High-energy neutrino and multi-messenger signatures from extreme astrophysical phenomena

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Pennsylvania State University

Fermilab Neutrino Seminar Series
Fermilab, Batavia, Illinois
March 21, 2024

Prologue

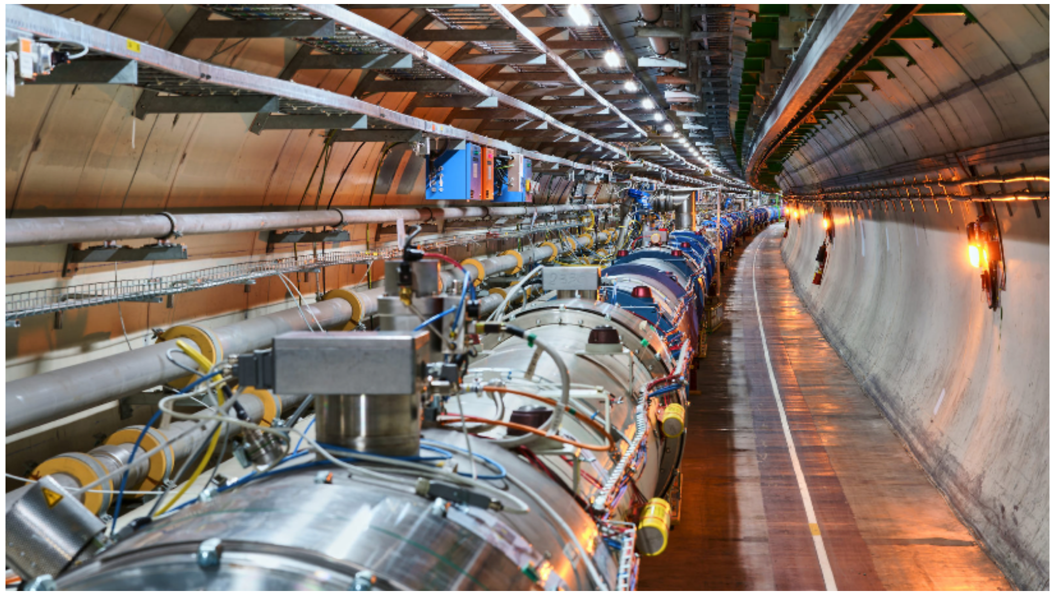
New physics, understanding the fundamentals,….

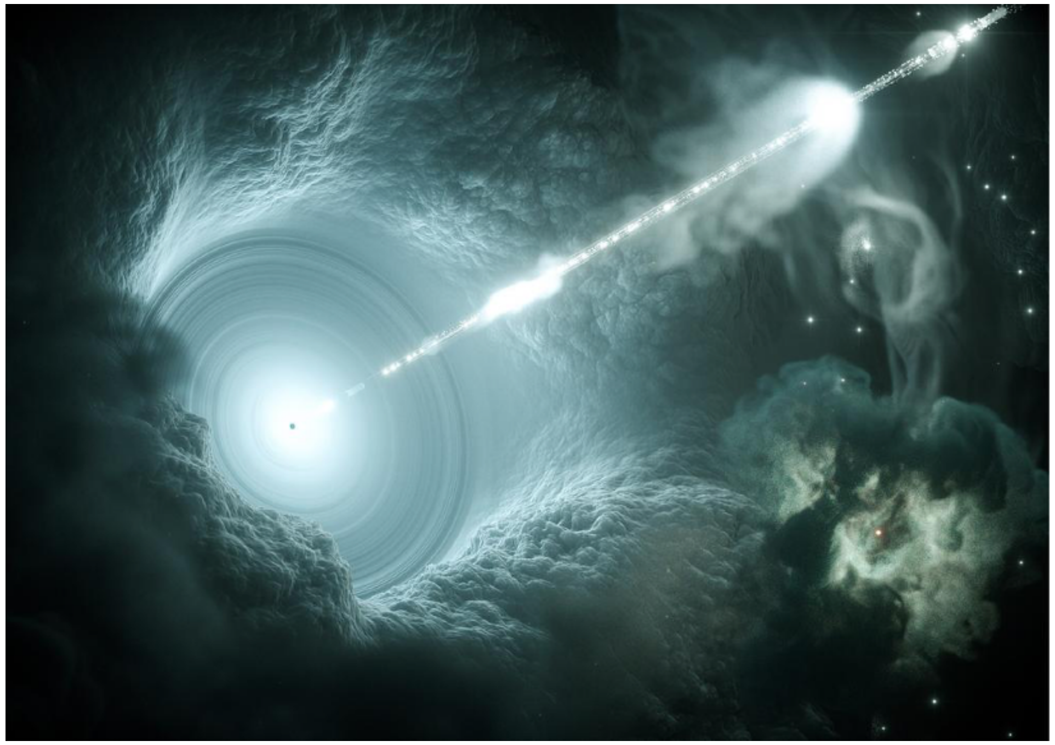
Man-made Accelerators

Cosmic Accelerators

Tevatron

LHC





Extreme astrophysical phenomena

Image credits: Wikipedia
Science Comm., DESY, Zeuthen

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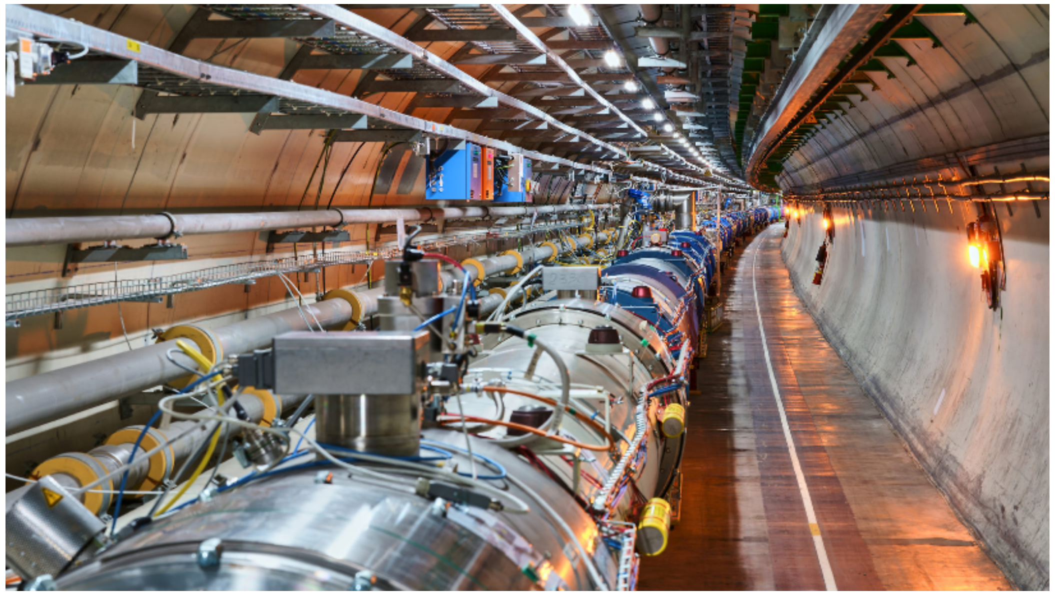
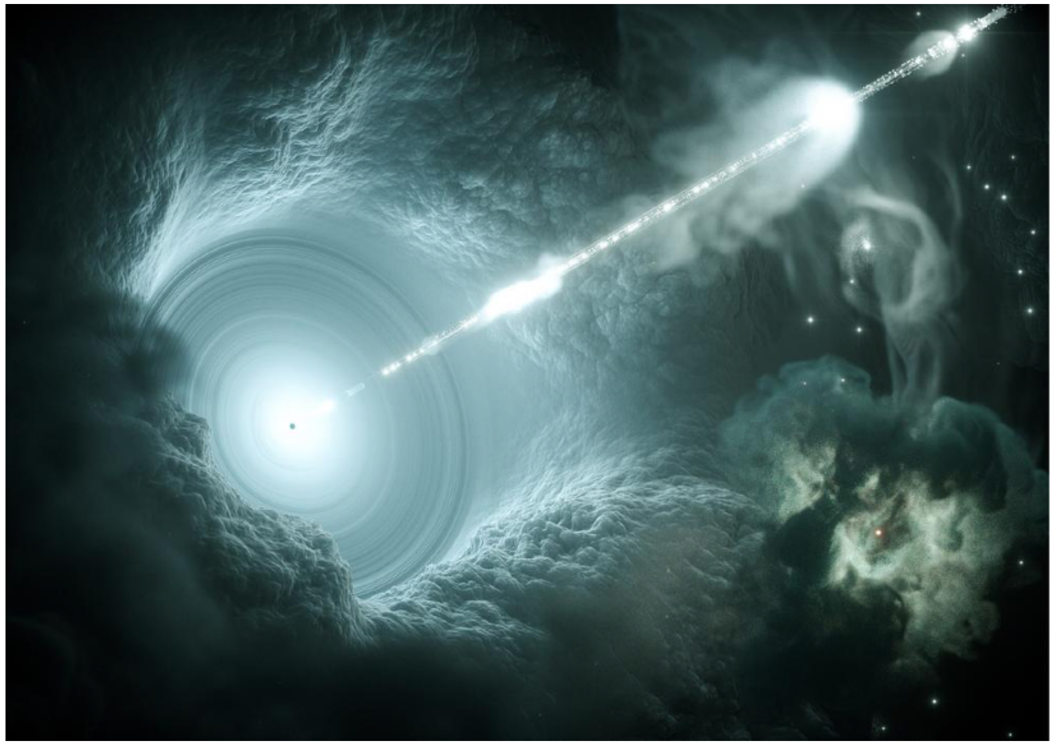


Cosmic Accelerators



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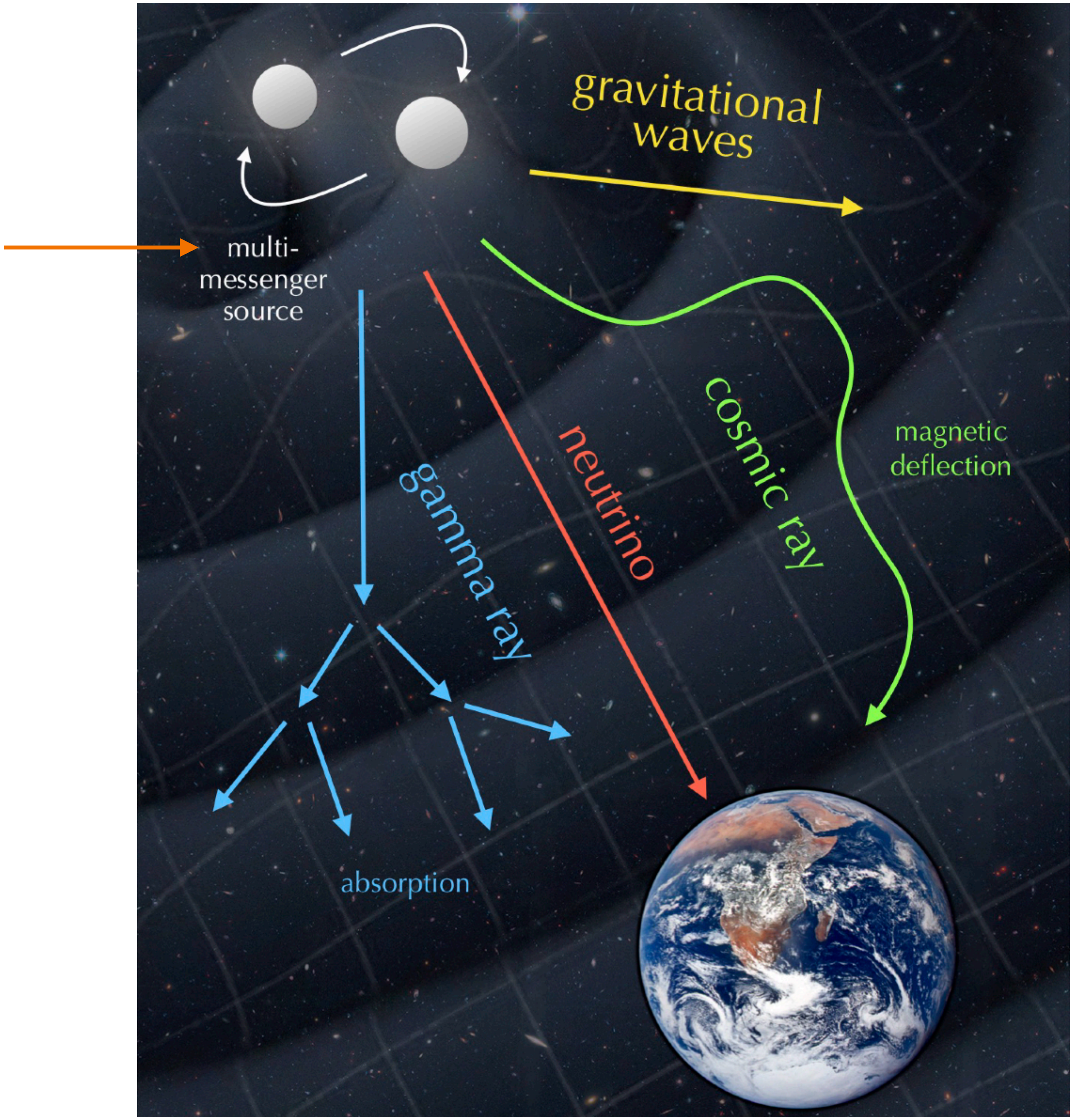
The multi-messenger paradigm

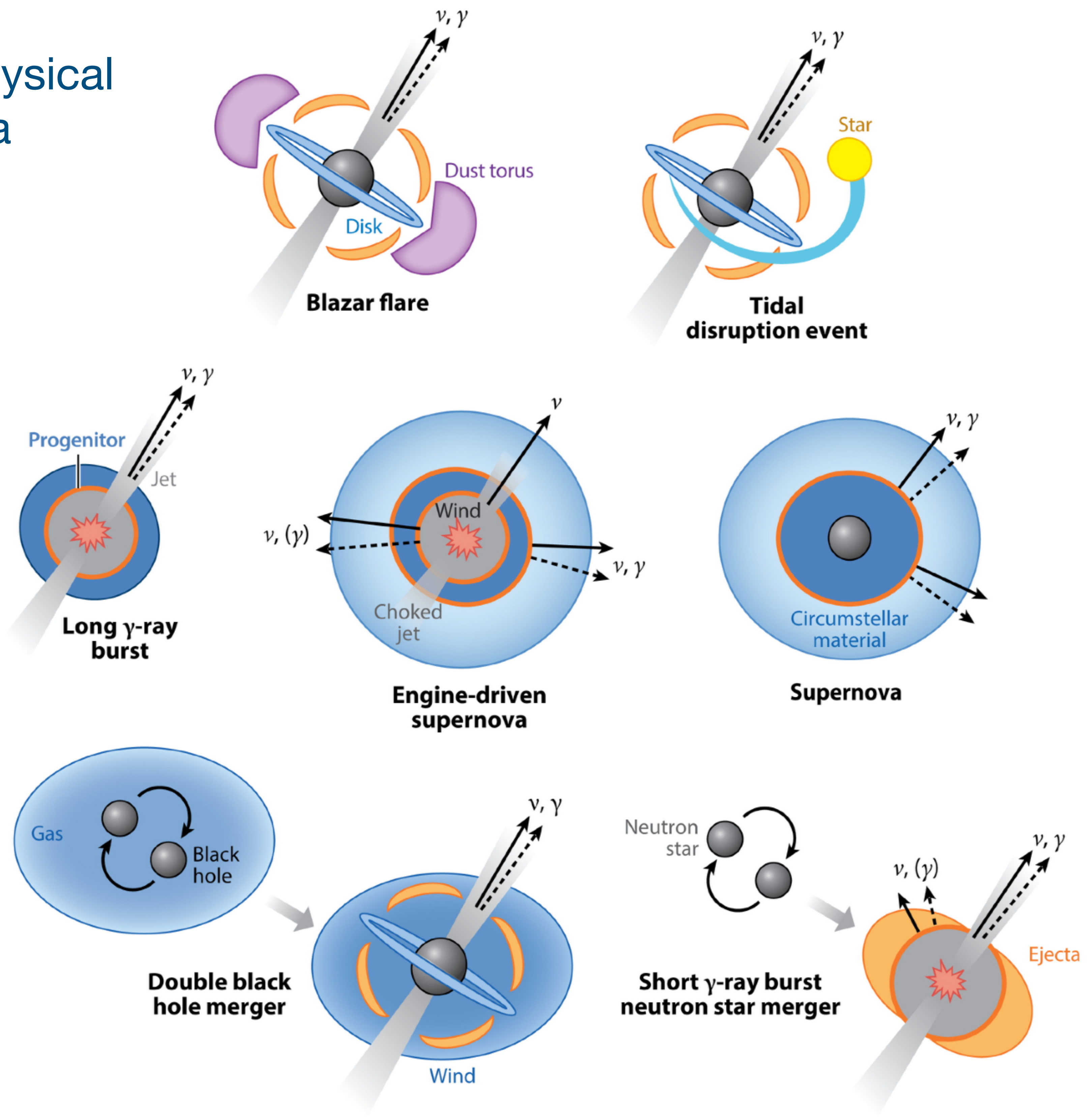


Compact object mergers, TDEs, CCSNe,….

Image credits: https://nbi.ku.dk/english/research/experimental-particle-physics/icecube/astroparticle-physics/

The high-energy multi-messenger transients

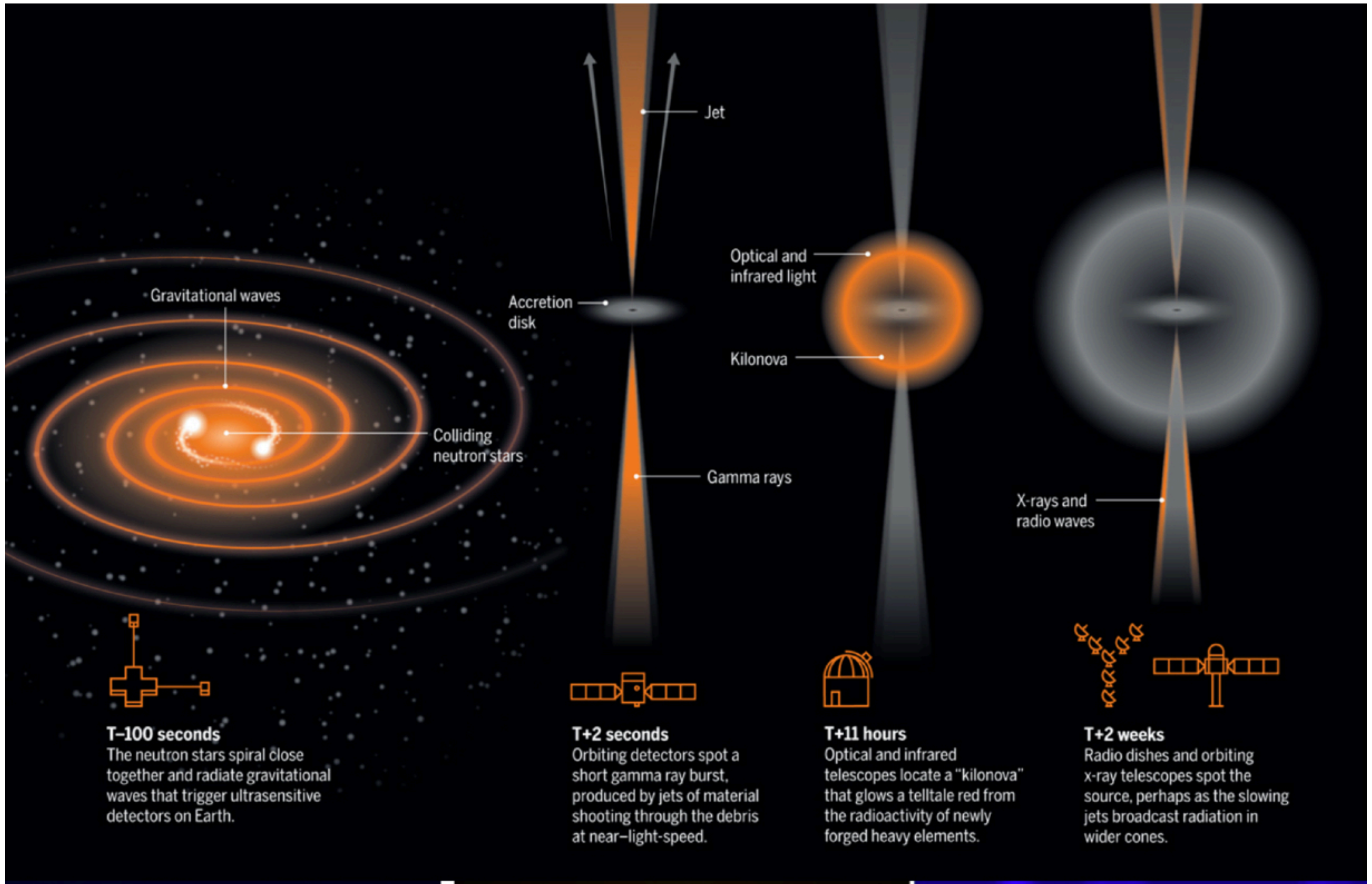
Extreme astrophysical phenomena



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

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.

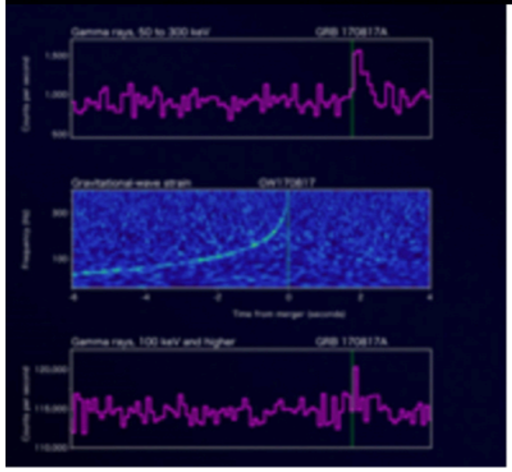
T+11 hours
Optical and infrared telescopes locate a "kilonova" that glows a telltale red from the radioactivity of newly forged heavy elements.

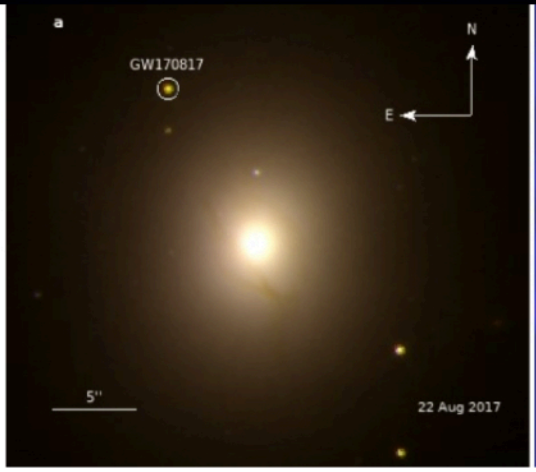
T+2 weeks
Radio dishes and orbiting x-ray telescopes spot the source, perhaps as the slowing jets broadcast radiation in wider cones.

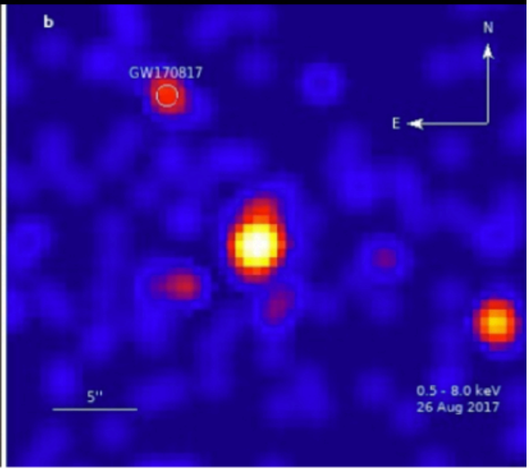
No neutrinos :(

Gamma rays (Fermi+Integral)

GW (Adv. LIGO+Virgo)







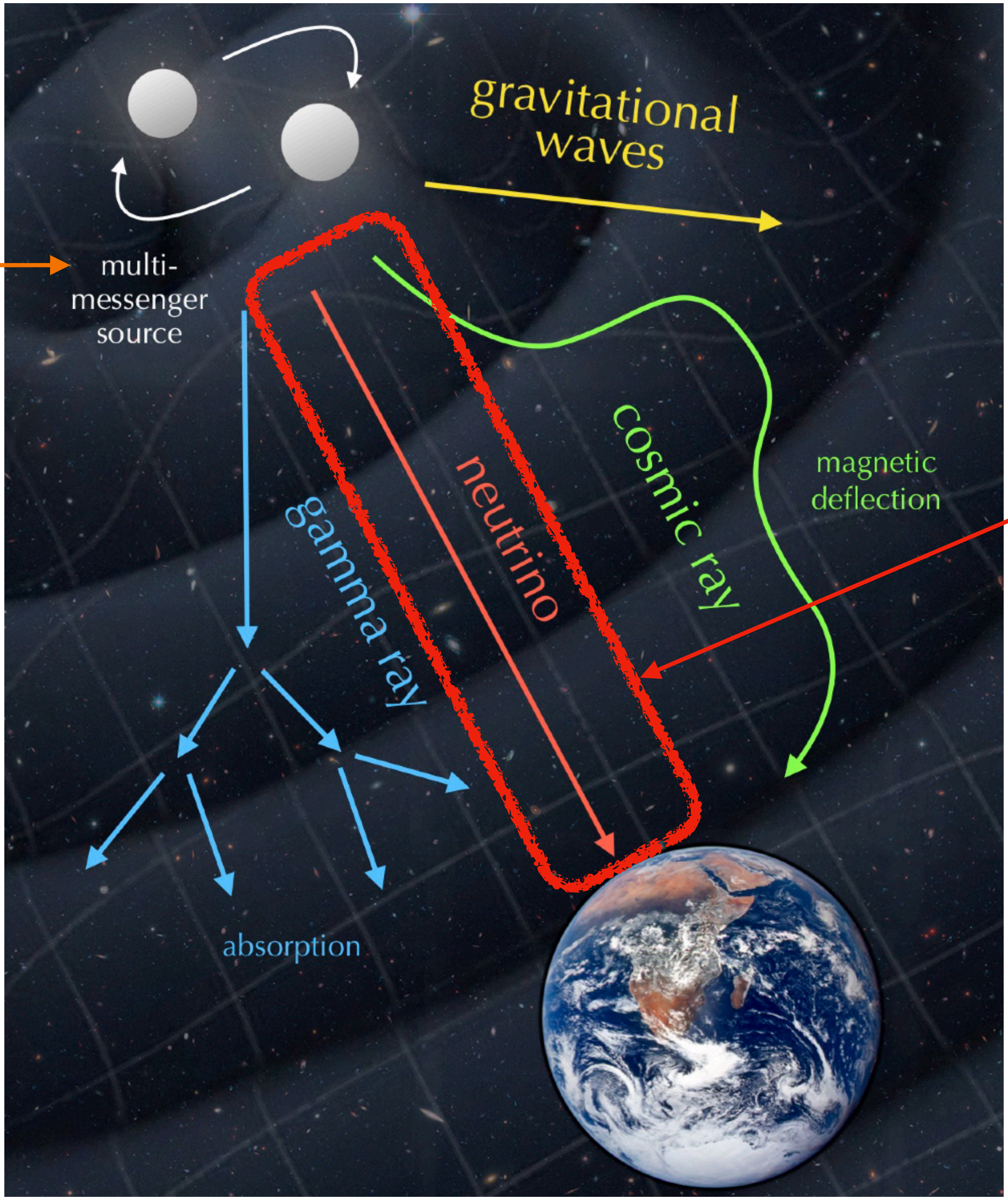
X-rays (Chandra)

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

The multi-messenger paradigm

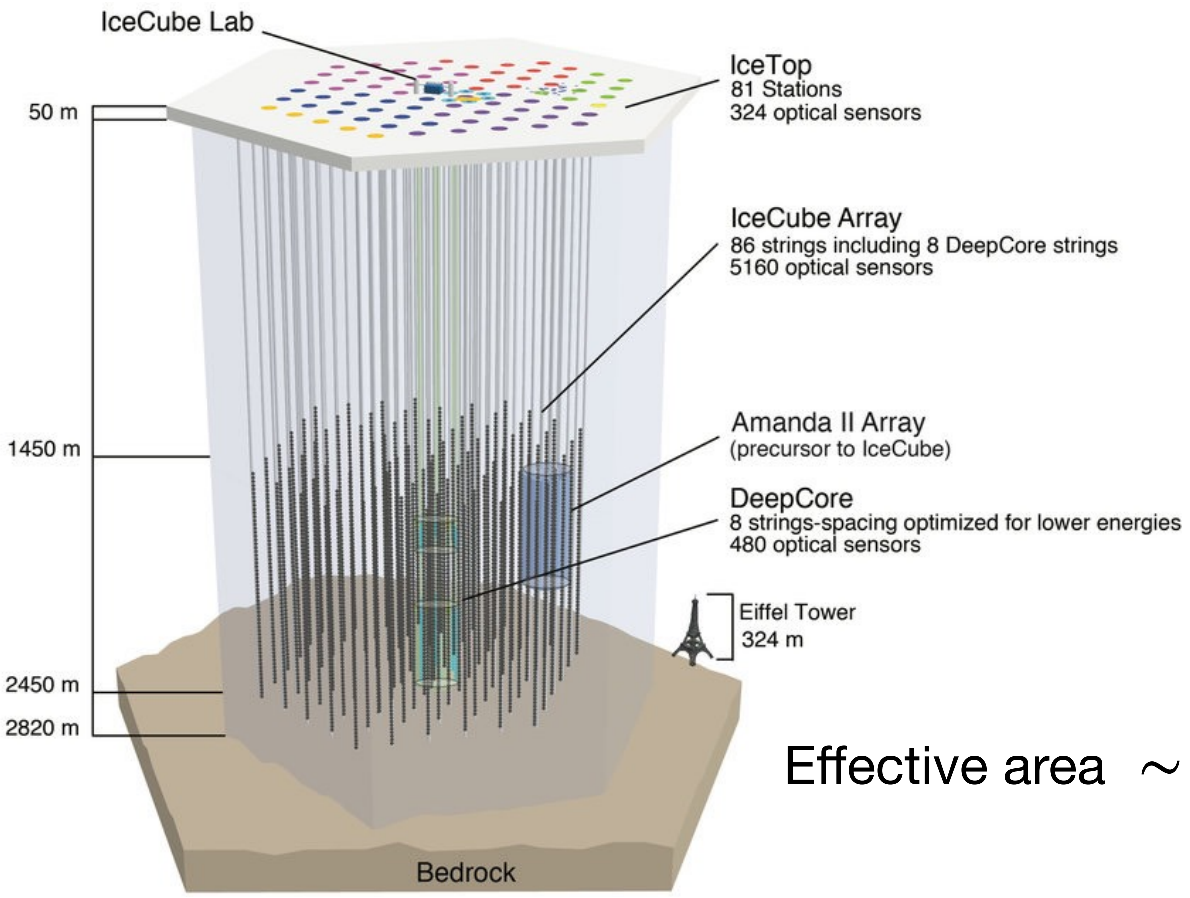
Compact object mergers, TDEs, CCSNe,….



High-energy neutrinos

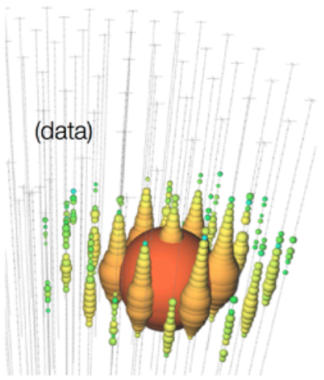
Image credits: https://nbi.ku.dk/english/research/experimental-particle-physics/icecube/astroparticle-physics/

High-energy neutrino detectors



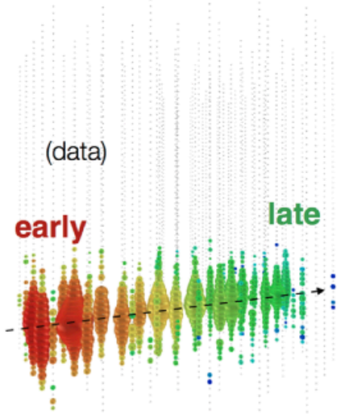
Effective area $\sim 1\ \mathrm{km}^3$

Neutral-current / ν_e



Isolated energy deposition (cascade) with no track

Charged-current ν_μ

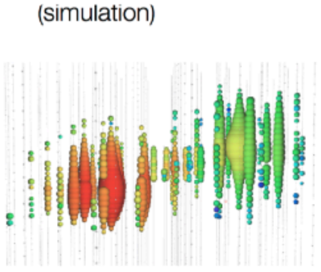


Up-going track

Charged-current ν_τ

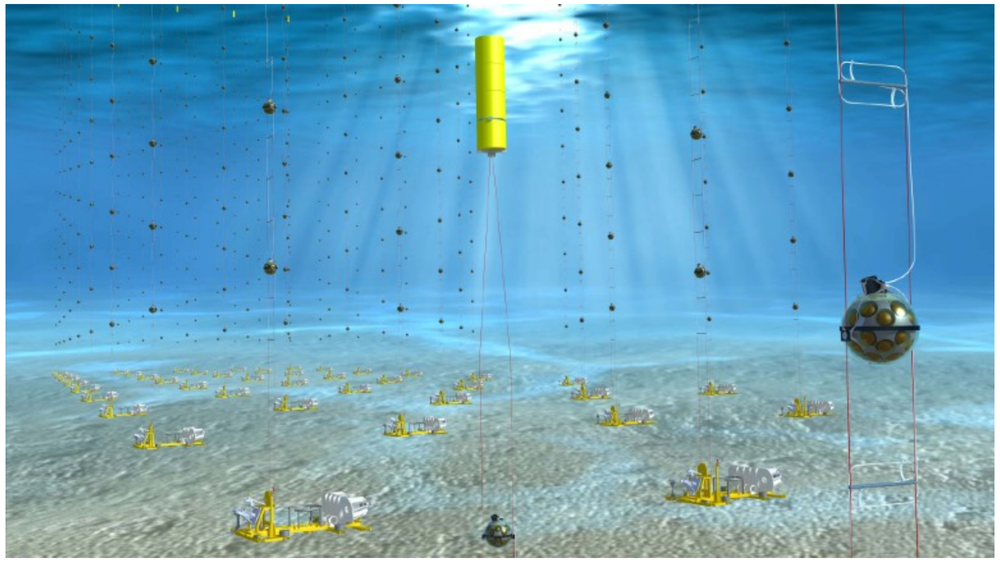
IceCube observes seven astrophysical tau neutrino can

Posted on March 7, 2024 by Alisa King-Klemperer



Double cascade

KM3NeT



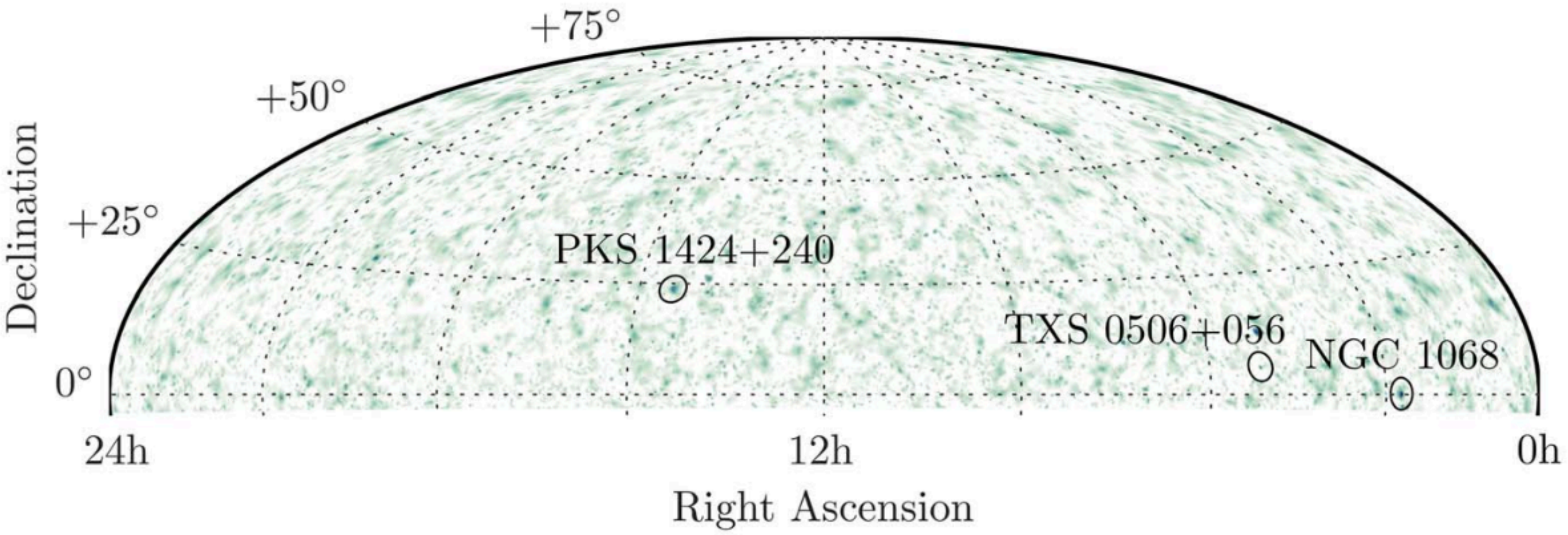
Baikal GVD

ANTARES

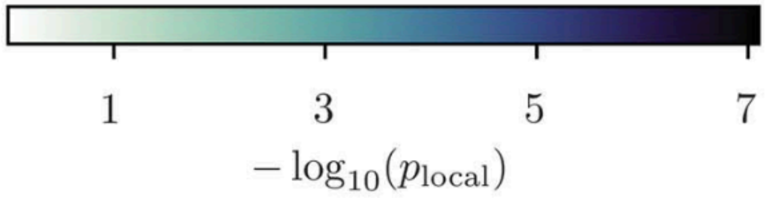
Future detectors: IceCube-Gen2, RNO-G, GRAND,….

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

NGC 1068 (also TXS 0506+056)

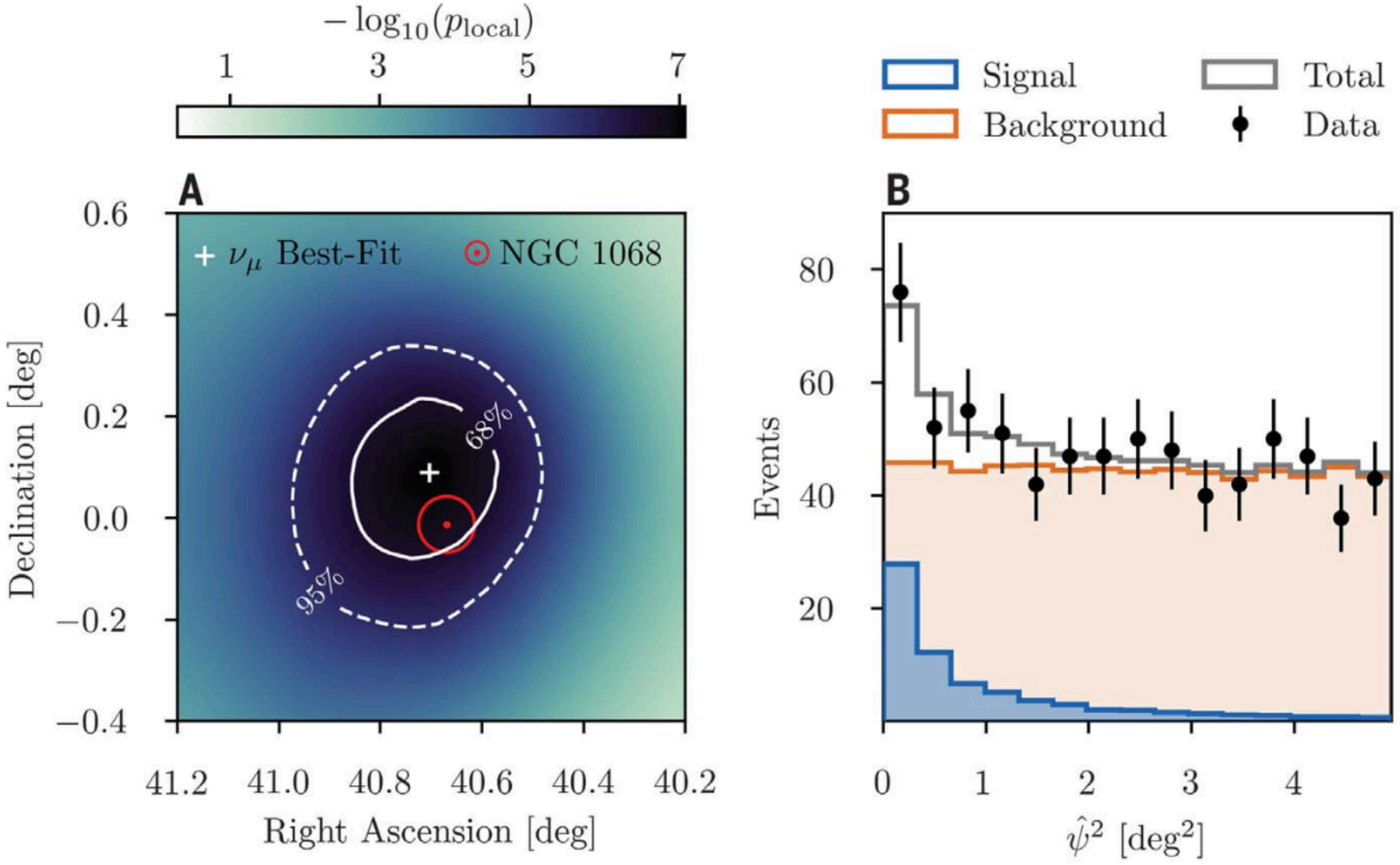


10 years of PS data (2011-2020)



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

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



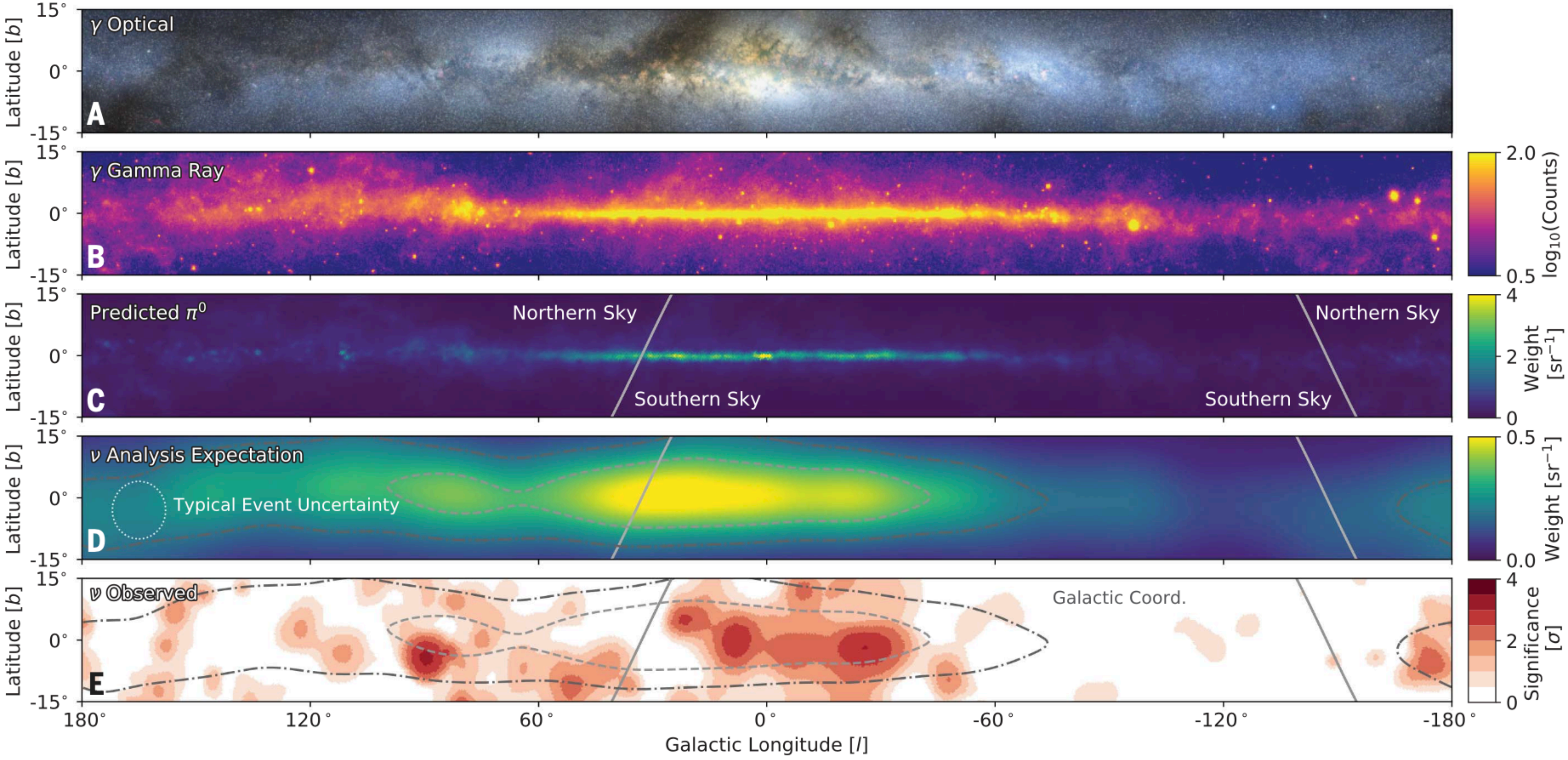
$\sim 79^{+22}_{-20}$ excess events

IceCube Collab.+ Science 2022

The Galactic plane

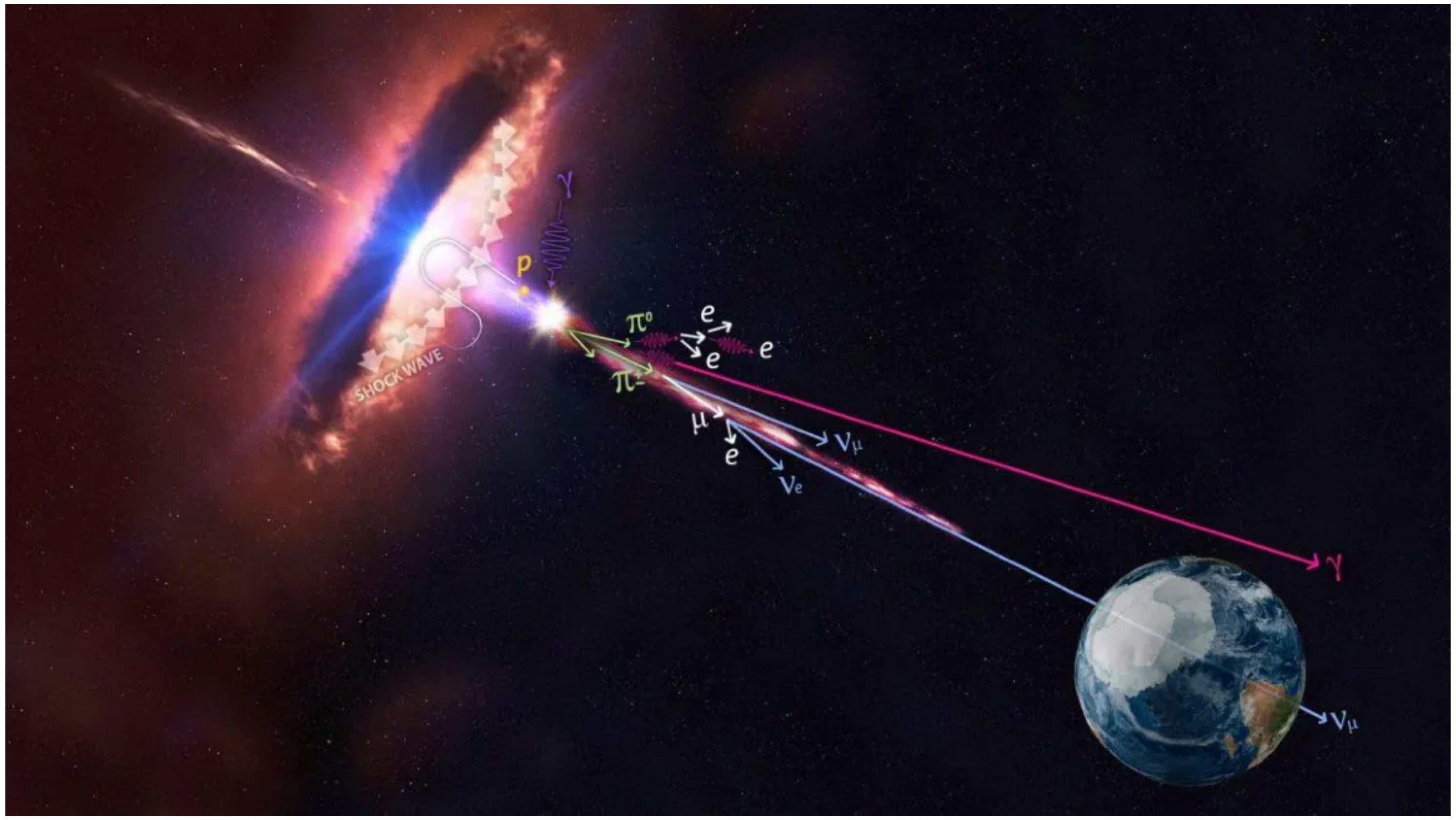
10 years of PS data
(2011-2020)

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



IceCube Collab.+ Science, 380, 2023

High-energy neutrinos



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

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

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

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

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

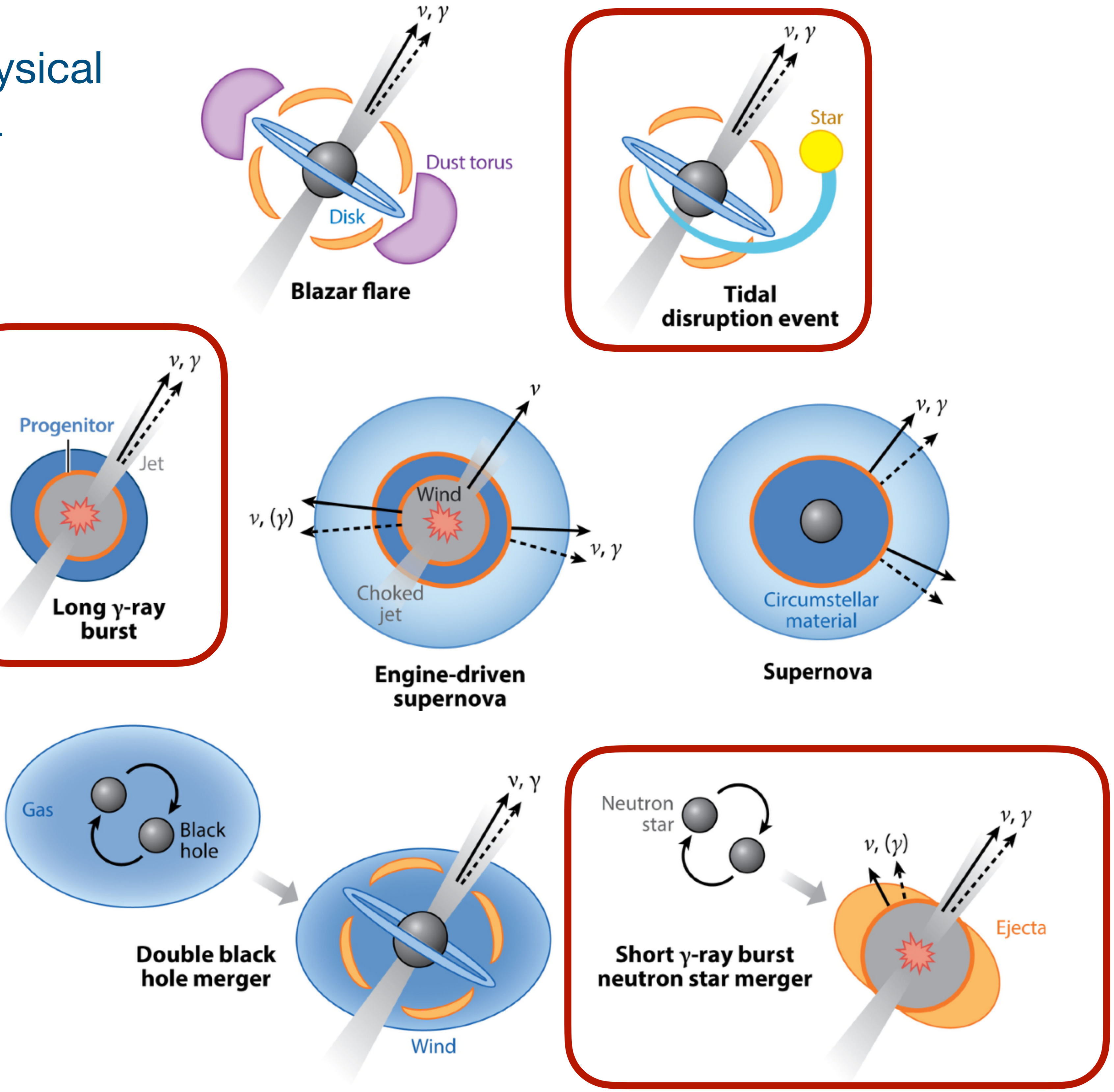
$$t_{p\gamma}^{-1}(\epsilon_p) = \frac{c}{2\gamma_p^2} \int_{\bar{\epsilon}_{\rm th}}^{\infty} d\bar{\epsilon}\, \kappa_{p\gamma}(\bar{\epsilon}) \sigma_{p\gamma}(\bar{\epsilon}) \bar{\epsilon} \int_{\bar{\epsilon}/2\gamma_p}^{\infty} d\epsilon\, \epsilon^{-2} n_\epsilon$$

Photon energy in proton rest frame

Proton energy loss due to p-p interactions

The high-energy multi-messenger transients

Extreme astrophysical phenomena



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Annu. Rev. Nucl. Part. Sci. 69:477–506

Outline

Part 1: Can choked delayed jets explain the neutrino coincidences associated with TDEs?

Based on: Multi-messenger signatures of delayed choked jets in tidal disruption events
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Part 2: Hunting for neutrinos from BNS mergers at next-generation GW and neutrino detectors

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Tidal disruption event (TDE)

The shredding apart of a star when it comes close to a SMBH, due to its tidal forces

Disruption starts

↓

~ Half the debris is lost: Unbound orbit

~ Half the debris falls back: Bound orbit

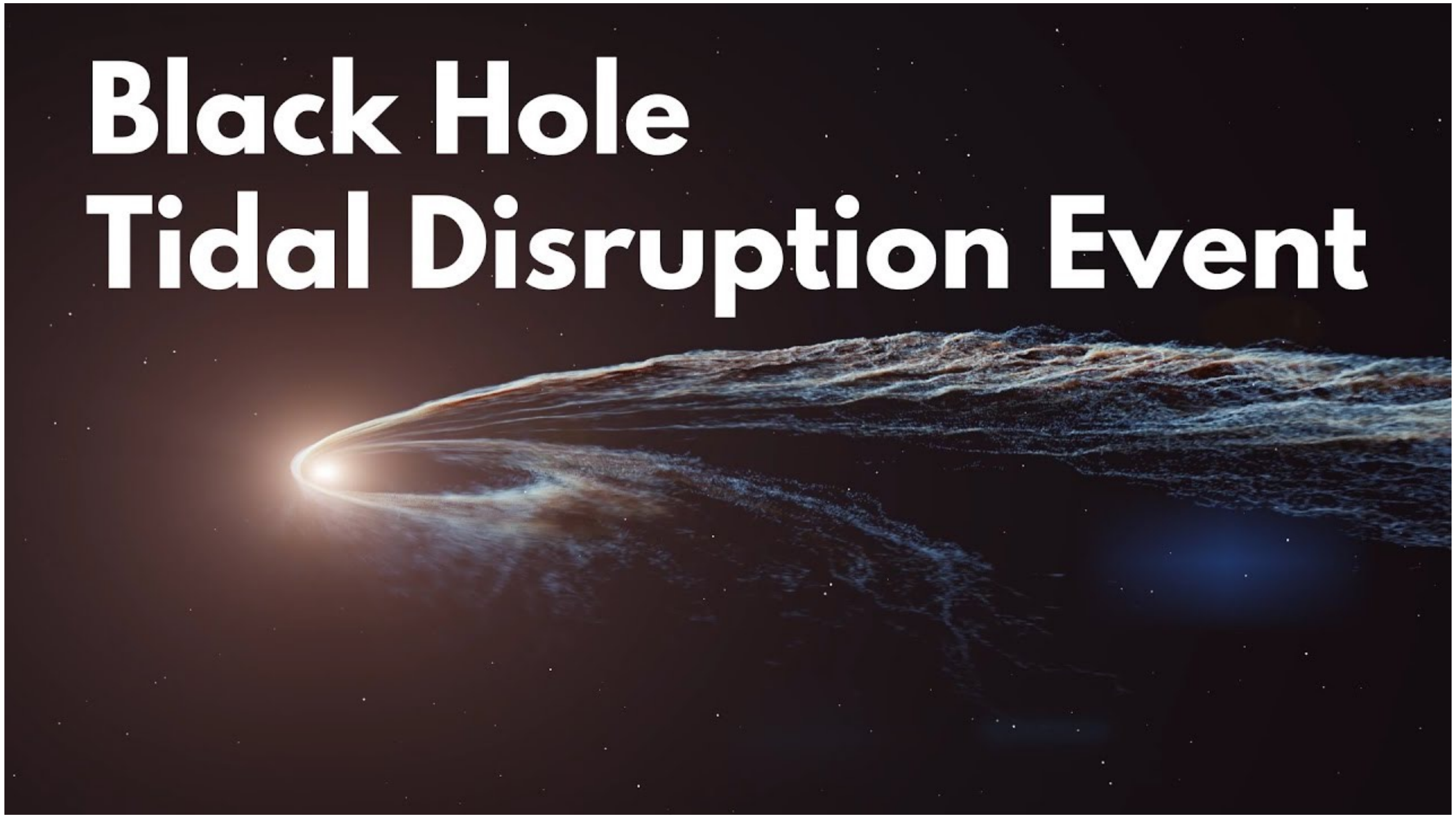
↓

Debris circularizes

↓

Part of the debris may form an accretion disk → Winds, Outflows, etc.

(Timescales are also uncertain)

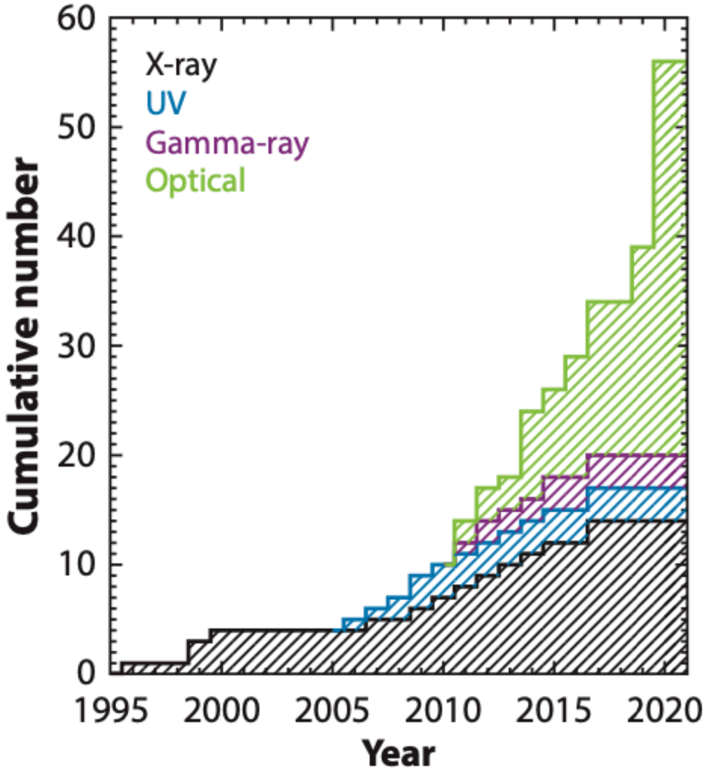


Credits: Science Communication Lab/DESY

Rees 1988
Stone et al. 2013
Komossa 2015

TDEs: particle accelerators and multi-messenger zoo

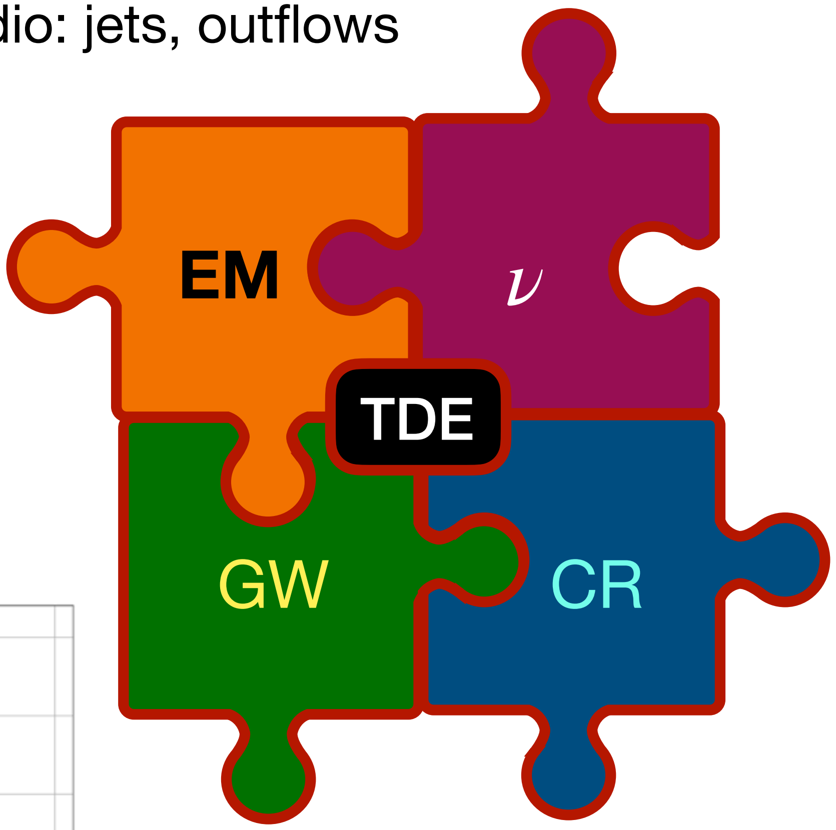
Observed



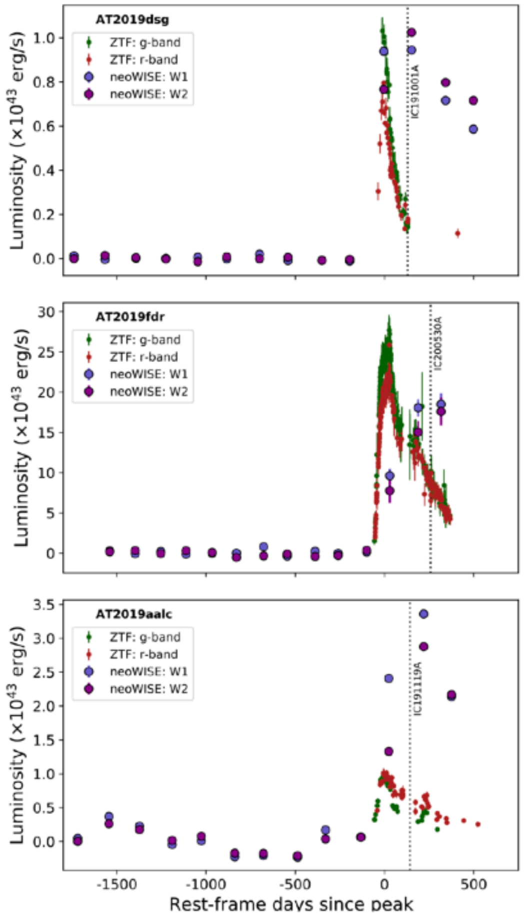
Optical-UV (blackbody): mass fallback $\sim t^{-5/3}$

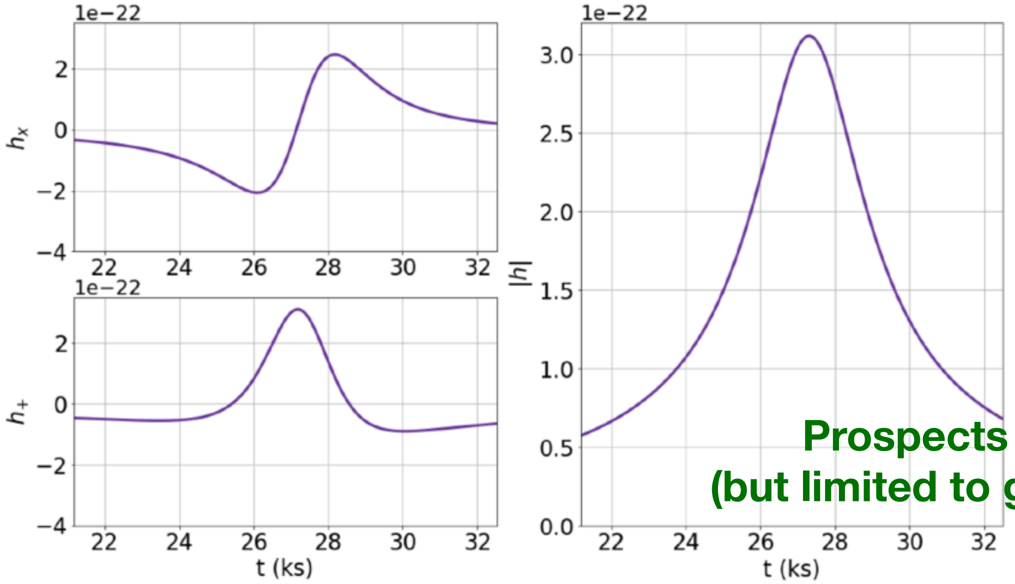
X-rays: wide variability

Radio: jets, outflows



Associations



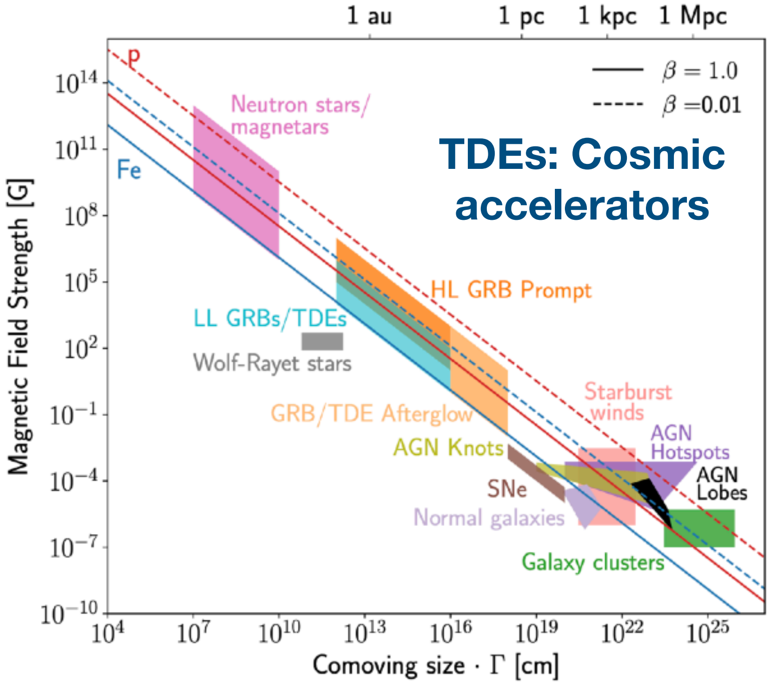


Prospects for LISA: IMBH-WD
(but limited to galactic scales ~ 10 kpc)

$$h \sim 2 \times 10^{-22} \beta \left(D/10\mathrm{Mpc}\right)^{-1}\ m_*^{4/3} r_*^{-1} M_{\mathrm{BH},6}^{2/3}$$

$$f \sim 6 \times 10^{-4}\mathrm{Hz}\ \beta^{3/2} m_*^{1/2} r_*^{-3/2}$$

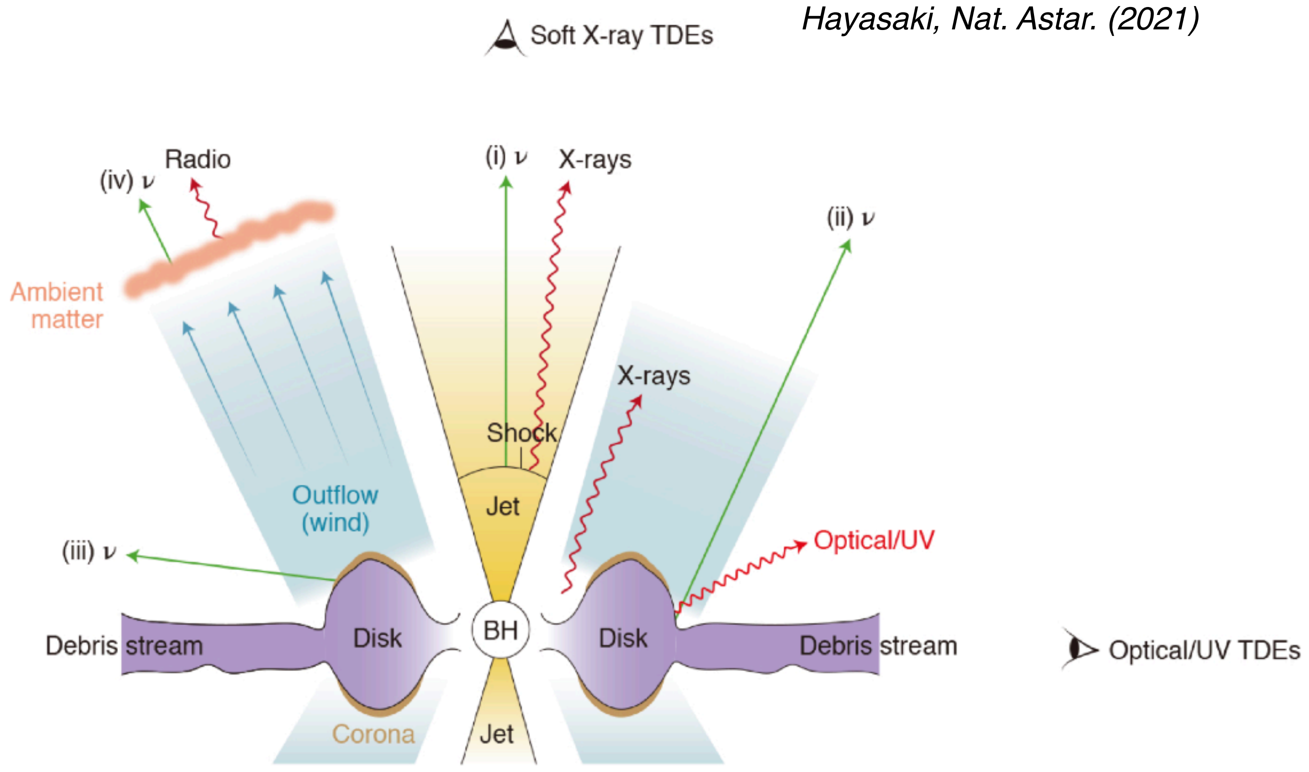
$$(\beta = R_T/R_S)$$



TDEs: Cosmic accelerators

S. Gezari, Annu. Rev. Astron. Astrophys. 2021. 59:21–58
Van Velzen et.al. (2021)
M. Toscani, G. Lodato, D.J. Price, D. Liptai, MNRAS (arXiv: 2111.05145)
Batista et al., Front. Astron. Space Sci. 6 (2019), 23

TDEs: high-energy neutrinos



Hayasaki, Nat. Astar. (2021)

(i) Relativistic jets

(Wang+16, Senno, Murase & Meszaros 17, Murase+ 20, Lunardini & Winter 17, 21)

(ii) Disk (RIAF - MAD)

(Hayasaki & Yamazaki 19, Murase+ 20)

(iii) Disk corona

(Murase+ 20)

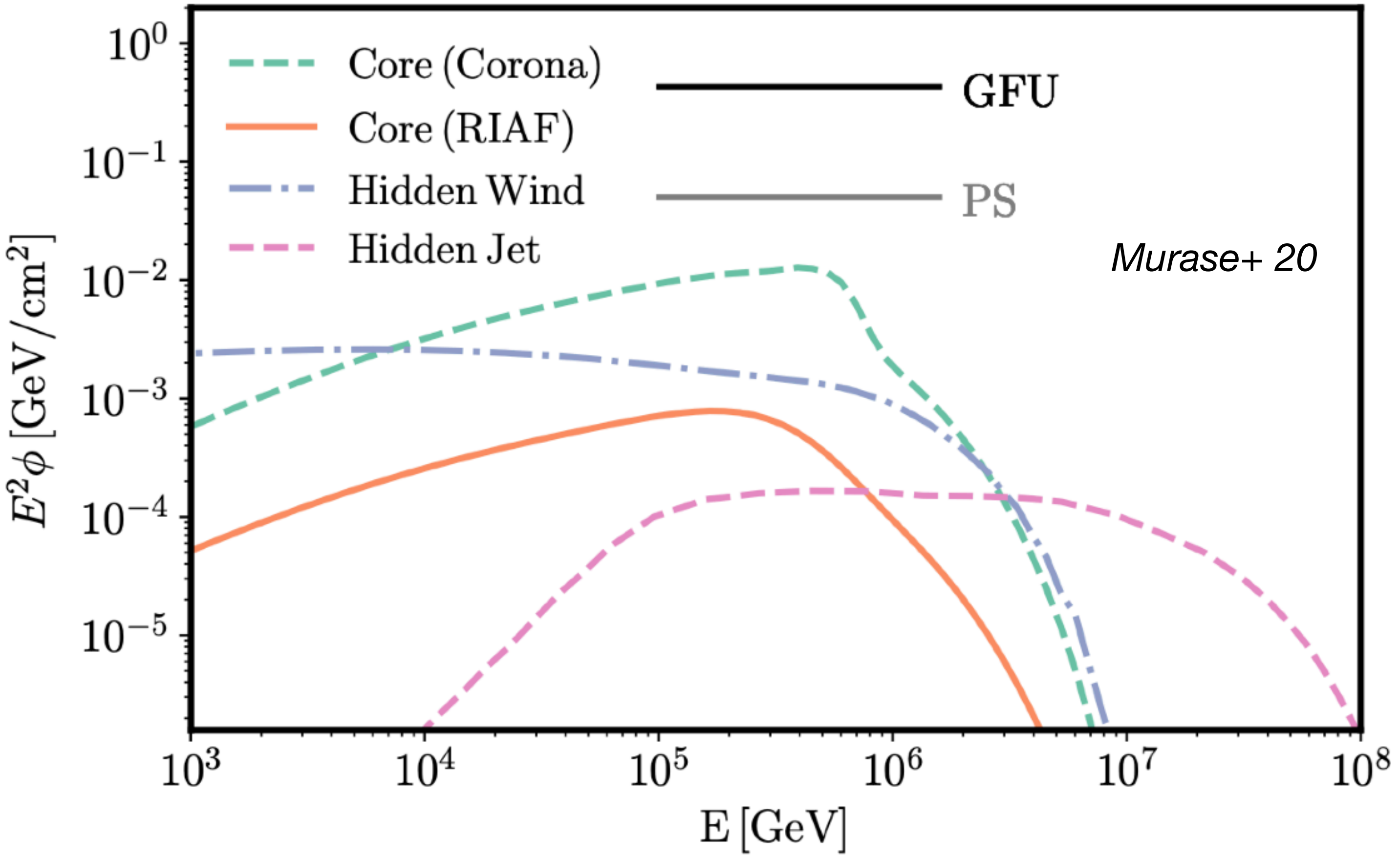
(iv) Wind/Outflow

(Murase+ 20, Wu+ 22, Winter & Lunardini 23)

TeV-PeV neutrinos

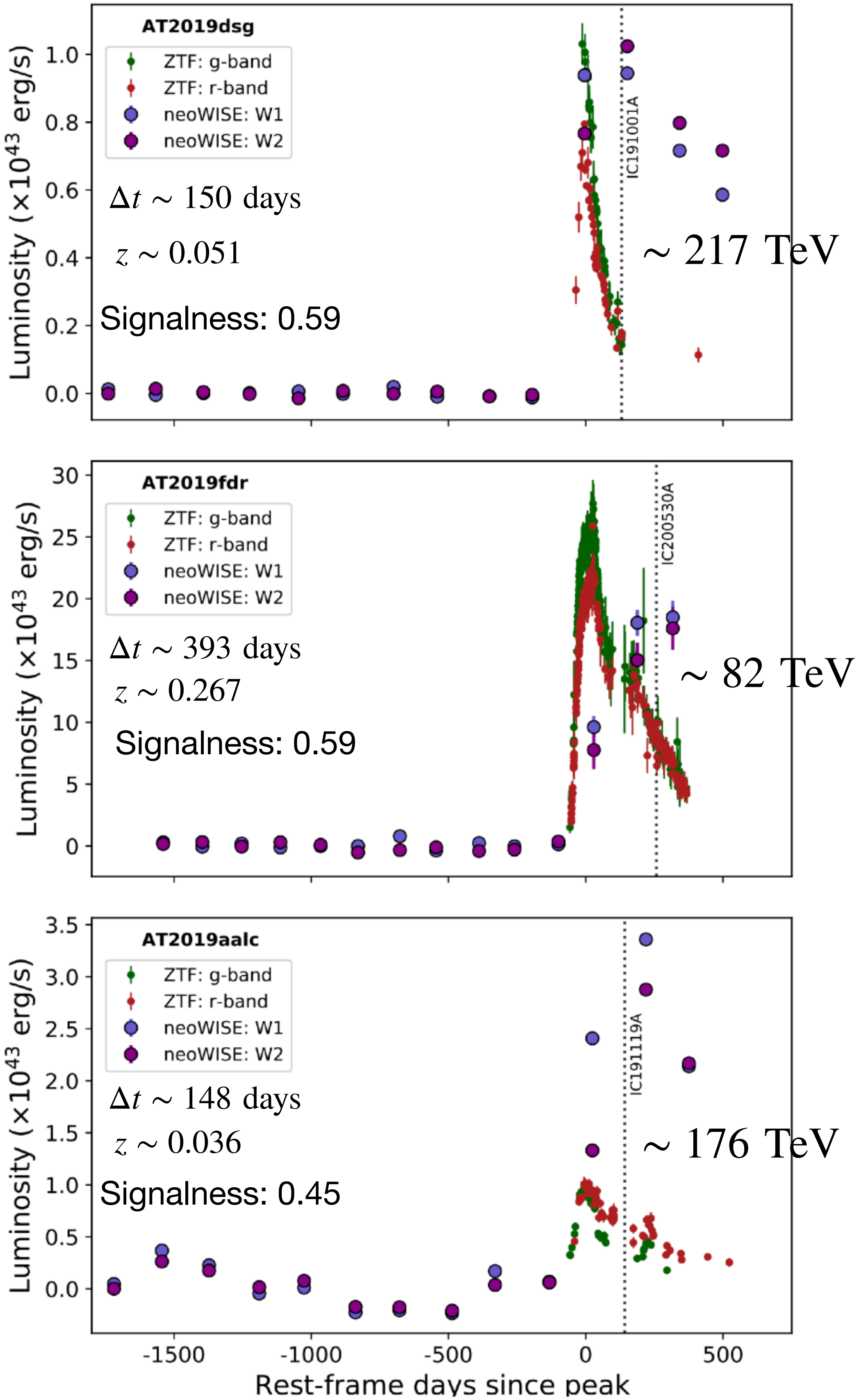
Various acceleration sites

Detectable at IceCube



Murase+ 20

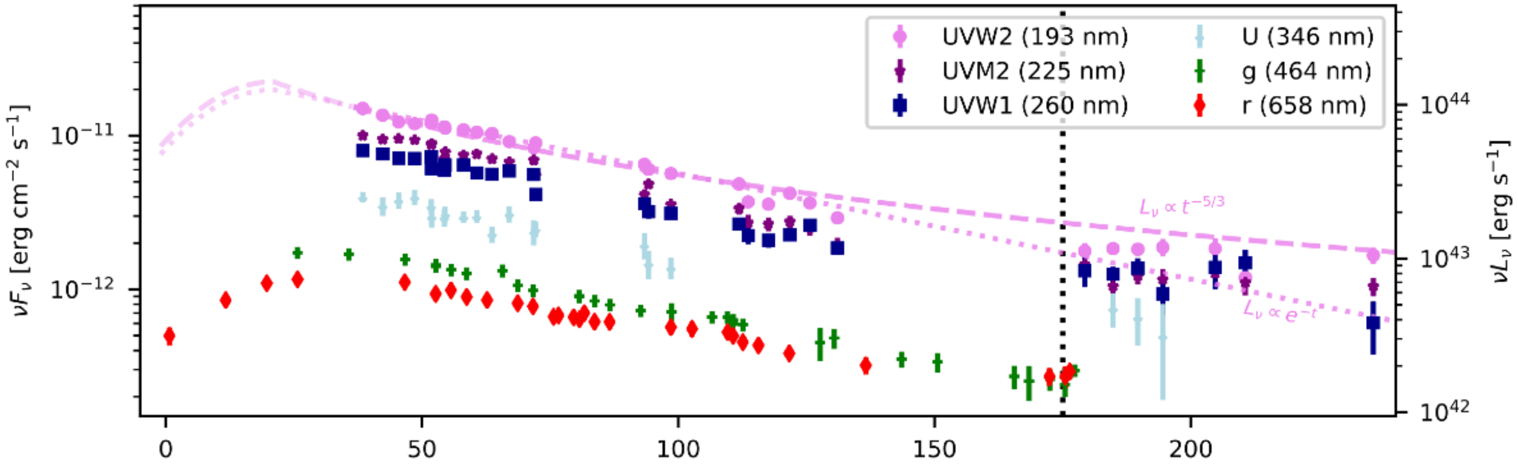
Observational aspects - ν Associations

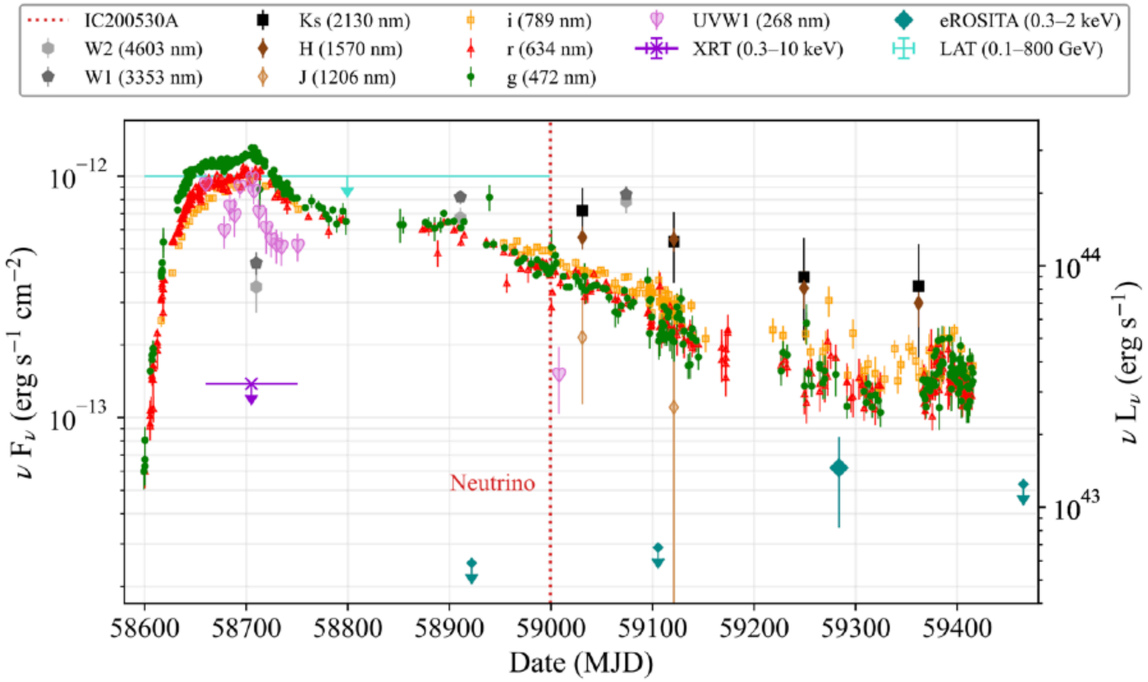


$\Delta t \sim 150$ days
$z \sim 0.051$
Signalness: 0.59
~ 217 TeV

$\Delta t \sim 393$ days
$z \sim 0.267$
Signalness: 0.59
~ 82 TeV

$\Delta t \sim 148$ days
$z \sim 0.036$
Signalness: 0.45
~ 176 TeV

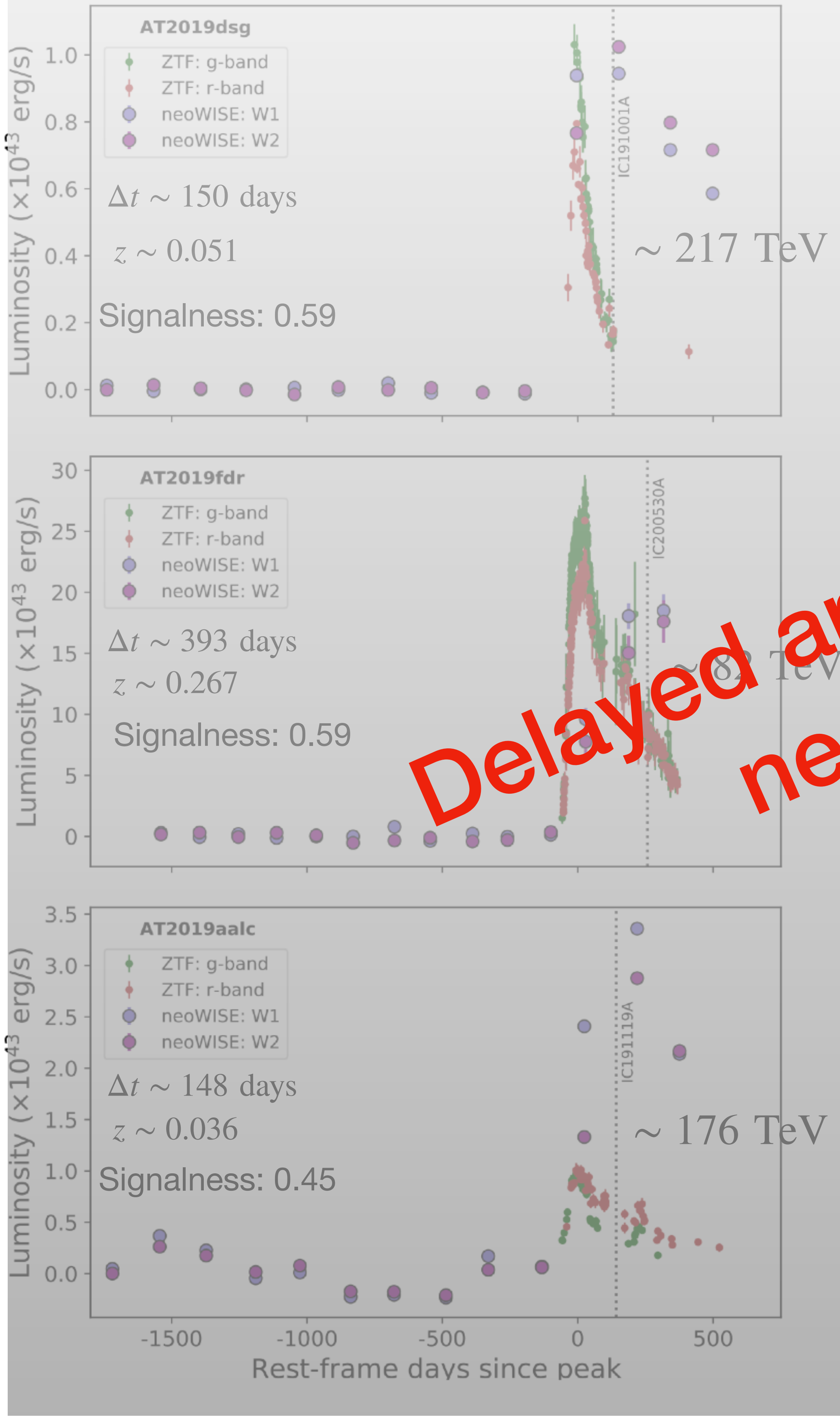


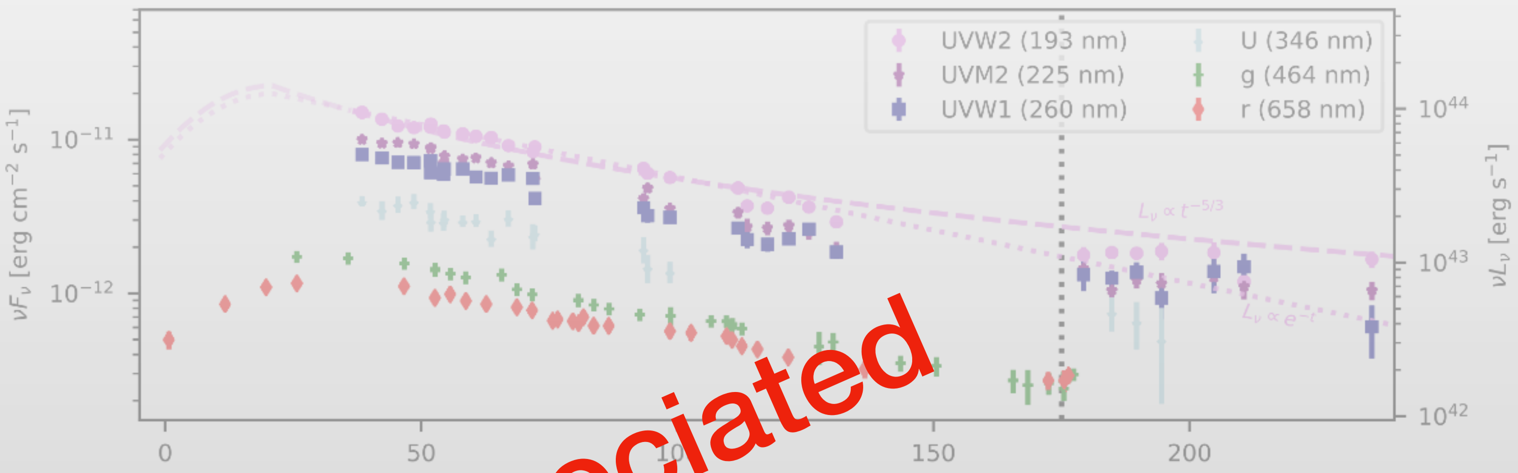


Flare name	Neutrino name	z	Δt days	Δd deg	X-ray temp. keV	*Fermi* limit erg/s/cm^2	$M_{\rm BH}$ $M_\odot$	$f_{\rm Edd}$
AT2019dsg	IC191001A	0.051	150	1.3	0.07 ± 0.01	$10^{-11.7}$	$10^{6.7}$	3.1
AT2019fdr	IC200530A	0.267	393	1.7	0.06 ± 0.03	$10^{-12.0}$	$10^{7.1}$	0.5
AT2019aalc	IC191119A	0.036	148	1.9	0.17 ± 0.01	$10^{-11.2}$	$10^{7.2}$	0.6

Stein et.al. (2021), Nat. Astro.
Reusch et.al. (2022), PRL
Van Velzen et.al. (2021)

Observational aspects - ν Associations





Delayed arrival of associated neutrino events

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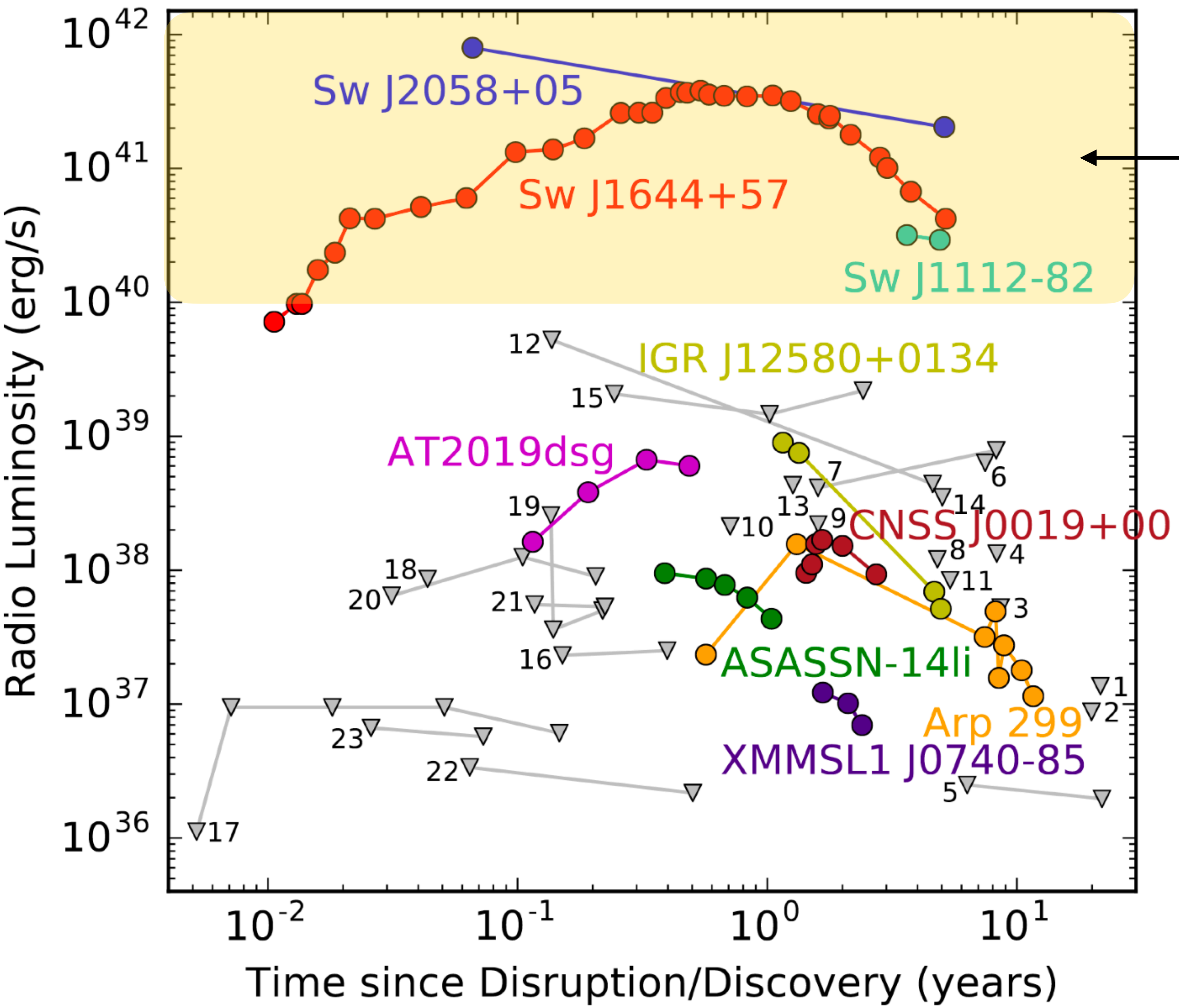
Jetted TDEs



Radio loud Jetted TDEs

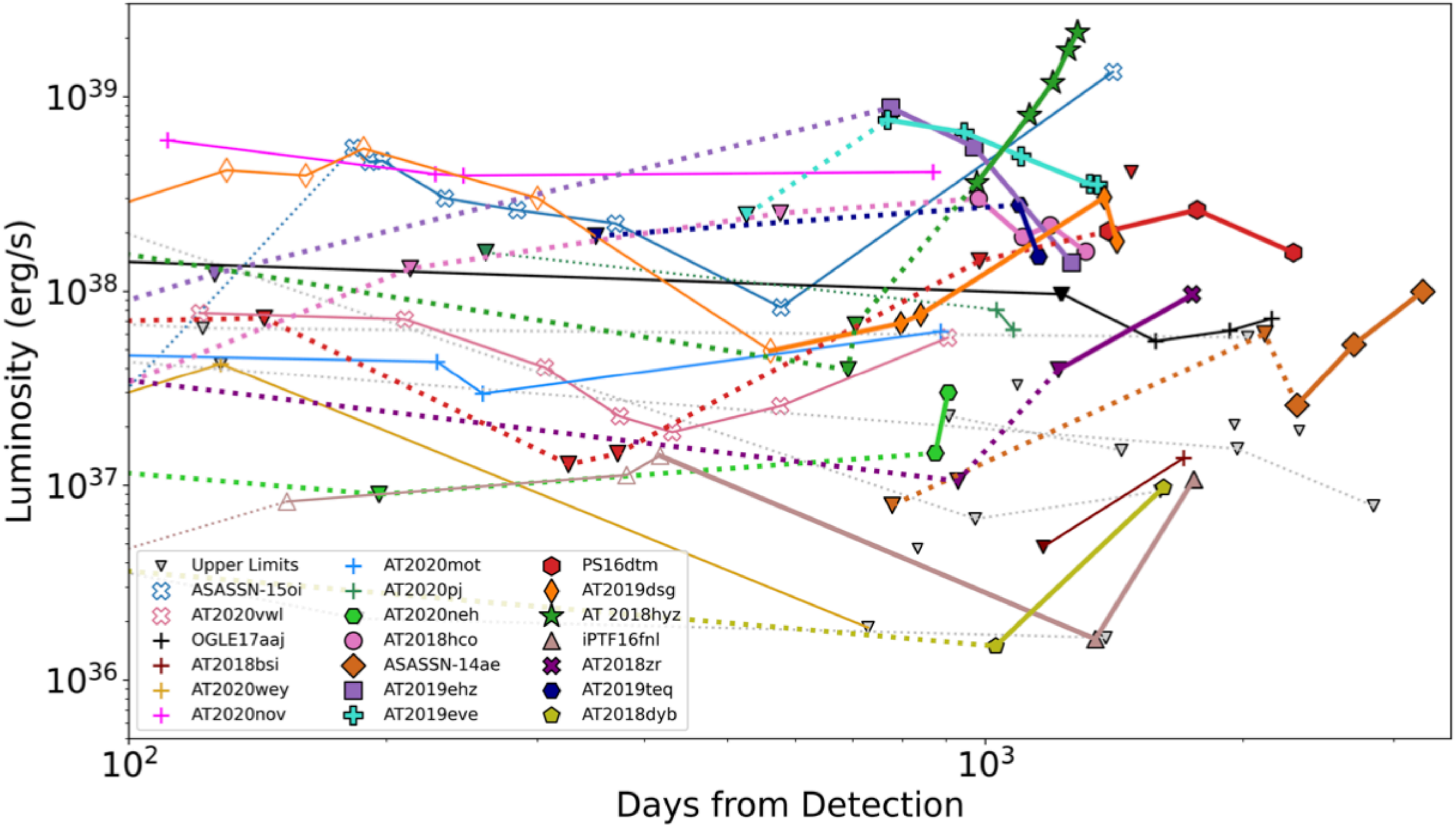
~ 1% of TDEs can be jetted

Non-relativistic outflows

Alexander et al (2020)

Observational aspects - EM radio flares

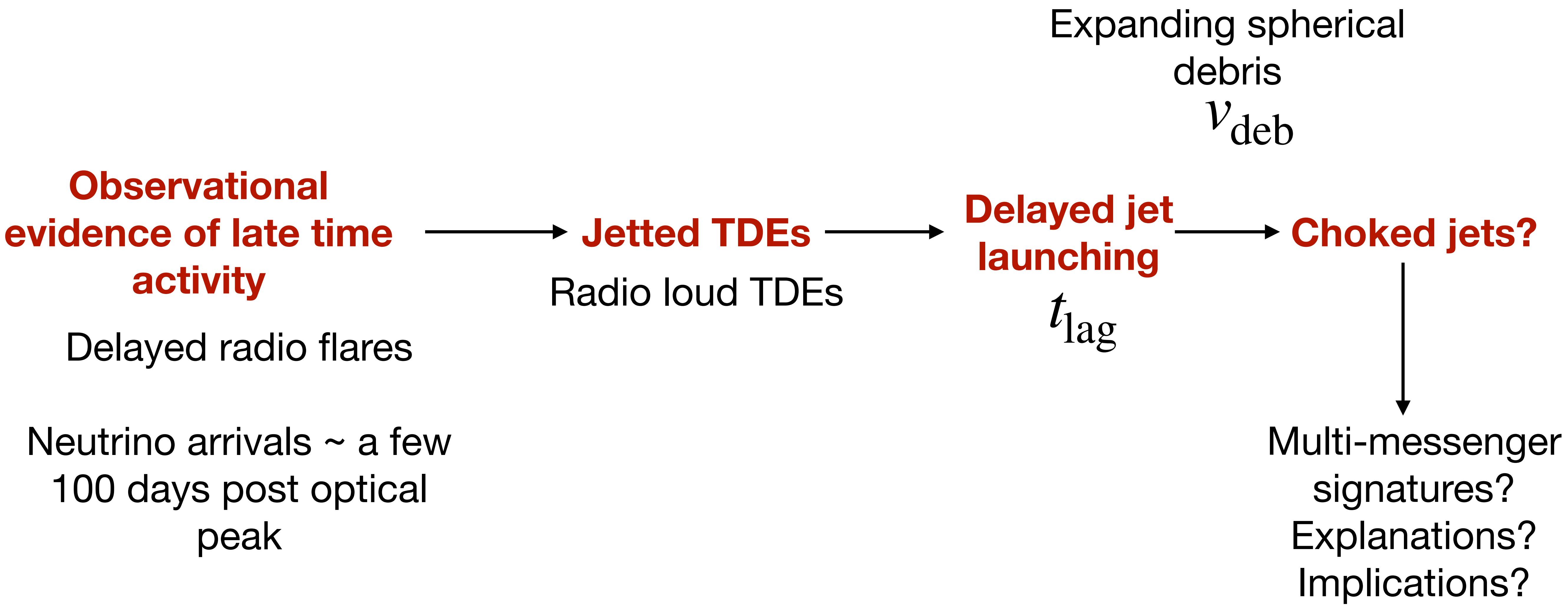
Delayed radio flares



Delayed radio flares: Evidence for late time-activity

Cendes at.al. ApJ 938, (2022)
Cendes+ (2023)

Motivations



Observational evidence of late time activity

Delayed radio flares

Neutrino arrivals ~ a few 100 days post optical peak

→ **Jetted TDEs**

Radio loud TDEs

→ **Delayed jet launching**

t_{lag}

Expanding spherical debris

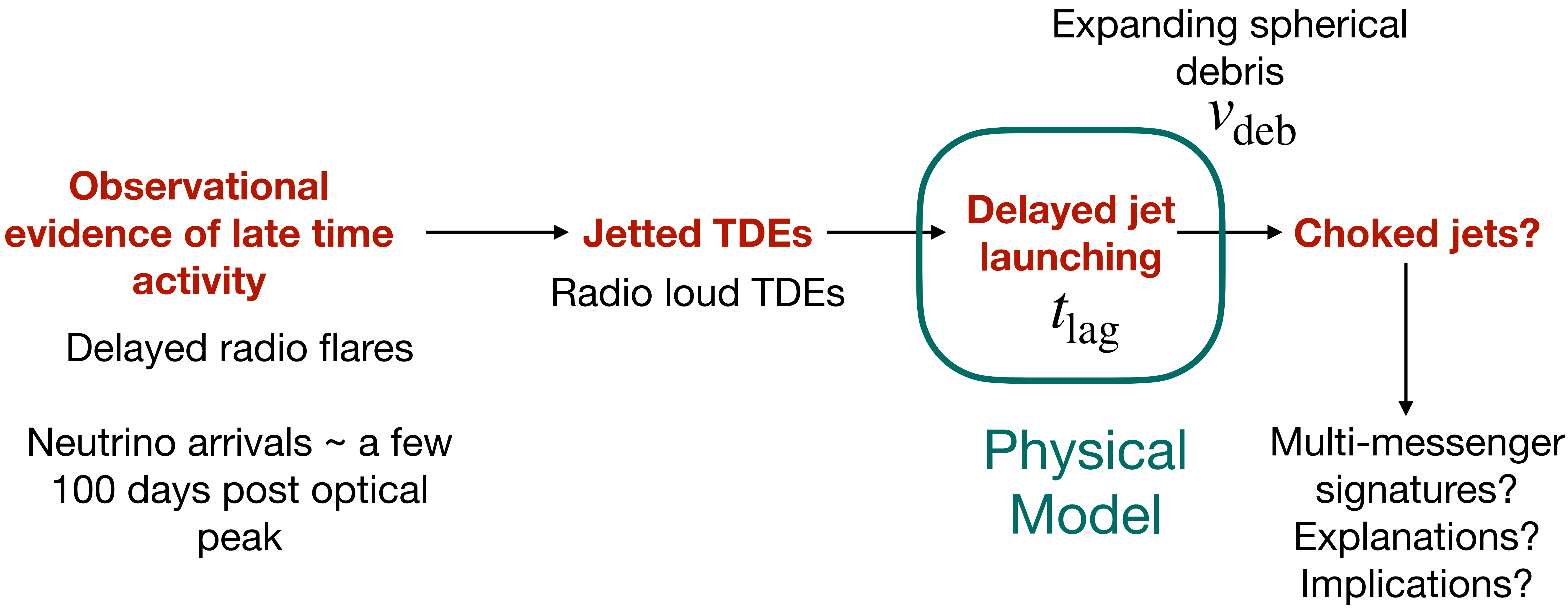
v_{deb}

→ **Choked jets?**

↓

Multi-messenger signatures?
Explanations?
Implications?

Motivations



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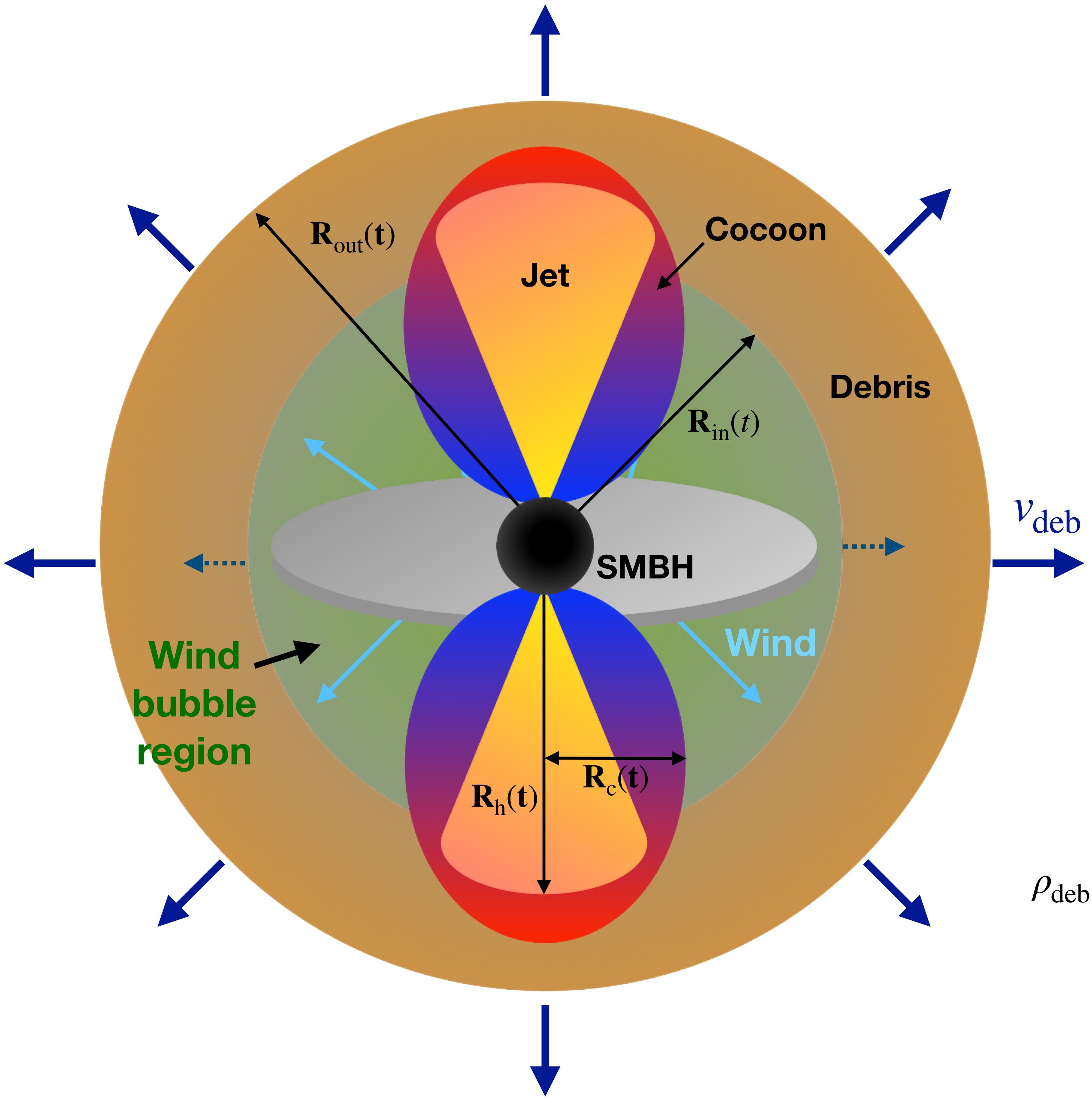
Physical Model

Choked jets?

Multi-messenger signatures?
Explanations?
Implications?

Physical Model: Expanding debris



$$\mathbf{t_{coc} < t < t_{br}} \text{ or } \mathbf{t_{coc} < t < t_{fin}}$$

Static and contracting envelopes have been considered

Convention:

T : Time since TDE

$$T = t + t_{lag}$$

t_{lag}: Time lag associated with the launching of the jet

t: Time since the launch of the jet

$$R_{out}(T) = v_{deb} T$$

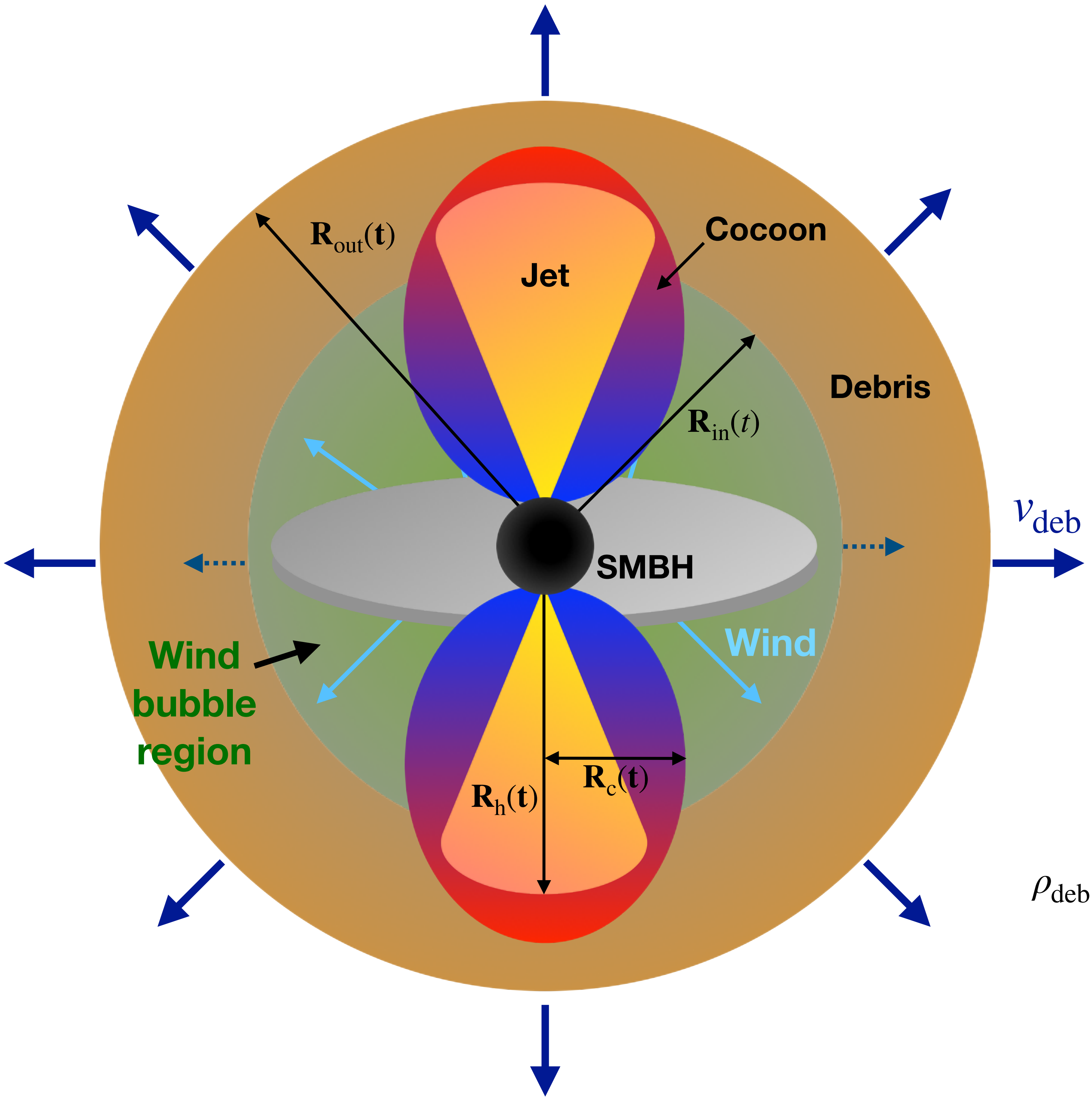
$$R_{in}(T) = \begin{cases} R_{circ},\ 0 < T \leq t_{fb}\,, \\ R_{circ}(T/t_{fb}),\ T > t_{fb} \end{cases}$$

$$\rho_{deb}(t,r) = \mathcal{N} \frac{M_{deb}}{4\pi R_{out}^3} \begin{cases} \left(r/R_{out}\right)^{-2}, r \geq R_{fb} \\ \left(R_{fb}/R_{out}\right)^{-2} \left(r/R_{fb}\right)^{-\delta}, r < R_{fb} \end{cases}$$

$\delta = 1$

$$R_{fb}(T) = \begin{cases} R_{in}(T=0), T < t_{fb} \\ R_{in}(T=0) + v_{deb}(T - t_{fb}), T \geq t_{fb} \end{cases}$$

Physical Model: Expanding debris



$$t_{coc} < t < t_{br} \text{ or } t_{coc} < t < t_{fin}$$

Static and contracting envelopes have been considered

Convention:

T : Time since TDE

$$T = t + \boxed{t_{\rm lag}}$$

$t_{\rm lag}$: Time lag associated with the launching of the jet

t: Time since the launch of the jet

$$R_{\rm out}(T) = \boxed{v_{\rm deb}} T$$

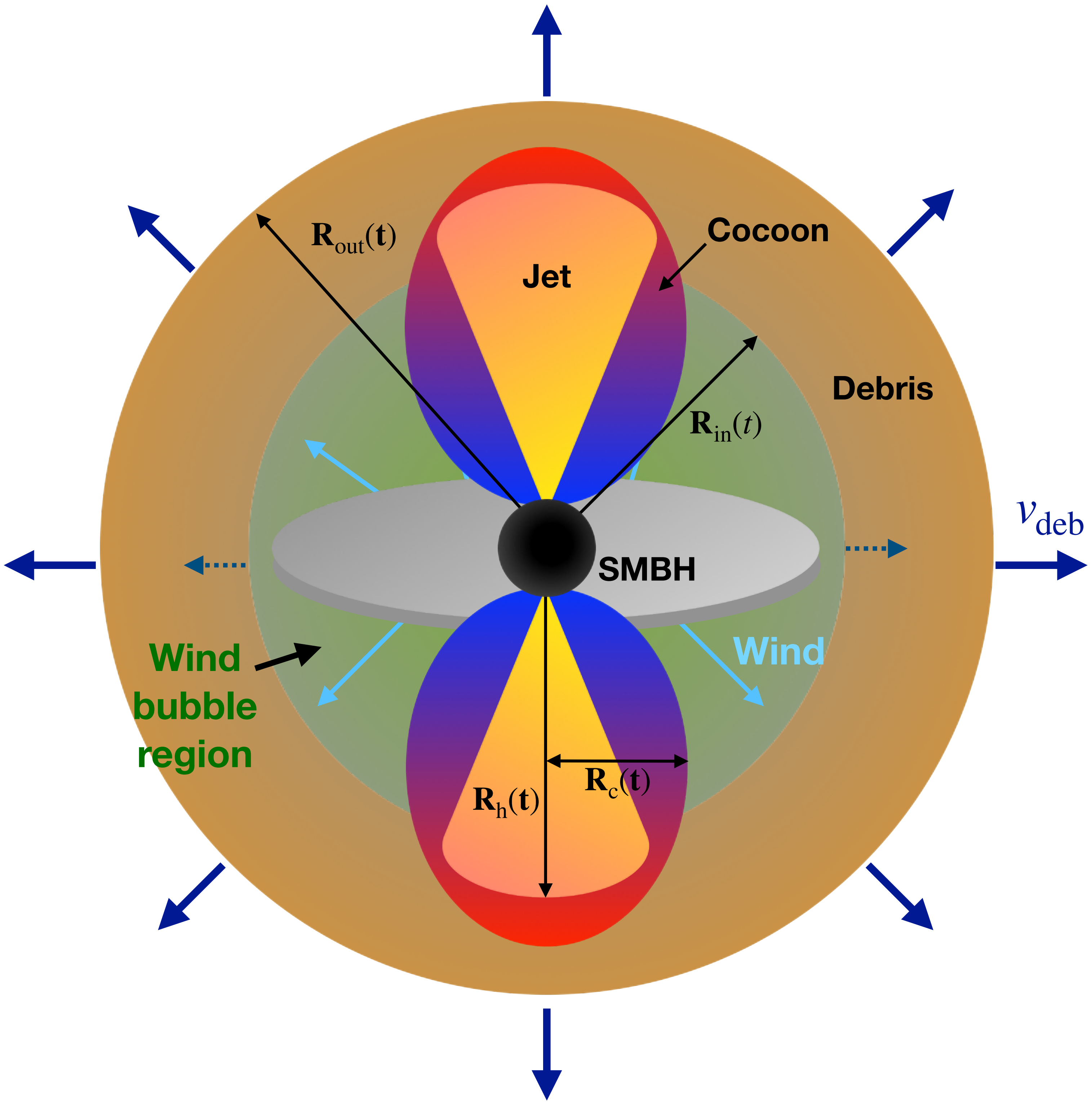
$$R_{\rm in}(T) = \begin{cases} R_{\rm circ},\ 0 < T \leq t_{\rm fb}\,, \\ R_{\rm circ}(T/t_{\rm fb}),\ T > t_{\rm fb} \end{cases}$$

$$\rho_{\rm deb}(t,r) = \mathcal{N}\frac{M_{\rm deb}}{4\pi R_{\rm out}^3}\begin{cases} \left(r/R_{\rm out}\right)^{-2},\ r \geq R_{\rm fb} \\ \left(R_{\rm fb}/R_{\rm out}\right)^{-2}\left(r/R_{\rm fb}\right)^{-\delta},\ r < R_{\rm fb} \end{cases}$$

$\delta = 1$

$$R_{\rm fb}(T) = \begin{cases} R_{\rm in}(T=0),\ T < t_{\rm fb} \\ R_{\rm in}(T=0) + v_{\rm deb}(T - t_{\rm fb}),\ T \geq t_{\rm fb} \end{cases}$$

Physical Model: Jet propagation in expanding debris



$$\mathbf{t}_{\mathrm{coc}} < \mathbf{t} < \mathbf{t}_{\mathrm{br}} \text{ or } \mathbf{t}_{\mathrm{coc}} < \mathbf{t} < \mathbf{t}_{\mathrm{fin}}$$

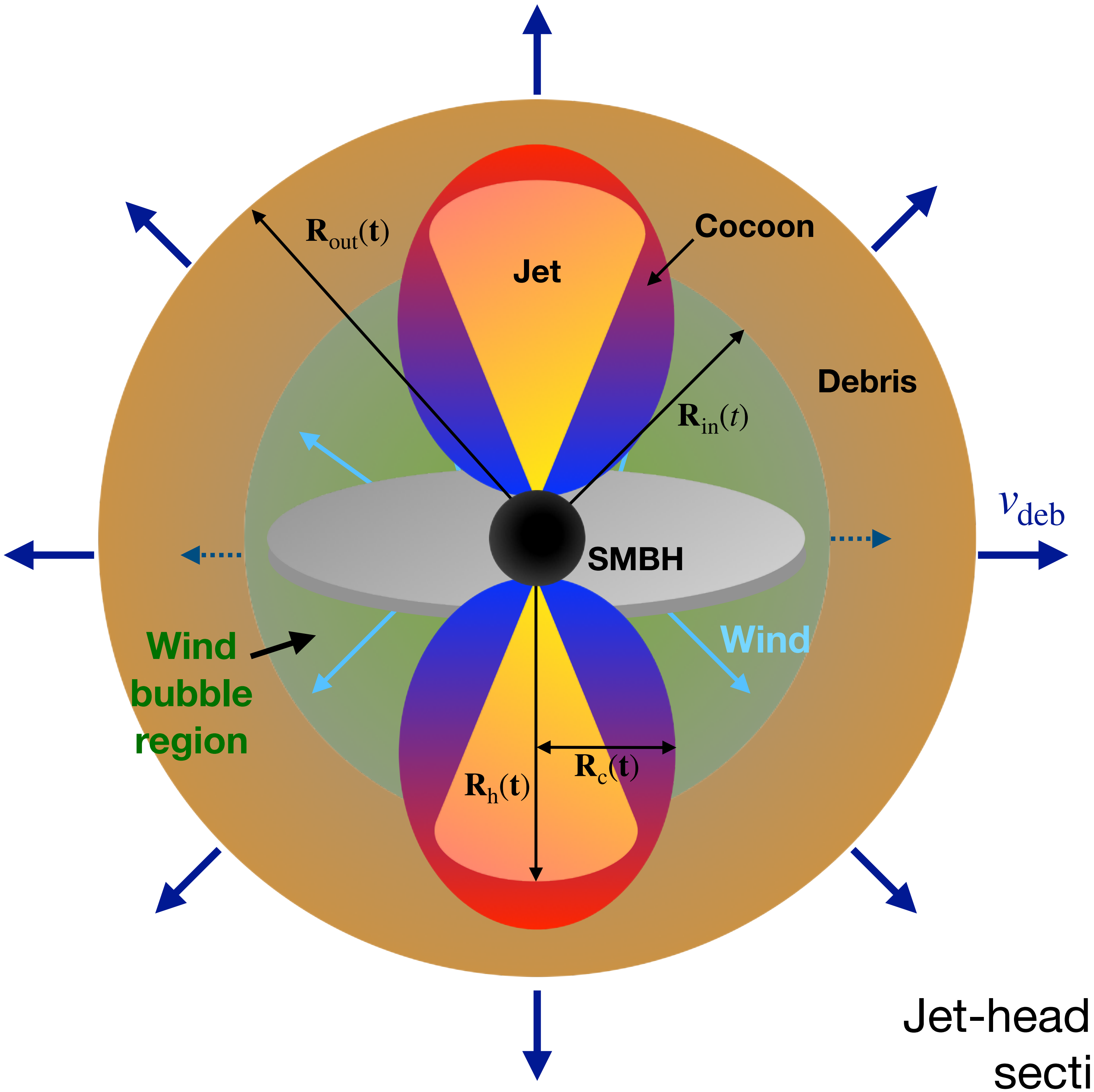
$$R_{\mathrm{h}}(t=0) = R_{\mathrm{s}} = 2GM_{\mathrm{BH}}/c^2$$

$$\dot{R}_{\mathrm{h}} = c\beta_{\mathrm{h}}$$

$$\beta_{\mathrm{h}} = \frac{\beta_{\mathrm{j}} - \beta_{\mathrm{a}}}{1 + \tilde{L}_{\mathrm{c}}^{-1/2}} + \beta_{\mathrm{a}}$$

Ambient medium: surrounding medium of jet-head

Physical Model: Jet propagation in expanding debris



$$\mathbf{t}_{\mathrm{coc}} < \mathbf{t} < \mathbf{t}_{\mathrm{br}} \text{ or } \mathbf{t}_{\mathrm{coc}} < \mathbf{t} < \mathbf{t}_{\mathrm{fin}}$$

$$R_{\mathrm{h}}(t_{\mathrm{dur}} = 0) = R_{\mathrm{s}} = 2GM_{\mathrm{BH}}/c^2$$

$$\dot{R}_{\mathrm{h}} = c\beta_{\mathrm{h}}$$

$$\beta_{\mathrm{h}} = \frac{\beta_{\mathrm{j}} - \beta_{\mathrm{a}}}{1 + \tilde{L}_{\mathrm{c}}^{-1/2}} + \beta_{\mathrm{a}}$$

$$\tilde{L}_c = N_s^2 \tilde{L}$$

Ratio of energy density between jet and ambient medium

Calibration factor

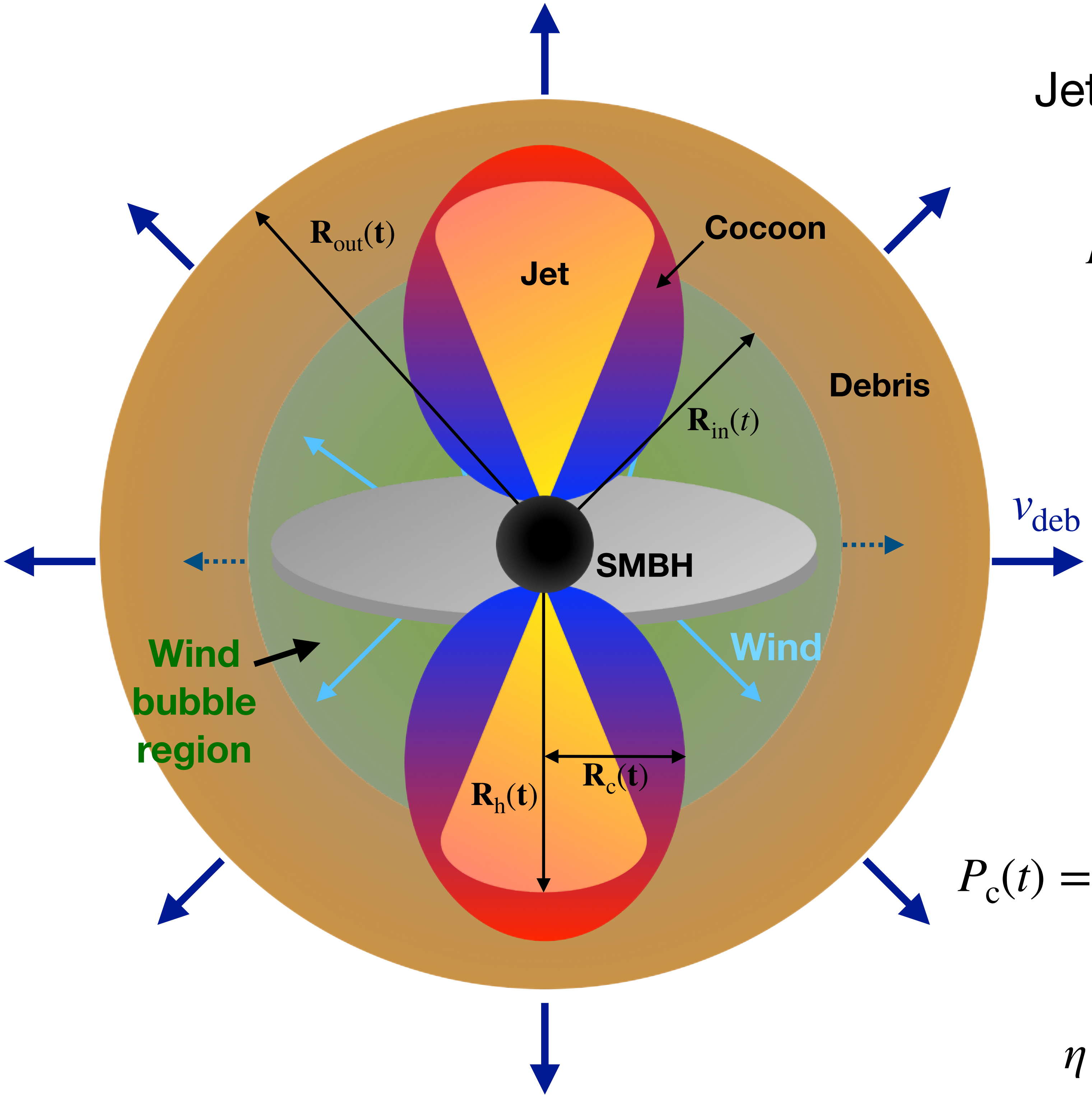
$$\tilde{L} = \frac{L_{\mathrm{j}}}{\Sigma_{\mathrm{j}}(t)\rho_{\mathrm{a}}(t)c^3\Gamma_{\mathrm{a}}^2}$$

Jet-head cross-section

$$\rho_{\mathrm{a}}(t) = \rho_{\mathrm{deb}}(t, r = R_h)$$

Density of ambient medium

Physical Model: Formation of cocoon and interaction



$\mathbf{t}_{\rm coc} < \mathbf{t} < \mathbf{t}_{\rm br}$ or $\mathbf{t}_{\rm coc} < \mathbf{t} < \mathbf{t}_{\rm fin}$

Jet head reaches the inner radius of the debris

$$R_c(t = t_{\rm coc}) = R_{\rm j}(t = t_{\rm coc}) = R_{\rm h}(t = t_{\rm coc})\theta_0$$

$$\dot{R}_{\rm c} = c\beta_{\rm c}$$

$$\beta_{\rm c} \approx \frac{1}{c}\sqrt{\frac{P_{\rm c}}{\rho_{\rm a}(t)}} + \frac{R_{\rm c}(t)}{R_{\rm out}(t)}\frac{v_{\rm w}}{c}$$

Cocoon pressure

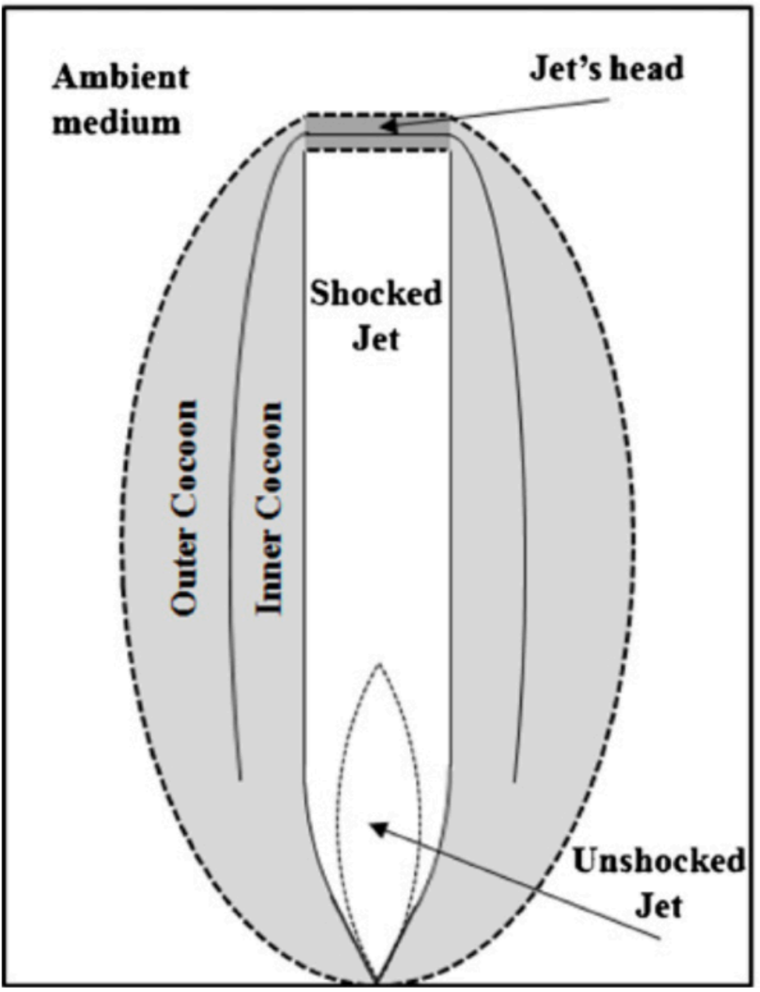
$$P_{\rm c}(t) = \frac{E_{\rm c}}{3V_{\rm c}} = \frac{\eta}{4\pi R_{\rm c}(t)^2 R_{\rm h}(t)}\int_{t_{\rm c}}^{t} d\tilde{t}\; L_{\rm j}(\tilde{t})\left(1 - \beta_{\rm h}(\tilde{t})\right)$$

η : Fraction of jet energy deposited in cocoon

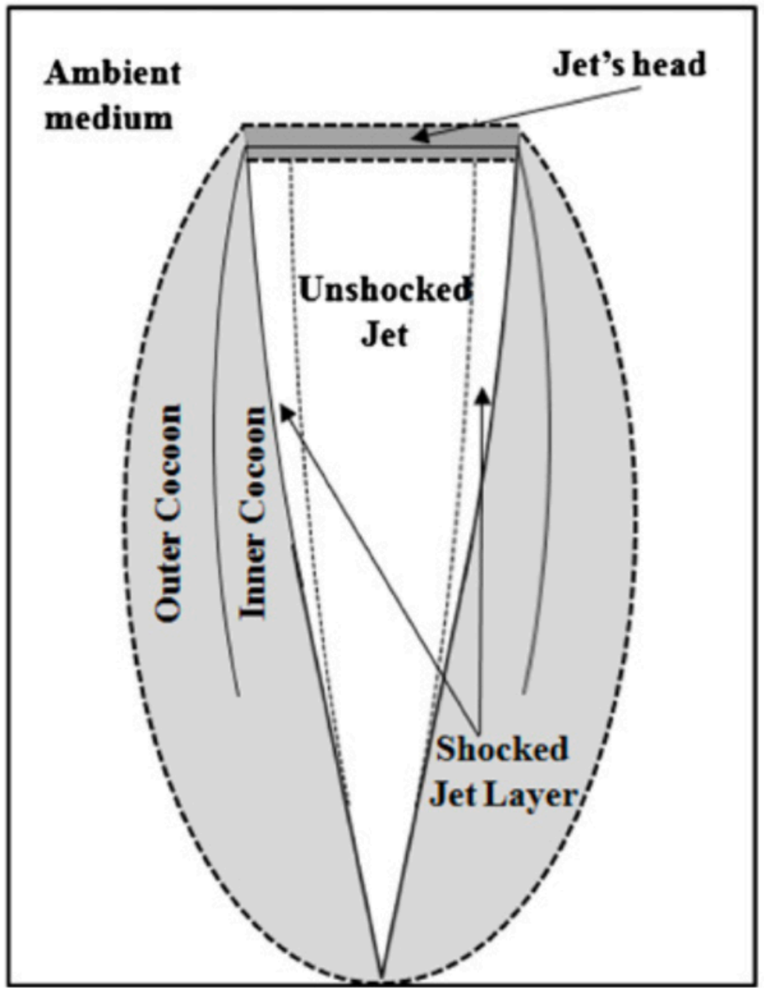
Dynamics: To collimate or not collimate

Jet pressure

Cocoon pressure
(Lateral)



Collimated



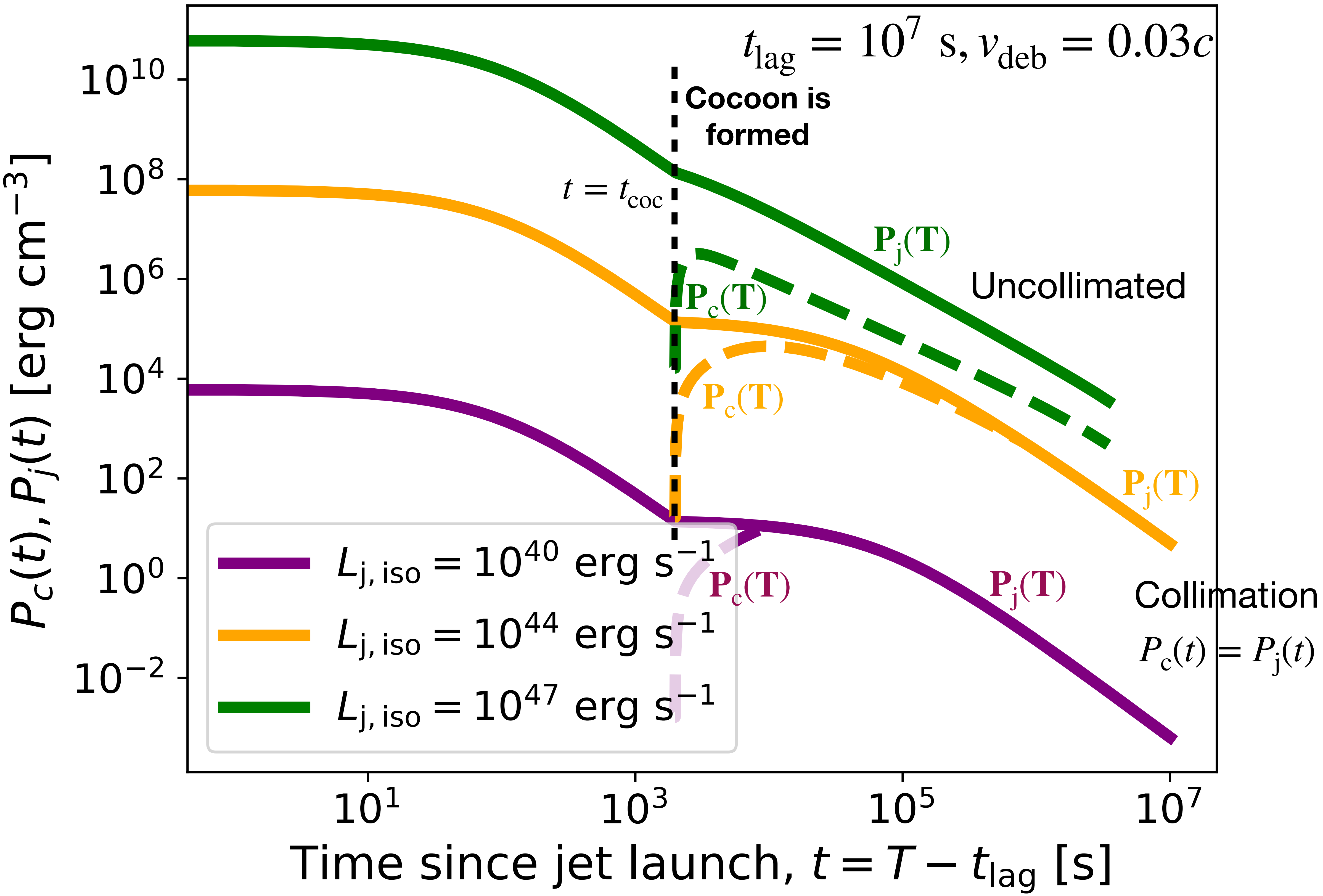
Uncollimated

Collimation criteria:

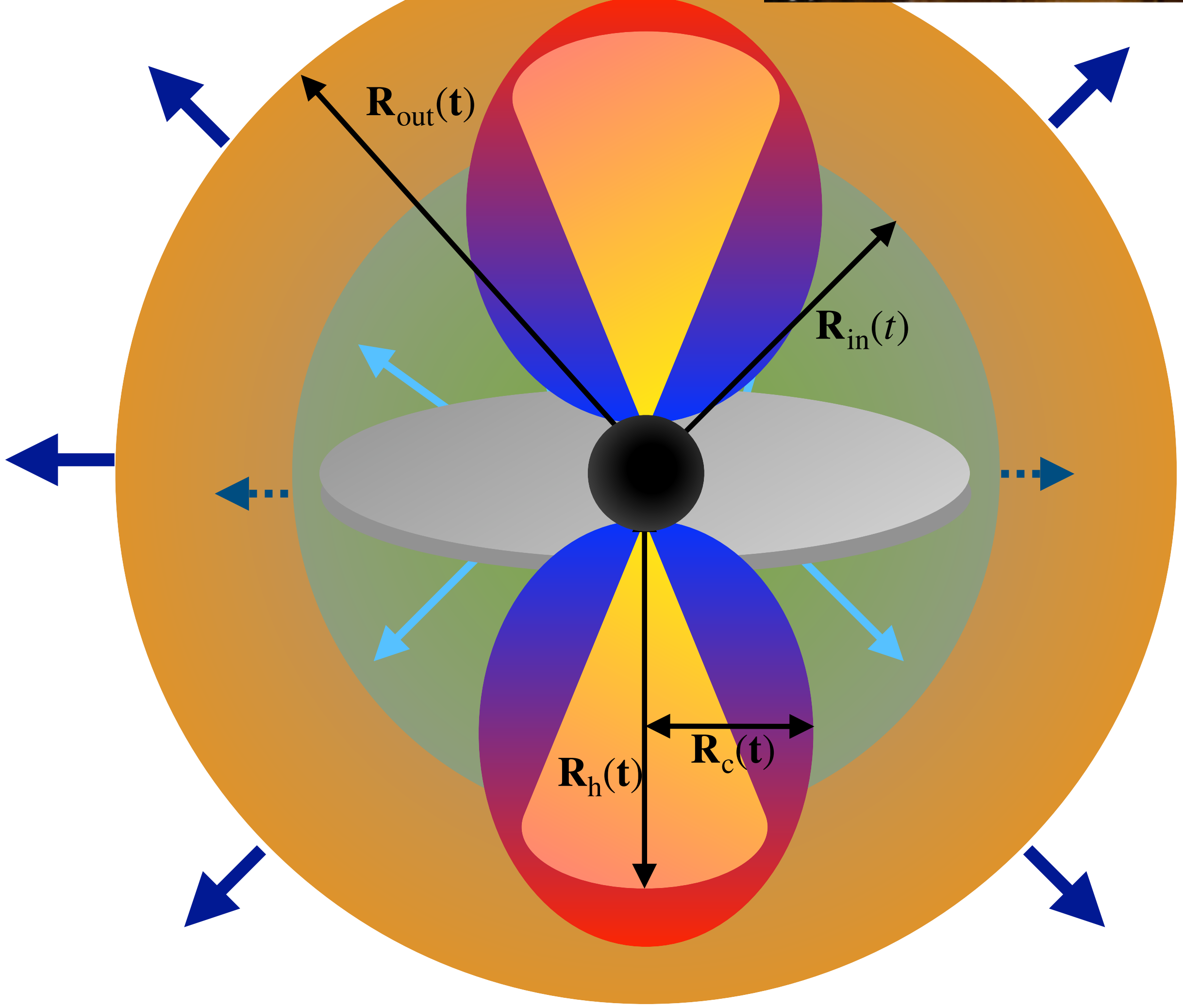
$$P_c(t) = P_j(t)$$

Bromberg et al (2011)

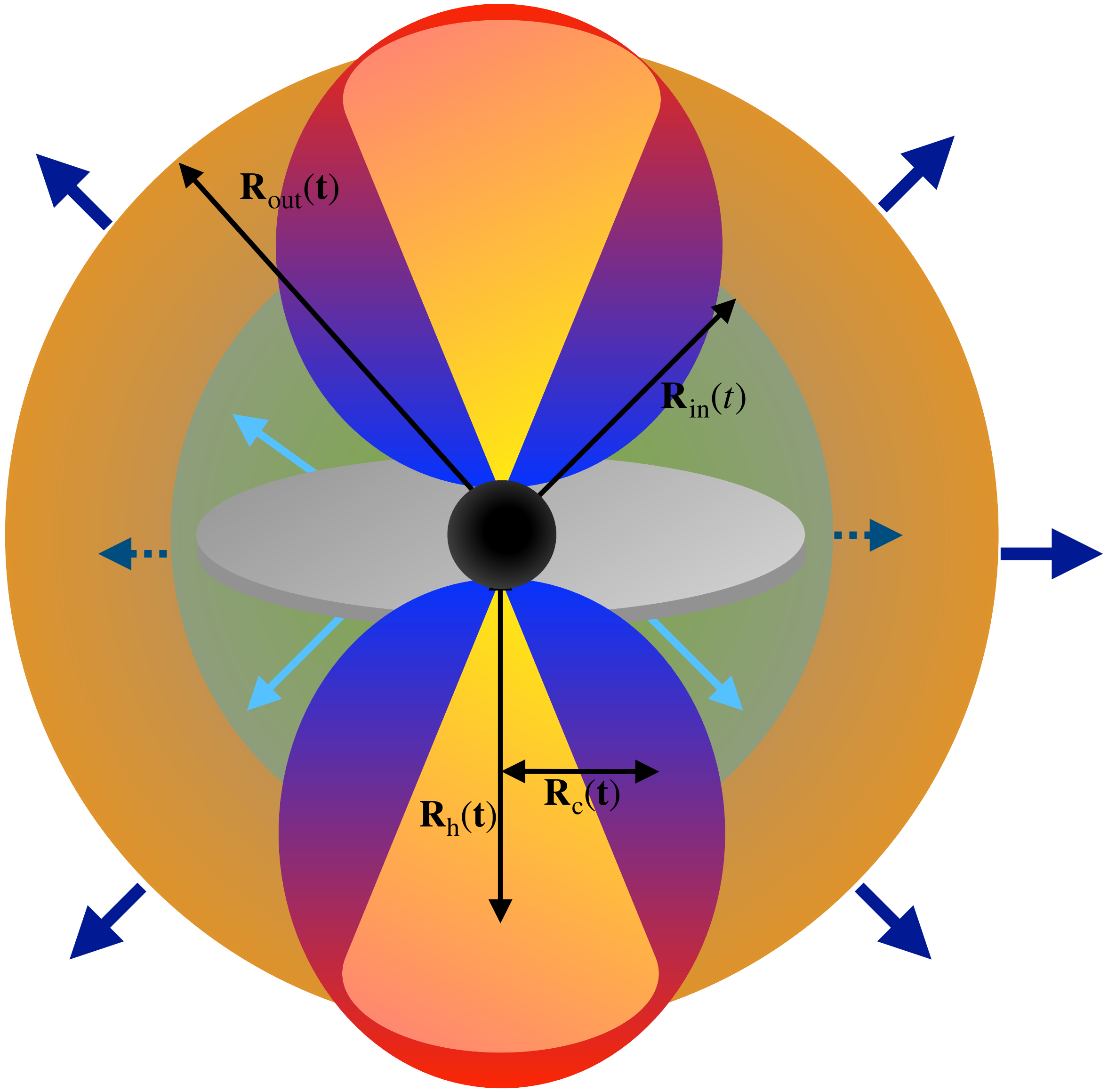
Dynamics: To collimate or not collimate



Dynamics: To choke or not to choke



Choked

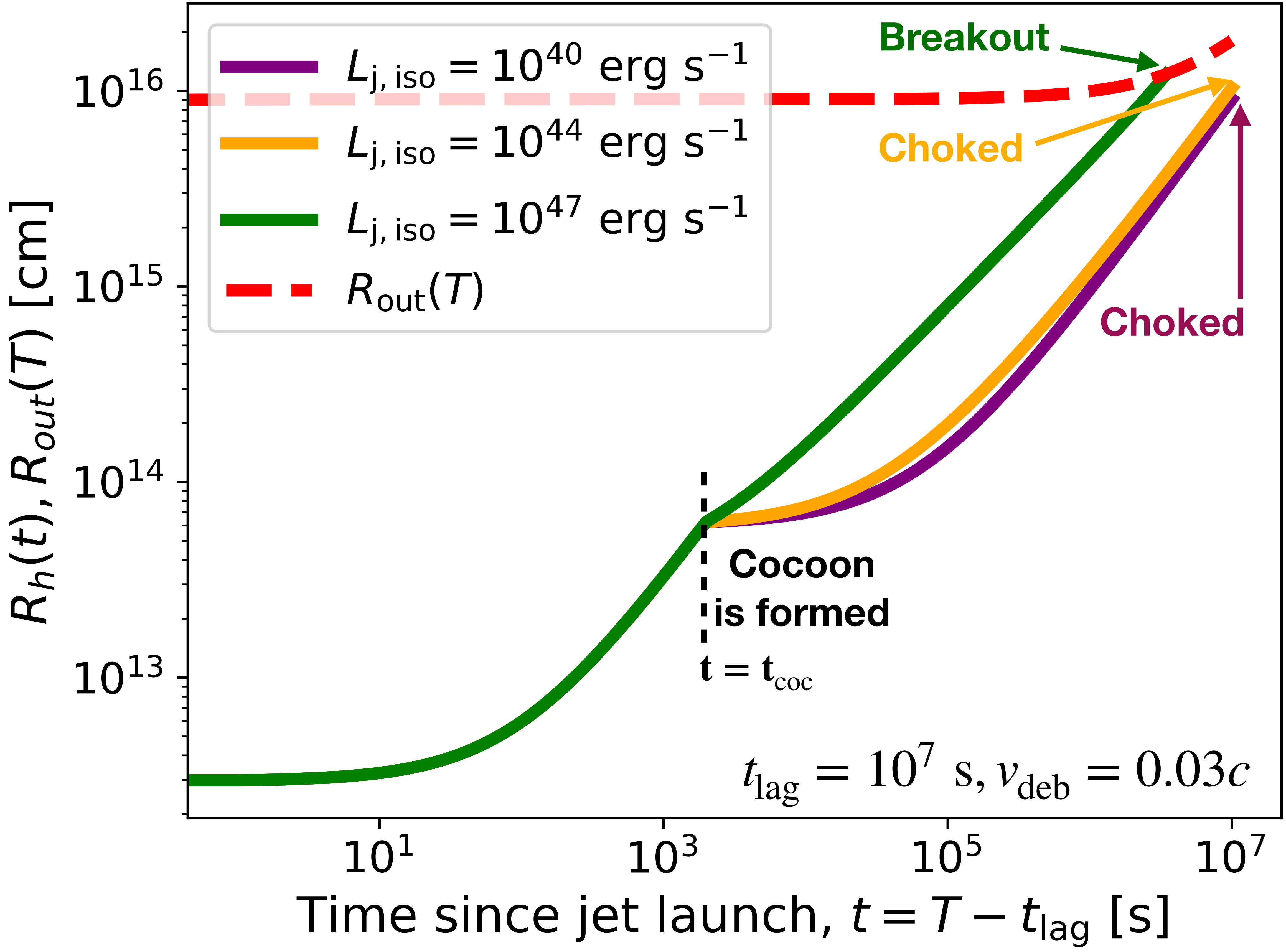


Breakout

Choking criteria:

$$R_h(t_{\rm dur}) \leq R_{\rm out}(T)$$

Dynamics: To choke or not to choke



Dynamics: Analytical estimate for choking

Choking criteria $R_\mathrm{h}(t_\mathrm{dur}) \le R_\mathrm{out}(t_\mathrm{fin})$

$$T = t_\mathrm{fin} = t_\mathrm{dur} + t_\mathrm{lag}$$

Total evolution time

$$R_\mathrm{out} \simeq 1.8 \times 10^{16}\,\mathrm{cm}\, \boxed{\left(\frac{\beta_\mathrm{deb}}{0.03}\right)} \left(\frac{t_\mathrm{dur}}{10^7 \mathrm{s}}\right) \boxed{\left(\frac{\chi_\mathrm{lag}}{2}\right)}$$

$$\chi_\mathrm{lag} = (1 + t_\mathrm{lag}/t_\mathrm{dur})$$

Assuming uncollimated jets

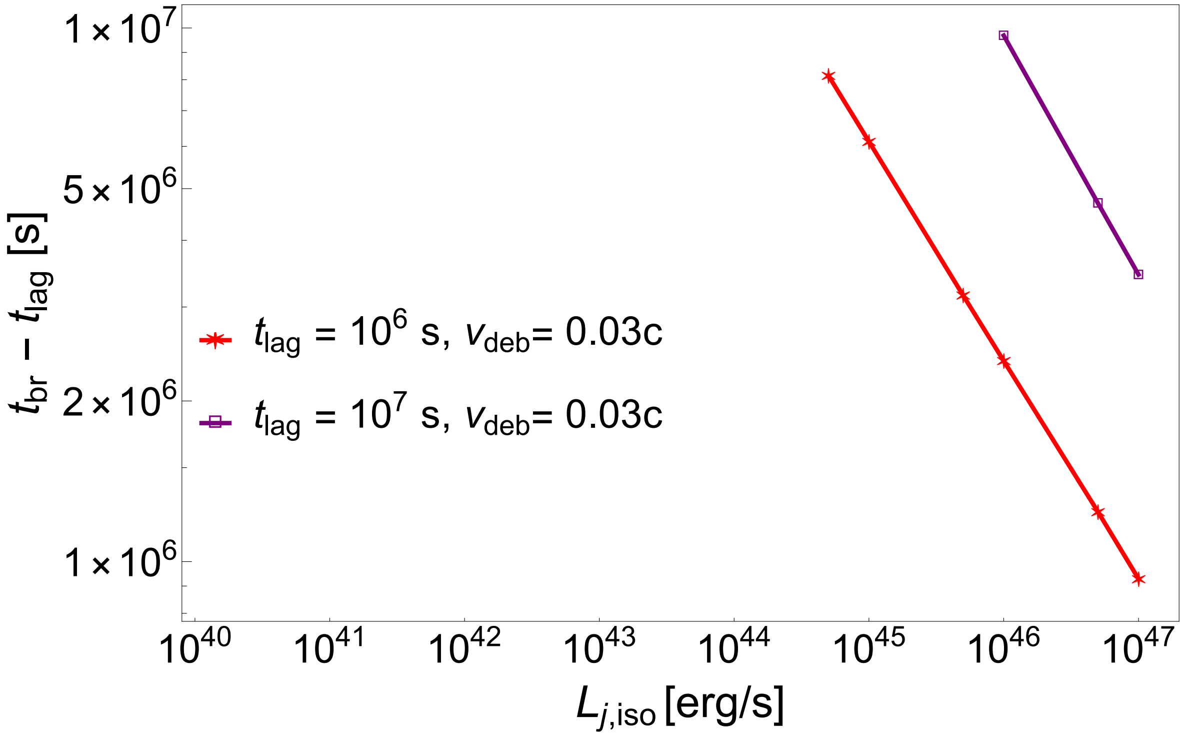
$$R_\mathrm{h} \simeq 5.6 \times 10^{15}\,\mathrm{cm} \left(\frac{N_s}{0.35}\right)^{5/3} \left(\frac{L_\mathrm{j,iso}}{10^{44}\,\mathrm{erg/s}}\right)^{1/3} \left(\frac{M_\mathrm{deb}}{0.5\,M_\odot}\right)^{-1/3} \left(\frac{\theta_0}{0.17}\right)^{-2/3} \left(\frac{\beta_\mathrm{deb}}{0.03}\right)^{1/3} \left(\frac{t_\mathrm{dur}}{10^7\,\mathrm{s}}\right)^{4/3} \left(\frac{\chi_\mathrm{lag}}{2}\right)^{1/3}$$

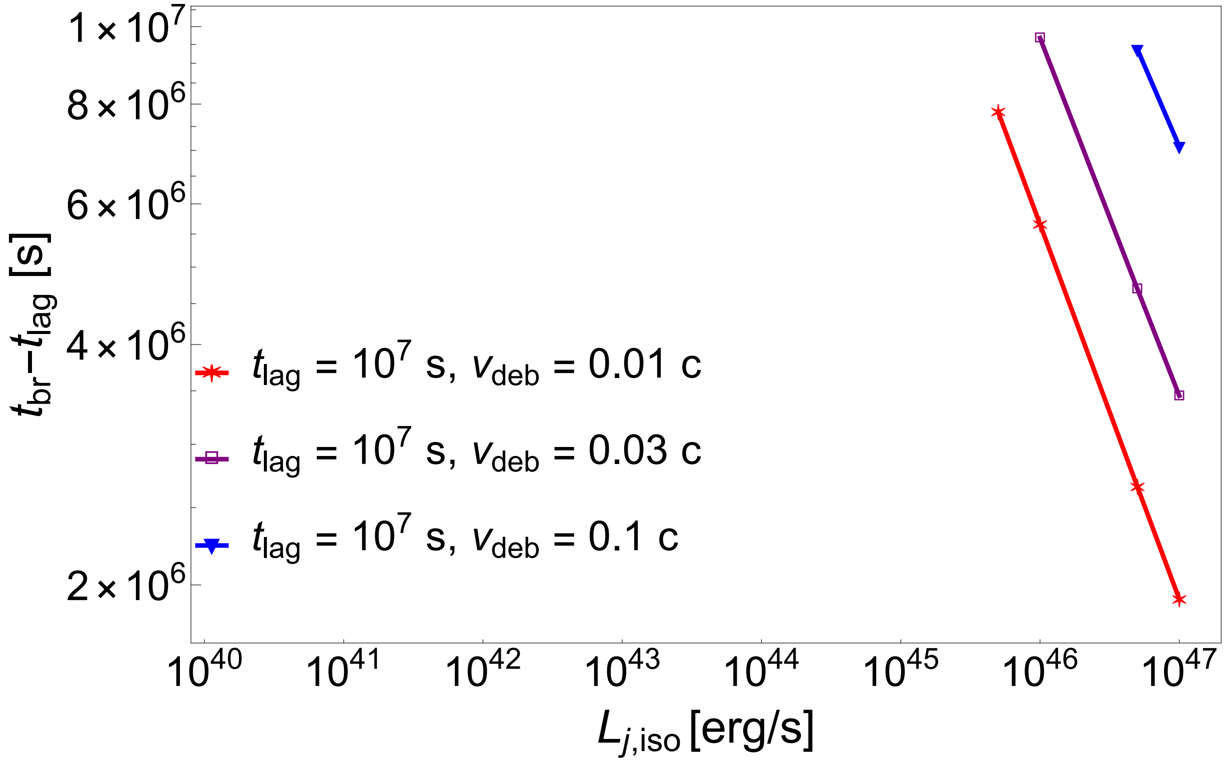
$$L_\mathrm{j,iso} \lesssim 3.2 \times 10^{45}\,\mathrm{erg/s} \left(\frac{N_s}{0.35}\right)^{-5} \left(\frac{M_\mathrm{deb}}{0.5 M_\odot}\right) \left(\frac{\theta_0}{0.17}\right)^{2} \left(\frac{\beta_\mathrm{deb}}{0.03}\right)^{2} \left(\frac{t_\mathrm{dur}}{10^7\,\mathrm{s}}\right)^{-1} \left(\frac{\chi_\mathrm{lag}}{2}\right)^{2}$$

Fairly good estimates

Dynamics: the land of choked jets

$$L_{\rm j,iso} \lesssim 3.2 \times 10^{45}\,{\rm erg/s} \left(\frac{N_s}{0.35}\right)^{-5} \left(\frac{M_{\rm deb}}{0.5 M_\odot}\right) \left(\frac{\theta_0}{0.17}\right)^{2} \left(\frac{\beta_{\rm deb}}{0.03}\right)^{2} \left(\frac{t_{\rm dur}}{10^7\,{\rm s}}\right)^{-1} \left(\frac{\chi_{\rm lag}}{2}\right)^{2}$$





$t_{\rm lag}$: $\uparrow$

The debris has more time to expand

Jets require higher luminosity to breakout

$v_{\rm deb}$: $\uparrow$

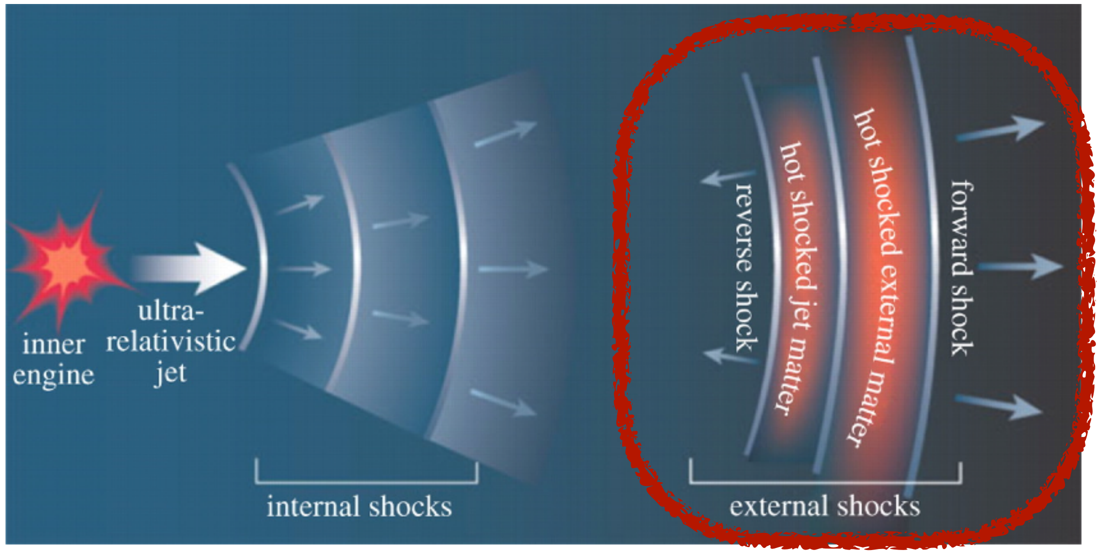
The debris expands with a higher velocity: extends to larger radii

Jets require higher luminosity to breakout

Electromagnetic (EM) and Neutrino Signatures

Signatures from delayed choked jets

Particle acceleration within jets:
- UHECRs
- High-energy neutrinos
- EM signatures



Jet-head

Relativistic (Initially) → Sub-relativistic

Interactions with the debris: cocoon

Deceleration

↓

Shocked regions → Forward shock, Reverse shock

↓

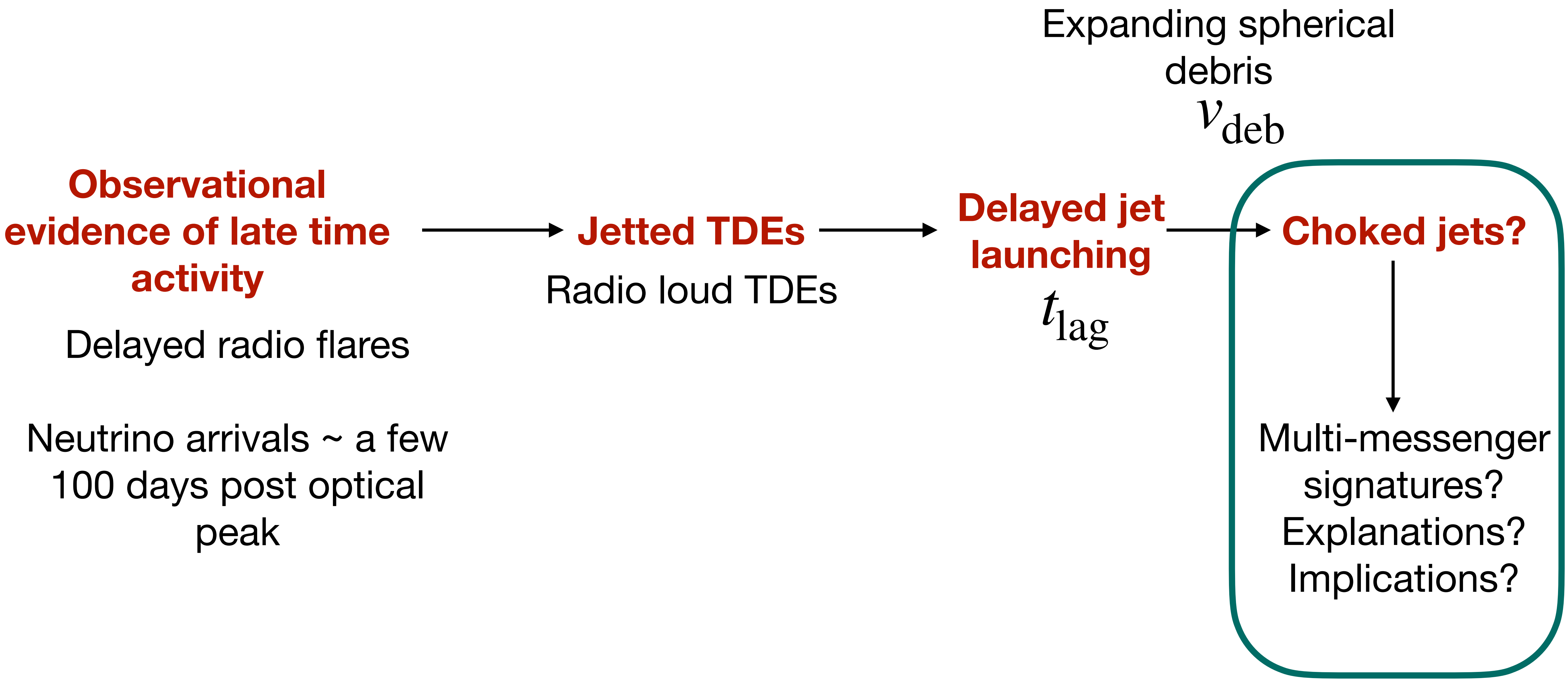
Relativistic electrons are accelerated

↓

Cool due to radiative losses:
Synchrotron, inverse Compton,….

Wheeler, Phil. Trans. R. Soc. (2012)

Motivations



Observational evidence of late time activity

Delayed radio flares

Neutrino arrivals ~ a few 100 days post optical peak

Jetted TDEs

Radio loud TDEs

Delayed jet launching

t_{lag}

Expanding spherical debris

v_{deb}

Choked jets?

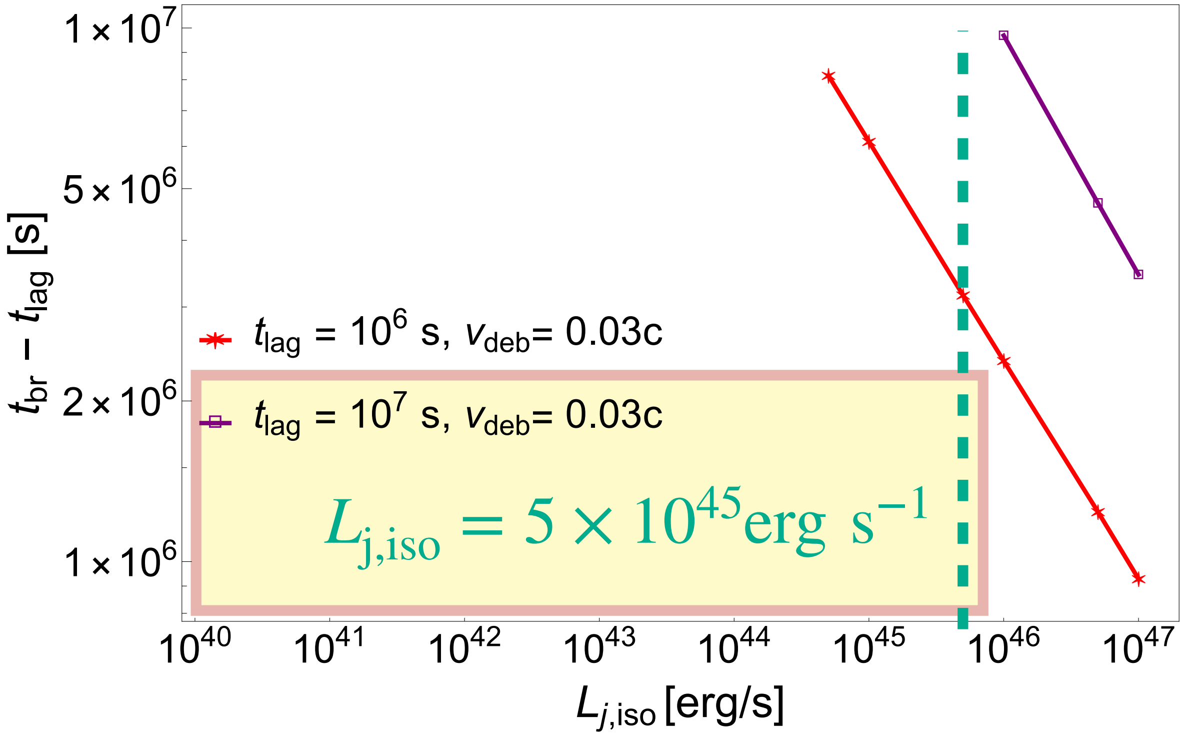
Multi-messenger signatures?

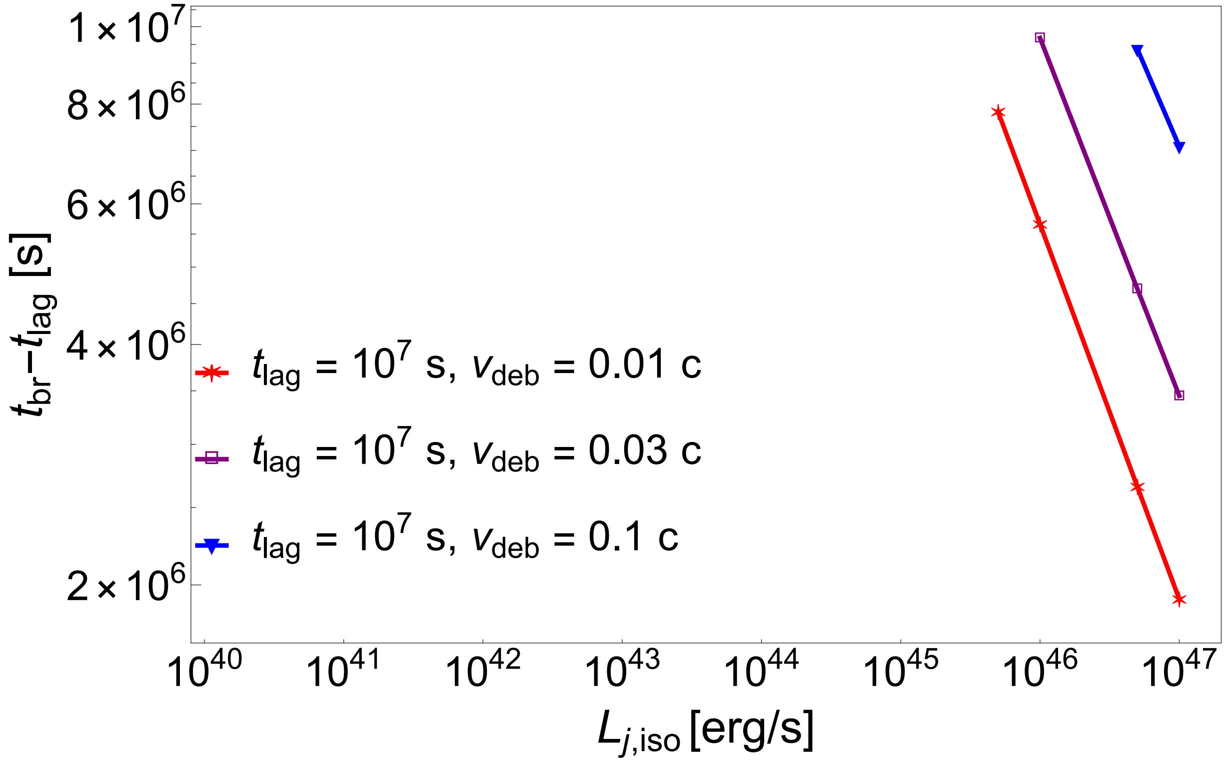
Explanations?

Implications?

Electromagnetic (EM) and Neutrino Signatures

$$L_{\rm j,iso} \lesssim 3.2\times10^{45}\,{\rm erg/s}\left(\frac{N_s}{0.35}\right)^{-5}\left(\frac{M_{\rm deb}}{0.5M_\odot}\right)\left(\frac{\theta_0}{0.17}\right)^2\left(\frac{\beta_{\rm deb}}{0.03}\right)^2\left(\frac{t_{\rm dur}}{10^7\,{\rm s}}\right)^{-1}\left(\frac{\chi_{\rm lag}}{2}\right)^2$$

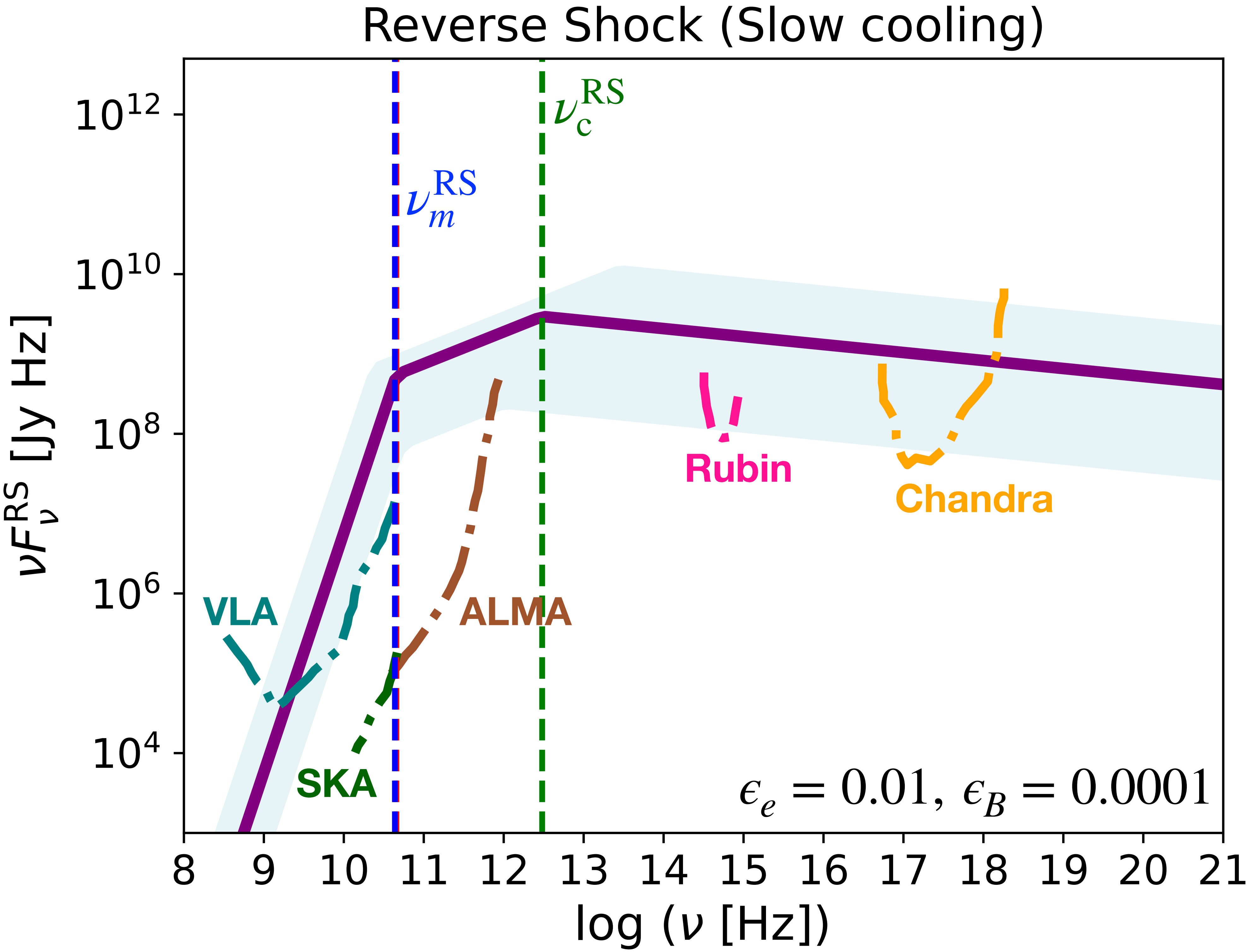




EM Signatures: Reverse Shock - Slow Cooling (z = 0.05)

$$F^{\rm RS}_{\rm syn,max} \simeq 37\ {\rm mJy}\ (f_e/0.48) n^{\rm RS}_{2.53} R^3_{\rm h,16.21} \Gamma^{\rm RS}_{0.70} B^{\rm RS} (1+z) d^{-2}_{L,26.82}$$

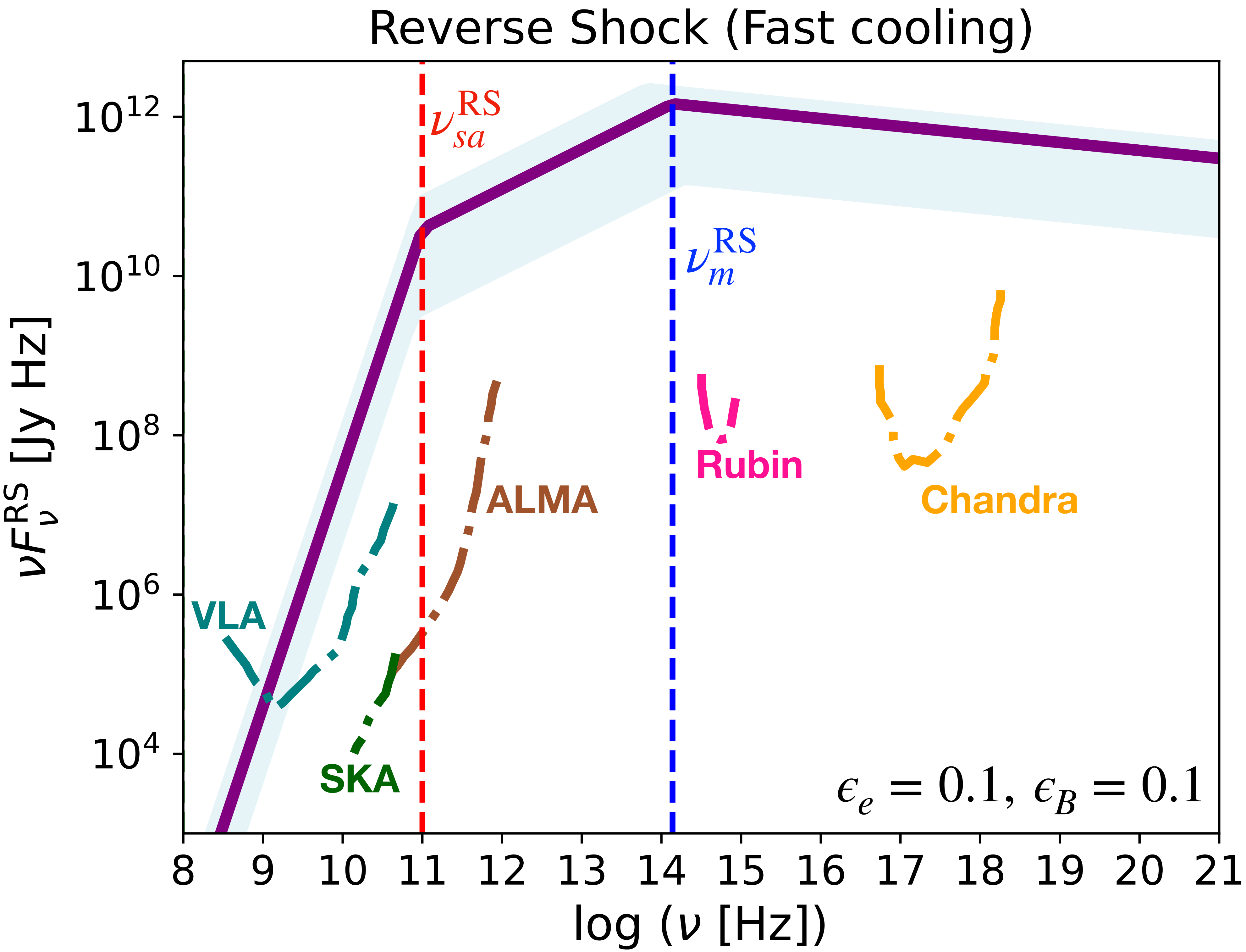
$$B^{\rm RS} \simeq 0.32\,{\rm G}$$



EM Signatures: Reverse Shock - Fast Cooling (z = 0.05)

$$F^{\rm RS}_{\rm syn,max} \simeq 37 \ {\rm mJy} \ (f_e/0.48) n^{\rm RS}_{2.53} R^3_{\rm h,16.21} \Gamma^{\rm RS}_{0.70} B^{\rm RS} (1+z) d^{-2}_{L,26.82}$$

$$B^{\rm RS} \simeq 10.25 \, {\rm G}$$

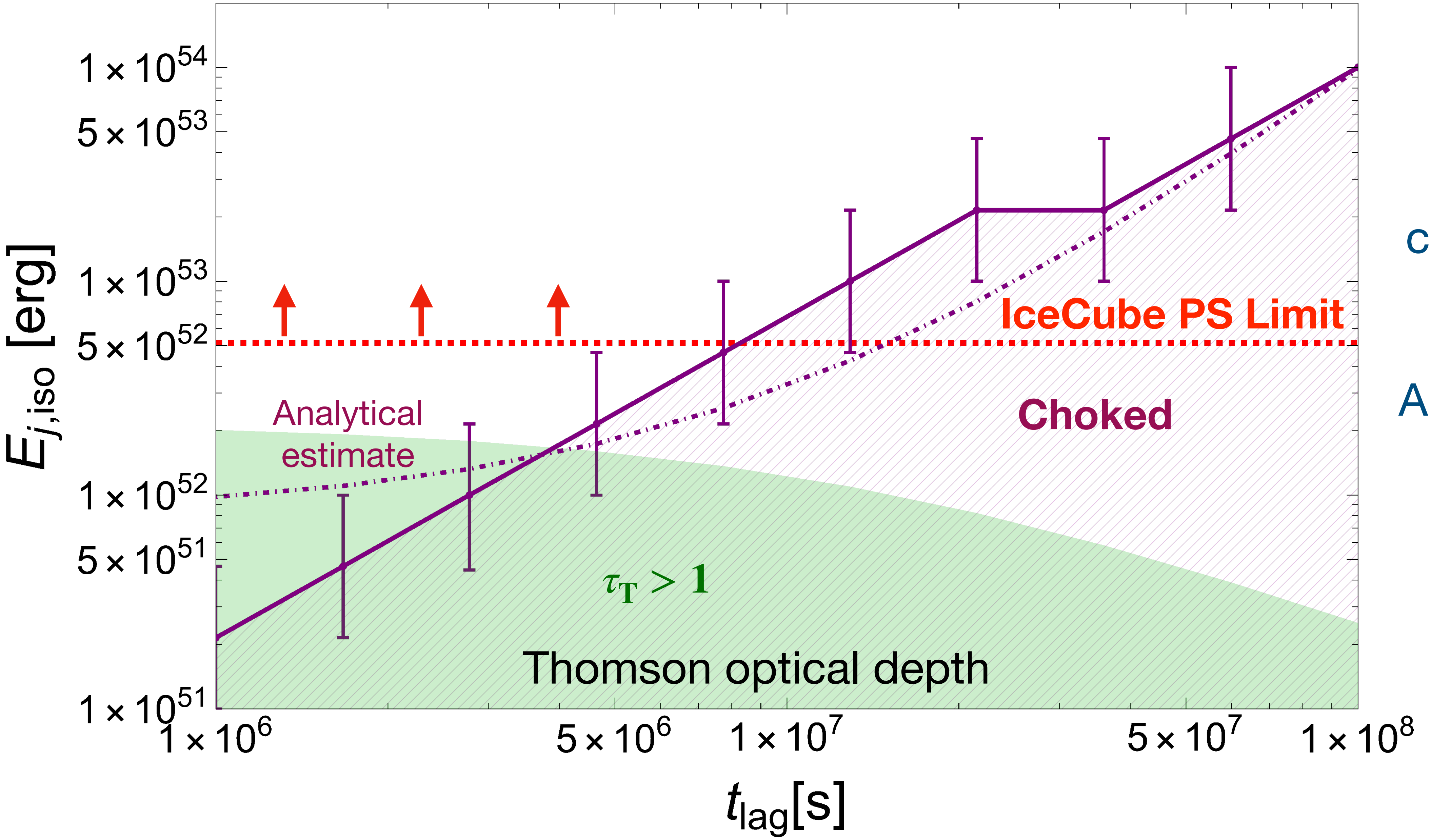


Neutrino Signatures: Choked jets ($t_{lag} = 10^7$ s, $z = 0.05$)

AT2019dsg

What is the energy budget required for the jet to produce 1 neutrino event given the IceCube point source (PS) limit

$$E_\nu = 1\,\%\ \text{of}\ E_j$$



Can explain the coincident neutrino observations

Also for AT2019aalc

AT2019fdr is still challenging

Outline

Part 1: Can choked delayed jets explain the neutrino coincidences associated with TDEs?

Based on: Multi-messenger signatures of delayed choked jets in tidal disruption events
MM, M. Bhattacharya, K. Murase
(submitted to MNRAS) (arXiv: 2309.02275).

Part 2: Hunting for 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)***

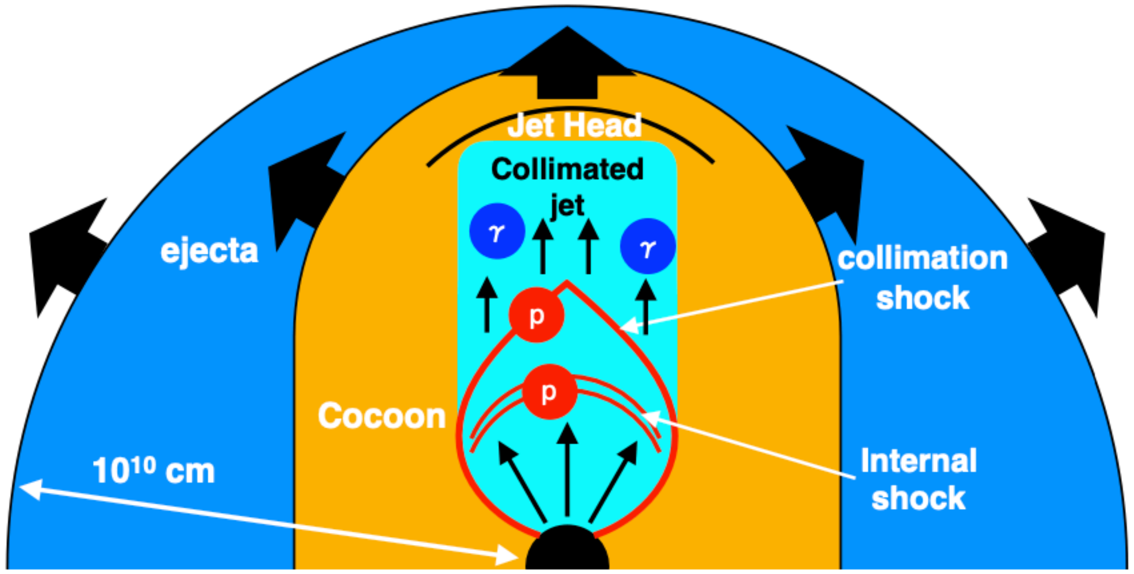
Part 3: Constraints from non-detection of neutrinos from the BOAT - GRB 221009A

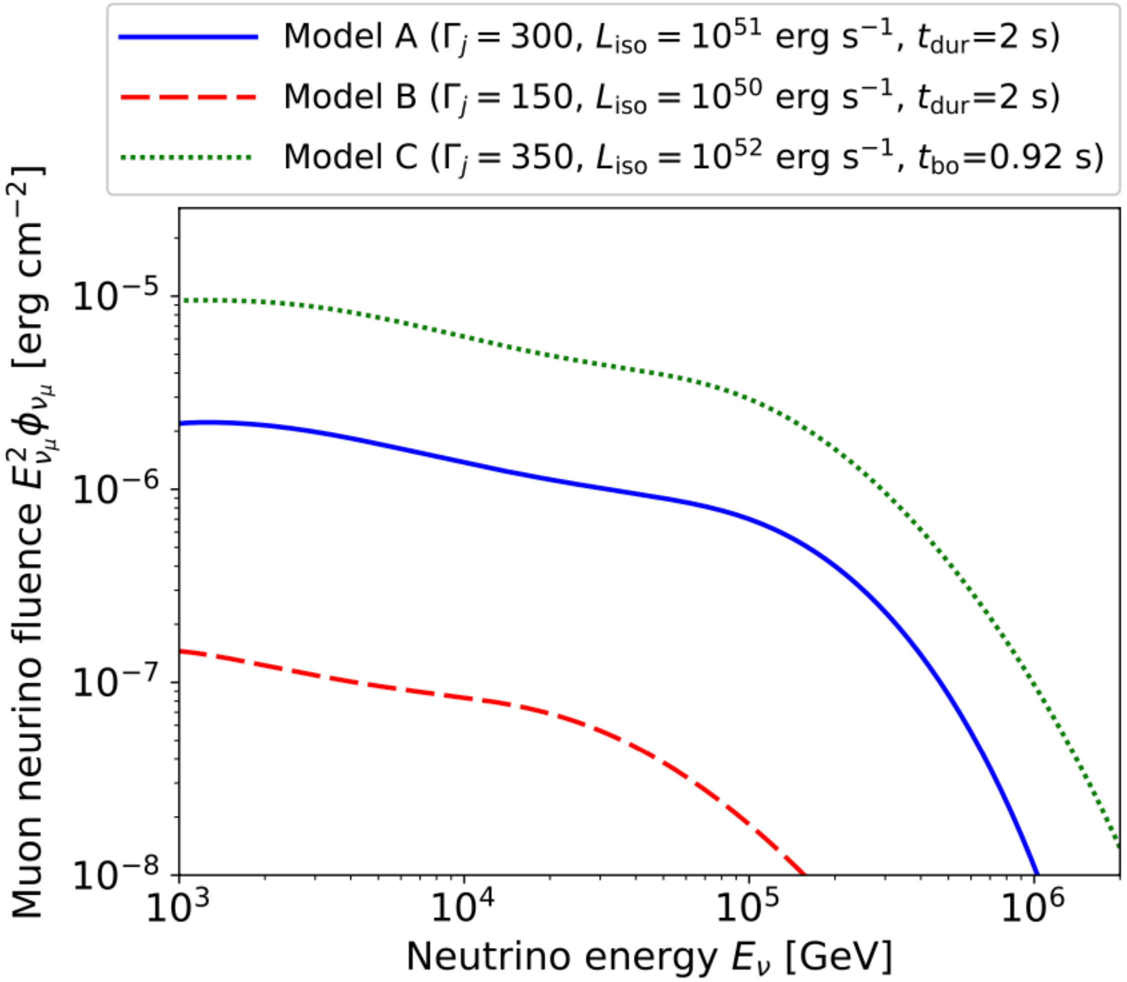
Based on: Neutrinos from the Brightest Gamma-Ray Burst?
K. Murase, MM, A. Kheirandish, S. S. Kimura, K. Fang
ApJ Letters 941 (2022) 1, L10 *(arXiv: 2210.15625)*

High energy neutrinos from BNS mergers

Swift Neutron Star
Collision v. 2
mation: Dana Berry
310-441-1735
uced by Erica Drezek

No detections yet :(

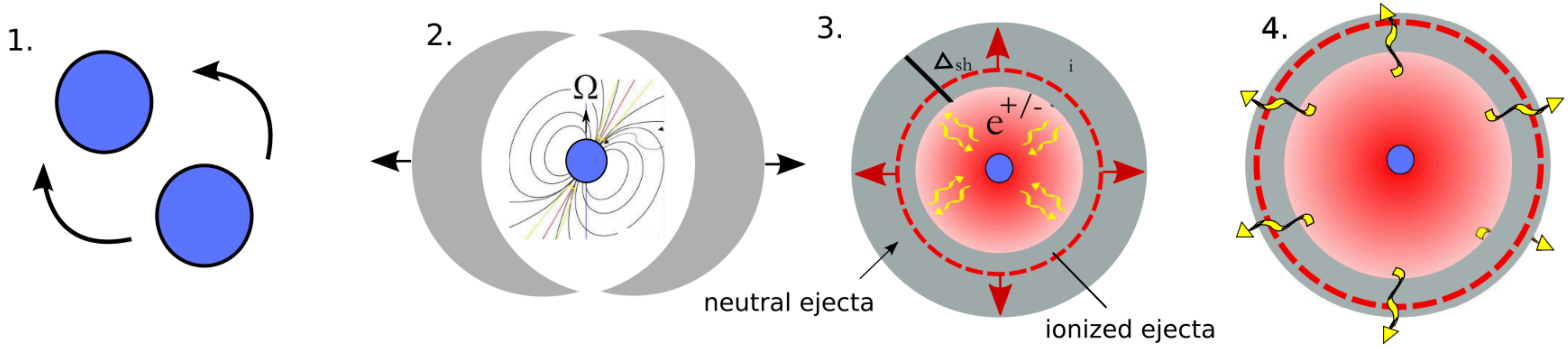


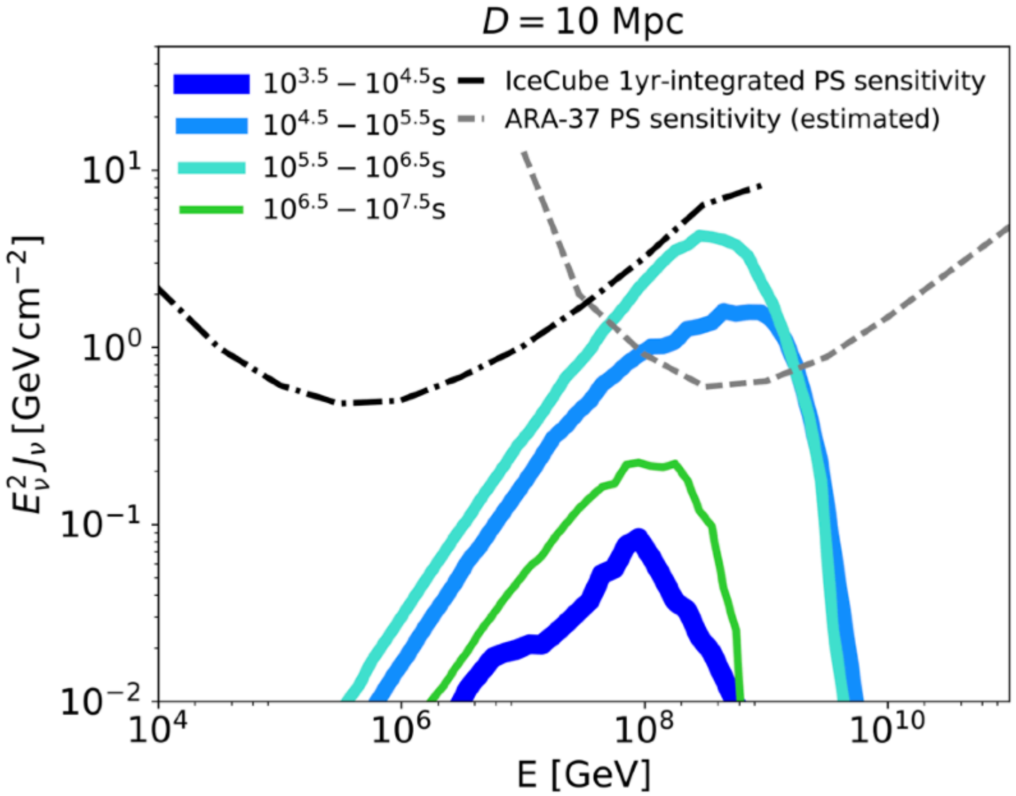


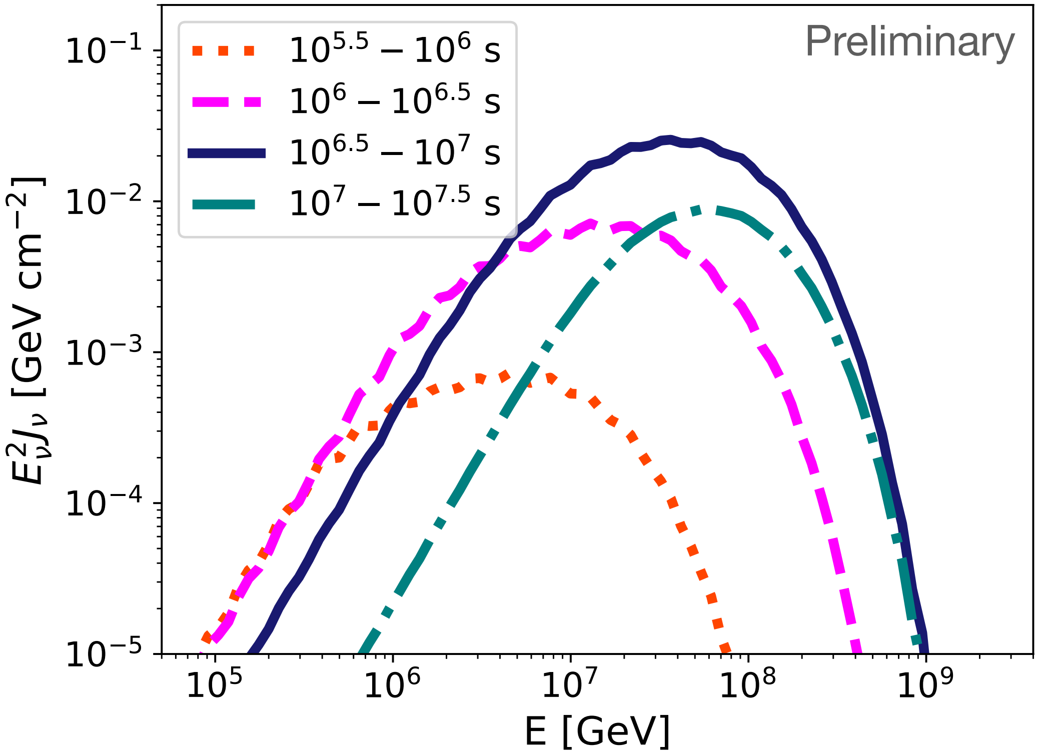
Kimura+, PRD (2018)

High energy neutrinos from BNS mergers

No detections yet :(

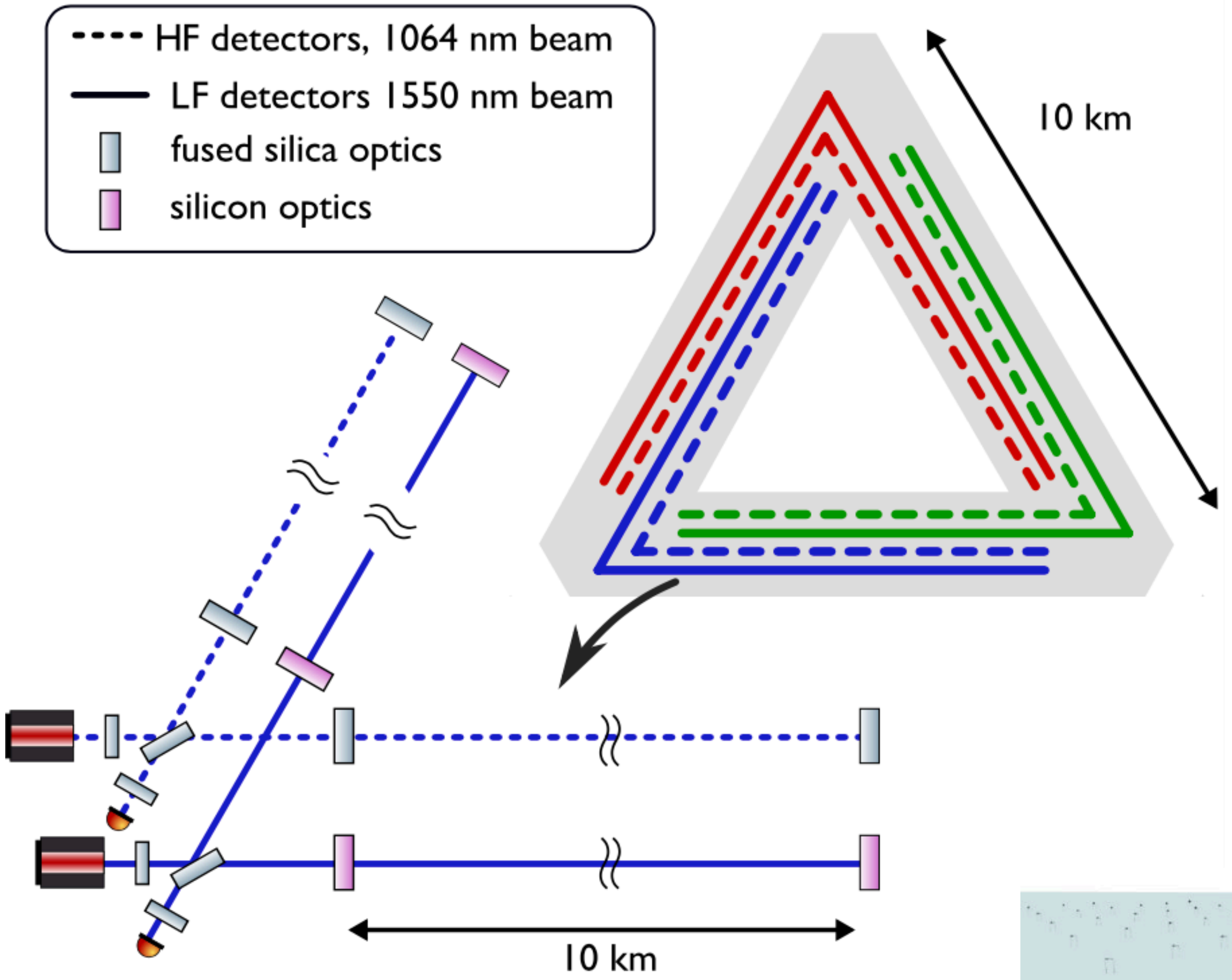


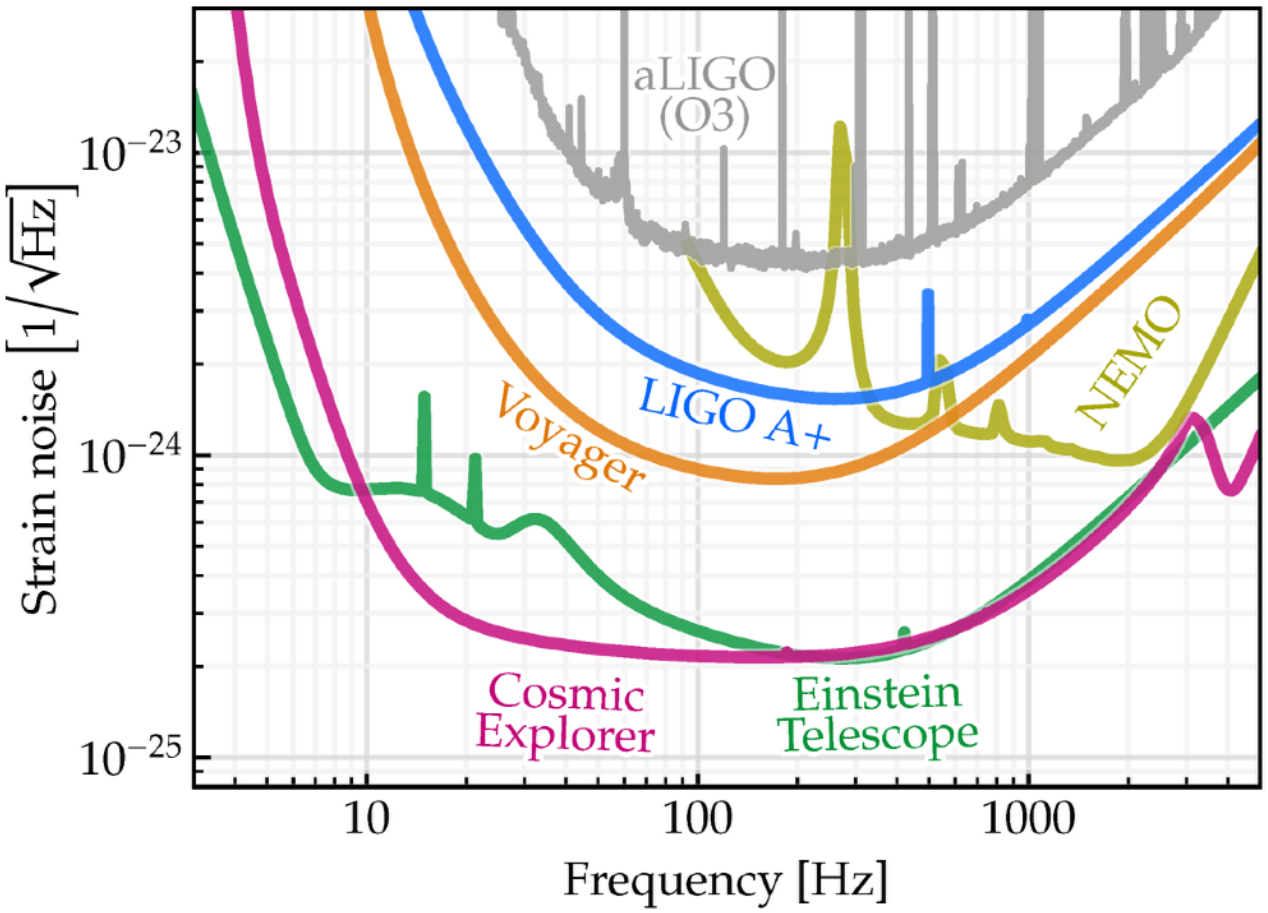




Fang and Metzger, ApJ (2017)
Metzger and Piro, MNRAS (2014)
MM and S.S. Kimura (in prep)

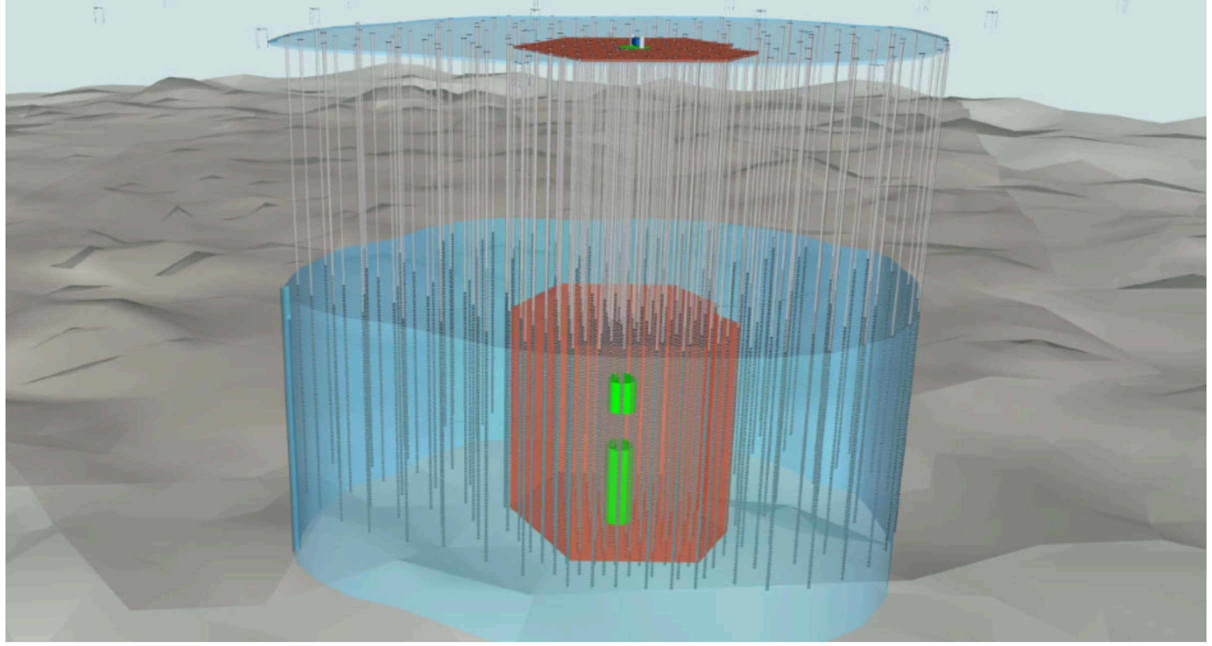
Next-generation GW and neutrino detectors





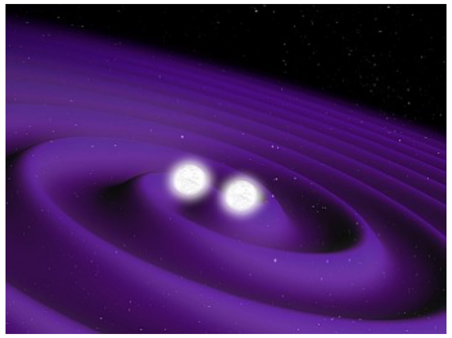
Einstein Telescope (ET)

IceCube-Gen2



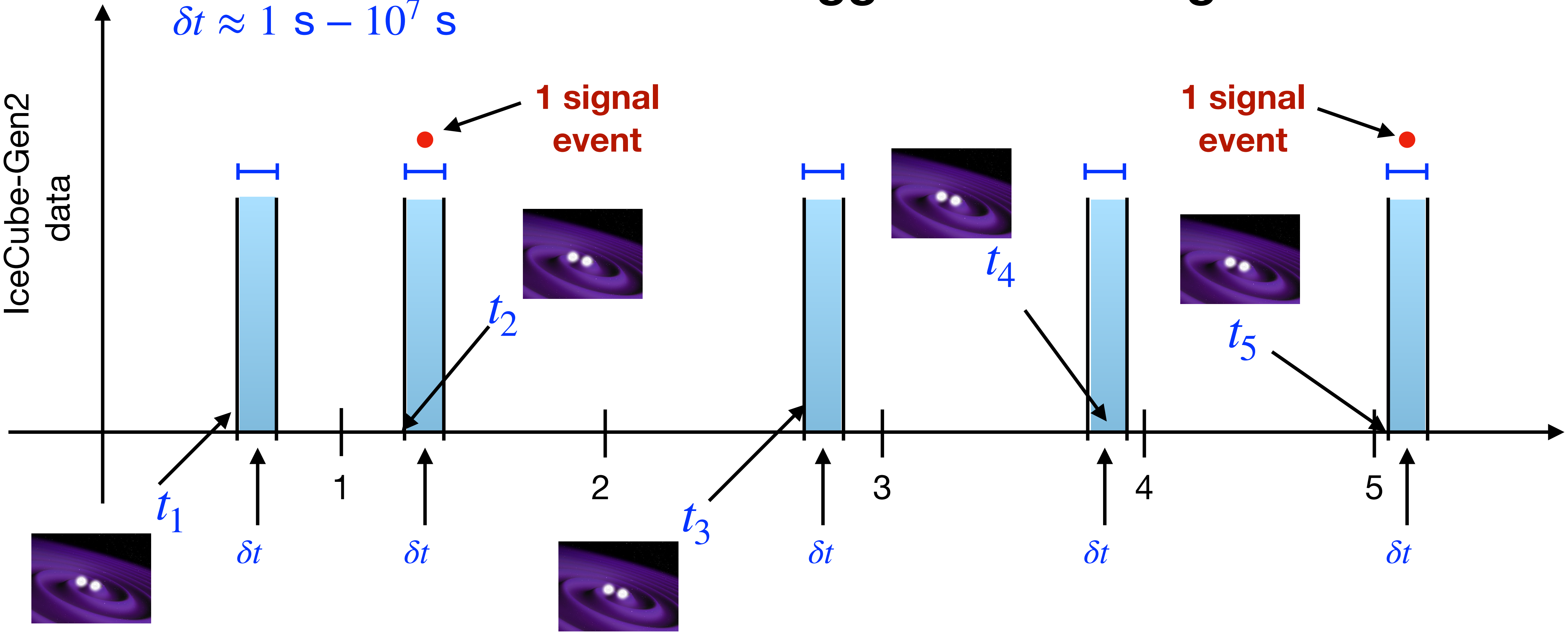
Evans et al., (2021)

Detection strategy: triggered stacking search

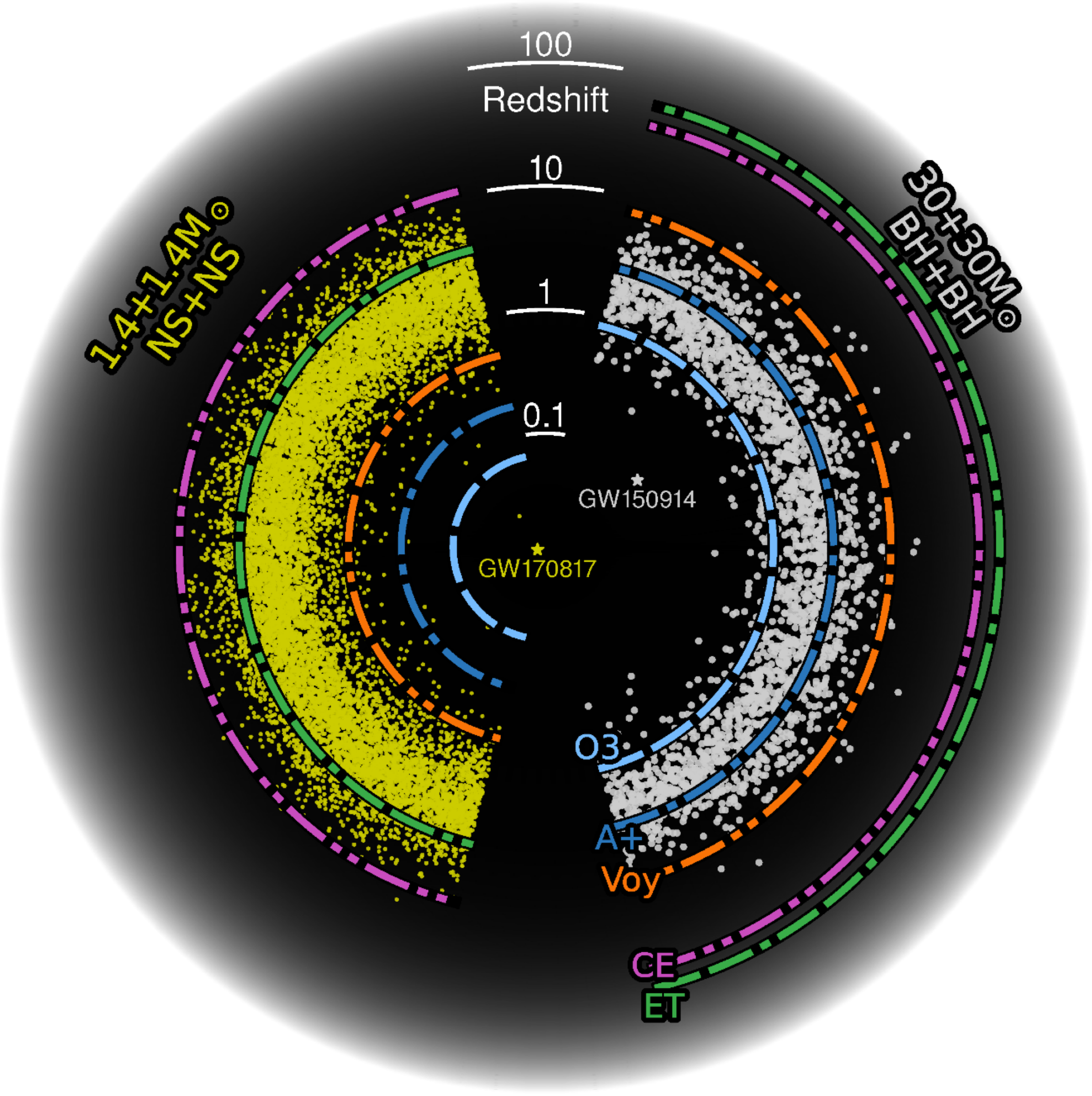


→ **Trigger from next-gen GW detectors** → **Neutrinos in IceCube-Gen 2**

Triggered-stacking searches



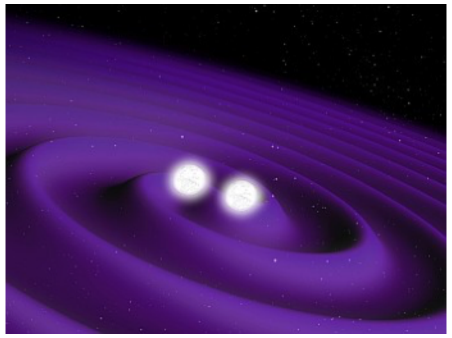
Next-generation GW detectors



Sensitive to NS-NS mergers from very high redshifts

Evans et al., (2021)

Impacts on triggered stacking searches

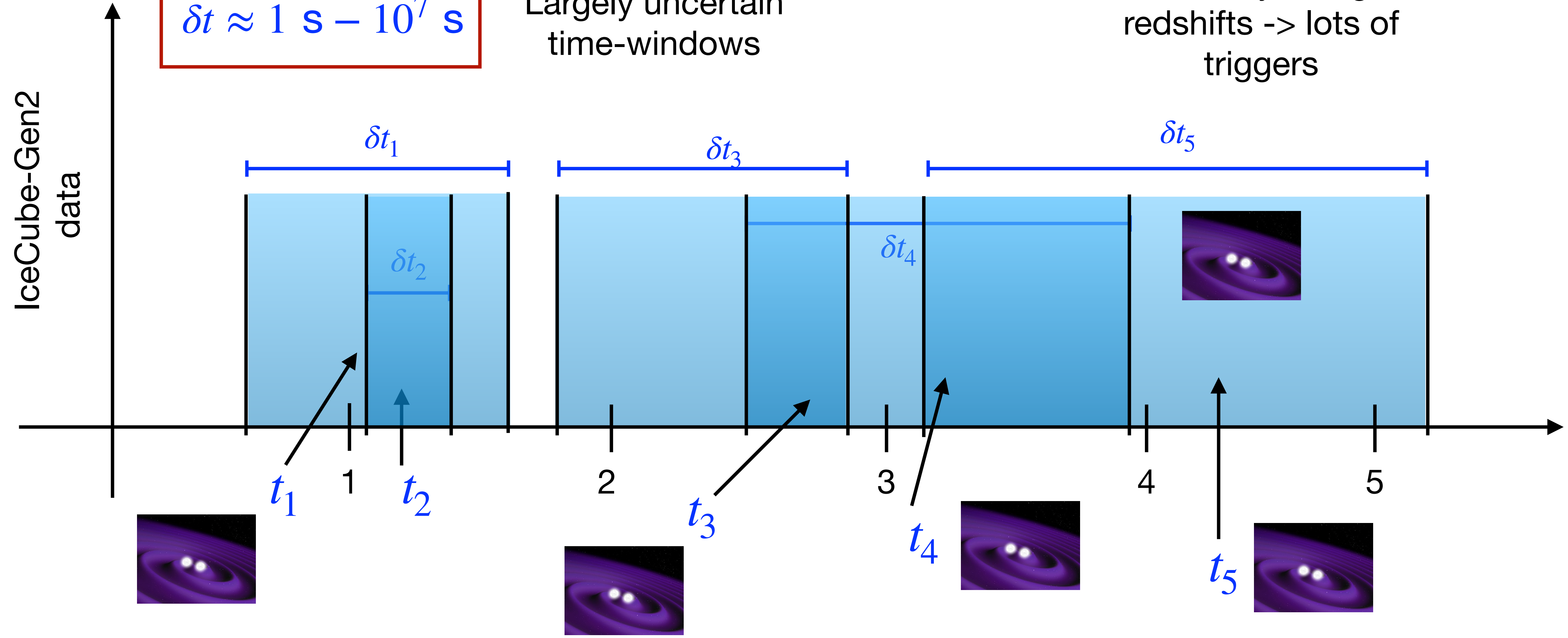


Trigger from next-gen GW detectors → **Neutrinos in IceCube-Gen 2**

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

Largely uncertain time-windows

Sensitivity to high-redshifts -> lots of triggers

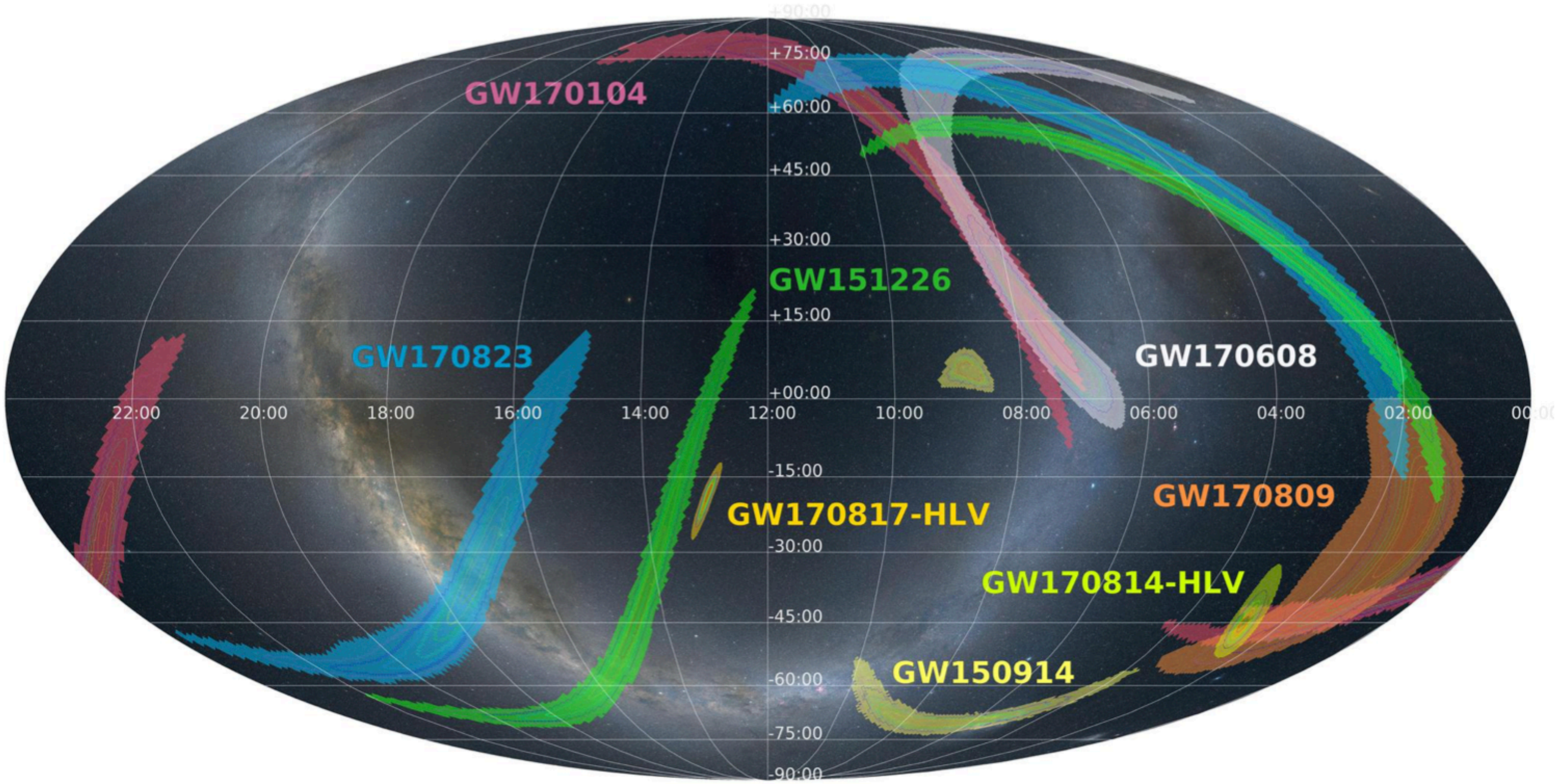


Spoils triggered stacking searches →

How do we find meaningful triggers?

Motivations: How to obtain meaningful triggers?

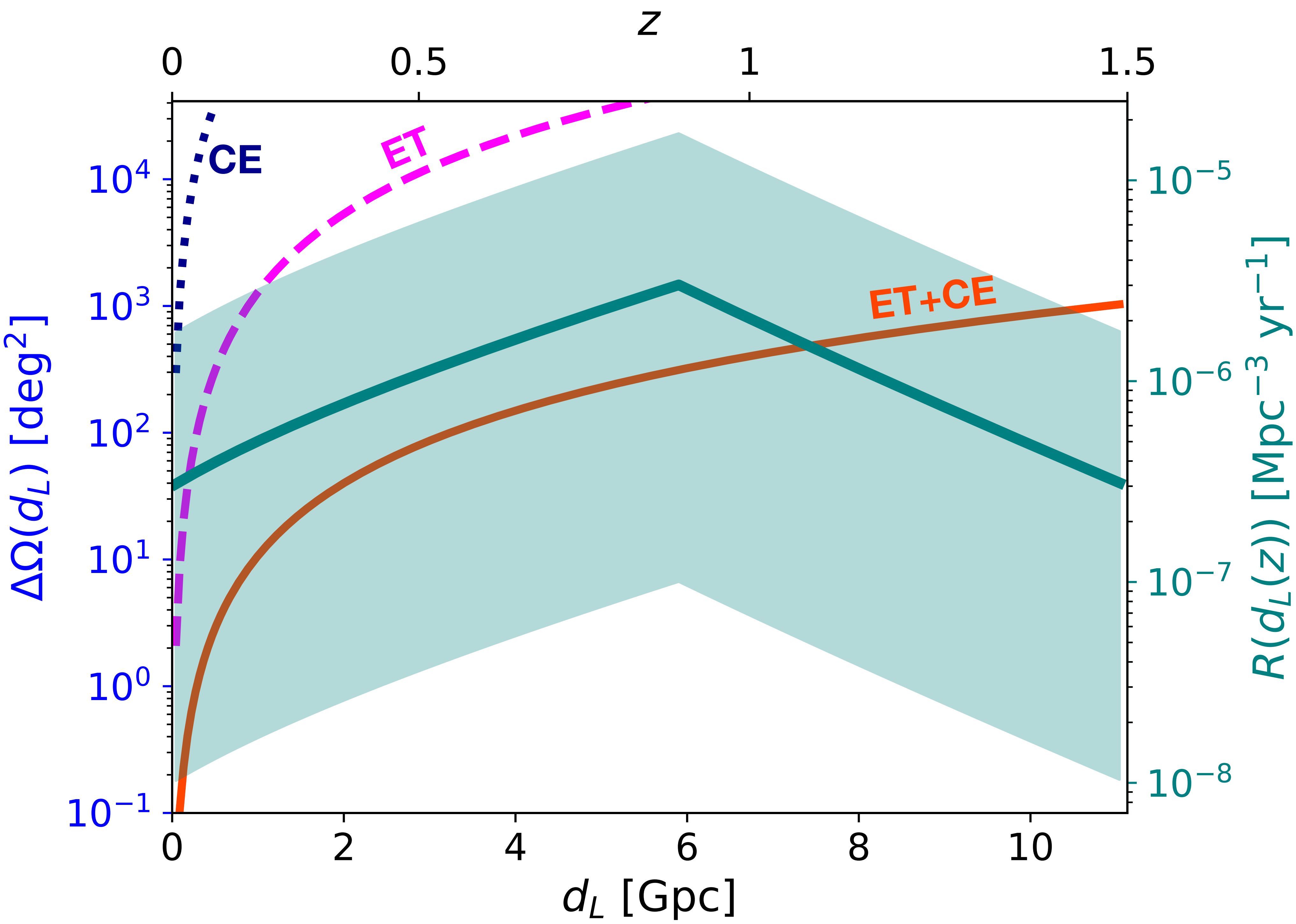
Use the sky localization capabilities of the GW detectors….



Fraction of total sky area covered → Set threshold: $f_{\rm th}$ → Obtain distance limits for GW detectors to collect meaningful triggers

Abbott et al., Liv. Rev. Rel. (2020)

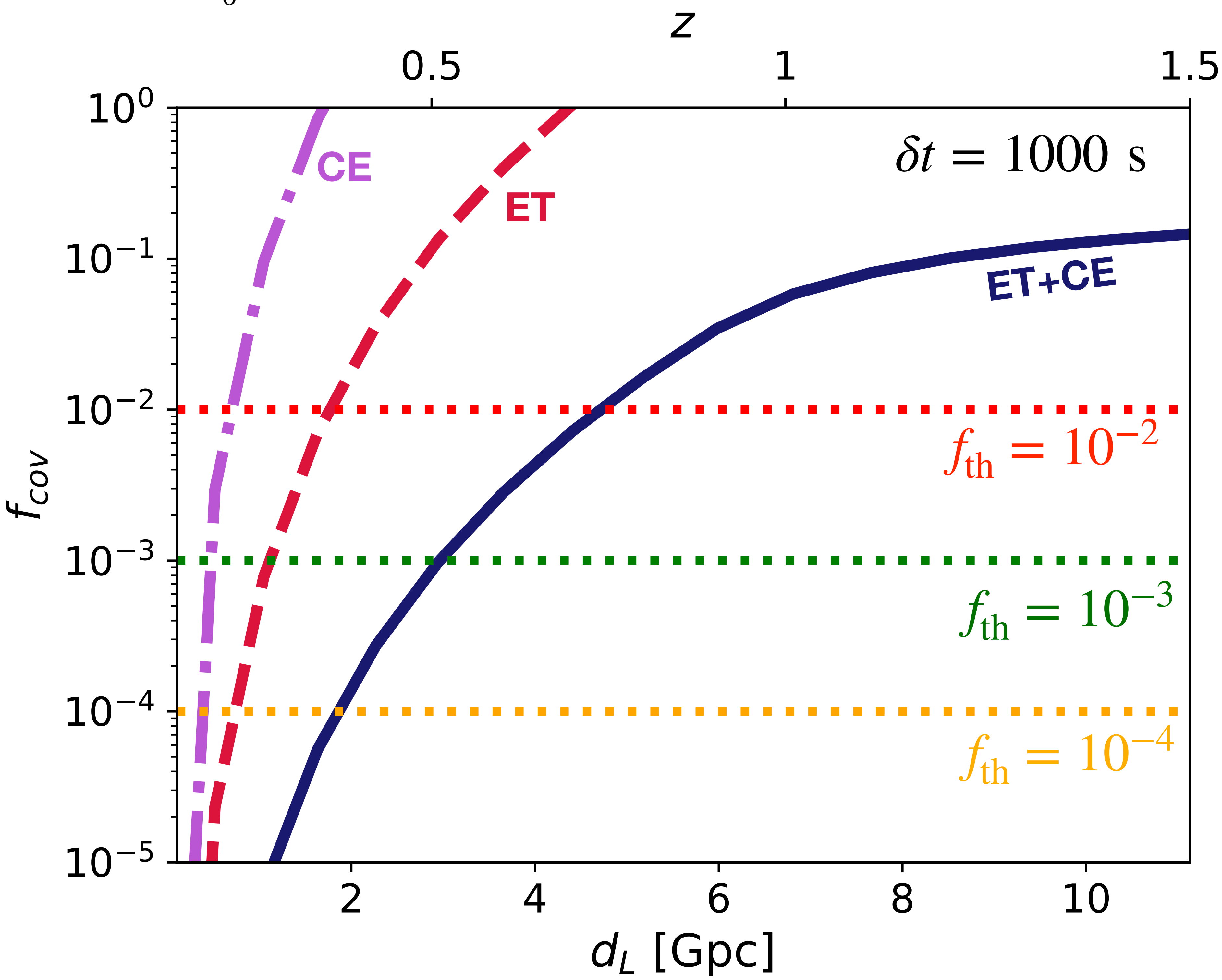
Sky localization and BNS merger rate



Chan et al., PRD (2018)
Wanderman & Piran, MNRAS (2015)

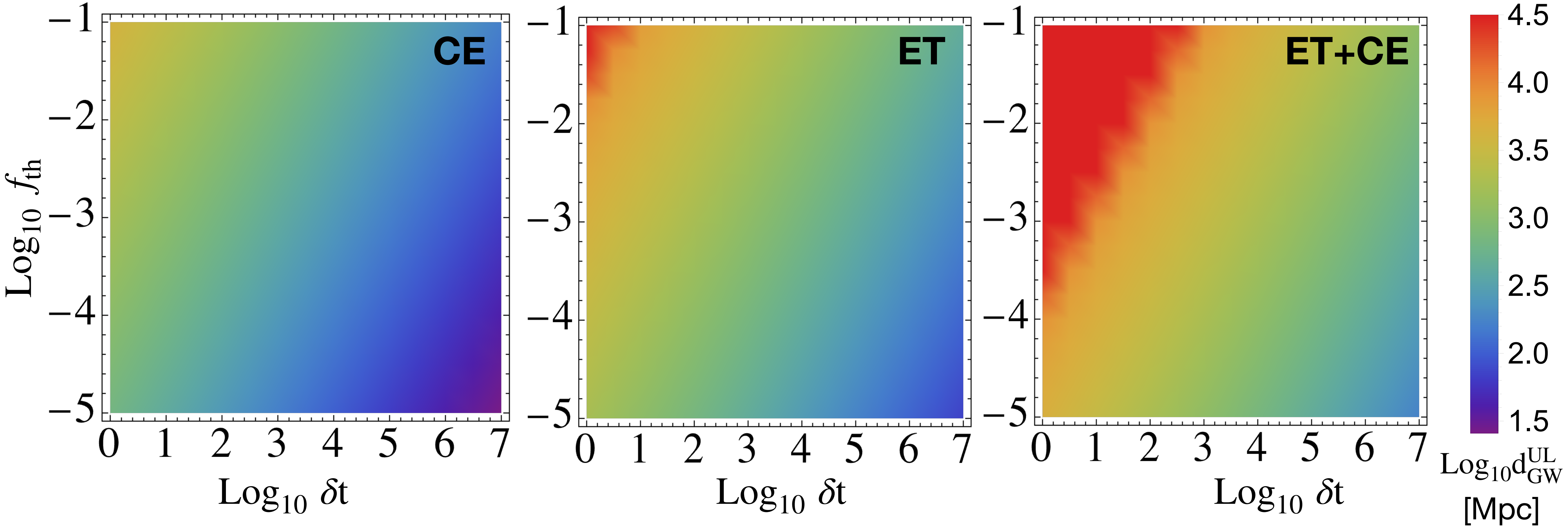
Distance limits for GW detectors

$$\int_0^{d_{\rm GW}^{\rm lim}} d\left(d_{\rm com}\right)\frac{\Delta\Omega\left(d_L\right)}{4\pi}R\left(z\right)4\pi d_{\rm com}^2\delta t = f_{\rm cov}(d_{\rm GW}^{\rm lim})$$



δt = 1000 s

Distance limits for GW detectors - $\delta t - f_{\rm th}$ plane



High energy neutrinos from BNS mergers

Probability to detect more than one neutrino associated with GW signal in T_{op}

$$q\left(d_{\rm GW}^{\rm UL}, T_{\rm op}\right) = 1 - \exp\left(- T_{\rm op} I\left(d_{\rm GW}^{\rm UL}\right)\right)$$

$$I\left(d_{\rm GW}^{\rm UL}\right) = 4\pi \int_0^{d_{\rm GW}^{\rm UL}} d(d_{\rm com}) \frac{T_{\rm op}}{\left(1+z\right)} R\left(z\right) d_{\rm com}^2 P_{n\geq 1}\left(d_L\right)$$

Probability to detect more than one neutrino

$$d_{\rm GW}^{\rm UL} = \min\left(d_{\rm GW}^{\rm lim}, d_{\rm GW}^{\rm hor}\right)$$

Depends on δt

Depends on f_ν

Assume a Poissonian probability

$$\phi_\nu(\mathscr{E}_\nu^{\rm HE,iso}, E_\nu, d_L) = \frac{(1+z)}{4\pi d_L^2} \frac{\mathscr{E}_\nu^{\rm HE,iso}}{\ln\left(\varepsilon_\nu^{\rm max}/\varepsilon_\nu^{\rm min}\right)} E_\nu^{-2}$$

The event rate is calculated is convoluting the IceCube 10 years point source effective area with the muon neutrino flux

$$\mathscr{E}_\nu^{\rm HE,iso} = \frac{\mathscr{E}_\nu^{\rm HE,true}}{f_{\rm bm}} = \left(\frac{f_\nu}{f_{\rm bm}}\right) \mathscr{E}_{\rm GW}$$

The flux is calculated assuming a $dN_\nu/dE_\nu \propto E_\nu^{-2}$spectrum.

$$\mathscr{E}_\nu^{\rm HE,true} = f_\nu \mathscr{E}_{\rm GW} \qquad \mathscr{E}_{\rm GW} \sim \alpha \mathscr{E}^{\rm tot} \qquad \alpha \sim 1\,\%$$

Results - varying f_ν and δt

f_ν

10^{-5}

5×10^{-5}

Fiducial Parameters:

$f_\nu = 2.5 \times 10^{-5}$

$\delta t = 1000 \ \mathrm{s}$

$E^{\mathrm{tot}} \sim 5 \times 10^{54} \mathrm{erg}$

Motivated by physical models

$1 \ \mathrm{s}$

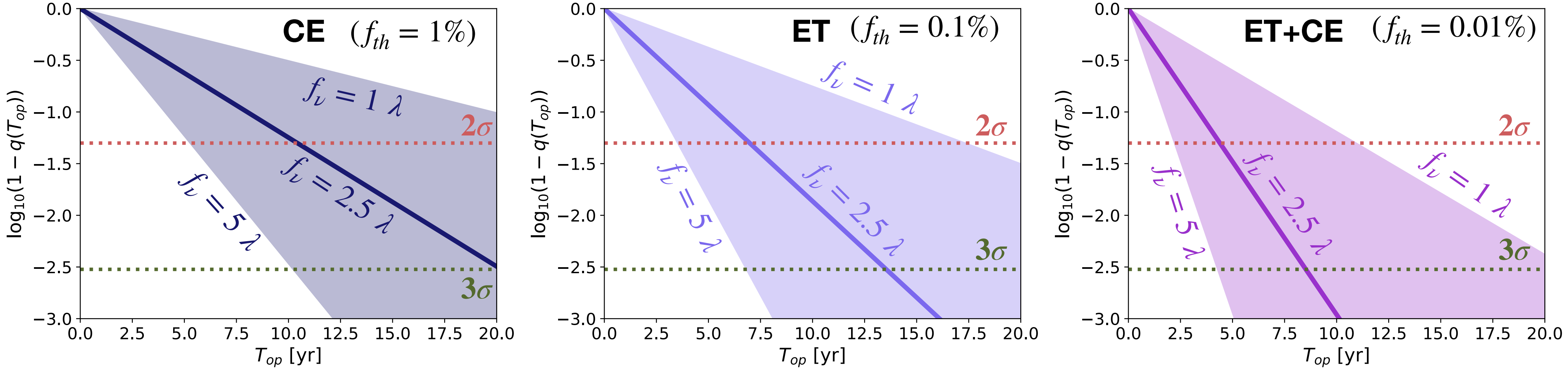
$10^6 \ \mathrm{s}$

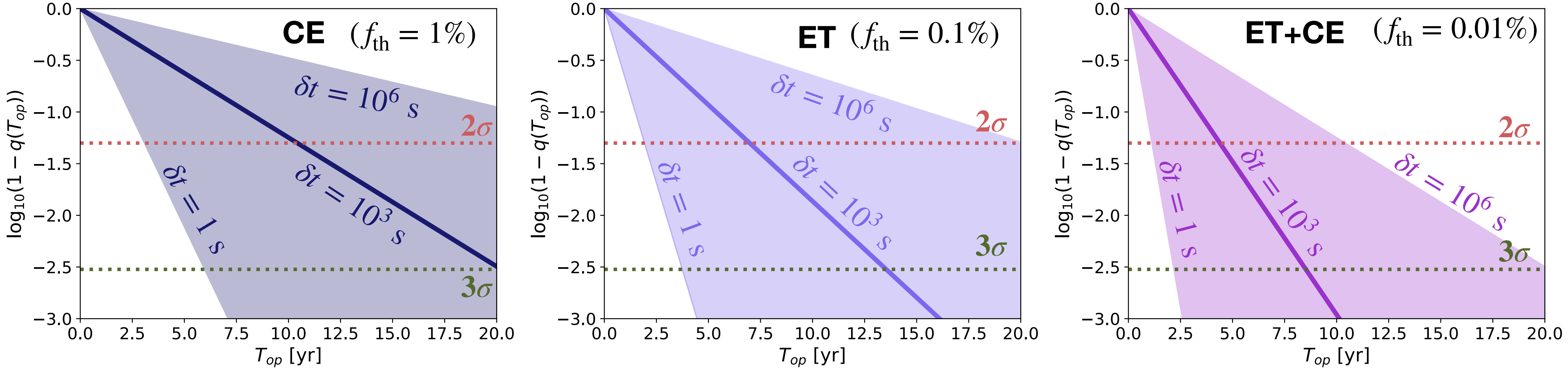
δt

Results - varying f_ν and δt

f_ν

$\delta t = 1000$ s



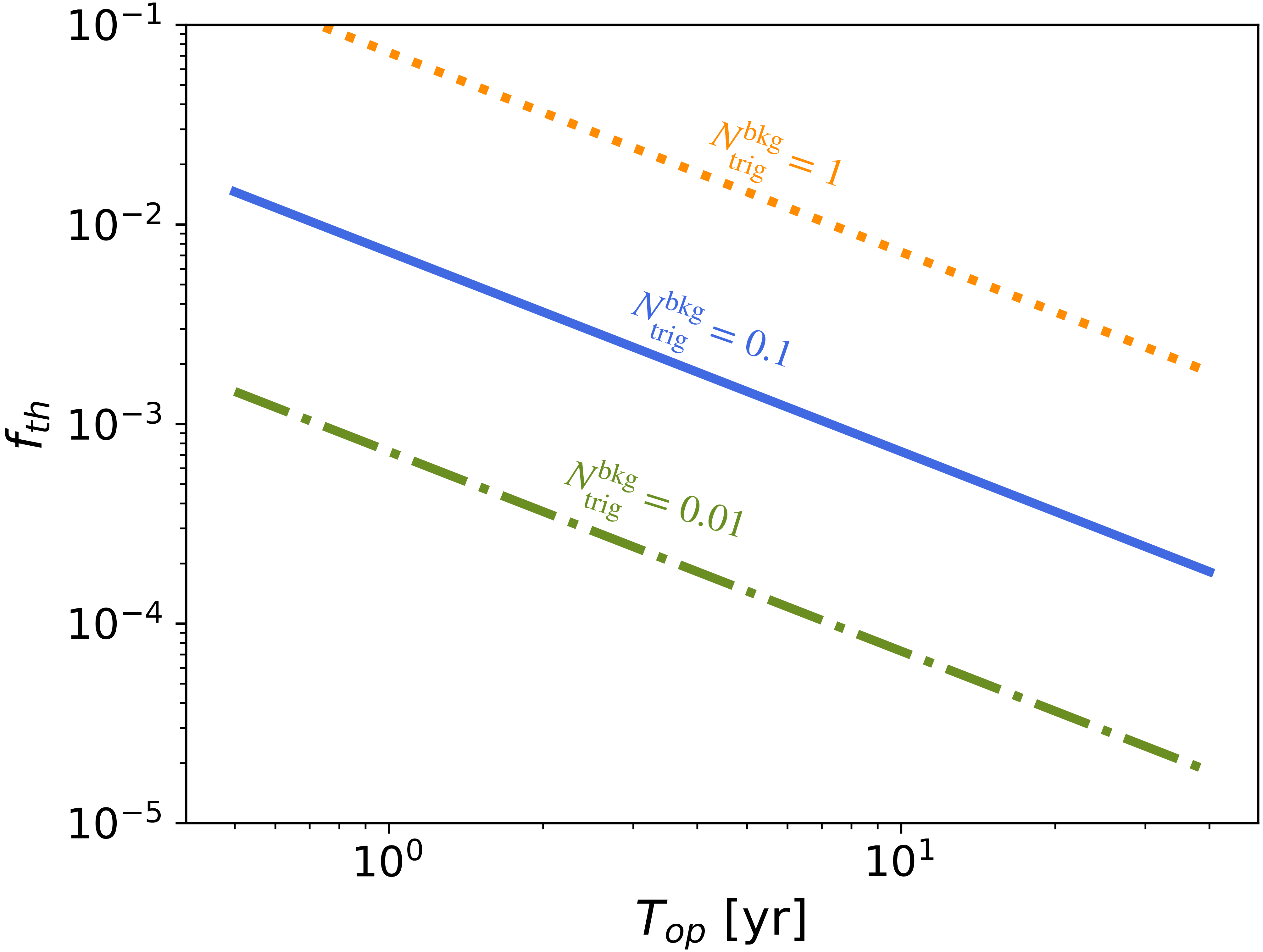


$f_\nu = 2.5\ \lambda$

δt

$\lambda = 10^{-5}$

Backgrounds



Takeaways

Part 1: Multi-messneger signatures of choked delayed jets in TDEs

Late time activity associated with the SMBH from observations:

- Delayed radio flares
- Coinicident neutrino detections: arrival after ~ 150 days, ~ 393 days, and 148 days post the optical peaks for AT2019dsg, AT2019fdr and AT2019aalc, respectively

Possibility of choked delayed jets

- Spherical debris envelope surrounding the SMBH, expanding outwards possibly driven by wind.
- Jet-cocoon interactions: collimation and choking - Higher delay times and debris velocities help with choking

Electromagnetic and neutrino signatures

- Synchrotron radiation from delayed choked jets: Reverse shock: slow and fast cooling cases
- Optical and X-ray observatories: good prospects, radio observations seem likely as well.
- Can explain the coincident observations by IceCube - AT2019dsg and AT2019aalc with this scenario of choked delayed jets.

Part 2: GW triggered searches for high energy neutrinos from BNS mergers: prospects for next-gen

- ET+CE can give coincident neutrino events or 3σ level constraints on the parameter space, due to extremely good sky localization capabilities over a timescale of ~ 20 years even for the less optimistic scenarios.

- ET can lead to 2σ constraints owing to its good sky localization capabilities over a time scale of 20 - 30 years for the less optimistic cases. CE has comparatively poor sky localization and hence may be good for coincident detections or 2σ-level constraints over reasonable time scales for optimistic parameters.

- Our analysis can constrain f_ν for a population of BNS sources: understanding emissions from BNS mergers

- Model independent analysis can help constrain models: neutrinos from choked jet scenarios and hence provide insights regarding GRB jets, neutrino emission sites and mechanisms.

Thank You!

Backup

What are TDEs?

The shredding apart of a star when it comes close to a SMBH, due to its tidal forces

Disruption starts

↓

~ Half the debris is lost: Unbound orbit

~ Half the debris falls back: Bound orbit

↓

Debris circularizes

↓

Part of the debris may form an accretion disk → Winds, Outflows, etc.

(Timescales are also uncertain)

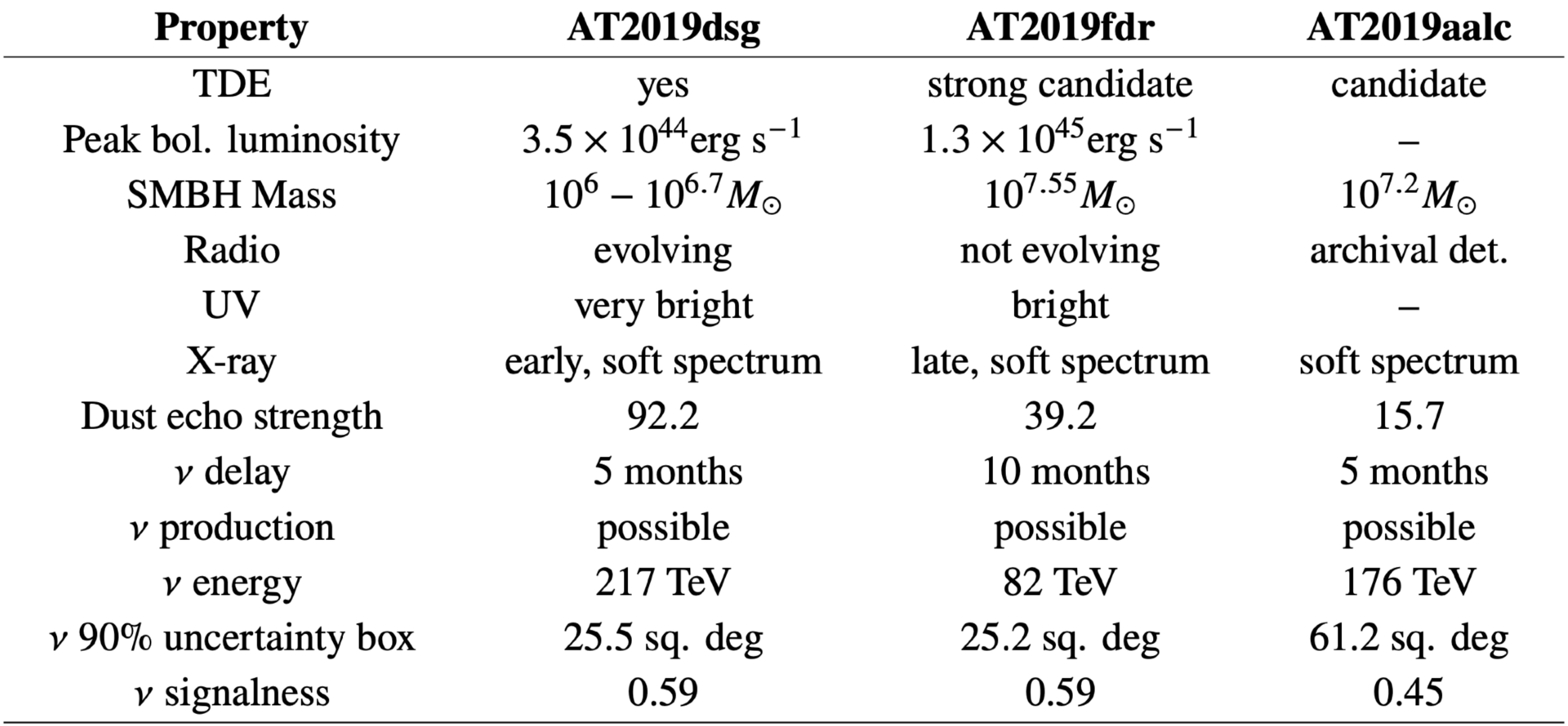
Tidal disruption radius: $\mathbf{R_T = R_* \frac{M_{BH}}{M_*}}$

Fallback time: $\mathbf{t_{fb} = 2\pi\sqrt{a^3_{min}/(GM_{BH})}}$

Semi-major axis: $\mathbf{a_{min} \approx R^2_T/(2R_*)}$

Circularization radius: $\mathbf{R_{circ} = 2R_T}$

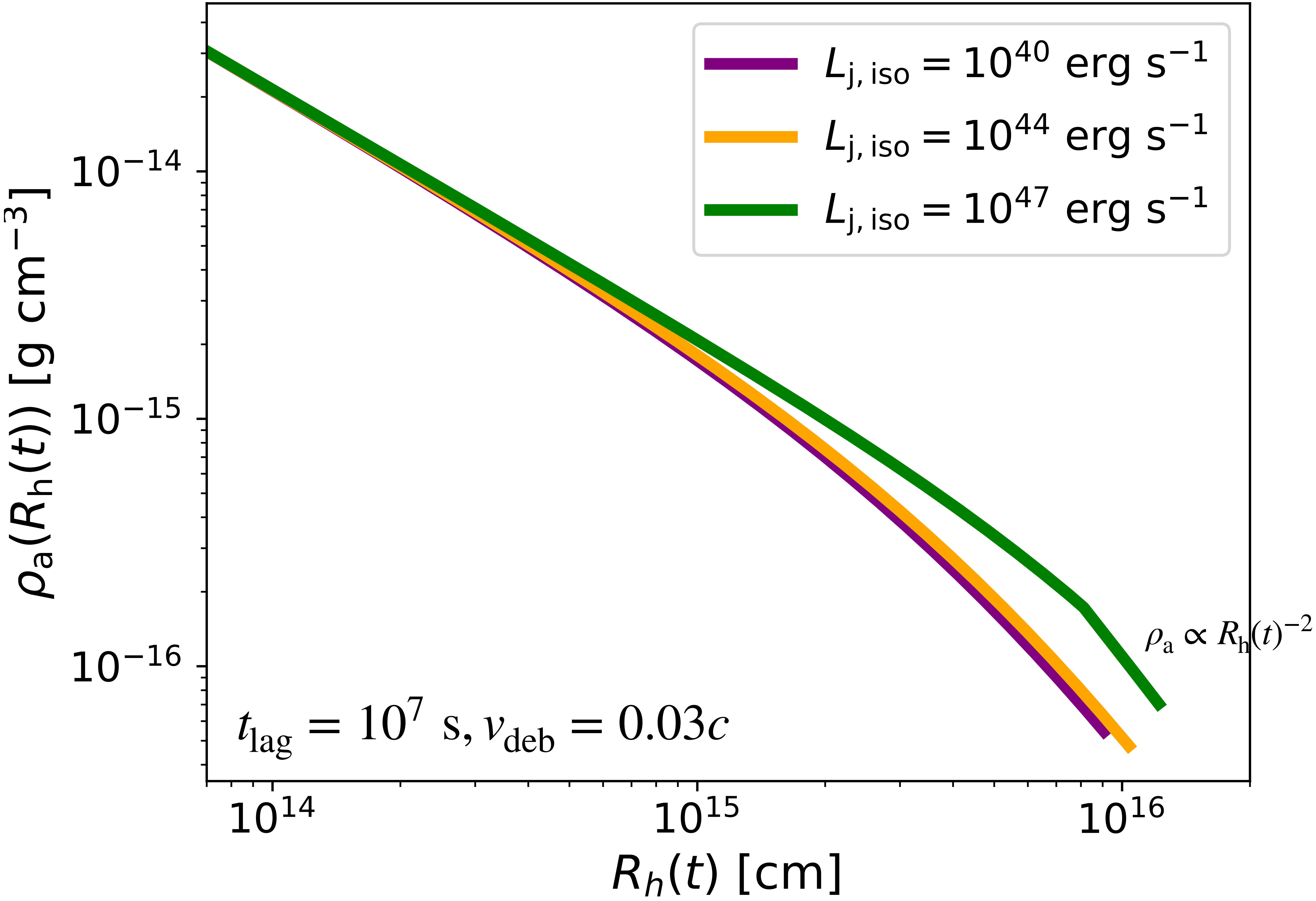
The neutrino associations



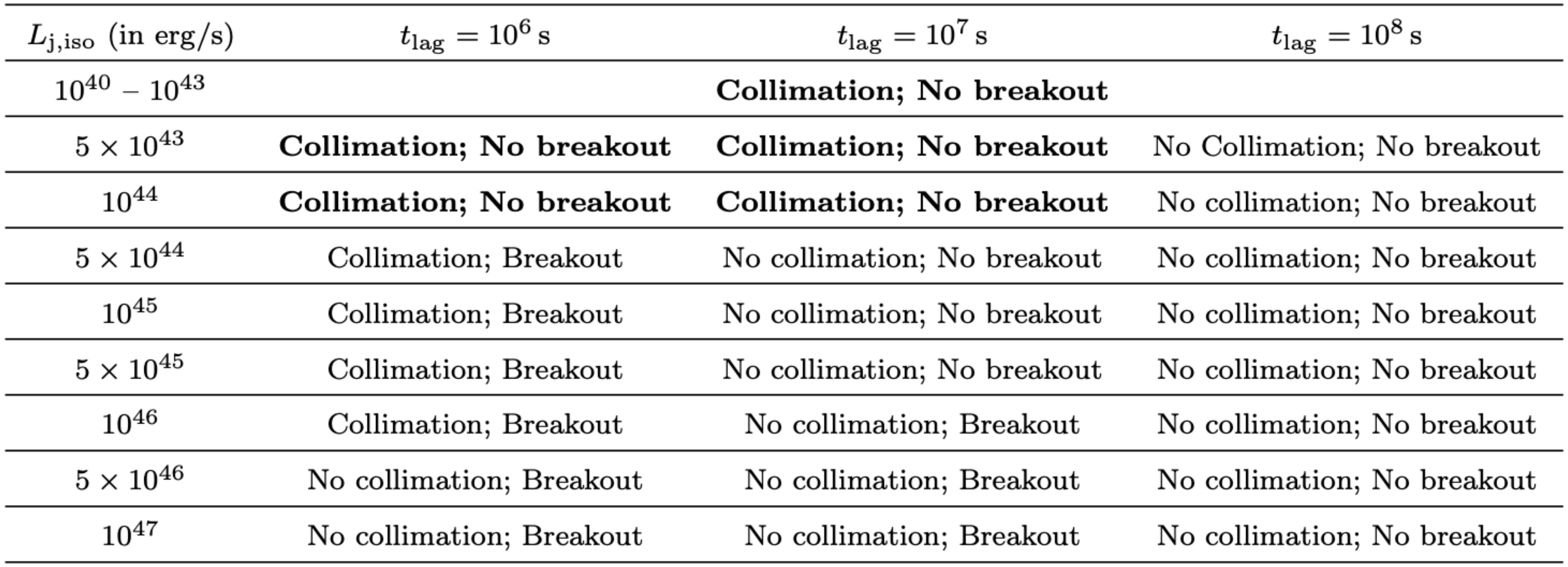
Property	AT2019dsg	AT2019fdr	AT2019aalc
TDE	yes	strong candidate	candidate
Peak bol. luminosity	3.5×10^{44}erg s^{-1}	1.3×10^{45}erg s^{-1}	–
SMBH Mass	$10^6 - 10^{6.7} M_\odot$	$10^{7.55} M_\odot$	$10^{7.2} M_\odot$
Radio	evolving	not evolving	archival det.
UV	very bright	bright	–
X-ray	early, soft spectrum	late, soft spectrum	soft spectrum
Dust echo strength	92.2	39.2	15.7
ν delay	5 months	10 months	5 months
ν production	possible	possible	possible
ν energy	217 TeV	82 TeV	176 TeV
ν 90% uncertainty box	25.5 sq. deg	25.2 sq. deg	61.2 sq. deg
ν signalness	0.59	0.59	0.45

Reusch ECRS 2022 (arXiv: 2307.00902)

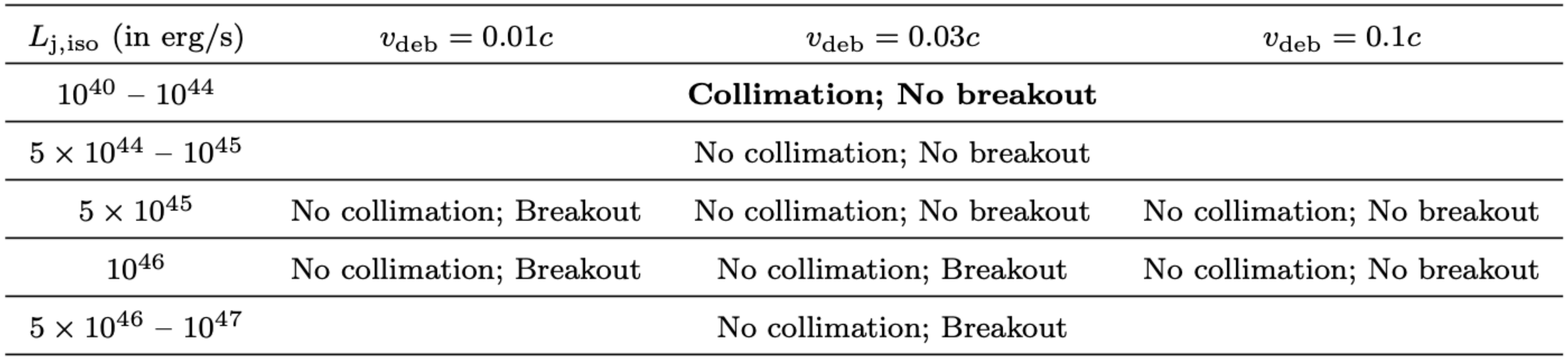
Ambient medium density (ρ_a)



Dynamics: the land of choked jets



$L_{\mathrm{j,iso}}$ (in erg/s)	$t_{\mathrm{lag}} = 10^6$ s	$t_{\mathrm{lag}} = 10^7$ s	$t_{\mathrm{lag}} = 10^8$ s
$10^{40} - 10^{43}$	**Collimation; No breakout**		
5×10^{43}	**Collimation; No breakout**	**Collimation; No breakout**	No Collimation; No breakout
10^{44}	**Collimation; No breakout**	**Collimation; No breakout**	No collimation; No breakout
5×10^{44}	Collimation; Breakout	No collimation; No breakout	No collimation; No breakout
10^{45}	Collimation; Breakout	No collimation; No breakout	No collimation; No breakout
5×10^{45}	Collimation; Breakout	No collimation; No breakout	No collimation; No breakout
10^{46}	Collimation; Breakout	No collimation; Breakout	No collimation; No breakout
5×10^{46}	No collimation; Breakout	No collimation; Breakout	No collimation; No breakout
10^{47}	No collimation; Breakout	No collimation; Breakout	No collimation; No breakout



$L_{\mathrm{j,iso}}$ (in erg/s)	$v_{\mathrm{deb}} = 0.01c$	$v_{\mathrm{deb}} = 0.03c$	$v_{\mathrm{deb}} = 0.1c$
$10^{40} - 10^{44}$	**Collimation; No breakout**		
$5 \times 10^{44} - 10^{45}$	No collimation; No breakout		
5×10^{45}	No collimation; Breakout	No collimation; No breakout	No collimation; No breakout
10^{46}	No collimation; Breakout	No collimation; Breakout	No collimation; No breakout
$5 \times 10^{46} - 10^{47}$	No collimation; Breakout		

Electromagnetic (EM) signatures

$$\nu_\alpha^{\mathrm{ES}} = \frac{3}{4\pi}\frac{eB^{\mathrm{ES}}}{m_e c}\frac{\Gamma^{\mathrm{ES}}}{(1+z)}\left(\gamma_\alpha^{\mathrm{ES}}\right)^2$$

ES: External shock can be Forward or Reverse shock region

α: Can be injection frequency (m) or cooling frequency (c)

B: Magnetic field strength in the region

Γ: Bulk Lorentz factor in the shocked region

γ: Lorentz factor associated with the electrons

The absorption frequency ν_{sa} is given by setting the synchrotron self-absorption optical depth to 1

$$B^{\mathrm{ES}} = \left[32\pi\underset{\uparrow}{\epsilon_B}\Gamma^{\mathrm{ES}}(\Gamma^{\mathrm{ES}}-1)n^{\mathrm{ES}}m_p c^2\right]^{1/2}$$

Fraction of electron energy converted
to magnetic field energy