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

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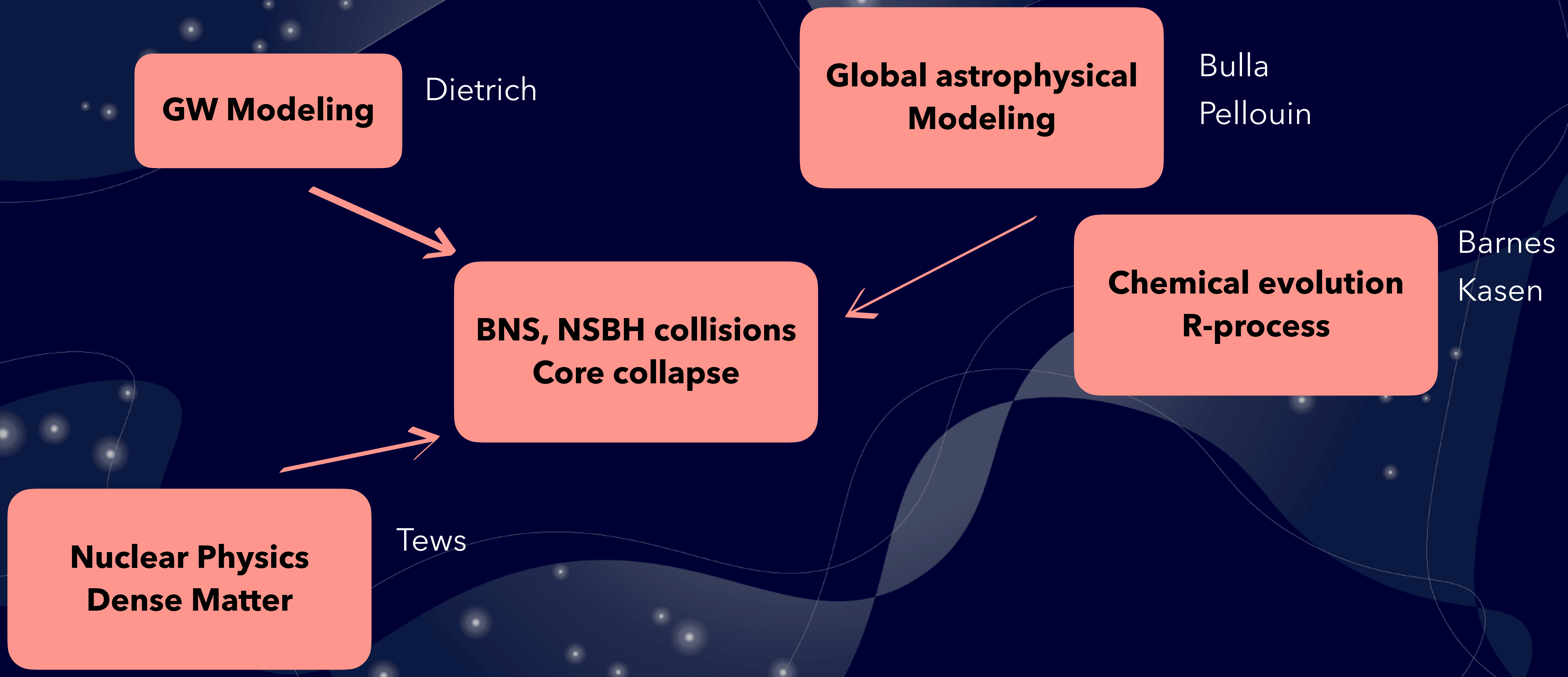
LIÈGE université

GRANDMA

Introduction



Introduction

GW Modeling

Dietrich

Global astrophysical Modeling

Bulla
Pellouin

Chemical evolution
R-process

Barnes
Kasen

BNS, NSBH collisions
Core collapse

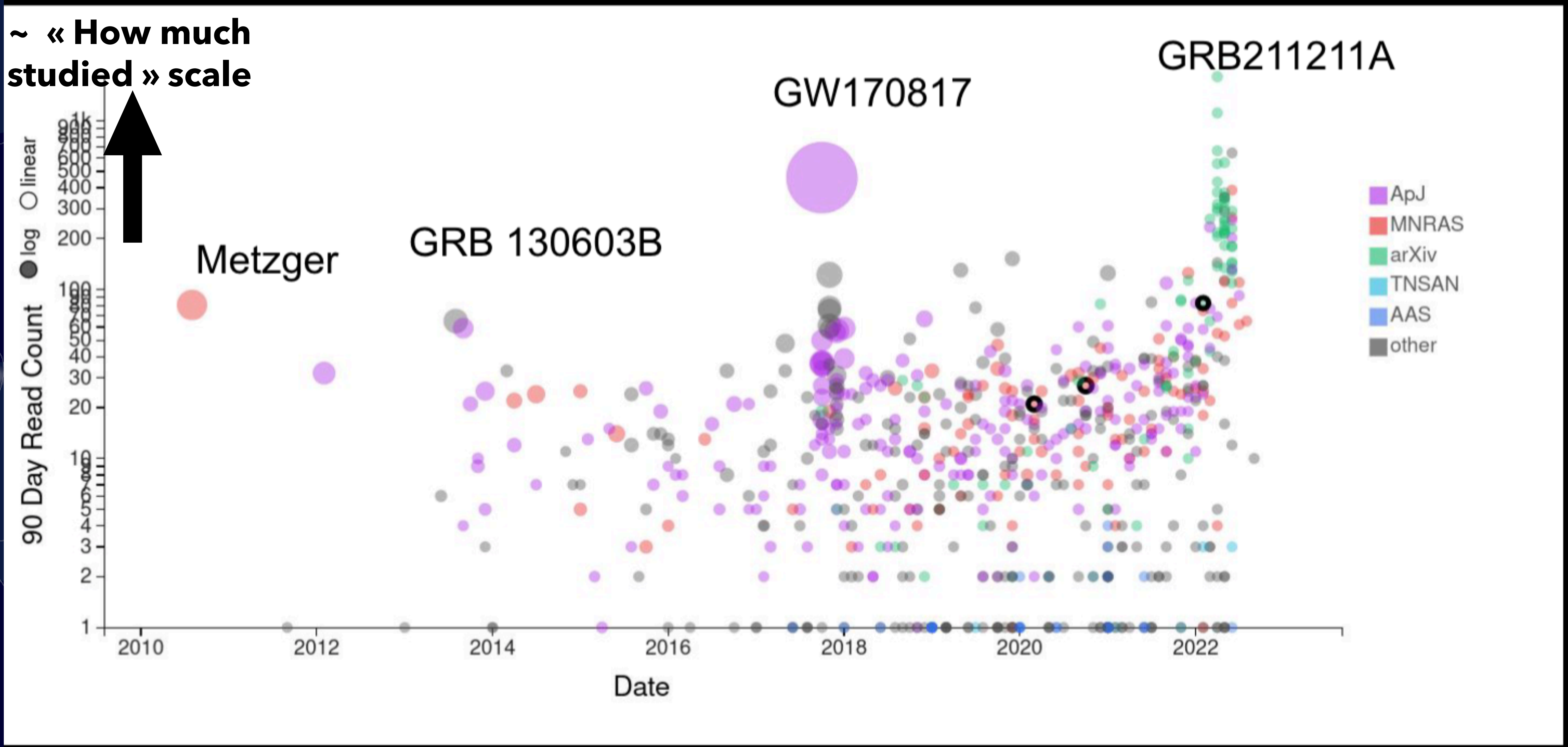
Nuclear Physics
Dense Matter

Tews

DATA

HERE I AM (AND SO IS MY TALK)

Introduction



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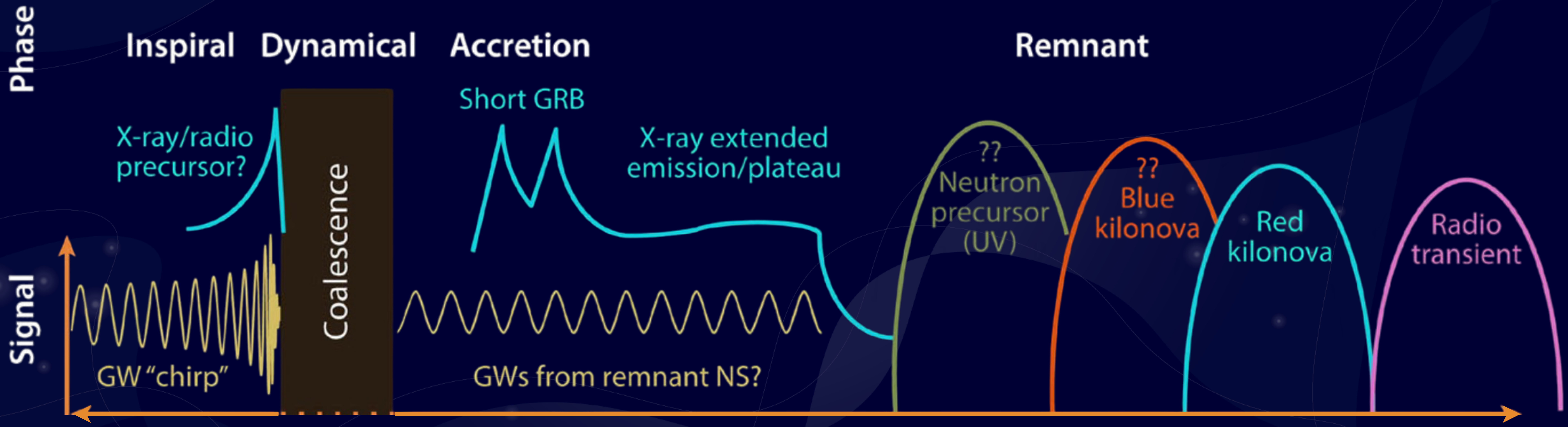
Introduction

Compact binary coalescence system with neutron stars (NS)

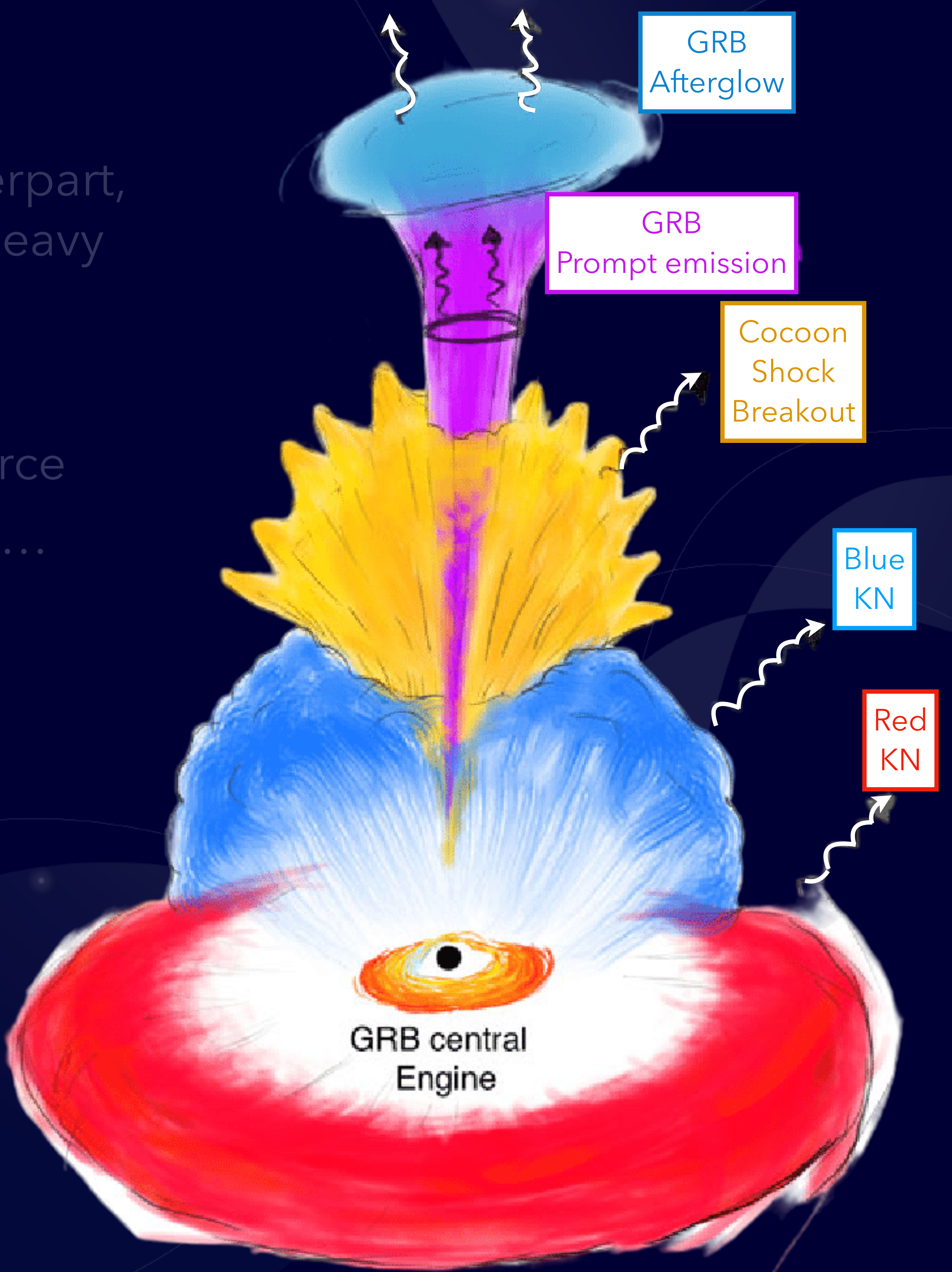


(Fernandez and Metzger, 2016)

Introduction

- **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** …

(Ascenzi et al, 2021)



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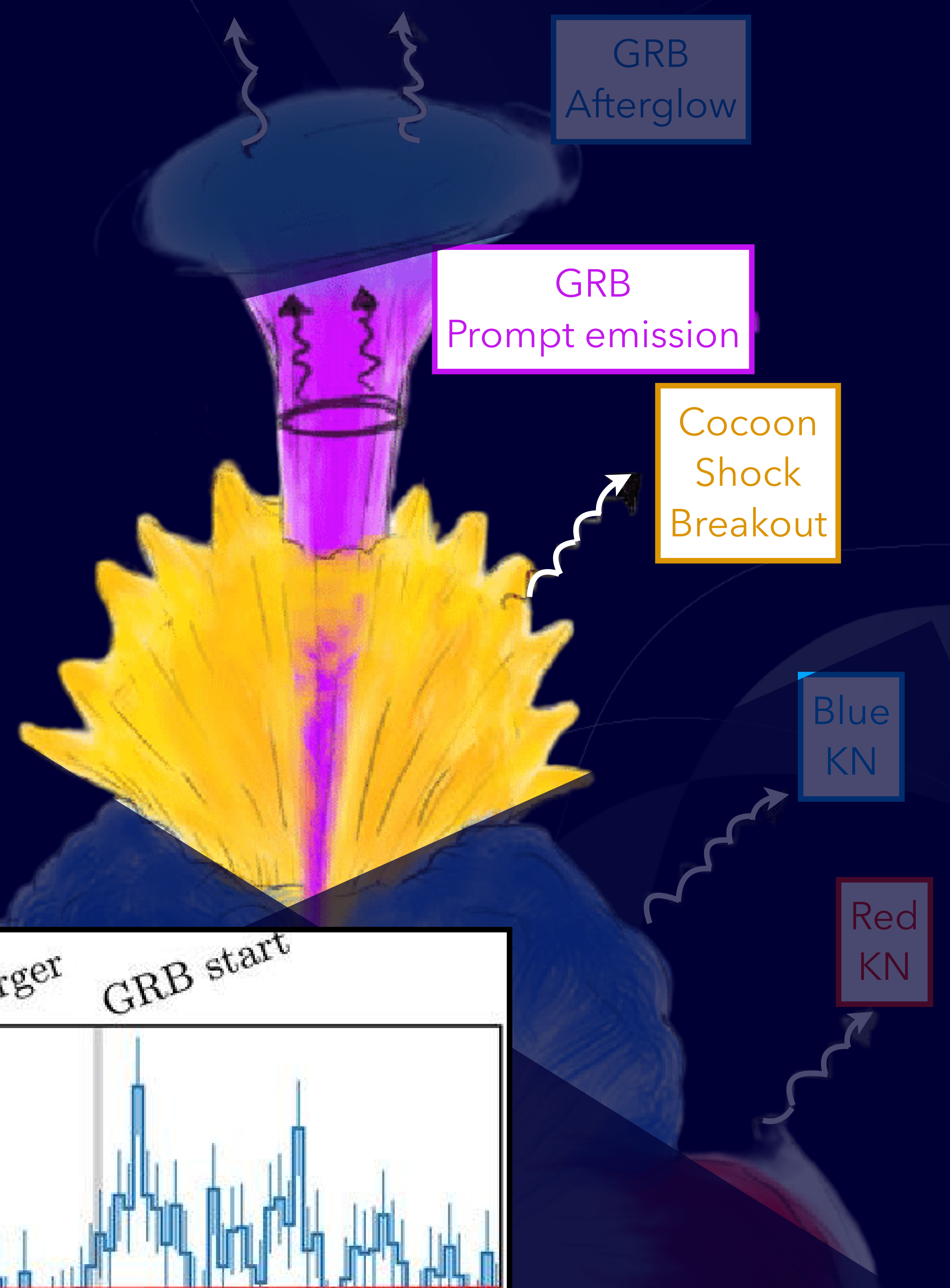

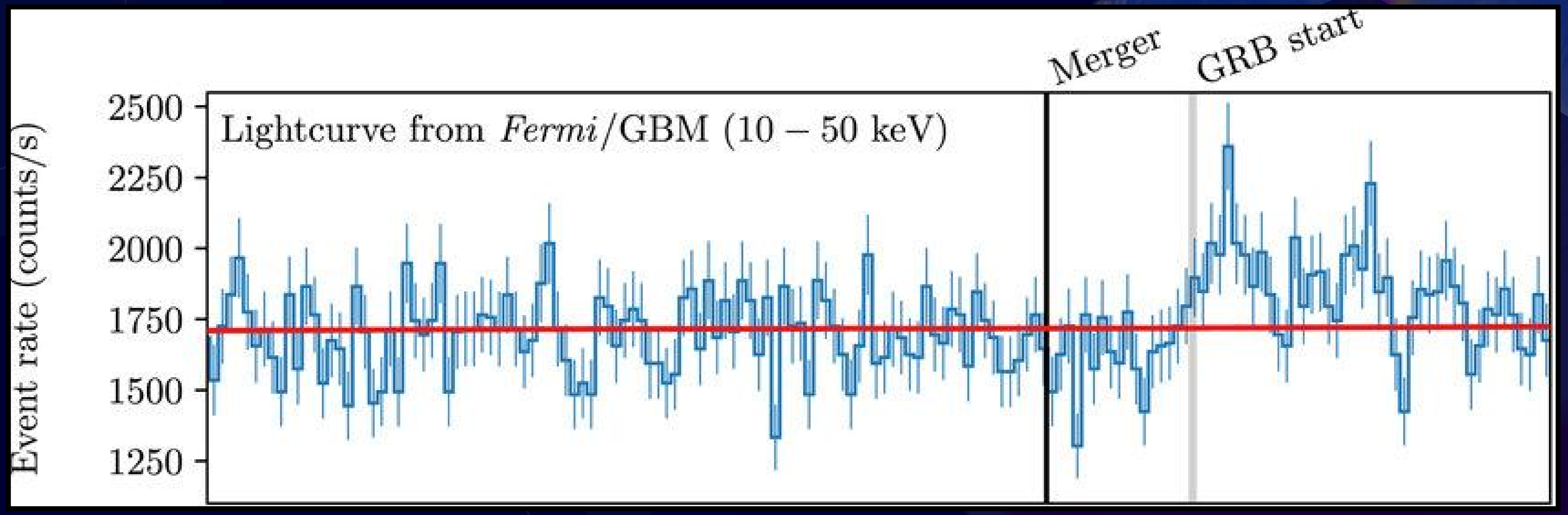

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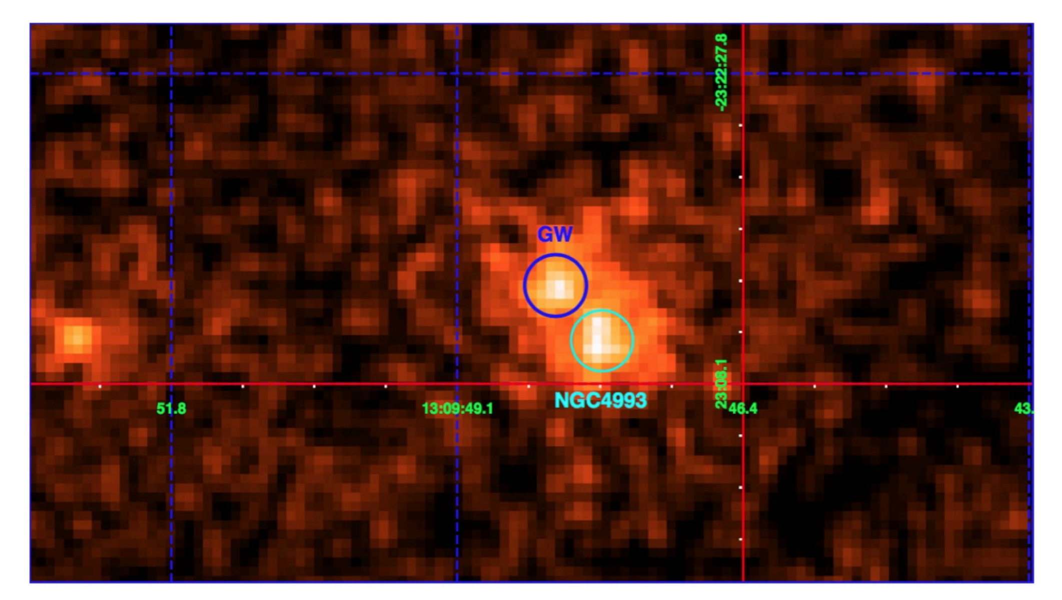

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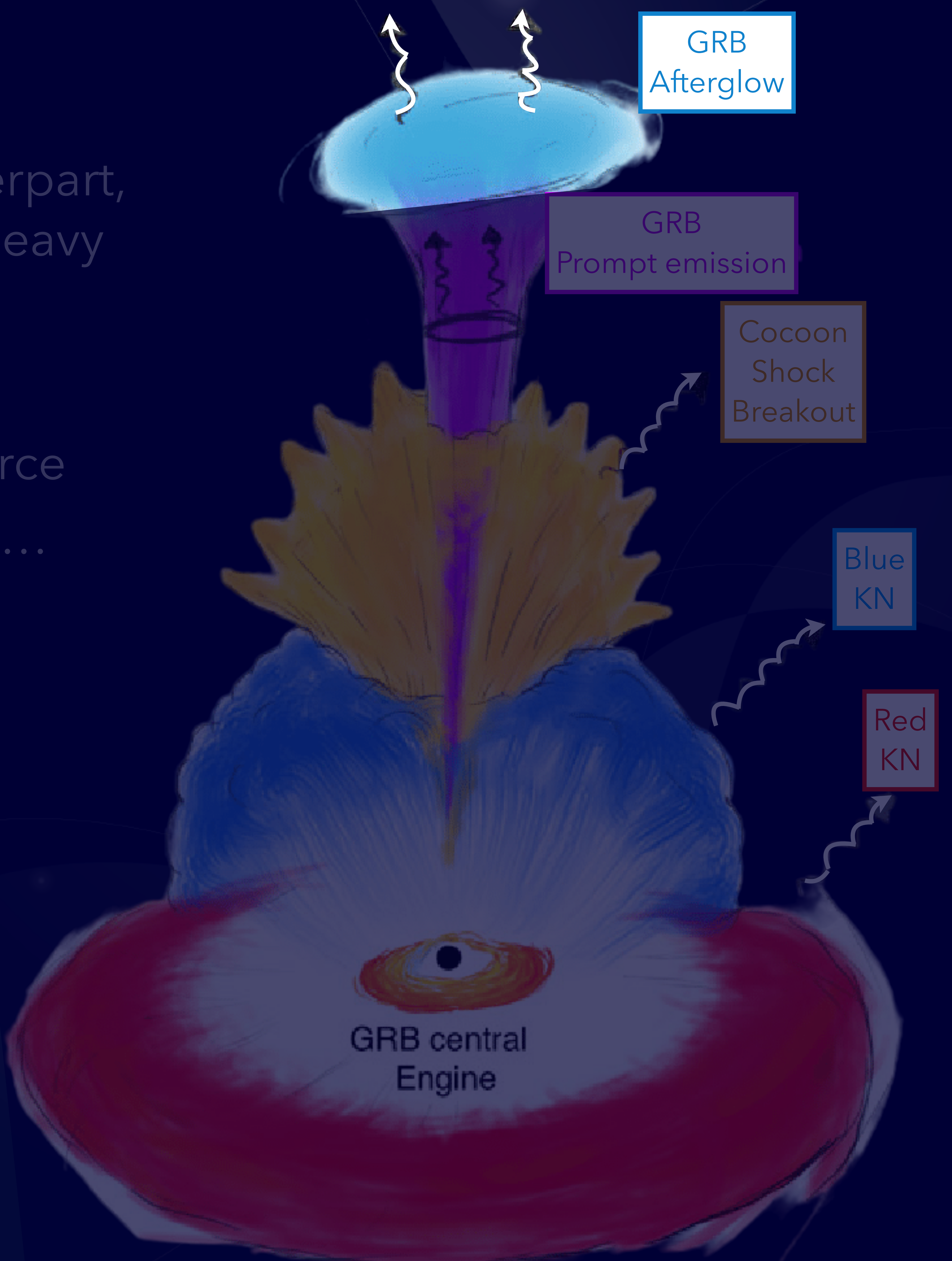

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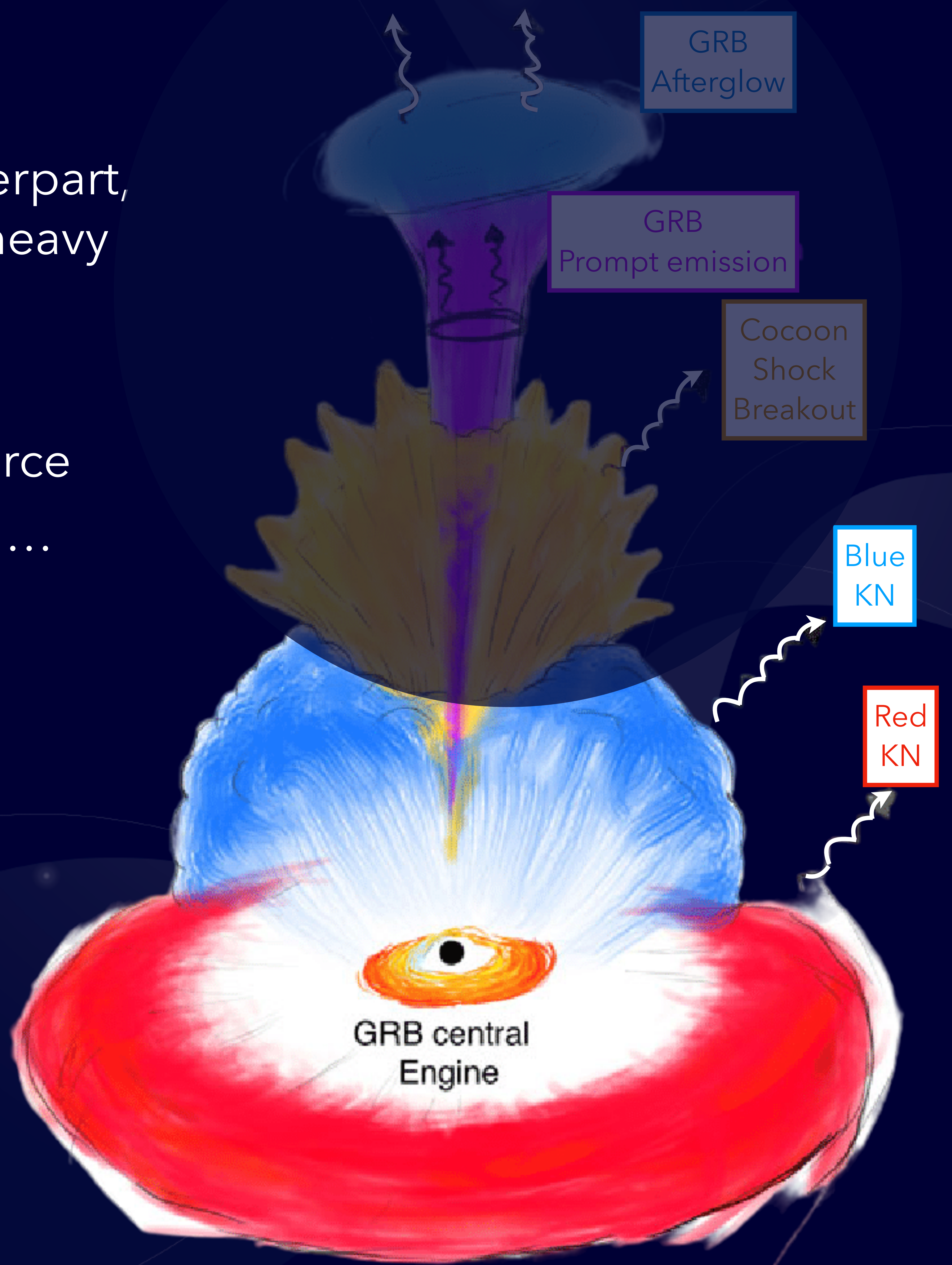
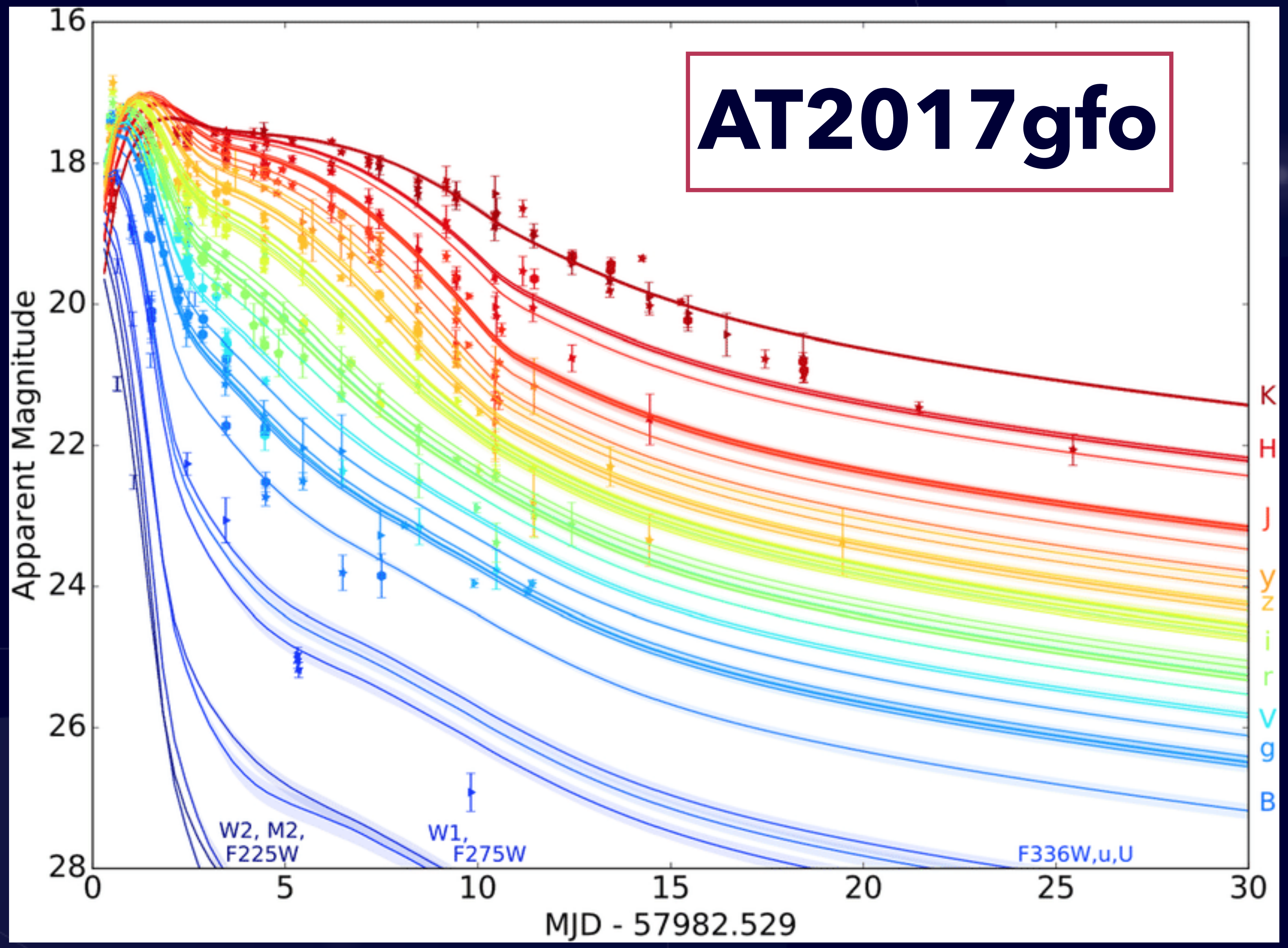
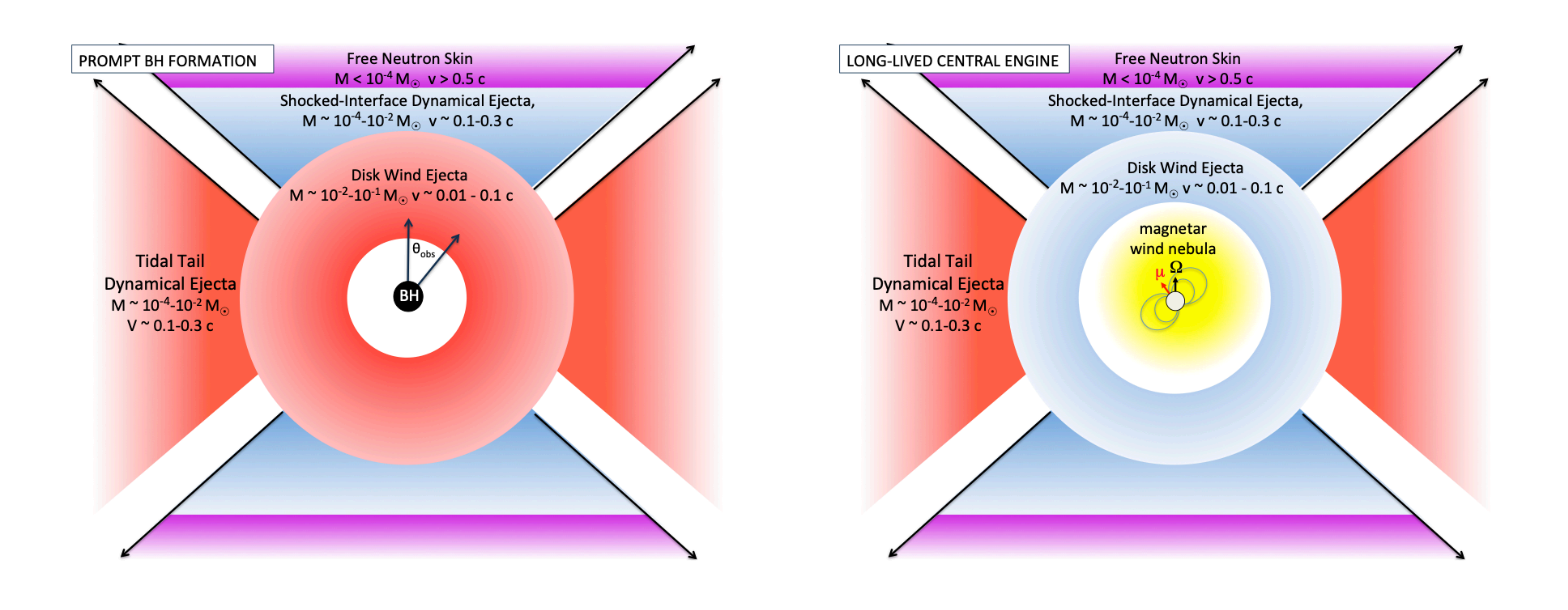




Modeling Kilonova from Binary Neutron Star merger



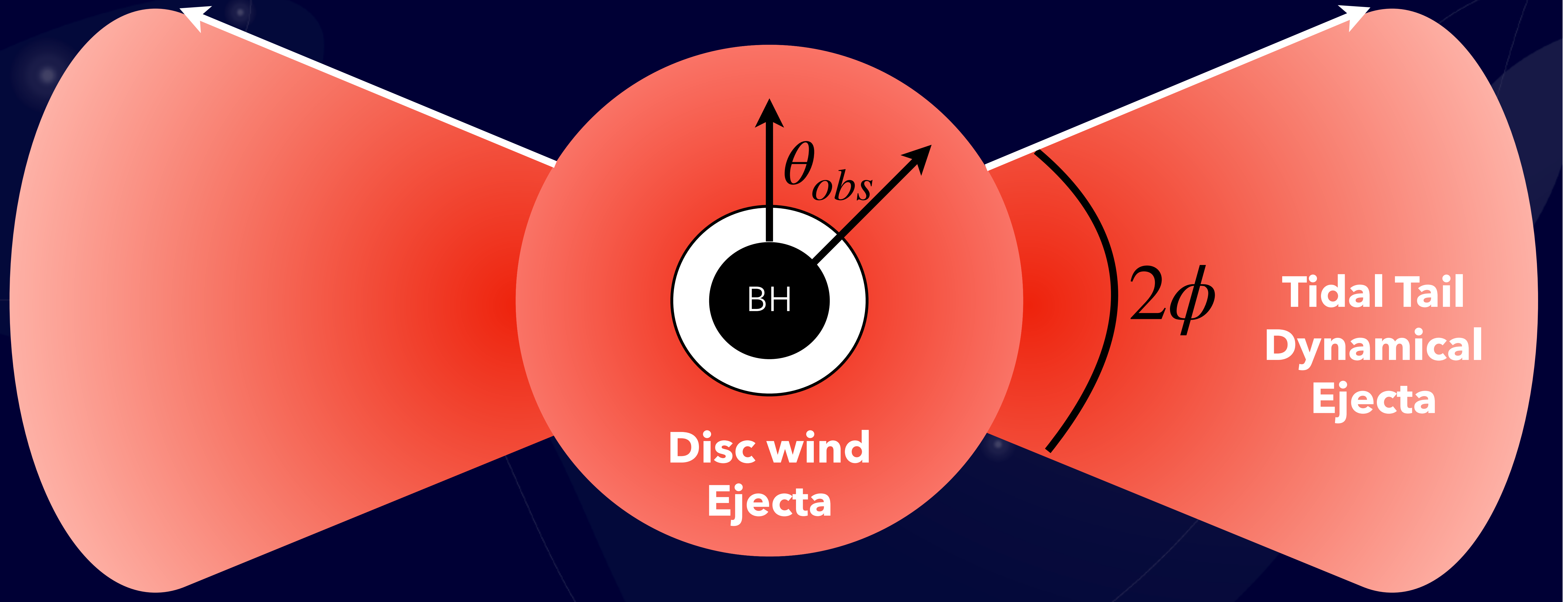
(Metzger, 2019)

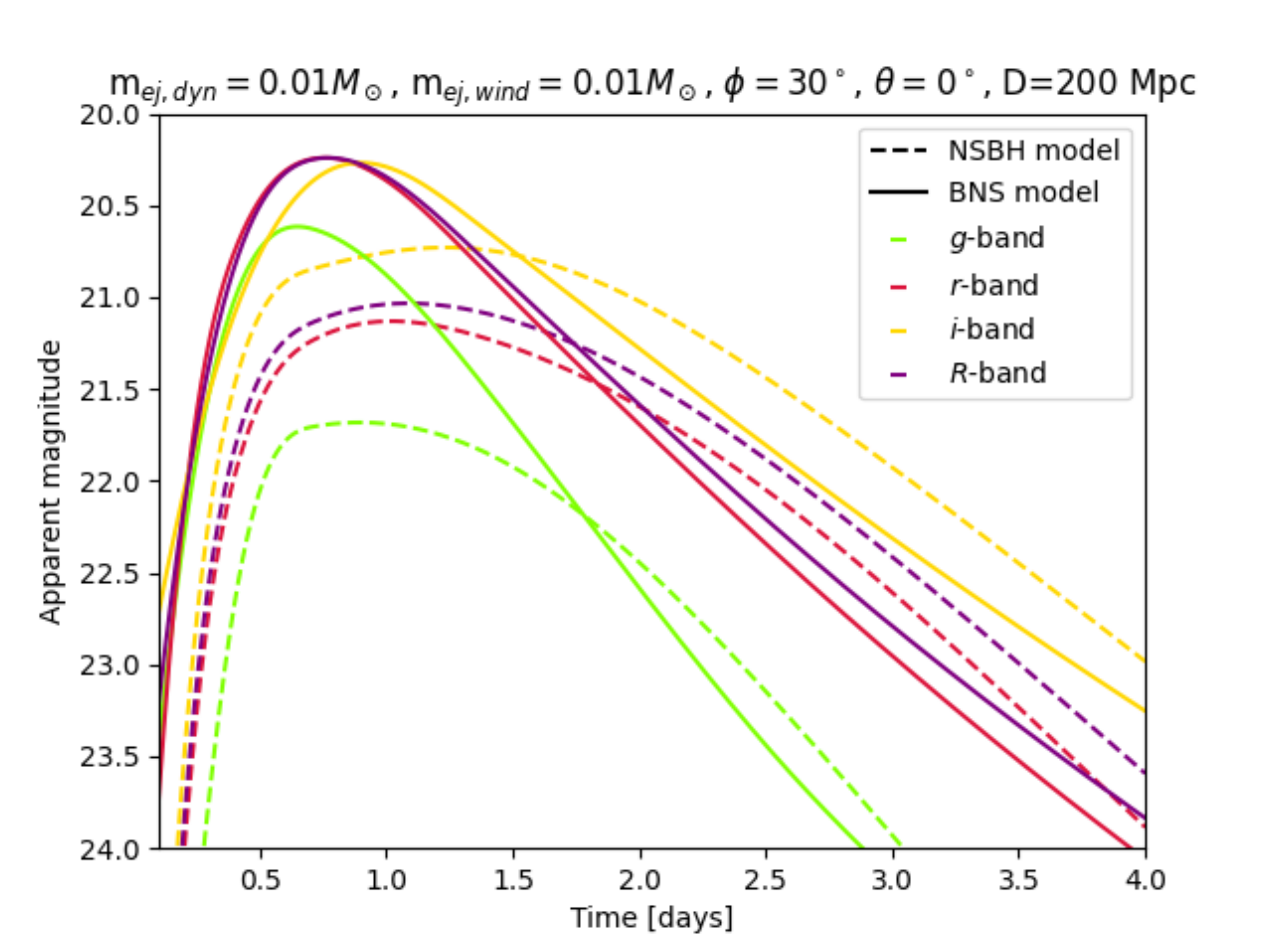
Modeling Kilonova from Neutron Star - Black Hole Merger

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

- Mass ratio (m2/m1)
- Black hole spin
- NS Equation of State
- …

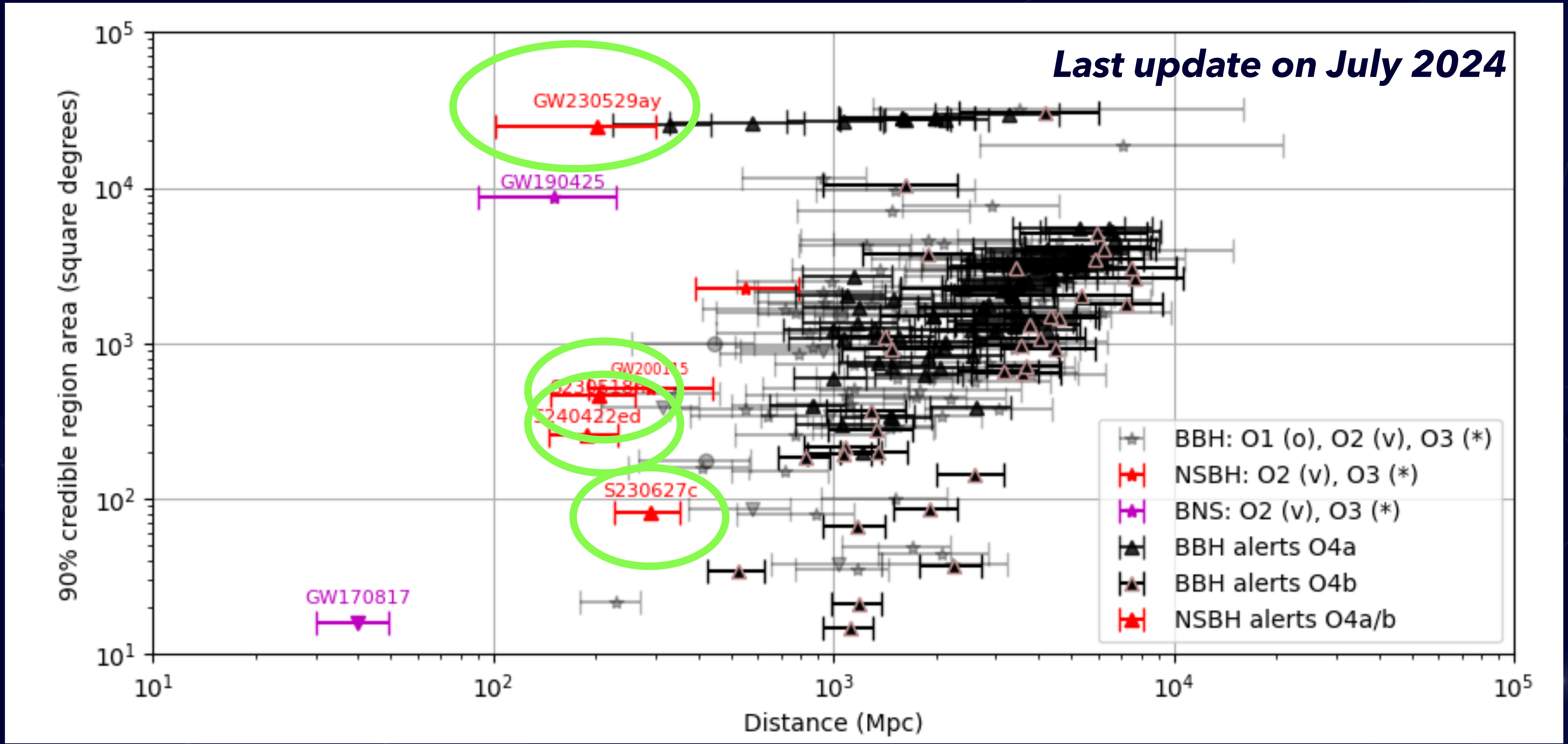
(Villar et al, 2017)





O4 campaign

- The Fourth GW Observing run (O4) has started in May 2023
  - > 100 gravitational-wave candidates
  - 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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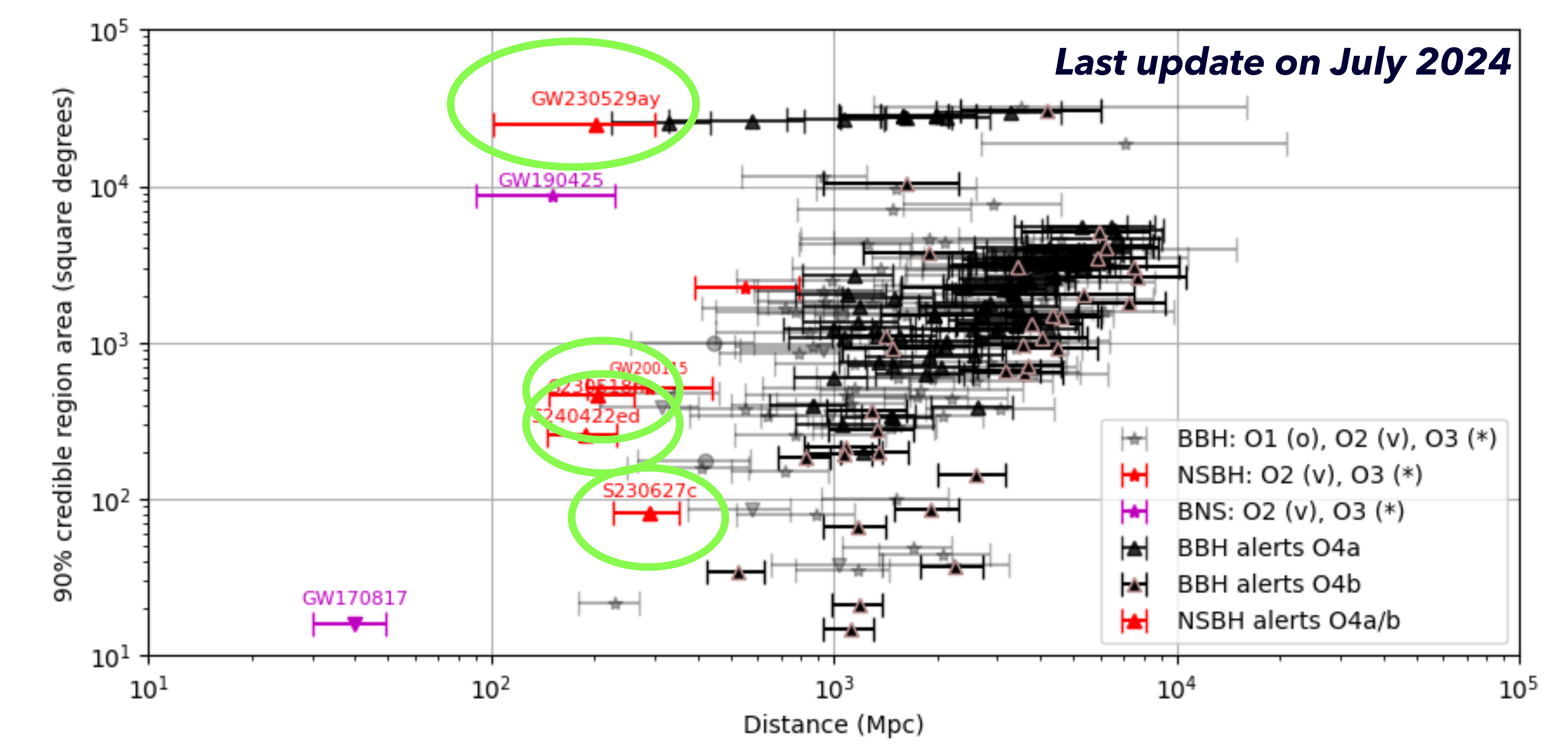
Even a non-detection can help constrain source properties (ejecta, viewing angle)



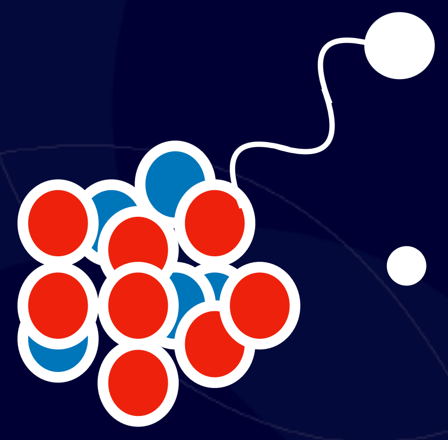
Choice of KN model

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

(Bulla, 2019 & Bulla, 2023)

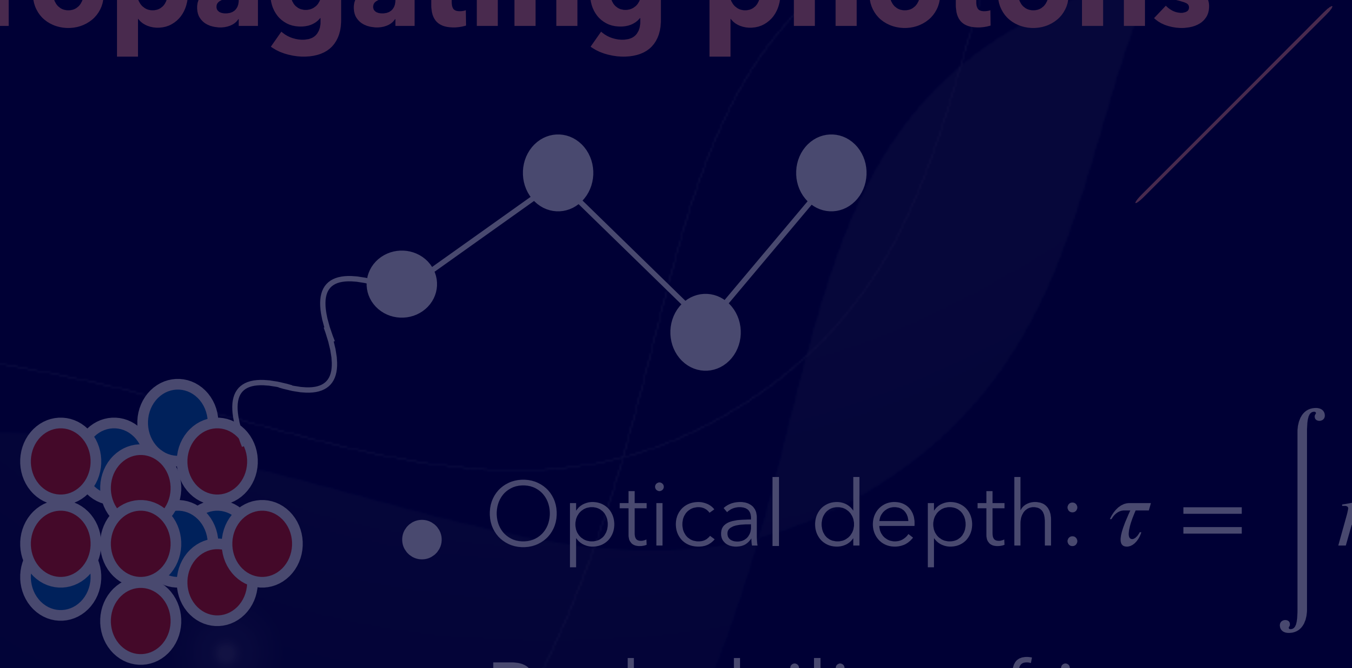
- 3D Monte Carlo code for modelling radiation transport in KN
- Does not solve the radiative transfer equation analytically but rather numerically with Monte Carlo photons representing radiation and propagating through the expanding ejecta→ **speed up the computation**
  - **Key ingredients:** input **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 …

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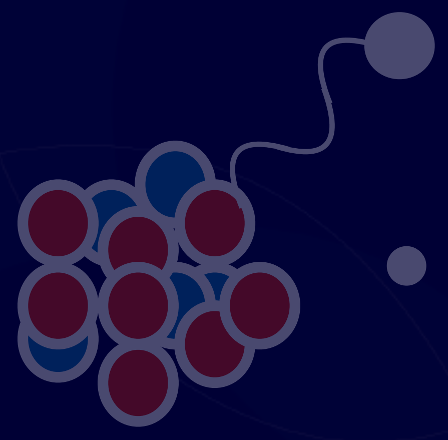

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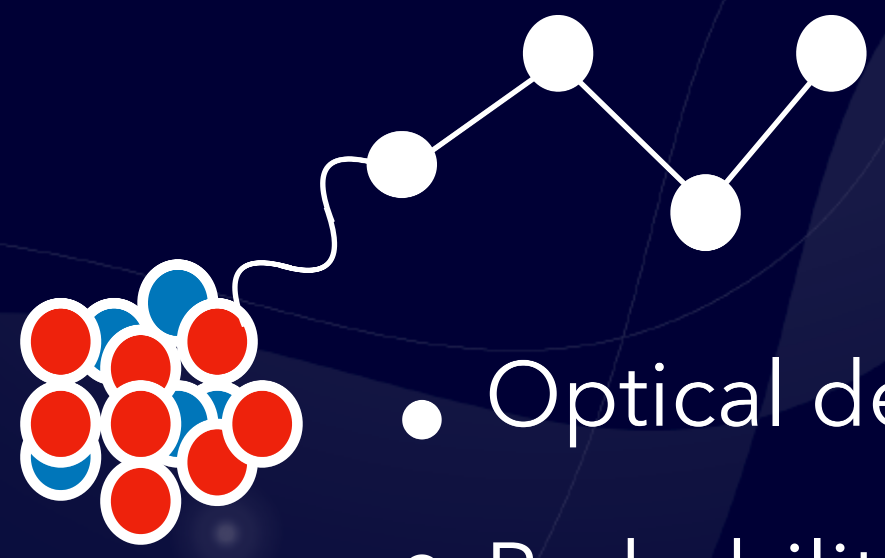

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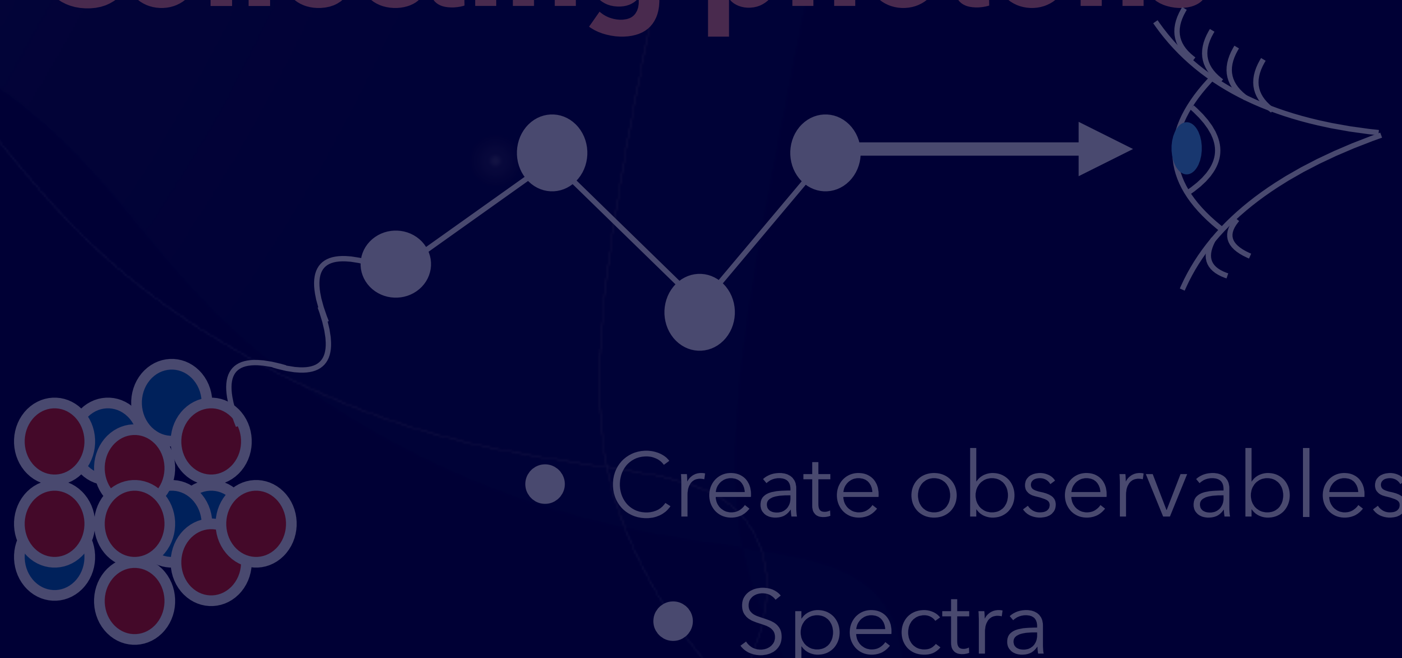

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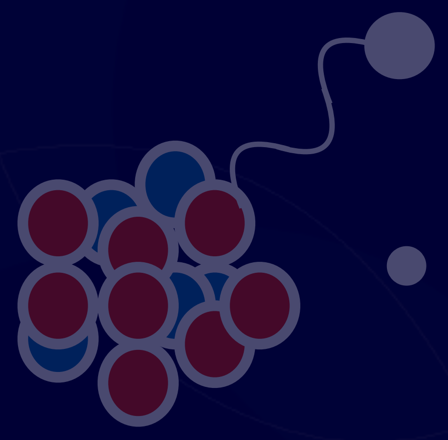

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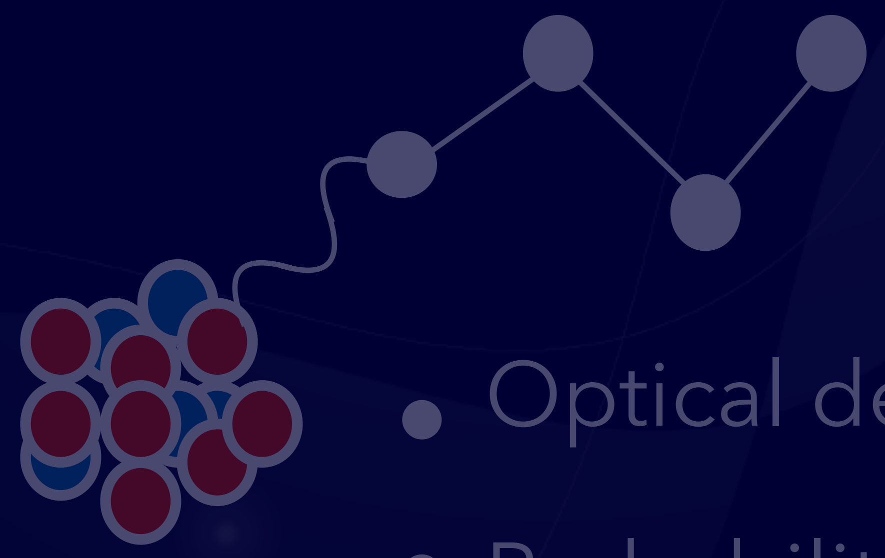

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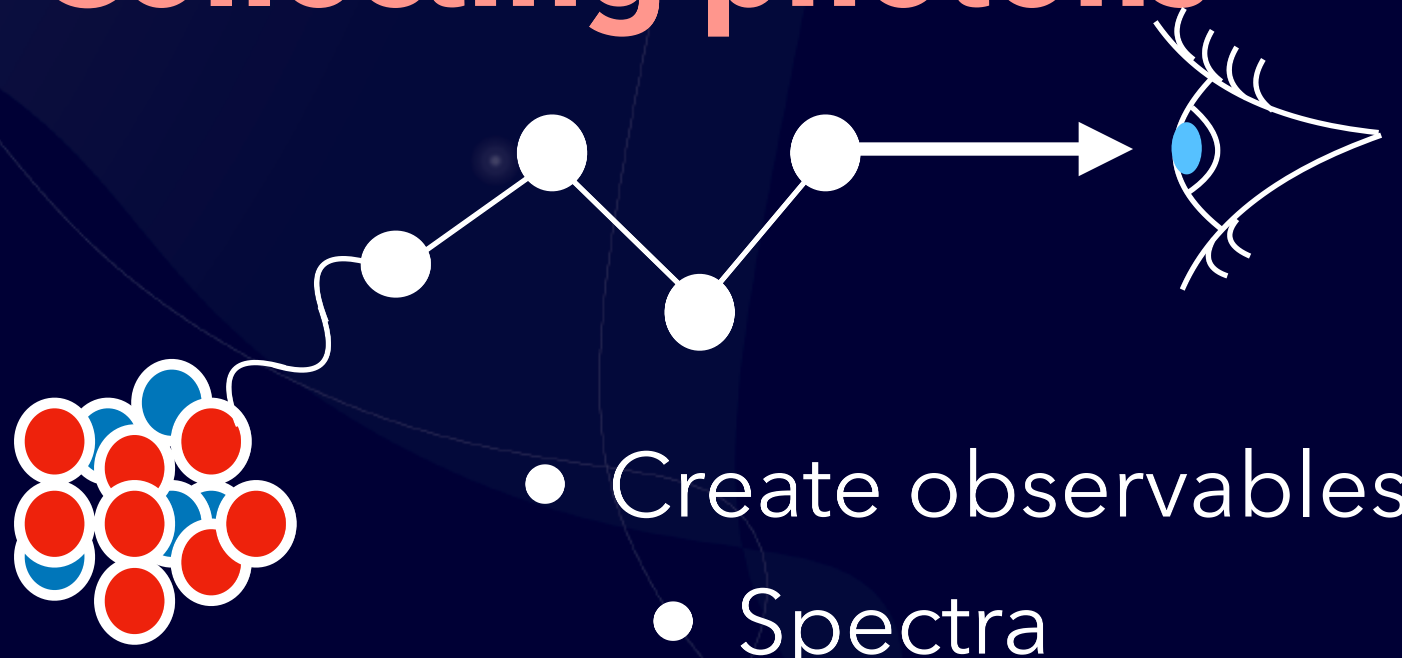


- Create observables:
  - Spectra
  - Light curves …

Choice of KN model

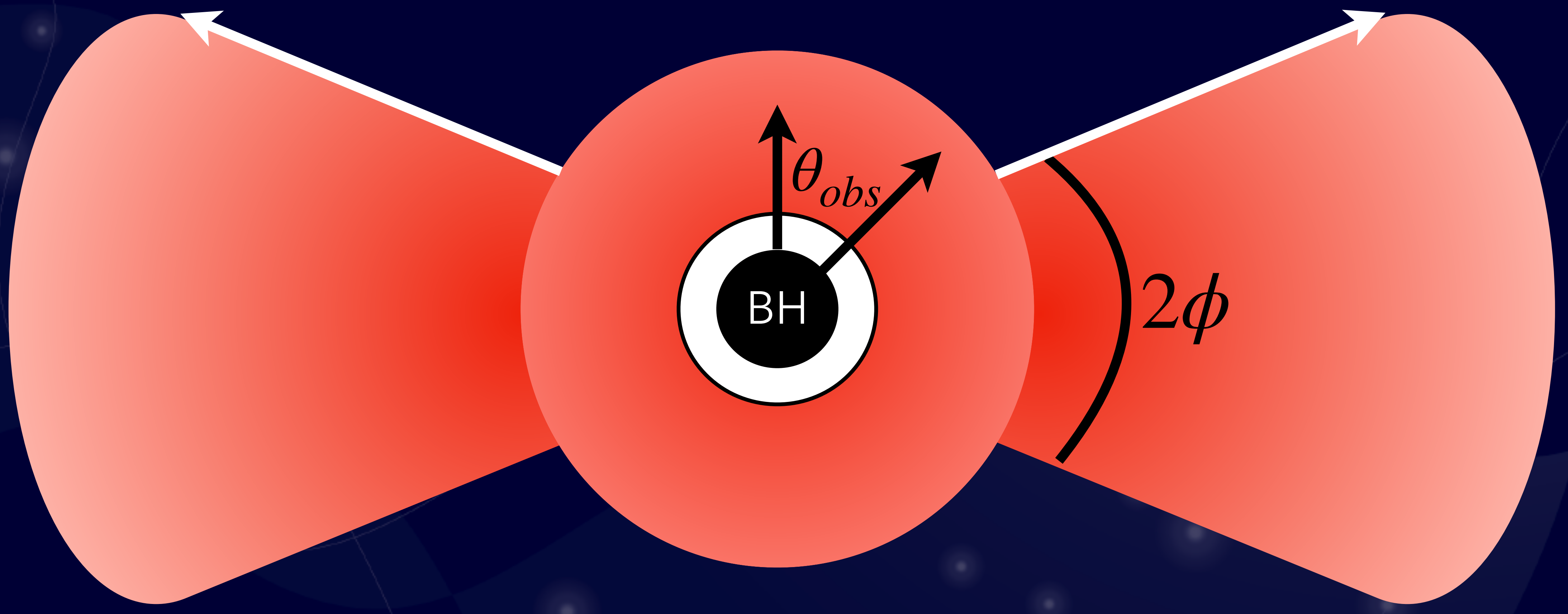
- m_{dyn}
- m_{wind}
- viewing angle θ
- half-opening angle ϕ

Included in this work

- 891 light curves
- 21 different filters

Set to 30 degrees

Ejecta from the NS disruption (M_{dyn})	
Mass Range	$0.01 - 1.0 M_\odot$
Ejecta from the accretion disk ($M_{disk,wind}$)	
Mass Range	$0.01 - 1.0 M_\odot$
Outflow	5% – 40% not accreted
Kilonova Light Curves	
Ejecta	• NSBH models computed with POSSIS Anand et al. (2021); Bulla (2019) with $m_{ej,dyn}, m_{ej,wind} \in [0.01, 0.09]\ M_\odot$ and $\theta \in [0, 90]$ degrees)



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

KN associated with O4 NSBH candidates

Goal:

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*:

**Acronyms:*

18h: S230518h, 29: GW230529, 27c: S230627c and 22ed: S240422ed

Observation strategy

Goal:

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:

- To ensure a KN detection, at least one observation should be done at the **time of brightness peak**
- Peak time depends on KN properties
- Compare time of optical observations with the predicted peak time from simulated KN light curves for numerous filters

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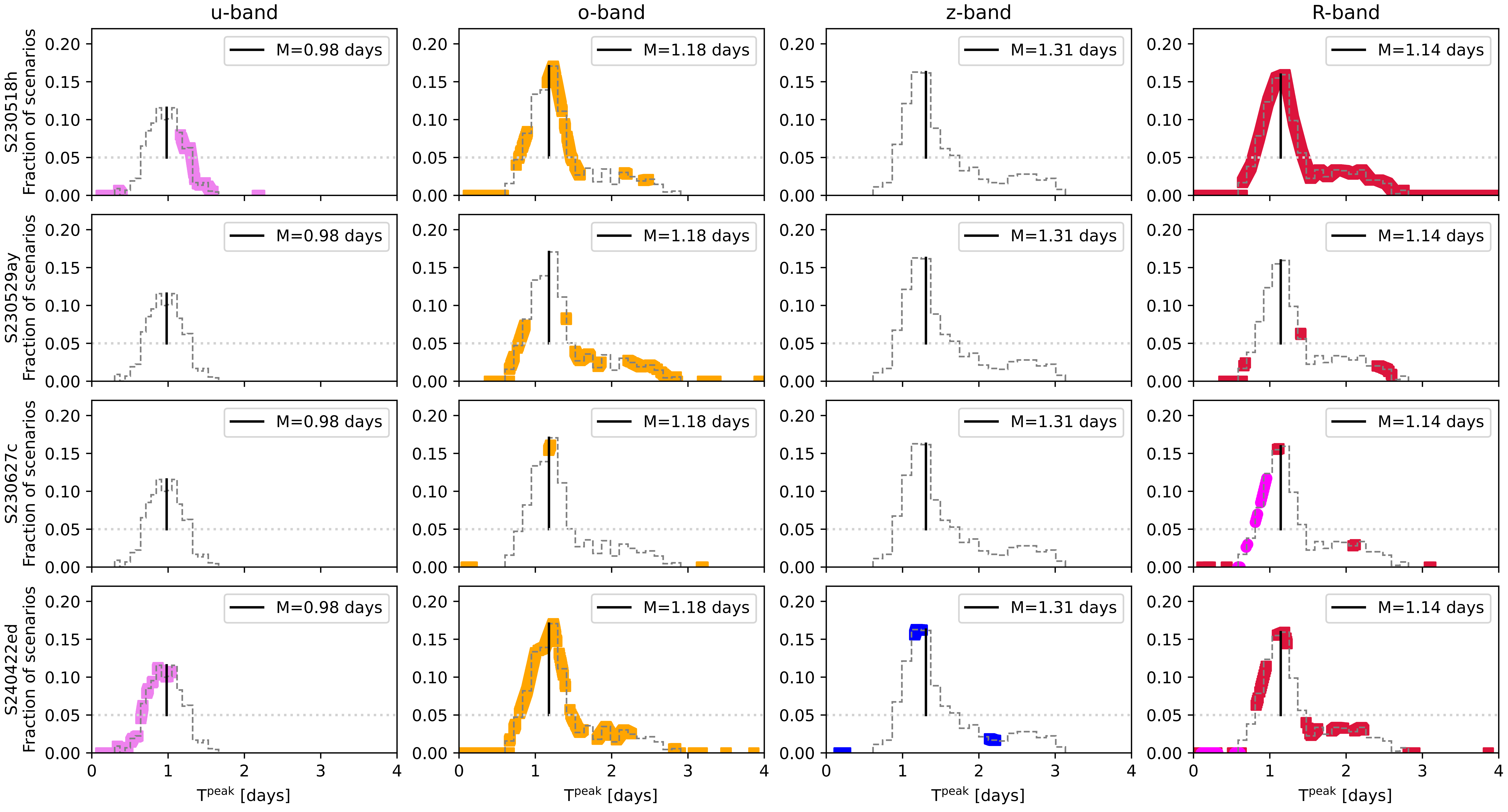
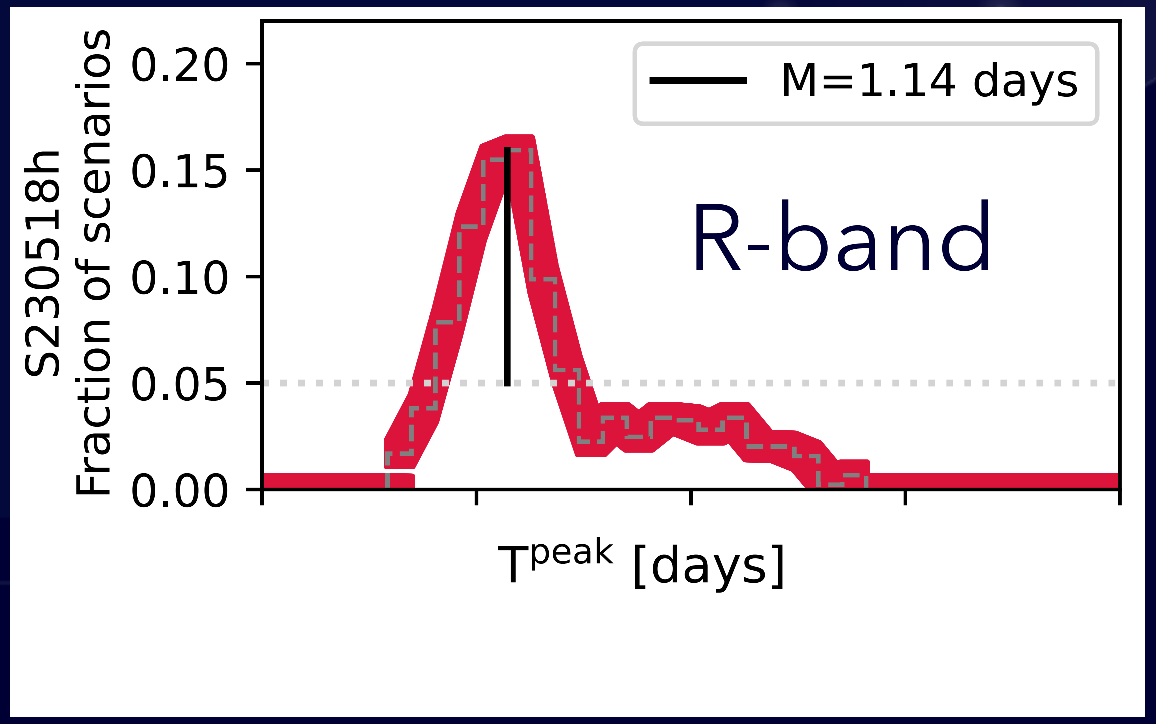
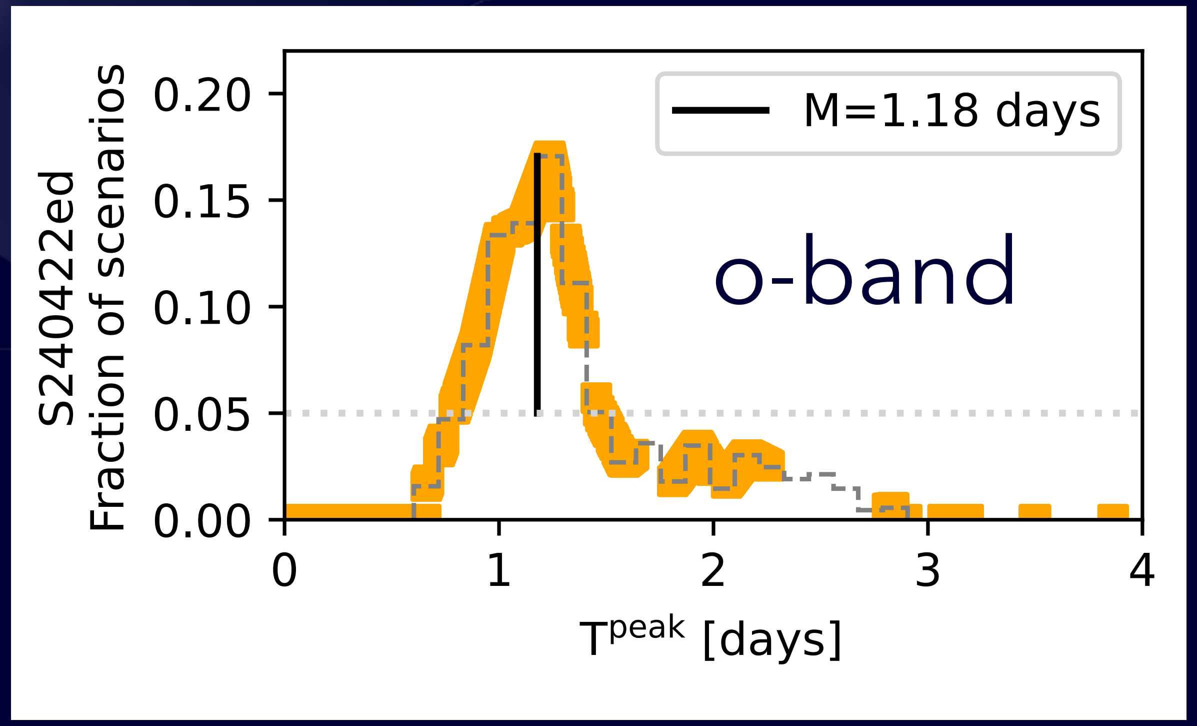


GRANDMA followup

Observation strategy

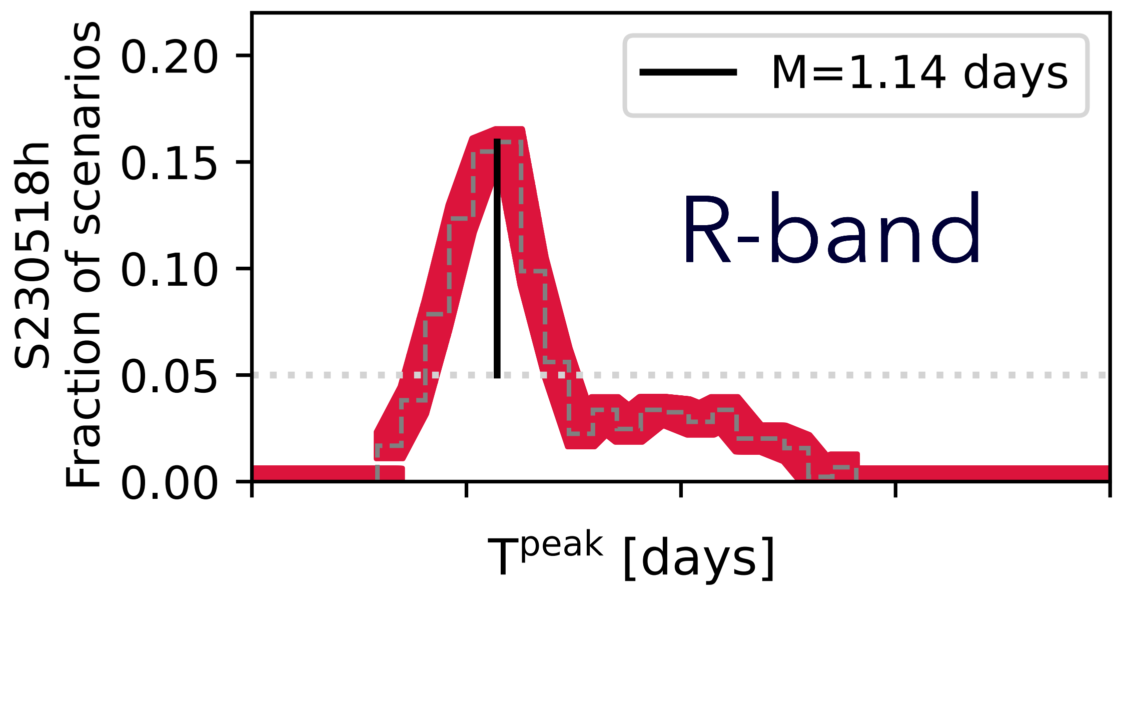


S230518h: Observations in R-band covered the KN peak time of ~100% of the population.



S240422ed: Observations consistent with the peak time of 90% of KN population in o-band.

Observation strategy



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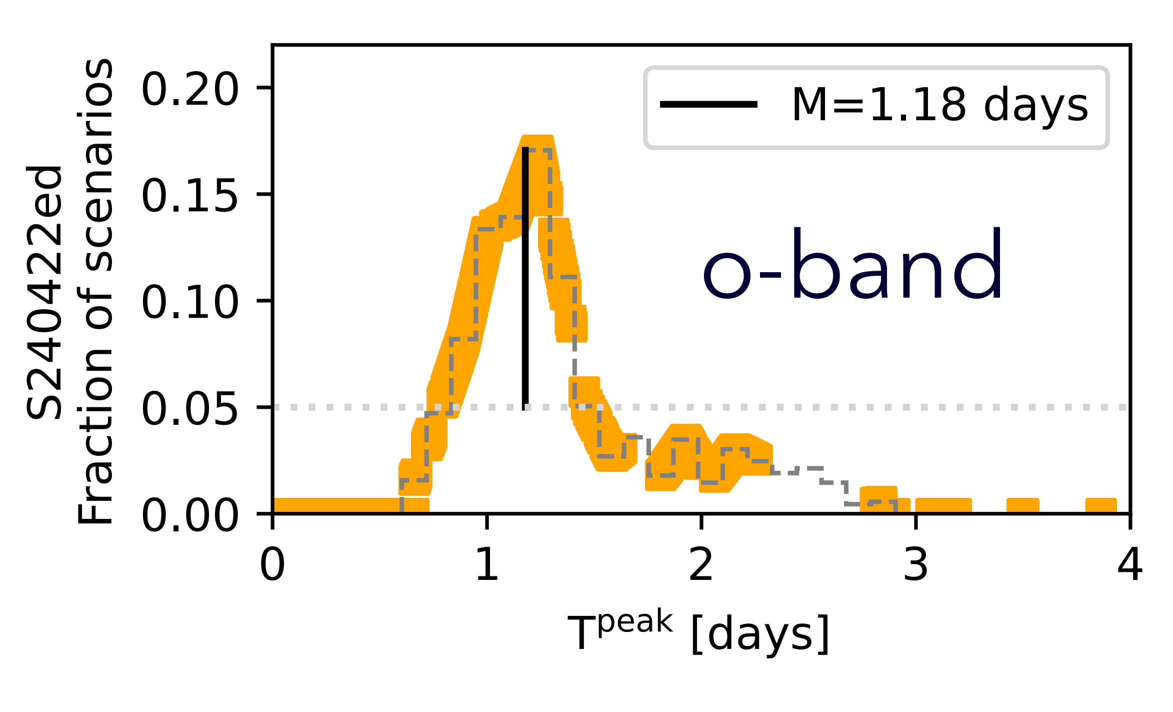

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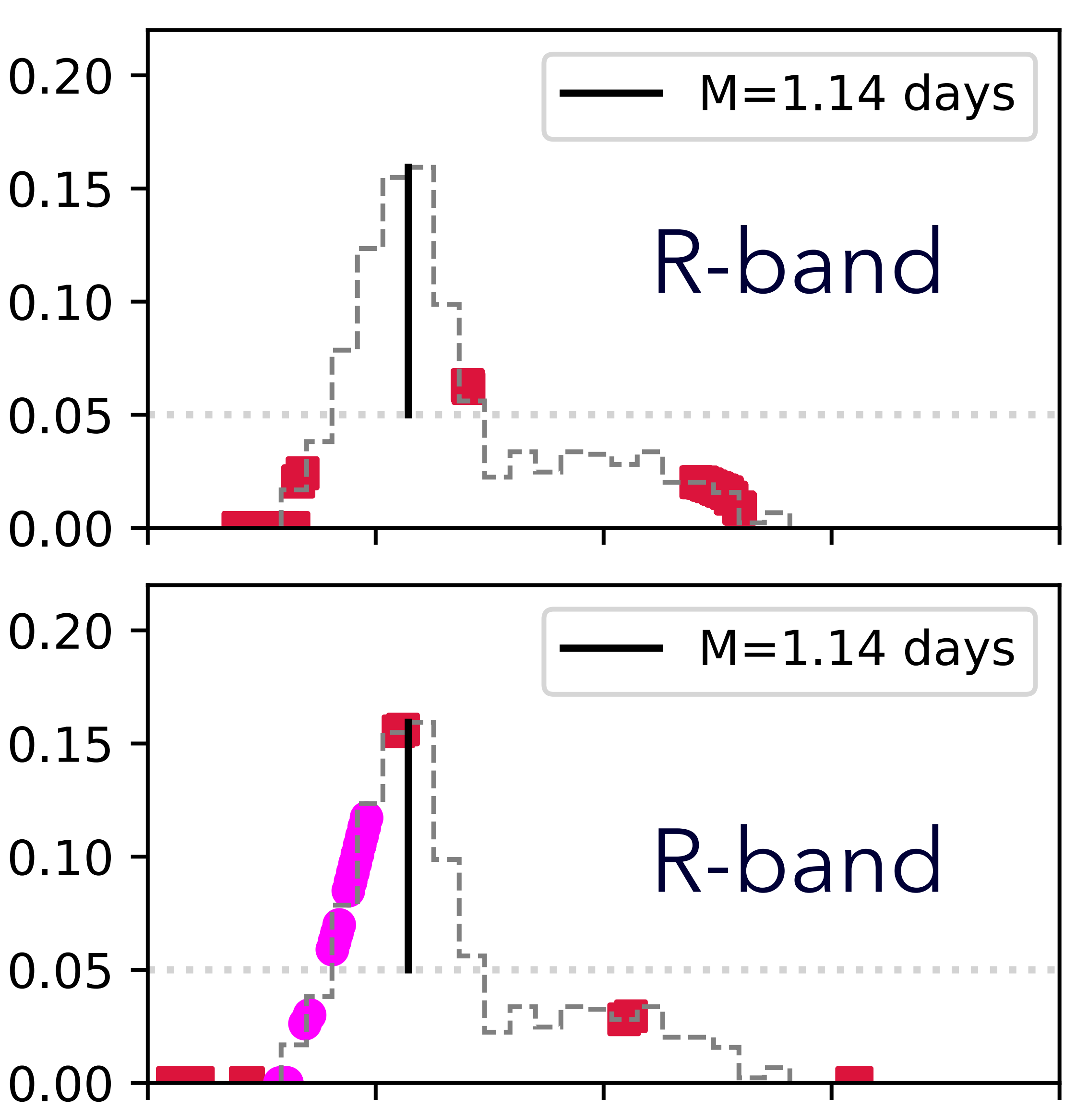
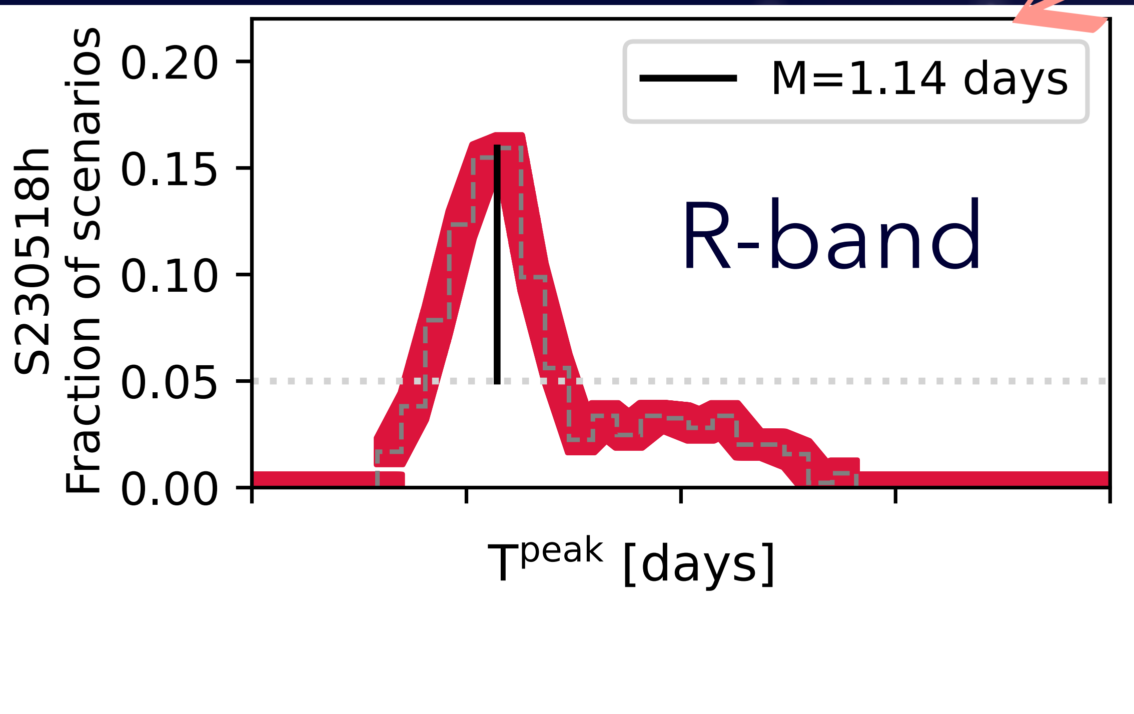


GW230529 & S230627c: Less observed - the « later time » strategy is not always realized while prompt strategy has been well demonstrated

Observation strategy



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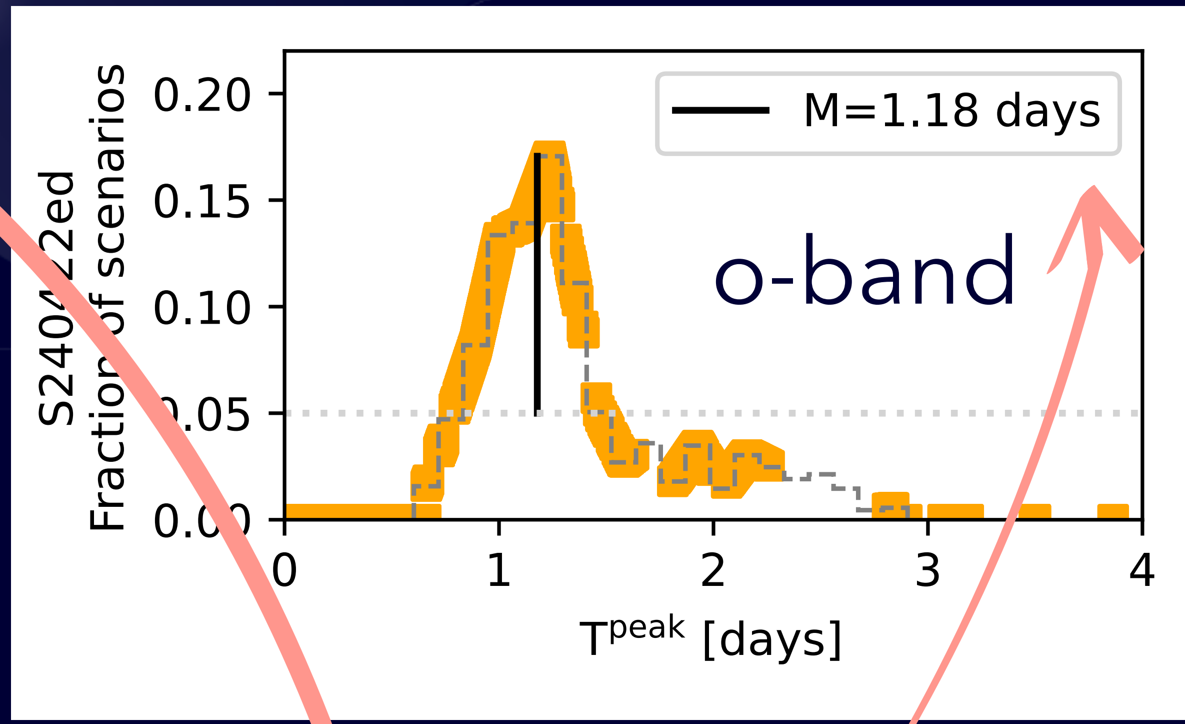

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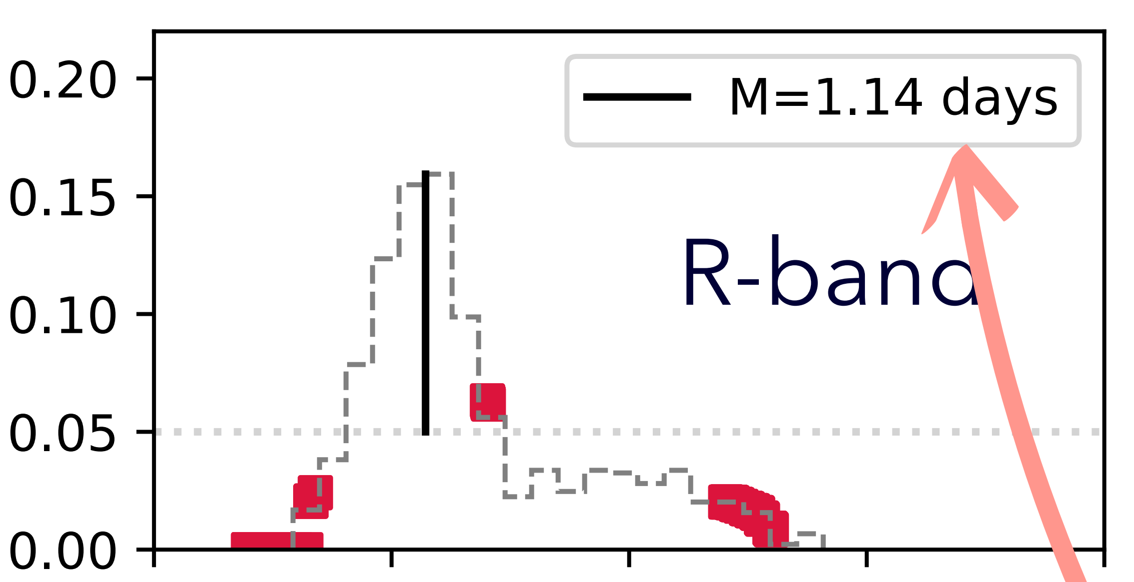
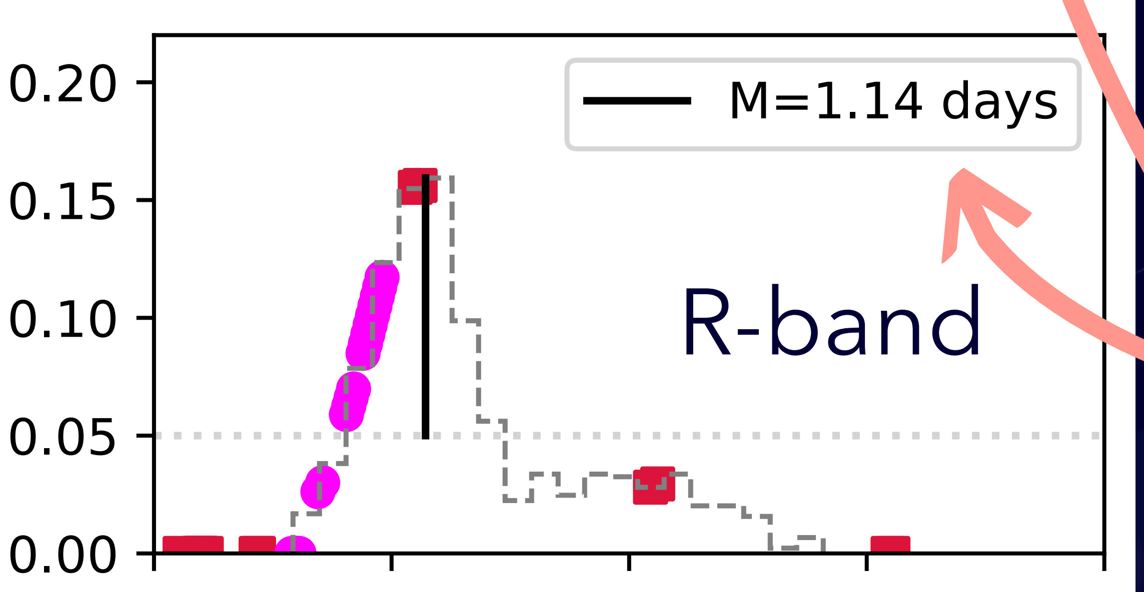
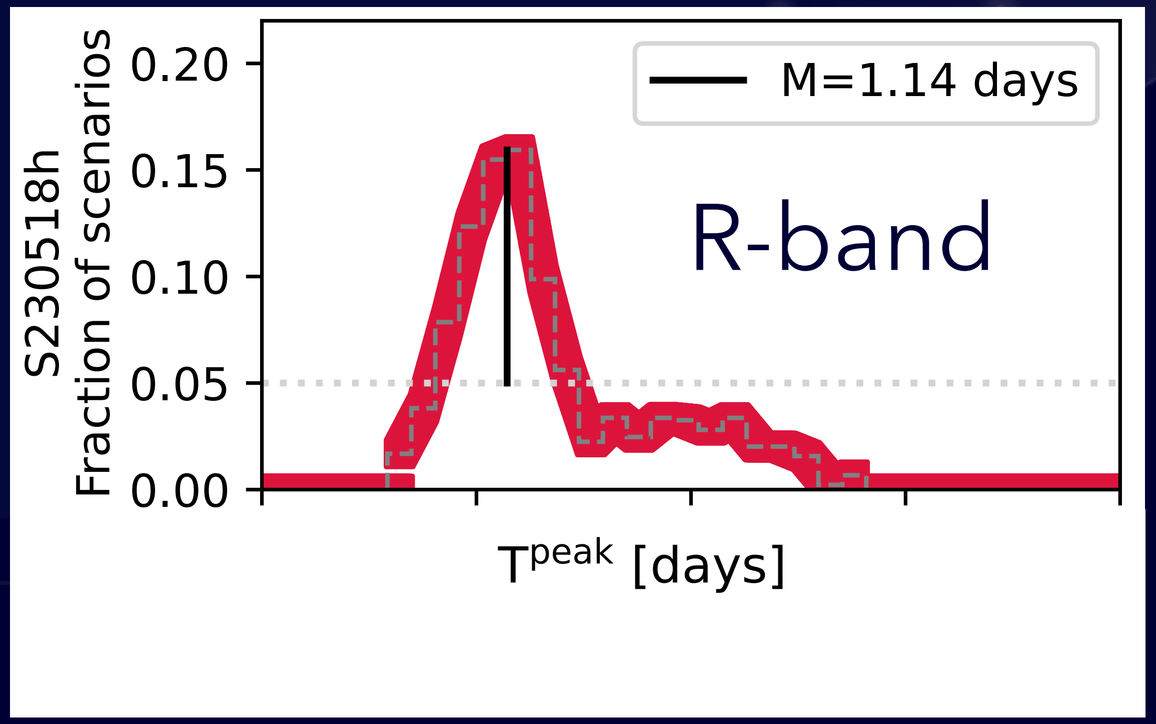




GW230529 & S230627c: Less observed - the « later time » strategy is not always realized while prompt strategy has been well demonstrated

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

Observation strategy



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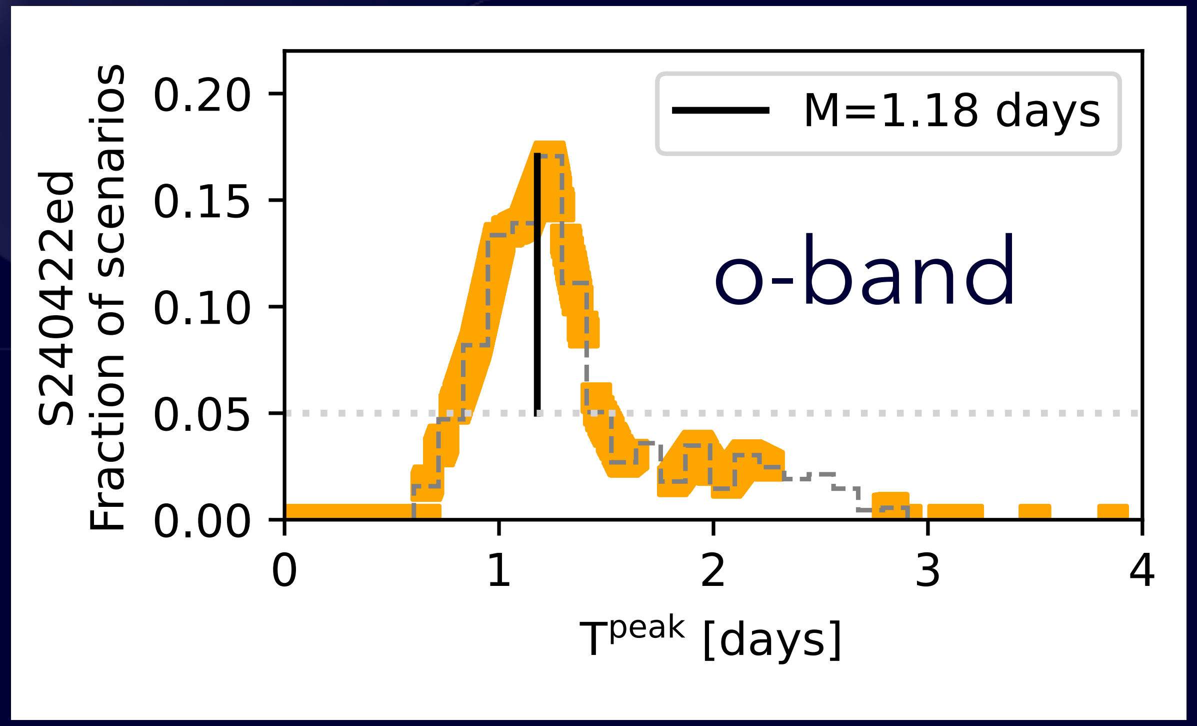

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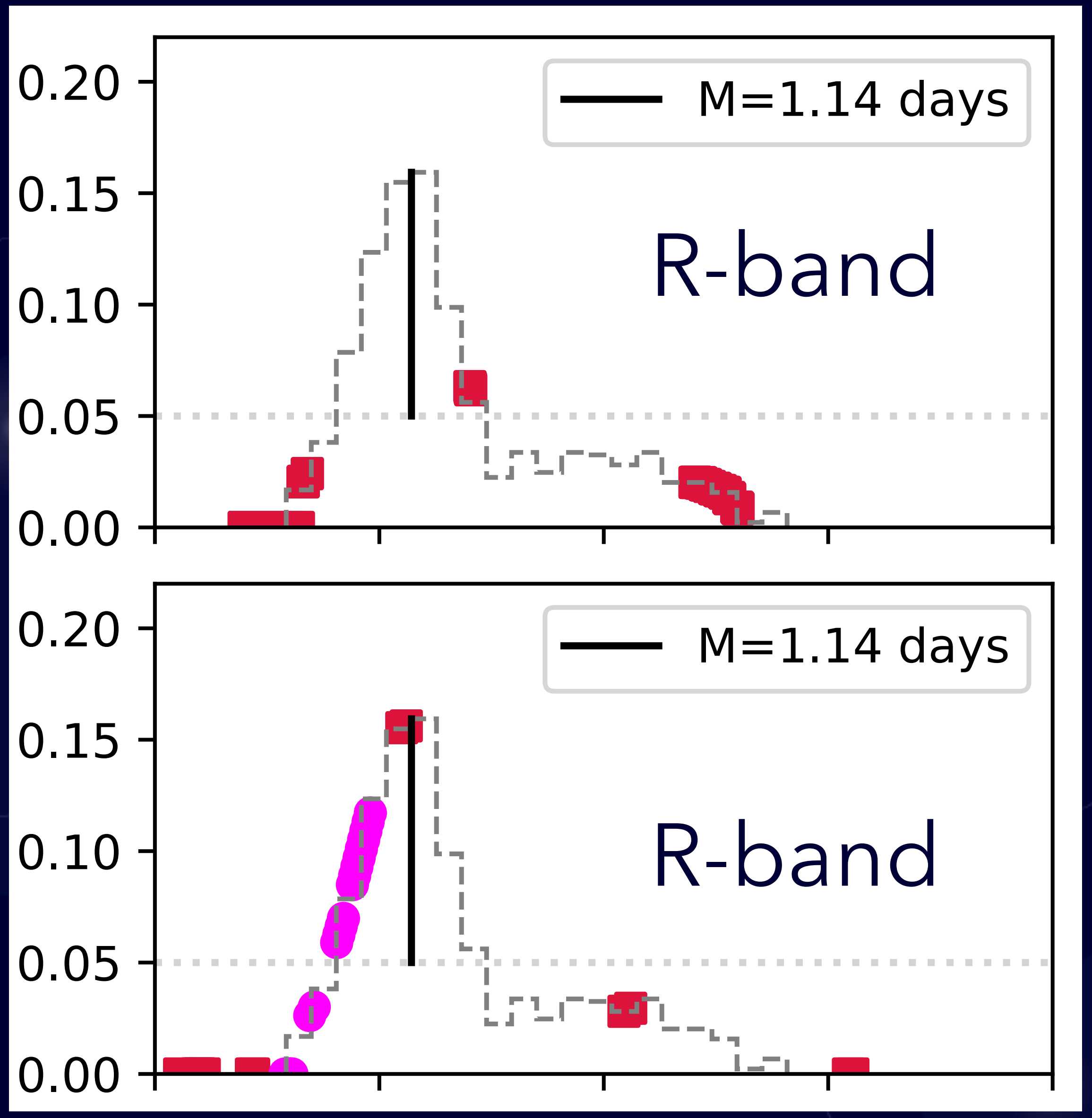

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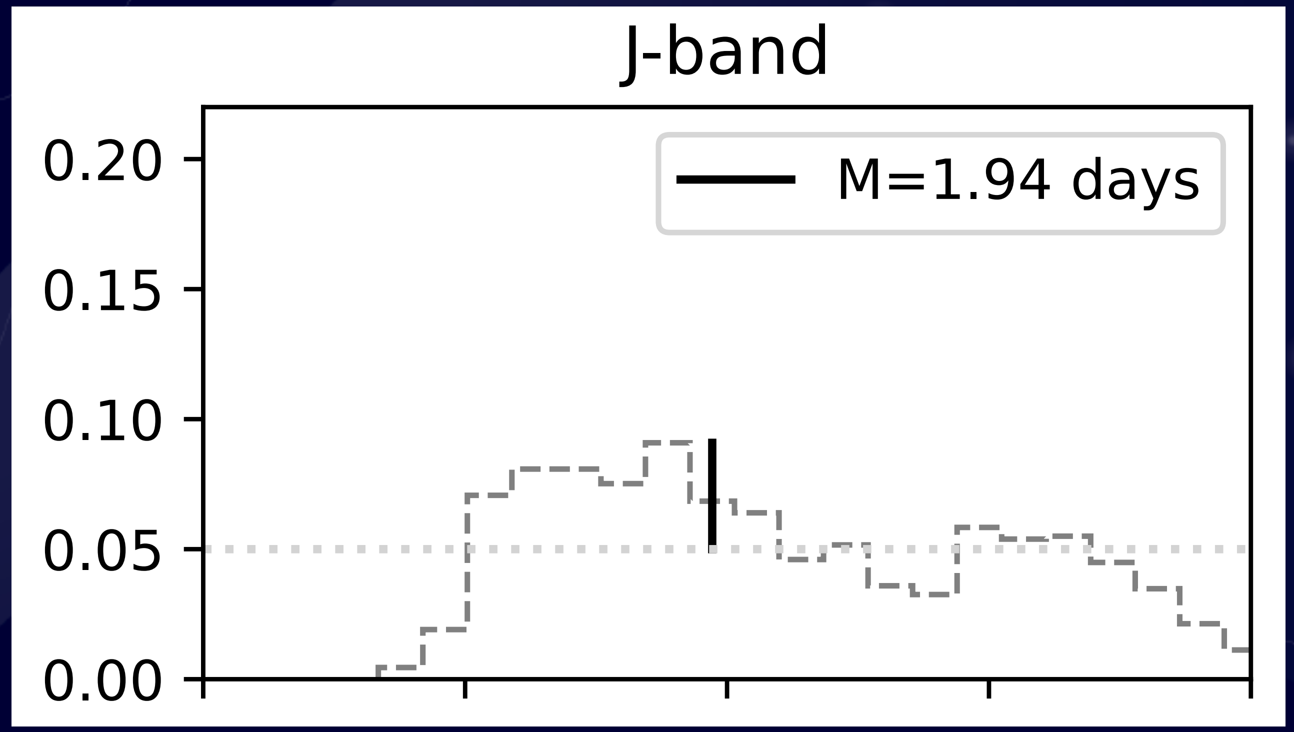
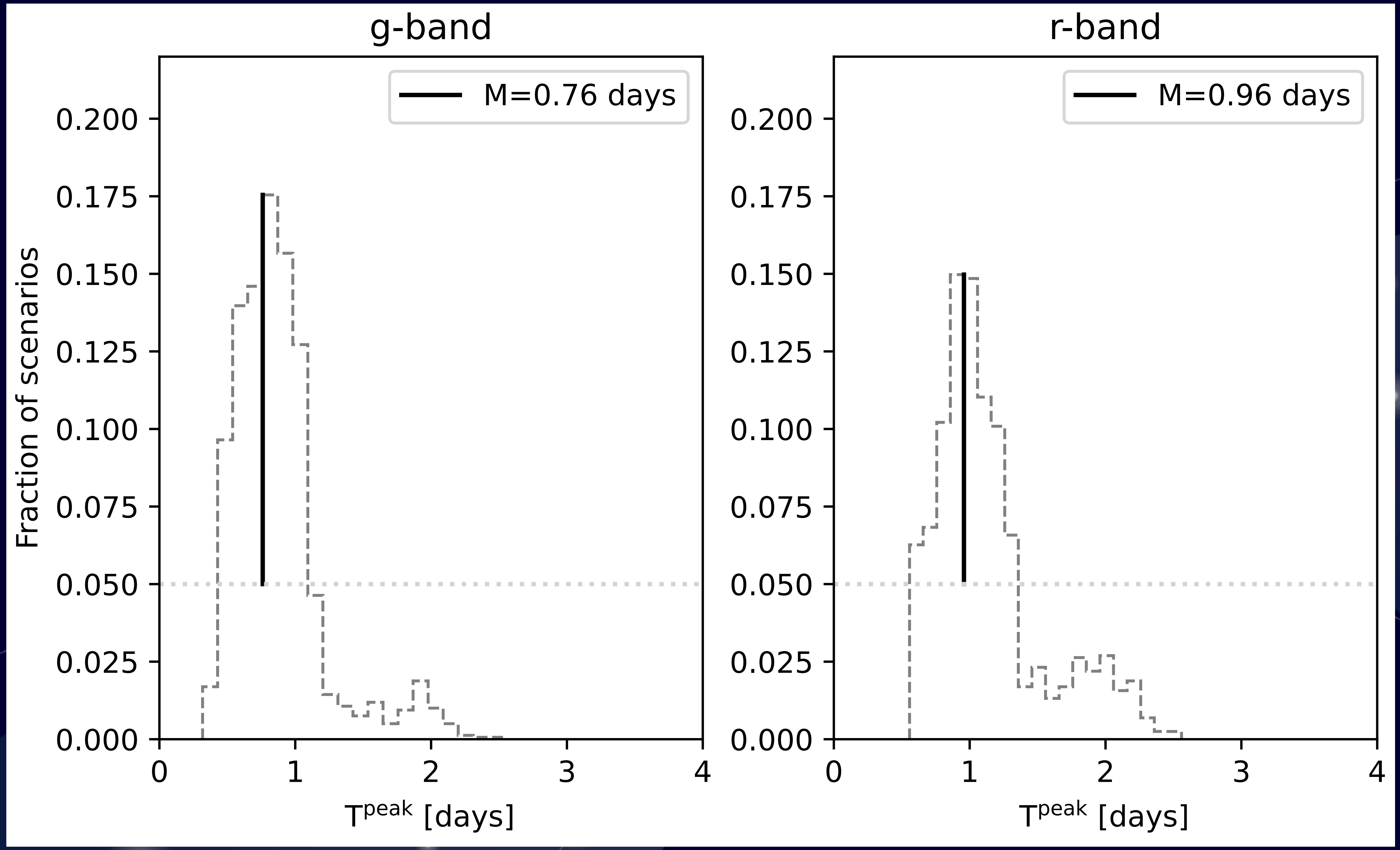


For J-band: advocate a more « relaxed » approach for near and infrared for which the peak time of the KN is more random

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

Observation strategy

Comparison with a model for KN emission from BNS



KN associated with O4 NSBH candidates

Goal:

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*:

- From the information released by LIGO/Virgo we can have a estimate of the chirp mass of each candidate, S230518h, GW230529, S230627c, S240422ed

- Compute a range of consistent ejected masses m_{dyn}, m_{wind} & select a corresponding set simulated of 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} (expected KN brighter than the observation): KN light curve incompatible with observation

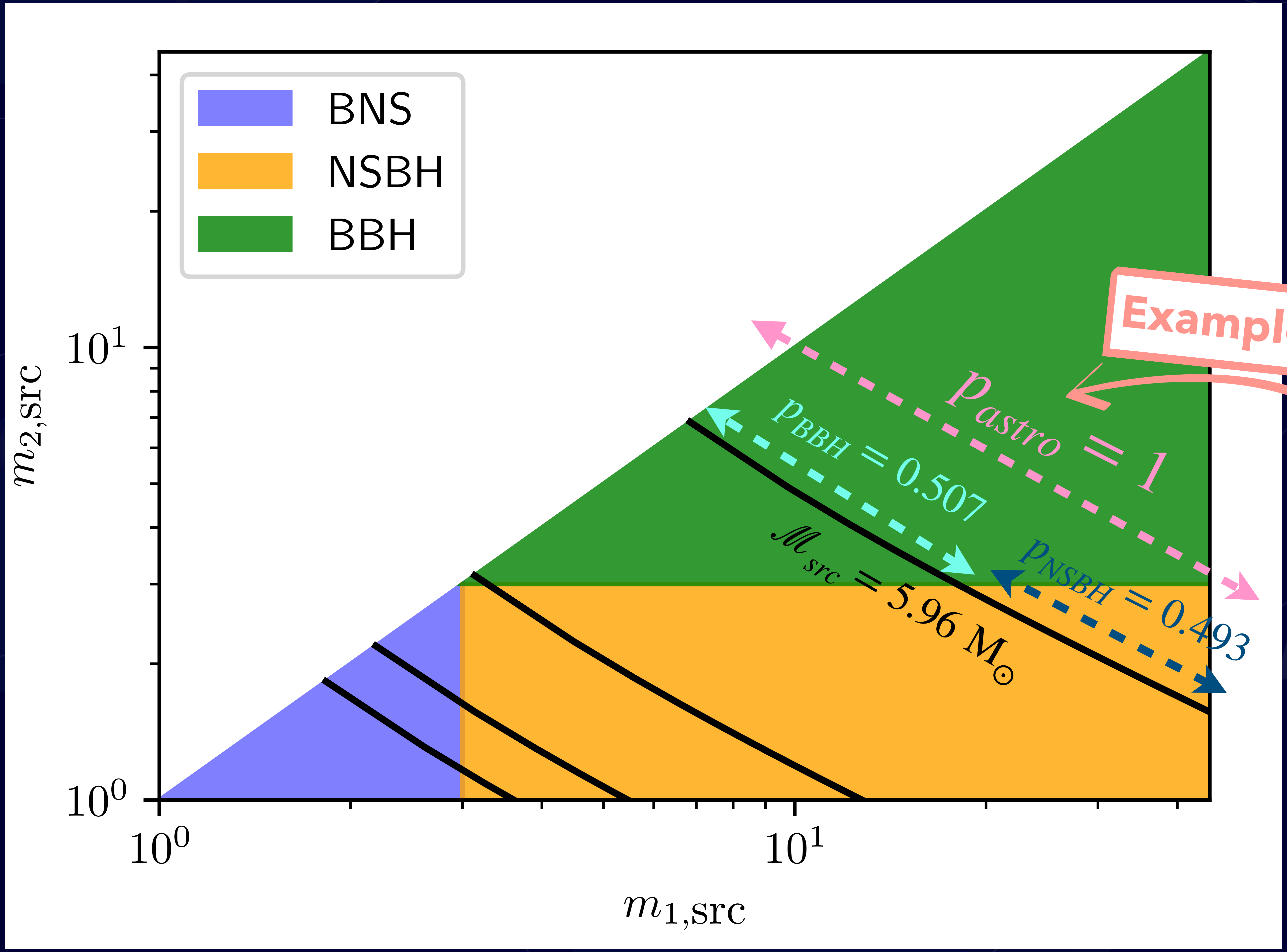
Acronyms:

18h: S230518h, 29: GW230529, 27c: S230627c and 22ed: S240422ed

KN associated with O4 NSBH candidates

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

(Villa-Ortega, 2022)



Candidate	BNS	NSBH	BBH	$\mathcal{M}_{src}\ [M_\odot]$
S230518h	0	0.959	0.041	$2.73^{+.07}_{-.06}$
S230529ay	0.329	0.671	0	$1.91^{+.06}_{-.05}$
S230627c	0	0.493	0.507	$5.96^{+.18}_{-.17}$
S240422ed	0.700	0.300	0	$1.60^{+.04}_{-.04}$

Consistent with public results about GW230529

KN associated with O4 NSBH candidates

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

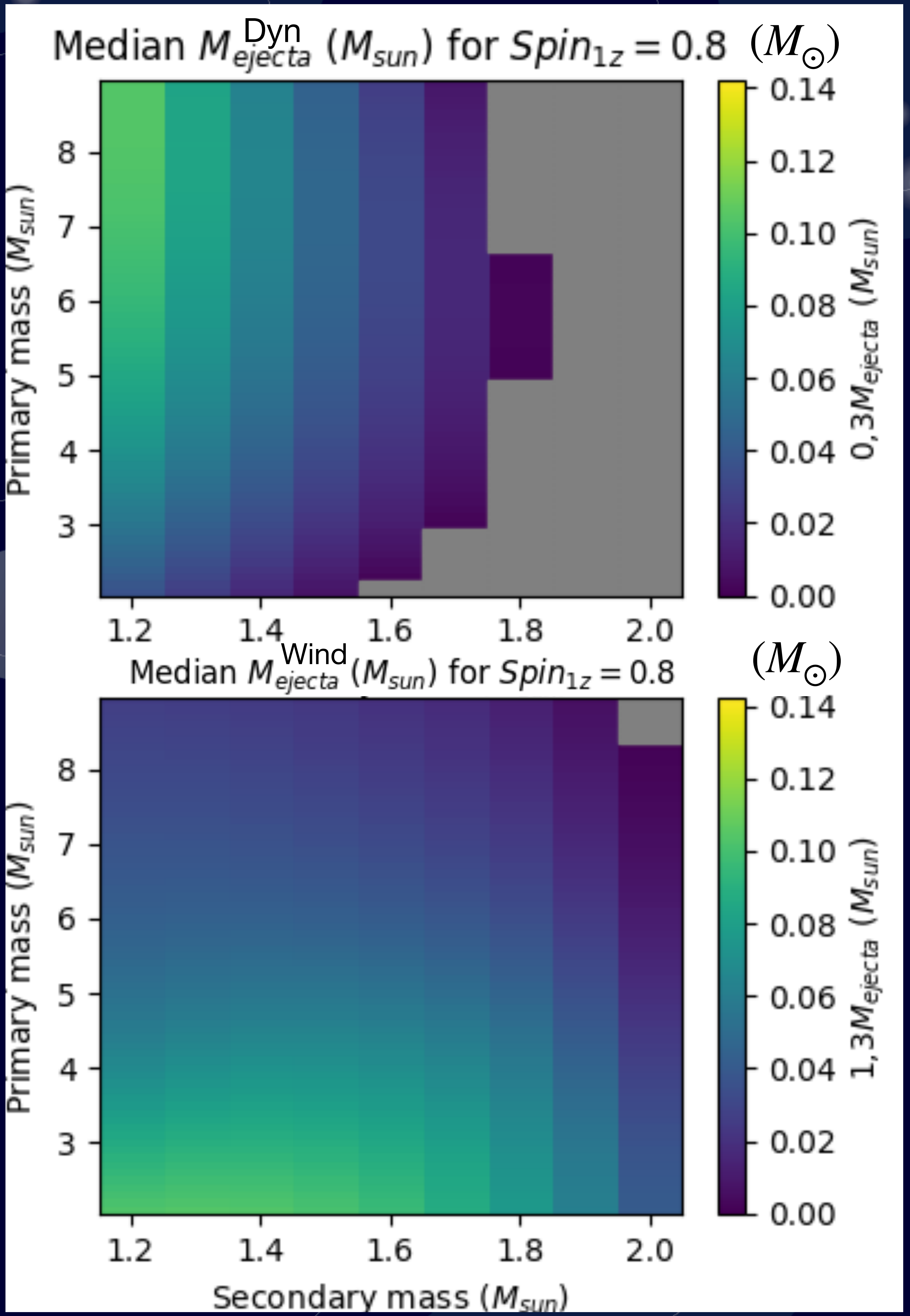
$$\frac{M_{\rm model}^{\rm rem}}{M_{\rm NS}^{b}} = [{\rm Max}(\alpha\frac{1-2C_{\rm NS}}{\eta^{1/2}} - \beta\hat{R}_{\rm ISCO}\frac{C_{\rm NS}}{\eta} + \gamma, 0)]^{\delta}$$

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

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

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

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*



KN associated with O4 NSBH candidates

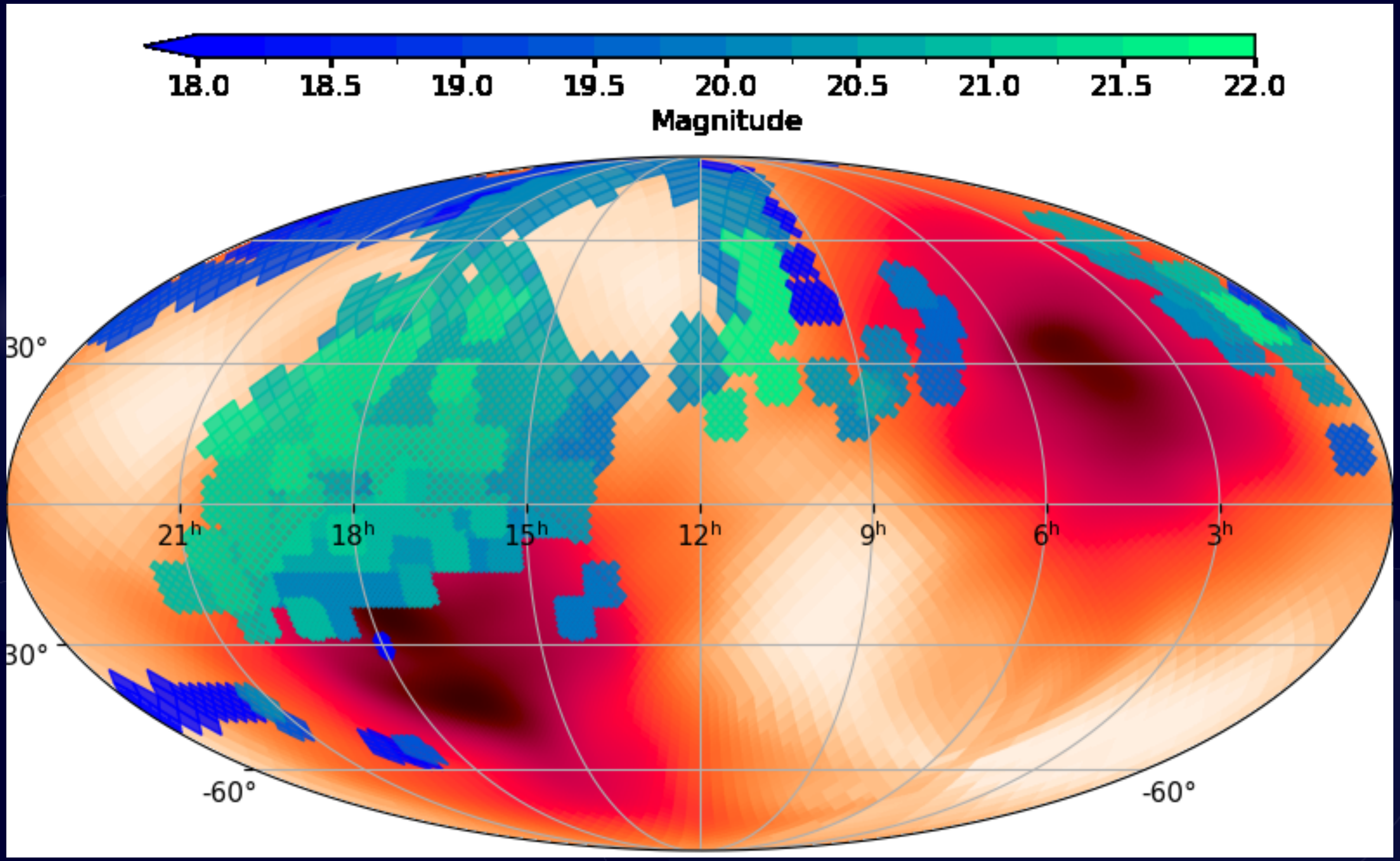
- **Compute a range of consistent ejected masses: m_{dyn}, m_{wind} select a corresponding set simulated of KN light curves**

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

KN associated with O4 NSBH candidates

- **Compare the magnitude of the light curve (M_{KN}) with the one of optical observations (M_{obs})**
  - Each optical telescope fields 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

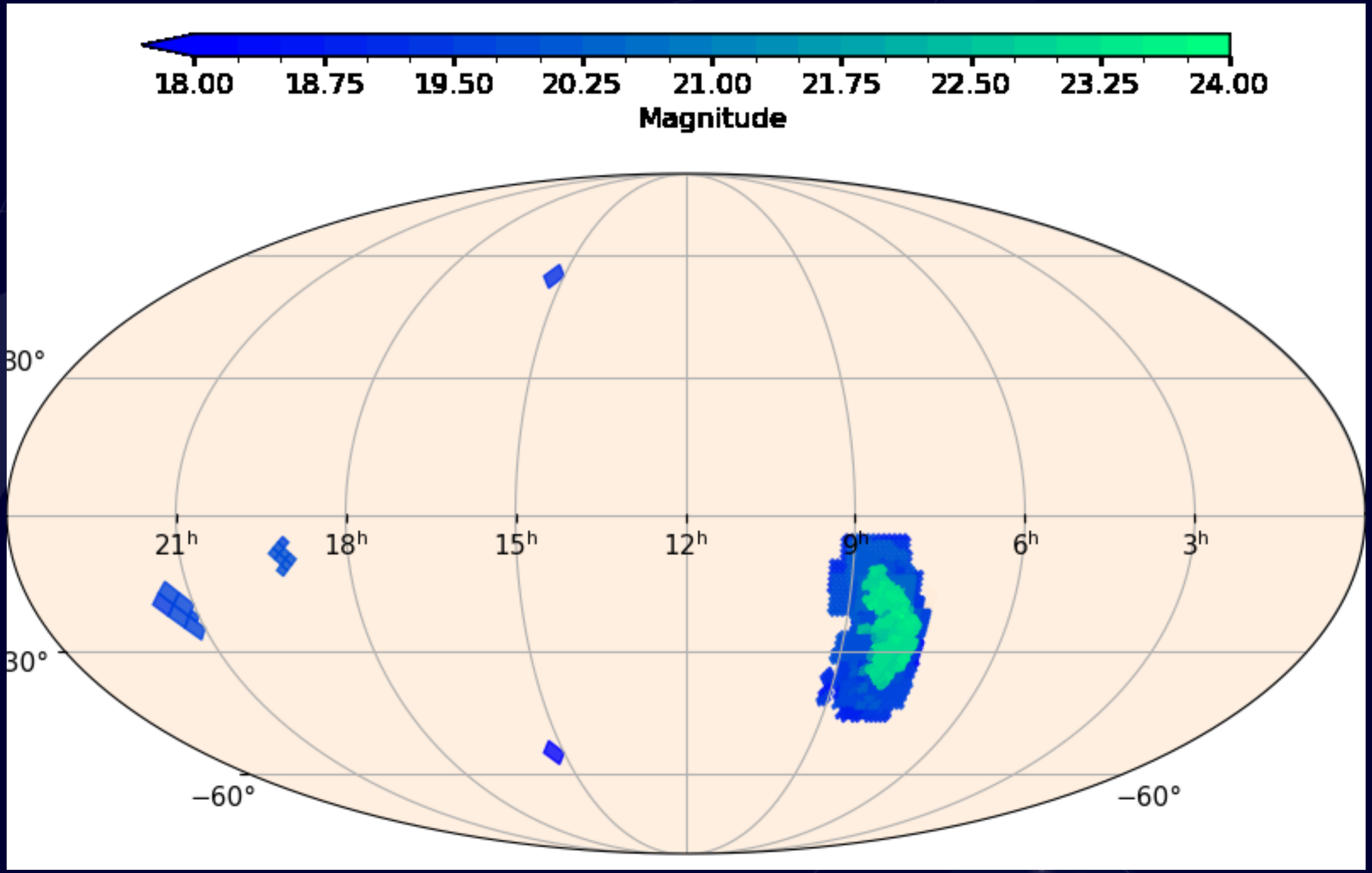
GW230529 (between 0 and 1 day)



Telescopes considered:
ATLAS, CSS, MASTER, ZTF

All filters!

S240422ed (between 0 and 1 day)



Telescopes considered: 7DT, ATLAS, BlackGEM, CSS, DECam, GOTO, GRANDMA, KMTNet, Las Cumbres 1m & 2m, Magellan, MASTER, MeerLIGHT, PRIME, Swift UVOT, WINTER, ZTF

KN associated with 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

KN associated with 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

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

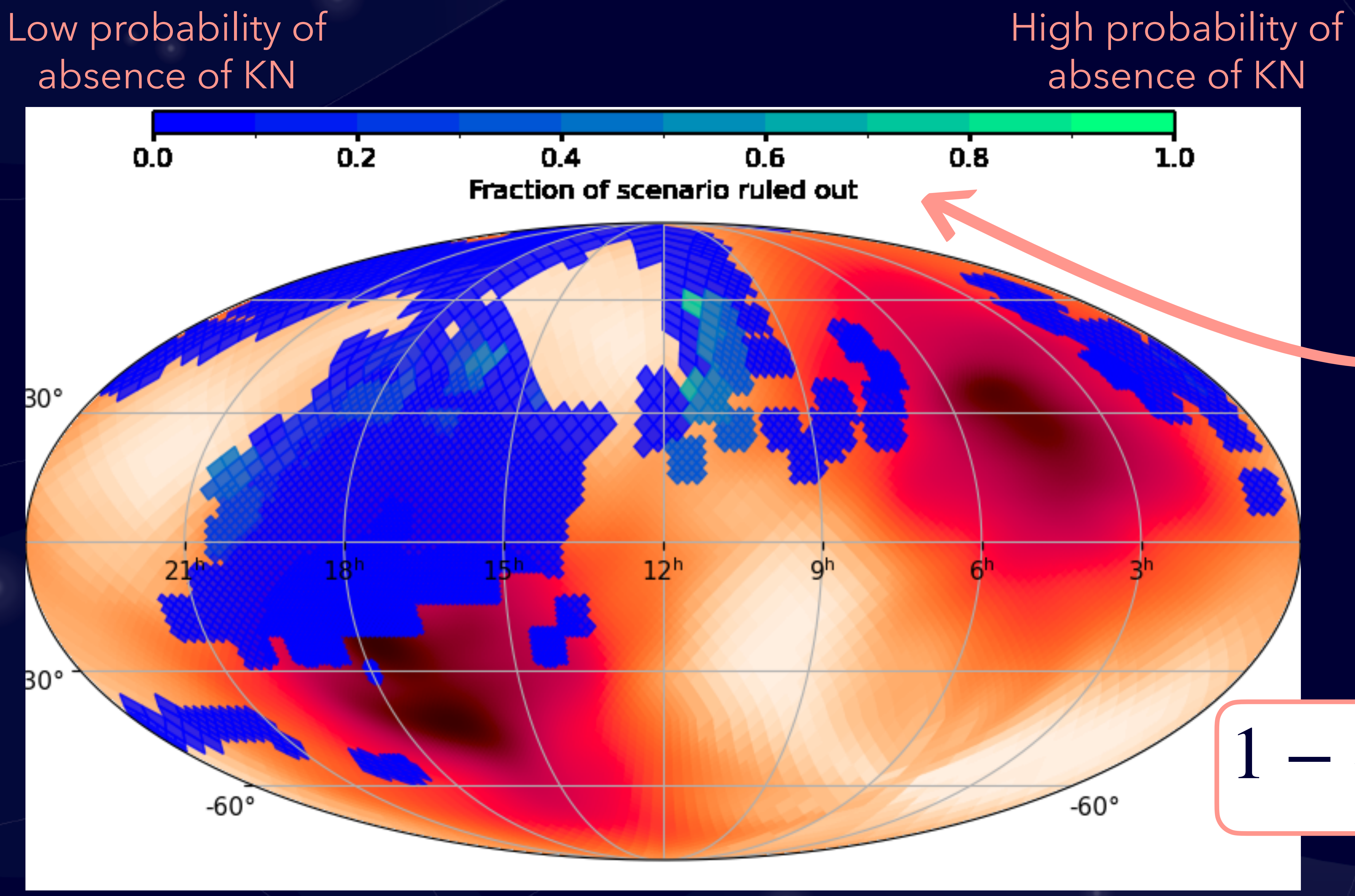
Total number of synthetic KNe from the grid considered for each event

Telescope observation

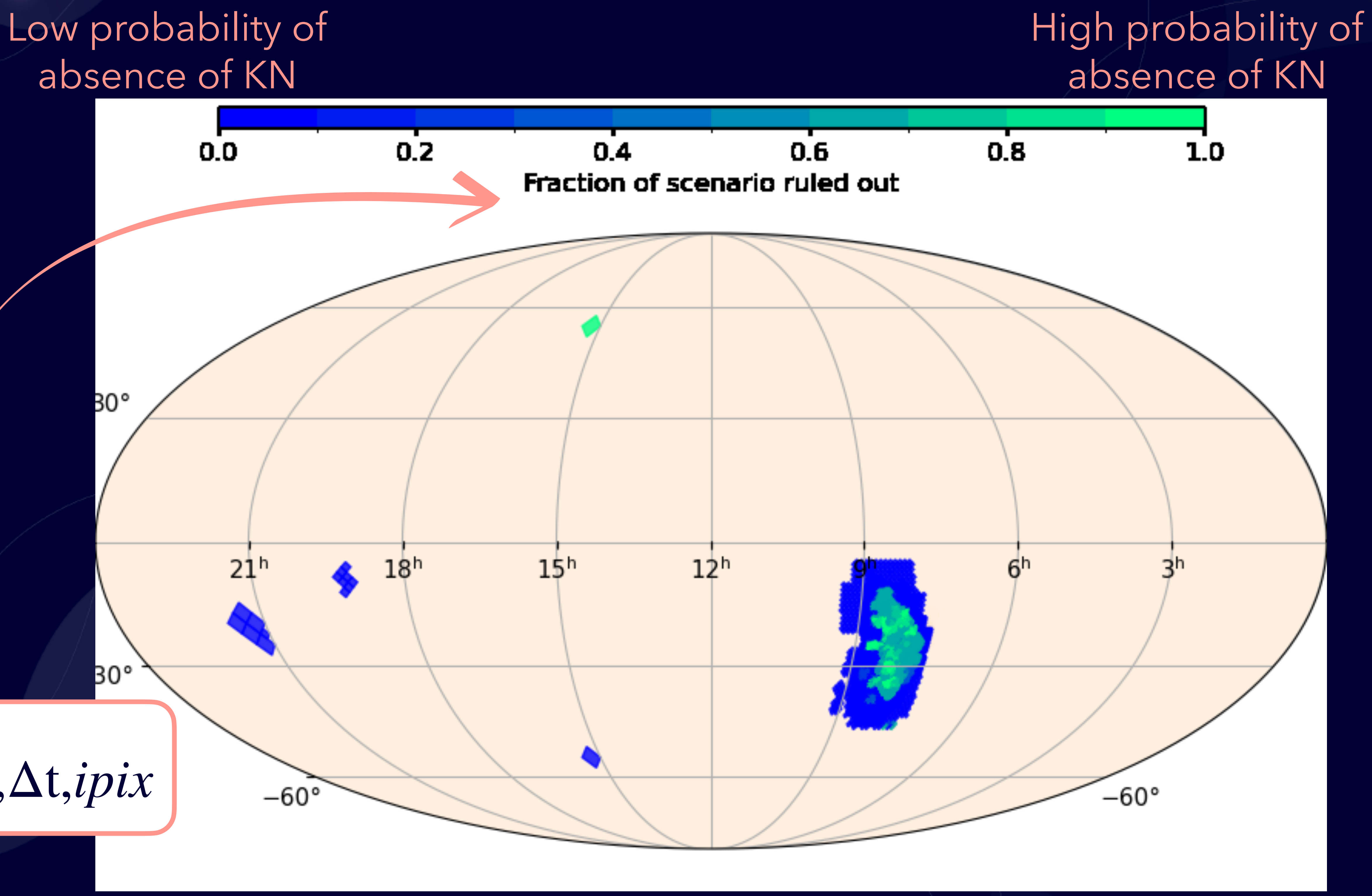
KN associated with O4 NSBH candidates

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

GW230529 (between 0 and 1 day)



S240422ed (between 0 and 1 day)



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

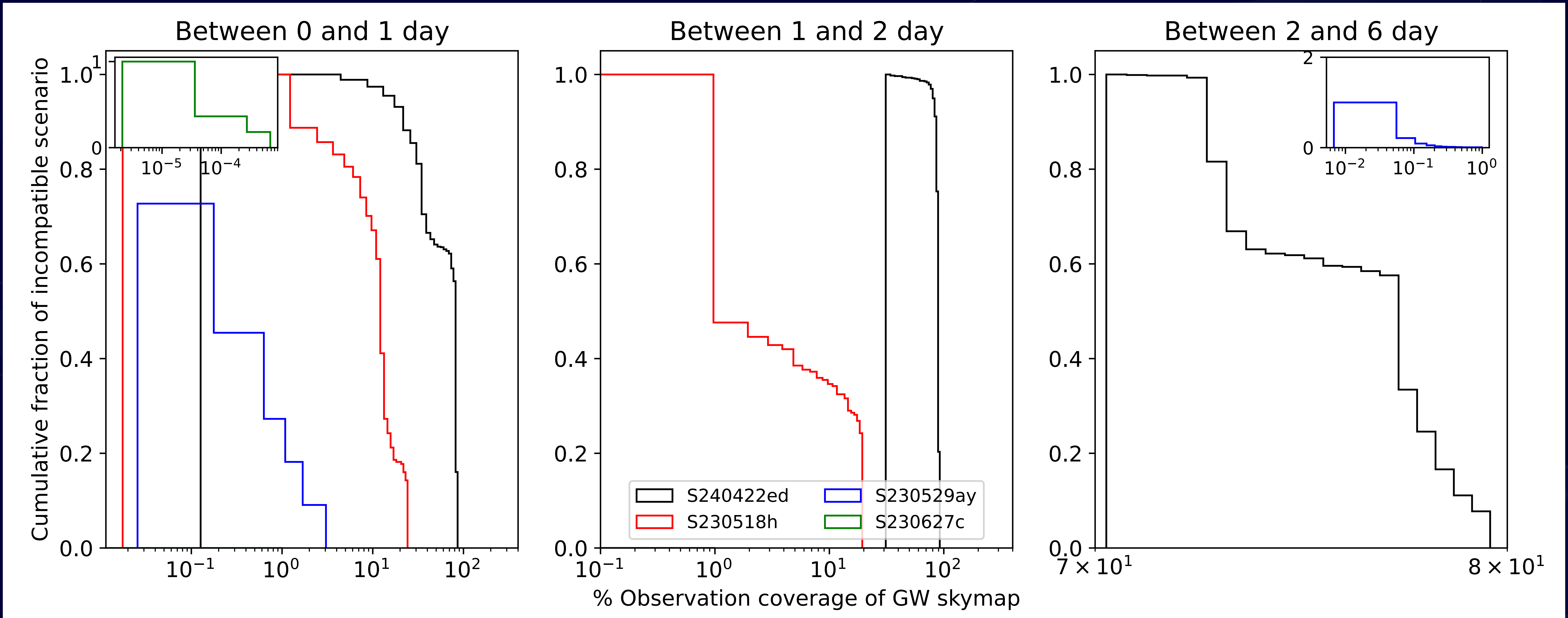
S240422ed: **218 deg²** within the 90% credible region (85% of the skymap), for t in [1,2[days, with a $1 - S_{KN,\Delta t,ipix}$ **> 0.7**: **probable absence of a KN in the observations**

KN associated with 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

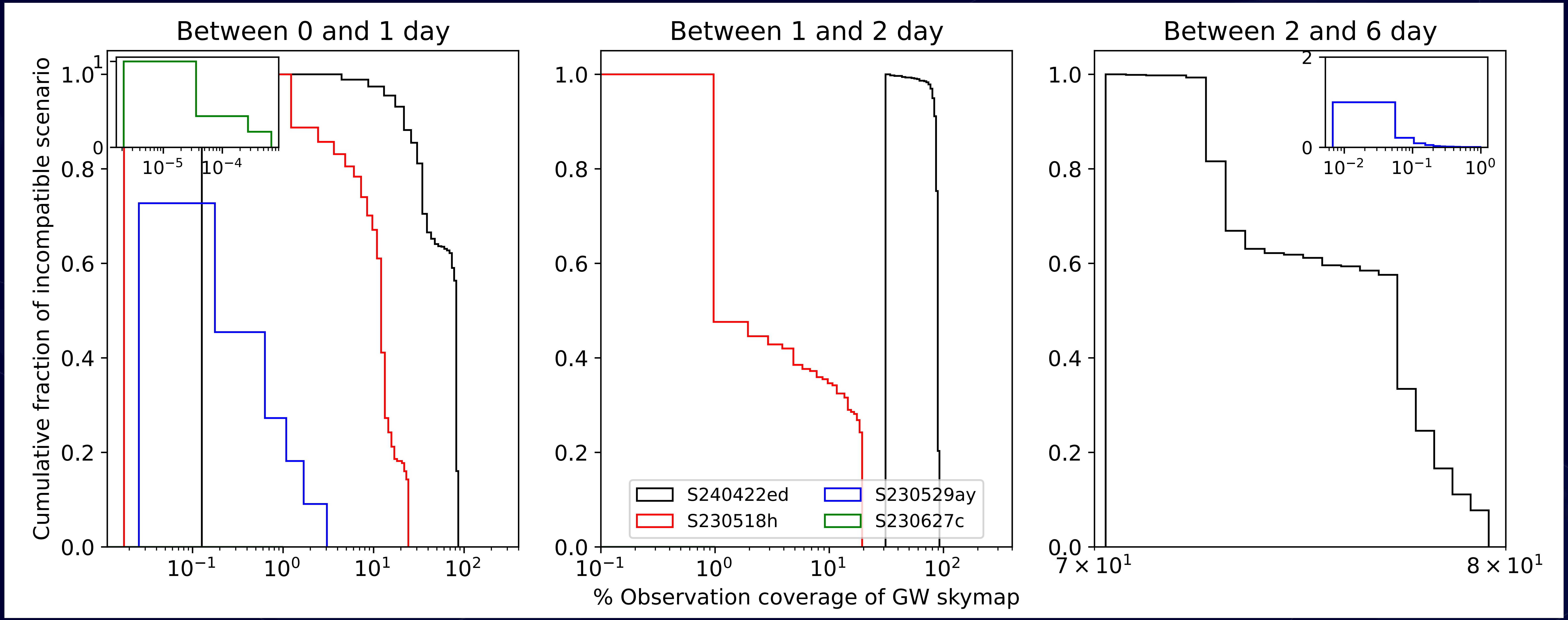
$$1 - \mathrm{P}_{\theta,m_{dyn},m_{wind},\Delta t} = \bar{P}_{\theta,m_{dyn},m_{wind},\Delta t} = \sum_{ipix} P(\mathrm{GW} \mid ipix) \times \begin{cases} 1 & \text{if } M_{KN}(fil,\theta,m_{dyn},m_{wind},t) < M_{obs}(filt,t,ipix) \\ 0 & \text{otherwise} \end{cases}$$



KN associated with O4 NSBH candidates

- **Discussion 2 & Key numbers:**

- 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 10% 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)**



KN associated with O4 NSBH candidates

Bottom line: Comparing models & observations is crucial

Robust models are important to allow us to:

Optimize followup by having an estimation of peak time

Choose the most optimized filter to observe with

Set constraints on source properties

Distinguish between central engines & find production modes

Observations are important for models:

Demonstrate their accuracy

« *Going further* »: Joint GRB-KN observations → understand the GRB and KN emission together & create joint models

KN Hunting still going on but large limitation dependancies on modelisation, spin effects etc.

THANK FOR YOUR ATTENTION!

KN associated with O4 NSBH candidates

- **Discussion 2 & Key numbers:**

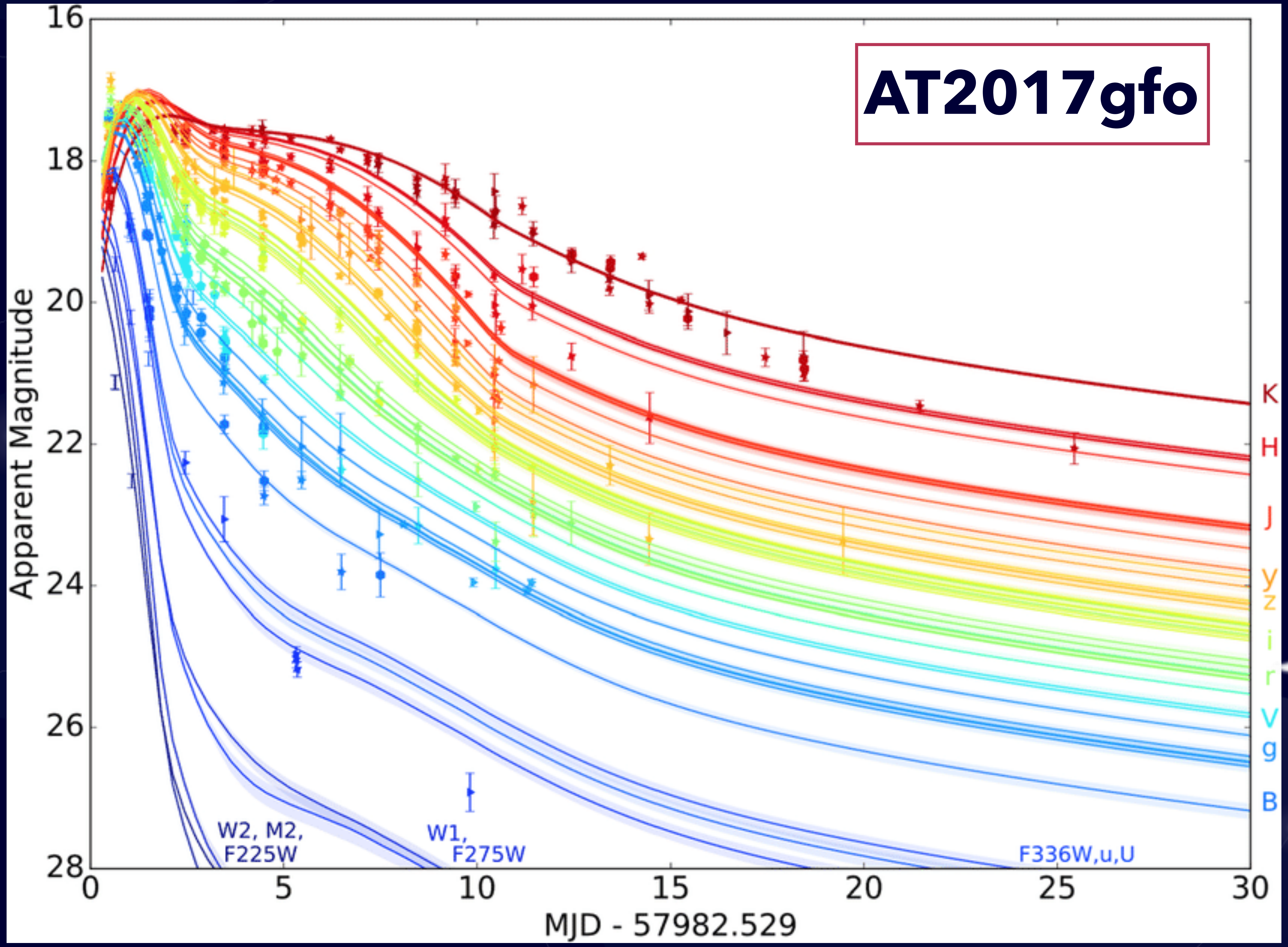
S240422ed

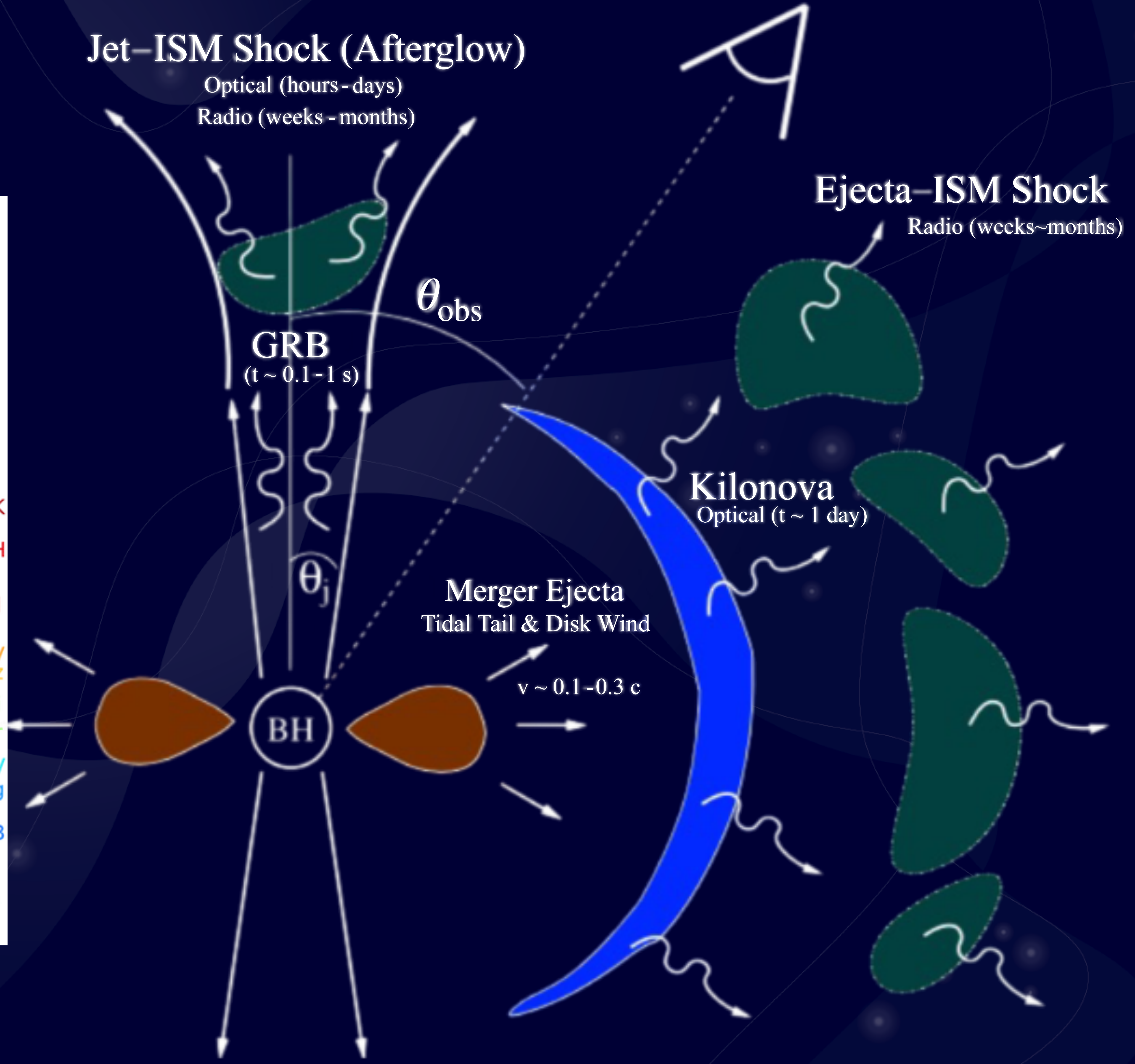
	mchirp	spin1z, BH =0.0 ($M_\odot$)	spin1z, BH=0.8 ($M_\odot$)
m_{dyn}	any	$SLy < 0.01$ $H4 < 0.03$	$SLy < 0.06$, $H4 < 0.10$
	1.6	$SLy < 0.01$, $H4 < 0.03$	$SLy < 0.04$, $H4 < 0.07$
	2.0	-, $H4 < 0.03$	$SLy < 0.06$, $H4 < 0.09$
	2.4		$SLy < 0.06$, $H4 < 0.1$
	2.8	-	$SLy < 0.03$, $H4 < 0.08$
	3.2	-	- $H4 < 0.03$
m_{wind}	any	$SLy < 0.02$, $H4 < 0.03$	$SLy < 0.09$, $H4 < 0.11$
	1.6	$SLy < 0.01$, $H4 < 0.03$	$SLy < 0.09$, $H4 < 0.11$
	2.0	-, $H4 < 0.01$	$SLy < 0.06$, $H4 < 0.09$
	2.4	-	$SLy < 0.04$, $H4 < 0.06$
	2.8	-	$SLy < 0.02$, $H4 < 0.04$
	3.2	-	$SLy < 0.01$, $H4 < 0.02$

Candidate	BNS	NSBH	BBH	$\mathcal{M}_{src}$ [$M_\odot$]
S230518h	0	0.959	0.041	$2.73^{+.07}_{-.06}$
S230529ay	0.329	0.671	0	$1.91^{+.06}_{-.05}$
S230627c	0	0.493	0.507	$5.96^{+.18}_{-.17}$
S240422ed	0.700	0.300	0	$1.60^{+.04}_{-.04}$

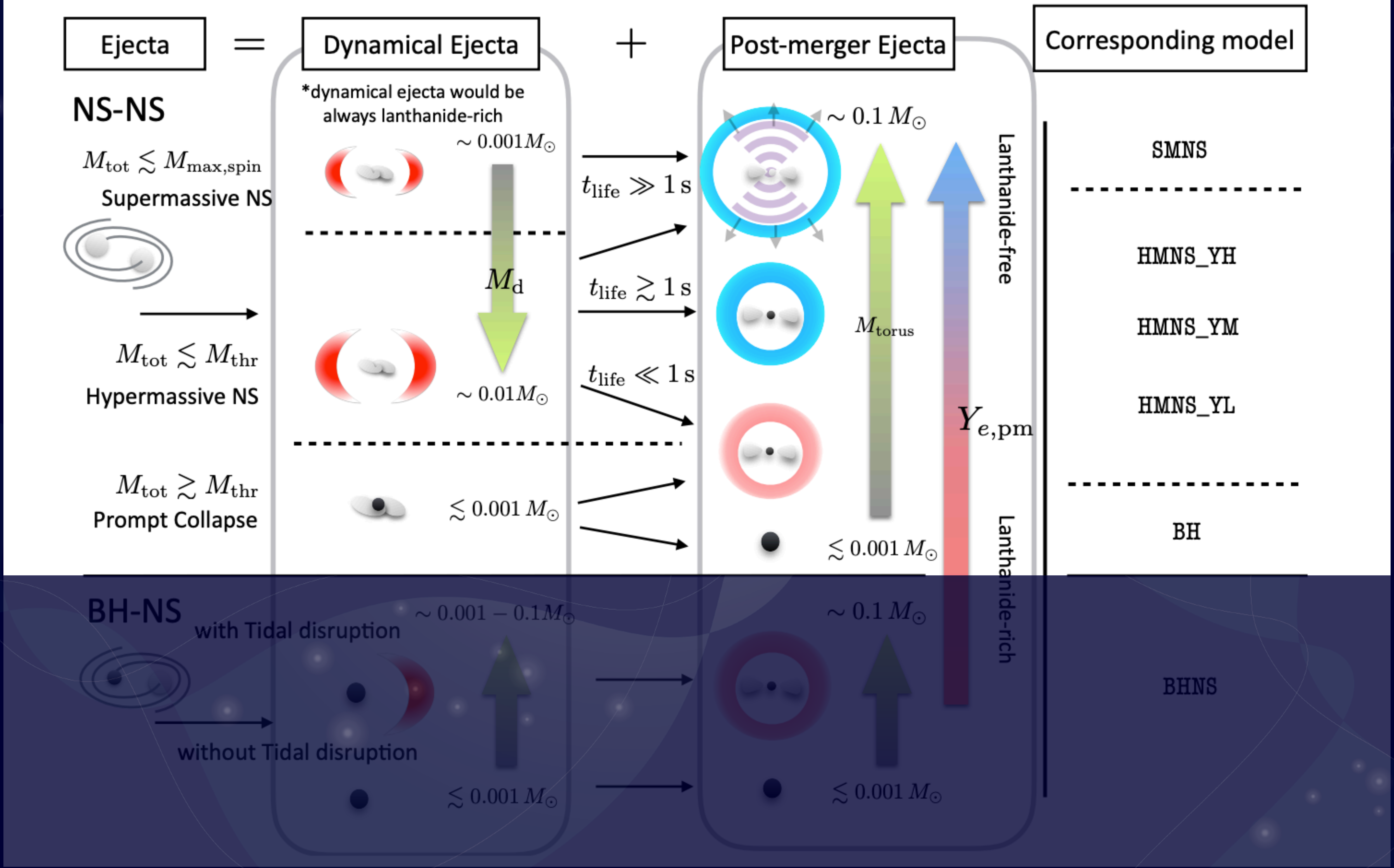
Introduction

- **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** …





Modeling Kilonova from Binary Neutron Star merger

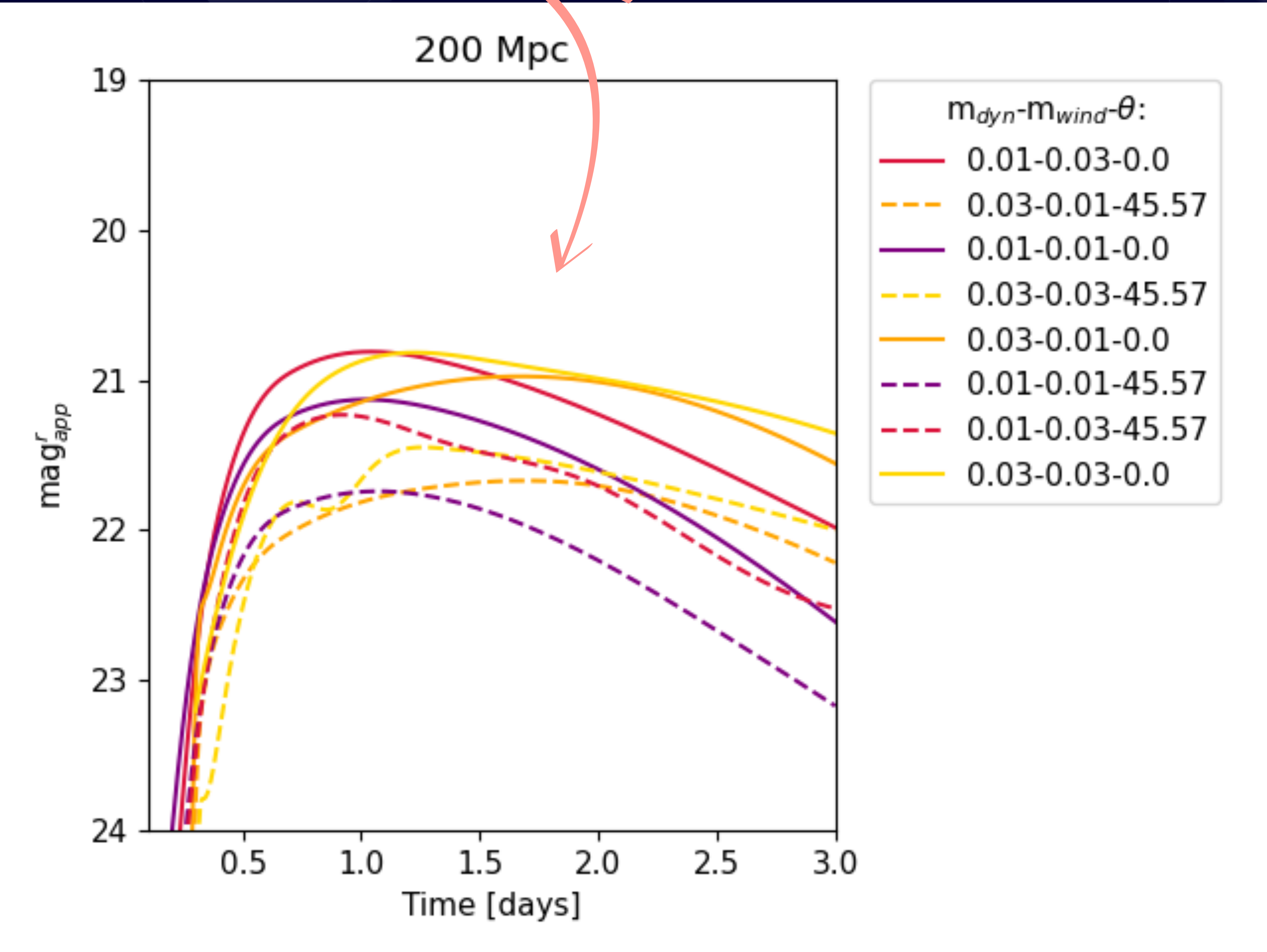


Modeling Kilonova from Neutron Star - Black Hole Merger

KN properties imprinted in the light curves:

- m_{dyn}
- m_{wind}
- viewing angle θ
- half-opening angle ϕ
- ejecta velocity
- ...

Exemple



POSSIS Light Curves

Model Grid: t_0, v_i, $\rho_{i,0}$, $T_{i,0}$, $Y_{e,i}$ for each cell i

- Homologous expansion
- Grid expanded at each step j: $\rho_{i,j} = \rho_{i,0} \times (t_j/t_0)^{-3}$
- And $T_{i,j} = T_{i,0} \times (t_j/t_0)^{-\alpha}$ with $\alpha > 0$

Opacity handled in POSSIS:

- Line opacity from bound-bound transitions
- Continuum opacity from either electron scattering, bound-free or free-free absorption
- Wavelength-dependent opacities can be given

POSSIS Light Curves

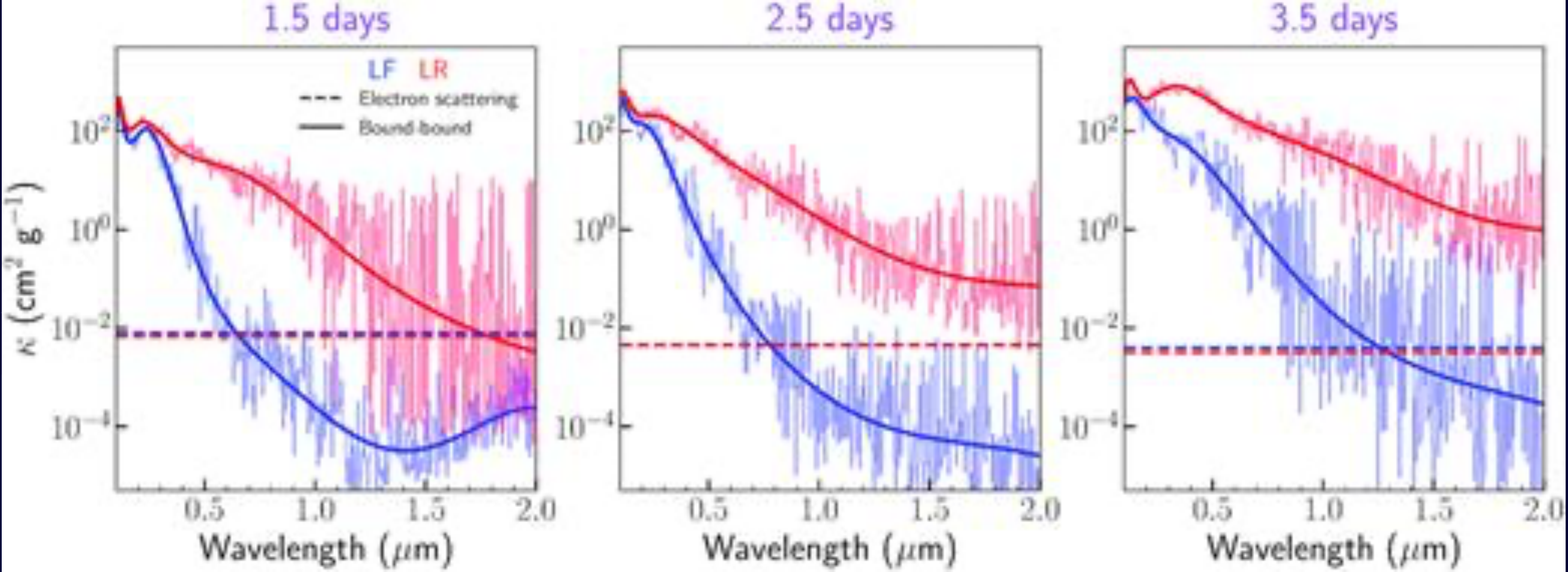
Creating photon packets:

- N_{ph} created at each step j with $\mathbf{x}$, e, ν, s
- More quanta are created at higher compared to lower densities
- $\mathbf{x}$ can be selected according to the distribution of radioactive material
- Initial direction n sampled assuming either isotropic emission or constant surface brightness
- Energy chosen from thermalization efficiency and nuclear heating rates
- Initial frequency from T

POSSIS Light Curves

Propagated photon packets:

- Continuum interaction: random number to define the nature of event
- If electron scattering: new direction & Stockes vector, ν unchanged
- Otherwise: re-emitted isotropically & new ν

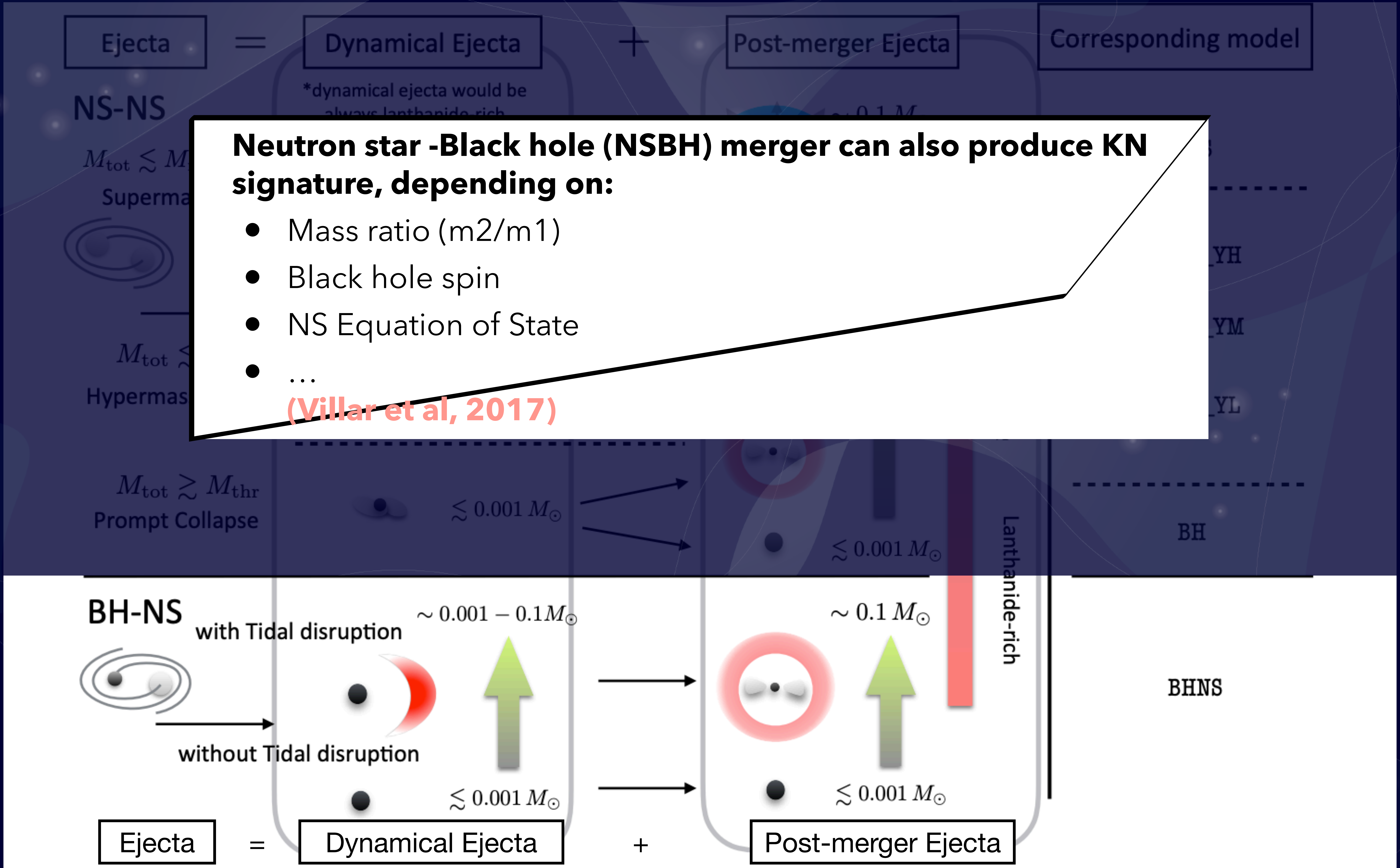


Modeling Kilonova from Neutron Star - Black Hole Merger

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

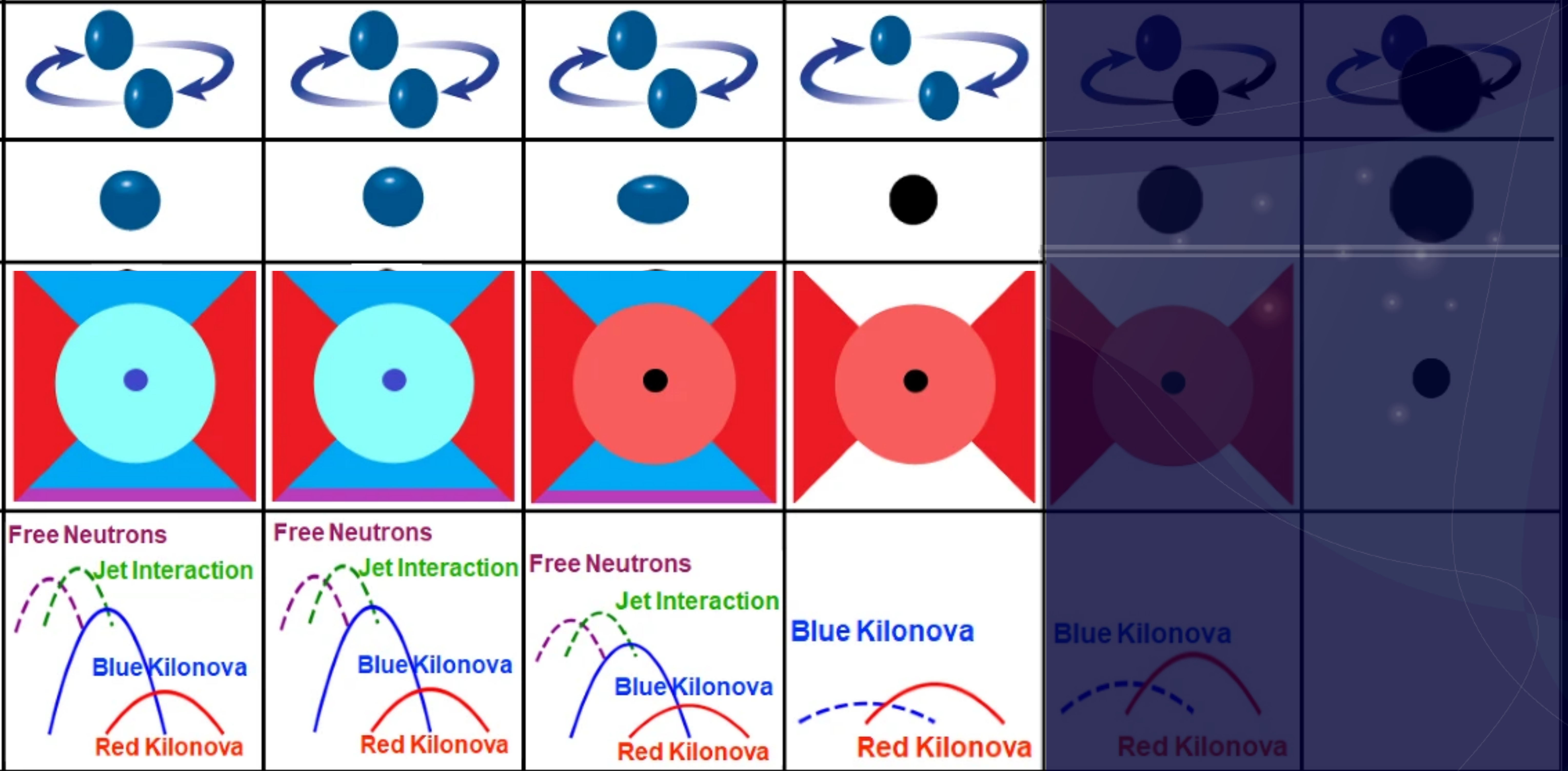
- Mass ratio (m2/m1)
- Black hole spin
- NS Equation of State
- …

(Villar et al, 2017)



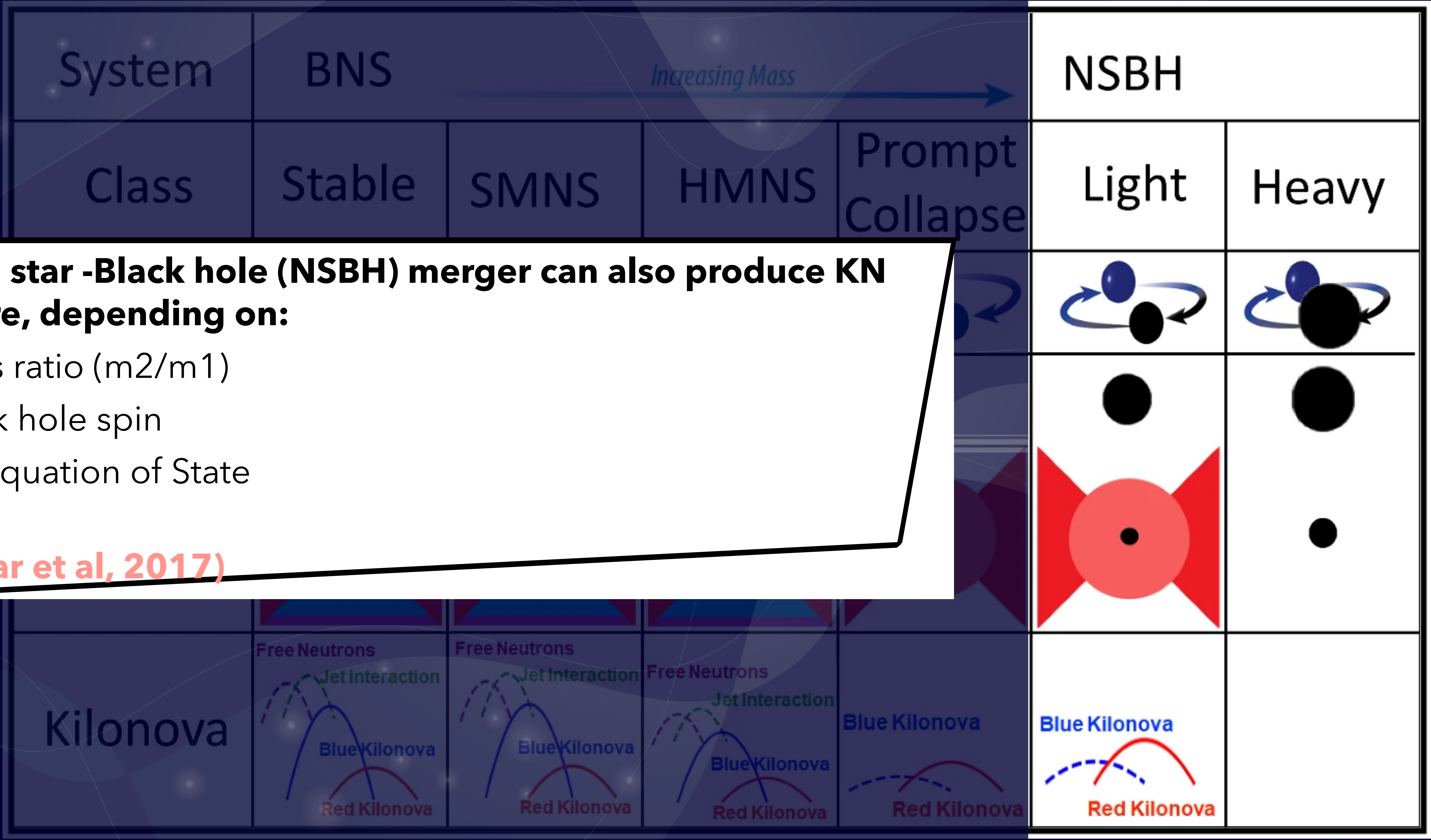
Modeling Kilonova from Binary Neutron Star merger

System	BNS	Increasing Mass →			NSBH	
Class	Stable	SMNS	HMNS	Prompt Collapse	Light	Heavy
Progenitor						
Remnant						
Ejecta						
Kilonova	Free Neutrons, Jet Interaction, Blue Kilonova, Red Kilonova	Free Neutrons, Jet Interaction, Blue Kilonova, Red Kilonova	Free Neutrons, Jet Interaction, Blue Kilonova, Red Kilonova	Blue Kilonova, Red Kilonova	Blue Kilonova, Red Kilonova	



- - - Signature to a specific scenario not certain, or signature theoretically expected but not yet confirmed observationally

Modeling Kilonova from Neutron Star - Black Hole Merger



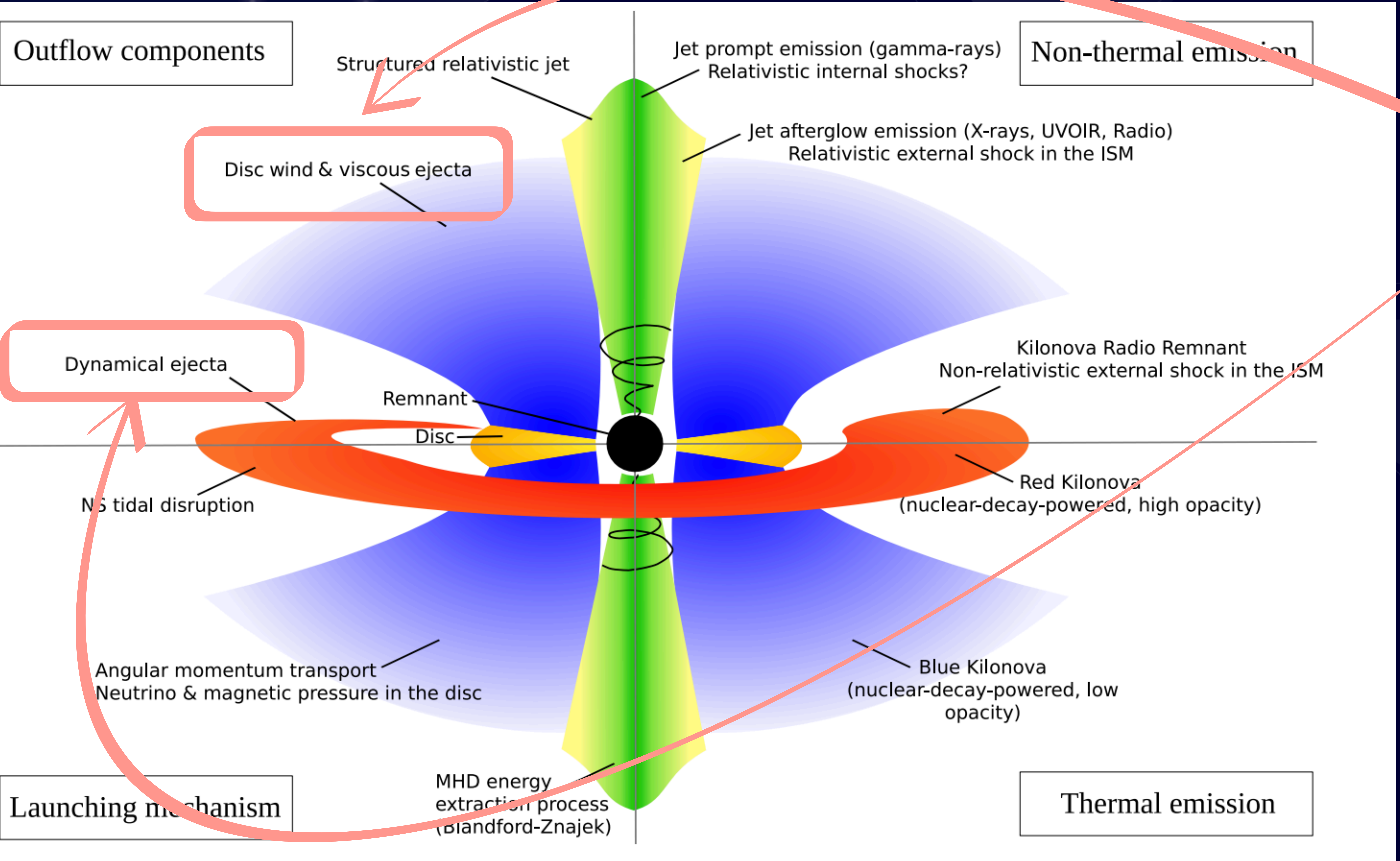
Neutron star -Black hole (NSBH) merger can also produce KN signature, depending on:

- Mass ratio (m2/m1)
- Black hole spin
- NS Equation of State
- …

(Villar et al, 2017)

- - - Signature to a specific scenario not certain, or signature theoretically expected but not yet confirmed observationally

Modeling Kilonova from Neutron Star - Black Hole Merger

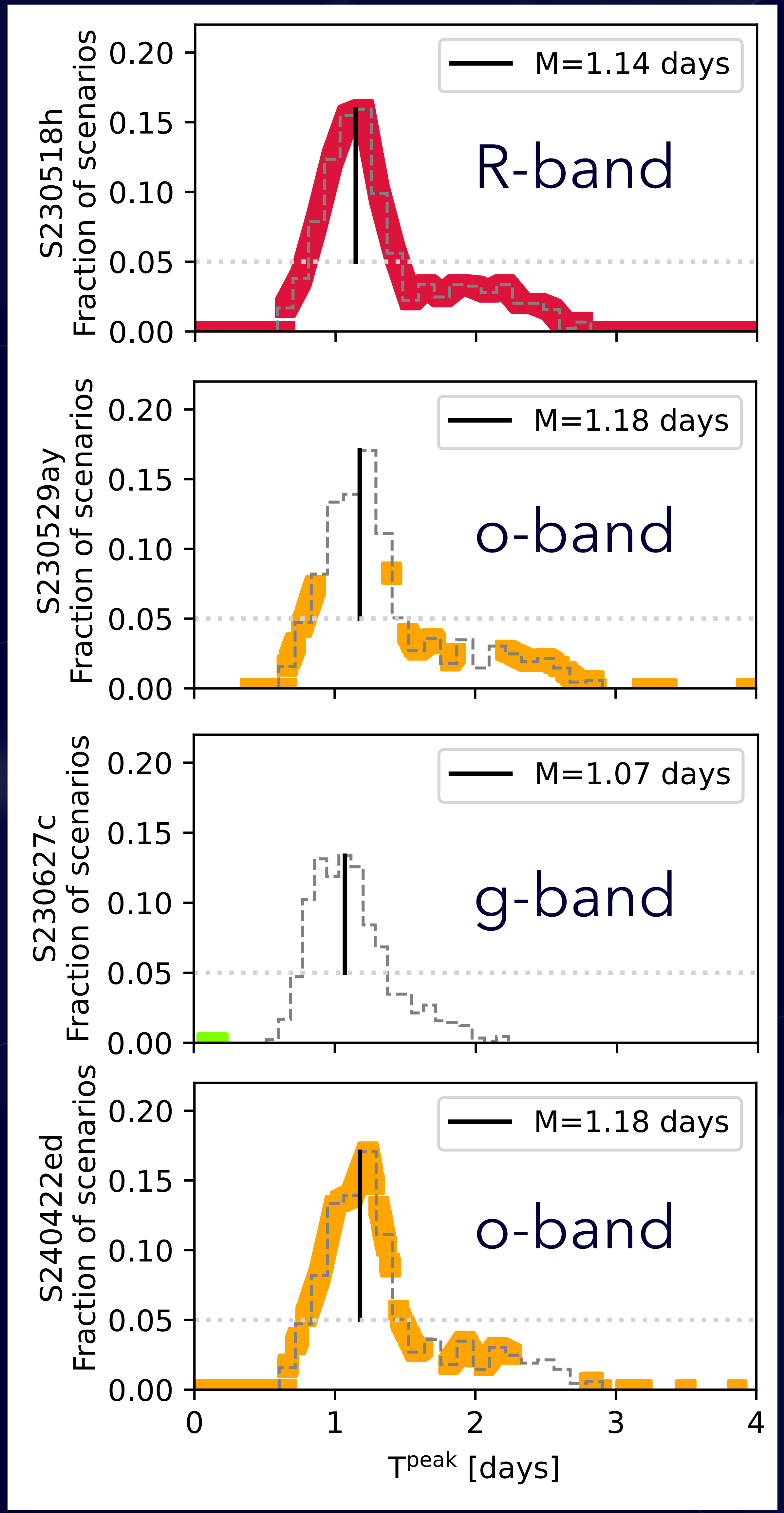


- Dynamical ejecta (non spherical, lanthanide-rich)
- Disc wind ejecta (spherical)

$$M_{ej,rem} = m_{dyn} + m_{wind}$$

Barbieri et al, 2019

Observation strategy



Key Numbers

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

GW230529: Observations in o-band covered the KN peak time of 51% of the population.

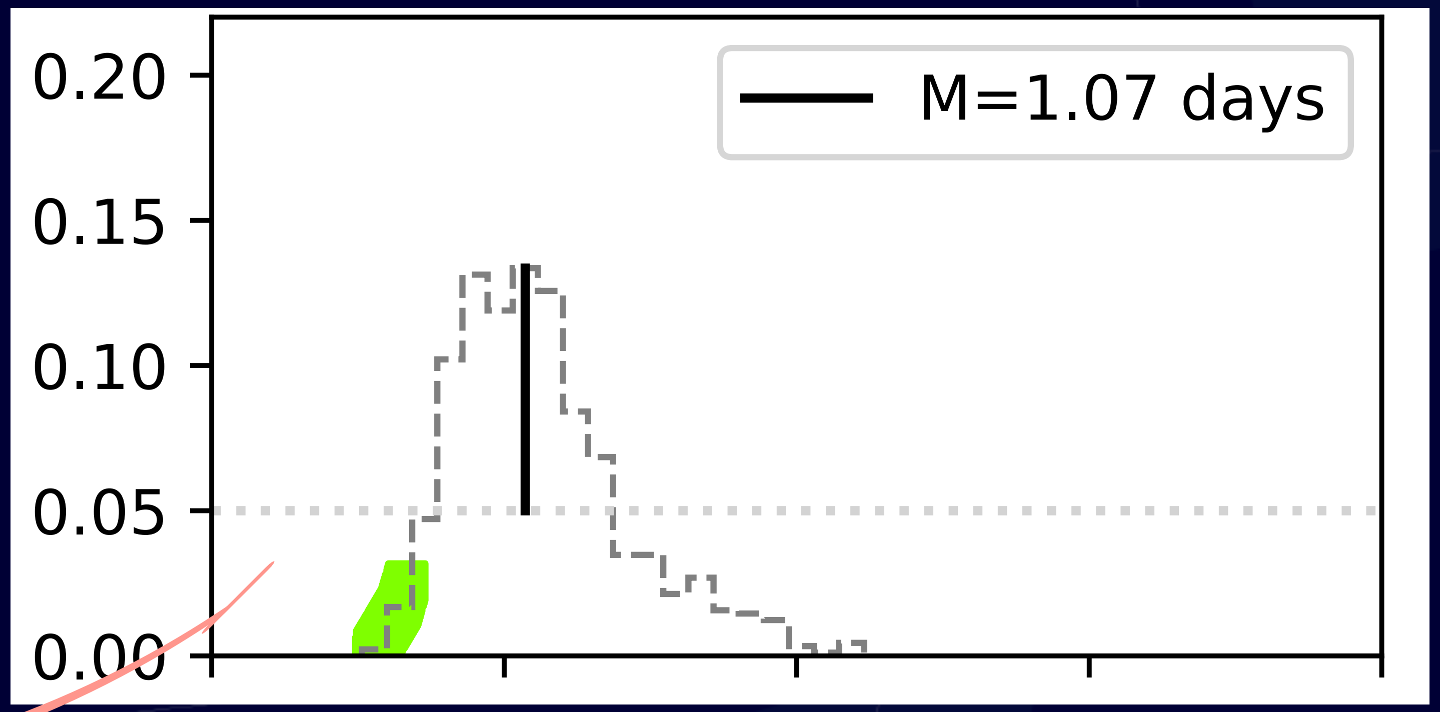
S260727c: Observations in g and r-band happened before the scenario's predicted peak time.

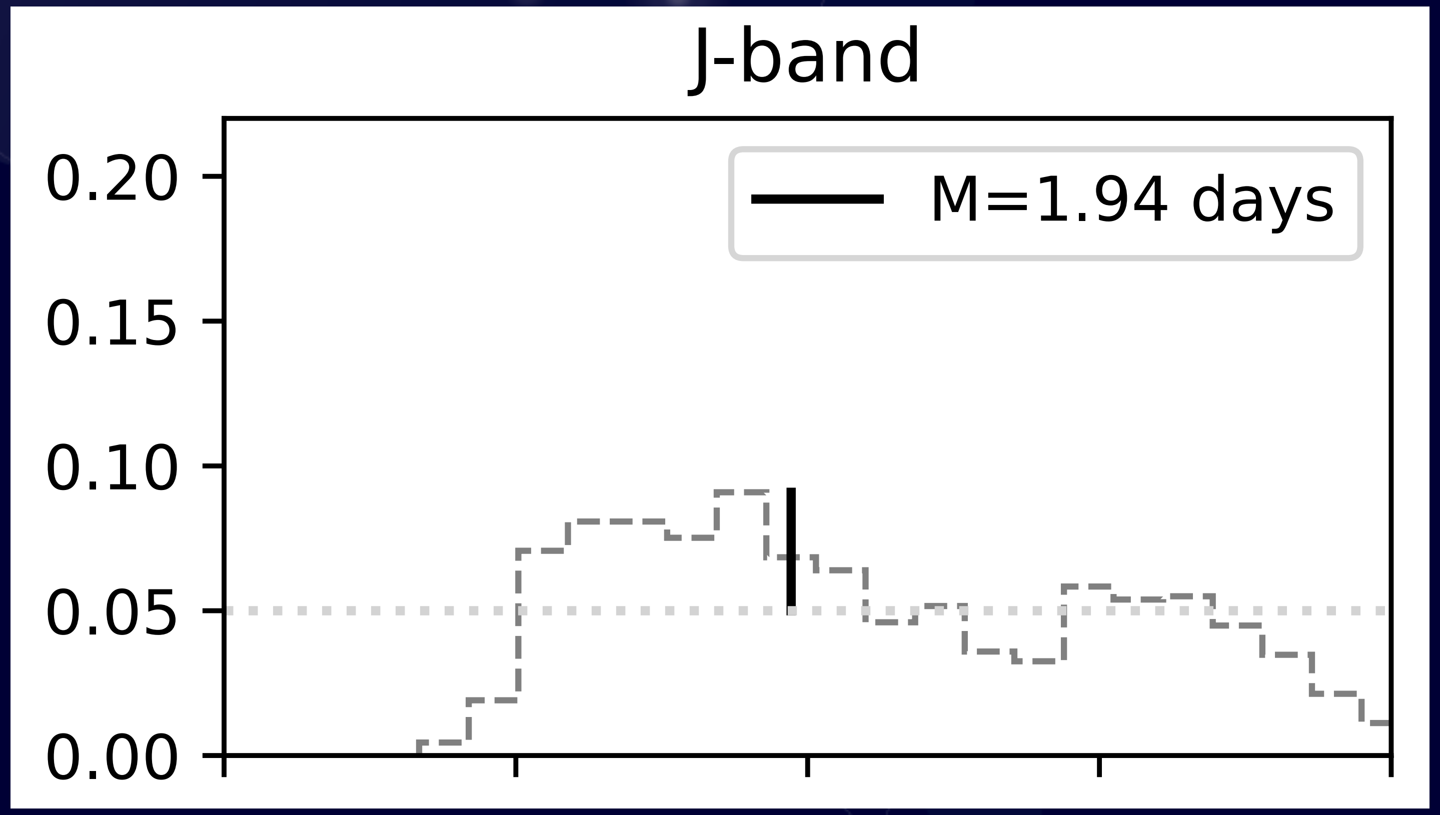
S240422ed: Observations consistent with the peak time of 90% of KN population in o-band.

Observation strategy

- **Discussion 1:**

- Necessity to image the first moment but also the importance of imaging 1 day post-merger
- Prompt strategy has been well demonstrated by the community, the « later time » strategy is not always realized.
- We advocate a more « relaxed » approach for near and infrared for which the peak time of the KN is more random.
- Measurements from the GW signal itself allows us to estimate a range of time at which we expect the maximum brightness → would be an important tool for follow-up.





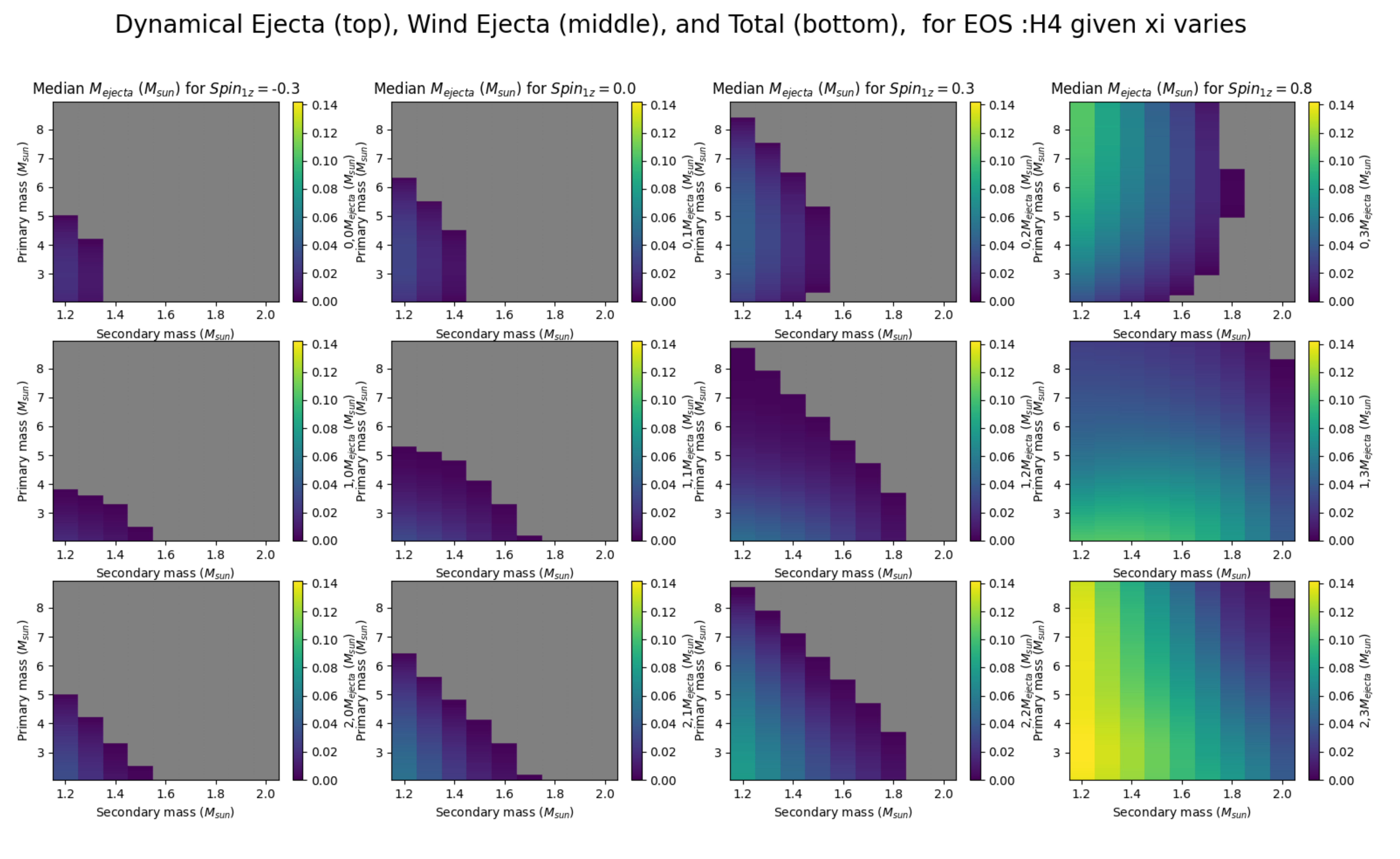
KN associated with O4 NSBH candidates

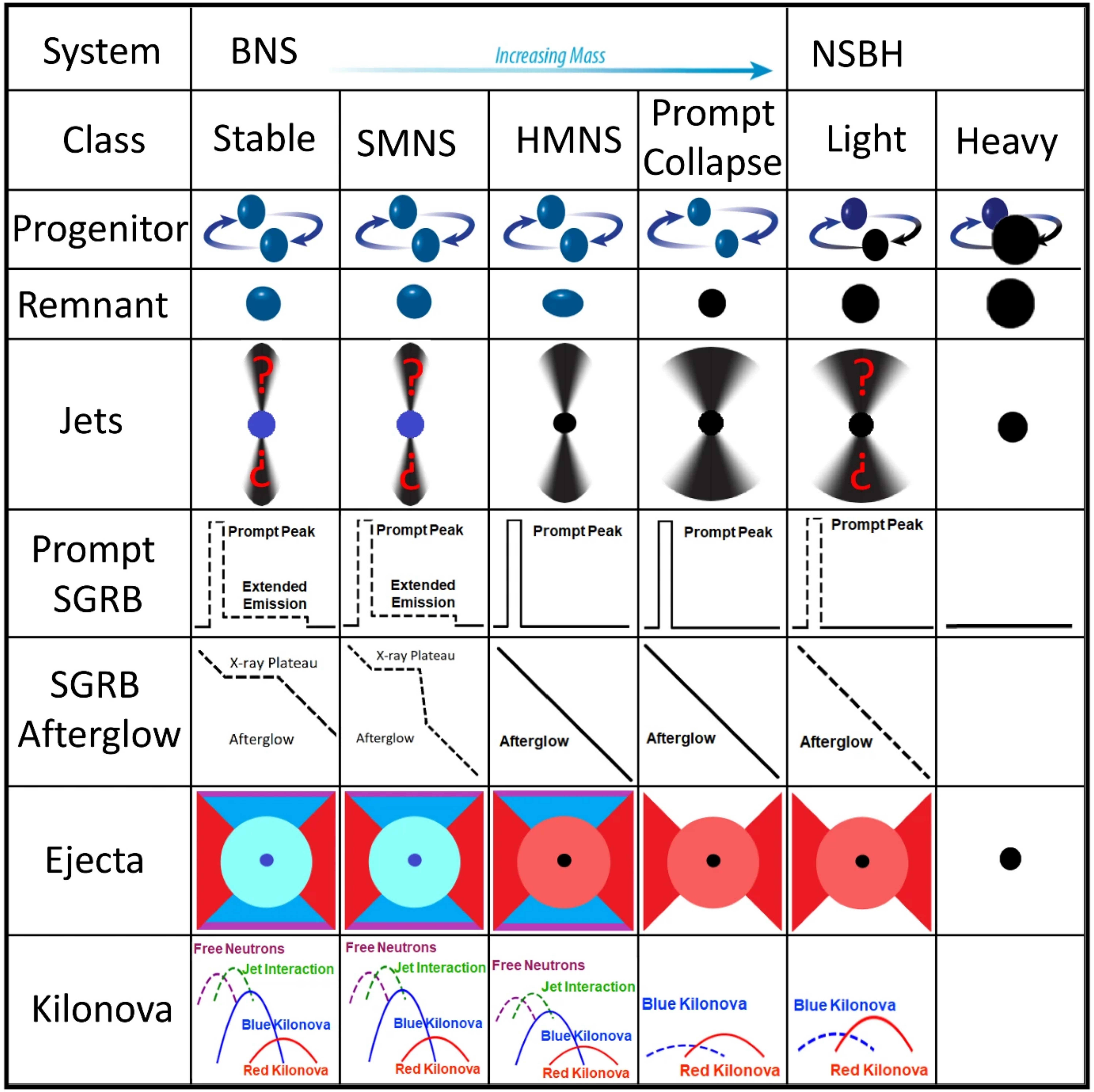
- **Compute a range of consistent ejected masses: m_{dyn}, m_{wind} select a corresponding set simulated of KN light curves**

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: $Spin1z_{\mathrm{BH}} \in \{-0.3, 0.0, 0.3, 0.8\}$ • NS Spin: None
Equation of State of matter	*SLy, H4*

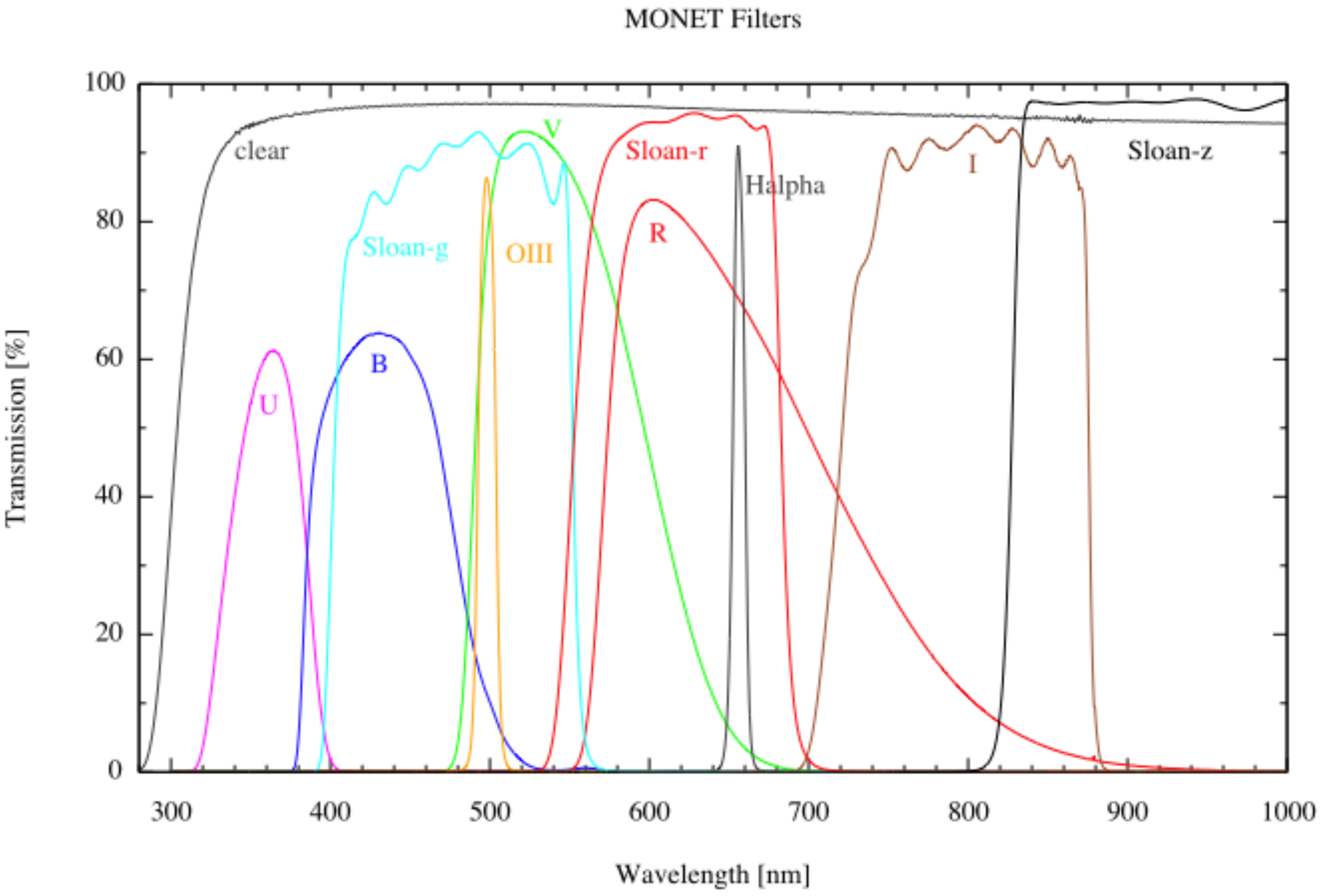
2 scenarios for ejecta computation:

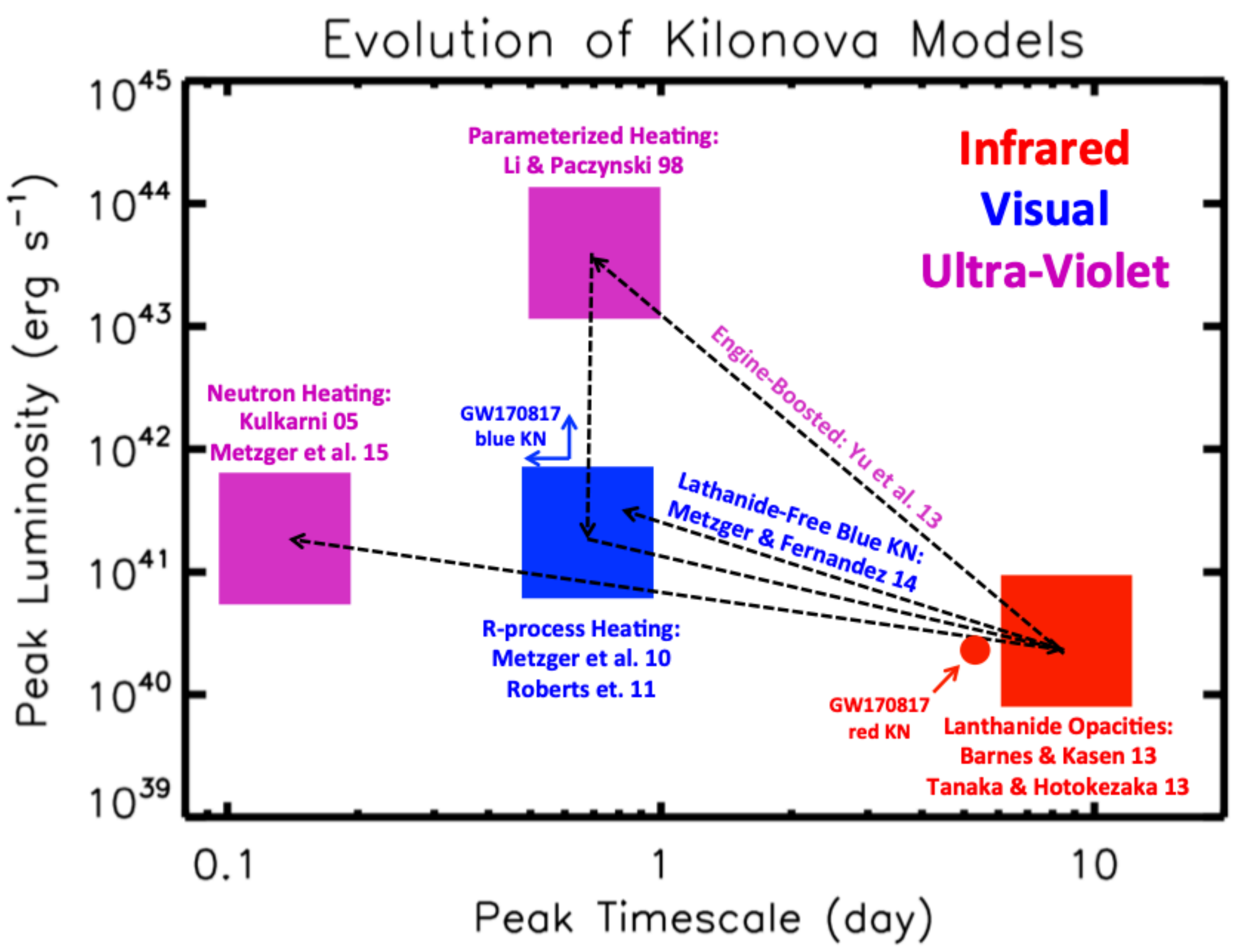
- Optimistic: $Spin1z_{BH}$ = 0.8 & EoS with tidal deformability
- Pessimistic: $Spin1z_{BH}$ = 0 & EoS with rigid NS

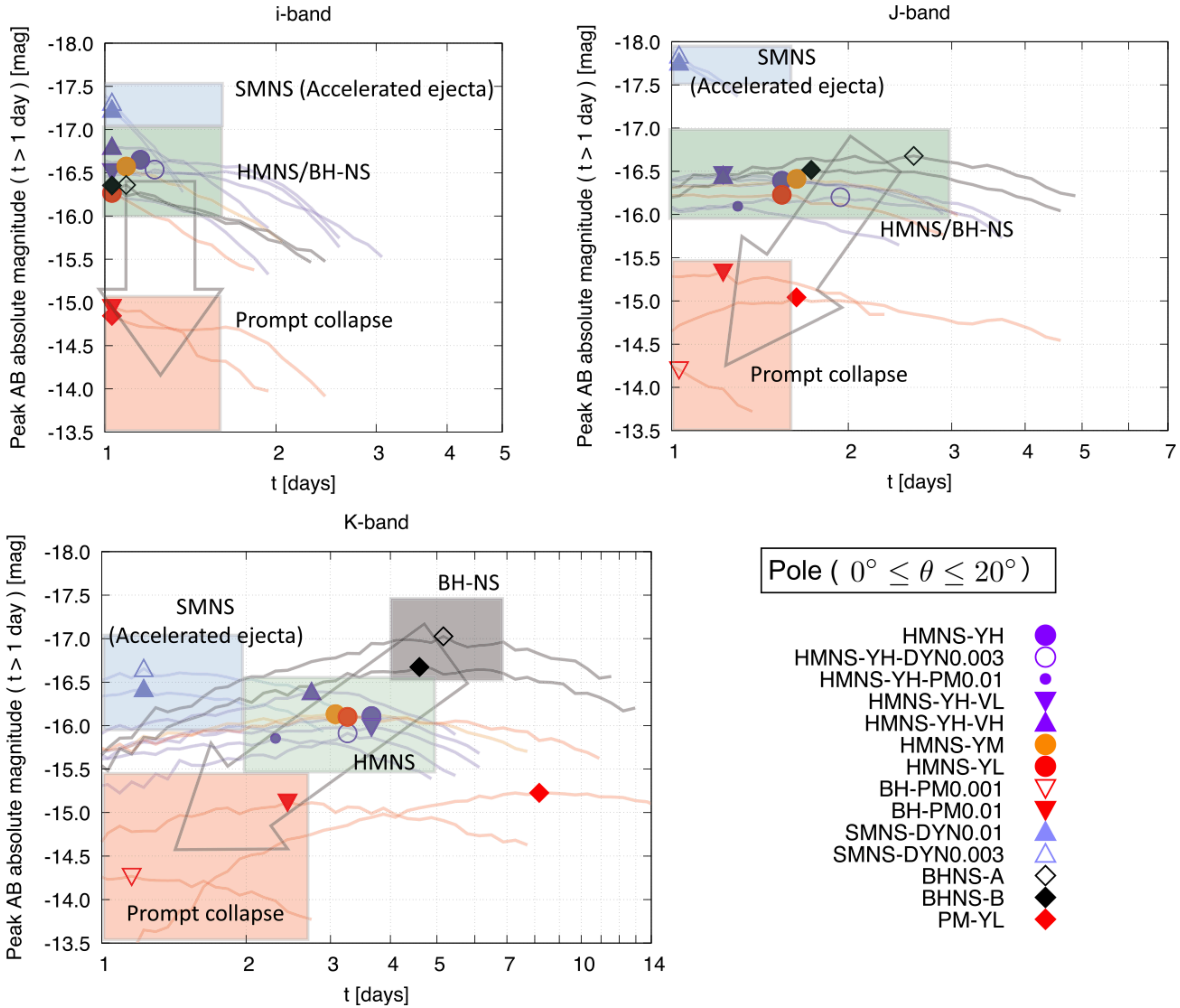



System
BNS
Increasing Mass
NSBH
Class
Stable
SMNS
HMNS
Prompt Collapse
Light
Heavy
Progenitor
Remnant
Jets
Prompt SGRB
Prompt Peak
Extended Emission
SGRB Afterglow
X-ray Plateau
Afterglow
Ejecta
Kilonova
Free Neutrons
Jet Interaction
Blue Kilonova
Red Kilonova

KN associated with O4 NSBH candidates




Evolution of Kilonova Models
Peak Luminosity (erg s^{-1})
Peak Timescale (day)
Infrared
Visual
Ultra-Violet
Parameterized Heating: Li & Paczynski 98
Neutron Heating: Kulkarni 05 Metzger et al. 15
GW170817 blue KN
R-process Heating: Metzger et al. 10 Roberts et. 11
Lathanide-Free Blue KN: Metzger & Fernandez 14
Engine-Boosted: Yu et al. 13
GW170817 red KN
Lanthanide Opacities: Barnes & Kasen 13 Tanaka & Hotokezaka 13

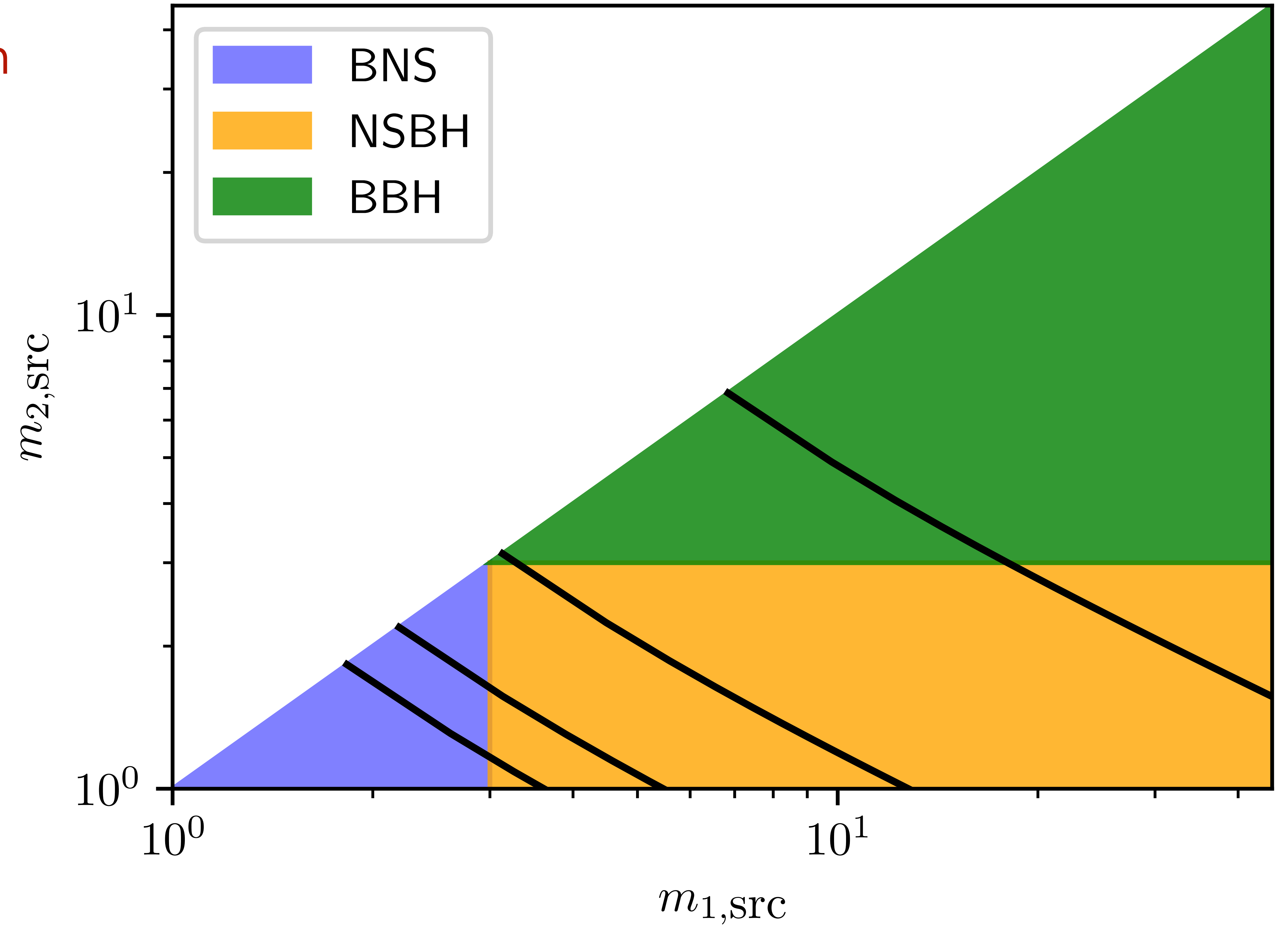

i-band
J-band
K-band
Peak AB absolute magnitude (t > 1 day) [mag]
t [days]
SMNS (Accelerated ejecta)
HMNS/BH-NS
Prompt collapse
HMNS
BH-NS
Pole ($0^\circ \leq \theta \leq 20^\circ$)
HMNS-YH
HMNS-YH-DYN0.003
HMNS-YH-PM0.01
HMNS-YH-VL
HMNS-YH-VH
HMNS-YM
HMNS-YL
BH-PM0.001
BH-PM0.01
SMNS-DYN0.01
SMNS-DYN0.003
BHNS-A
BHNS-B
PM-YL

KN associated with O4 NSBH candidates

- PyCBC Live method to compute the p_{astro}: deterministic mapping between the source-frame chirp mass and its source classification probabilities
- Assumptions:
  - Astrophysical origin of the event
  - Uniform mass distribution in source-frame component masses
  - Only the detector-frame chirp mass is well measured
- Redshift estimate derived from effective distance and SNR to estimate the $\mathscr{M}_{src}$ from a detector-frame point estimate

→ process reversed

- Uncertainty derived from the one on the distance



Candidate	BNS	NSBH	BBH	$\mathcal{M}_{src}$ $[M_\odot]$
S230518h	0	0.959	0.041	$2.73^{+.07}_{-.06}$
S230529ay	0.329	0.671	0	$1.91^{+.06}_{-.05}$
S230627c	0	0.493	0.507	$5.96^{+.18}_{-.17}$
S240422ed	0.700	0.300	0	$1.60^{+.04}_{-.04}$

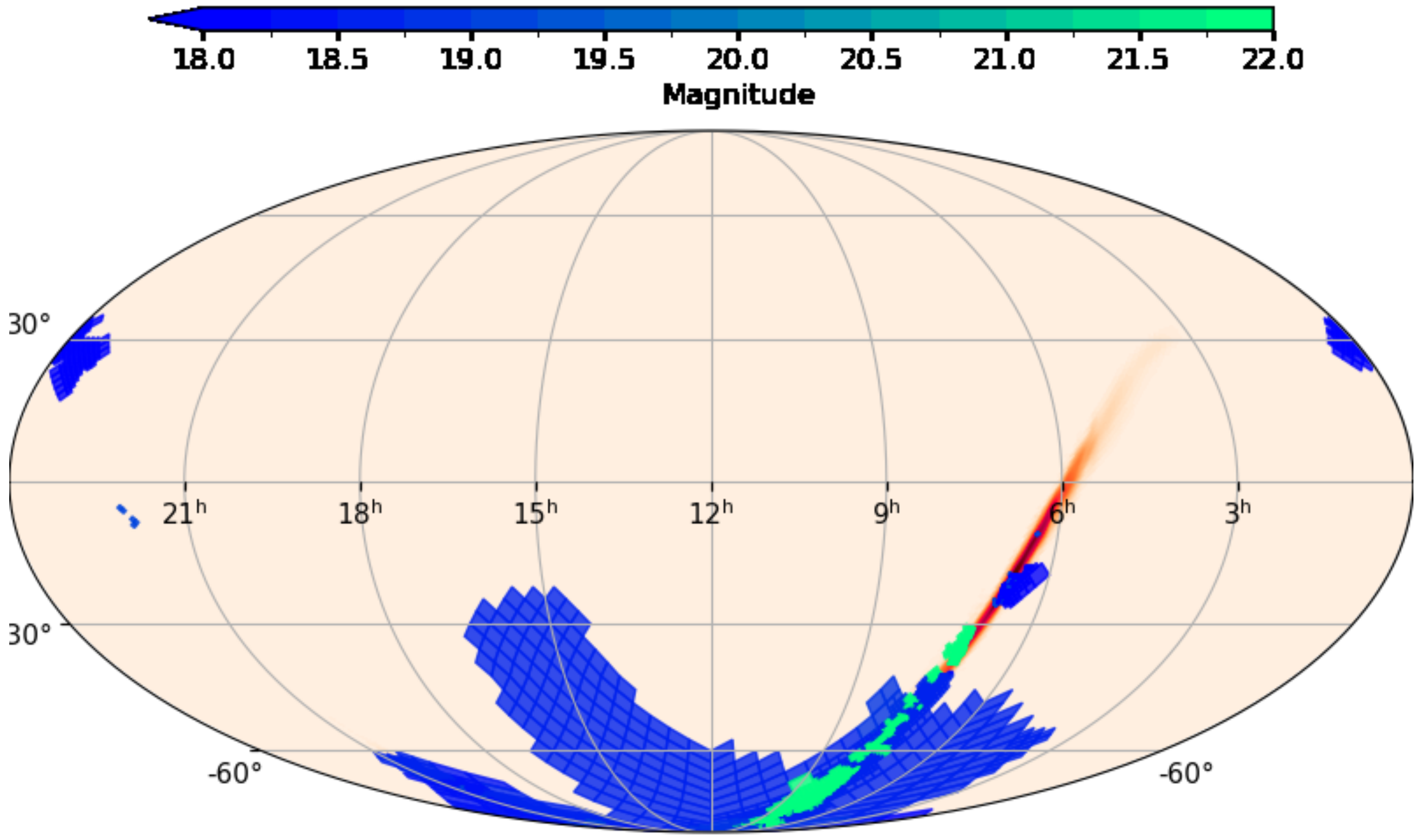
Consistent with public results about GW230529

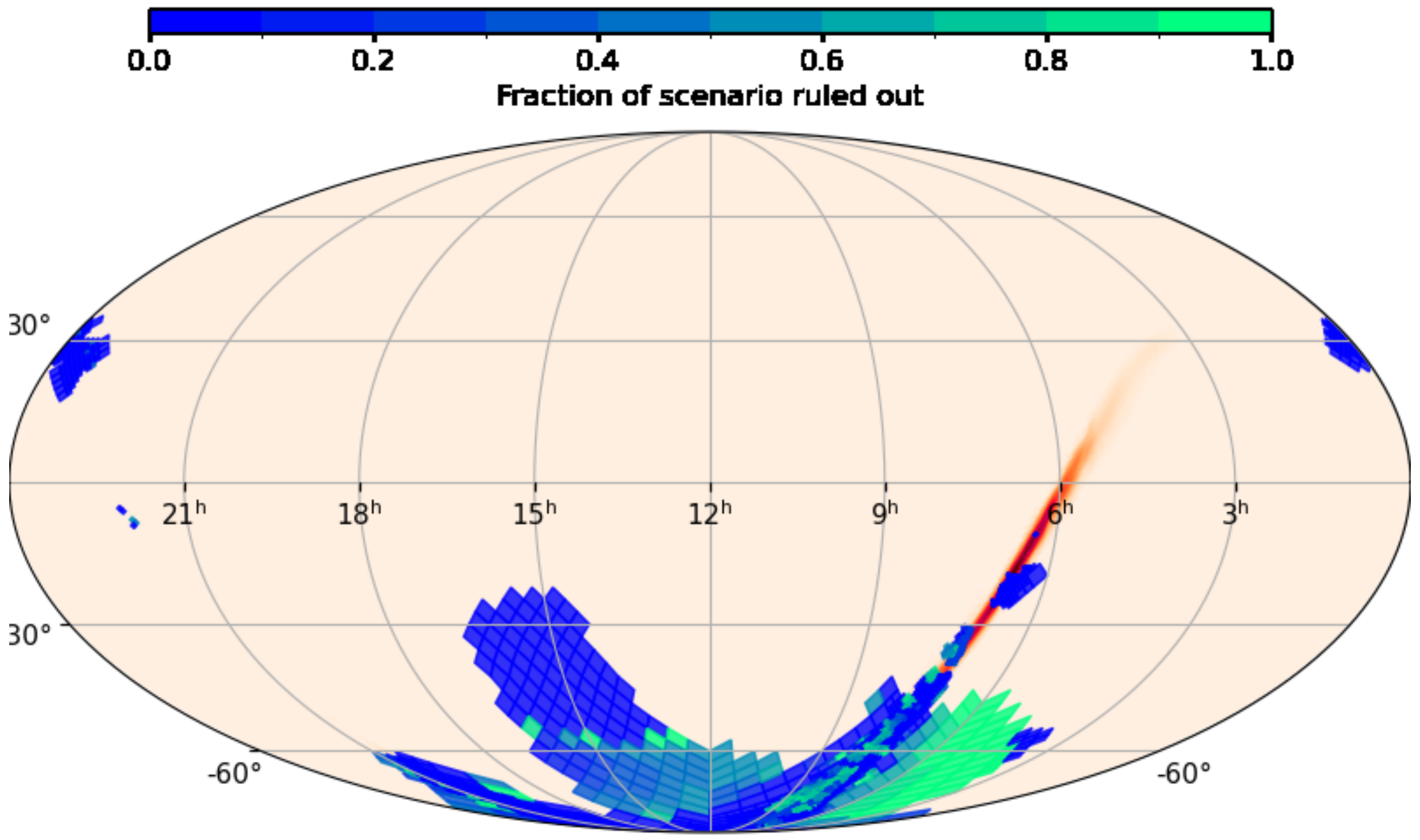
KN associated with O4 NSBH candidates

	mchirp	$spin1z, BH = 0.0$ ($M_\odot$)	$spin1z, BH = 0.8$ ($M_\odot$)
m_{dyn}	any	$SLy < 0.01$ $H4 < 0.03$	$SLy < 0.06$, $H4 < 0.10$
	1.6	$SLy < 0.01$, $H4 < 0.03$	$SLy < 0.04$, $H4 < 0.07$
	2.0	-, $H4 < 0.03$	$SLy < 0.06$, $H4 < 0.09$
	2.4		$SLy < 0.06$, $H4 < 0.1$
	2.8	-	$SLy < 0.03$, $H4 < 0.08$
	3.2	-	- $H4 < 0.03$
m_{wind}	any	$SLy < 0.02$, $H4 < 0.03$	$SLy < 0.09$, $H4 < 0.11$
	1.6	$SLy < 0.01$, $H4 < 0.03$	$SLy < 0.09$, $H4 < 0.11$
	2.0	-, $H4 < 0.01$	$SLy < 0.06$, $H4 < 0.09$
	2.4	-	$SLy < 0.04$, $H4 < 0.06$
	2.8	-	$SLy < 0.02$, $H4 < 0.04$
	3.2	-	$SLy < 0.01$, $H4 < 0.02$
$Total$	any	$SLy < 0.02$, $H4 < 0.05$	$SLy < 0.11$, $H4 < 0.16$
	1.6	$SLy < 0.02$, $H4 < 0.05$	$SLy < 0.11$, $H4 < 0.14$
	2.0	$SLy < 0.001$, $H4 < 0.04$	$SLy < 0.10$, $H4 < 0.14$
	2.4	-	$SLy < 0.09$, $H4 < 0.14$
	2.8	-	$SLy < 0.05$, $H4 < 0.11$
	3.2	-	-, $SLy < 0.01$,$H4 < 0.05$

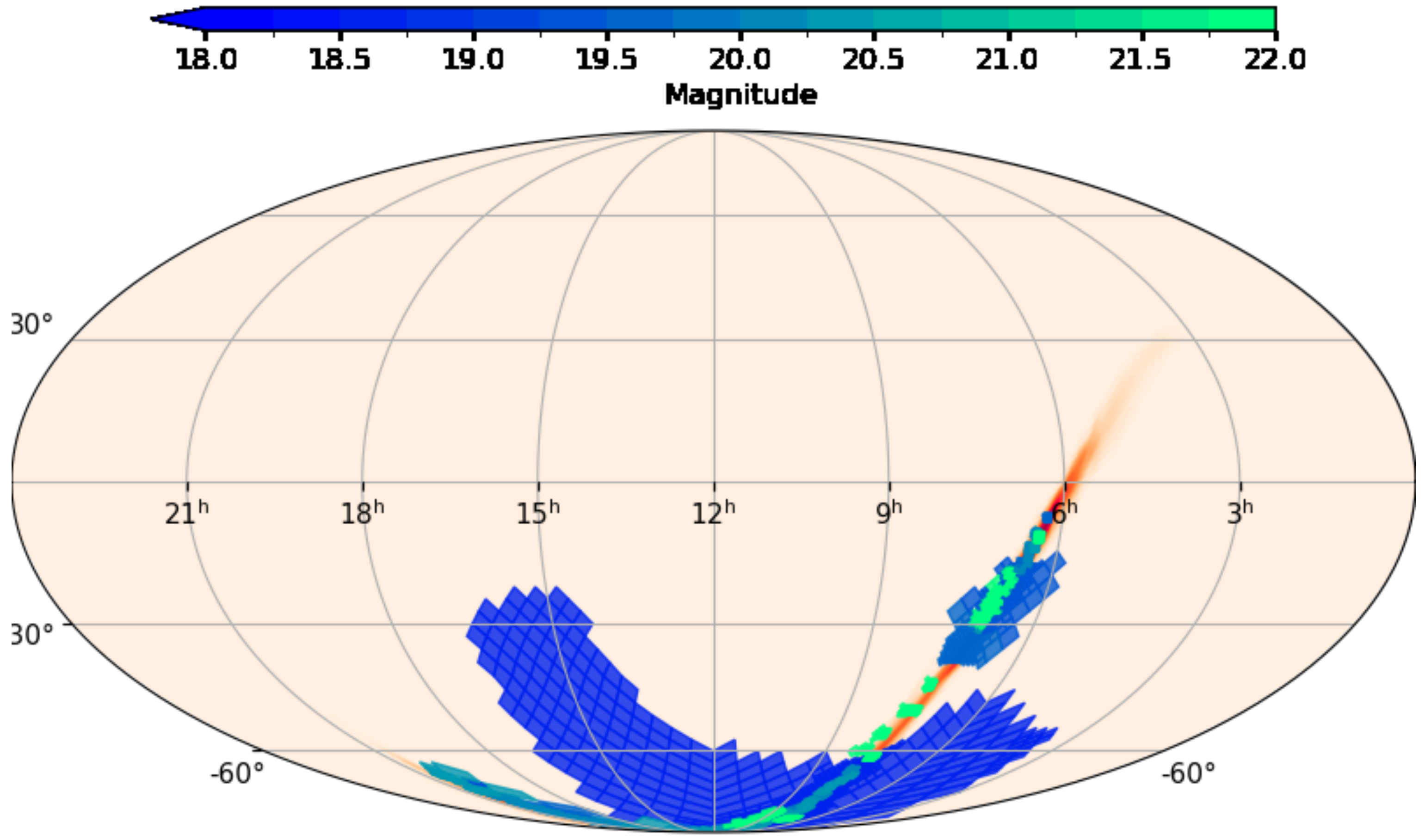
S230518h

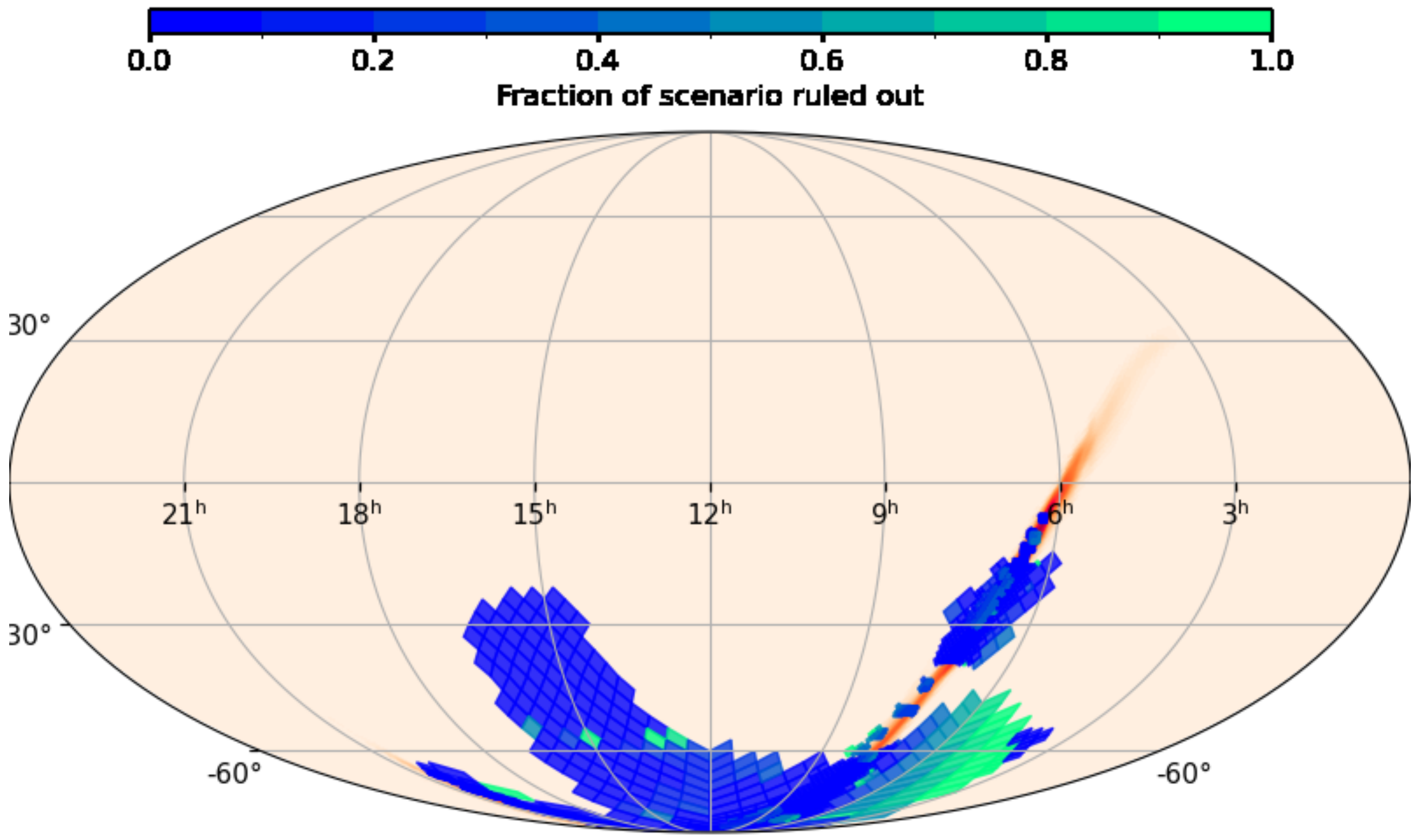
Between 0 and 1 day



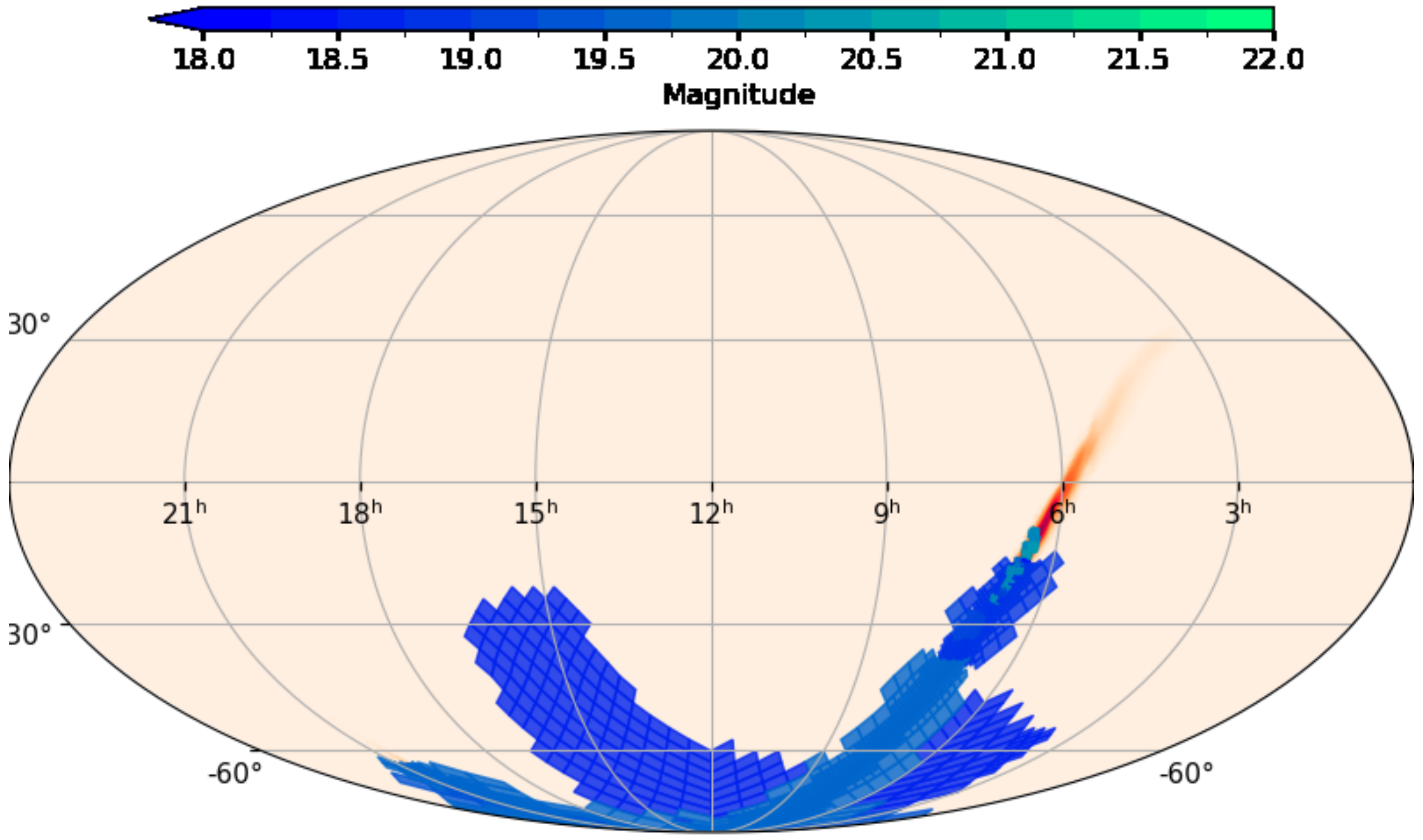


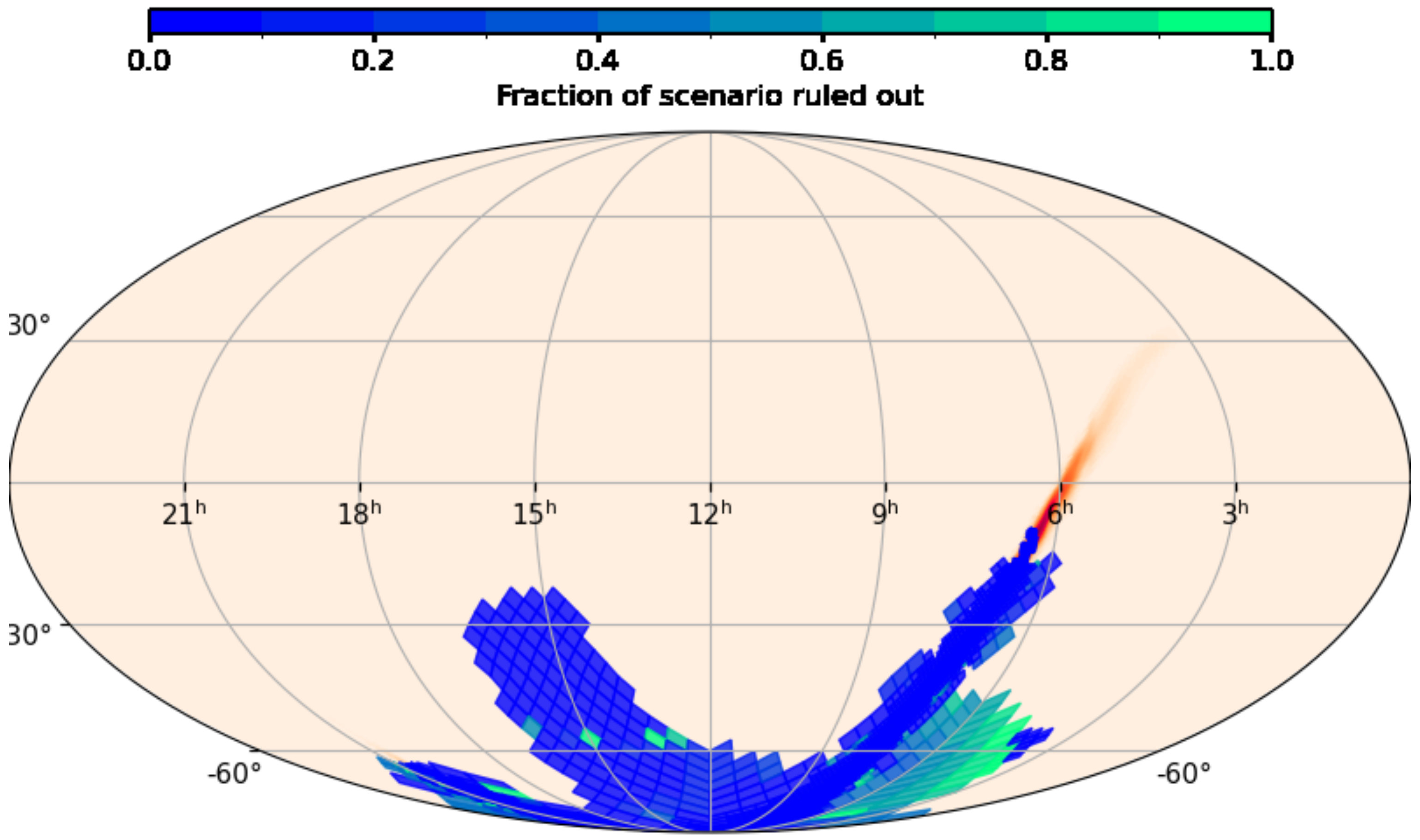
Between 1 and 2 day



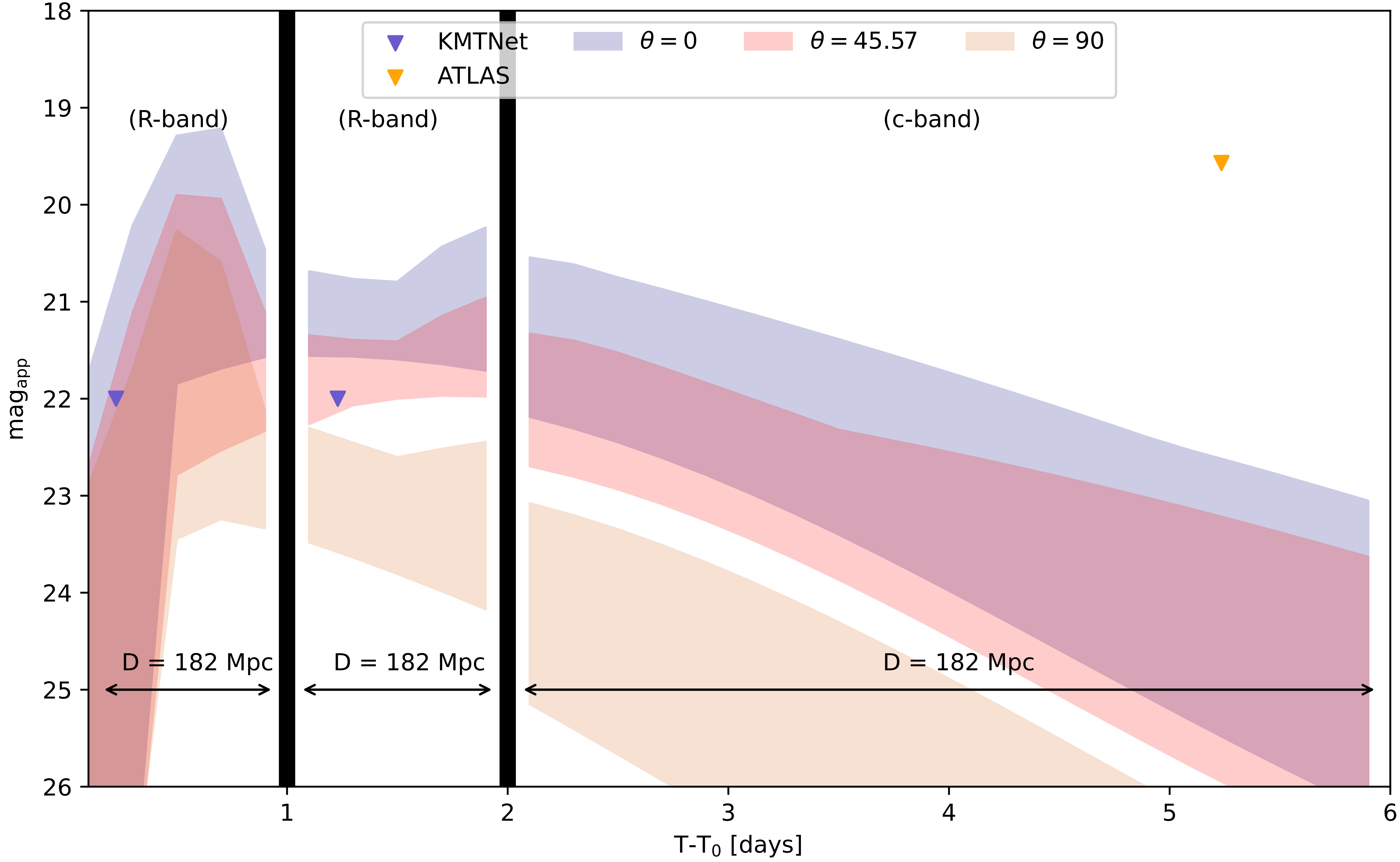


Between 2 and 6 day





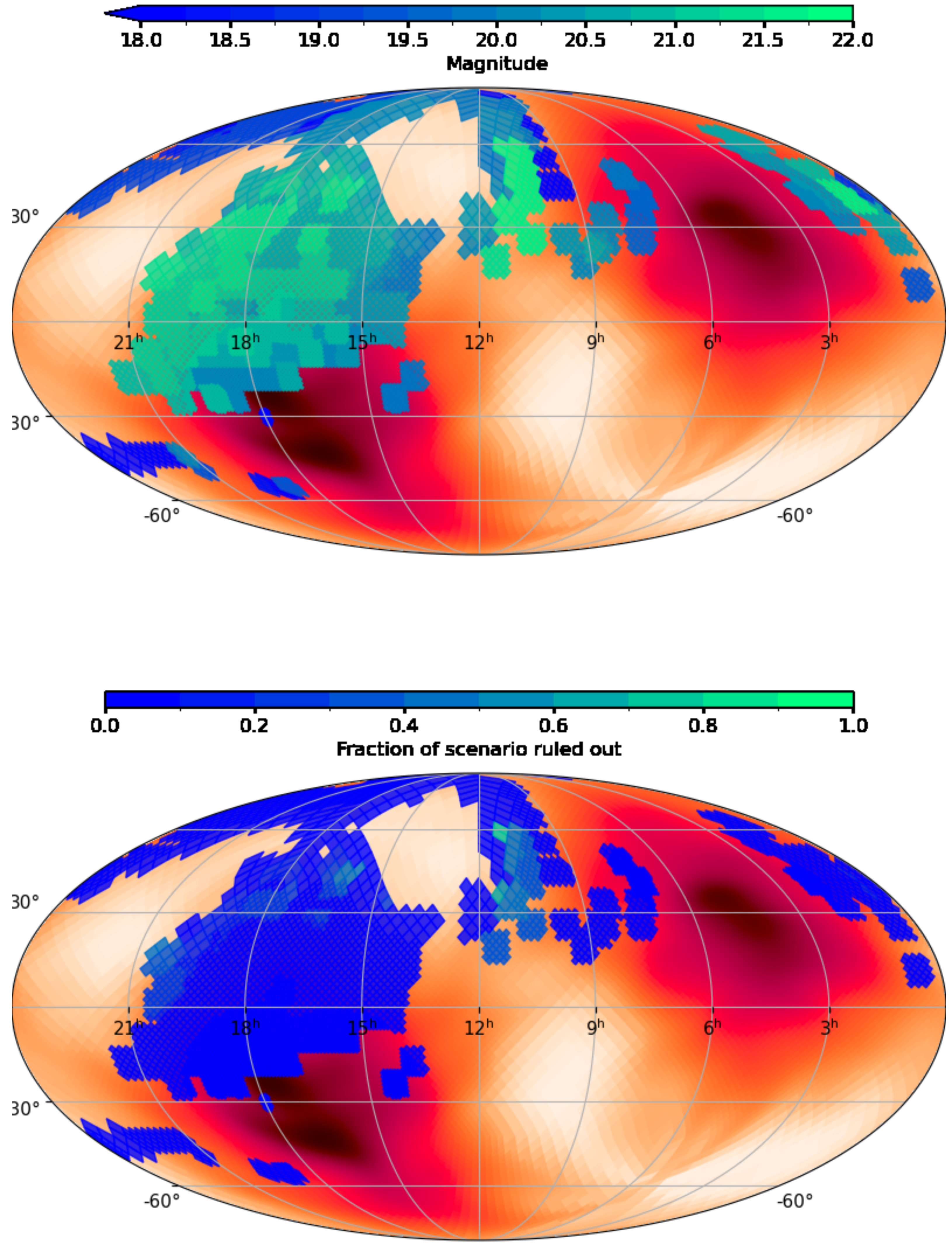
S230518h



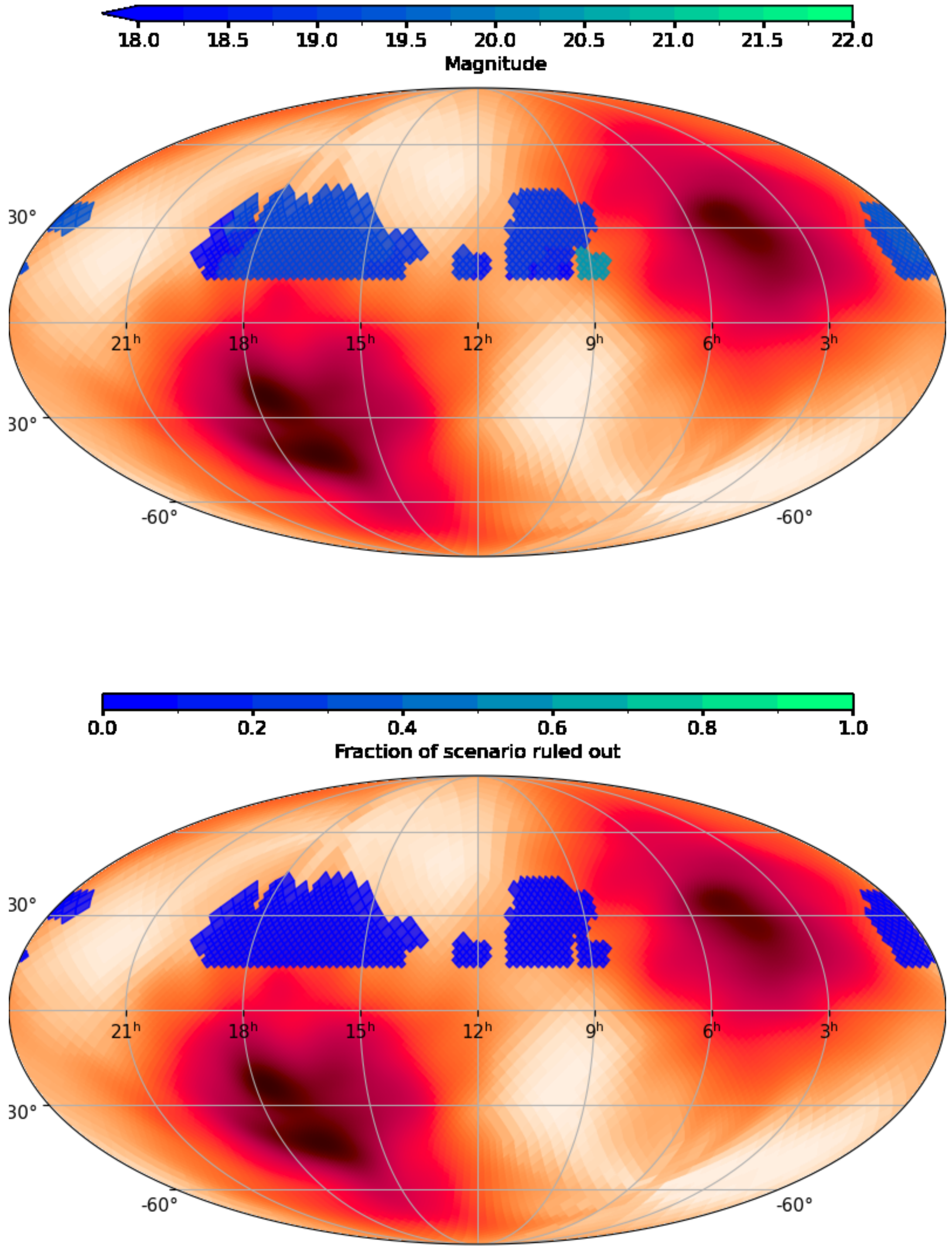
KMTNet
ATLAS
$\theta = 0$
$\theta = 45.57$
$\theta = 90$
(R-band)
(R-band)
(c-band)
D = 182 Mpc
D = 182 Mpc
D = 182 Mpc
mag_{app}
T-T_0 [days]
18
19
20
21
22
23
24
25
26
1
2
3
4
5
6

GW230529

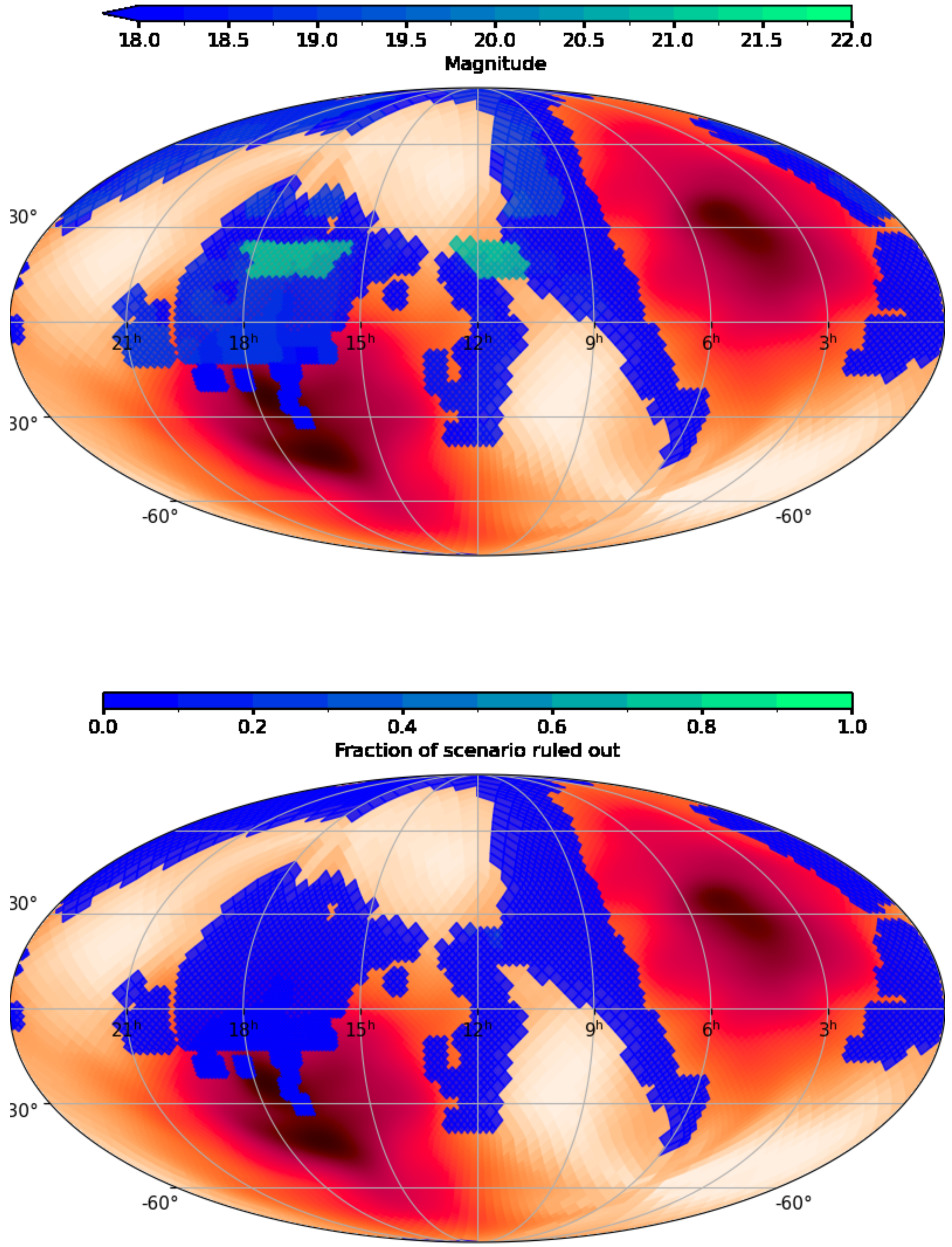
Between 0 and 1 day



Between 1 and 2 day

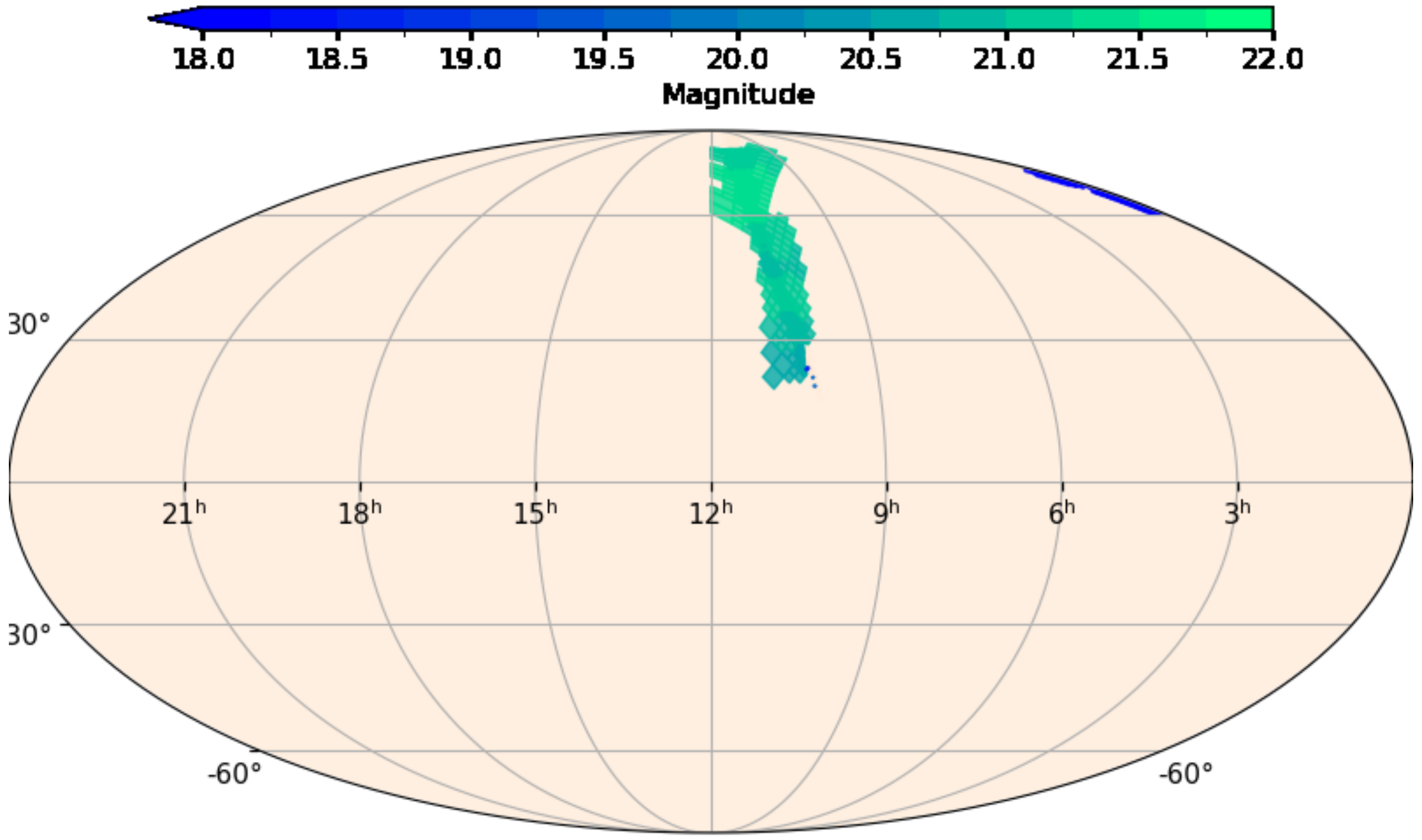


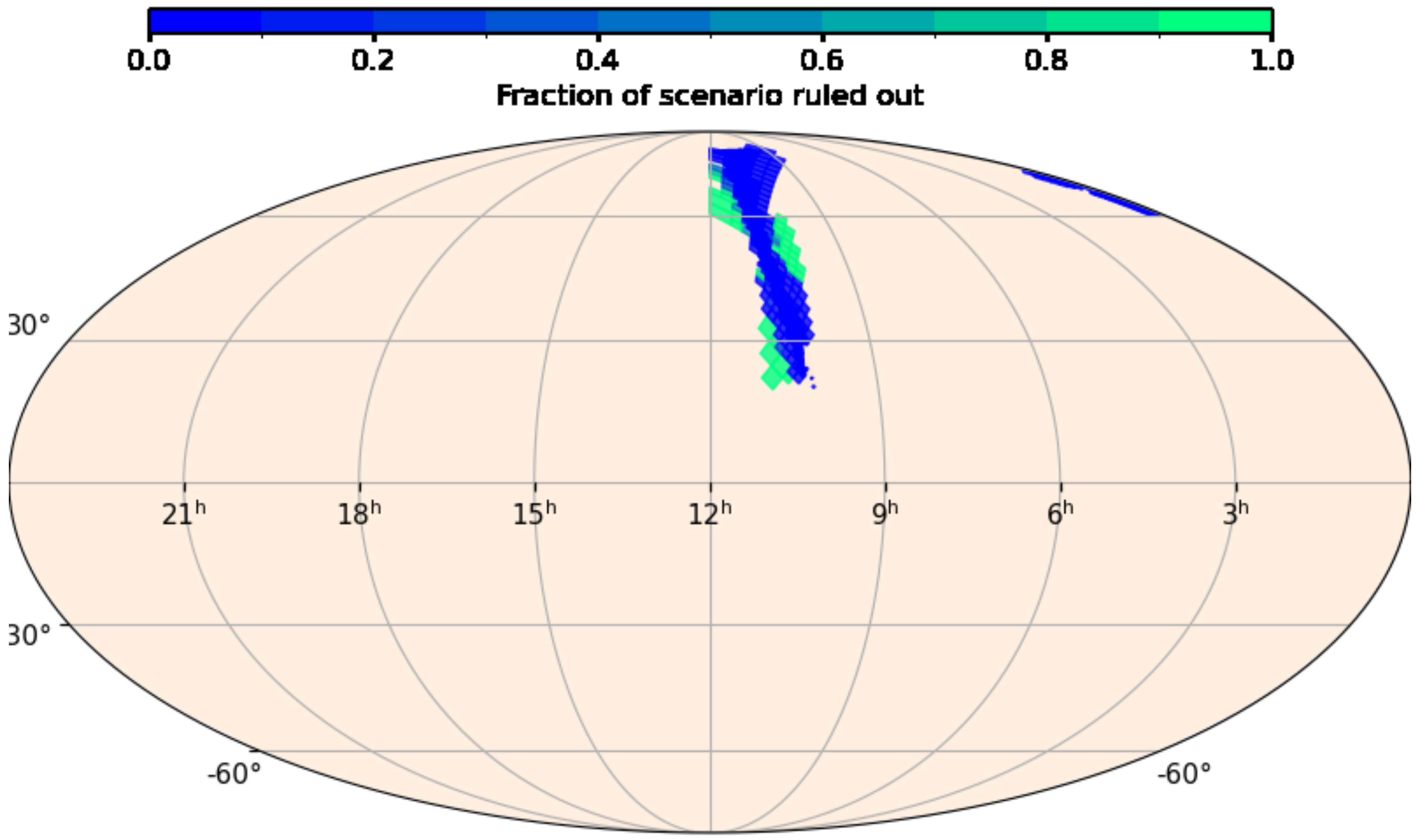
Between 2 and 6 day



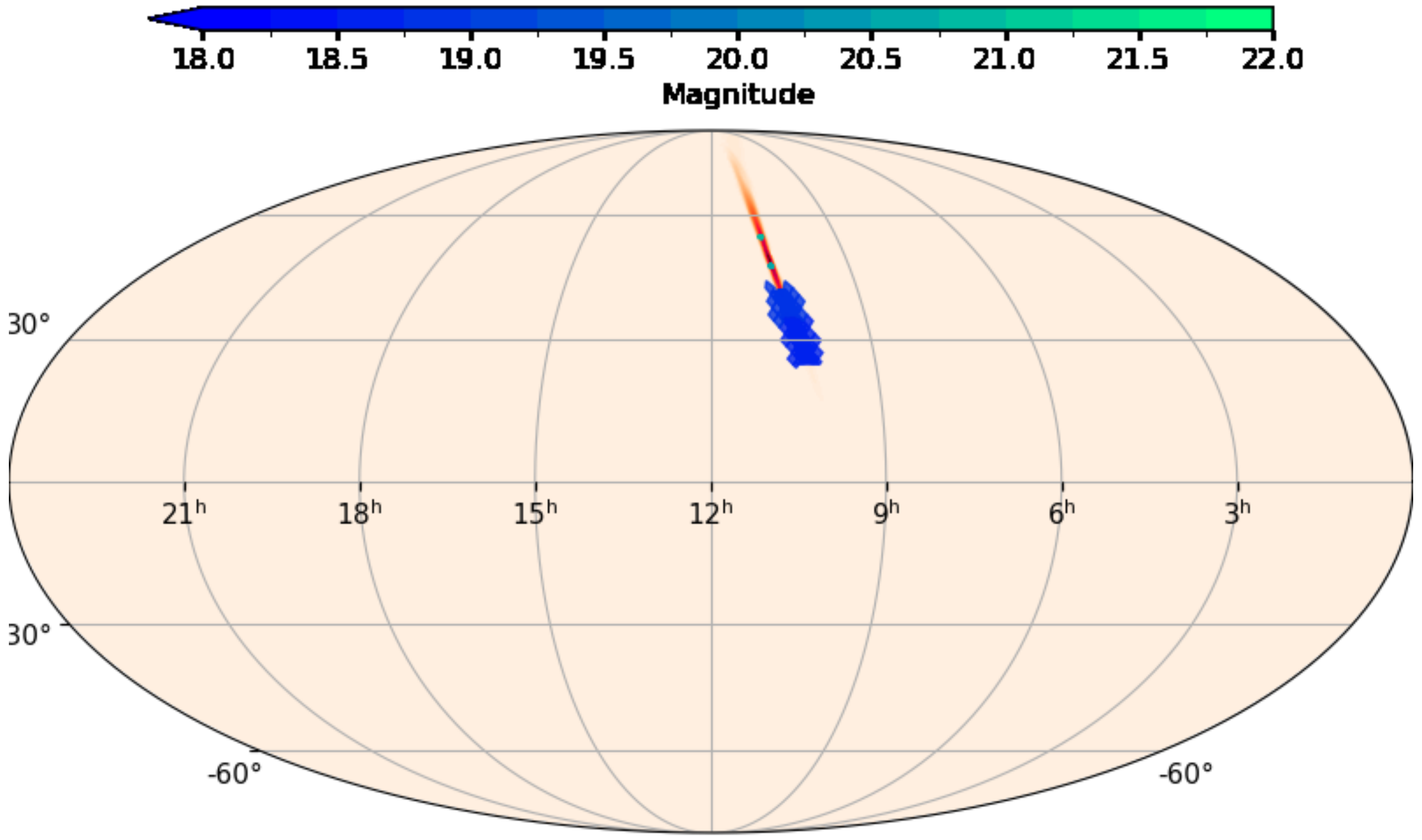
S230627c

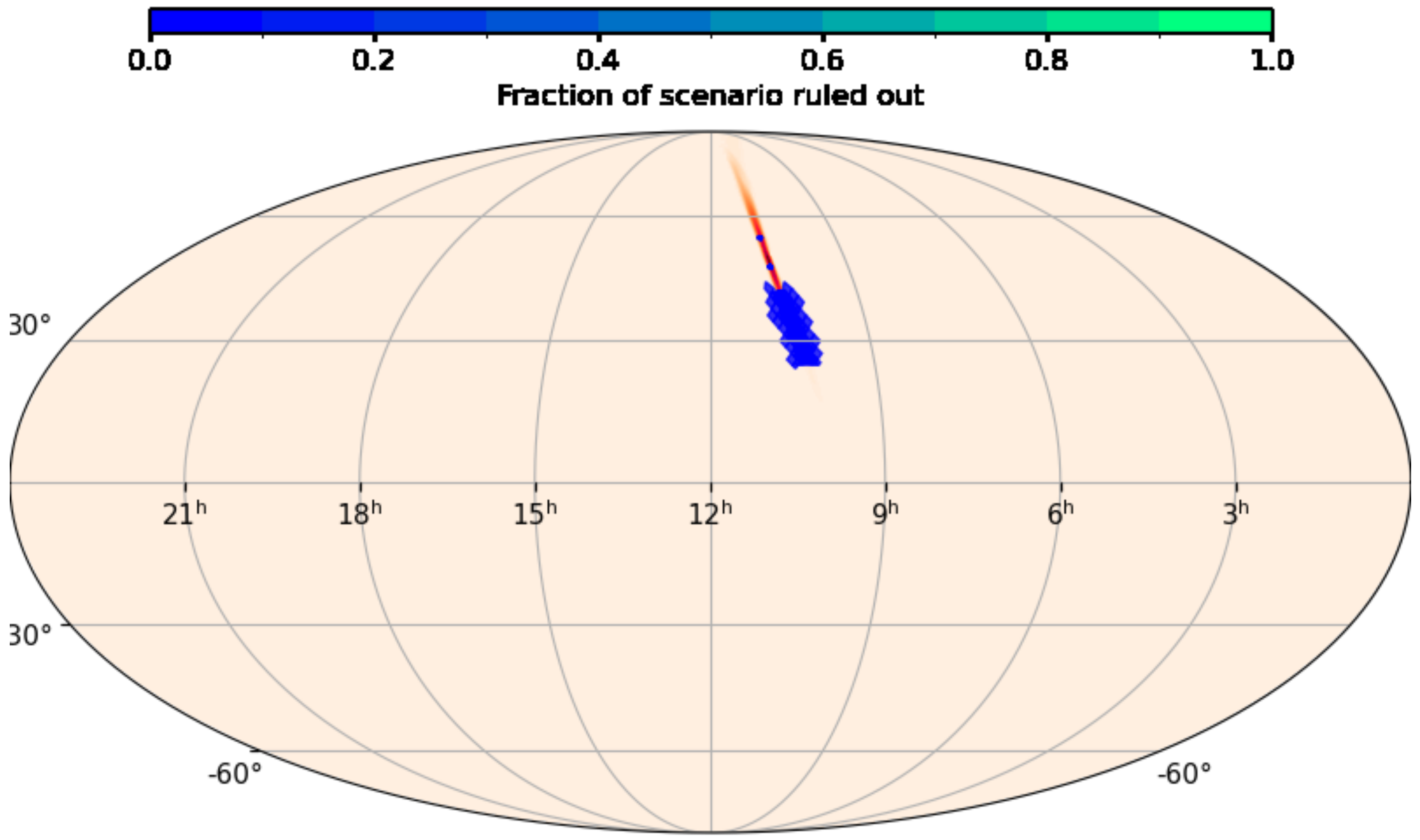
Between 0 and 1 day



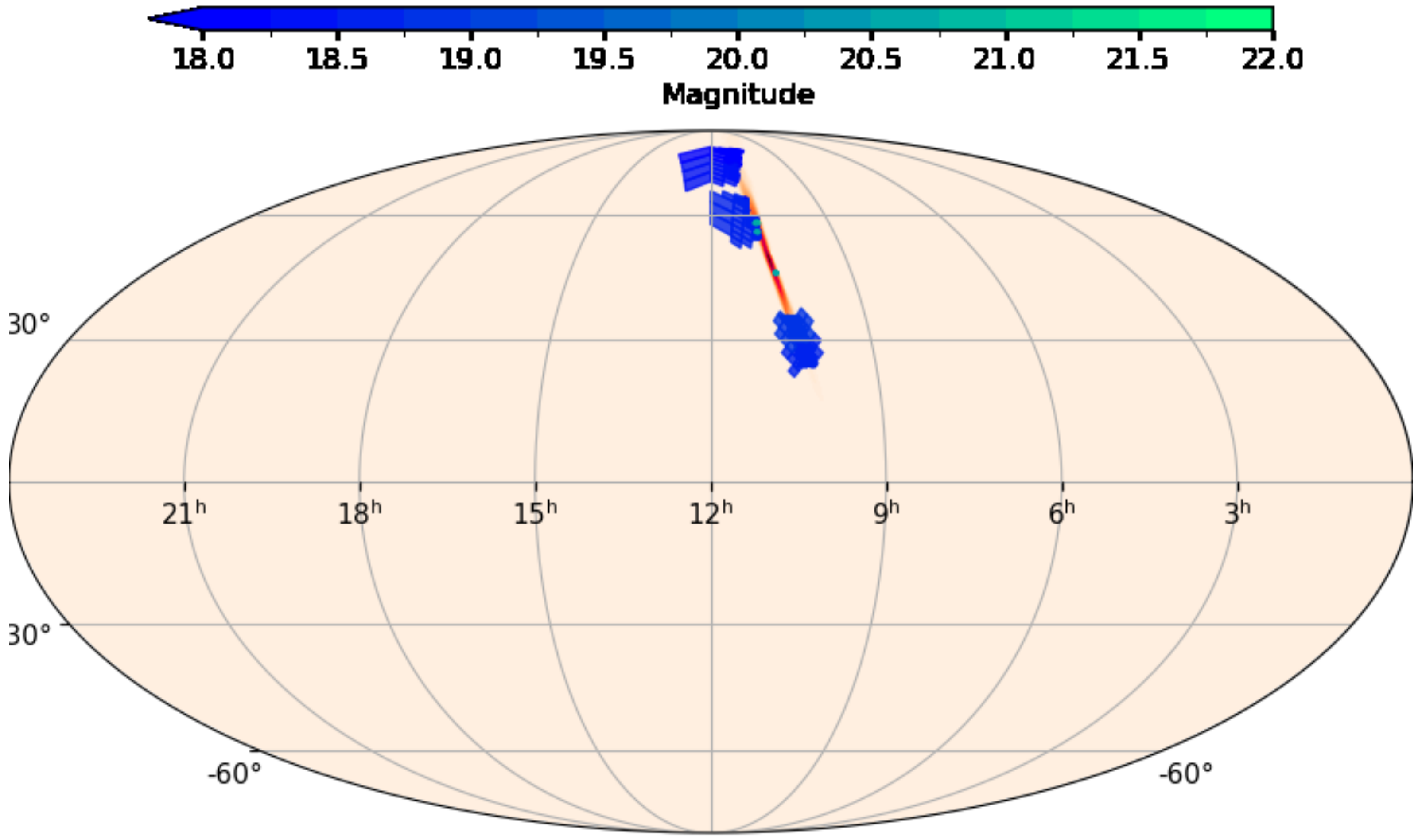


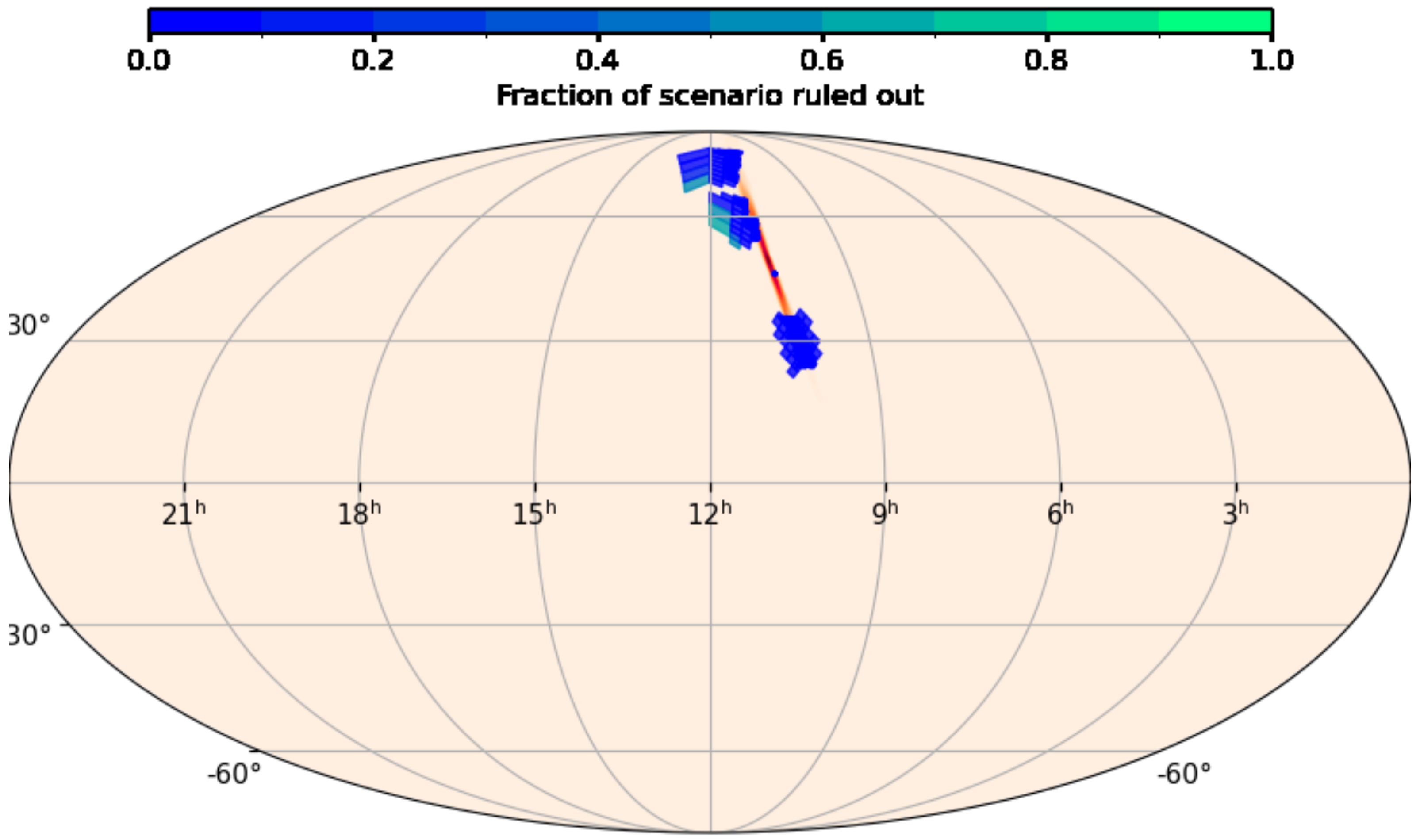
Between 1 and 2 day



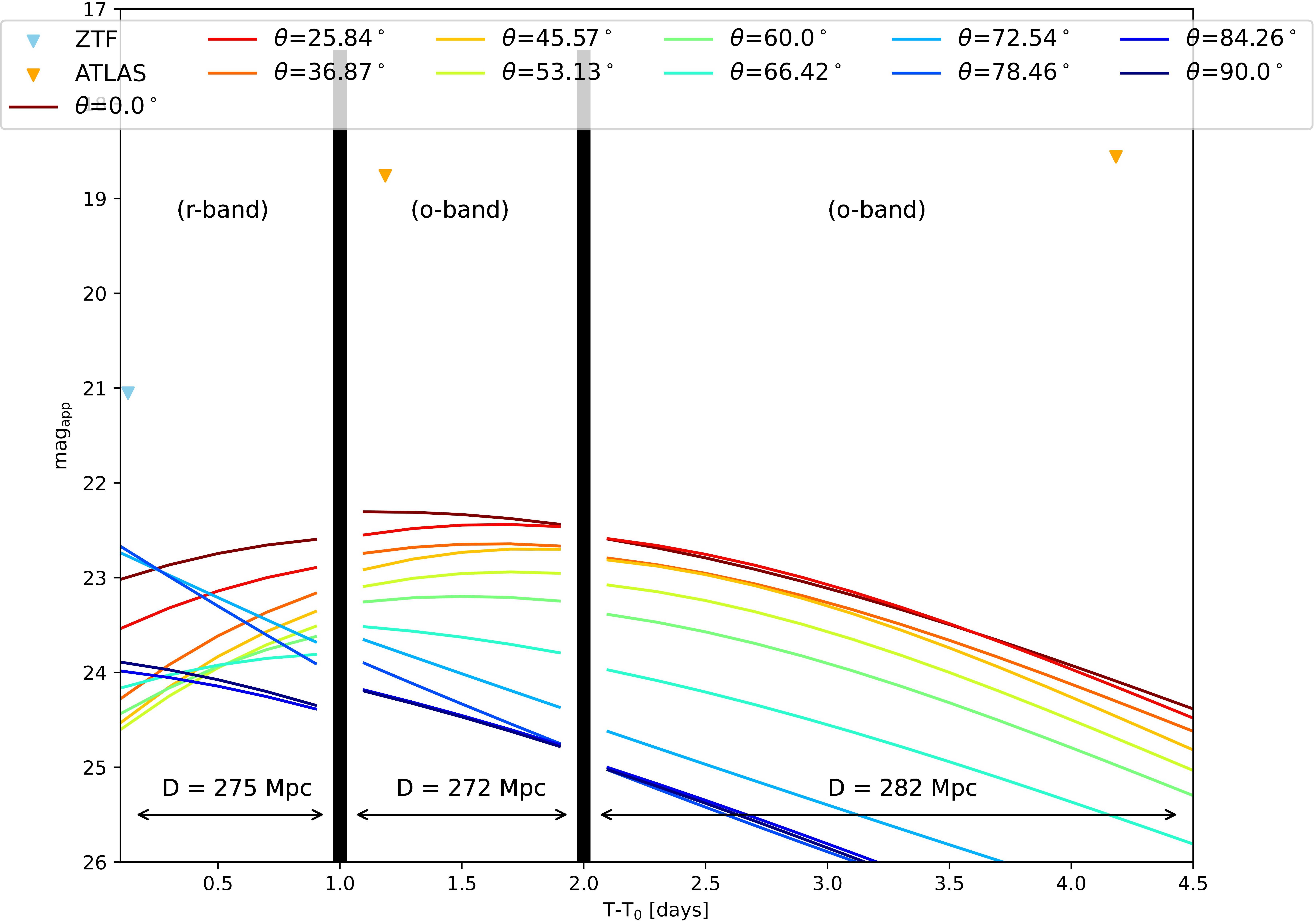


Between 2 and 6 day



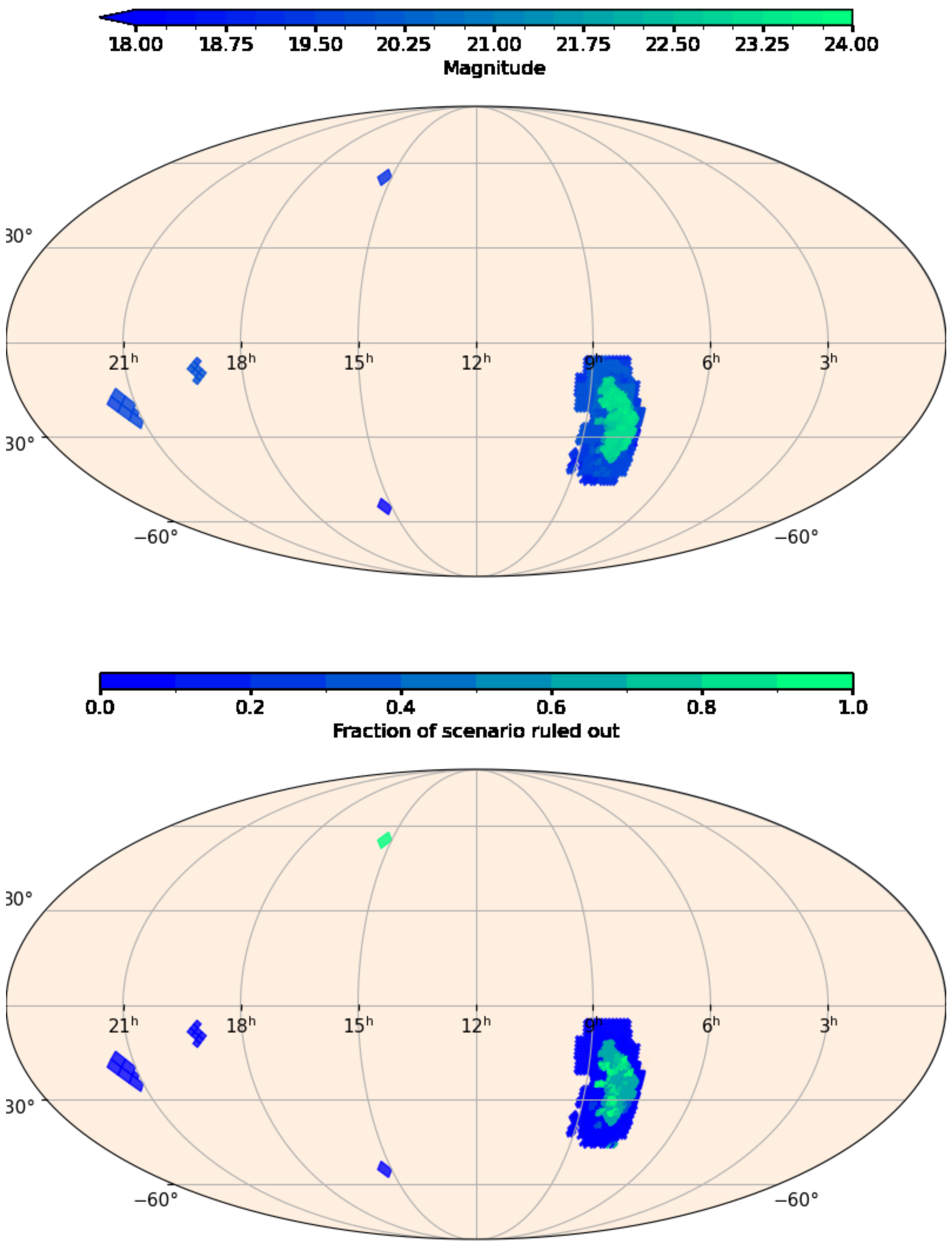


S230627c

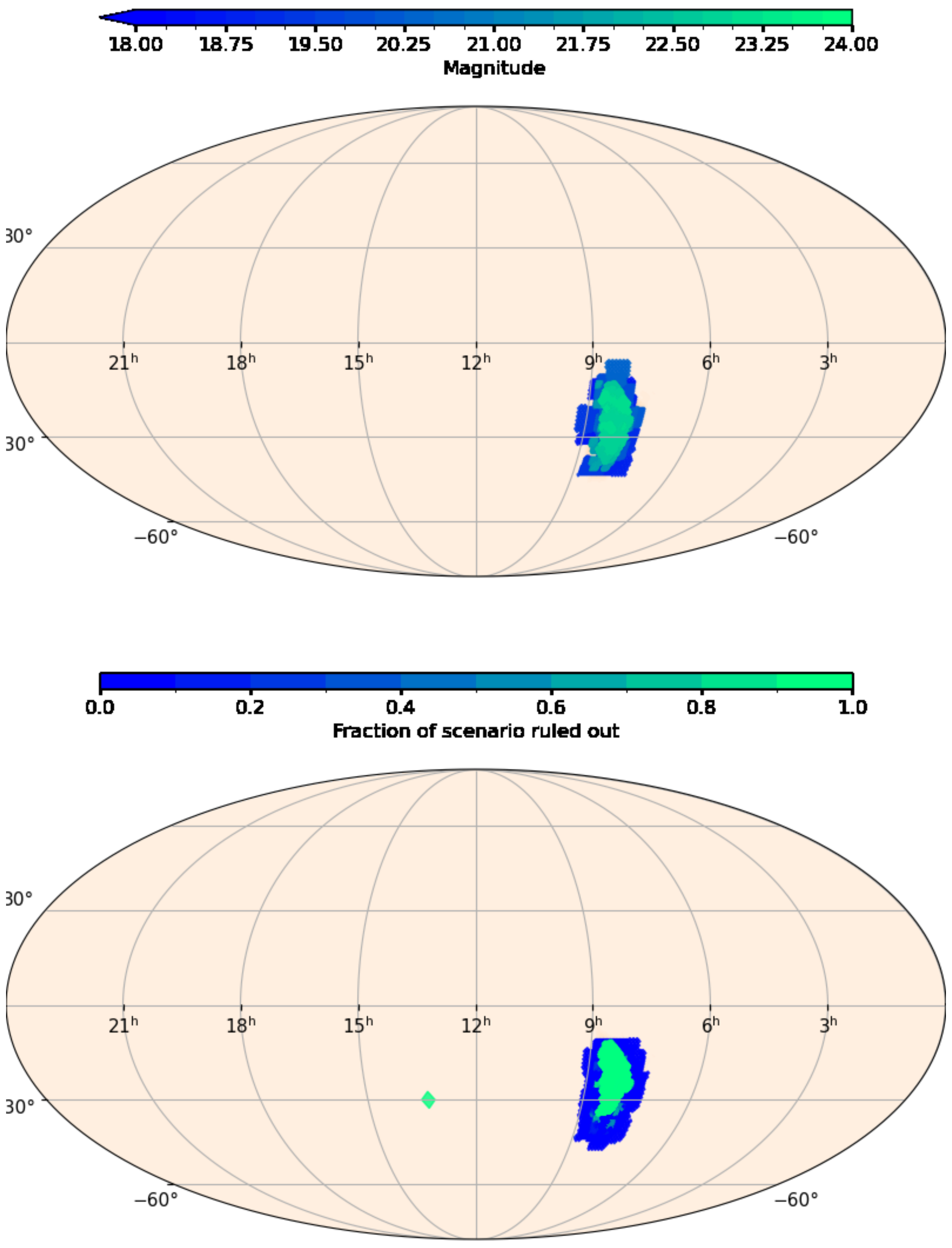

ZTF
ATLAS
θ=0.0°
θ=25.84°
θ=36.87°
θ=45.57°
θ=53.13°
θ=60.0°
θ=66.42°
θ=72.54°
θ=78.46°
θ=84.26°
θ=90.0°
(r-band)
(o-band)
(o-band)
D = 275 Mpc
D = 272 Mpc
D = 282 Mpc
mag_app
T-T0 [days]
17
19
20
21
22
23
24
25
26
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5

S240422ed

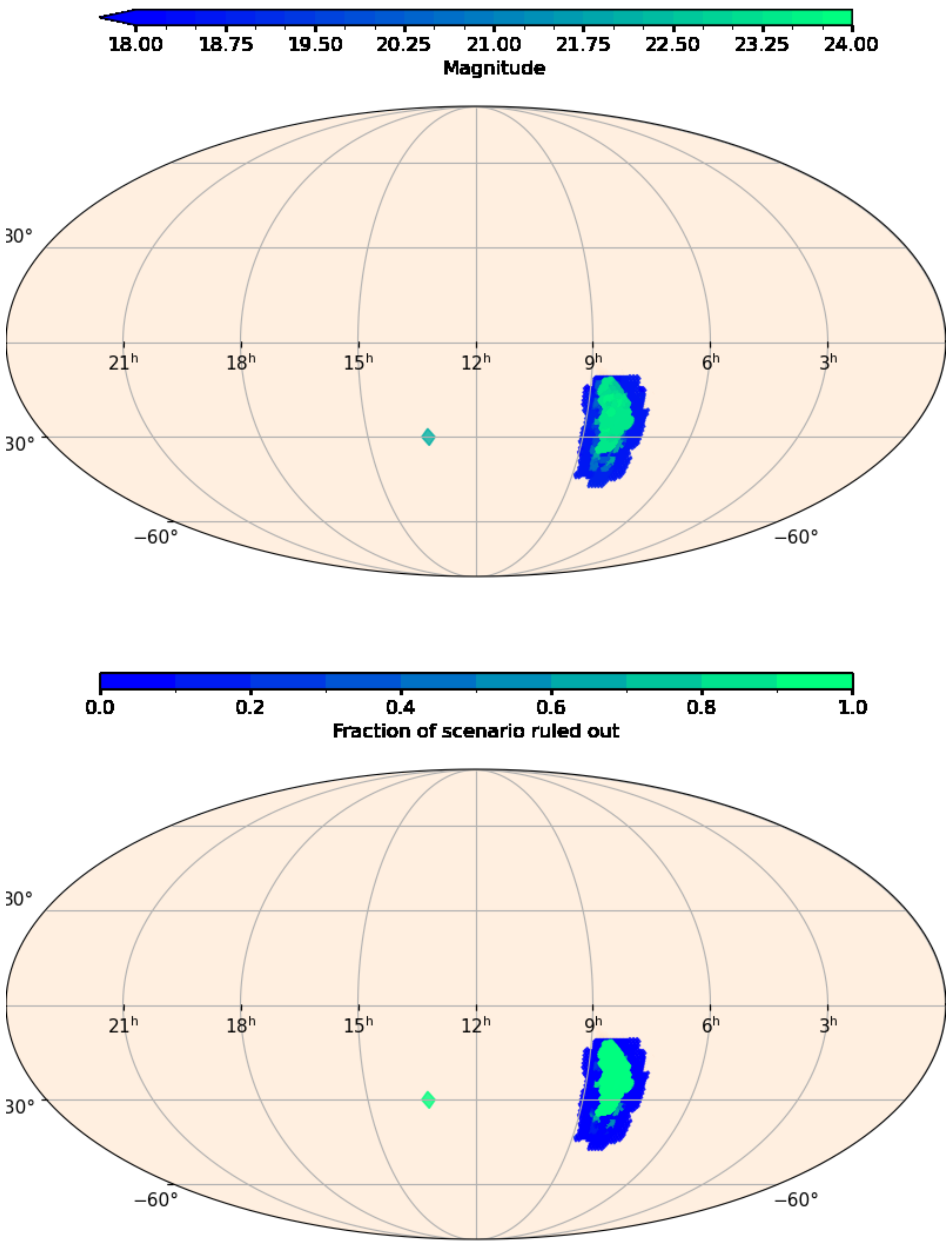
Between 0 and 1 day



Between 1 and 2 day



Between 2 and 6 day



Candidate	GCNs	Discovery Date	Findings and Comments
Optical Candidate Counterparts			
AT 2024hdr	3	2024-04-22 23:42:30.196	ATLAS forced photometry detections extending over 200 days before the GW event examined. Host galaxy z=0.0416 based on weak emission line features. Considering the characteristics of nuclear transients and ruling out their association with the GW event: the candidate is not a GW counterpart. Not GW Counterpart
AT 2024hdo	5	2024-04-22 23:48:39.928	Associated (Pcc = 0.002) with host galaxy WISEJ080327.75-260039.2 from GLADE at $z=0.09 \pm 0.02$ (D=∼404 Mpc). Inconsistent host galaxy photometric redshift with distance inferred from the GW event. The spectrum revealed strong emission lines at z=0.0658 and broad P-Cygni H-alpha emission consistent with Type II SN at the same z. Unlikely GW association
AT 2024hdq	3	2024-04-22 23:50:15.764	Nuclear transient. ZTF detections indicated periodic behavior since 2022. Not GW Counterpart
AT 2024hfj	1	2024-04-22 23:51:46.851	One candidate host is situated within 1 arcmin: WISEA J075010.62-261059.0. Source was not fast fading (>0.2 mag/day) and did not exhibit significant color evolution. Likely unrelated to the GW event
AT 2024hdp	3	2024-04-22 23:53:19.570	Associated (Pcc = 0.001) with the host galaxy WISEJ080210.31-271529.7 from GLADE at $z = 0.09 \pm 0.02$ (D=∼411 Mpc). ATLAS forced photometry detections were recorded ∼3-18 days before the GW event. Unlikely GW Association
AT 2024hdw	1	2024-04-23 00:09:22.464	Two candidate hosts situated to the north within 1 arcmin: WISEA+J080141.03-292637.1 and WISEA+J080142.38-292621.8. Source was not fast fading (>0.2 mag/day) and did not exhibit significant color evolution. Likely unrelated to the GW event
AT 2024hdk	2	2024-04-23 00:52:49.715	Three marginal ($\sim \sigma$) ATLAS forced photometry detections observed ∼3-5 days before the GW event, which ruled the candidate unrelated to the GW event alongside color and spectroscopic information. Unrelated to S240422ed.
AT 2024hel	1	2024-04-23 00:59:08.448	Candidate host is identified at a small offset: WISEA J083612.37-164424.5. Source was not fast fading (>0.2 mag/day) and did not exhibit significant color evolution. Likely unrelated to the GW event.
AT 2024hfr	3	2024-04-23 01:06:53.381	Source located within 0.3 arcsec from the object WISEA J084103.91-183532.4. Galaxy 2MASS photometric z=0.049. No indication of a fast (>0.3 mag/day) rise/fade in its light curve based on preliminary photometry. Likely not associated with GW event.