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

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GdR Ondes Gravitationnelles
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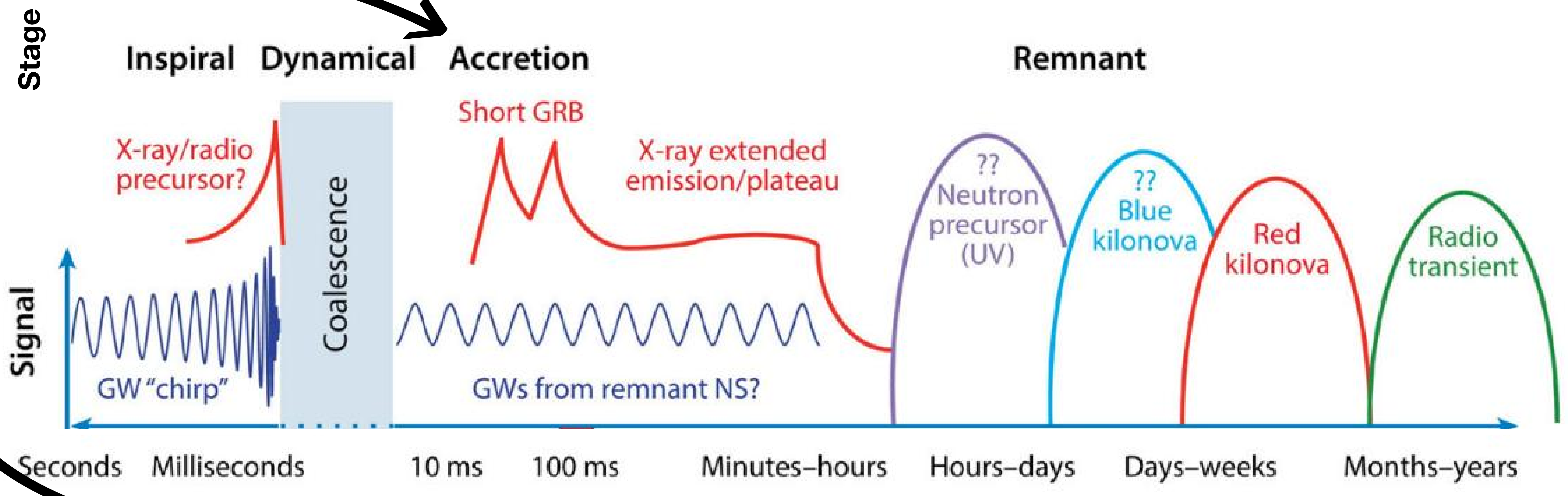
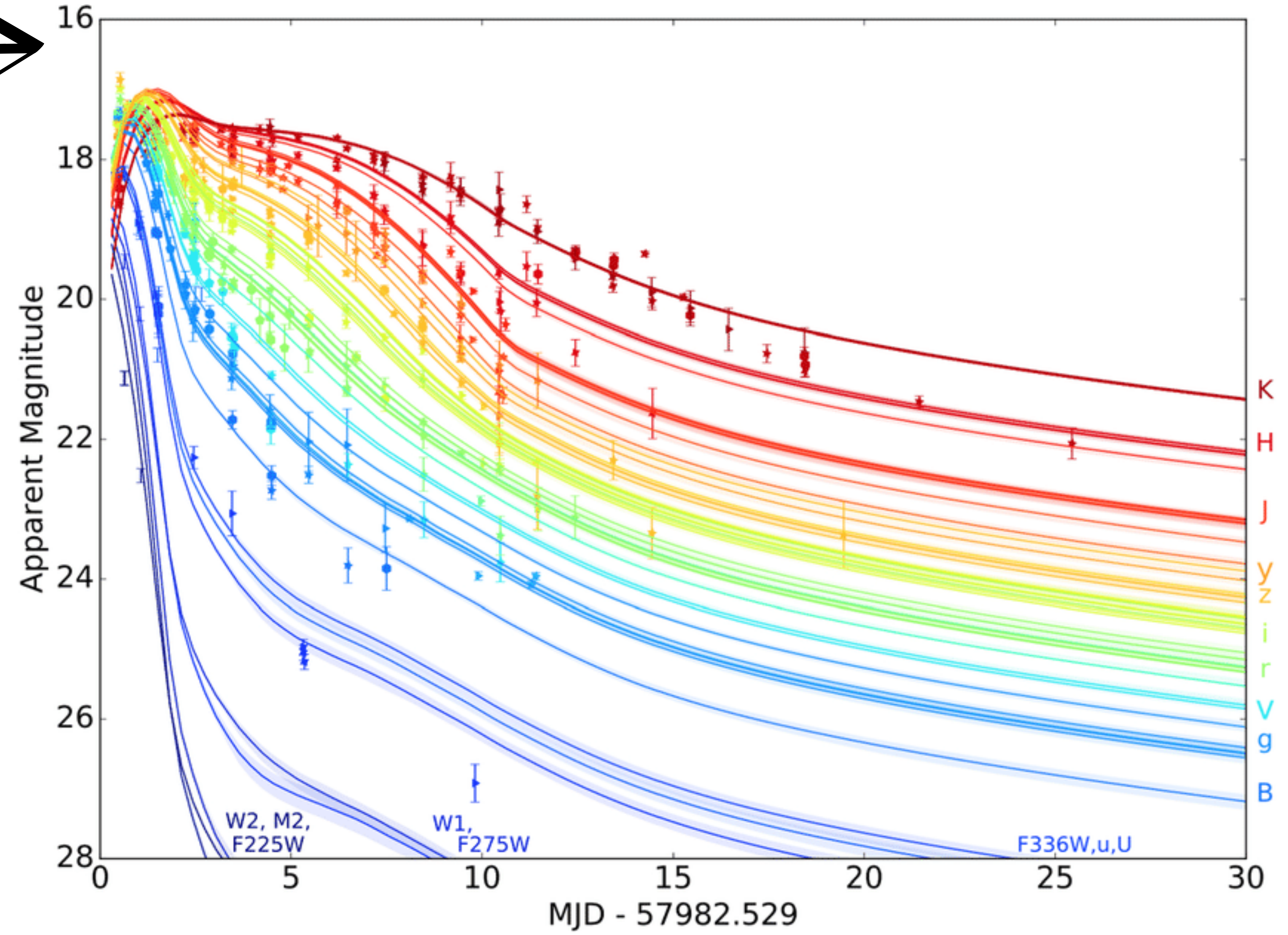
Introduction

- Compact Binary Coalescence (CBC) systems with neutron star (NS) can produce **electromagnetic** (EM) counterpart in addition to **gravitational-wave** (GW) emission
- First and unique KN associated with GW: **AT2017gfo**
- **Kilonova** (KN) - Optical counterpart, witness to the nucleosynthesis of heavy elements during the merger



- Neutron star - Black Hole (NSBH) merger can also produce KN signature, depending on:
  - Mass ratio
  - Black hole spin
  - NS EoS

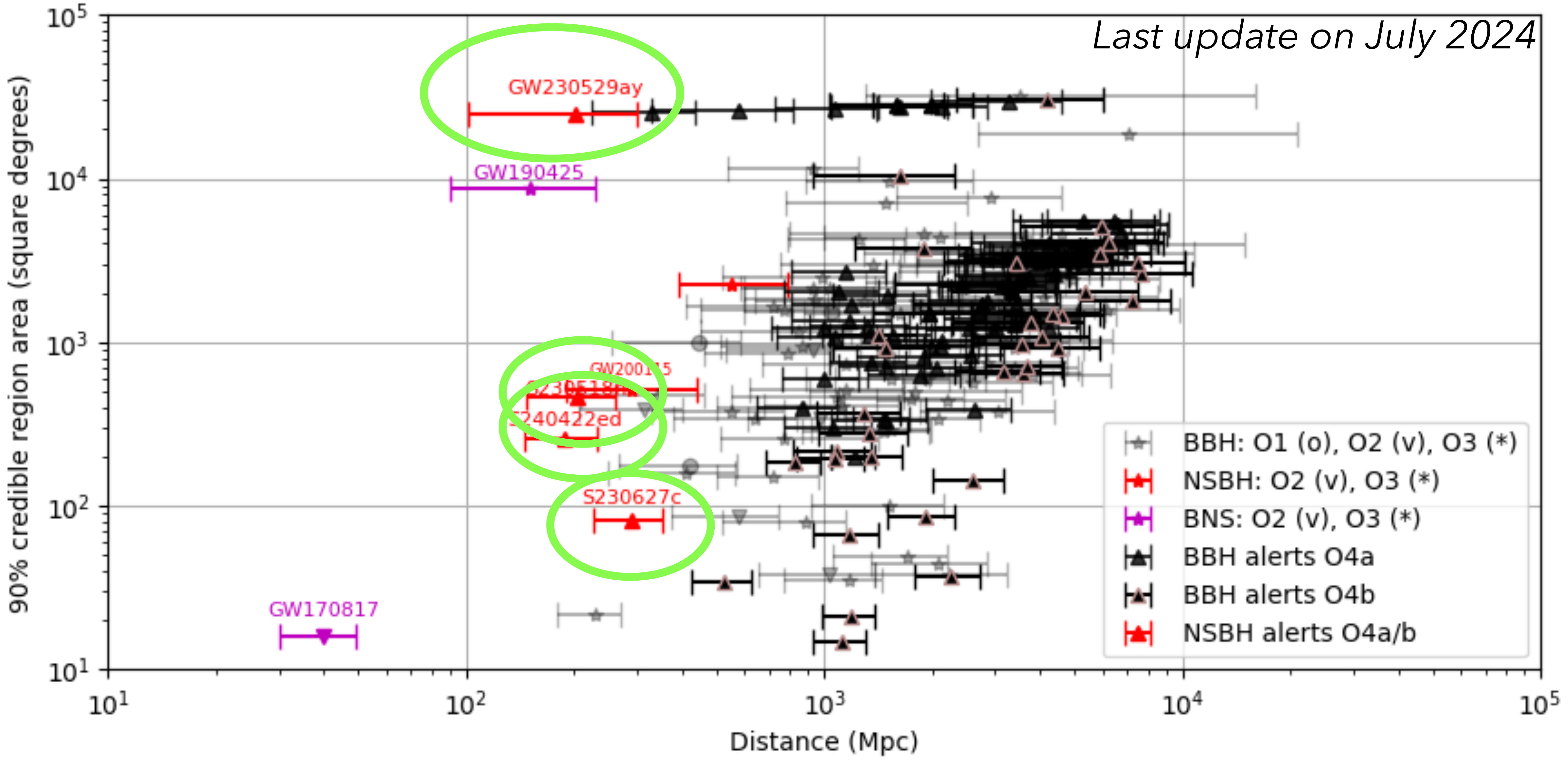
    (Villar et al, 2017)



- KN brings information about:
  - Sky location of the source
  - **Merger environment** …

Introduction

- In O3, first confirmed NSBH event: GW200115
- O4 has started in May 2023
    - > 100 GW 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



Introduction

- In O3, first confirmed NSBH event: GW200115
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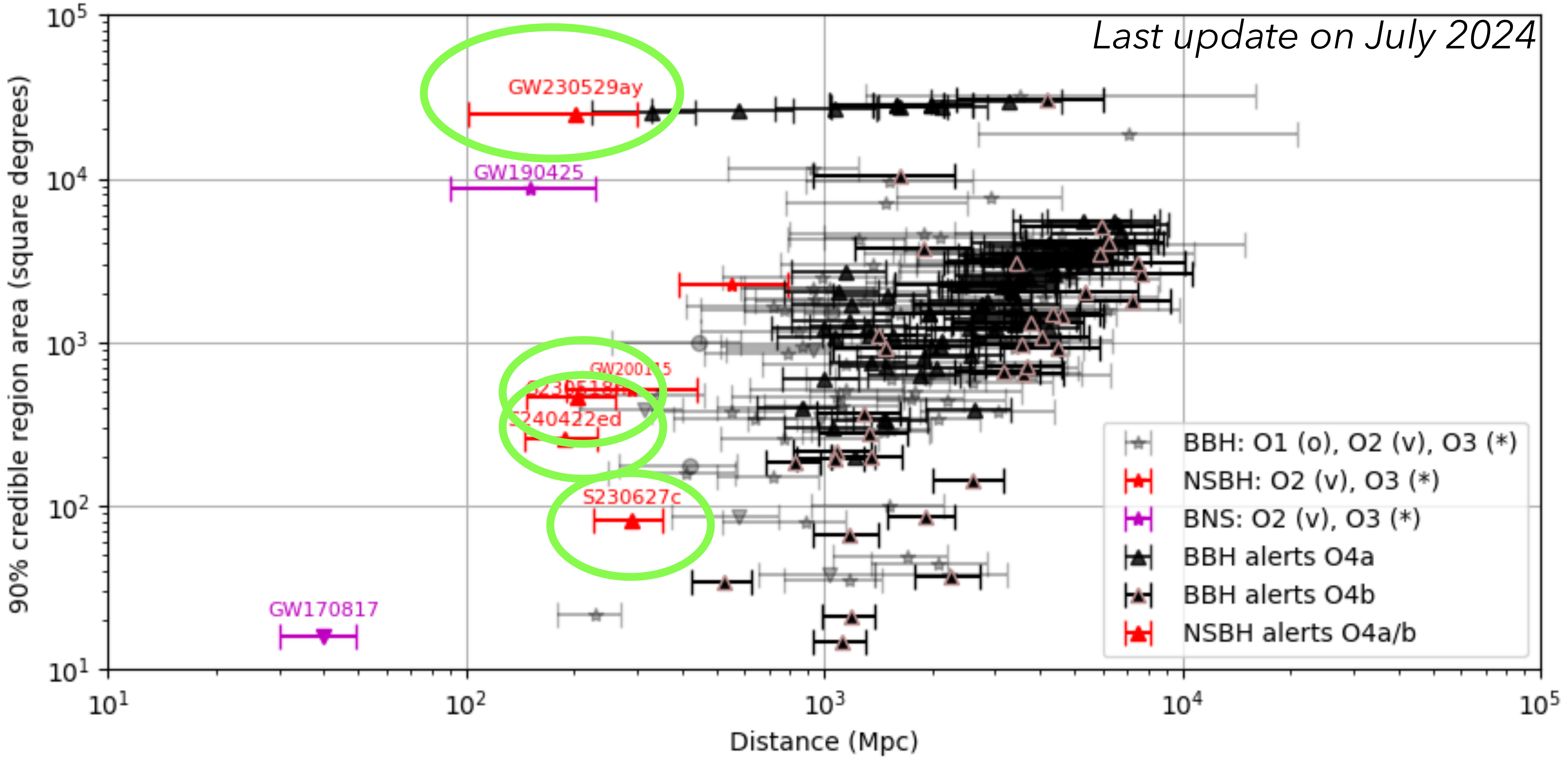
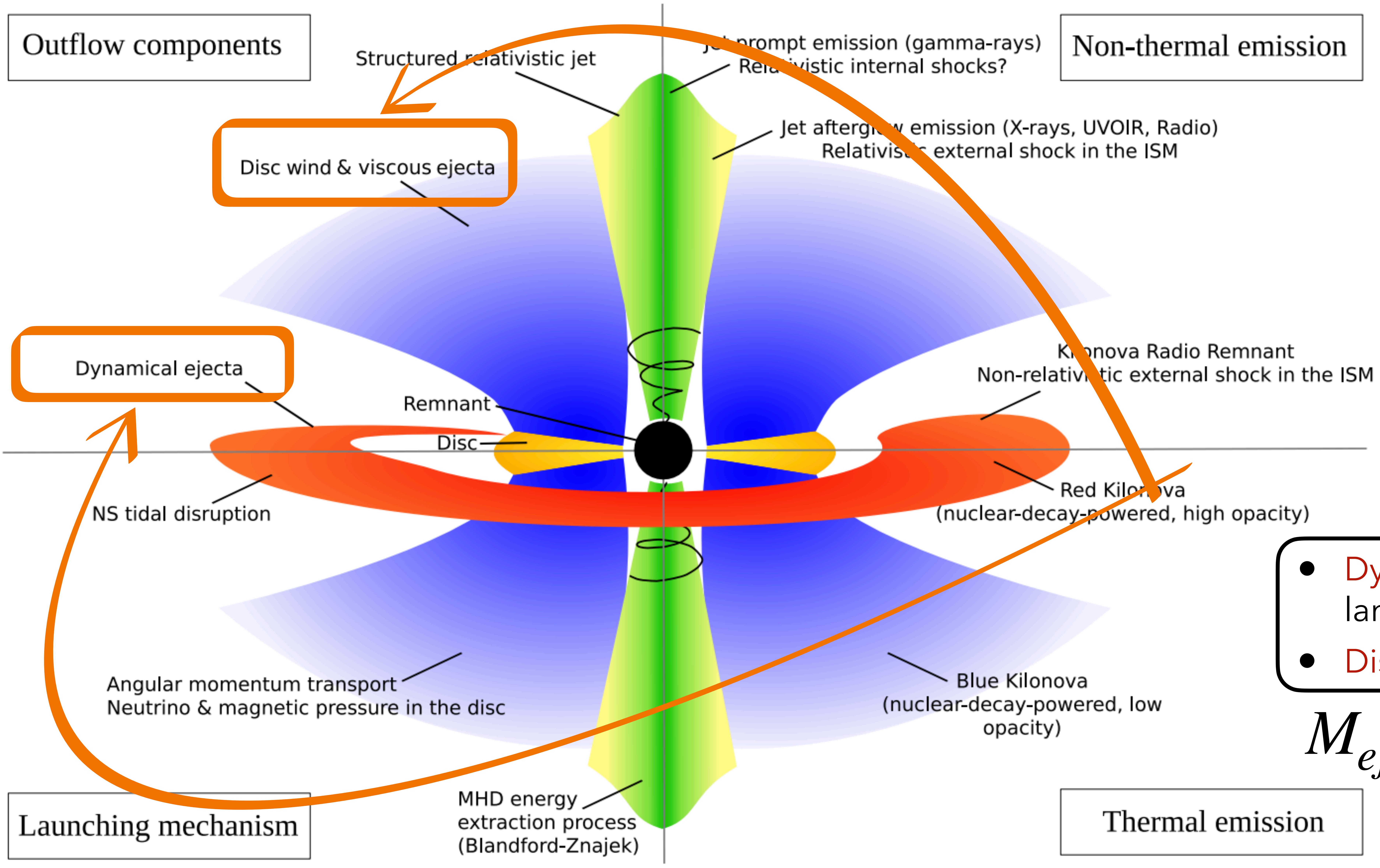
Even a non-detection can help constrain source properties (ejecta, viewing angle)



Modeling Kilonova from NSBH



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

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

Barbieri et al, 2019

Modeling Kilonova from NSBH

Kilonova properties imprinted in the light curves:

- m_{dyn}
- m_{wind}
- viewing angle θ (between line of sight and orbital momentum direction)
- half-opening angle ϕ of the lanthanide-rich component ($\phi = 0 \rightarrow$ lanthanide-free)
- ejecta velocity
- …

Included in this work (m_{dyn}, m_{wind}, viewing angle θ)

Anand 2021-Bulla 2019

- 891 light curves
- 21 different filters

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) • 1D bolometric

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

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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*:

- Start from GraceDB public information for each NSBH candidate, S230518h, GW230529, S230627c, S240422ed:

Probability of astrophysical origin (p_{astro})

- Estimate the chirp mass of each candidate
- 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:

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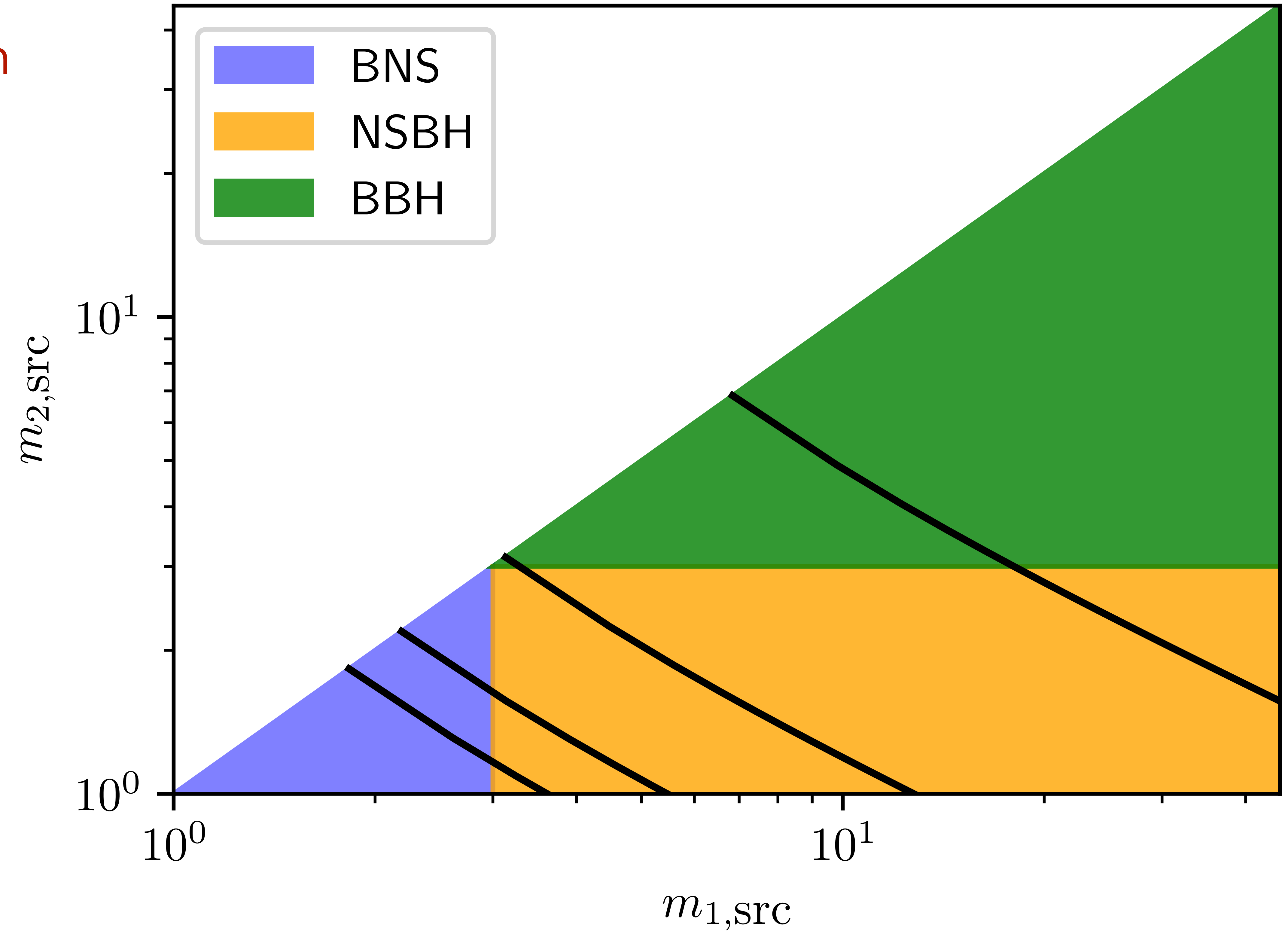
KN associated with O4 NSBH candidates

- 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 $\mathscr{M}_{\rm src}$ from a detector-frame point estimate

→ process reversed

- Uncertainty derived from the one on the distance



Candidate	BNS	NSBH	BBH	$\mathcal{M}_{\rm src}$ $[M_\odot]$
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

2) 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

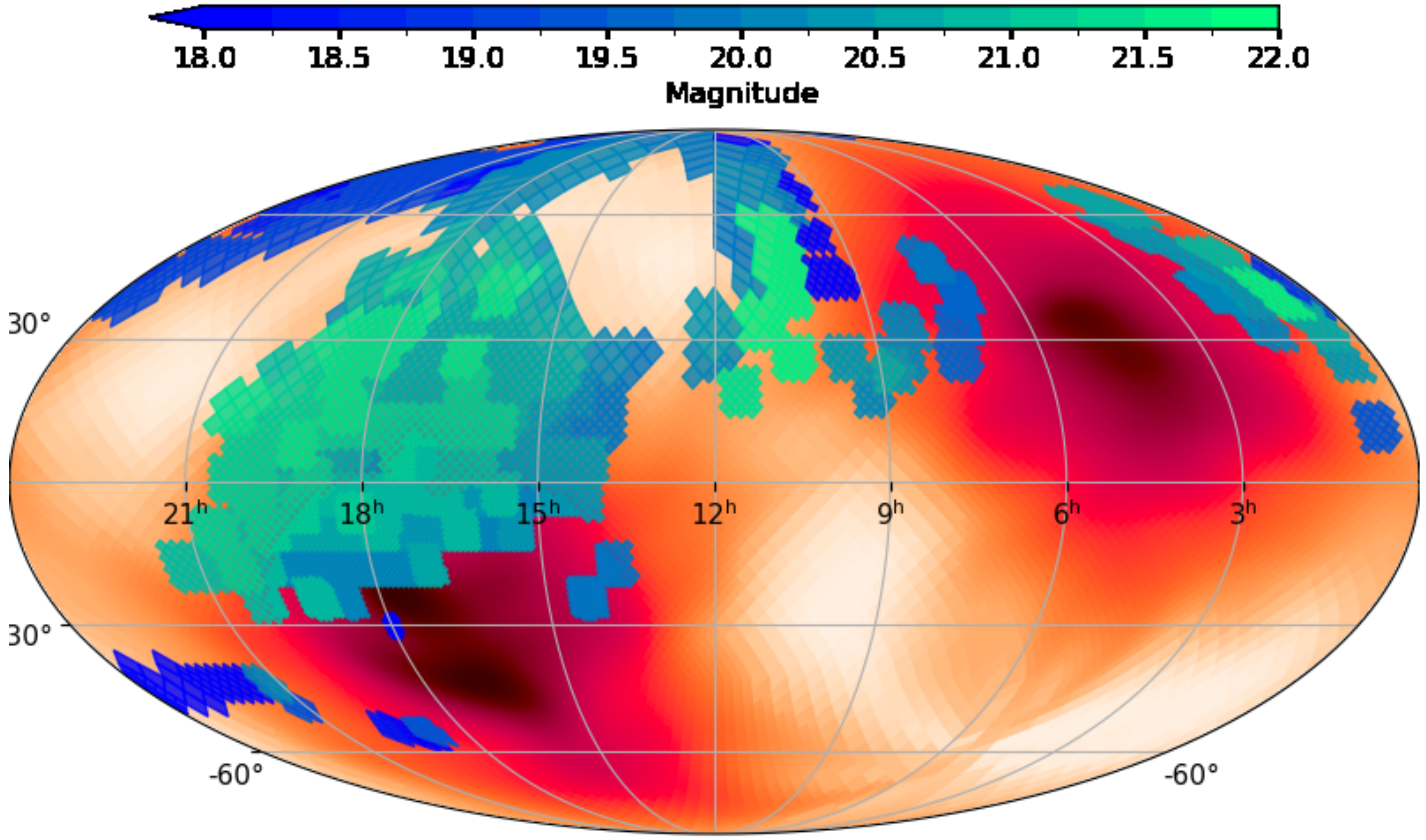
- For GW230529: use public results (posterior distribution of masses, spins and later viewing angle, computed with IMRPhenomXP waveform model)
- **Results (we take the broader upper limit between EoS and spins)**
  - S230518h: $m_{dyn} < 0.08\ \mathrm{M}_\odot$ & $m_{wind} < 0.04\ \mathrm{M}_\odot$ + θ unconstrained
  - GW230529: m_{dyn}, $m_{wind} < 0.01\ \mathrm{M}_\odot$ + θ unconstrained
  - S230627c: m_{dyn}, $m_{wind} < 0.01\ \mathrm{M}_\odot$ + θ unconstrained
  - S240422ed: given the low significance, select all the synthetic light curves of the grid

KN associated with O4 NSBH candidates

3) 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

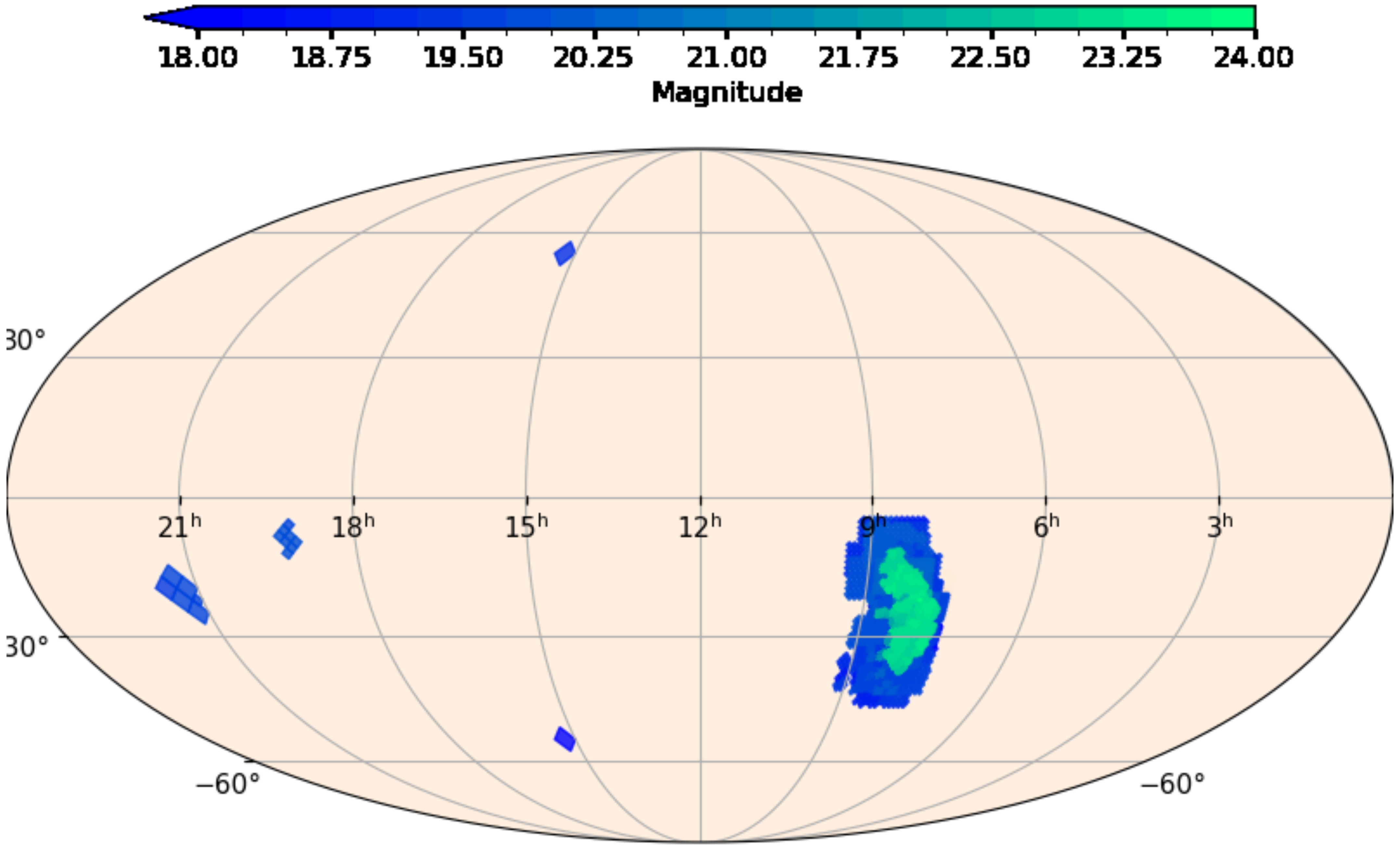
GW230529 (between 0 and 1 day)



Telescopes considered:
ATLAS, CSS, MASTER, ZTF

All filters!

S240422ed (between 0 and 1 day)



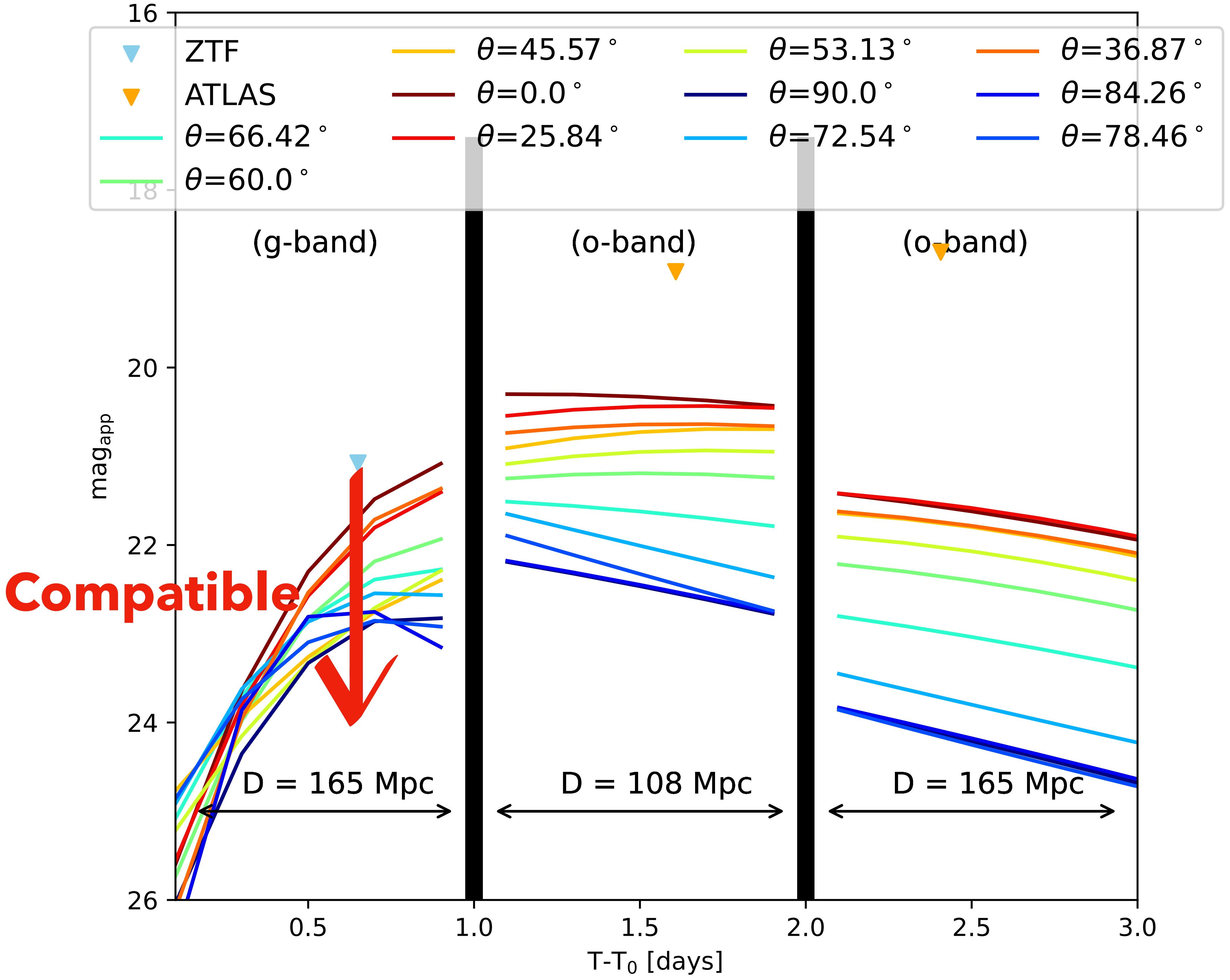
Telescopes considered: 7DT, ATLAS, BlackGEM, CSS, DECam, GOTO, GRANDMA, KMTNet, Las Cumbres 1m & 2m, Magellan, MASTER, MeerLIGHT, PRIME, Swift UVOT, WINTER, ZTF

KN associated with O4 NSBH candidates

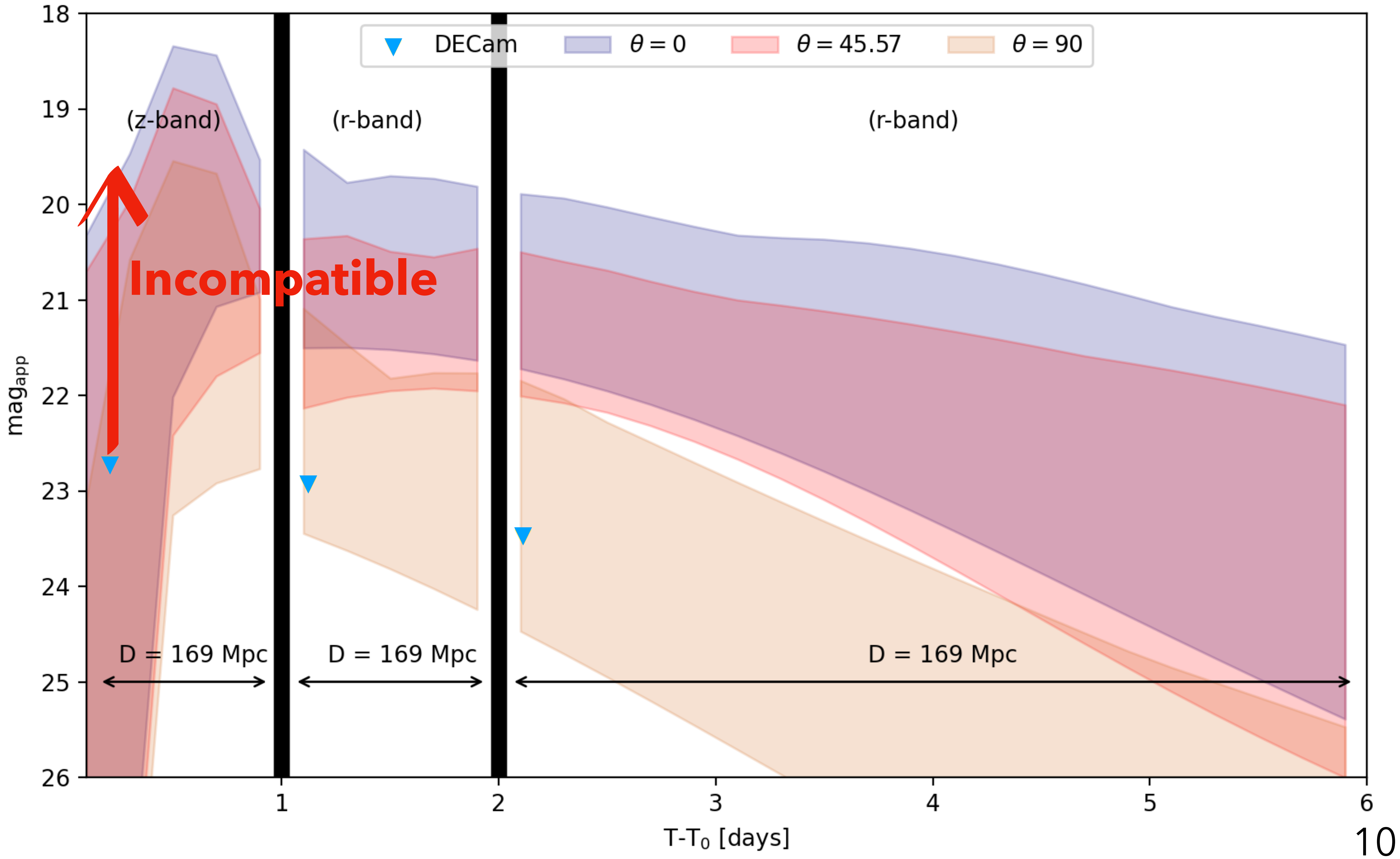
4)

- Compute the apparent M_{KN} of the synthetic kilonova light curves for each pixel and at the corresponding distance
- Compare the brightness of the simulated kilonova with the upper limits of the fields that contains the pixel at the epoch of the field
- If $M_{KN} < M_{obs}$ (expected KN brighter than the observation): KN light curve incompatible with observation

GW230529



S240422ed



KN associated with O4 NSBH candidates

4) If $M_{KN} < M_{obs}$ (expected KN brighter than the observation): KN light curve incompatible with observation

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

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

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

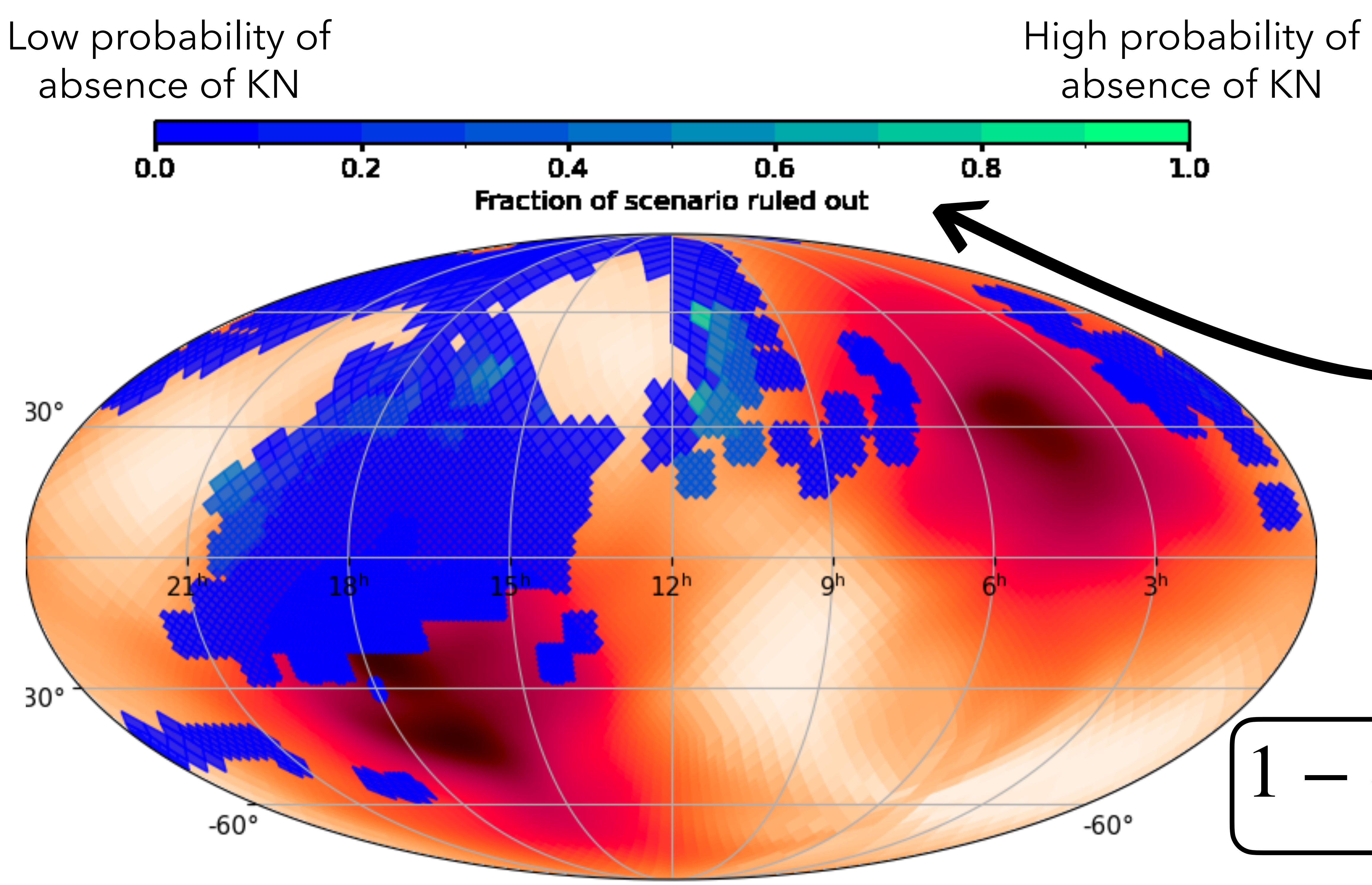
Total number of synthetic kilonovae from the grid considered for each event

Telescope observation

KN associated with O4 NSBH candidates

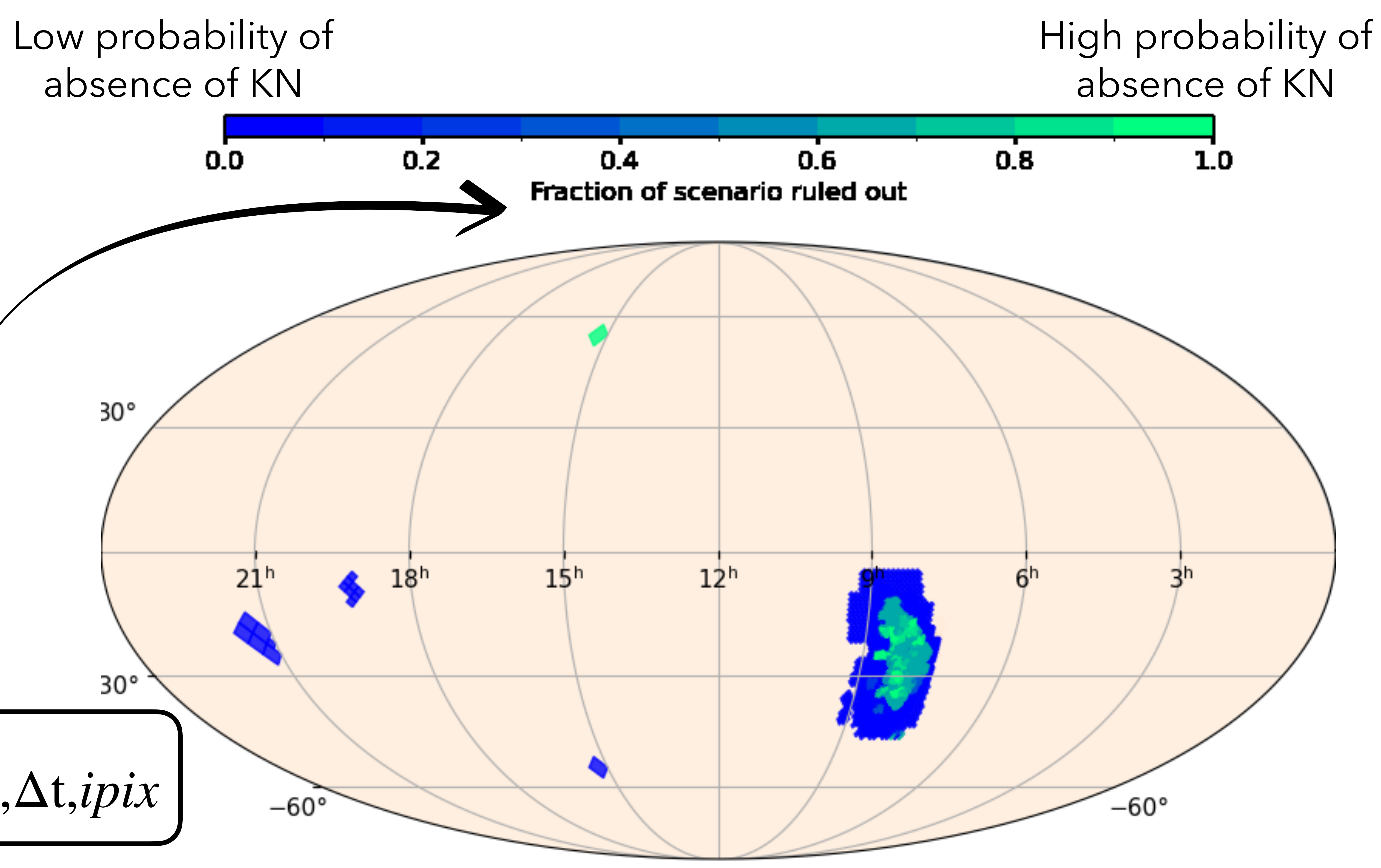
4) If $M_{KN} < M_{obs}$ (expected KN brighter than the observation): KN light curve incompatible with observation

GW230529 (between 0 and 1 day)



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

S240422ed (between 0 and 1 day)



Threshold of of a fraction of 0.7:

GW230529: **0 deg²** within the 90% credible region > 0.7

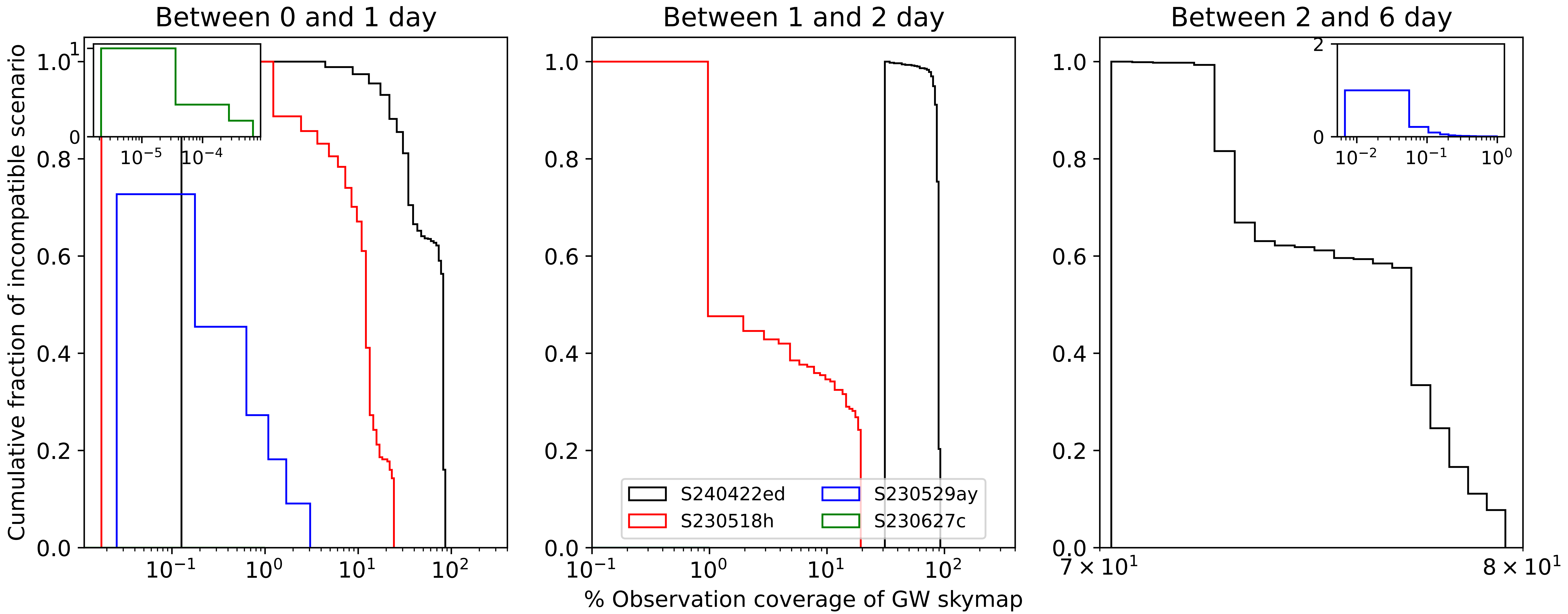
S240422ed: **79 deg²** within the 90% credible region (259 deg²) for t in [0,1[days, **218 deg²** for t in [1,2[and **178 deg²** for t in [2,6[: **probable absence of a kilonova in the observations**

KN associated with O4 NSBH candidates

4) If $M_{KN} < M_{obs}$ (expected KN brighter than the observation): KN light curve incompatible with observation

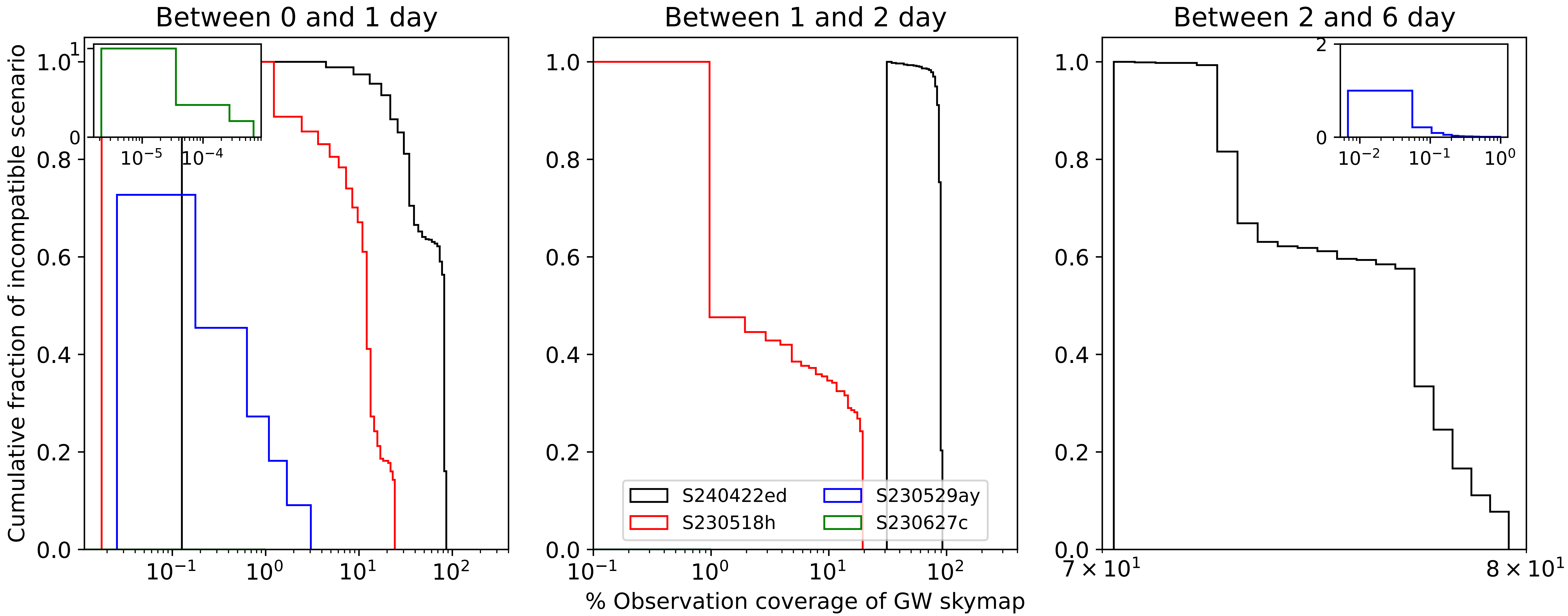
- Associate a deterministic probability to each KN scenario $(\theta, m_{dyn}, m_{wind})$ of being ruled out

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



KN associated with O4 NSBH candidates

- **Discussion & Key numbers:**
  - S230518h: it has not been possible to observe kilonovae emitted from an on-axis collision up to a viewing angle of $\theta = 25^\circ$, assuming a minimum confidence of 10% for the presence of the source in this region
  - GW230529: for $t \in [0,1[$ days, $\theta = 0^\circ,\ 25^\circ,\ 36^\circ$ incompatible by observations that covered ~3%, ~2% & ~1% of the skymap → we cannot exclude the presence of a kilonova in the observations
  - S230627c: we cannot exclude the presence of a kilonova in the observations
  - S240422ed: **observations ruled out the presence of a kilonova (with or without GWs)**



KN associated with O4 NSBH candidates

- **Discussion & 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	-	$SLy < 0.01$, $H4 < 0.02$

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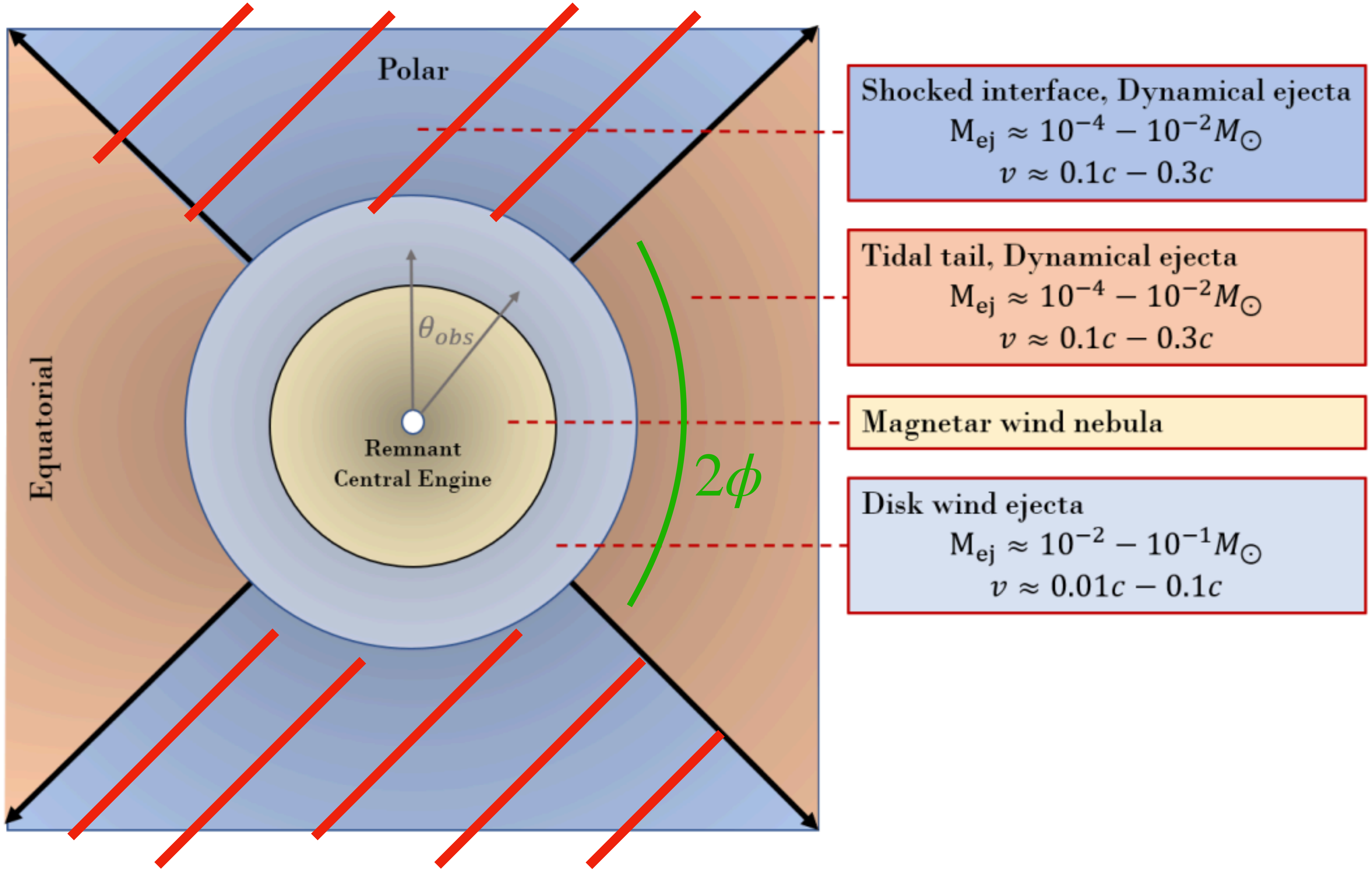
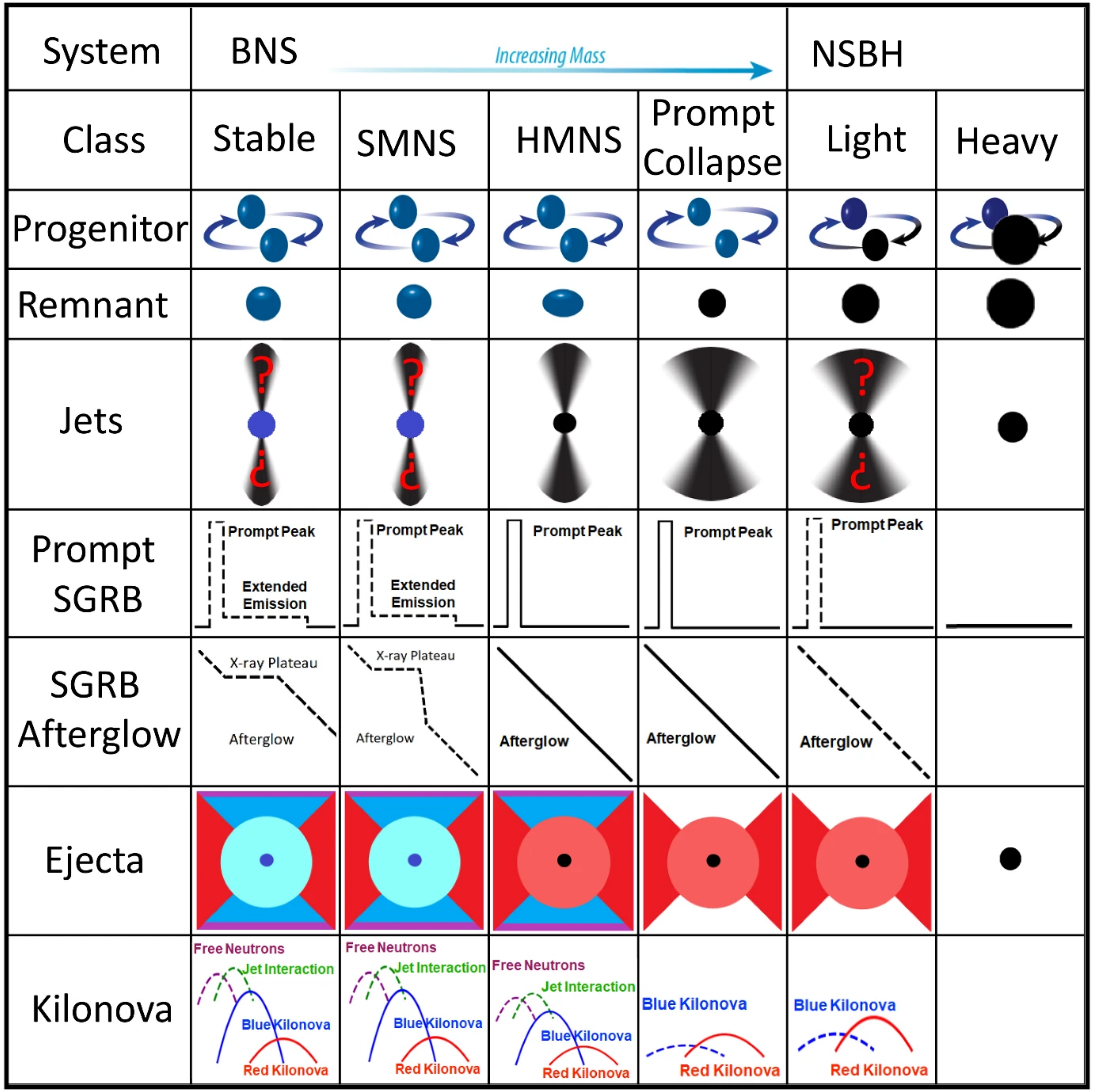
THANK FOR YOUR ATTENTION!

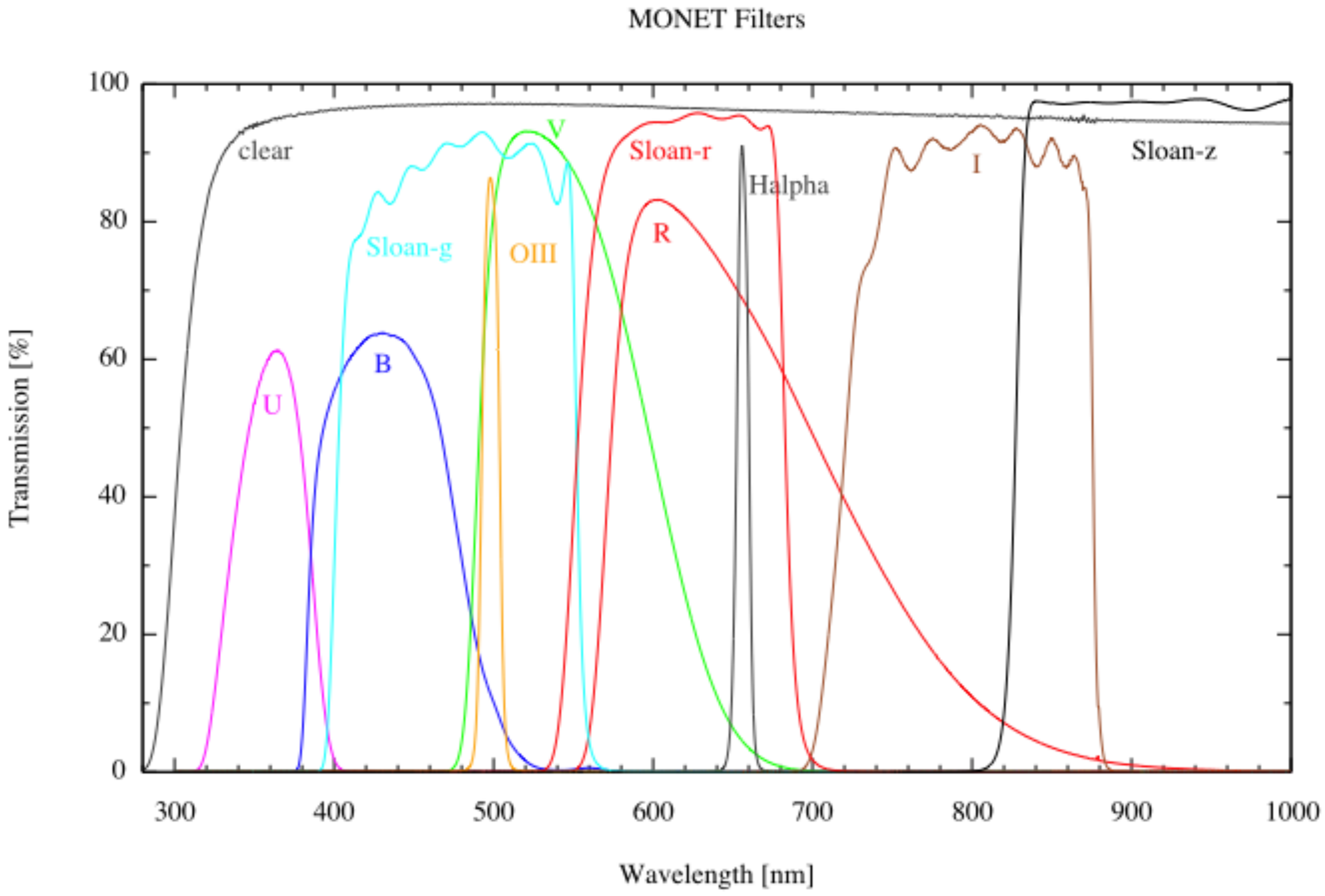
BACKUP



Not in the NSBH case


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



KN associated with O4 NSBH candidates

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	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	-	-, $SLy < 0.01$,$H4 < 0.05$

KN associated with O4 NSBH candidates

Goal:

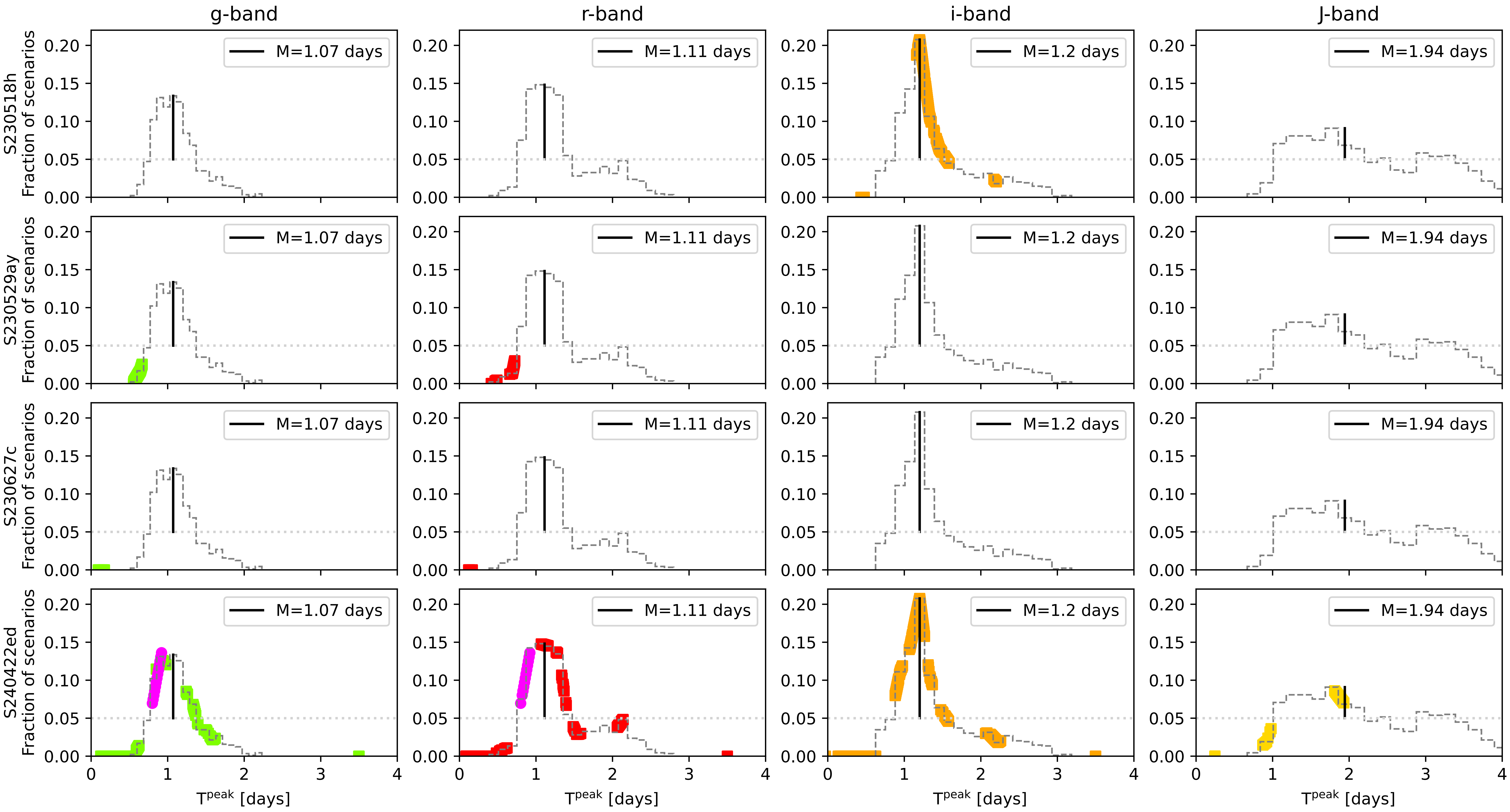
1) Take a critical look at observation strategies from the optical community
2) Given the non-observation of a KN, set constraints on source ejecta and viewing angle properties of the 4 NSBH candidates:

1)

- 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

KN associated with O4 NSBH candidates

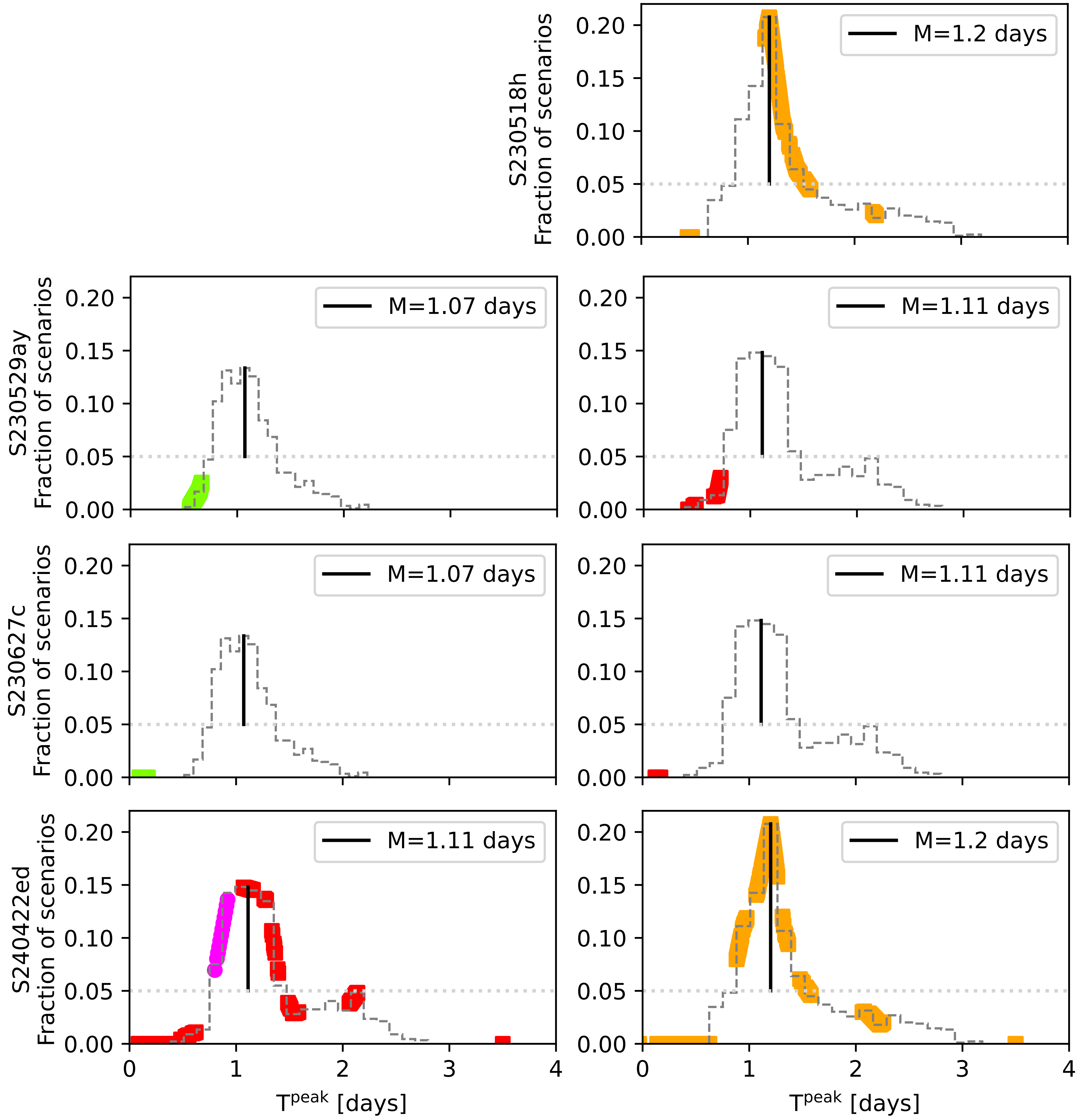
1) Compare time of optical observations with the predicted peak time from simulated KN light curves



GRANDMA followup

(see Thomas Hussenot talk for details about GRANDMA followup)

KN associated with O4 NSBH candidates



- **Key numbers:**

S230518h: Observations in i-band covered the kilonova time peak of 44% of the population

GW230529ay: only 2% of our simulated sample population the predicted peak was covered by these observations in g and r-band –> expected given the large skymap

S260727c: observations in g and r-band happened before most of the scenario's predicted peak time

S240422ed: - observations consistent with the peak time of 76% and 60% of kilonova of our population in r and i-band respectively.
- in r-band, no observations between 0.6 and 1.06 days while 25% of kilonova peak in this time range.

KN associated with O4 NSBH candidates

- **Discussion 1:**

- Necessity to image the first moment but also the importance of imaging 1 day in g, r, i post-merger, especially for shallower images, as the magnitude of the kilonova may vary up to ~11 magnitudes between prompt observations to the peak time (computed for a distance of 200 Mpc)

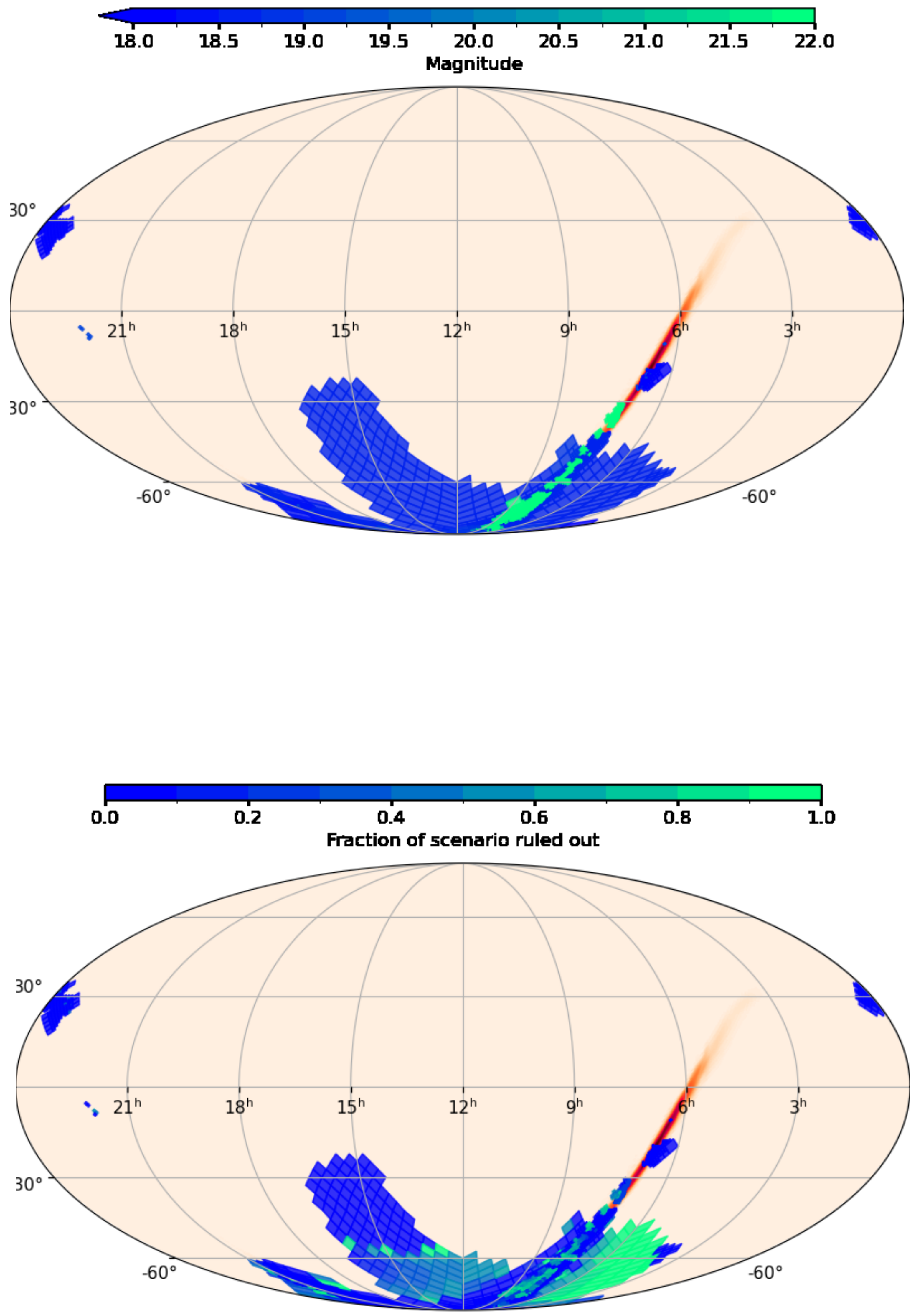
- Prompt strategy has been well demonstrated by the community, the « later time » strategy is not always realized.

- We advocate a more « relaxed » approach for near and infrared for which the maximum of the peak time of the kilonova is less obvious.

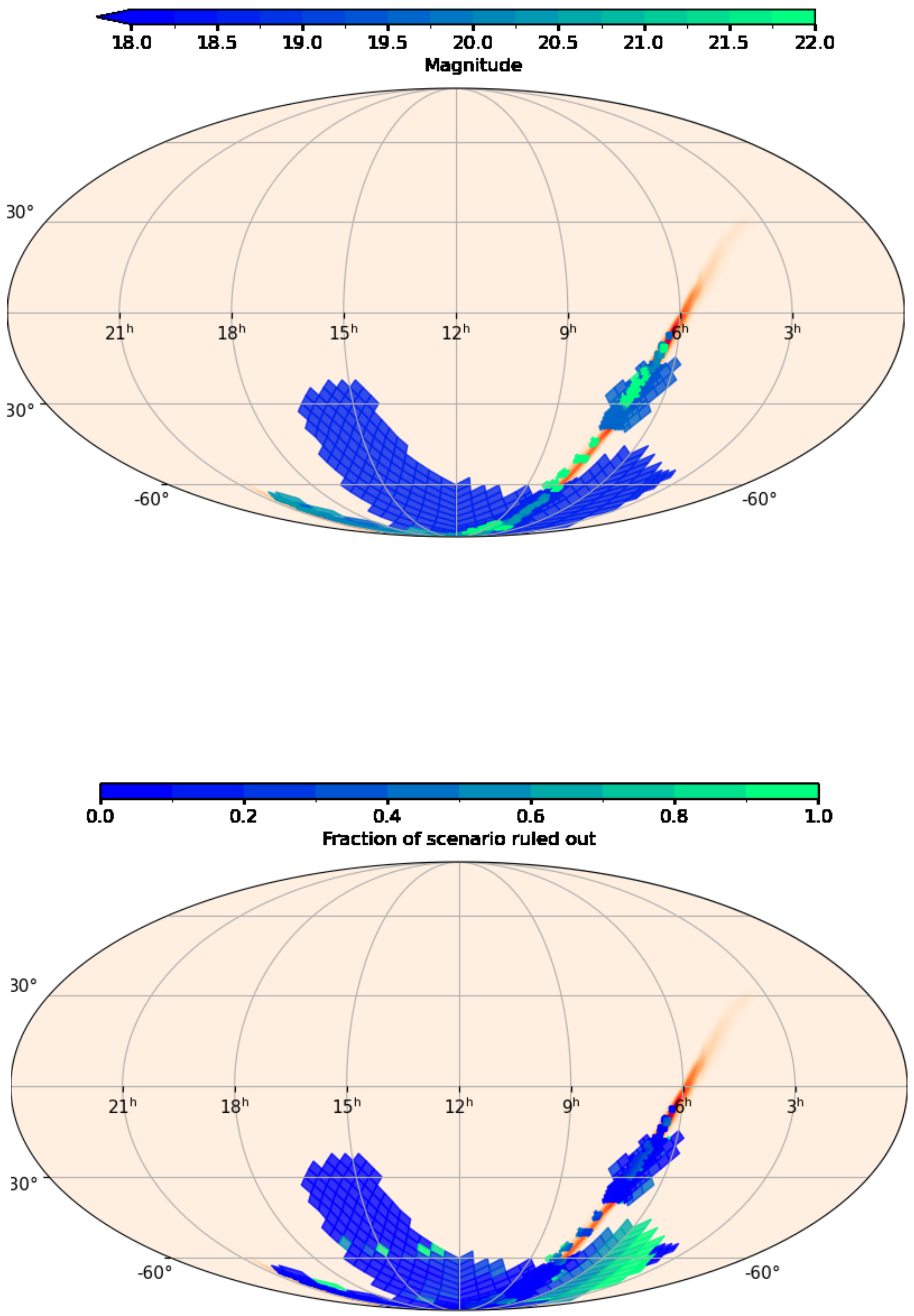
- Motivation for taking into account additional measurements from the GW signal itself, especially the chirp mass –> allows us to estimate a range of time at which you expect the maximum brightness ; would be an important tool for follow-up of NS merger events.

S230518h

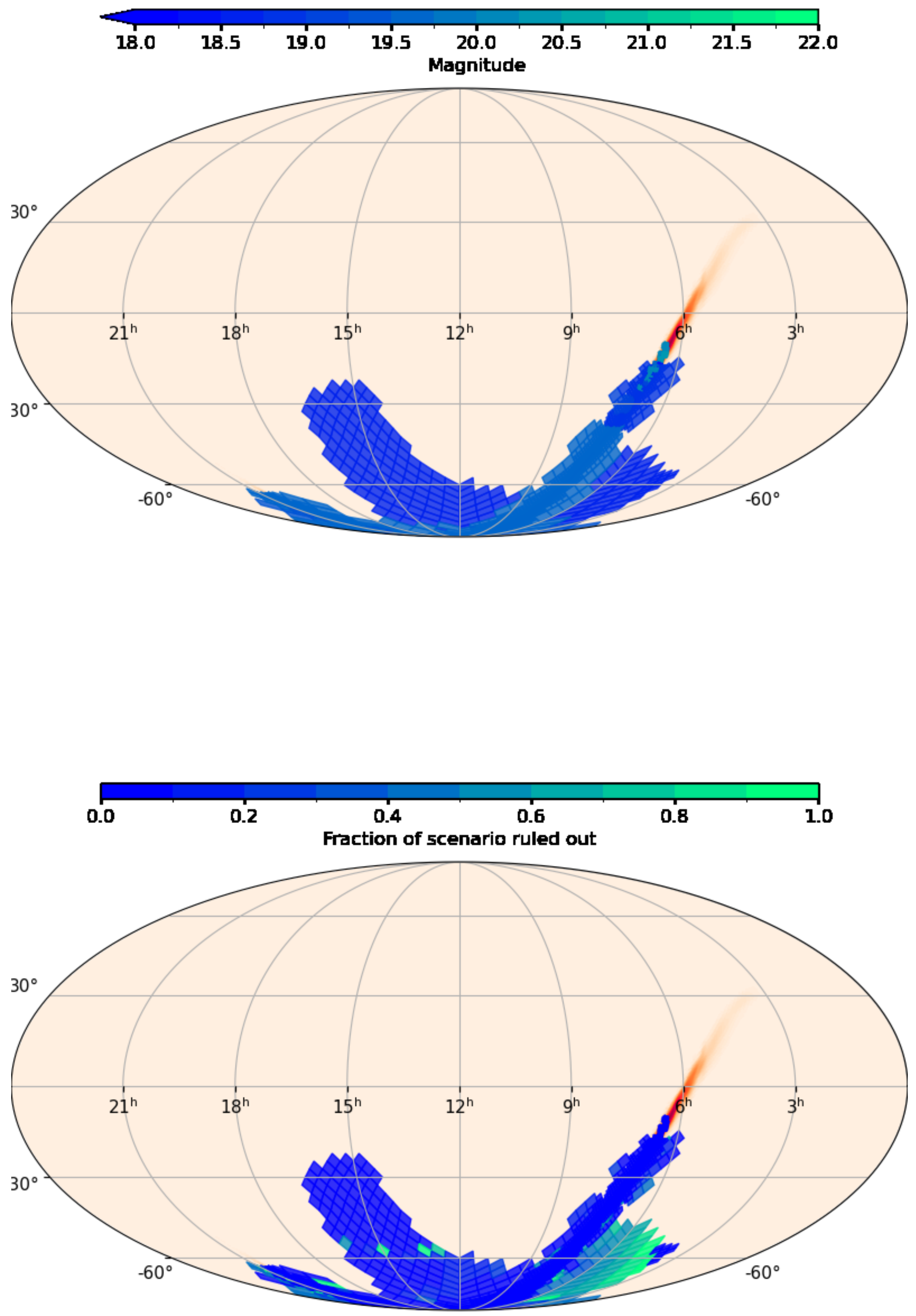
Between 0 and 1 day



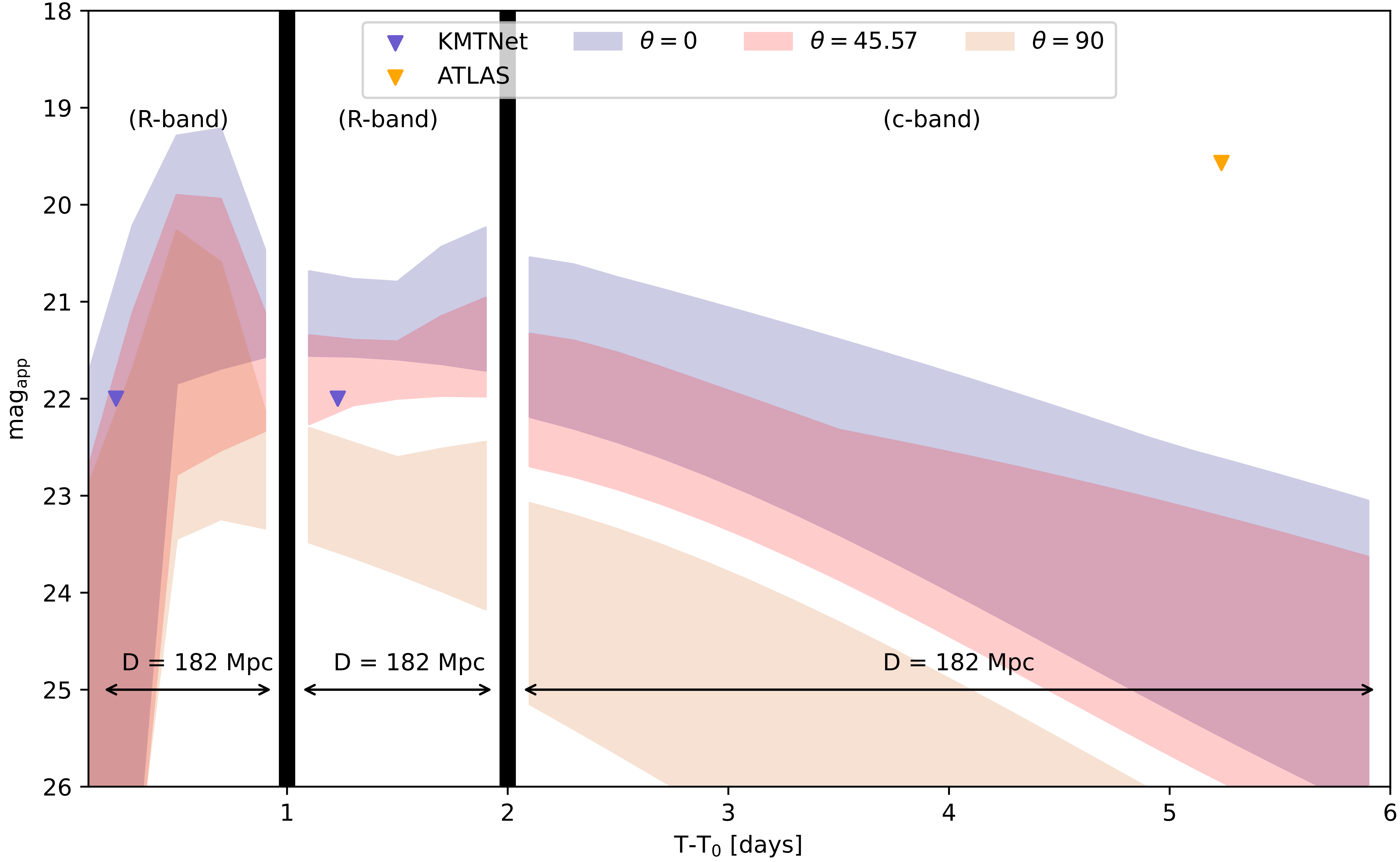
Between 1 and 2 day



Between 2 and 6 day



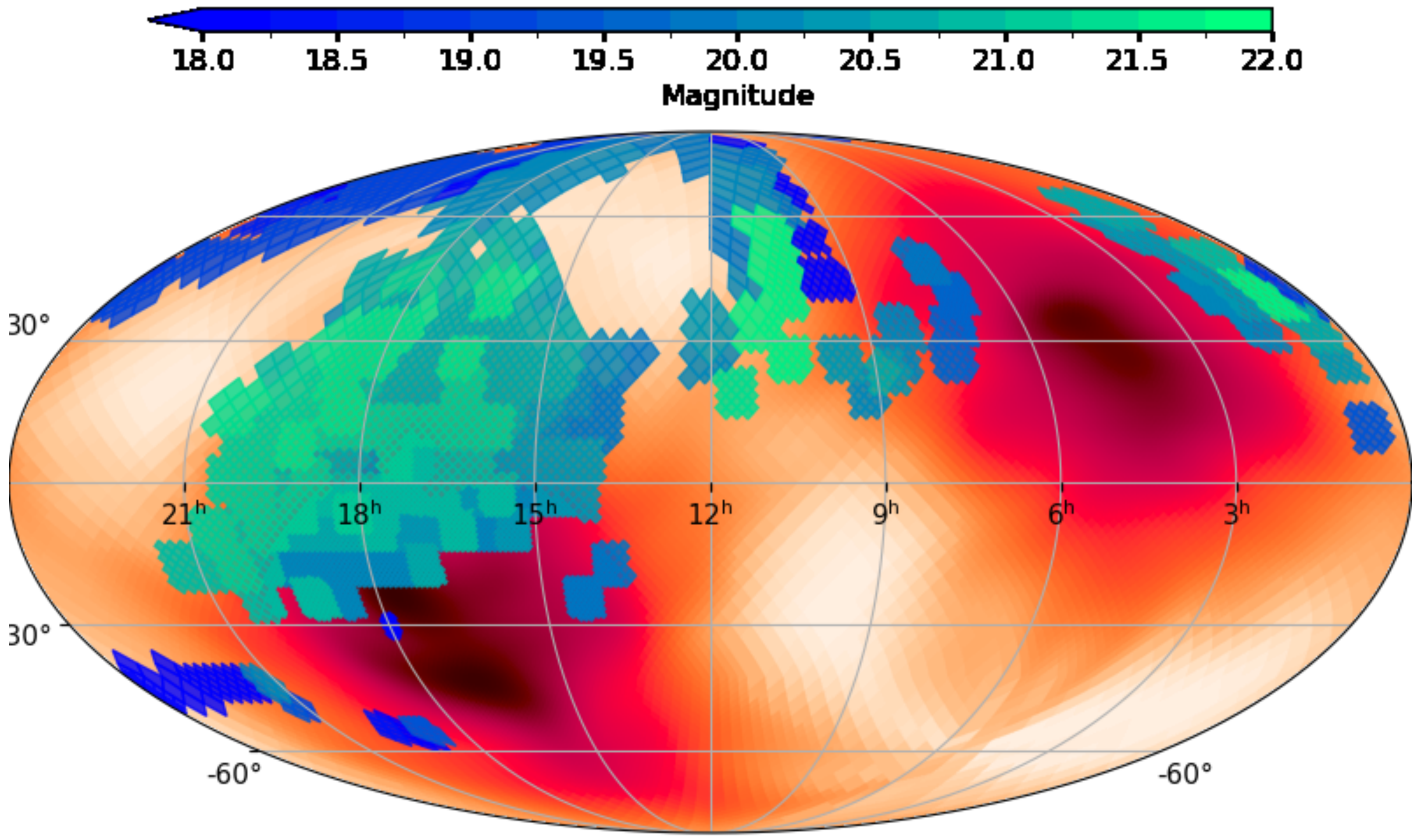
S230518h

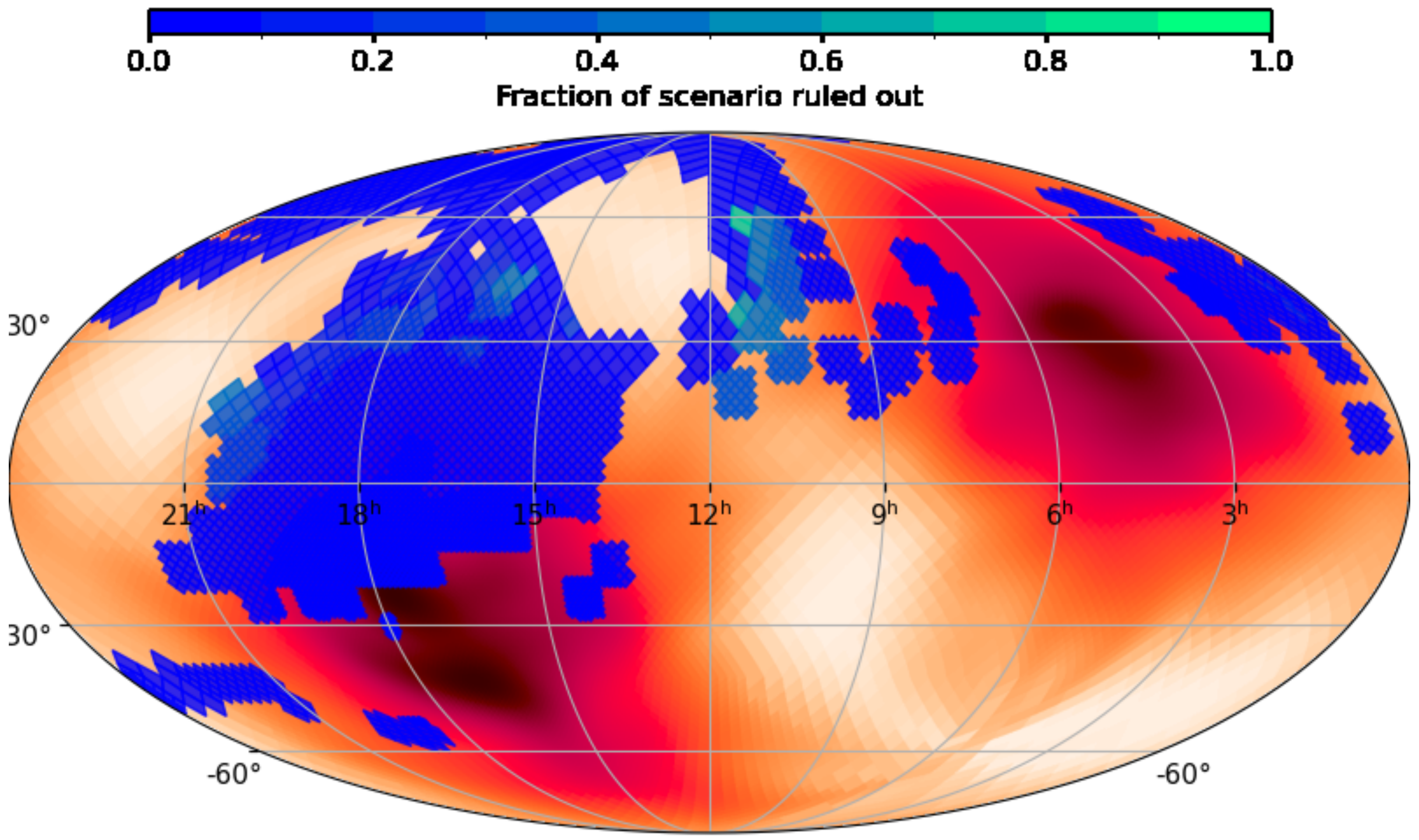


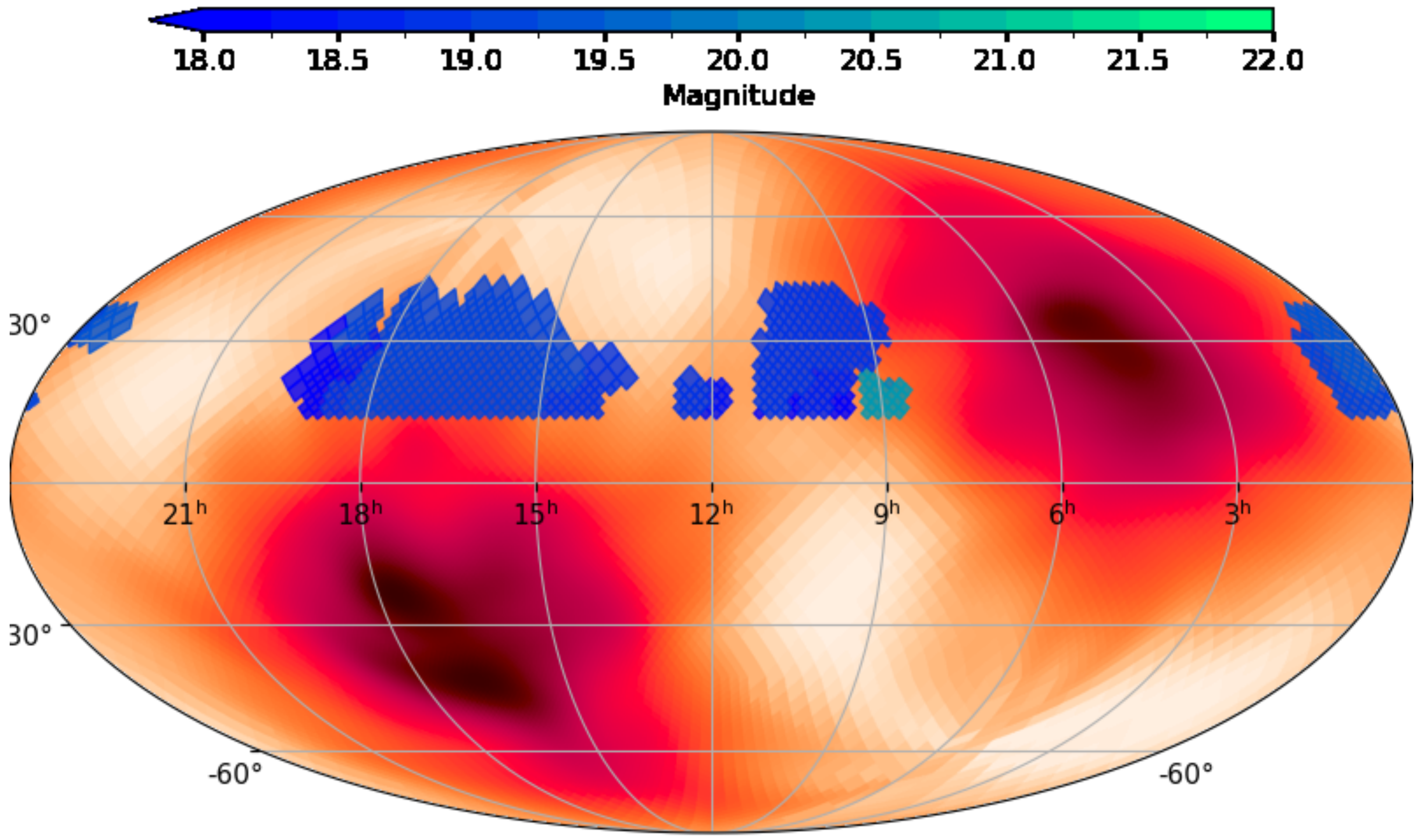
KMTNet
ATLAS
$\theta = 0$
$\theta = 45.57$
$\theta = 90$
(R-band)
(R-band)
(c-band)
D = 182 Mpc
D = 182 Mpc
D = 182 Mpc
mag_{app}
T-T$_0$ [days]
18
19
20
21
22
23
24
25
26
1
2
3
4
5
6

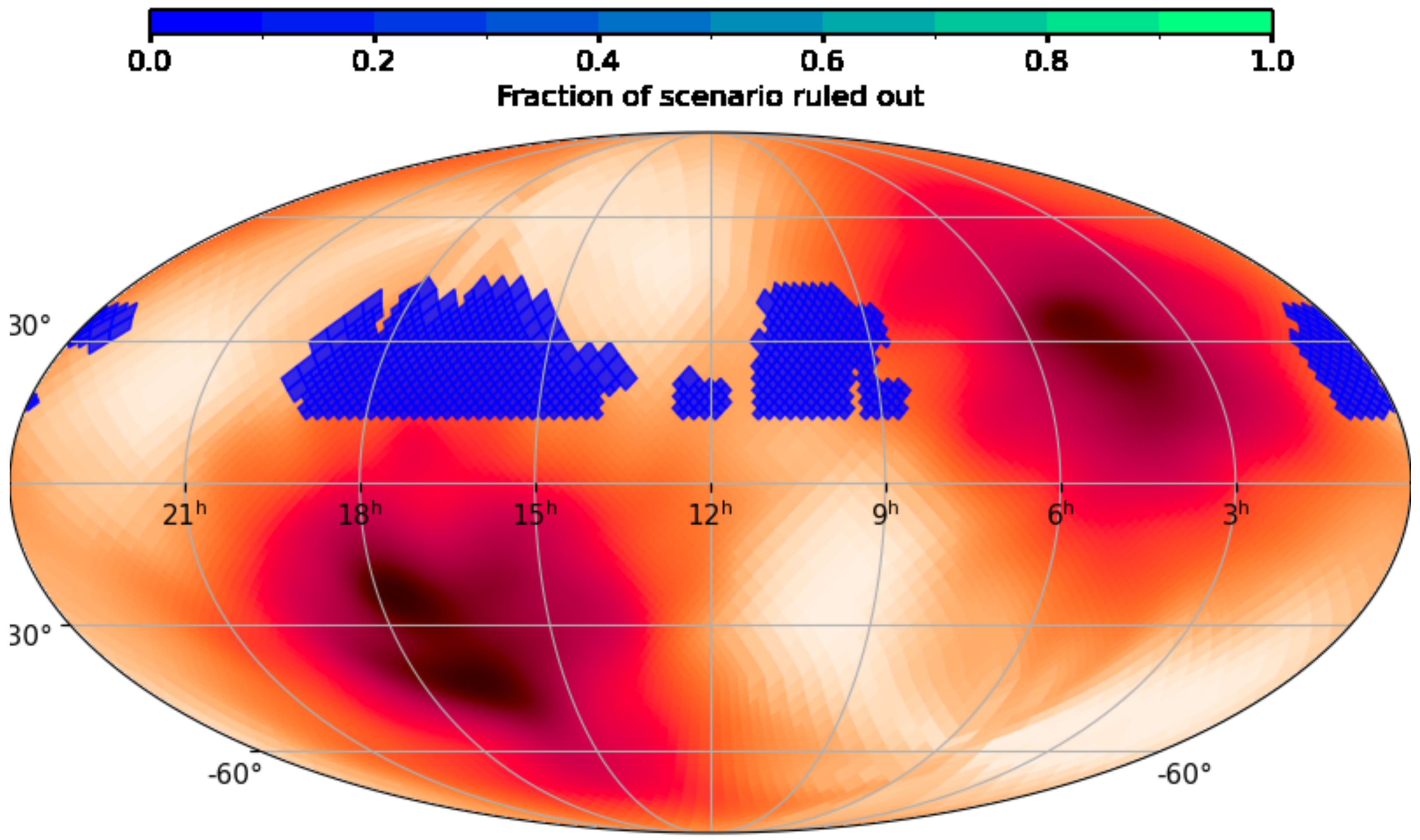
GW230529

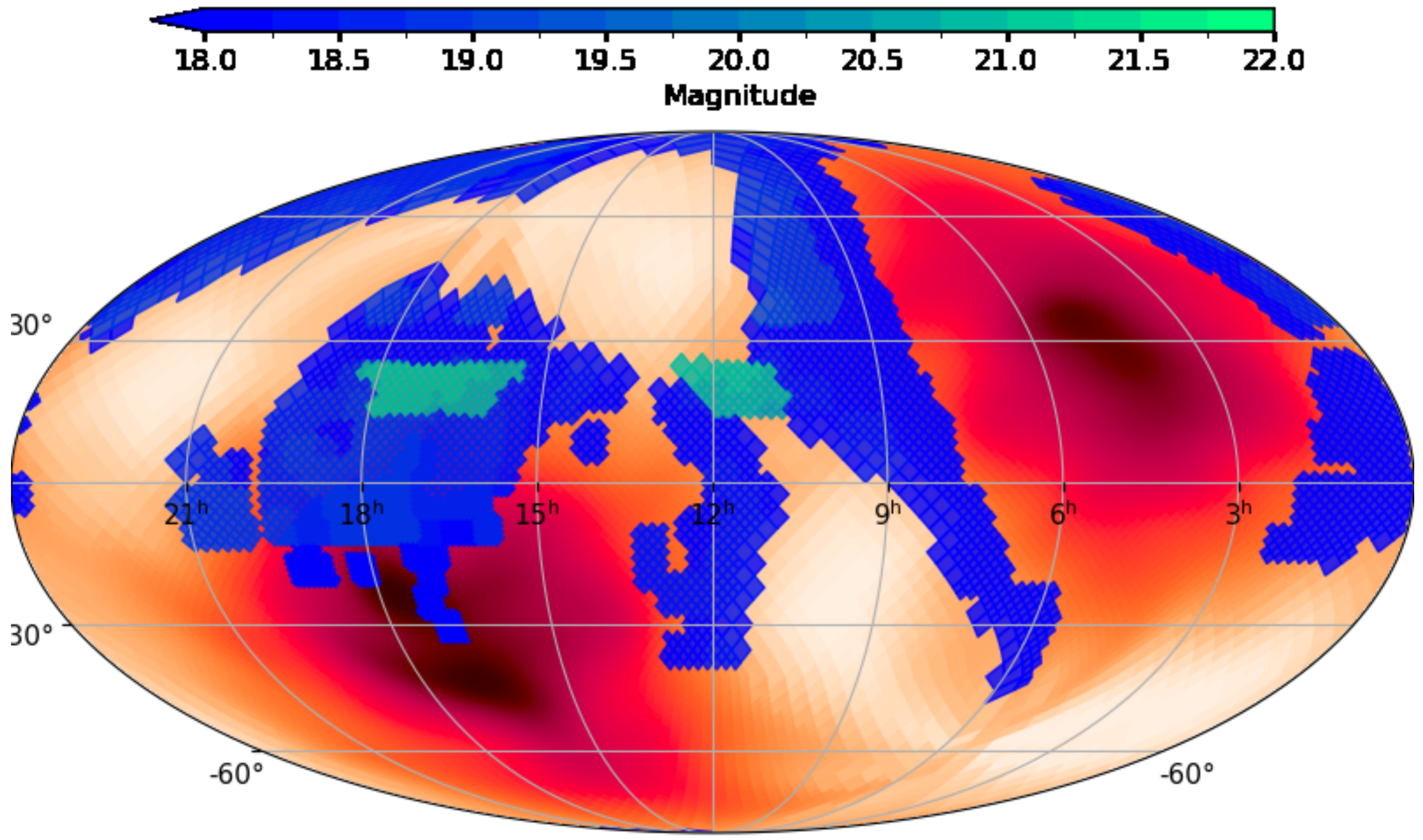
Between 0 and 1 day	Between 1 and 2 day	Between 2 and 6 day

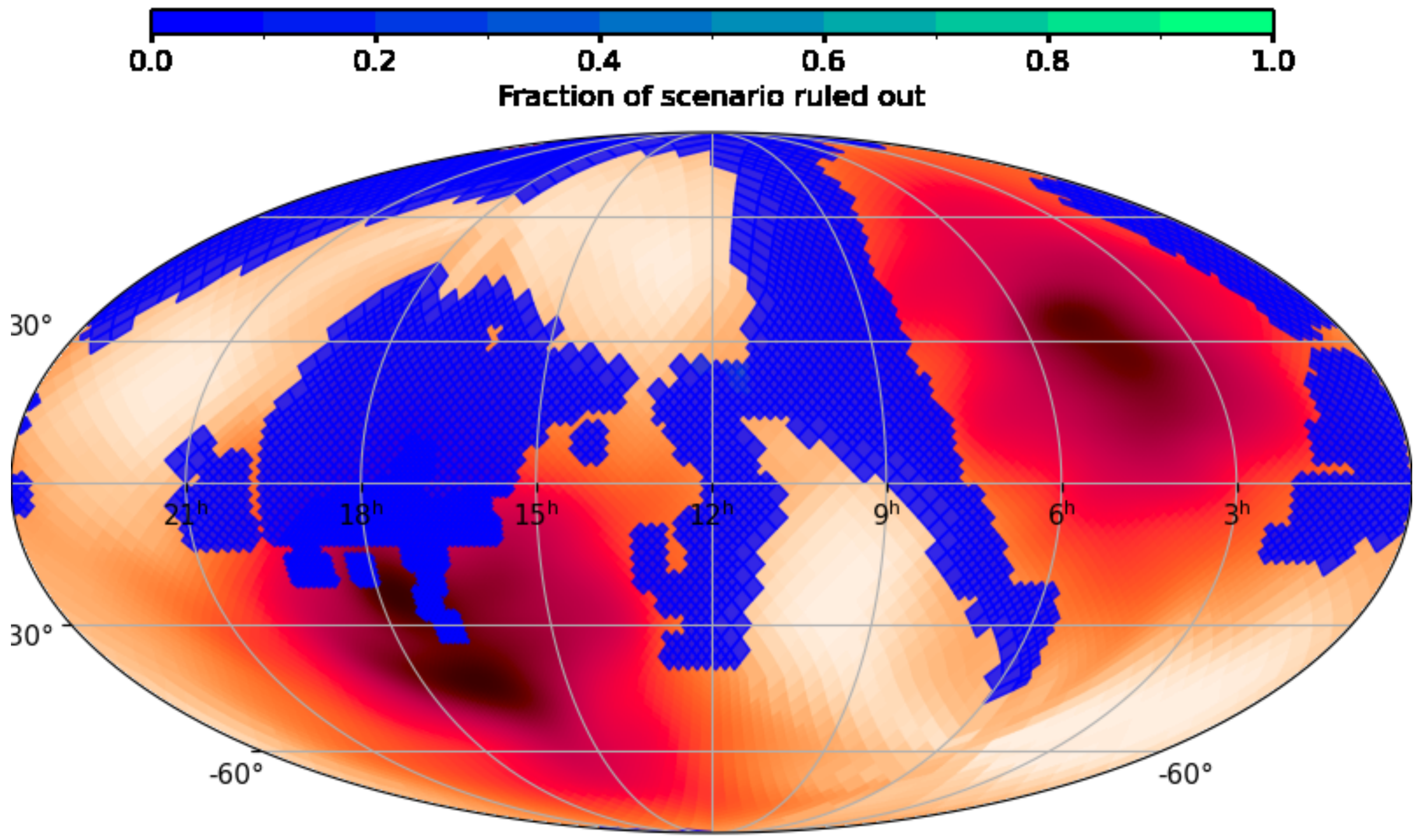






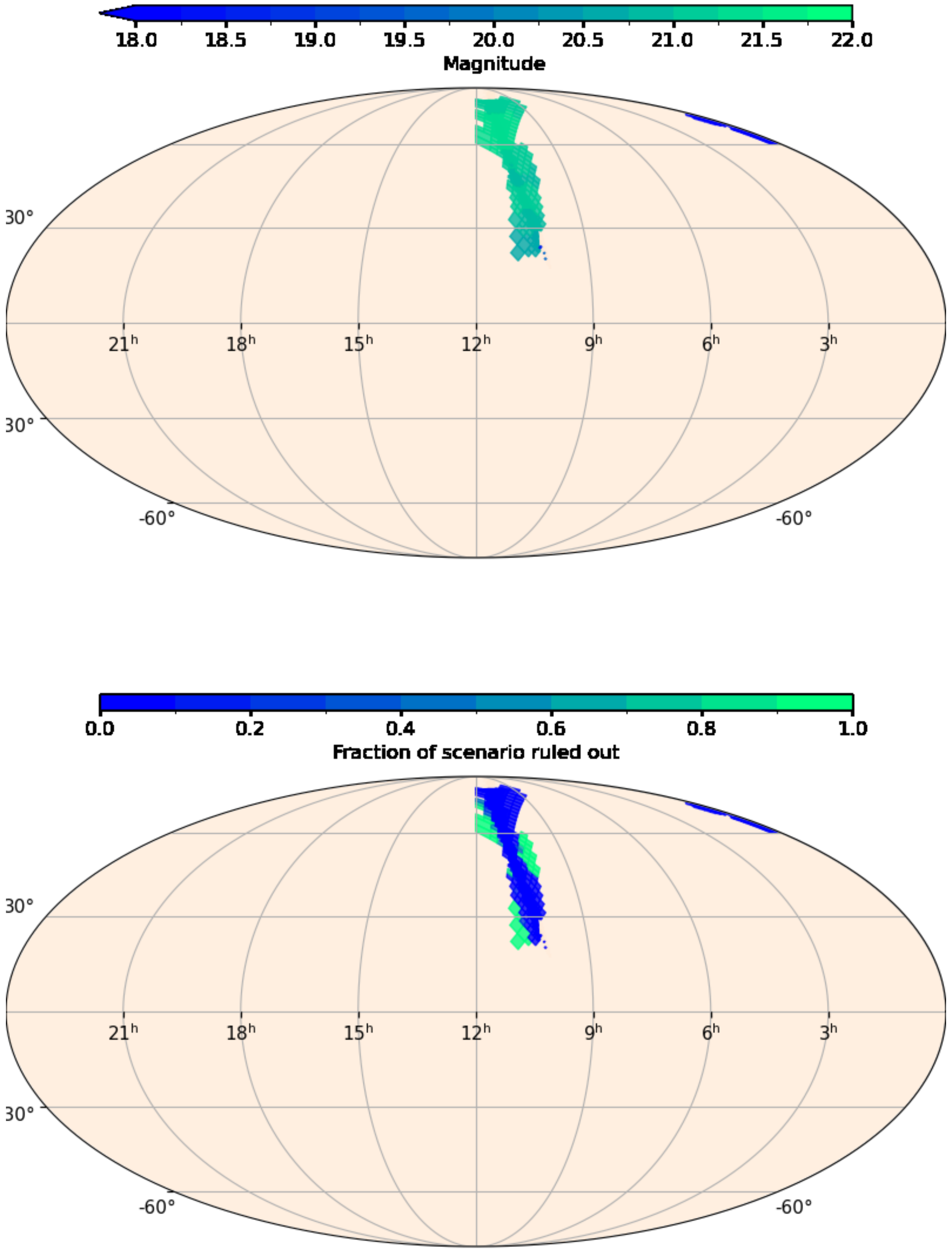




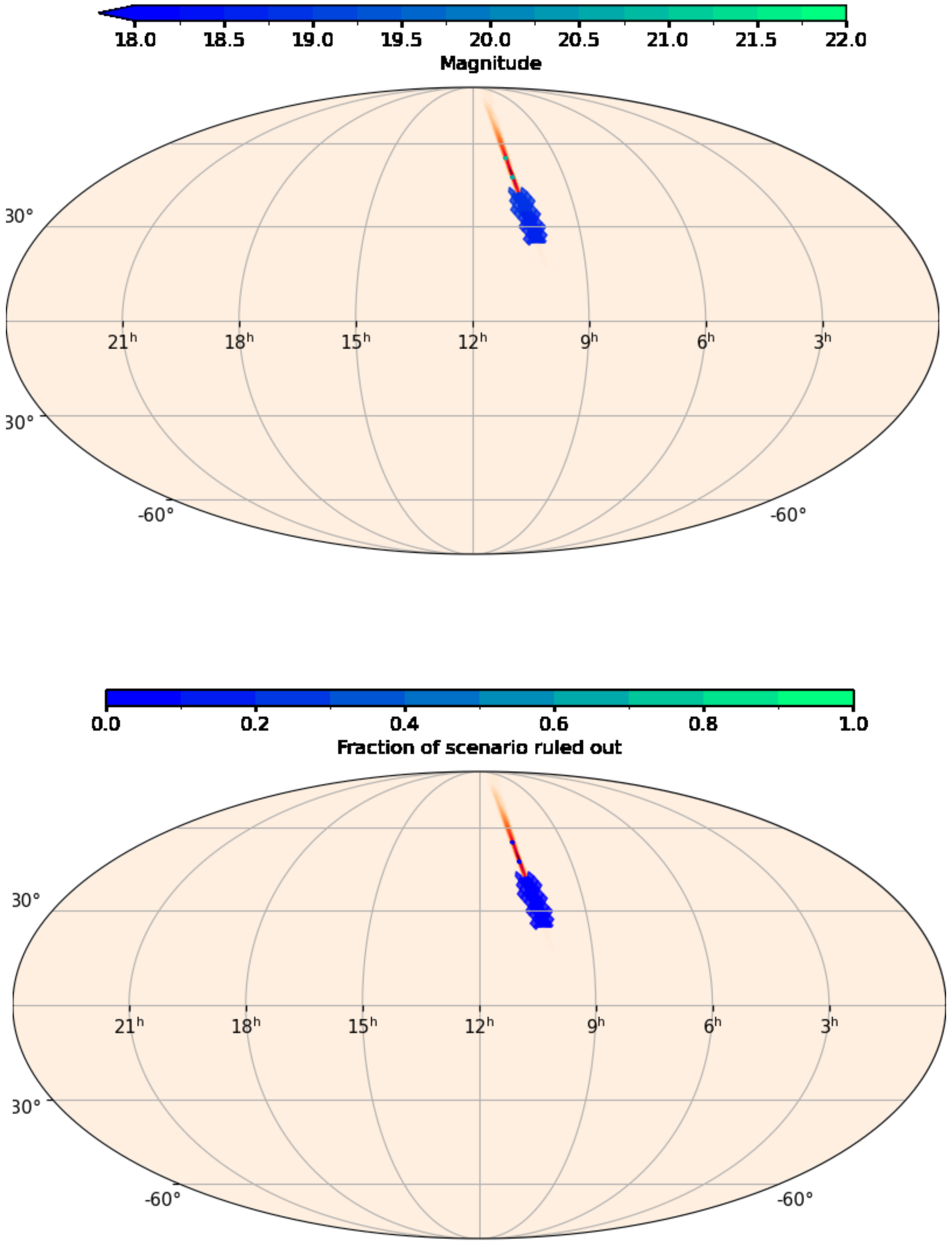


S230627c

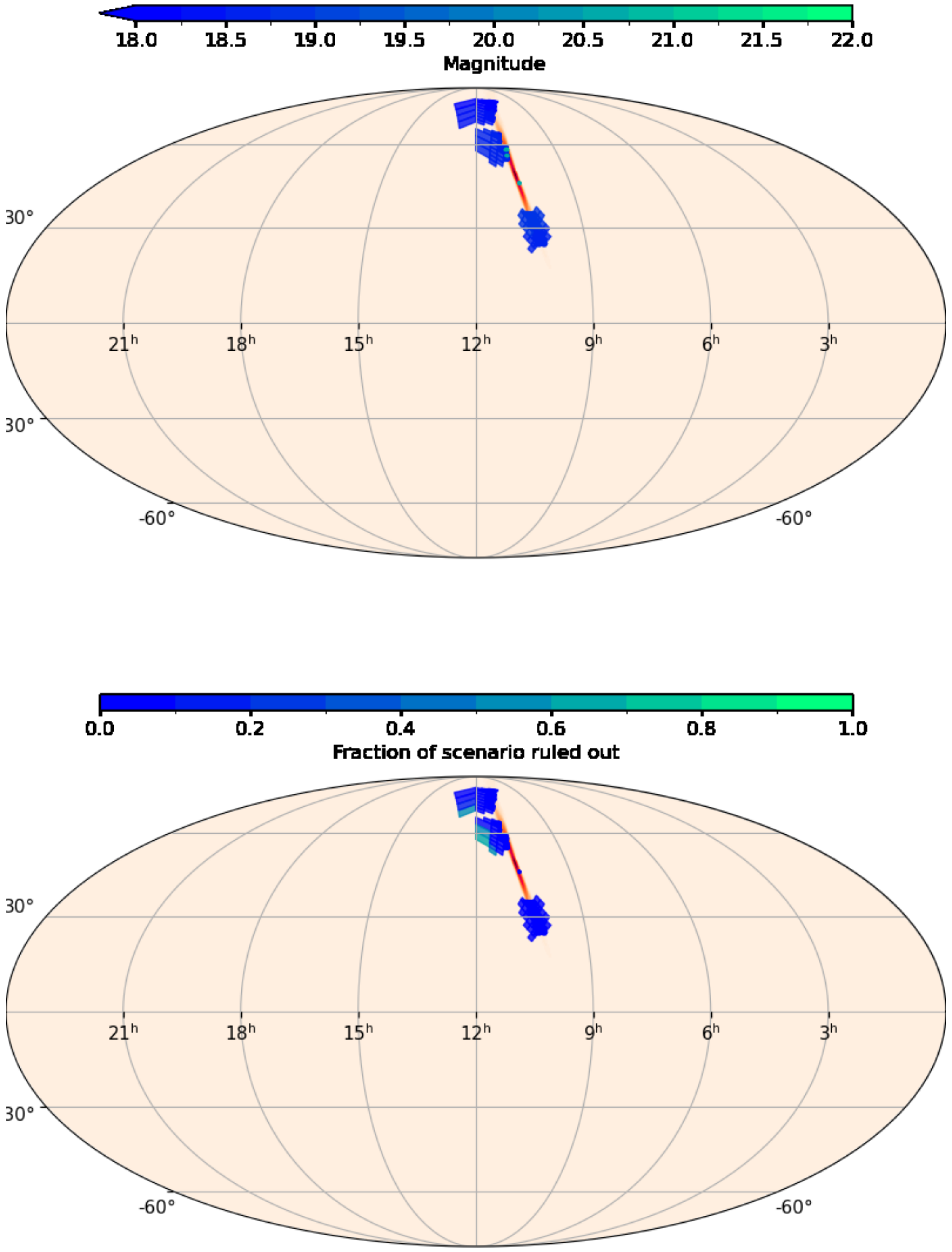
Between 0 and 1 day



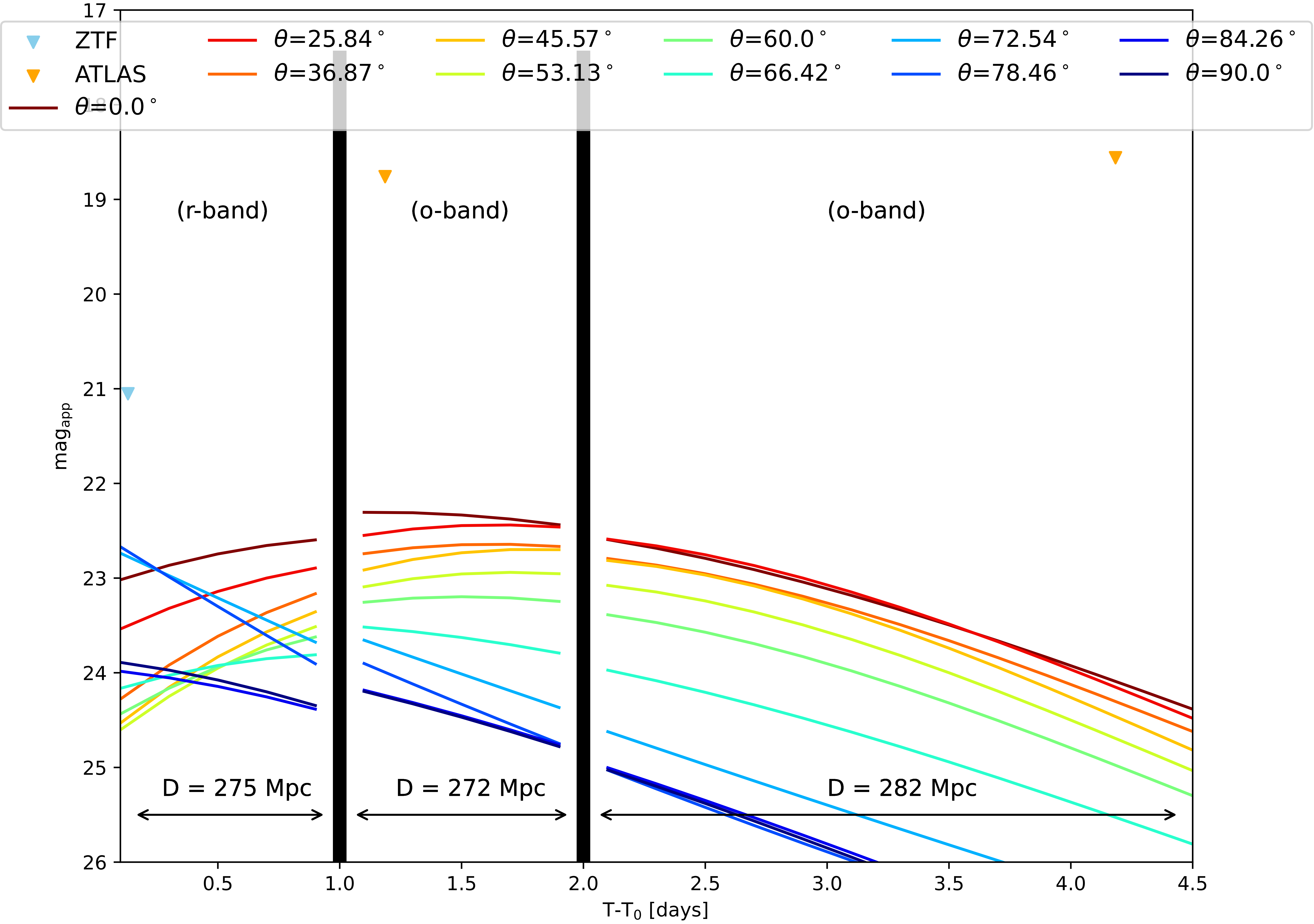
Between 1 and 2 day



Between 2 and 6 day

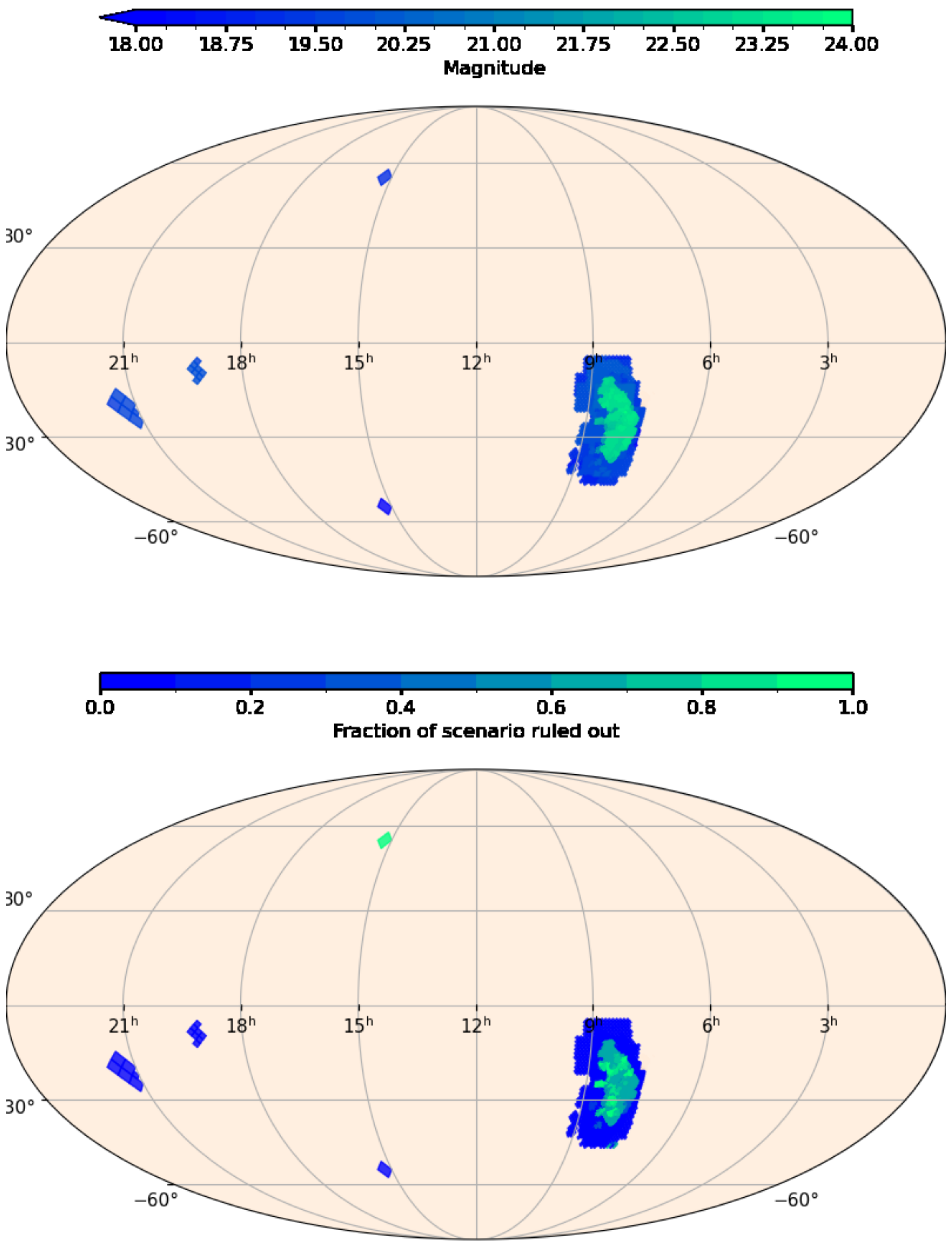


S230627c

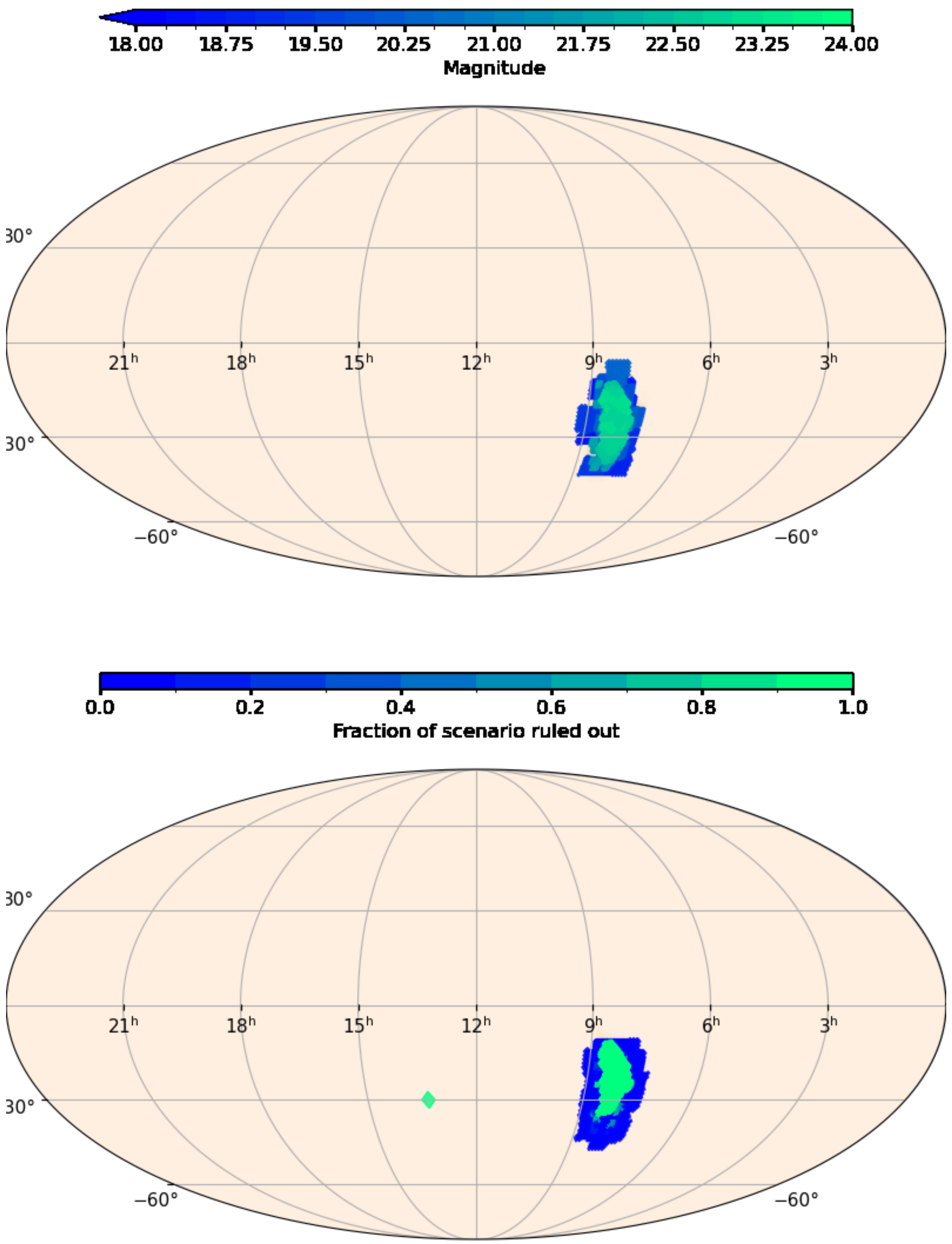

ZTF
ATLAS
θ=0.0°
θ=25.84°
θ=36.87°
θ=45.57°
θ=53.13°
θ=60.0°
θ=66.42°
θ=72.54°
θ=78.46°
θ=84.26°
θ=90.0°
(r-band)
(o-band)
(o-band)
D = 275 Mpc
D = 272 Mpc
D = 282 Mpc
mag_app
T-T0 [days]
17
19
20
21
22
23
24
25
26
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5

S240422ed

Between 0 and 1 day



Between 1 and 2 day



Between 2 and 6 day