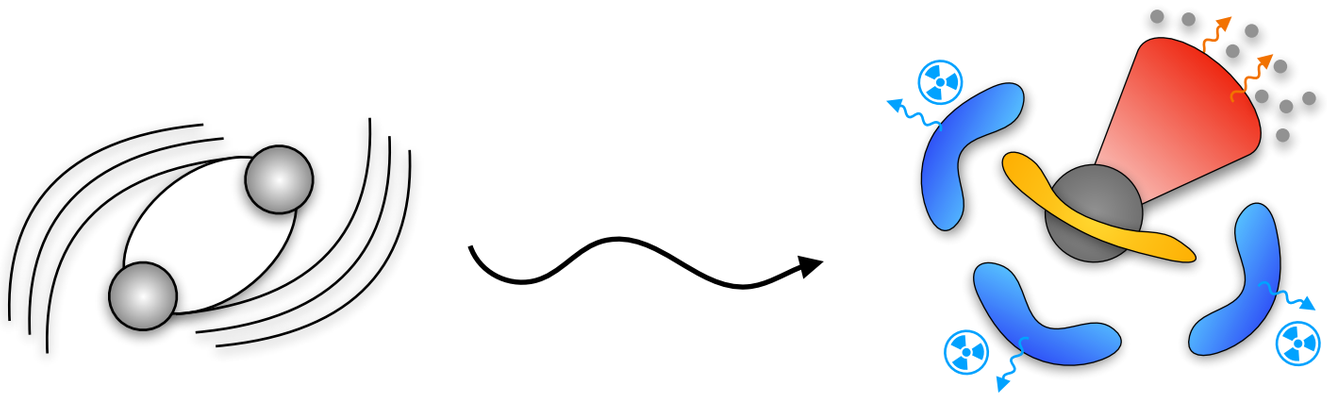
Gravitational Waves Science Review

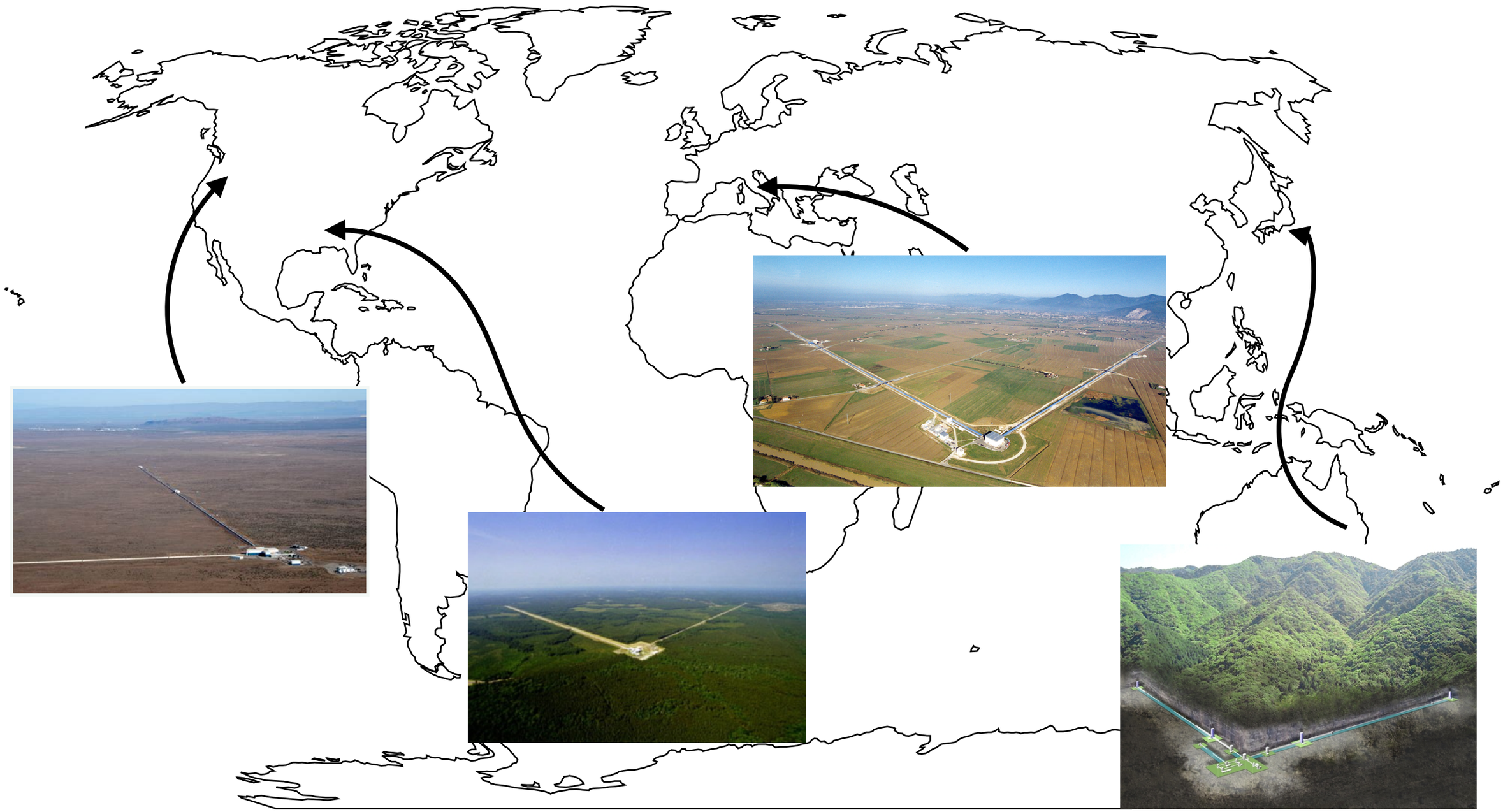
Binary Neutron Star and Black Hole - Neutron Star Mergers



Alberto Colombo - INFN

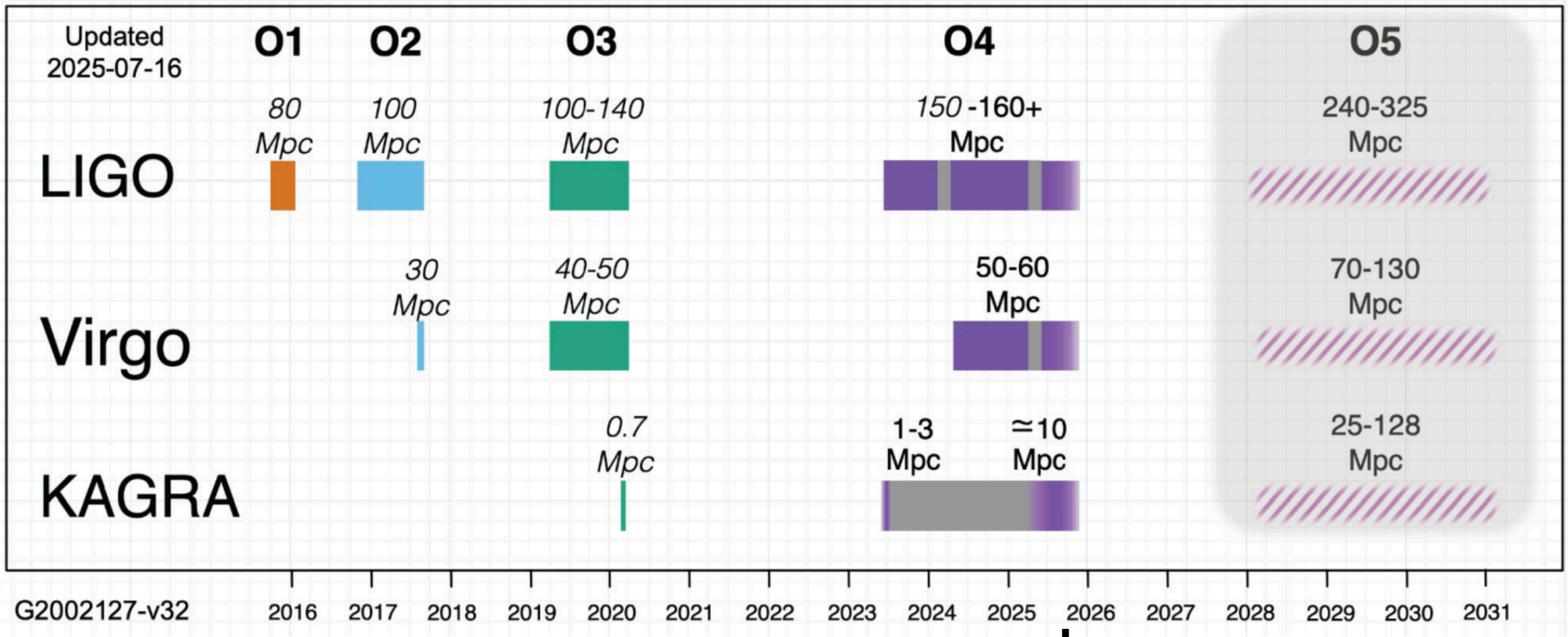
Towards high-performance mm_VLBI science operations with multi-band receivers

The LIGO, Virgo and KAGRA Collaborations (LVK)



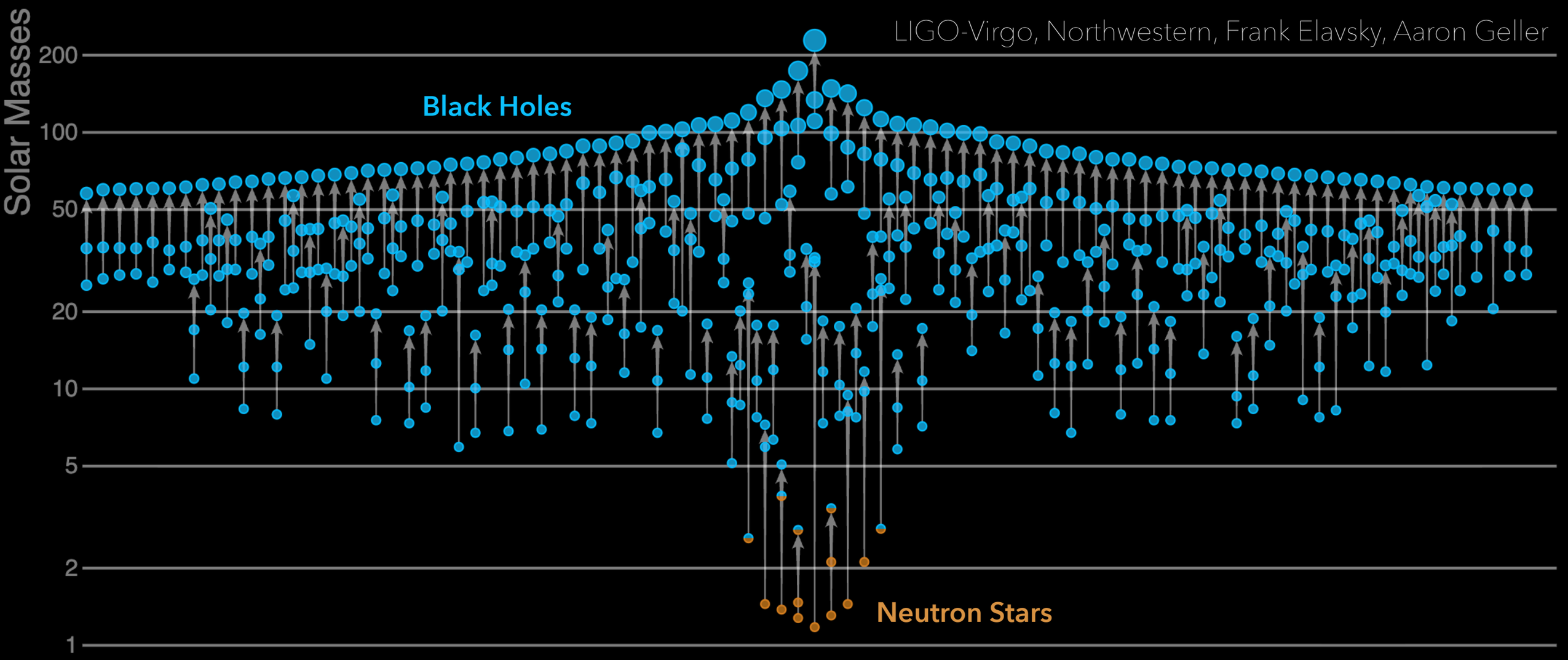
Observing Runs

Credit LVK

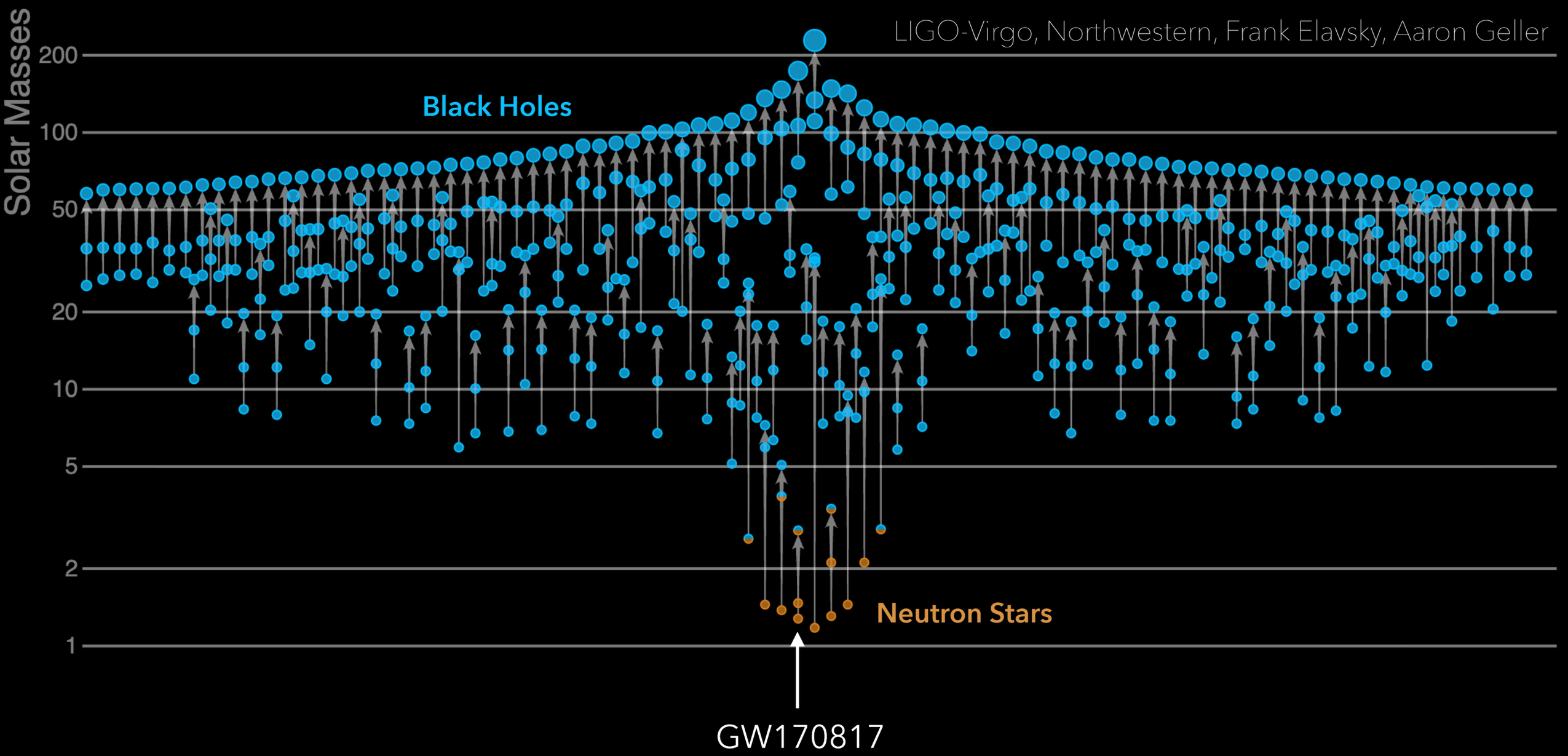


We are here!

So far


LIGO-Virgo, Northwestern, Frank Elavsky, Aaron Geller
Solar Masses
200
100
50
20
10
5
2
1
Black Holes
Neutron Stars

So far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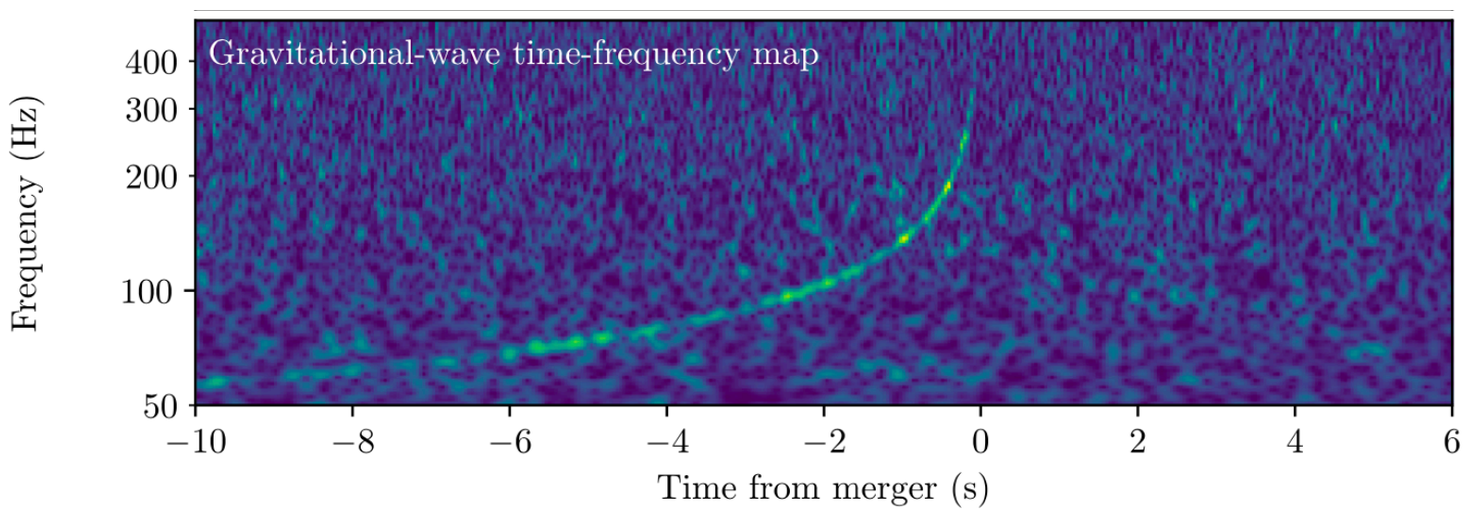
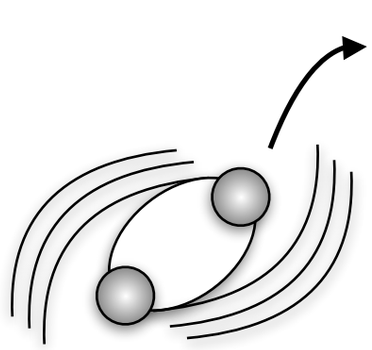
GW170817

GW170817
The First Multi-Messenger Observation



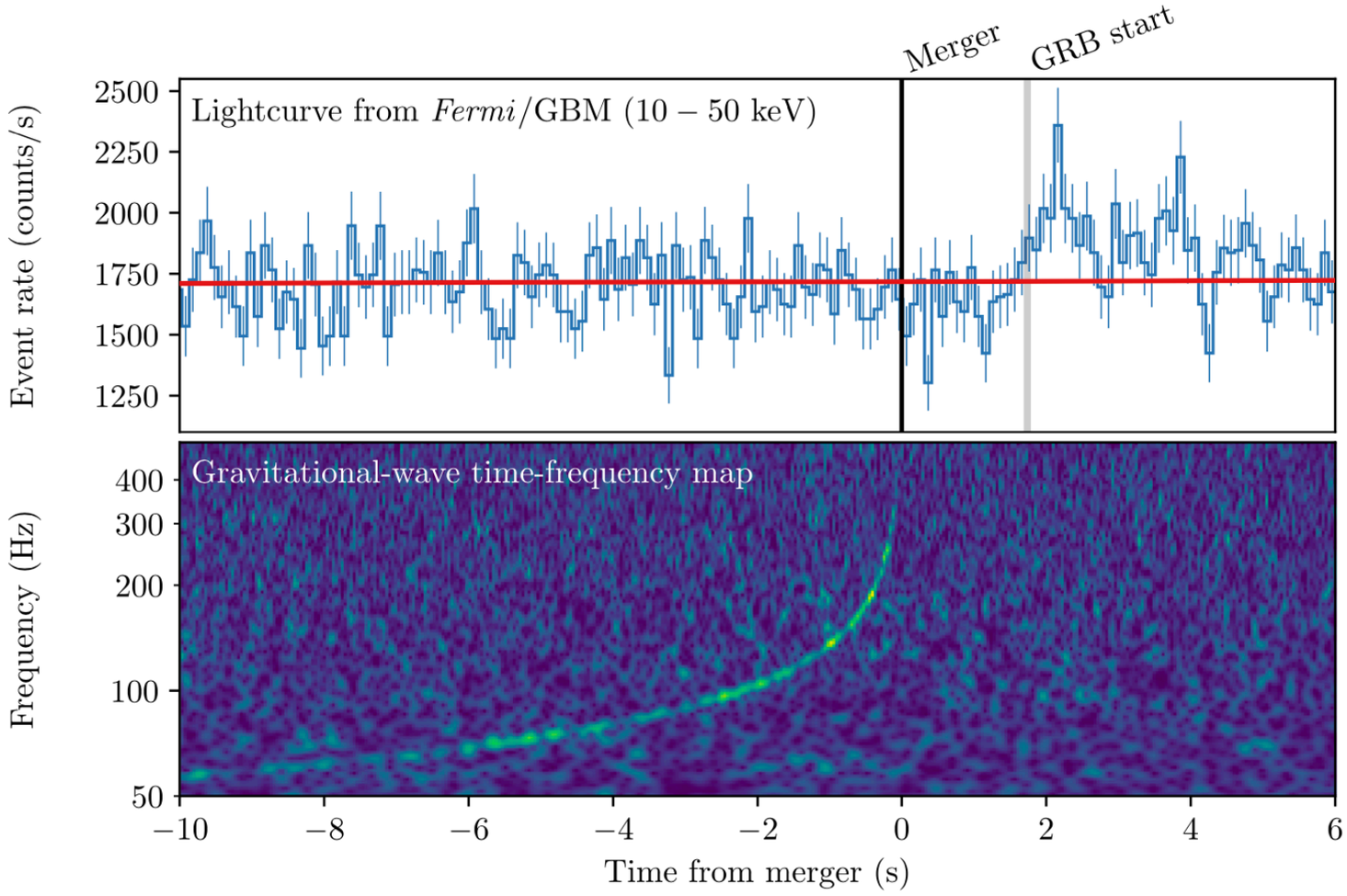


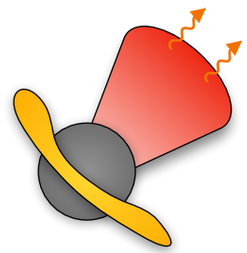
$M_1 = 1.46^{+0.12}_{-0.10} M_\odot$

$M_2 = 1.27^{+0.09}_{-0.09} M_\odot$

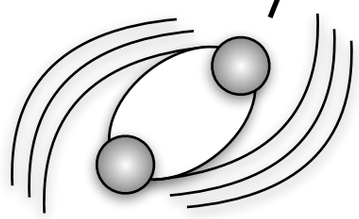
Abbott et al. (2017)

GW170817
The First Multi-Messenger Observation





GRB170817A



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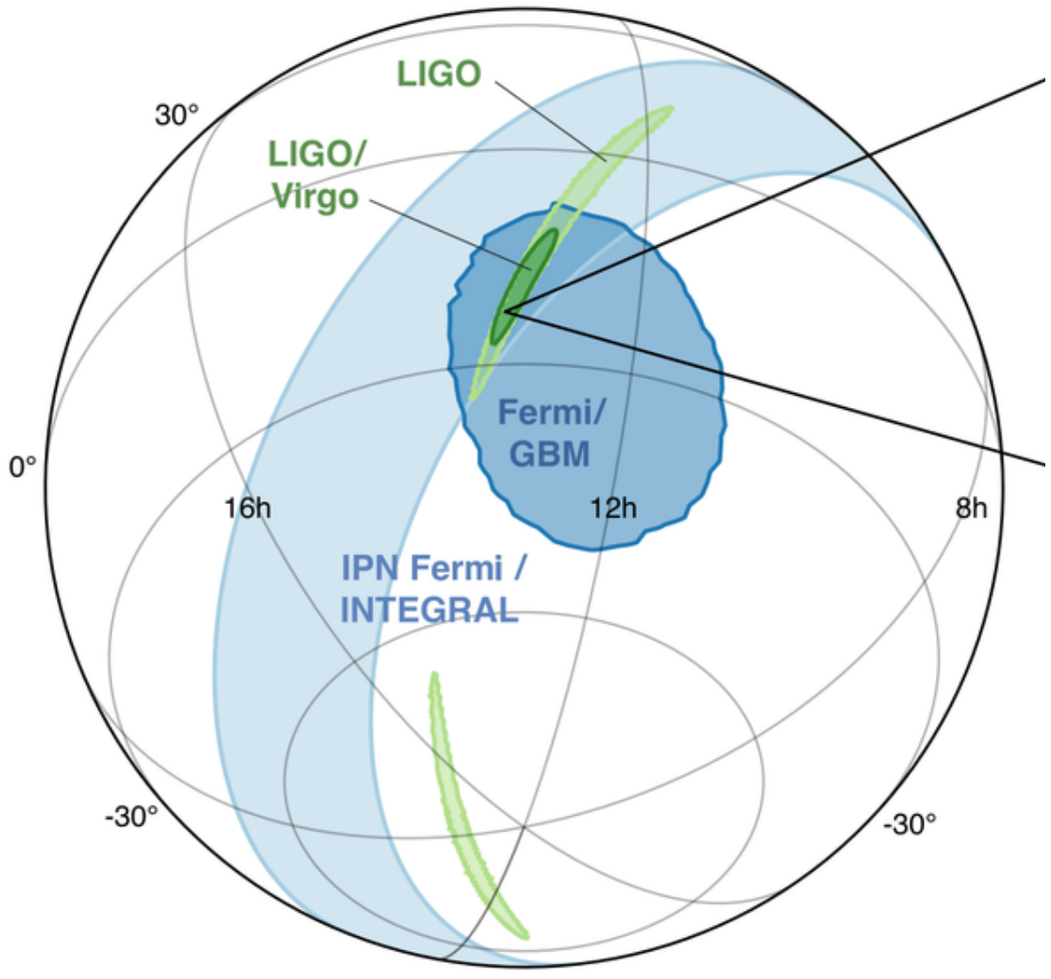

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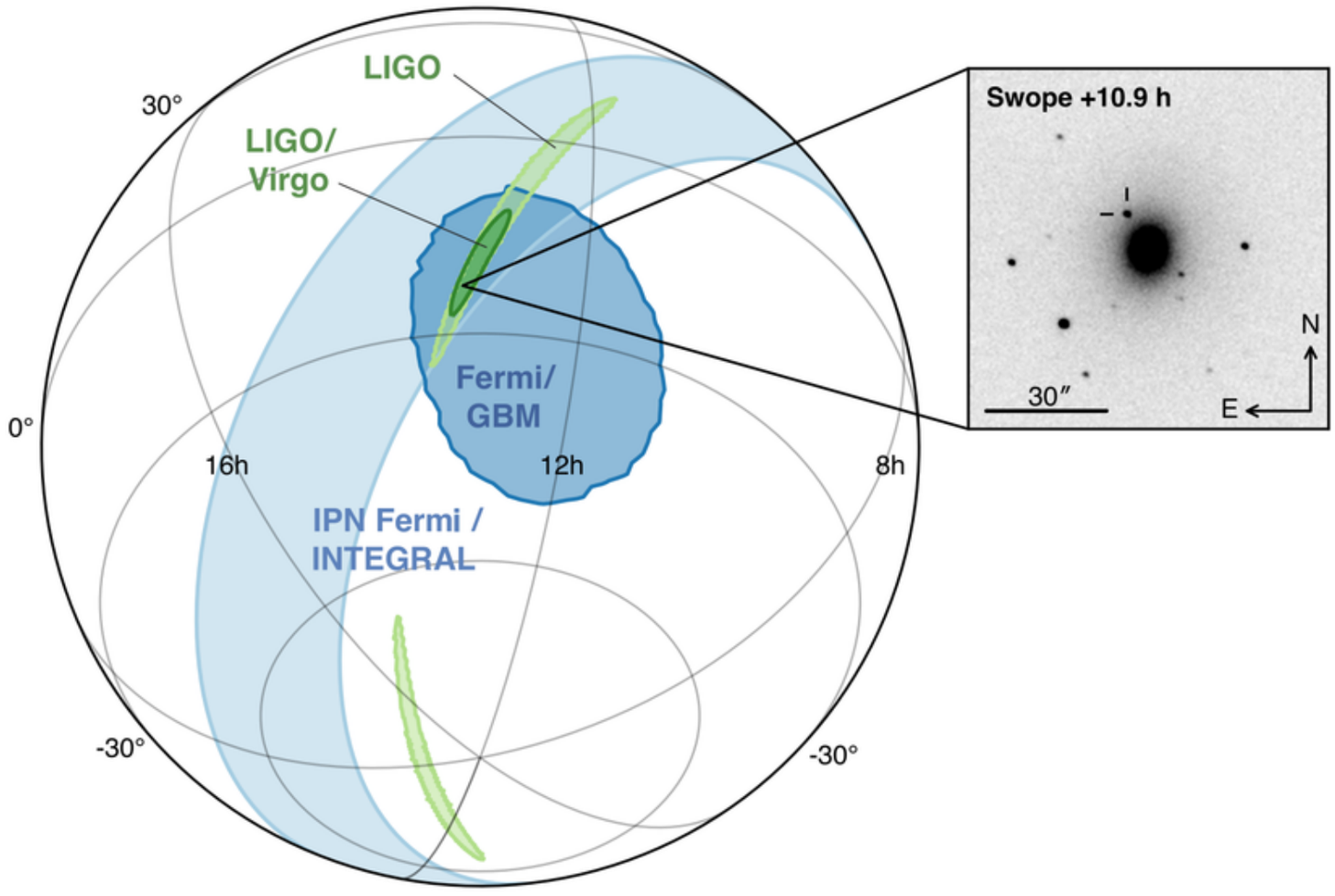

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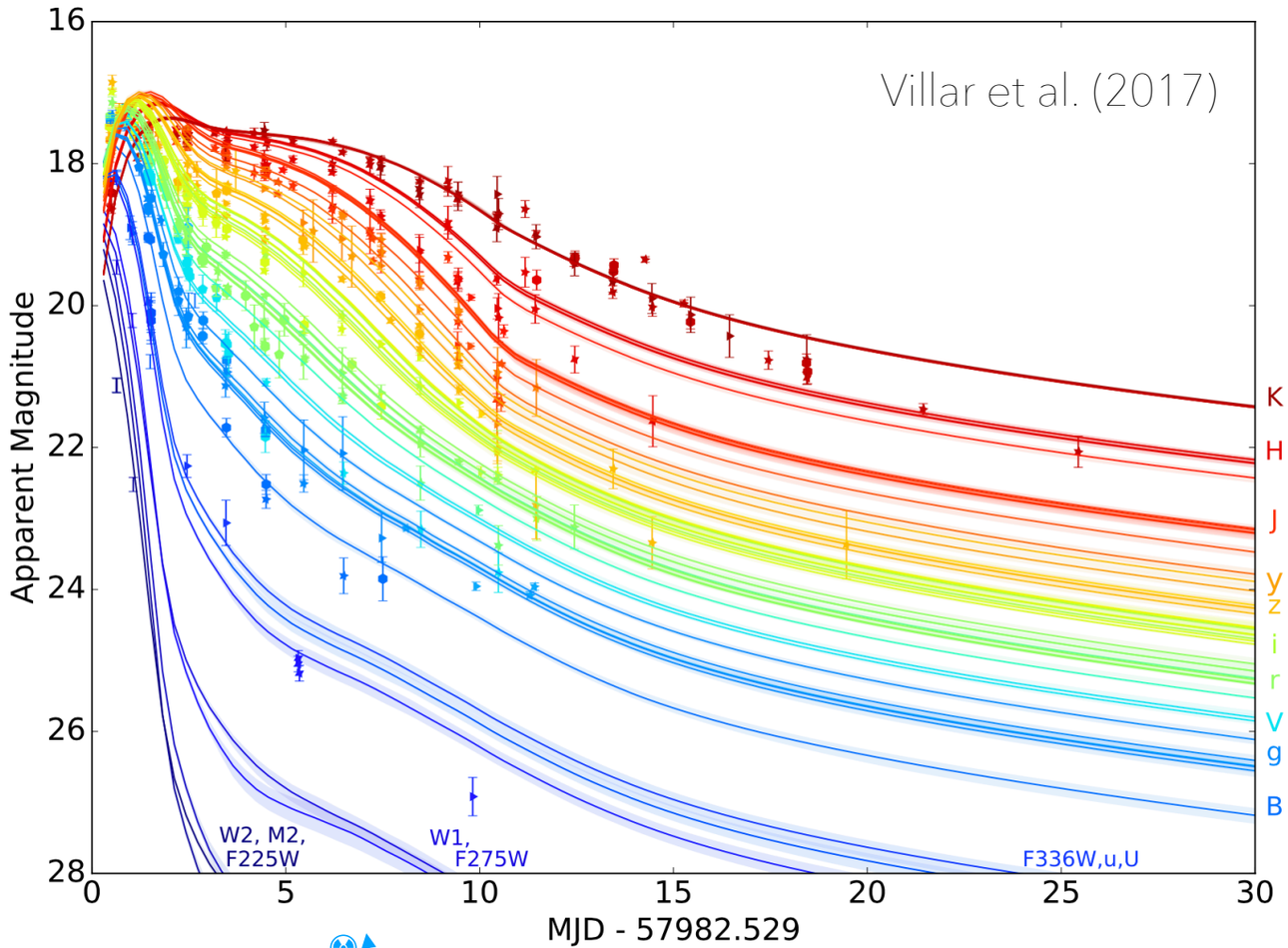
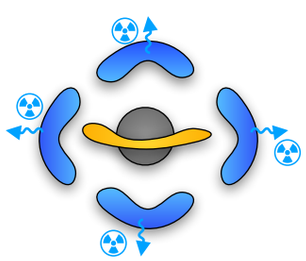
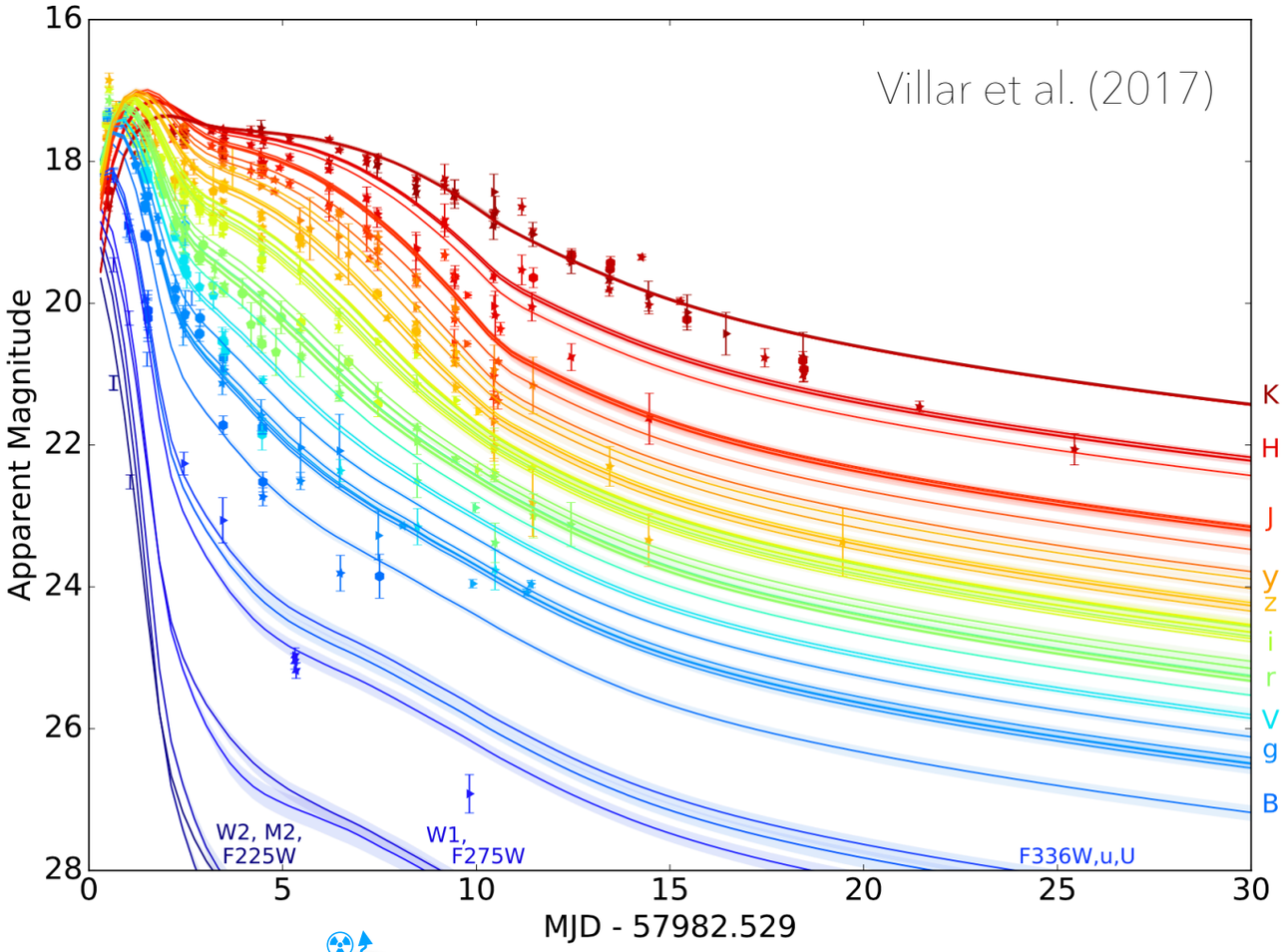


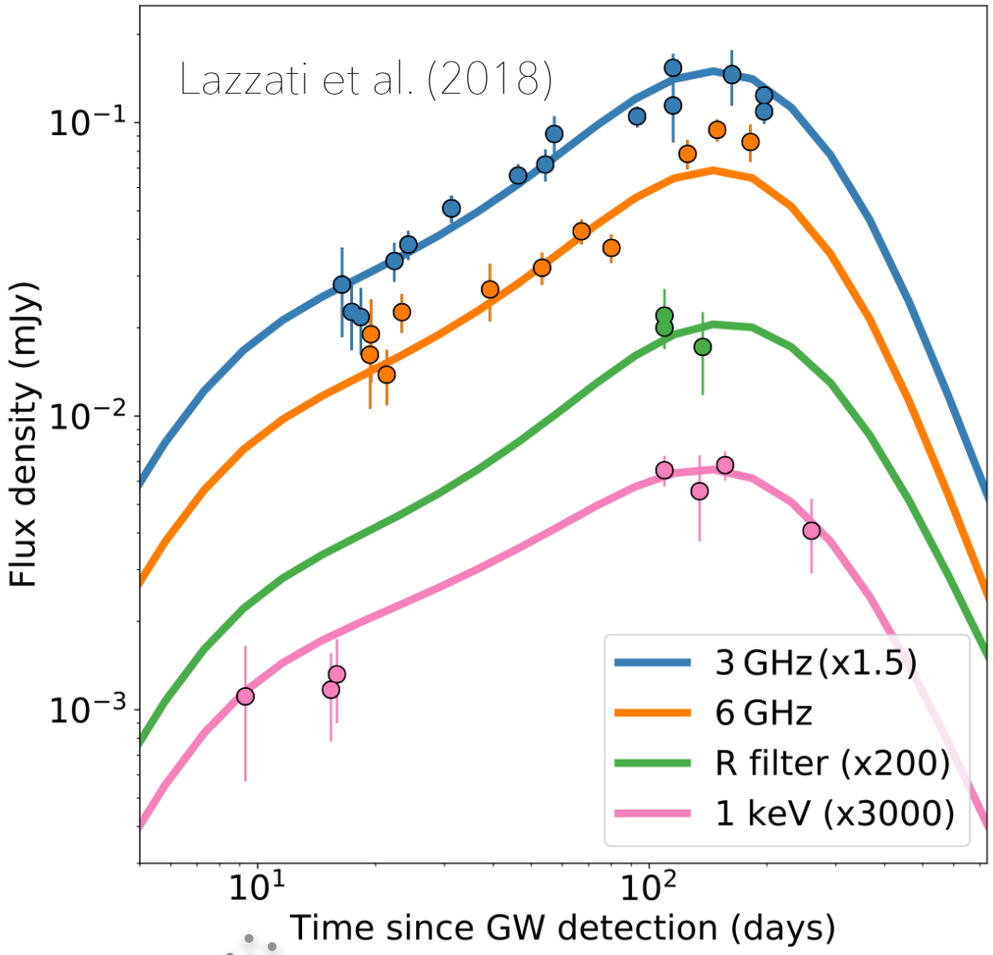


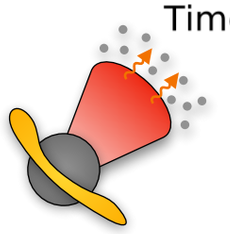
Kilonova

GW170817
The First Multi-Messenger Observation



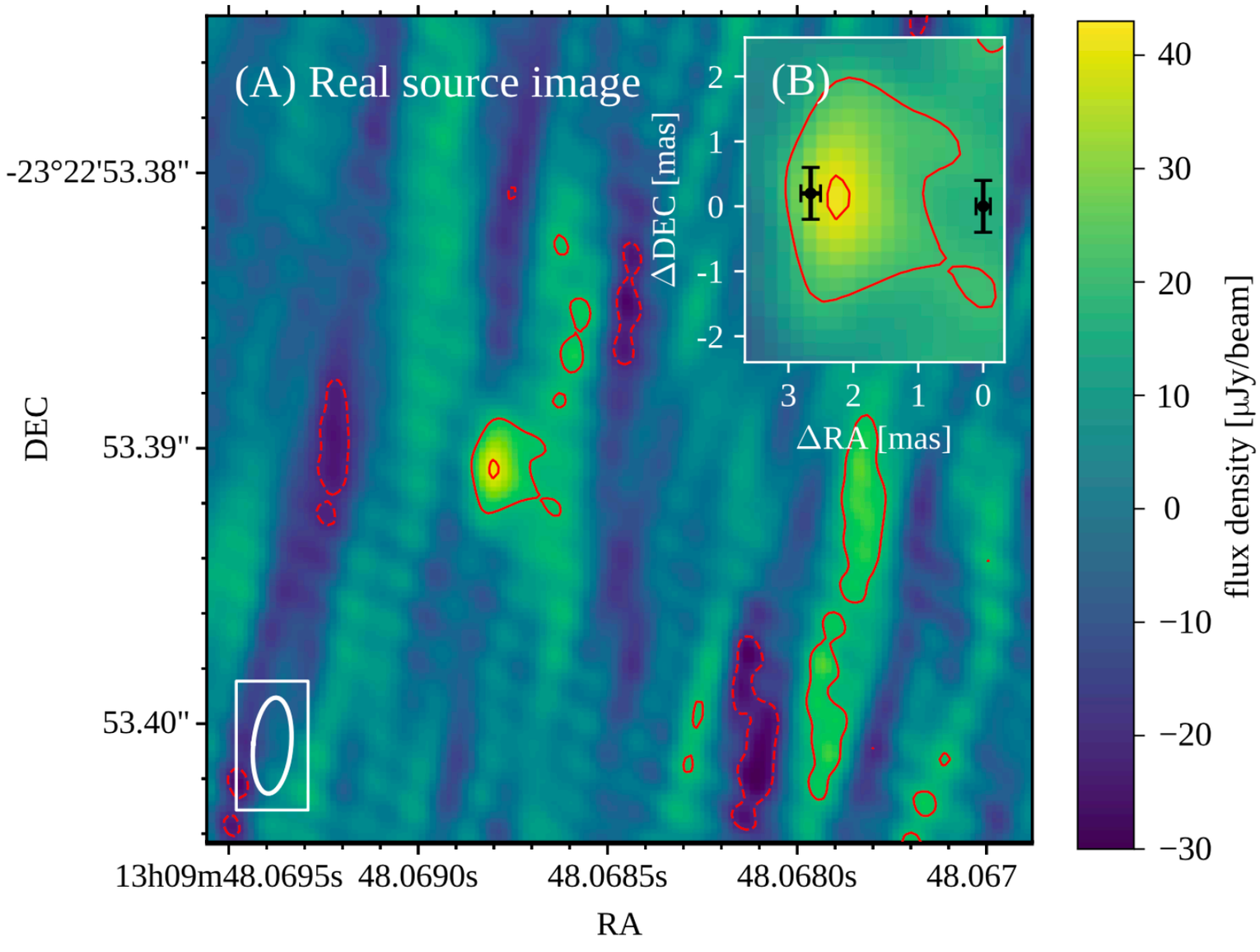
Kilonova





GRB Afterglow

GW170817 and VLBI



Ghirlanda et al. (2019)
See also Mooley+18

Constraining parameters

Abbott+2019
Barbieri+2020

Nuclear matter physics

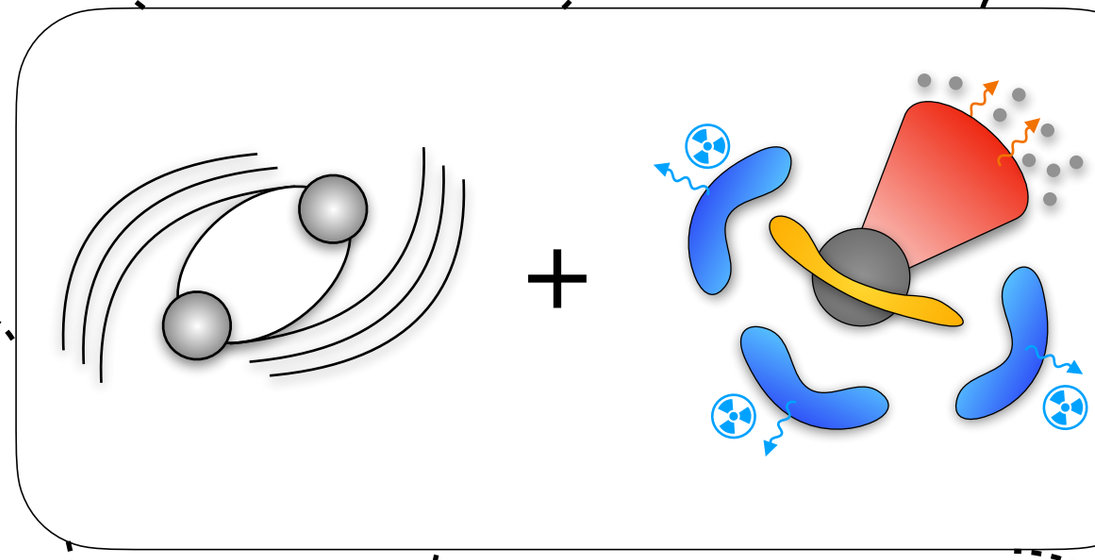
Abbott+2018

Formation pathways

Kruckow+2018
Mapelli+2018

High energy phenomena

Abbott+2017c
Mooley+2018
Ghirlanda+2019



Cosmology

Abbott+2017a

Heavy elements

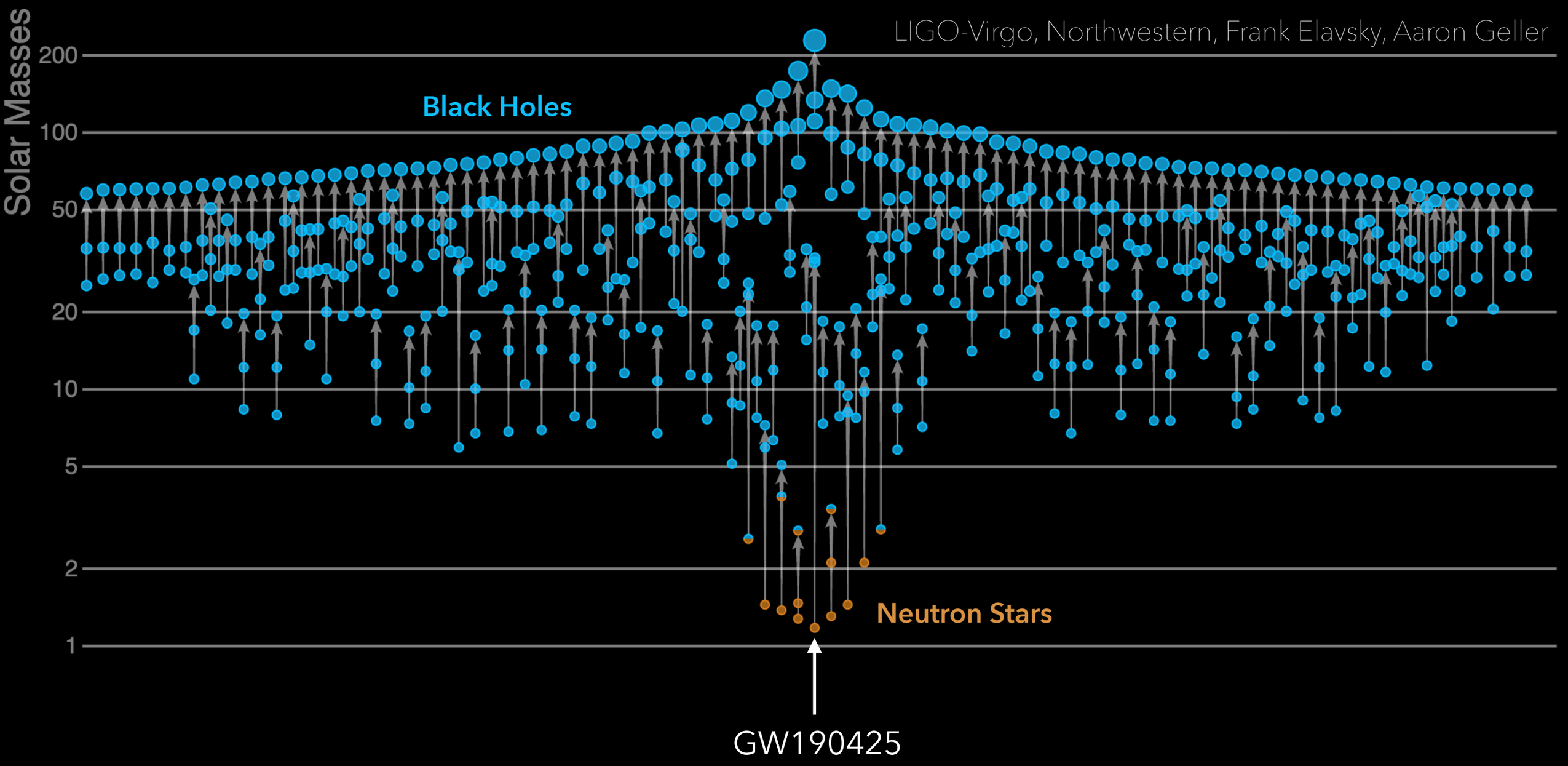
Coulter+2017
Pian+2017
Kasen+2017
Kajino+2019

Abbott+2019
Baker+2017
Creminelli+2017

Fundamental physics

But…

So far


LIGO-Virgo, Northwestern, Frank Elavsky, Aaron Geller
Solar Masses
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Black Holes
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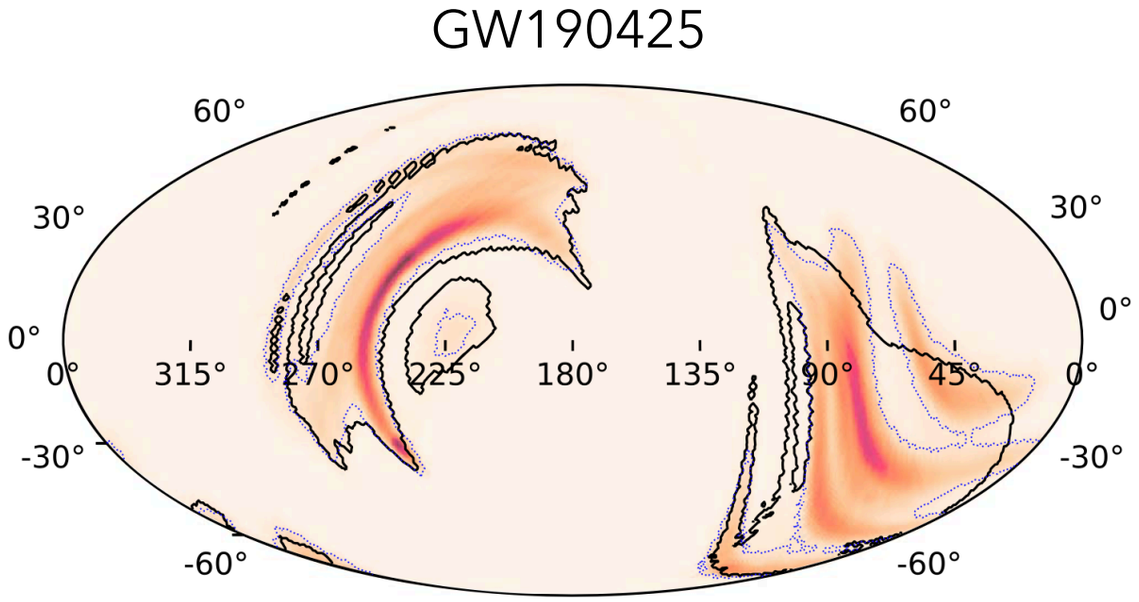
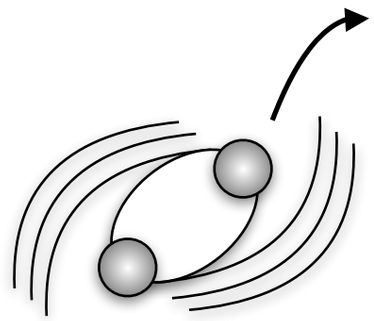
GW190425

A Second NSNS Merger
No EM counterparts



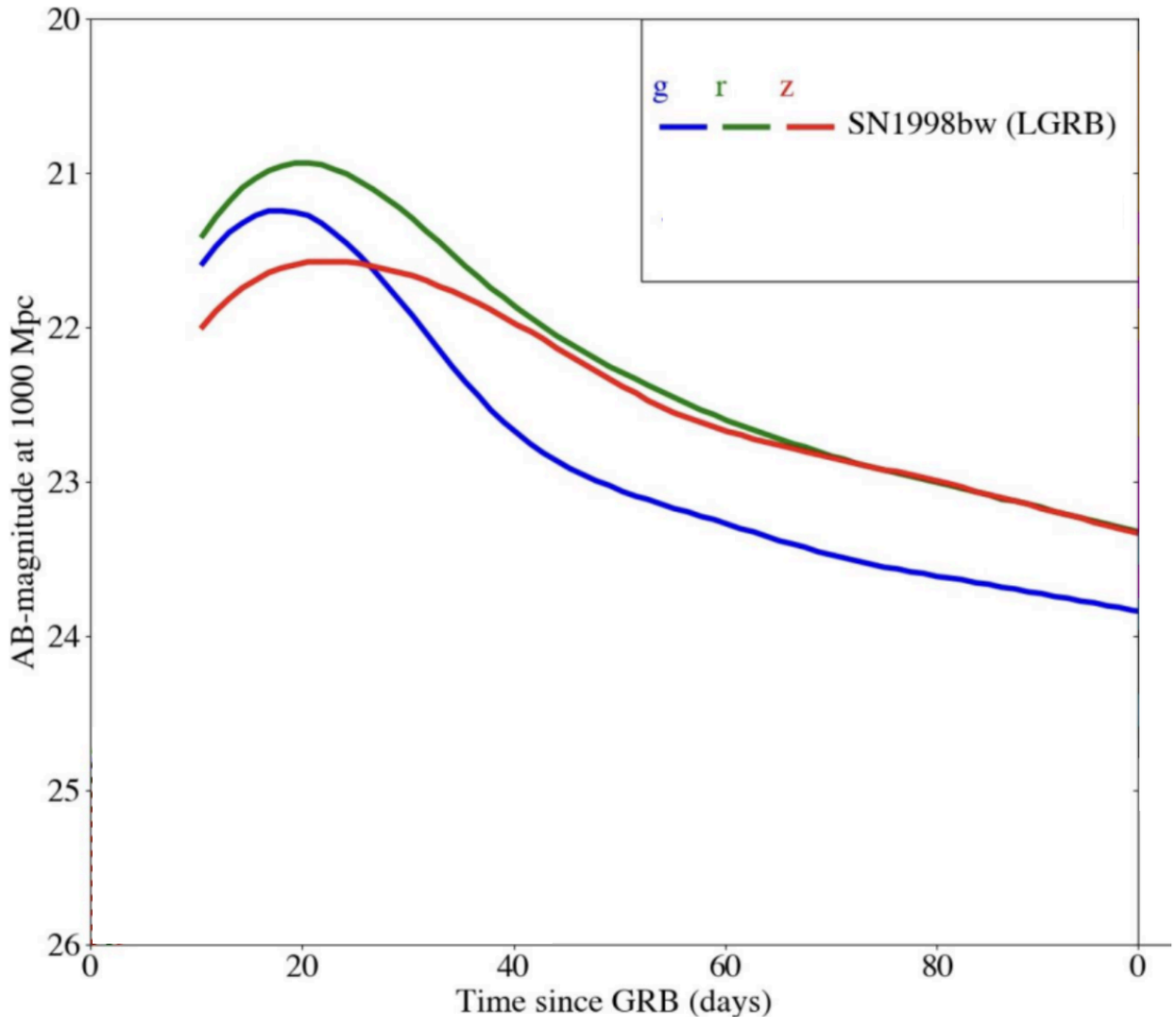


$M_1 \in 1.61 - 2.52\, M_\odot$

$M_2 \in 1.12 - 1.68\, M_\odot$

Abbott et al. (2020)

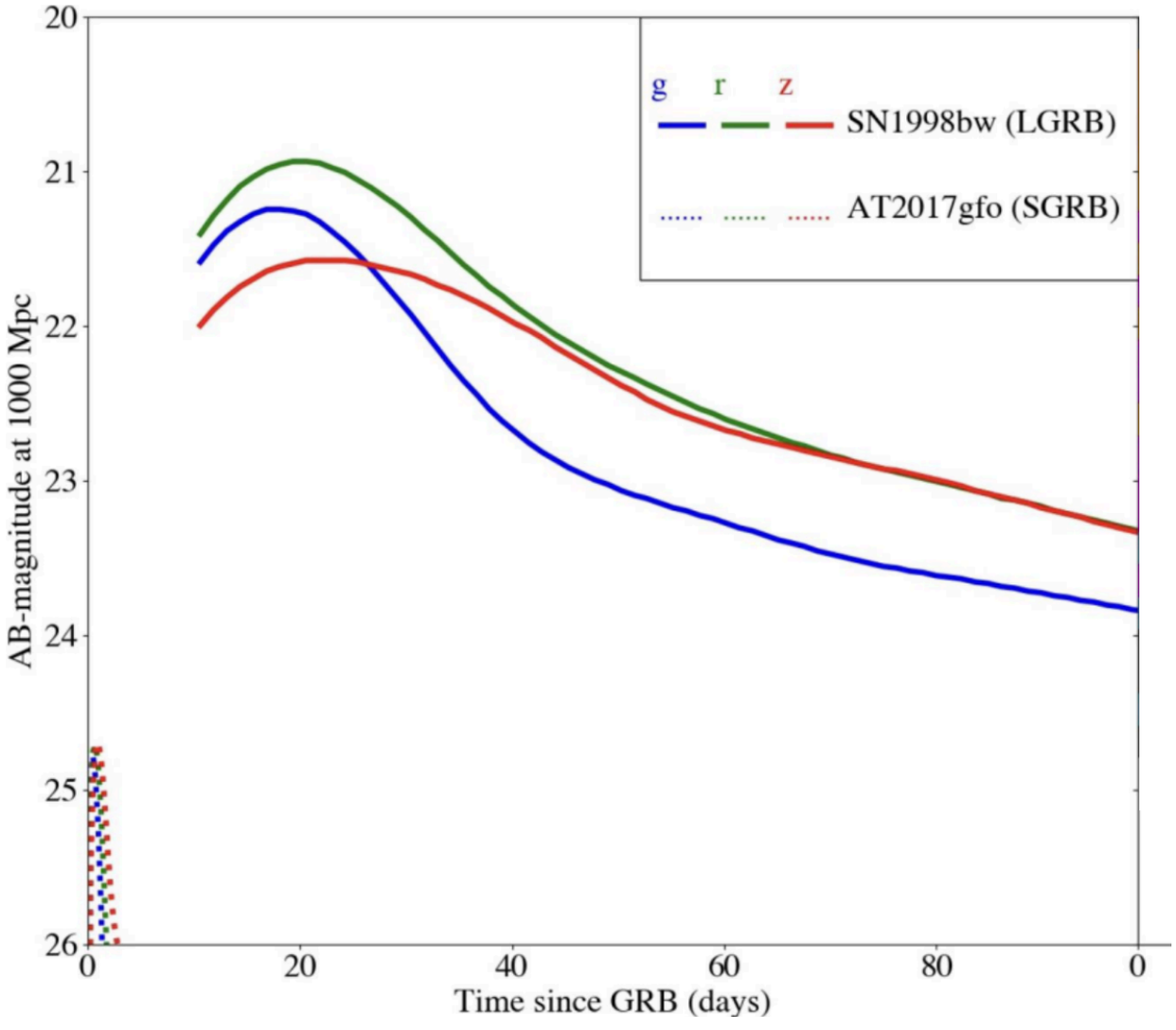
The Multi-Messenger Challenge



Levan et al. (2023)

- Localization volume can be **extremely large**
- Many **contaminant** transients
-

The Multi-Messenger Challenge



Levan et al. (2023)

- Localization volume can be **extremely large**
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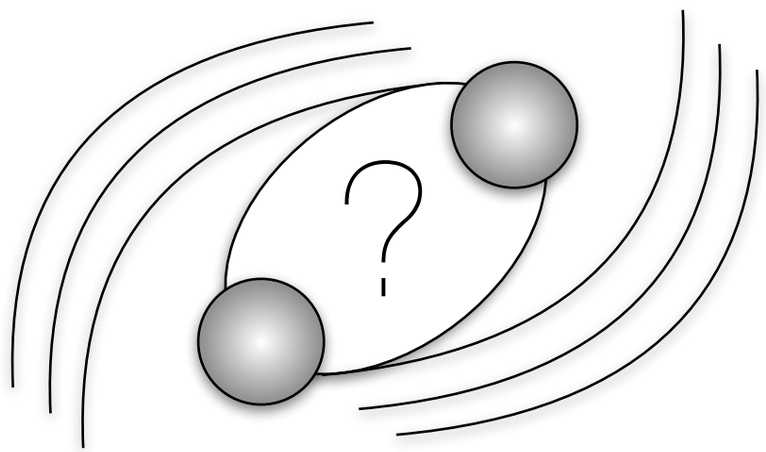
- **Kilonovae are fast**, must be detected the first/second night

The Multi-Messenger Challenge

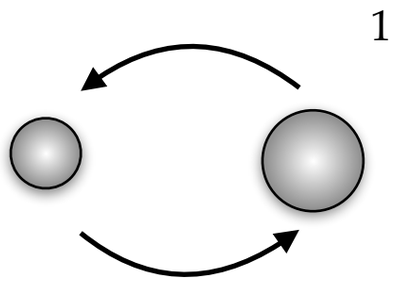


- Localization volume can be **extremely large**
- Many **contaminant** transients
- **Kilonovae are fast**, must be detected the first/second night
- No EM counterparts detected during **O3** and no BNSs in **O4a**

We have to be prepared!

What are the number and the properties of future multi-messenger events?

NSNS Merger and Kilonova Emission



NSNS Merger and Kilonova Emission

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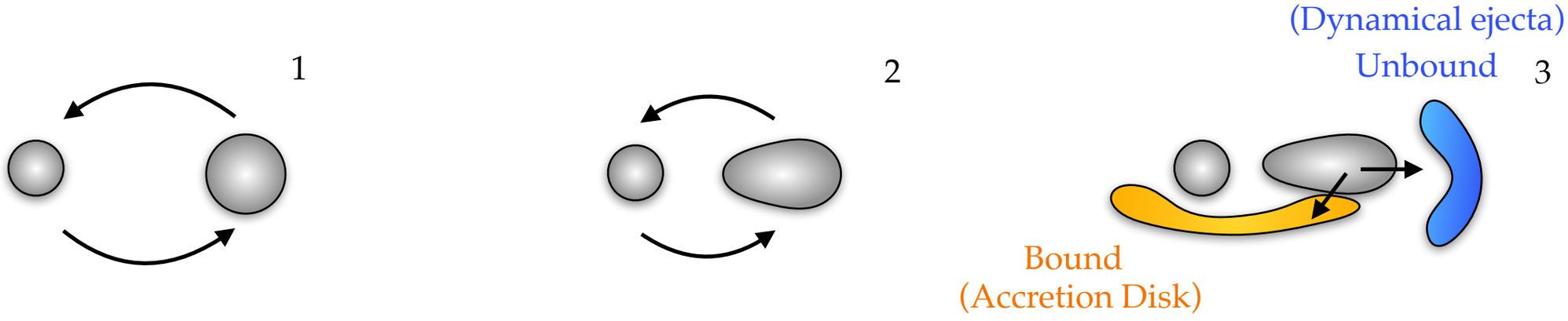

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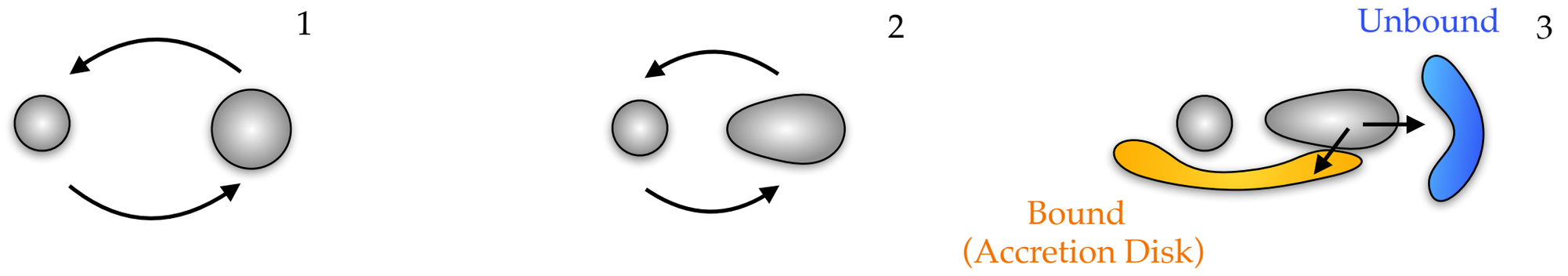

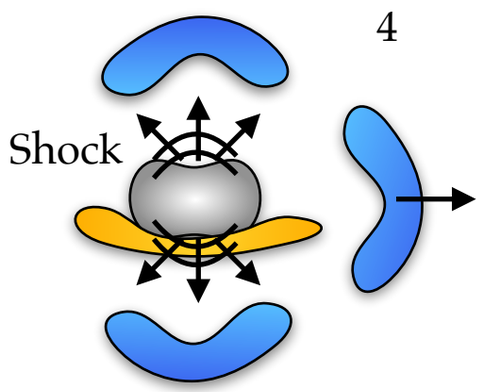

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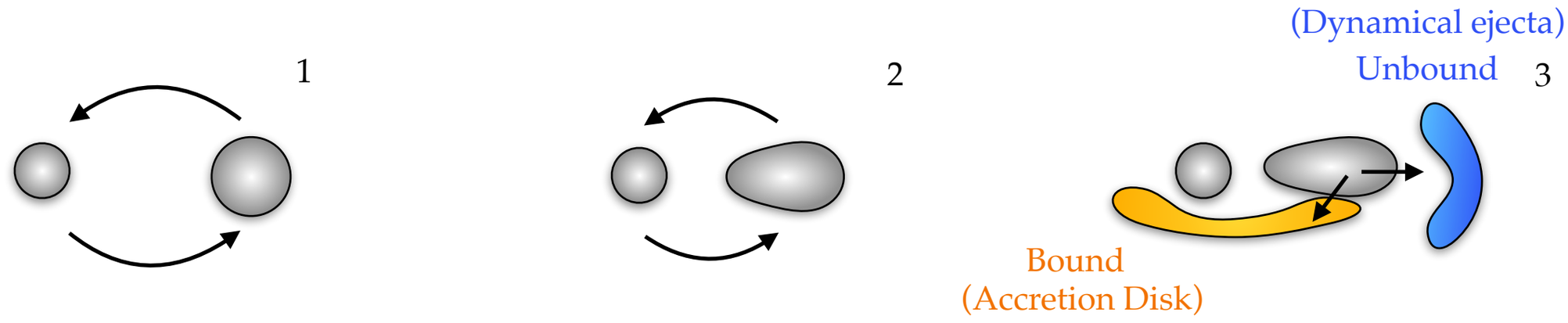
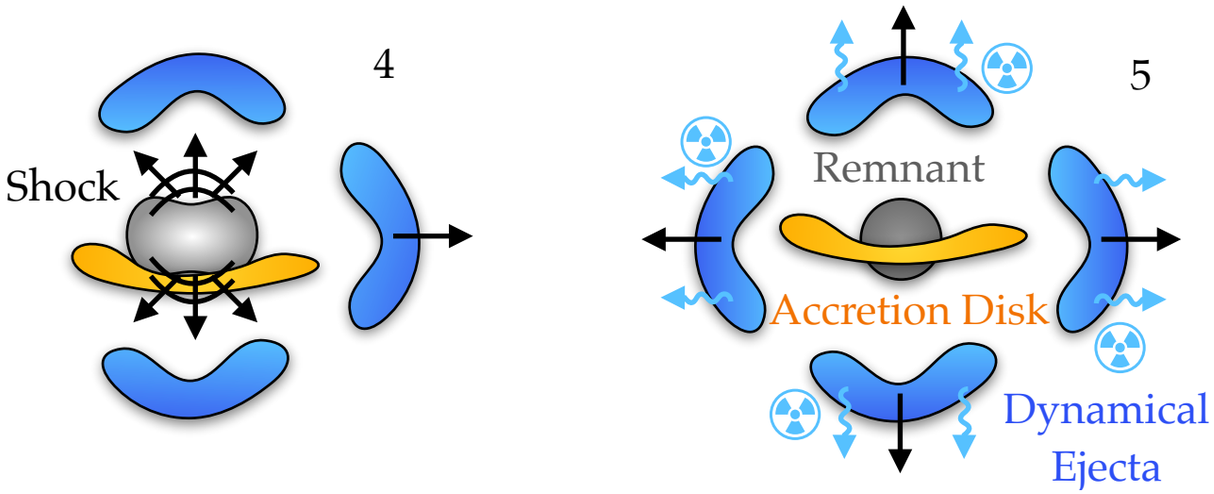
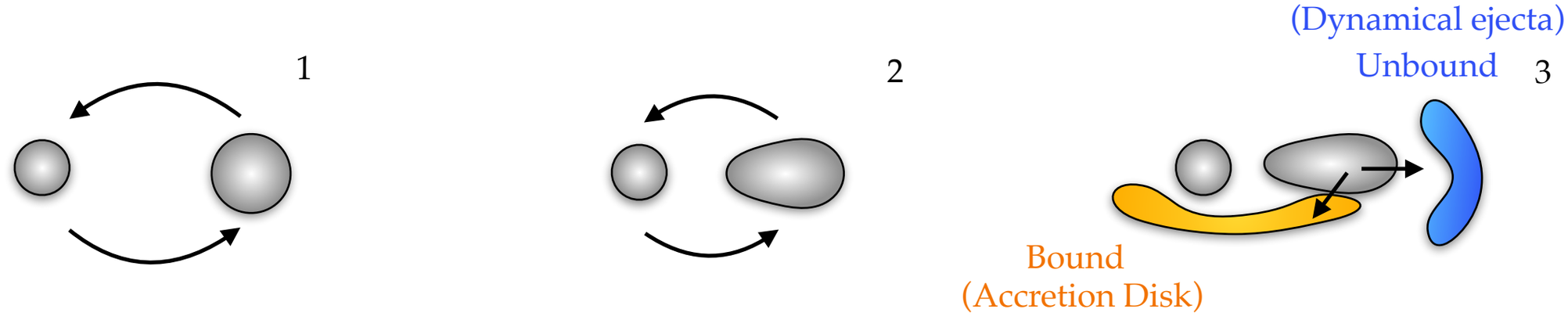
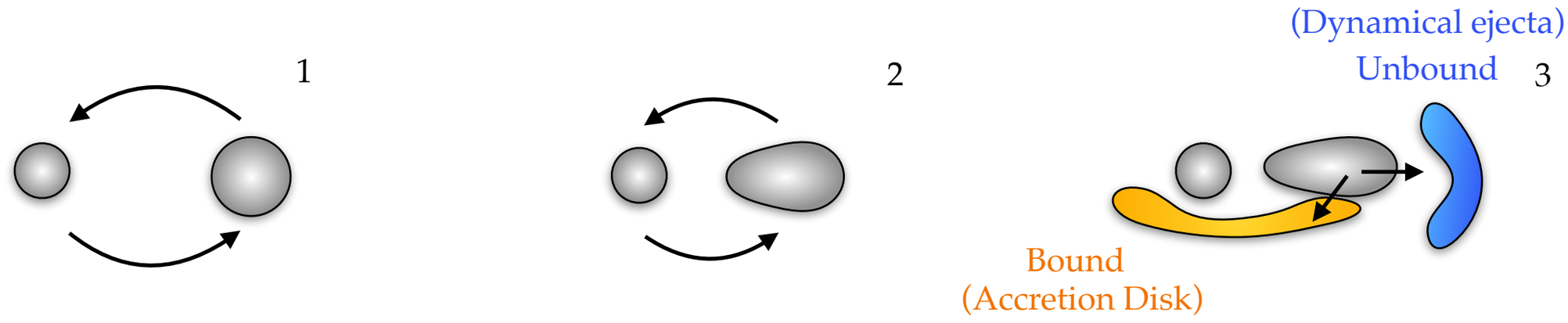




NSNS Merger and Kilonova Emission



NSNS Merger and Kilonova Emission

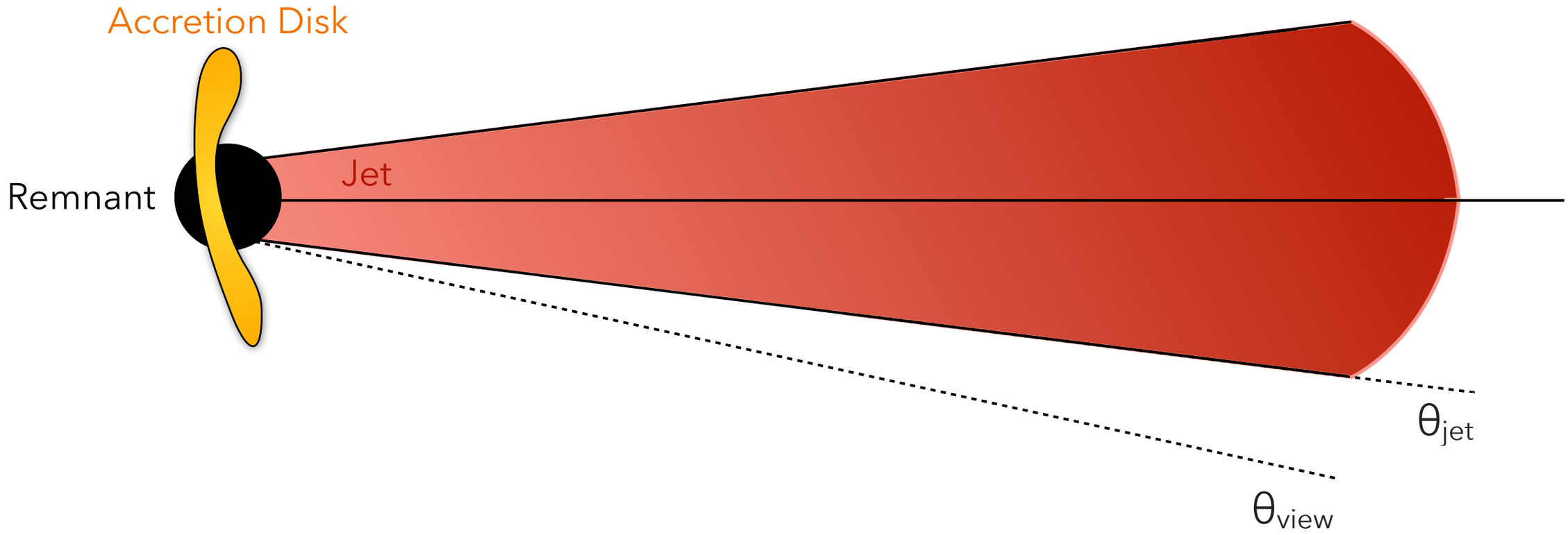


Possible radio emission!

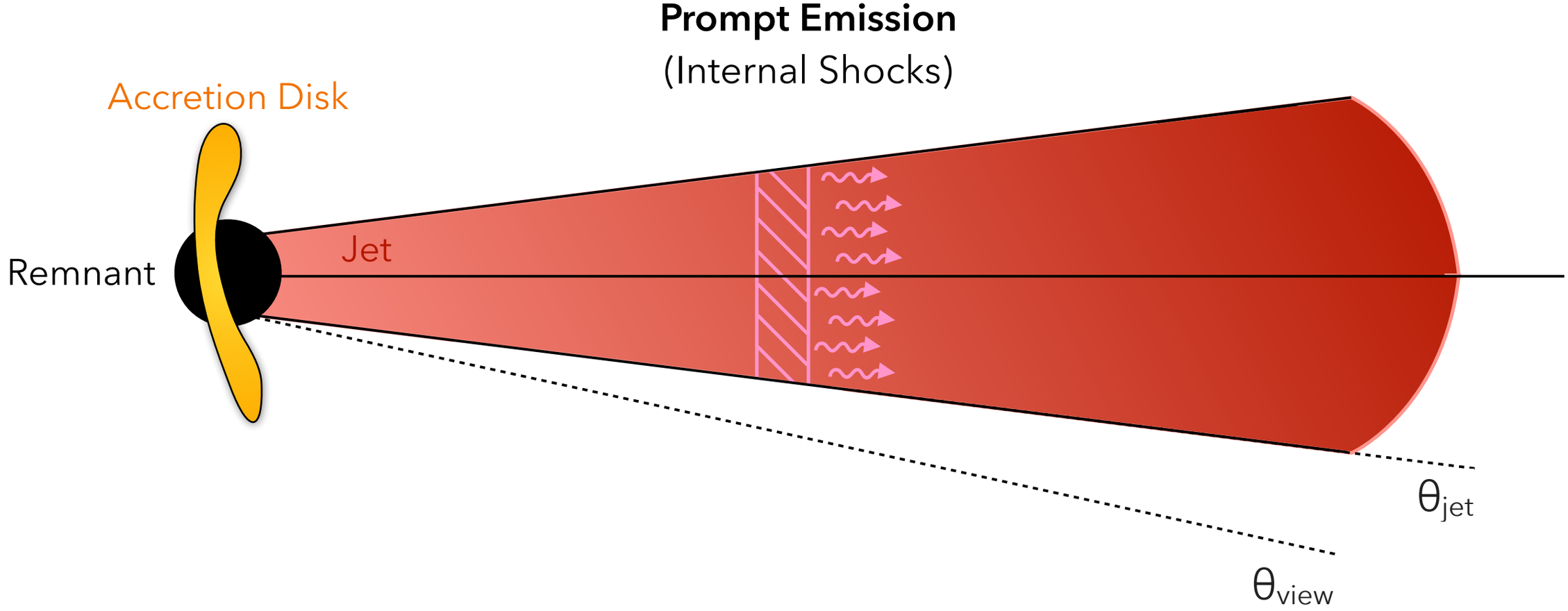
Barbieri+19

Hotokezaka+15

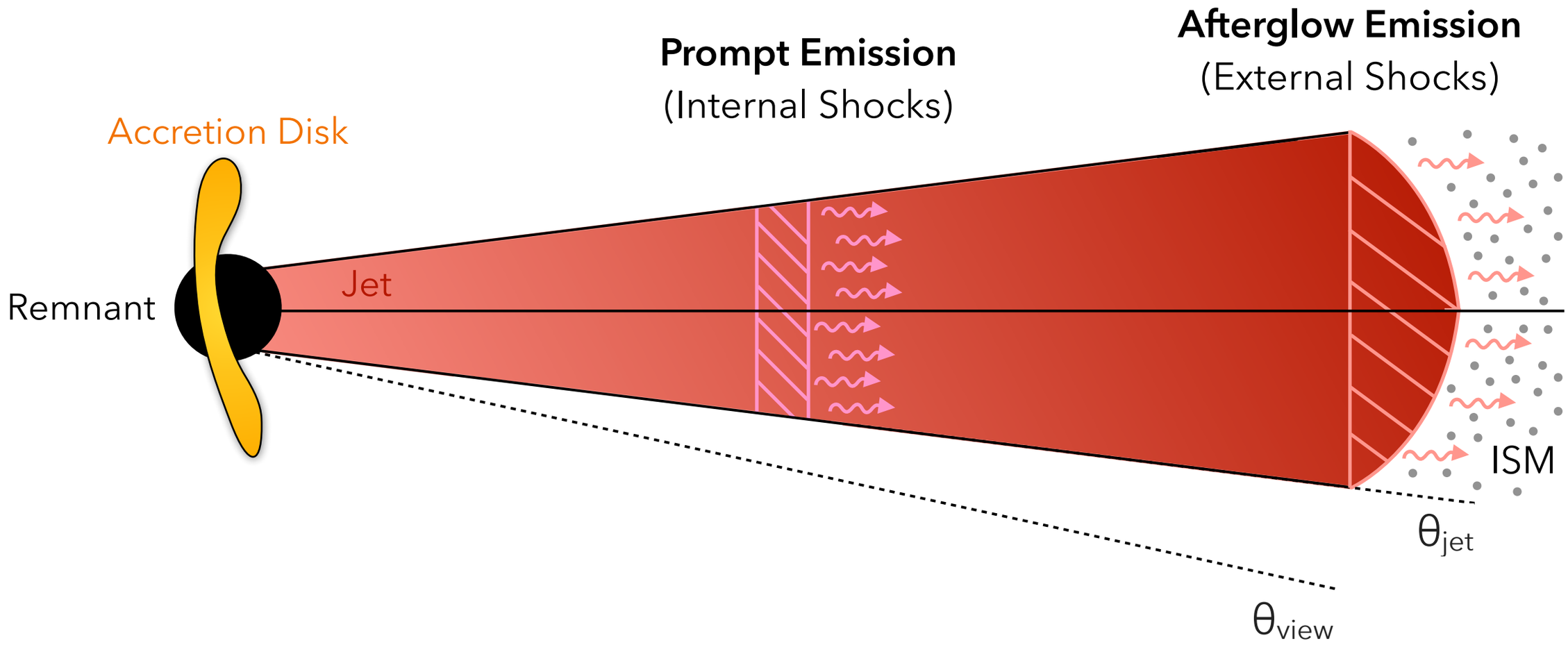
GRB Prompt and Afterglow Emissions



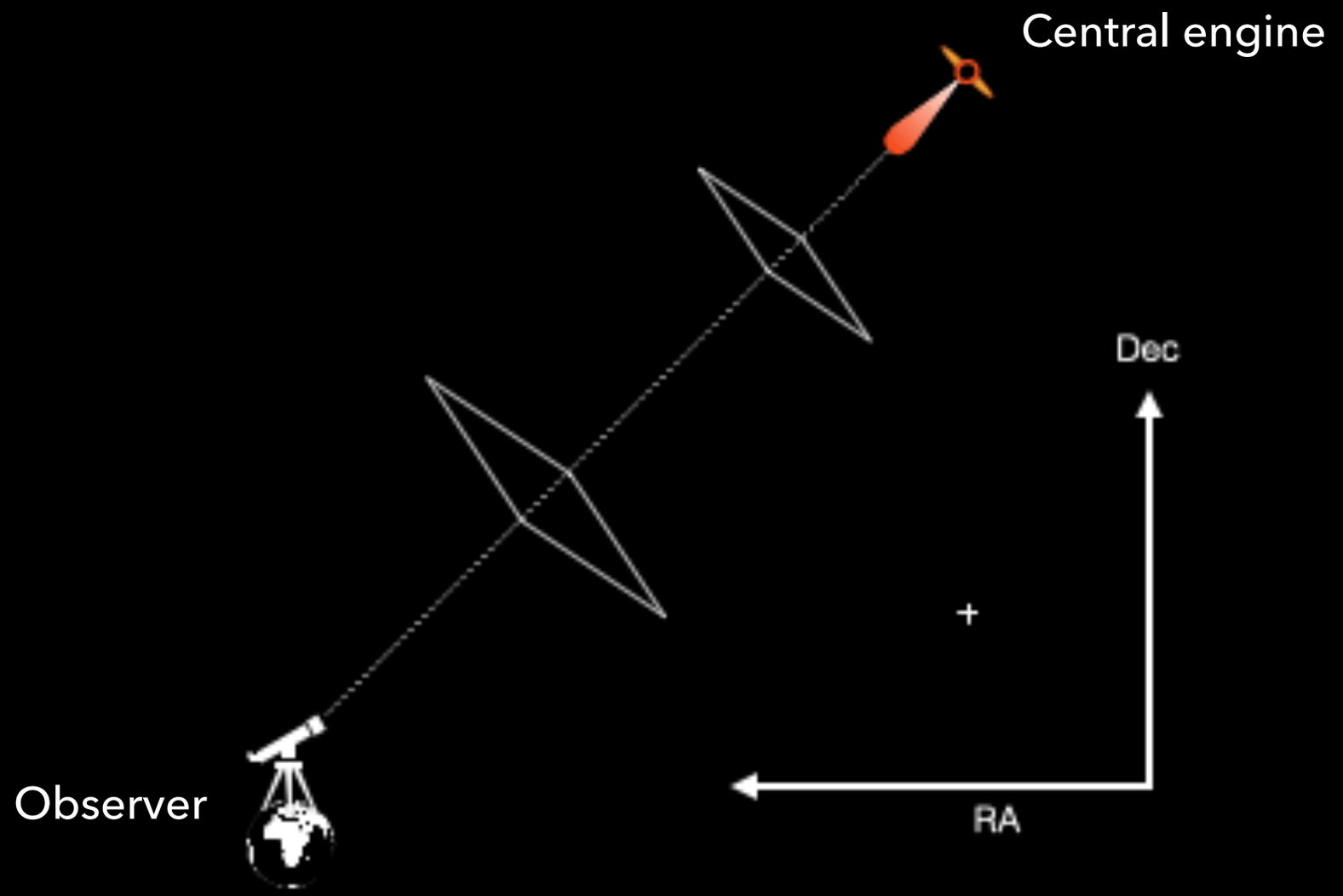
GRB Prompt and Afterglow Emissions



GRB Prompt and Afterglow Emissions

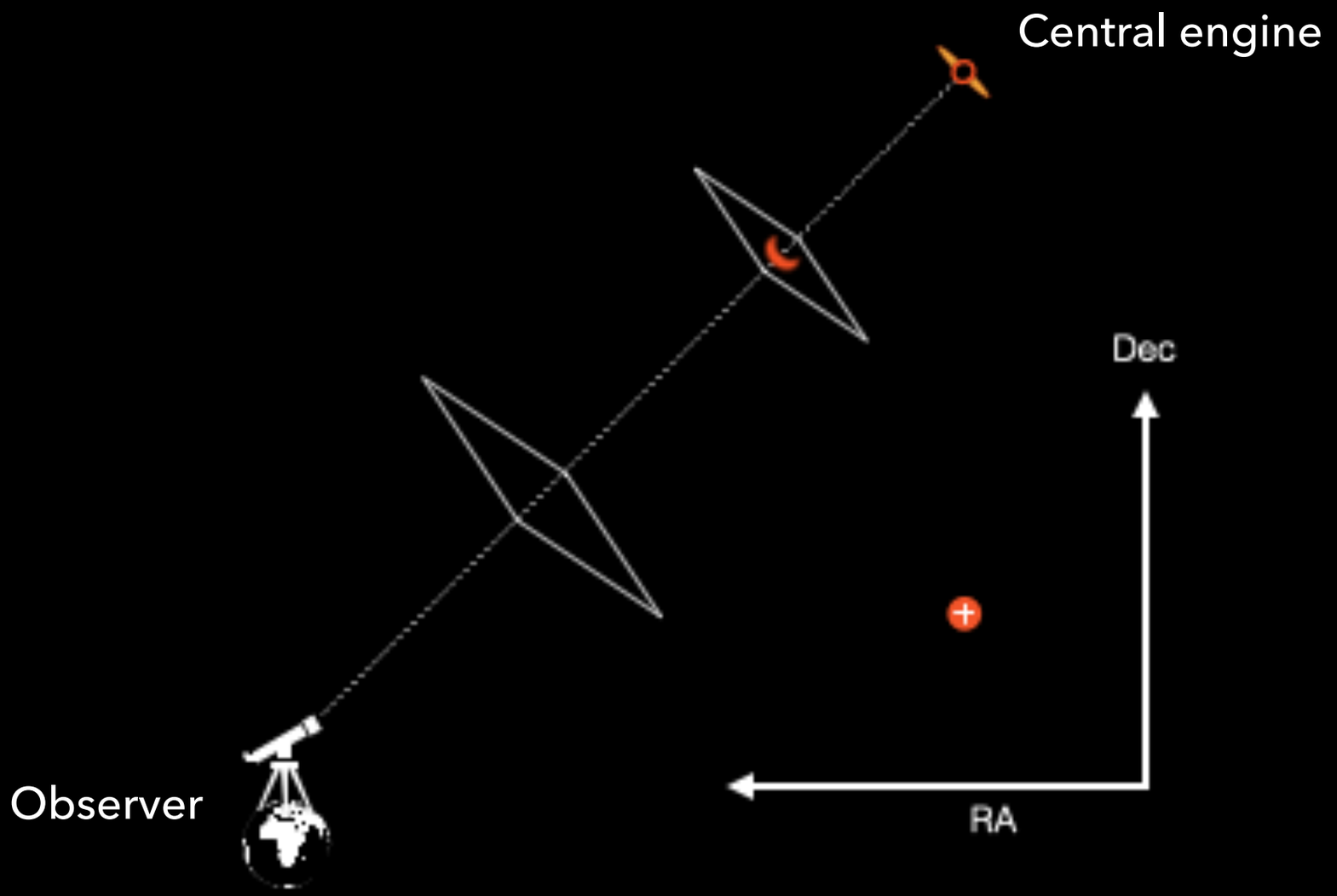


VLBI on-axis view



Courtesy of S. Giarratana

VLBI on-axis view



Courtesy of S. Giarratana

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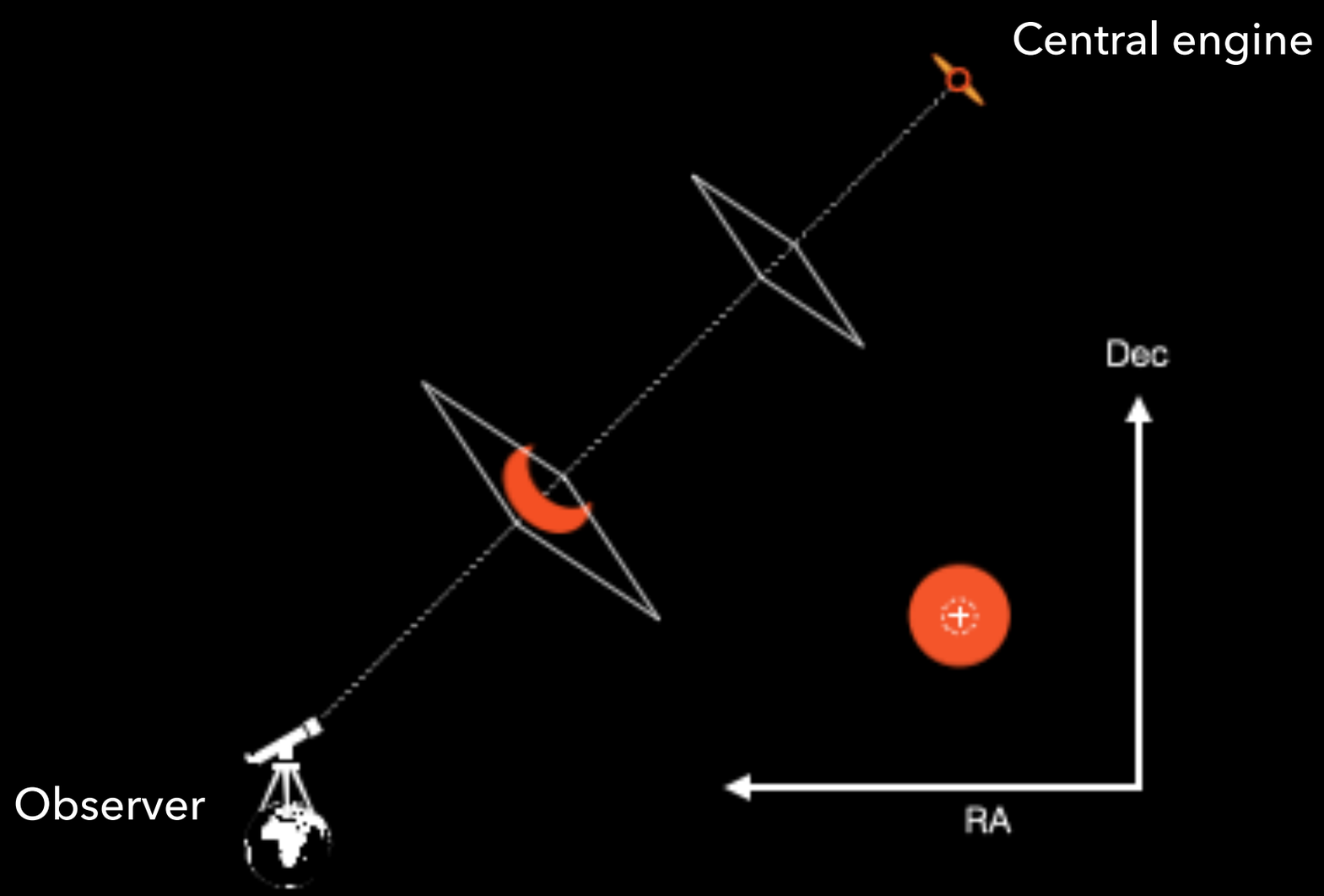

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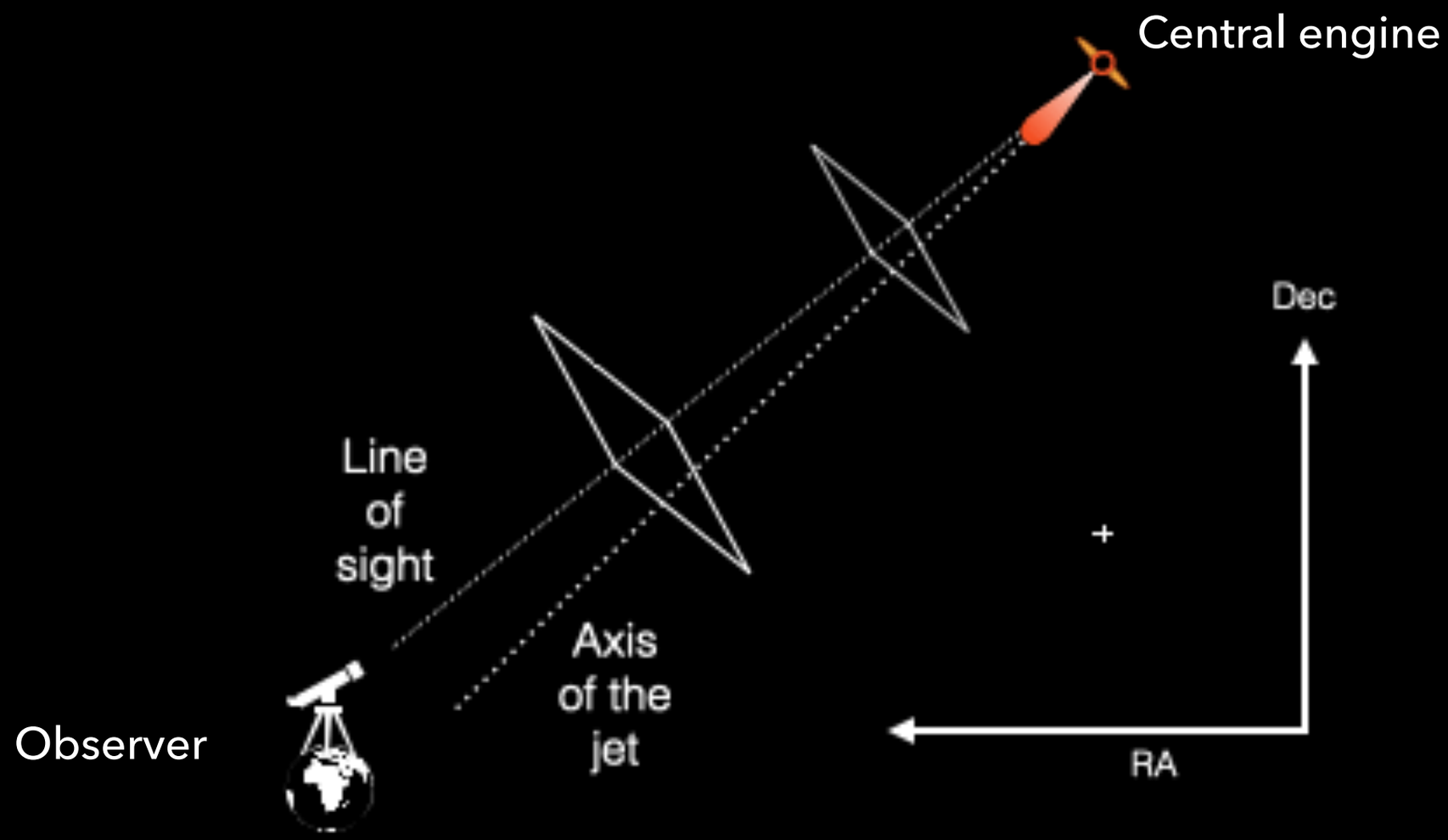

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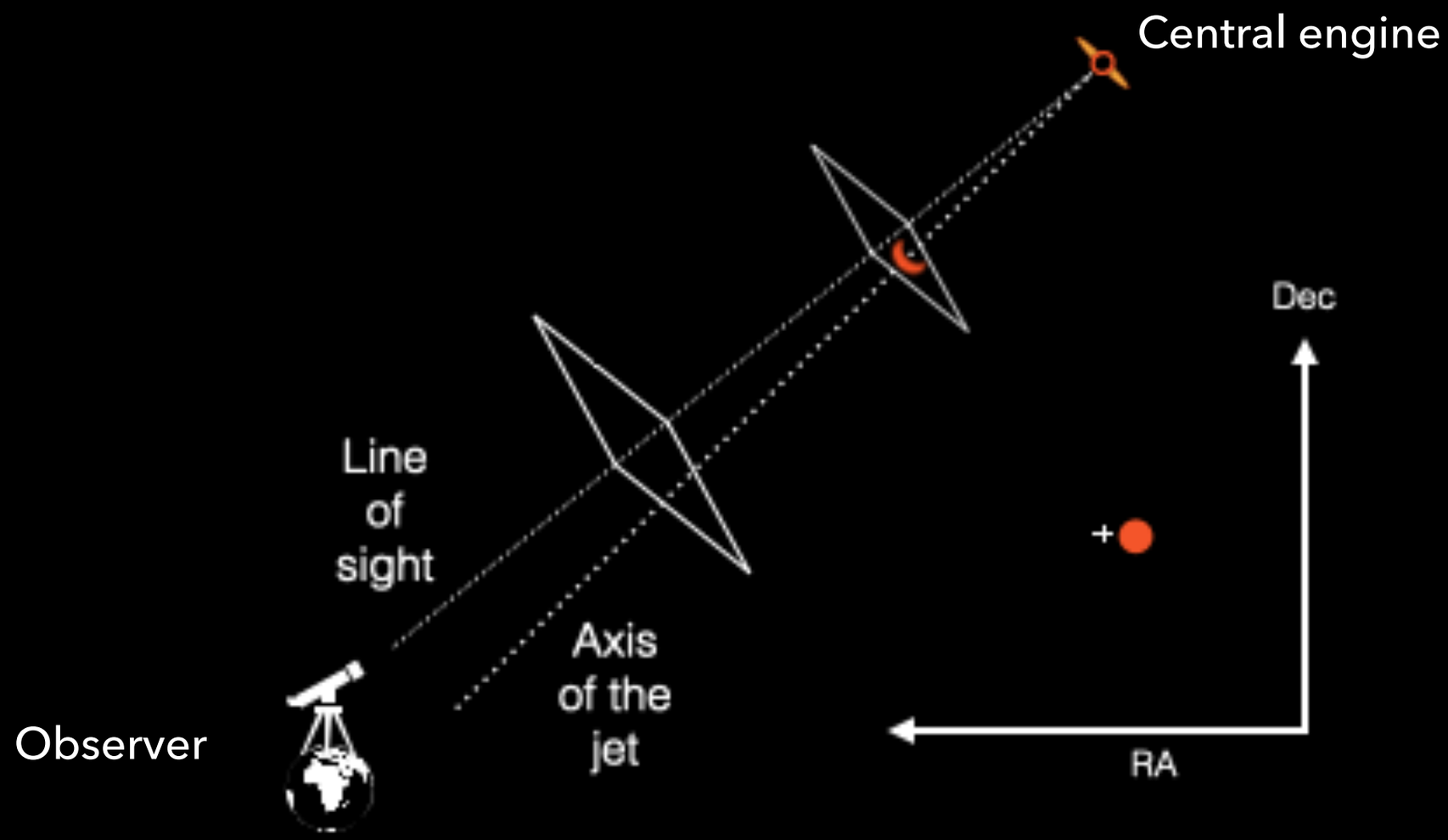

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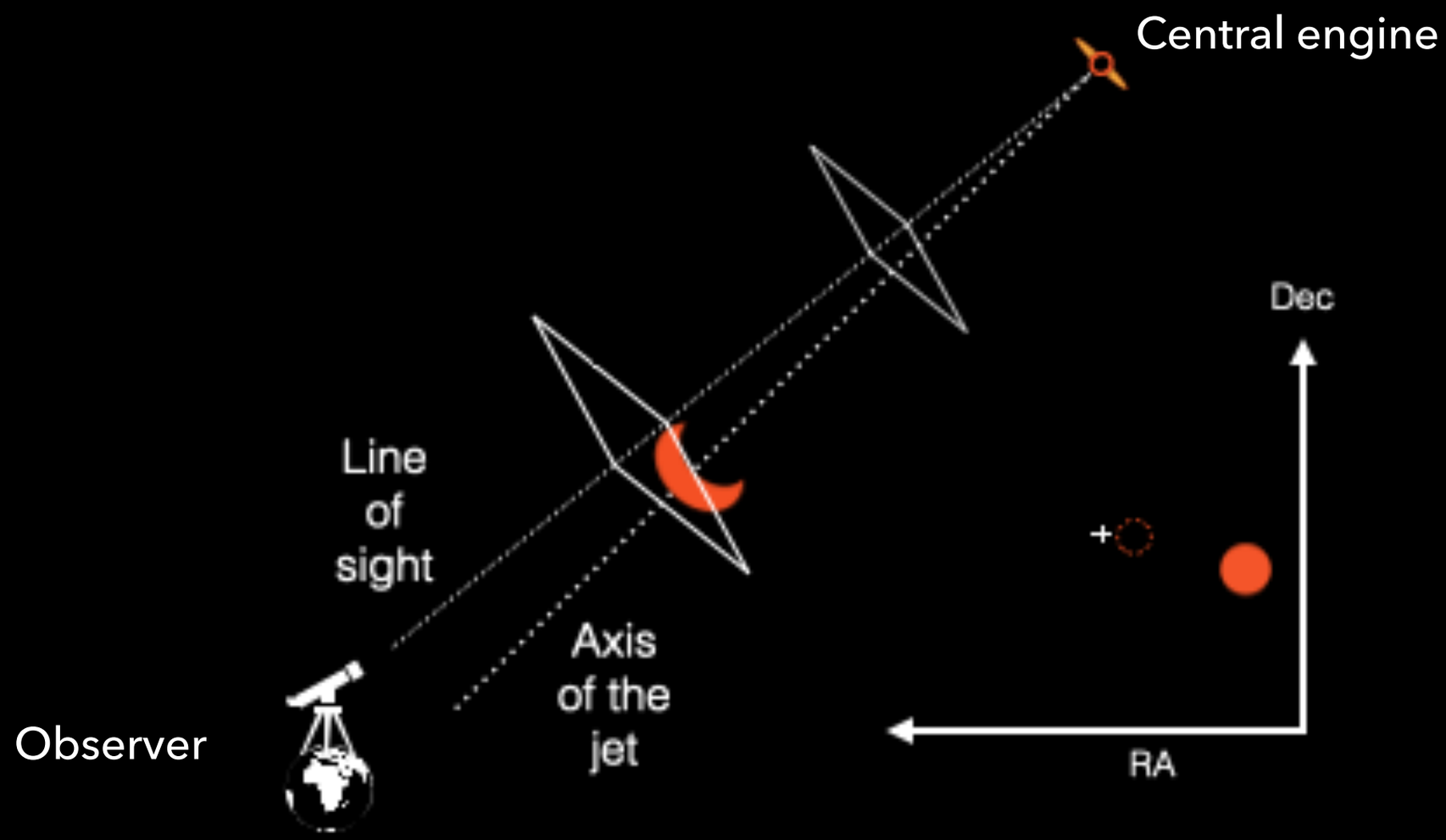
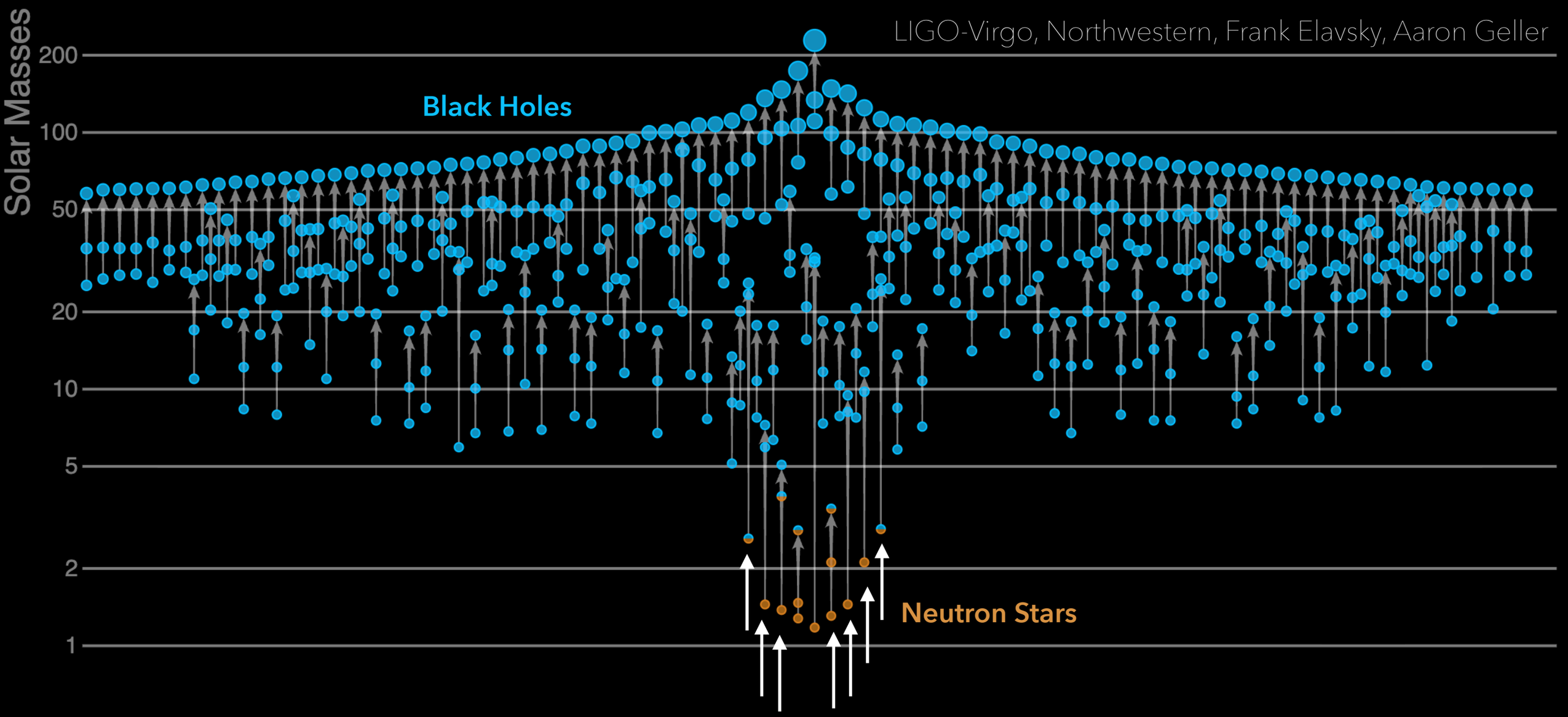
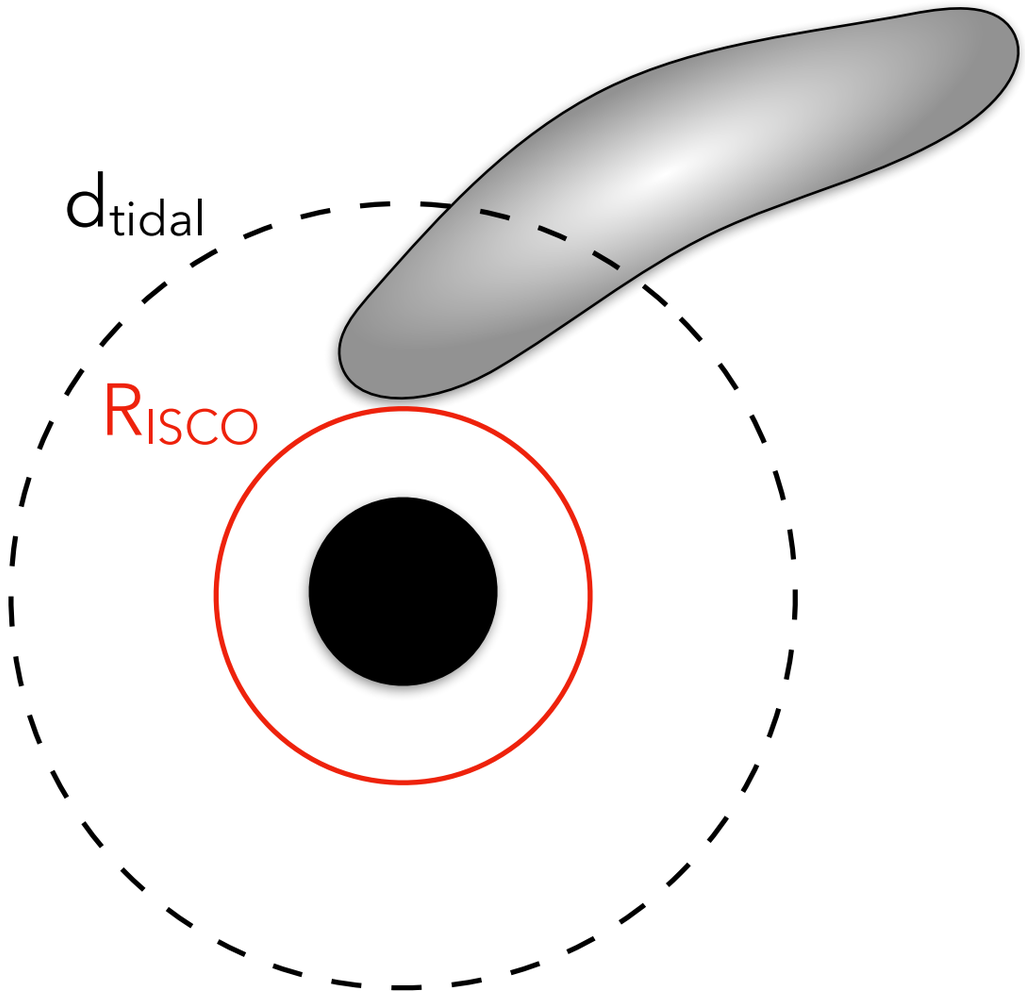


Courtesy of S. Giarratana

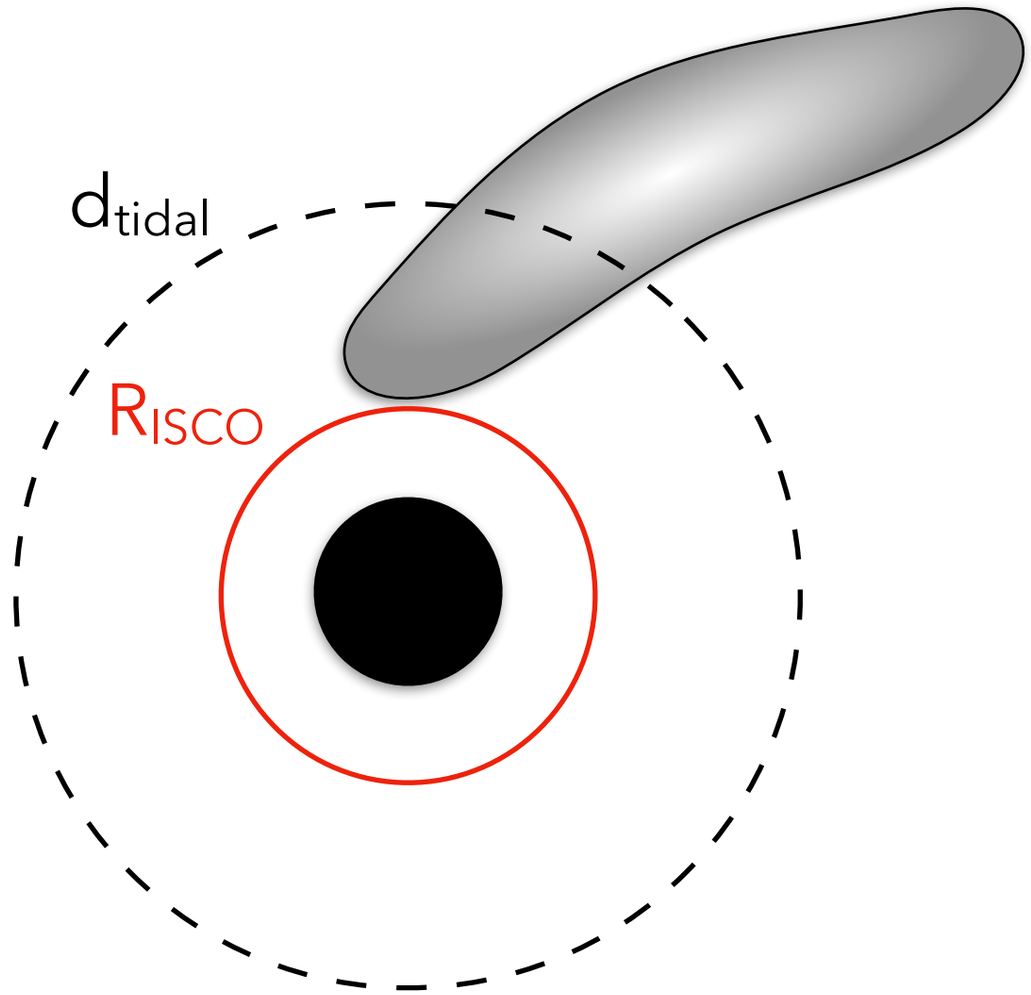
BHNS candidates



BHNS merger

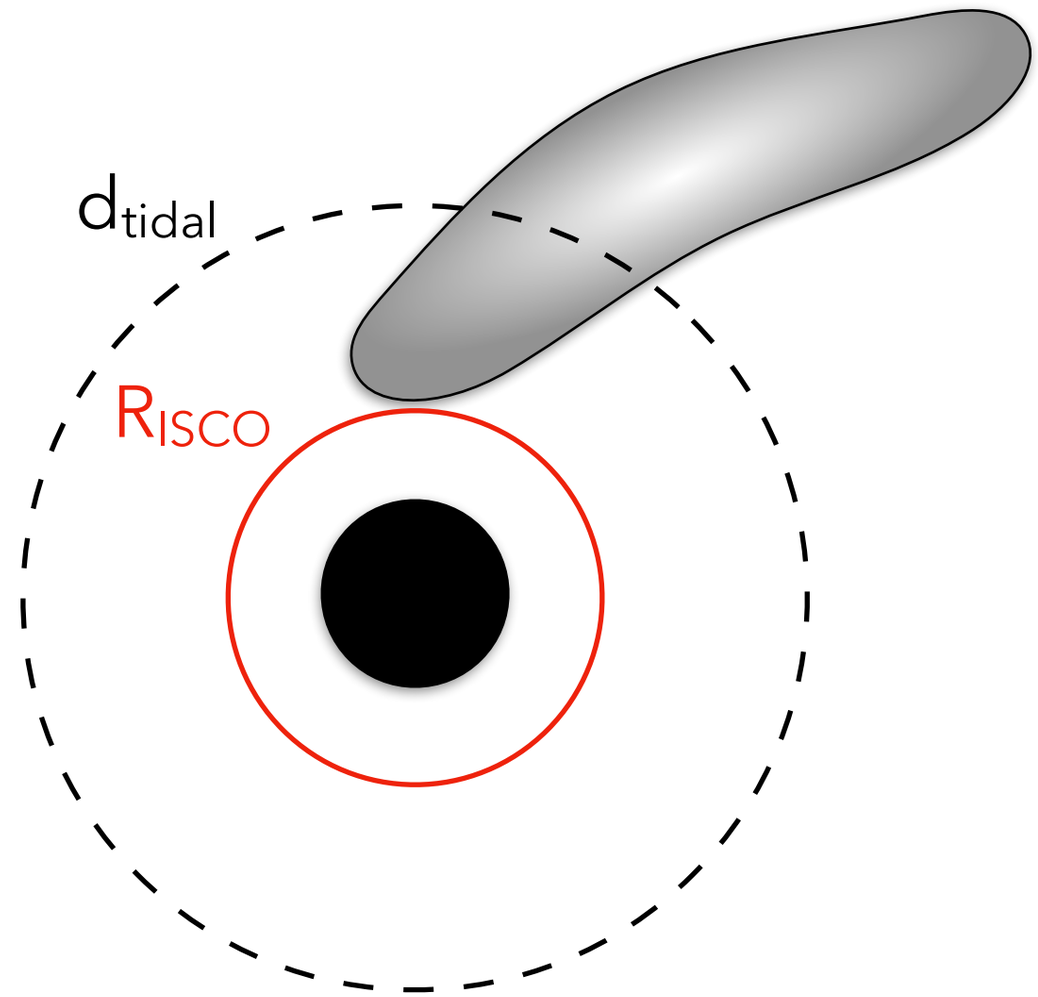


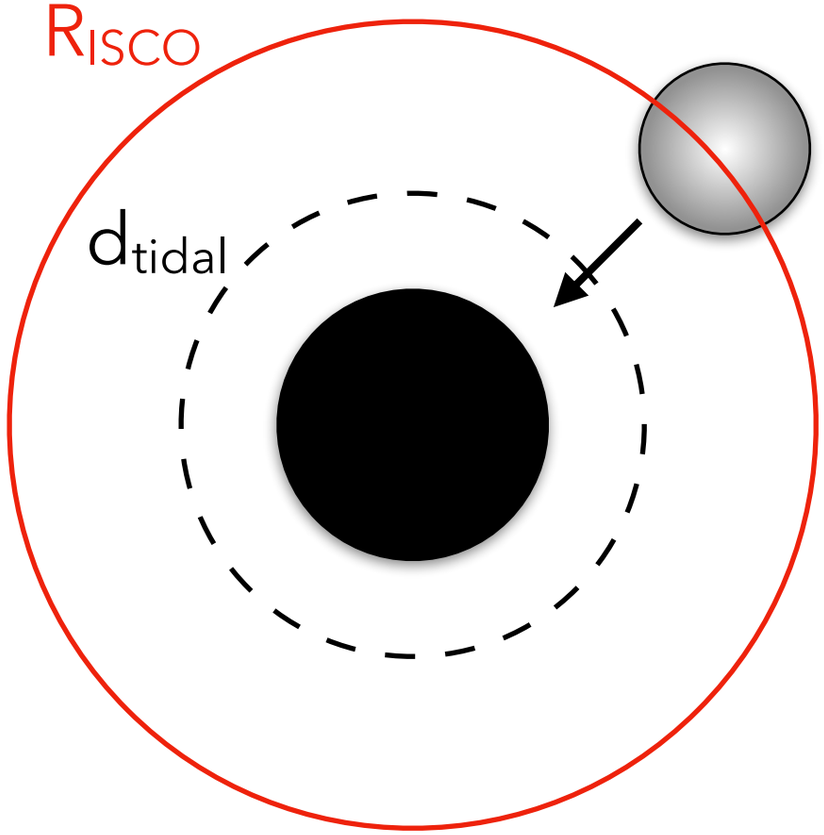
BHNS merger



Low massive and/or rapidly spinning BH

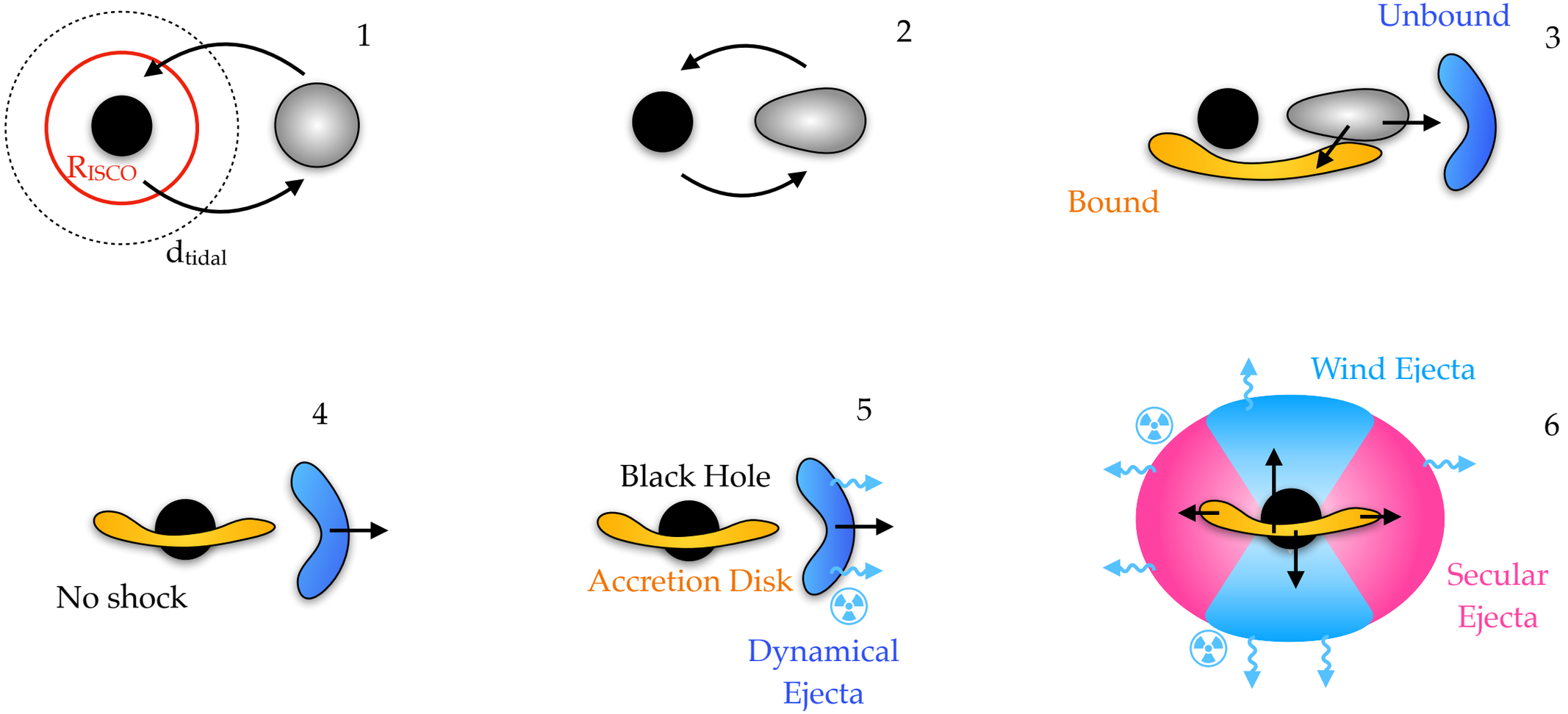
BHNS merger



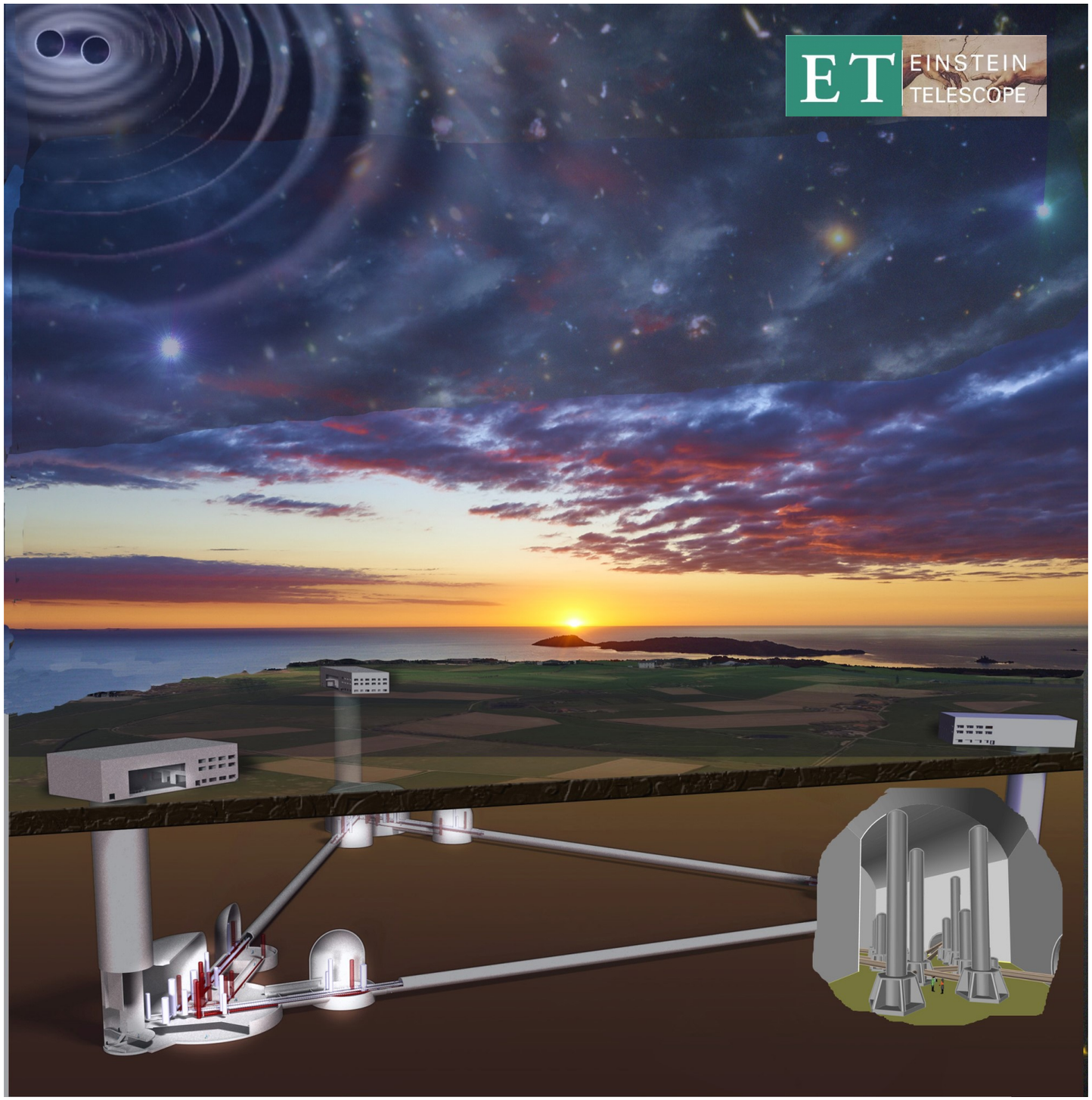


Low massive and/or rapidly spinning BH

BHNS Merger and Kilonova Emission



Einstein Telescope



- Online in 2035
- Triangular or 2L shape
- 10-15 km arms
- Underground
- Cryogenic
- Increase laser power
- Xylophone
- Sardinia or Nederlands?

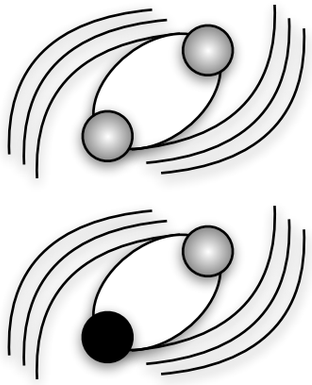
See Branchesi+23

What are the number and the properties of future multi-messenger events?

Our model

1 Let’s start from a population of merging **NSNS** or **BHNS**

- Mass distribution
- Redshift distribution
- BH spin
- NS EoS



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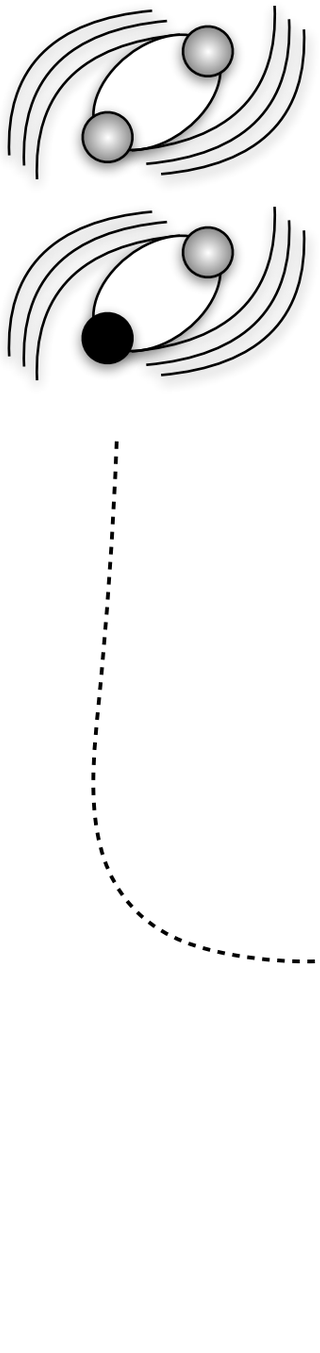
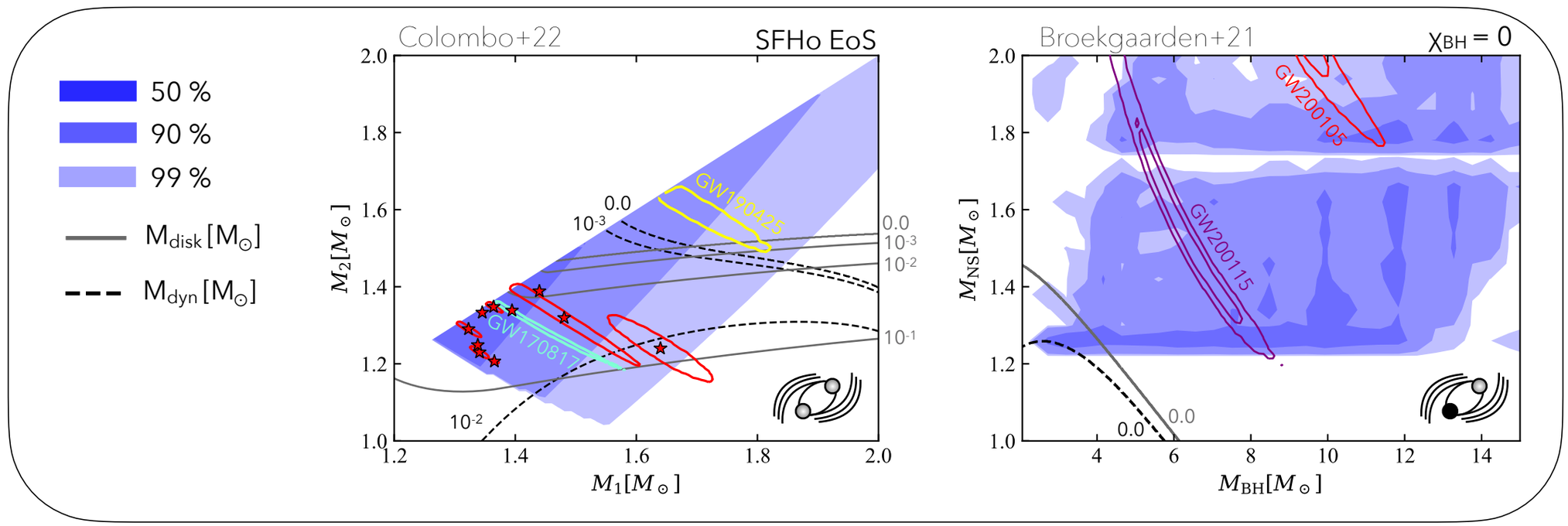
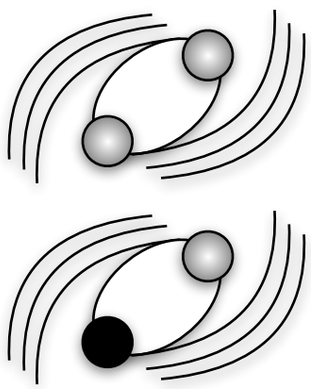




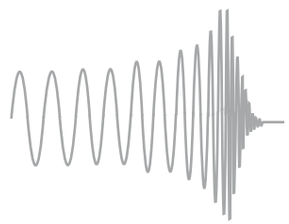
Our model

1 Let's start from a population of merging **NSNS** or **BHNS**
- Mass distribution
- Redshift distribution
- BH spin
- NS EoS



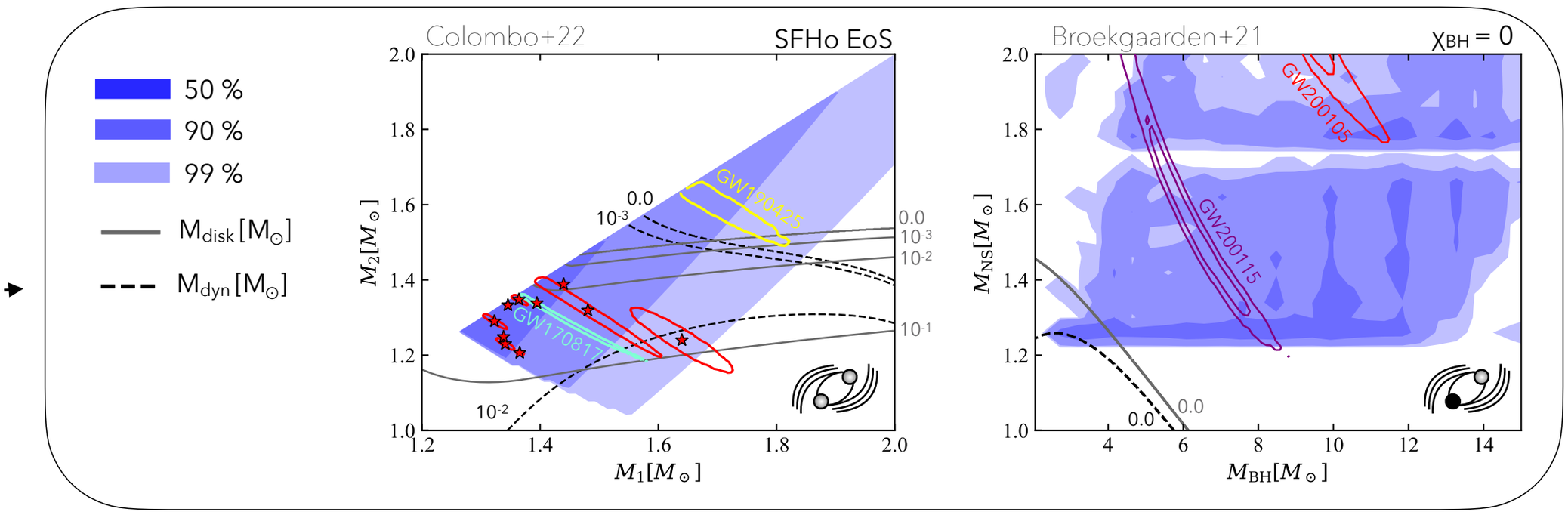
2 Compute the **GW signal** using GWFAST
- IMRPhenomNSBH
- IMRPhenomD_NRTidalv2
- delta, 2L, CE
- 85% duty cycle

Iacovelli+22



GW

S/N, Δd_L, $\Delta\Omega$



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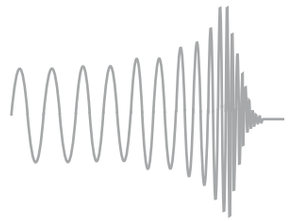
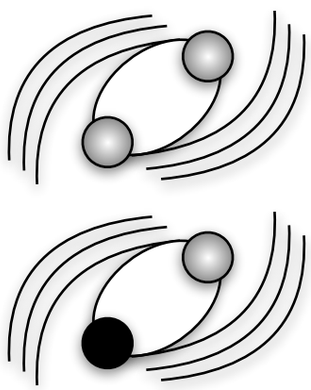
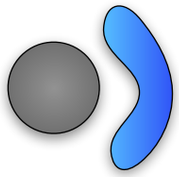


GW

S/N, Δd_L, $\Delta\Omega$



Kawaguchi+16
Radice+18

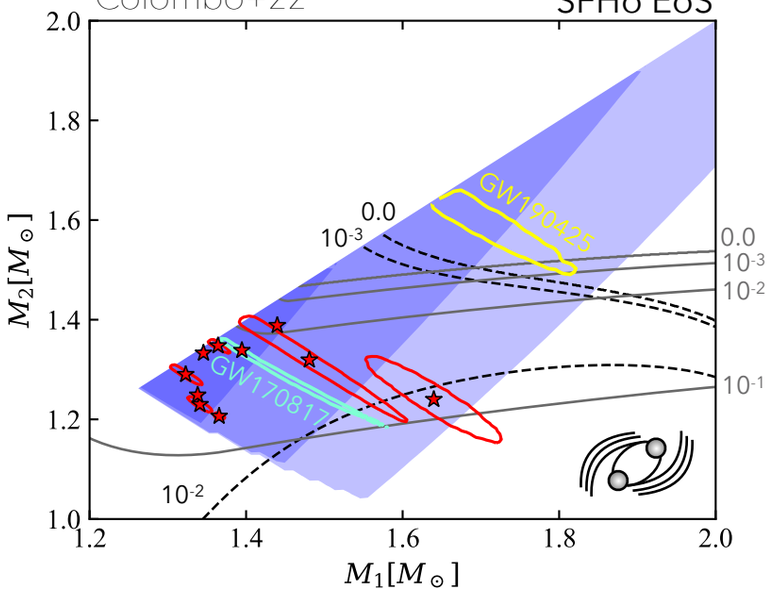


Barbieri+20
Krüger+22

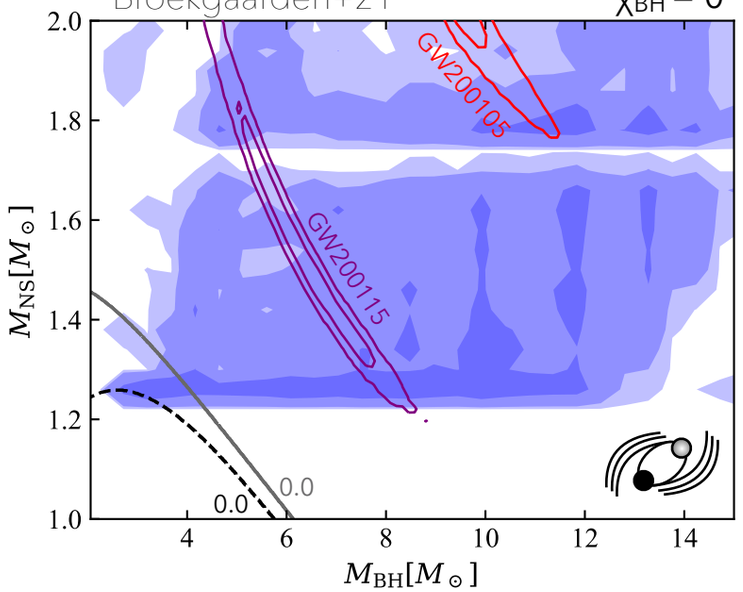
3 Compute **ejecta** and **accretion disk** properties using fitting formulae
- M_{dyn} v_{dyn} M_{disk}

50 %
90 %
99 %
$M_{disk}\,[M_\odot]$
$M_{dyn}\,[M_\odot]$

Colombo+22 SFHo EoS



Broekgaarden+21 $\chi_{BH} = 0$



Our model

1 Let's start from a population of merging **NSNS** or **BHNS**

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- Redshift distribution
- BH spin
- NS EoS

2 Compute the **GW signal** using GWFAST

- IMRPhenomNSBH
- IMRPhenomD_NRTidalv2
- delta, 2L, CE
- 85% duty cycle

Iacovelli+22

GW

S/N, Δd_L, $\Delta\Omega$

Kawaguchi+16
Radice+18

Breschi+21
Barbieri+19
Perego+17

Kilonova

g,z,J

Barbieri+20
Krüger+22

Ghirlanda+19
Salafia+19

GRB Afterglow

radio, optical, x

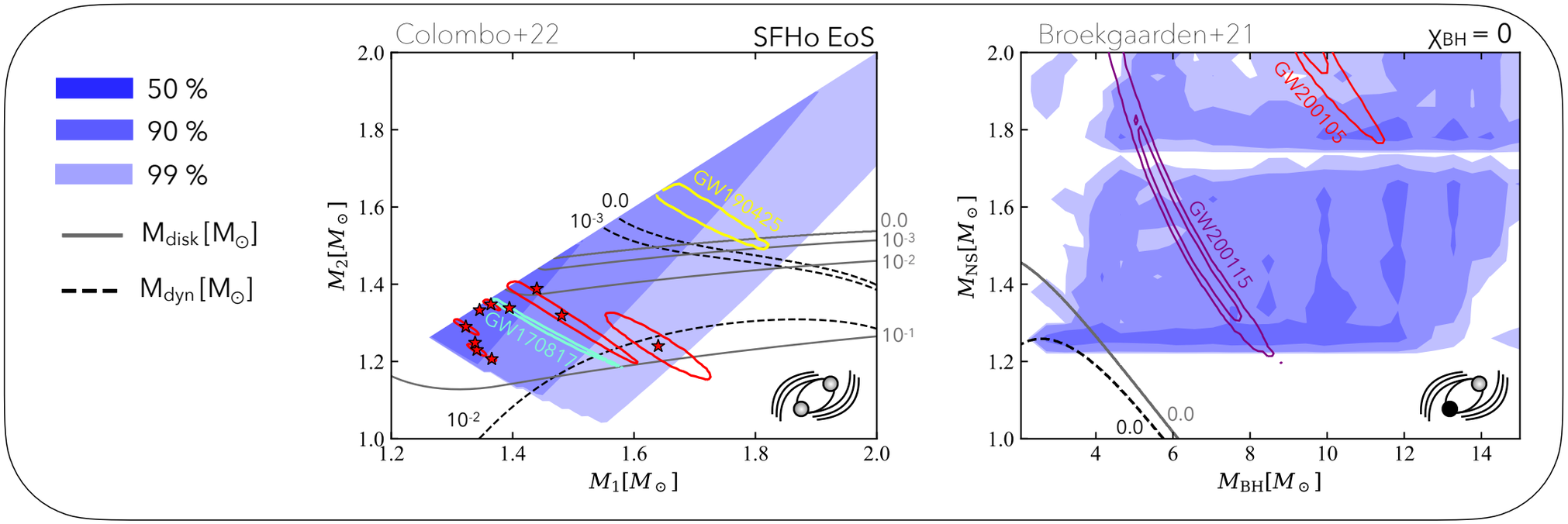
GRB Prompt

GBM, BAT

3 Compute **ejecta** and **accretion disk** properties using fitting formulae

- M_{dyn} v_{dyn} M_{disk}

4 Compute **Kilonova**, **GRB Prompt** and **GRB Afterglow** properties with semi-analytical models



5 years

NSNS

BHNS

$z = 1.0$

$z = 0.5$

Earth

GW

5 years

NSNS

BHNS

$z = 1.0$

$z = 0.5$

Earth

GW

KN

5 years

NSNS

BHNS

$z = 1.0$

$z = 0.5$

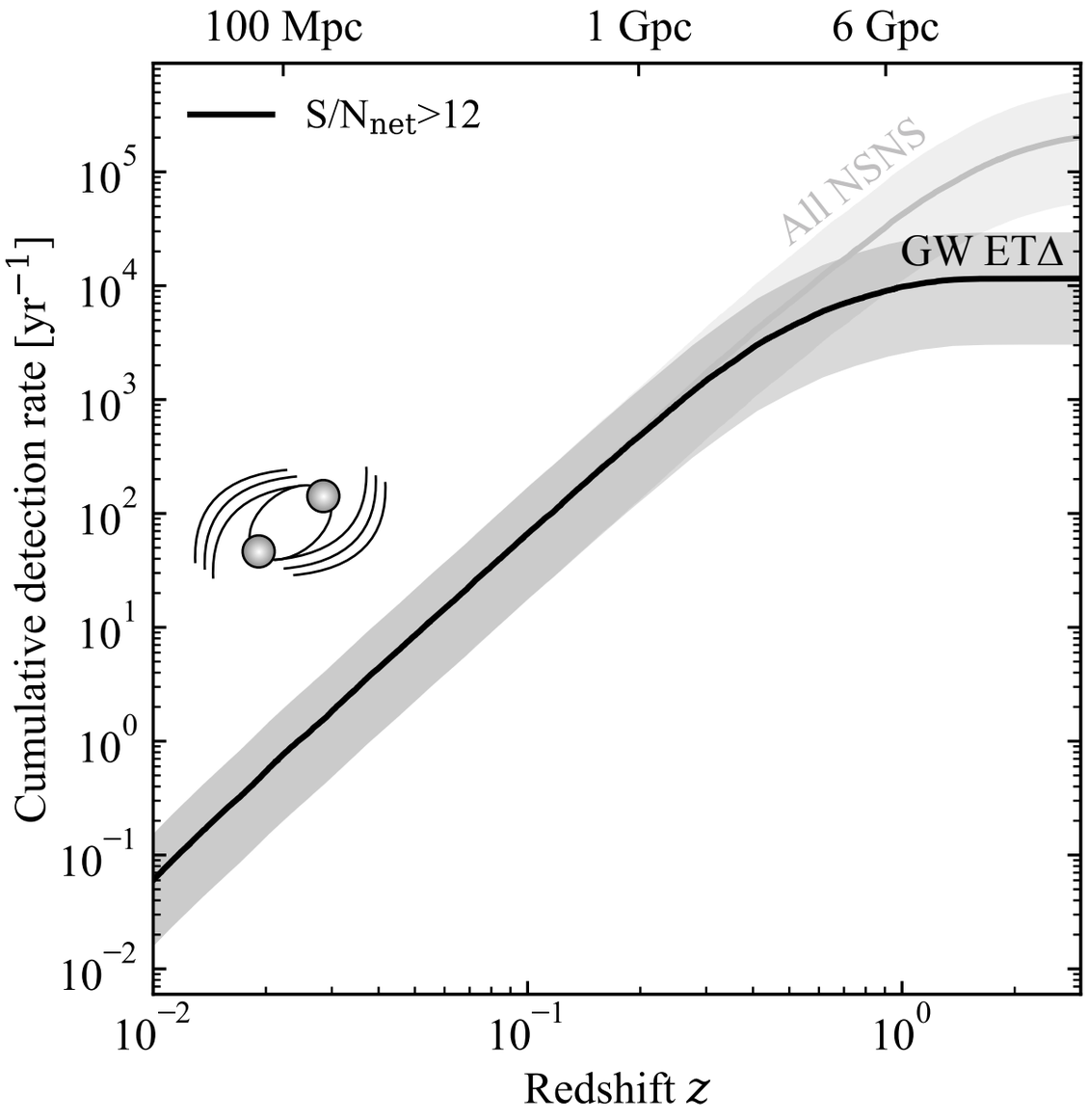
Earth

GW

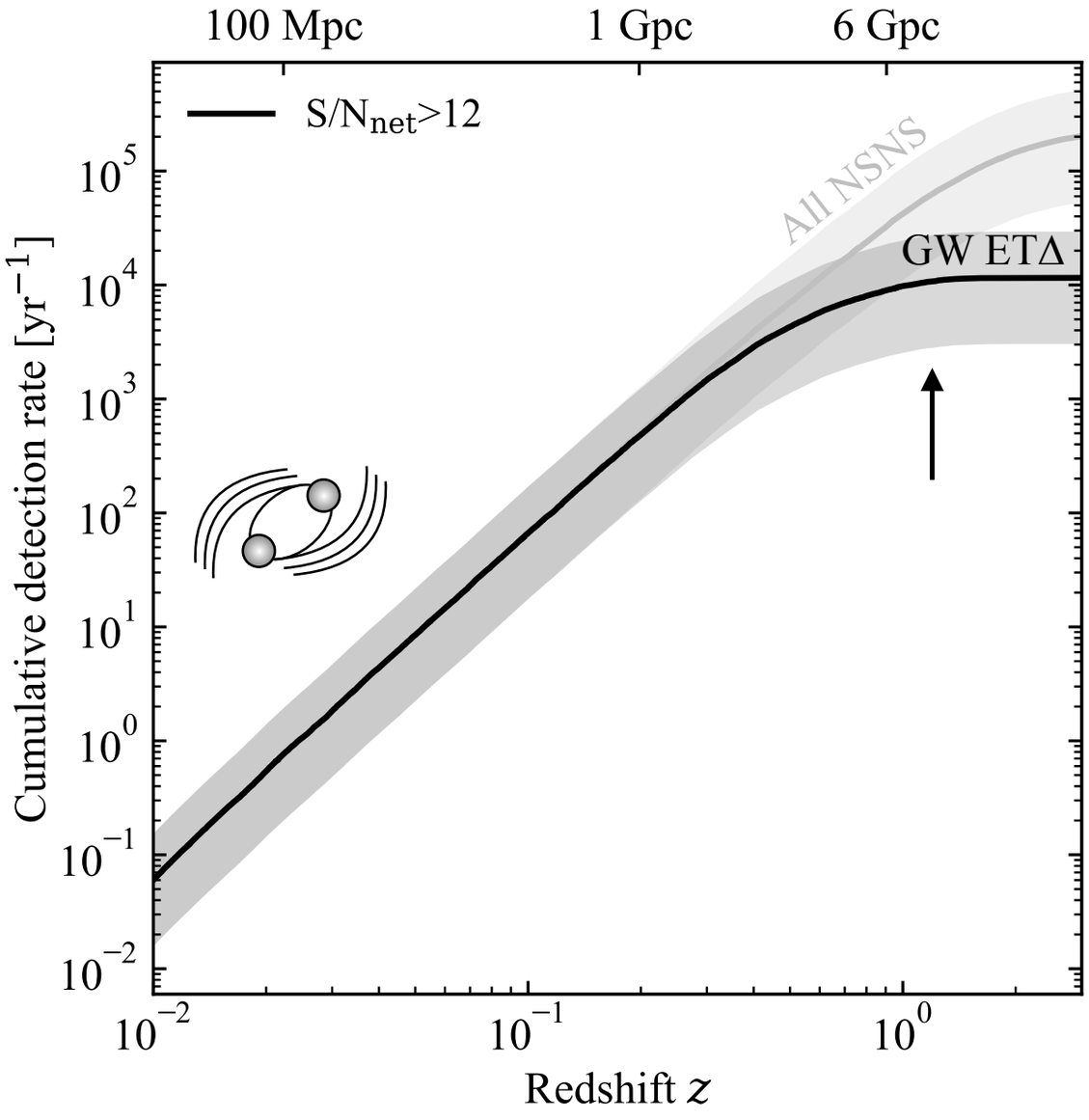
KN

GRB

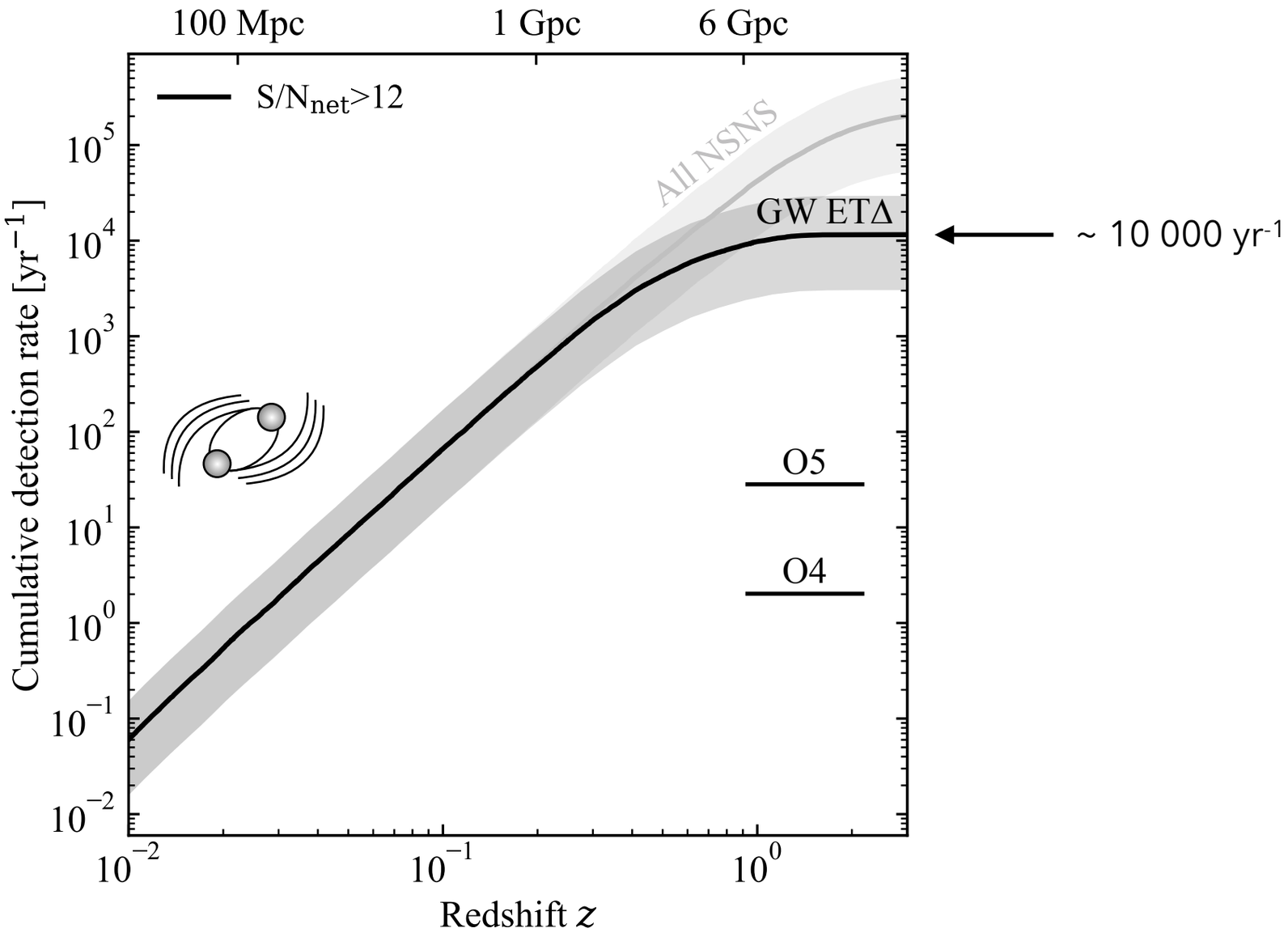
The Einstein Telescope Era (2035): NSNS



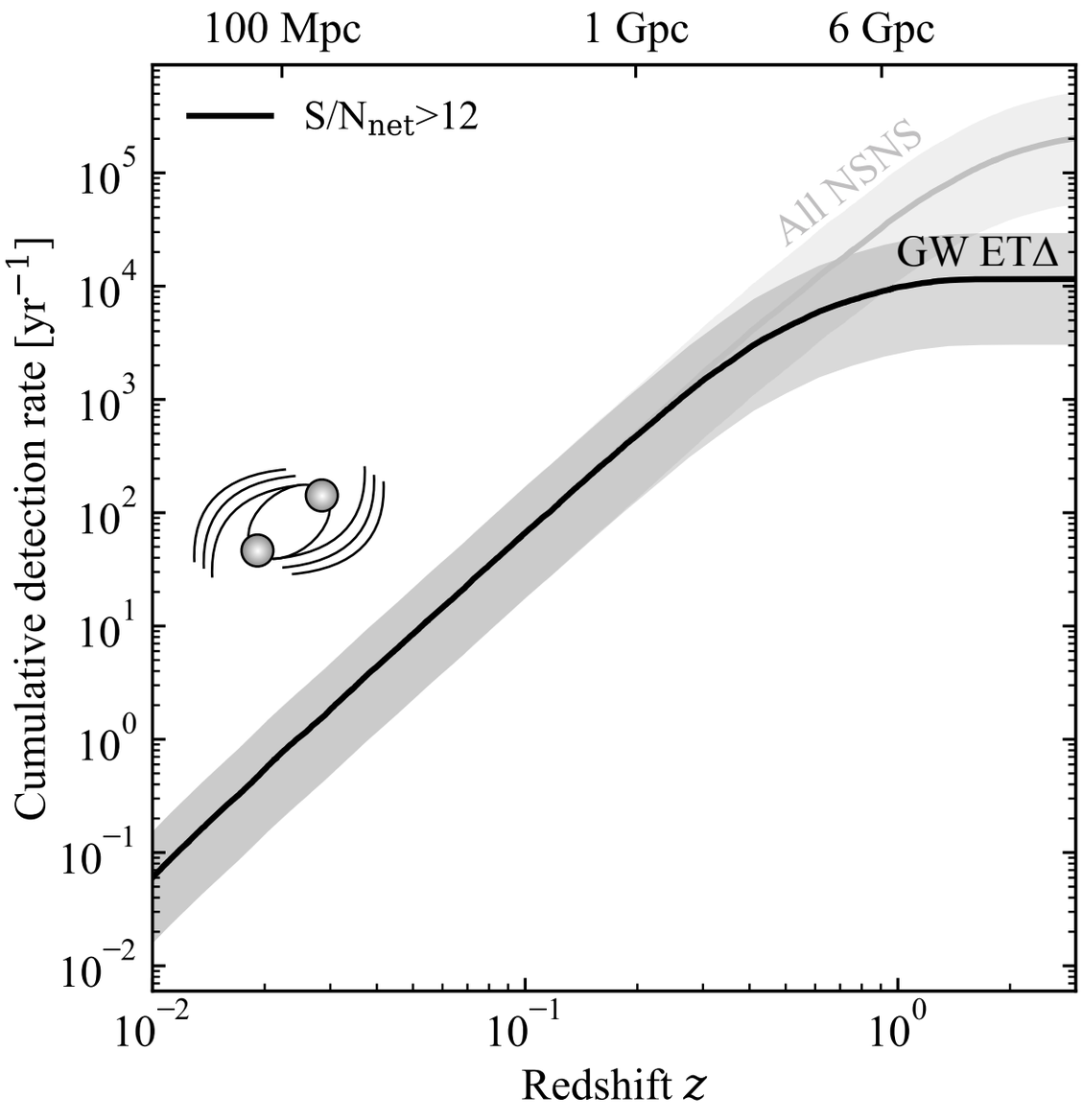
The Einstein Telescope Era (2035): NSNS

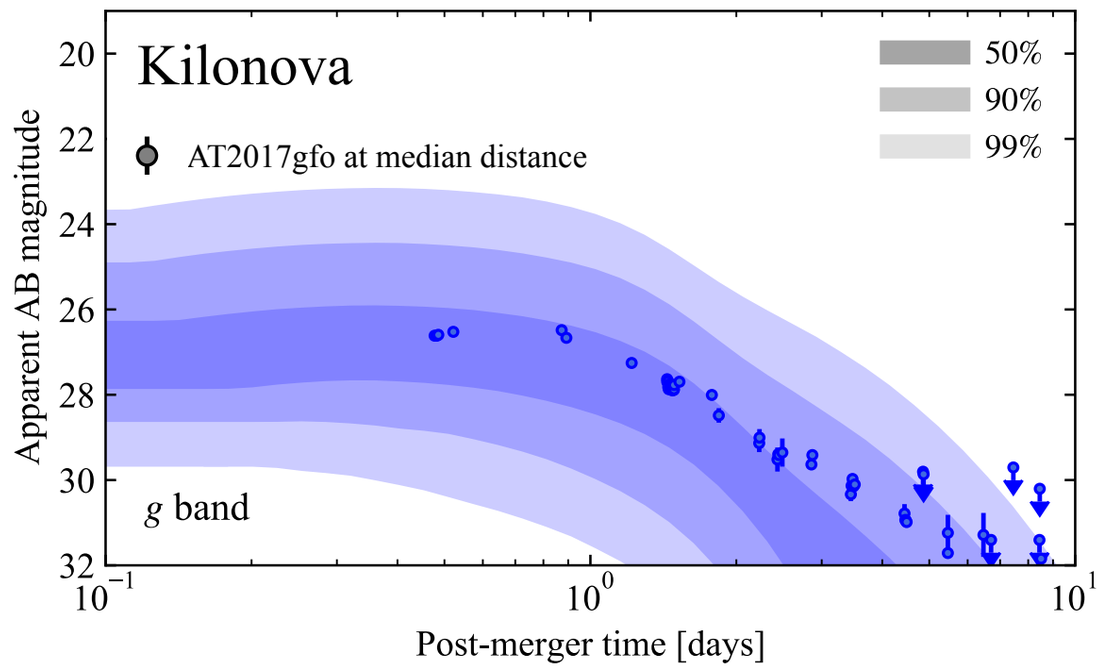


The Einstein Telescope Era (2035): NSNS

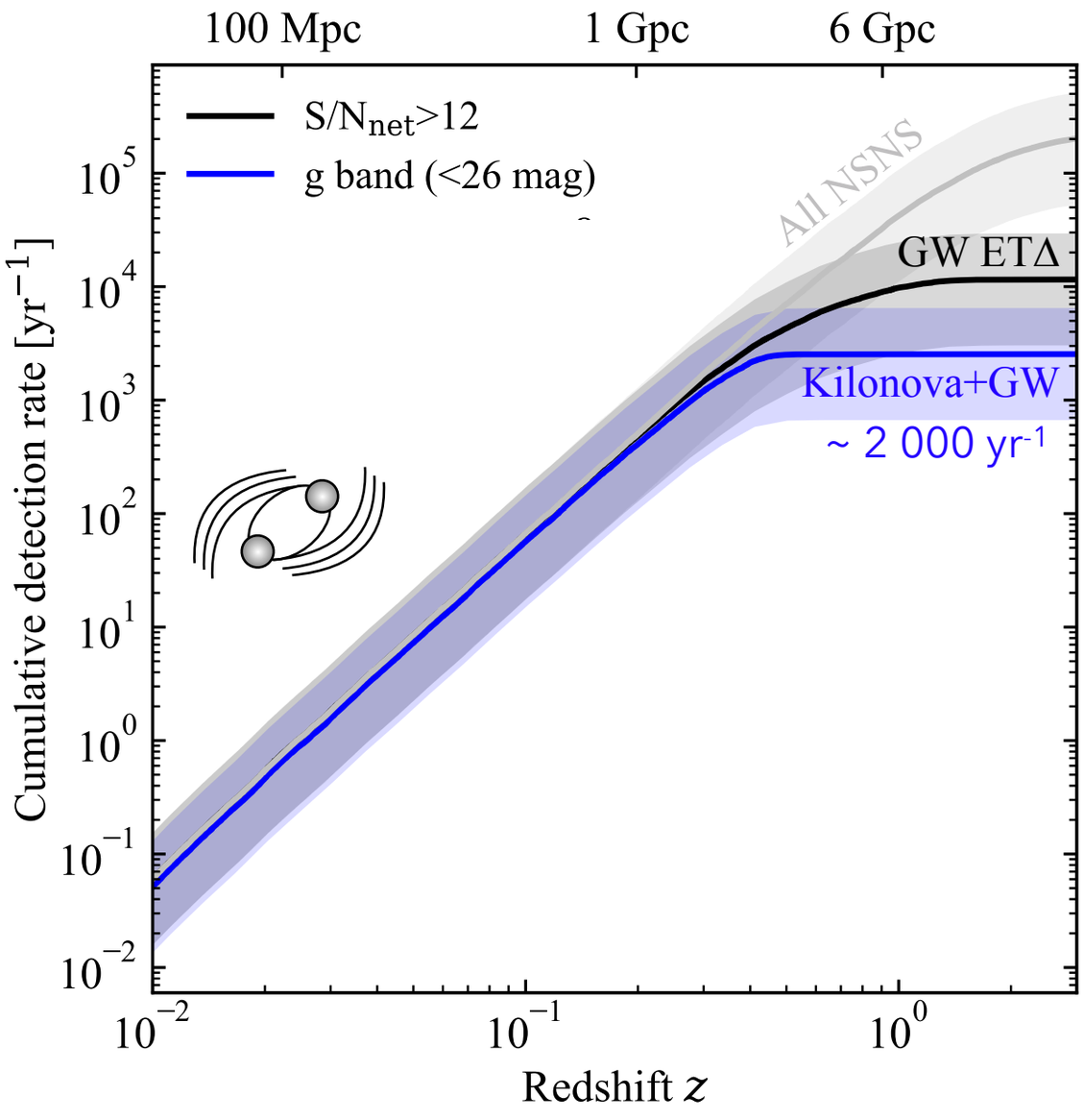


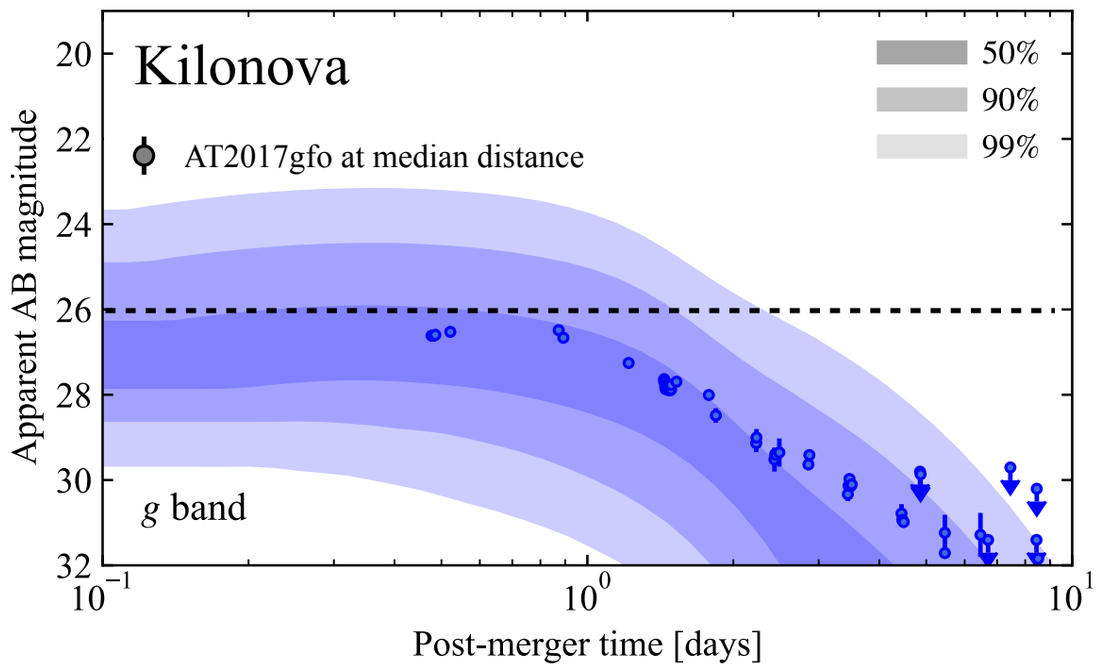
The Einstein Telescope Era (2035): NSNS



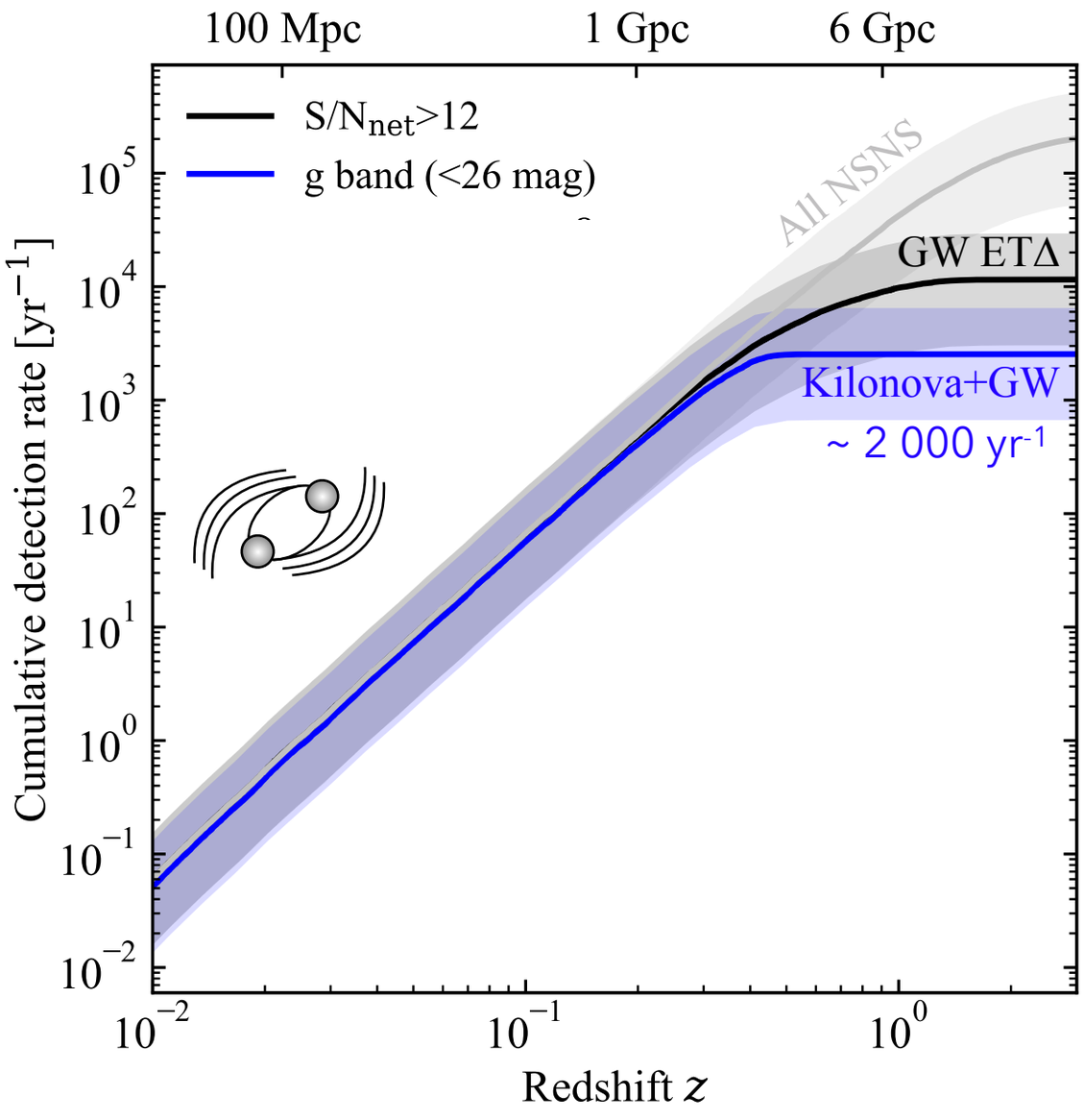


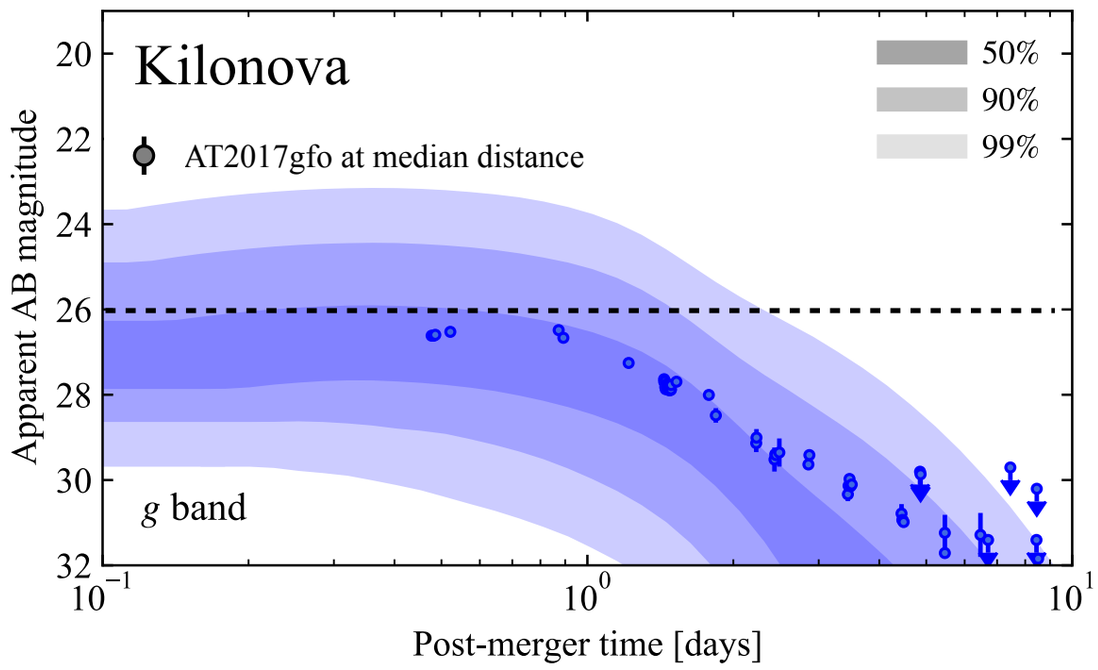
The Einstein Telescope Era (2035): NSNS





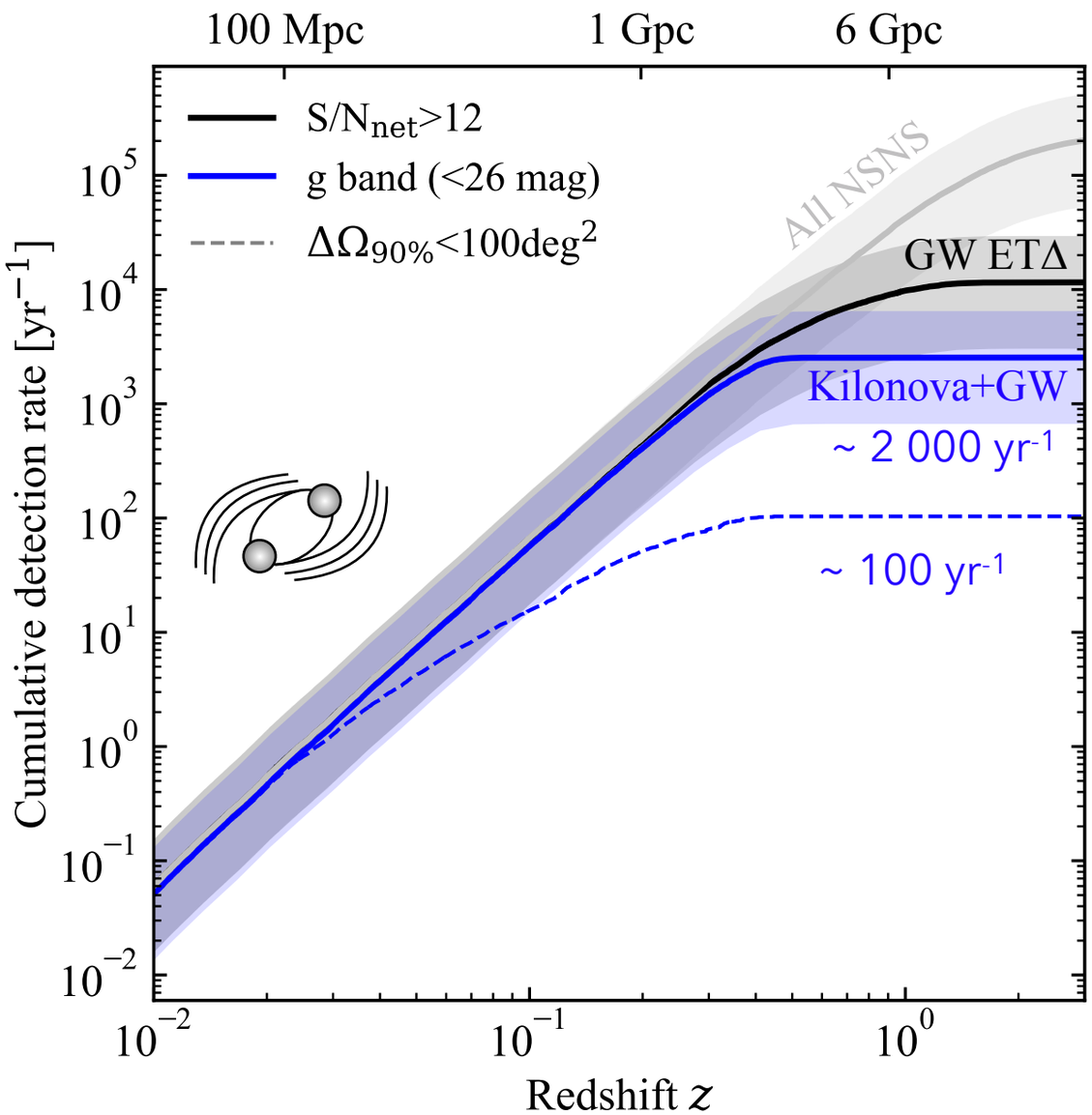
The Einstein Telescope Era (2035): NSNS

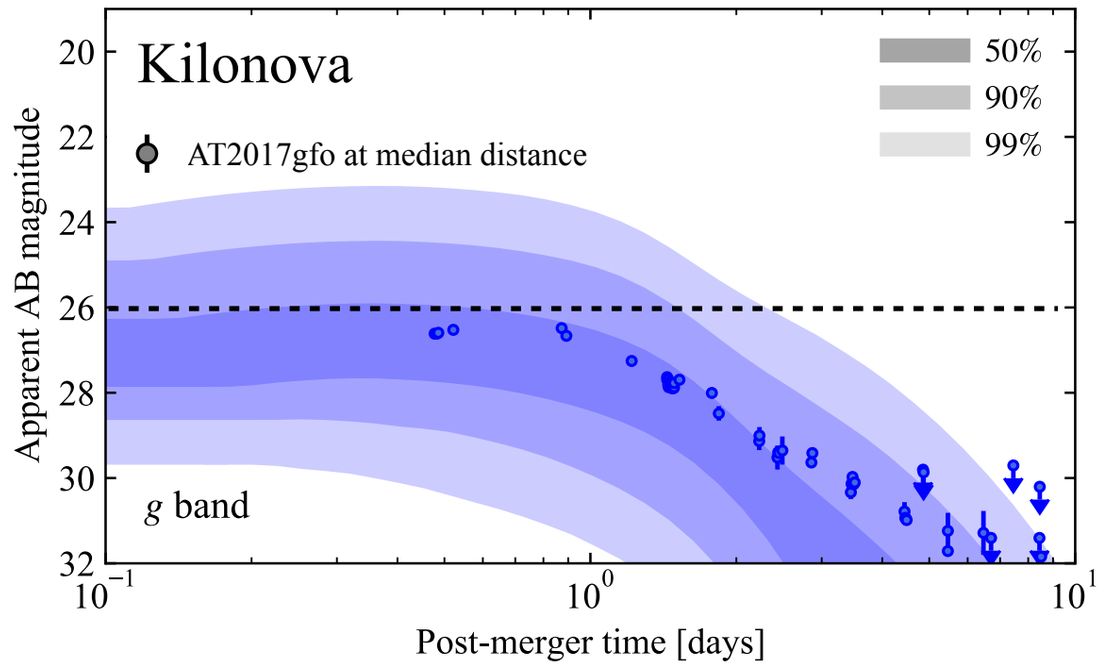




We must choose!

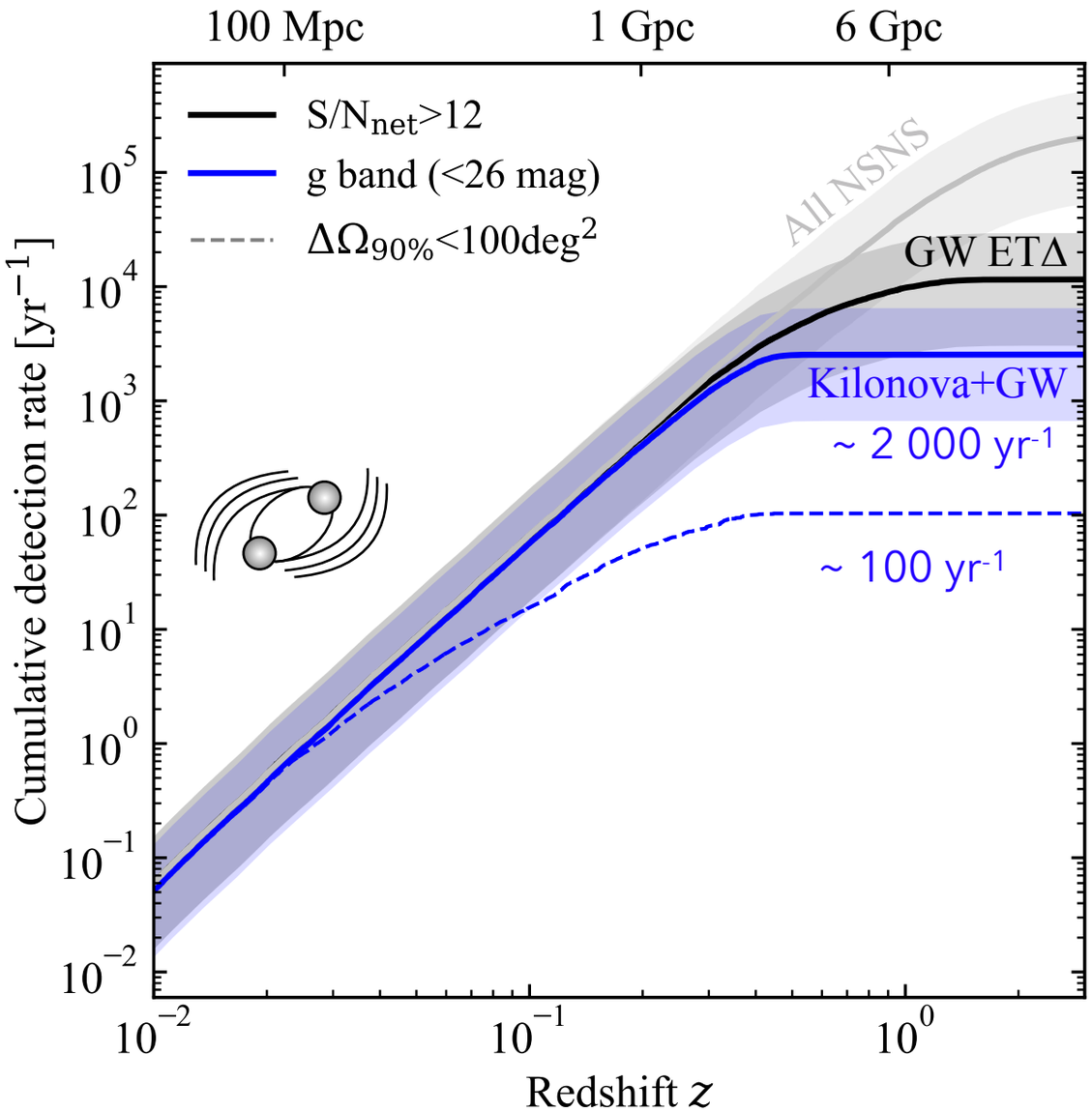
The Einstein Telescope Era (2035): NSNS

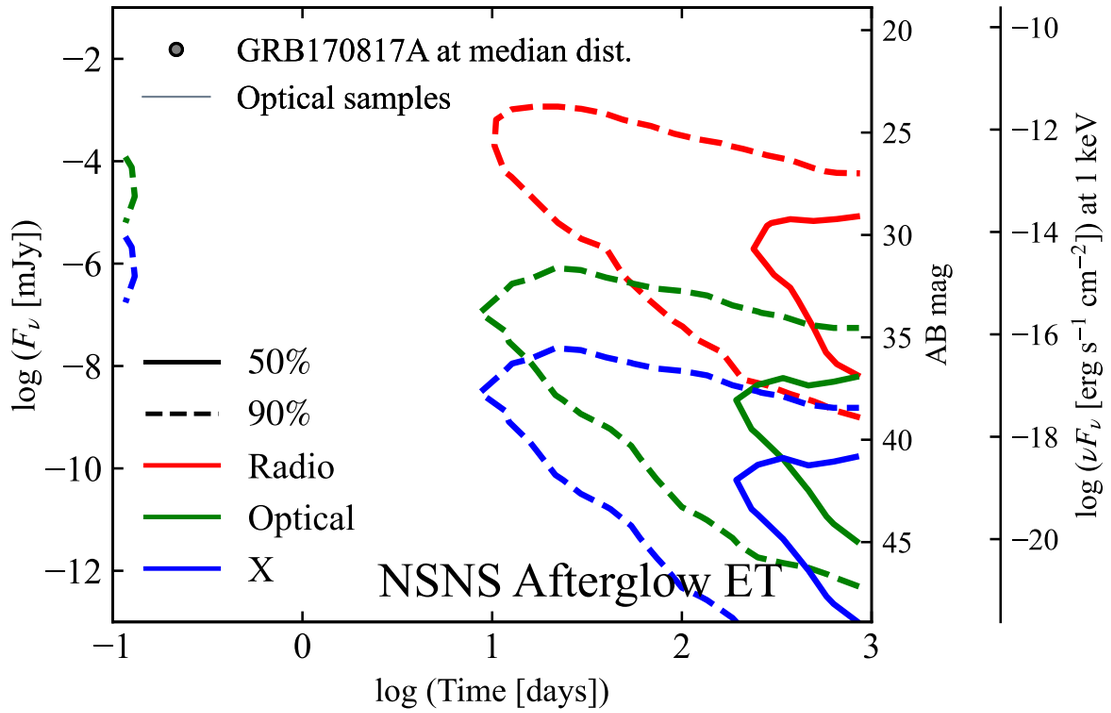




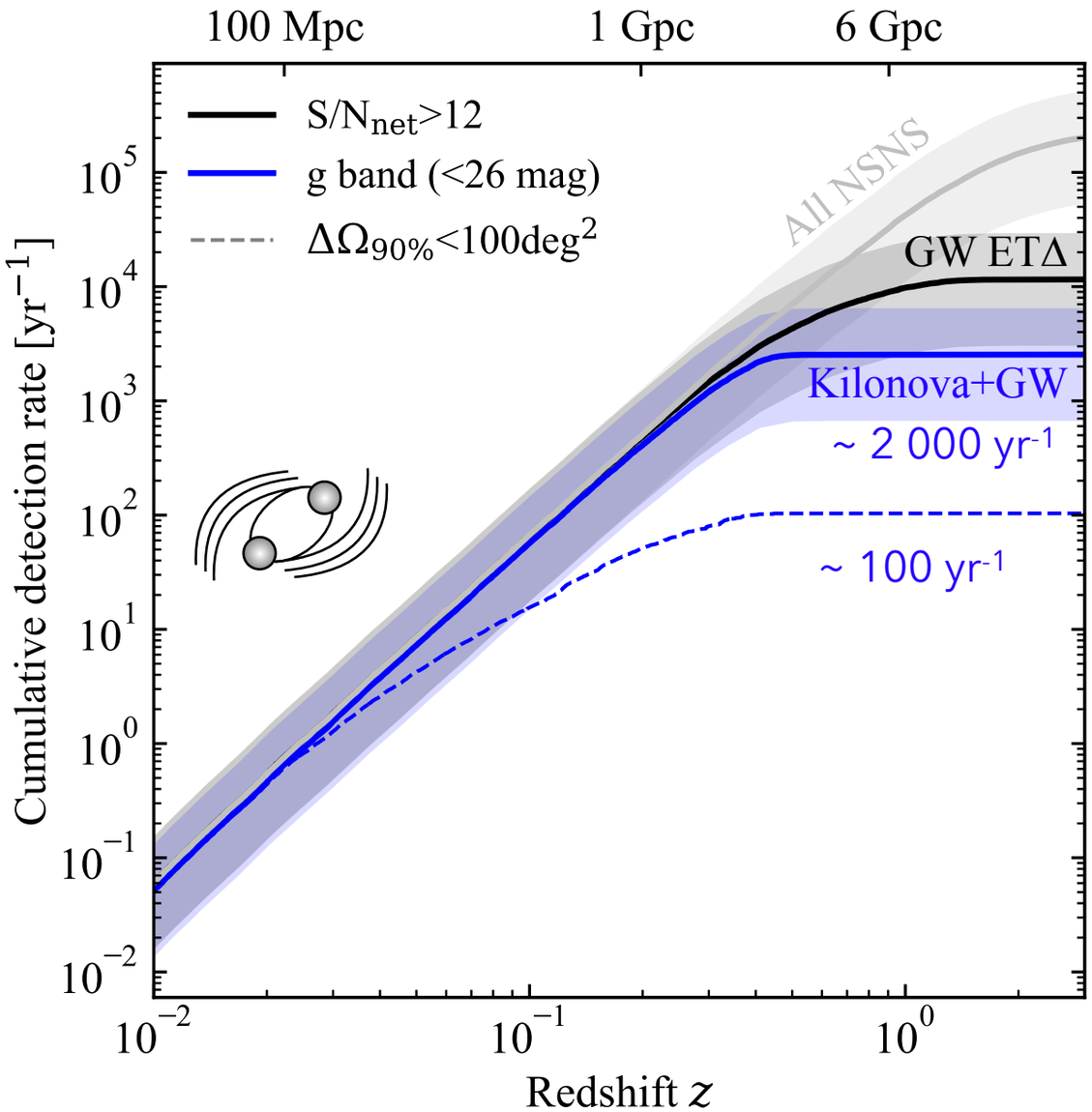
We must choose!

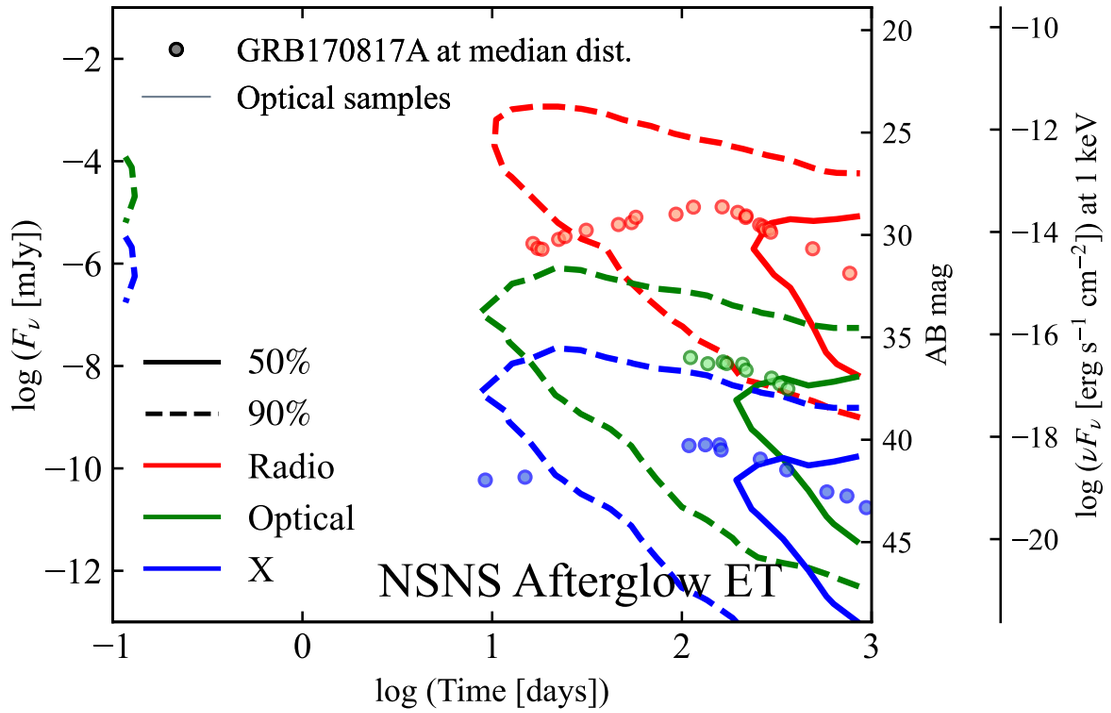
The Einstein Telescope Era (2035): NSNS



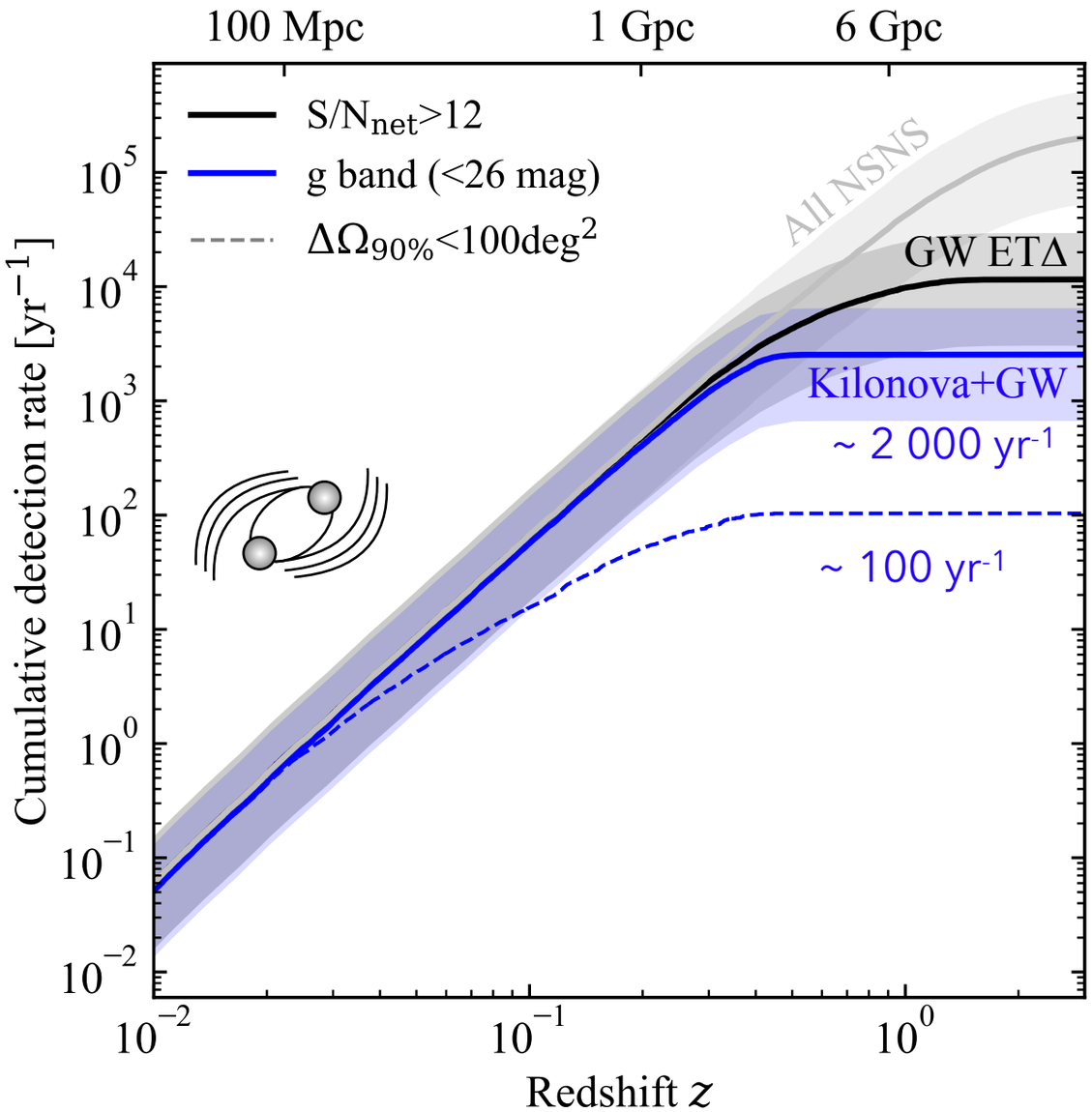


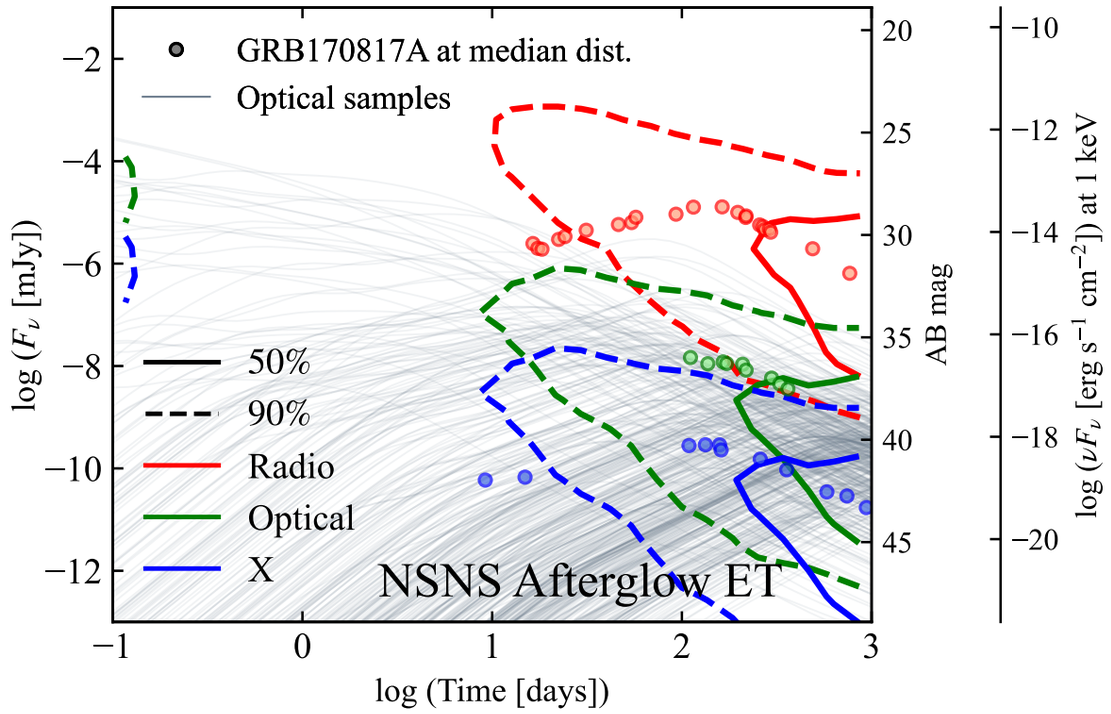
The Einstein Telescope Era (2035): NSNS



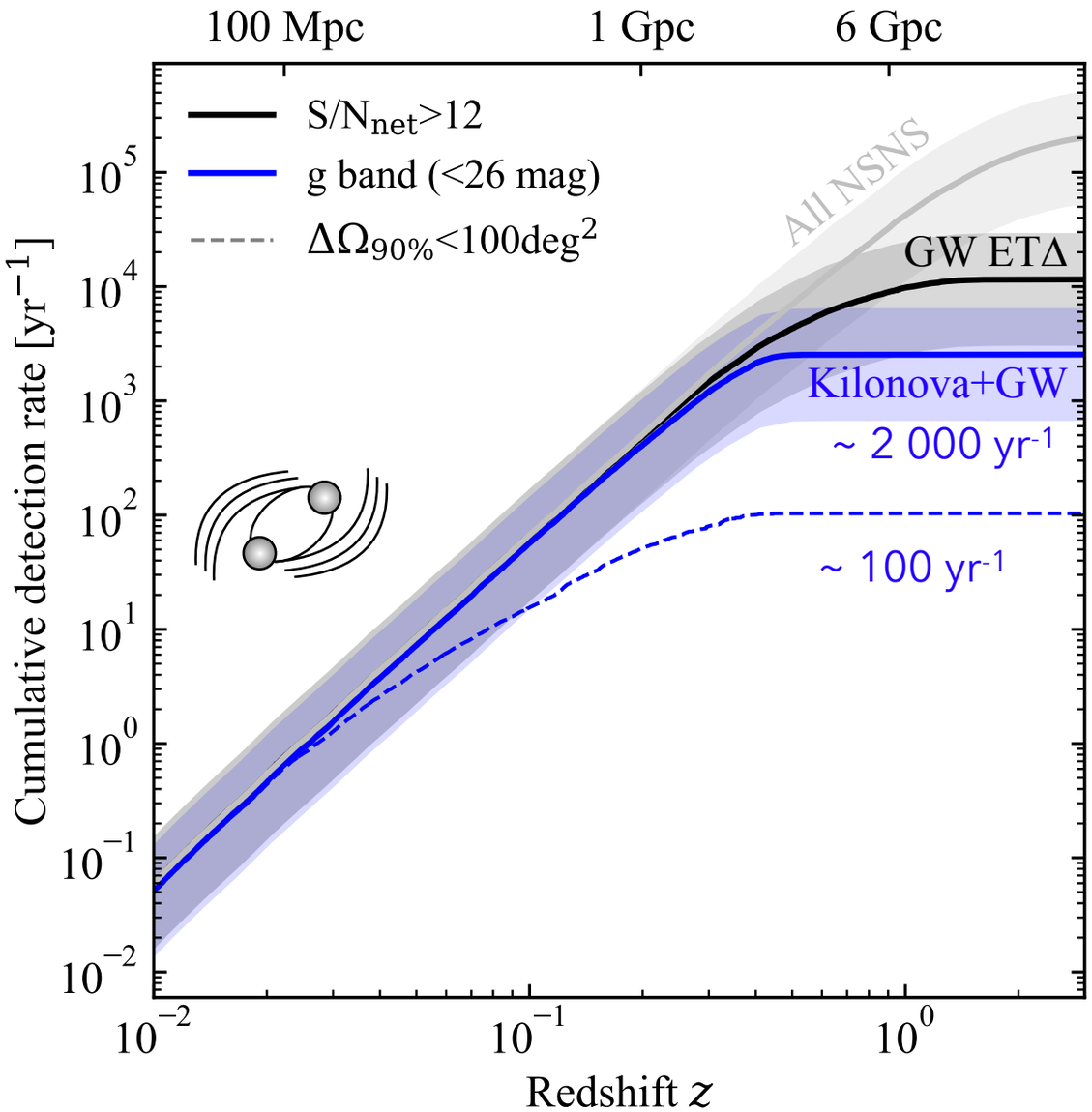


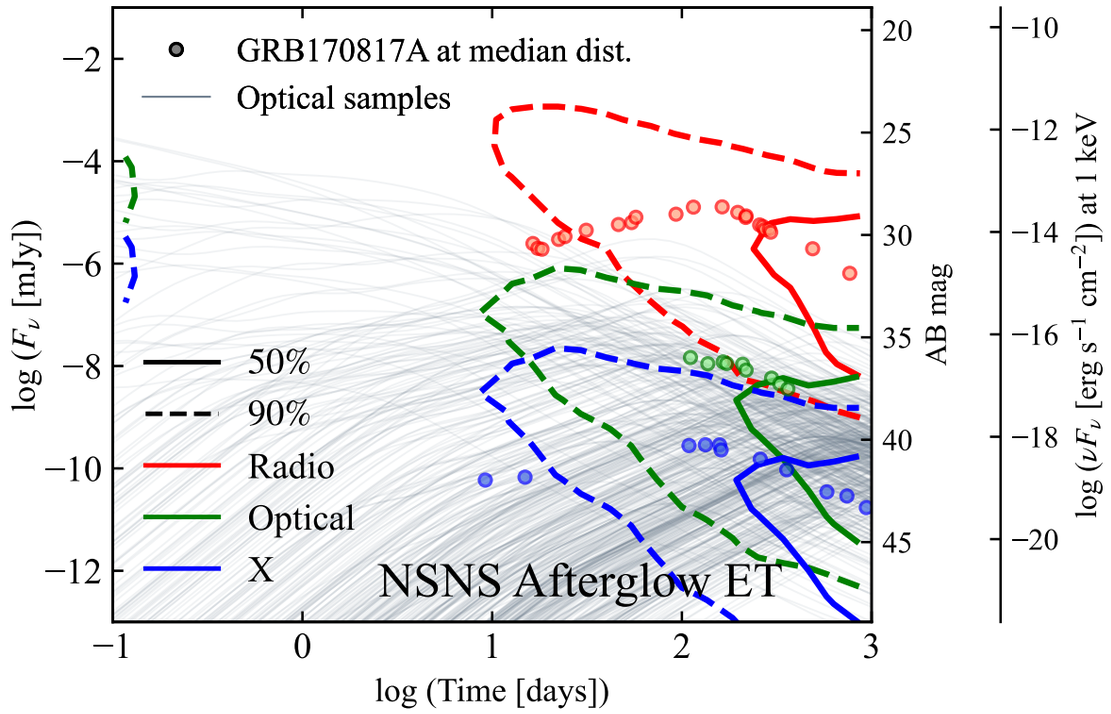
The Einstein Telescope Era (2035): NSNS

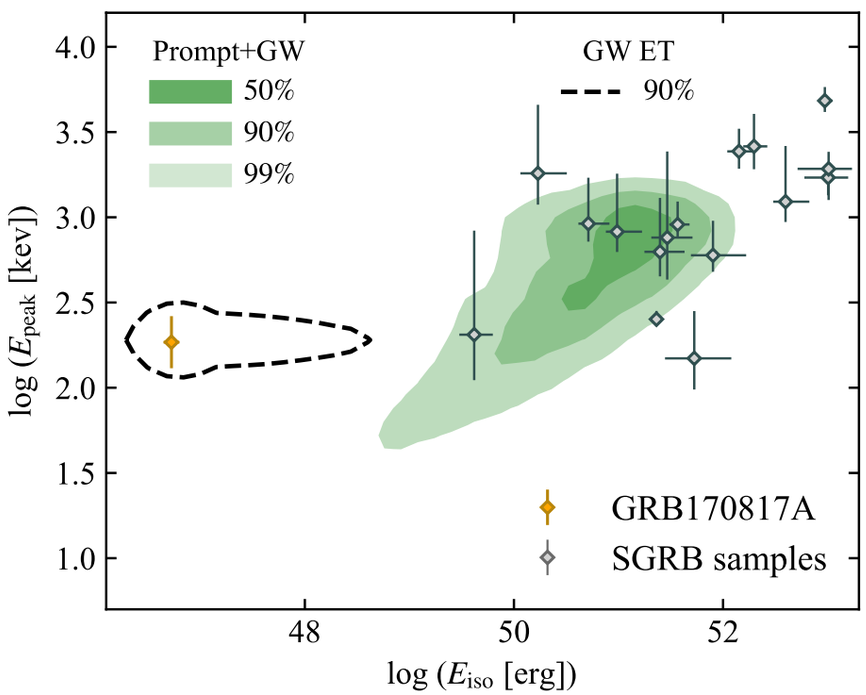




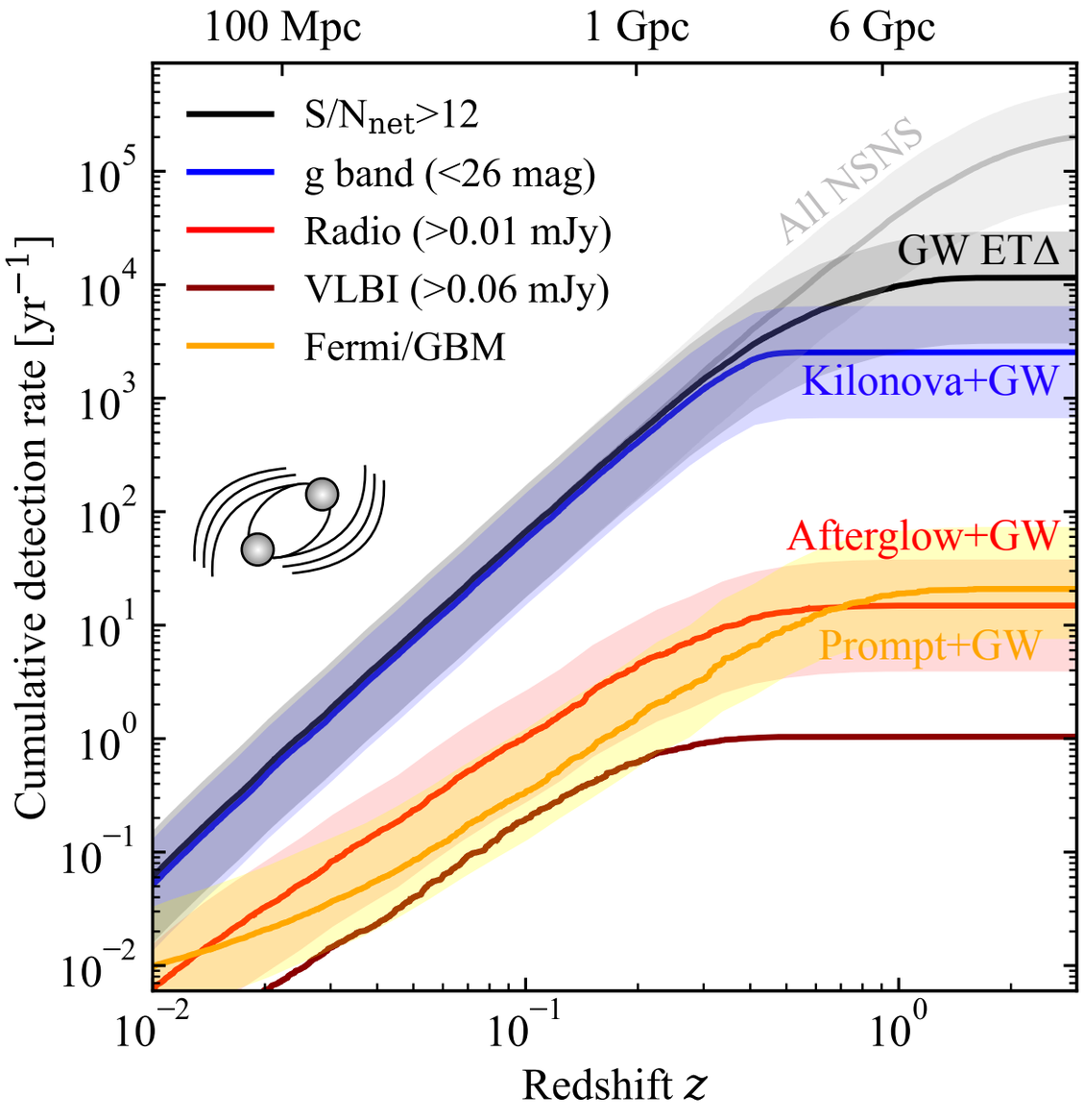
The Einstein Telescope Era (2035): NSNS

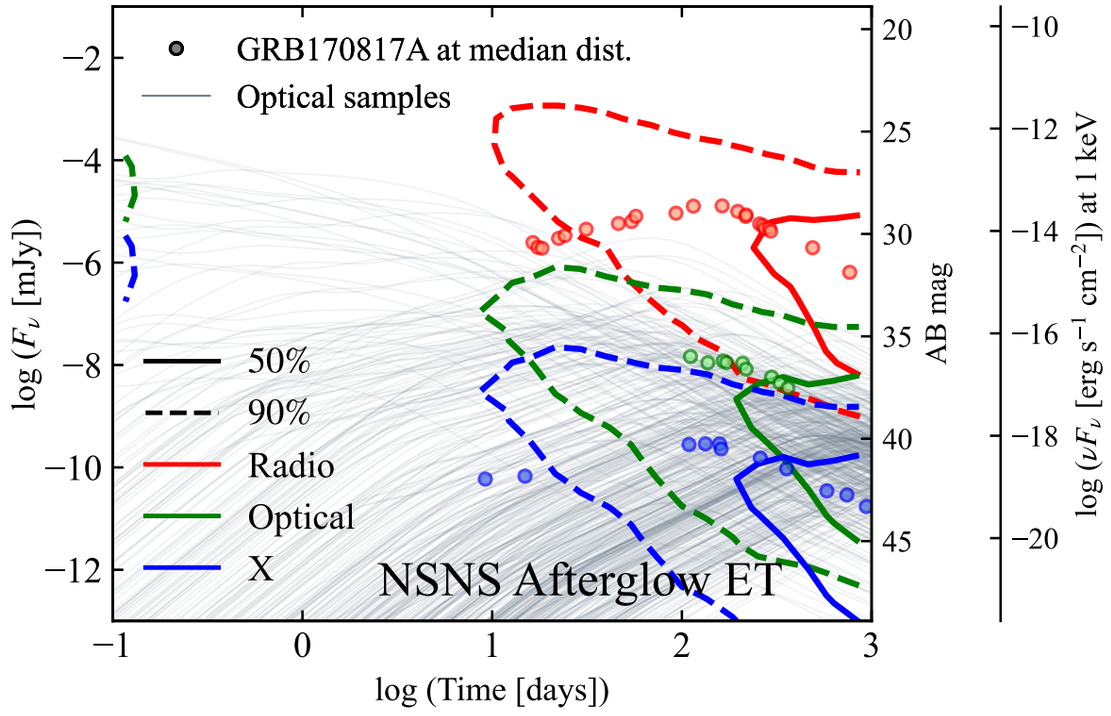


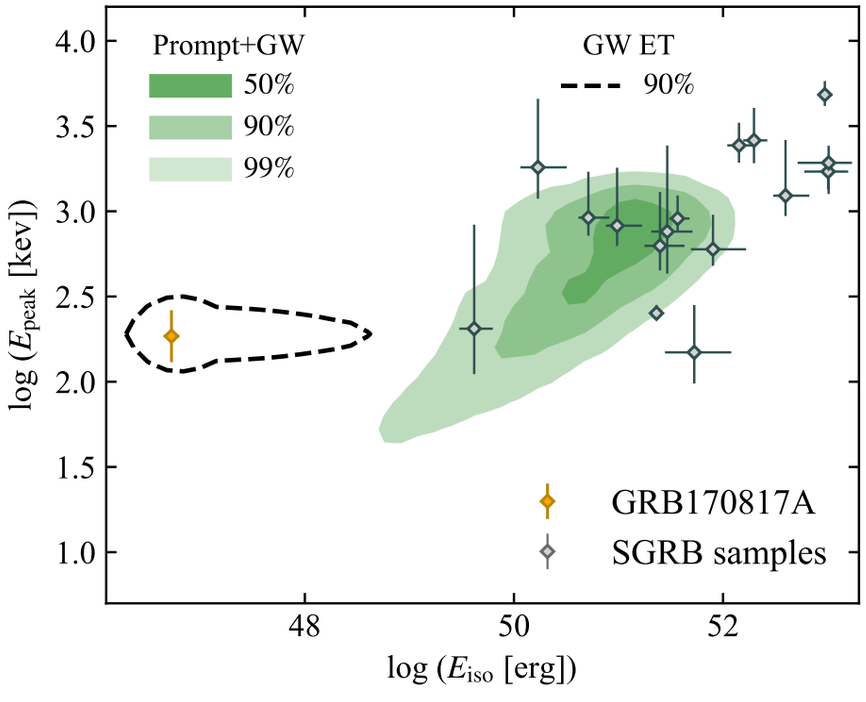




The Einstein Telescope Era (2035): NSNS







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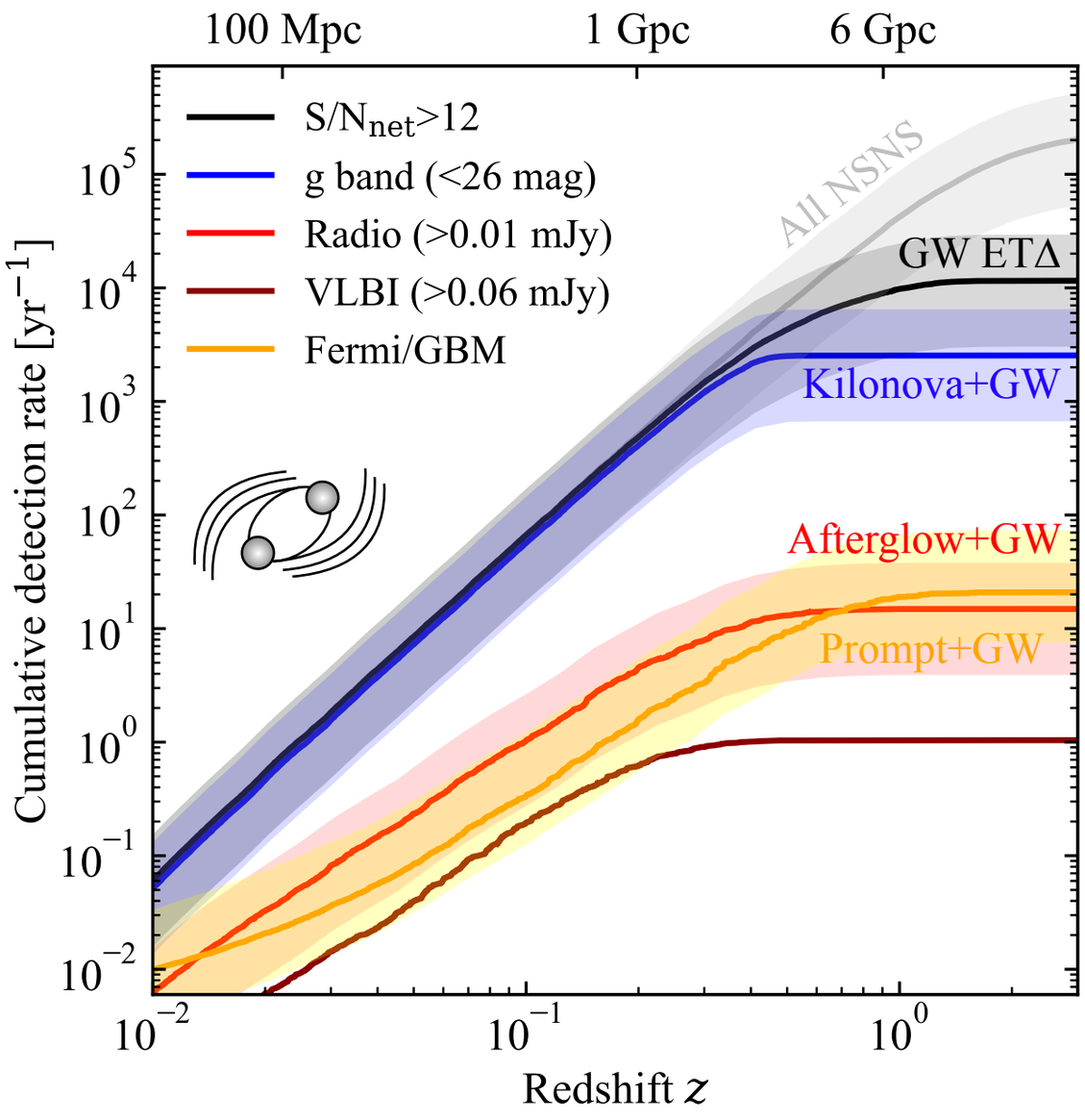
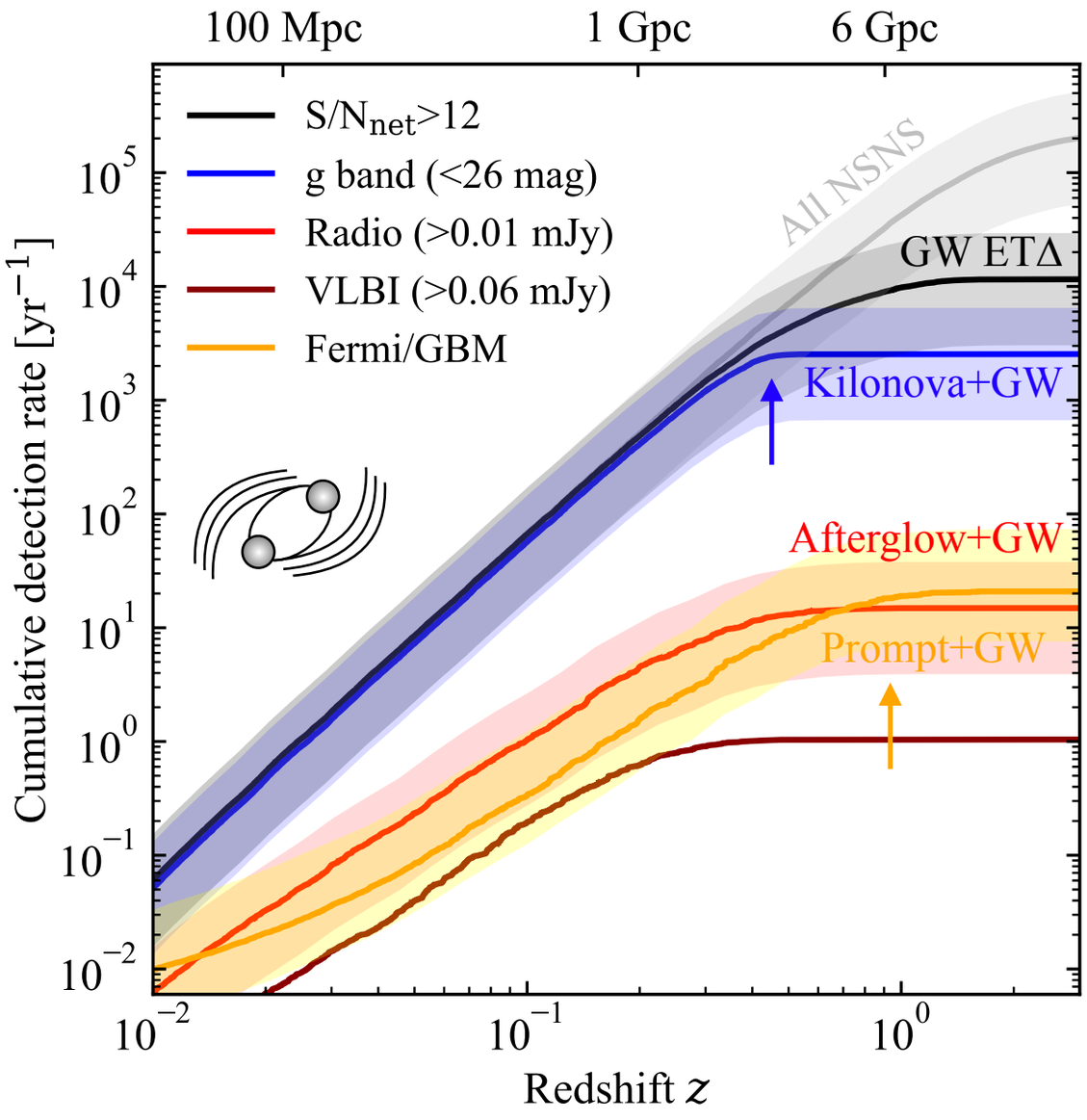
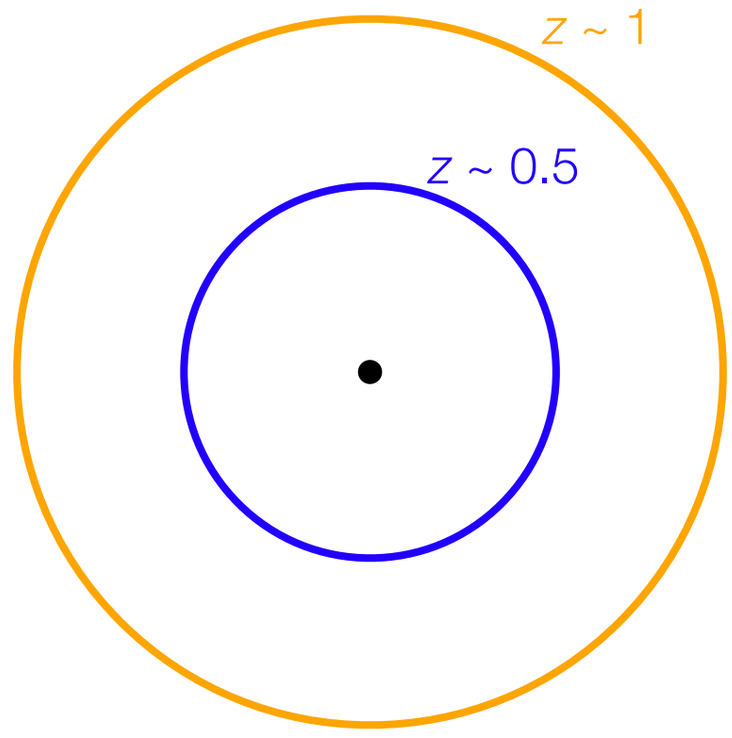


← The majority of short GRBs will have a GW counterpart!

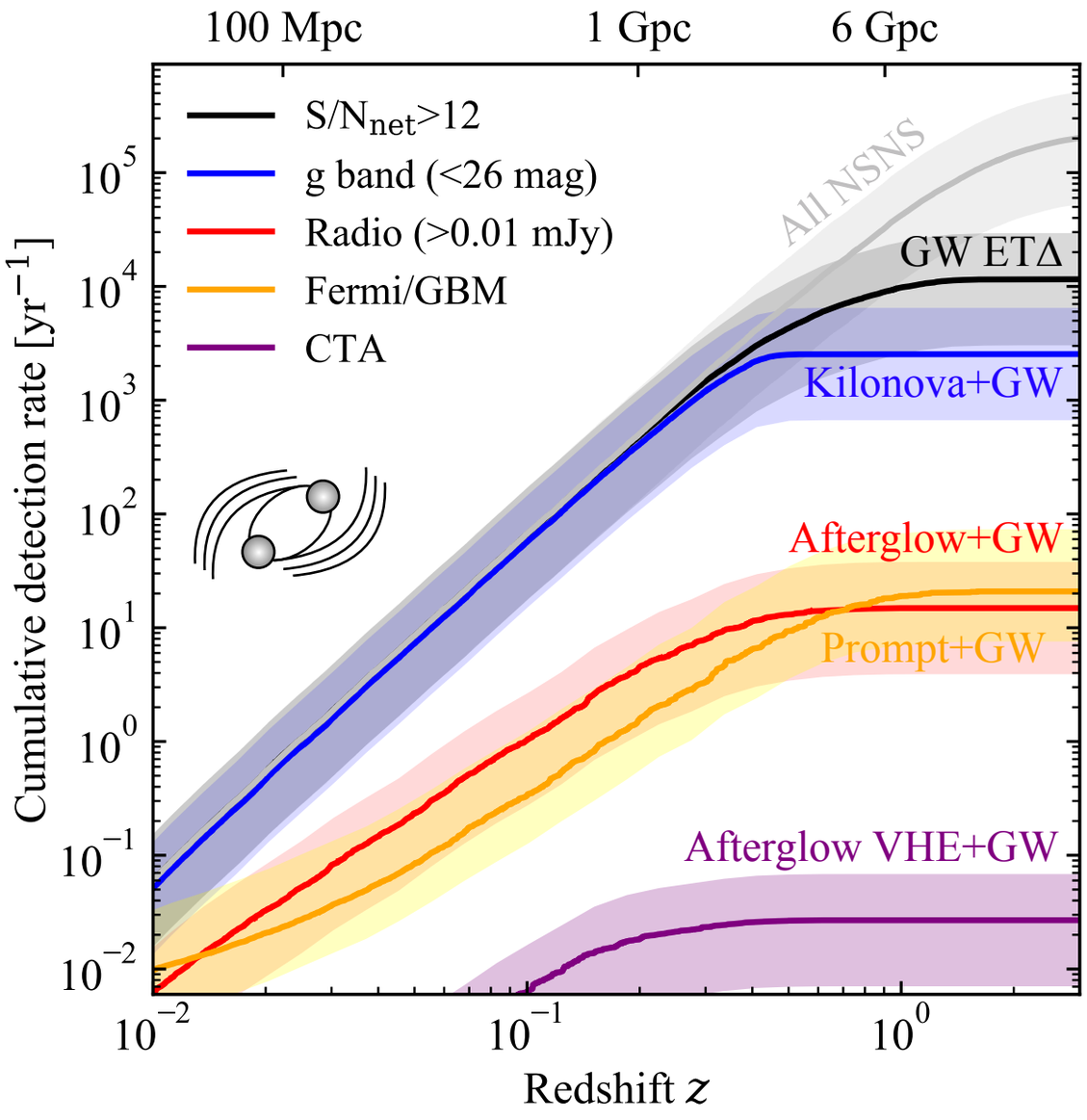
~ 21 yr^{-1}

The Einstein Telescope Era (2035): NSNS

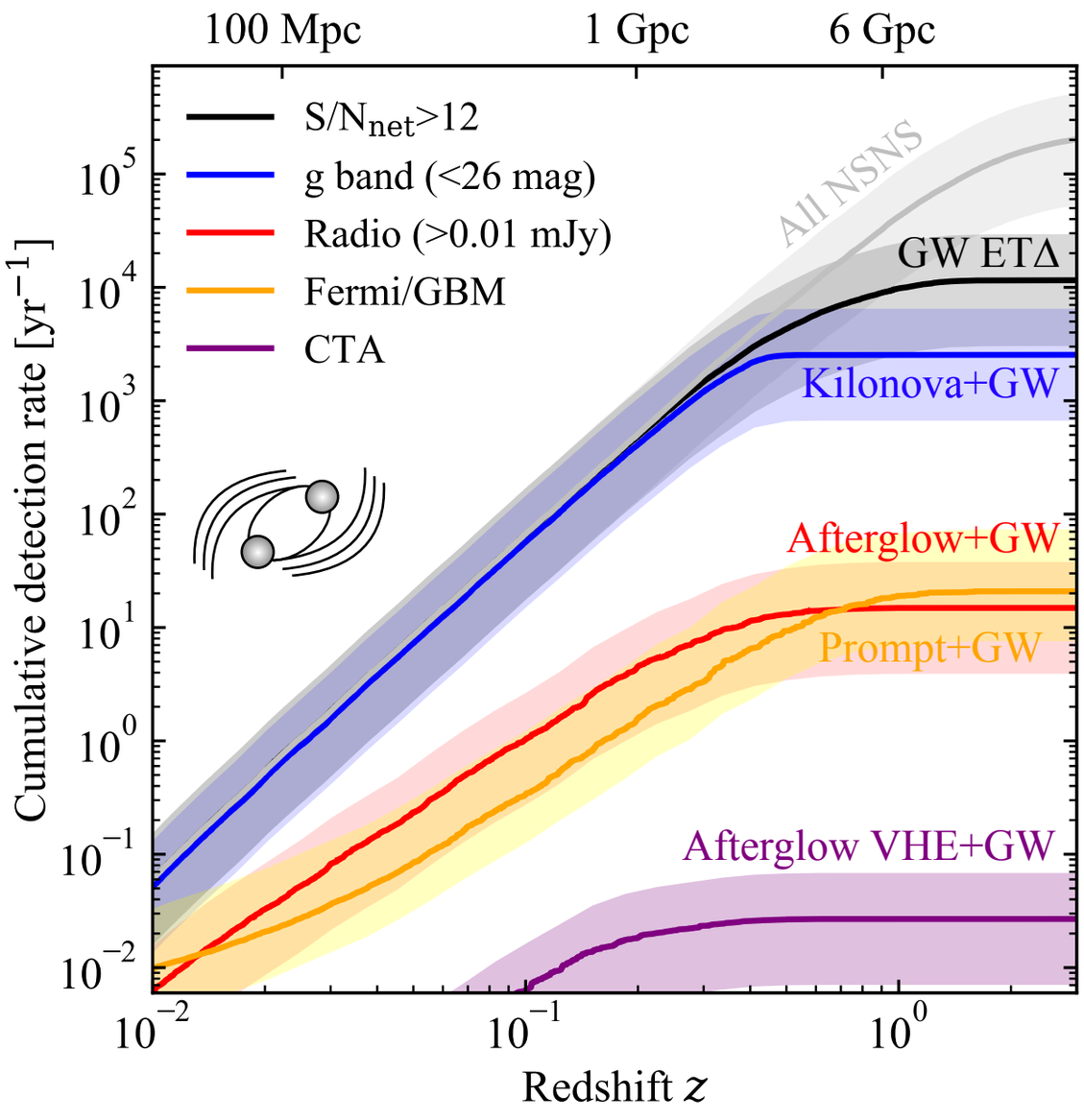


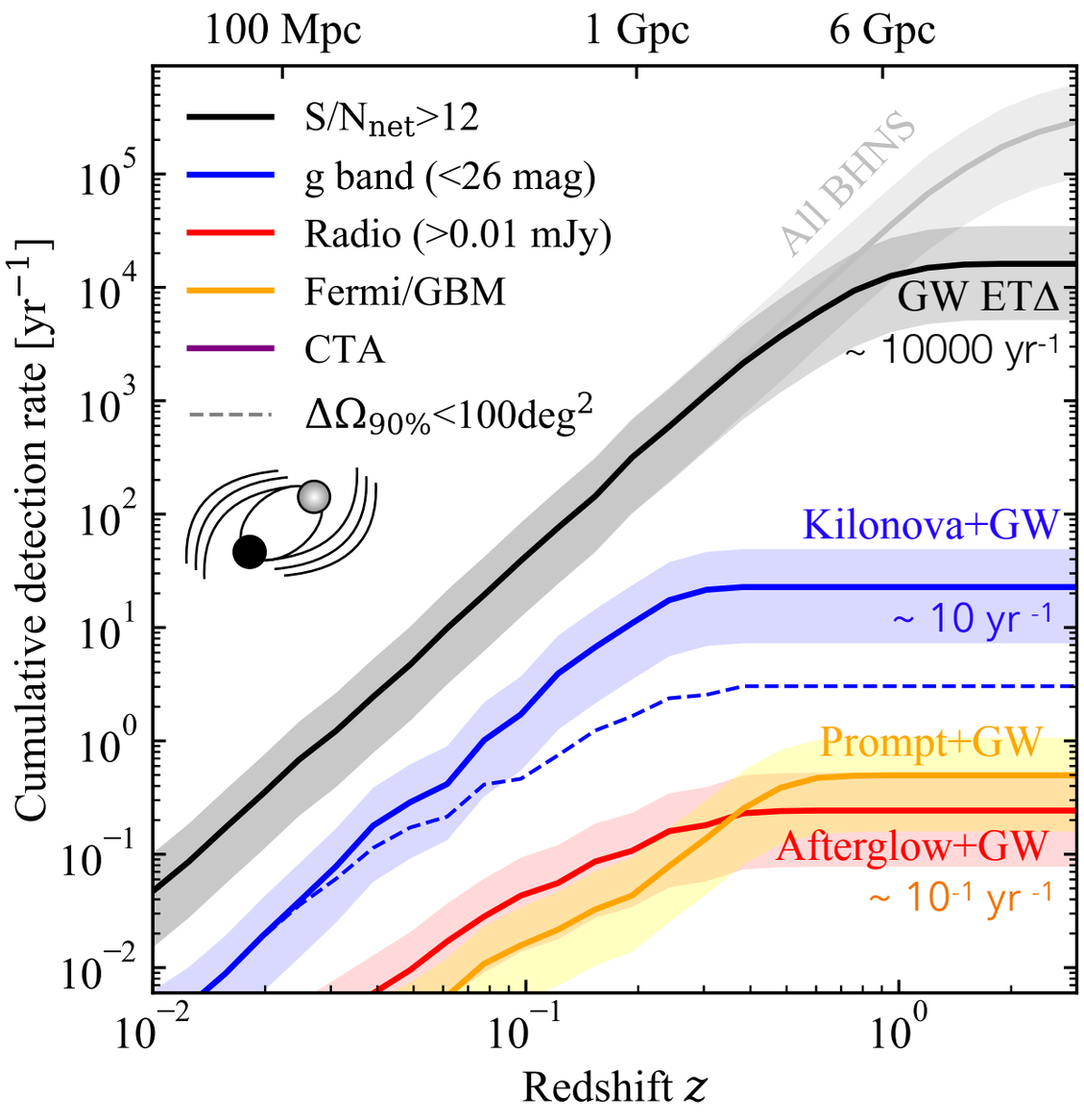


The Einstein Telescope Era (2035): NSNS

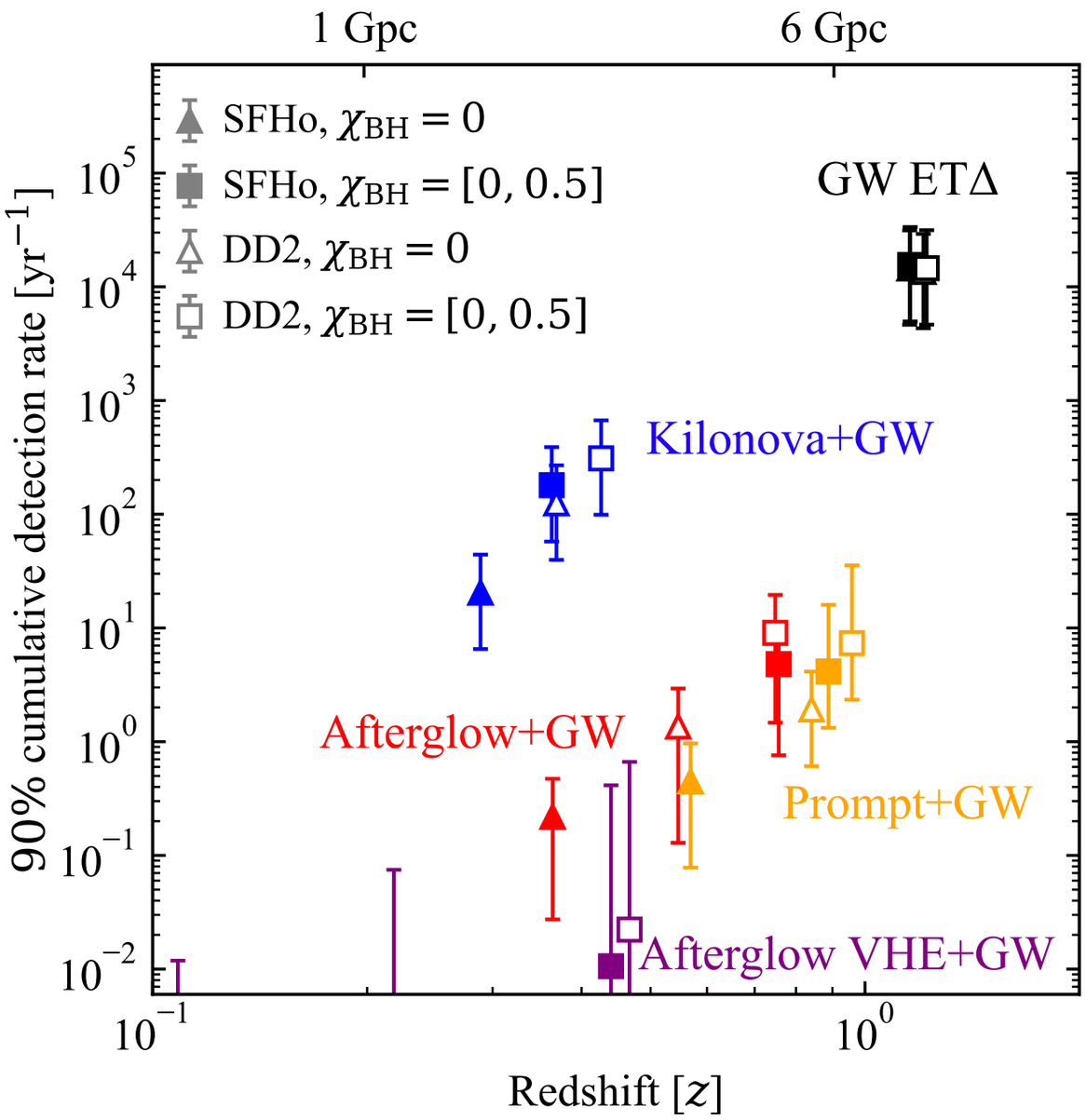


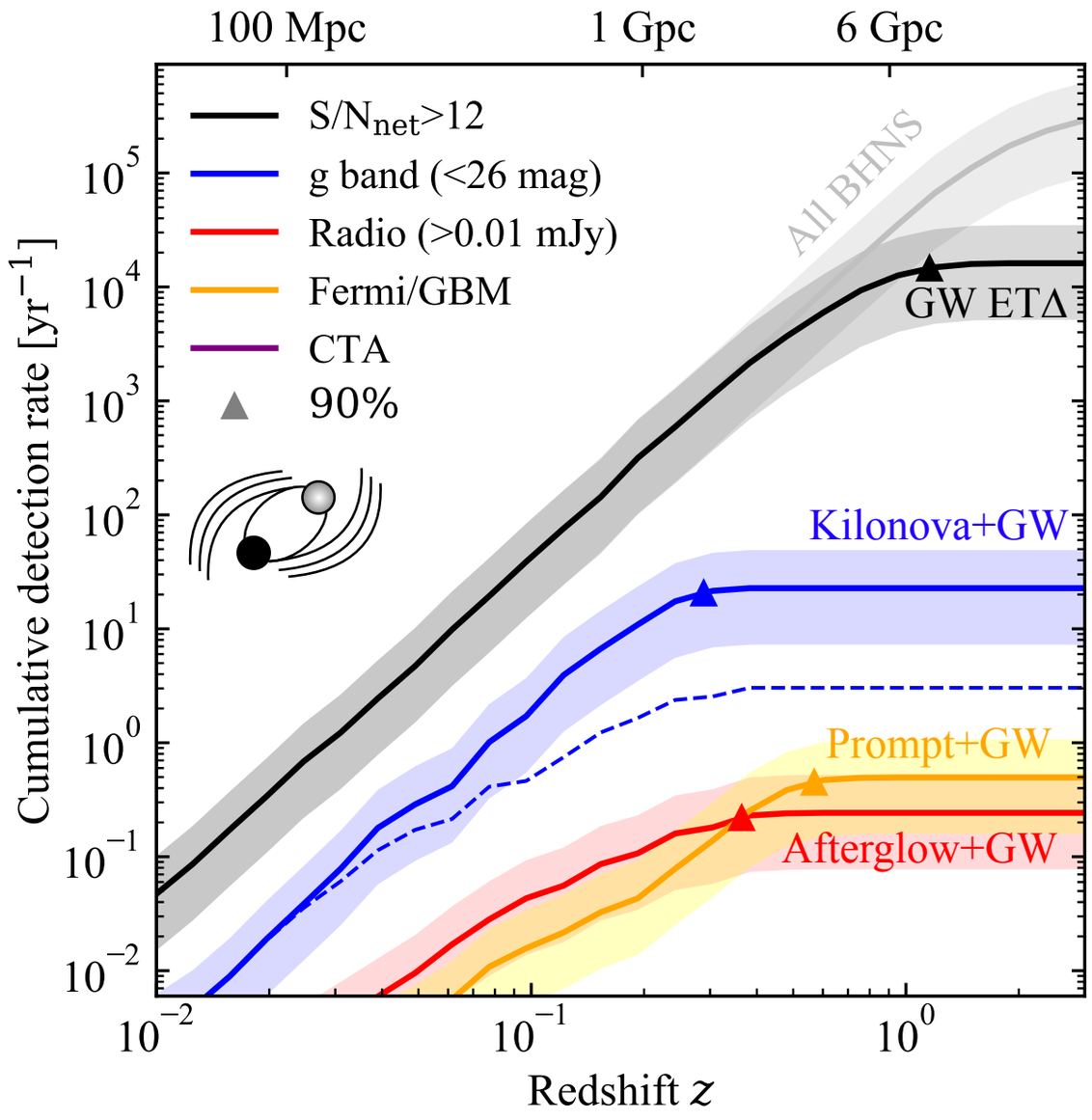
The Einstein Telescope Era (2035): BHNS





The Einstein Telescope Era (2035): BHNS





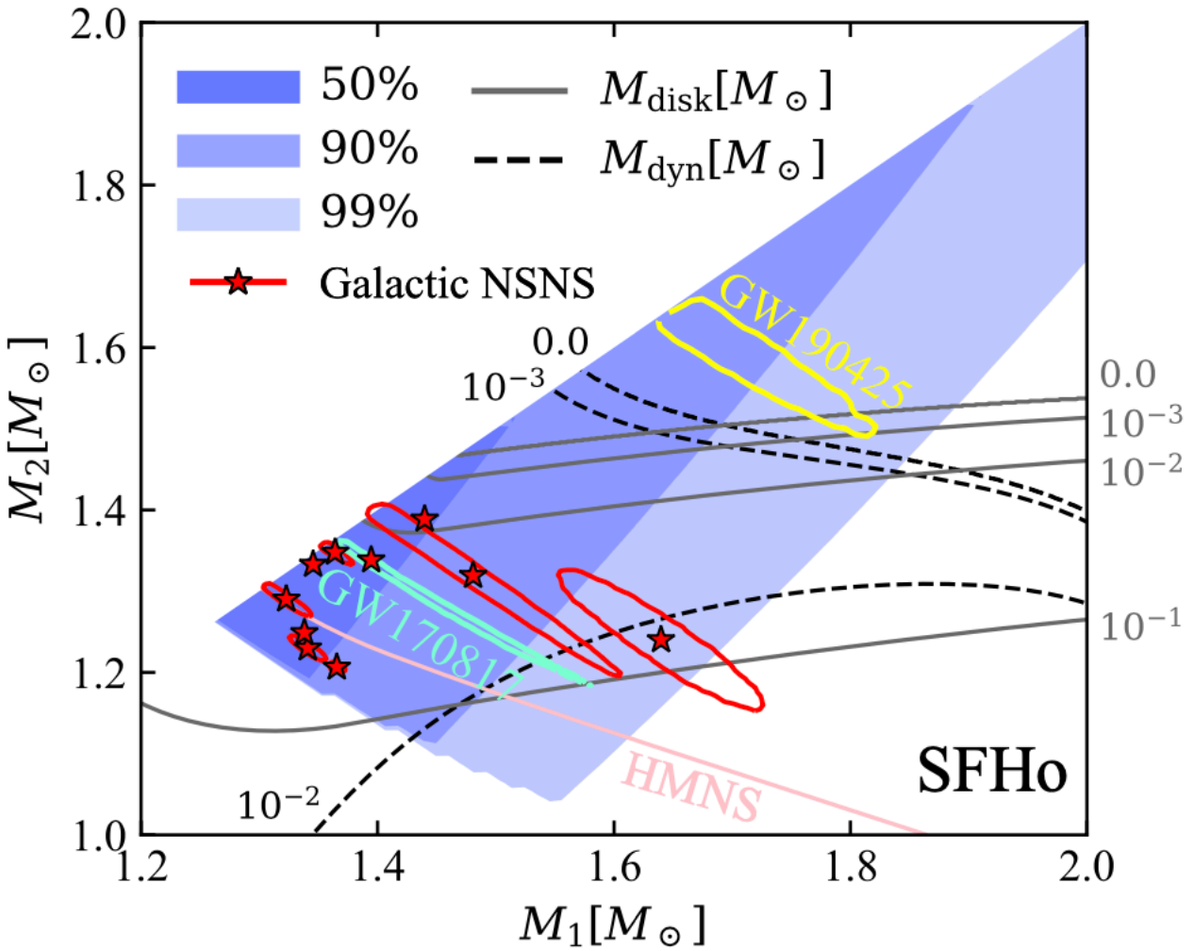
Summary: GWs Science Review

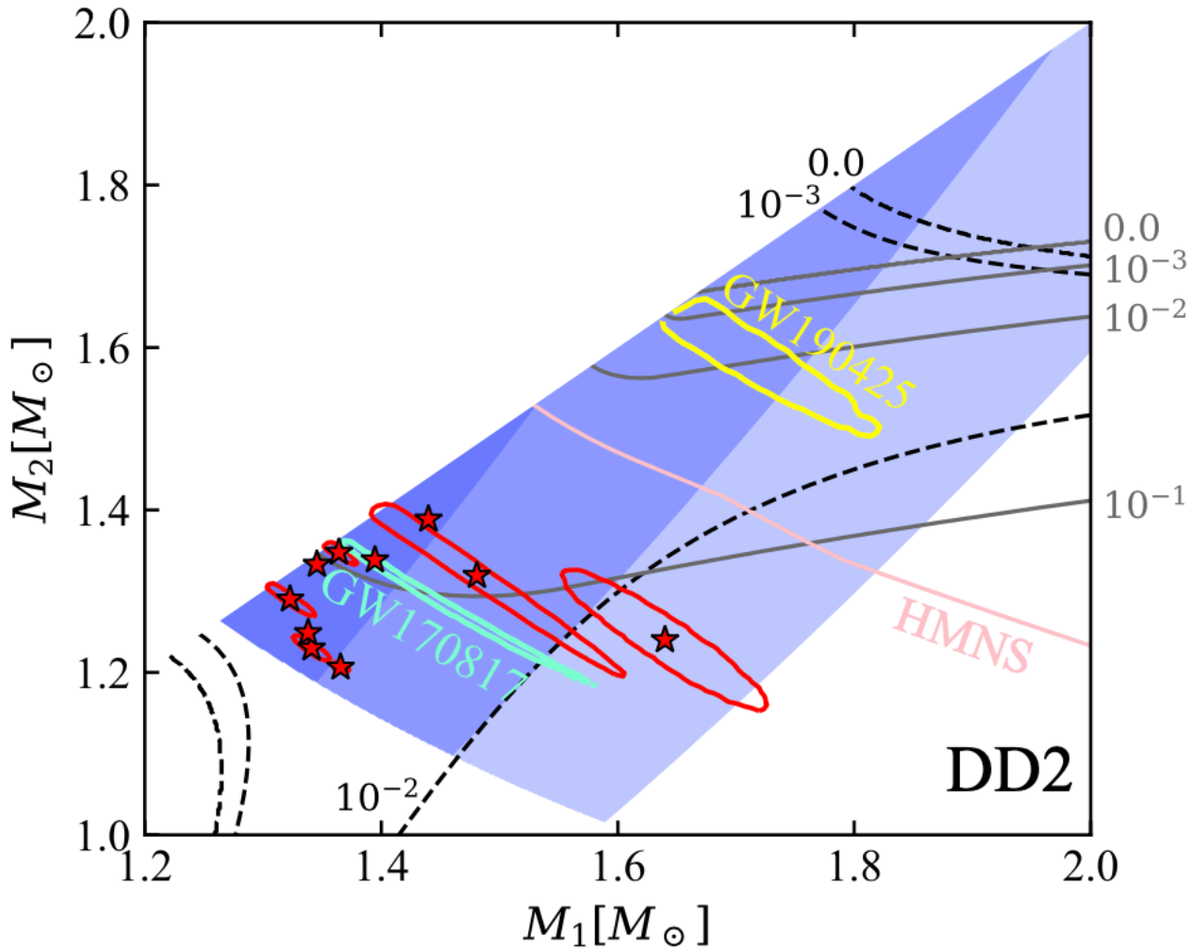
- **Multi-messenger observations** are pivotal for cosmology, high-energy phenomena, fundamental physics
- **GW170817** is the only event so far
- **Radio observations** are fundamental for GRBs
- **VLBI** is fundamental for size and position
- **Einstein Telescope** will increase the rate of a factor 10
- Up to ~**100 KNe** detections per year for NSNS
- The majority of short **GRB**s will have a **GW counterpart**
- **BHNS** mergers can also be a promising multi-messenger source
- Our model can be applied to **specific EM facilities**

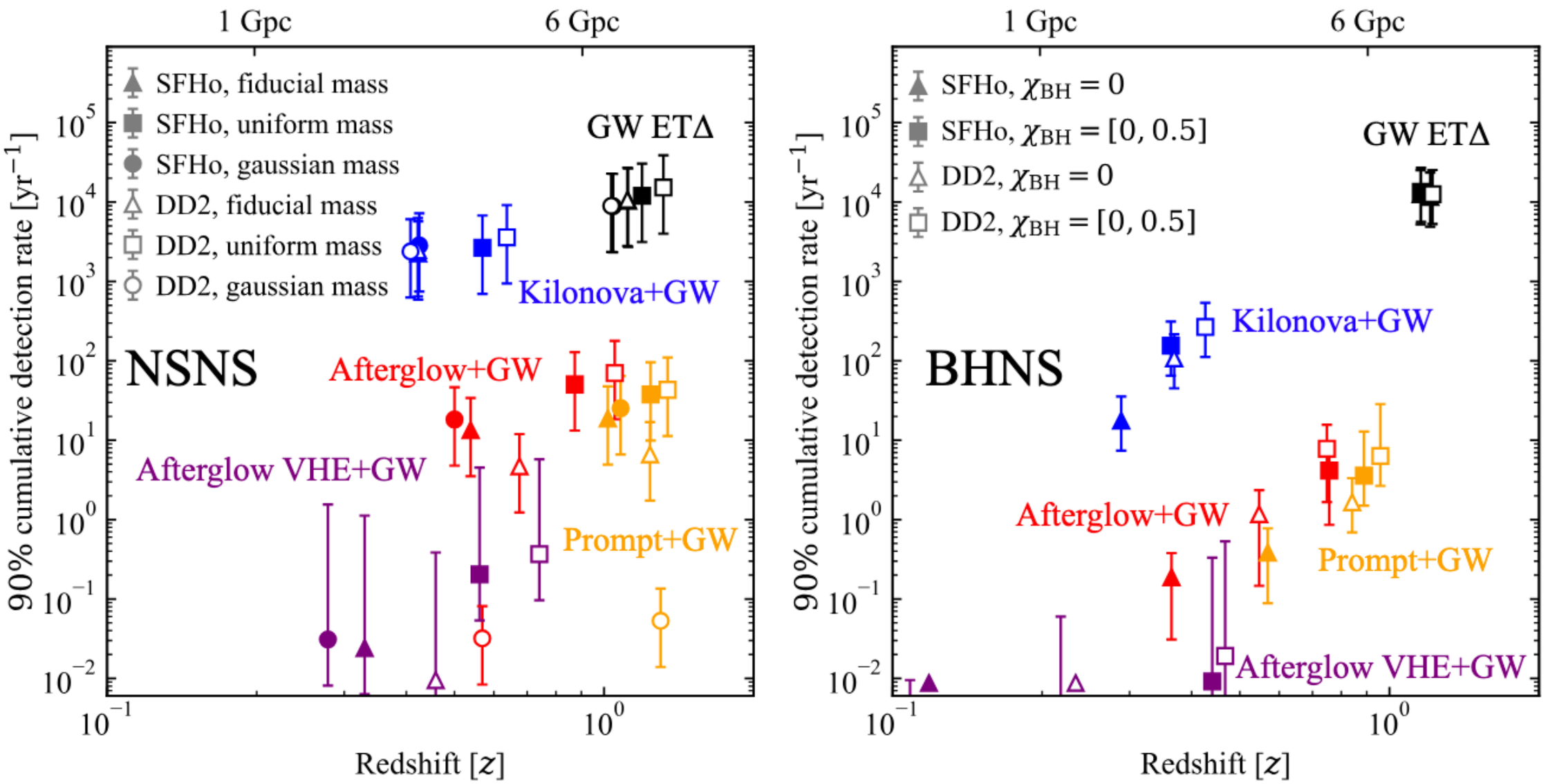
This work is supported by ERC grant GravitySirens 101163912. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Thank you!

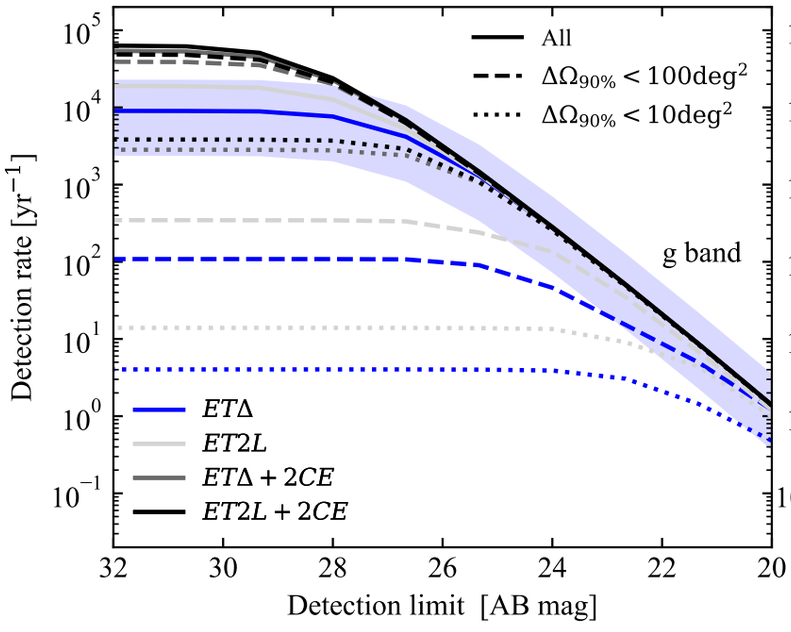
Back up slides

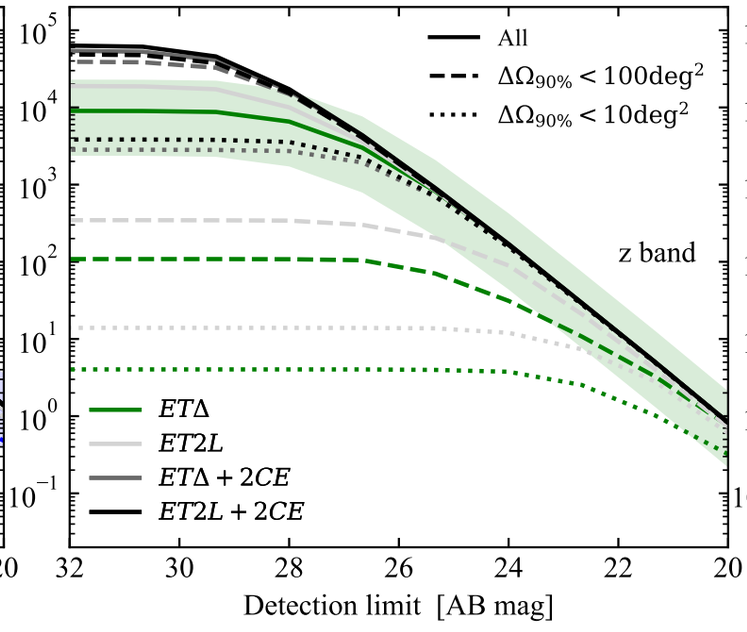

50%
90%
99%
$M_{\rm disk}[M_\odot]$
$M_{\rm dyn}[M_\odot]$
Galactic NSNS
GW190425
GW170817
HMNS
SFHo
0.0
10^{-3}
10^{-2}
10^{-1}
$M_1[M_\odot]$
$M_2[M_\odot]$

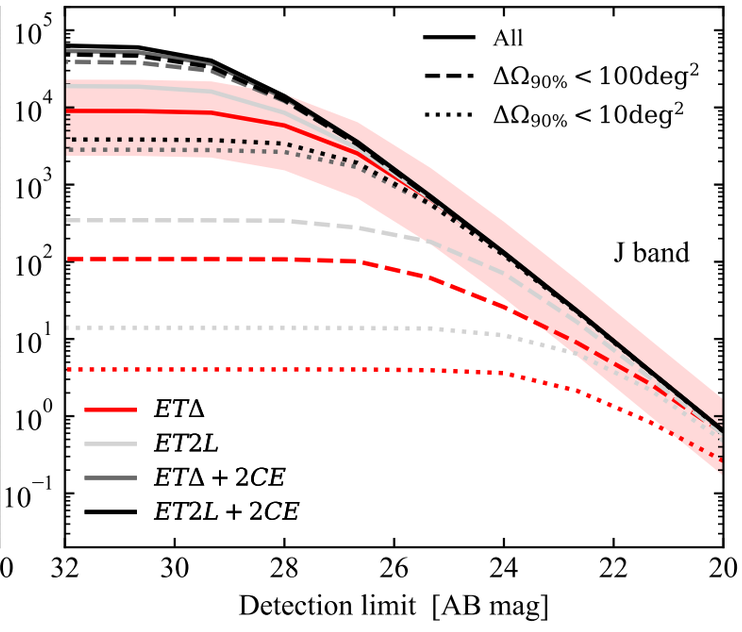

GW190425
GW170817
HMNS
DD2
0.0
10^{-3}
10^{-2}
10^{-1}
$M_1[M_\odot]$
$M_2[M_\odot]$


1 Gpc
6 Gpc
SFHo, fiducial mass
SFHo, uniform mass
SFHo, gaussian mass
DD2, fiducial mass
DD2, uniform mass
DD2, gaussian mass
GW ETΔ
Kilonova+GW
NSNS
Afterglow+GW
Afterglow VHE+GW
Prompt+GW
90% cumulative detection rate [yr^{-1}]
Redshift [z]
SFHo, $\chi_{\rm BH} = 0$
SFHo, $\chi_{\rm BH} = [0, 0.5]$
DD2, $\chi_{\rm BH} = 0$
DD2, $\chi_{\rm BH} = [0, 0.5]$
BHNS

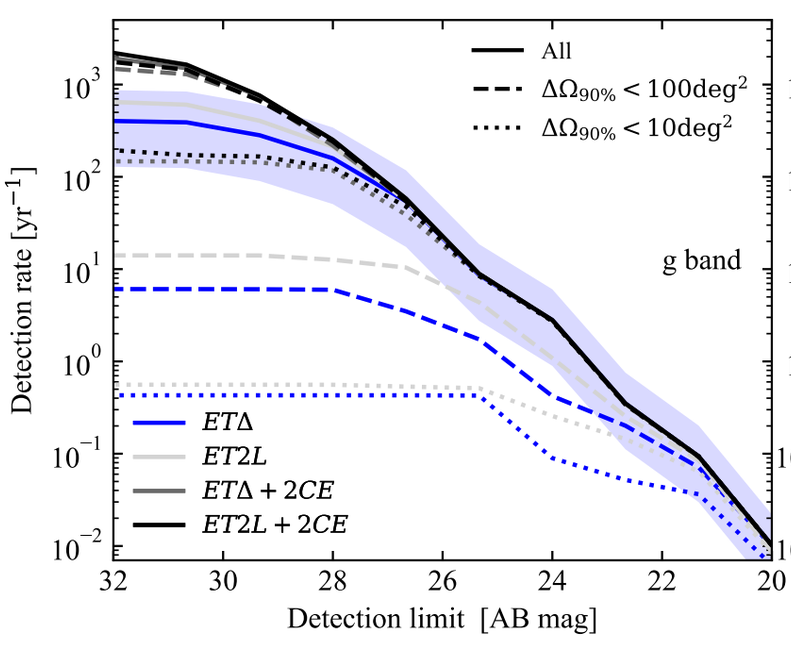
NSNS

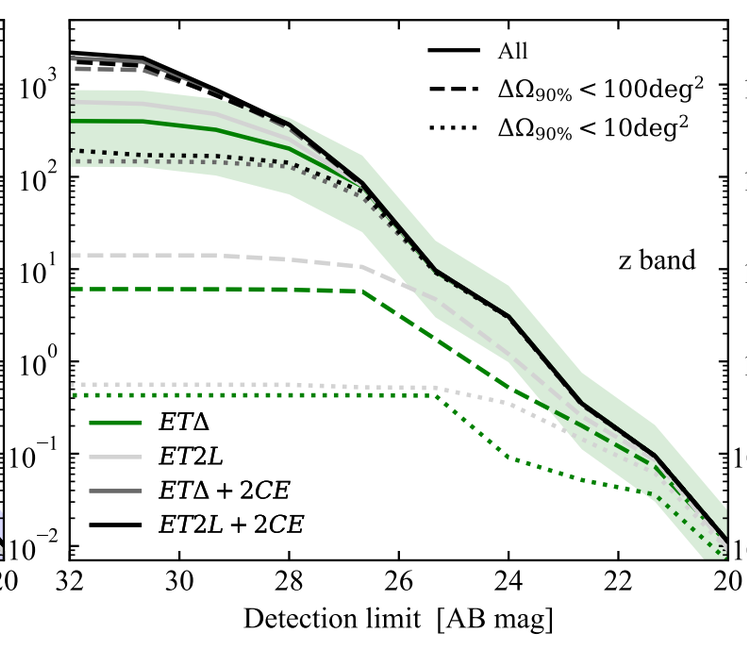

All
$\Delta\Omega_{90\%} < 100\mathrm{deg}^2$
$\Delta\Omega_{90\%} < 10\mathrm{deg}^2$
g band
$ET\Delta$
$ET2L$
$ET\Delta + 2CE$
$ET2L + 2CE$
Detection rate [yr^{-1}]
Detection limit [AB mag]

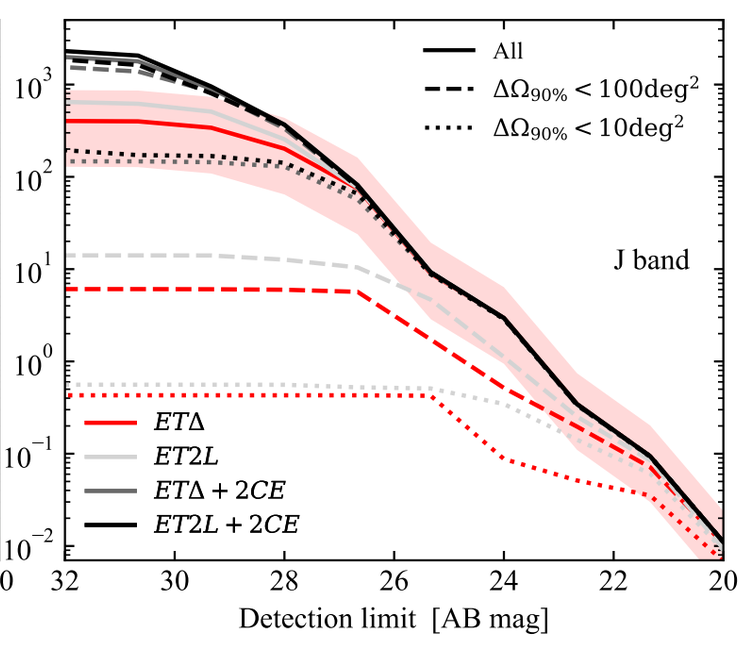

All
$\Delta\Omega_{90\%} < 100\mathrm{deg}^2$
$\Delta\Omega_{90\%} < 10\mathrm{deg}^2$
z band
$ET\Delta$
$ET2L$
$ET\Delta + 2CE$
$ET2L + 2CE$
Detection limit [AB mag]


All
$\Delta\Omega_{90\%} < 100\mathrm{deg}^2$
$\Delta\Omega_{90\%} < 10\mathrm{deg}^2$
J band
$ET\Delta$
$ET2L$
$ET\Delta + 2CE$
$ET2L + 2CE$
Detection limit [AB mag]

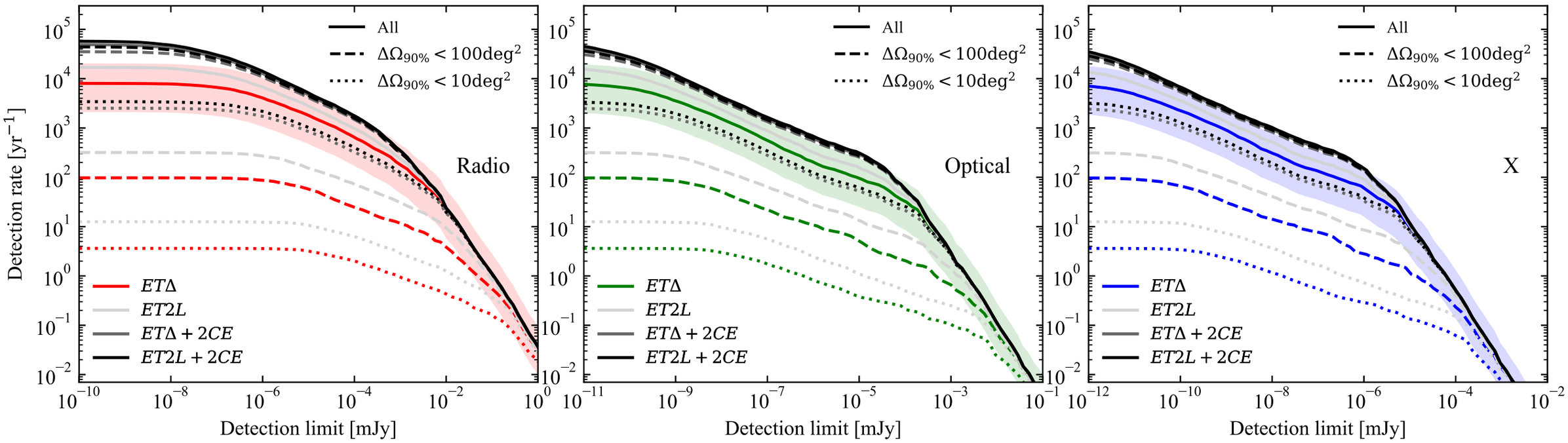
BHNS


All
$\Delta\Omega_{90\%} < 100\mathrm{deg}^2$
$\Delta\Omega_{90\%} < 10\mathrm{deg}^2$
g band
$ET\Delta$
$ET2L$
$ET\Delta + 2CE$
$ET2L + 2CE$
Detection rate [yr^{-1}]
Detection limit [AB mag]

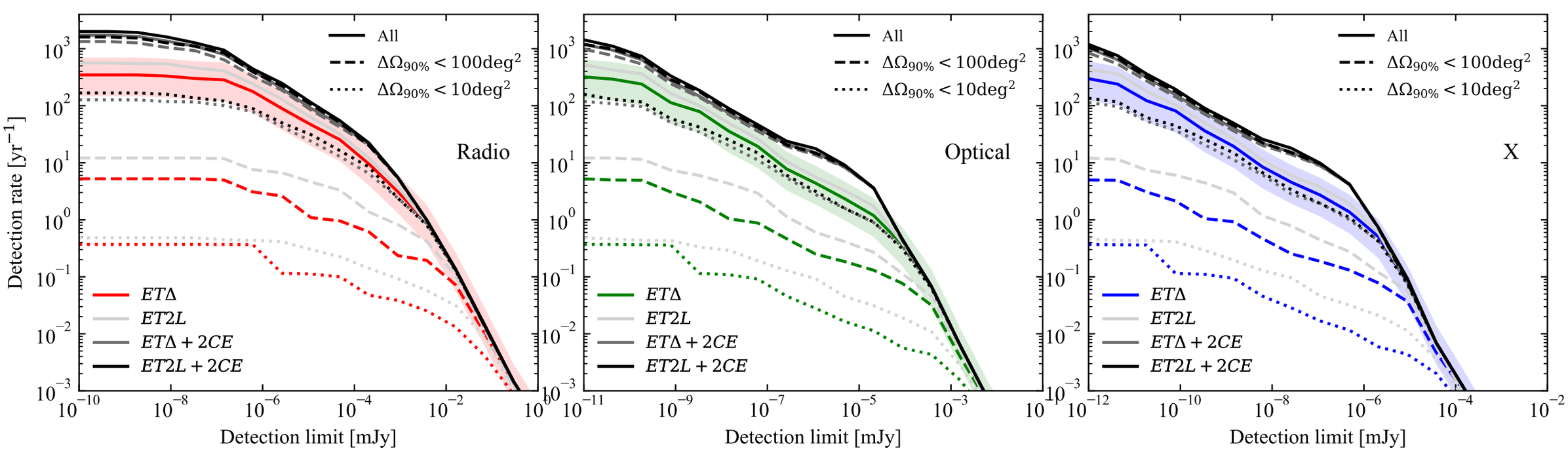

All
$\Delta\Omega_{90\%} < 100\mathrm{deg}^2$
$\Delta\Omega_{90\%} < 10\mathrm{deg}^2$
z band
$ET\Delta$
$ET2L$
$ET\Delta + 2CE$
$ET2L + 2CE$
Detection limit [AB mag]


All
$\Delta\Omega_{90\%} < 100\mathrm{deg}^2$
$\Delta\Omega_{90\%} < 10\mathrm{deg}^2$
J band
$ET\Delta$
$ET2L$
$ET\Delta + 2CE$
$ET2L + 2CE$
Detection limit [AB mag]

NSNS


All
$\Delta\Omega_{90\%} < 100\mathrm{deg}^2$
$\Delta\Omega_{90\%} < 10\mathrm{deg}^2$
Radio
Optical
X
$ET\Delta$
$ET2L$
$ET\Delta + 2CE$
$ET2L + 2CE$
Detection rate [yr^{-1}]
Detection limit [mJy]

BHNS


All
$\Delta\Omega_{90\%} < 100\mathrm{deg}^2$
$\Delta\Omega_{90\%} < 10\mathrm{deg}^2$
Radio
Optical
X
$ET\Delta$
$ET2L$
$ET\Delta + 2CE$
$ET2L + 2CE$
Detection rate [yr^{-1}]
Detection limit [mJy]

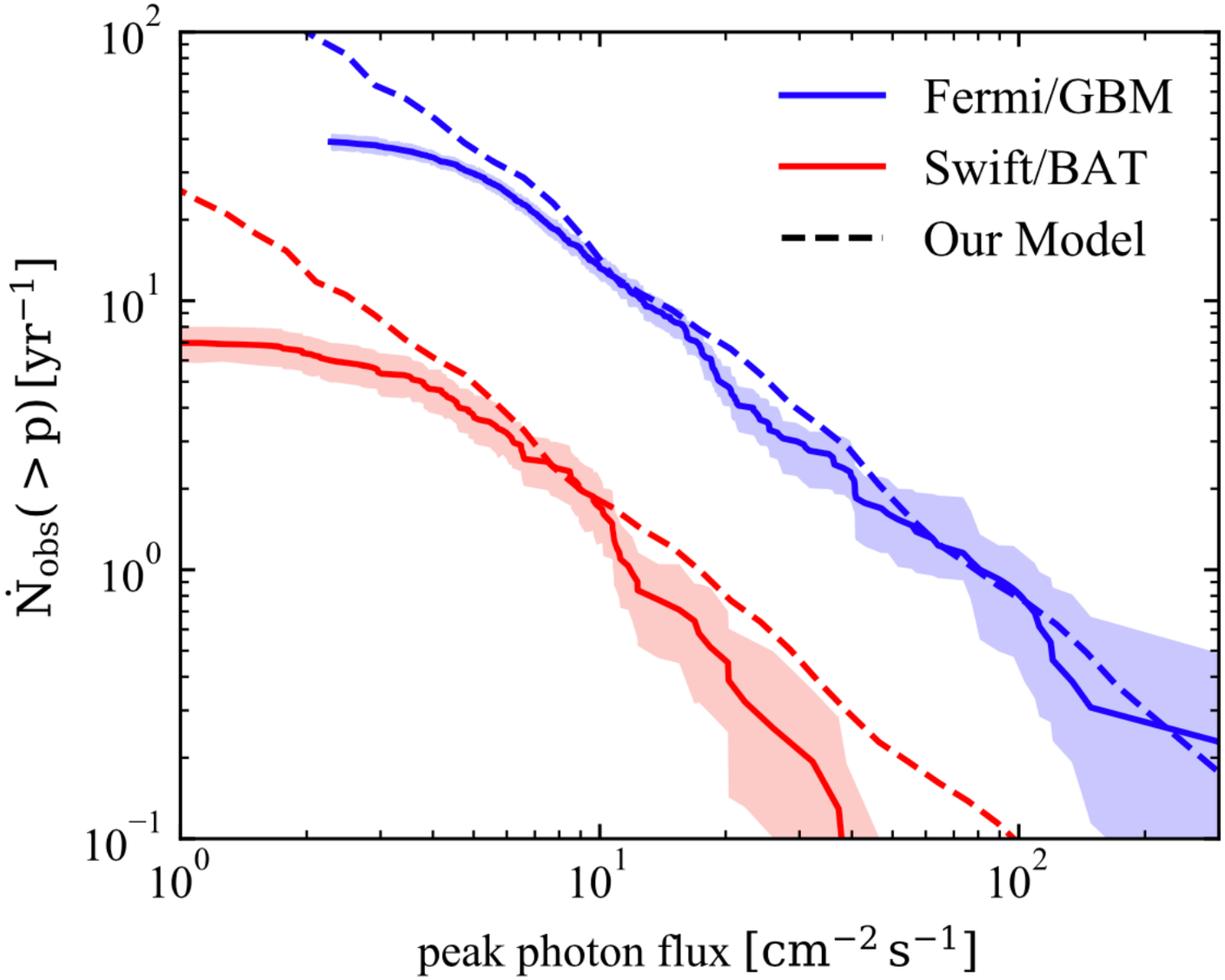
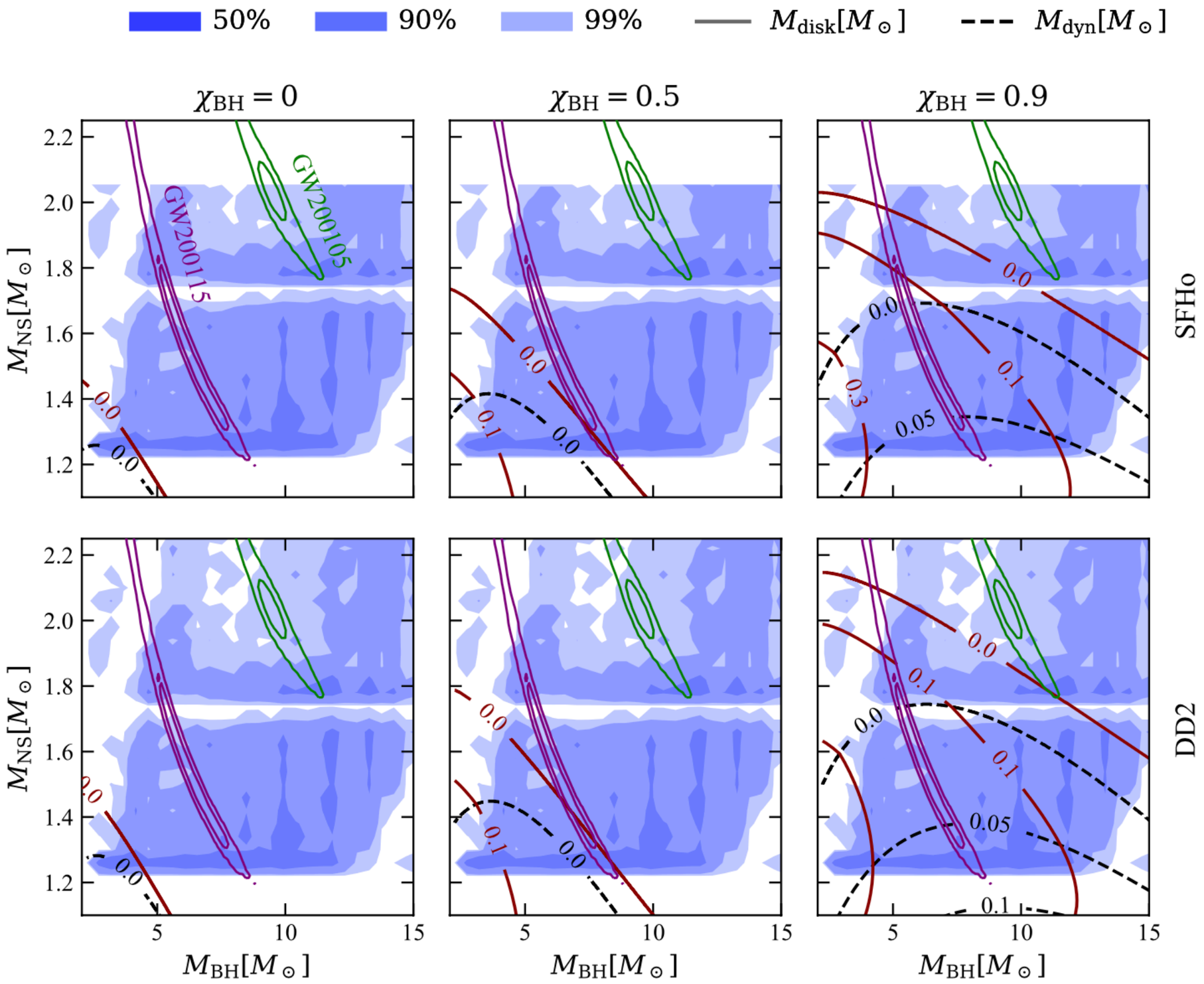
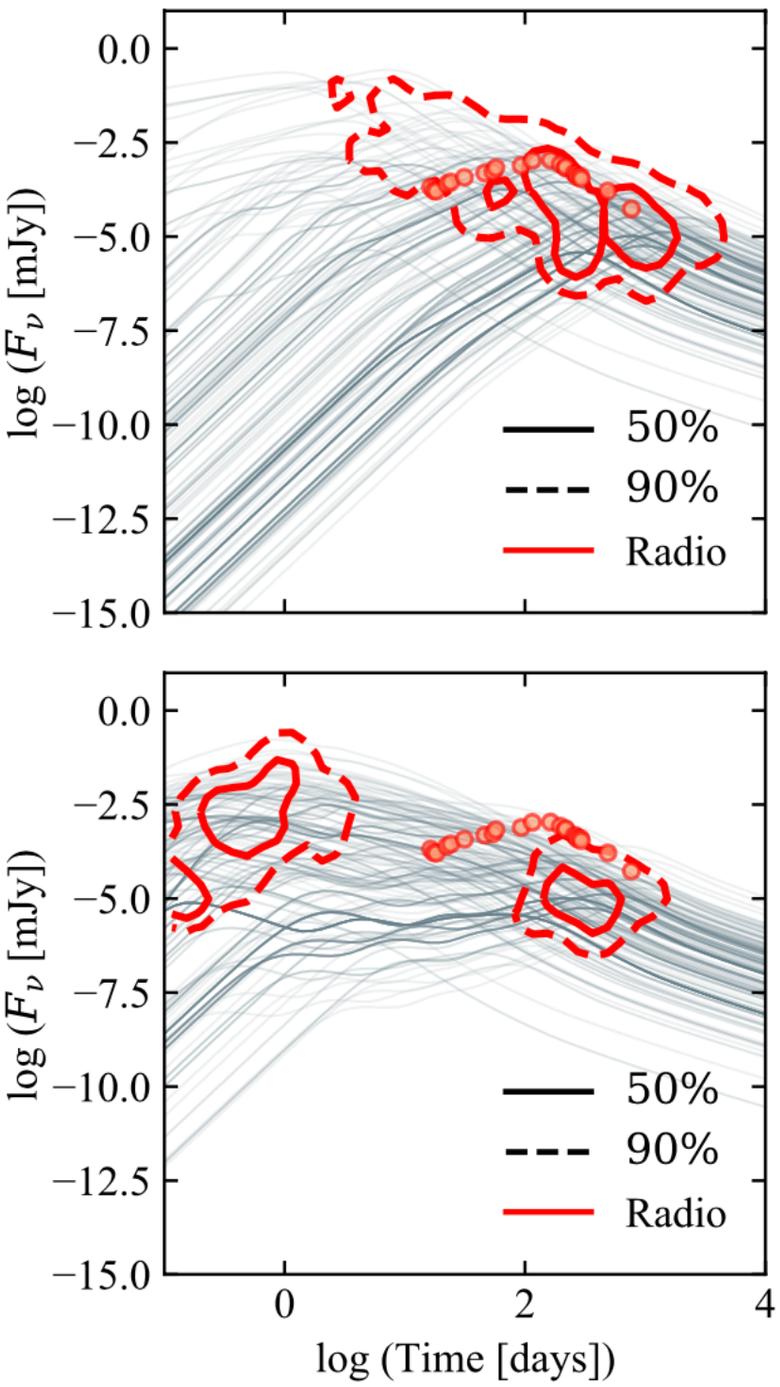
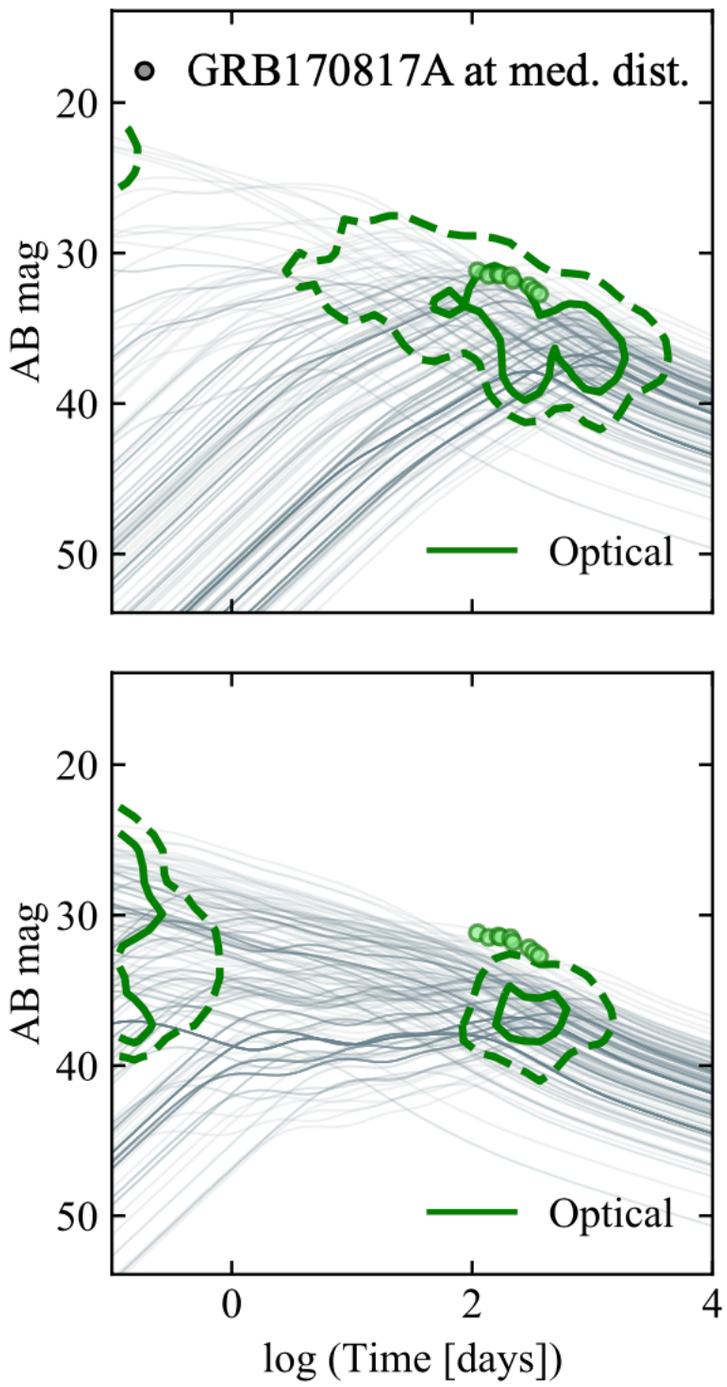
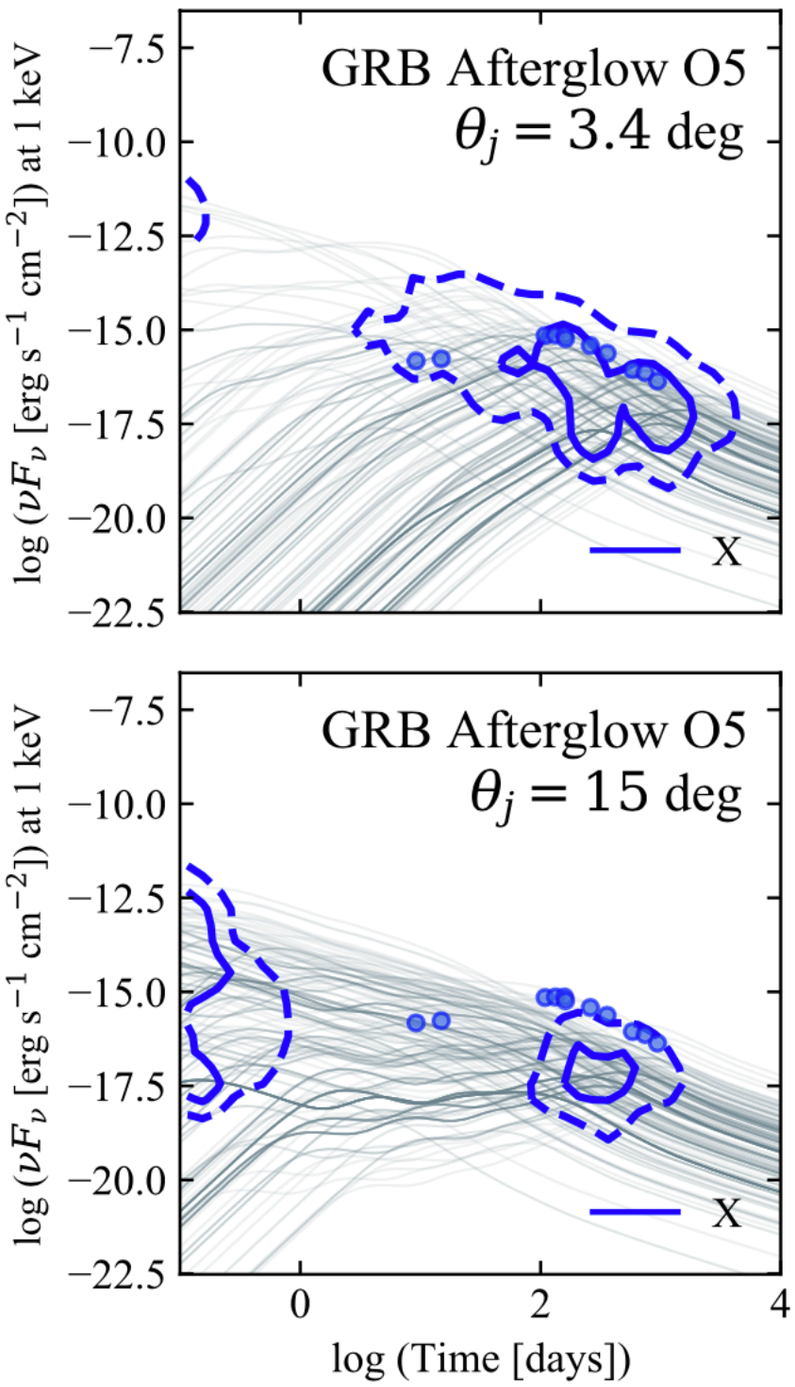


Figure 12. Fermi/GBM (Swift/BAT) observed inverse cumulative distribution of 64 ms (20 ms) binned photon fluxes in the 10–1000 (15–150) keV band (the colored band shows the 90% confidence band due to Poisson and measurement uncertainties) compared with our model (dashed line).


50%
90%
99%
$M_{\rm disk}[M_\odot]$
$M_{\rm dyn}[M_\odot]$
$\chi_{\rm BH} = 0$
$\chi_{\rm BH} = 0.5$
$\chi_{\rm BH} = 0.9$
SFHo
DD2
GW200105
GW200115
$M_{\rm NS}[M_\odot]$
$M_{\rm BH}[M_\odot]$
2.2
2.0
1.8
1.6
1.4
1.2
5
10
15
0.0
0.1
0.3
0.05


log (F_ν [mJy])
log (Time [days])
50%
90%
Radio


GRB170817A at med. dist.
AB mag
log (Time [days])
Optical


GRB Afterglow O5
$\theta_j = 3.4$ deg
$\theta_j = 15$ deg
log (νF_ν [erg s^{-1} cm^{-2}]) at 1 keV
log (Time [days])
X