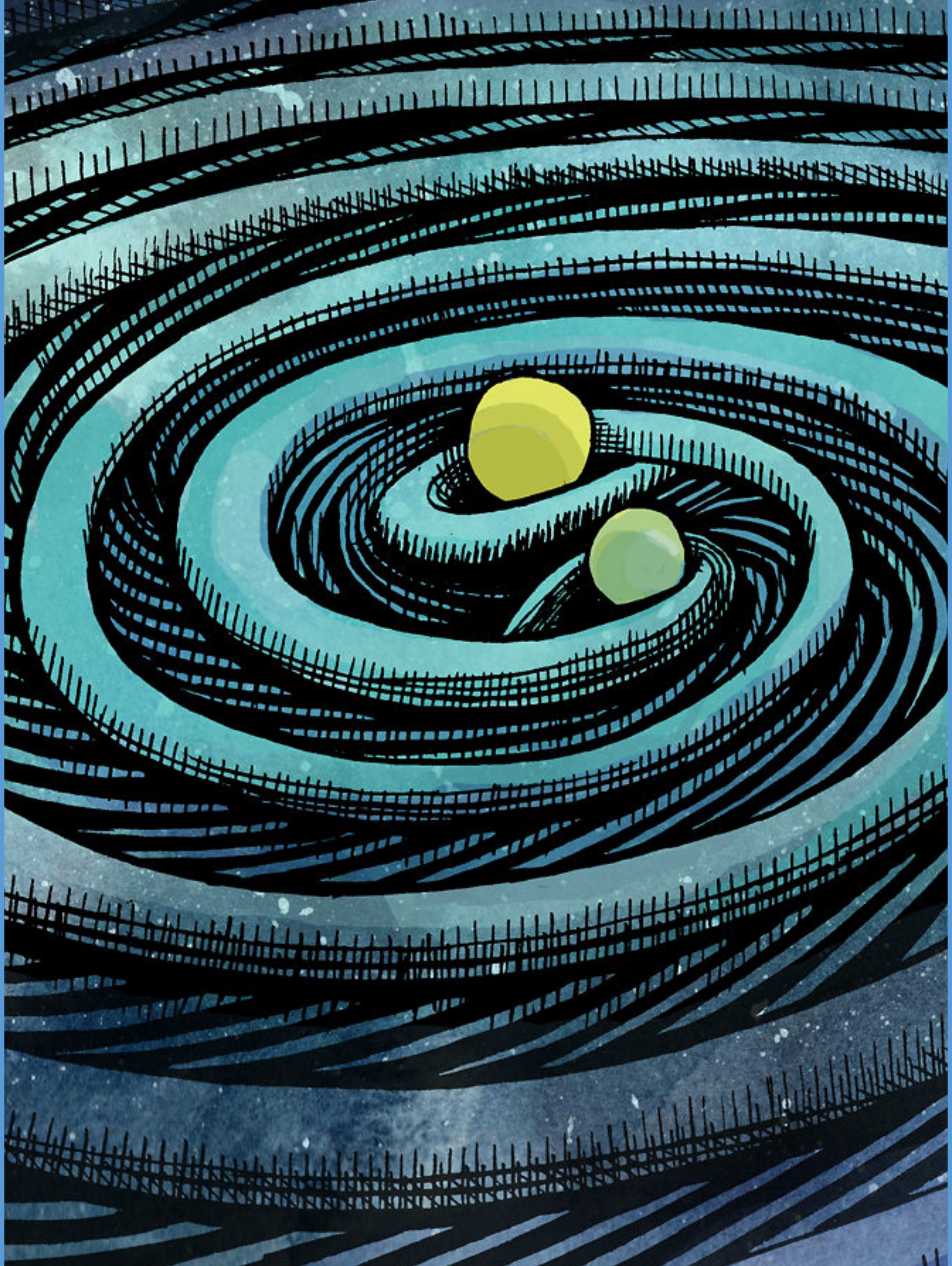

Formation of GW230529 from Isolated Binary Evolution and Multimessenger sources of NSBH Mergers

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OzGrav Postdoctoral Research Fellow

Major Collaborators: Bing Zhang (UNLV), Rui-Chong Hu (UNLV), and Ying Qin (ANU)

11th Fermi Symposium 2024
Sep. 10th 2024

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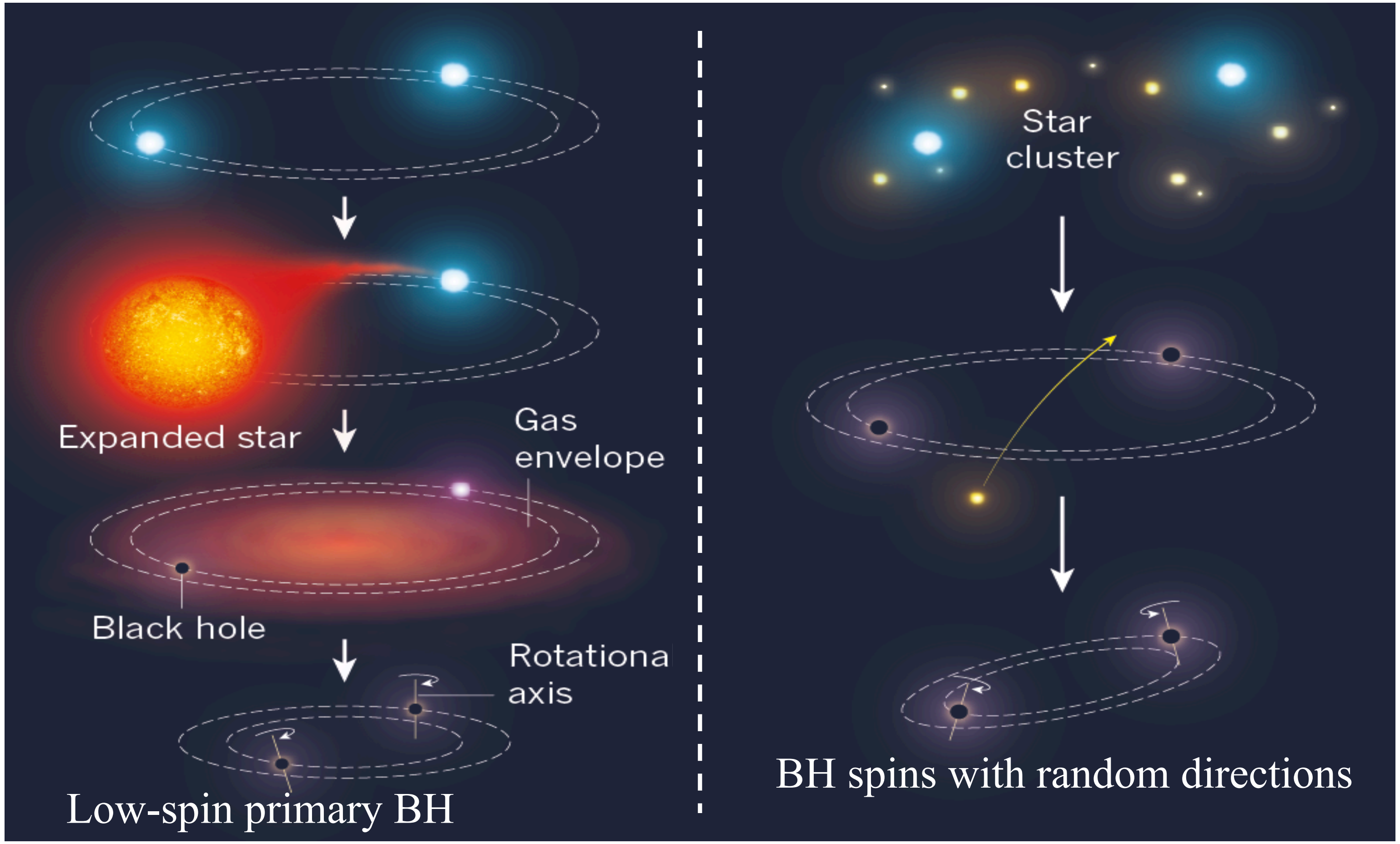
ARC Centre of Excellence for Gravitational Wave Discovery

Formation Channel of NS Mergers



Low-spin primary BH

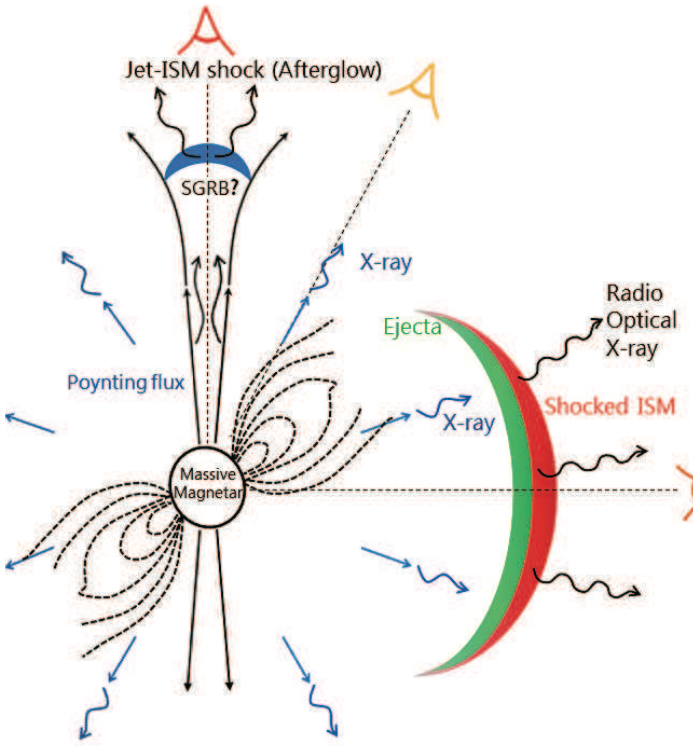
BH spins with random directions

Isolated Binary Evolution Channel

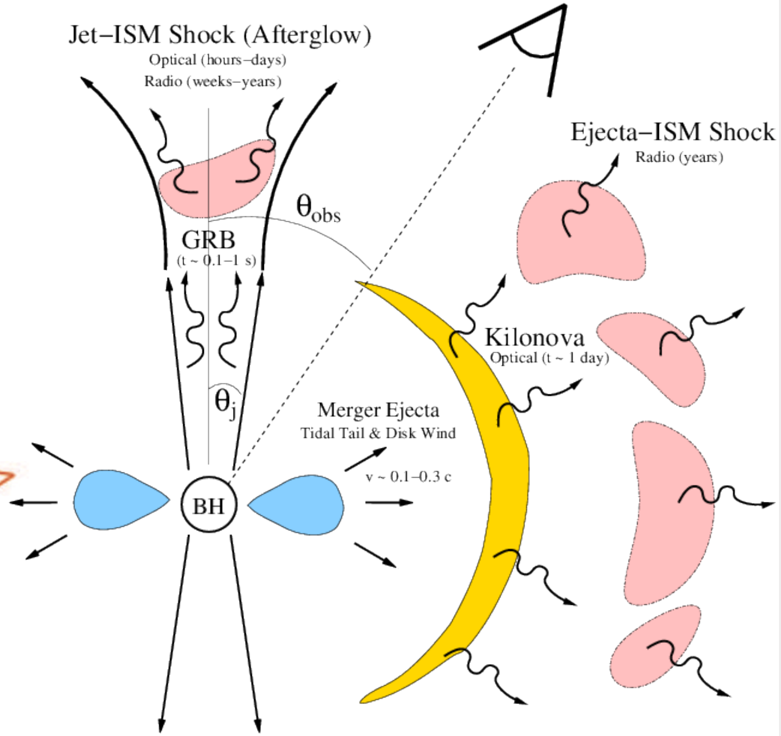
Dynamical Channel

$R_{\mathrm{BNS,NSBH}} \sim$ a few $100\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ $\gg$ $R_{\mathrm{BNS,NSBH}} < 0.1\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

Introduction



Gao et al. (2013)

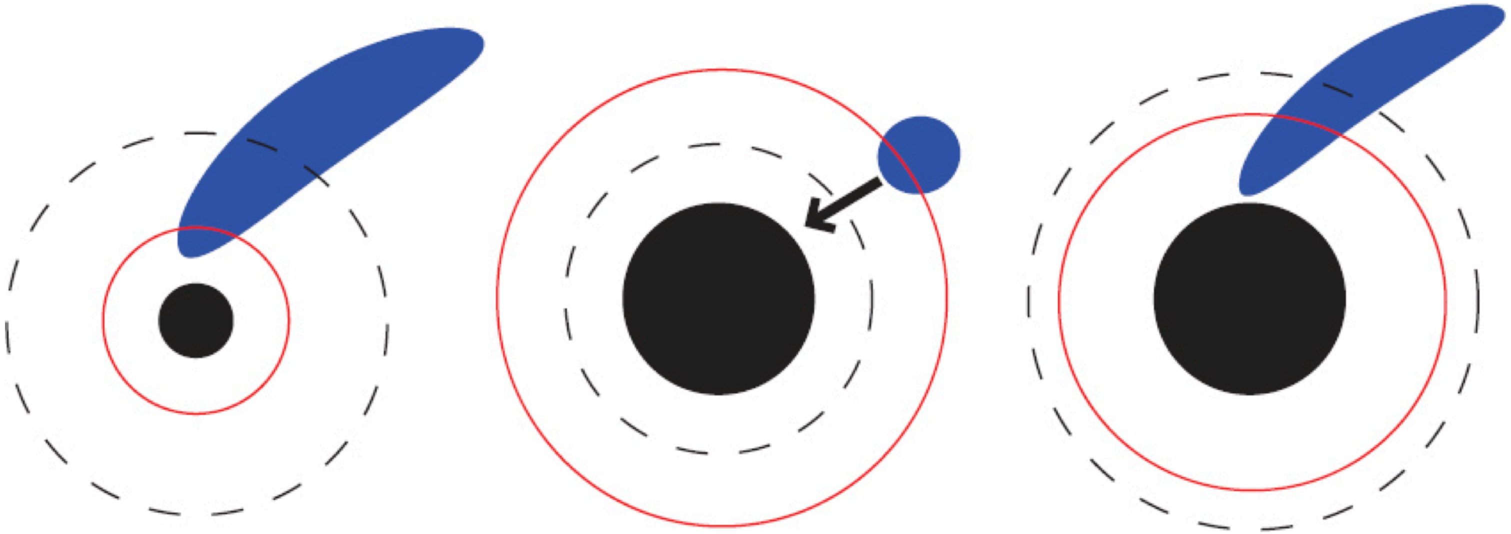


Metzger & Berger (2012)

Multimessenger emissions take place during the merger of binary neutron stars or a neutron star-black hole mergers

- Gravitational-waves in LIGO and LISA bands
- Gamma-ray Bursts (<2s)
- Jet afterglow emissions from radio to X-ray (~a few seconds to a few years)
- Ultraviolet-optical-infrared kilonova emissions (~1day to a week)

Tidal Disruption of NSBH Mergers



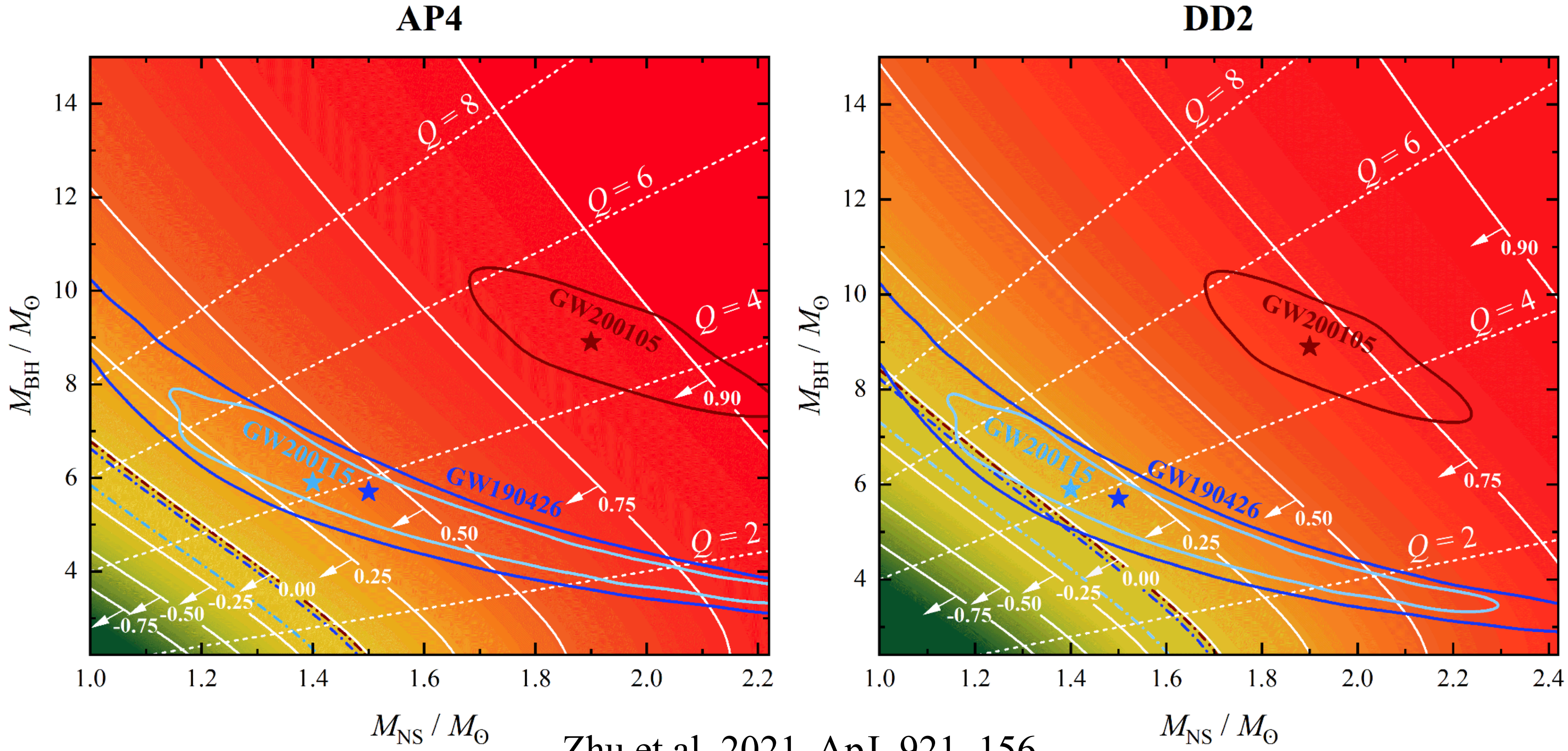
Shibata & Taniguchi (2008), Kyutoku et al. (2015), Foucart et al. (2018)

R_{ISCO} (red line): the radius of innermost stable circular orbit.
R_{tidal} (dotted black line): the radius at which the tidal disruption occurs.

- **If $R_{\mathrm{tidal}} < R_{\mathrm{ISCO}}$, the NS will plunge into BH without no mass outside the remained BH.**
- **If $R_{\mathrm{tidal}} > R_{\mathrm{ISCO}}$, the NS can be tidally disrupted by the BH while forming an accretion disk around the BH and a dynamical tail.**

Which NSBH merger is more likely to lead to tidal disruption: a less massive black hole, a highly aligned spin black hole, a less massive neutron star, or a neutron star with a stiffer equation of state

Tidal Disruption of NSBH Mergers



Zhu et al. 2021, ApJ, 921, 156

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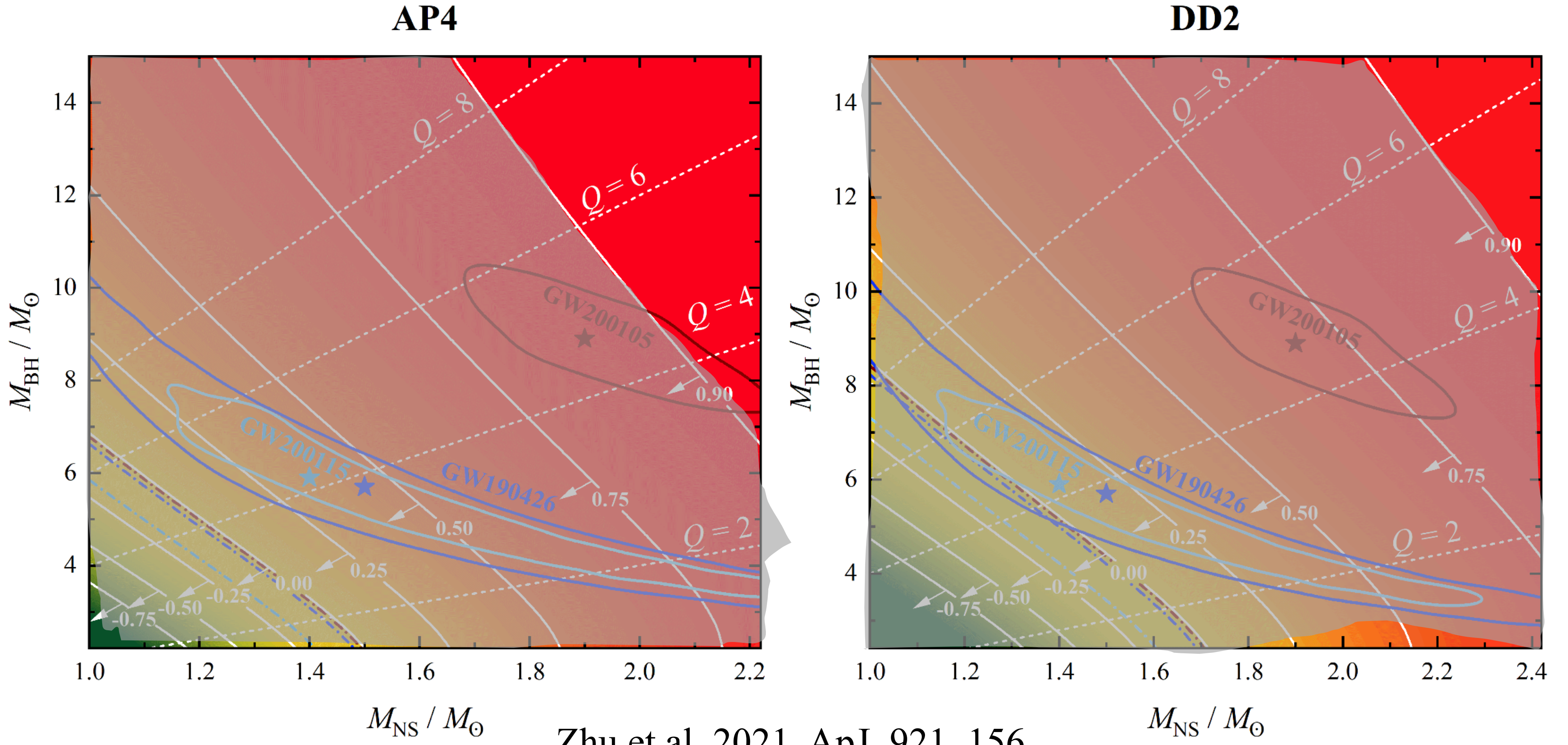
Tidal Disruption of NSBH Mergerss



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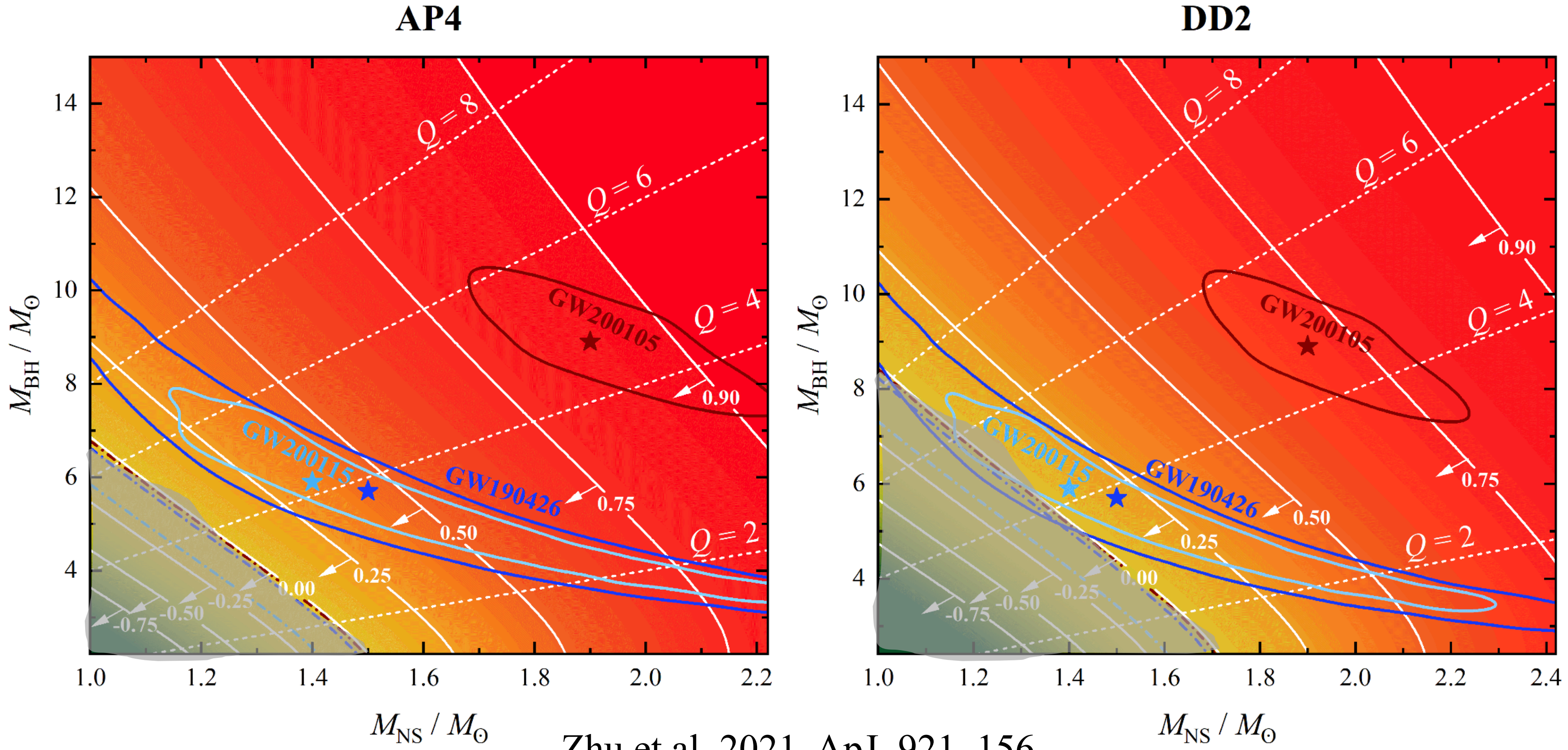
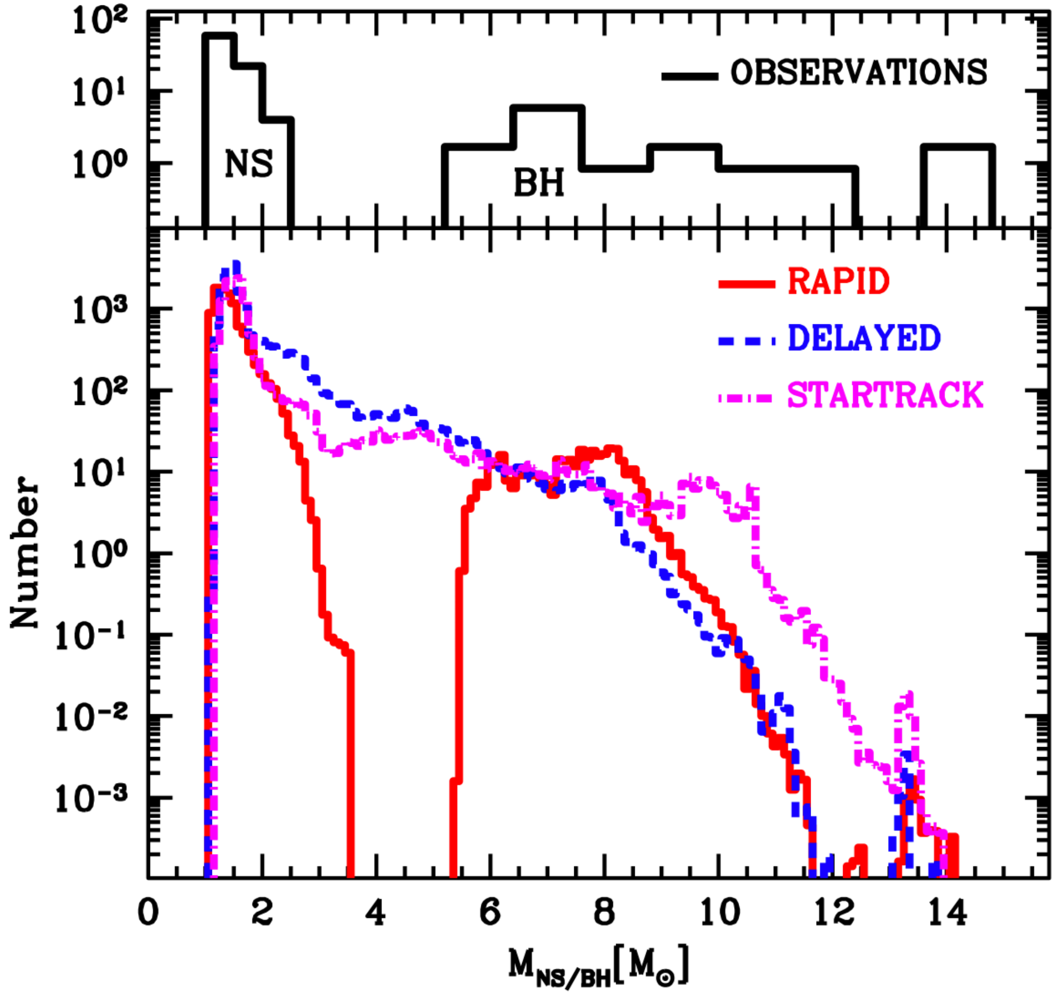
Tidal Disruption of NSBH Mergers



Zhu et al. 2021, ApJ, 921, 156

Which NSBH merger is more likely to lead to tidal disruption: a less massive black hole, a highly aligned spin black hole, a less massive neutron star, or a neutron star with a stiffer equation of state

Isolated Binary Formation Channel



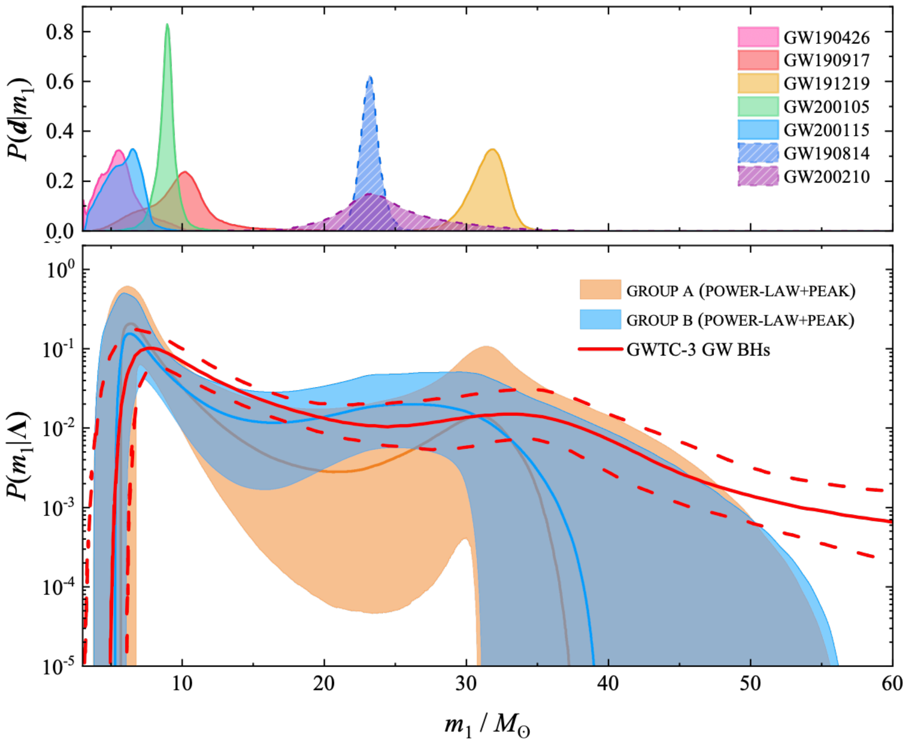
Belczynski et al. (2011)

Delayed Collapse: In lower-mass stars, a SN explosion may leave behind an NS. If the core mass later exceeds a critical threshold (~2.5 solar masses), the NS collapses into a BH. This model does not directly create the mass gap but results in smaller BHs.

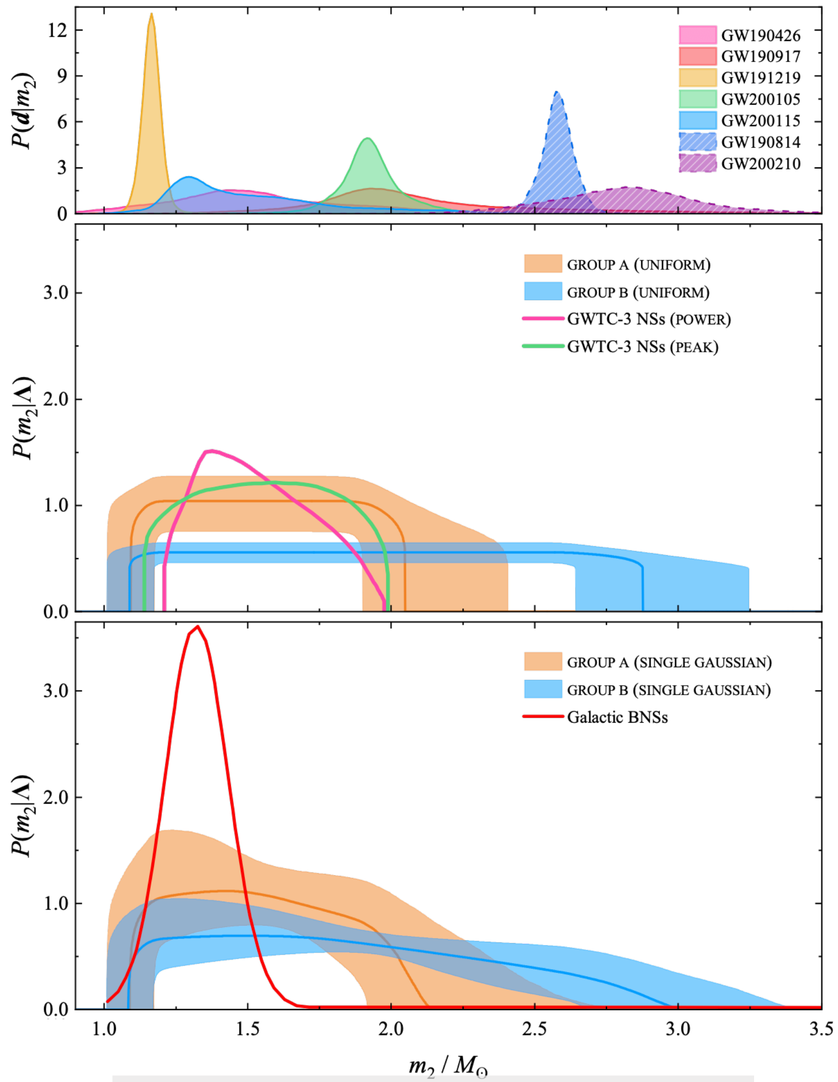
Fast Collapse: In more massive stars, the core can directly collapse into a BH, often skipping the mass gap region, with BH masses exceeding 5 solar masses.

Early observations on Galactic X-ray binaries supported Rapid model.

GW results in O3



Primary Mass Distribution

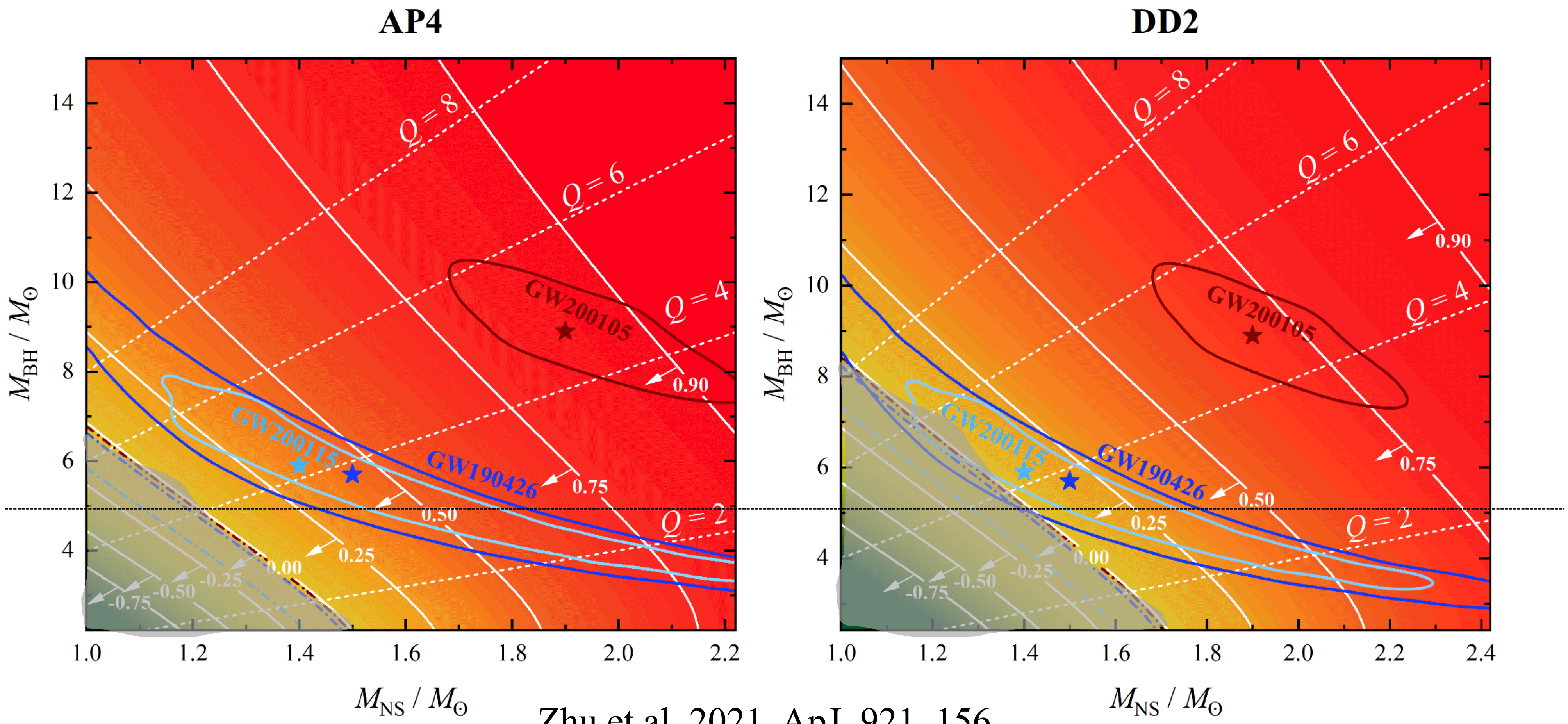


Secondary Mass Distribution

The minimum BH mass is $5.1^{+1.1}_{-1.7}$ solar mass. GWTC-3 supported the existence of mass gap in NSBH mergers

Zhu et al. 2022, ApJ, 928, 167

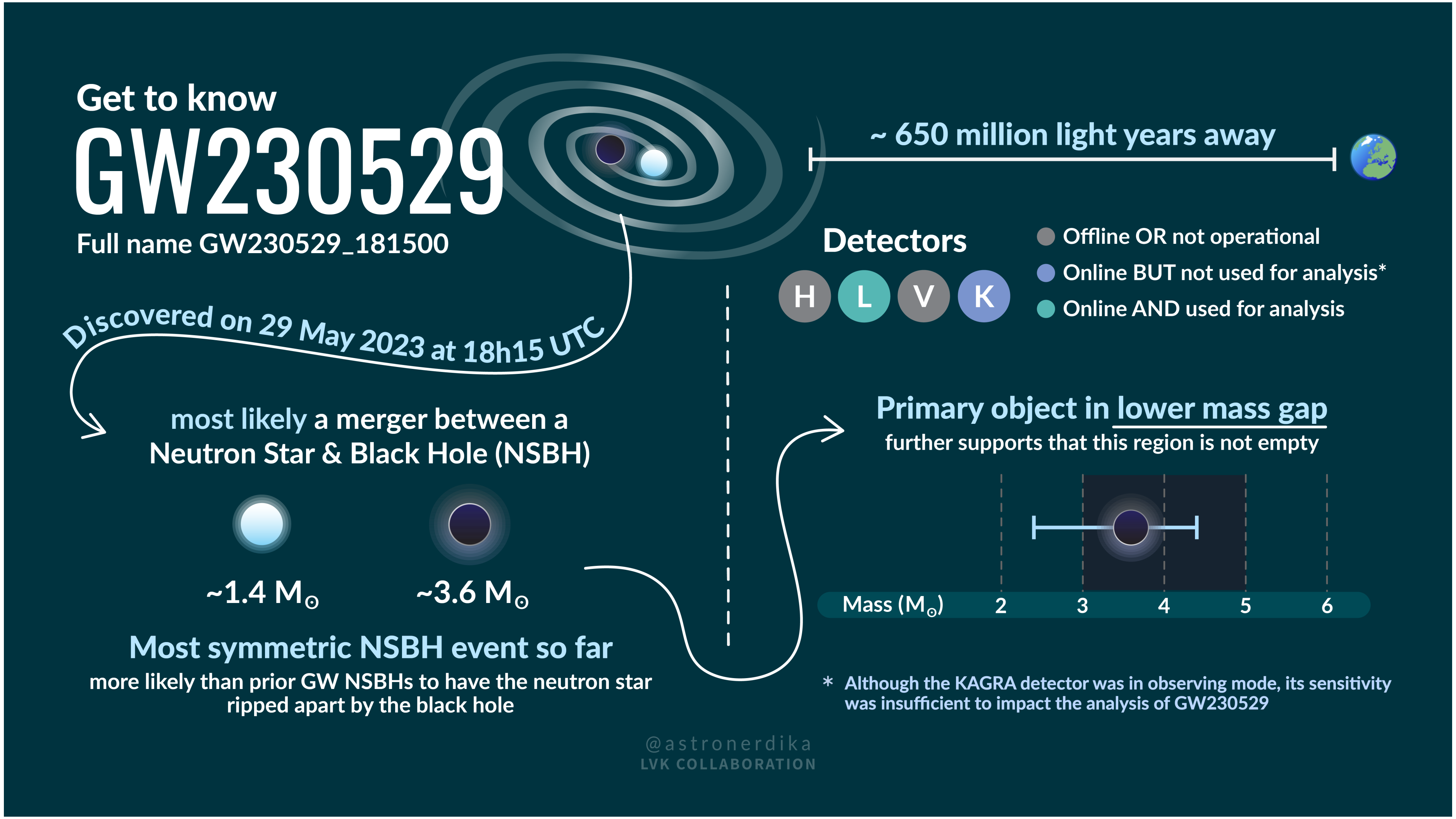
Tidal Disruption of NSBH Mergers



Zhu et al. 2021, ApJ, 921, 156

Which NSBH merger is more likely to lead to tidal disruption: a less massive black hole, a highly aligned spin black hole, a less massive neutron star, or a neutron star with a stiffer equation of state

GW230529



Get to know

GW230529

Full name GW230529_181500

Discovered on 29 May 2023 at 18h15 UTC

most likely a merger between a Neutron Star & Black Hole (NSBH)

~1.4 $M_\odot$ ~3.6 $M_\odot$

Most symmetric NSBH event so far

more likely than prior GW NSBHs to have the neutron star ripped apart by the black hole

~ 650 million light years away

Detectors

H L V K

- ● Offline OR not operational
- ● Online BUT not used for analysis*
- ● Online AND used for analysis

Primary object in lower mass gap

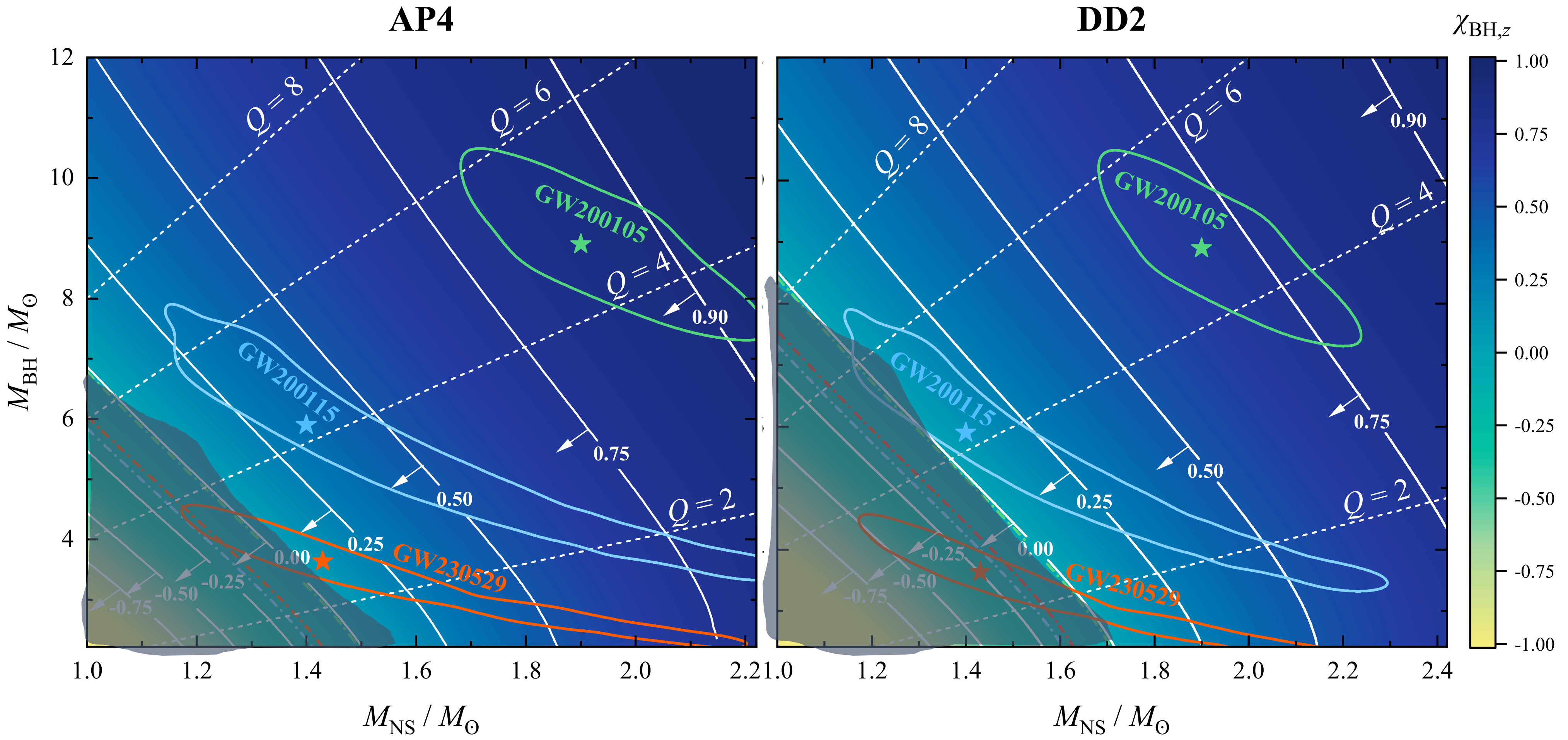
further supports that this region is not empty

* Although the KAGRA detector was in observing mode, its sensitivity was insufficient to impact the analysis of GW230529

@astronerdika
LVK COLLABORATION

Credit: Shanika Galaudage

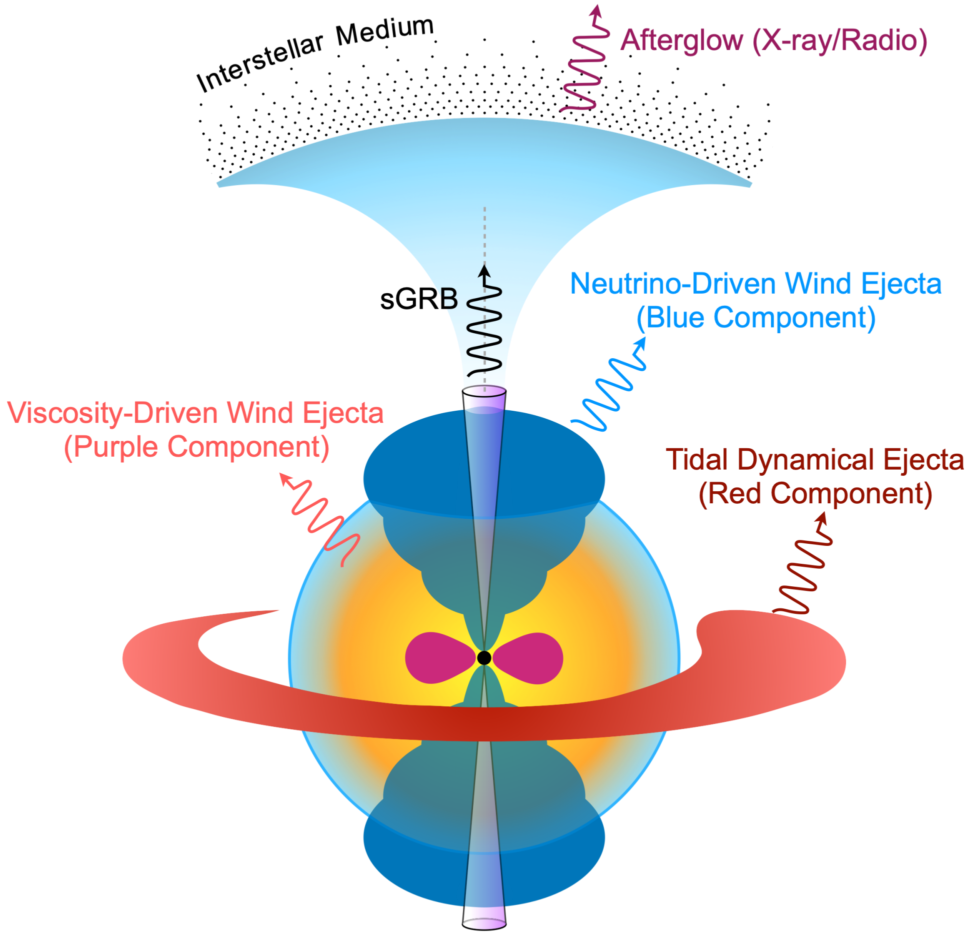
GW230529



Zhu et al. 2024, arXiv:2404.10596(accepted by ApJ)

GW230529 is highly possible to occur tidal disruption and generate bright EM signals.

NSBH kilonovae

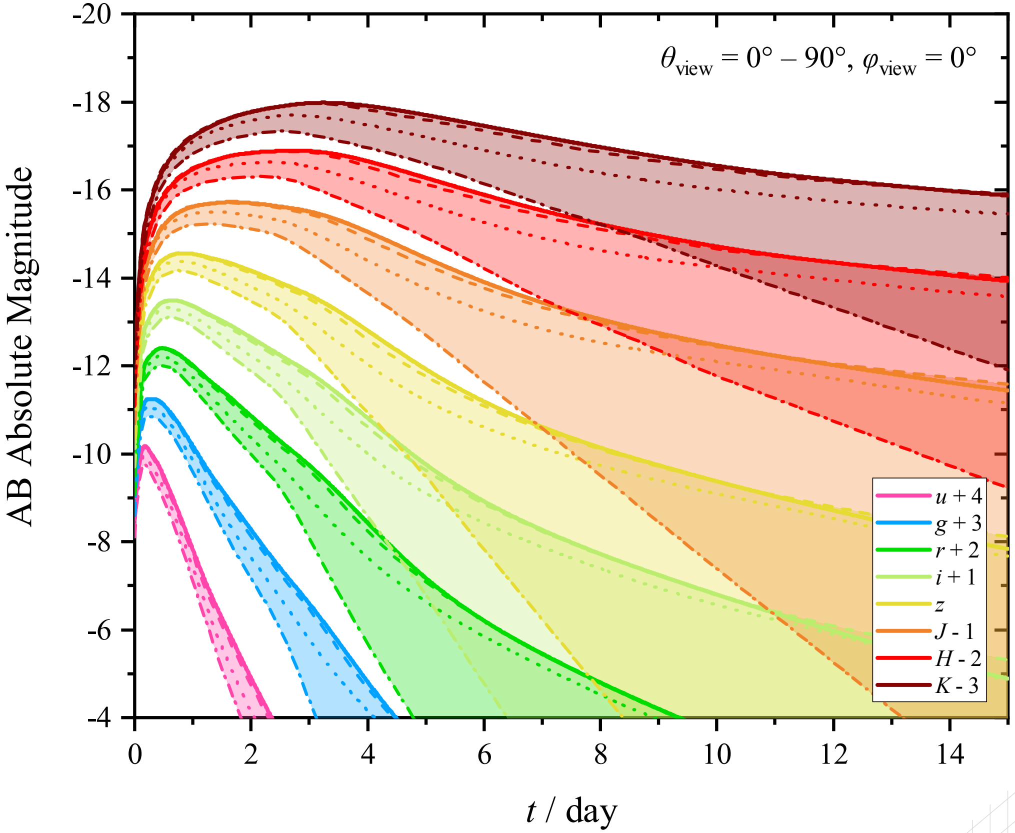


Zhu et al. 2020, ApJ, 897, 20

Ejecta Components:

- **Neutrino-driven Wind Ejecta**
  $\kappa \sim 1\ \mathrm{cm^2\ g^{-1}}$
- **Viscosity-driven Wind Ejecta**
  $\kappa \sim 3 – 5\ \mathrm{cm^2\ g^{-1}}$
- **Tidal Dynamical Ejecta**
  $\kappa \sim 10 – 100\ \mathrm{cm^2\ g^{-1}}$

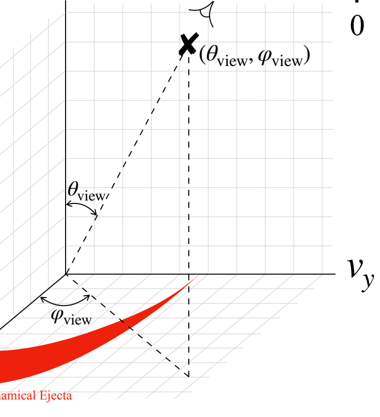
NSBH kilonovae

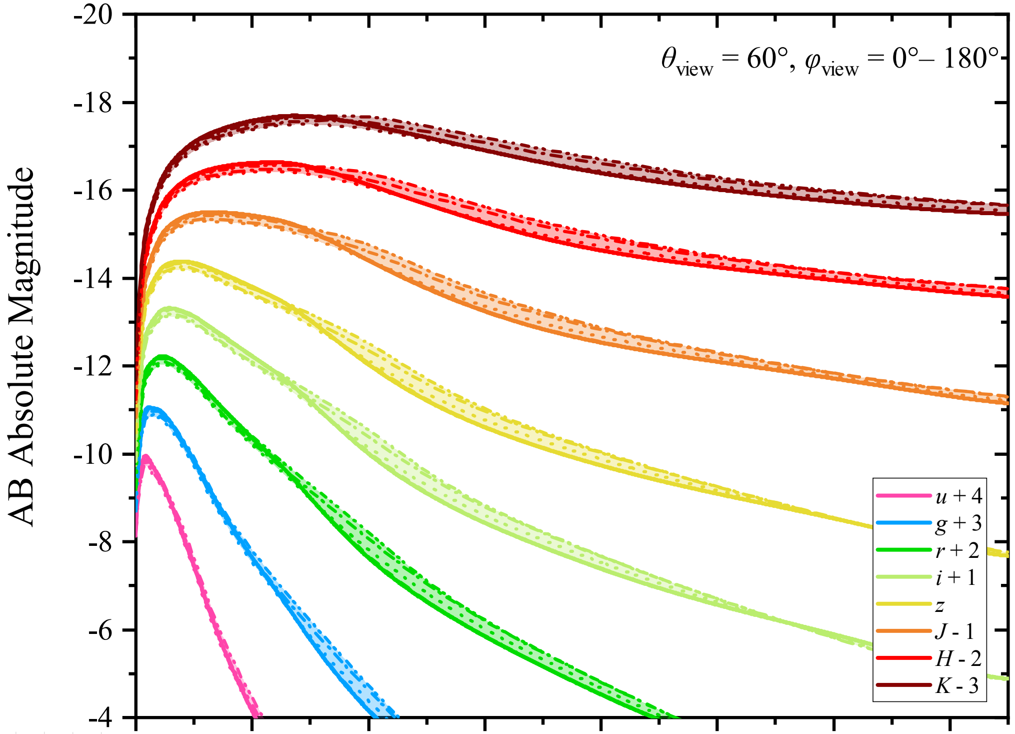


$\theta_{\rm view}$ – dependent light curve

$\varphi_{\rm view} = 0°$

$\theta_{\rm view} = 0° – 90°$





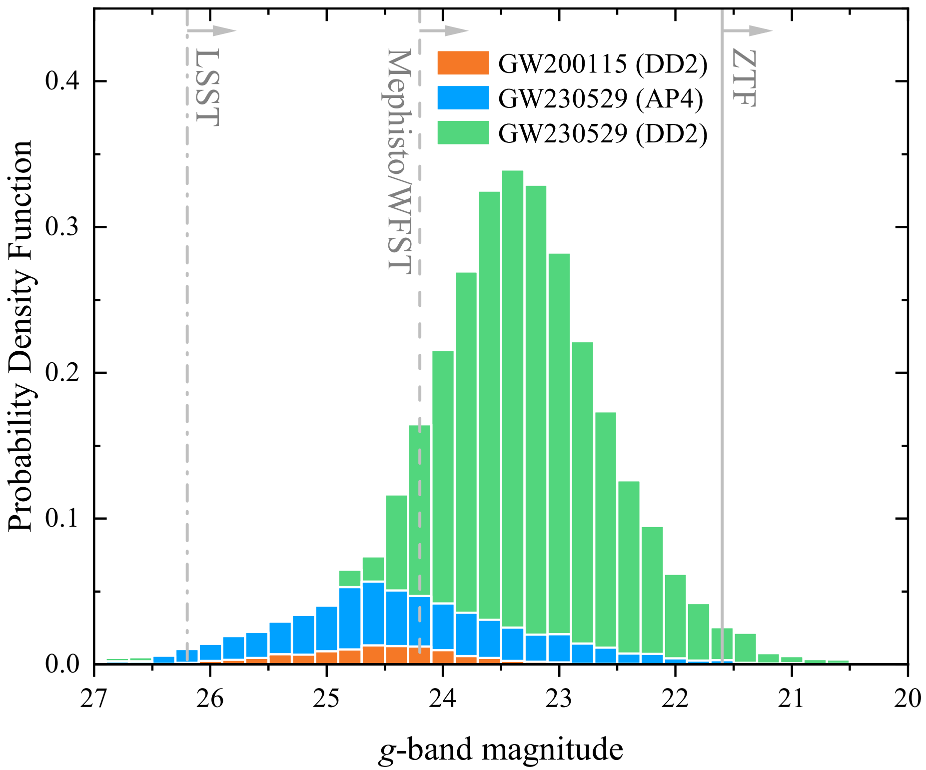
$\varphi_{\rm view}$ – dependent light curve

$\varphi_{\rm view} = 0° – 180°$

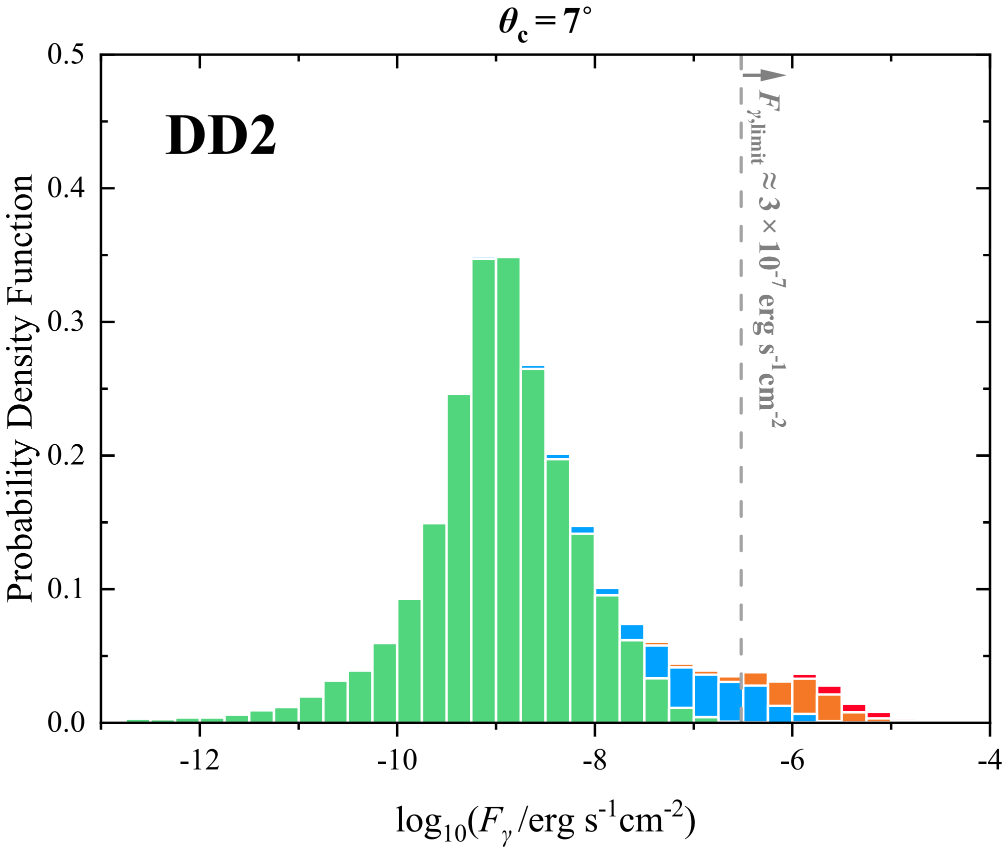
$\theta_{\rm view} = 30°$

Zhu et al. 2020, ApJ, 897, 20

Detectability of EM signals from GW230529



Kilonova brightness distribution



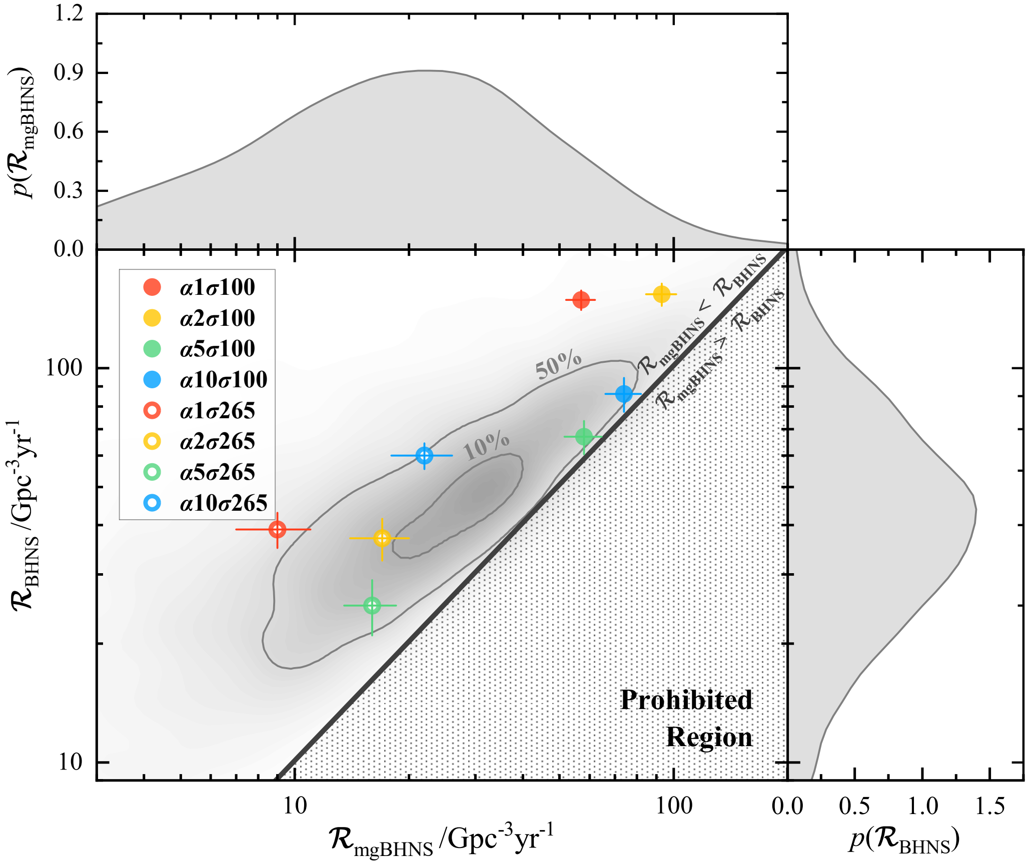
GRB brightness distribution

Zhu et al. 2024, arXiv:2404.10596(accepted by ApJ)

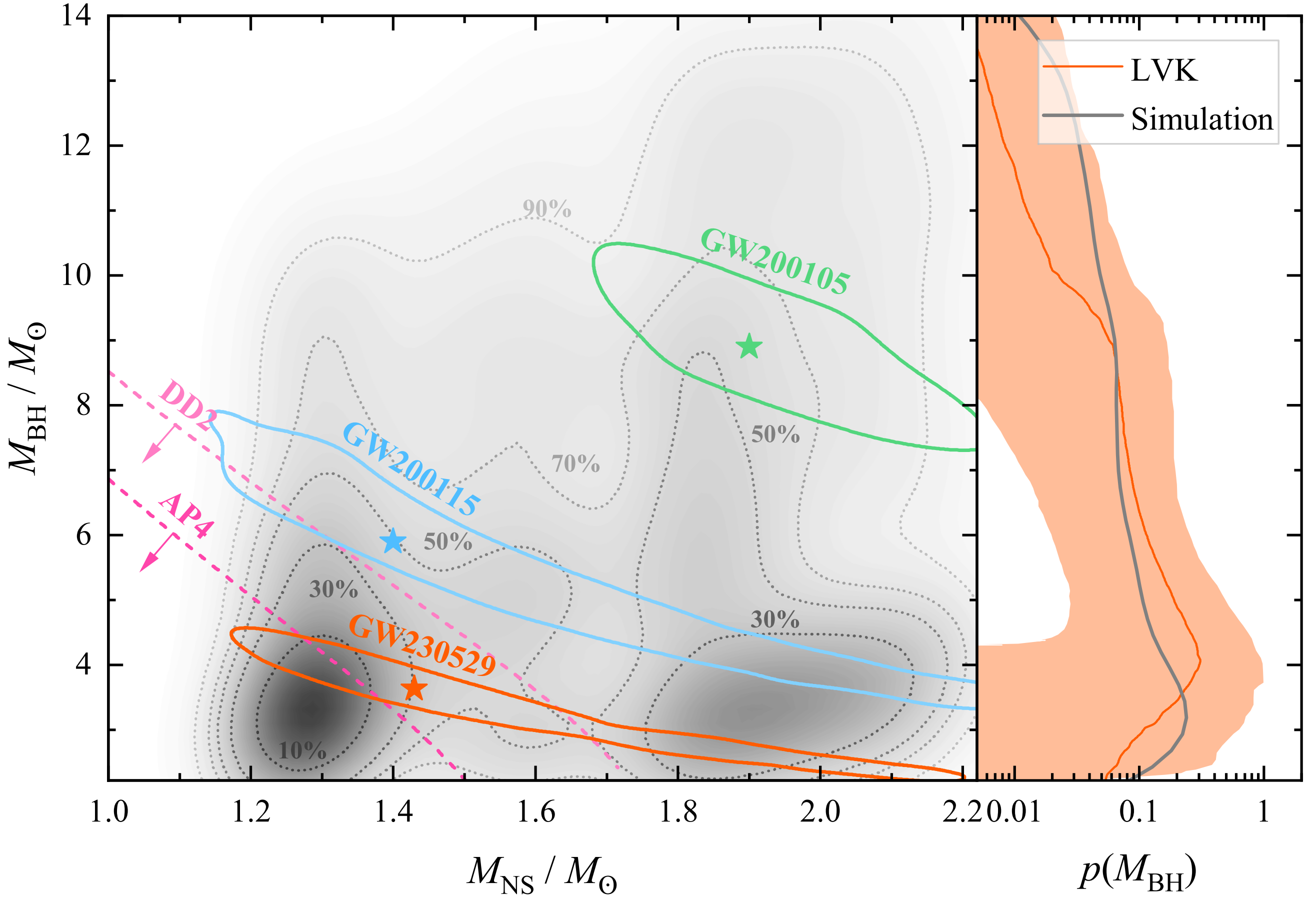
Kilonova associated with GW230529 is too dim to be detected by present survey projects.

Associated GRB jet could be off-axis based on the GW observation.

Formation of GW230529 from Isolated Binary Channel



Population event rates

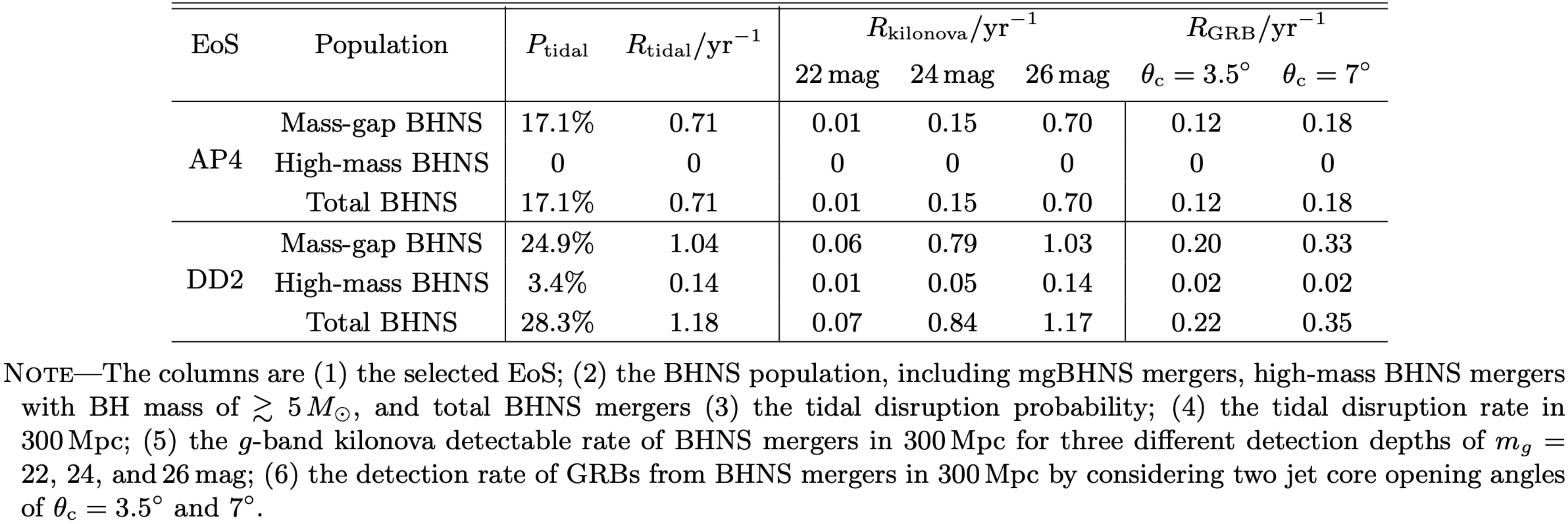


Mass Distribution

Zhu et al. 2024, arXiv:2404.10596(accepted by ApJ)

GW230529 can be formed through classic isolated binary evolution channel with the delayed SN mechanism.

Mass-gap BHNS Mergers are Multimessenger sources



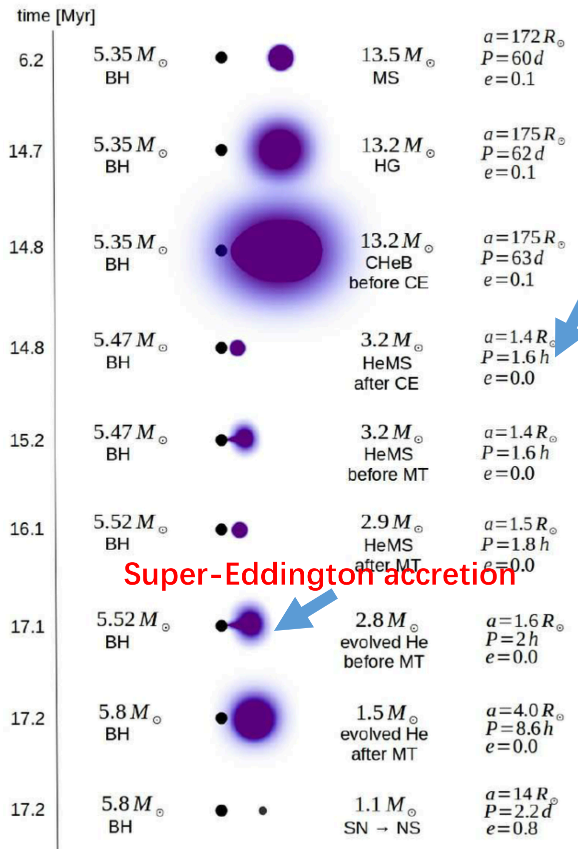
EoS	Population	$P_{\rm tidal}$	$R_{\rm tidal}/{\rm yr}^{-1}$	$R_{\rm kilonova}/{\rm yr}^{-1}$			$R_{\rm GRB}/{\rm yr}^{-1}$	
				22 mag	24 mag	26 mag	$\theta_{\rm c}=3.5^\circ$	$\theta_{\rm c}=7^\circ$
AP4	Mass-gap BHNS	17.1%	0.71	0.01	0.15	0.70	0.12	0.18
	High-mass BHNS	0	0	0	0	0	0	0
	Total BHNS	17.1%	0.71	0.01	0.15	0.70	0.12	0.18
DD2	Mass-gap BHNS	24.9%	1.04	0.06	0.79	1.03	0.20	0.33
	High-mass BHNS	3.4%	0.14	0.01	0.05	0.14	0.02	0.02
	Total BHNS	28.3%	1.18	0.07	0.84	1.17	0.22	0.35

NOTE—The columns are (1) the selected EoS; (2) the BHNS population, including mgBHNS mergers, high-mass BHNS mergers with BH mass of $\gtrsim 5\,M_\odot$, and total BHNS mergers (3) the tidal disruption probability; (4) the tidal disruption rate in 300 Mpc; (5) the *g*-band kilonova detectable rate of BHNS mergers in 300 Mpc for three different detection depths of $m_g = 22$, 24, and 26 mag; (6) the detection rate of GRBs from BHNS mergers in 300 Mpc by considering two jet core opening angles of $\theta_{\rm c} = 3.5^\circ$ and 7°.

Zhu et al. 2024, arXiv:2404.10596(accepted by ApJ)

Future observation rate for <300Mpc BHNS mergers is ~0.2-0.3 yr^{-1} by Fermi.

Formation channels of High-spin BHNS Mergers



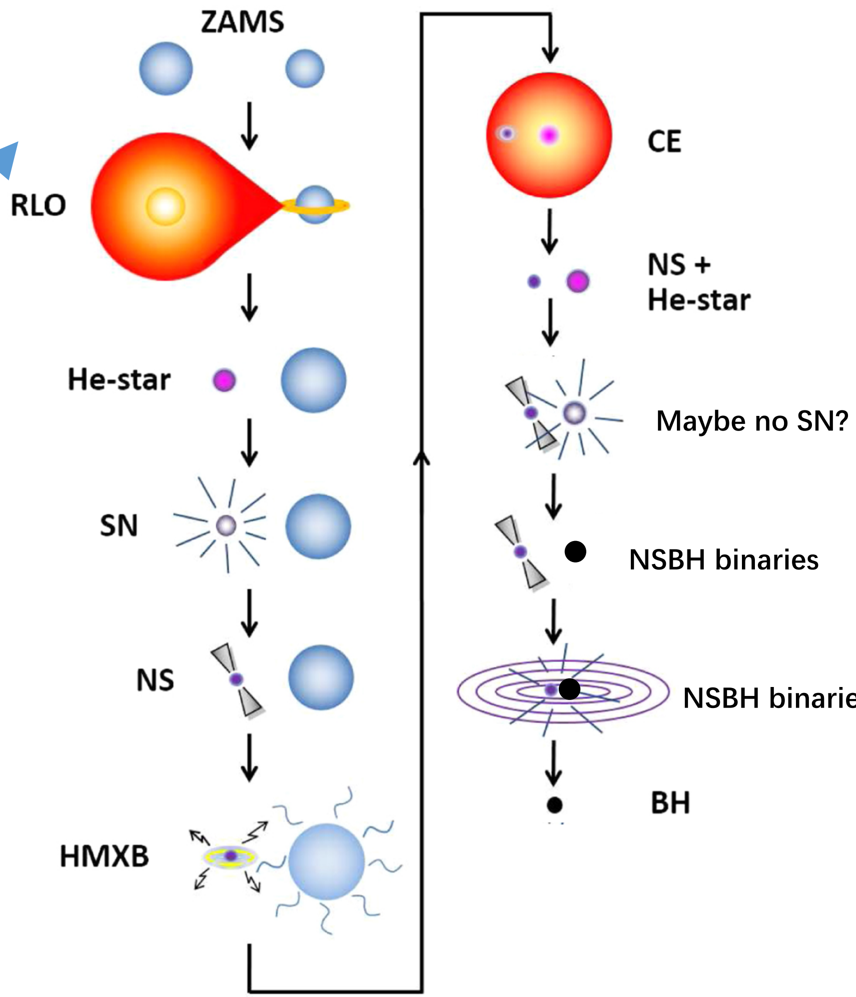
Standard Isolated Formation Channel:

- BHs born first
- Low-spin primary BH
- *Q*~5

NS-first-born Formation Channel (~1%-10%):

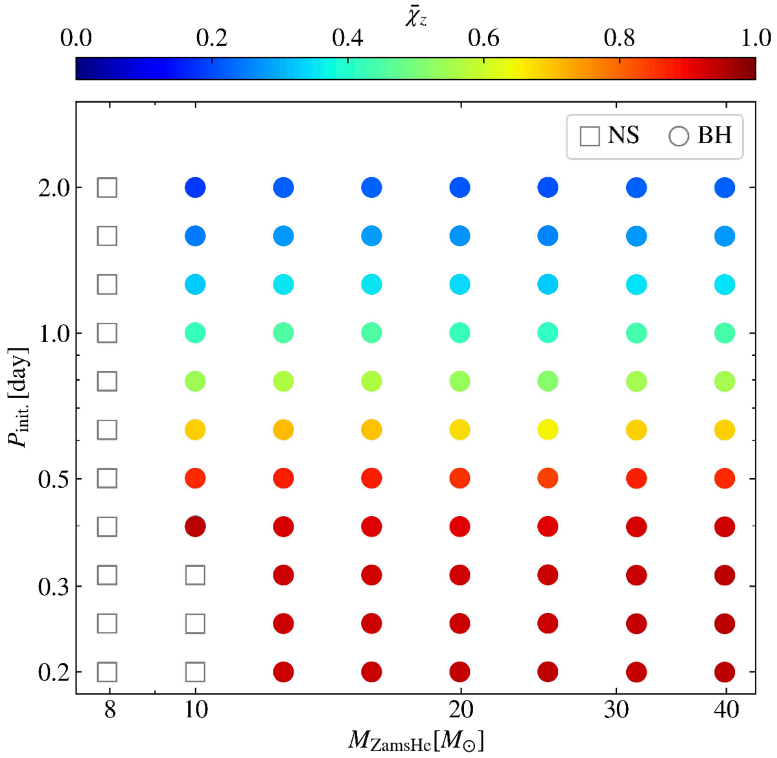
- NSs born first
- High-spin secondary BH

Hu, **Zhu**, et al. 2022, ApJ, 928, 163. Wang, Hu, Qin, **Zhu** et al. 2024, ApJ, 965,177

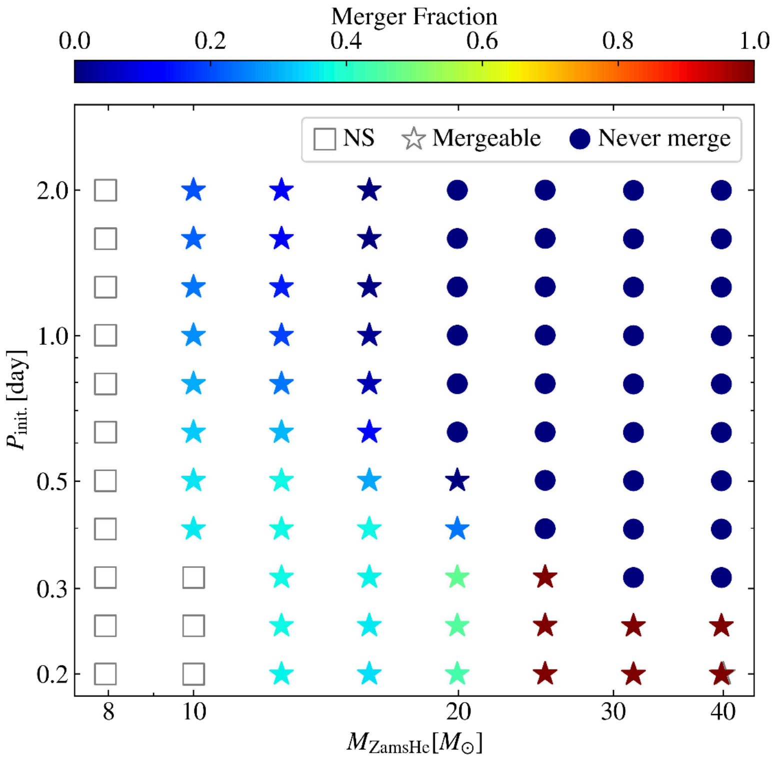


Formation channels of High-spin BHNS Mergers

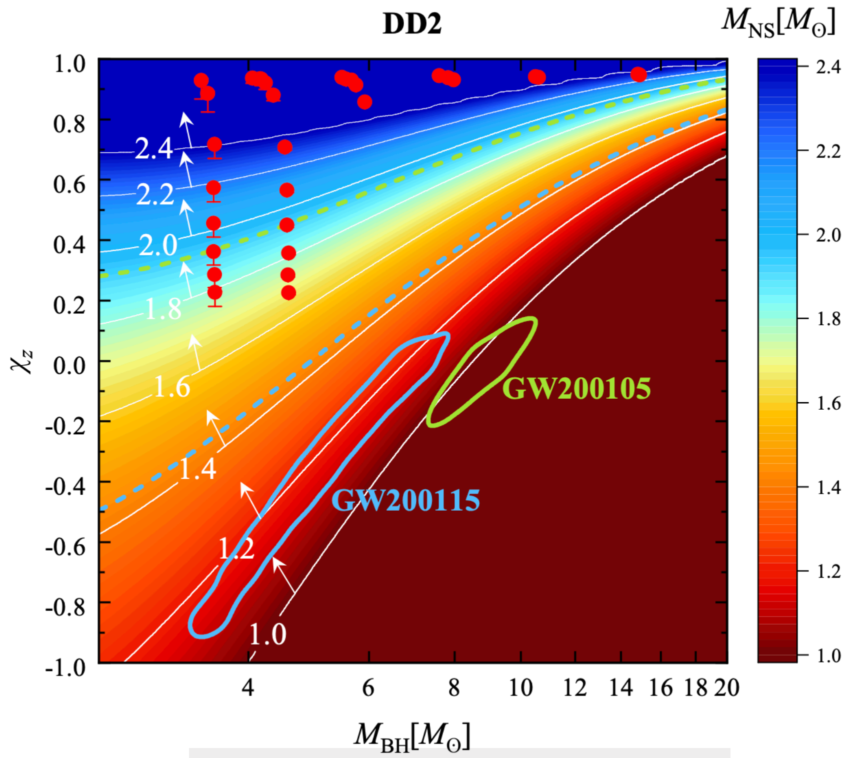
Hu, **Zhu**, Qin et al. 2022



BH Projected Aligned-spins



Merger Fraction



Tidal Disruption Region

- **<10% NSBH binaries would be formed via NS-first-born formation channel (Román-Garza et al. 2021; Chattopadhyay et al. 2021) and have high-spin BHs.**
- **NS-first-born NSBH mergers would easily make tidal disruption as multimessenger sources.**

Summary

1. **GW230529 can form through classic isolated binary evolution channel by adopting the delayed SN mechanism.**
2. **Kilonova associated with GW230529 is too dim to be detected by present survey projects. Associated GRB jet could be off-axis based on the GW observation.**
3. **BHNS mergers can still be multimessenger sources. But most disrupted BHNS mergers should contain a mass-gap BH.**

Zhu et al. 2020, ApJ, 897, 20; **Zhu** et al. 2021, ApJ, 917, 24; **Zhu** et al. 2021, ApJ, 921, 156; **Zhu** et al. 2022, ApJ, 928, 167; **Zhu** et al. 2022, ApJL, 936, L10; **Zhu** et al. 2024, arXiv:2404.10596(accepted by ApJ); Hu, **Zhu** et al. 2022, ApJ, 928, 163; Wang, Hu, Qin, **Zhu** et al. 2024, 965, 177