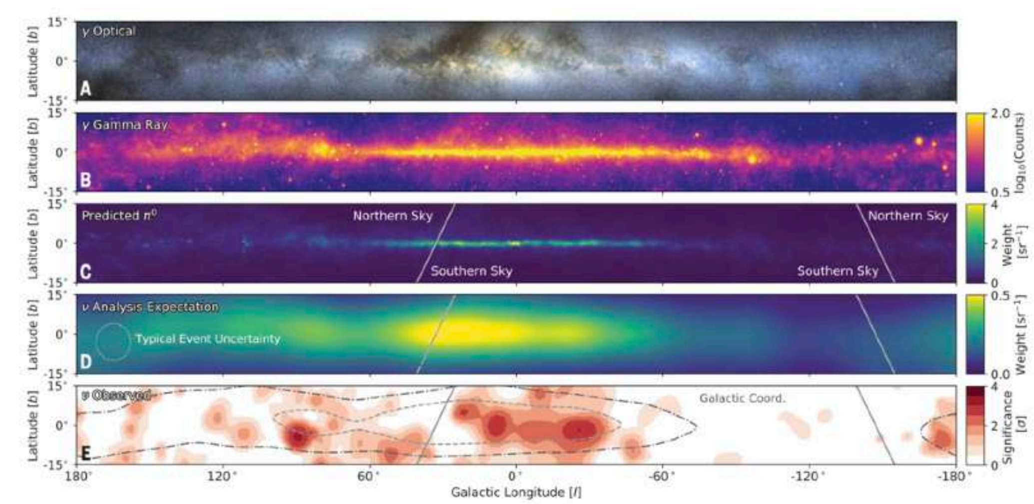




High-energy neutrinos



Point Sources

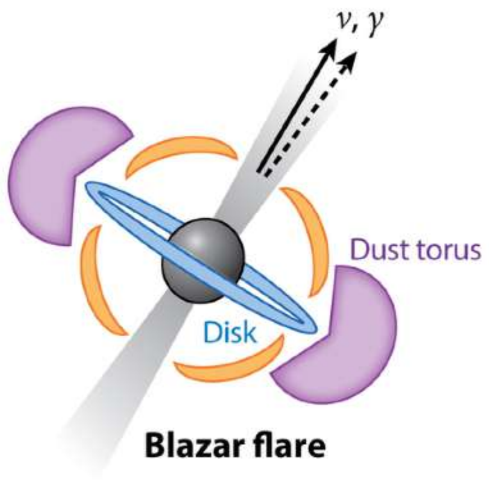


The Galactic plane

Image credits: NBI
IceCube Collab.+ Science 2022
IceCube Collab.+ Science, 380, 2023

The high-energy multi-messenger transients

Extreme astrophysical phenomena



Murase K, Bartos I. 2019.
Annu. Rev. Nucl. Part. Sci. 69:477–506

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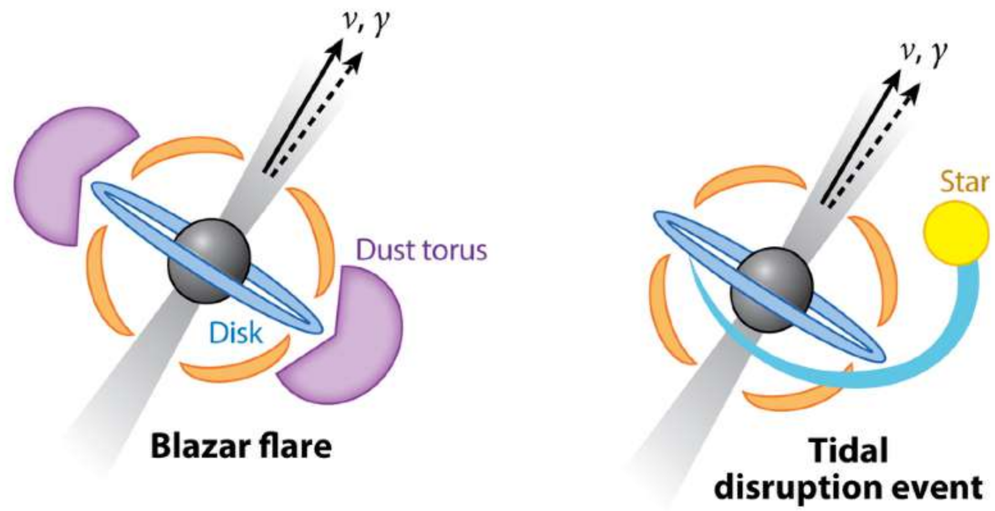

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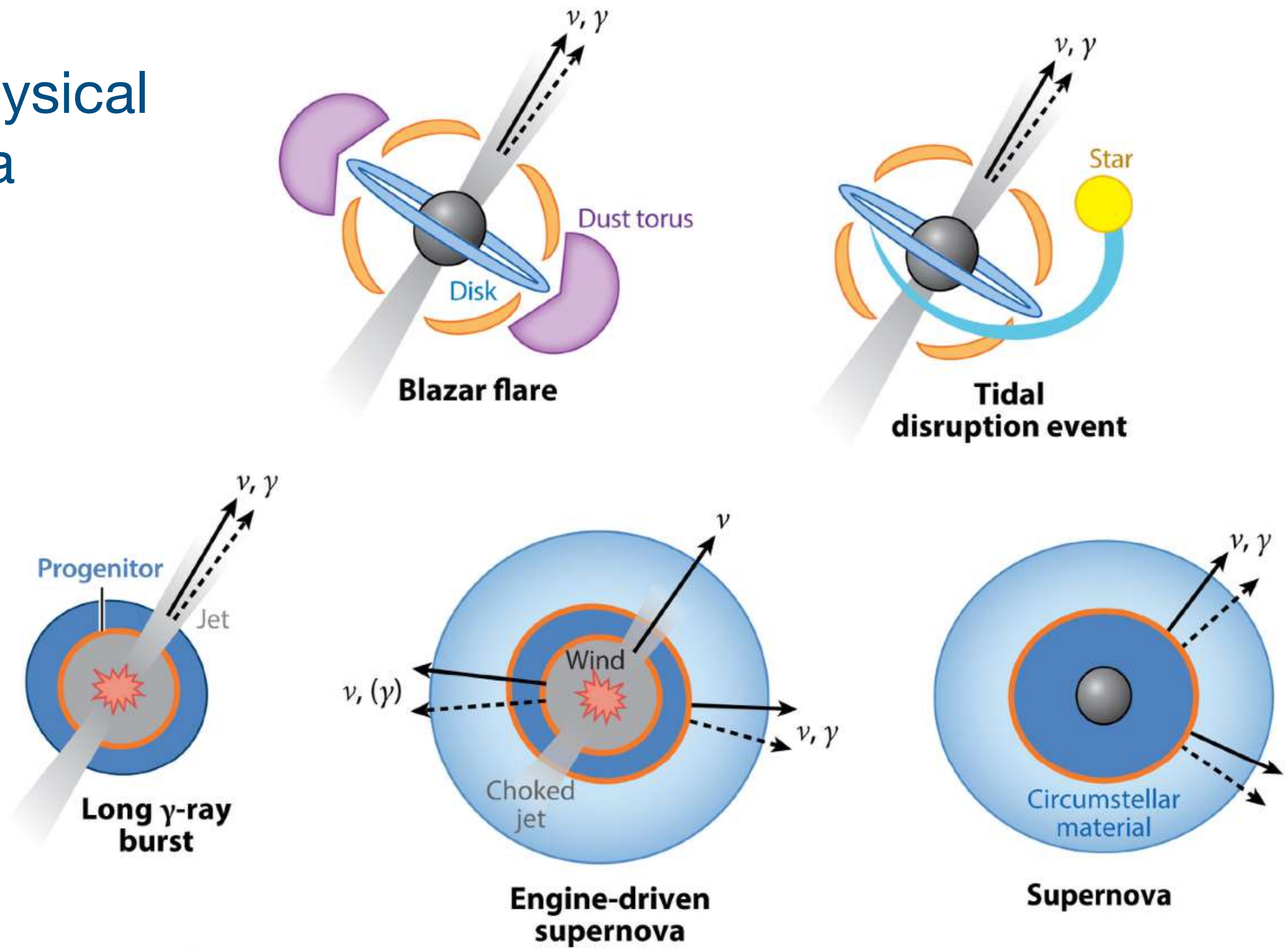

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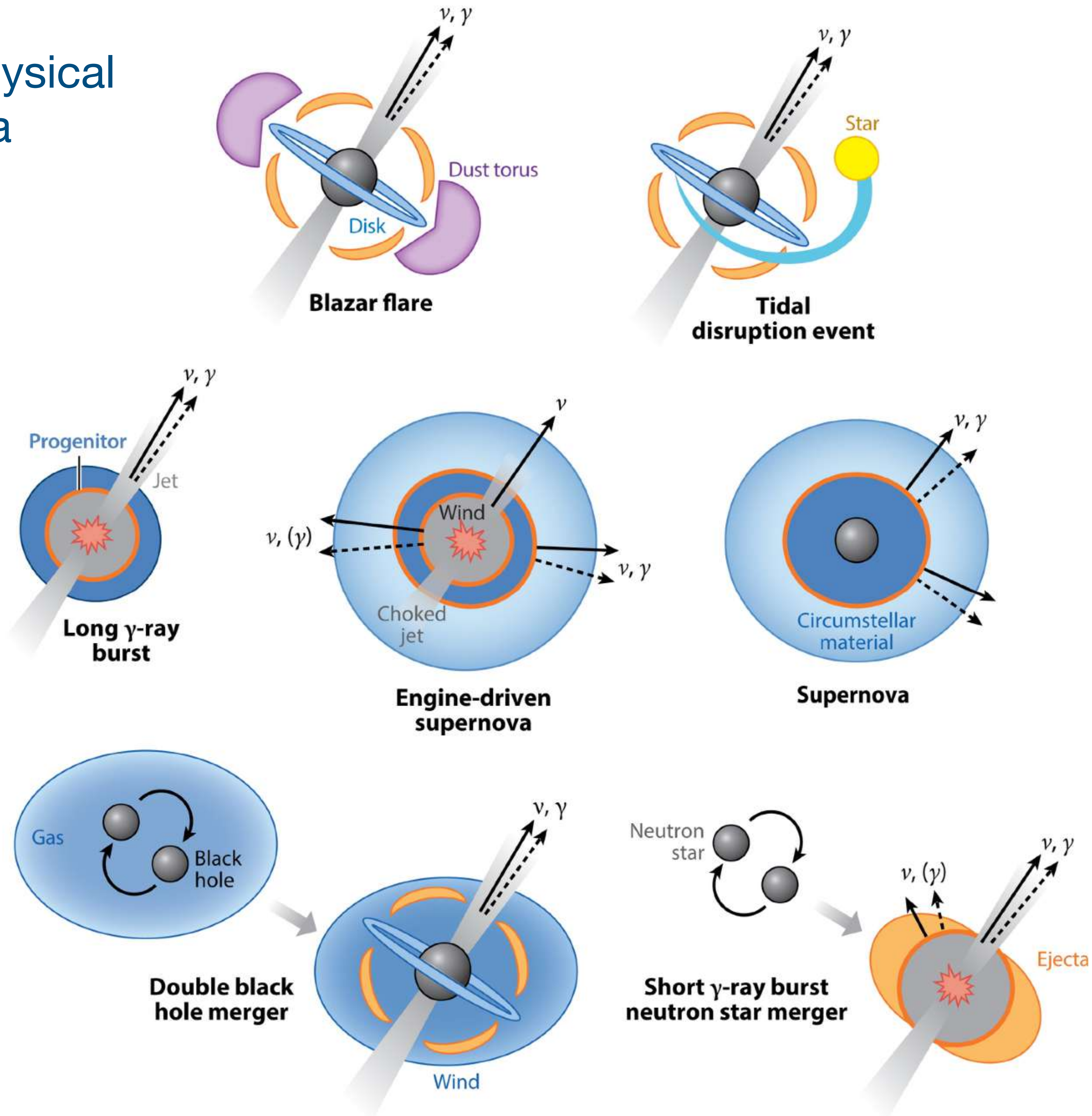

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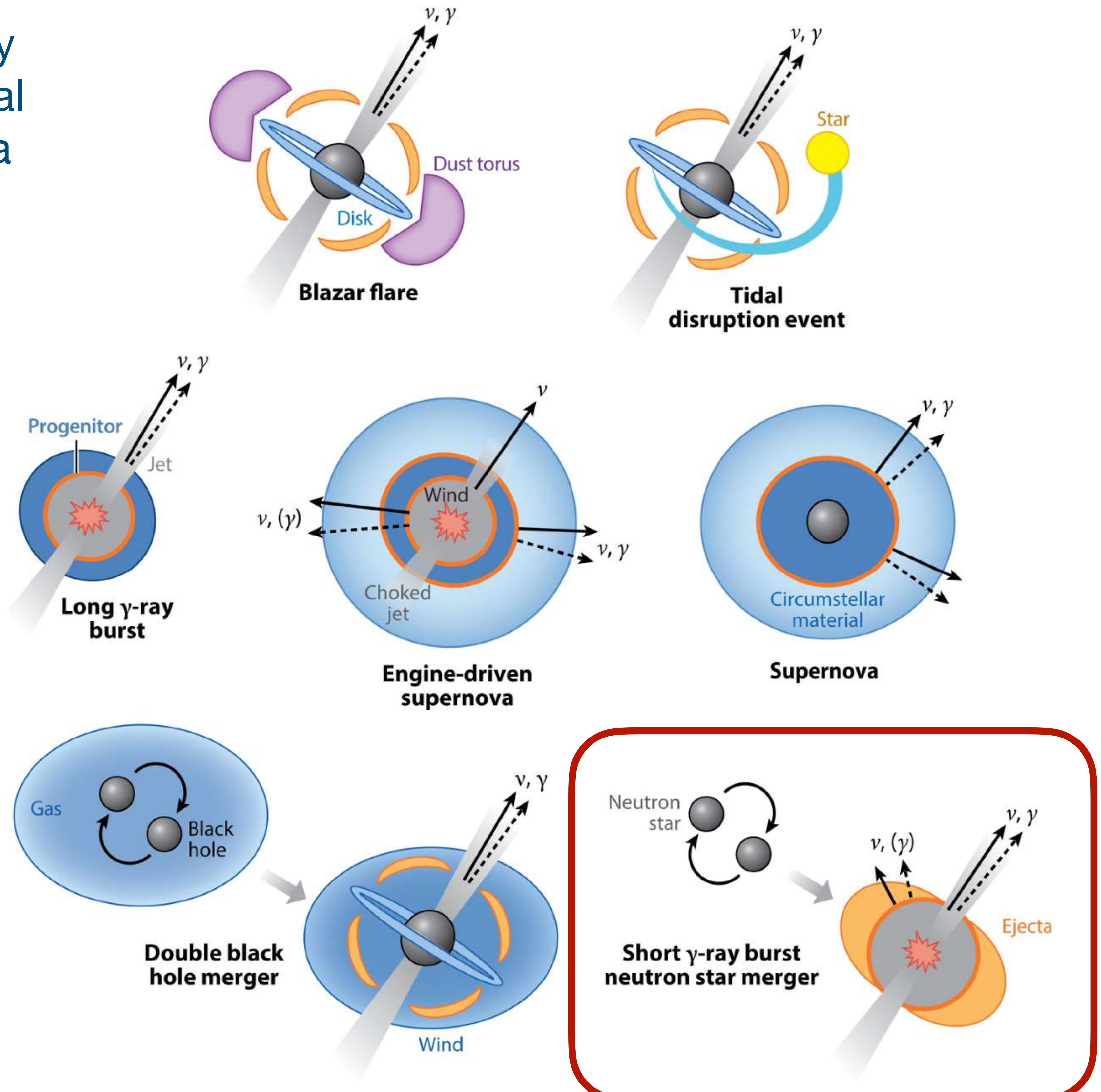

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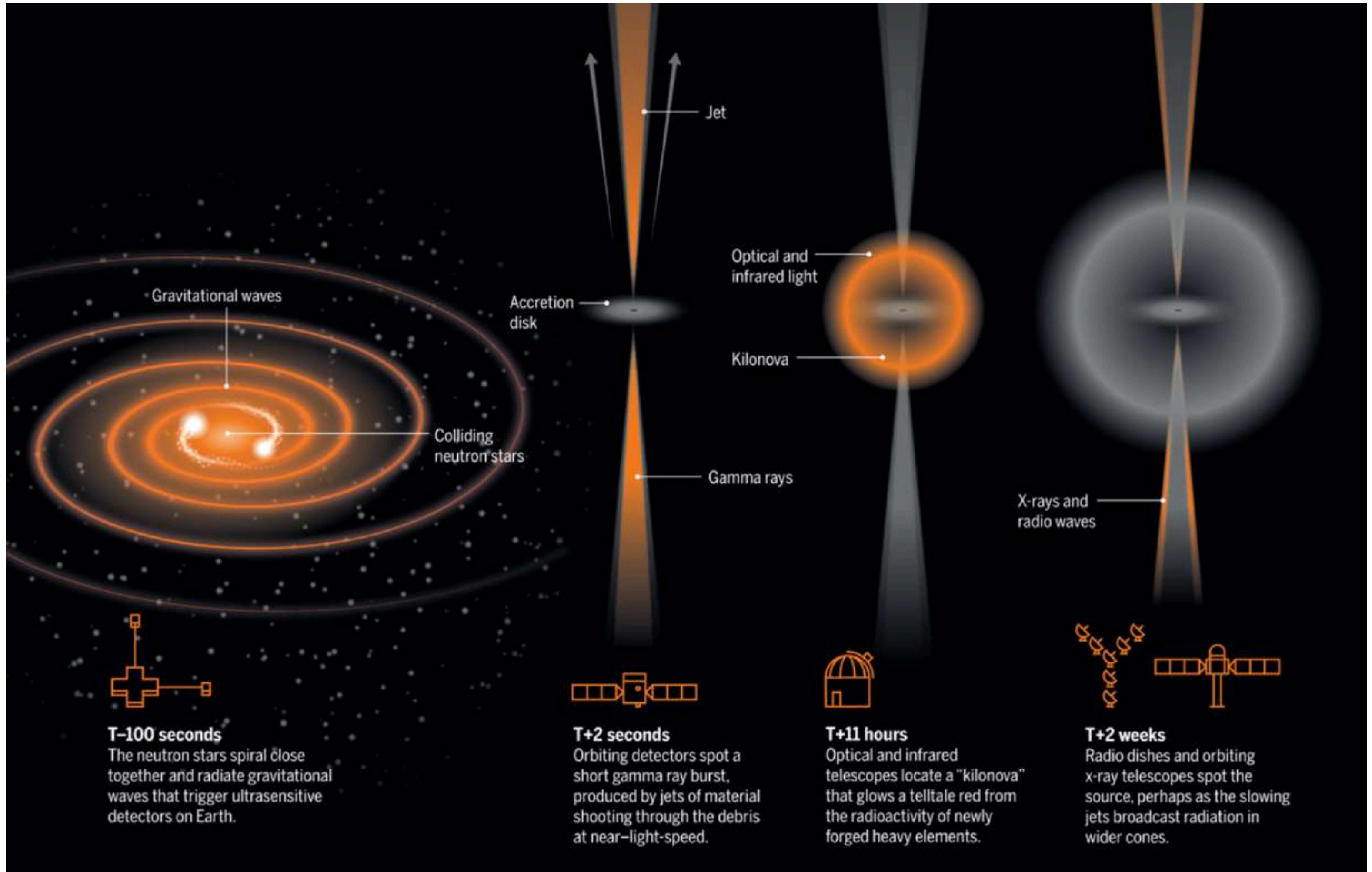
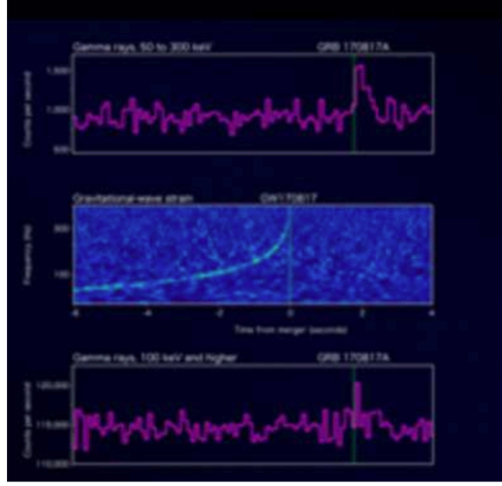
GW170817

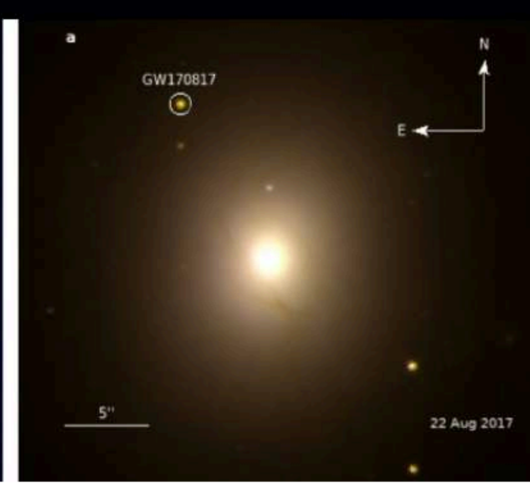
~ 40 Mpc (NGC 4993)

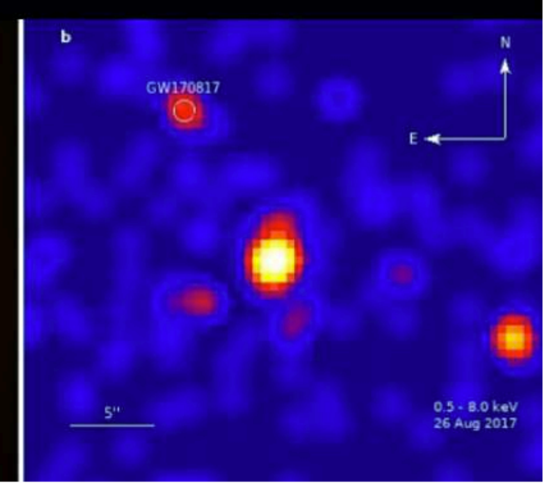


Gamma rays (Fermi+Integral)

GW (Adv. LIGO+Virgo)







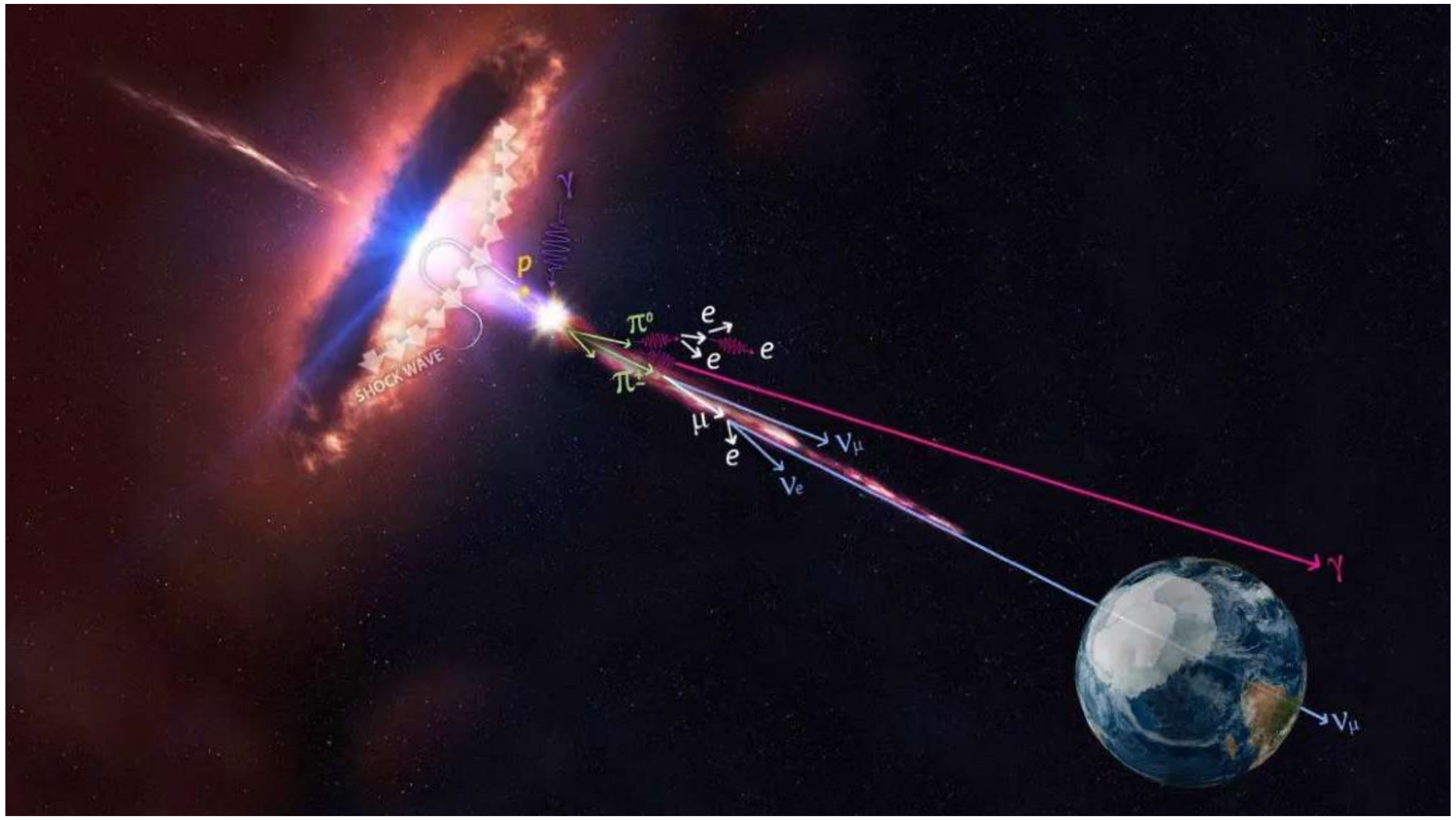
Optical (HST)

No neutrinos :(

X-rays (Chandra)

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

High-energy (HE) neutrinos



$$p + p \to N\pi + X \qquad p + \gamma \to N\pi + X$$

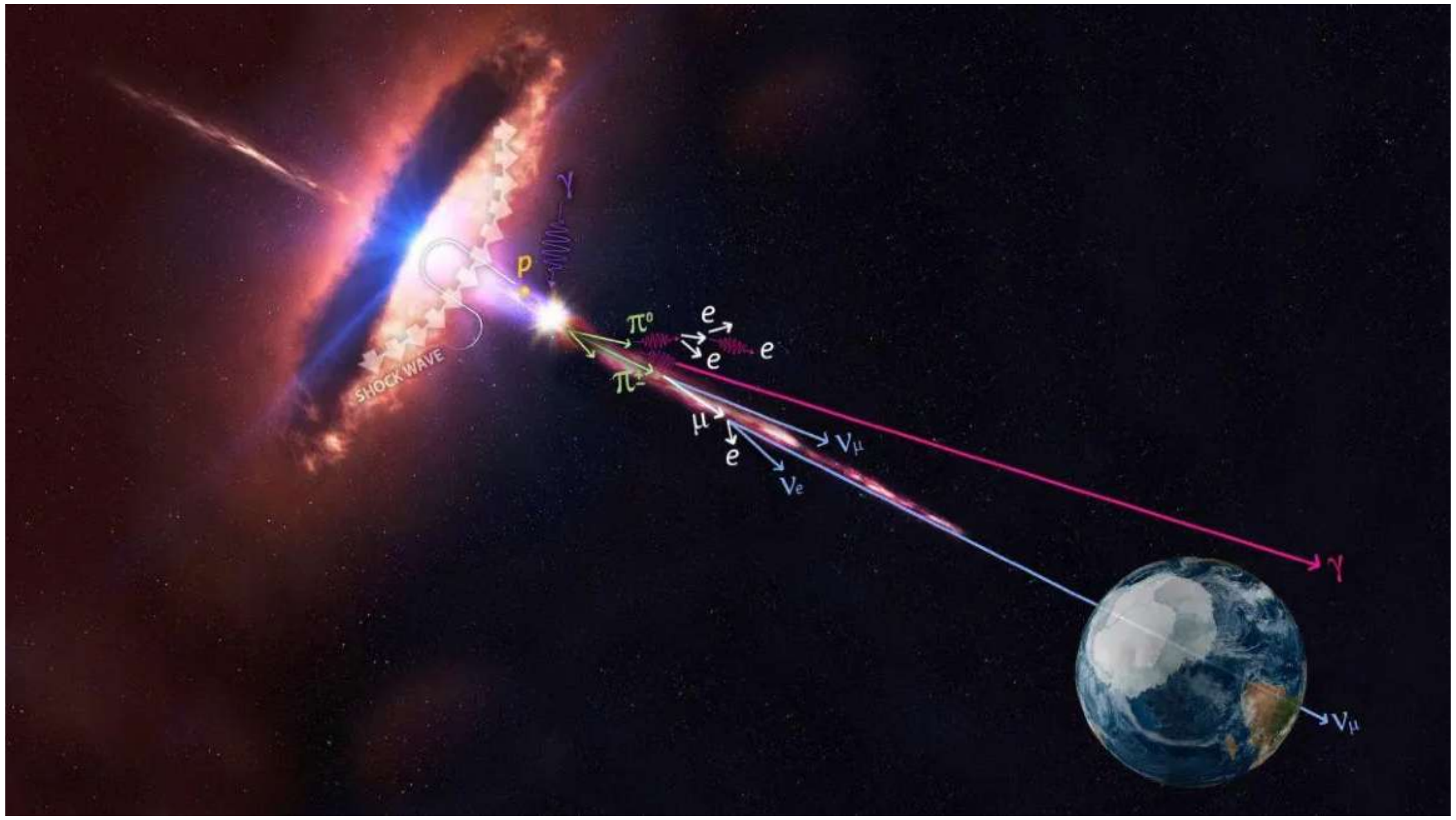
$$\downarrow$$

$$\pi^{\pm} \to \nu_\mu + \bar{\nu}_\mu + \nu_e(\text{or } \bar{\nu}_e) + e^{\pm}$$

$$\downarrow$$

$$\pi^0 \to \gamma + \gamma$$

High-energy (HE) neutrinos



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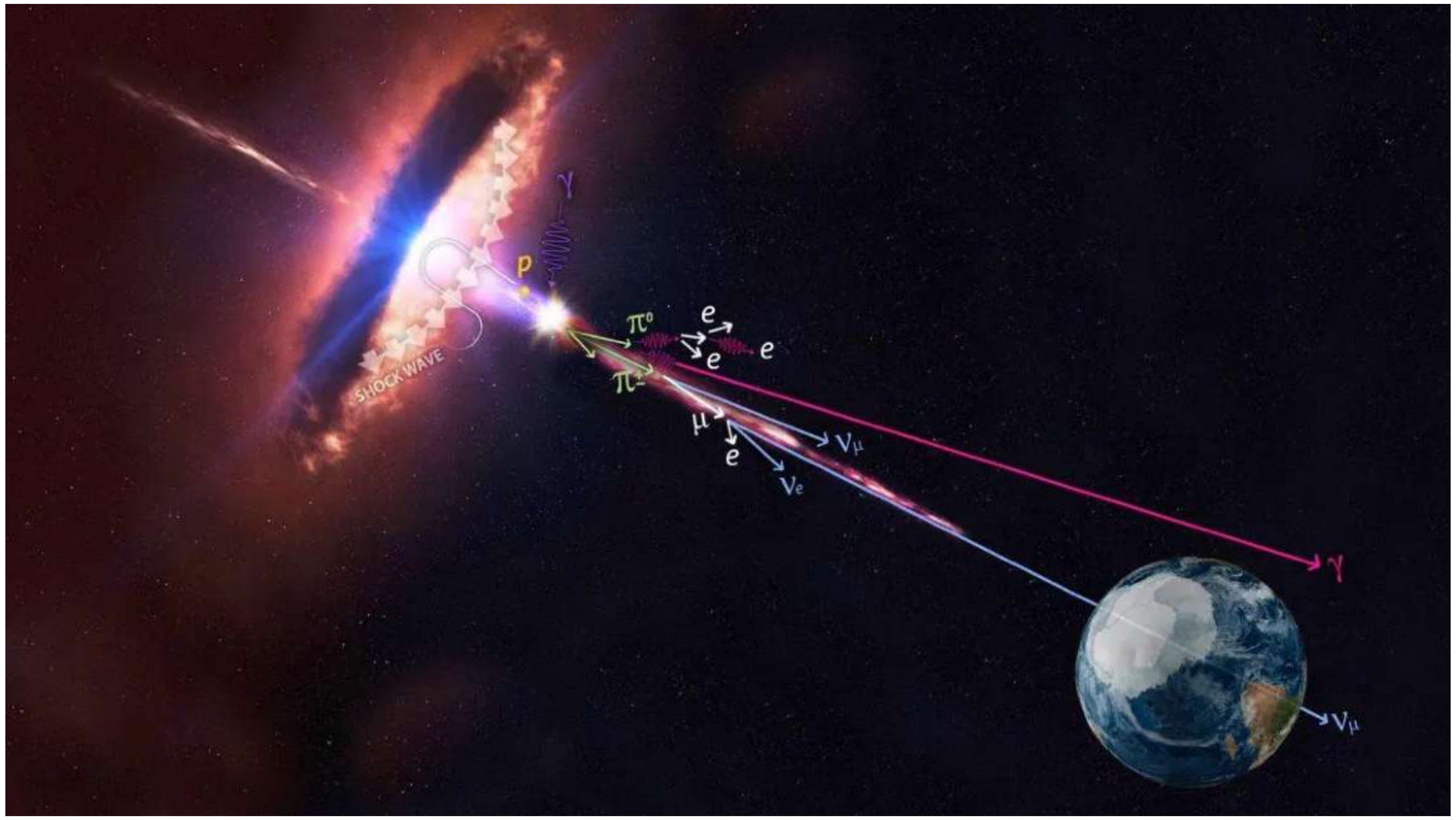
Conditions for HE-ν production:

a) Acceleration of ions (p and nuclei) to sufficiently high energies - Shocks, magnetic reconnection, stochastic acceleration aided by turbulence
b) Rate of acceleration > Rate of energy loss

High-energy (HE) neutrinos



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$$\pi^{0} \rightarrow \gamma + \gamma$$

Proton energy loss due to p-p interactions

$$t_{pp}^{-1} = n_N \kappa_{pp} \sigma_{pp} c$$

Nucleon density

p-p cross-section

Proton inelasticity

Proton energy

p-γ cross-section

$$t_{p\gamma}^{-1}(\epsilon_p) = \frac{c}{2\gamma_p^2} \int_{\bar{\epsilon}_{\text{th}}}^{\infty} d\bar{\epsilon} \kappa_{p\gamma}(\bar{\epsilon}) \sigma_{p\gamma}(\bar{\epsilon}) \bar{\epsilon} \int_{\bar{\epsilon}/2\gamma_p}^{\infty} d\epsilon \epsilon^{-2} n_{\epsilon}$$

Photon energy in proton rest frame

Proton energy loss due to p-γ interactions

Conditions for HE-ν production:

a) Acceleration of ions (p and nuclei) to sufficiently high energies - Shocks, magnetic reconnection, stochastic acceleration aided by turbulence
b) Rate of acceleration > Rate of energy loss
c) Significant density on target media - matter and radiation
d) (a) and (b) -> production of charged mesons - pions that decay into neutrinos, charged leptons, and gamma-rays

BNS mergers: particle accelerators and multi-messenger zoo

BNS

S. Gezari, Annu. Rev. Astron. Astrophys. 2021. 59:21–58
Kimura+, PRD (2018), Fang & Metzger (2017)
Mukhopadhyay & Kimura (2024)
LIGO Collab (2017)

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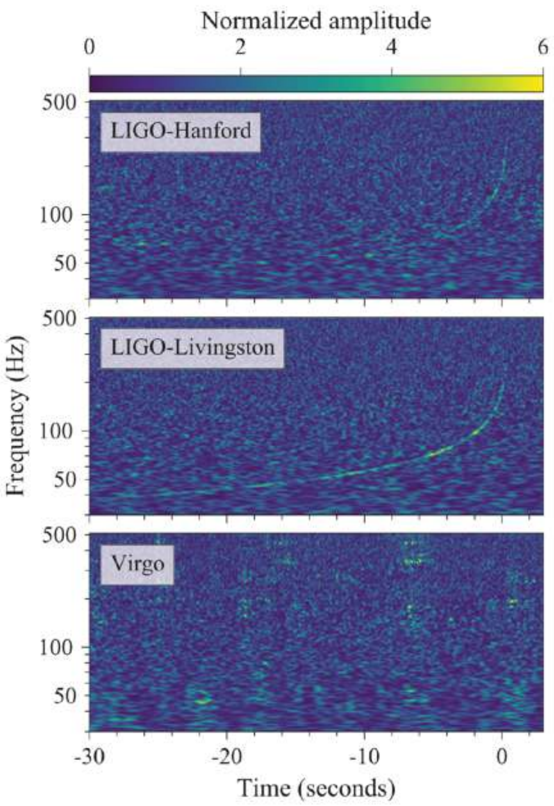
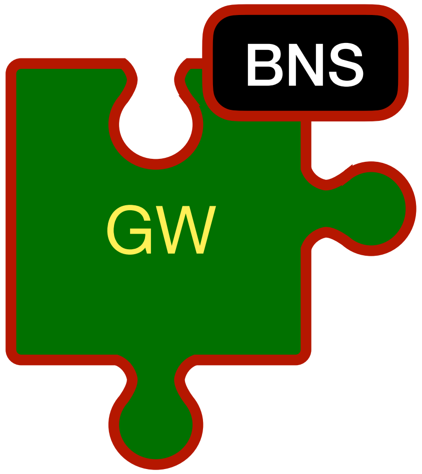


Observed



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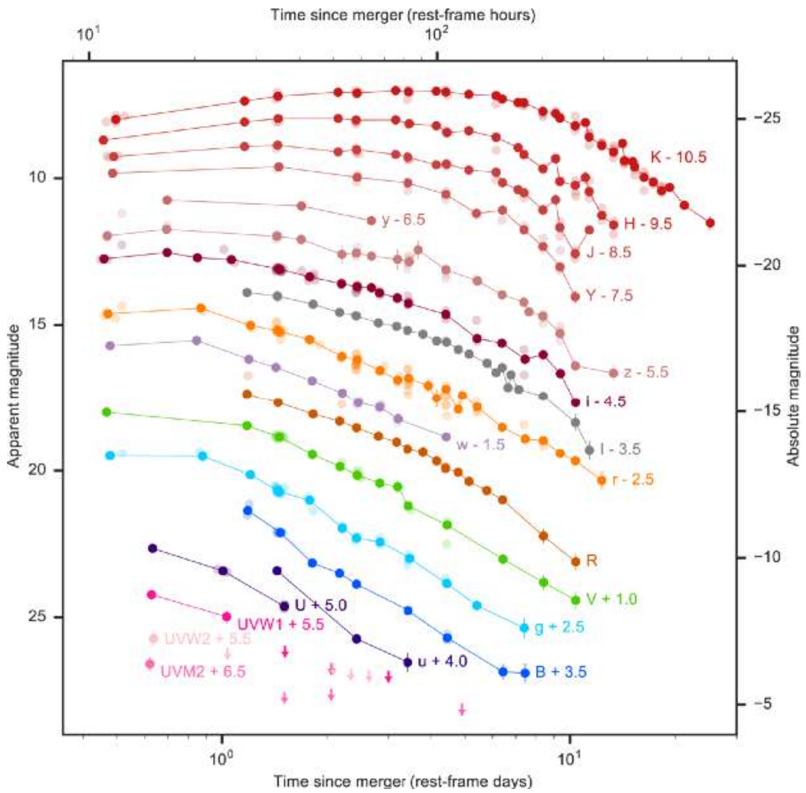
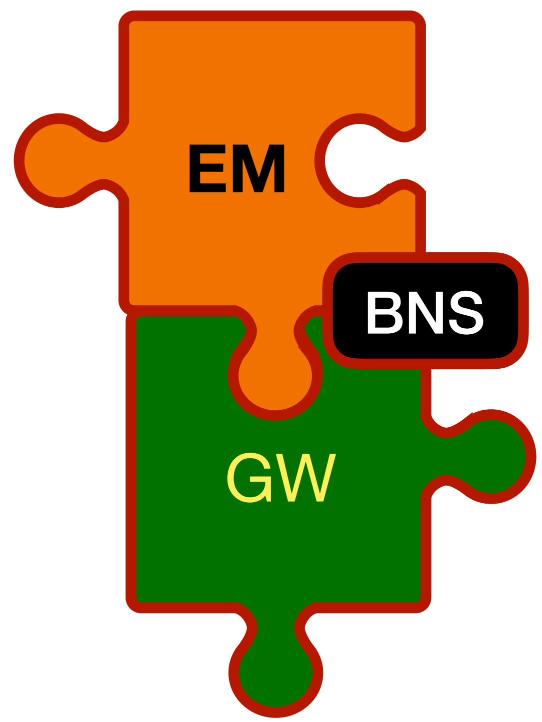
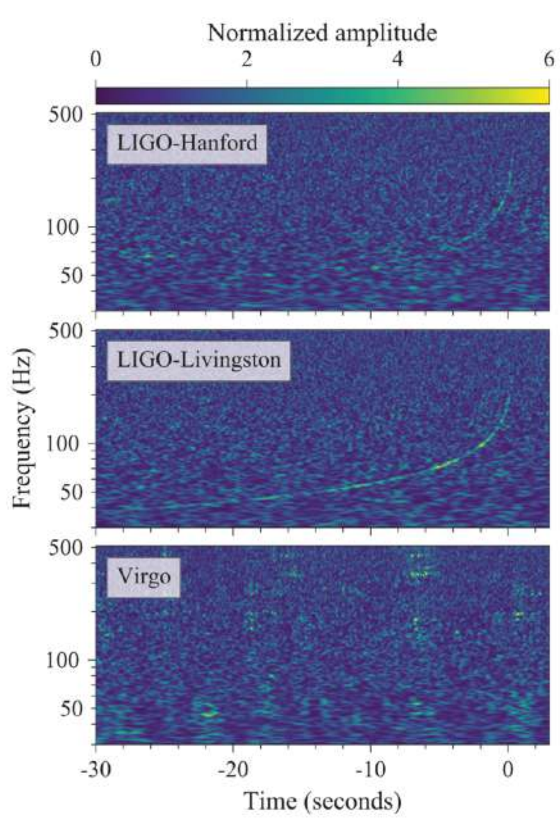


Kilonova emission
Afterglow emission
Short GRB





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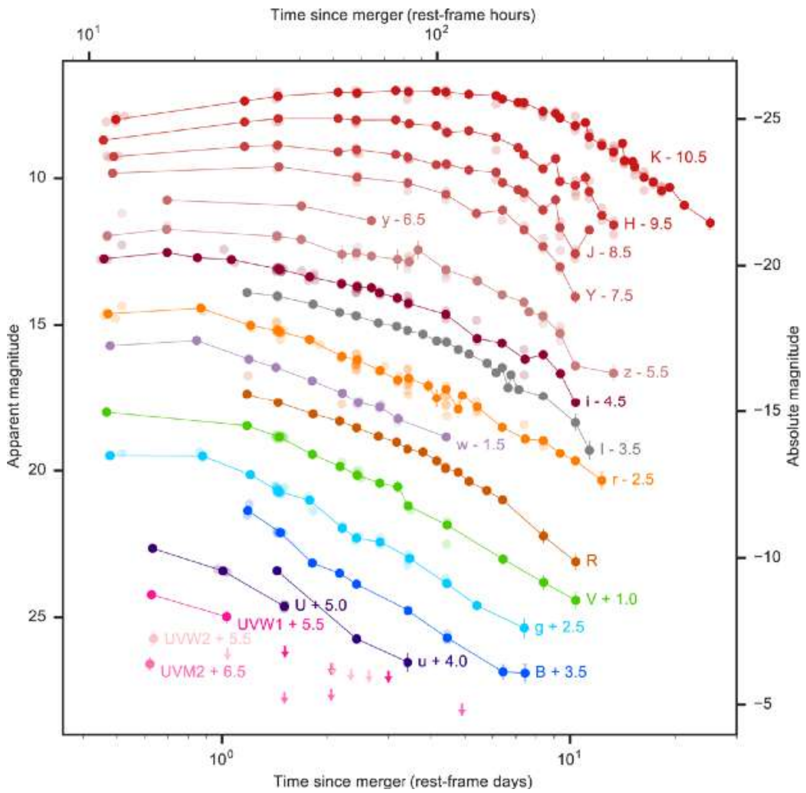

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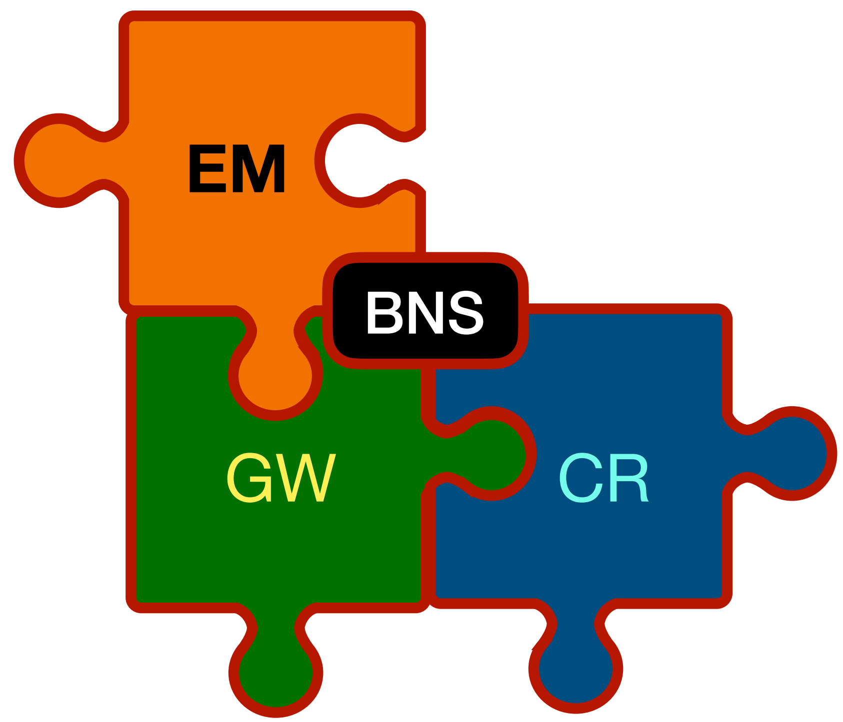

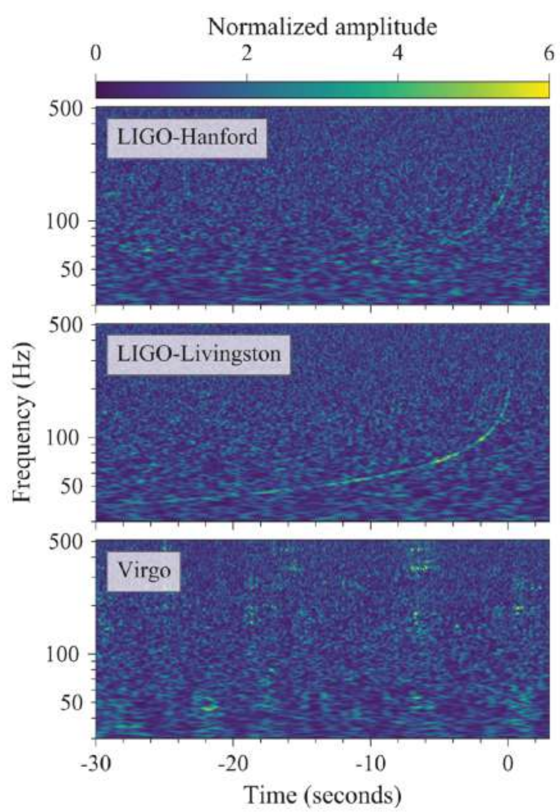

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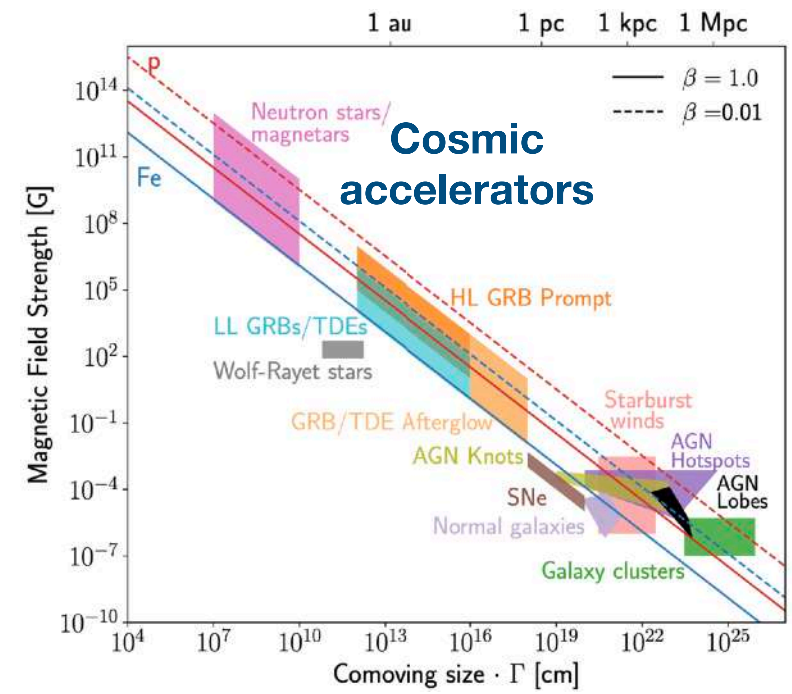

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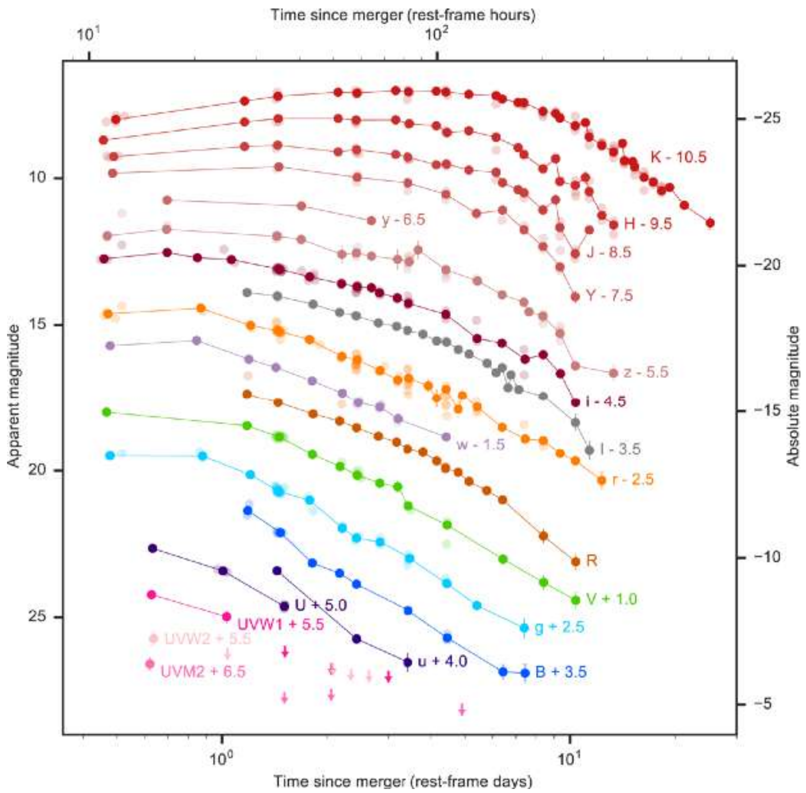

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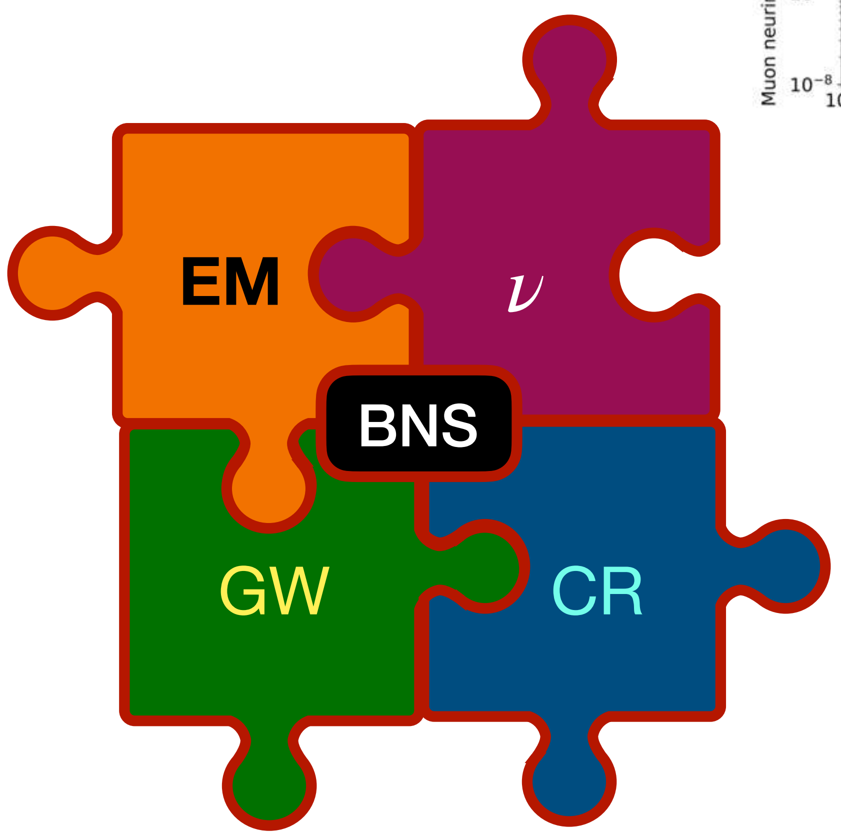

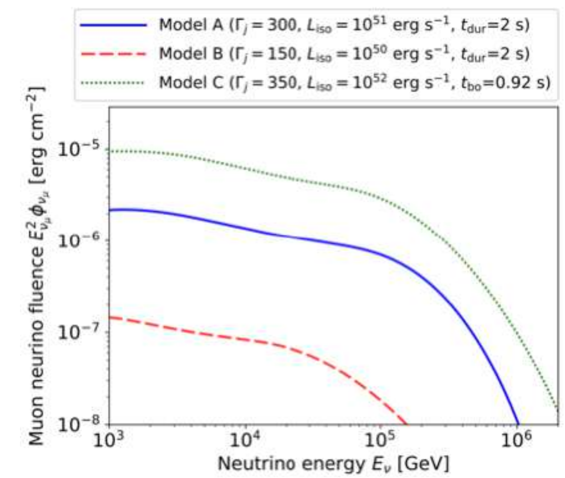

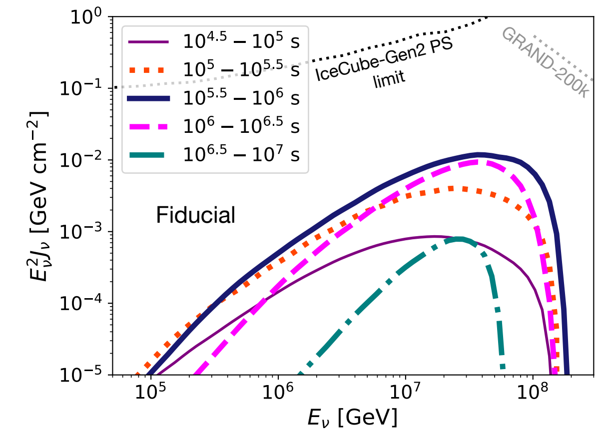

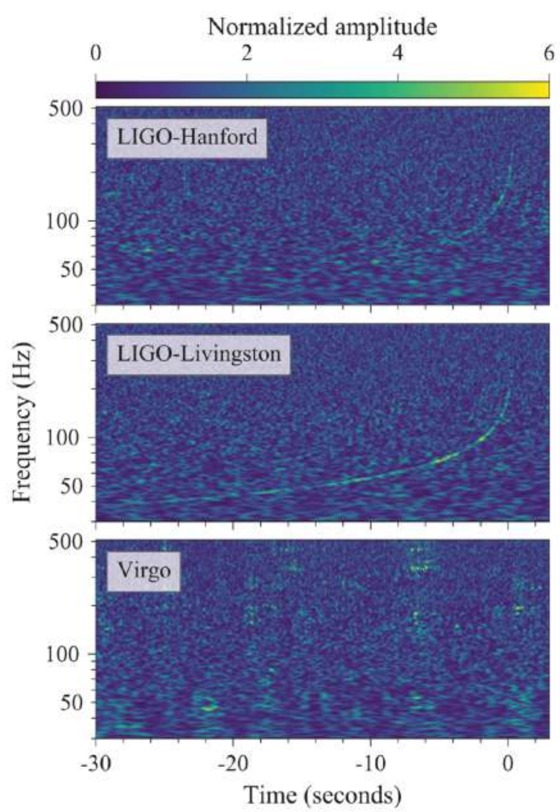

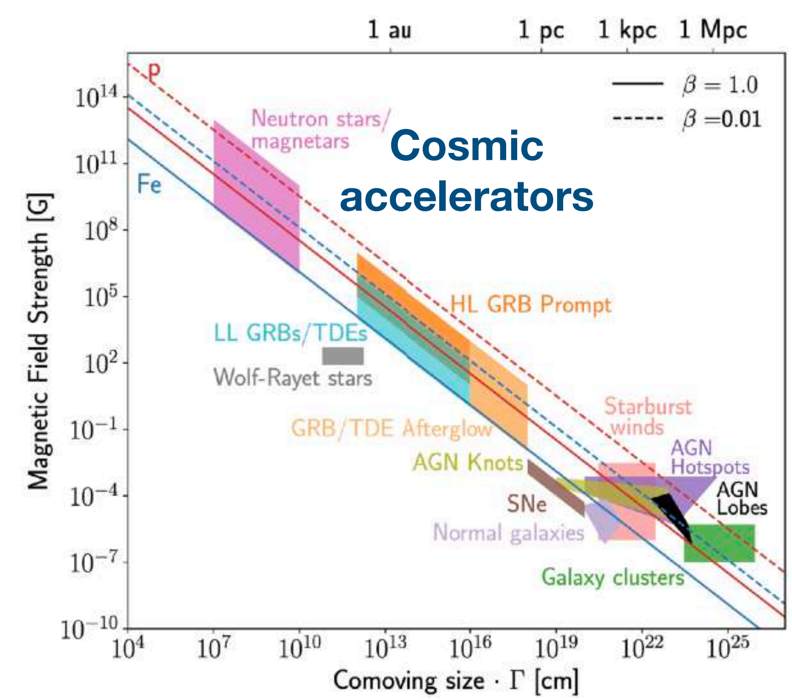

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Batista et al., Front. Astron. Space Sci. 6 (2019), 23
Kimura+, PRD (2018), Fang & Metzger (2017)
Mukhopadhyay et al. (2024)
LIGO Collab (2017)

Based on

High-energy neutrino and EM emissions from magnetars

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
Accepted in ApJ *(arXiv: 2407.04767)*

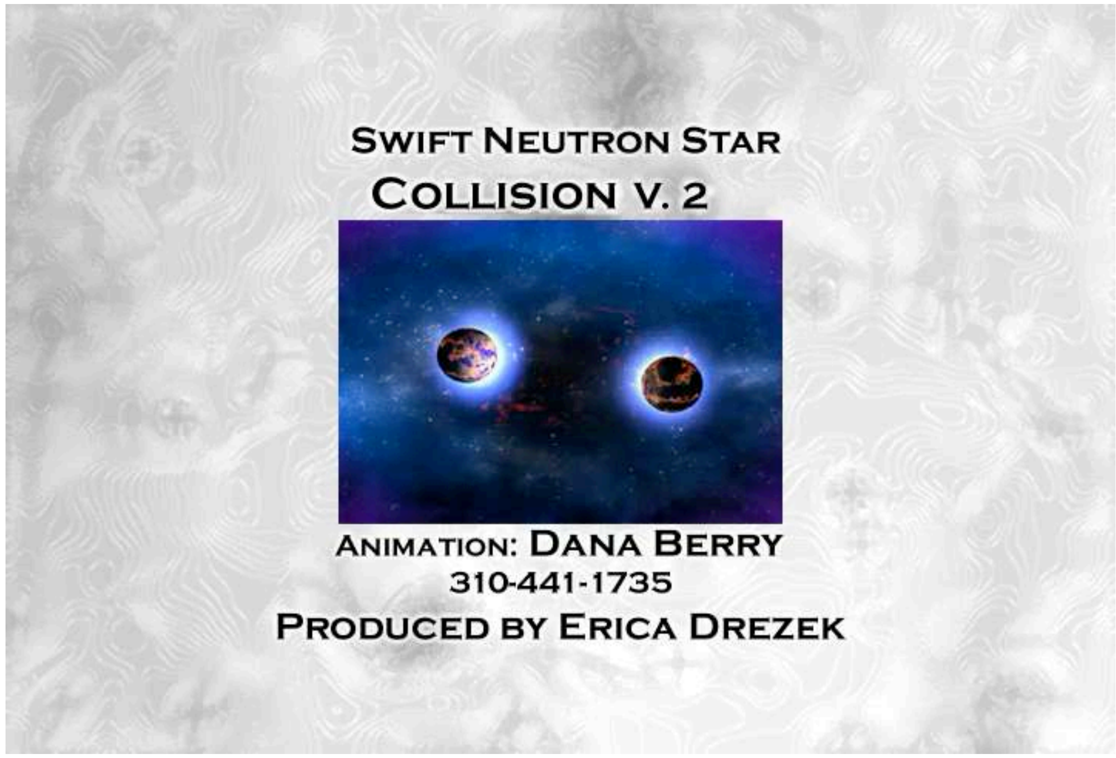
Electromagnetic signatures from pulsar remnants of binary neutron-star mergers
MM, S.S. Kimura
Submitted to ApJL *(arXiv: 2506.09157)*

Hunting for high-energy and ultrahigh energy neutrinos from BNS mergers at next-generation GW and neutrino detectors

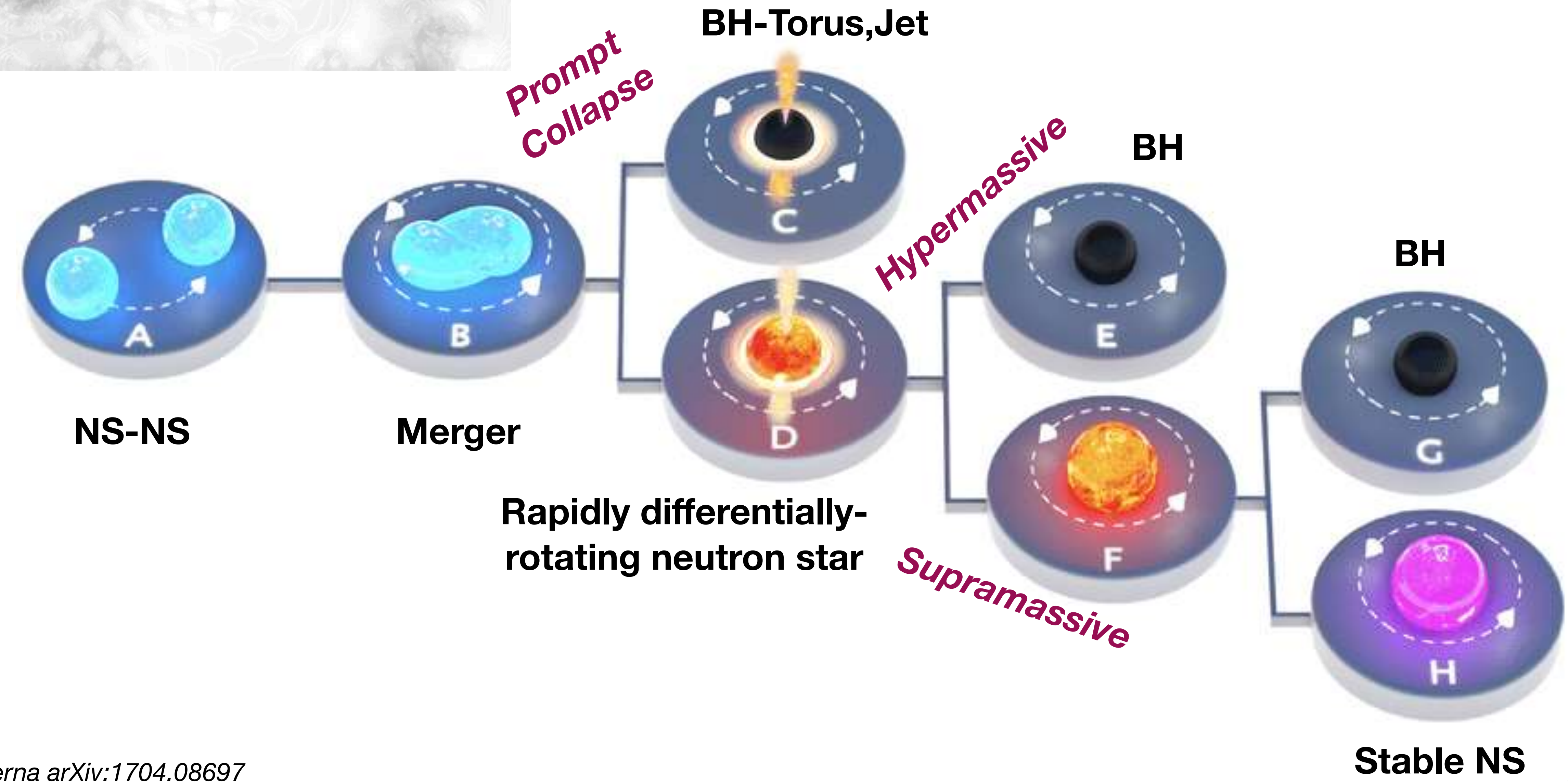
Based on: Gravitational wave triggered high energy neutrino searches from BNS mergers: prospects for next generation detectors
MM, S. S. Kimura, K. Murase
Phys. Rev. D 109, 4, 043053 (2024) *(arXiv: 2310.16875)*

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
Phys. Rev. D 110, 6, 063004 *(arXiv: 2406.19440)*

Fate of NS-NS mergers



Fate decided by EOS, Mass, Spin, ….



Piro, Giacomazzo, Perna arXiv:1704.08697

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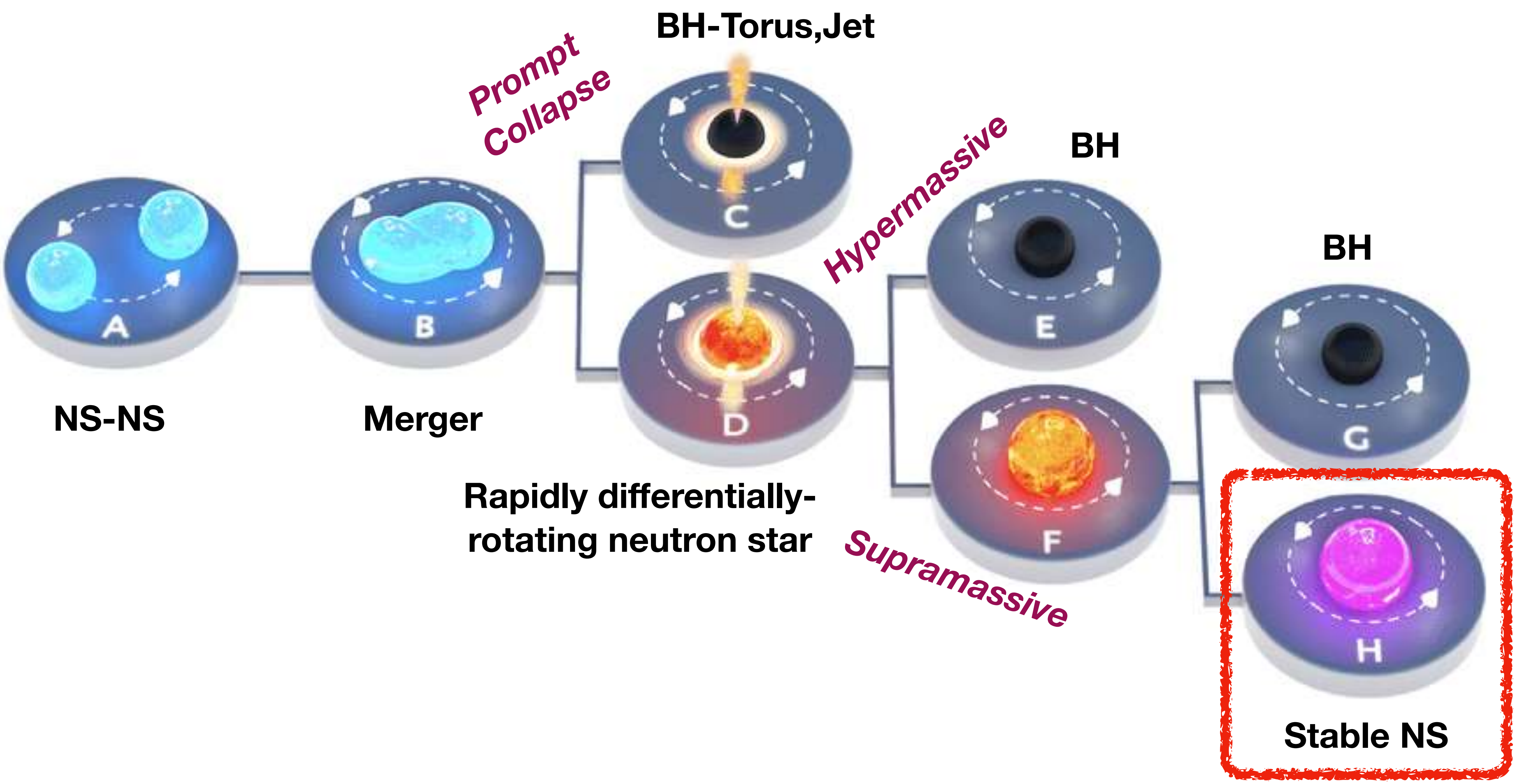

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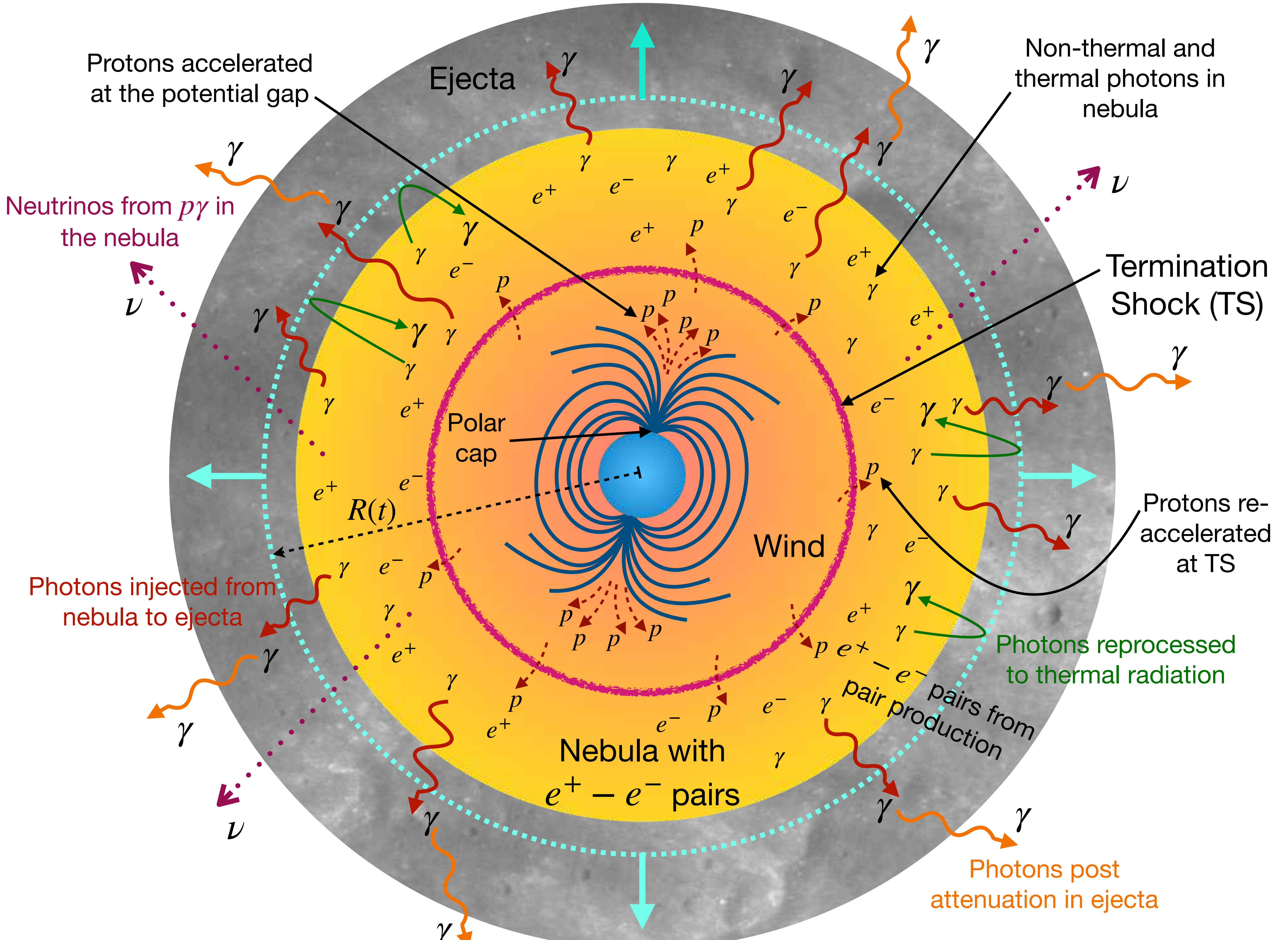
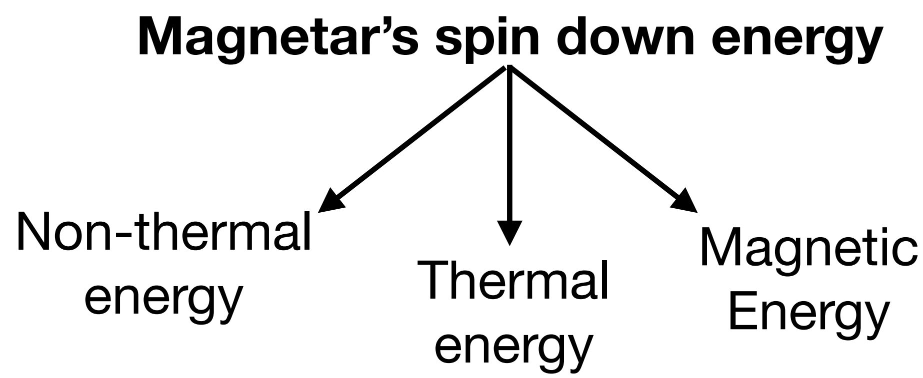
Model



Protons accelerated at the potential gap
Ejecta
Non-thermal and thermal photons in nebula
Neutrinos from $p\gamma$ in the nebula
Termination Shock (TS)
Polar cap
$R(t)$
Wind
Protons re-accelerated at TS
Photons injected from nebula to ejecta
$e^+ - e^-$ pairs from pair production
Photons reprocessed to thermal radiation
Nebula with $e^+ - e^-$ pairs
Photons post attenuation in ejecta

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



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

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

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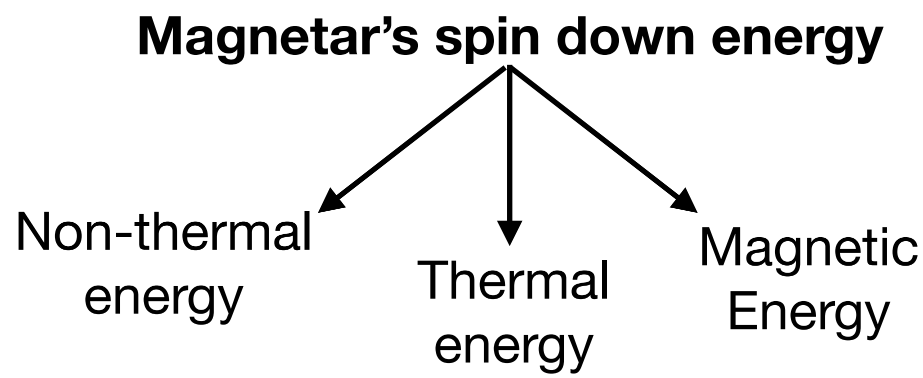
Magnetic field strength amplification parameter

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

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



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

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

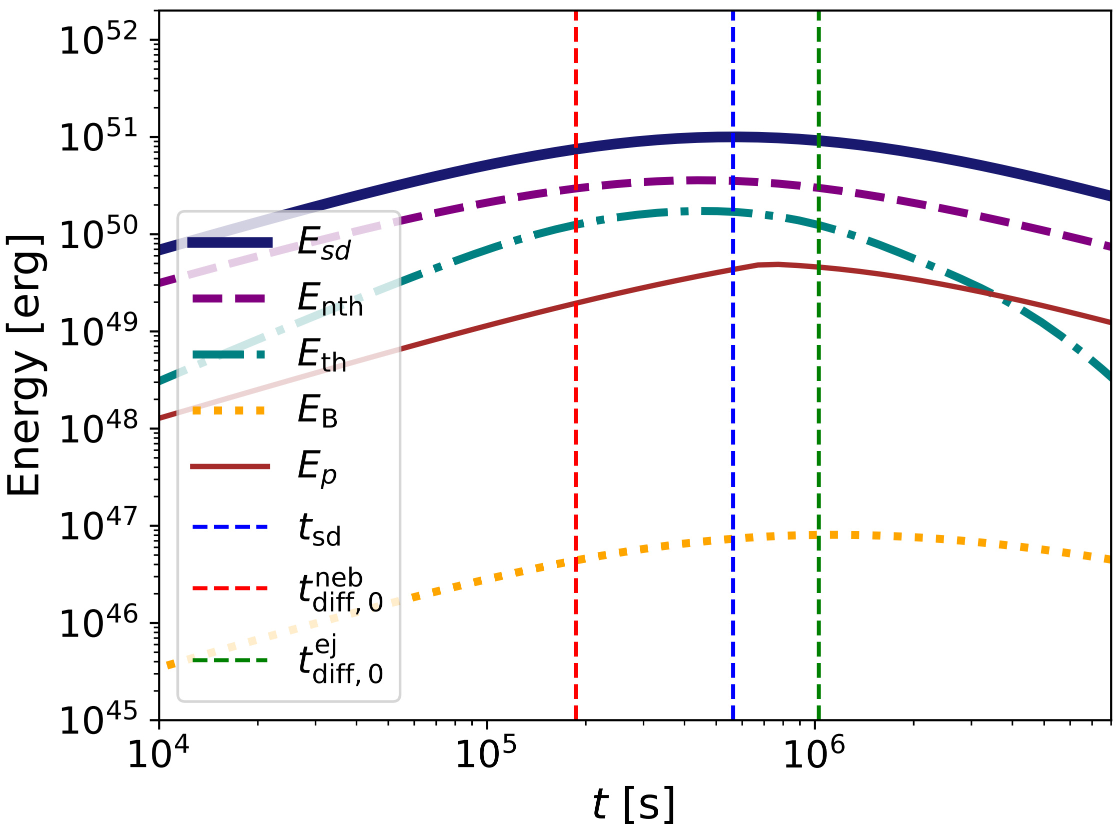
Magnetic energy

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

Work done on the ejecta

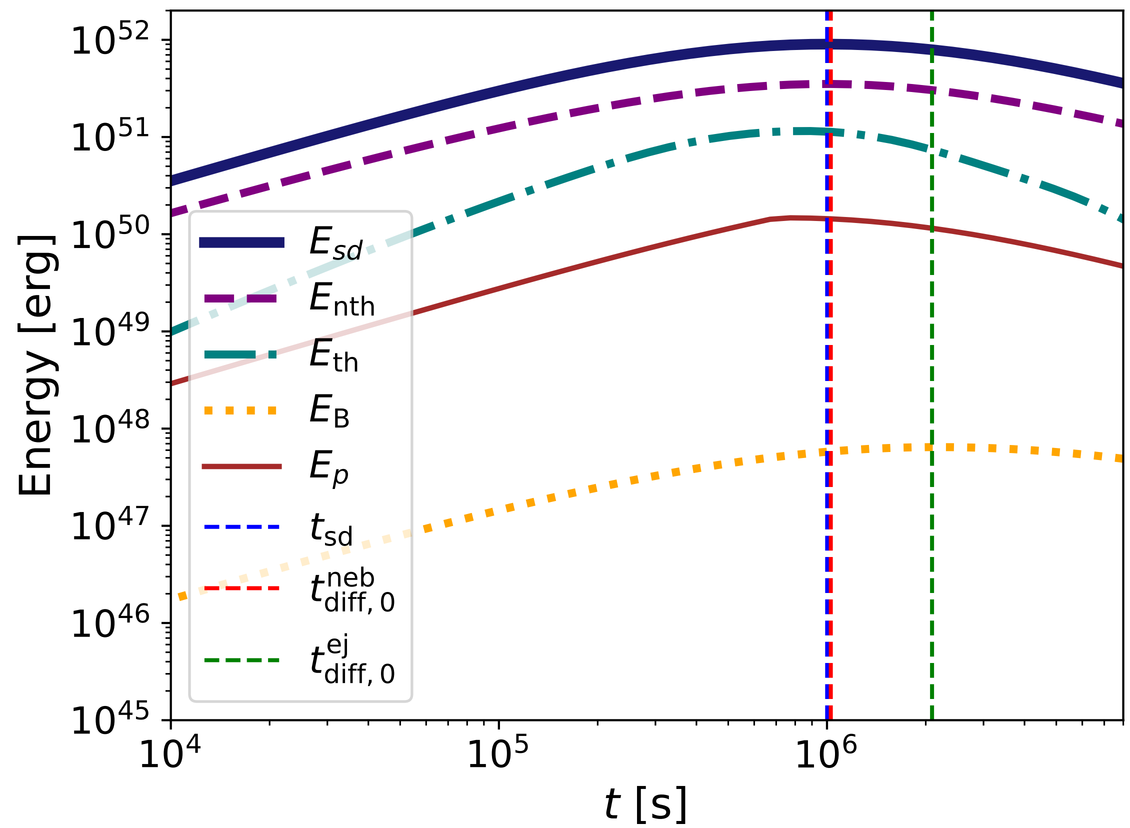
$$\frac{d}{dt}E_{\rm kin} = \frac{d}{dt}\left[M_{\rm ej}c^2(\Gamma_{\rm ej} - 1)\right] = \frac{v}{R}\left(E_{\rm nth} + E_{\rm th} + E_B\right)$$

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



Fiducial:

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



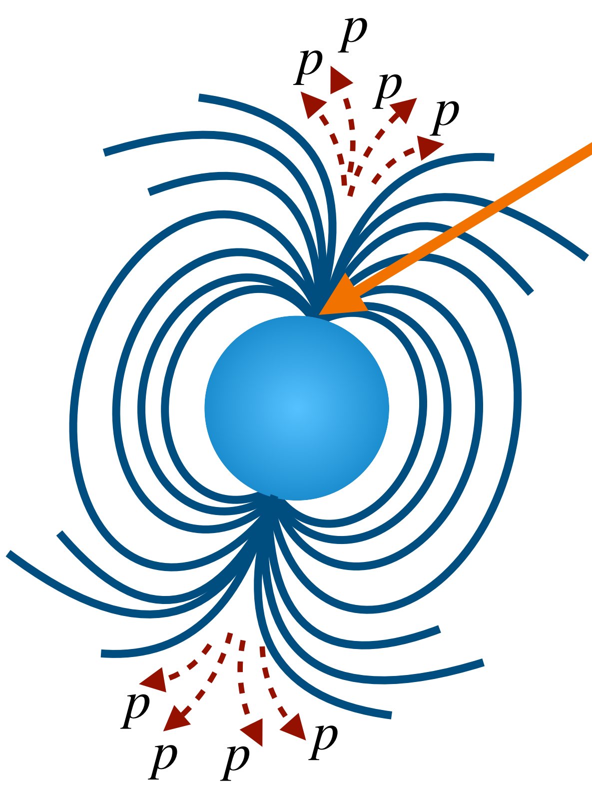
Optimistic:

$B_d = 2.5 \times 10^{13}$ 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

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

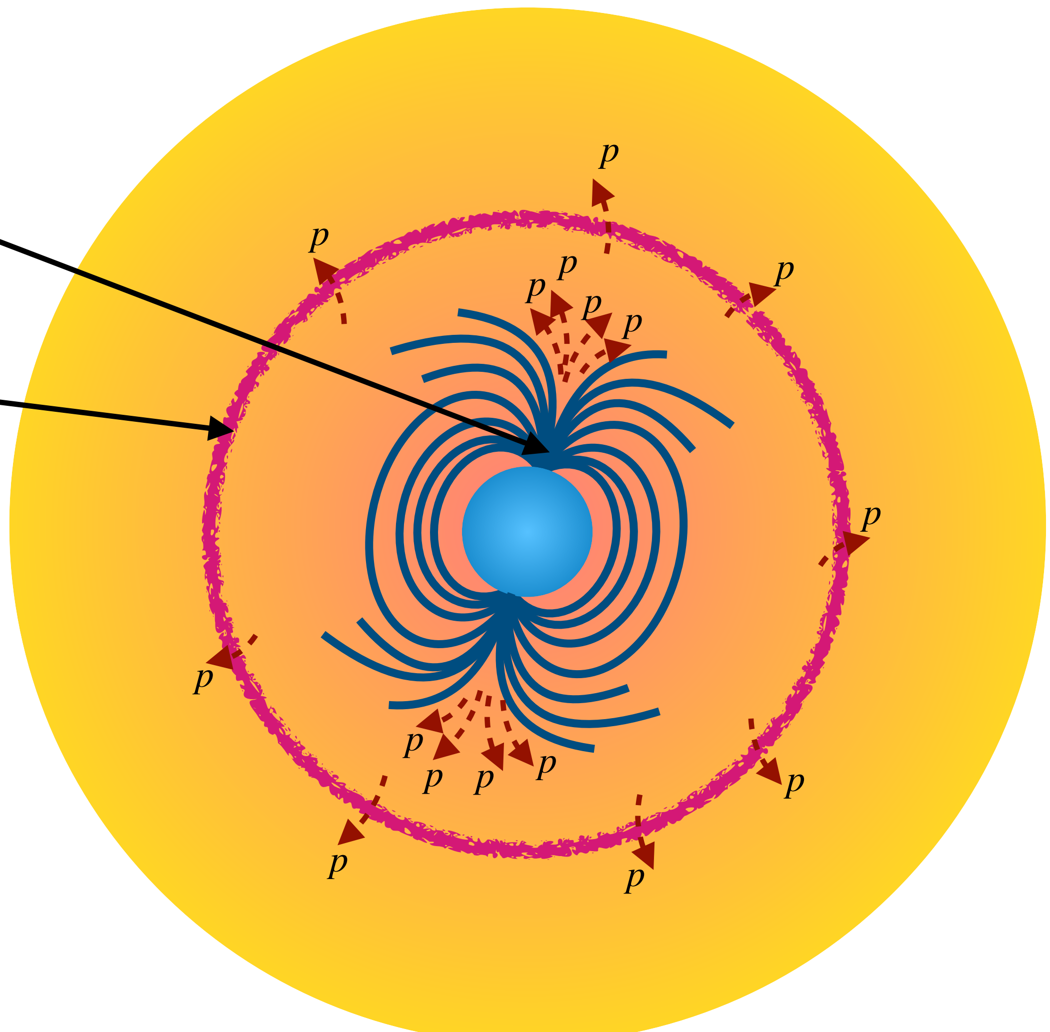
$$\dot{N}_p = n_{\rm GJ} 2A_{\rm pc}c = \frac{4\pi^2}{Ze}\frac{R_*^3}{c}\frac{B_0}{P^2}$$

Acceleration sites:

Polar cap

+

Termination shock (TS)



Cosmic ray (CR) proton acceleration: injection spectra

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

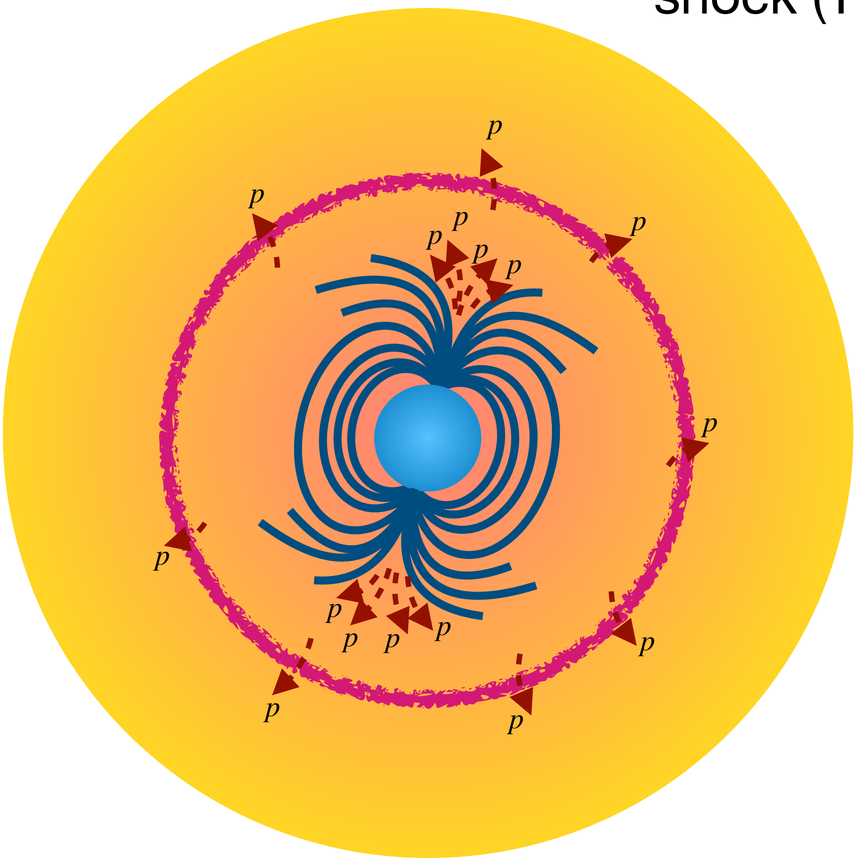
$$\varepsilon_p'^{\rm cutoff} = \max\left[\varepsilon_p'^{\rm cutoff,pc}, \varepsilon_p'^{\rm cutoff,TS}\right]$$

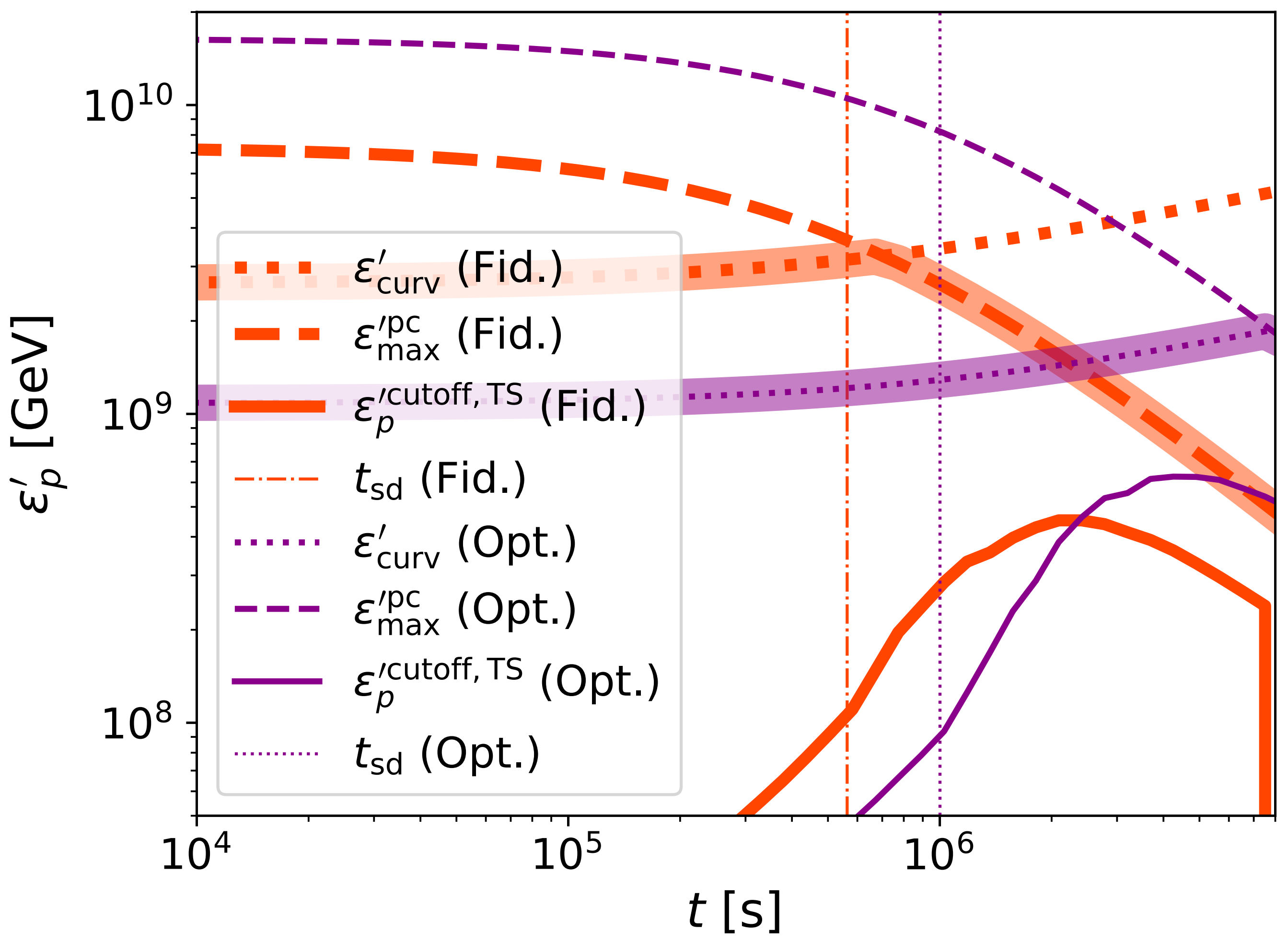
Acceleration sites:

Polar cap

+

Termination shock (TS)





Cosmic ray (CR) proton acceleration: injection spectra

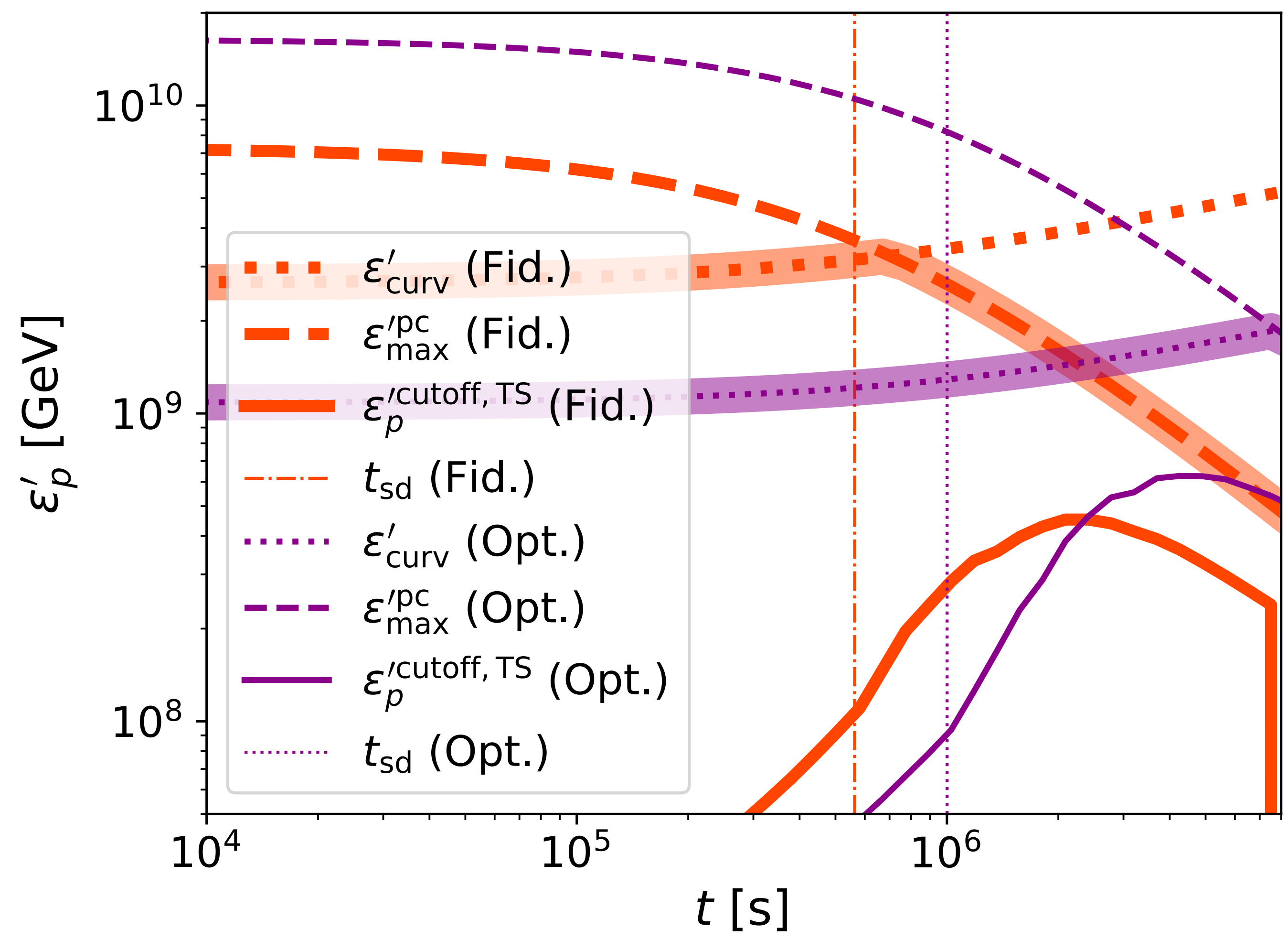
$$\frac{d\dot{N}_{p,\mathrm{inj}}}{d\varepsilon'_p} = \dot{N}_p^{\mathrm{norm}} Q_p^{\mathrm{inj}}(\varepsilon'_p) = \dot{N}_p^{\mathrm{norm}} \delta\left(\varepsilon'_p - \varepsilon_p^{\prime\mathrm{cutoff,pc}}\right)$$

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

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

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

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



Cosmic ray (CR) proton acceleration: injection spectra

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

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

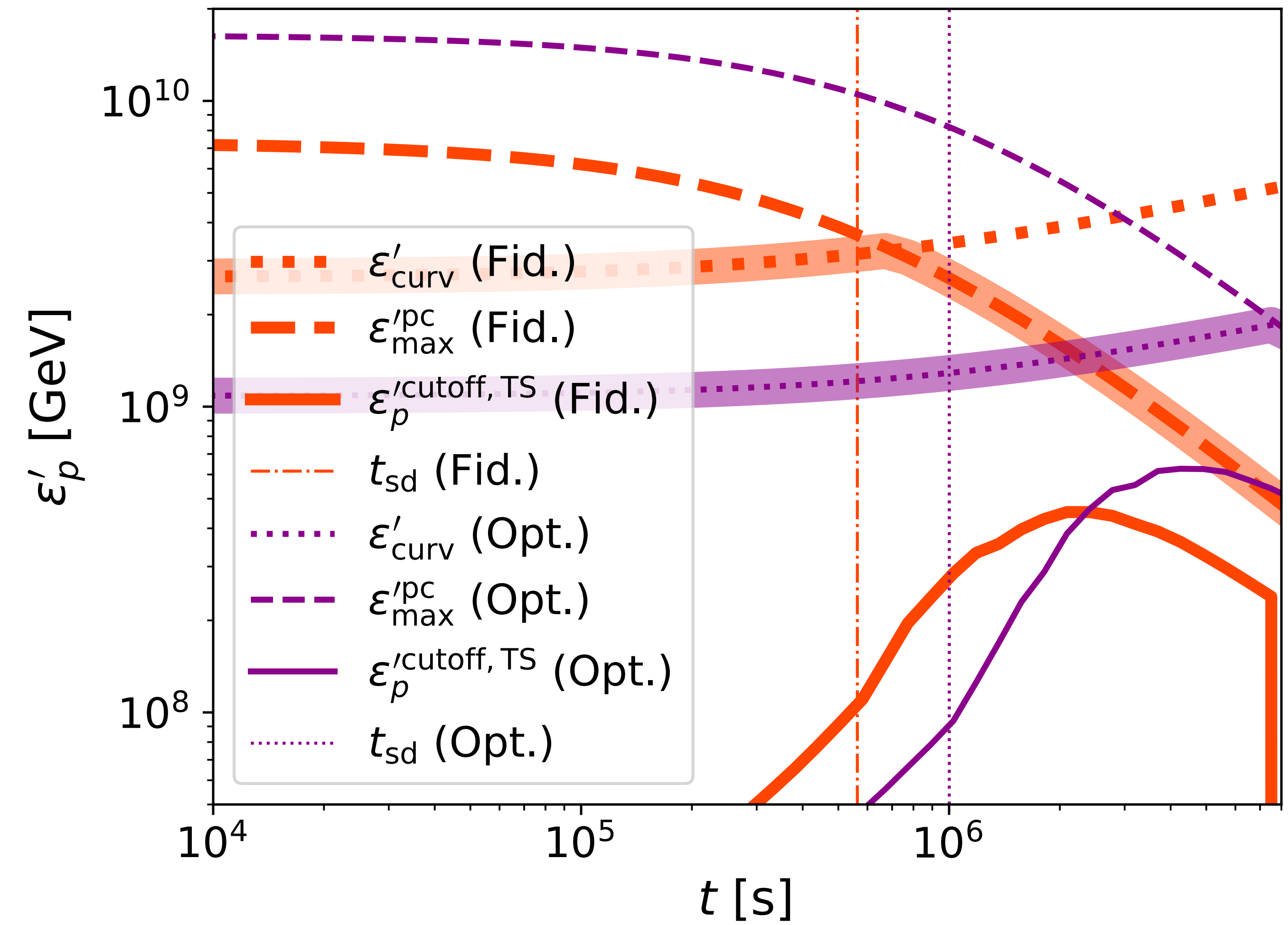
$$t'^{-1}_{\mathrm{acc}} = t'^{-1}_{\mathrm{loss}}$$

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

$$t'^{-1}_{\mathrm{loss}} = t'^{-1}_{\mathrm{esc}} + t'^{-1}_{\mathrm{cool}}$$

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

$$t'^{-1}_{\mathrm{cool}} = t'^{-1}_{pp} + t'^{-1}_{\mathrm{p}\gamma} + t'^{-1}_{\mathrm{sync}} + t'^{-1}_{\mathrm{BH}} + t'^{-1}_{\mathrm{dyn}}$$



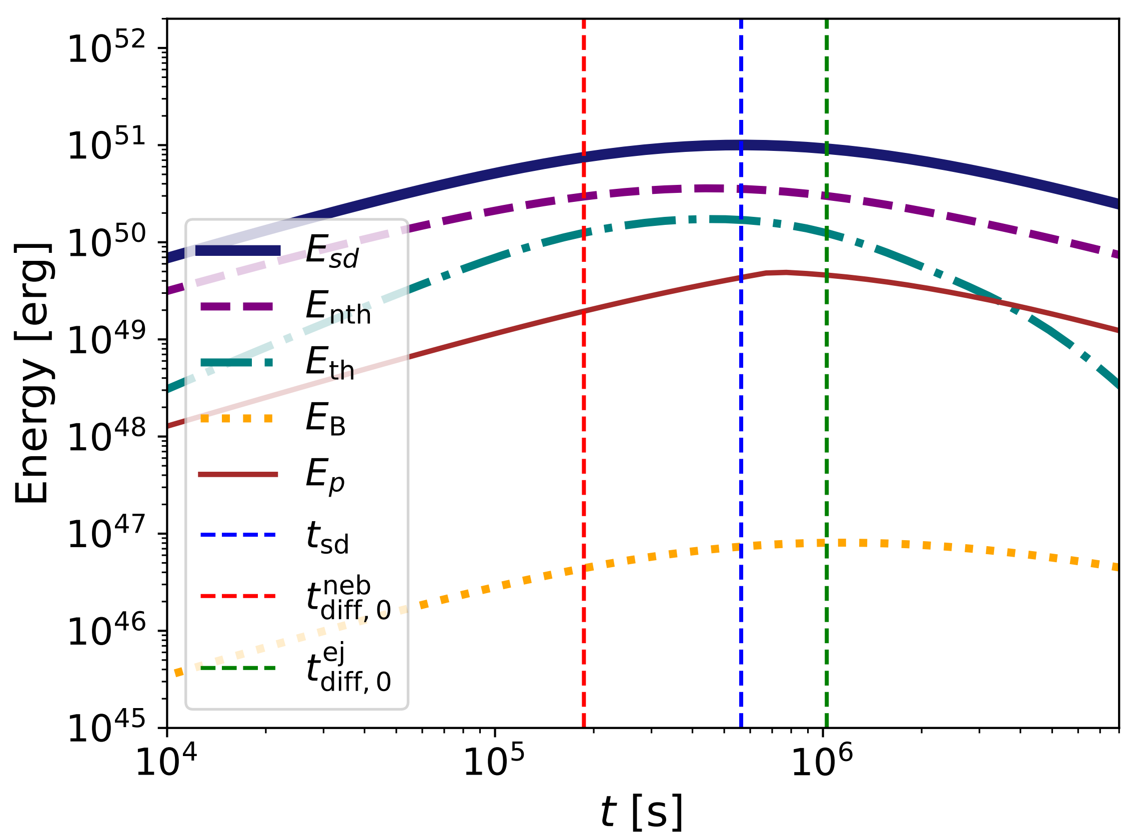
Cosmic ray (CR) proton acceleration

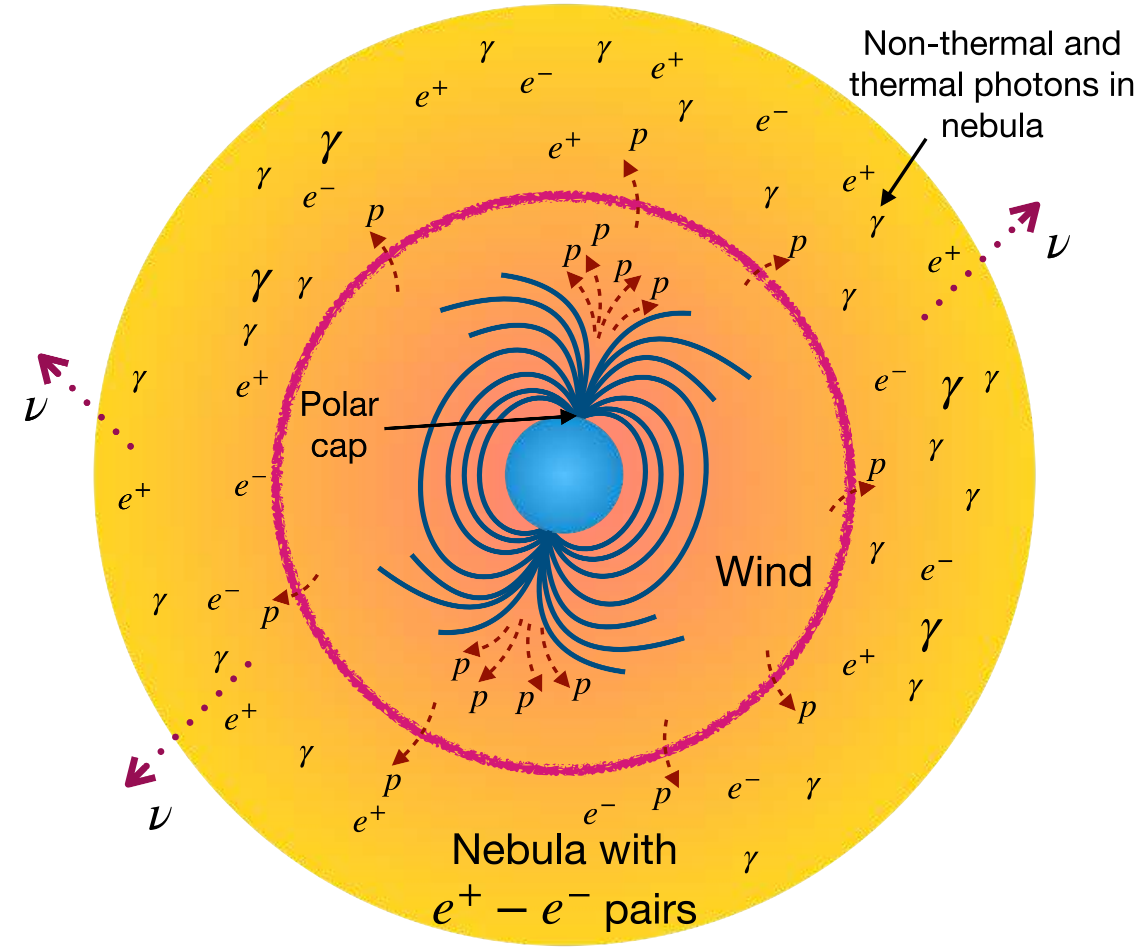
Compute steady state CR spectrum by solving the transport equation

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

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

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





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

Cosmic ray (CR) proton acceleration

Compute steady state CR spectrum
by solving the transport equation

↓

This along with the photon field spectrum
gives the neutrino fluences

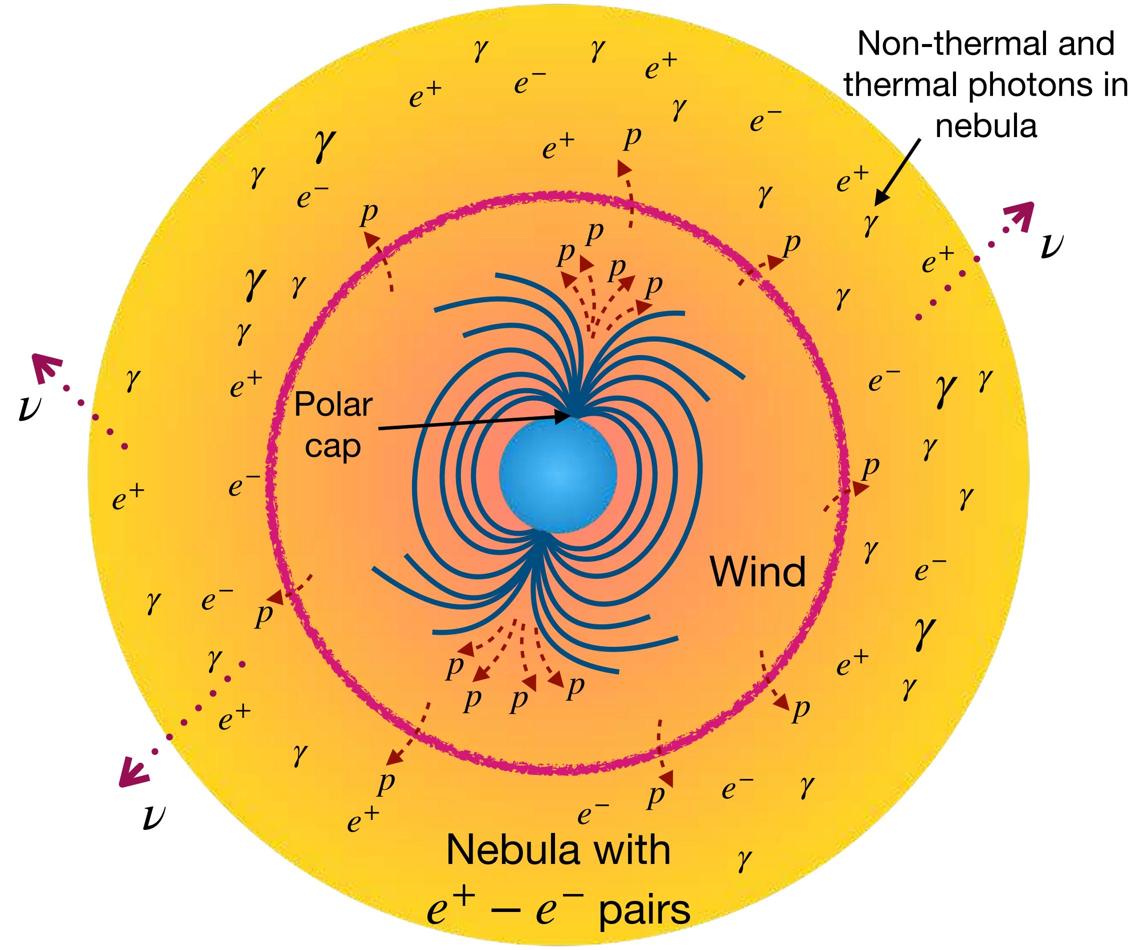
$e^+ - e^-$ spectra

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

Electron break Lorentz factor

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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$e^+ - e^-$ spectra

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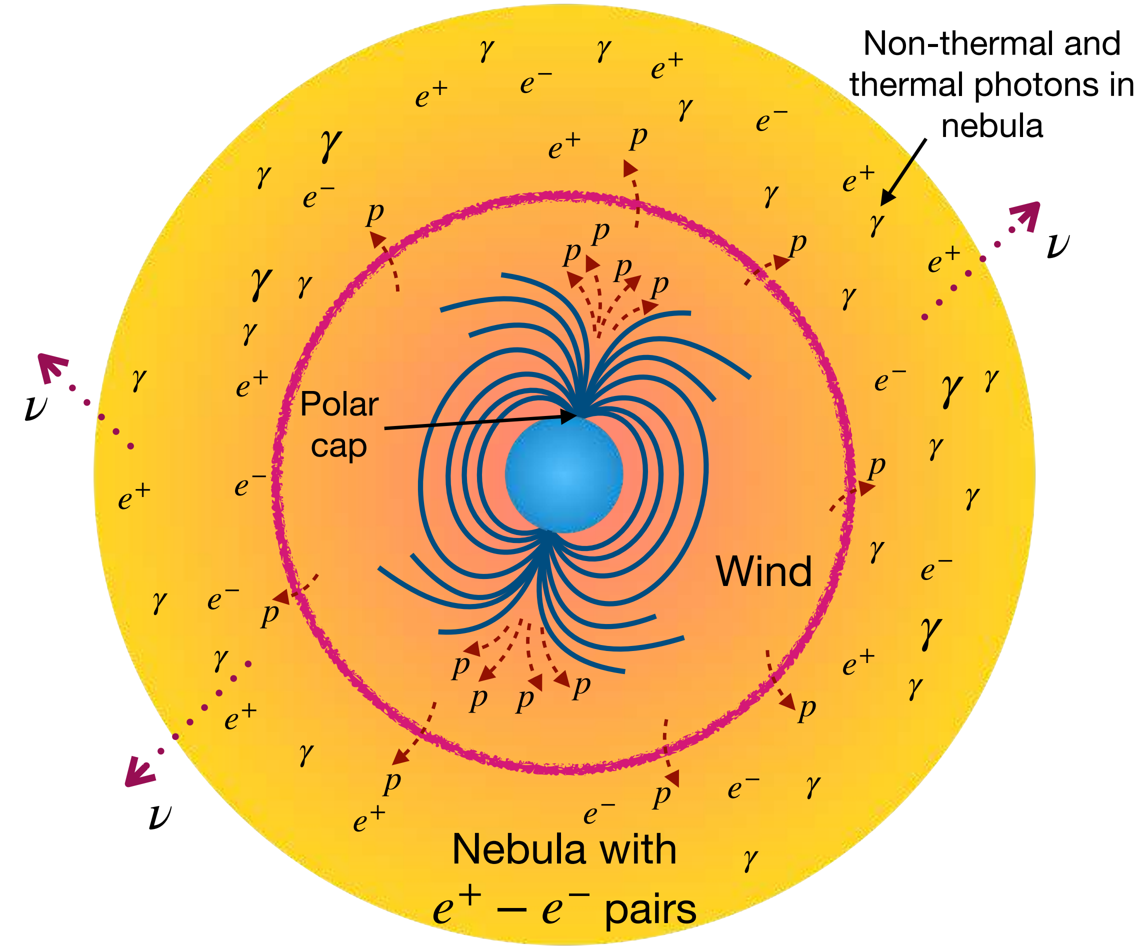
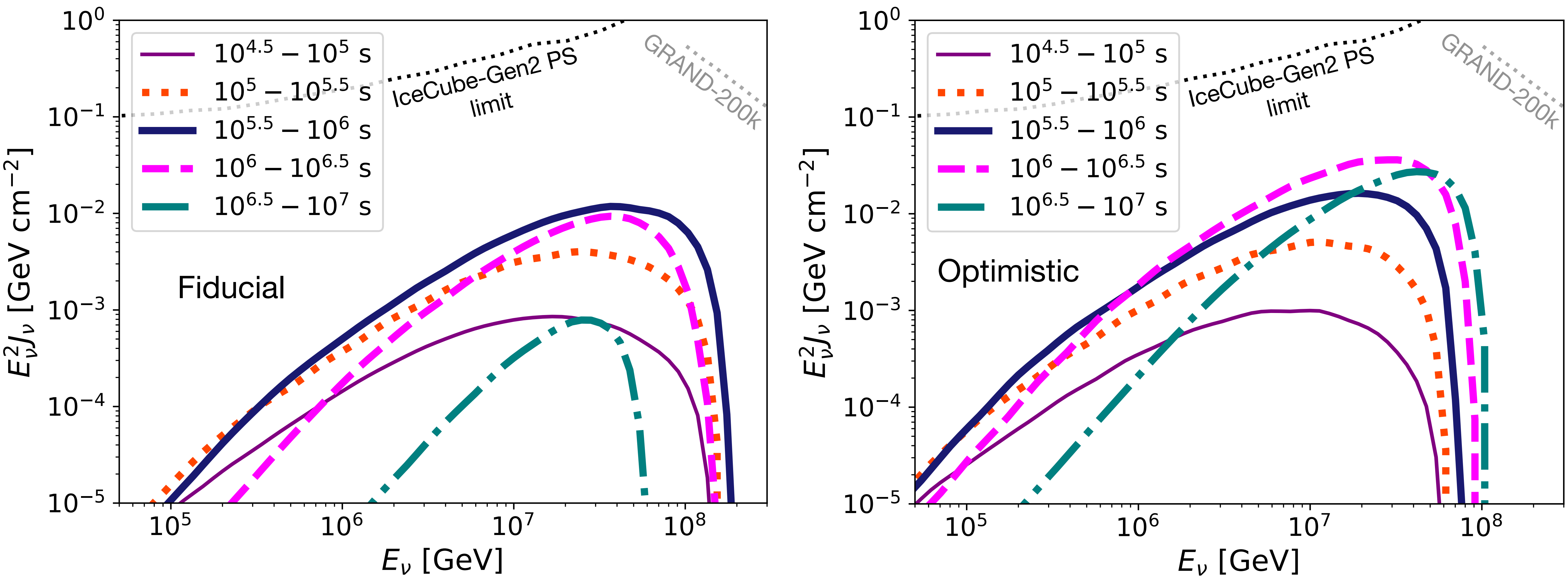
Transport Equation

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}

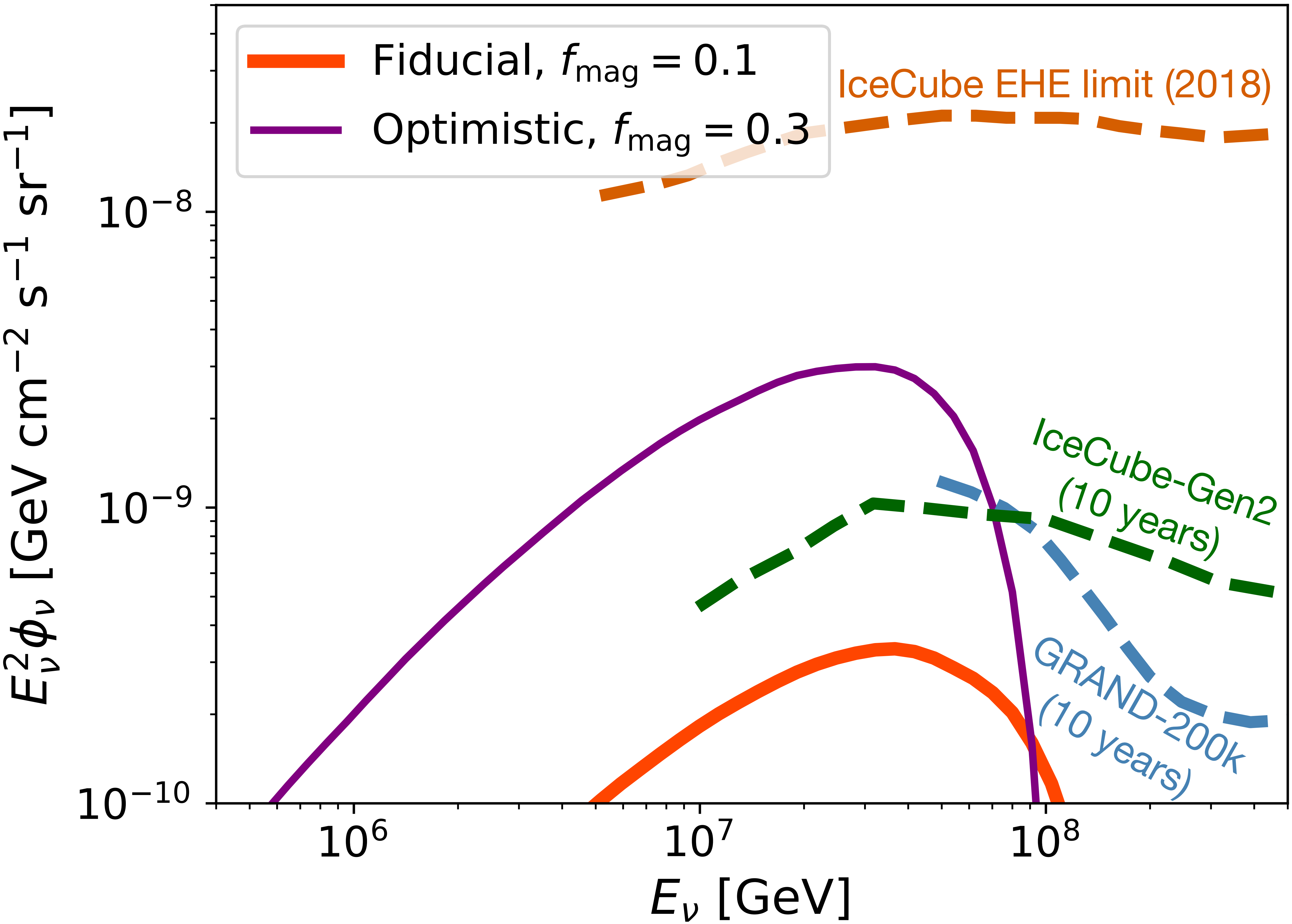
Peak fluence: $\sim 4 \times 10^{-2}$ GeV cm^{-2}

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

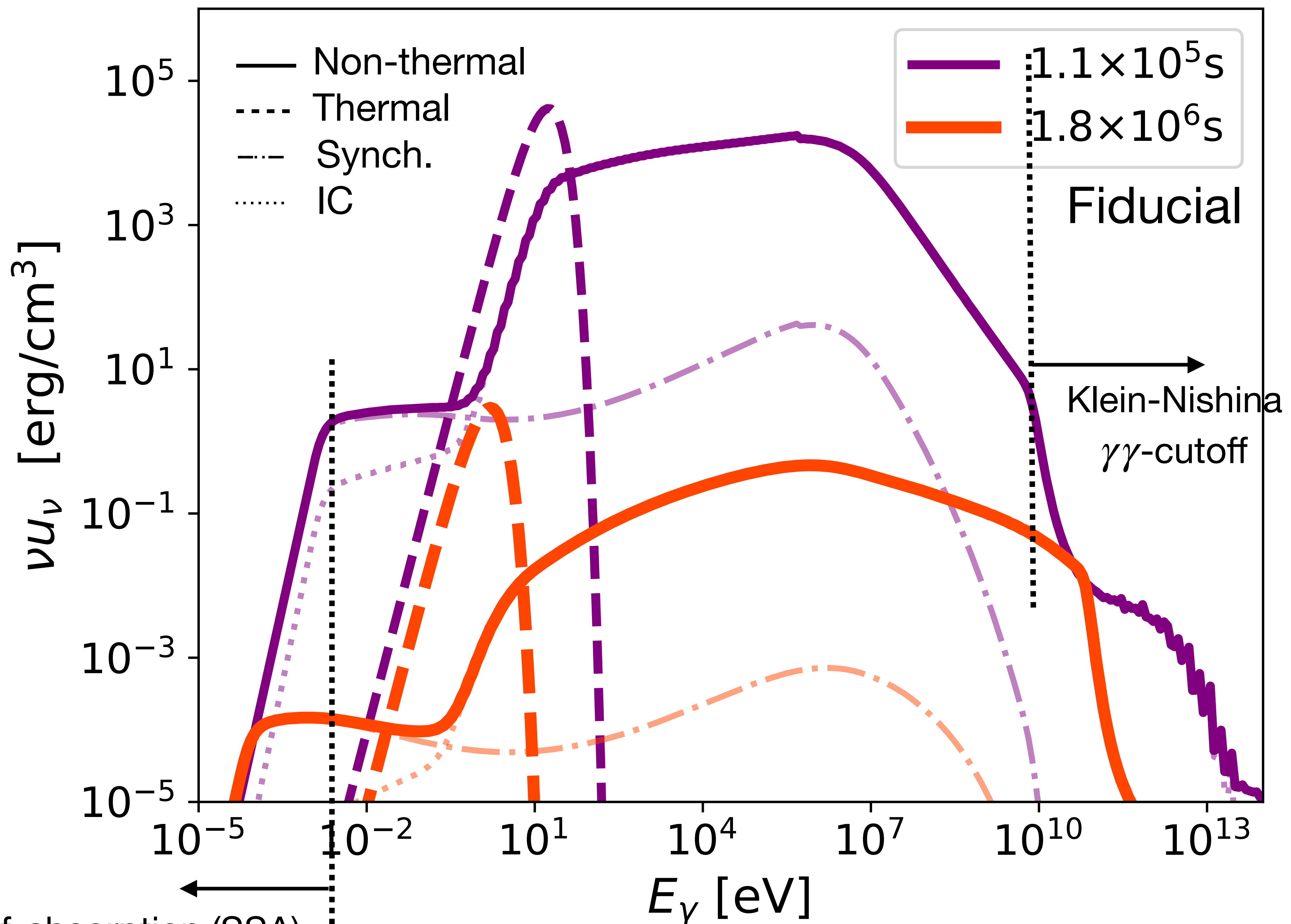
Peak fluence $\sim 10^{5.5}$ s $- 10^6$ s post-merger

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

Diffuse neutrino flux

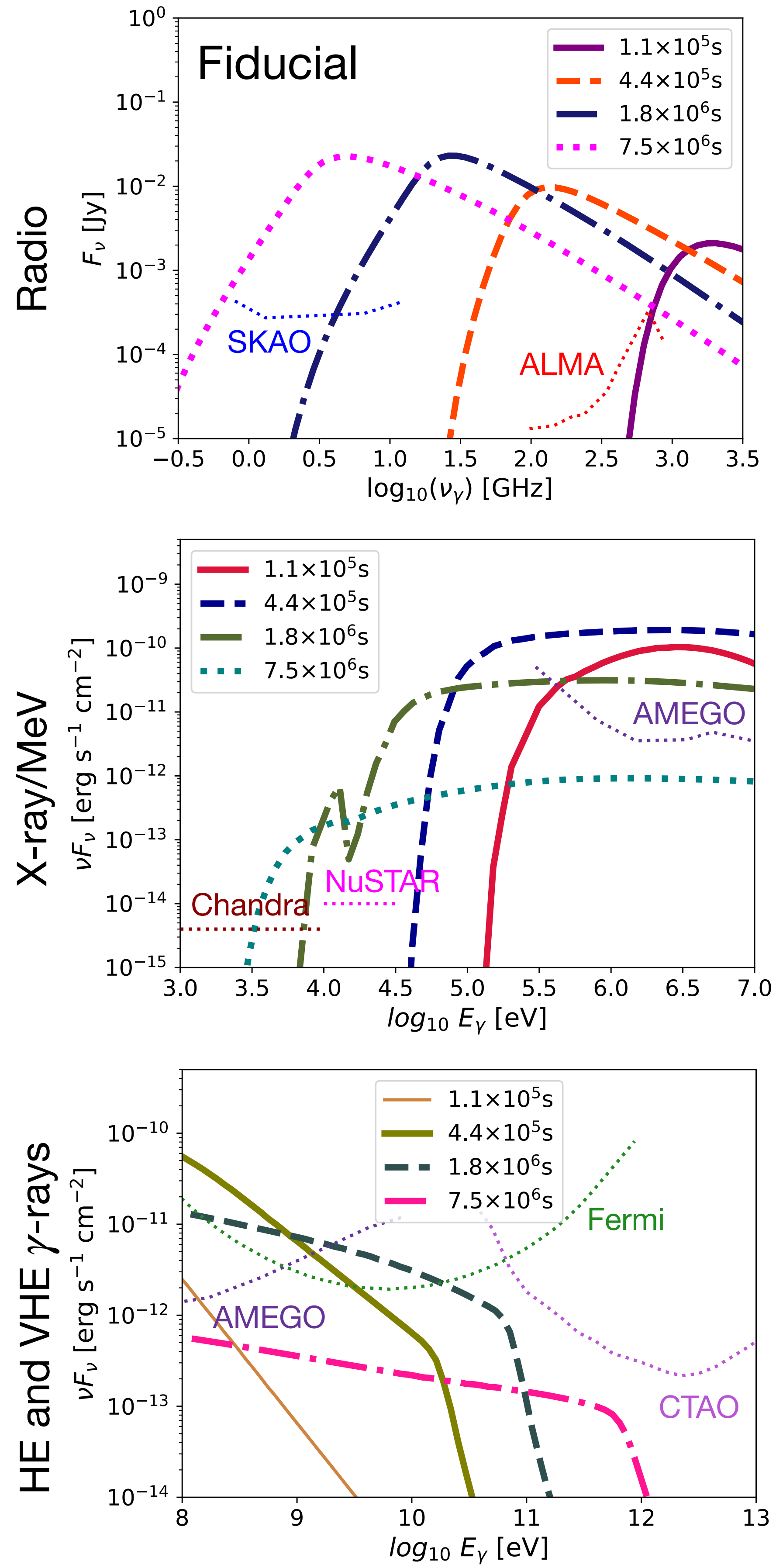


Nebula attenuated photon spectra

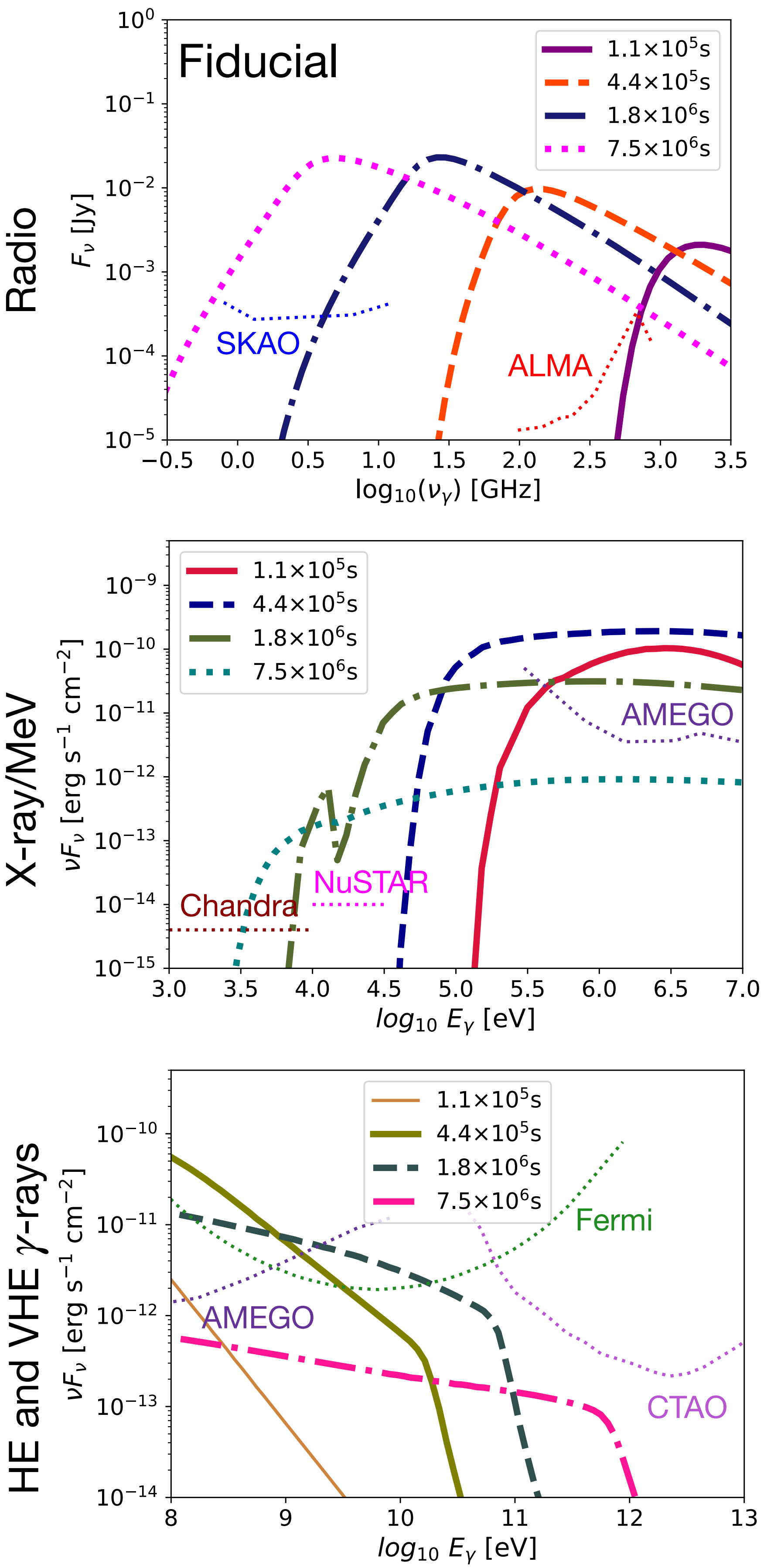


Synchrotron self-absorption (SSA)

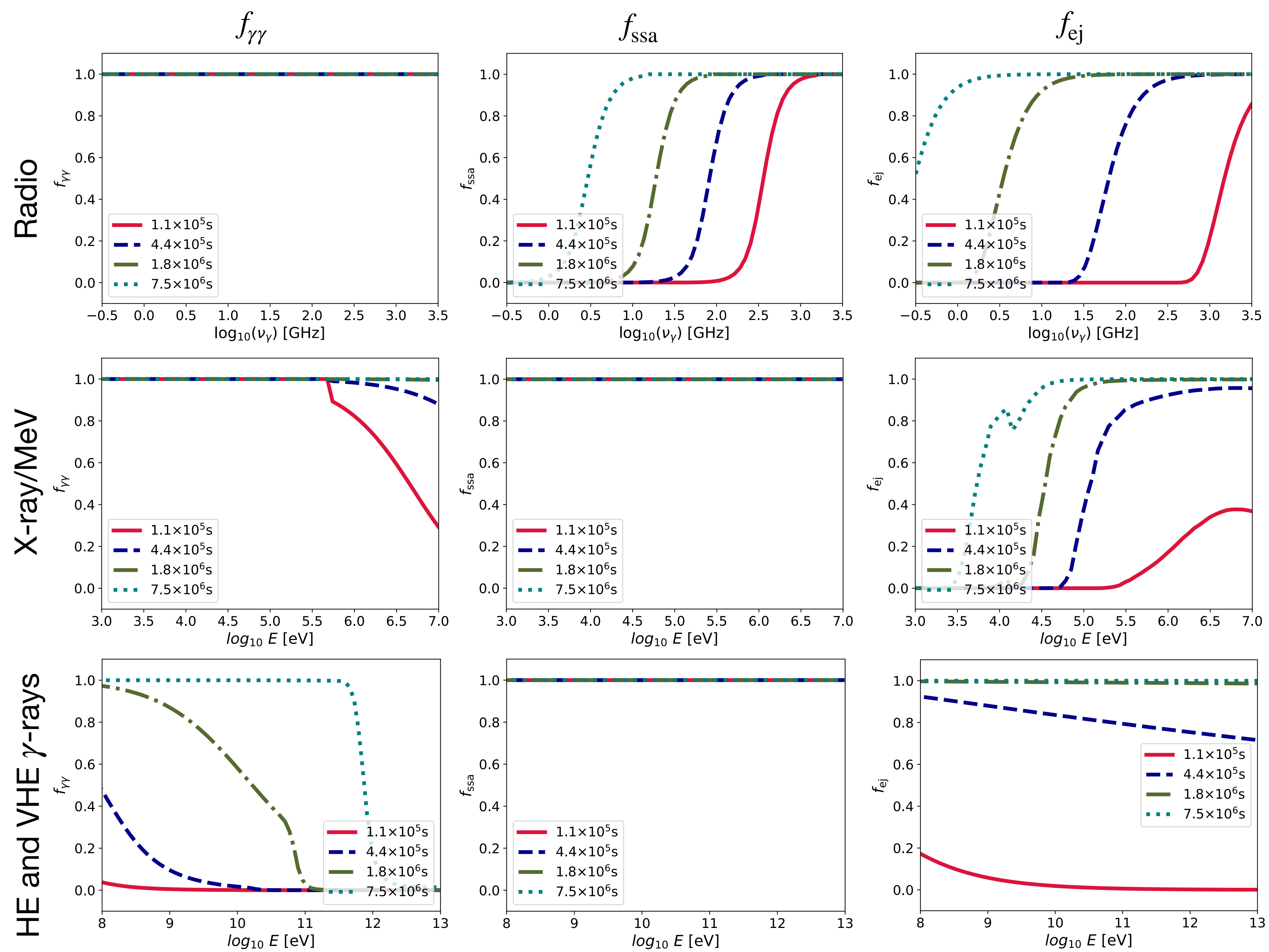
Photon spectra (d=100 Mpc)



Photon spectra (d=100 Mpc)



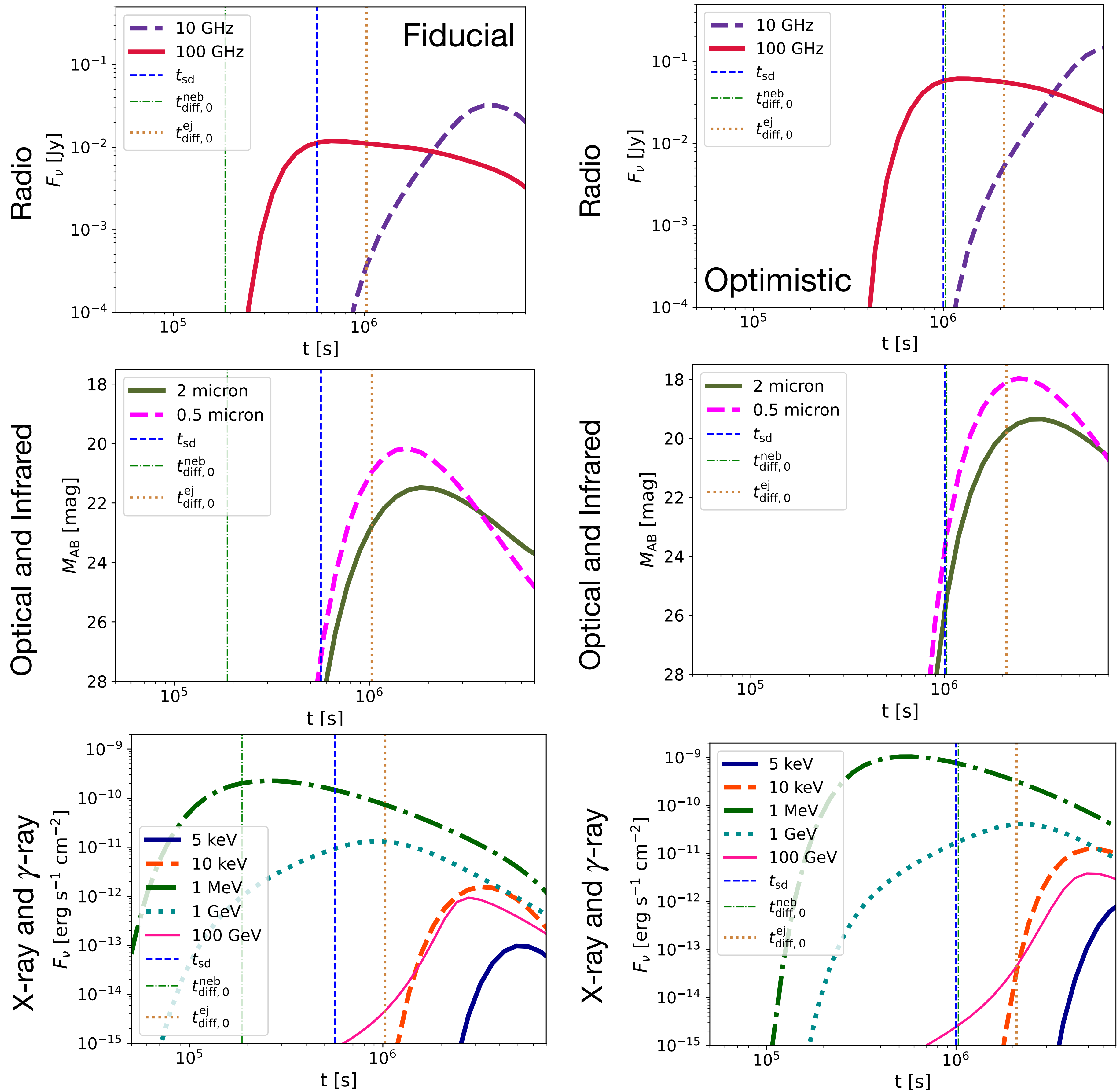
Attenuation



In the nebula

In the ejecta

Light curves (d=100 Mpc)



Distance Horizons

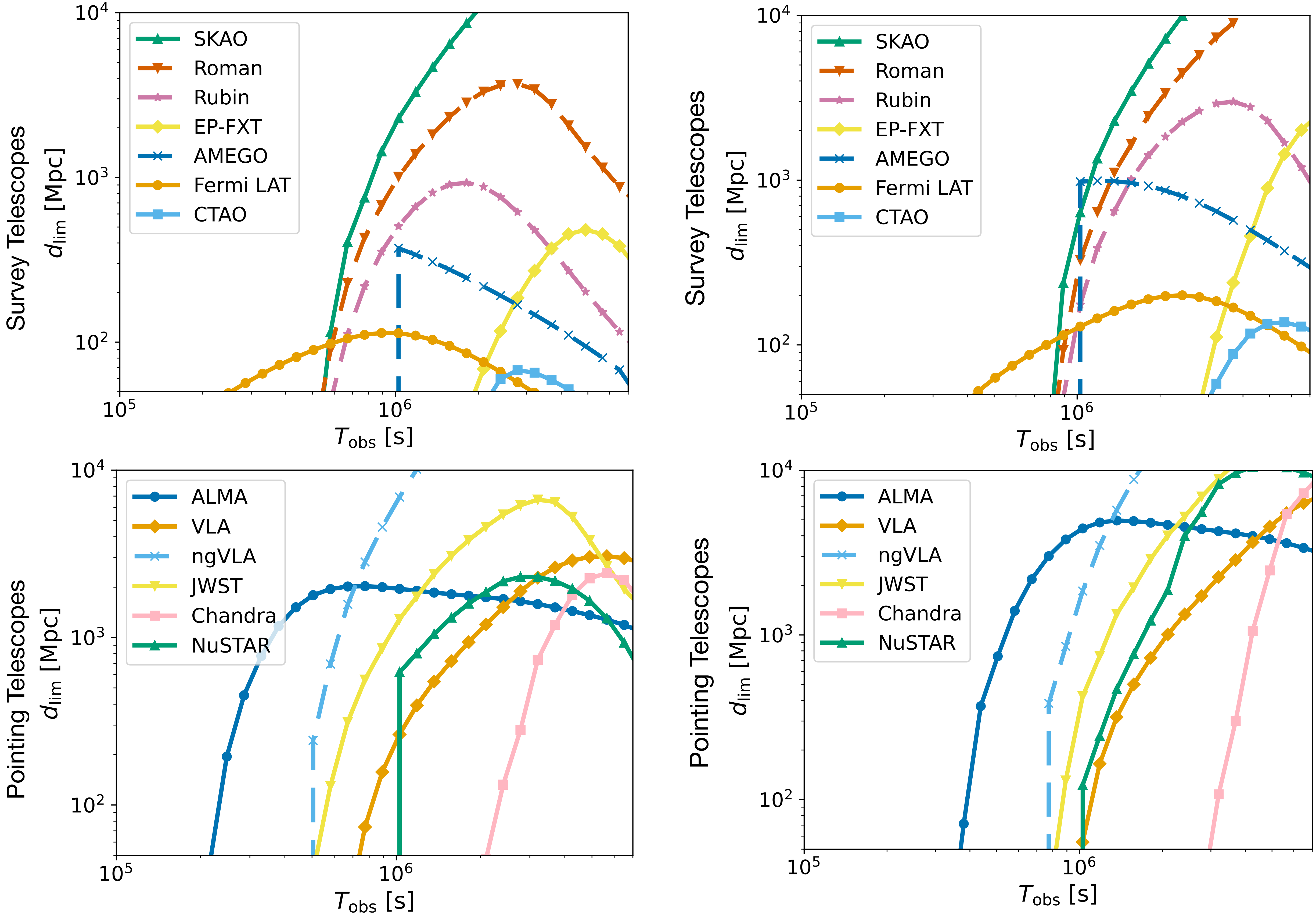
$$F_\nu^{\mathrm{obs}}(\nu_{\mathrm{obs}}, T_{\mathrm{obs}}, d_L) = \frac{(1+z)L_{\nu_{\mathrm{src}}}(T_{\mathrm{src}})}{4\pi d_L^2}$$

$$\int_{T_{\mathrm{obs}}}^{T_{\mathrm{obs}}+\Delta T_{\mathrm{int}}} dt_{\mathrm{obs}}\; F_\nu^{\mathrm{obs}}(\nu_{\mathrm{obs}}, T_{\mathrm{obs}}, d_L = d_{\mathrm{lim}}) = F_{\mathrm{sens}}(\nu_{\mathrm{obs}}, \Delta T_{\mathrm{int}})$$

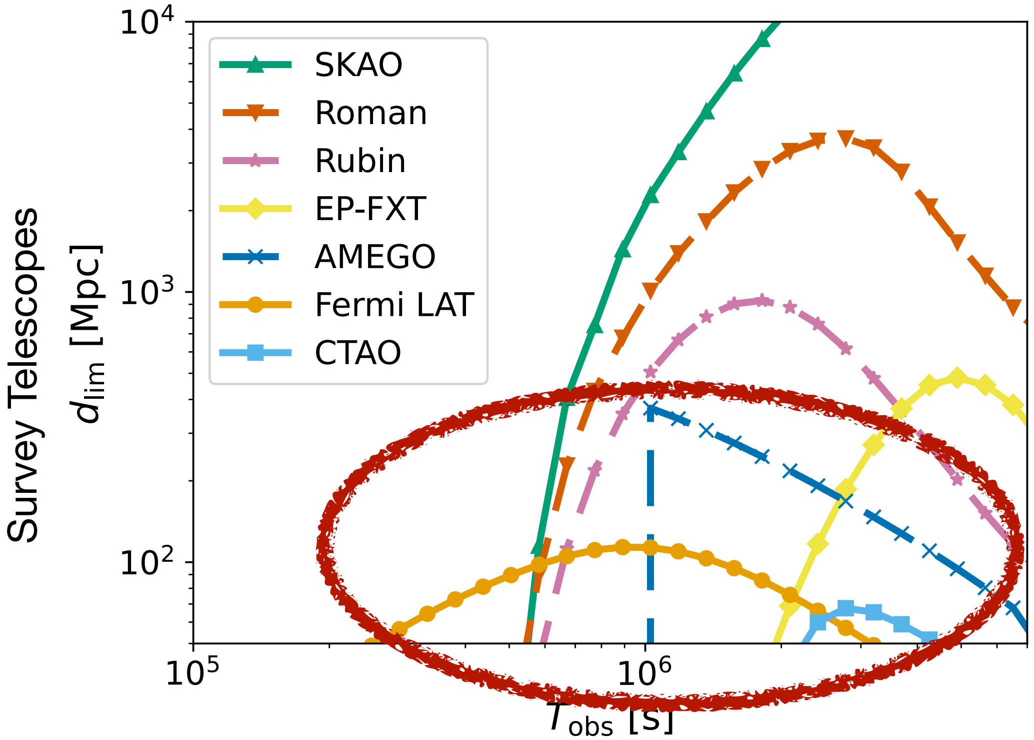
$$T_{\mathrm{obs}} = (1+z)T_{\mathrm{src}} \qquad \nu_{\mathrm{obs}} = \nu_{\mathrm{src}}/(1+z)$$

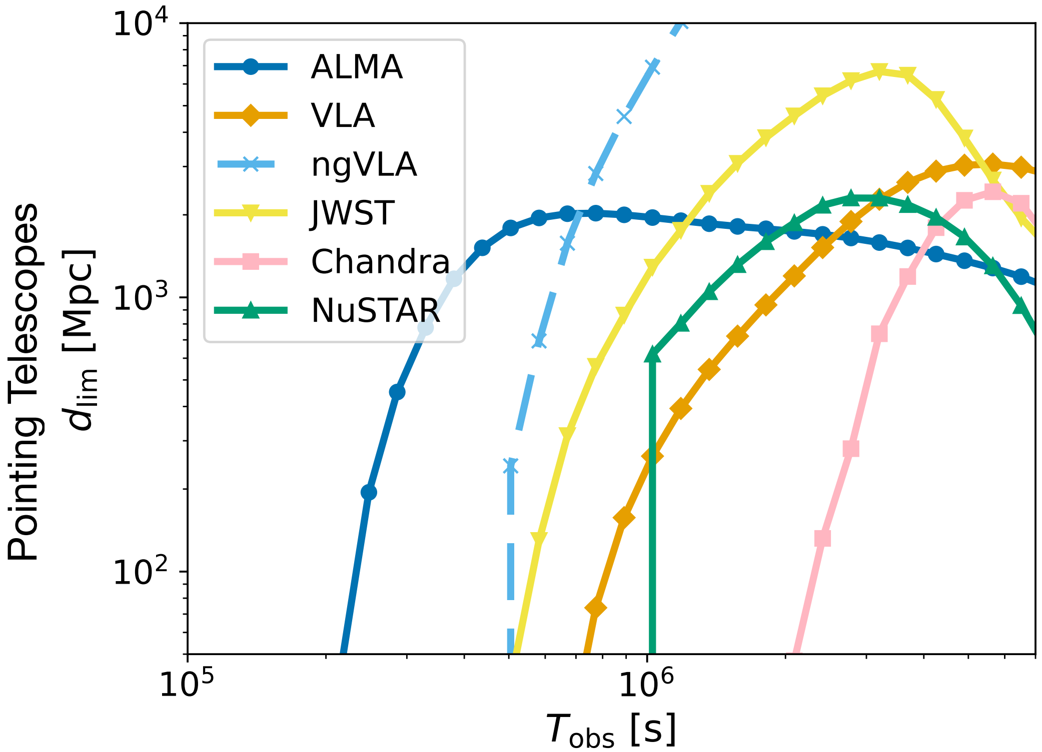
Distance Horizons

Fiducial | **Optimistic**



Unique-identification

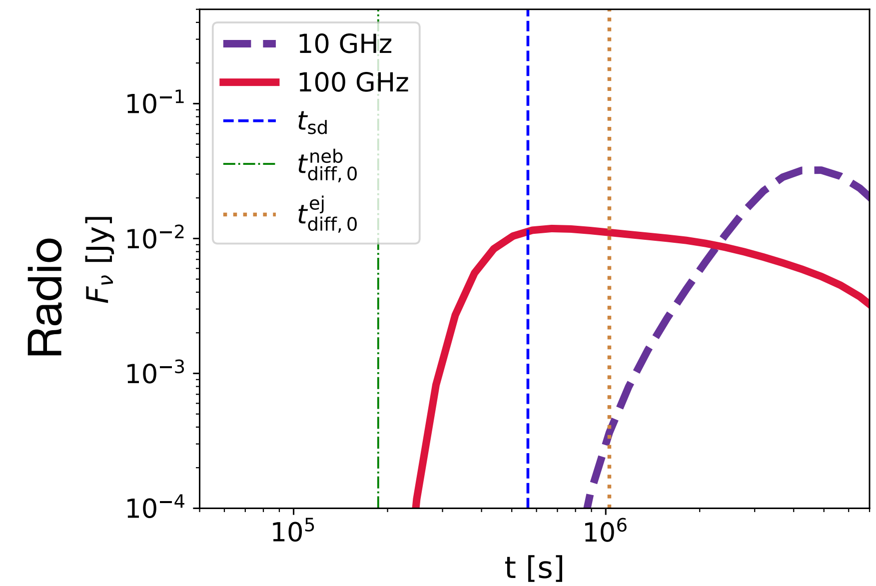


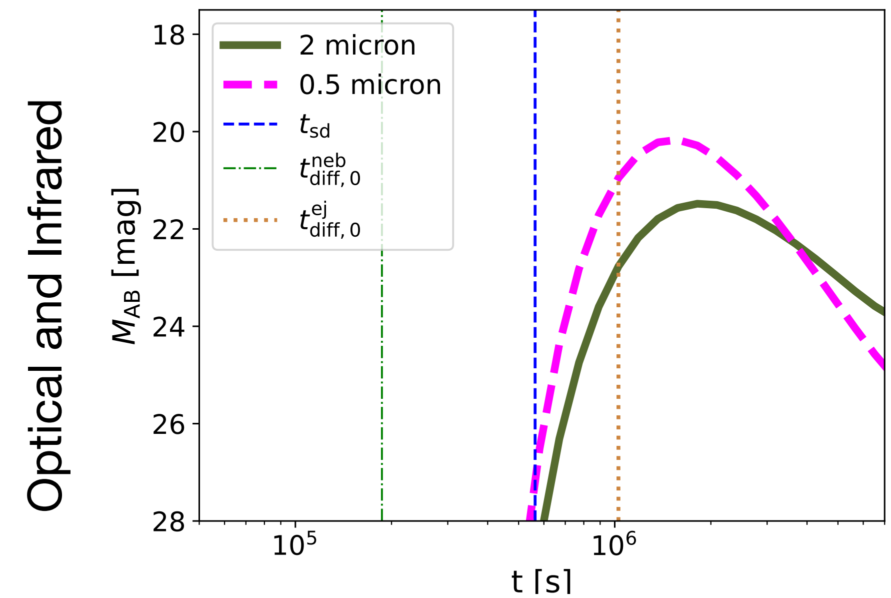


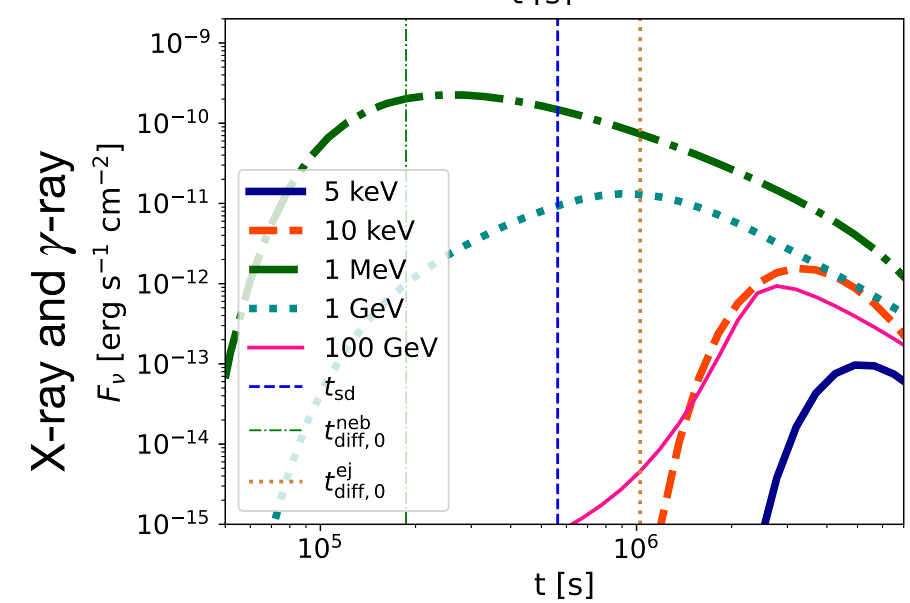
$$d_L \lesssim 100 \text{ Mpc}$$

Main background: GRBs
On and off-axis

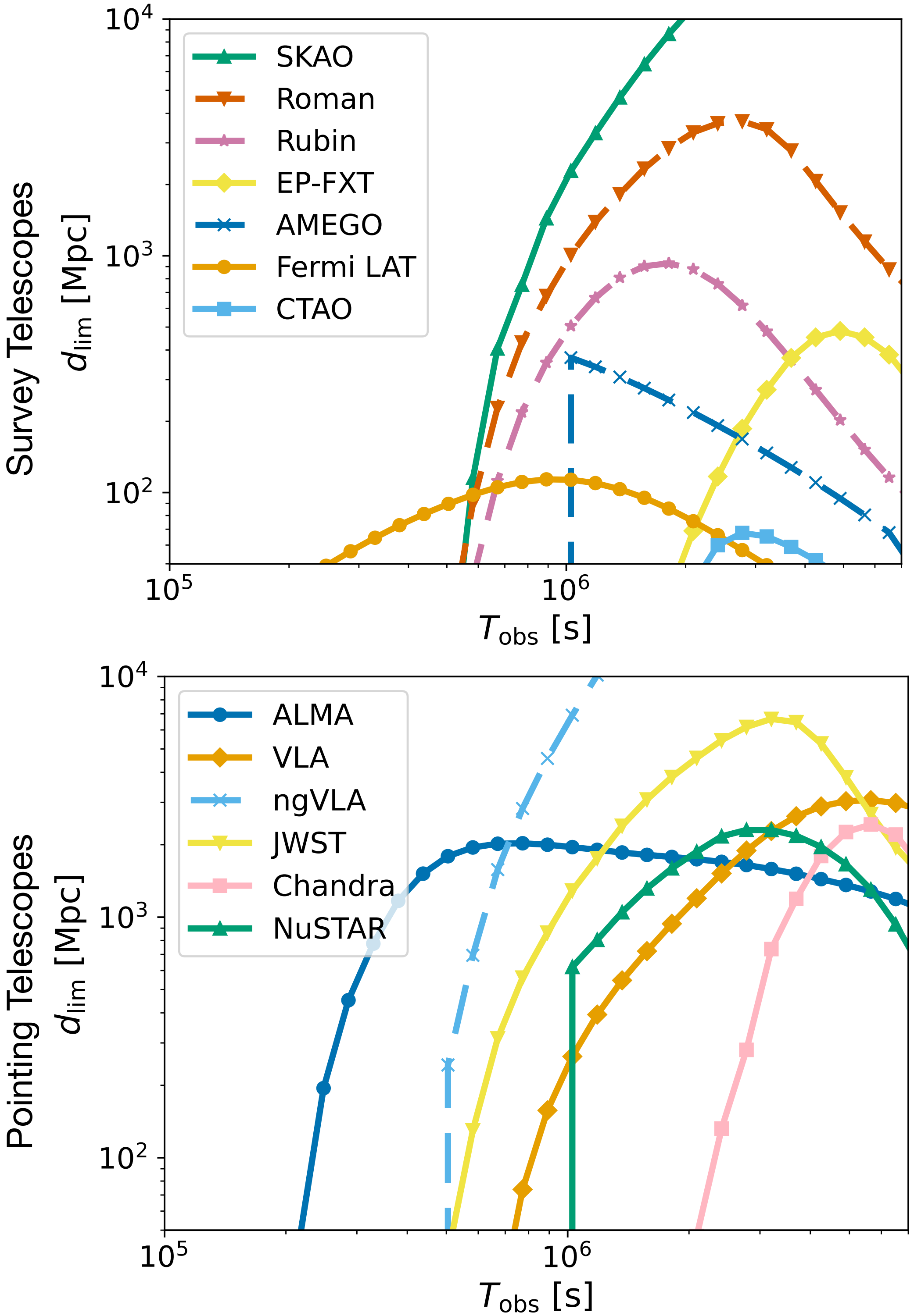
Main background: GRBs
On and off-axis





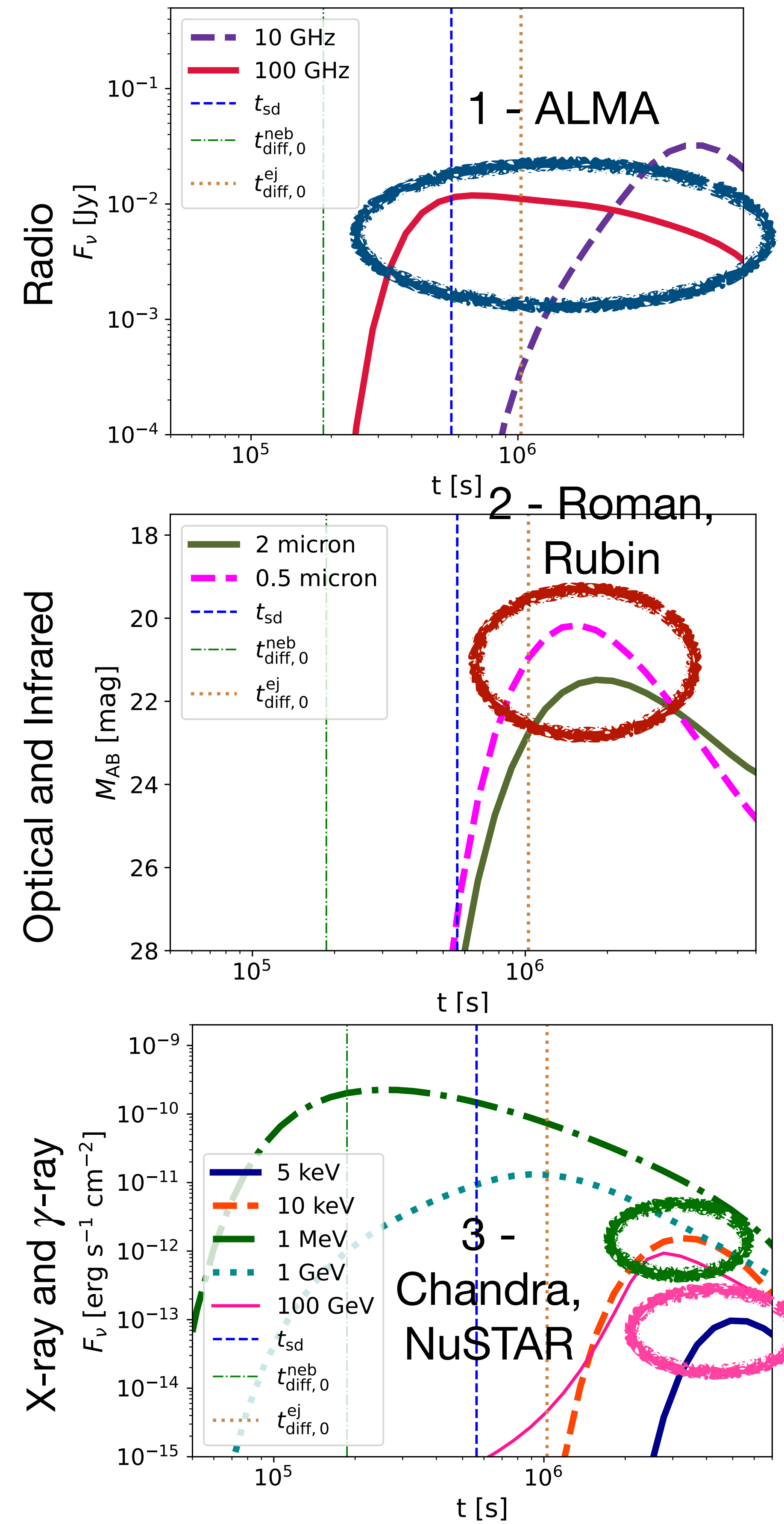


Unique-identification

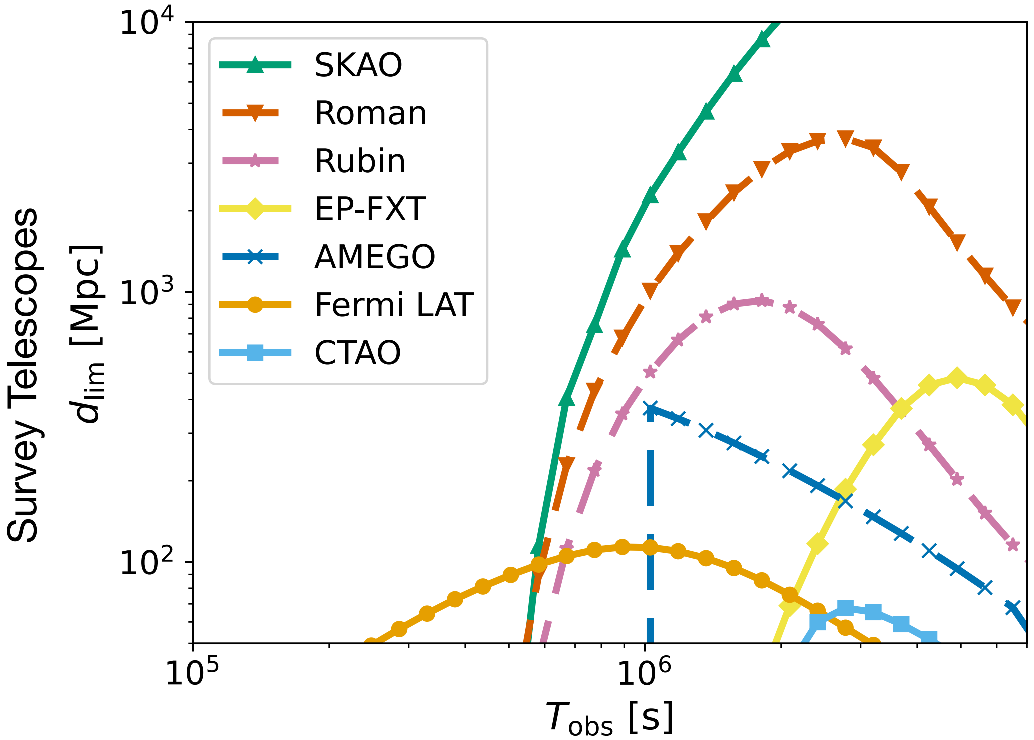


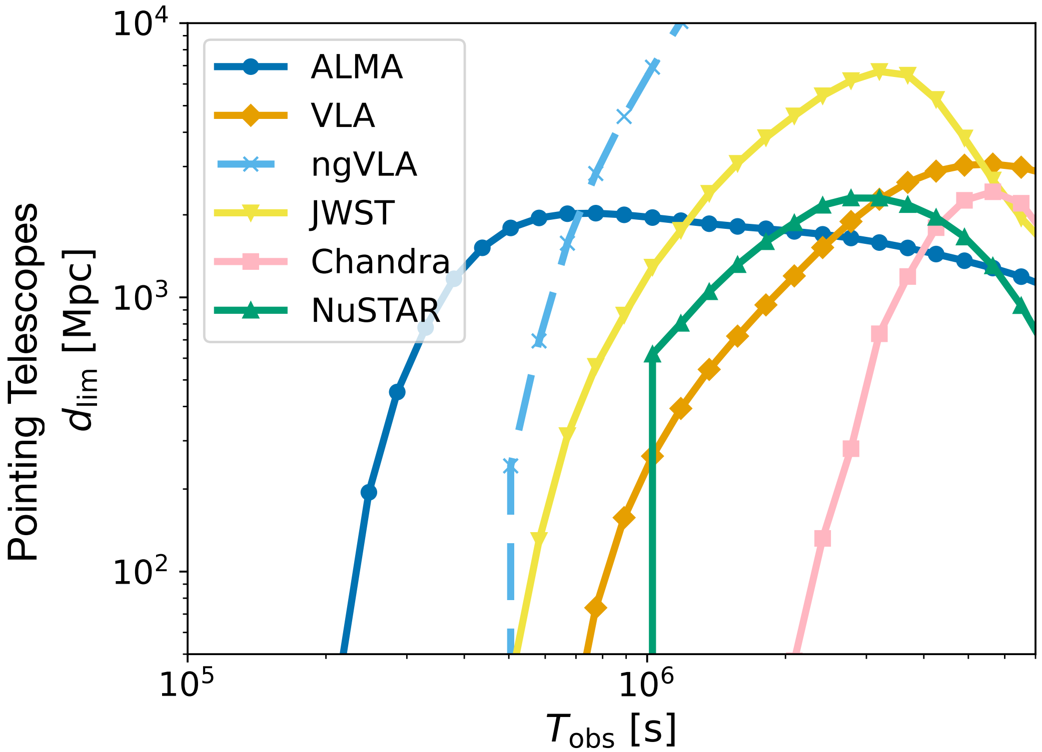
$d_L \lesssim 1$ Gpc

Main backgrounds: SNe, stellar flares, novae, accretion flows in low mass X-ray binaries



Unique-identification

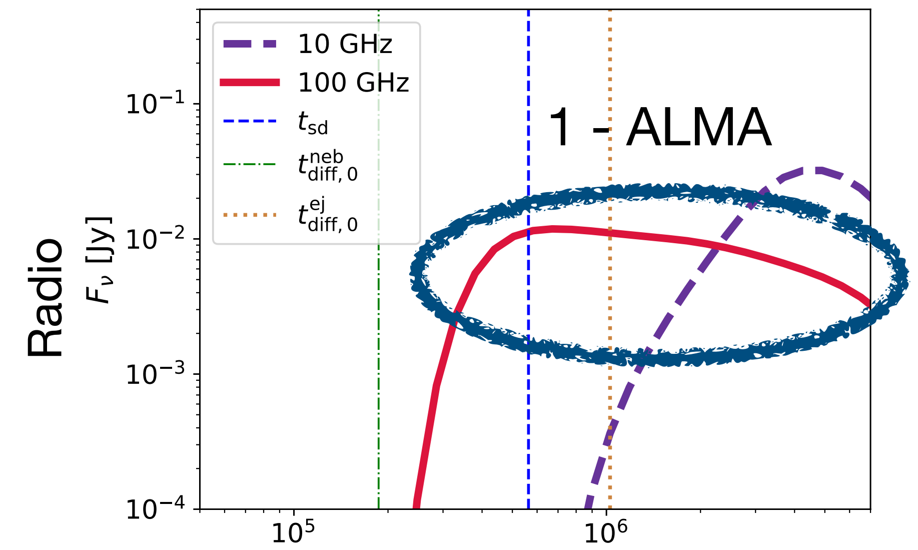


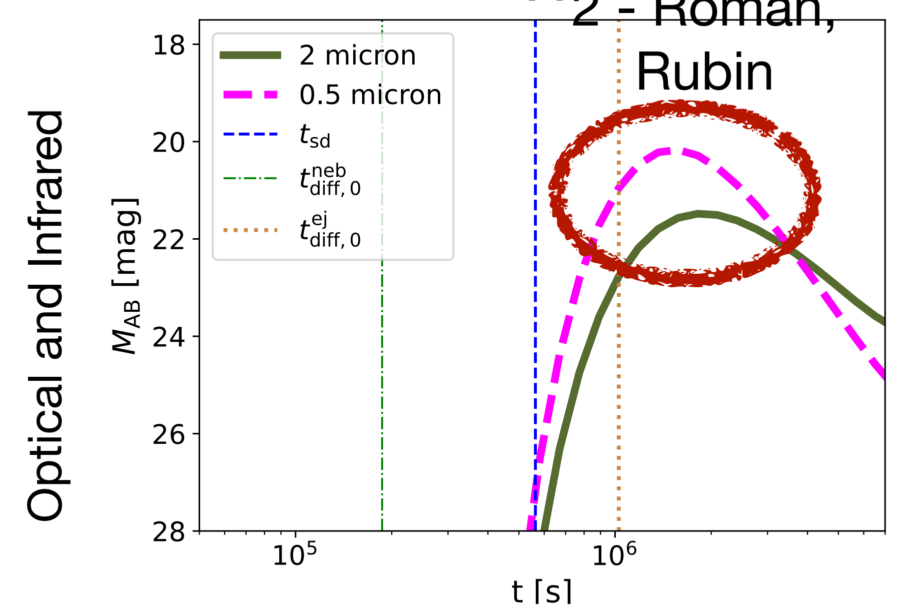


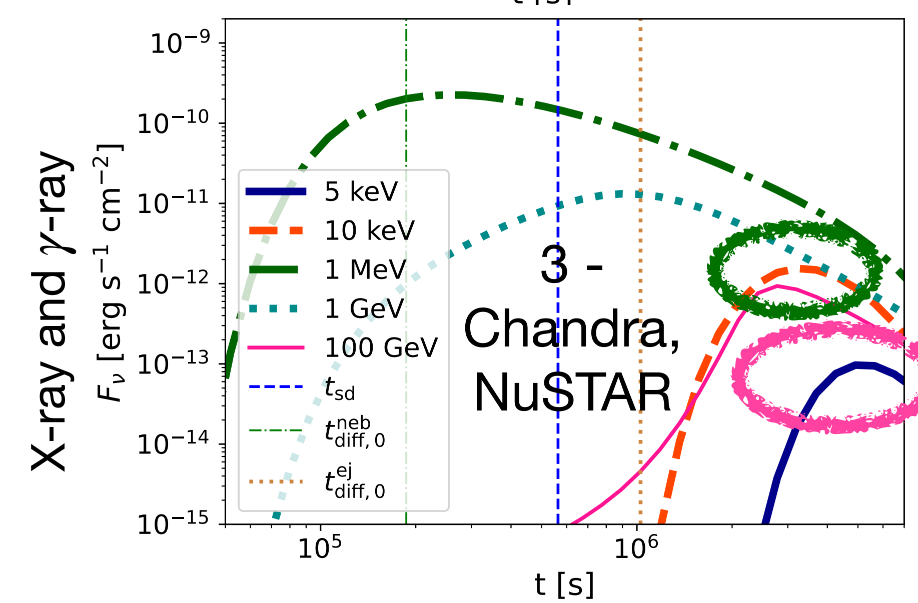
$$d_L \lesssim 1 \text{ Gpc}$$

Main backgrounds: SNe, stellar flares, novae, accretion flows in low mass X-ray binaries

Also distinguishable from kilonovae: strong X-ray and radio signatures along with delayed optical/infrared peak







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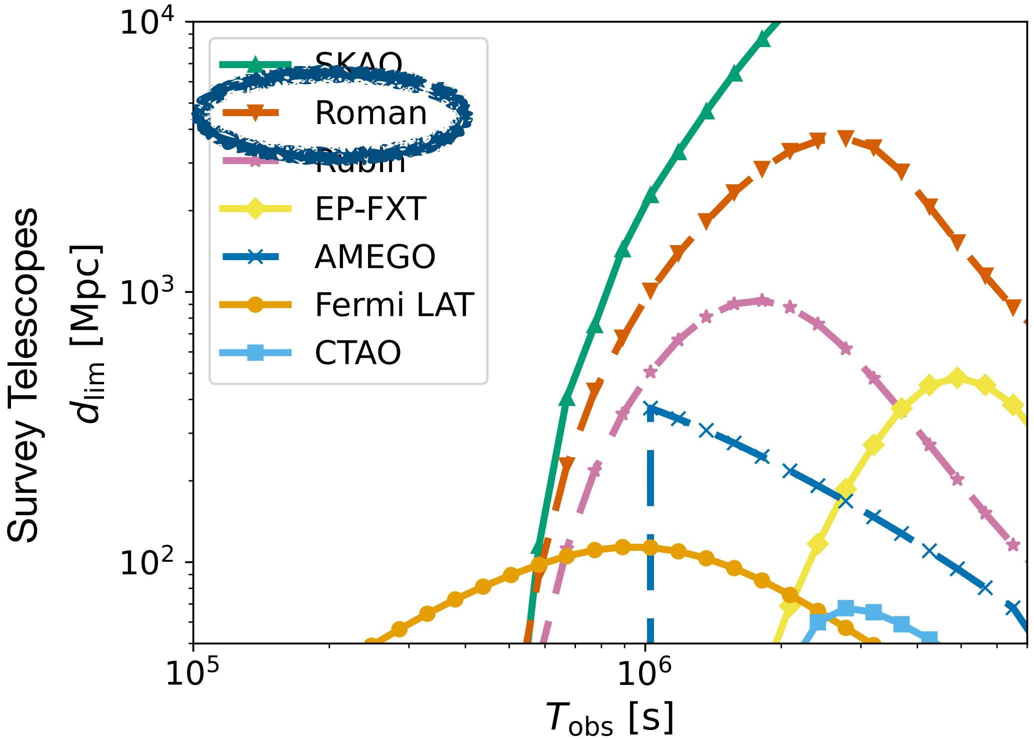
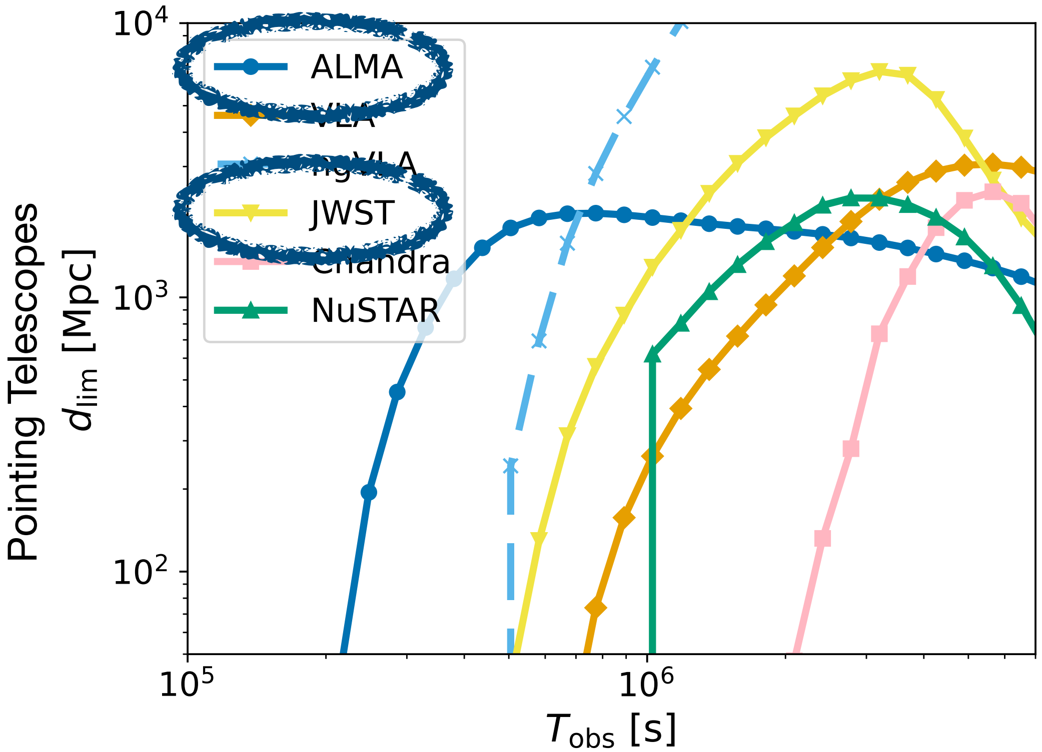
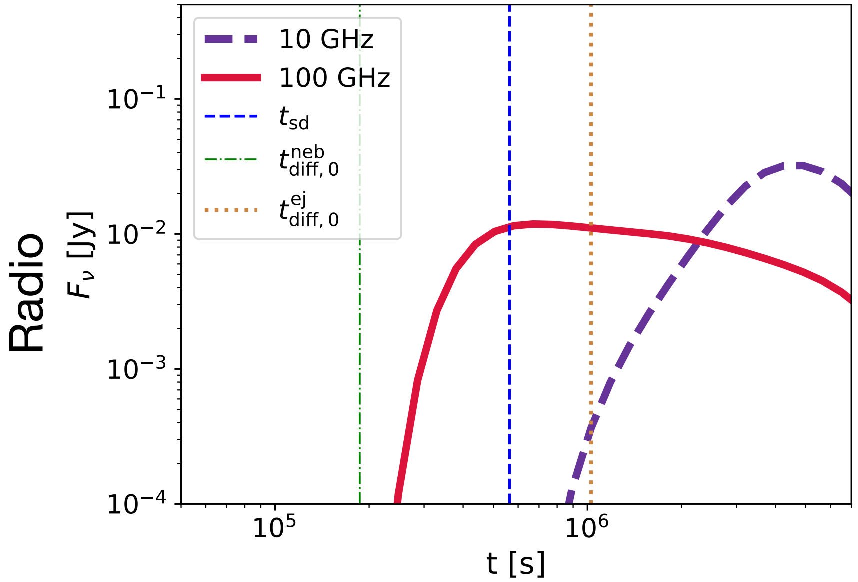
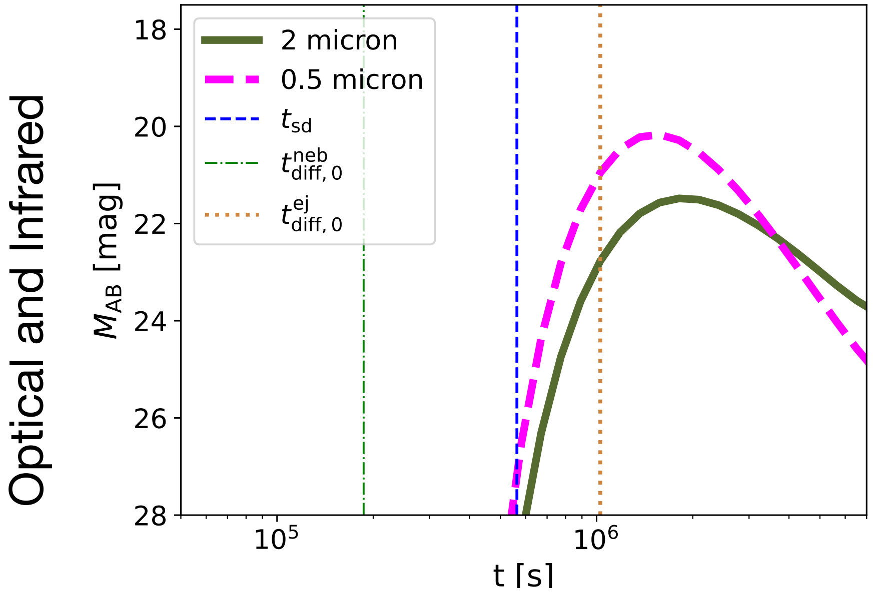


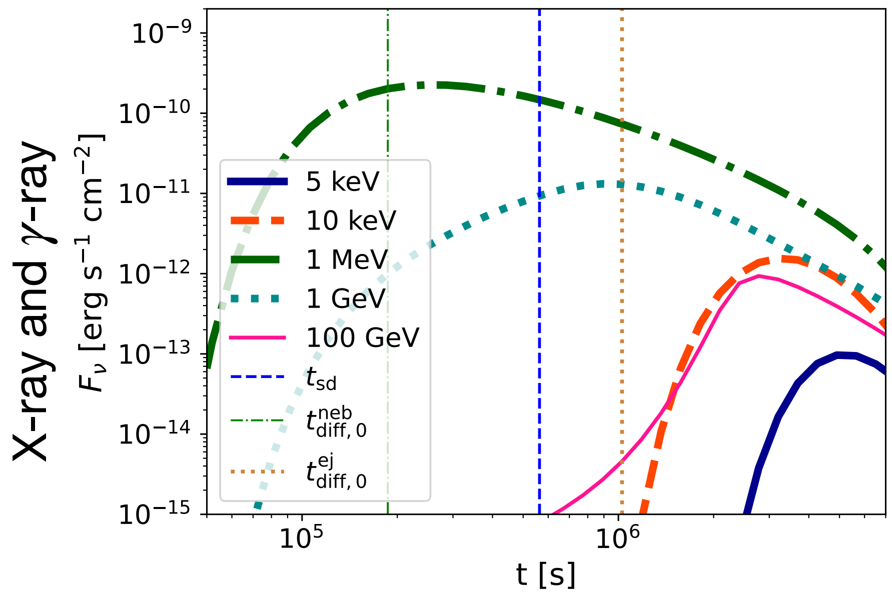


$d_L \gtrsim 1$ Gpc

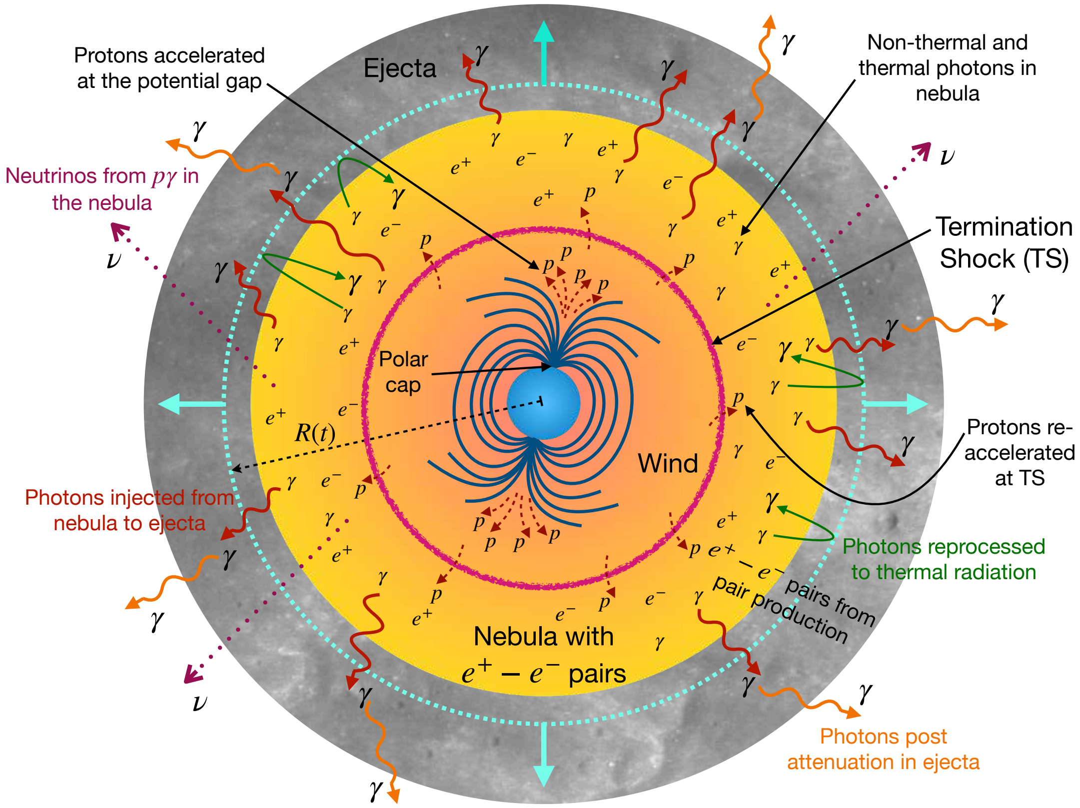
Challenging! :(



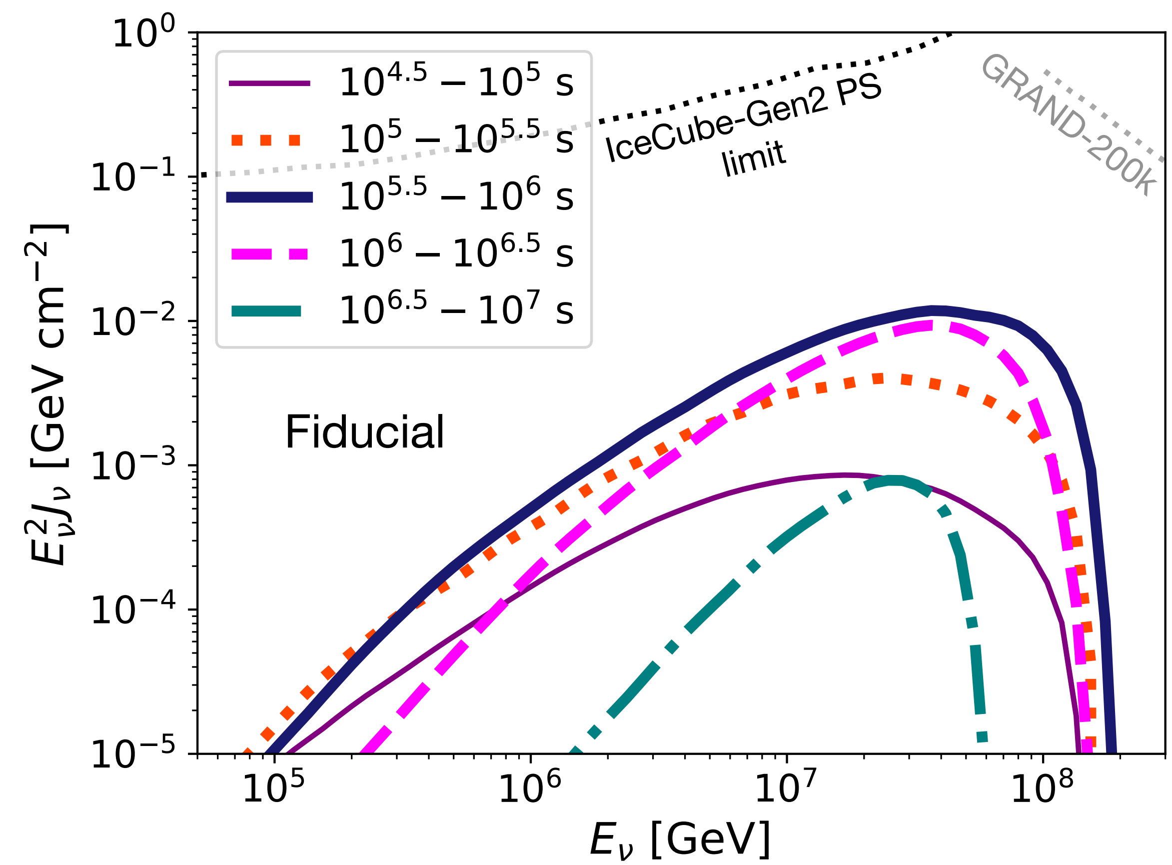




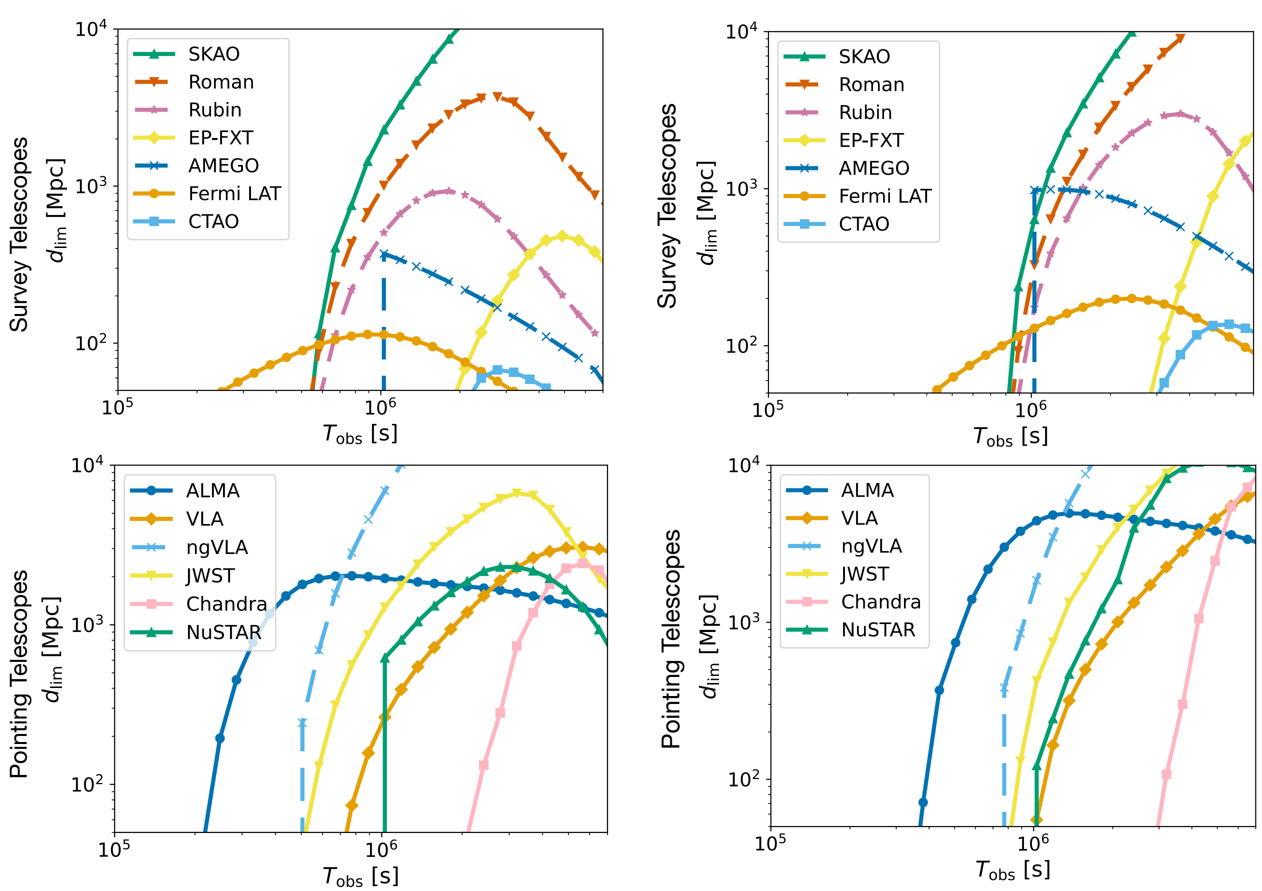
Takeaways



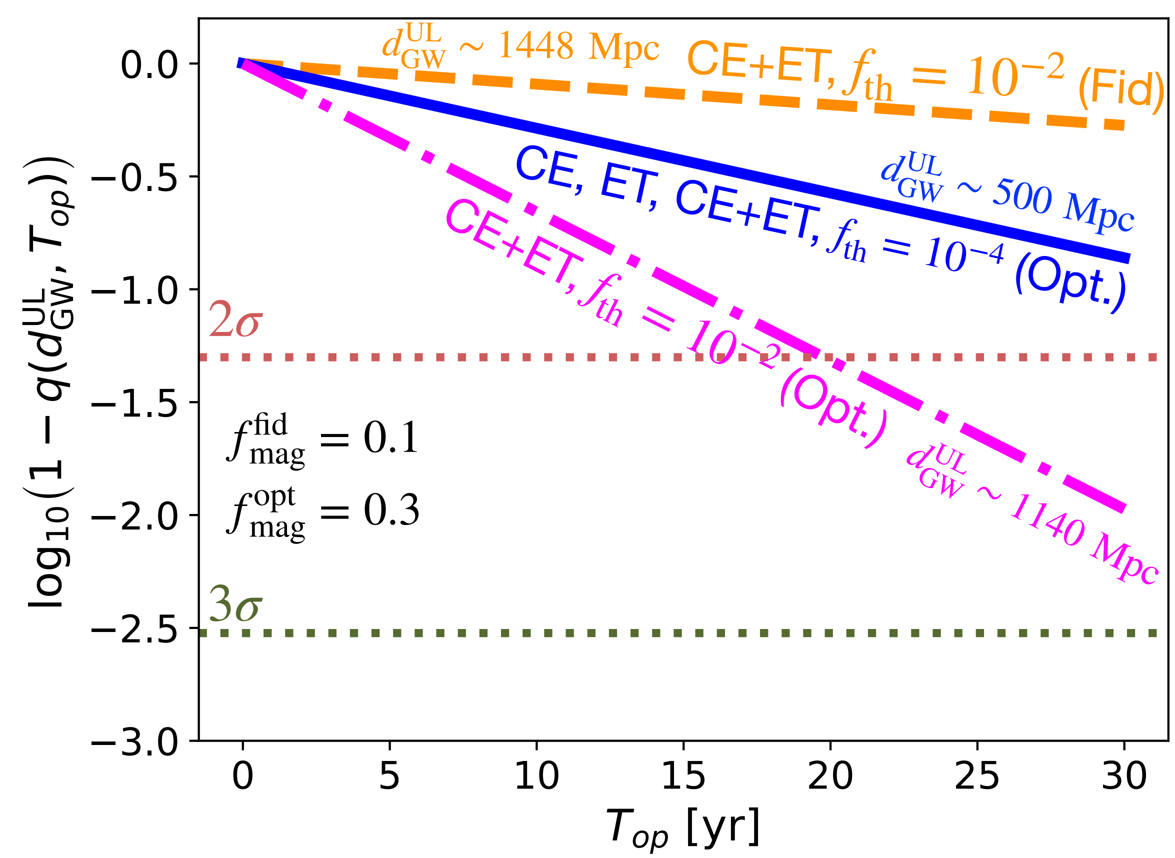
Protons accelerated at the potential gap
Ejecta
Non-thermal and thermal photons in nebula
Neutrinos from $p\gamma$ in the nebula
Termination Shock (TS)
Polar cap
$R(t)$
Wind
Protons re-accelerated at TS
Photons injected from nebula to ejecta
Photons reprocessed to thermal radiation
$e^+ - e^-$ pairs from pair production
Nebula with $e^+ - e^-$ pairs
Photons post attenuation in ejecta



$10^{4.5} - 10^5$ s
$10^5 - 10^{5.5}$ s
$10^{5.5} - 10^6$ s
$10^6 - 10^{6.5}$ s
$10^{6.5} - 10^7$ s
IceCube-Gen2 PS limit
GRAND-200k
Fiducial
$E_\nu^2 J_\nu$ [GeV cm^{-2}]
E_ν [GeV]



SKAO
Roman
Rubin
EP-FXT
AMEGO
Fermi LAT
CTAO
Survey Telescopes
ALMA
VLA
ngVLA
JWST
Chandra
NuSTAR
Pointing Telescopes
$d_{\rm lim}$ [Mpc]
$T_{\rm obs}$ [s]



$d_{\rm GW}^{\rm UL} \sim 1448$ Mpc CE+ET, $f_{\rm th} = 10^{-2}$ (Fid)
CE, ET, CE+ET, $f_{\rm th} = 10^{-4}$ (Opt.)
$d_{\rm GW}^{\rm UL} \sim 500$ Mpc
CE+ET, $f_{\rm th} = 10^{-2}$ (Opt.)
$d_{\rm GW}^{\rm UL} \sim 1140$ Mpc
2σ
3σ
$f_{\rm mag}^{\rm fid} = 0.1$
$f_{\rm mag}^{\rm opt} = 0.3$
$\log_{10}(1 - q(d_{\rm GW}^{\rm UL}, T_{op}))$
T_{op} [yr]

Future prospects: the big picture

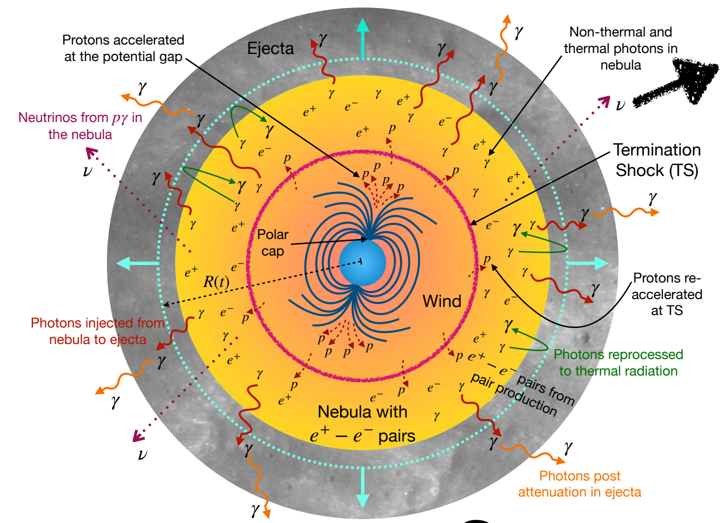
Fate of BNS merger remnants (in particular stable remnants) - Composition of the ejecta

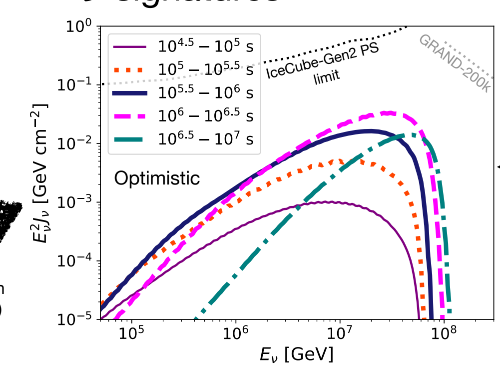
Understanding: (a) **Sites**: polar cap vs. equatorial current sheets and (b) **Mechanisms**: turbulence, magnetic reconnection, of **particle acceleration**

Magnetar origins of **superluminous supernovae (SLSNe)** and radio emissions from SLSNe, like, PTF10hgi

Magnetar boosted kilonovae (broadband emission from short GRBs, like, GRB 200522A) - detectable unto 100 Mpc

Probing physics beyond the Standard Model:
10^{13} G – 10^{15} G magnetic fields (axions, ...)





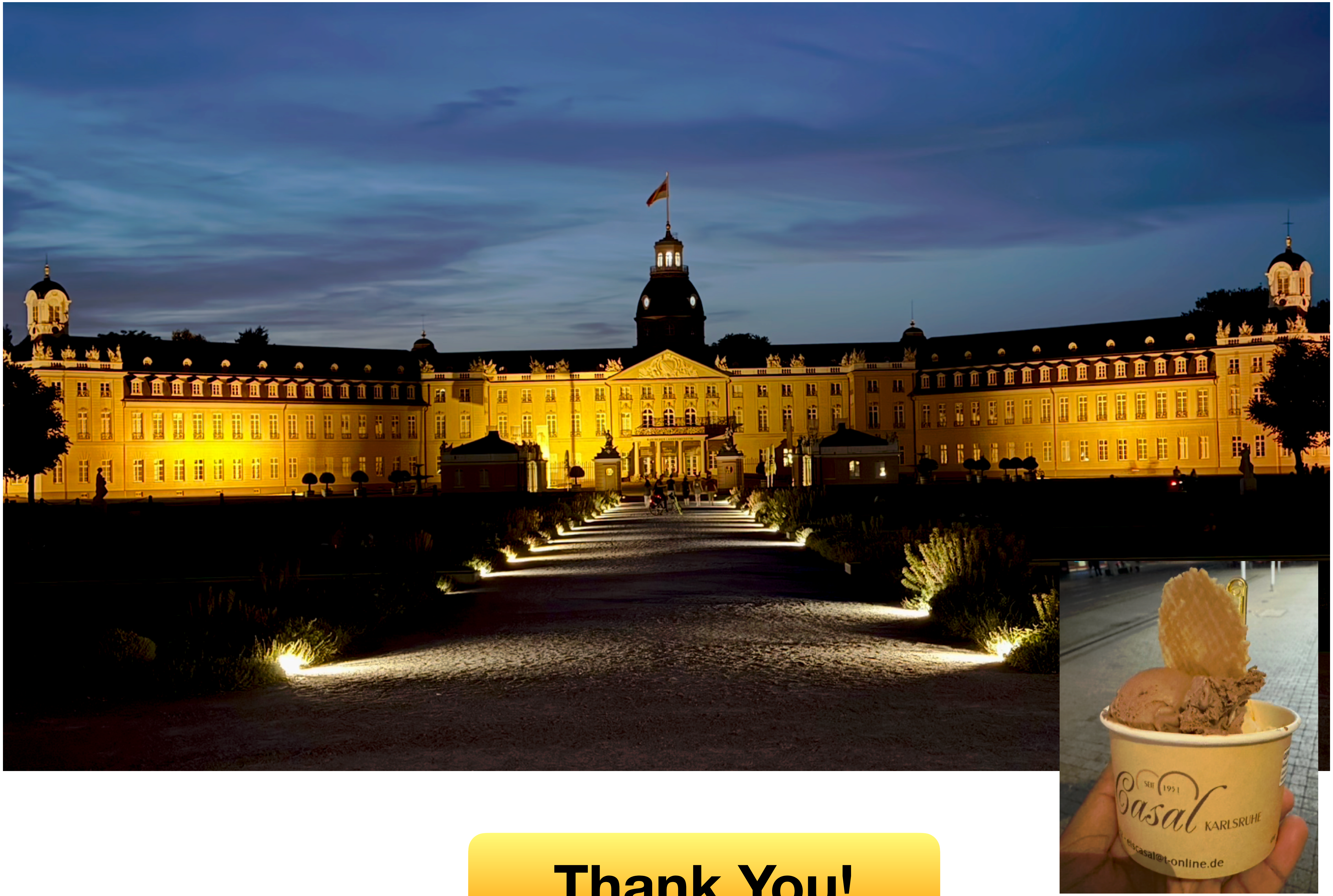
?

GW signatures

EM signatures

Fermi, NuSTAR, Roman, Rubin LSST, UVEX, COSI, ...

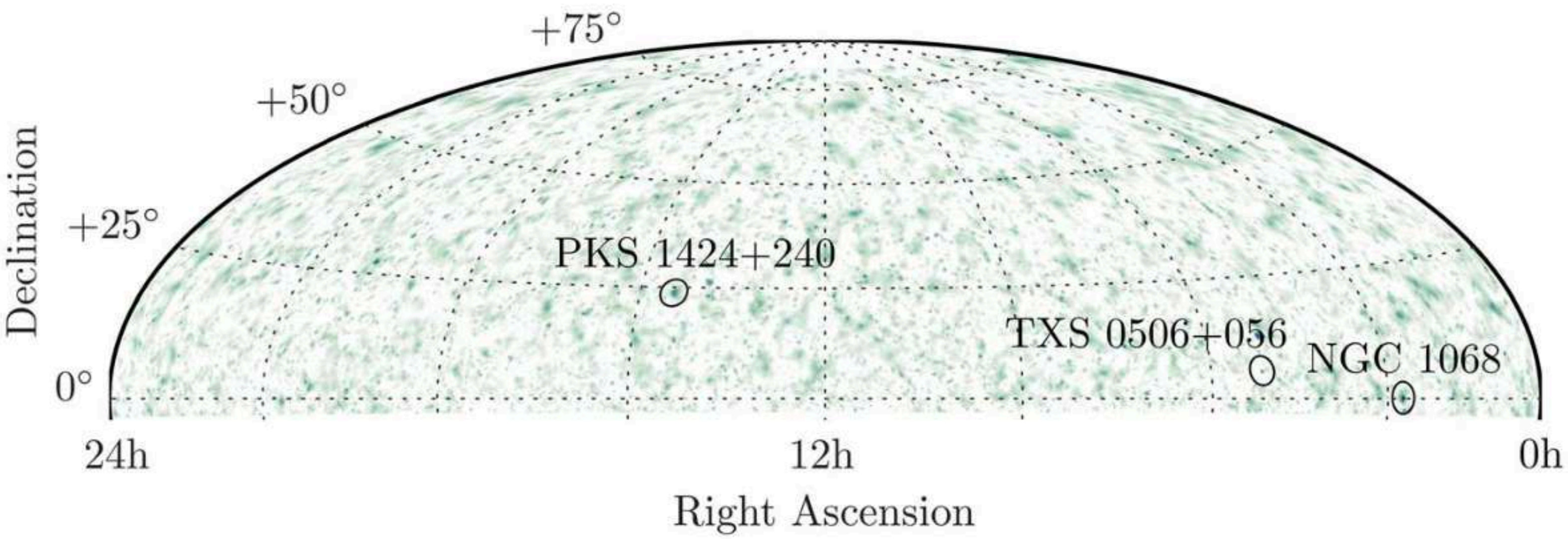
Triggered searches for neutrinos



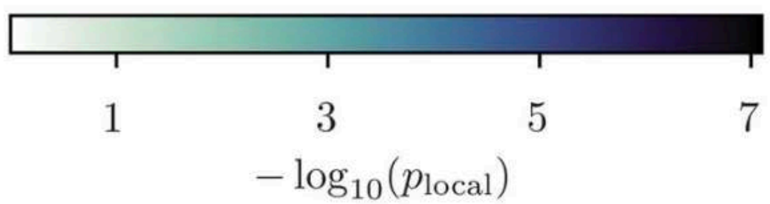
Thank You!

Backup

NGC 1068 (also TXS 0506+056)

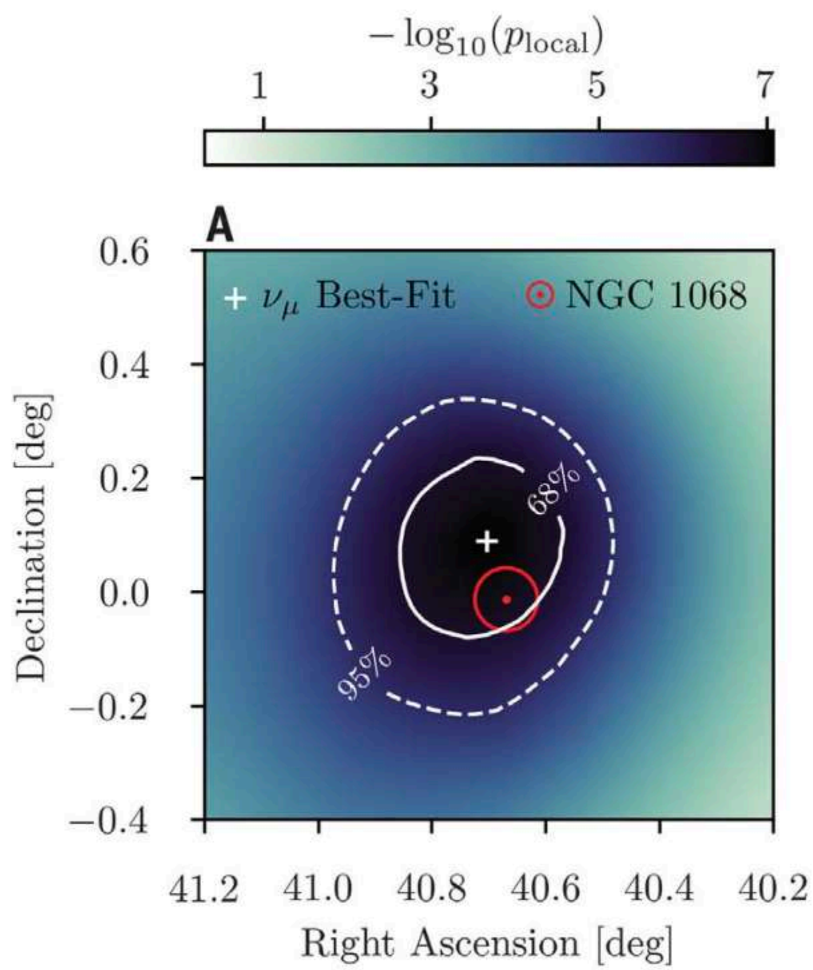


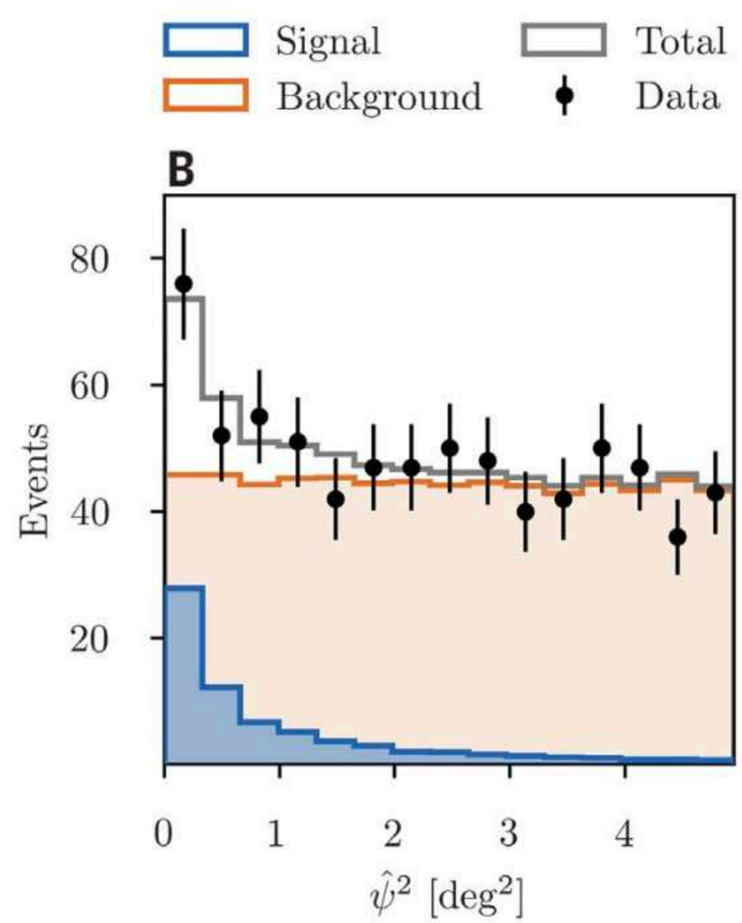
10 years of PS data (2011-2020)



$\sim 4.2\sigma$ w.r.t 110 known gamma ray sources

Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{\mathrm{local}}$	$\Phi_{90\%}$
NGC 1068	SBG/AGN	40.67	-0.01	79	3.2	7.0 (5.2 σ)	9.6
PKS 1424+240	BLL	216.76	23.80	77	3.5	4.0 (3.7 σ)	11.4
TXS 0506+056	BLL/FSRQ	77.36	5.70	5	2.0	3.6 (3.5 σ)	7.5





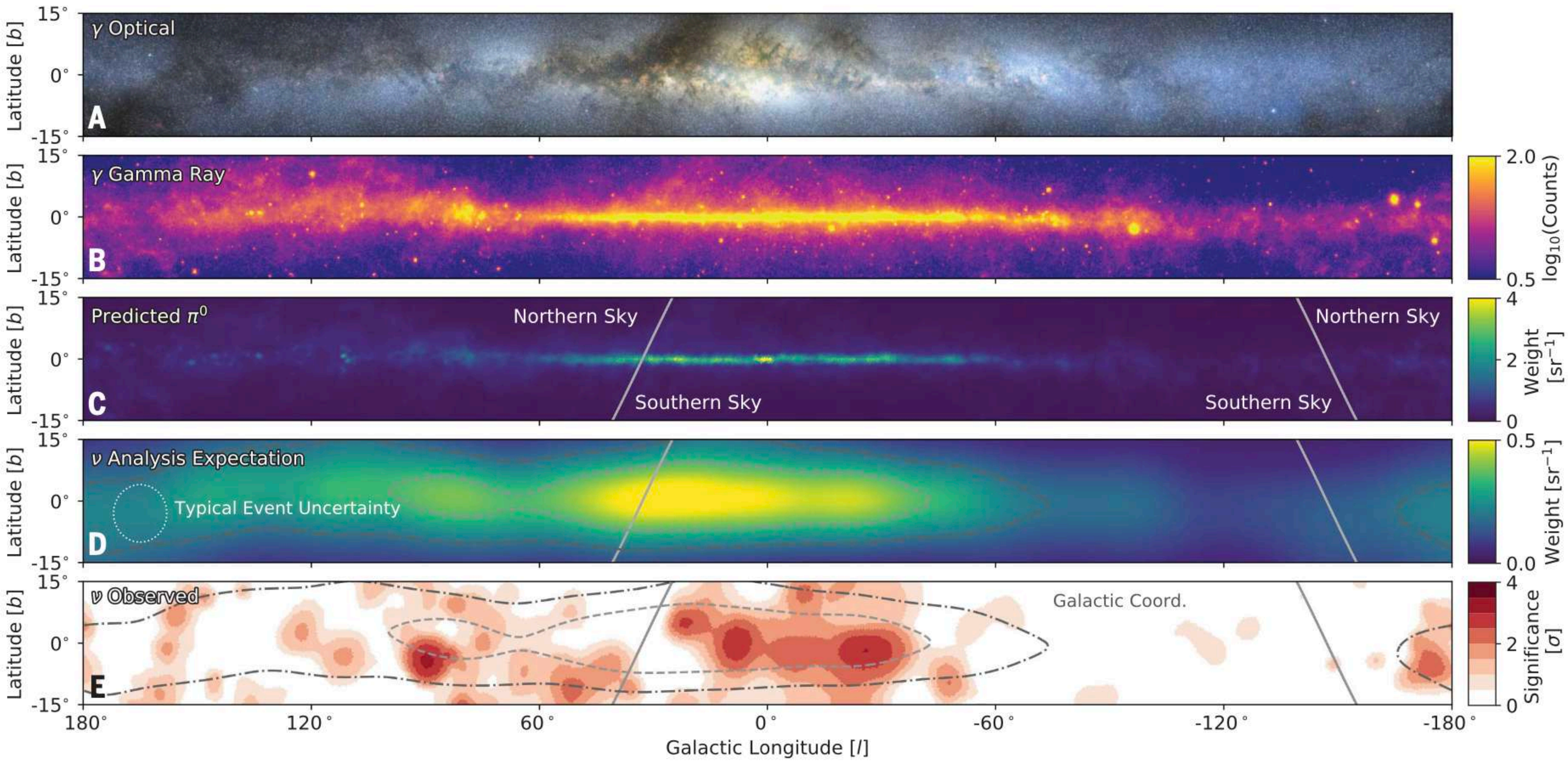
$\sim 79^{+22}_{-20}$ excess events

IceCube Collab.+ Science 2022

The Galactic plane

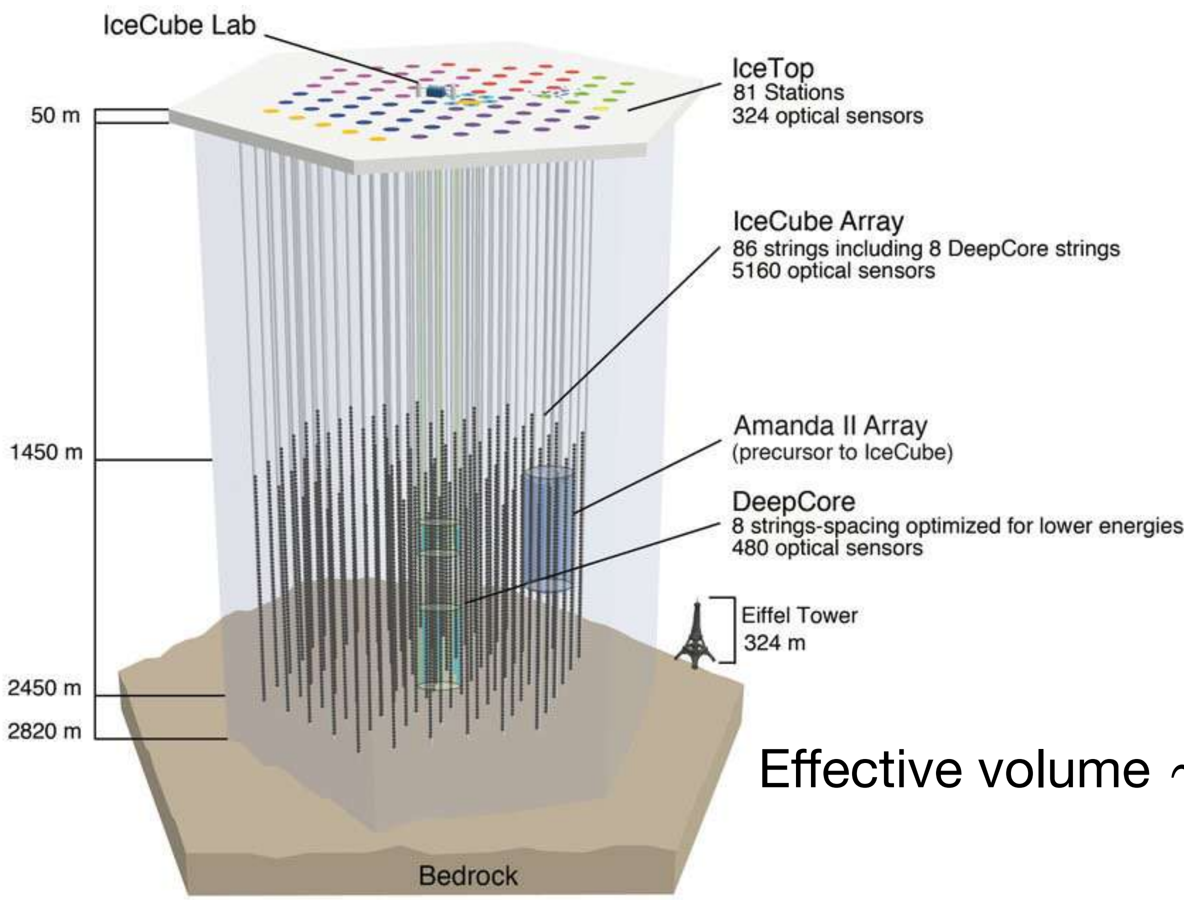
10 years of PS data
(2011-2020)

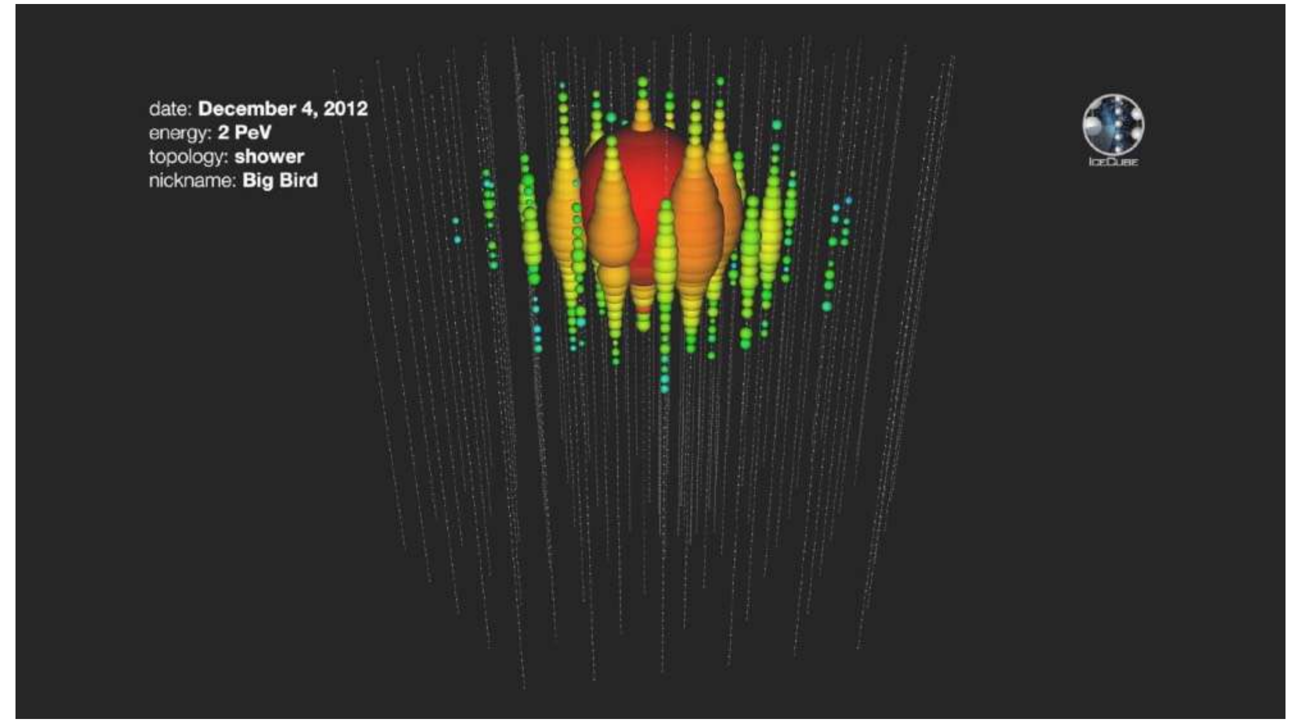
$\sim 4.5\sigma$ diffuse emission models
w.r.t background only hypothesis



IceCube Collab.+ Science, 380, 2023

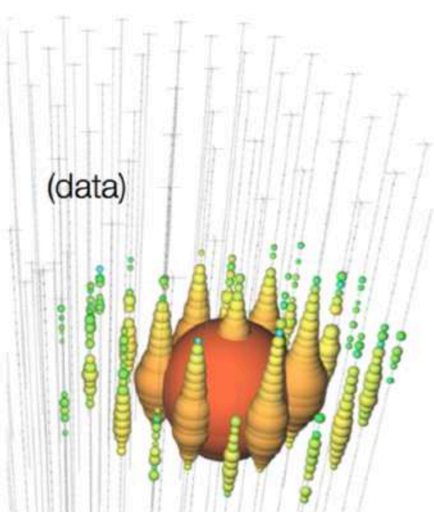
High-energy neutrino detectors





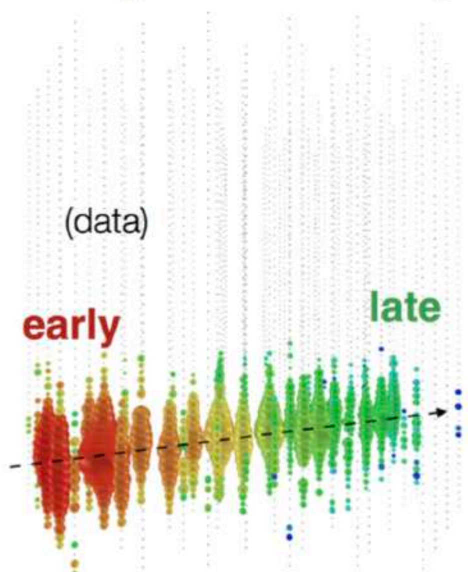
Effective volume $\sim 1\ \mathrm{km}^3$

Neutral-current / ν_e



Isolated energy deposition (cascade) with no track

Charged-current ν_μ

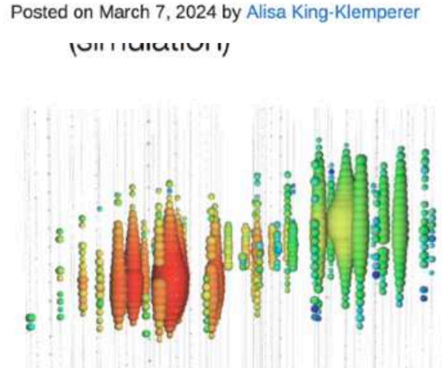


Up-going track

Charged-current ν_τ

IceCube observes seven astrophysical tau neutrino candidates

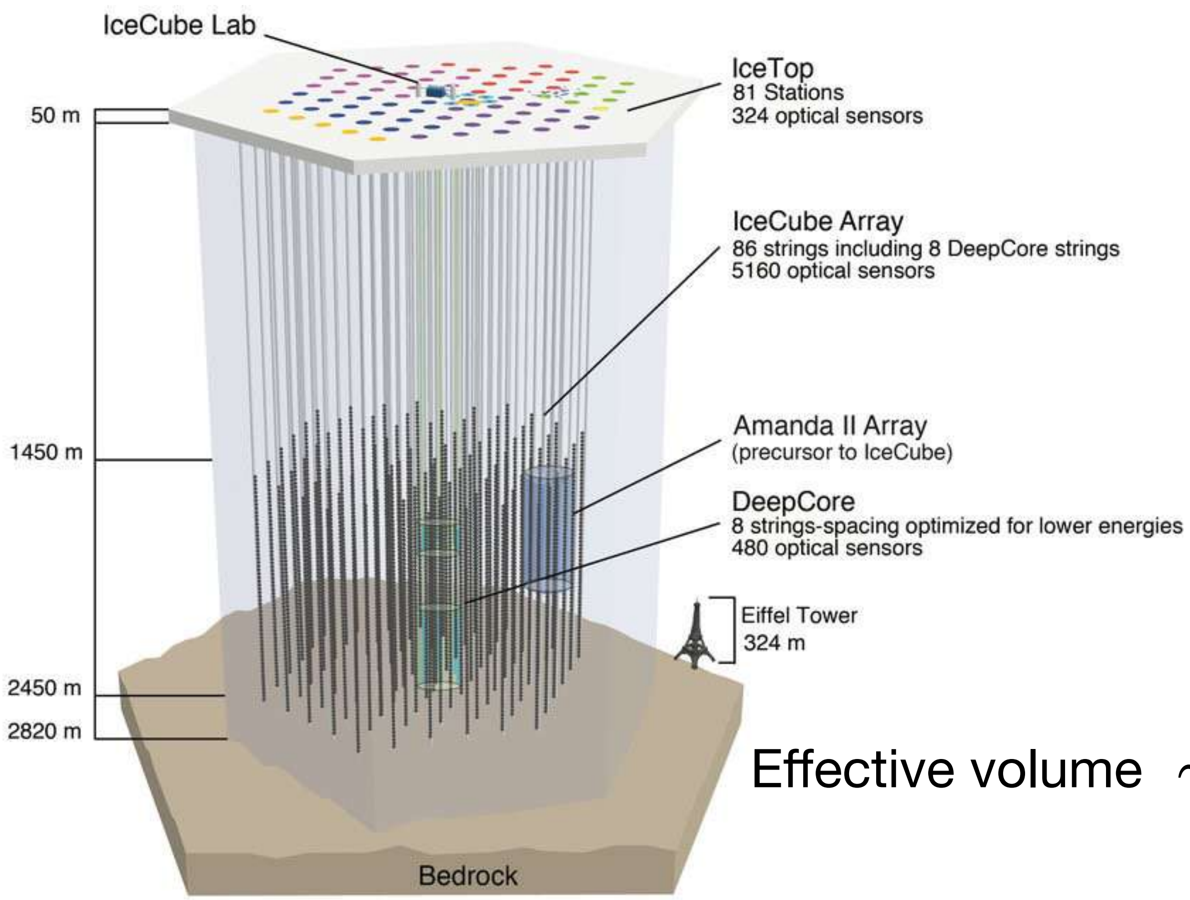
Posted on March 7, 2024 by Alisa King-Klemperer



Double cascade

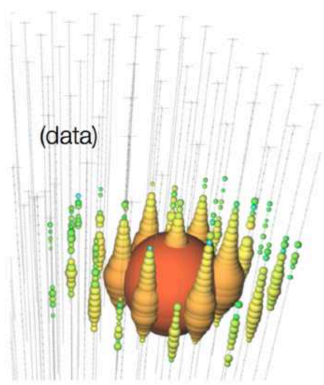
Image credits: icecube.wisc.edu

High-energy neutrino detectors



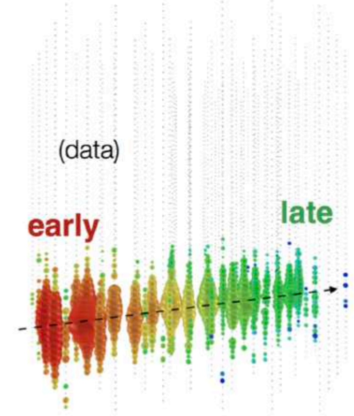
Effective volume $\sim 1\ \mathrm{km}^3$

Neutral-current / ν_e



Isolated energy deposition (cascade) with no track

Charged-current ν_μ



Up-going track

Charged-current ν_τ

IceCube observes seven astrophysical tau neutrino candidates

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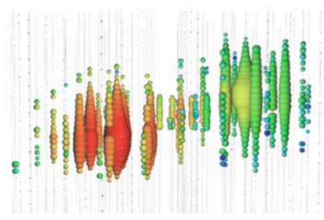
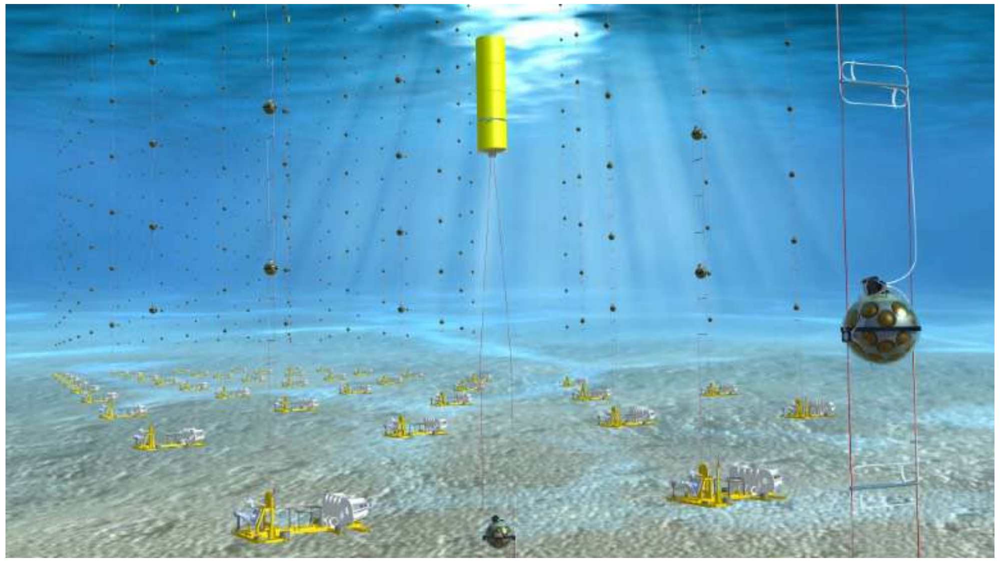
(simulation)



Double cascade

KM3NeT



Baikal GVD

ANTARES

Future detectors: IceCube-Gen2, RNO-G, GRAND, P-ONE….

Image credits: icecube.wisc.edu
KM3NeT: Edward Berber, Nikhef

Details about r-process heating rate

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

Fraction of photons that have thermalized (non-trivial)

Fraction of thermalized photons that diffuse from ejecta to the nebula

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

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

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

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

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

Time at which ejecta becomes transparent to gamma-rays

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

Rate of energy generated from r-process nuclei decay

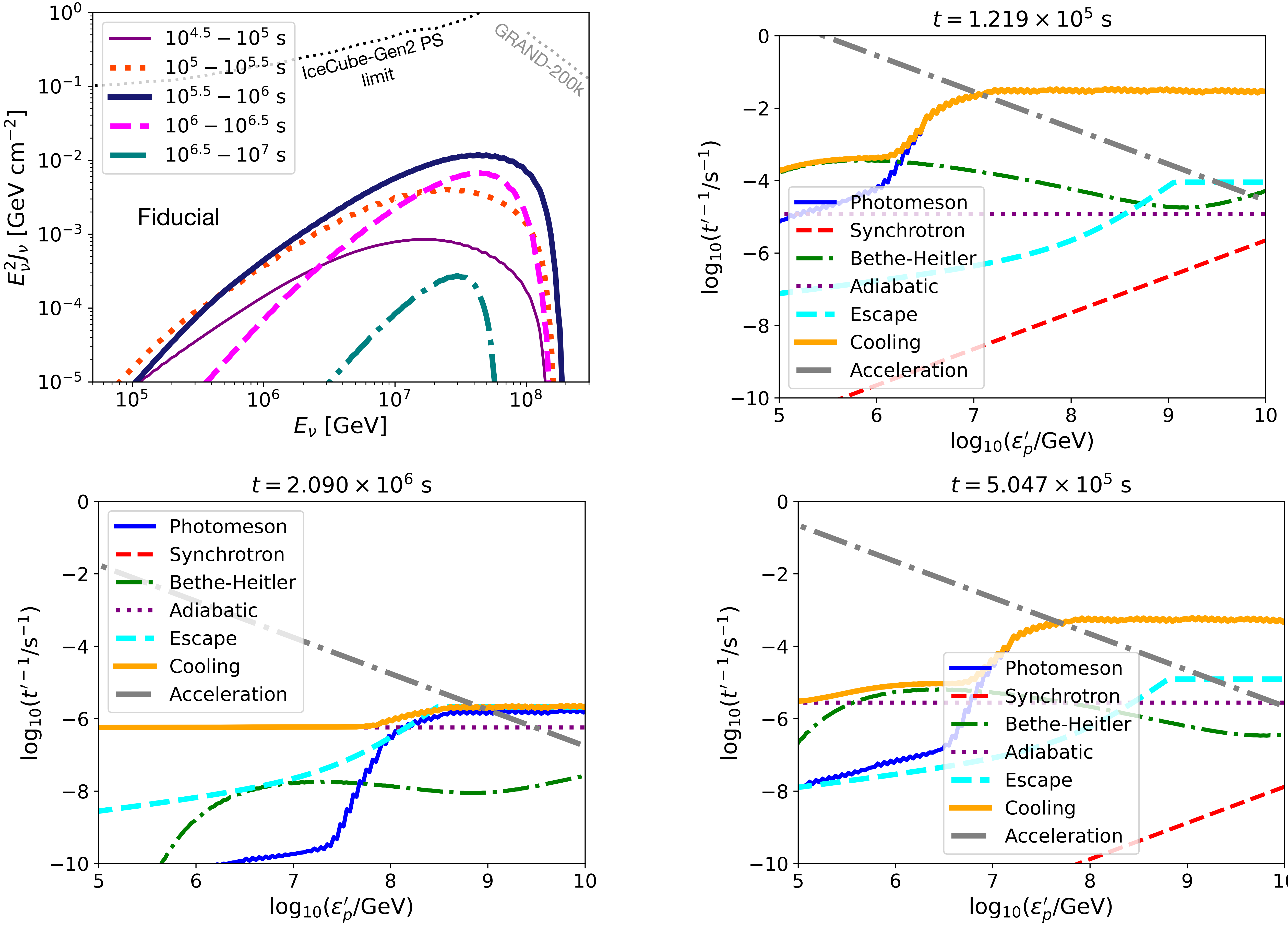
$$\dot{E}_{rp} = \dot{E}_{0,rp} \left(\frac{t}{t_{0,rp}}\right)^{-1.3}$$

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

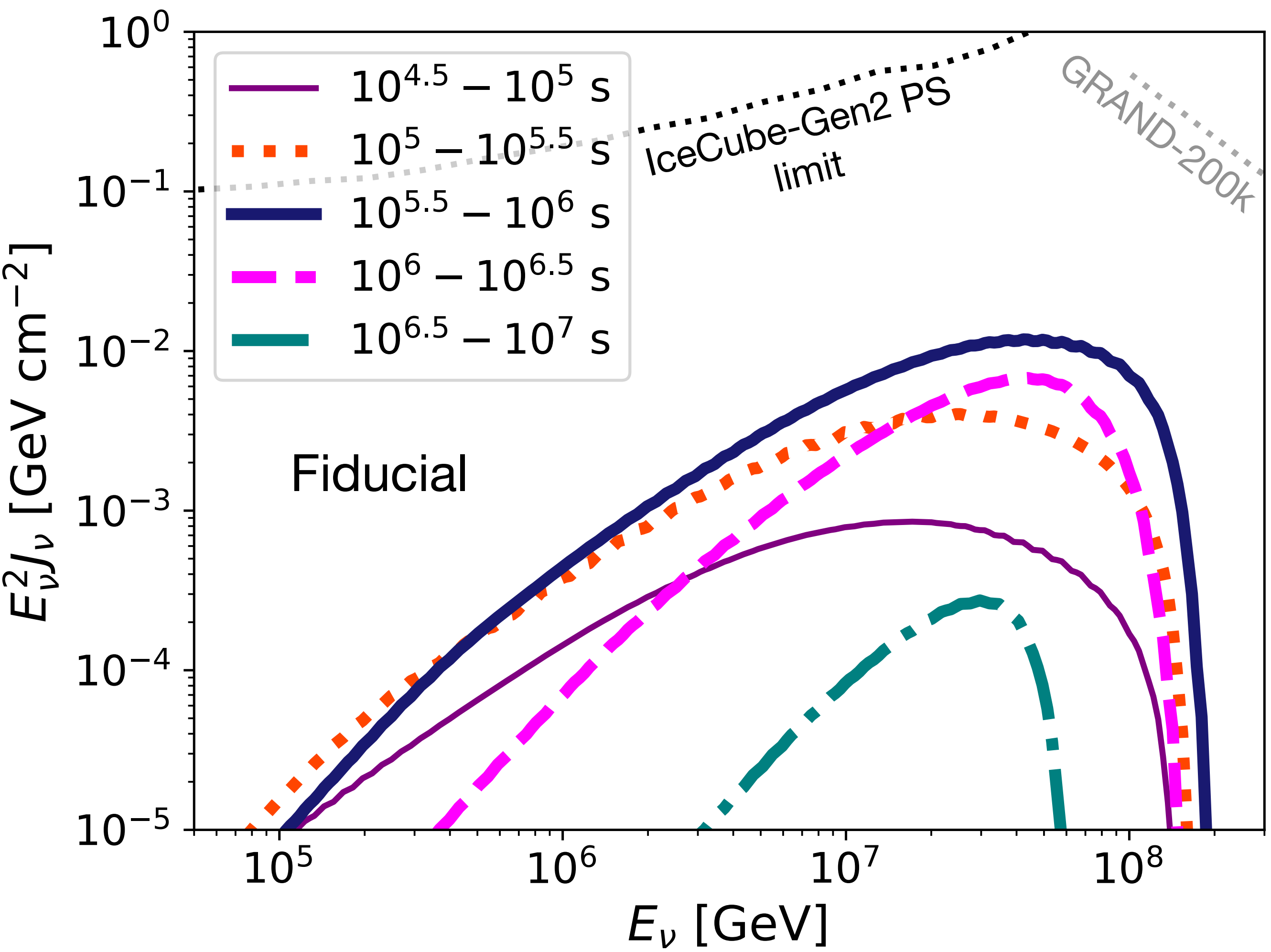
$$t_{0,rp} = 10^4 \text{s}$$

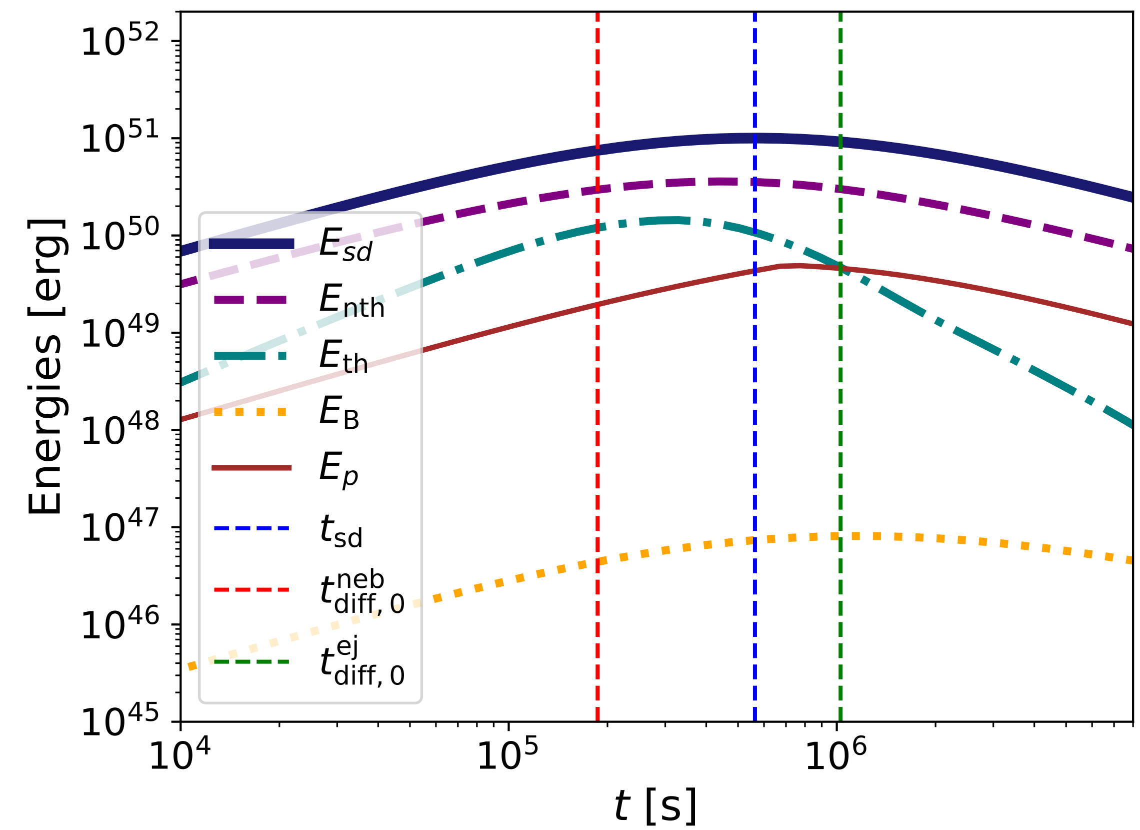
Hotokezaka et al. (2016)

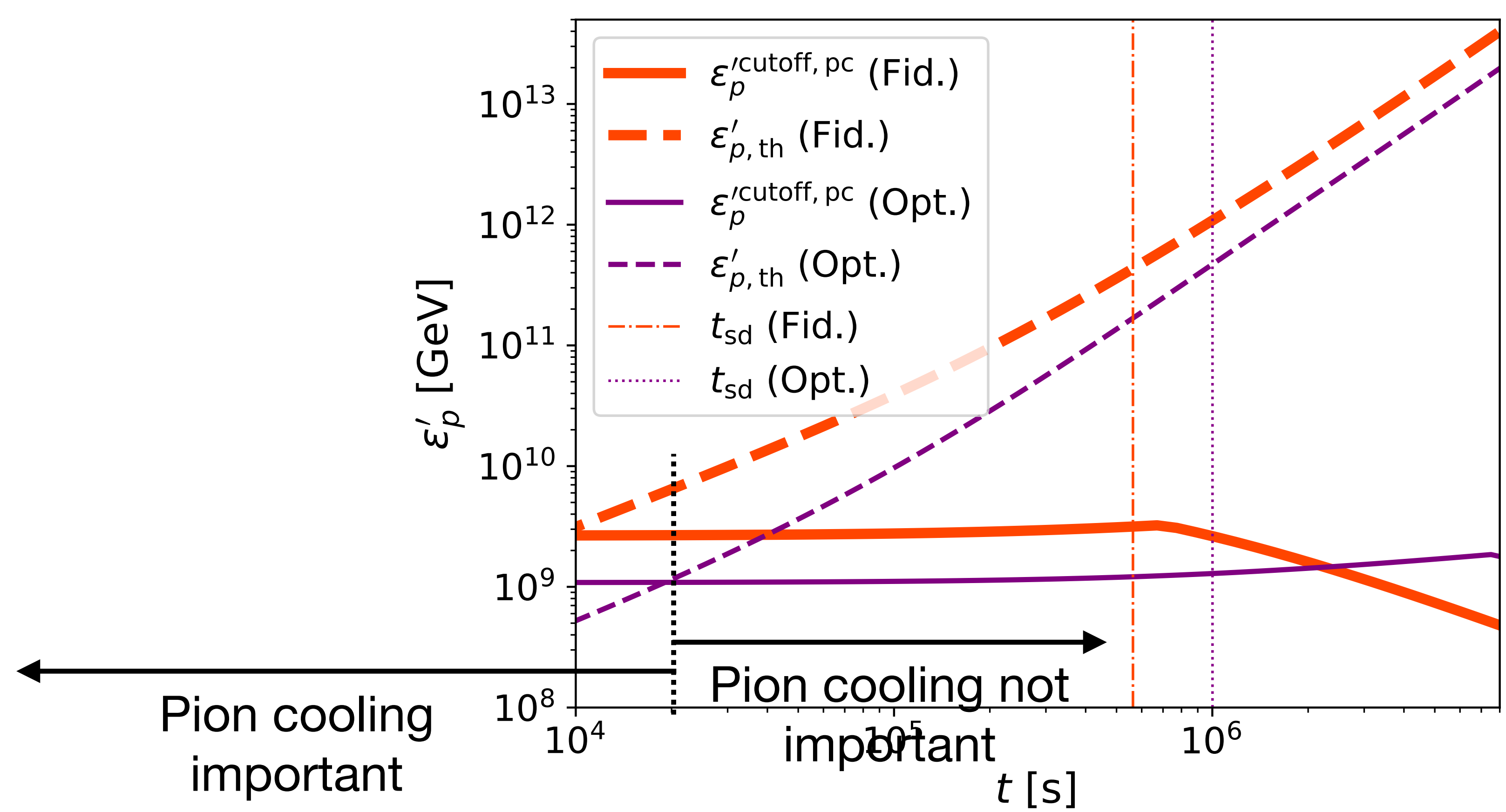
Neutrino fluences: timescales

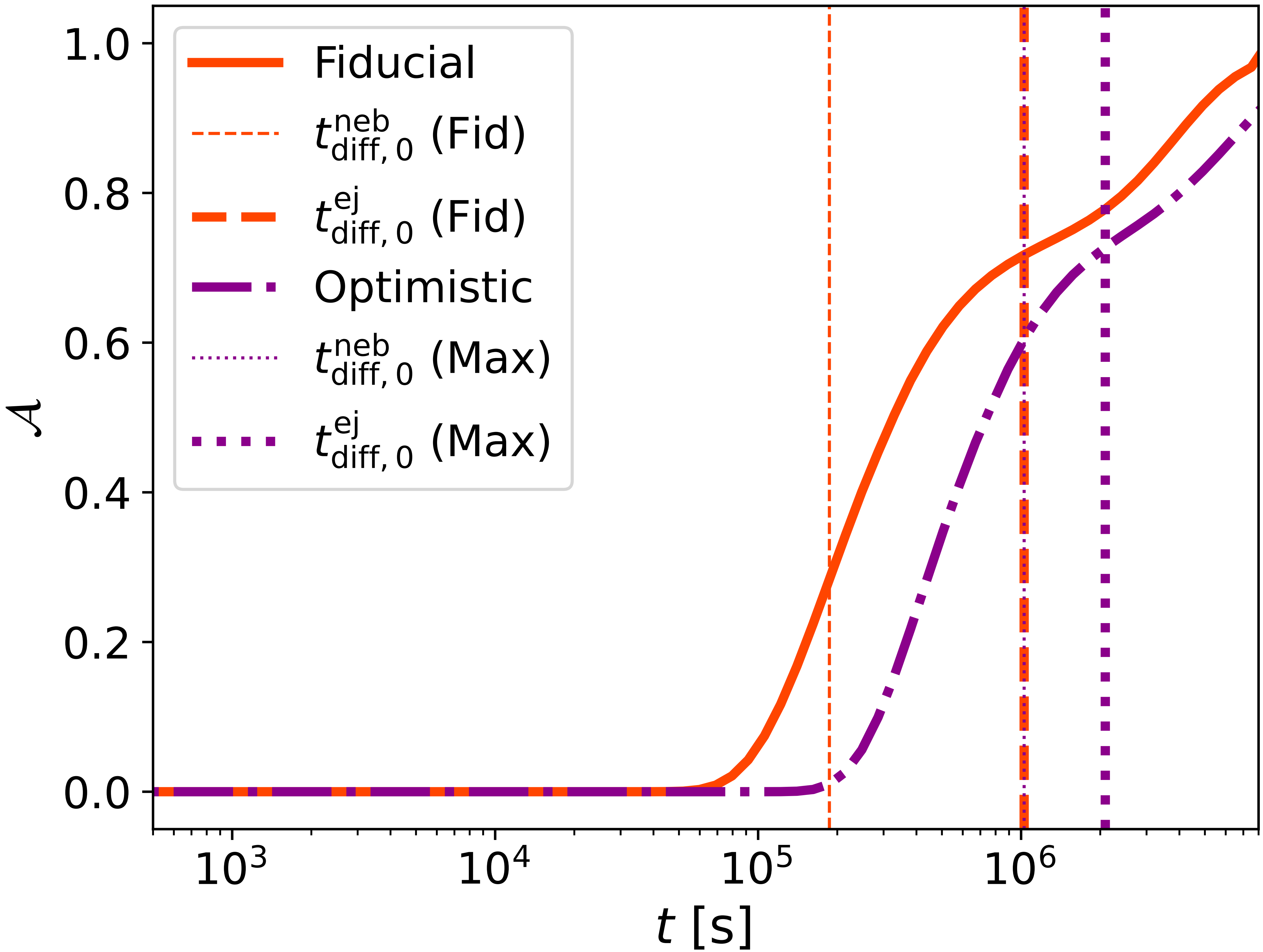


Neutrino fluences: importance of pion cooling









Fiducial
$t^{\mathrm{neb}}_{\mathrm{diff,0}}$ (Fid)
$t^{\mathrm{ej}}_{\mathrm{diff,0}}$ (Fid)
Optimistic
$t^{\mathrm{neb}}_{\mathrm{diff,0}}$ (Max)
$t^{\mathrm{ej}}_{\mathrm{diff,0}}$ (Max)
$\mathcal{A}$
1.0
0.8
0.6
0.4
0.2
0.0
10^3
10^4
10^5
10^6
t [s]