Multi-messenger view of Transients

Astrophysical inferences for Gamma Ray Bursts and Kilonovae

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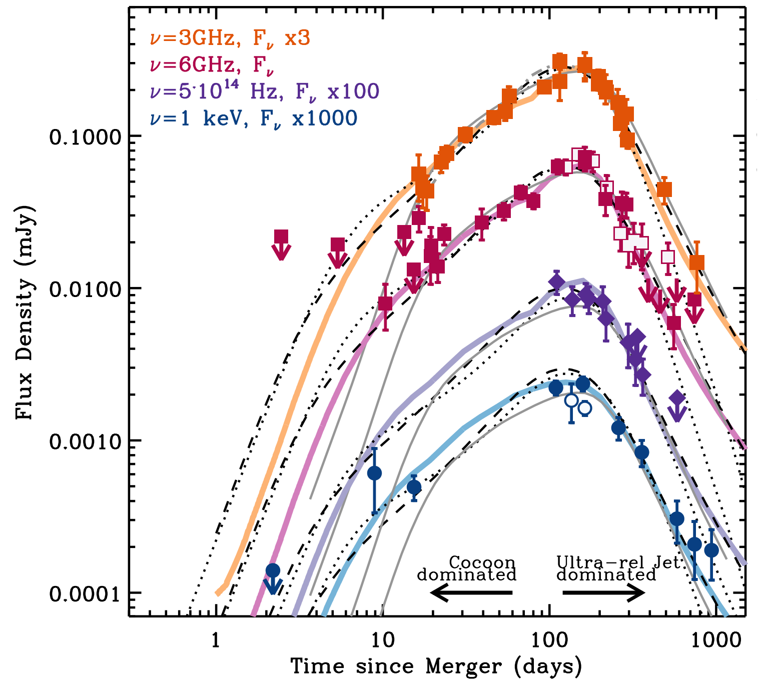
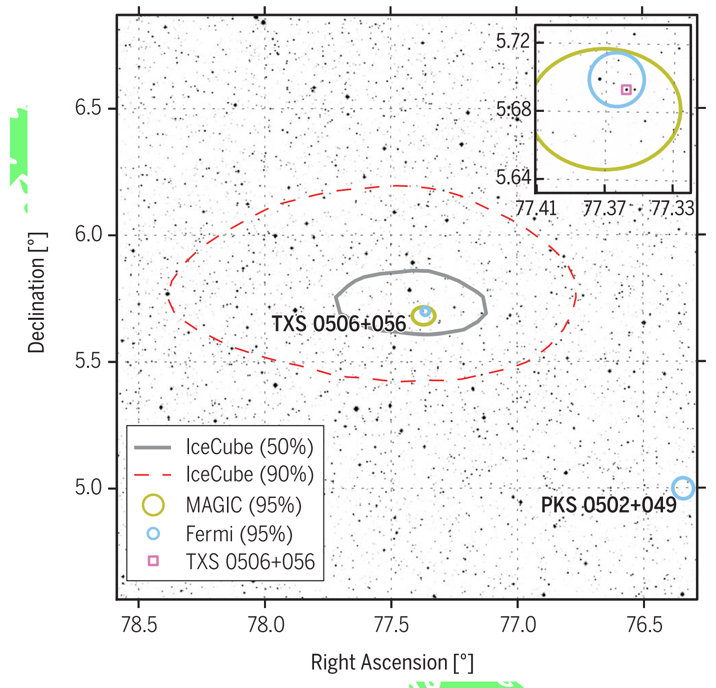
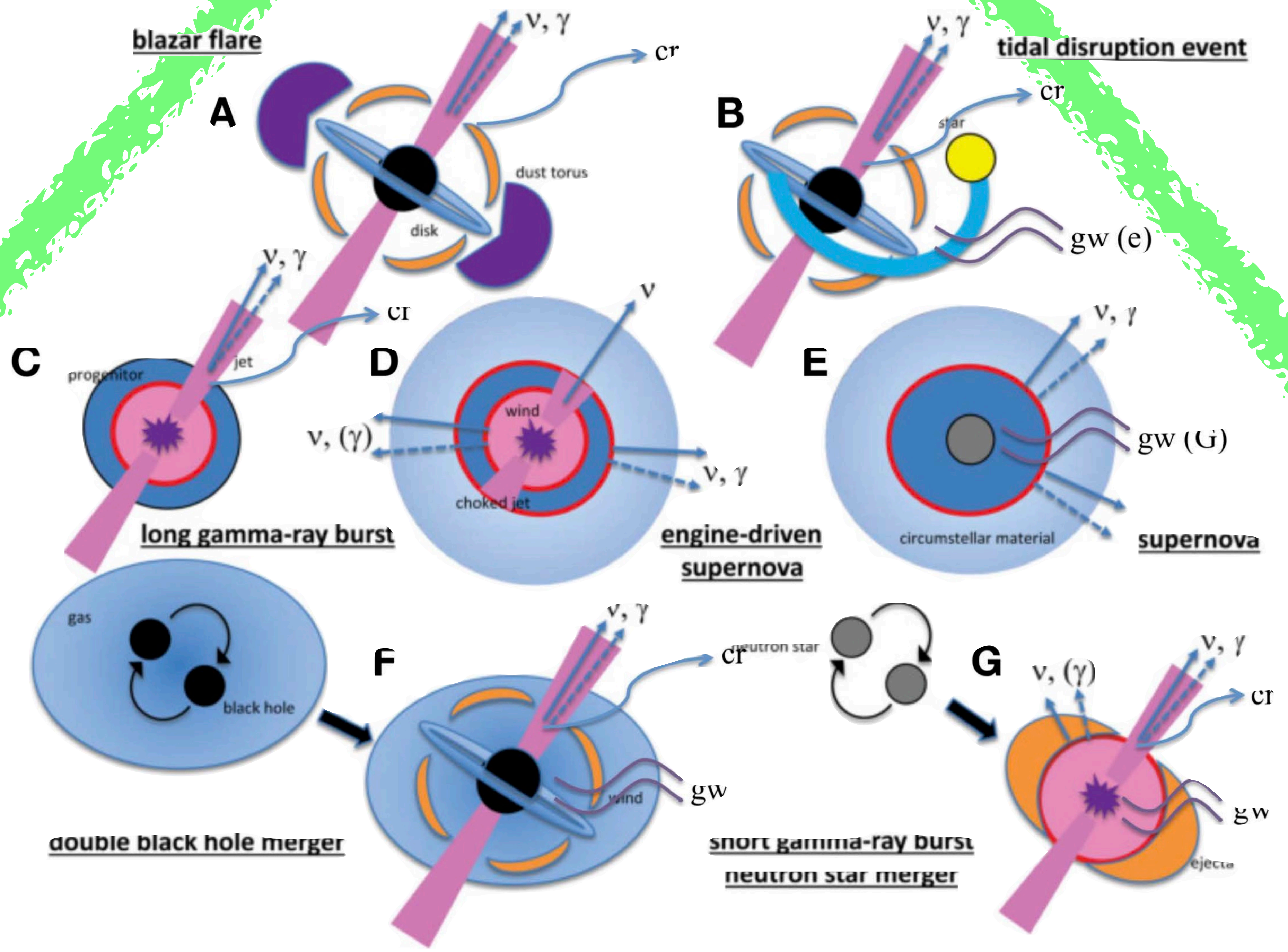
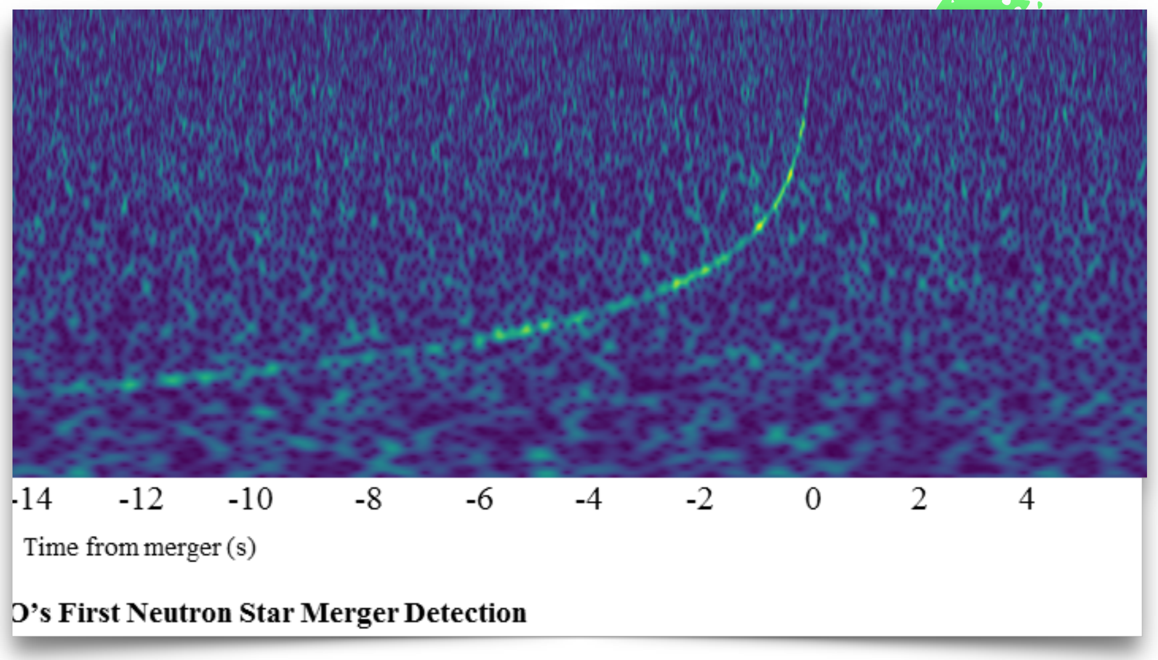
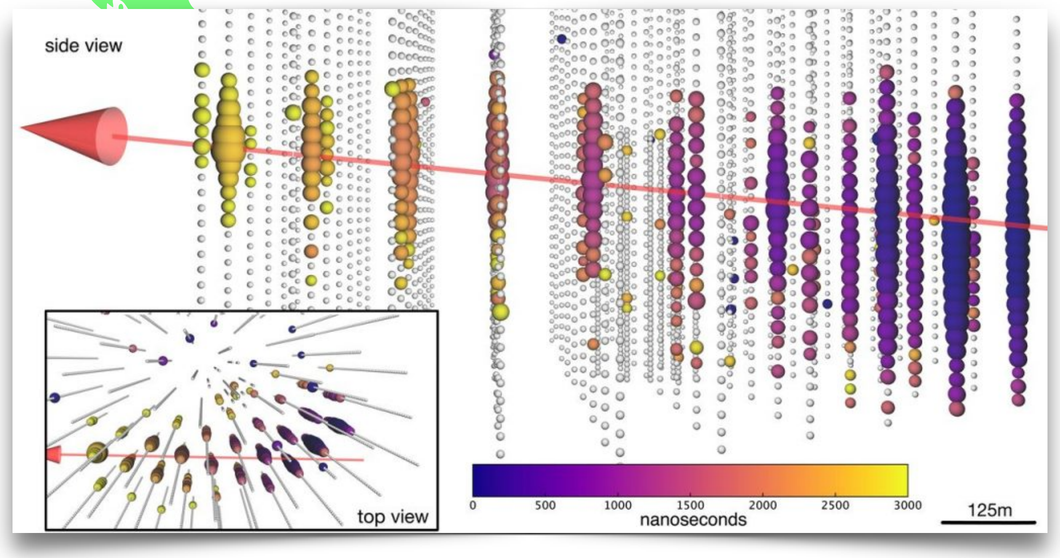
Multi-messenger astronomy





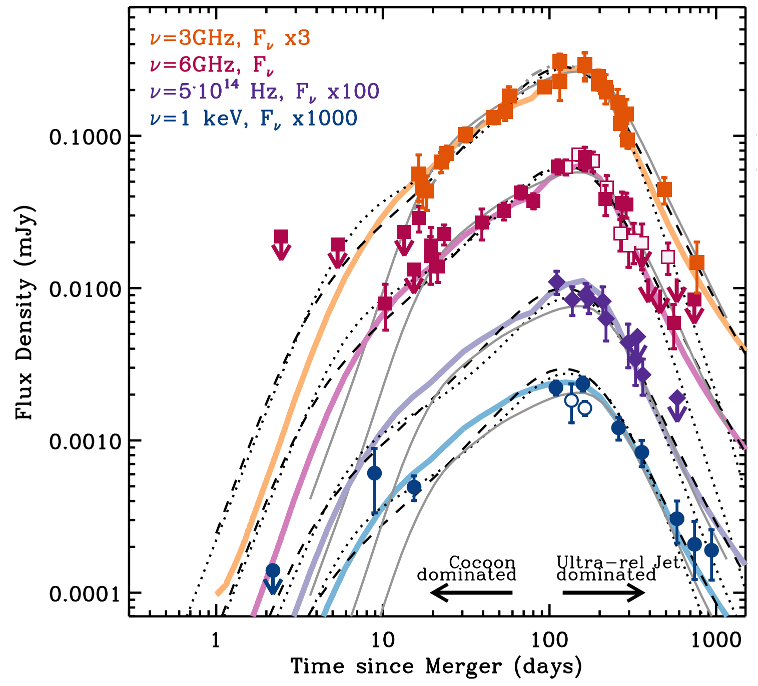


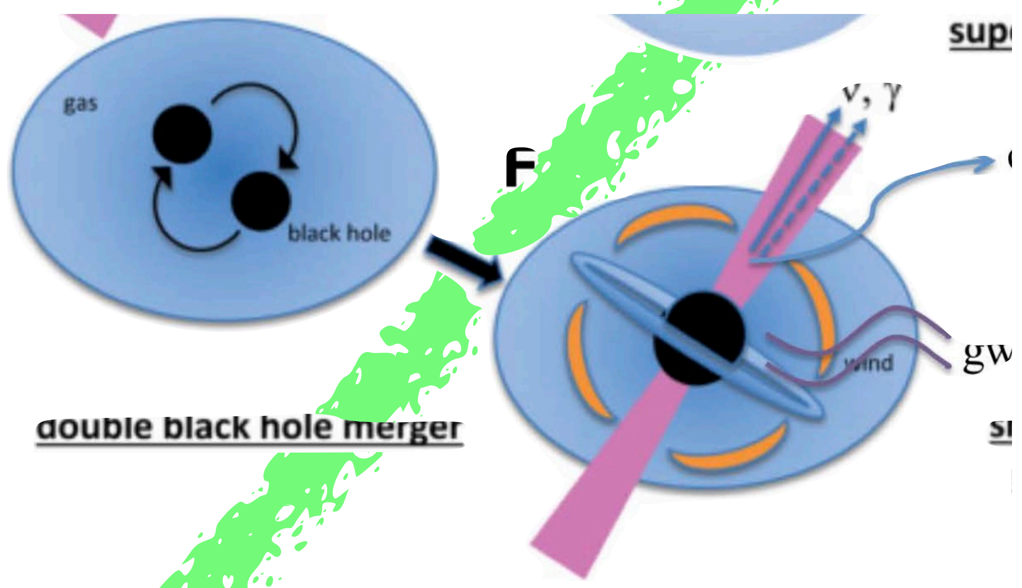


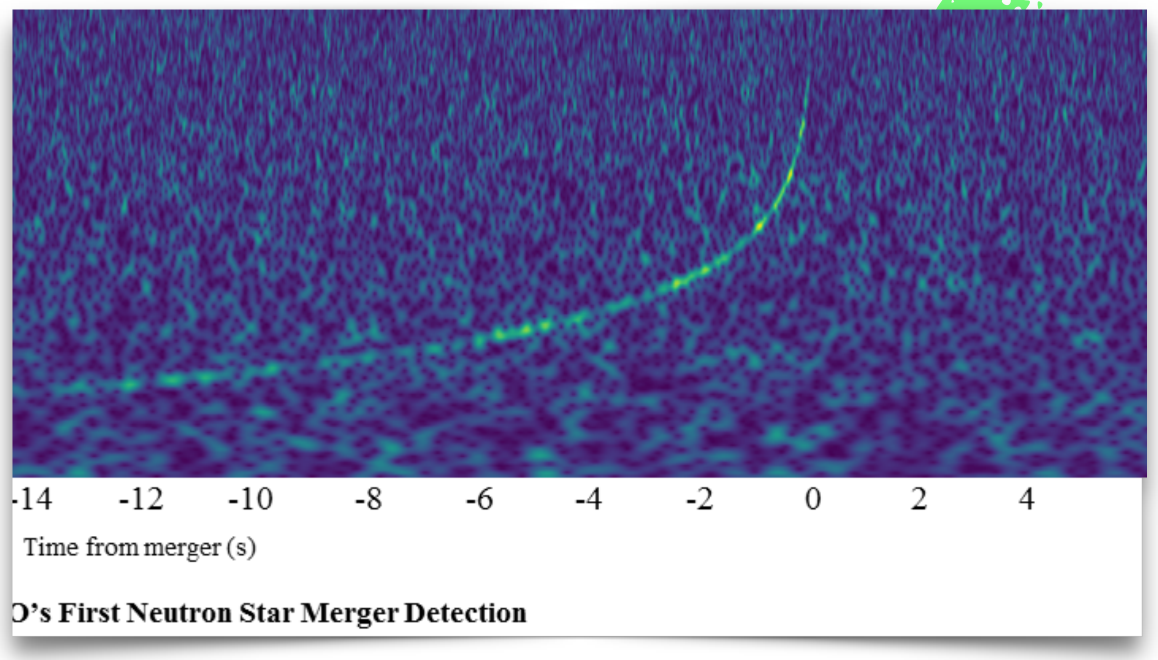


P. Meszaros 2019 for a short review

Multi-Messenger: gravitational waves and light







Astrophysics

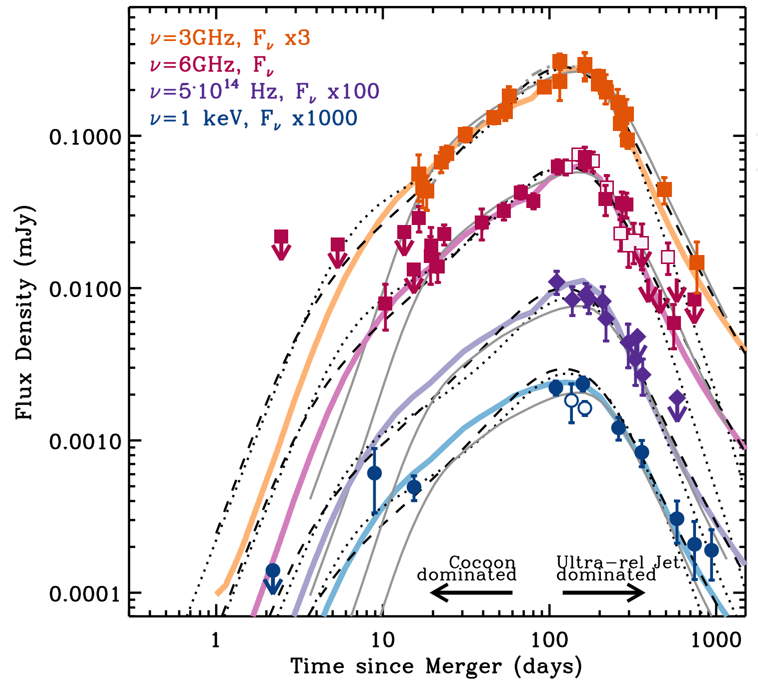
Cosmology

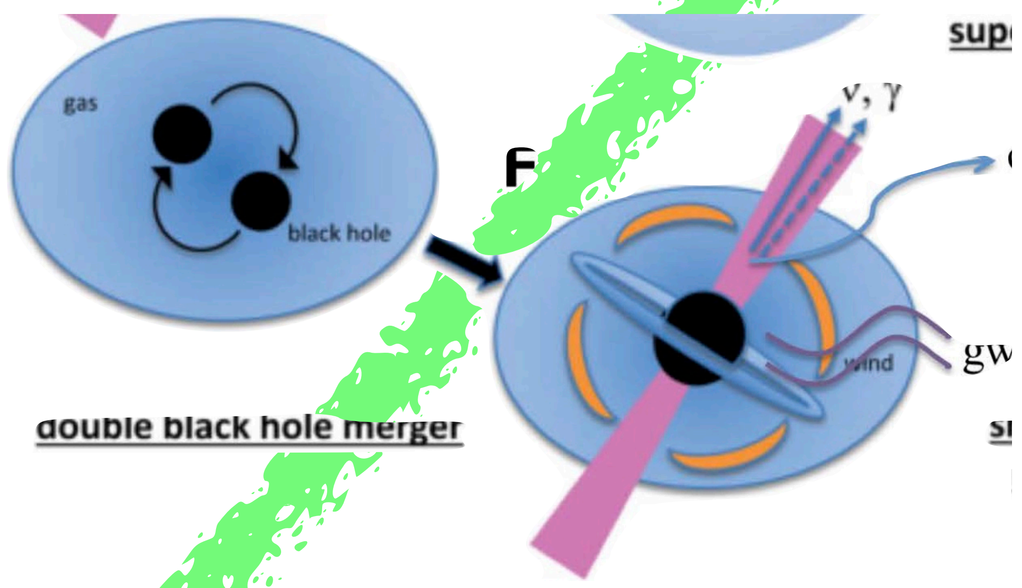
Fundamental physics

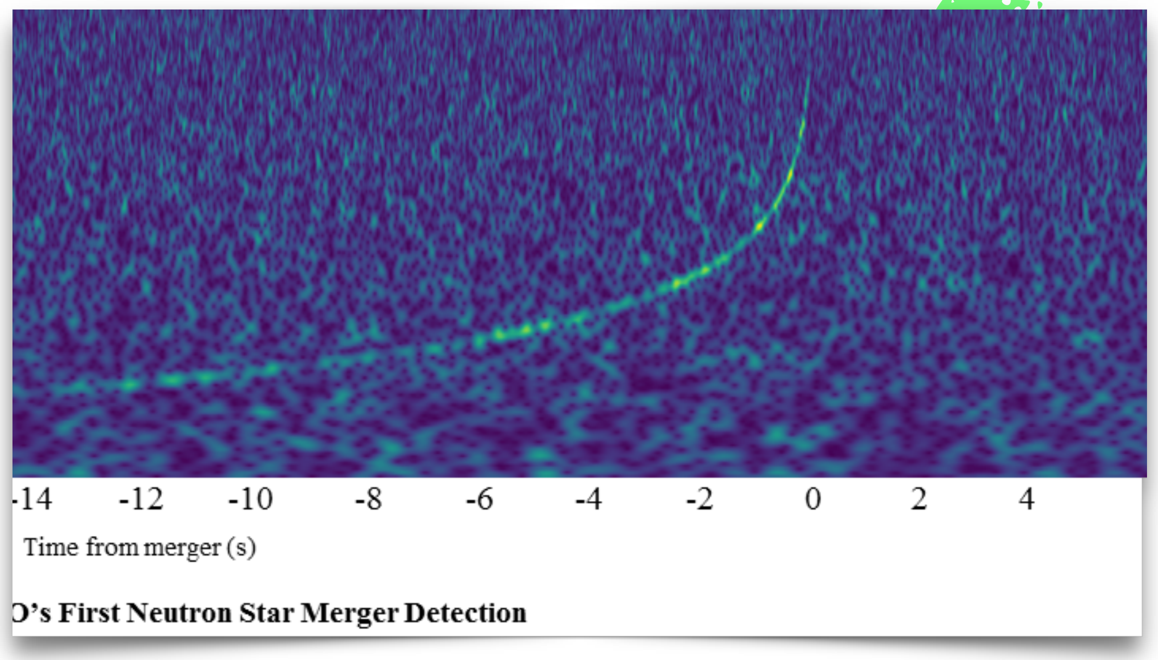
Multi-Messenger: gravitational waves and light

TOC

- What learned (170817)
- What is ahead
- A change of perspective





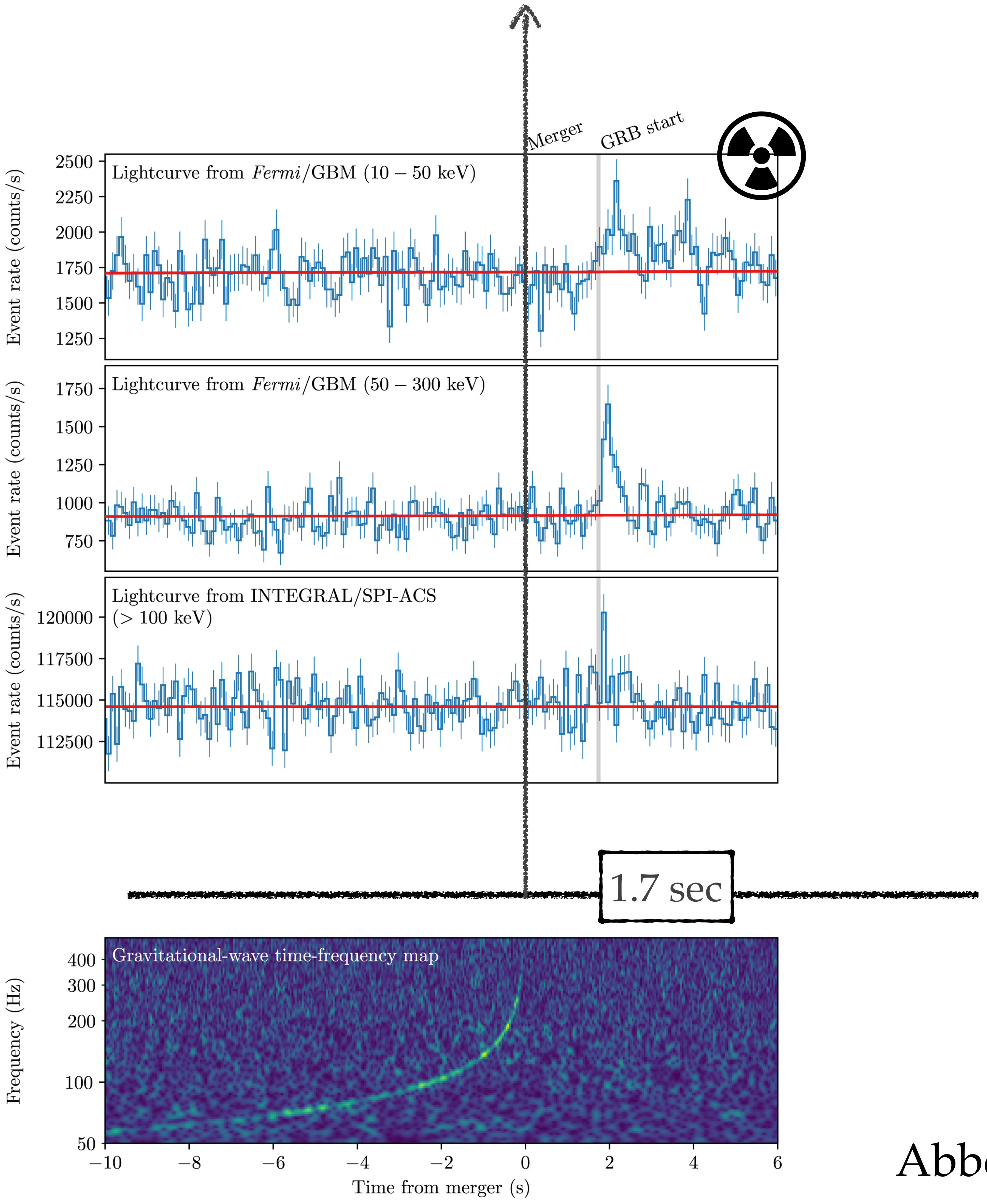


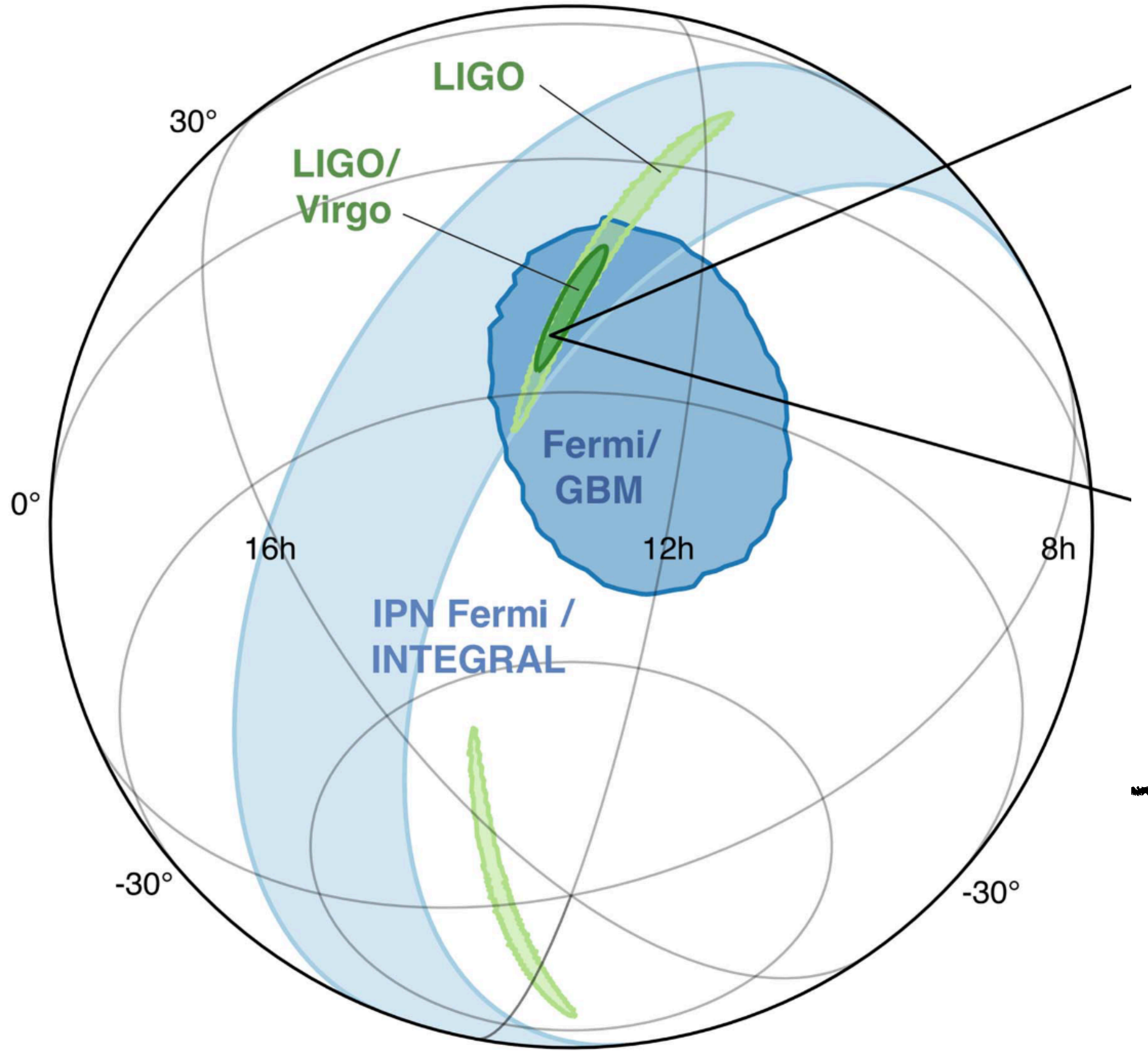
Astrophysics

Cosmology

Fundamental physics

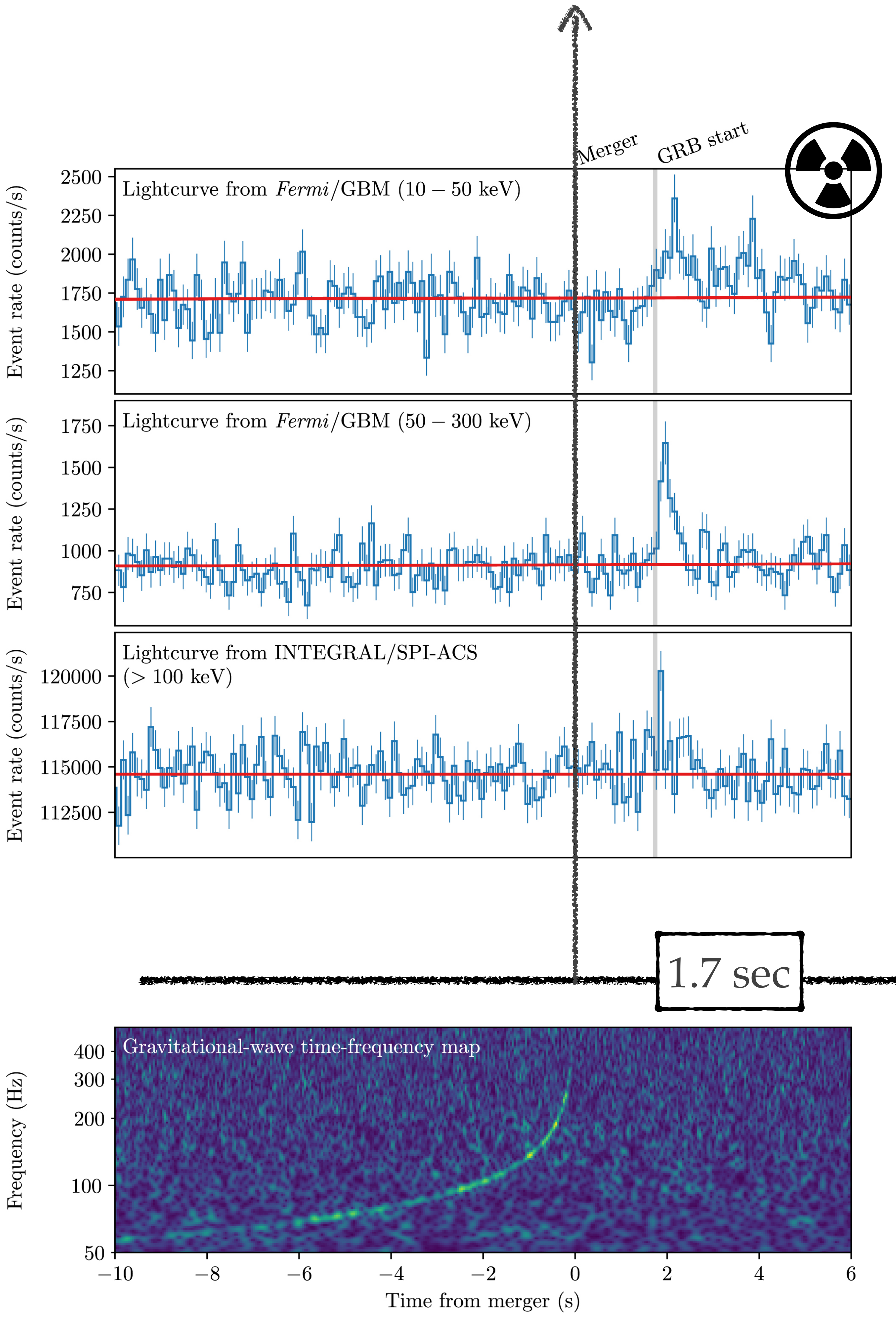
170817 - The discoveries





Abbott et al. 2017

170817 - The discoveries



1.7 sec

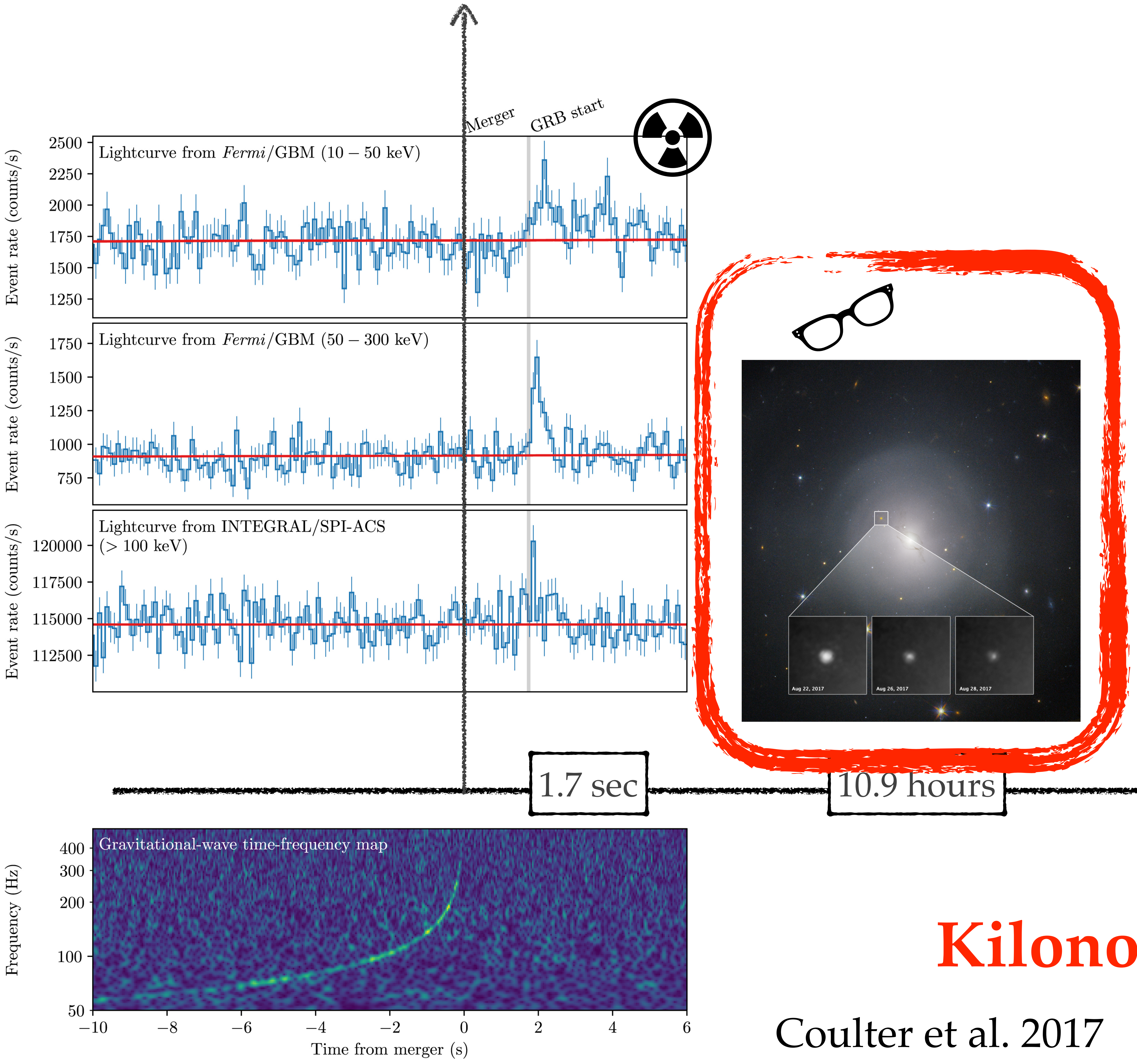
10.9 hours

Coulter et al. 2017

Pian et al. 2017

Smartt et al. 2017

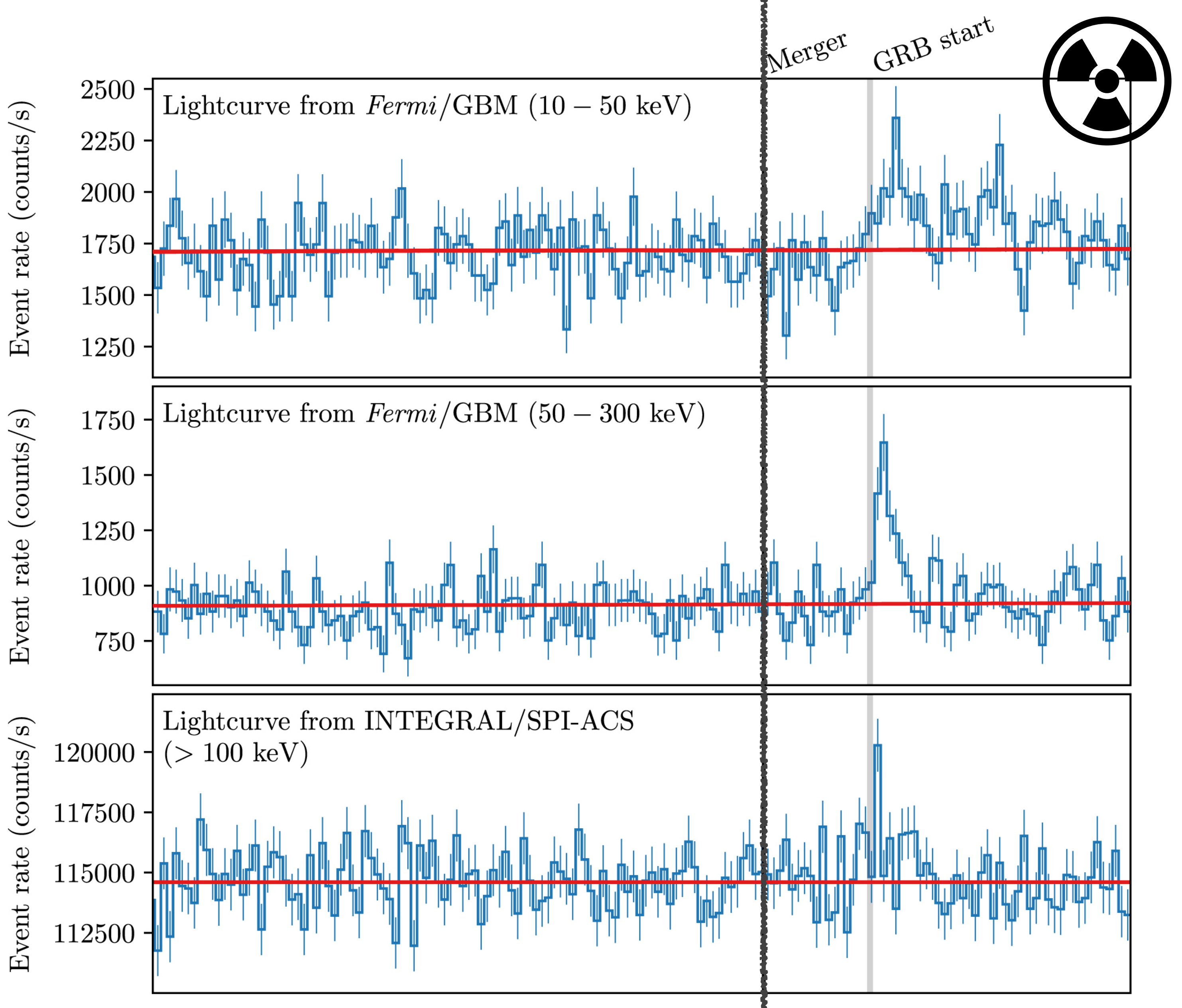
170817 - The discoveries

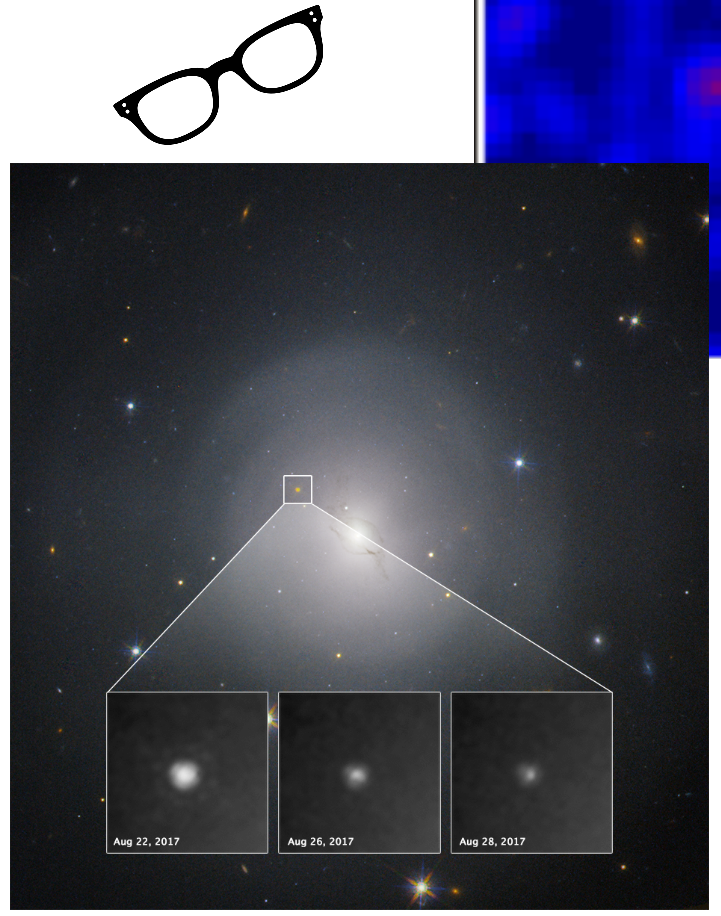


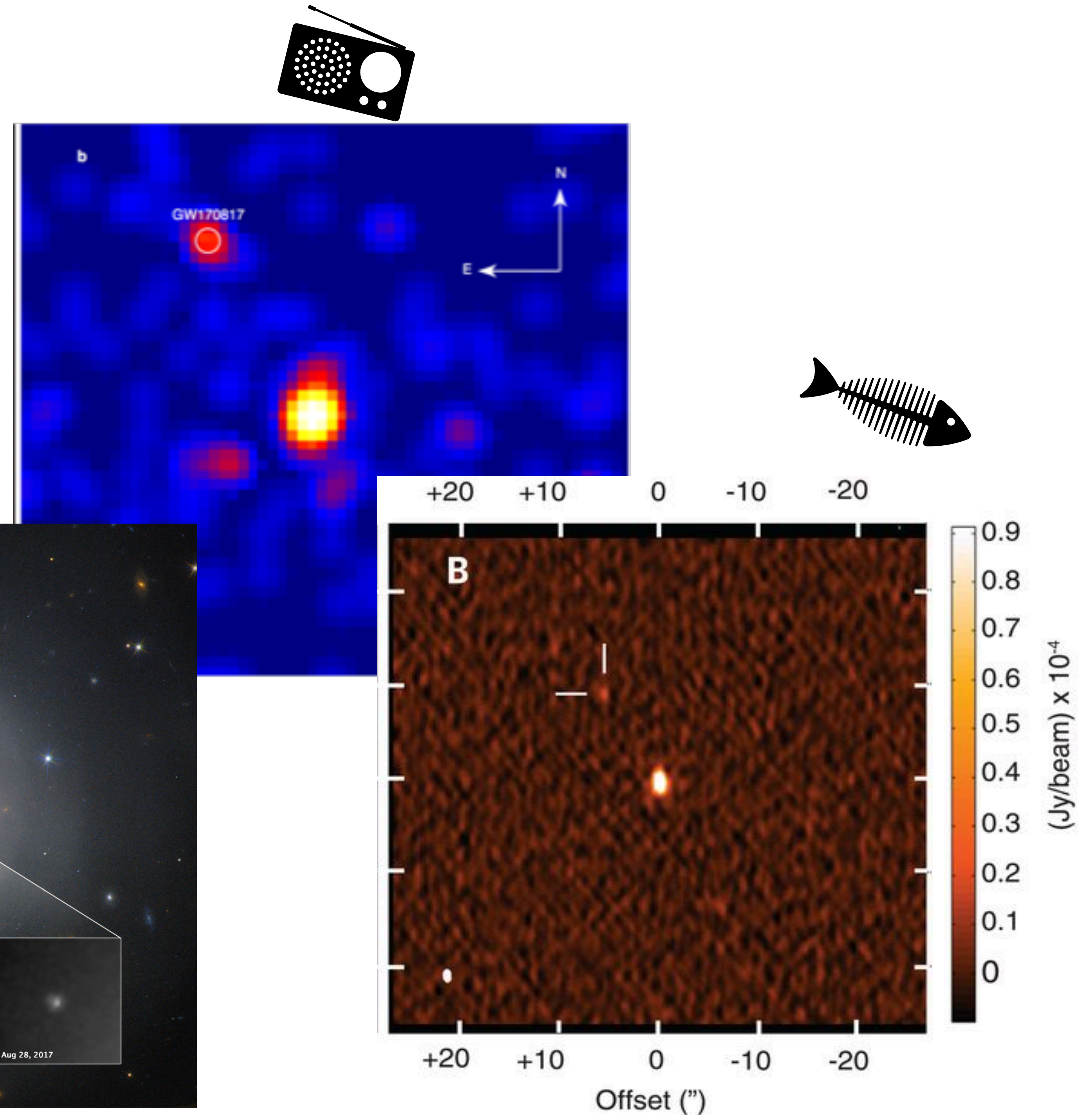
Kilonova

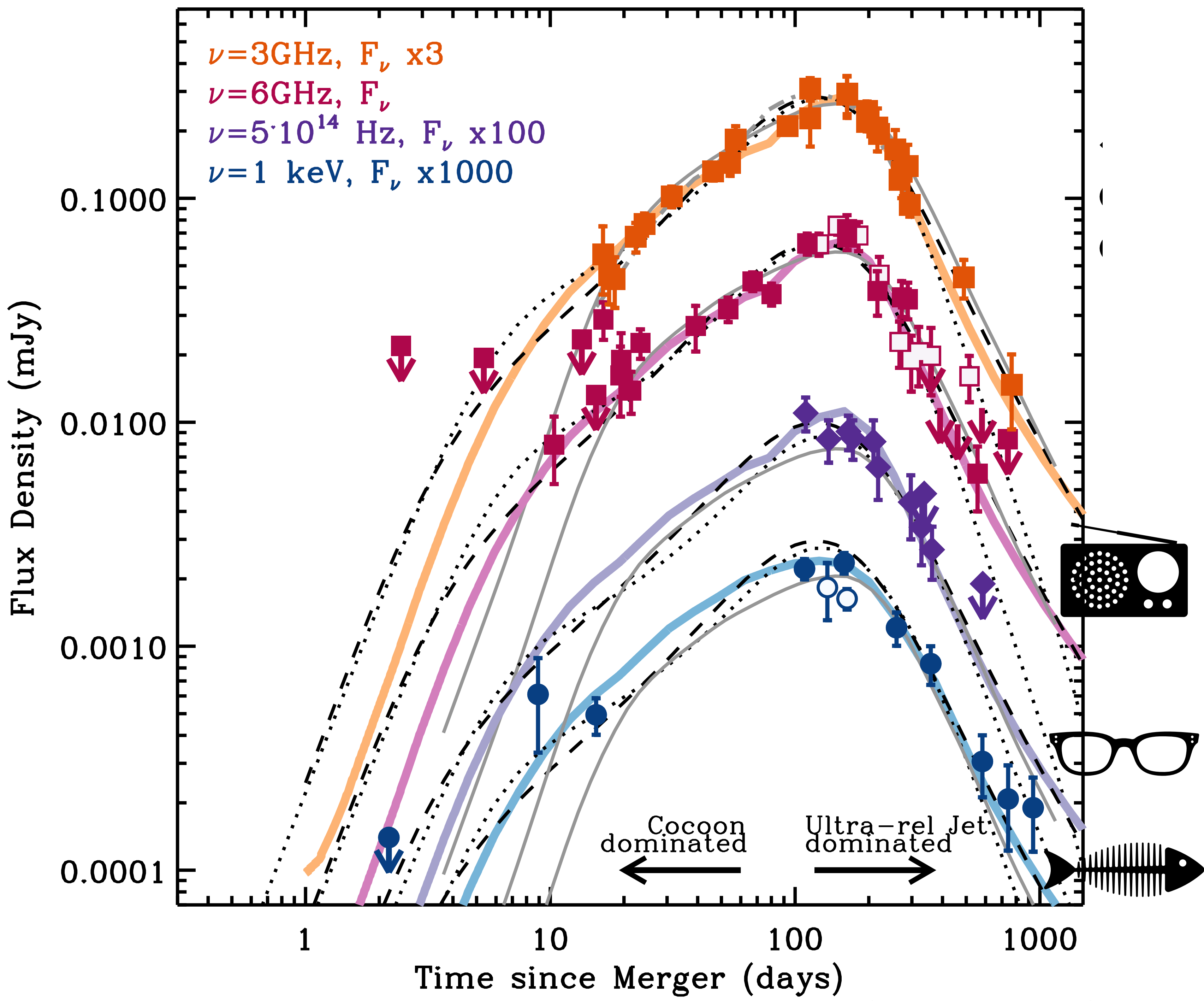
Coulter et al. 2017
Pian et al. 2017
Smartt et al. 2017

170817 - The discoveries

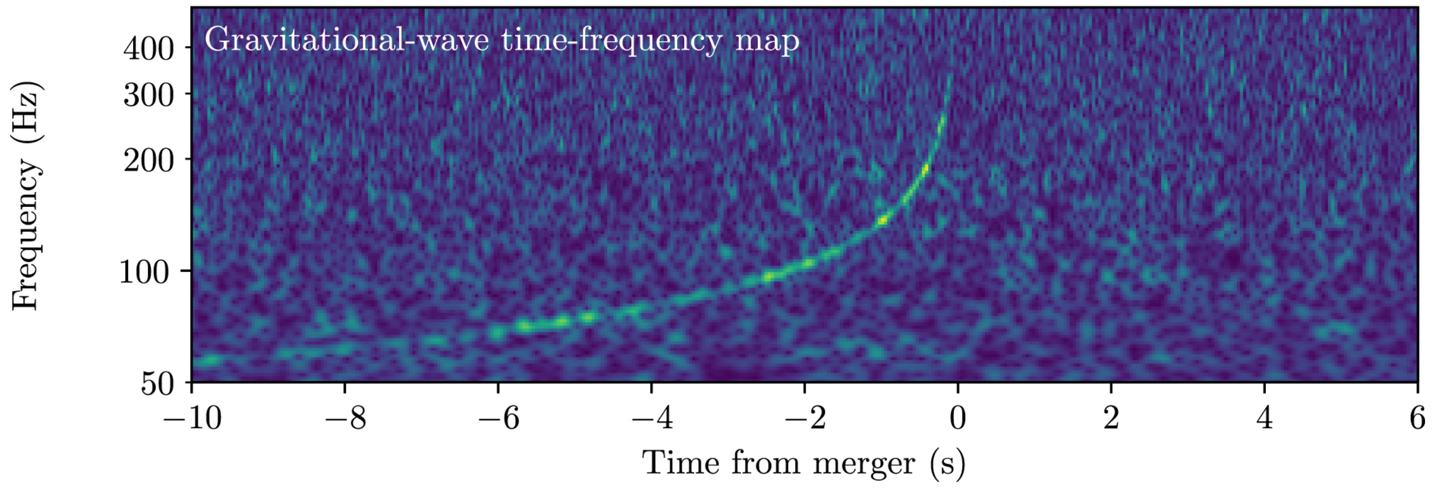








1.7 sec | 10.9 hours | 9 days | 16 days | 2.7 years

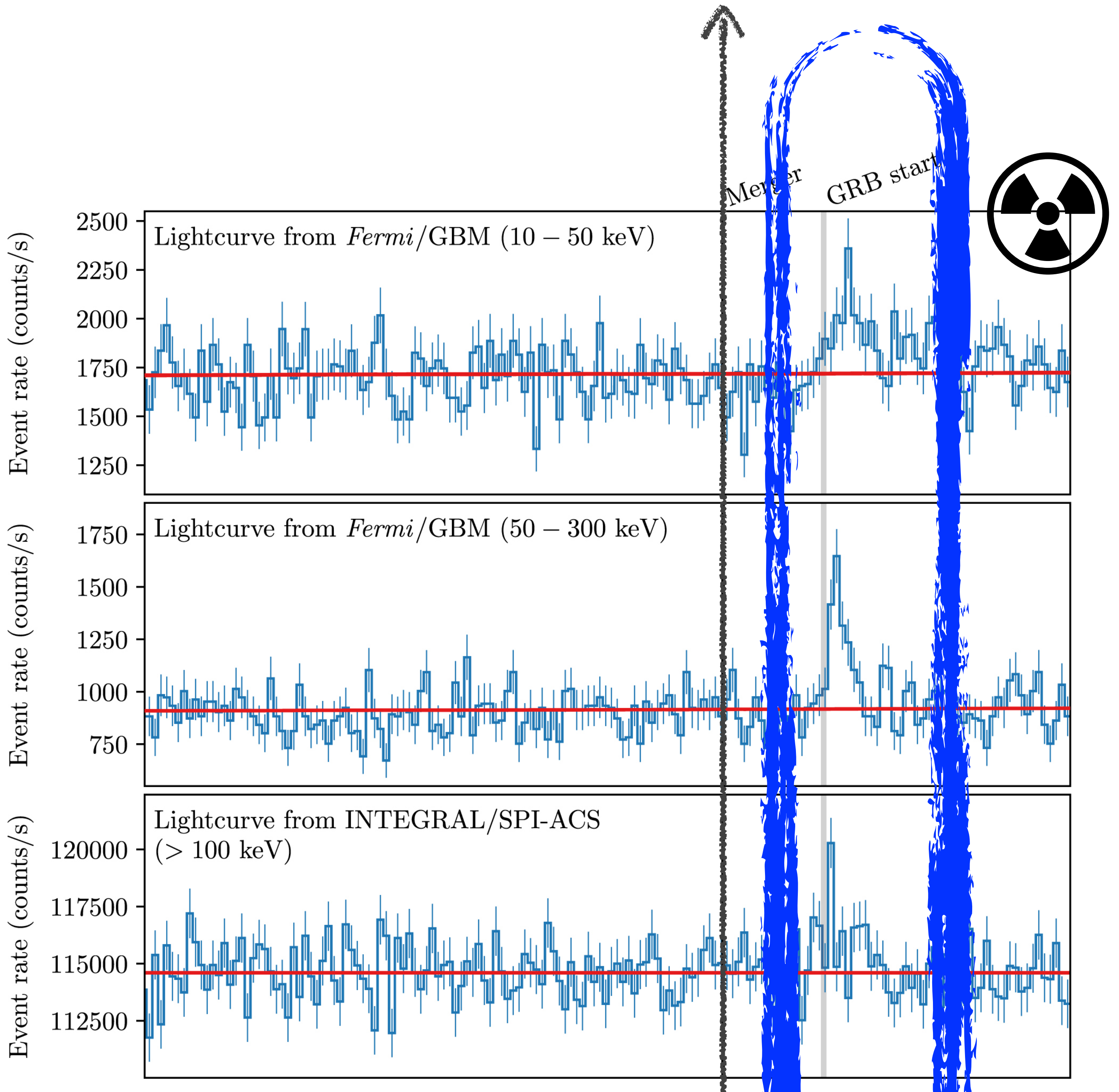


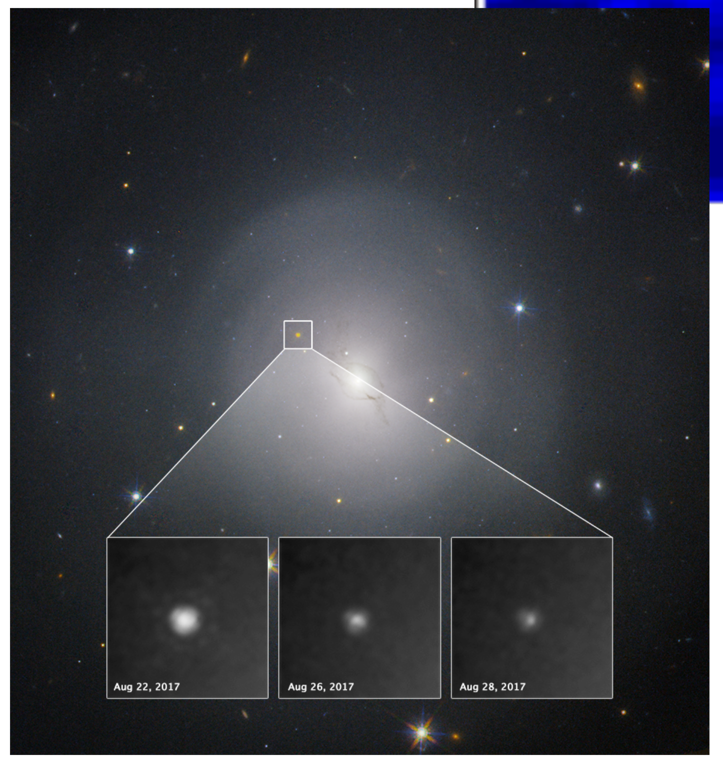
Hallinan et al. 2017

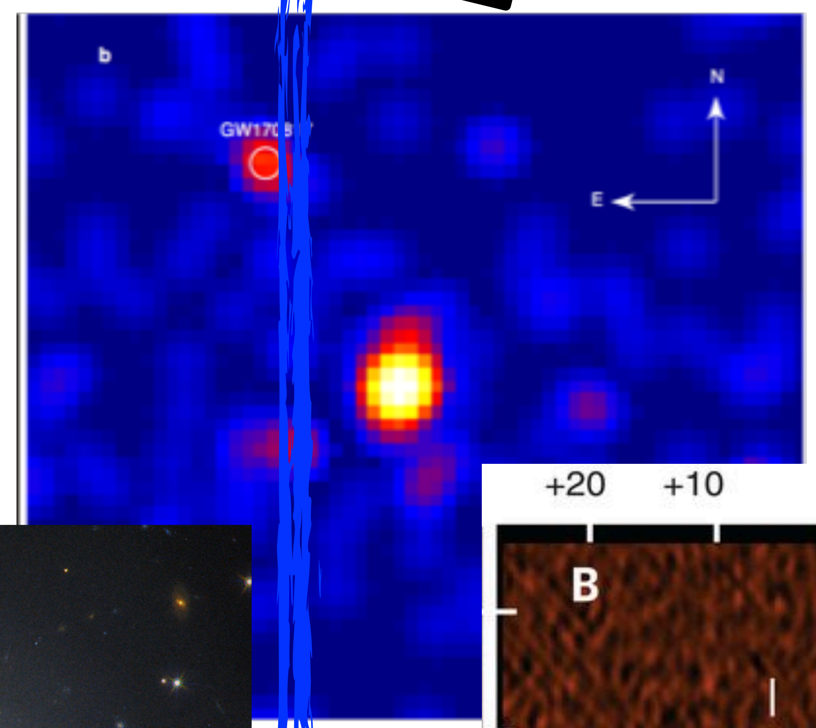
Troja et al. 2017

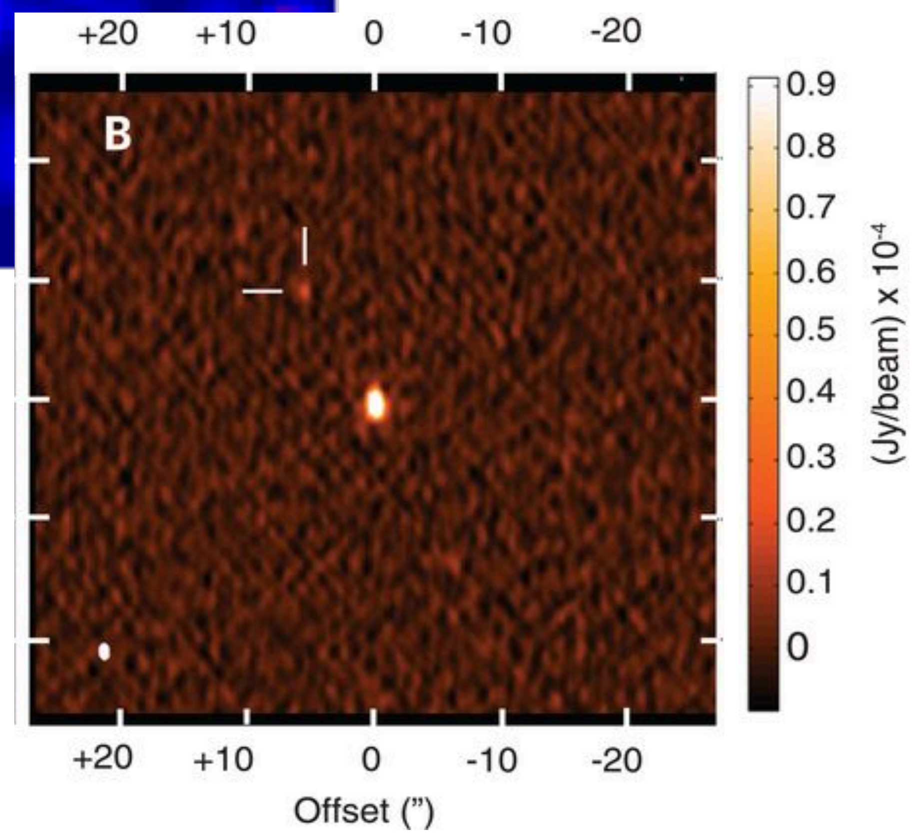
Margutti et al. 2017

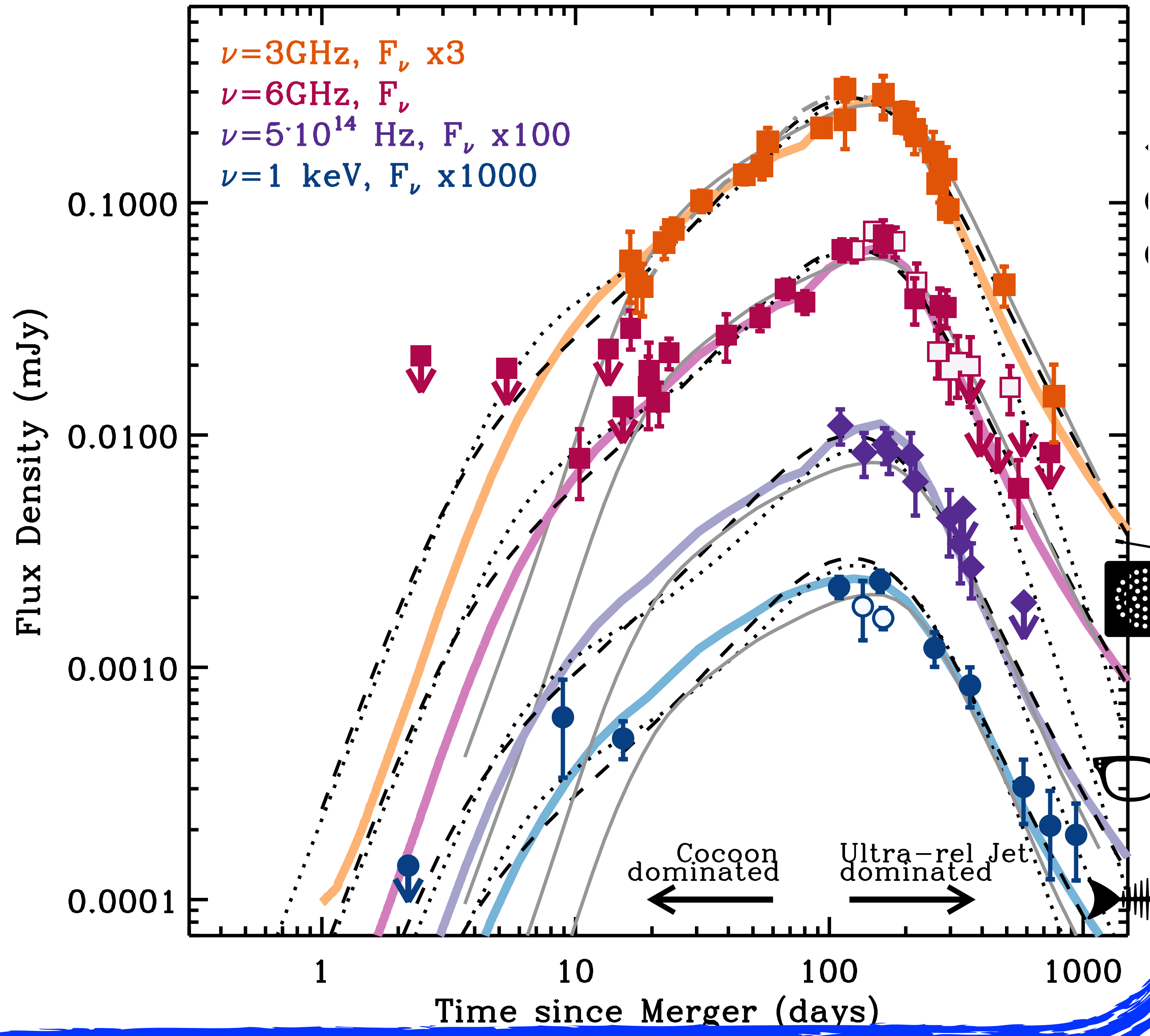
170817 - The discoveries











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Margutti et al. 2017

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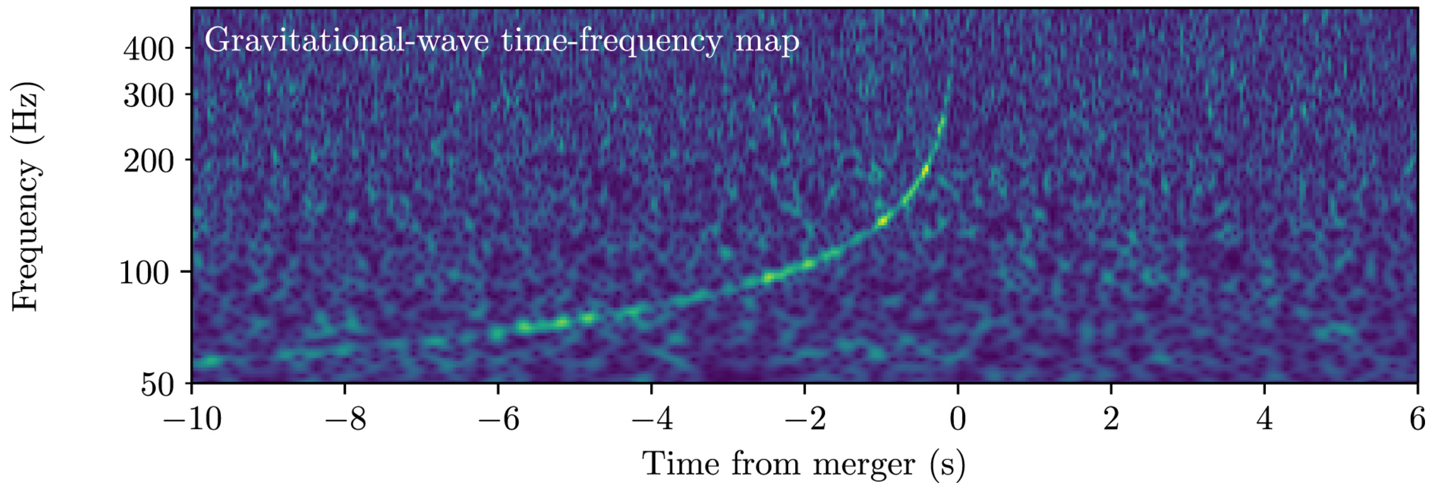
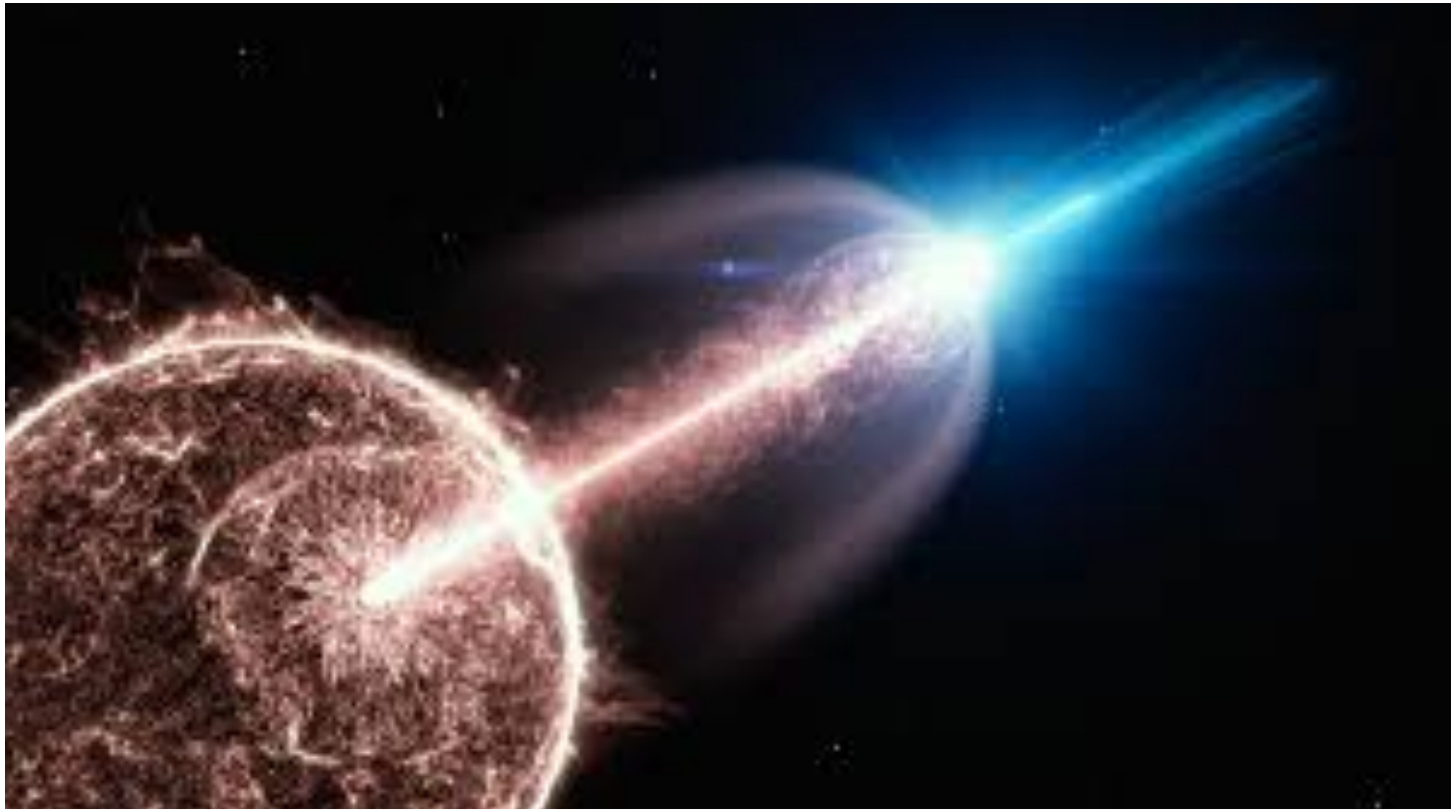


Prompt emission

Afterglow emission

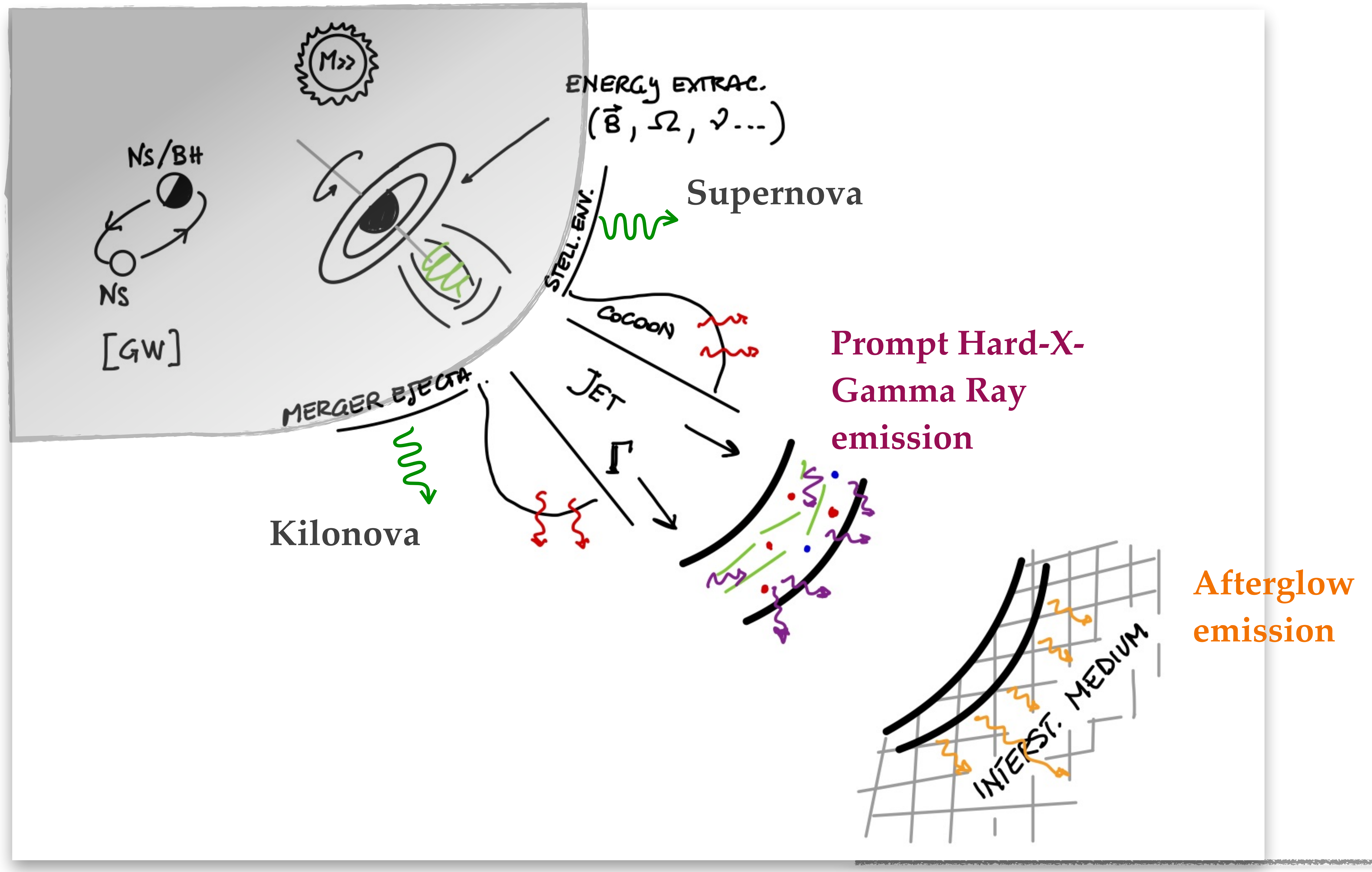
Gamma Ray Burst

Gamma Ray Bursts

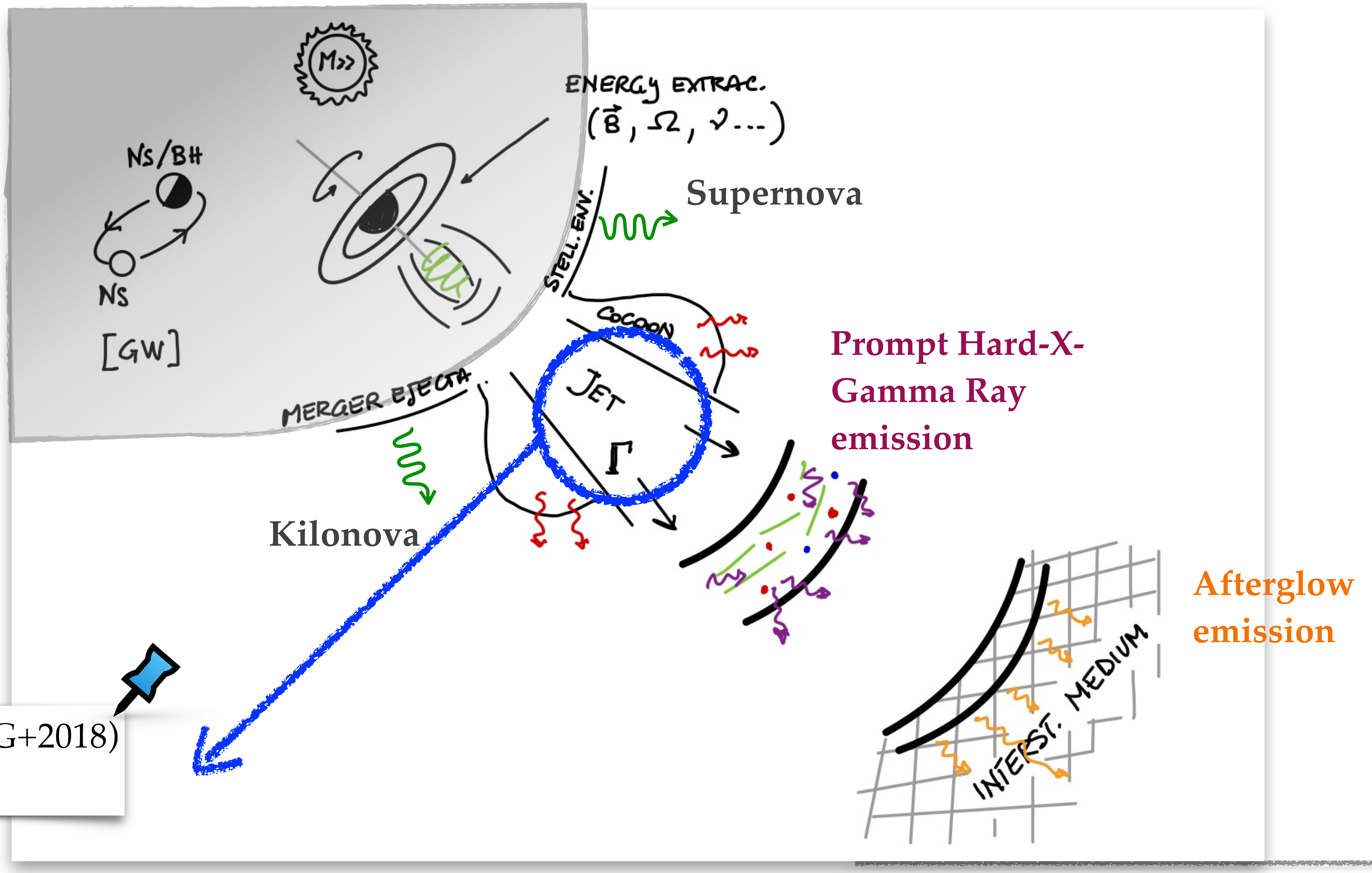


1) Powerful transients
2) Highest redshift transients
3) Life/death of massive stars
4) Collimated/relativistic jets
5) Accretion/ejection physics
6) Counterparts of GW events
7) Possible sources of high-E particles
8) …

Gamma Ray Burst: a schematic scenario



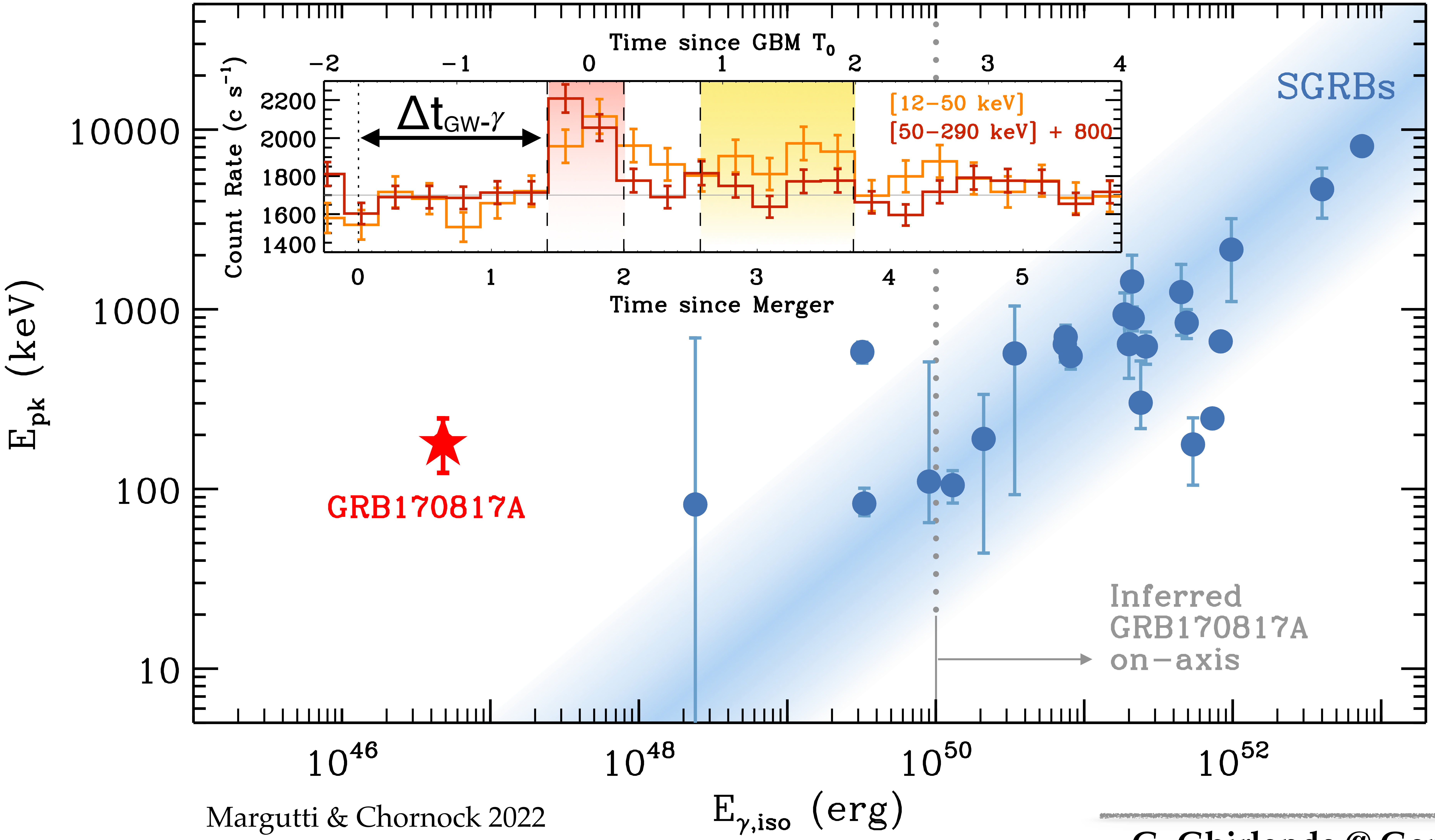
Gamma Ray Burst: a schematic scenario



$\Gamma \sim 100 - 1000$ (e.g. GG+2018)
$\theta_{jet} \sim 3 - 10$ deg

GRB170817 vs short GRBs

1. Under energetic in γ-rays
2. γ-rays are 2 sec delayed wrt GW

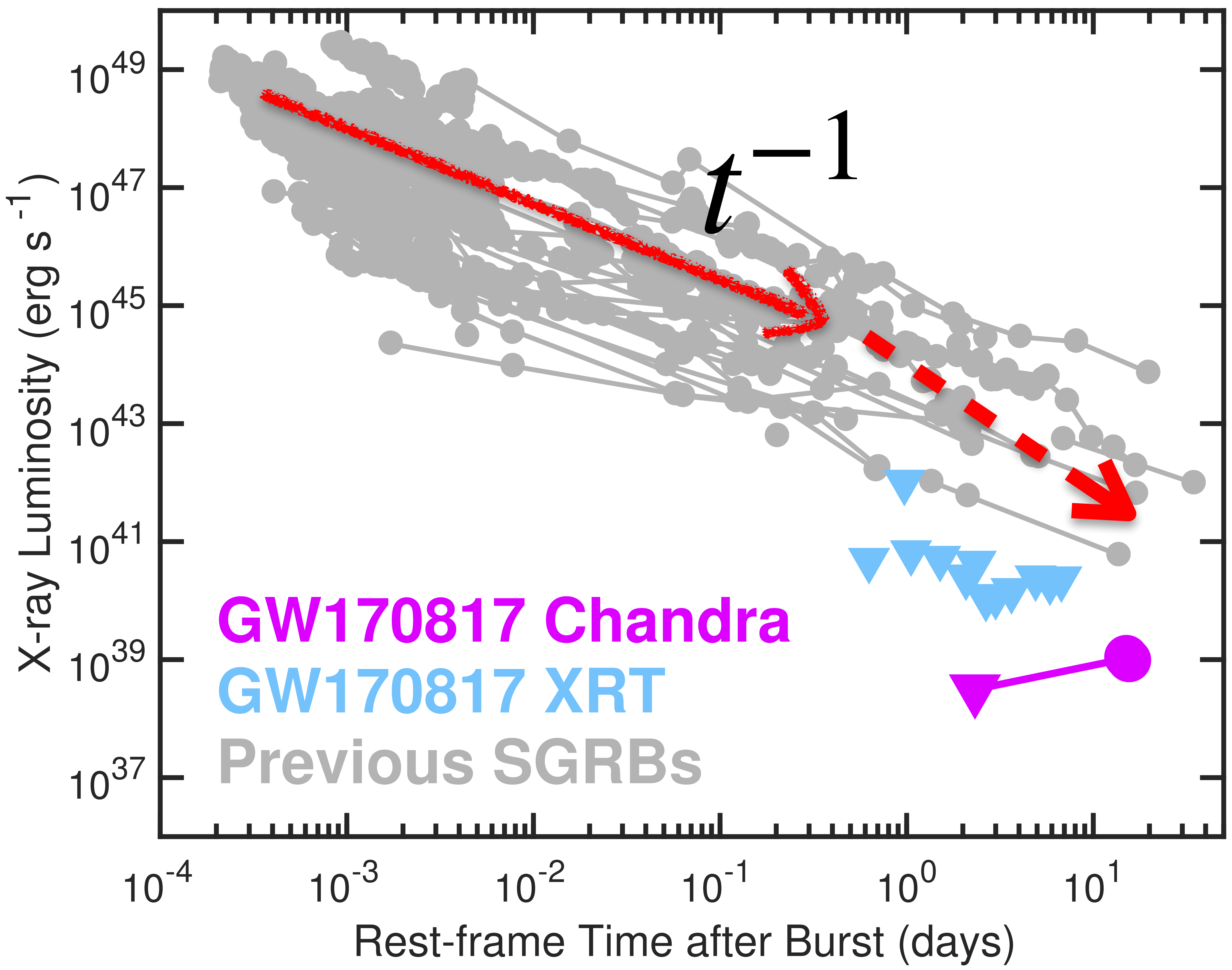


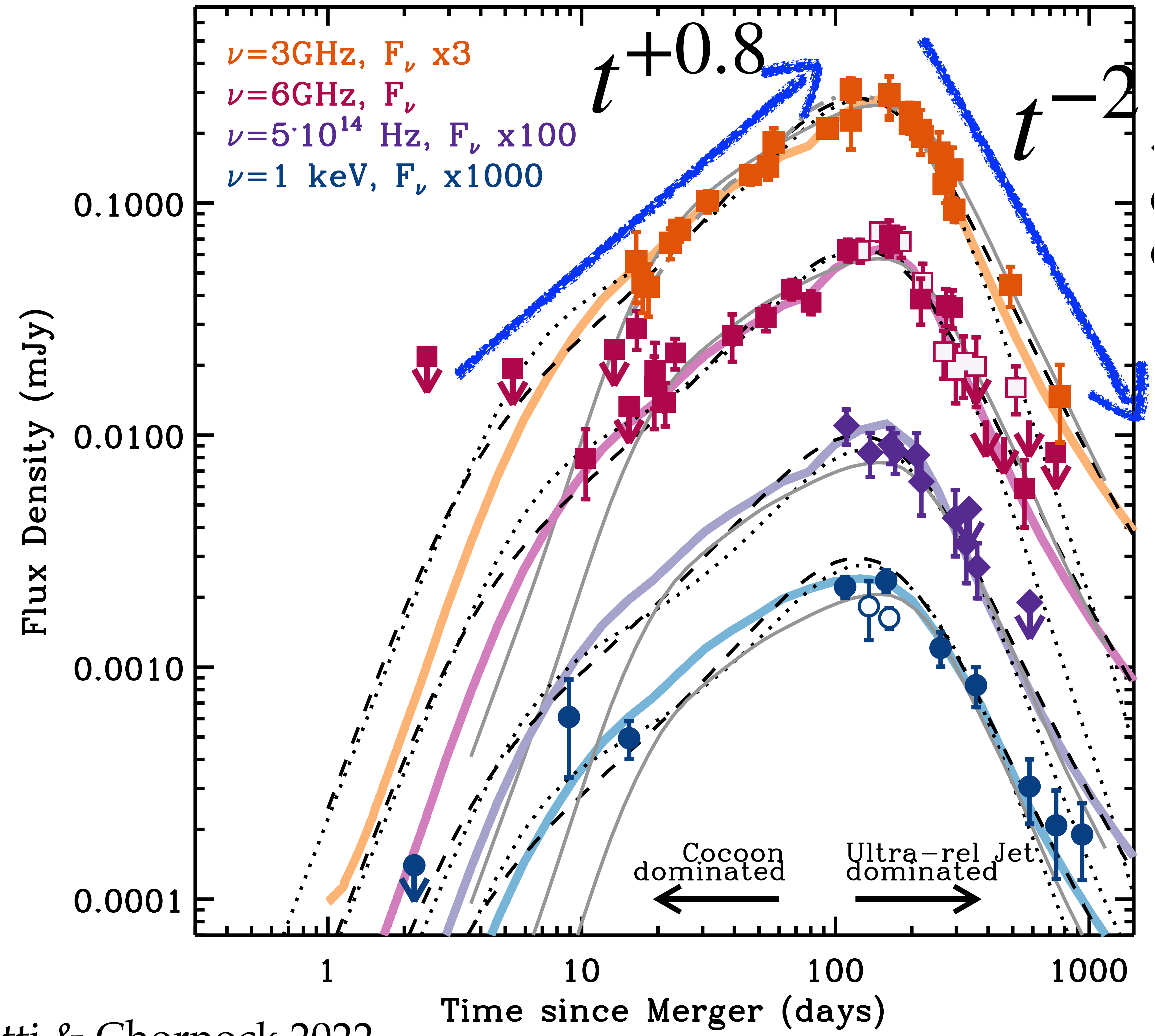
Margutti & Chornock 2022

GRB170817 vs short GRBs

1. Under energetic in γ-rays
2. γ-rays are 2 sec delayed wrt GW
3. Afterglow appears at late times
4. … shallow rise and 150d peak

Fong+2020



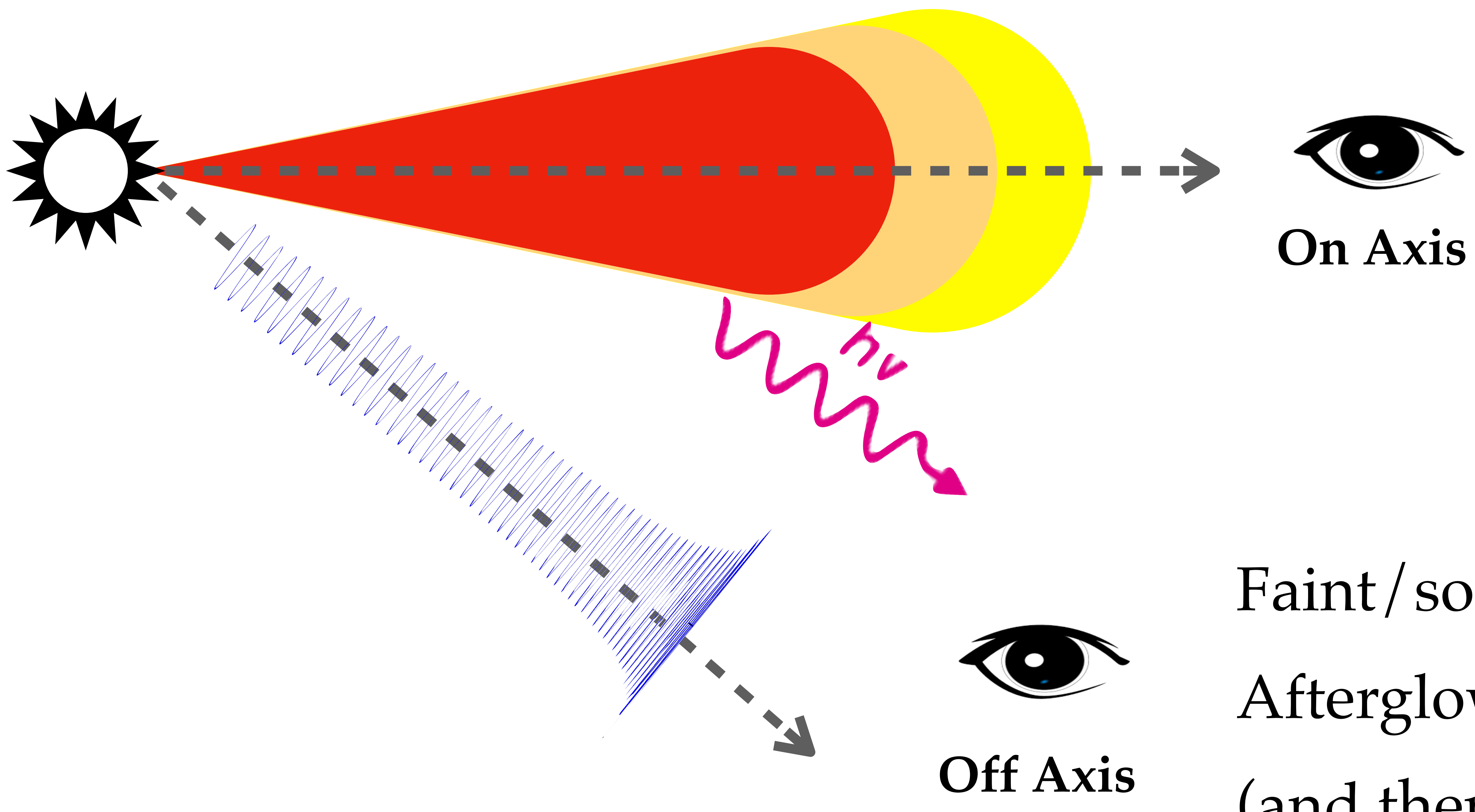


Margutti & Chornock 2022

View point matters

- [x] Under energetic in γ-rays
- [x] γ-rays are 2 sec delayed wrt GW
- [x] Afterglow appears at late times
- [ ] … shallow rise and 150d peak

$$\Gamma(t_1) > \Gamma(t_2) > \Gamma(t_3)$$



Luminous/hard burst

Monotonic decaying afterglow

Faint/soft burst

Afterglow appears at late times

(and then decays)

Delay GW-EM

$$L_\nu(t,\theta_{view}) = L(t,0)\left(\frac{1}{1+\Gamma^2\theta^2_{view}}\right)^3$$

$$\frac{1}{\Gamma(t)} \sim \theta_{\rm view}$$

View point matters

- [x] Under energetic in γ-rays
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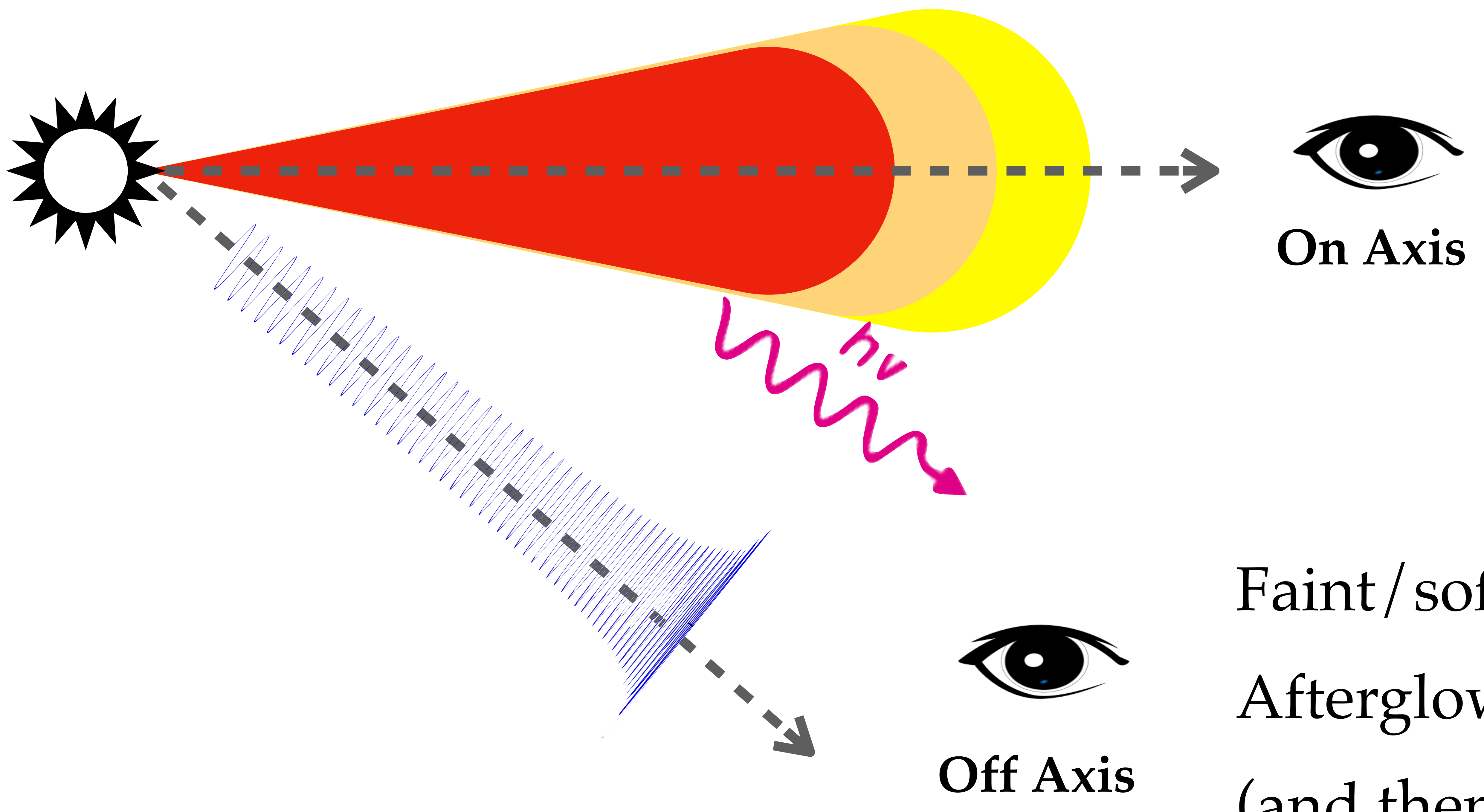

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$$\frac{1}{\Gamma(t)} \sim \theta_{\rm view}$$

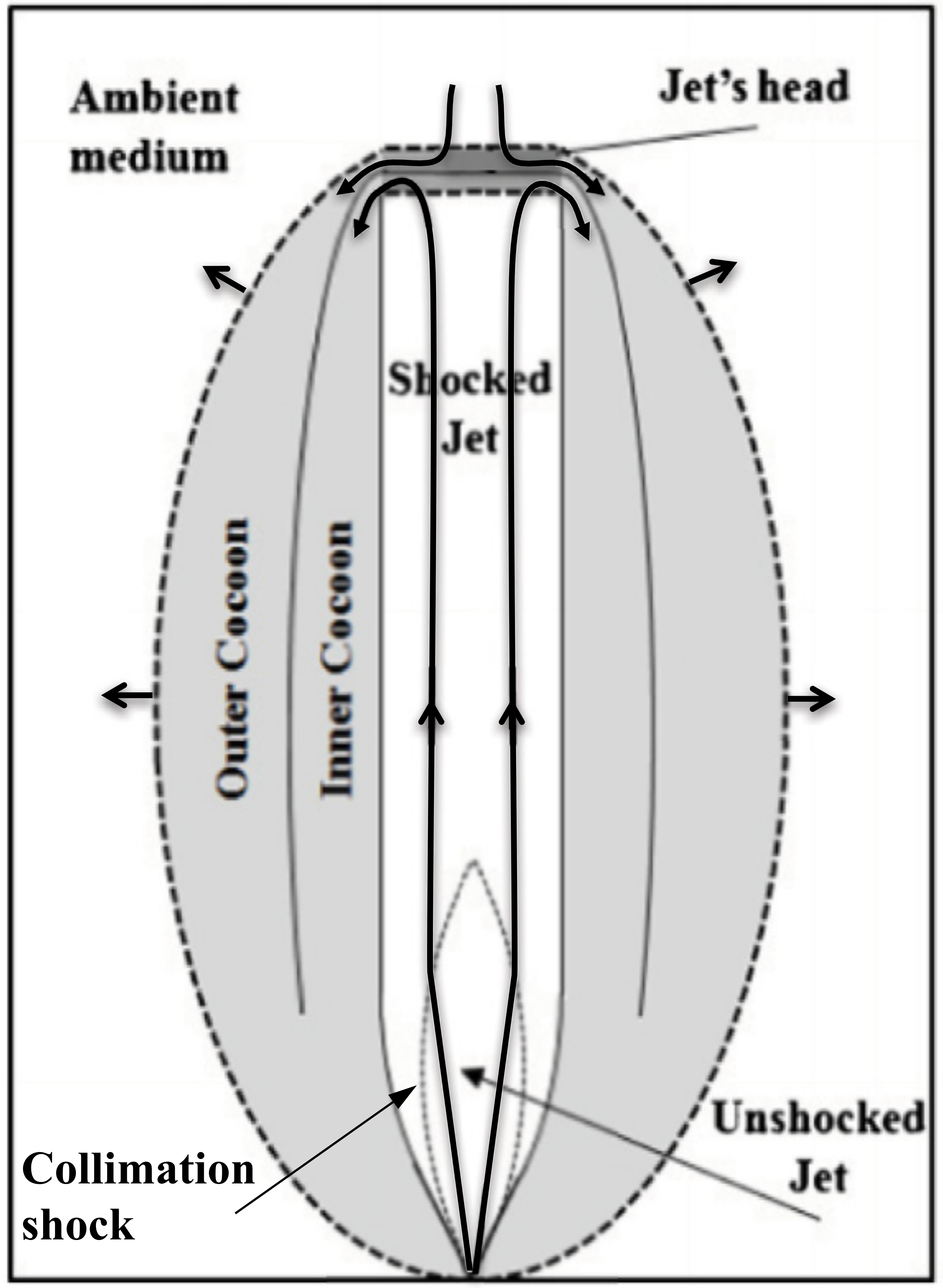
A realistic jet

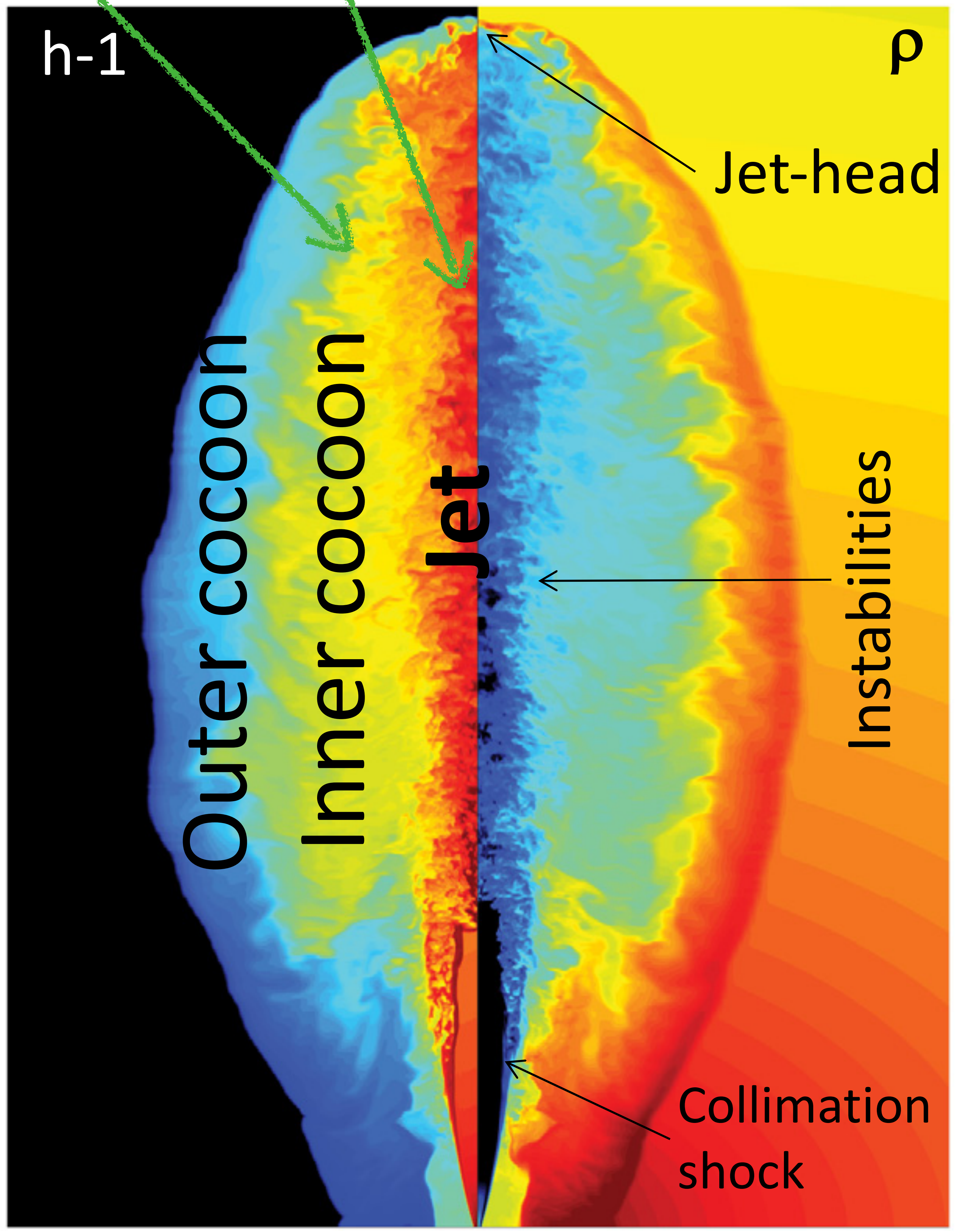
Jet - environment interaction

(stellar envelope - LGRB)
(merger ejecta - SGRB)

Shocked ejecta material

Shocked jet material





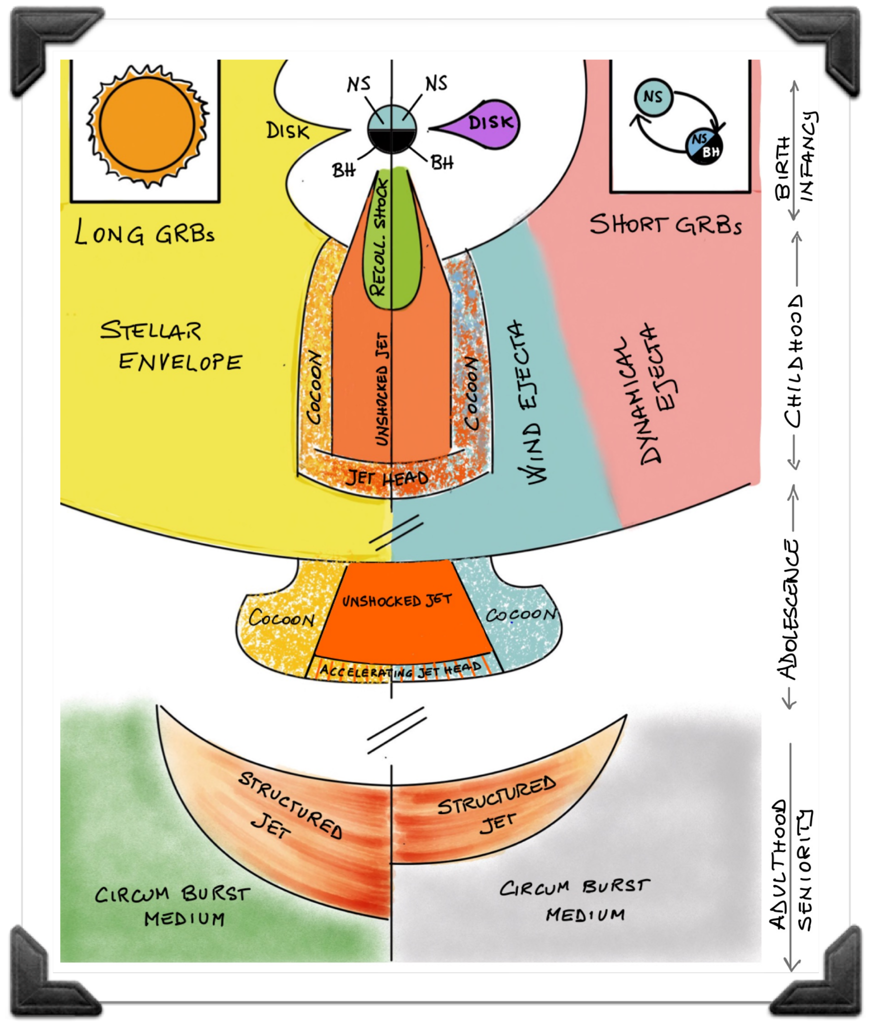
Akira 2013 … … Nakar 2020

Breakout condition

$$E_j > E_{crit} = kE_{ej}\theta_j^2$$

(See A. Colombo present.)

THM: Jet properties (energy, velocity etc.) should be angularly structured

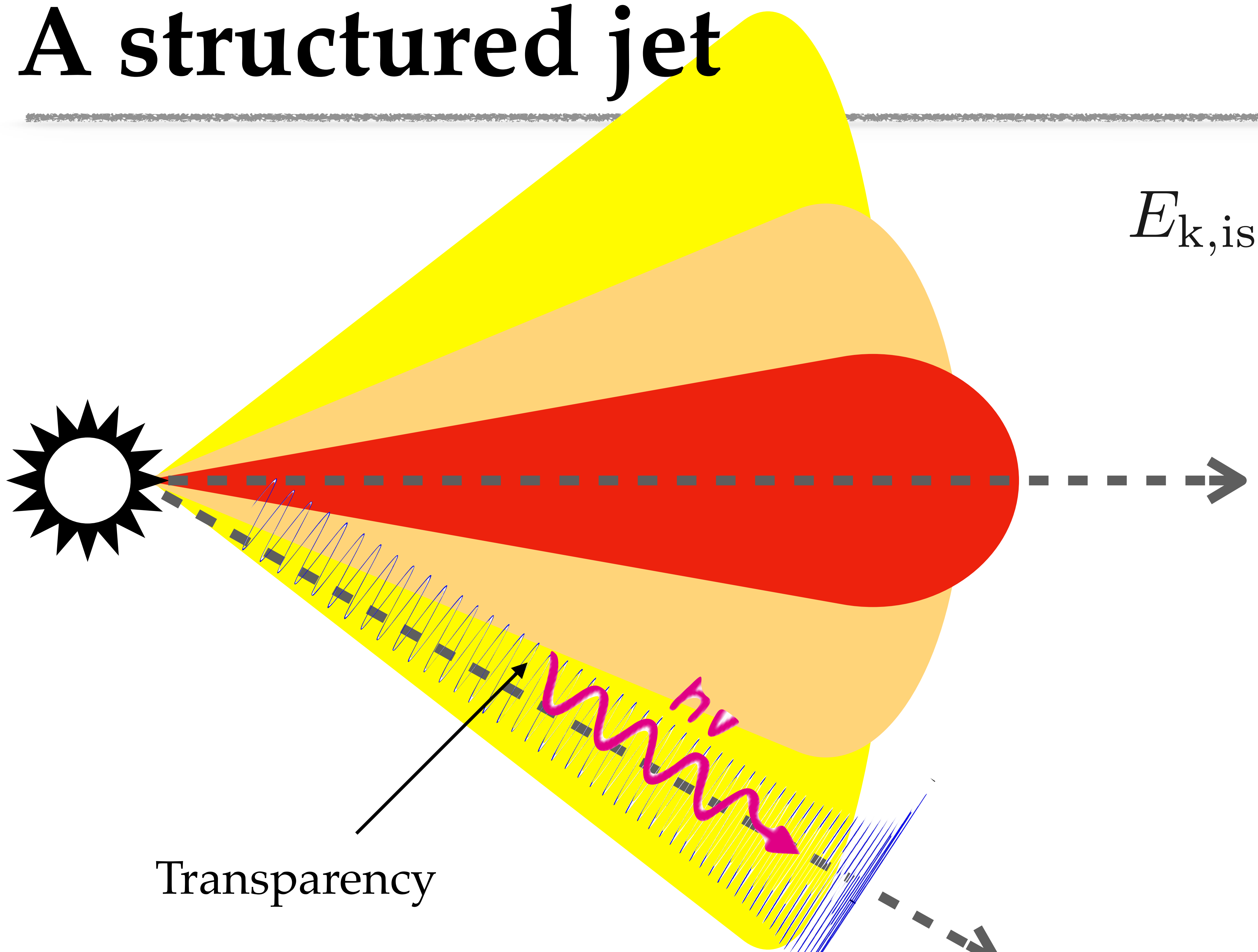


Salafia & Ghirlanda 2021 (review)

A structured jet

- ☑ Under energetic in γ-rays
- ☑ γ-rays are 2 sec delayed wrt GW
- ☑ Afterglow appears at late times
- ☑ … shallow rise and 150d peak

$$E_{\mathrm{k,iso}}(\theta) = \frac{E_{\mathrm{core}}}{1-(\theta/\theta_{\mathrm{core}})^{s_1}}$$



On Axis

Luminous/hard burst

Monotonic decaying afterglow

Off Axis

Faint/soft burst

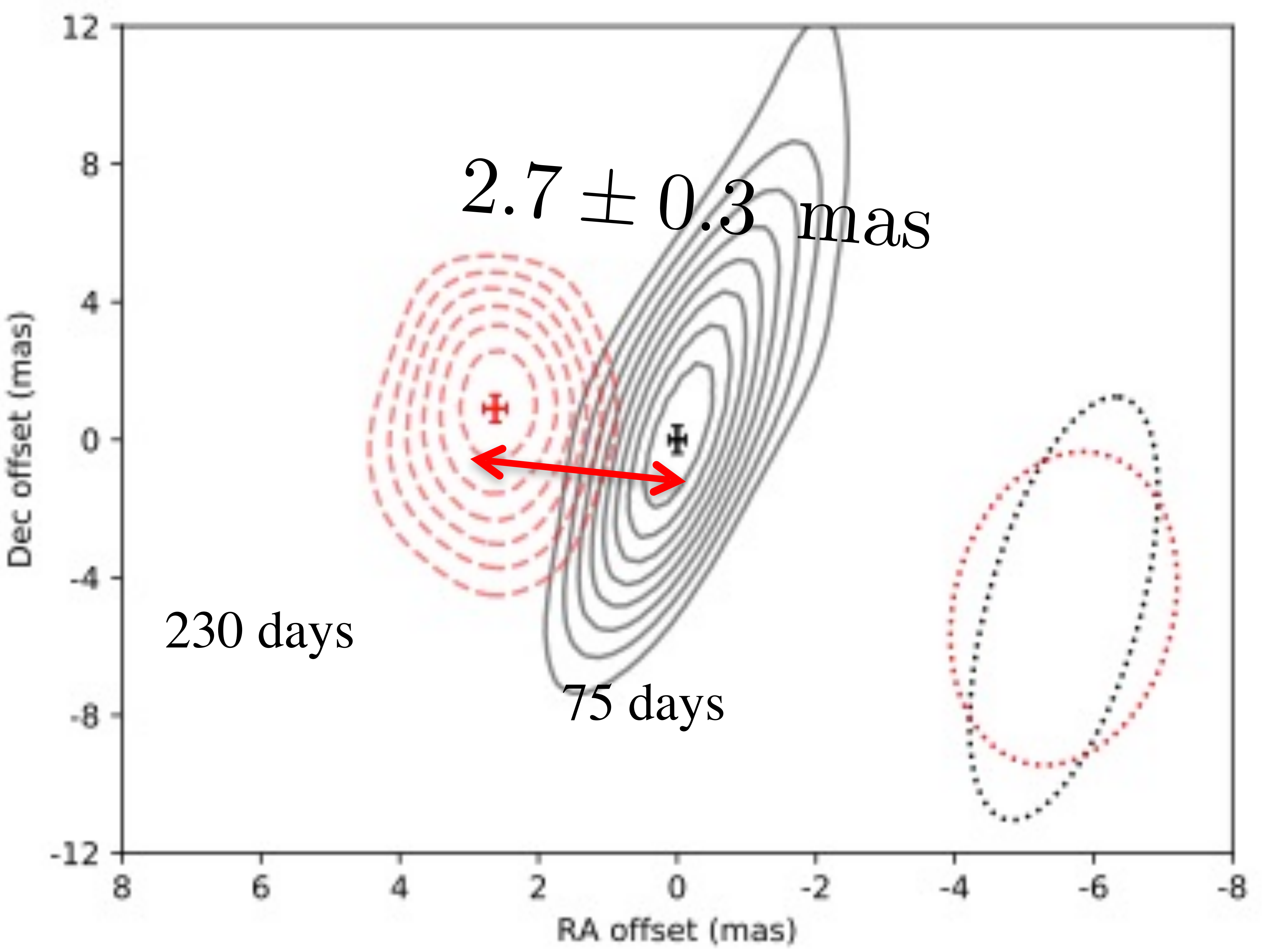
Afterglow appears at late times + shallow rise in time

Delay GW-EM

THM: A structured jet can account for most observational proprieties of 170817 but there are alternative models …

Two killing observations

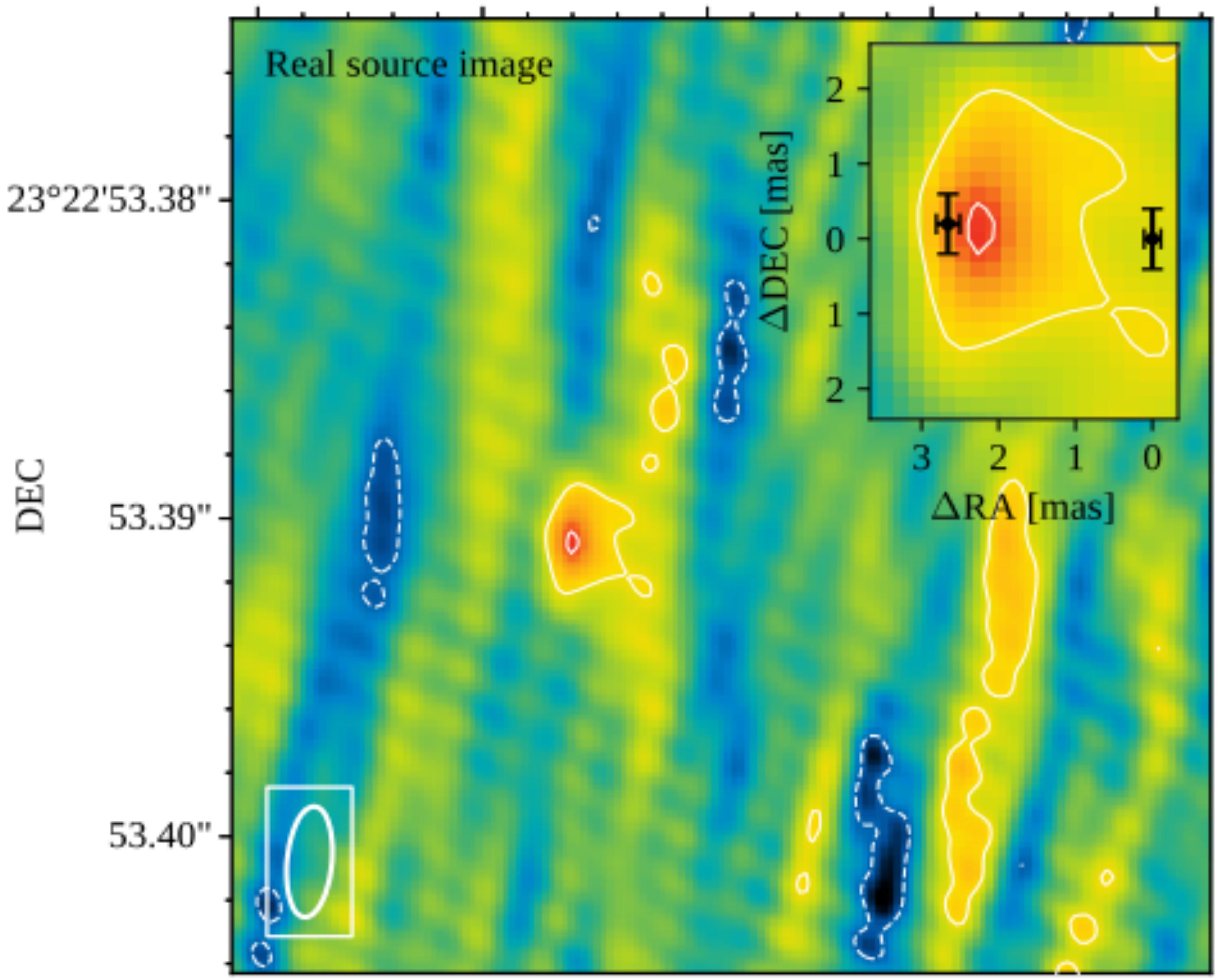
VLBA + VLA + GBT: 2/4 epochs (Sept 2017 – Apr. 2018, L,S,C,C) @ <75d> and <230d> (4.5 GHz)



Mooley+2018

$\beta_{\rm app} \sim 4$

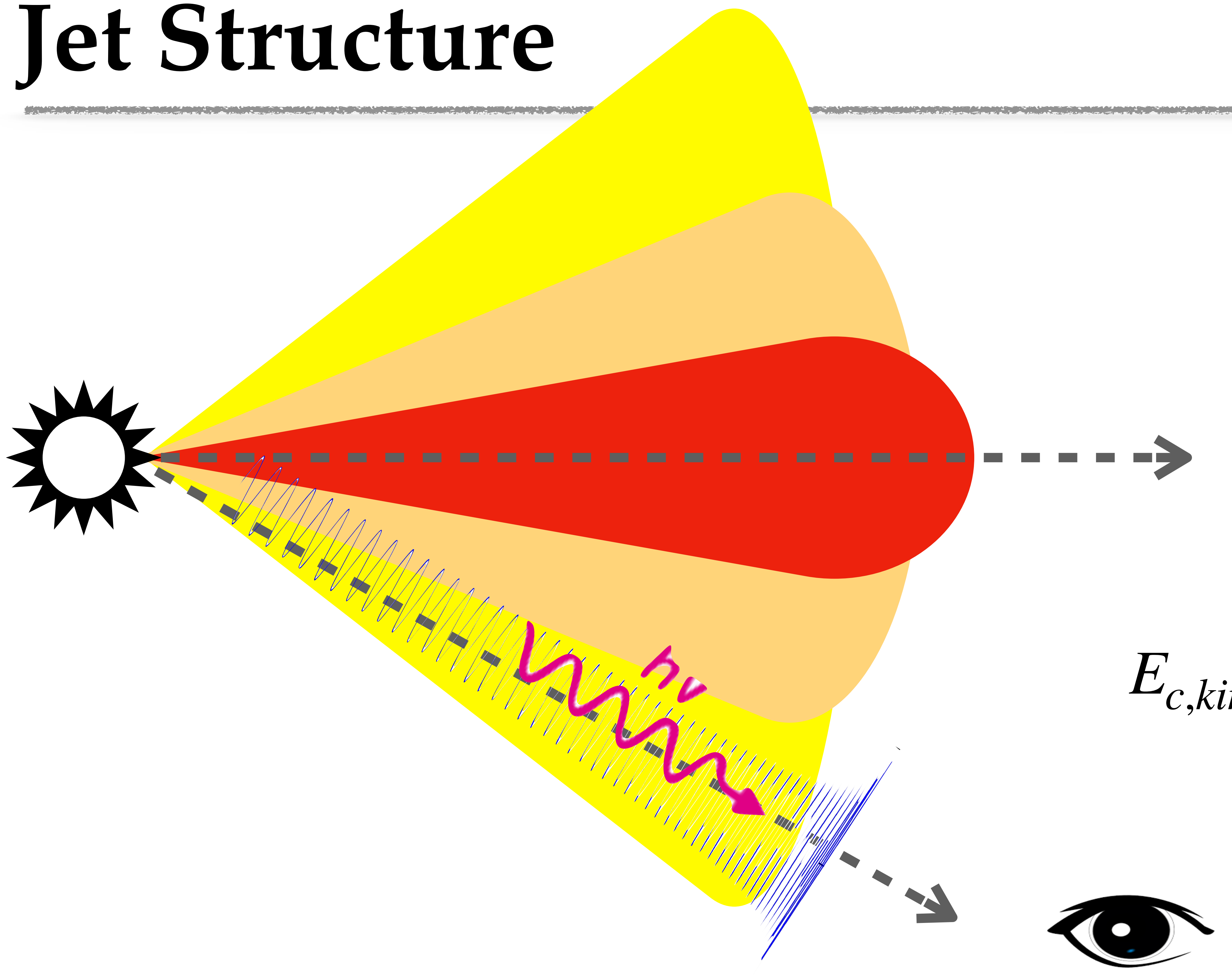
12-13 March 2018 = 204.7 days @ 5 GHz (32 ant. but VLA)



G.Ghirlanda. O. S. Salafia+2019

$\beta_{\rm app} \sim \Gamma$ $\theta_{\rm jet} - \theta_{\rm view} \sim 1/\Gamma \sim 0.25$

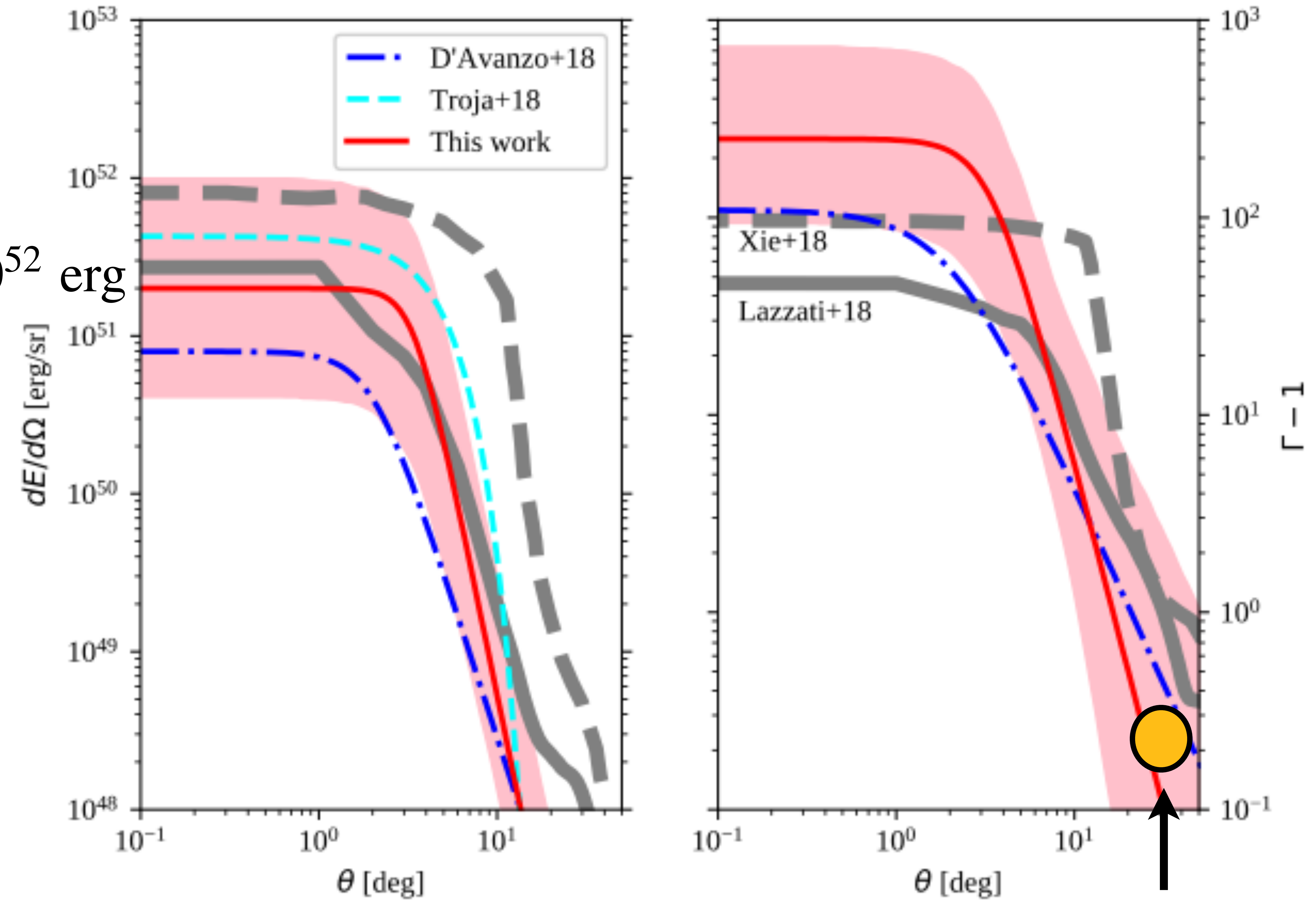
Jet Structure



Off Axis

$$E_{\mathrm{k,iso}}(\theta) = \frac{E_{\mathrm{core}}}{1-(\theta/\theta_{\mathrm{core}})^{s_1}} \qquad \Gamma(\theta) = 1 + \frac{\Gamma_{\mathrm{core}}-1}{1+(\theta/\theta_{\mathrm{core}})^{s_2}}$$

$E_{c,kin} \sim 10^{52}$ erg

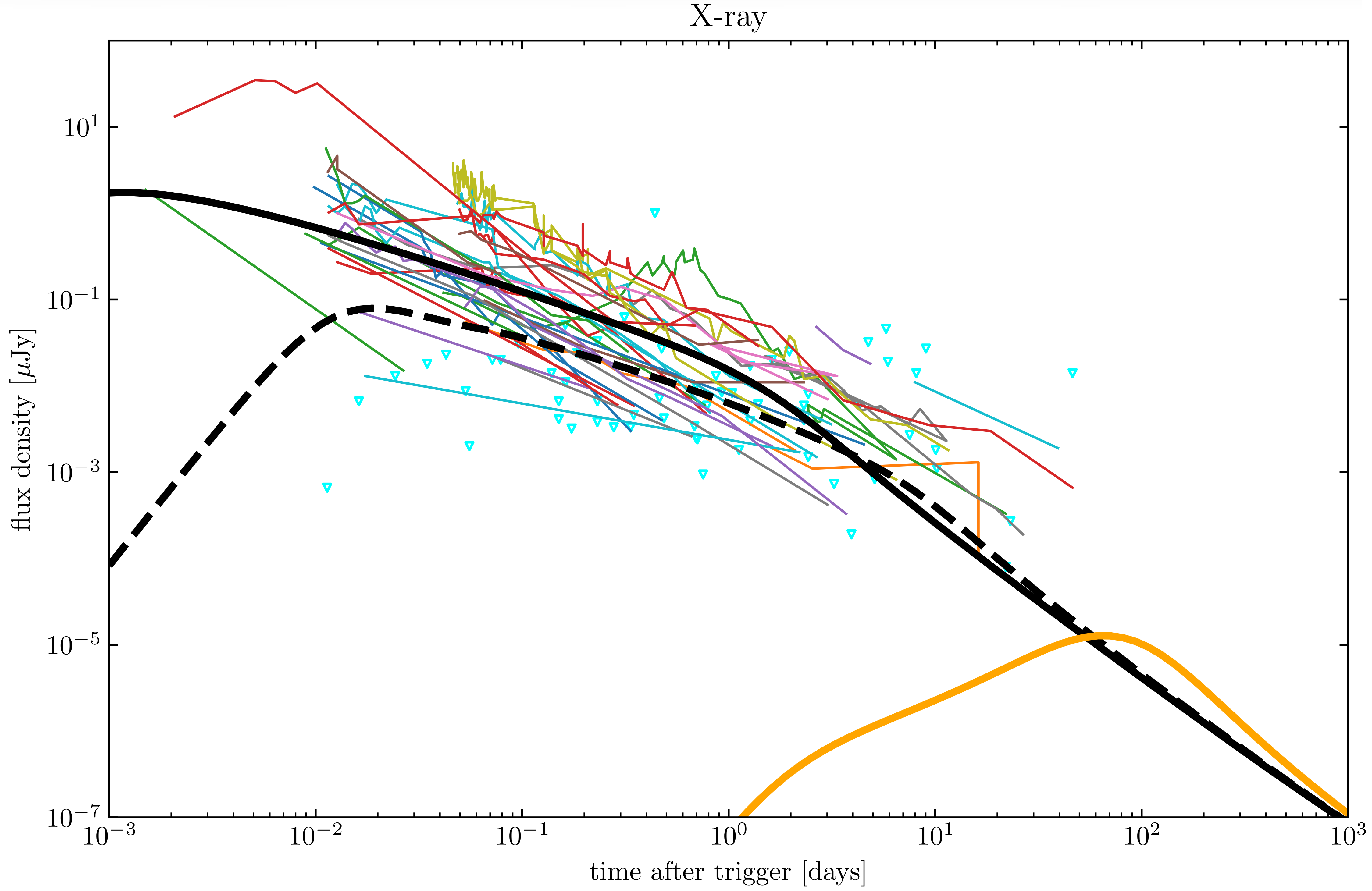


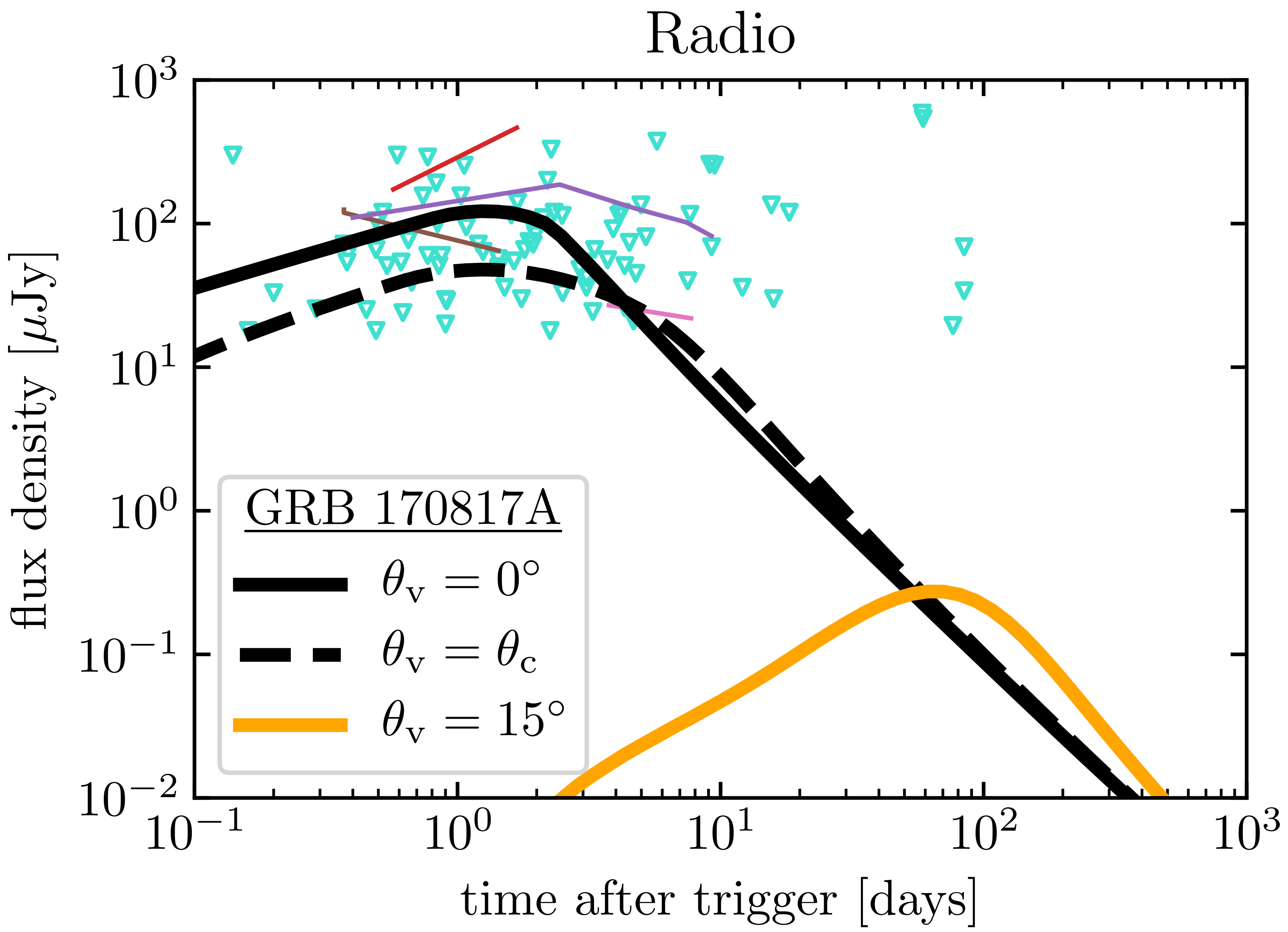
$\theta_{view} \sim 20^{\circ}$

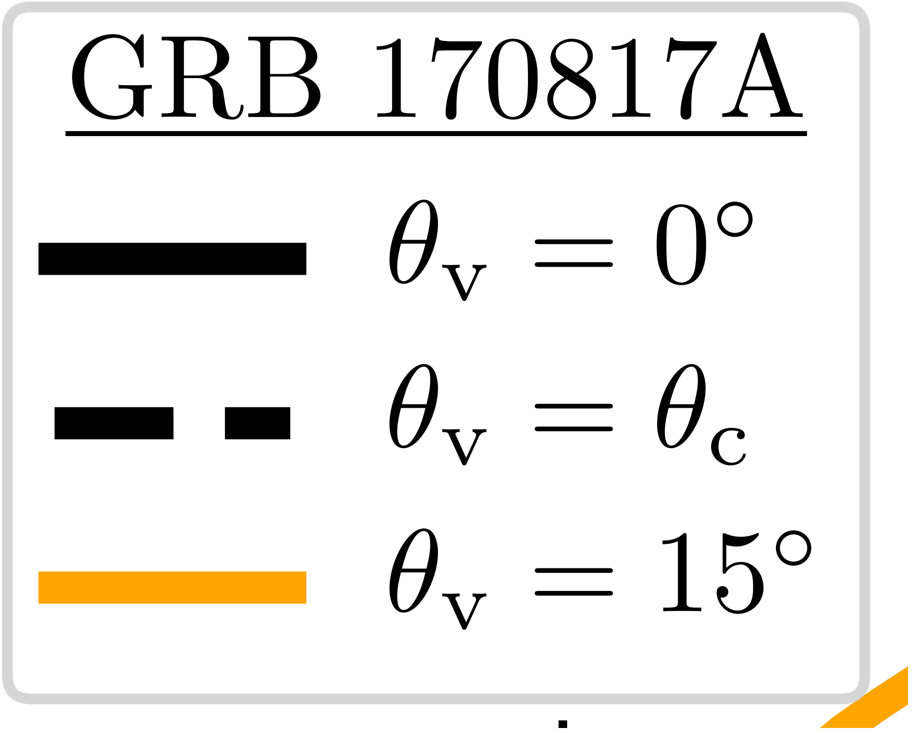
G.Ghirlanda. O. S. Salafia+2019

- ☑ Under energetic in γ-rays
- ☑ γ-rays are 2 sec delayed wrt GW
- ☑ Afterglow appears at late times
- ☑ … shallow rise and 150d peak
- ☑ VLBI proper motion and size constraints

Is 170817 a typical GRB?

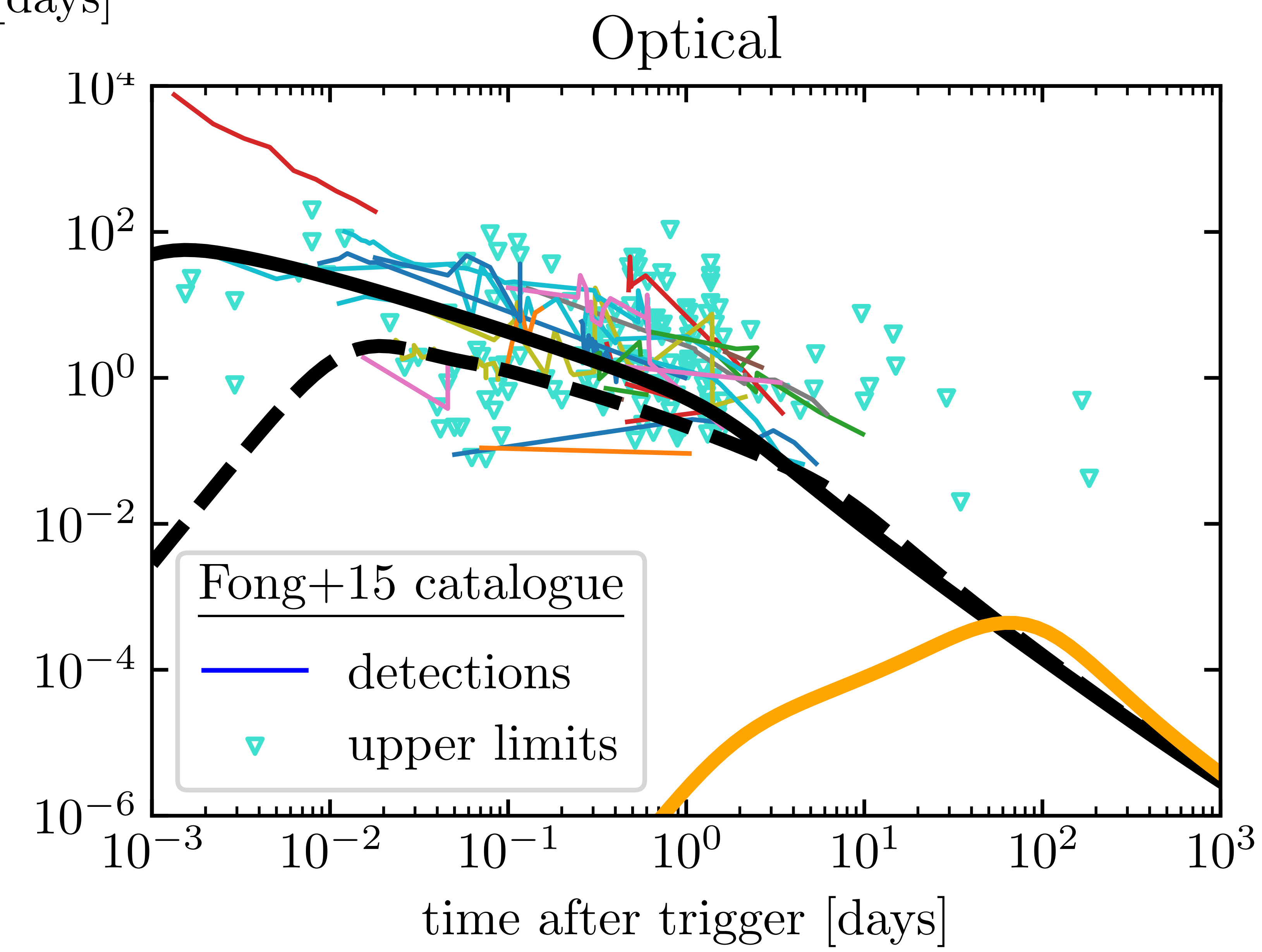






Salafia, GG et al. 2019

Afterglow emission



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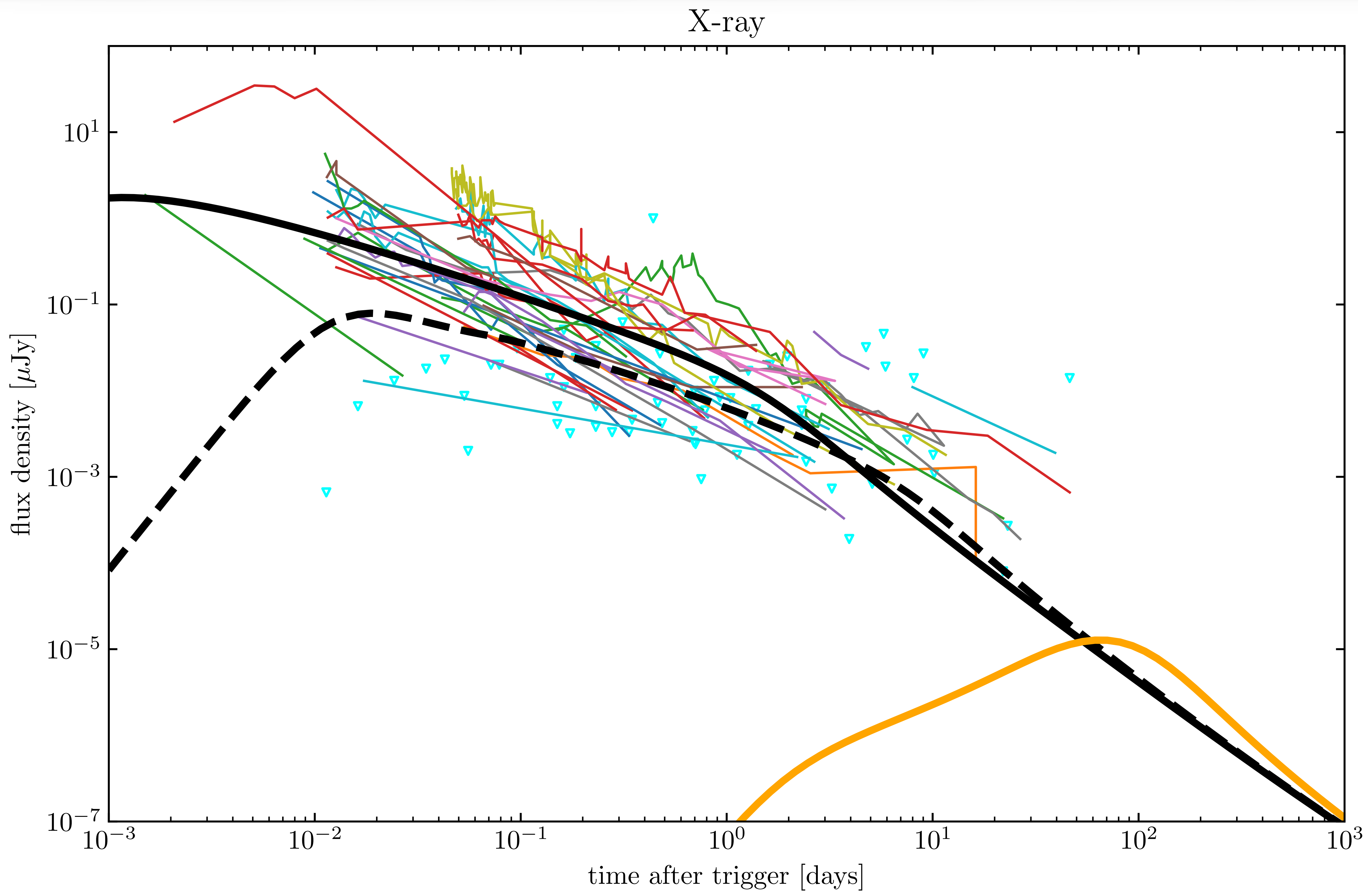
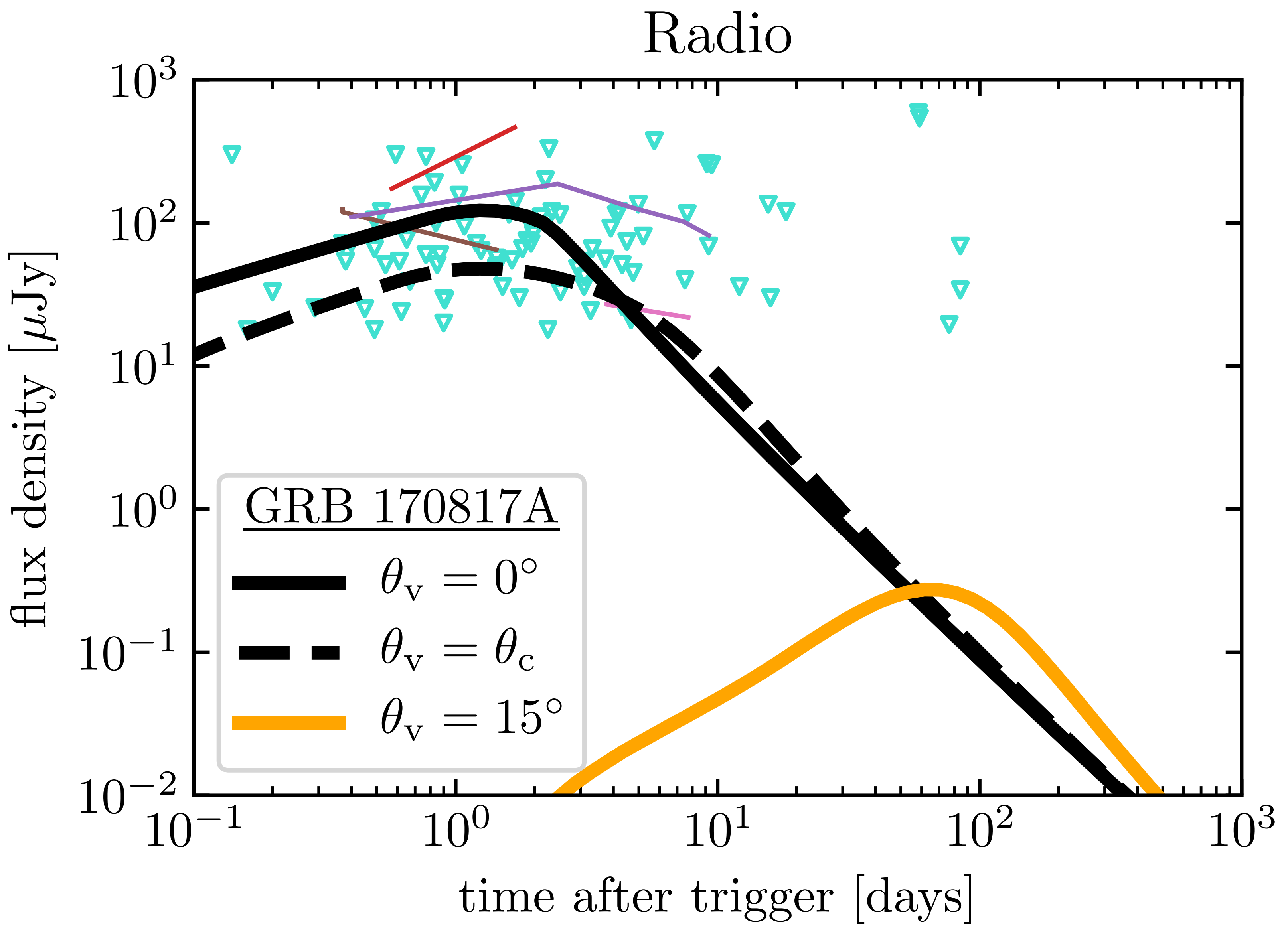
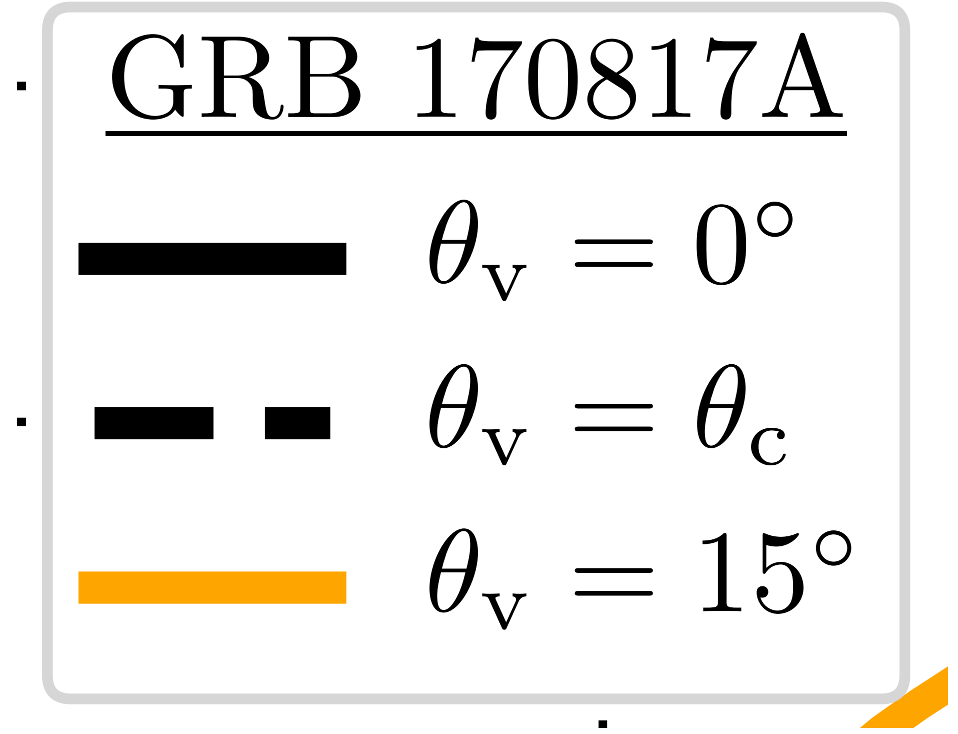
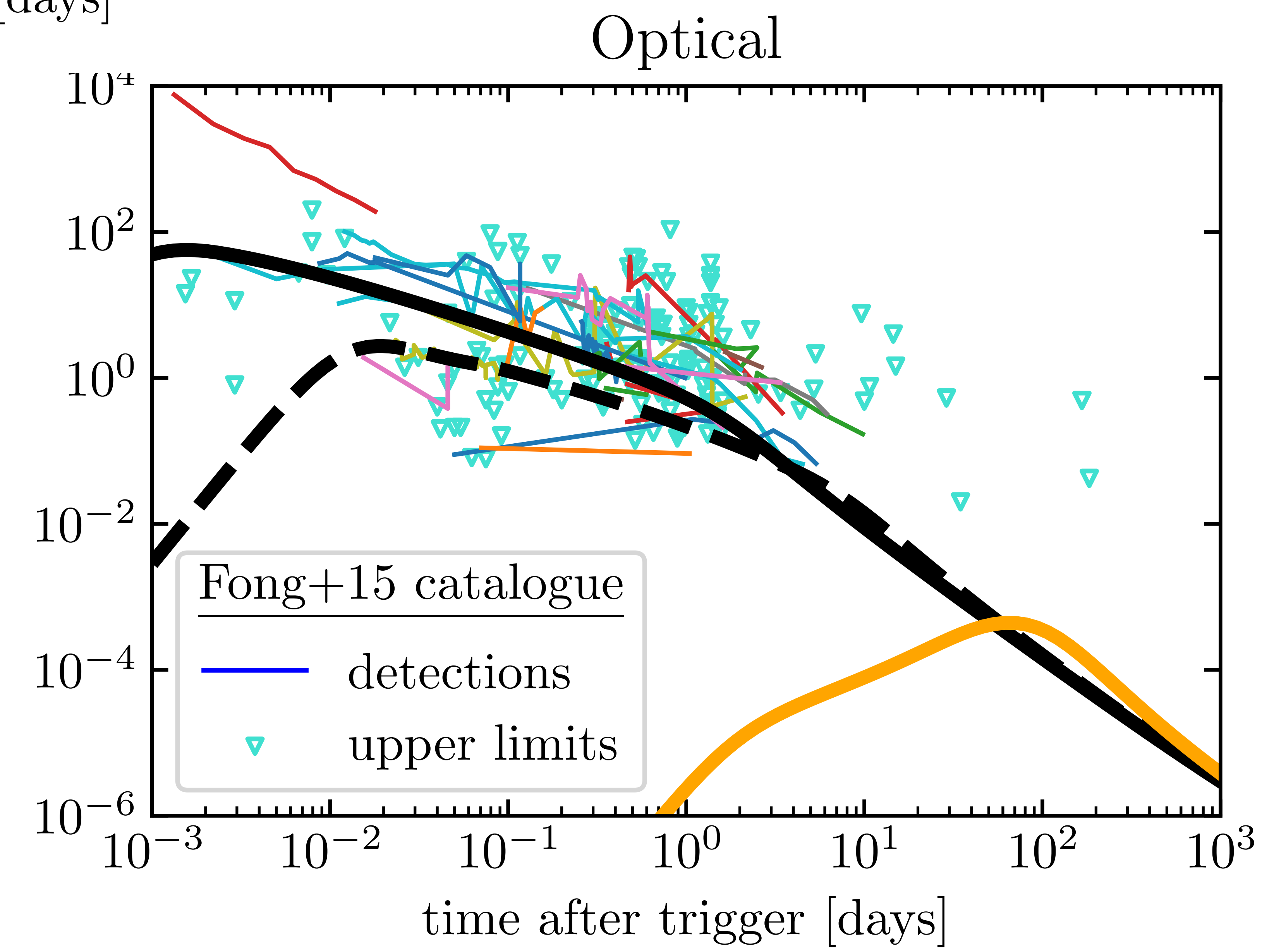






Salafia, GG et al. 2019

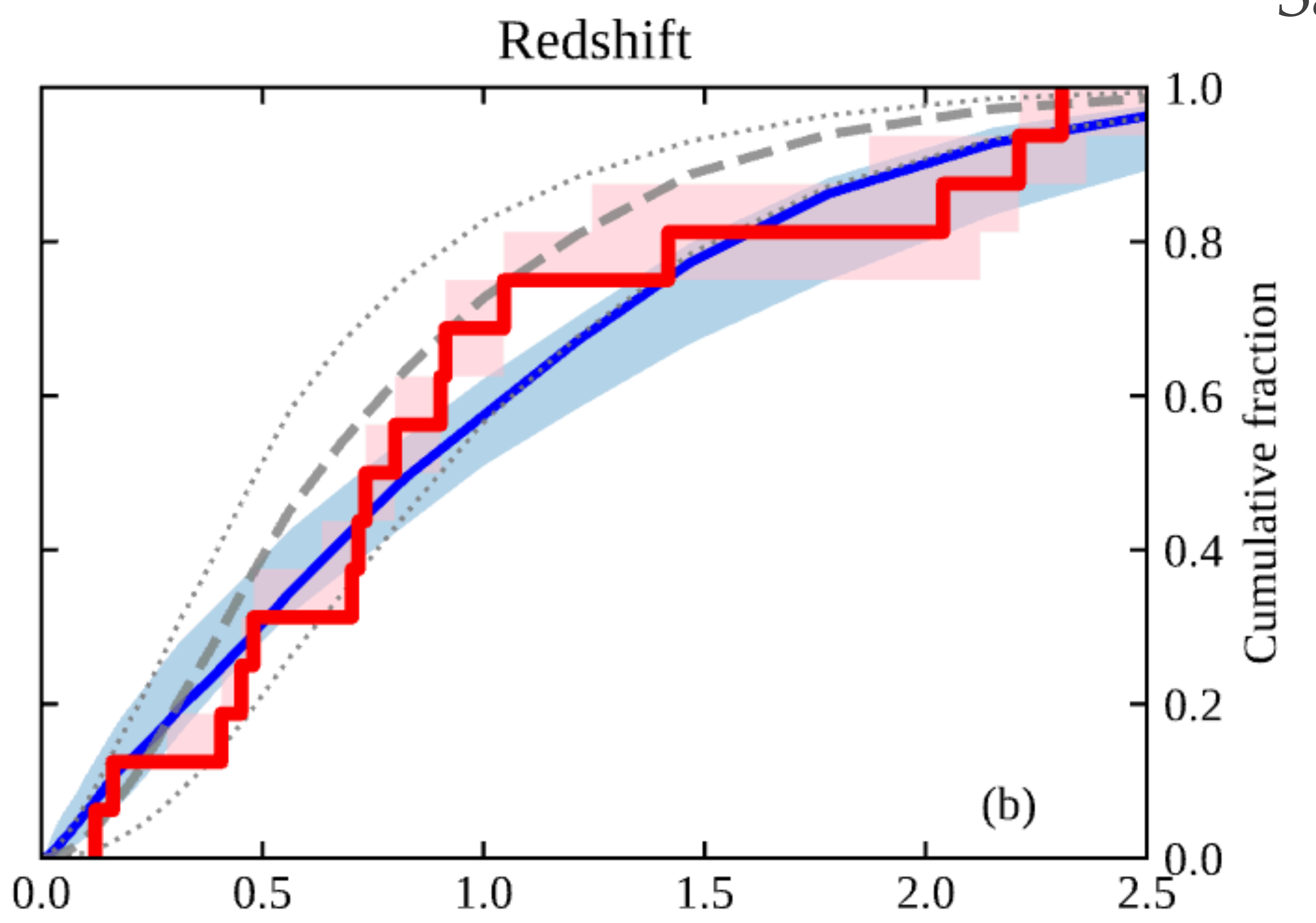
Afterglow emission

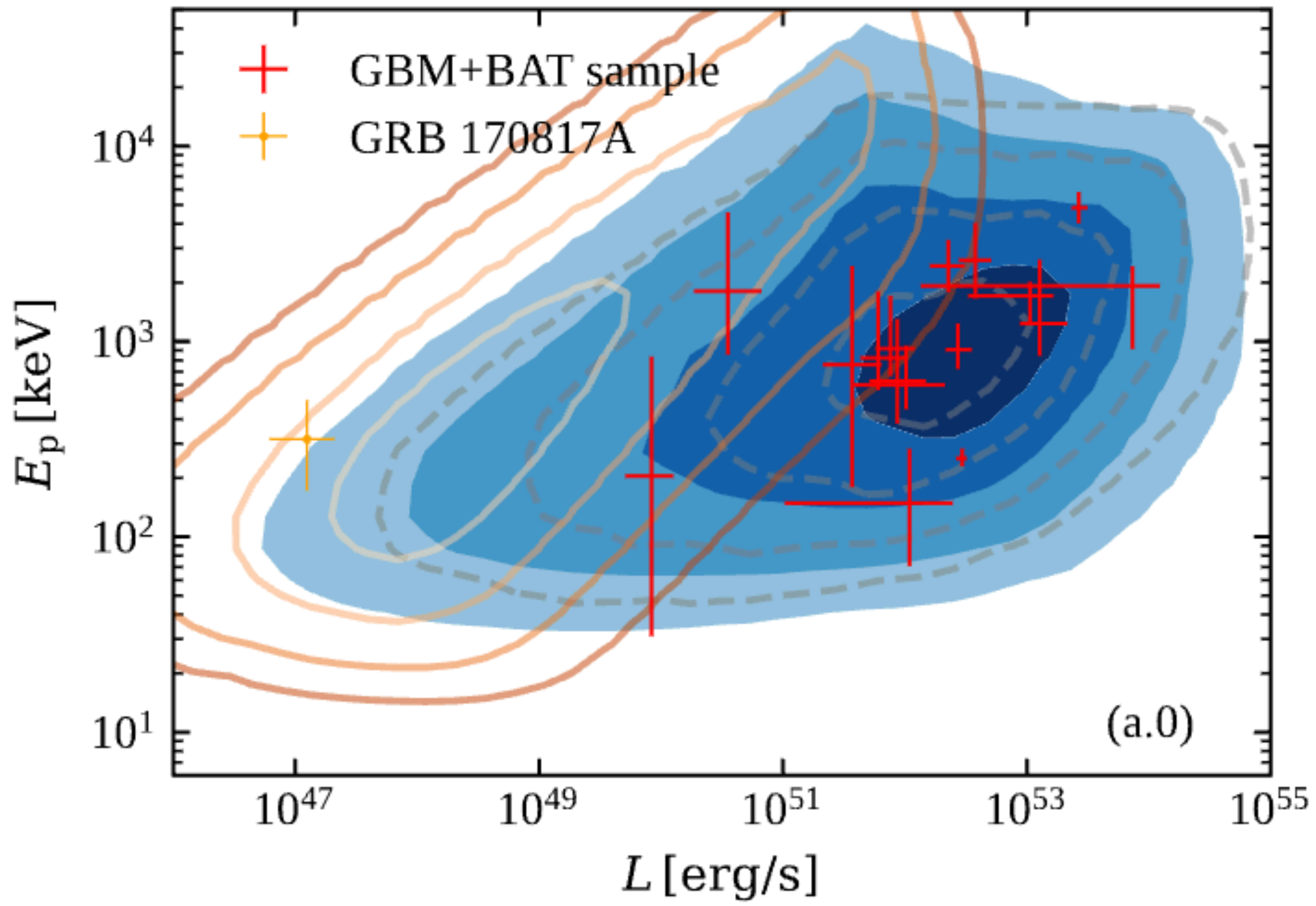


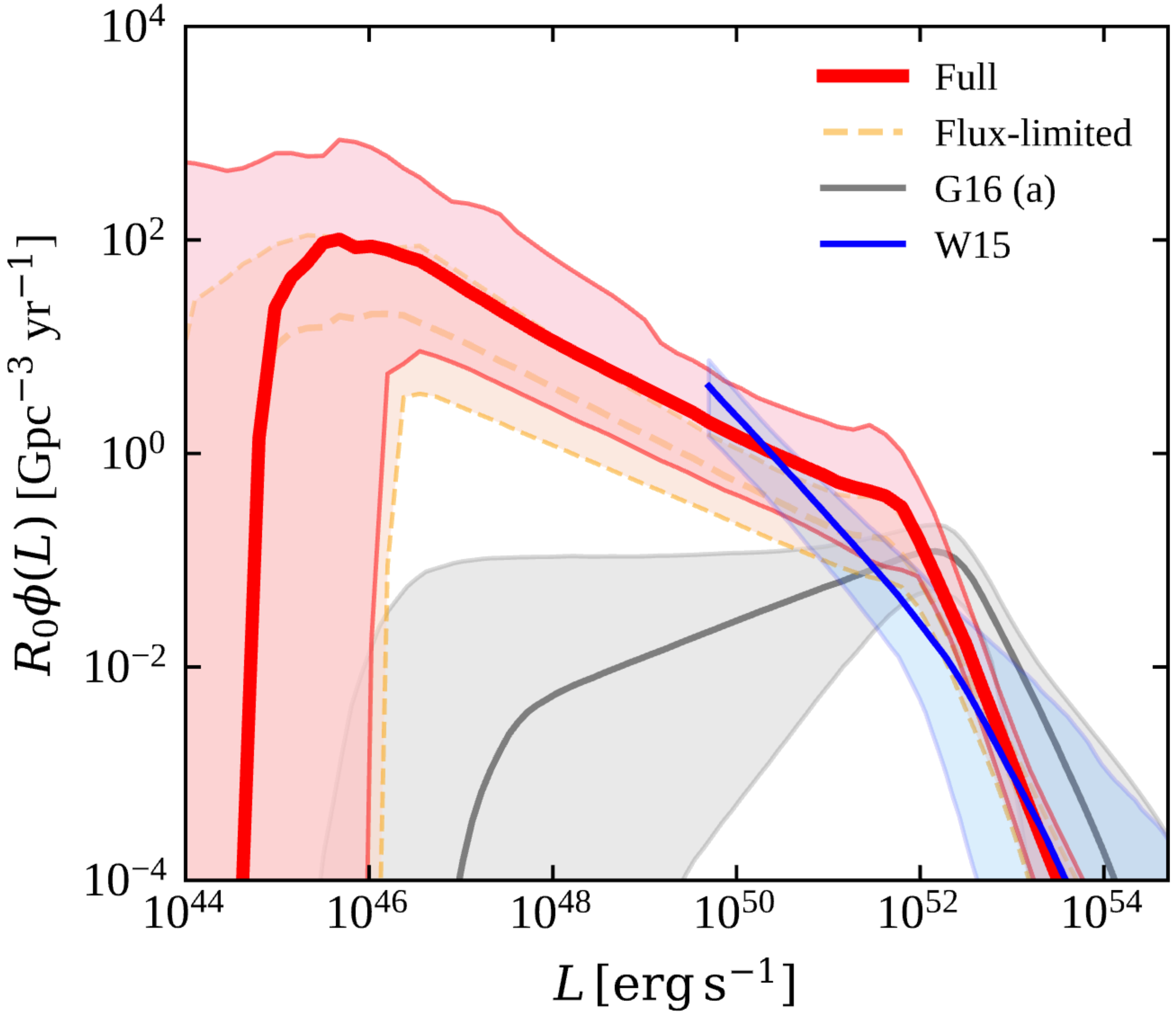
Q: A Universal jet in GRBs?

Universal jet structure

Salafia, … , GG, et al. 2023





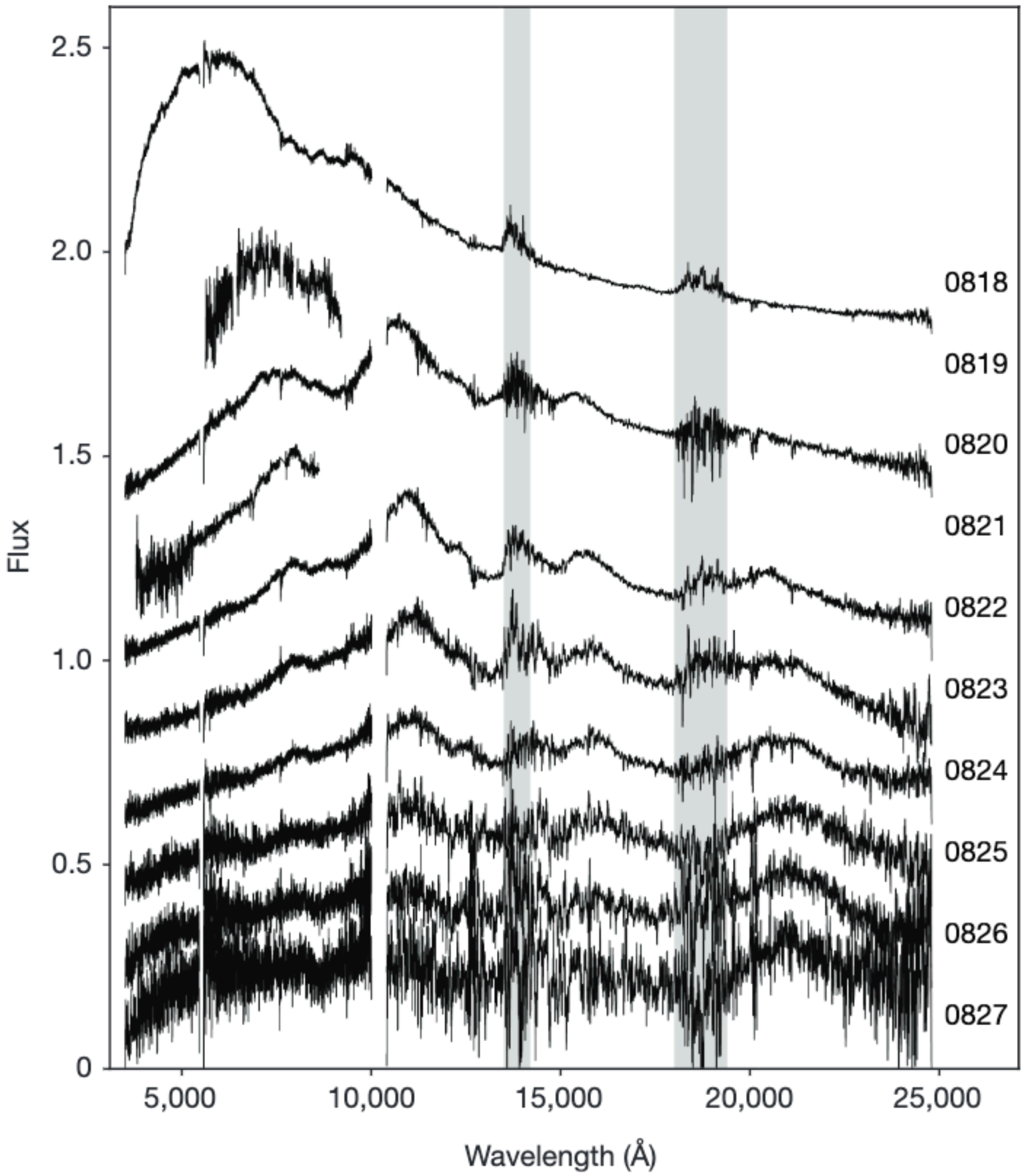


Confirms Pescalli, GG et al. 2015

THM: currently known short GRB population is consistent with the presence of a QUASI universal jet 170817-like

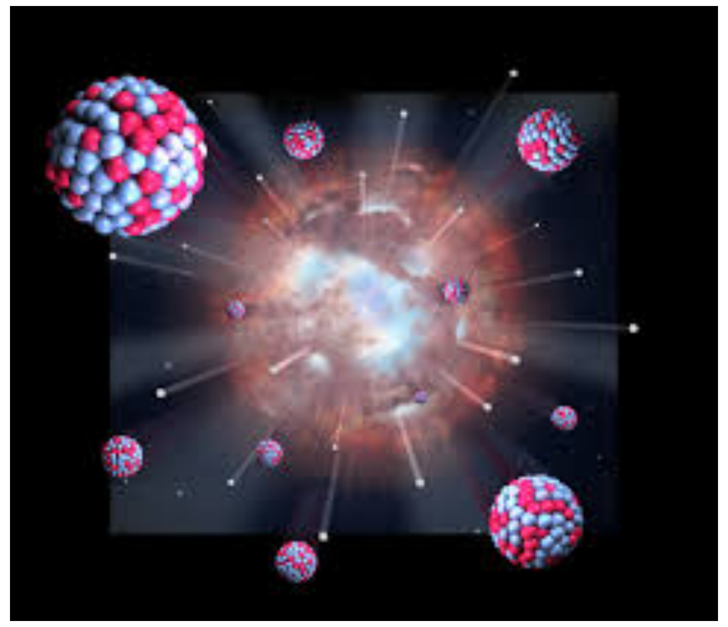
Kilonova

Pian E., D'Avanzo P., et al. 2017



- Luminous fast evolving emission
- Blue (more luminous) to red evolution
- Broad emission lines

Kilonova: a simplified model



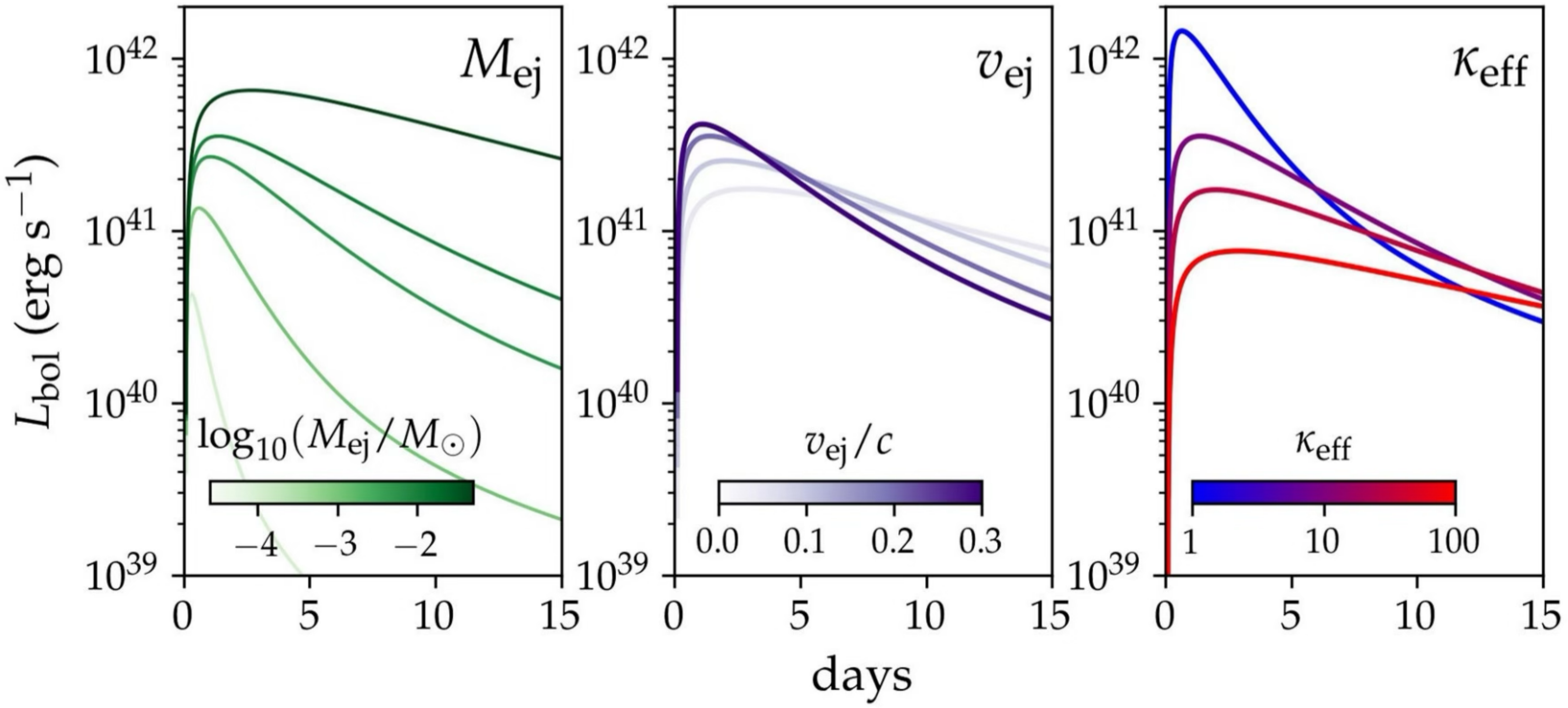
Idea (Lattimer et al. 1974, 1976) and first BNS model (Li&Paczynski 1998)

1. Rapid neutron capture —> heavy nuclei isotopes (τ_{exp}, s_B, $\mathbf{Y_e}$)
2. Nuclear decay (β, α) —-> heating
3. Dynamics (M_{ej}, v_{ej}, k_{ej})

EOS

Barnes 2020 (for an essential review)

$\dot{E}_{nuc} \sim t^{-1.3}$



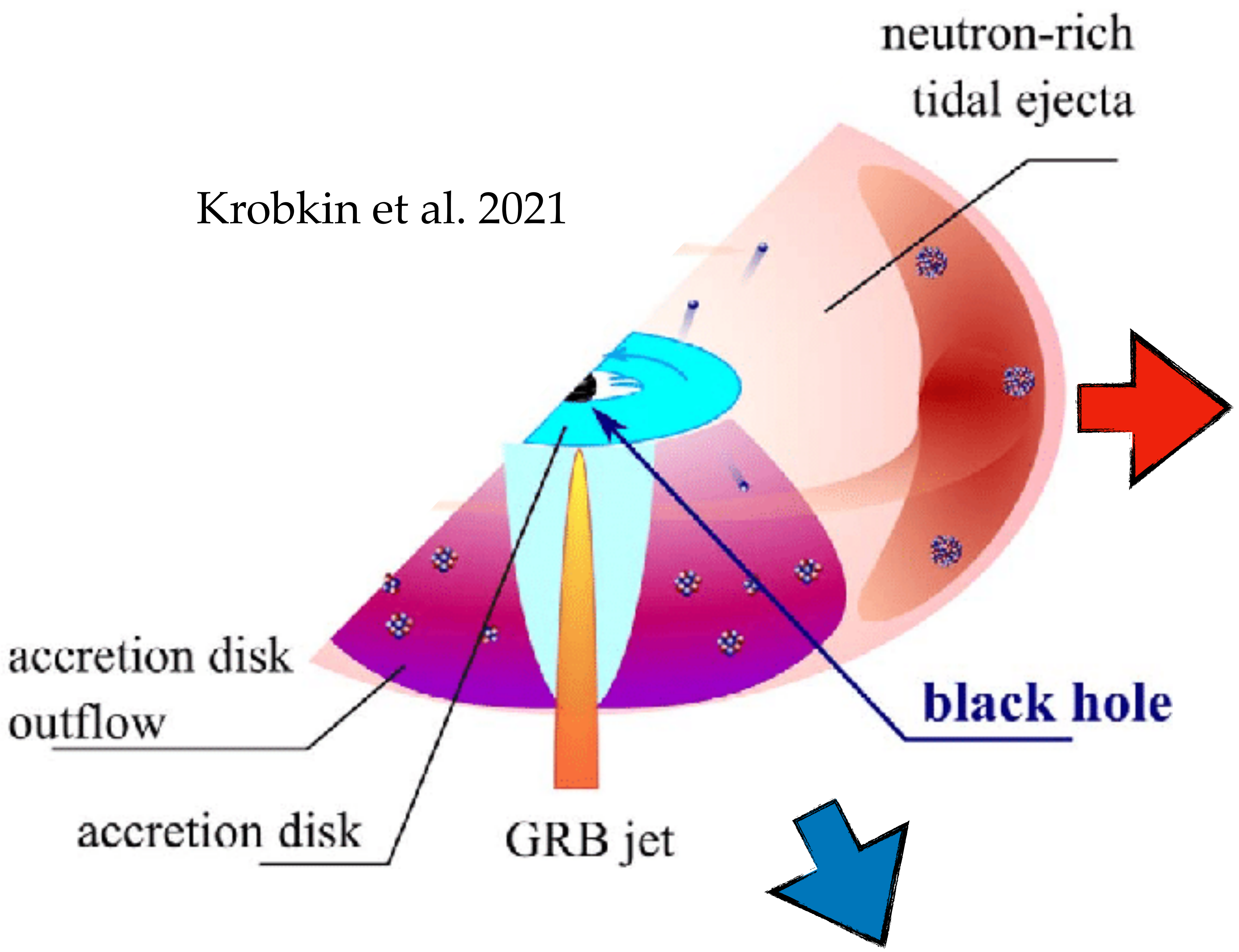
THM: KN light curves/spectra encode merger driven mass ejection and nucleosynthesis.

Kilonova

Some open questions:

1) Blue kilonova
2) Contribution to Universe nucleosynthesis
3) NSBH Kilonovae diversity

Krobkin et al. 2021



Red Kilonova $L \sim 10^{40}$ erg/s $t_p \sim 1$ week (Lanthanide rich)

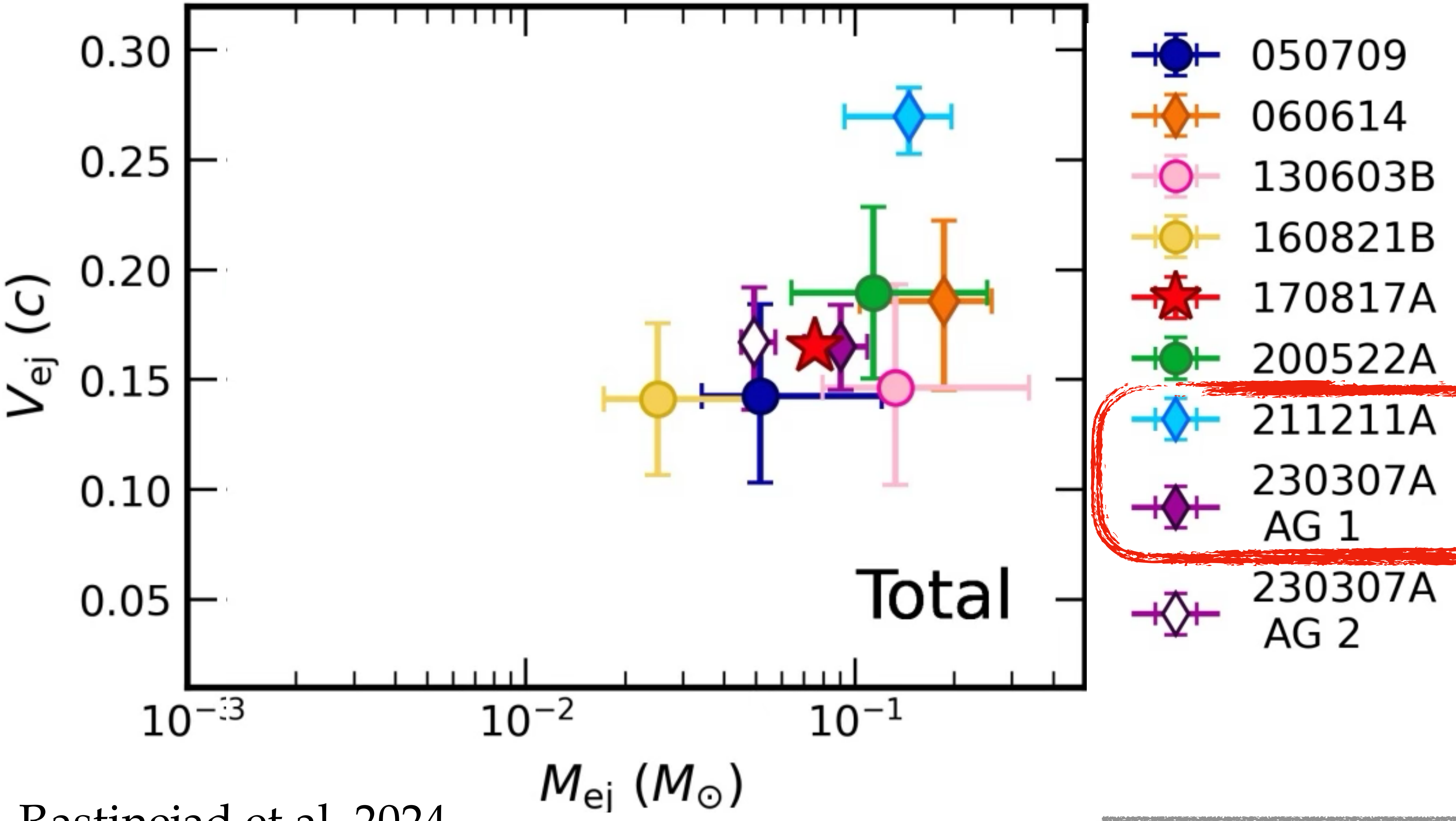
Blue Kilonova $L \sim 10^{41}$ erg/s $t_p \sim 1$ day (Lanthanide free)

AT2017gfo & other Kilonovae

More than one KN …

- 170817A / KN2017gfo (the "MM KN")
- 5 Short GRB with KN signatures
- 2 Long GRBs with KN signatures (211211A, 230307A - see also A. Levan talk)

Initial sample proprieties
(Ascenzi et al. 2019)



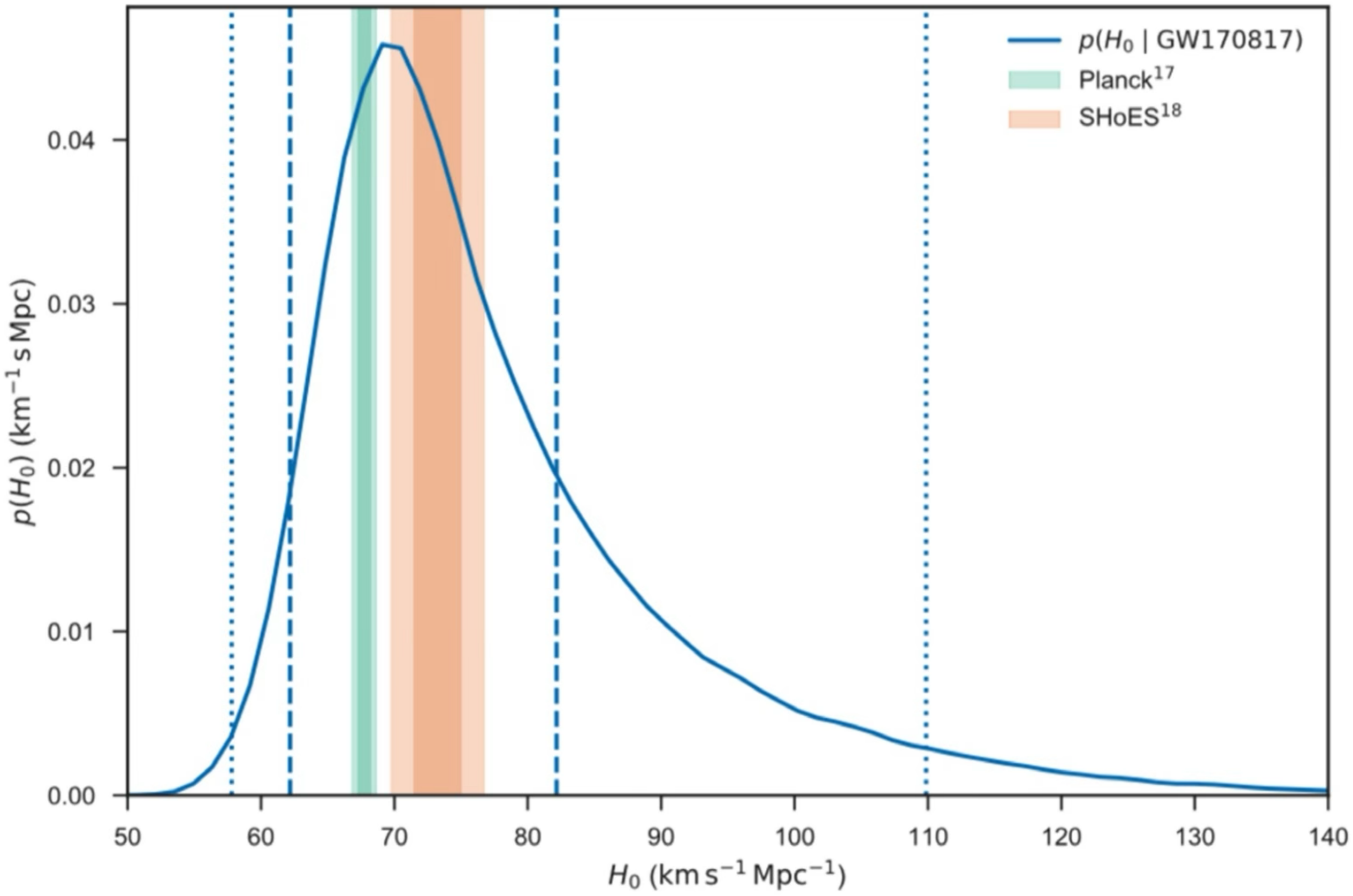
Long GRBs with CBC progenitor (see also A. Levan talk)

Rastinejad et al. 2024

Multi Messenger

Cosmology

DM → Tue Session (talk G. Bertone)



(Review: Mastrogiovanni et al. 2022 - adapted from Abbott et al. 2017)

Standard Sirens:

1. Bright: EM —> z (+ i)

   170817:

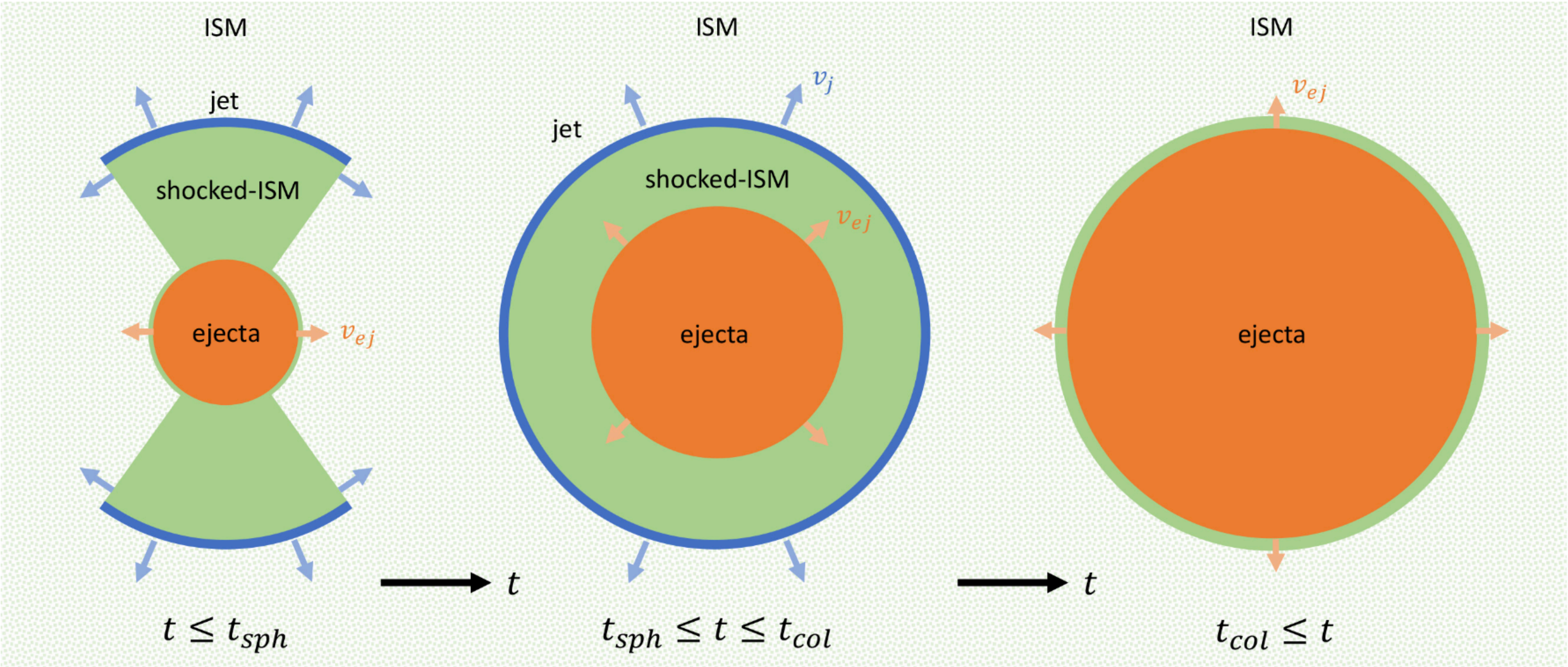
   $H_0 = 70^{+12}_{-8} \rightarrow 68 \pm 4.6$ km/s/Mpc

2. Dark
   - Galaxy catalog
   - $M_z = (1+z)M$

NS EoS → Talk V. Graber

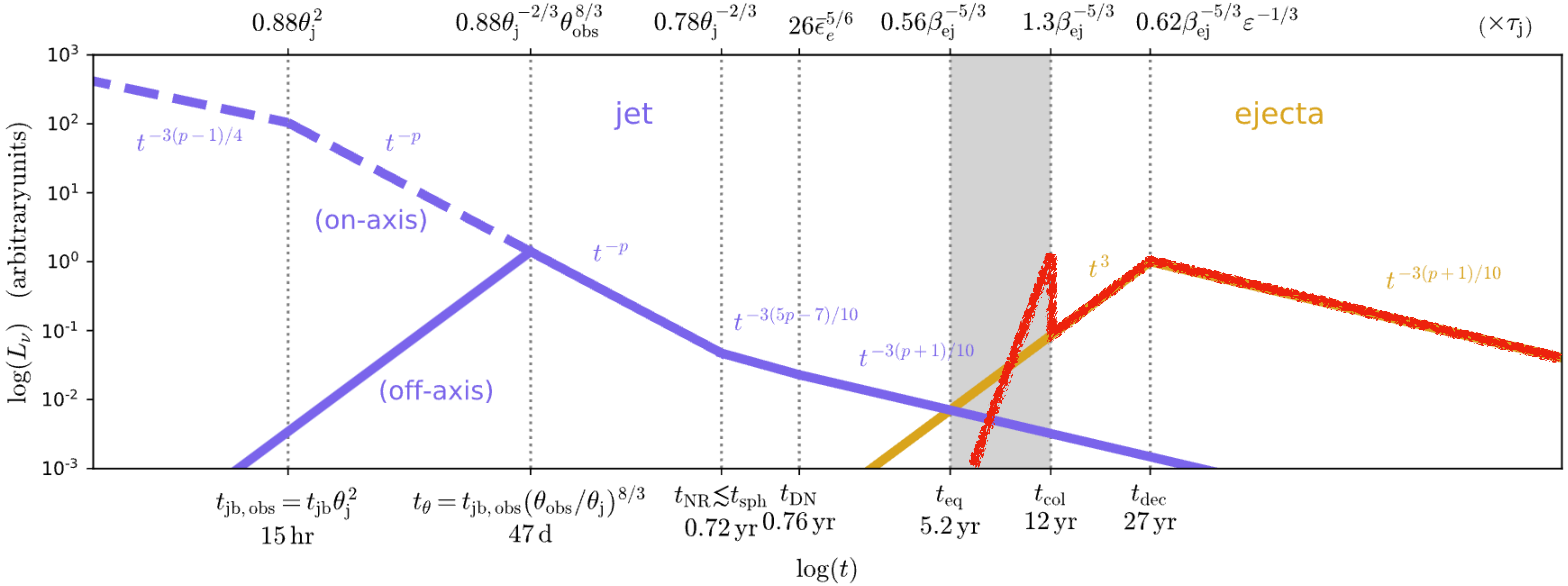
Fund. Phys. → Talk A. Gosh

Late time EM signals

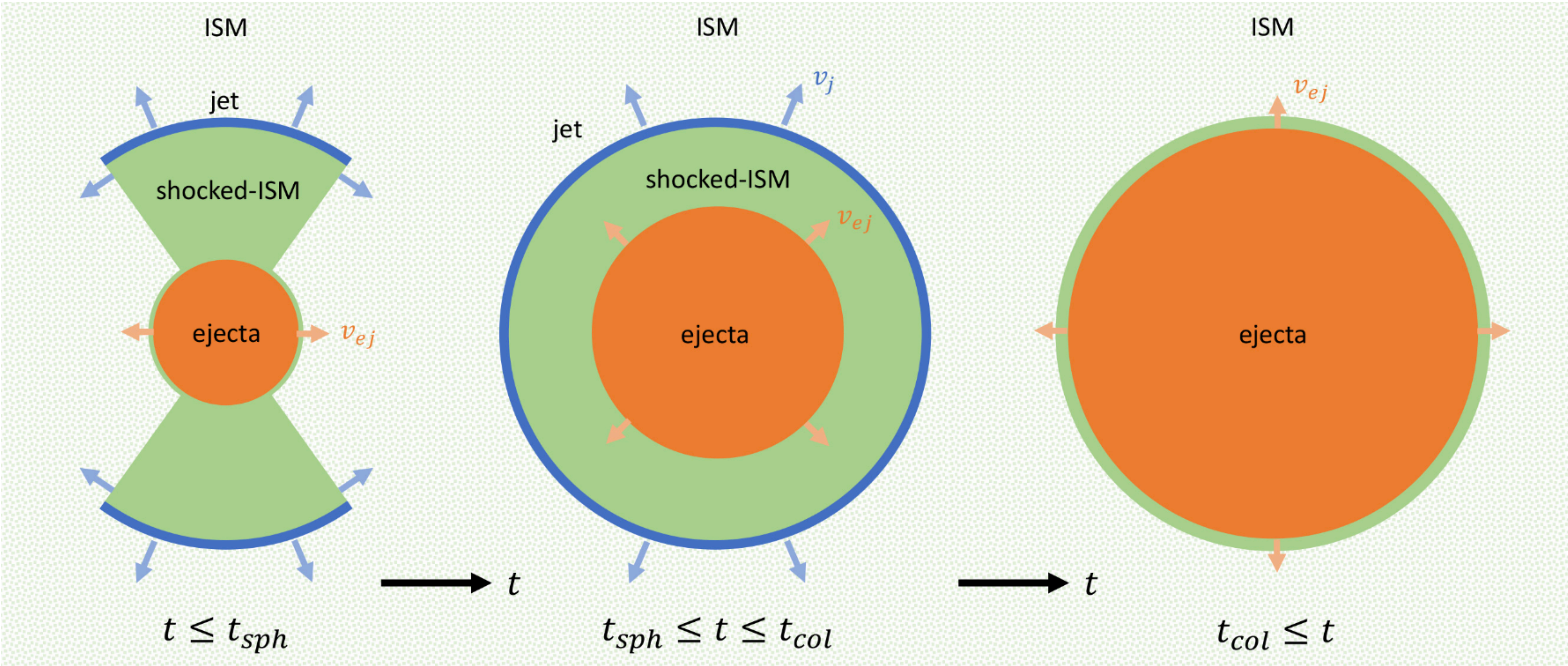


Jet (faster) and ejecta (slower) are not independent

Margalit & Piran 2020
[Nakar & Piran 2011 …]



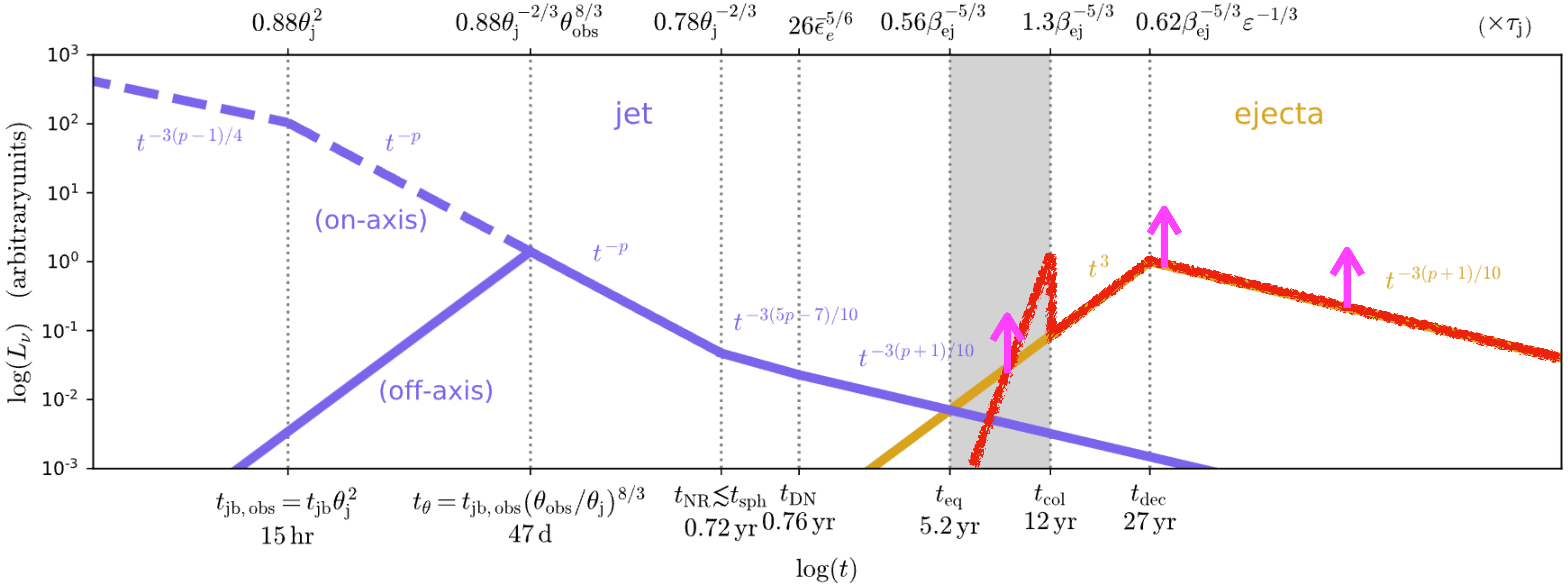
Late time EM signals



Jet (faster) and ejecta (slower) are not independent

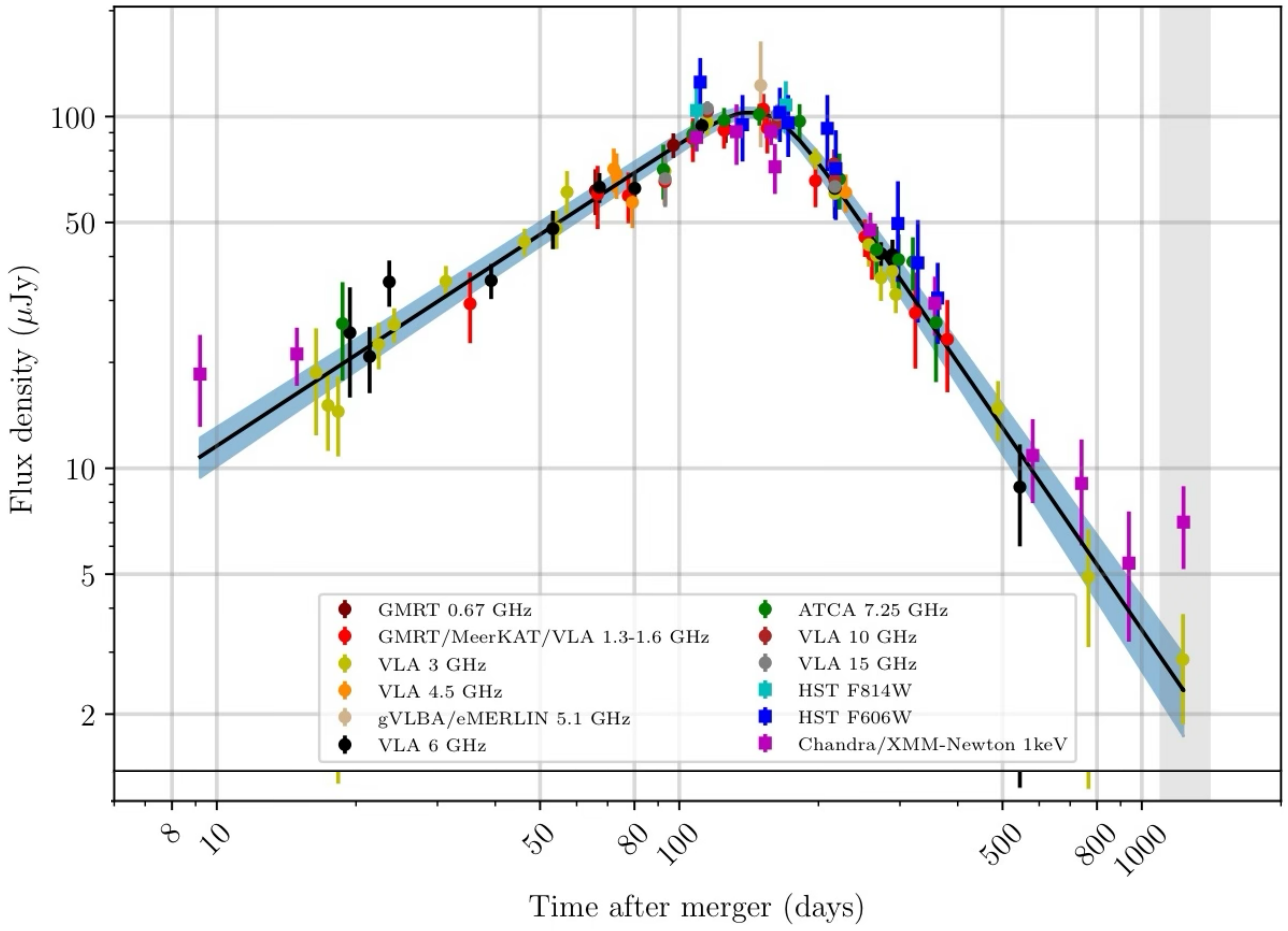
Margalit & Piran 2020
[Nakar & Piran 2011 …]

Extra power if Magnetar rather than BH

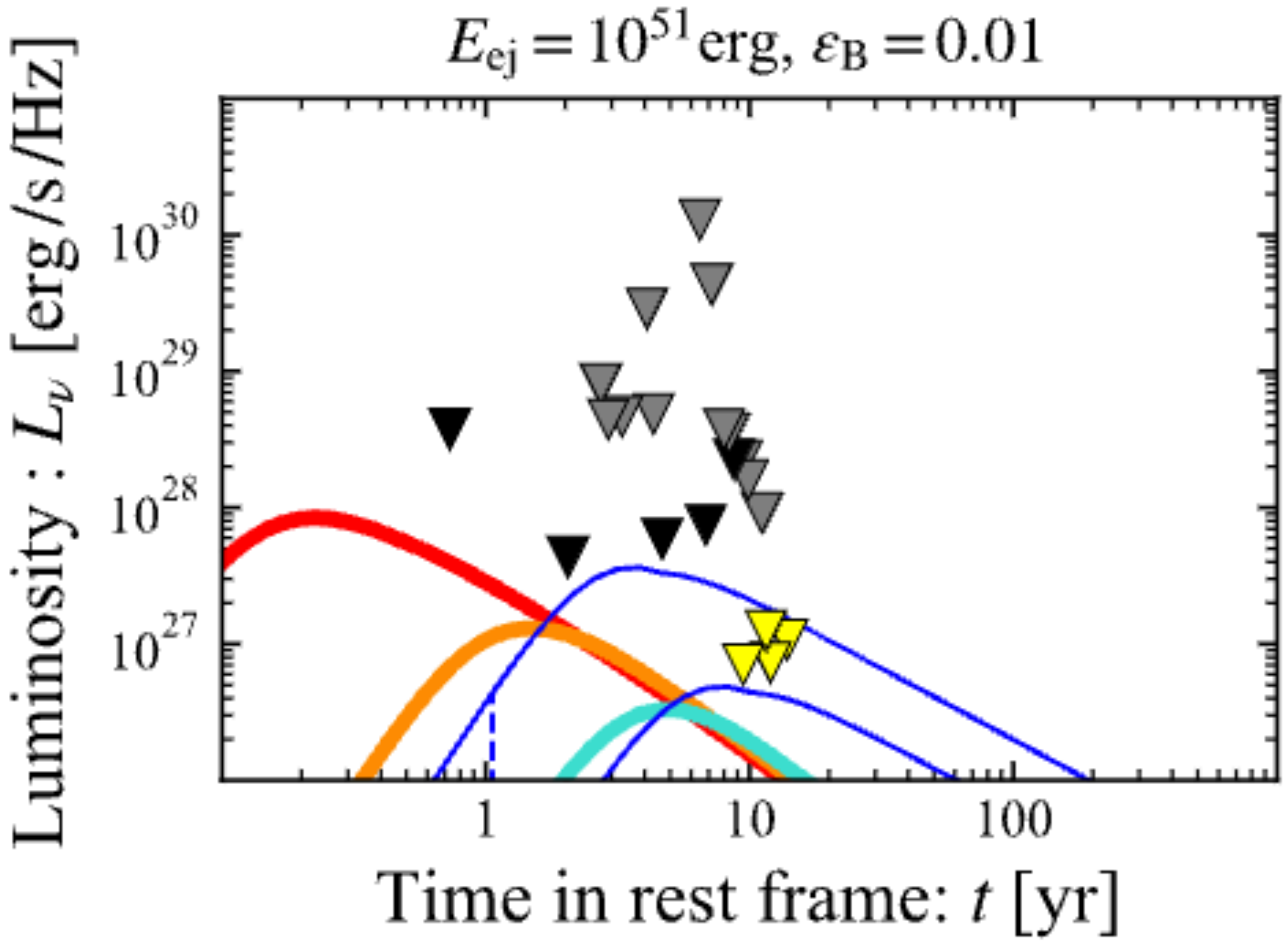


Late time EM signals

Balasubramanian et al. 2021



Bruni et al. 2021

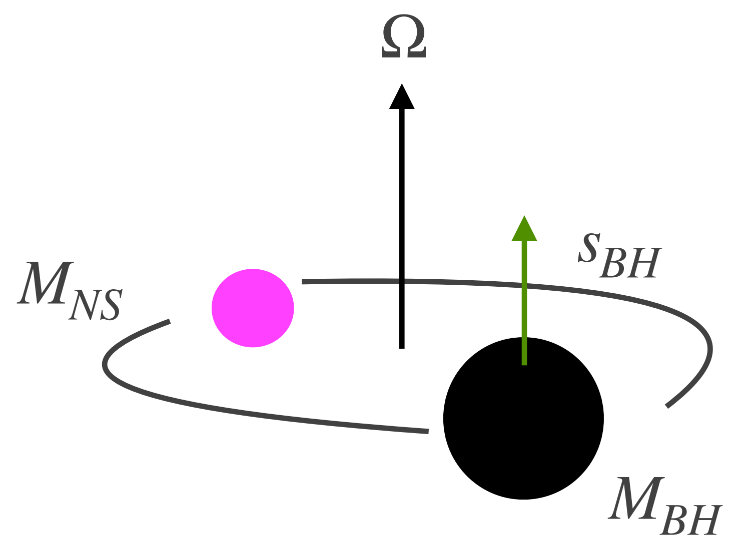


BH-NS systems

$M_{NS}, \Lambda_{NS}, M_{BH}, \chi_{BH}, i_{BH}$

$R_{tidal} \sim \left(\frac{M_{BH}}{M_{NS}}\right)^{1/3} R_{NS}$

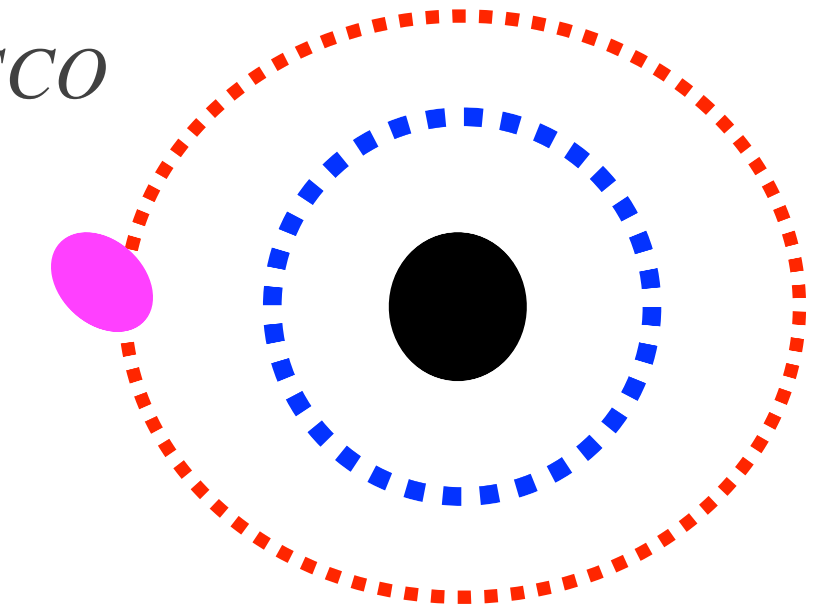
$R_{ISCO}(M_{BH}, \chi_{BH})$



Tidal NS disruption
(EM bright)

$R_{tidal} > R_{ISCO}$

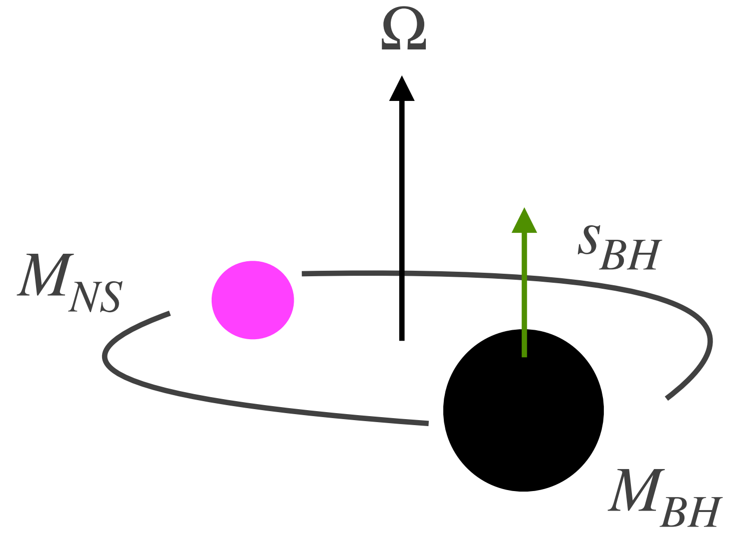
$M_{out} \neq 0$



BH-NS systems

M_{NS}, Λ_{NS}, $M_{BH}, \chi_{BH}, i_{BH}$

$R_{tidal} \sim \left(\frac{M_{BH}}{M_{NS}}\right)^{1/3} R_{NS}$ $\quad R_{ISCO}(M_{BH}, \chi_{BH})$



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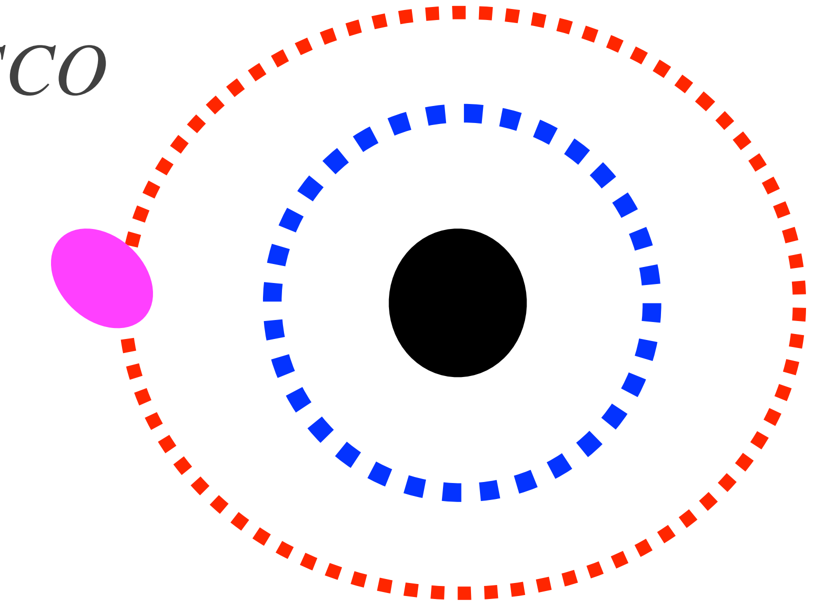
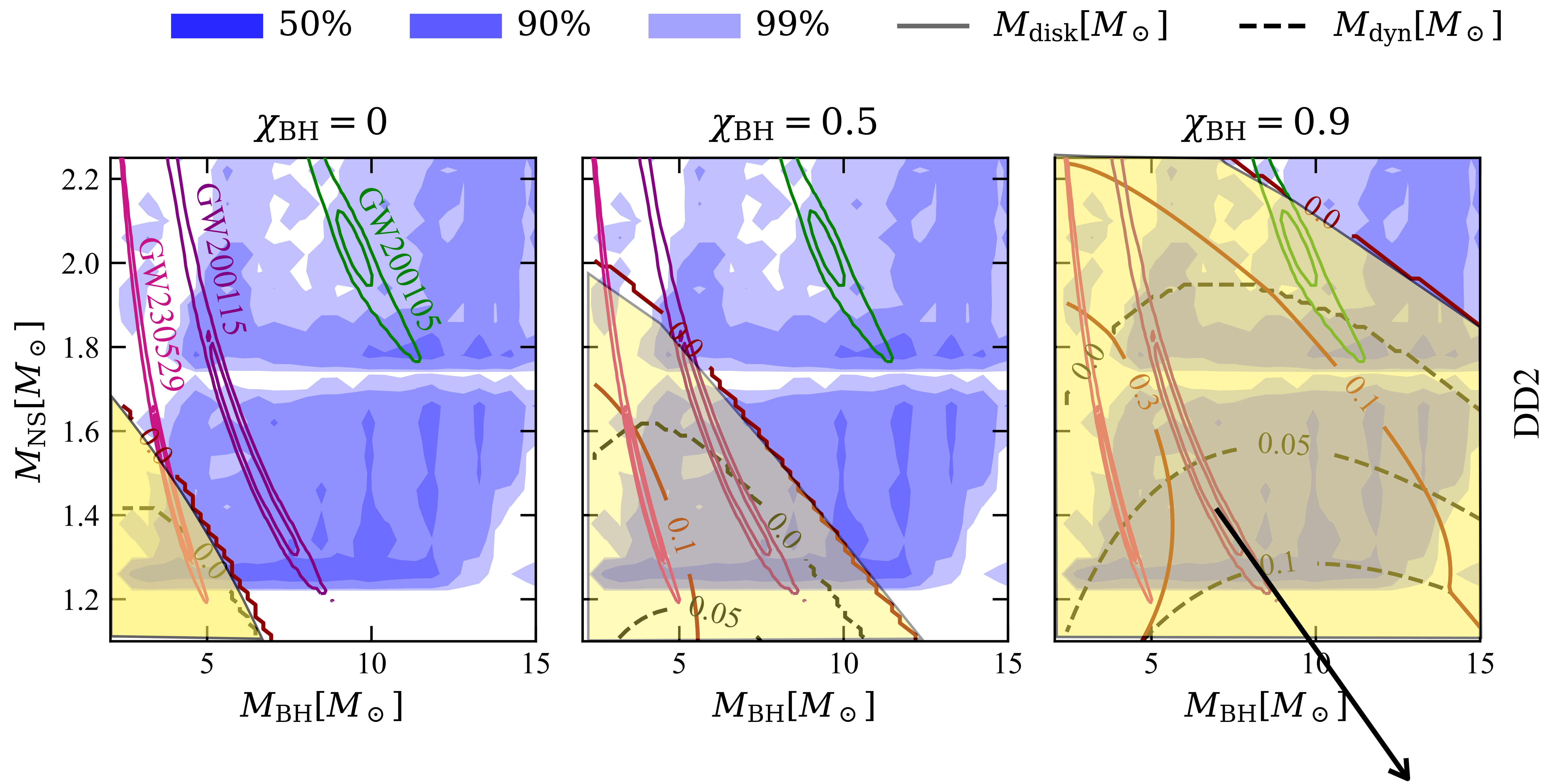


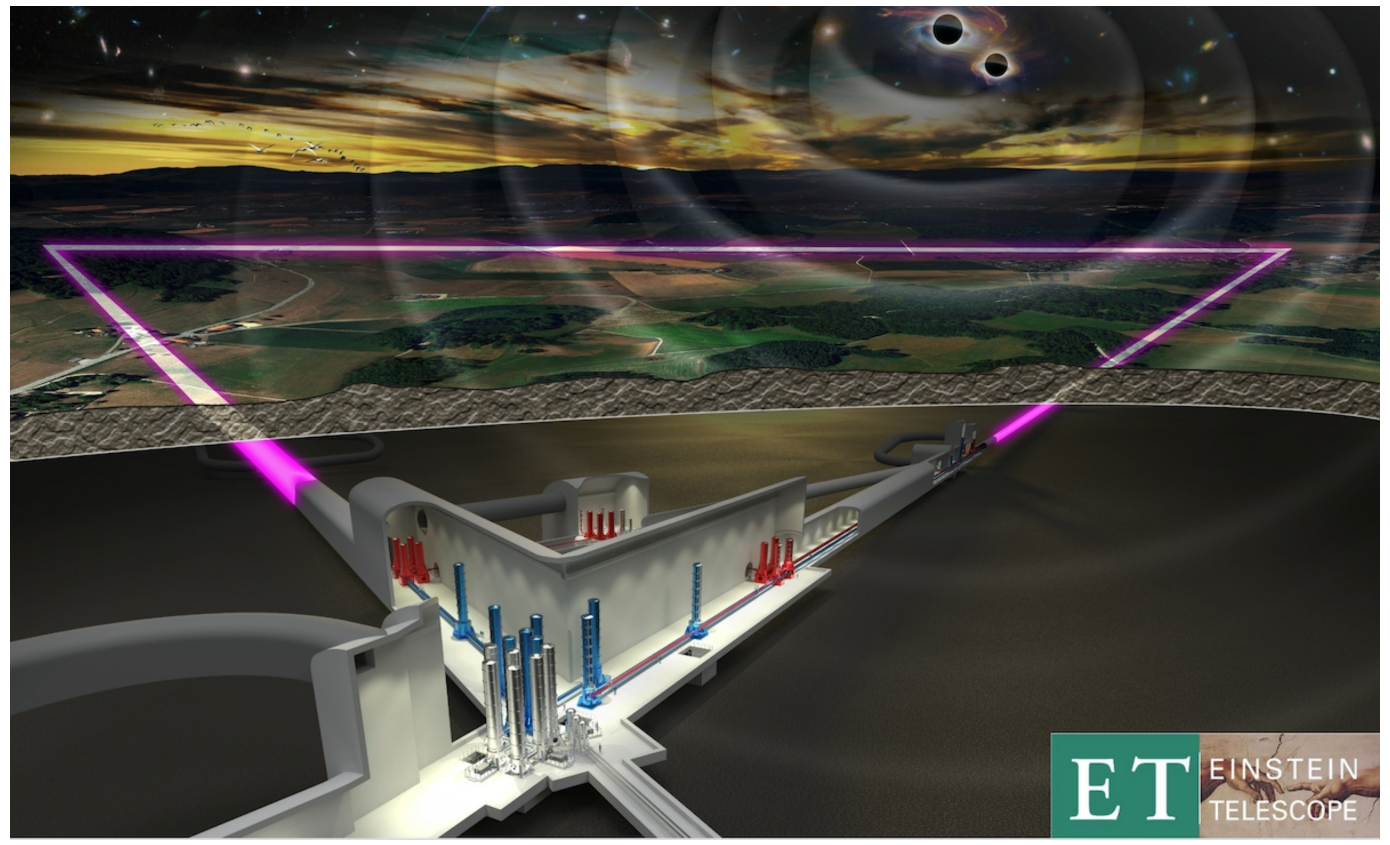
Colombo et al. in preparation



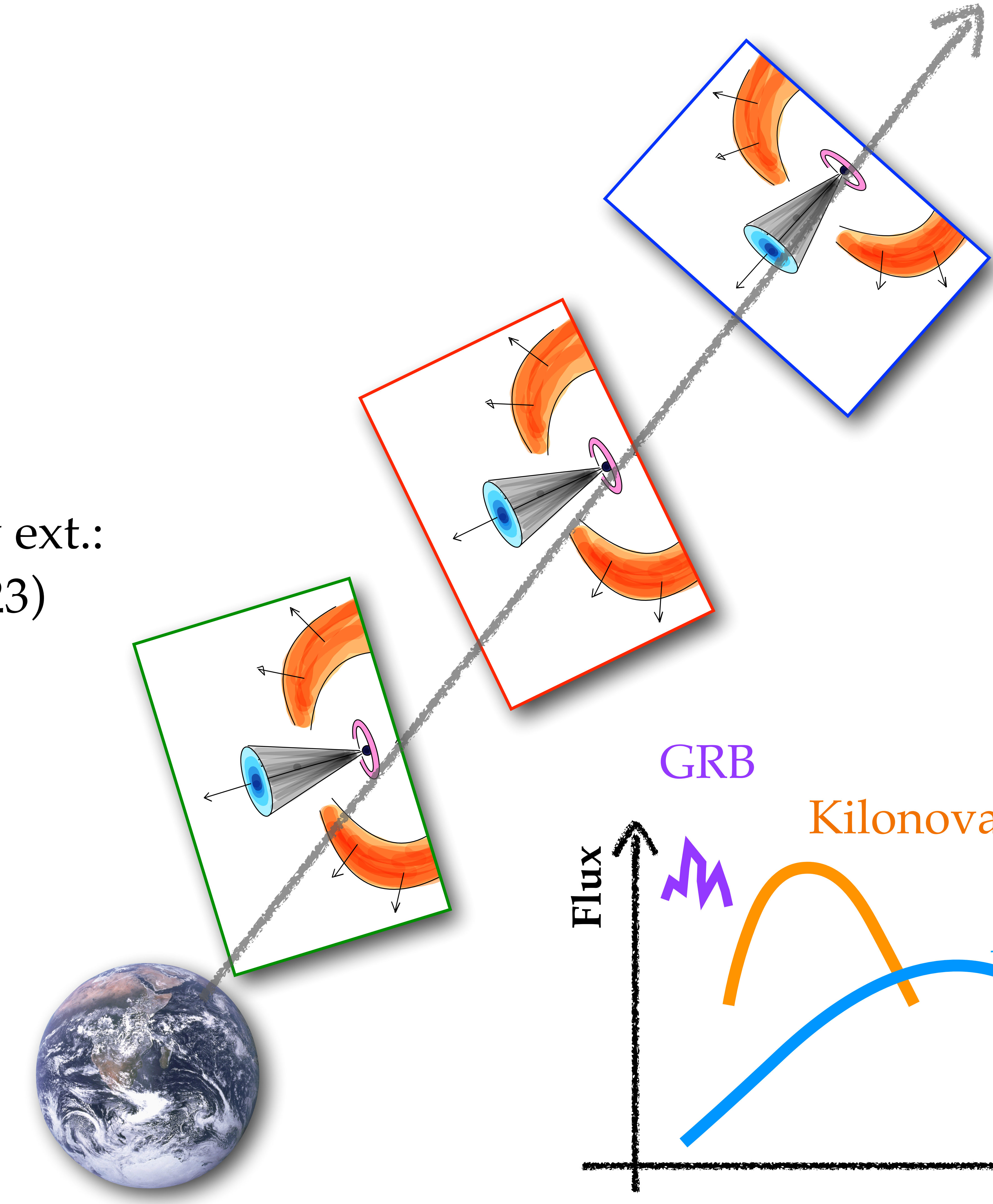
230529 (Abac et al. 2024, LVK collaboration)
$M_{BH} \in [2.5, 4.5]\ M_\odot$

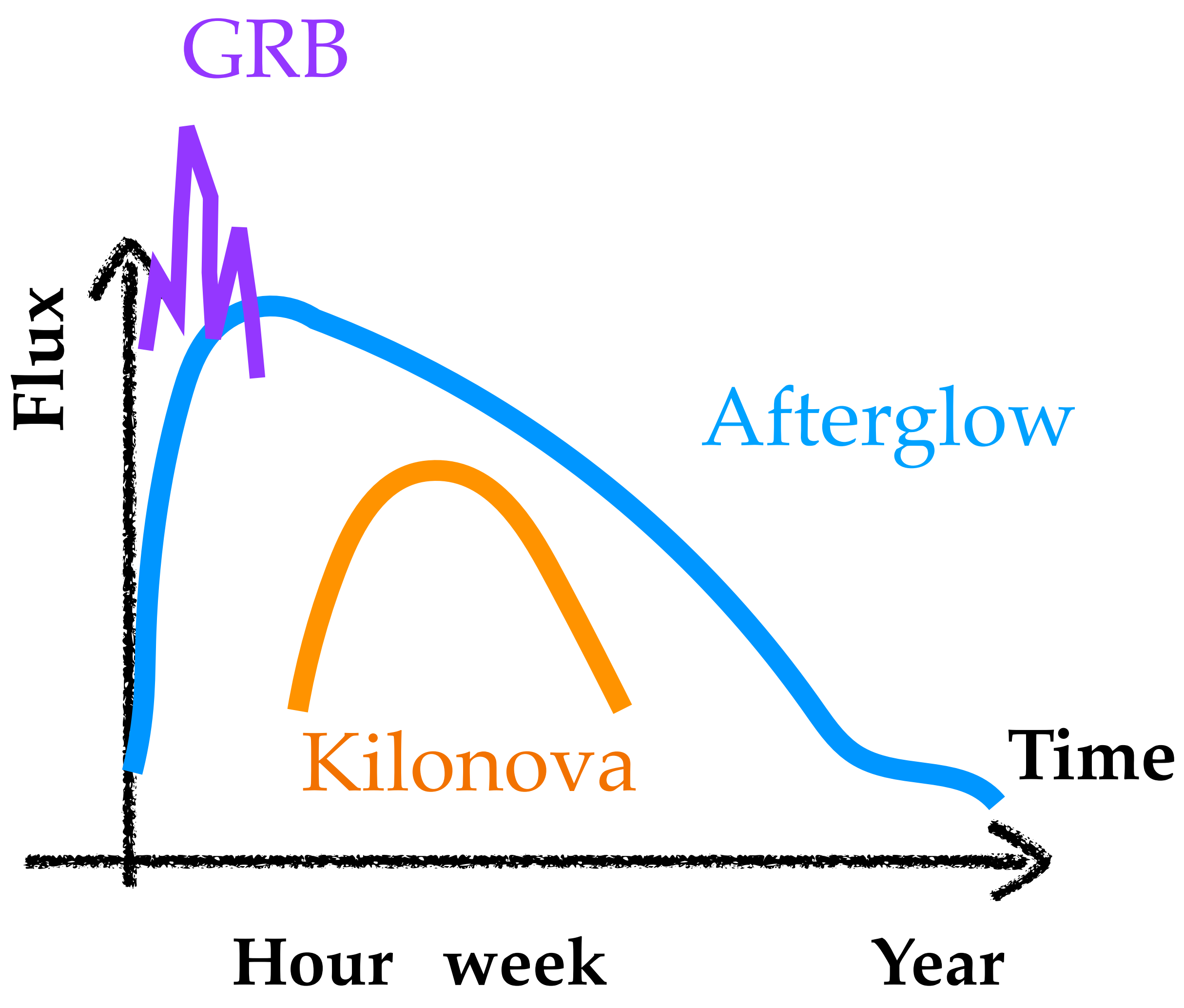
EM bright

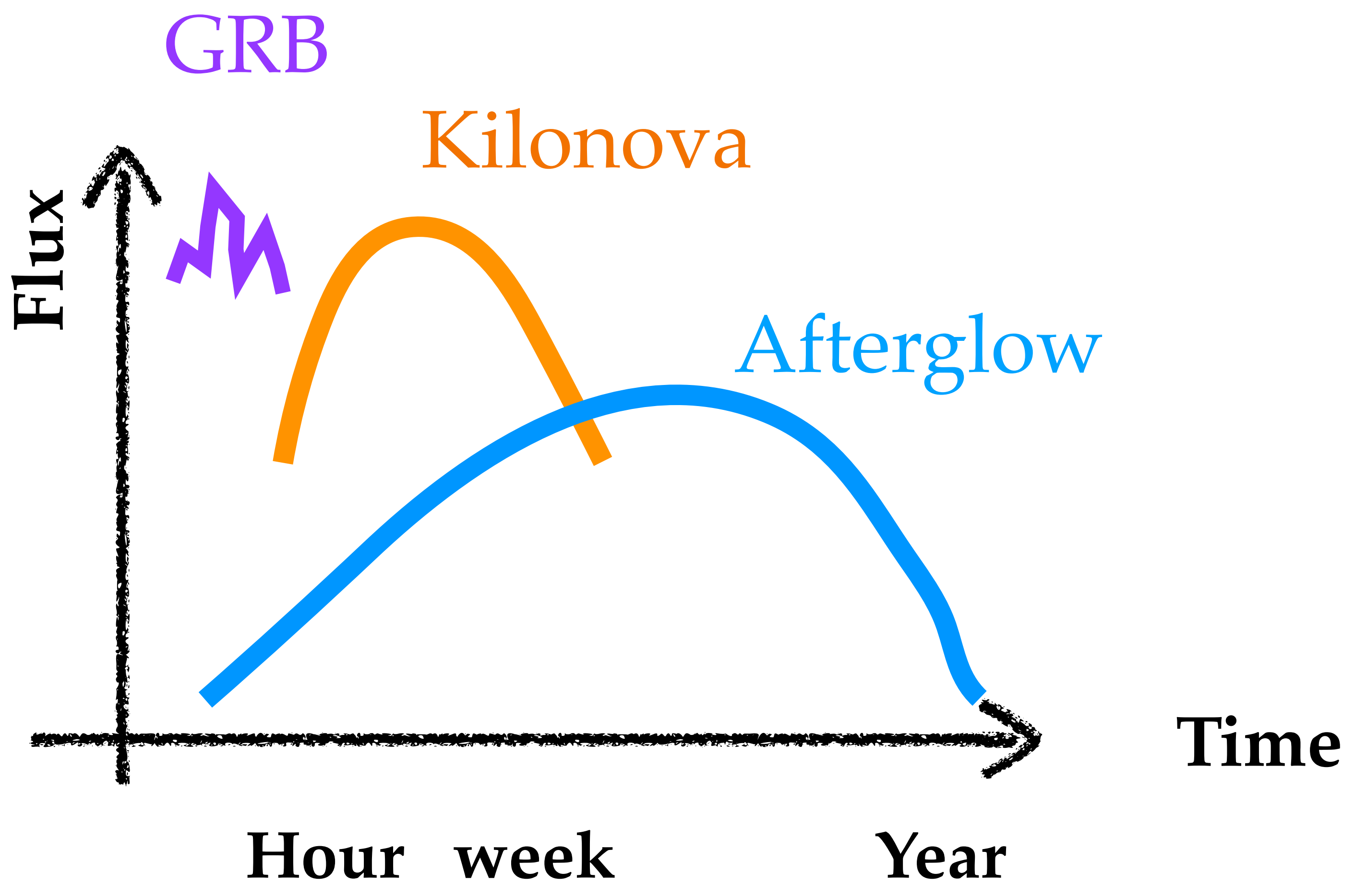
3rd Generation - Einstein Telescope



Einstein Telescope: x10 sensitivity + low frequency ext.:
$O(10^{4-5})\ yr^{-1}$ CBC up to z>>2 (see Branchesi+2023)







Different upcoming facilities (radio-opt-Gamma)
Sensitivity, field of view, agility, synergies

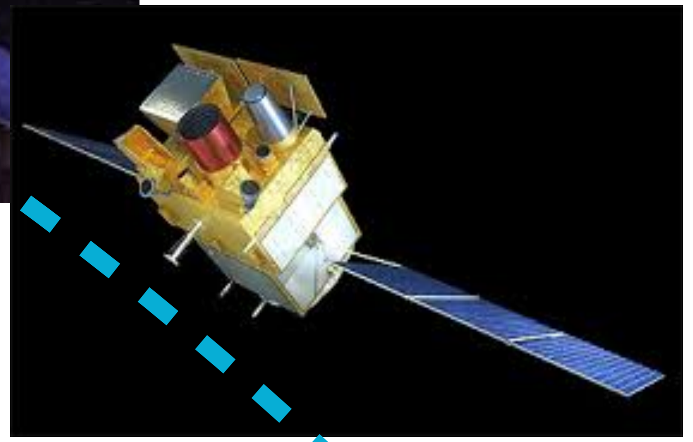
Each prompt GRB will have a GW counterpart
(Ronchini+2020; Colombo+2023, 2024)

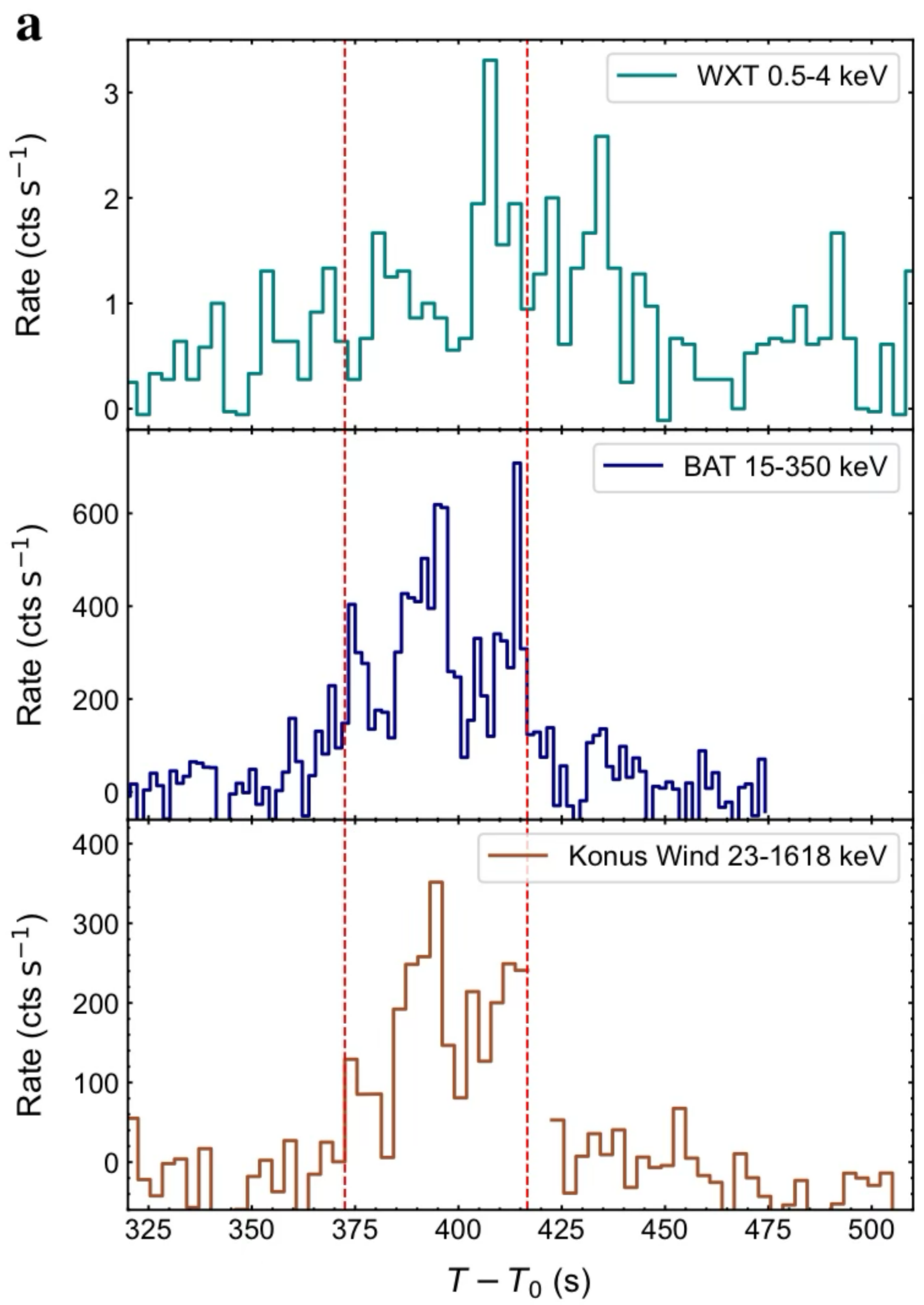
→ Talk L. Naticchioni & S. Piranomonte

Multi-Messenger perspectives

Einstein Probe (CAS, ESA, CNRS)

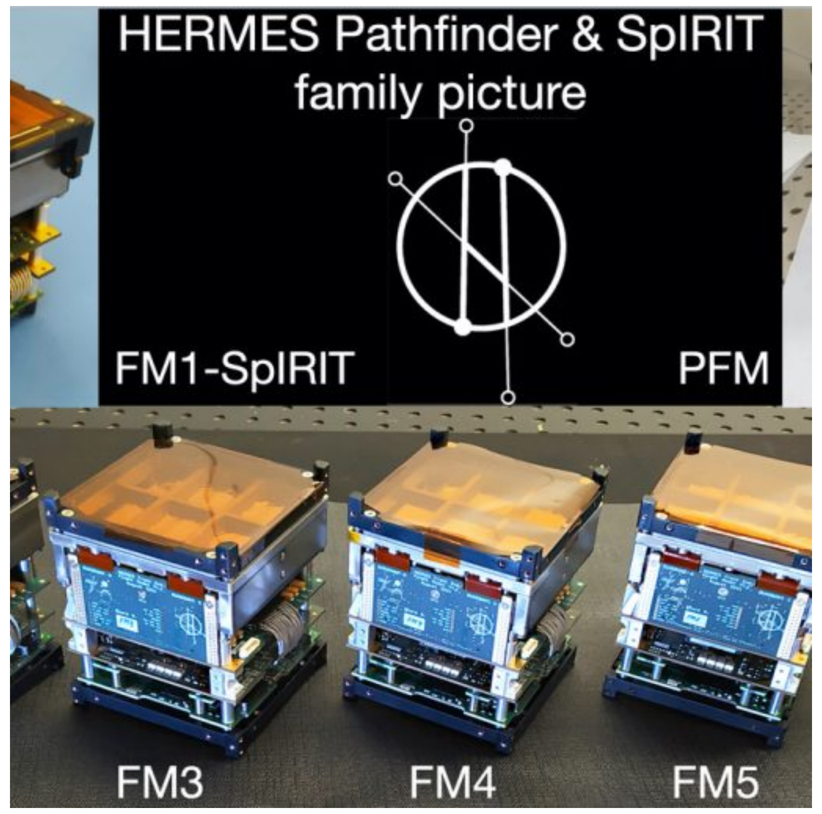
SVOM (CAS, CNRS)



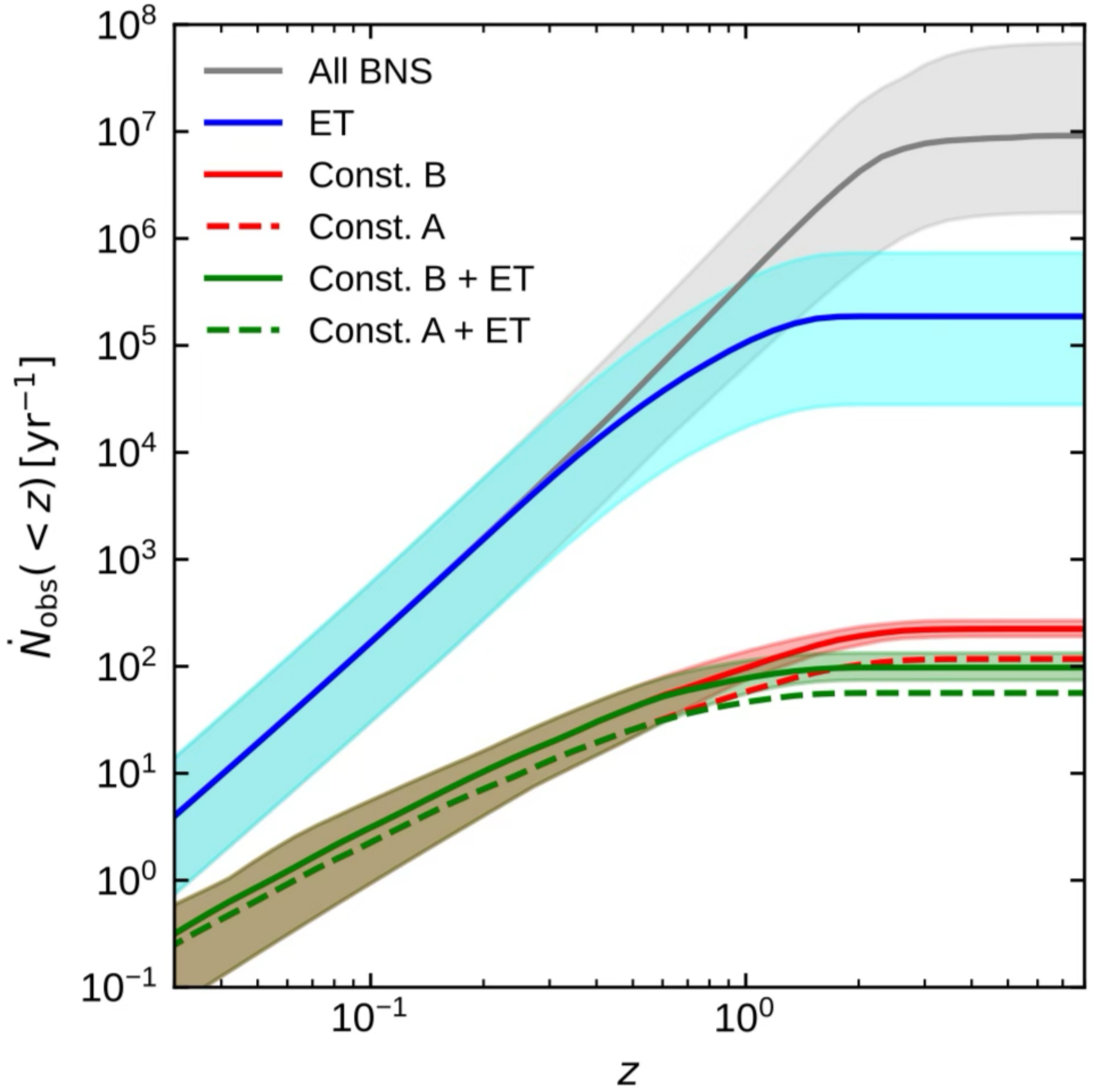


Liu, …, GG, et al. 2024

Hermes

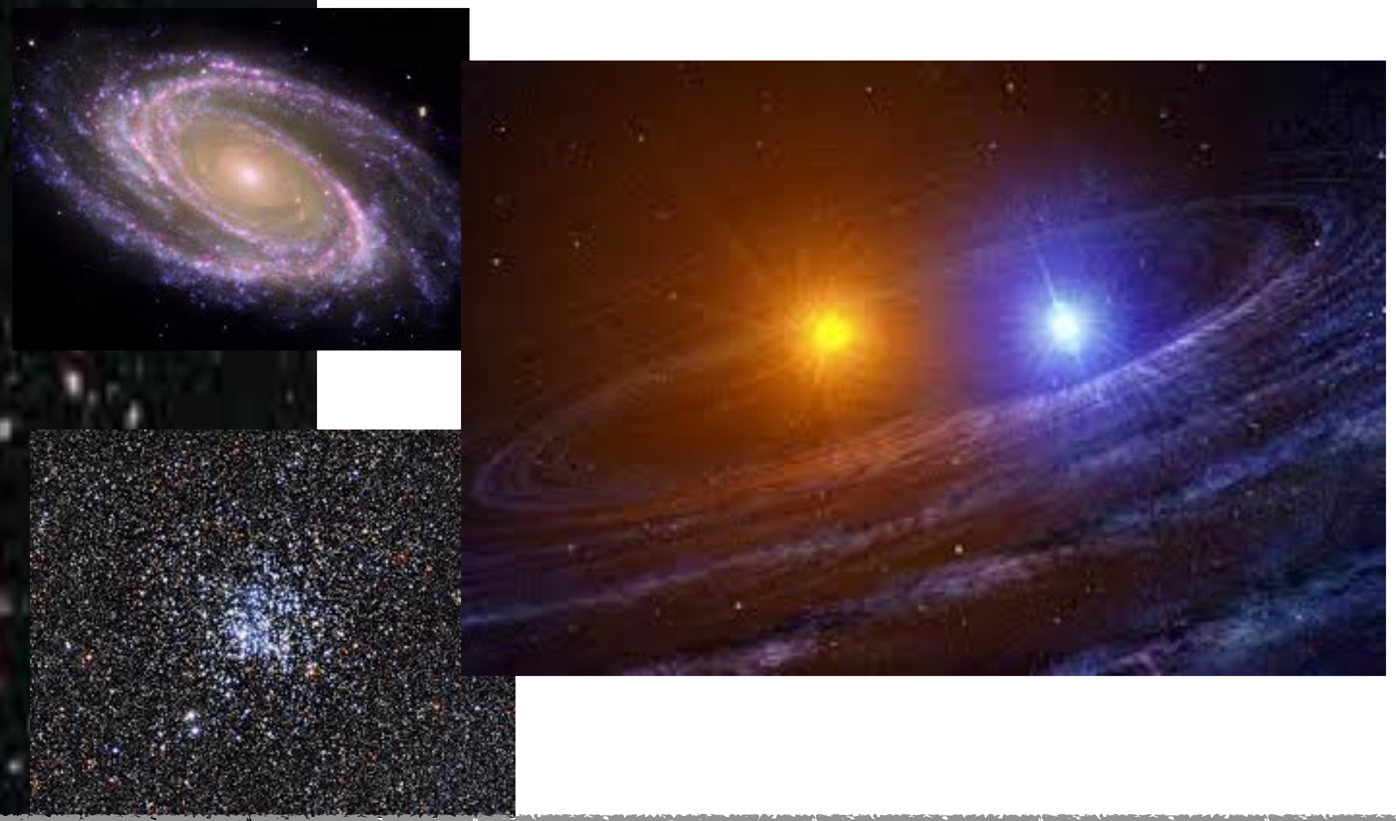


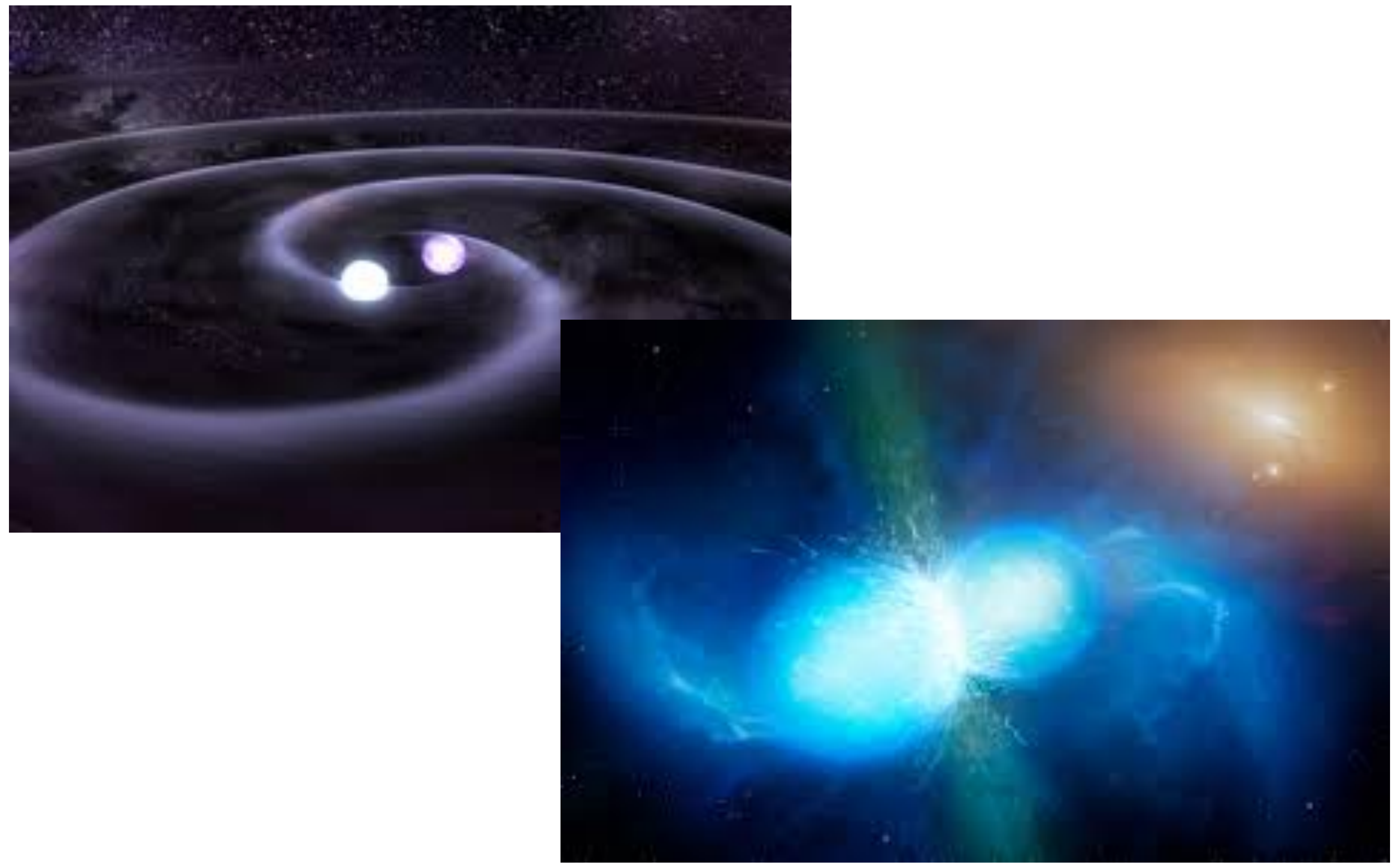
→ Talk L. Amati



GG et al. 2024

Conclusions





INFERENCE EM OBS

GW DATA ANALYSIS

DIRECT EM OBSERVATIONS

Binary stellar evolution

Inspiral and final phases

Collimated and isotropic ejecta

Formation sites and channels

Nature of the remnant(s)

- Still non detected EM signals
- Counterparts of BHNS
- From individual sources to population studies

Conclusions

- Still non detected EM signals
- Counterparts of BHNS
- From individual sources to population studies