Kilonovae Associated with Neutron Star-Black Hole Mergers: an example study with O4 NSBH candidates

Marion Pillas & members of ATLAS, CSS/SAGUARO, DECam, GECKO, GOTO, GRANDMA, TESS, WINTER, ZTF and LIGO/VIRGO collaborations

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Table of content

Part I

Introduction

Kilonovae from neutron star - black hole mergers?

Table of content

Observation Strategy

How did we search for these events?

Part I

Part II

Introduction

Kilonovae from neutron star - black hole mergers?

Table of content

Part I

Introduction

Kilonovae from neutron star - black hole mergers?

Part II

Observation Strategy

How did we search for these events?

Part III

Constraints on these events

Ejected matter? Viewing angle?

Table of content

Part I

Introduction

Kilonovae from neutron star - black hole mergers?

Part II

Observation Strategy

How did we search for these events?

Part III

Constraints on these events

Ejected matter? Viewing angle?

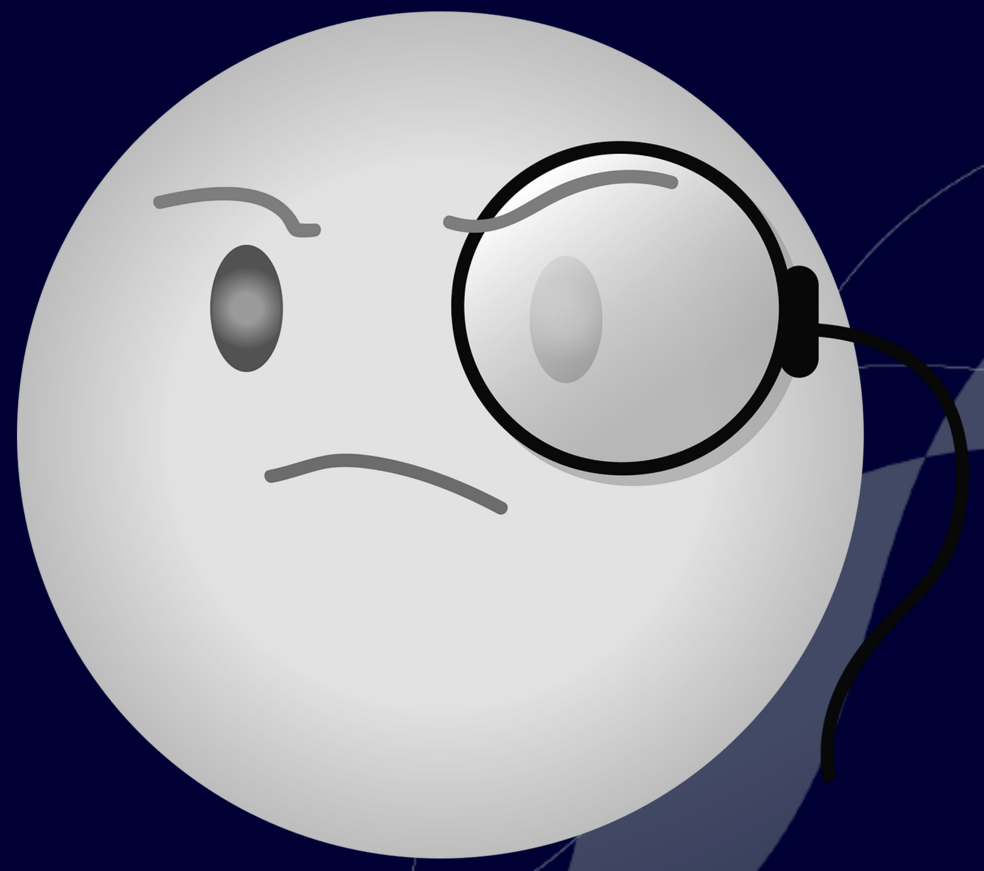
Part IV

Conclusion

What did we learn?

Objective of the talk

Why didn't we detect kilonova counterpart of NSBH candidates in O4?



SCAN ME!

« Limits on the Ejecta Mass During the Search for Kilonovae Associated with Neutron Star-Black Hole Mergers: A case study of S230518h, GW230529, S230627c and the Low-Significance Candidate S240422ed », Pillas et al, 2025, ***arXiv:2503.15422***

Part I. Introduction

GW Modeling

Dietrich…

Global astrophysical Modeling

Bulla,
Pellouin…

BNS, NSBH collisions
Core collapse

Chemical evolution
R-process

Barnes,
Kasen…

Nuclear Physics
Dense Matter

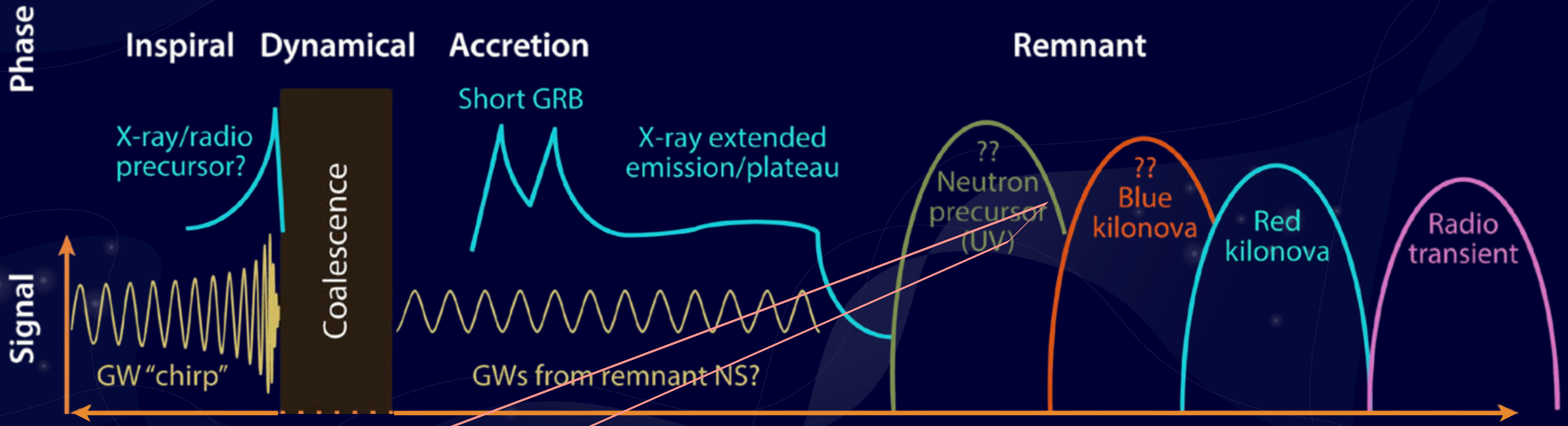
Tews…

DATA

HERE I AM (AND SO IS MY TALK)

Part I. Introduction

Compact binary coalescence system with neutron stars: **multi-messenger event**

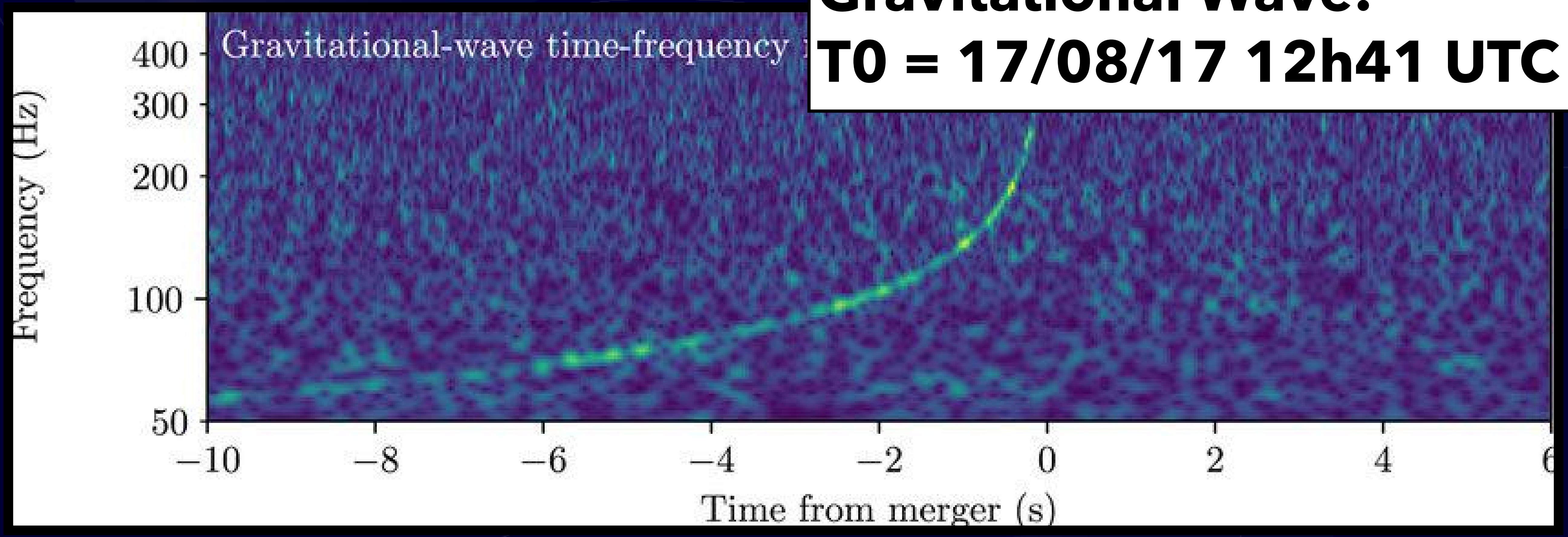


(Fernandez and Metzger, 2016)

Only example so far: **GW170817 - GRB 170817A**

Part I. Introduction

- **GW170817 - GRB 170817A**



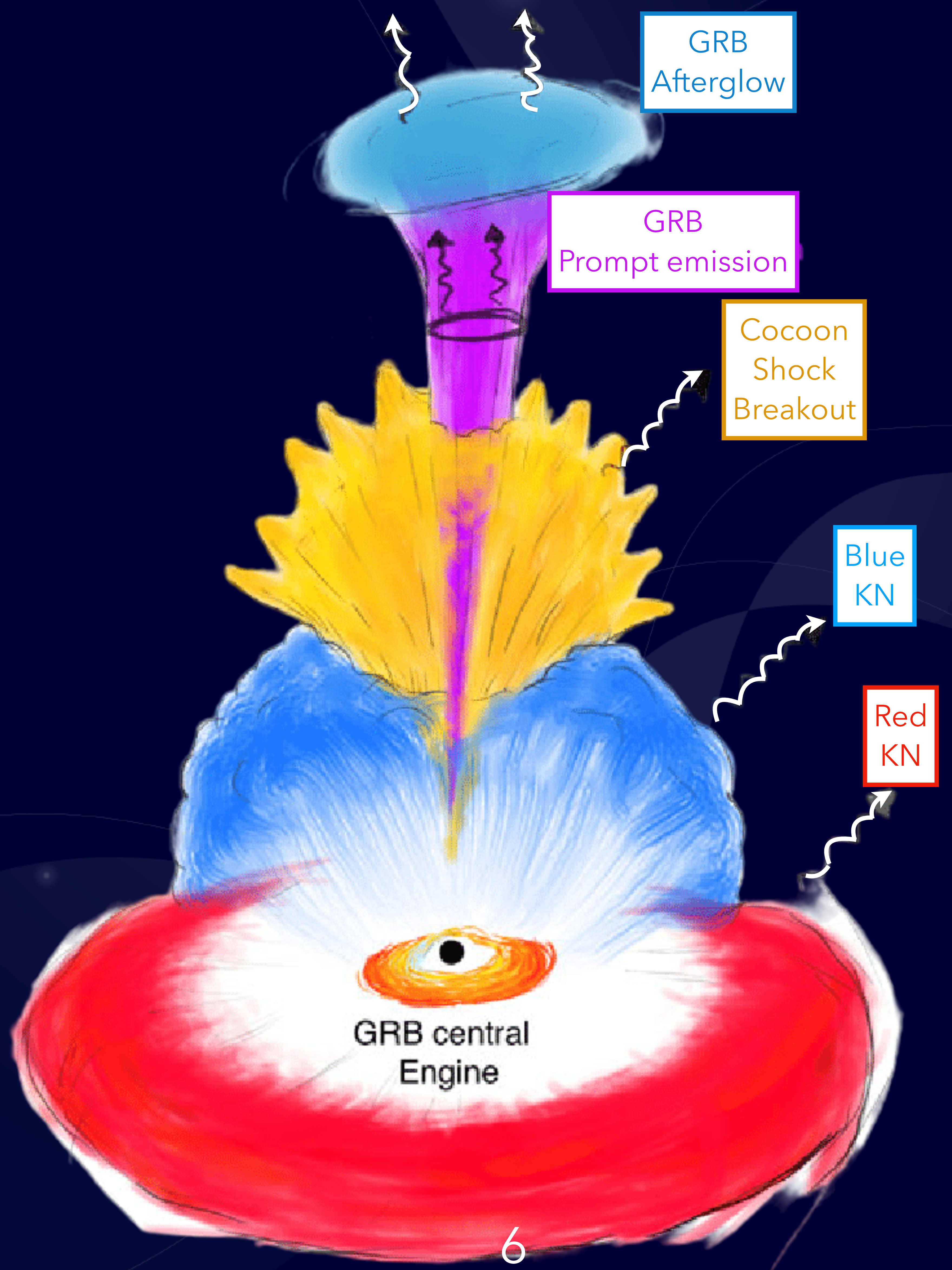
Gravitational Wave:
T0 = 17/08/17 12h41 UTC

5

Part I. Introduction

(Ascenzi et al, 2021)

- **GW170817 - GRB 170817A**



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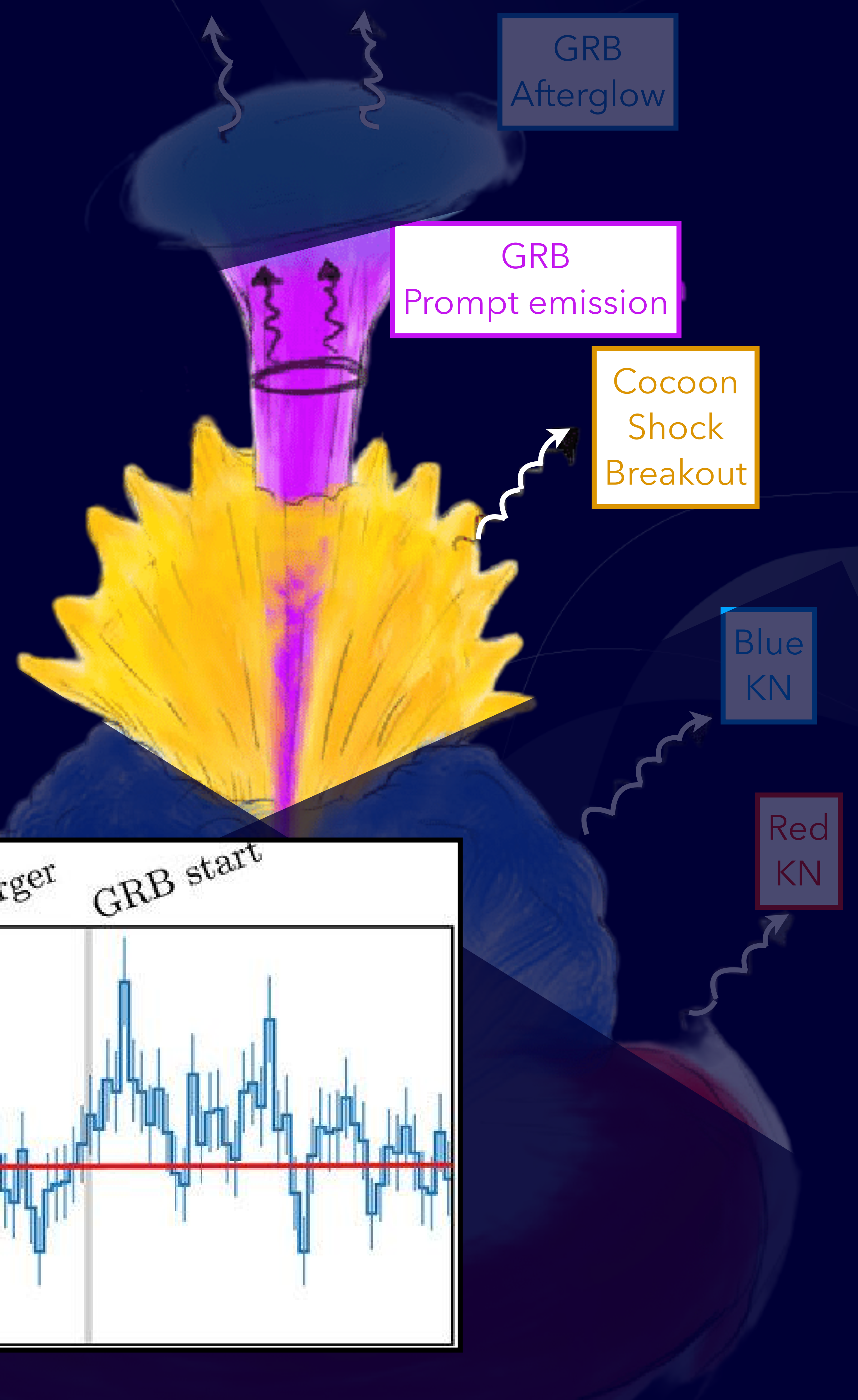

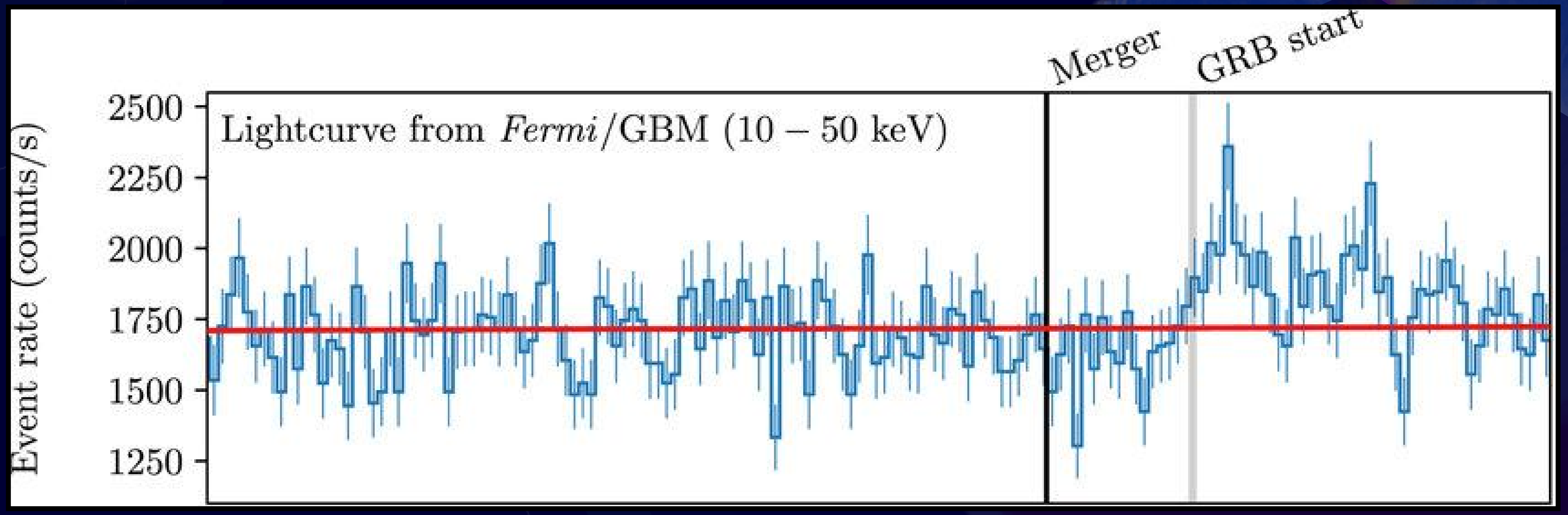

7

Part I. Introduction

(Ascenzi et al, 2021)

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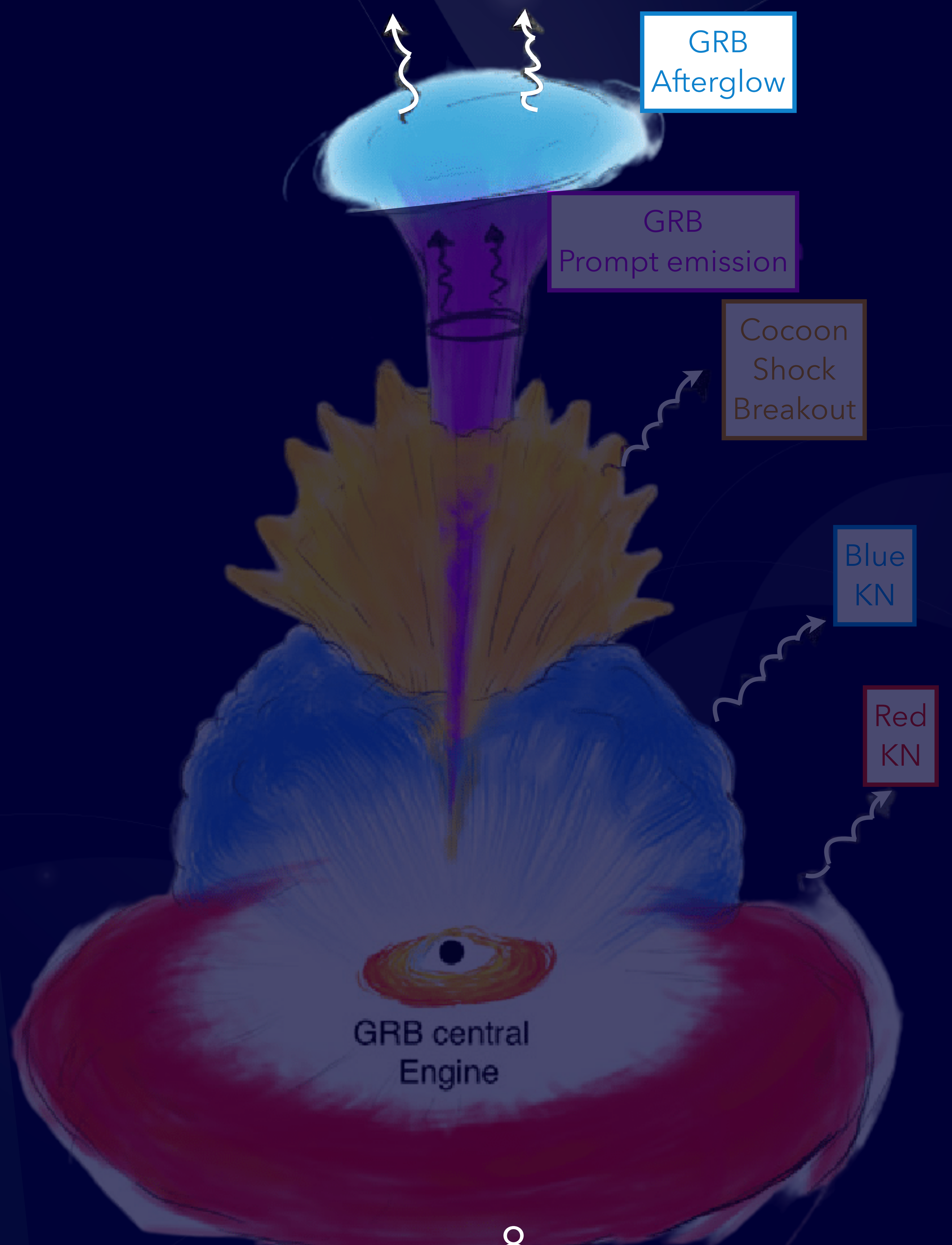
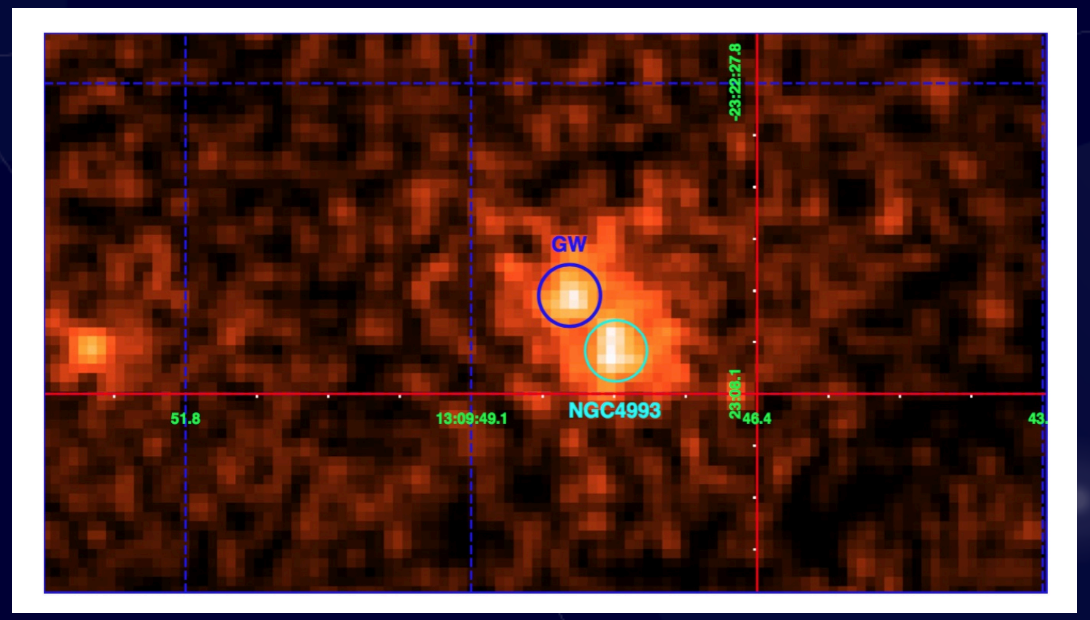
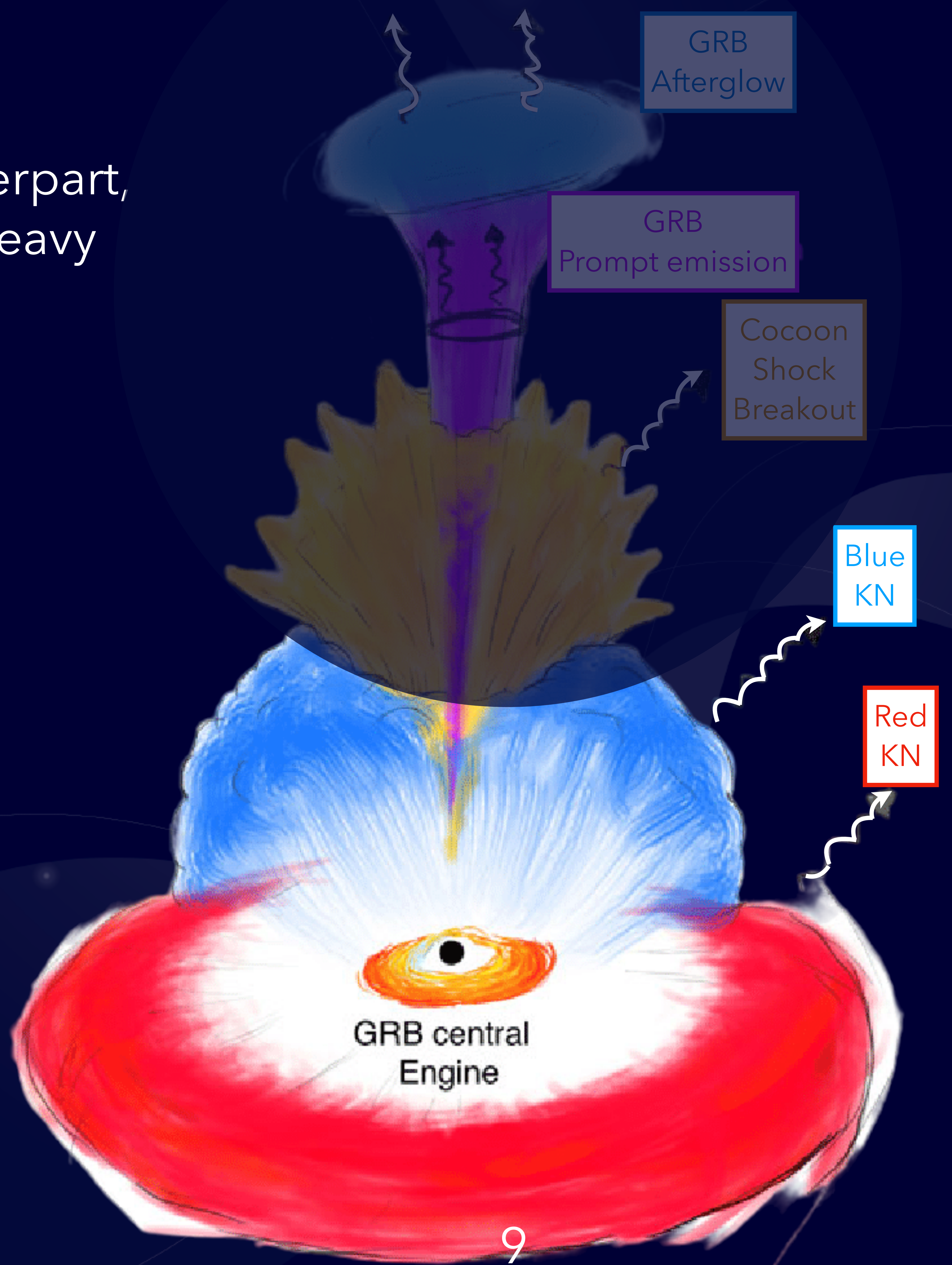


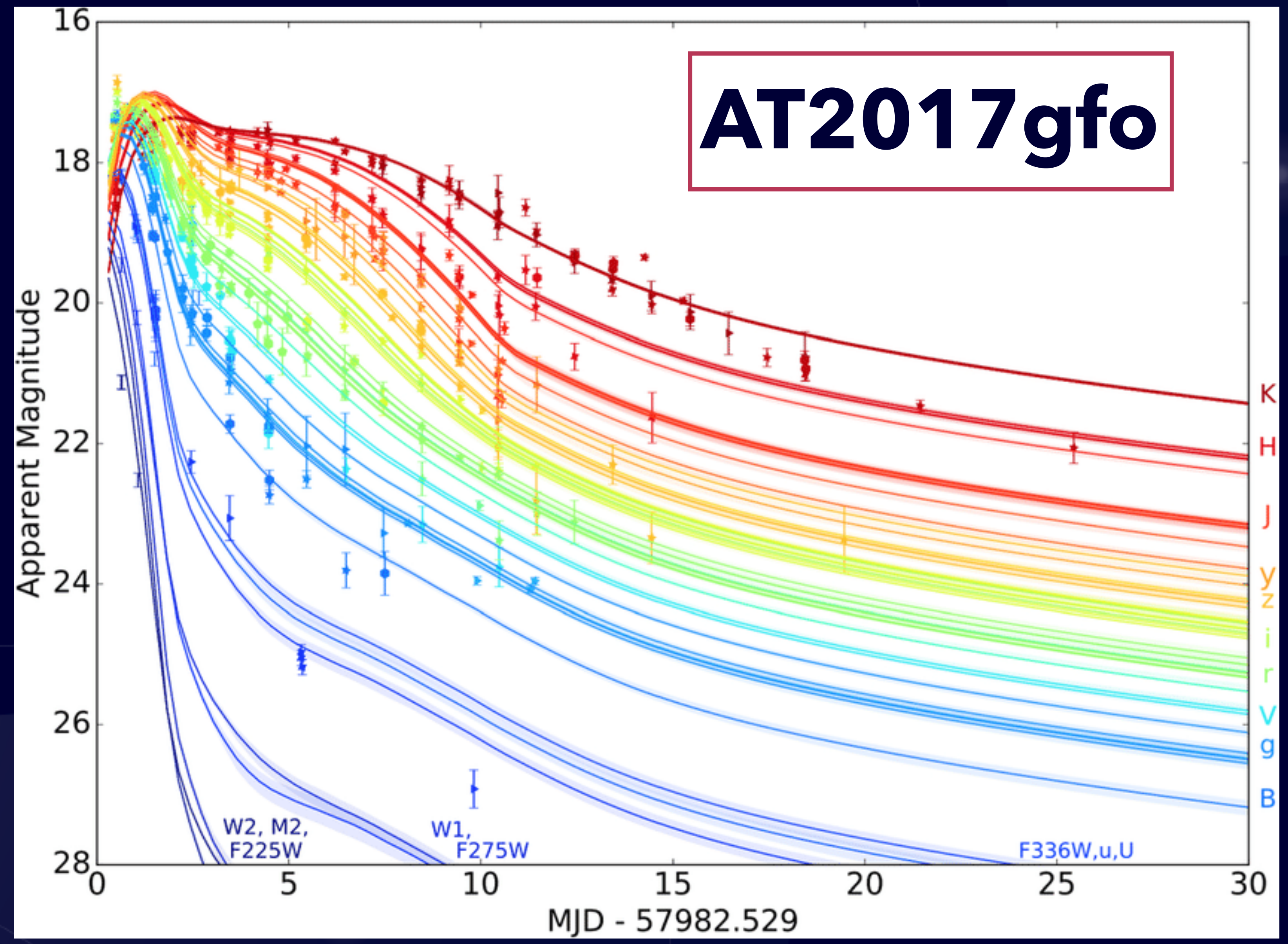


Part I. Introduction

(Ascenzi et al, 2021)

- **GW170817 - GRB 170817A**
- **Kilonova** (KN) - Optical-NIR counterpart, witness to the nucleosynthesis of heavy elements during the merger
- KN brings information about:
    - Sky location of the source
    - **Merger environment** …



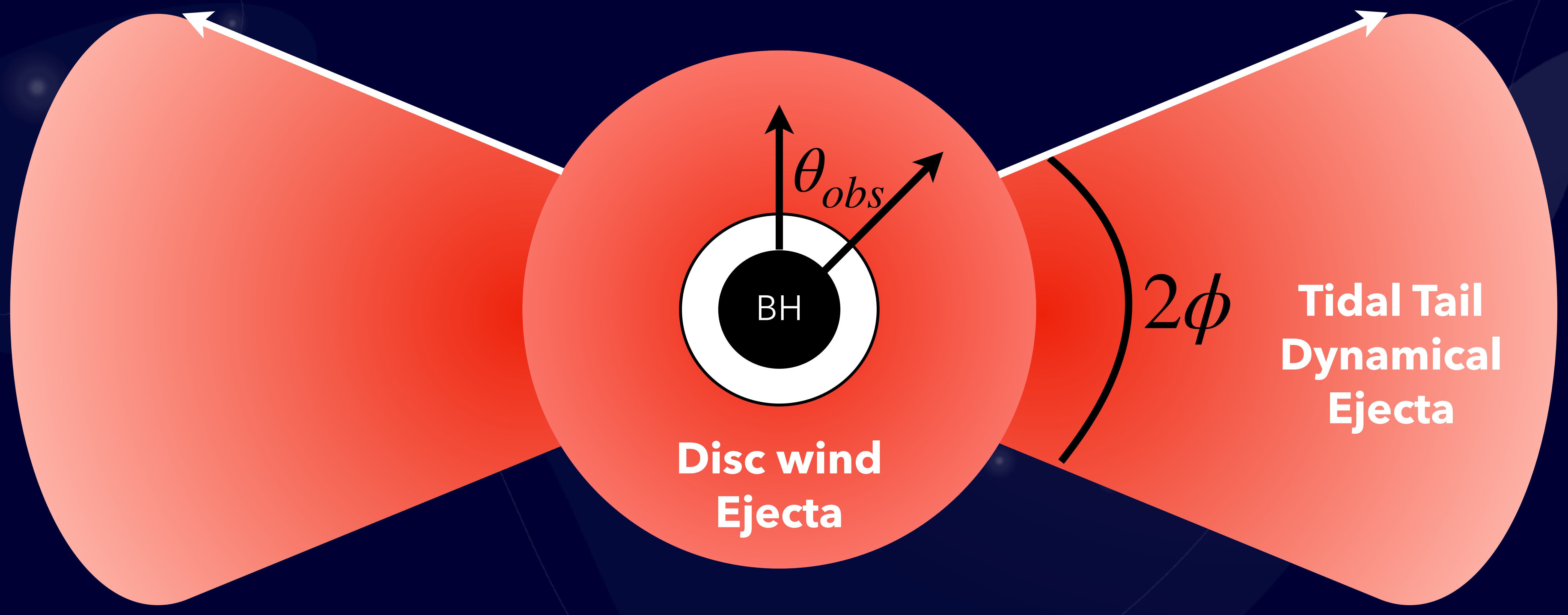


Part I. Introduction

Neutron star - Black hole (NSBH) merger can also produce KN signature, depending on:

- Small mass ratio (m1/m2)
- High black hole spin
- NS Equation of State
- …

(Villar et al, 2017)



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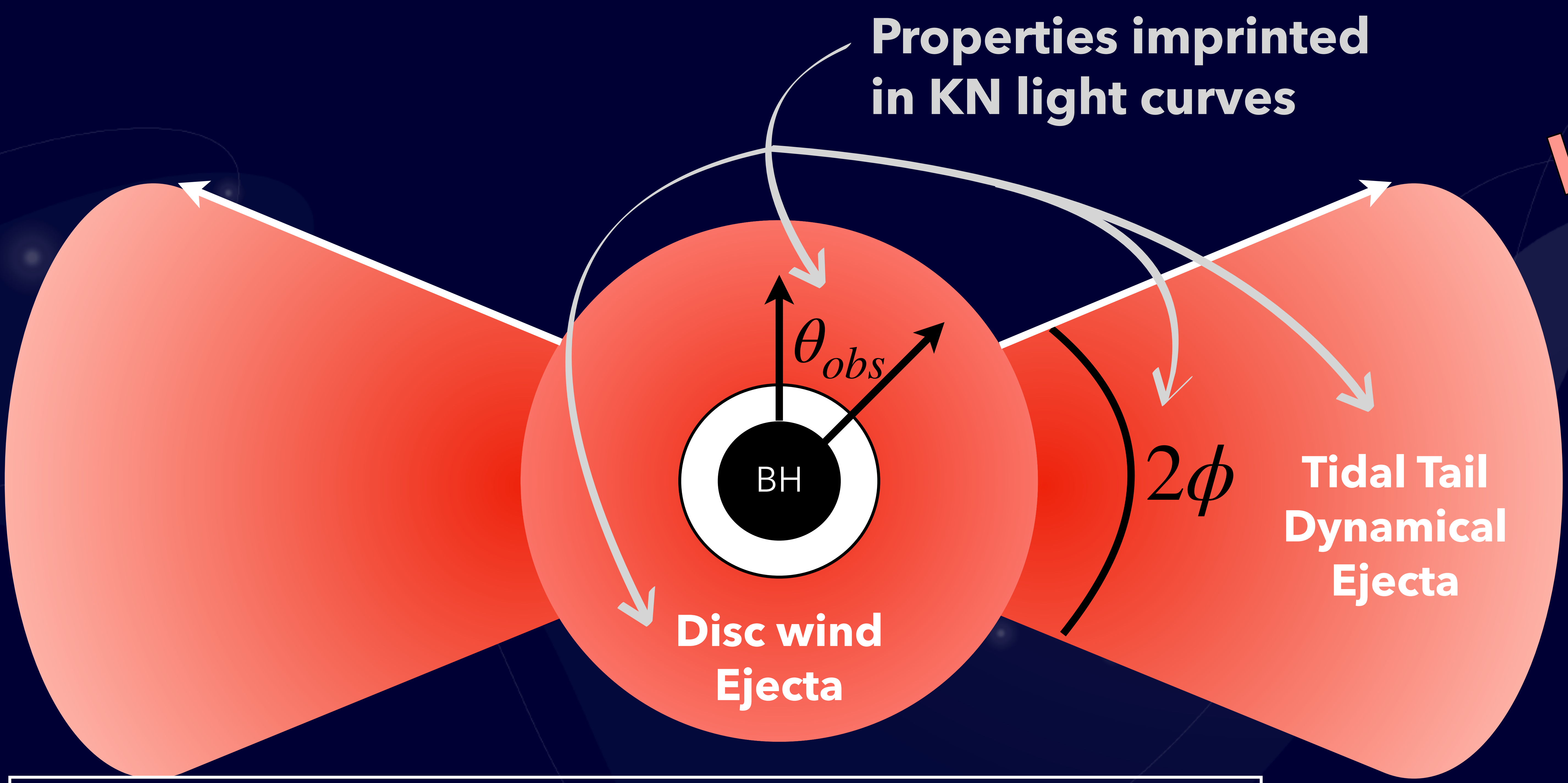


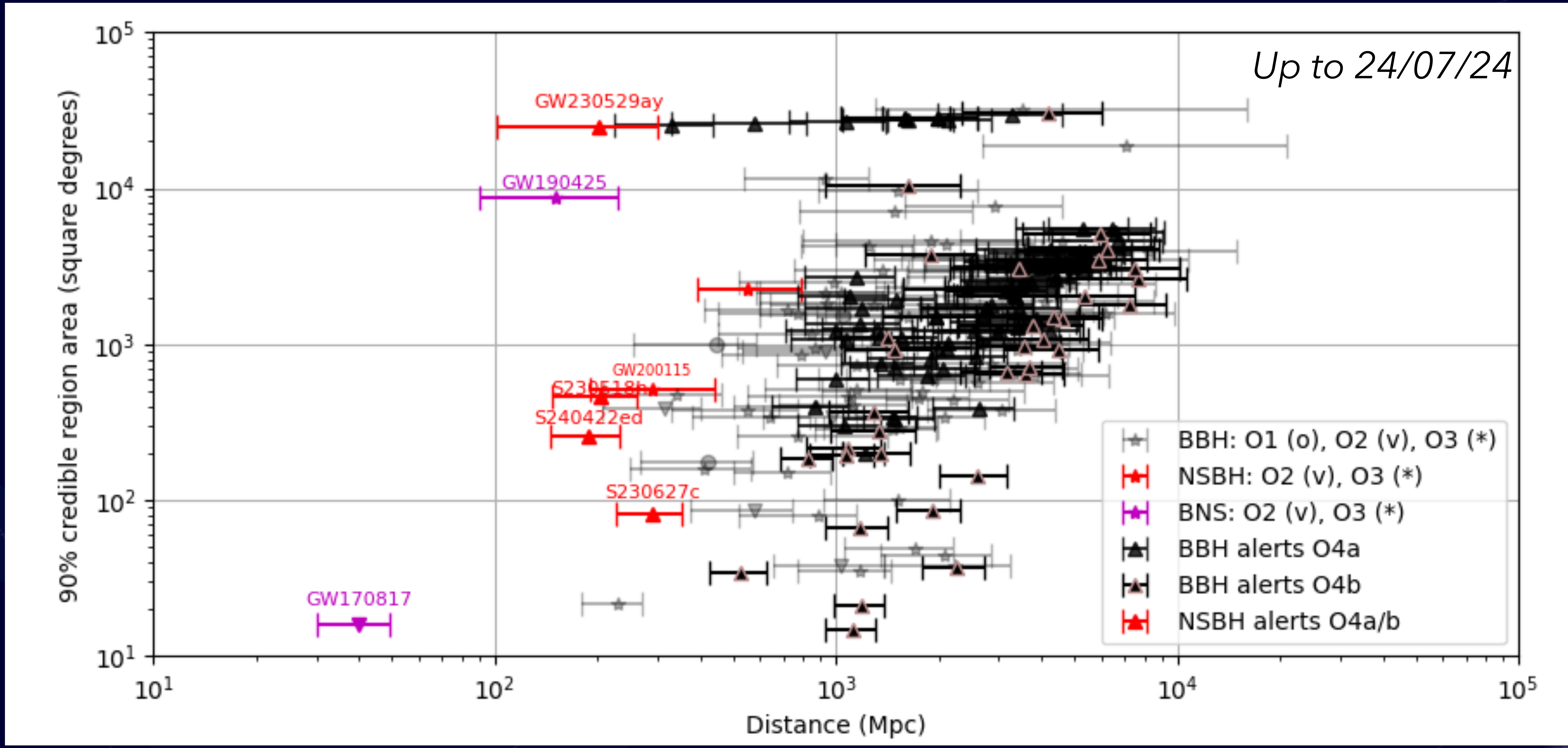
In this work:

Ejecta frm the NS disruption (m_{dyn})	
Mass range	$0.01 - 1.0\ M_{\odot}$
Ejecta frm the NS disruption ($m_{disk,wind}$)	
Mass range	$0.01 - 1.0\ M_{\odot}$
Outflow	5% – 40% not accreted
Kilonova Light Curves	
Model	NSBH models computed with POSSIS, Anand et al. (2021) - Bulla (2019)
m_{dyn}	$0.01 - 0.09\ M_{\odot}$
m_{wind}	$0.01 - 0.09\ M_{\odot}$
θ	[0, 90] degrees
ϕ	30 degrees
Light curves	891 different light curves
Filters	21 different filters

We define a kilonova scenario by: m_{dyn} , m_{wind} , θ

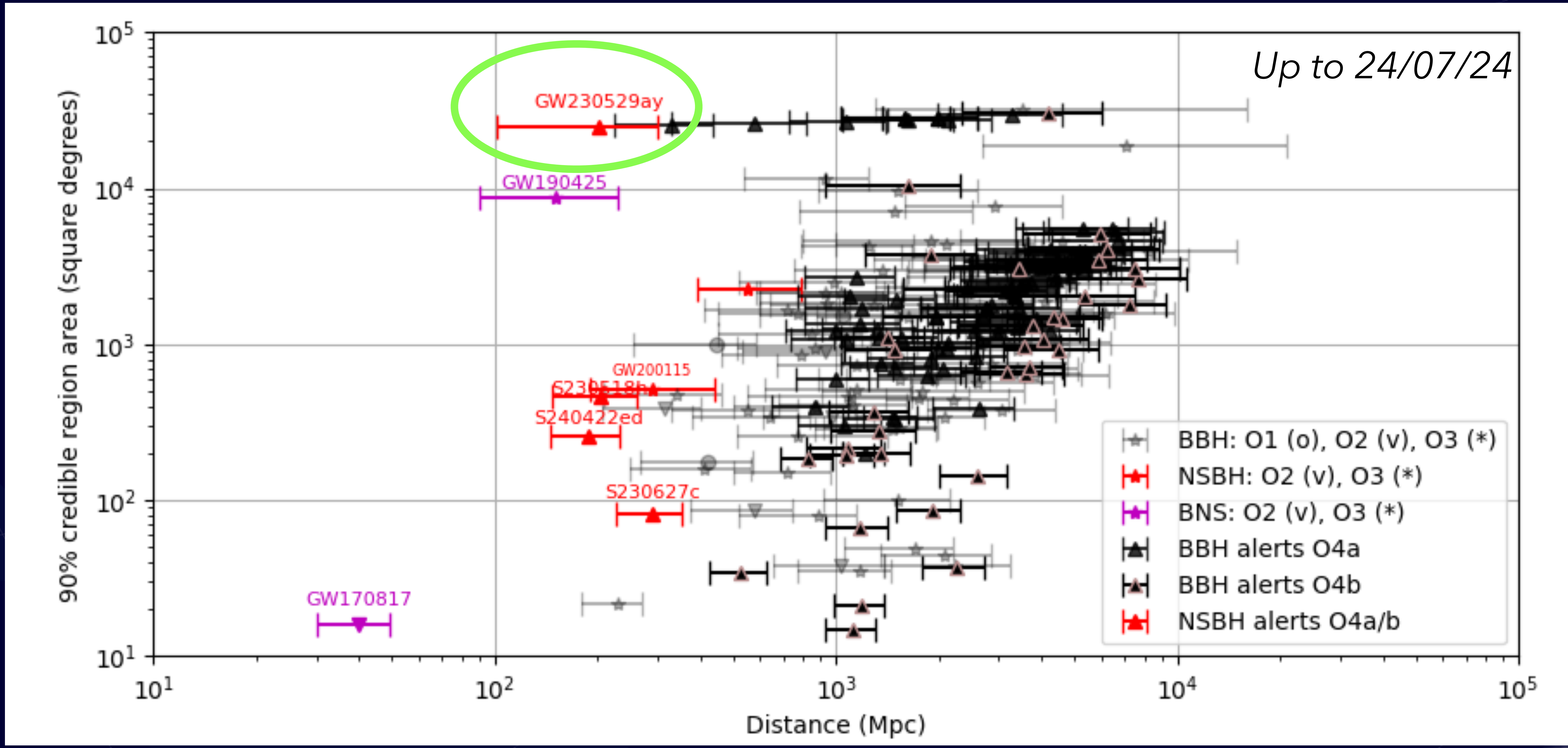
Part I. Introduction

- O4 has started in May 2023



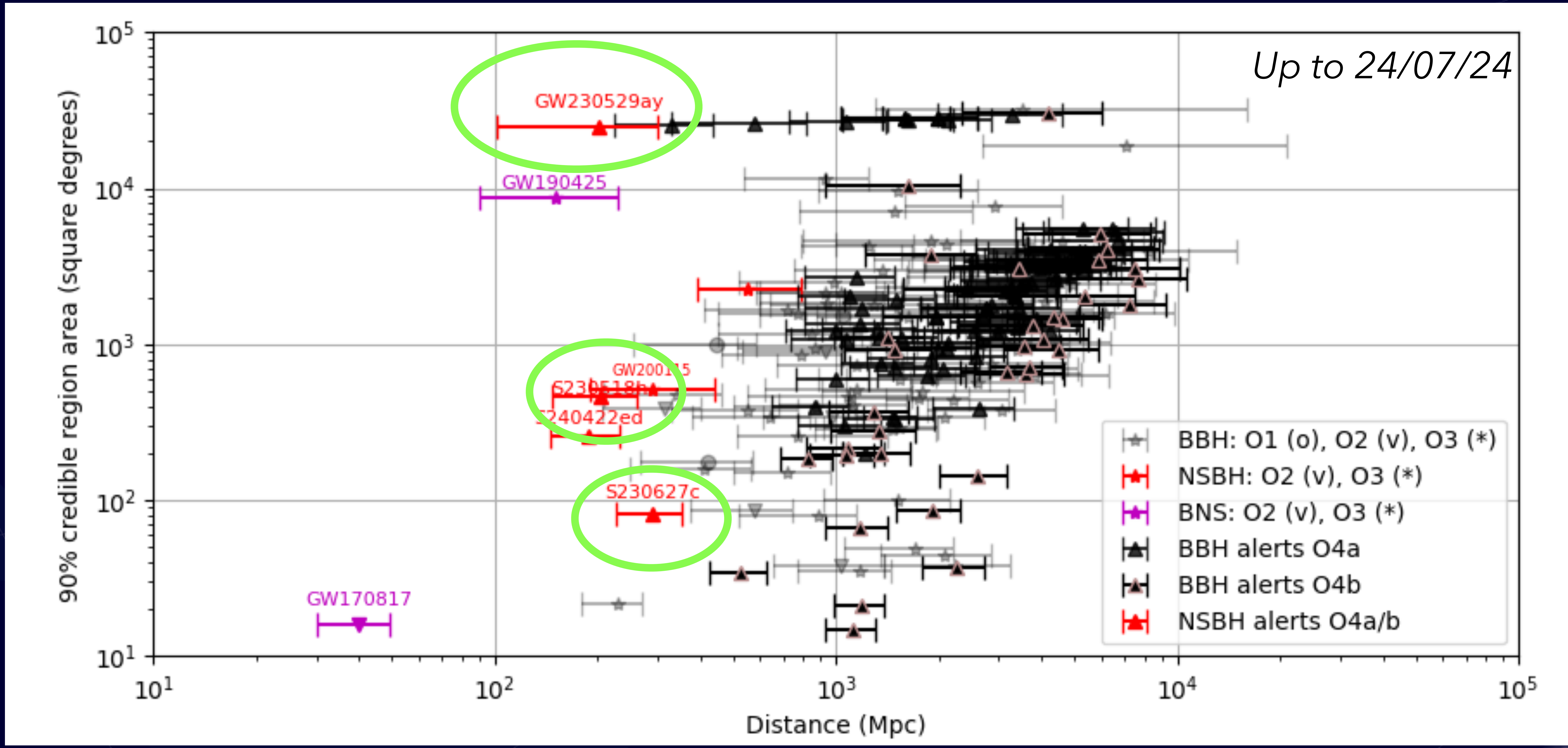
Part I. Introduction

- O4 has started in May 2023
  - 1 confirmed NSBH: **GW230529**



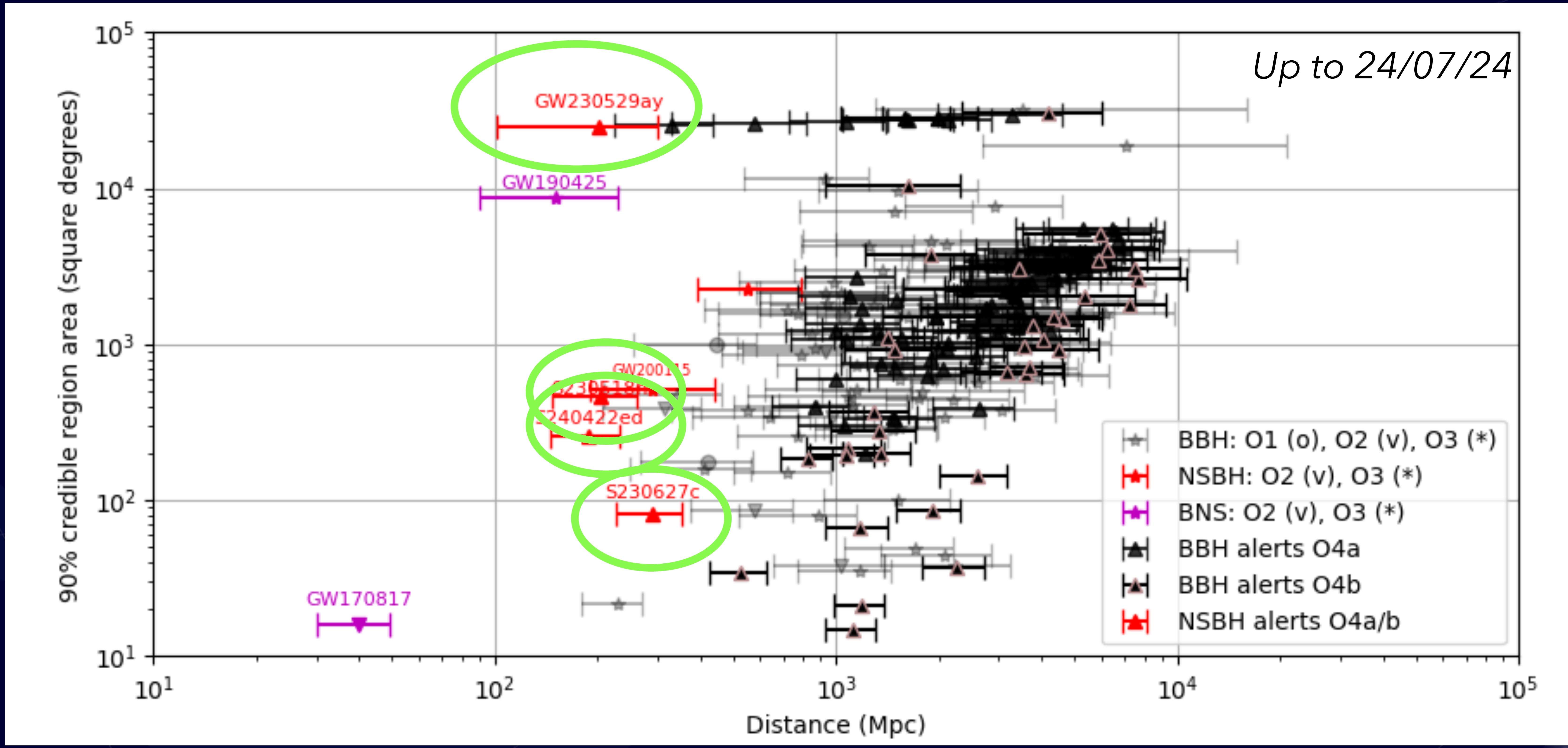
Part I. Introduction

- O4 has started in May 2023
  - 1 confirmed NSBH: **GW230529**
  - 2 NSBH candidates: **S230518h, S230627c**



Part I. Introduction

- O4 has started in May 2023
  - 1 confirmed NSBH: **GW230529**
  - 2 NSBH candidates: **S230518h, S230627c**
  - 1 low-significance NSBH candidate: **S240422ed**
  - Massive followup from the optical community but no discovery of a clear KN counterpart



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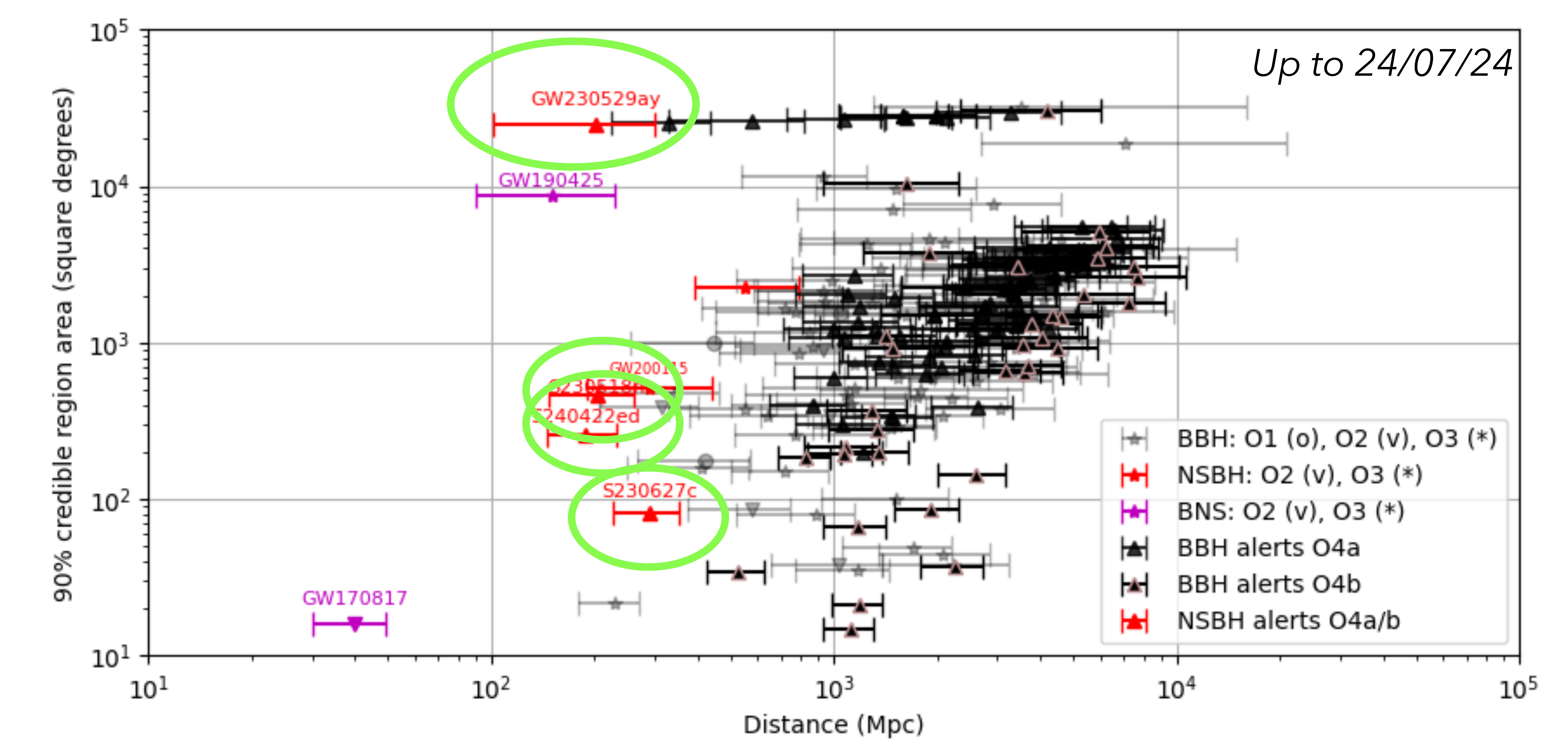
Even a non-detection can help constrain source properties (ejecta, viewing angle)



Part I. Introduction

In this work:

1) Take a critical look at observation strategies from the optical community
2) Given the non-observation of a KN, set constraints on source ejecta and viewing angle properties of the 4 NSBH candidates

Part II. Observation strategy

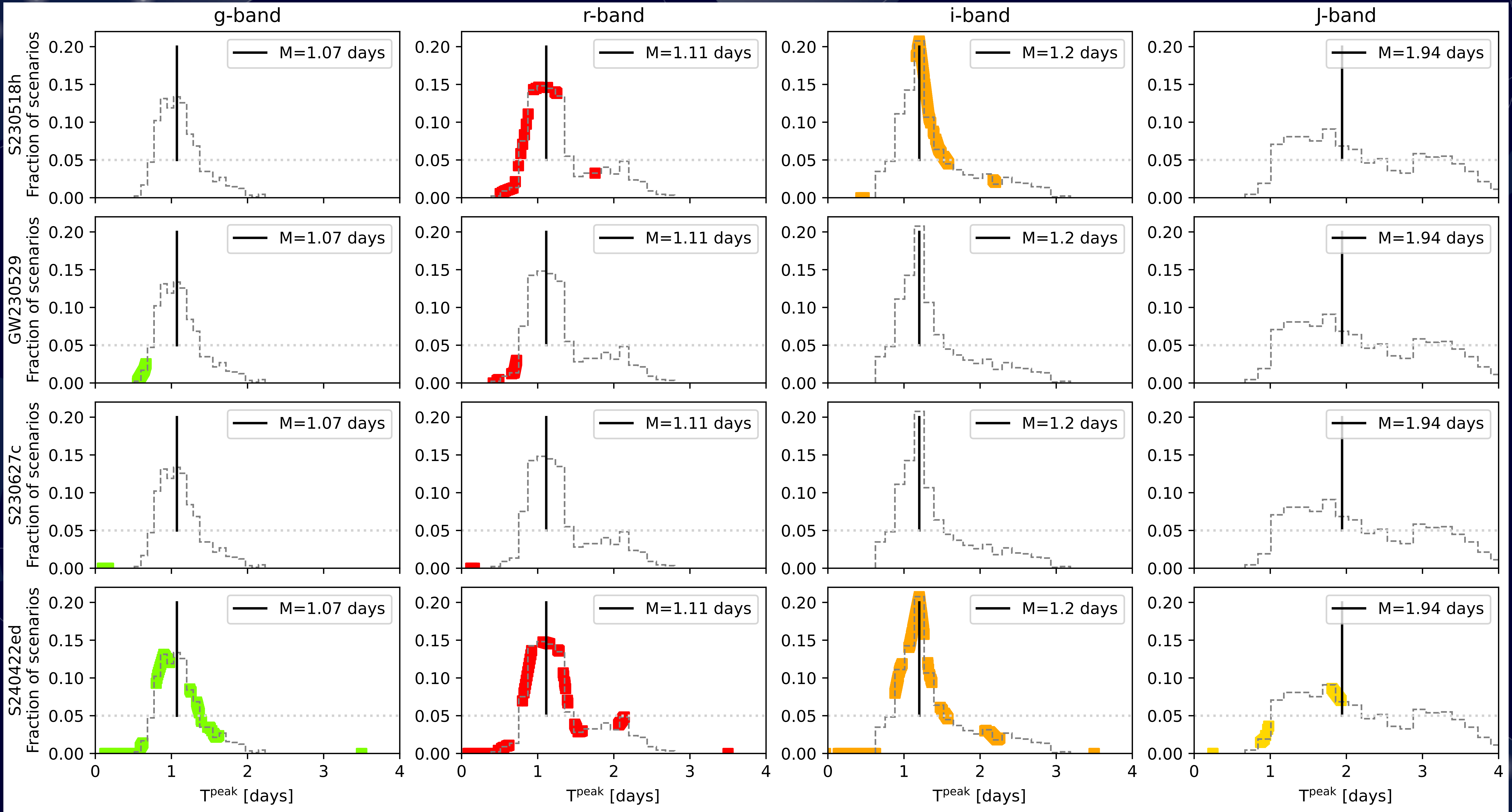
In this work:

1) Take a critical look at observation strategies from the optical community

- At least one observation should be done at the **time of brightness peak**
- Compare time of optical observations with the predicted peak time from simulated KN light curves for numerous filters

Part II. Observation strategy

- **Compare time of optical observations with the predicted peak time from simulated KN light curves**



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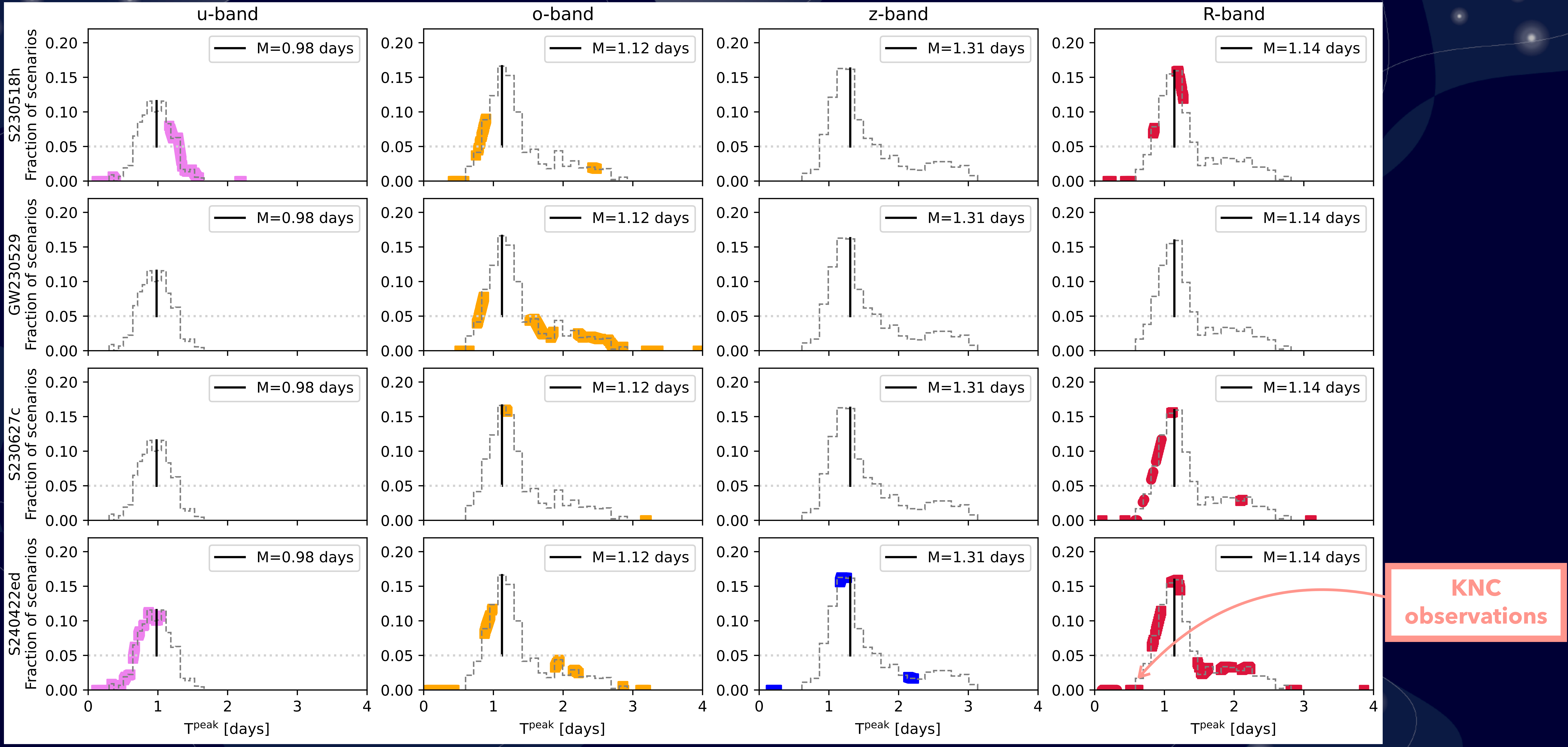

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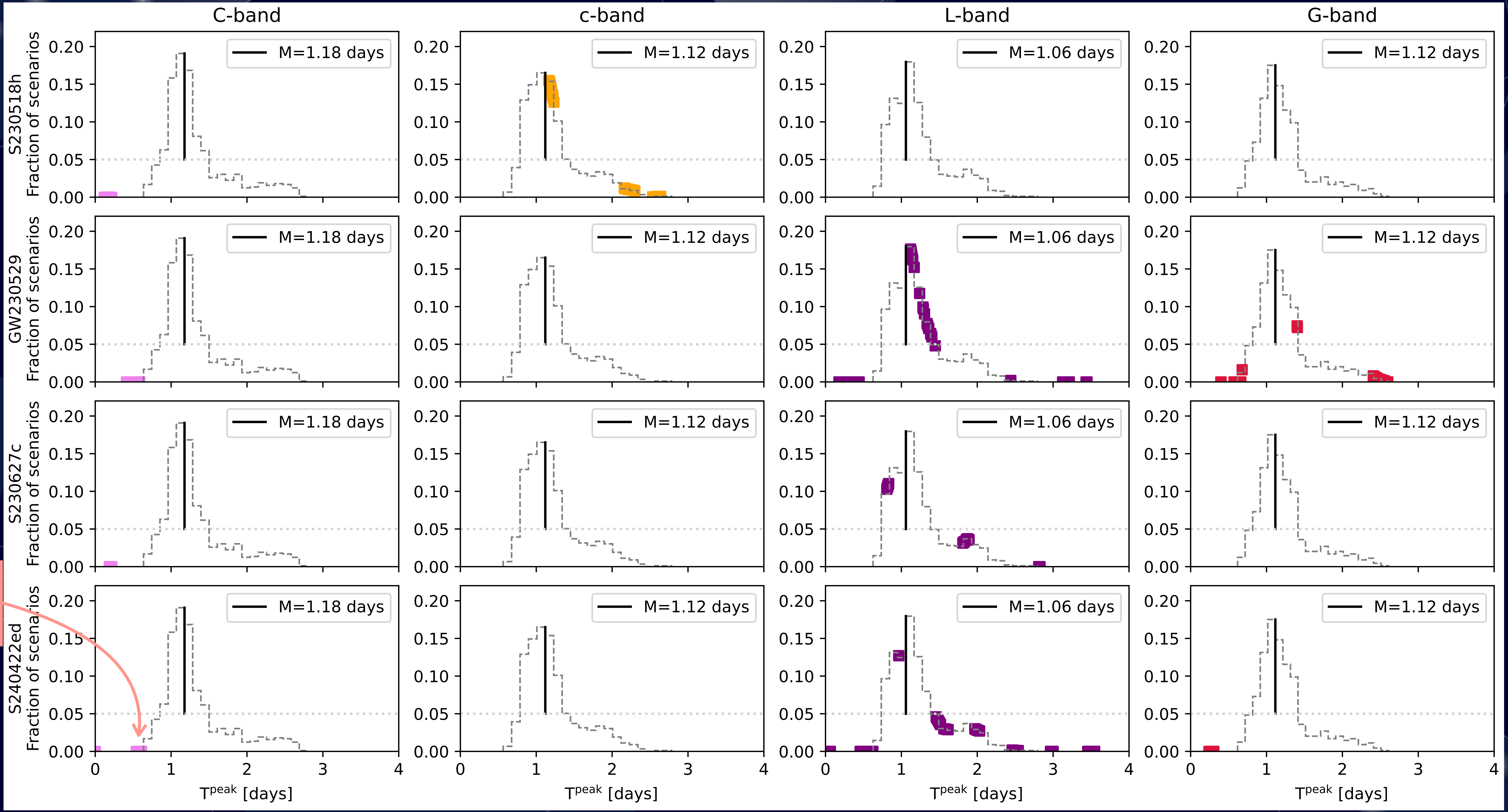
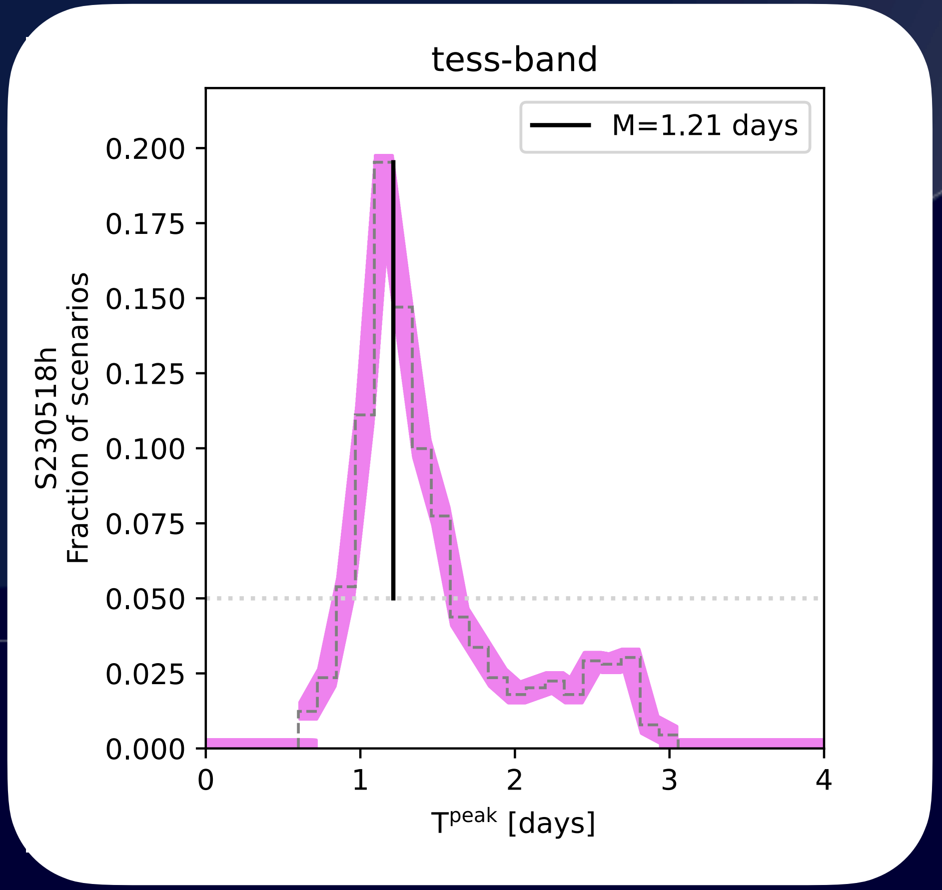
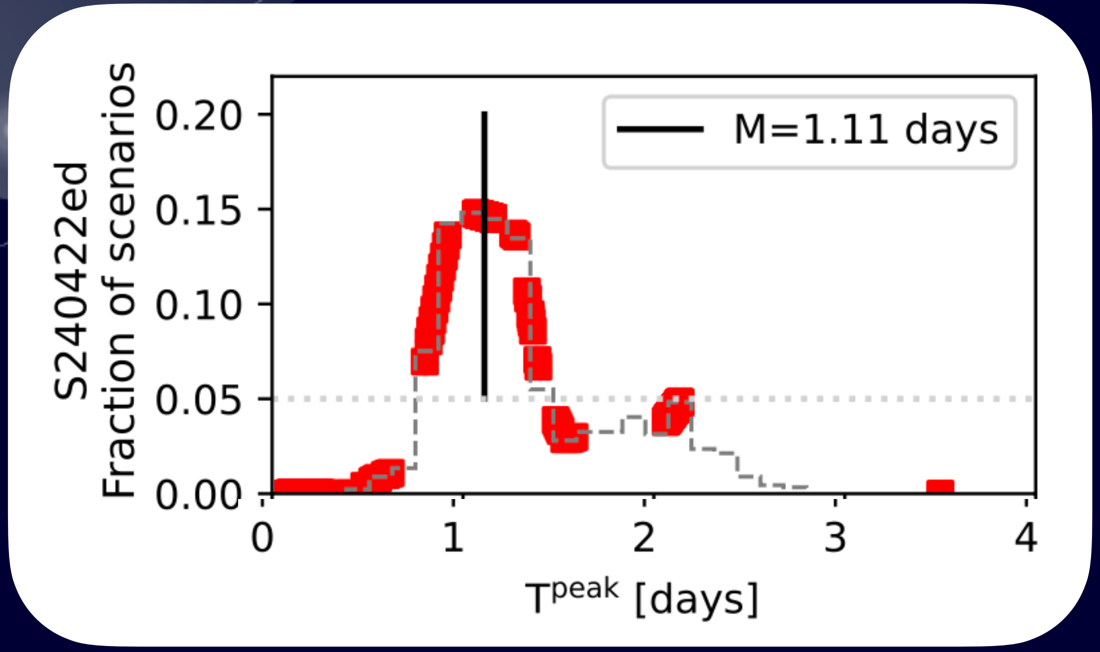


KNC observations

Part II. Observation strategy

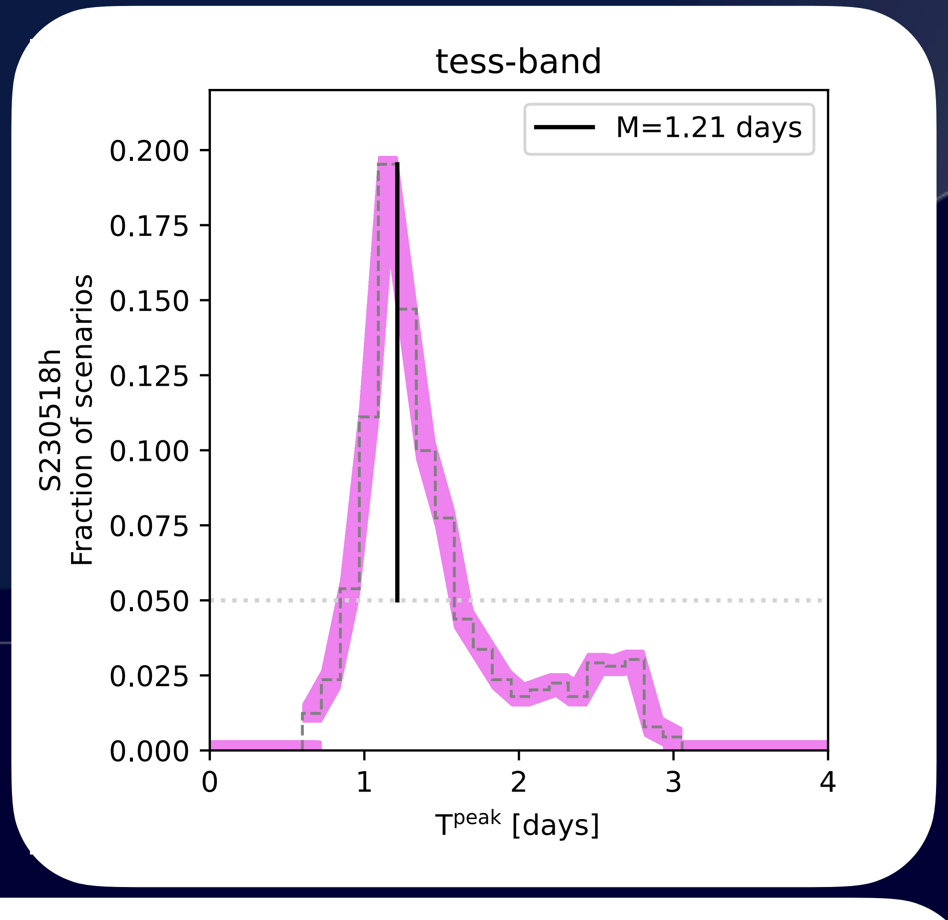


S230518h: Observations in TESS-band covered the KN peak time of ~100% of the population.



S240422ed: Observations consistent with the peak time of 82% of KN population in r-band.

Part II. Observation strategy



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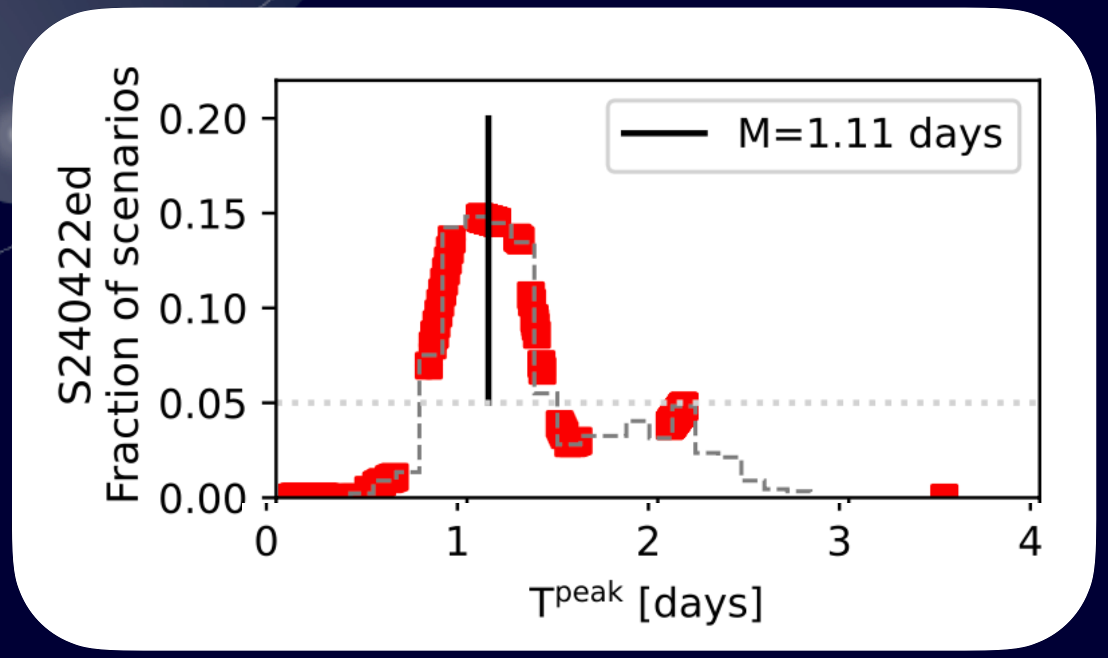

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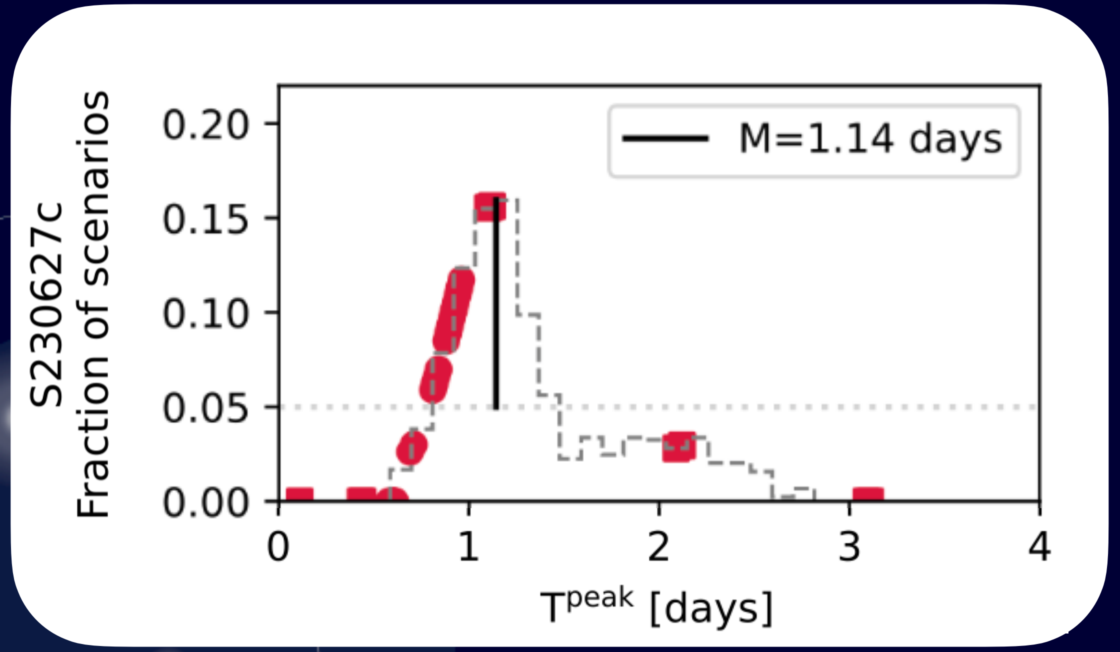
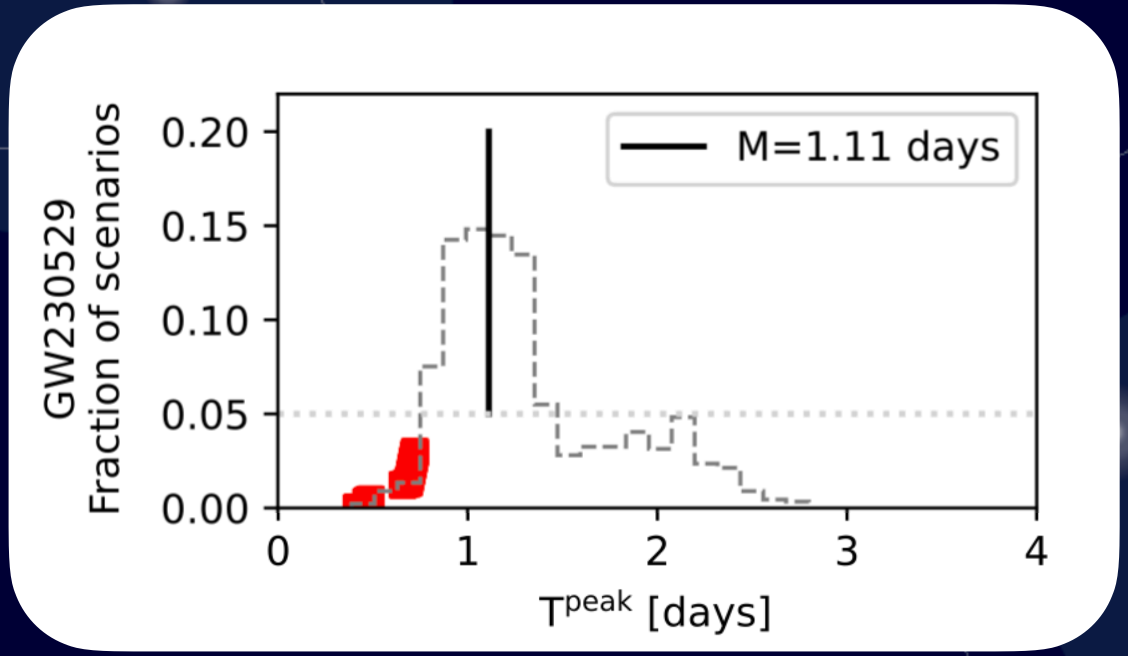
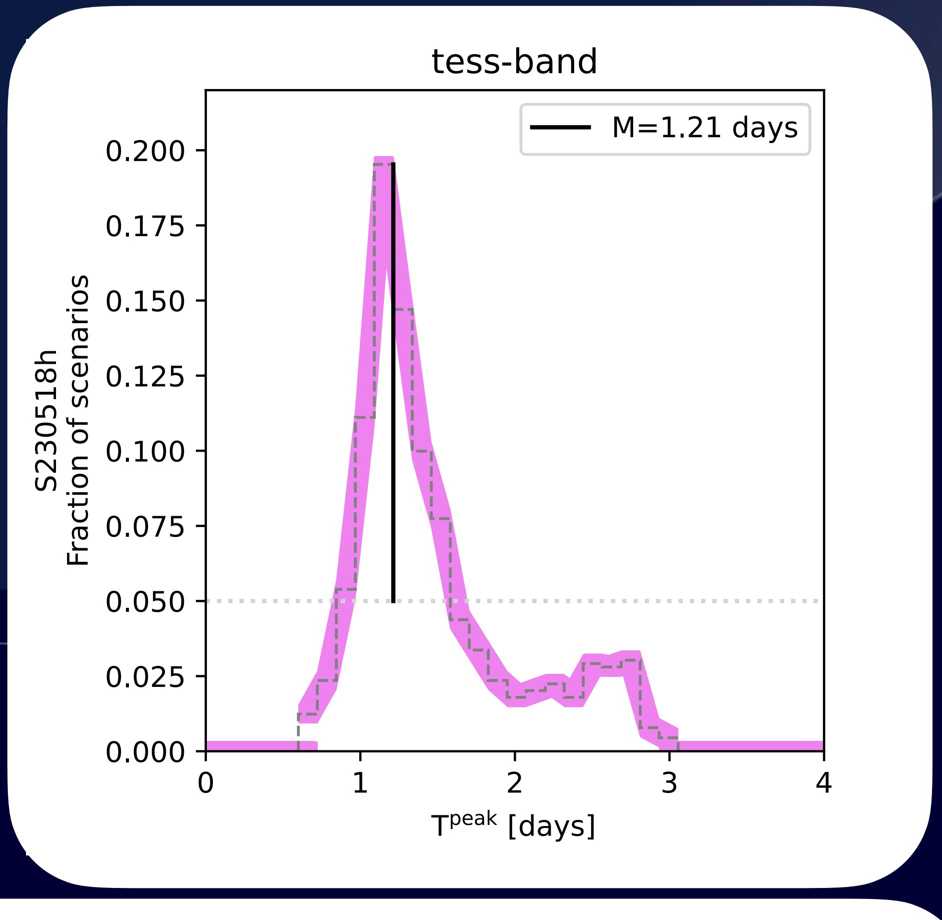




GW230529 & S230627c: Less observed - the « later time » strategy is not always realized while prompt strategy has been well demonstrated

Part II. Observation strategy



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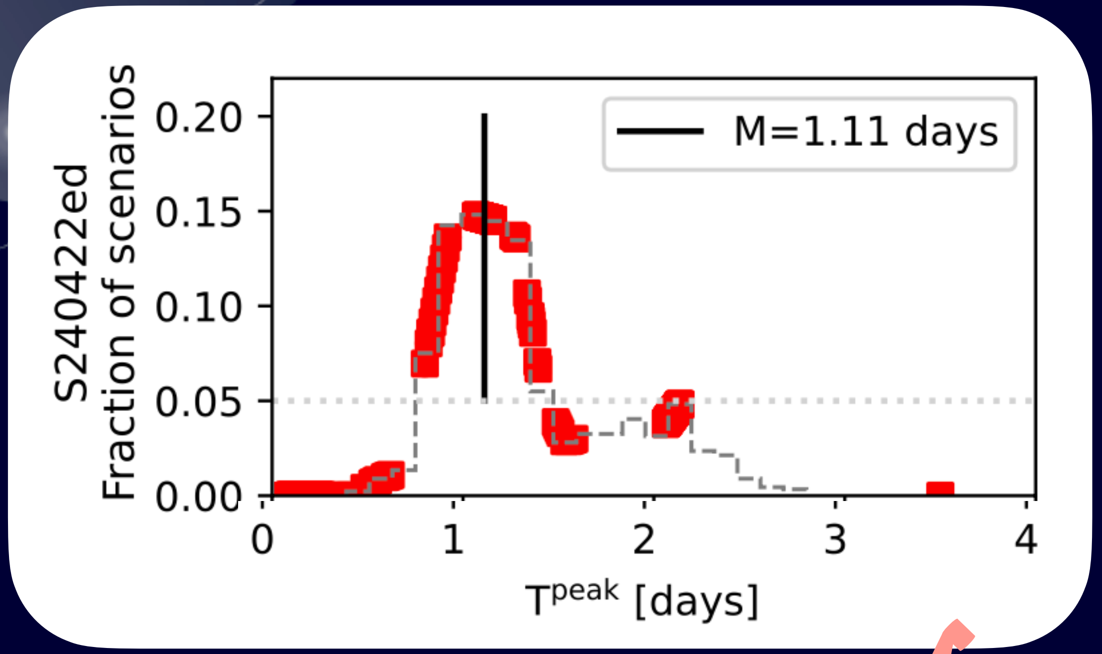

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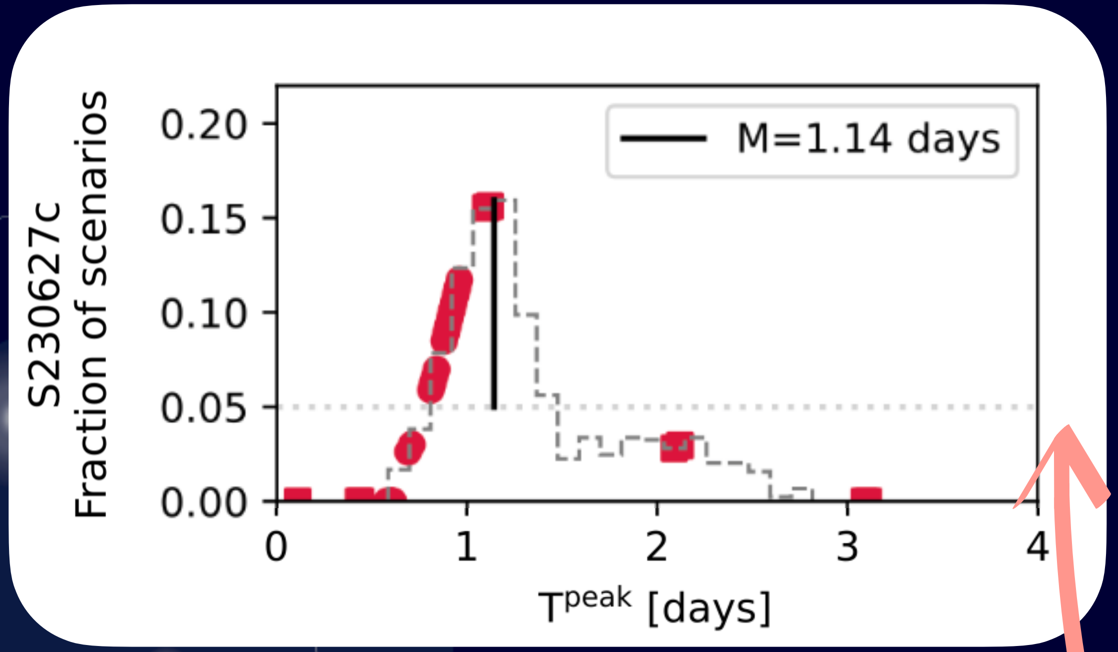
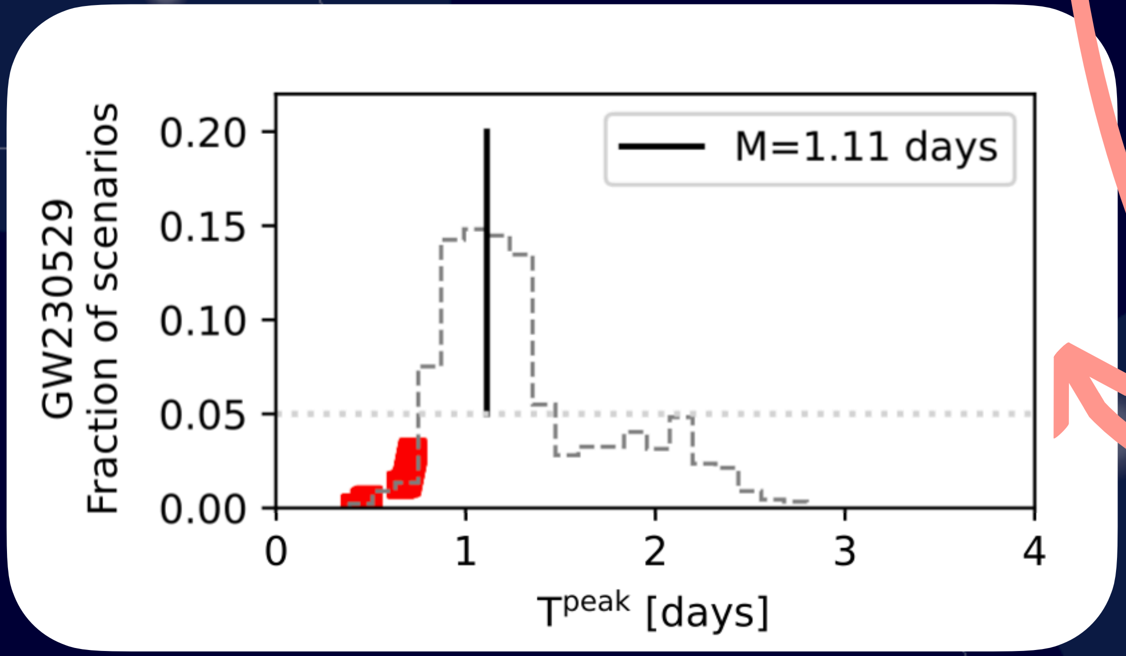
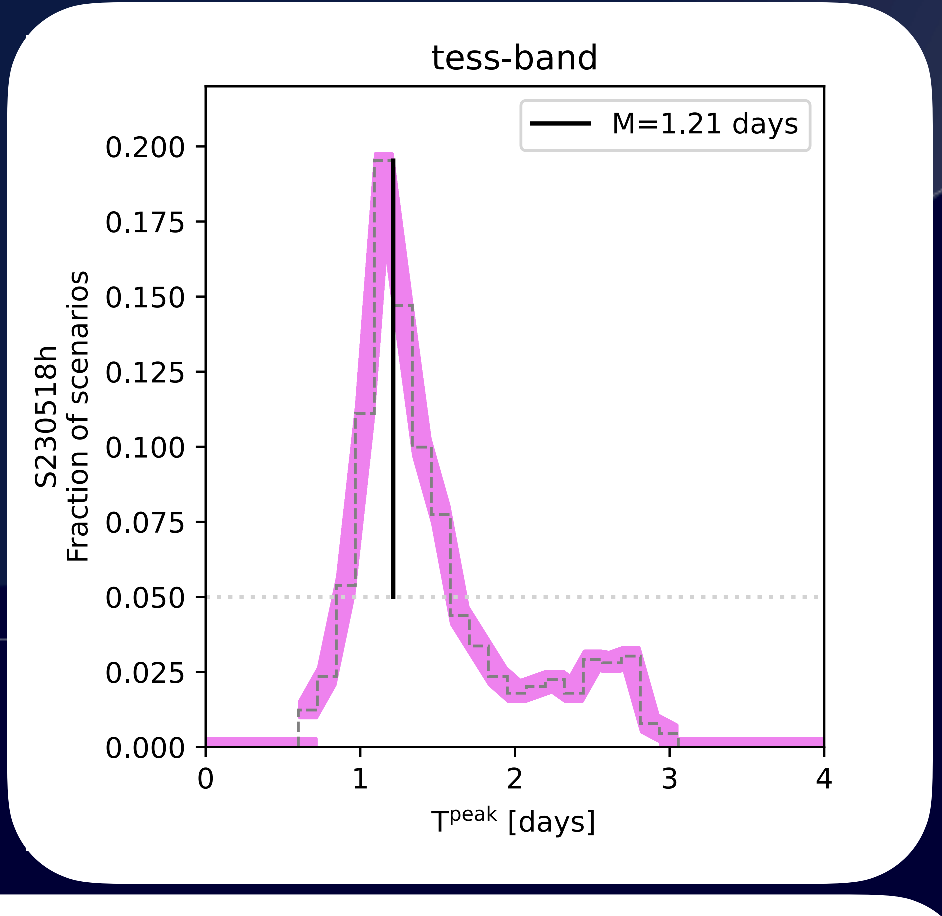




GW230529 & S230627c: Less observed - the « later time » strategy is not always realized while prompt strategy has been well demonstrated

In general: Necessity to image the first moment but also the importance of imaging 1 day post-merger

Part II. Observation strategy



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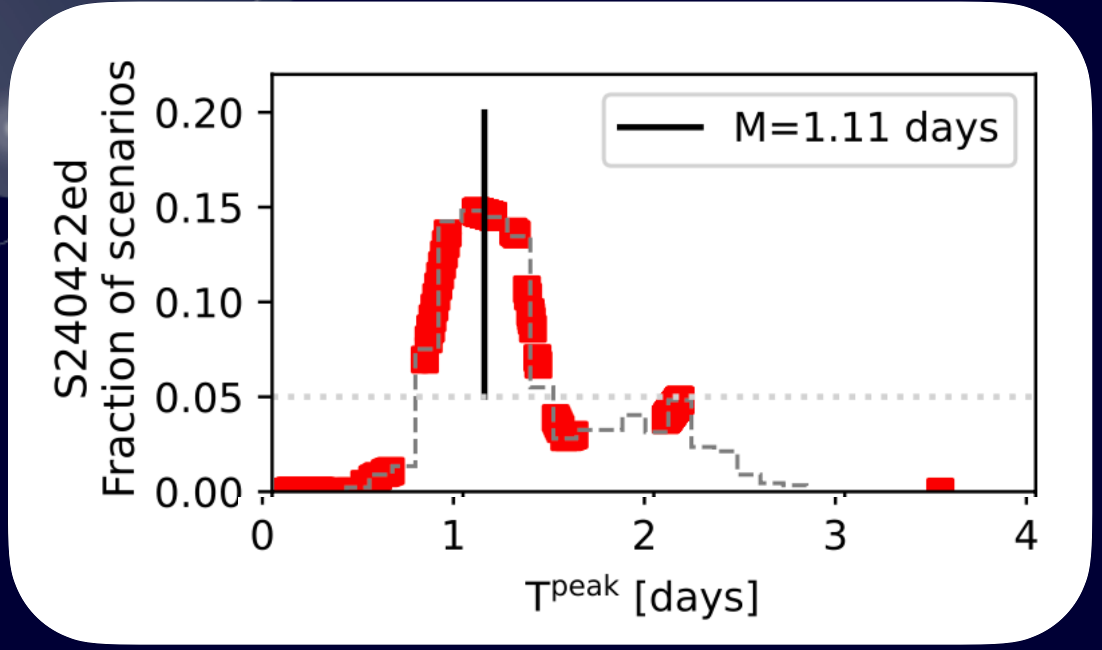

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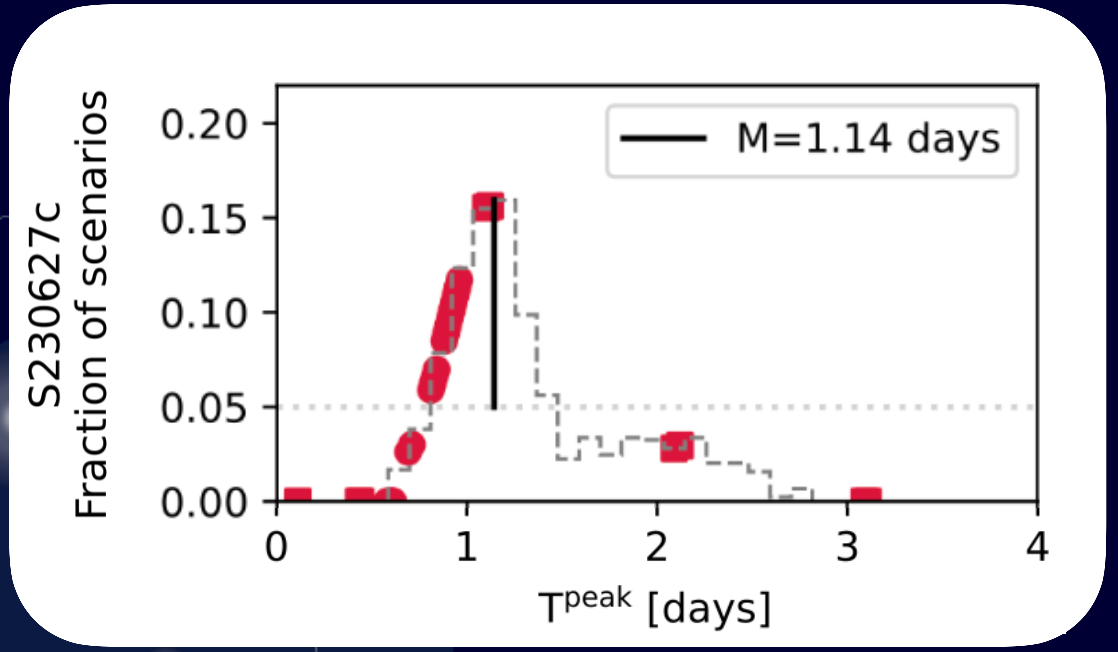

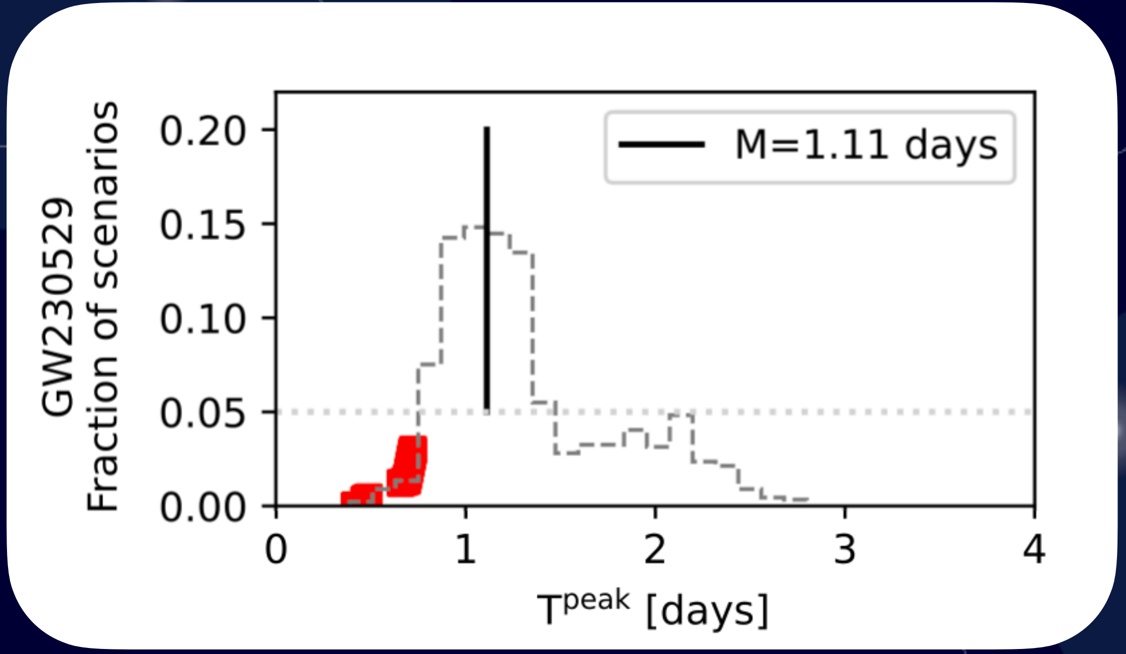

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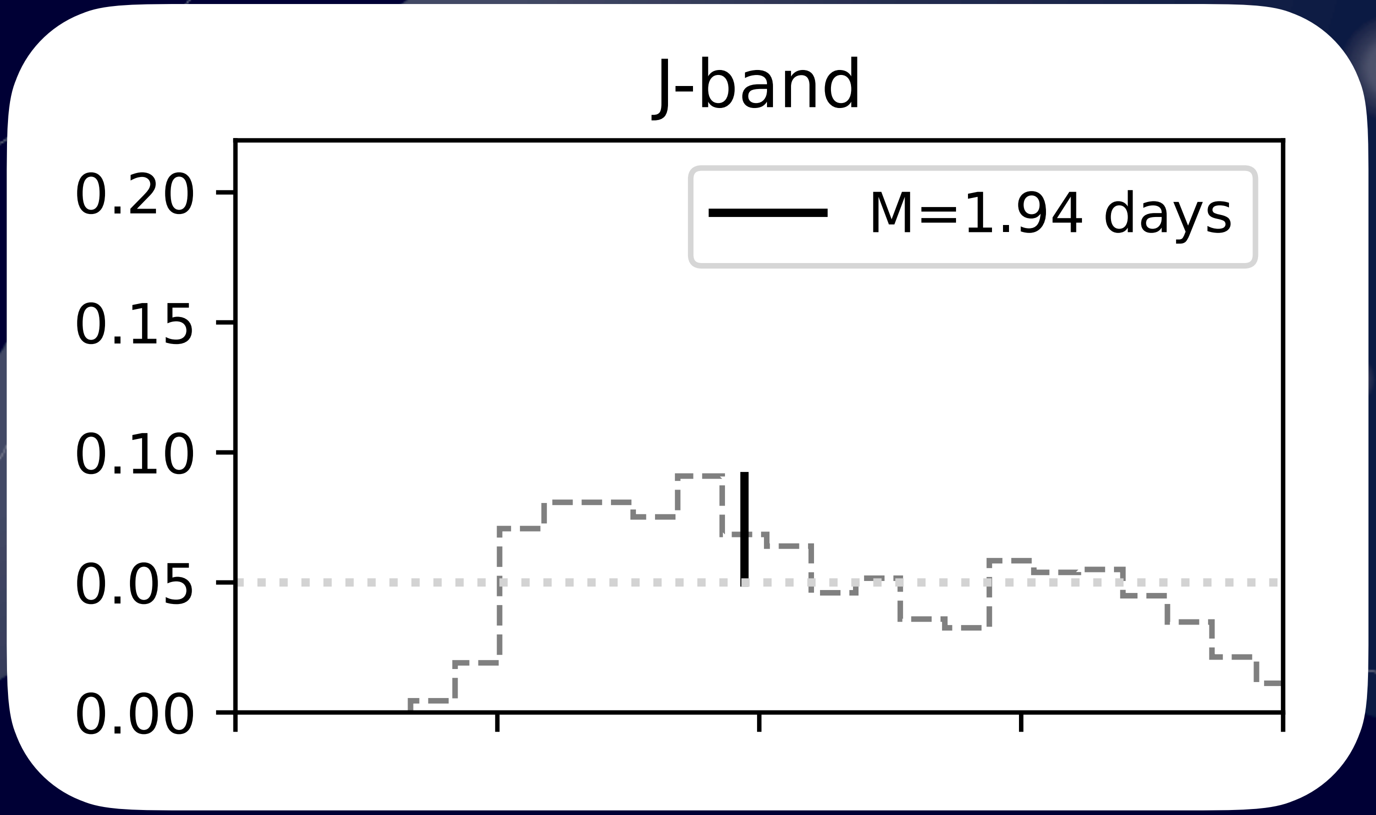


For J-band: advocate a more « flexible » approach for near and infrared for which the peak time of the KN is less obvious

In general: Necessity to image the first moment but also the importance of imaging 1 day post-merger

Part III. Constraints of KN from O4 NSBH candidates

In this work:

2) Given the non-observation of a KN, set constraints on source ejecta and viewing angle properties of the 4 NSBH candidates:

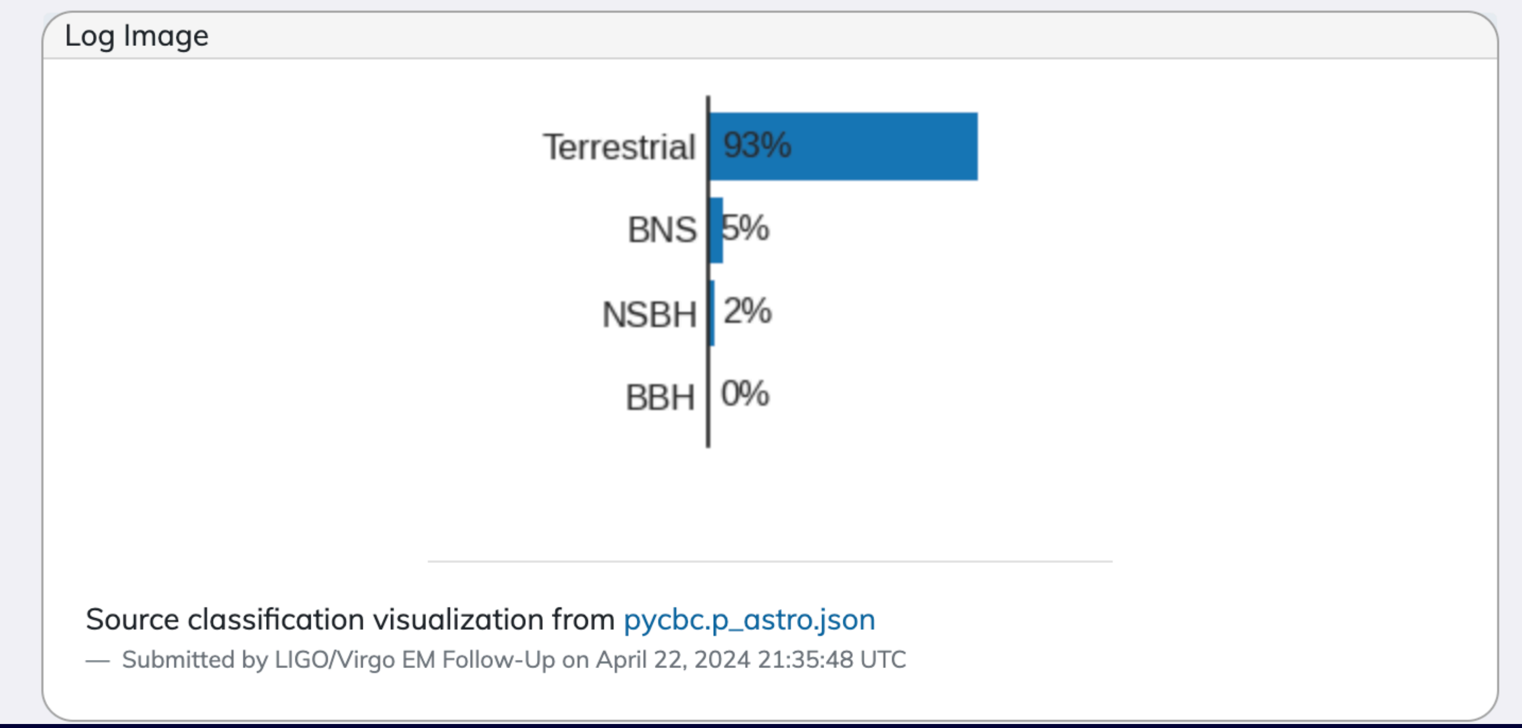
- Start from GW public information (GraceDB) to estimate a range of consistent ejected masses m_{dyn}, m_{wind} & select a corresponding set of simulated KN light curves

- Compare the magnitude of the light curves (M_{KN}) to the upper limit from optical observations (M_{obs})

- If M_{KN} **>** M_{obs}: KN light curve incompatible with observation

Part III. Constraints of KN from O4 NSBH candidates

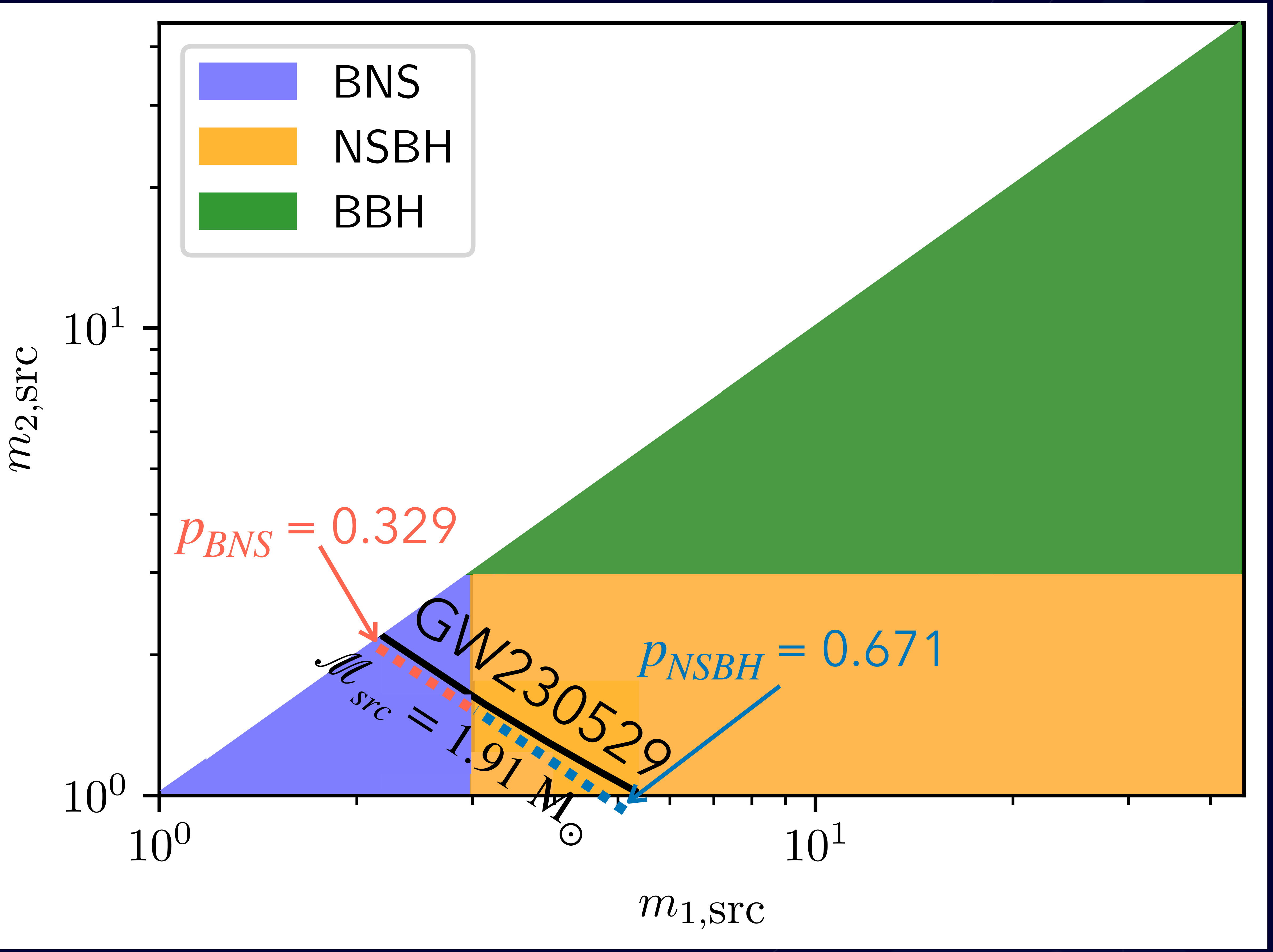
- **PyCBC Live method to compute the p_{astro}: deterministic mapping between the source-frame chirp mass and its source classification probabilities**



Method from Villa-Ortega, 2022

Source classification (rescaled to 1)

Candidate	BNS	NSBH	BBH
S230518h	0	0.959	0.041
S230529ay	0.329	0.671	0
S230627c	0	0.493	0.507
S240422ed	0.700	0.300	0



Part III. Constraints of KN from O4 NSBH candidates

- **Compute a range of consistent ejected masses: m_{dyn}, m_{wind} select a corresponding set simulated of KN light curves**

$$\frac{M^{\rm rem}_{\rm model}}{M^b_{\rm NS}} = [\mathrm{Max}(\alpha\frac{1-2C_{\rm NS}}{\eta^{1/2}} - \beta\hat{R}_{\rm ISCO}\frac{C_{\rm NS}}{\eta} + \gamma, 0)]^{\delta}$$

$$\frac{M_{\rm dyn}}{M^b_{\rm NS}} = a_1 Q^{n_1}\frac{1-2C_{\rm NS}}{C_{\rm NS}} - a_2 Q^{n_2}\frac{R_{\rm ISCO}}{M_{\rm BH}} + a_4$$

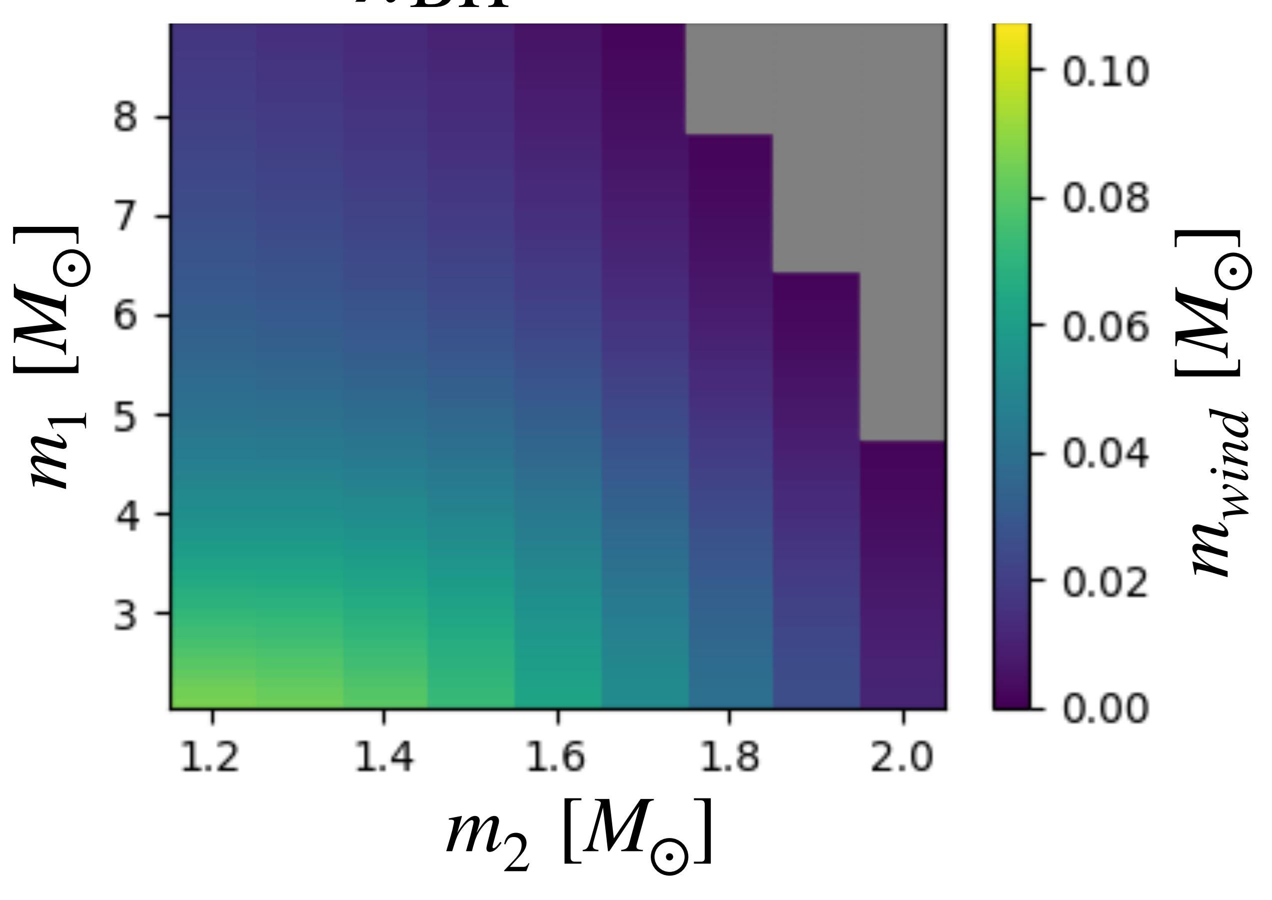
(Foucart et al, 2018, Kruger & Foucart, 2020)

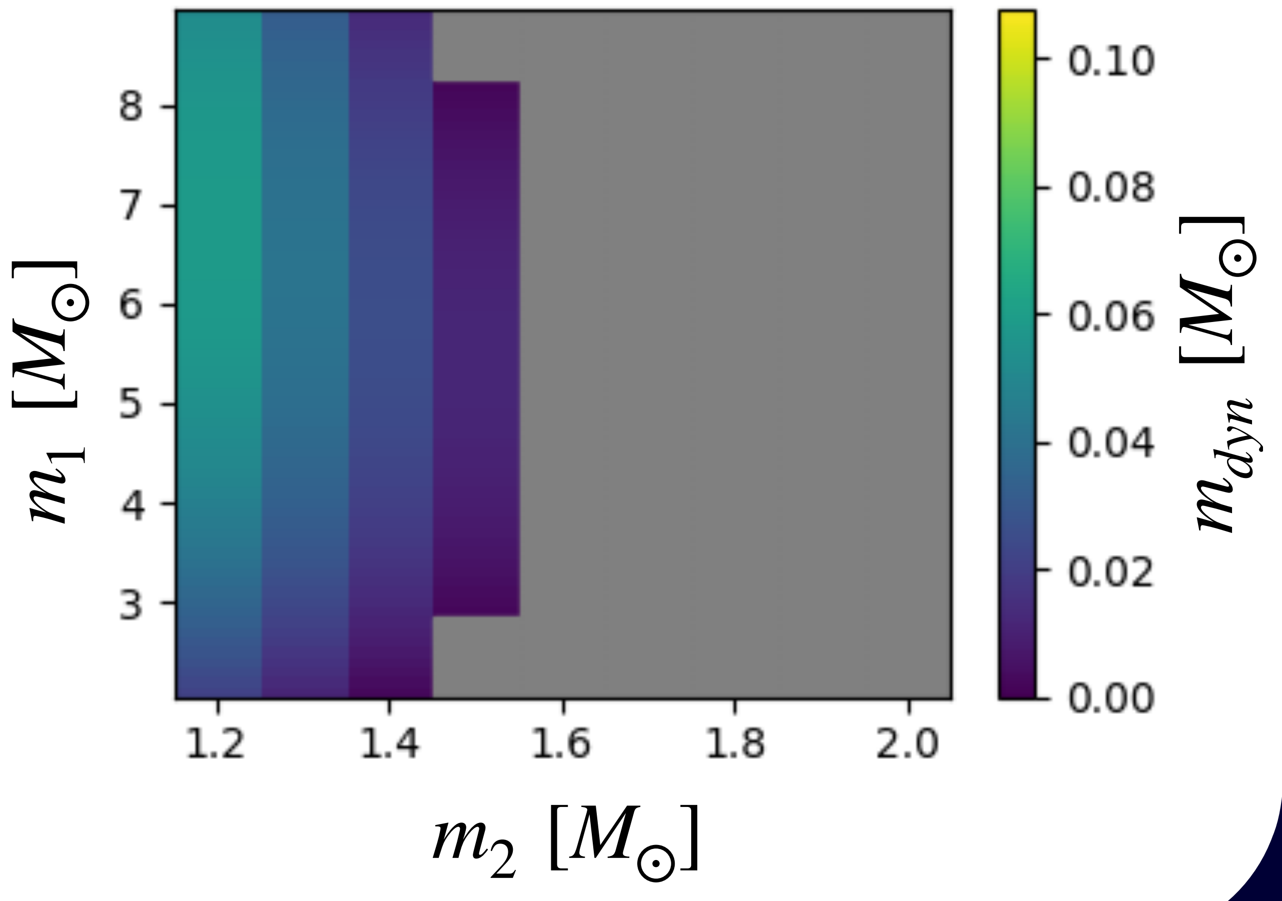
$$M^{\rm model}_{\rm rem} = M_{\rm dyn} + \zeta \times (M_{\rm disk} - M_{\rm dyn})$$

Aspect	Details
Source Properties of NS-BH Event	
NS Mass	$1.2 - M_{max,NS} M_\odot$
BH Mass	$3.0 - 9.0 M_\odot$
Spins	• BH Spin: $Spin1z_{\rm BH} \in \{-0.3, 0.0, 0.3, 0.8\}$ • NS Spin: None
Equation of State of matter	*SLy*, *H4*

19

Example for SLy EOS & $\chi_{\rm BH} = 0.8$





Part III. Constraints of KN from O4 NSBH candidates

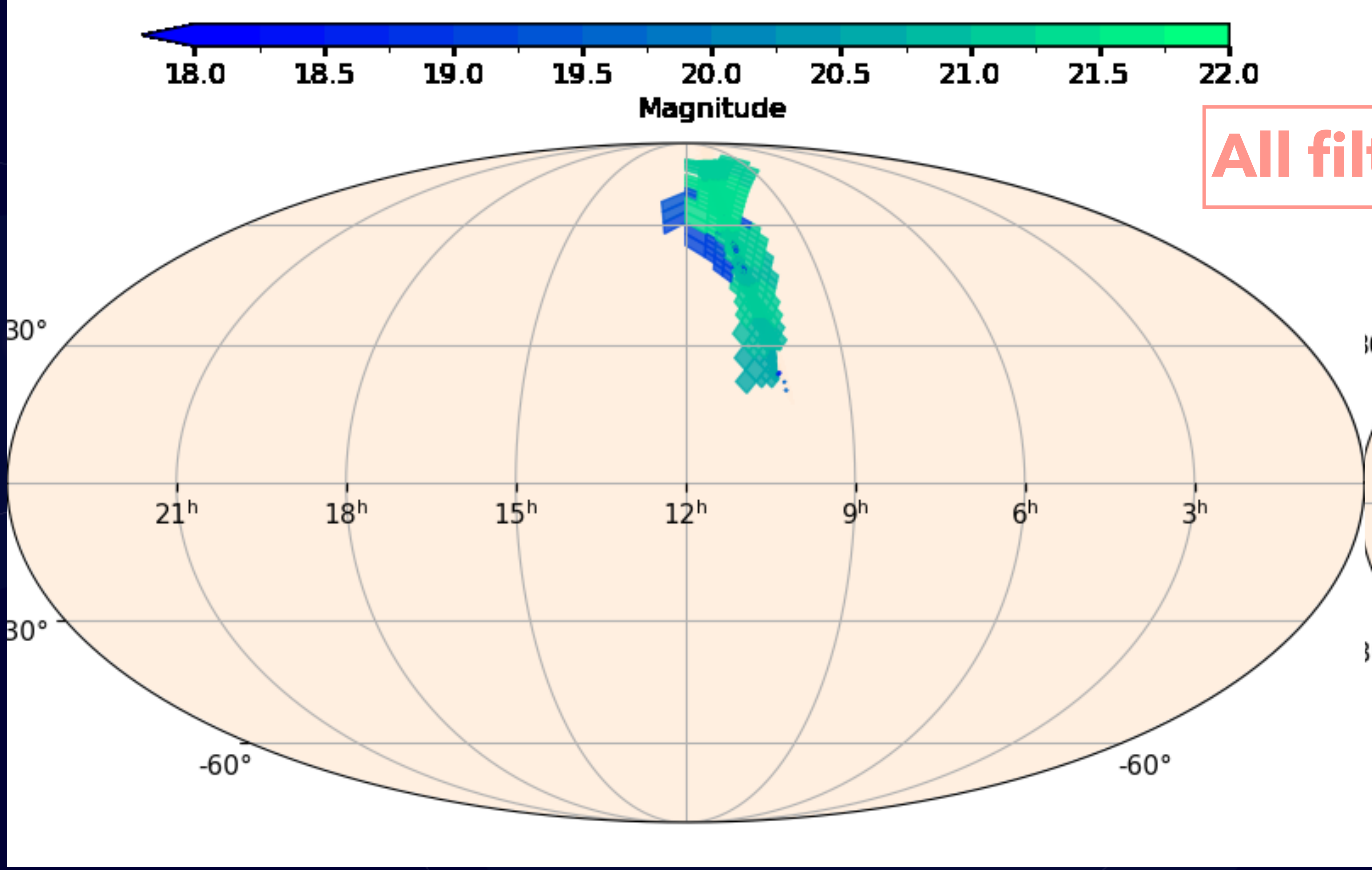
- **Compute a range of consistent ejected masses: m_{dyn}, m_{wind} select a corresponding set simulated of KN light curves**

- **Results (we take the broader upper limit between EoS and spins)**
  - S230518h: $m_{dyn} < 0.08\ M_{\odot}$ & $m_{wind} < 0.04\ M_{\odot}$
  - GW230529: $m_{dyn}, m_{wind} \leq 0.01\ M_{\odot}$
  - S230627c: $m_{dyn}, m_{wind} \leq 0.01\ M_{\odot}$
  - S240422ed: given the low significance, select all the synthetic light curves of the grid

Part III. Constraints of KN from O4 NSBH candidates

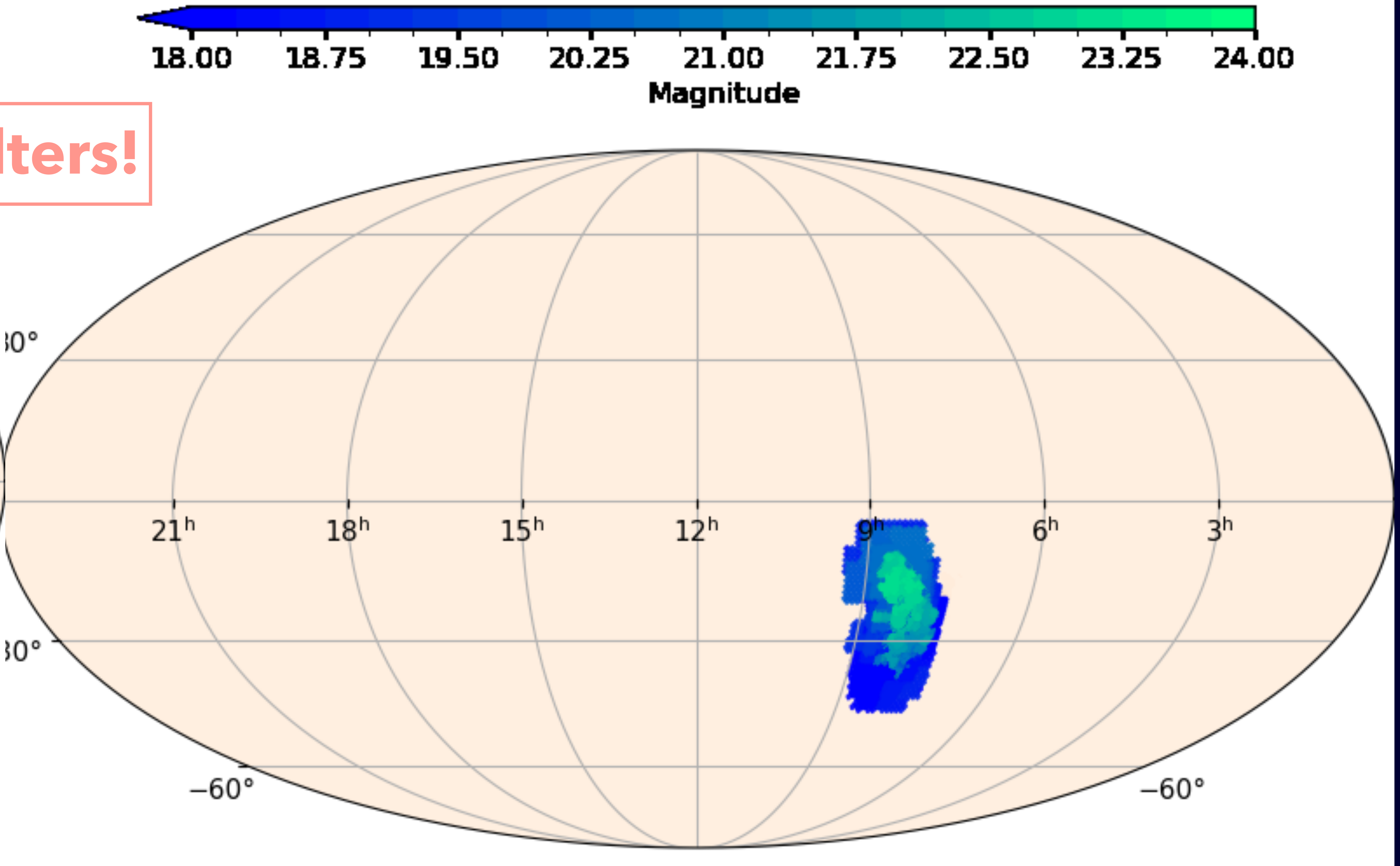
- **Compare the magnitude of the light curve (M_{KN}) with the one of optical observations (M_{obs})**
  - Each optical telescope field has a specific field of view, filter, limiting magnitude and epoch
  - Report these fields on the GW HEALPix skymap
  - Extract pixels of the skymap in each field and their associated distances

S230627c (between 0 and 1 day)



All filters!

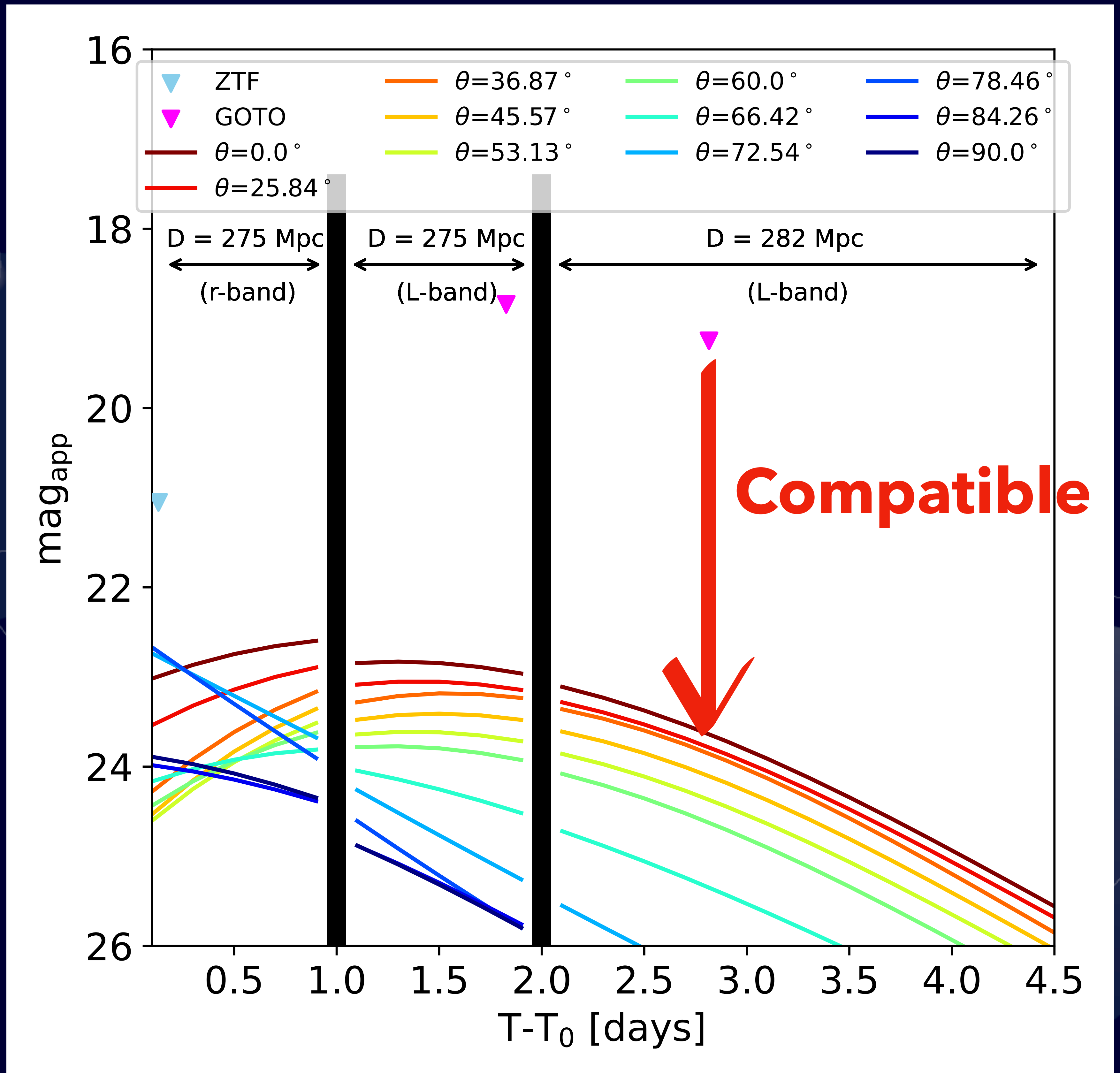
S240422ed (between 0 and 1 day)



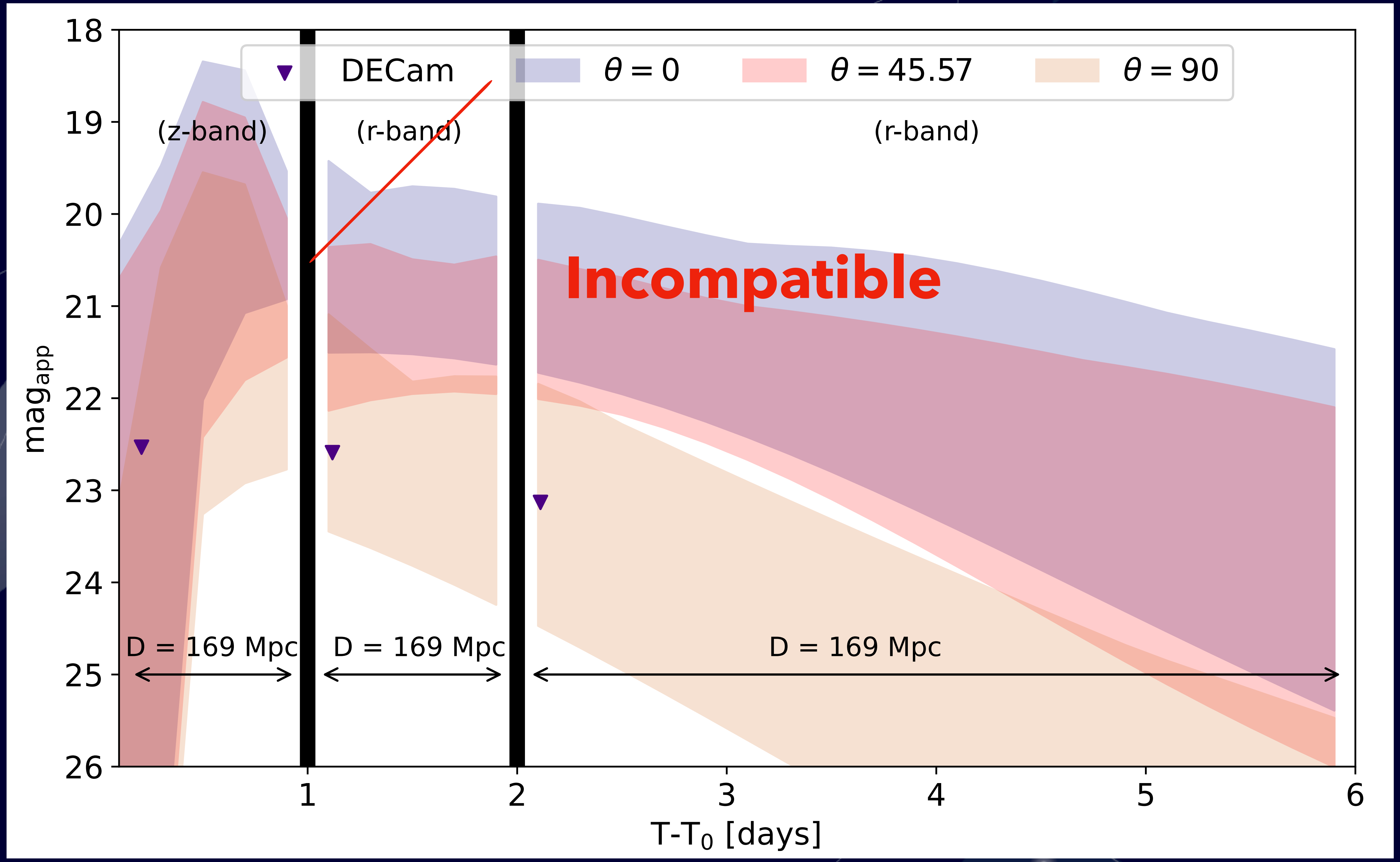
Part III. Constraints of KN from O4 NSBH candidates

- Compute the apparent M_{KN} of the synthetic KN light curves for each pixel and at the corresponding distance
- Compare the brightness of the simulated KN with the upper limits of the fields that contain the pixel at the epoch of the field
- If $M_{KN} > M_{obs}$: KN light curve incompatible with observation

S230627c



S240422ed



Part III. Constraints of KN from O4 NSBH candidates

- **If M_{KN} > M_{obs}: KN light curve incompatible with observation**

- Compute a scale reflecting the possibility of the « presence » of a KN:

Time range of the observations that occurred at time $t \in \Delta t = [0,1[, [1,2[$ or $[2,6[$ days

Synthetic KN from Bulla-Anand

Filter

$$S_{\mathrm{KN},\Delta\mathrm{t},ipix} = \frac{1}{n_{\mathrm{tot,KN}}} \times \sum_{k=1}^{n_{\mathrm{tot,KN}}} \begin{cases} 1 & \text{if } M_{KN}(fil, \theta, m_{dyn}, m_{wind}, t) > M_{obs}(fil, t, ipix) \\ 0 & \text{otherwise} \end{cases}$$

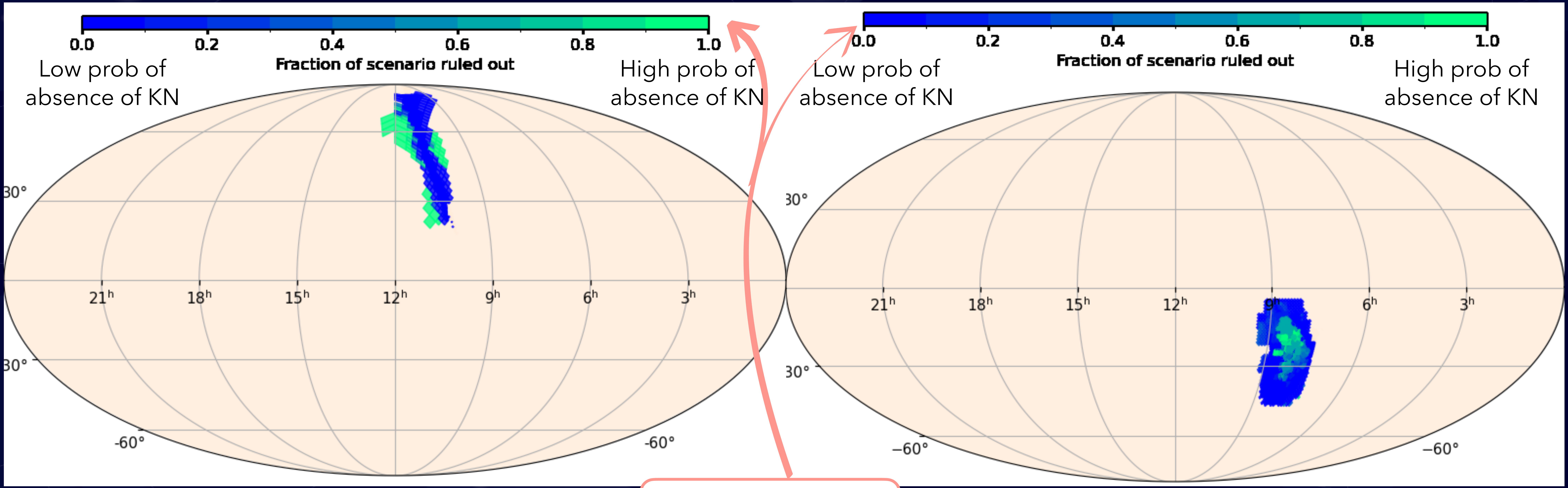
Total number of synthetic KNe from the grid considered for each event

Telescope observation

Part III. Constraints of KN from O4 NSBH candidates

- If $M_{KN} > M_{obs}$: **KN light curve incompatible with observation**

S230627c (between 0 and 1 day) **S240422ed (between 0 and 1 day)**

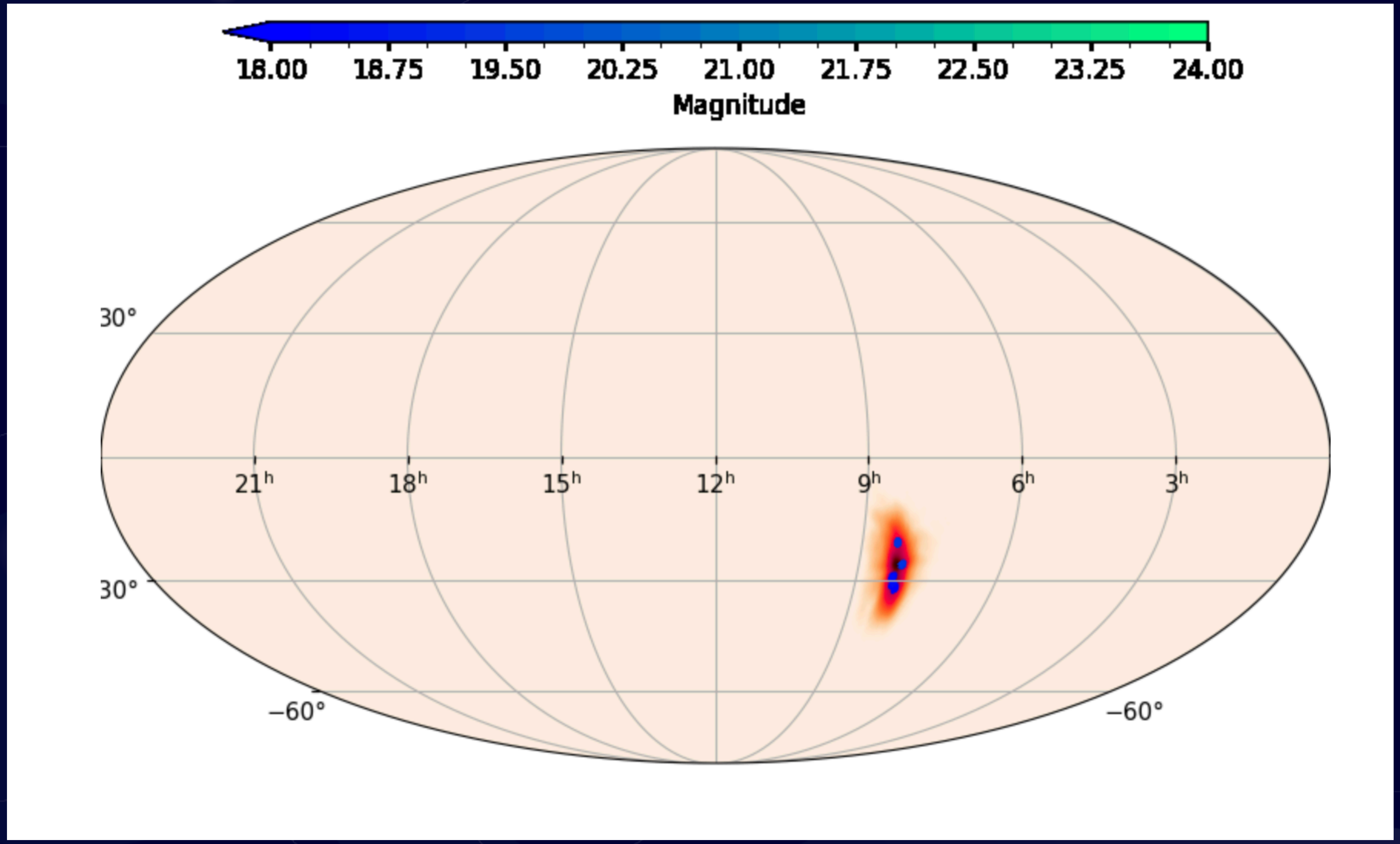


$1 - S_{\mathrm{KN},\Delta t,ipix}$

S240422ed: **178 deg²** within the 90% credible region (72% of the skymap), for t in [2,6] days, with a $1 - S_{\mathrm{KN},\Delta t,ipix}$ **> 0.7**: **probable absence of a KN in the observations**

Part III. Constraints of KN from O4 NSBH candidates

Focus on KNC observations of S240422ed:



Scenarii ruled out by KNC observations: ~5% of the KN population

- Configurations with viewing angle $\theta < 36^\circ$
- Configurations with $m_{ej,dyn} \geq 0.02\ M_\odot$
- Configurations with $m_{ej,dyn} \geq 0.01\ M_\odot$

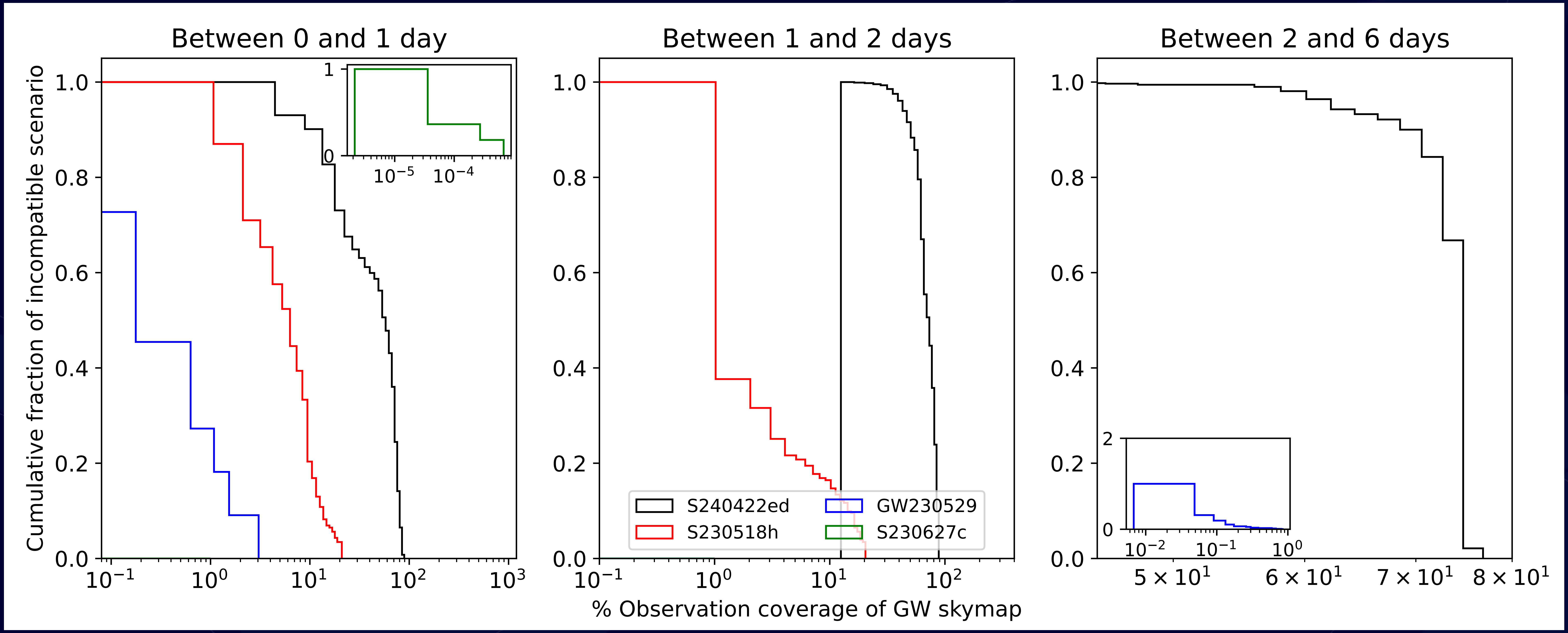
→ Observations deep enough to constraint ejecta and viewing angle properties!

Part III. Constraints of KN from O4 NSBH candidates

- **If M_{KN} > M_{obs}: KN light curve incompatible with observation**

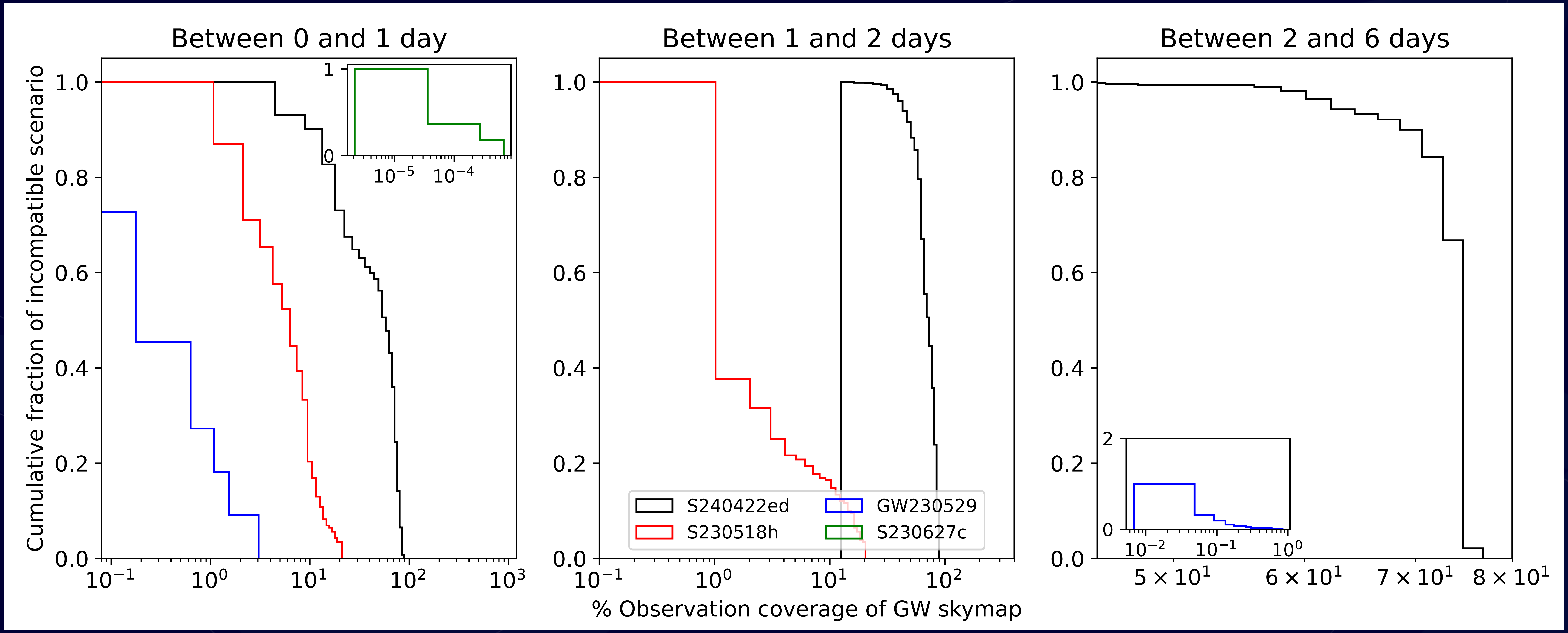
- Associate a deterministic probability to each KN scenario $(\theta, m_{dyn}, m_{wind})$ of being ruled out

$$1 - \mathrm{P}_{\theta,m_{dyn},m_{wind},\Delta t} = \bar{P}_{\theta,m_{dyn},m_{wind},\Delta t} = \sum_{ipix} P(\mathrm{GW} \mid ipix) \times \begin{cases} 1 & \text{if } M_{KN}(fil, \theta, m_{dyn}, m_{wind}, t) < M_{obs}(filt, t, ipix) \\ 0 & \text{otherwise} \end{cases}$$



Part IV. Conclusion

- S230518h: it has not been possible to observe KN emitted from an on-axis collision up to a viewing angle of $\theta = 25°$, assuming a minimum confidence of 8% for the presence of the source in this region
- GW230529: we cannot exclude the presence of a KN in the observations
- S230627c: we cannot exclude the presence of a KN in the observations
- S240422ed: **observations ruled out the presence of a KN (with or without GWs)**



Part IV. Conclusion

- S240422ed: **observations ruled out the presence of a KN (with or without GWs)**
  - A null ejecta is consistent with $p_{BNS} \leq 0.3$ → Inconsistent with the p_{astro} from the alert:

Candidate	BNS	NSBH	BBH
S230518h	0	0.959	0.041
S230529ay	0.329	0.671	0
S230627c	0	0.493	0.507
S240422ed	0.700	0.300	0

What could be the reason?

- KN-model dependant
- BNS instead of NSBH model?
- Candidate not of astrophysical origin

THANK YOU! QUESTIONS?

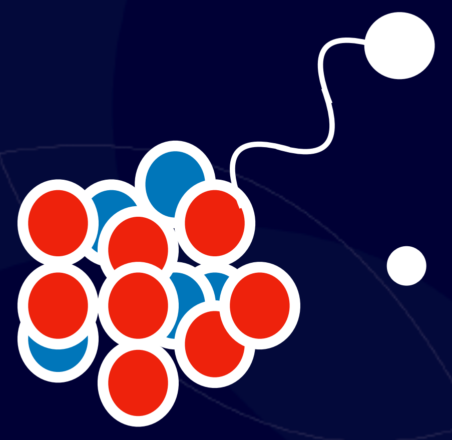
Choice of KN model

Anand 2021-Bulla 2019 model: light curves computed with POSSIS

(Bulla, 2019 & Bulla, 2023)

- 3D Monte Carlo code for modelling radiation transport in KN
- Does not solve the radiative transfer equation analytically but rather numerically with Monte Carlo photons representing radiation and propagating through the expanding ejecta → **speed up the computation**
  - **Key ingredients:** input **energy** (from radioactive decay of r-process nuclei) and **opacity** (controlling the diffusion of Monte Carlo photons)

Creating photons

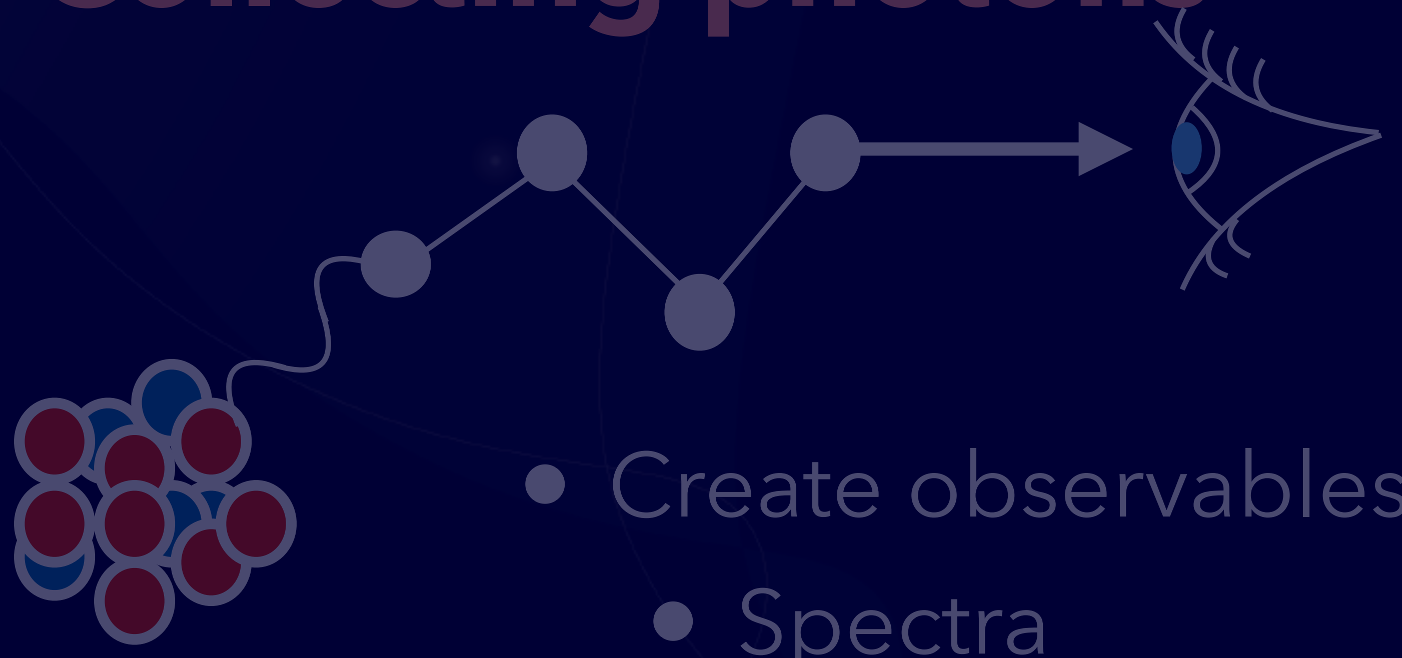


- Inputs:
  - Frequency
  - Energy

Propagating photons

- Optical depth: $\tau = \int \kappa \rho dr$
- Probability of interacting with matter: $P = 1 - e^{-\tau}$

Collecting photons



- Create observables:
  - Spectra
  - Light curves …

Choice of KN model

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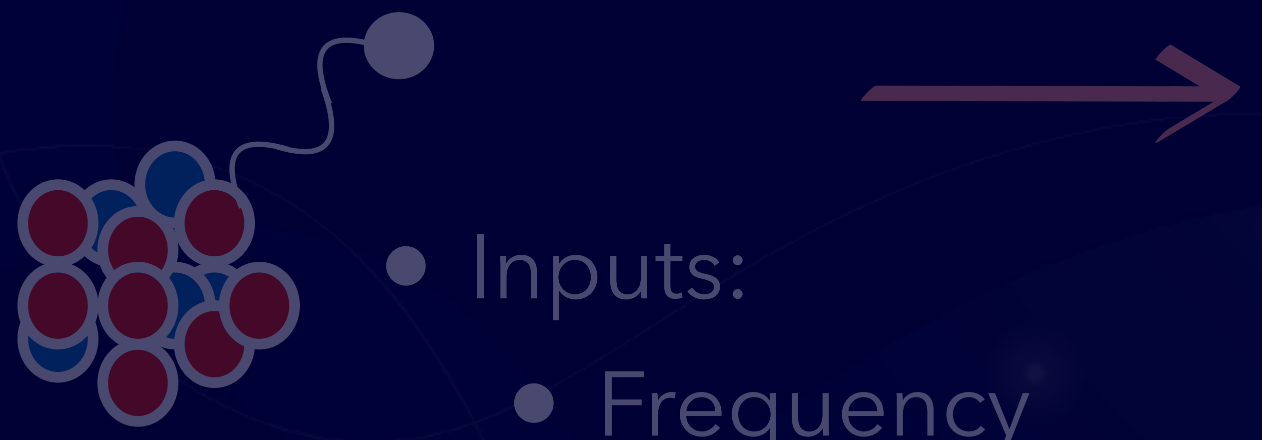
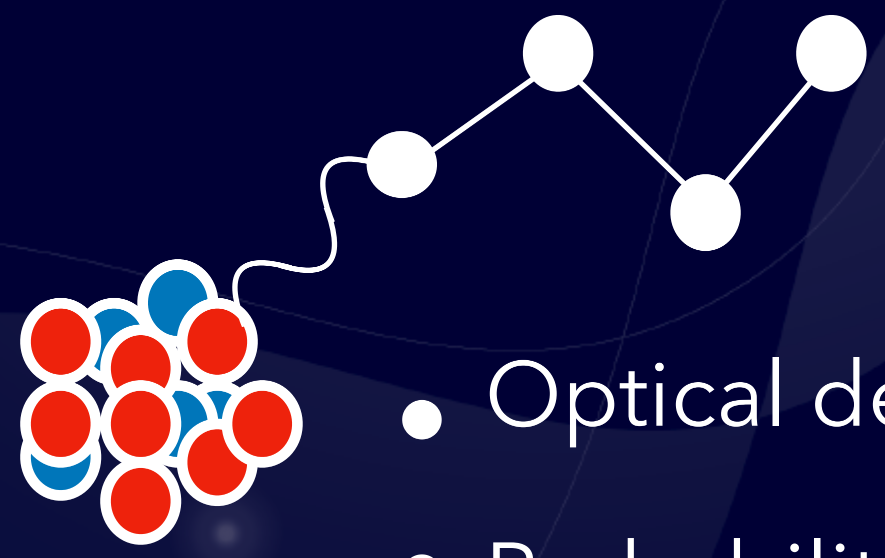
Creating photons



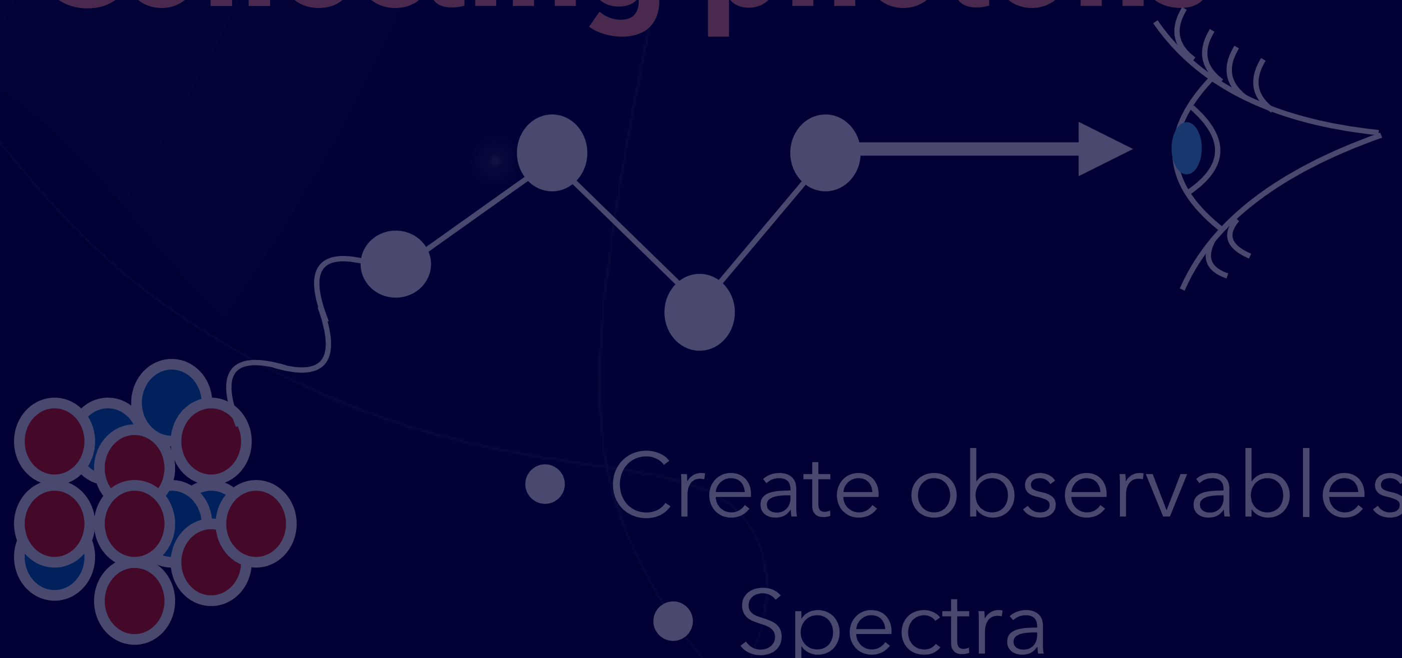
- Inputs:
  - Frequency
  - Energy

Propagating photons



- Optical depth: $\tau = \int \kappa\rho dr$
- Probability of interacting with matter: $P = 1 - e^{-\tau}$

Collecting photons



- Create observables:
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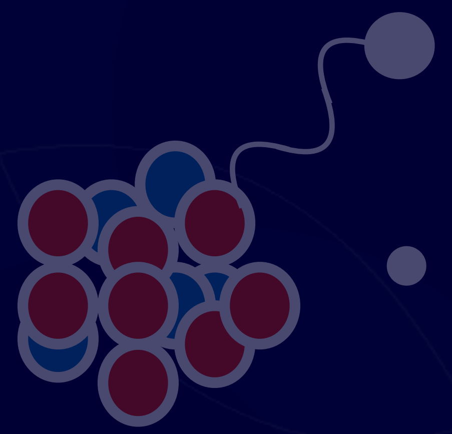
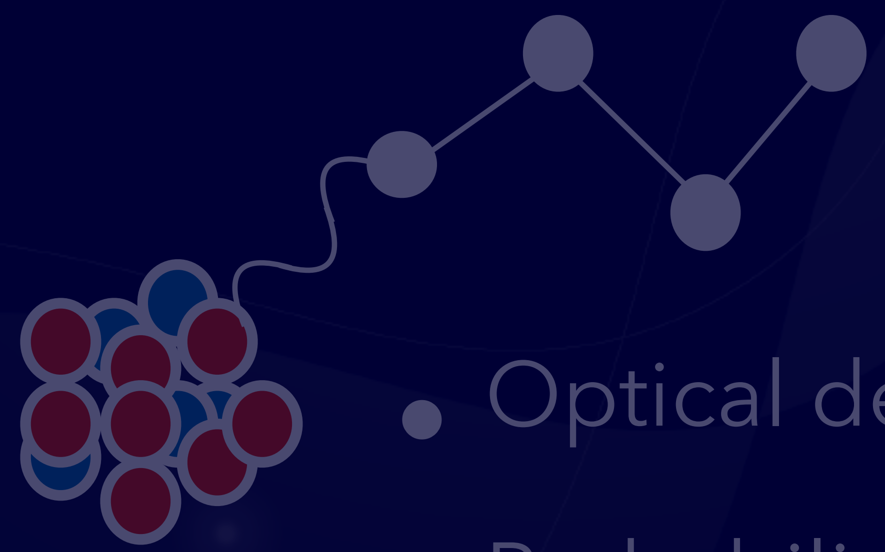
Creating photons



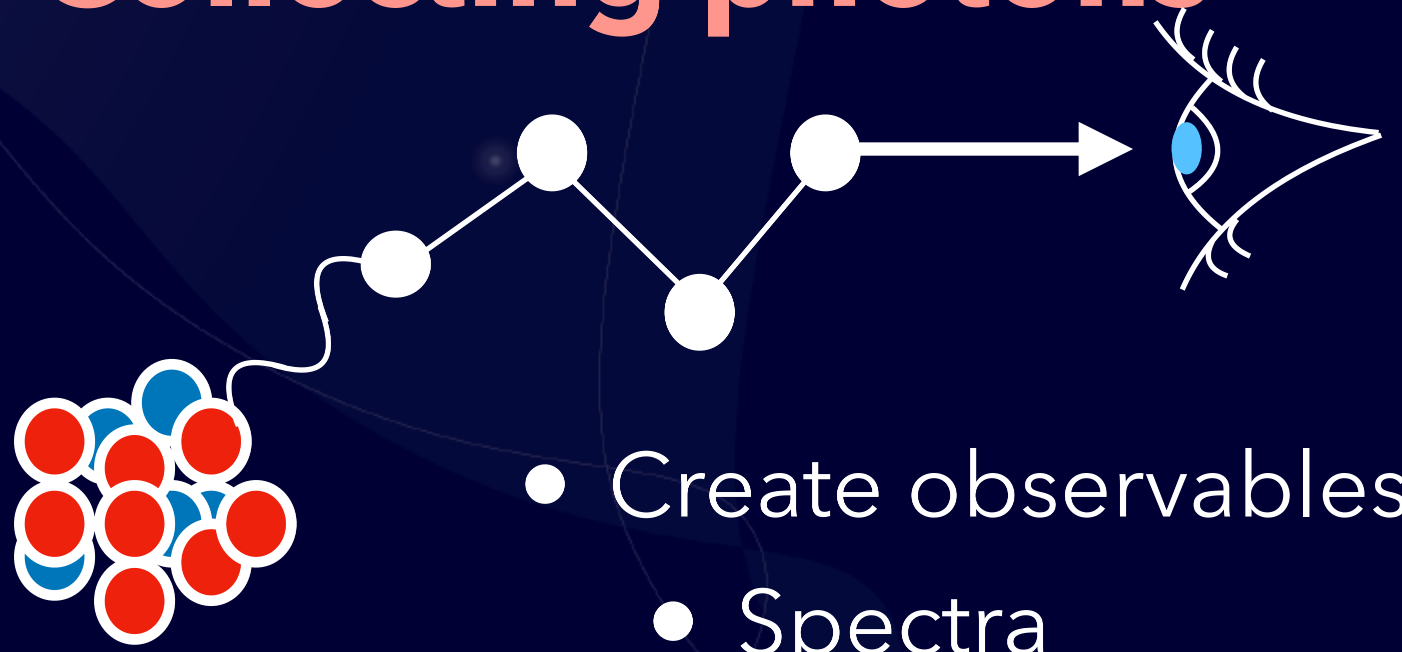
- Inputs:
  - Frequency
  - Energy

Propagating photons

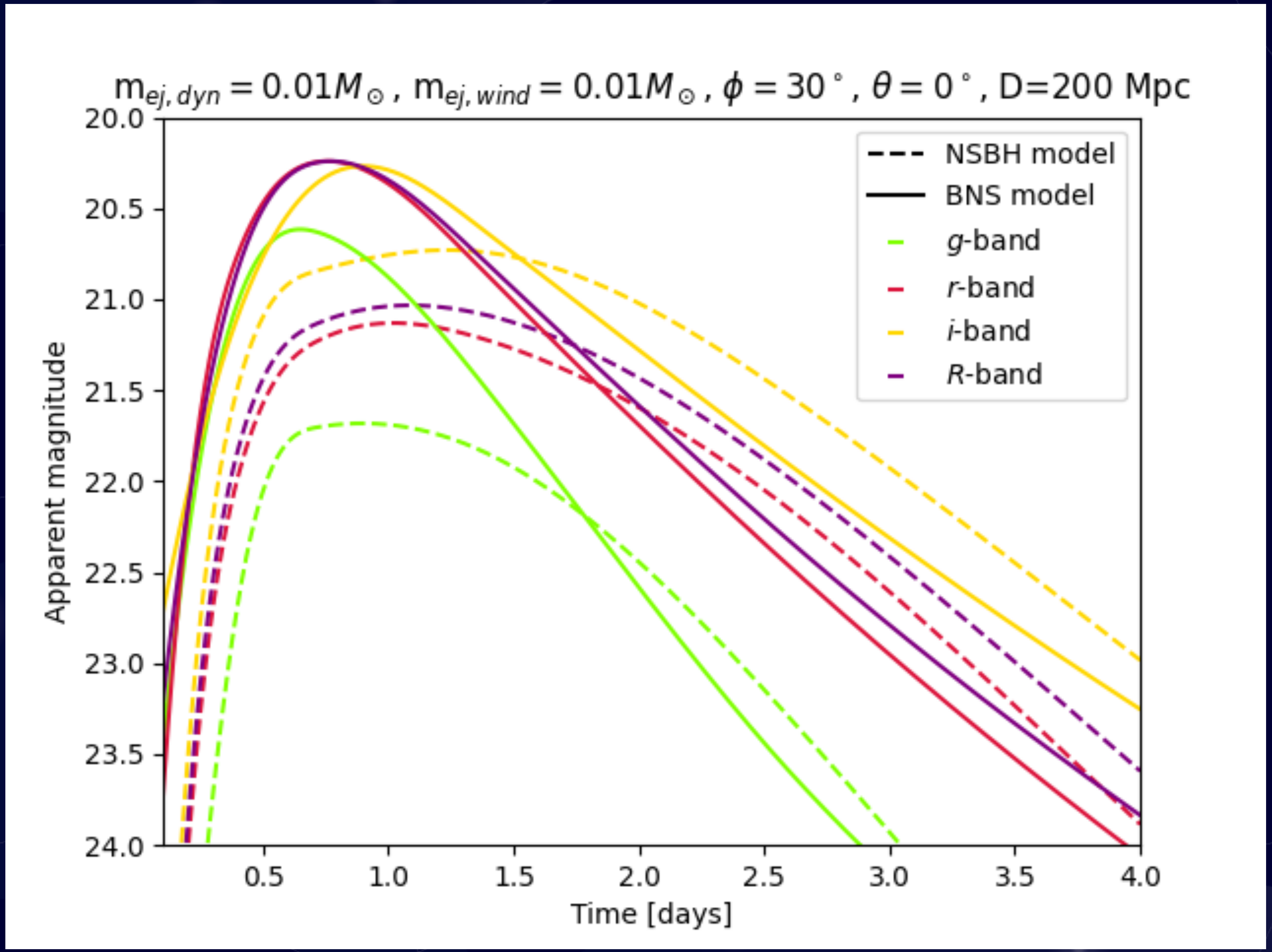


- Optical depth: $\tau = \int \kappa \rho dr$
- Probability of interacting with matter: $P = 1 - e^{-\tau}$

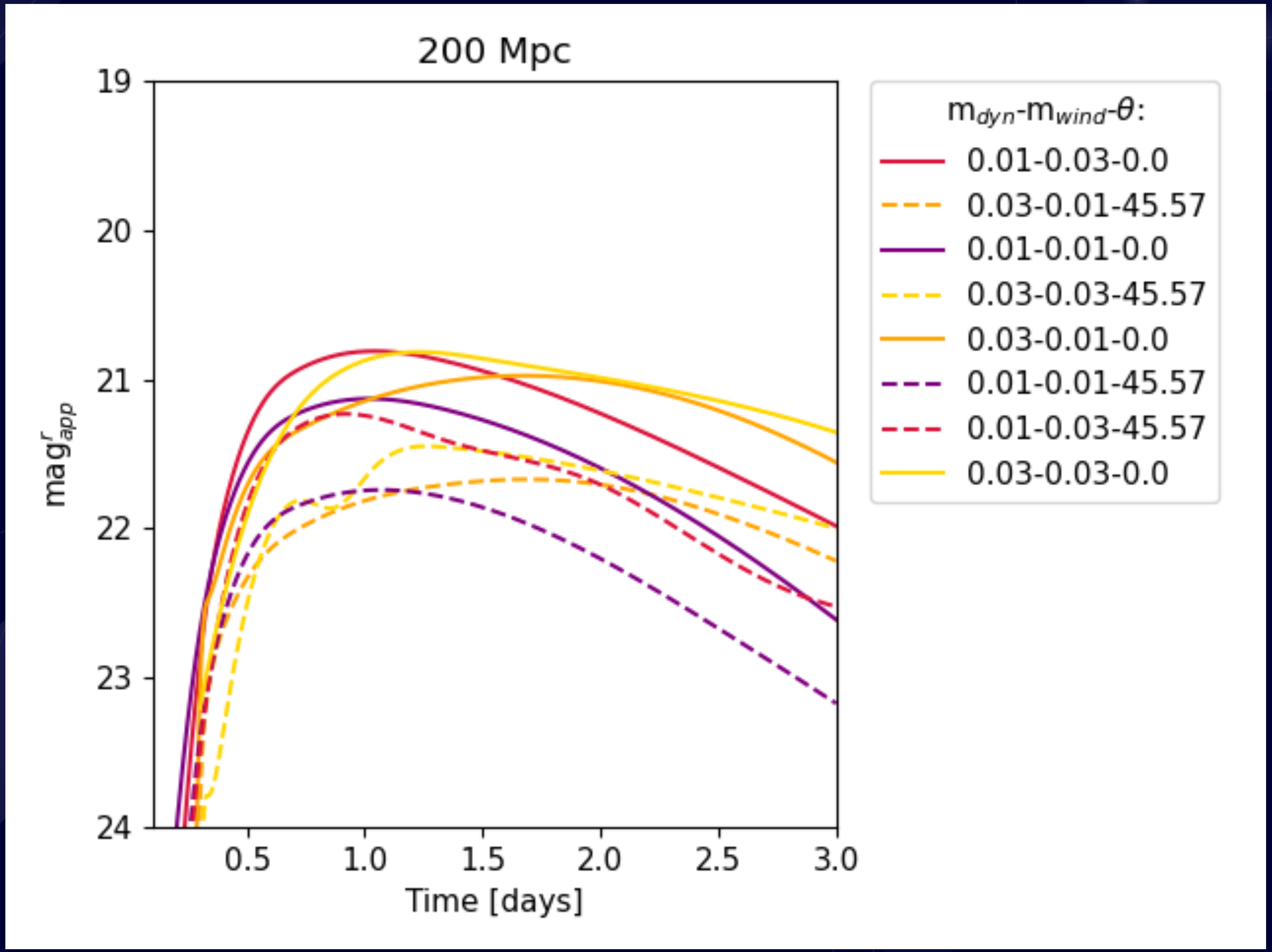
Collecting photons



- Create observables:
  - Spectra
  - Light curves …

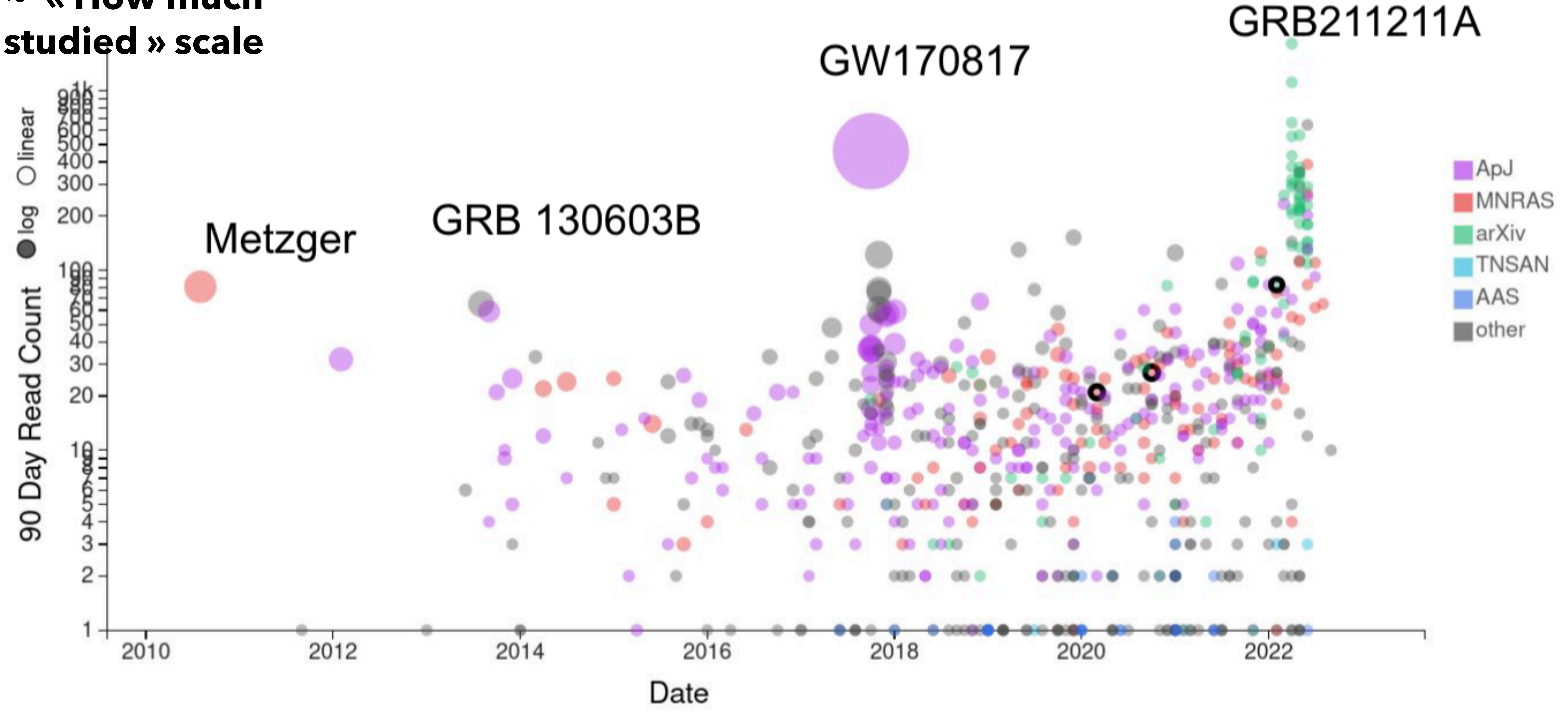


$m_{ej,dyn} = 0.01M_\odot$, $m_{ej,wind} = 0.01M_\odot$, $\phi = 30^\circ$, $\theta = 0^\circ$, D=200 Mpc
NSBH model
BNS model
g-band
r-band
i-band
R-band
Apparent magnitude
Time [days]

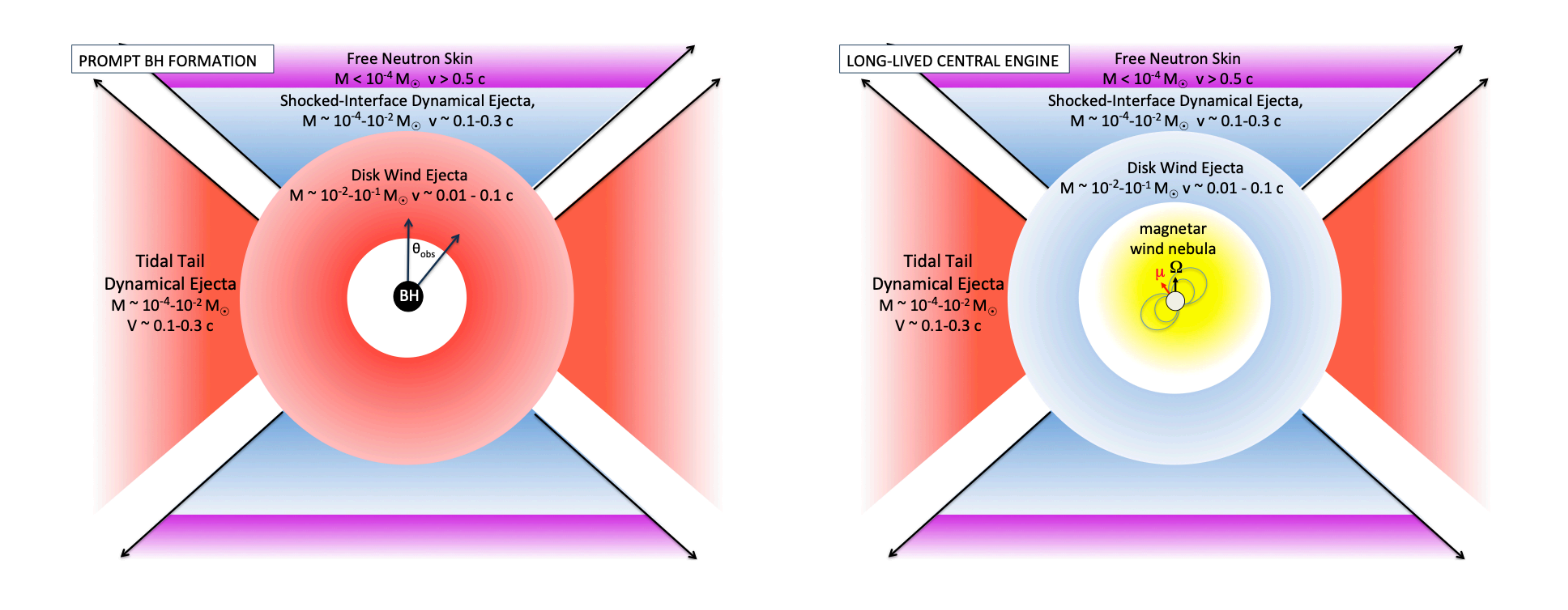


200 Mpc
m_{dyn}-m_{wind}-θ:
0.01-0.03-0.0
0.03-0.01-45.57
0.01-0.01-0.0
0.03-0.03-45.57
0.03-0.01-0.0
0.01-0.01-45.57
0.01-0.03-45.57
0.03-0.03-0.0
mag^r_{app}
Time [days]

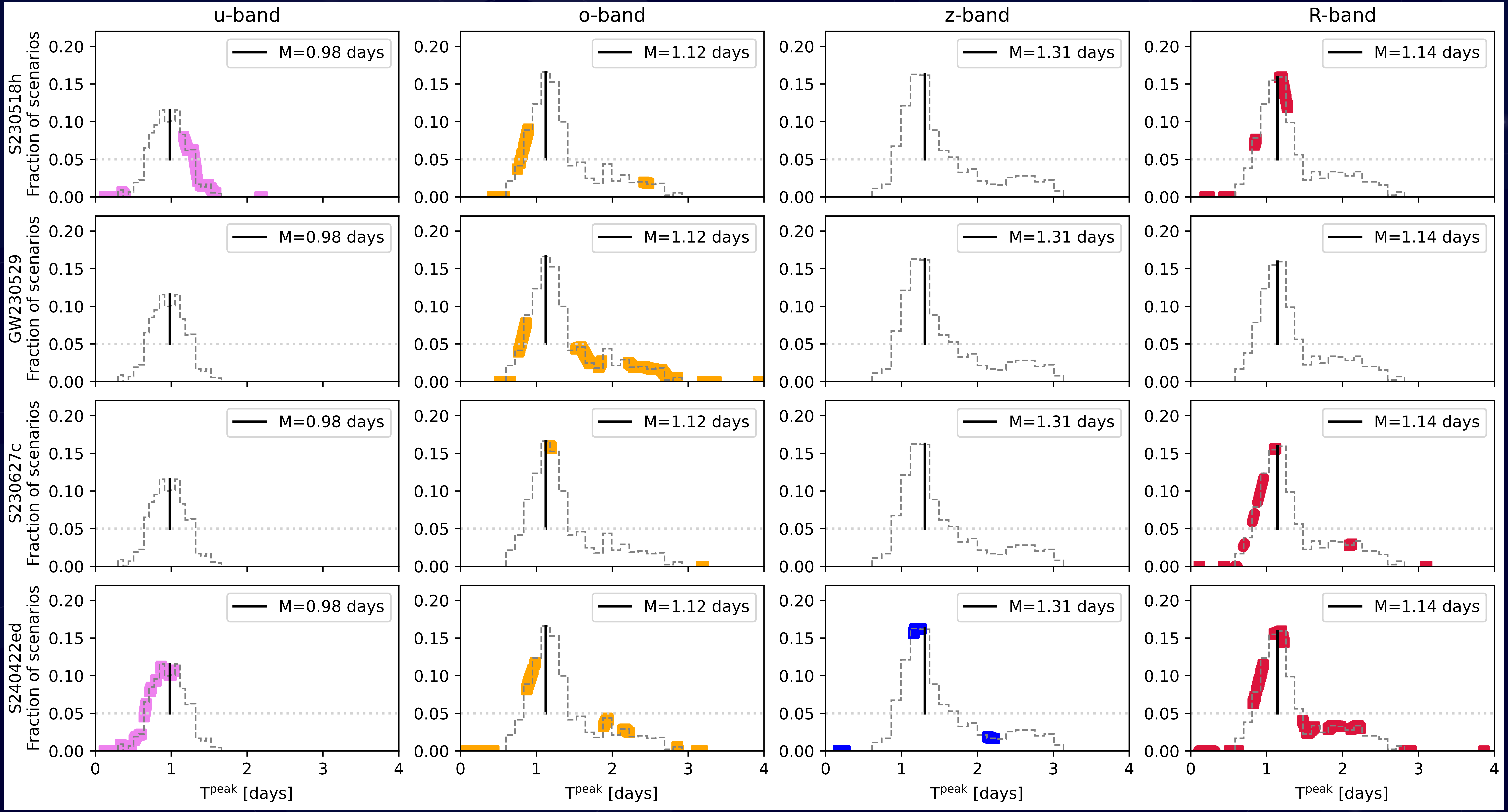
~ « How much studied » scale



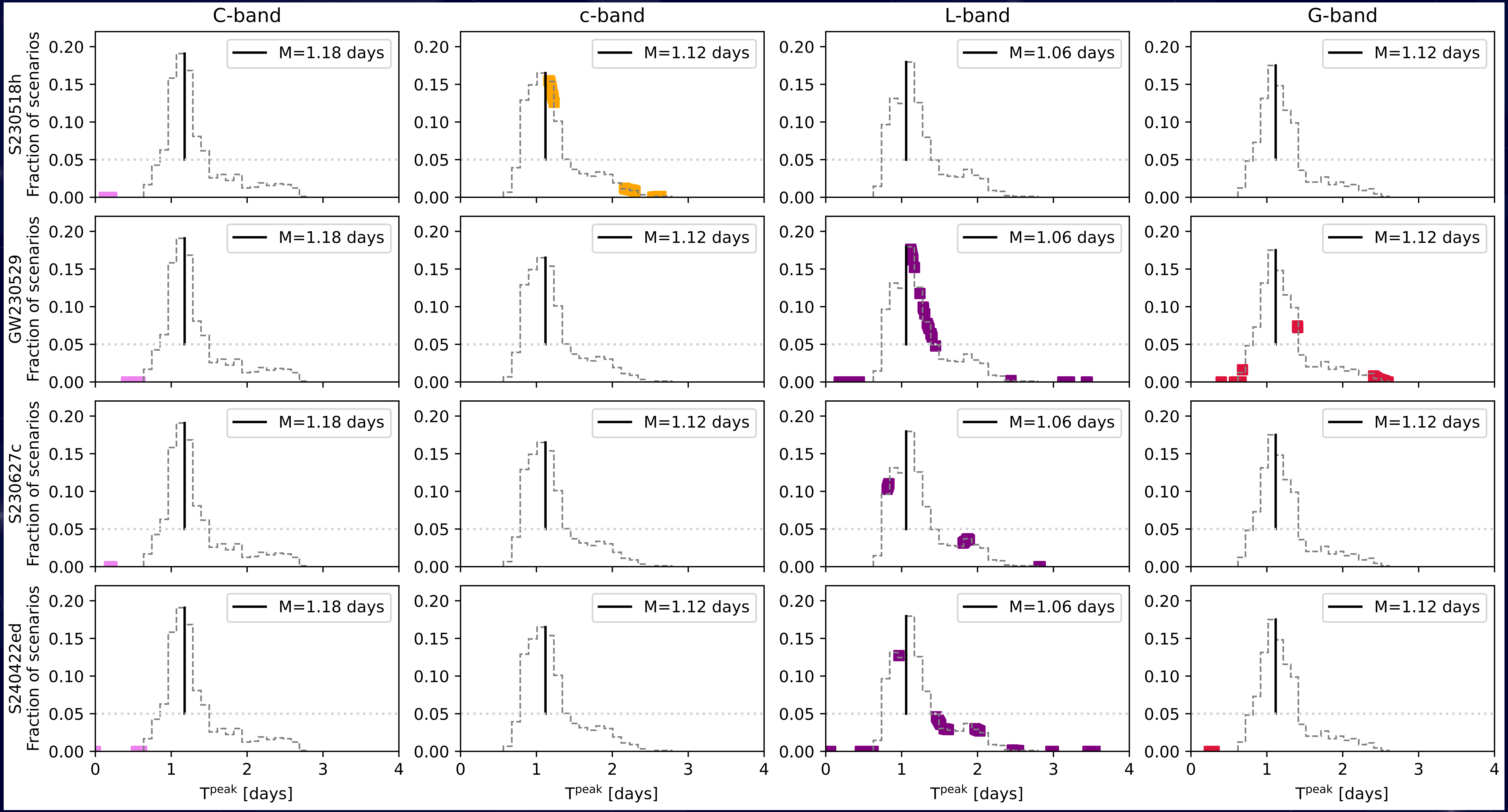
Modeling Kilonova from Binary Neutron Star merger



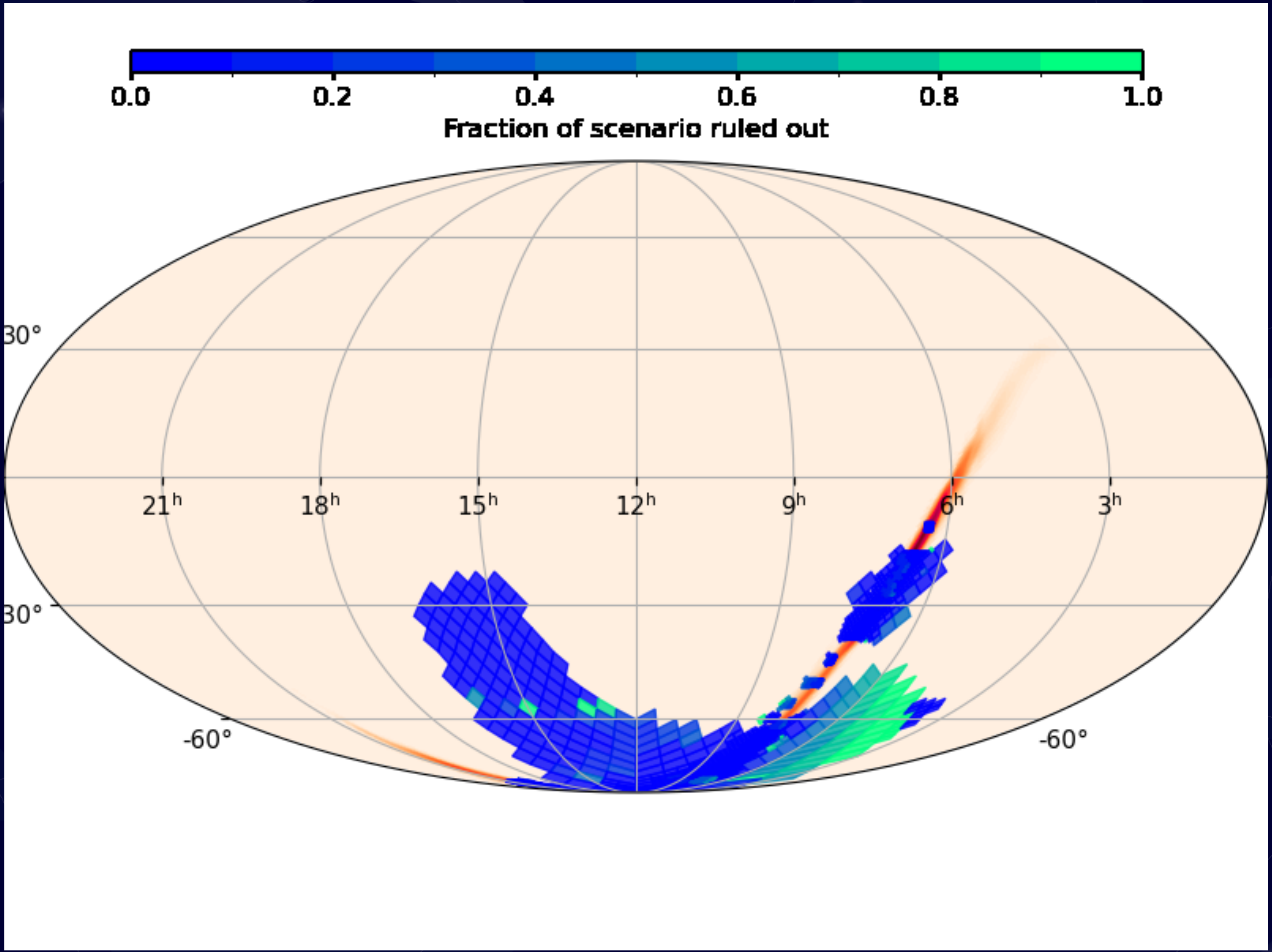
(Metzger, 2019)

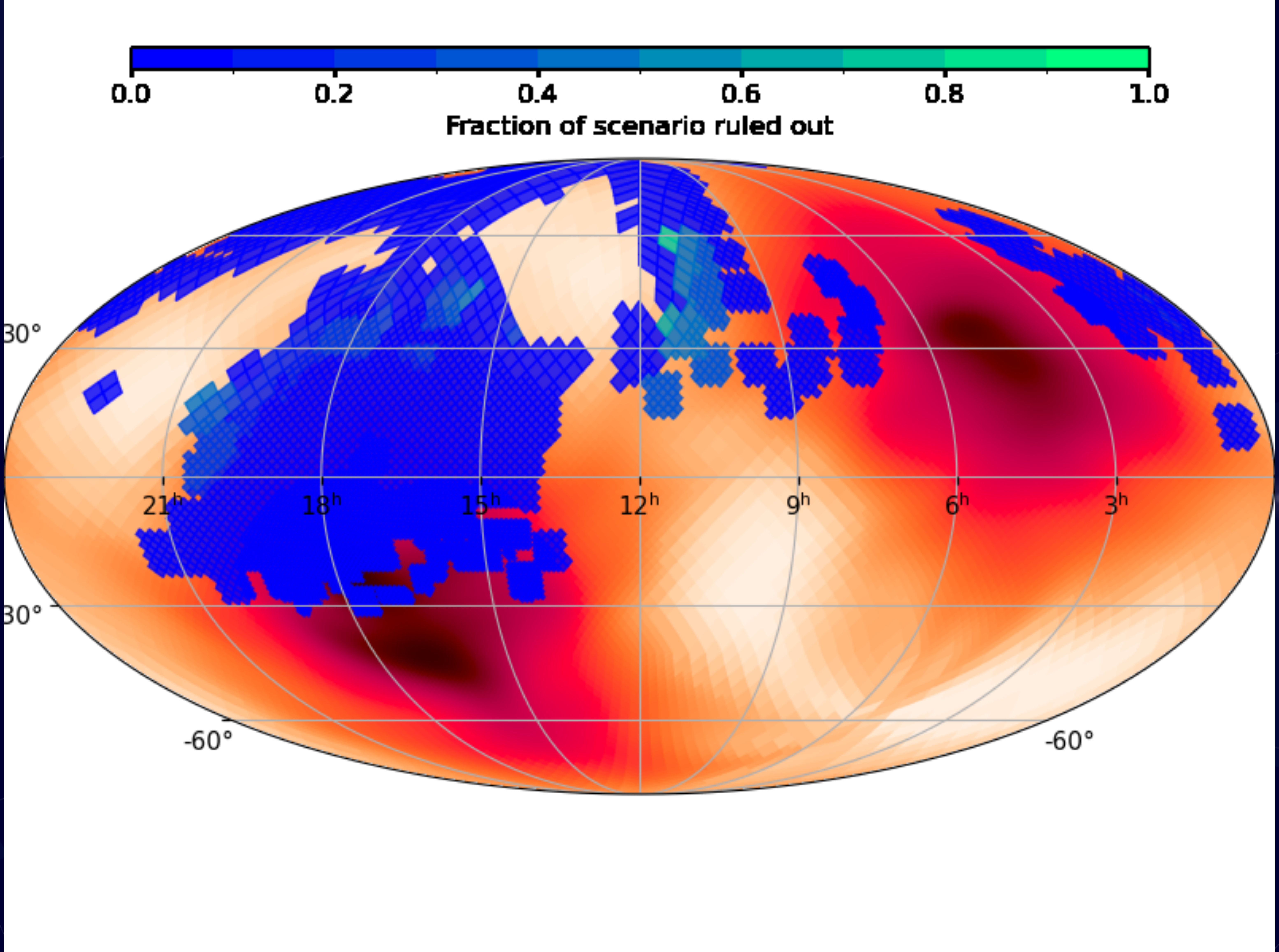


u-band
o-band
z-band
R-band
M=0.98 days
M=1.12 days
M=1.31 days
M=1.14 days
S230518h
GW230529
S230627c
S240422ed
Fraction of scenarios
T^{peak} [days]



C-band
c-band
L-band
G-band
M=1.18 days
M=1.12 days
M=1.06 days
S230518h
GW230529
S230627c
S240422ed
Fraction of scenarios
T^{peak} [days]


0.0
0.2
0.4
0.6
0.8
1.0
Fraction of scenario ruled out
30°
-30°
-60°
-60°
21h
18h
15h
12h
9h
6h
3h



0.0
0.2
0.4
0.6
0.8
1.0
Fraction of scenario ruled out
30°
-30°
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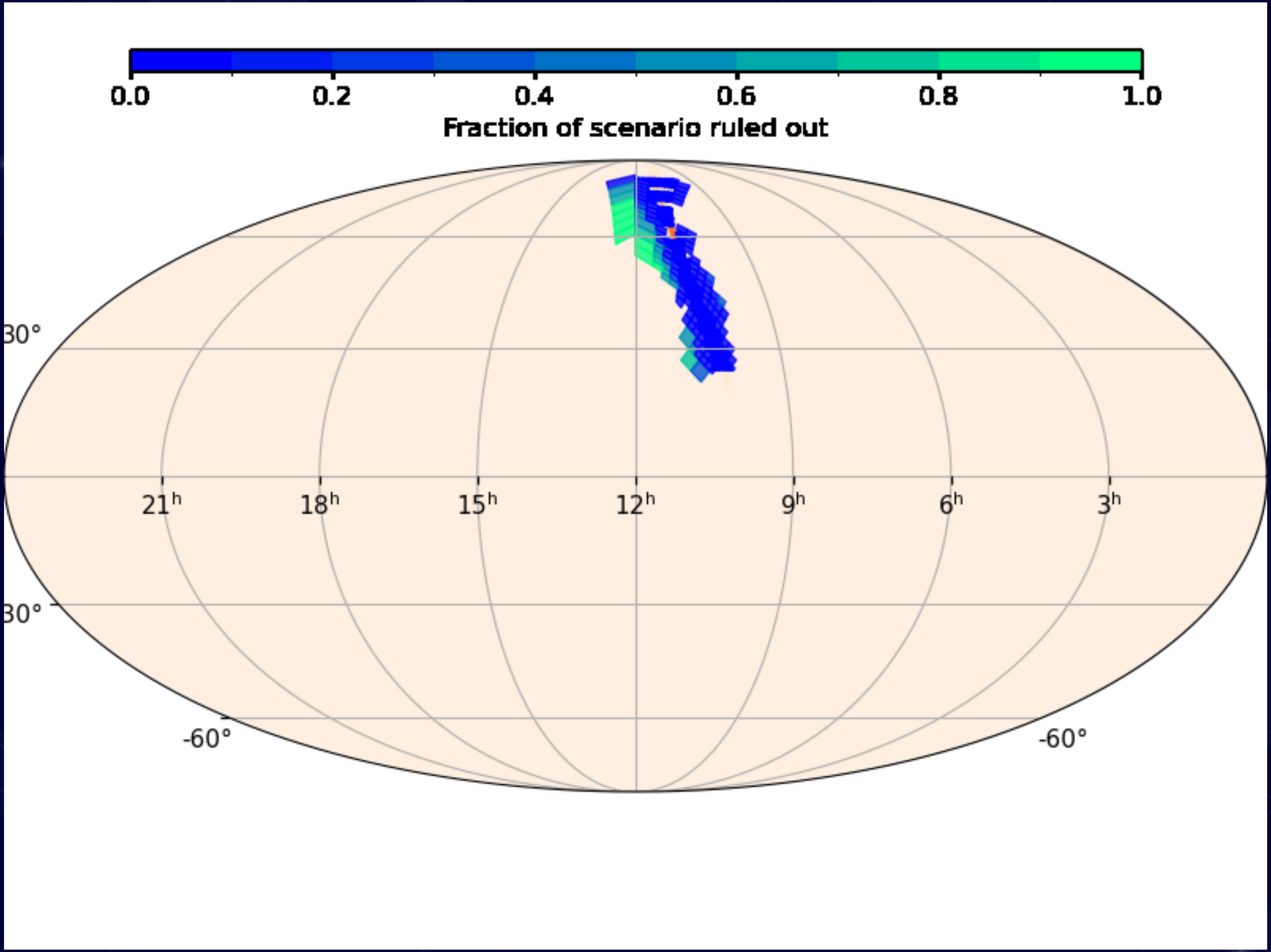
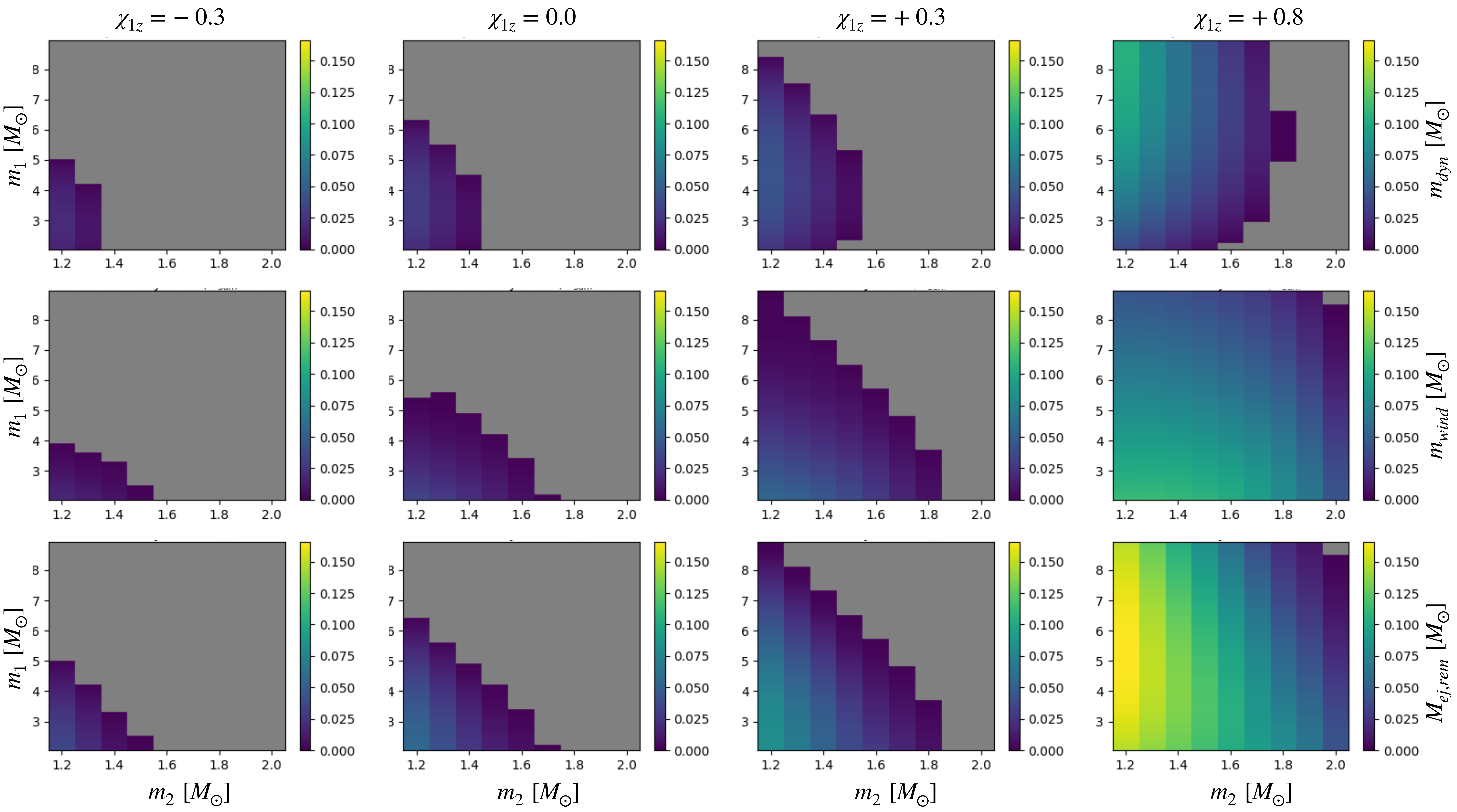
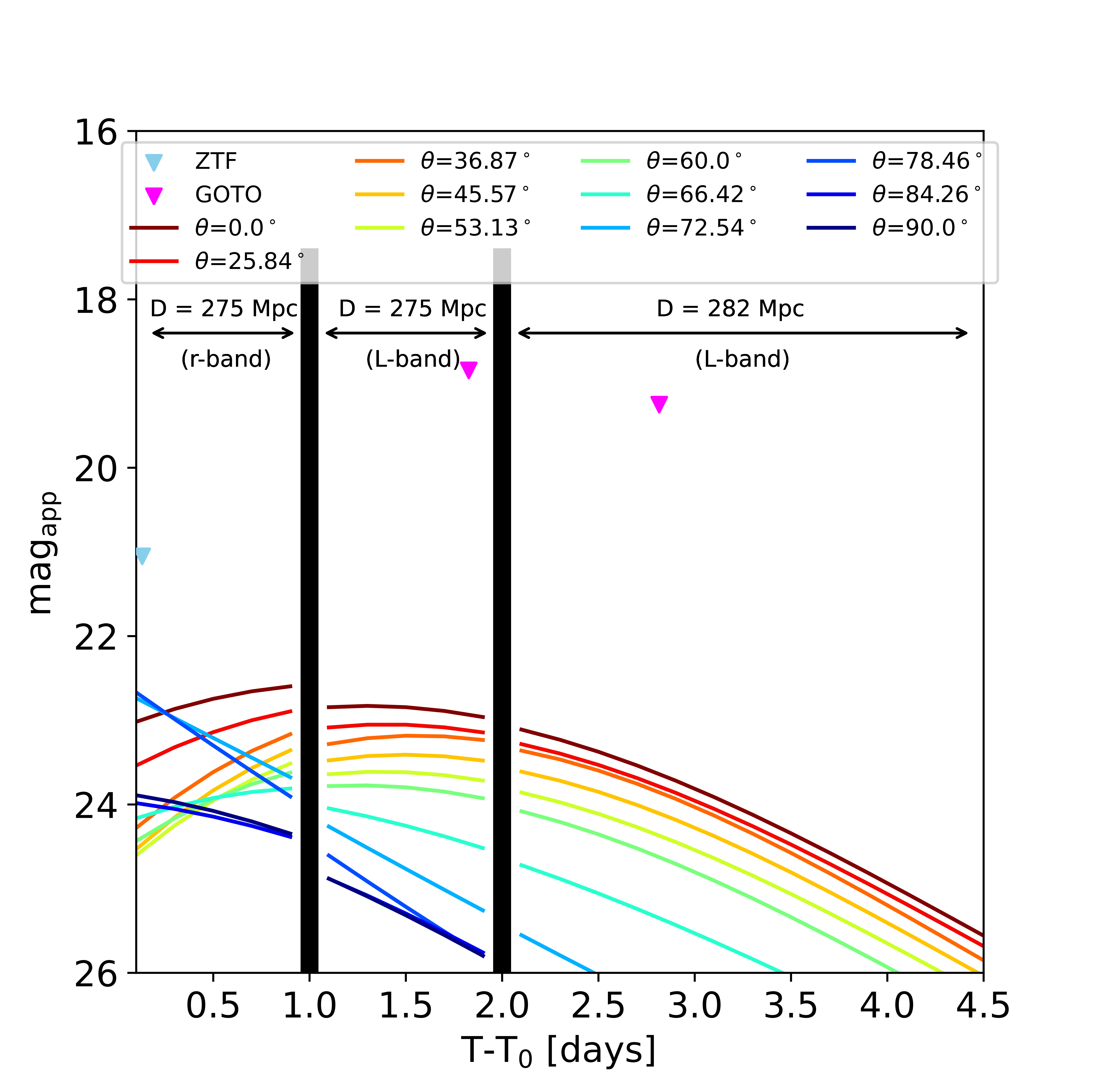
21h
18h
15h
12h
9h
6h
3h


0.0
0.2
0.4
0.6
0.8
1.0
Fraction of scenario ruled out
30°
21h
18h
15h
12h
9h
6h
3h
30°
-60°
-60°

b) $H4$ equation of state





ZTF
GOTO
θ=0.0°
θ=25.84°
θ=36.87°
θ=45.57°
θ=53.13°
θ=60.0°
θ=66.42°
θ=72.54°
θ=78.46°
θ=84.26°
θ=90.0°
D = 275 Mpc
(r-band)
D = 275 Mpc
(L-band)
D = 282 Mpc
(L-band)
mag_app
T-T_0 [days]
16
18
20
22
24
26
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5