第二届地下和空间粒子物理与宇宙物理前沿问题研讨会

7–12 May, 2023

理解LIGO/Virgo引力波源的起源

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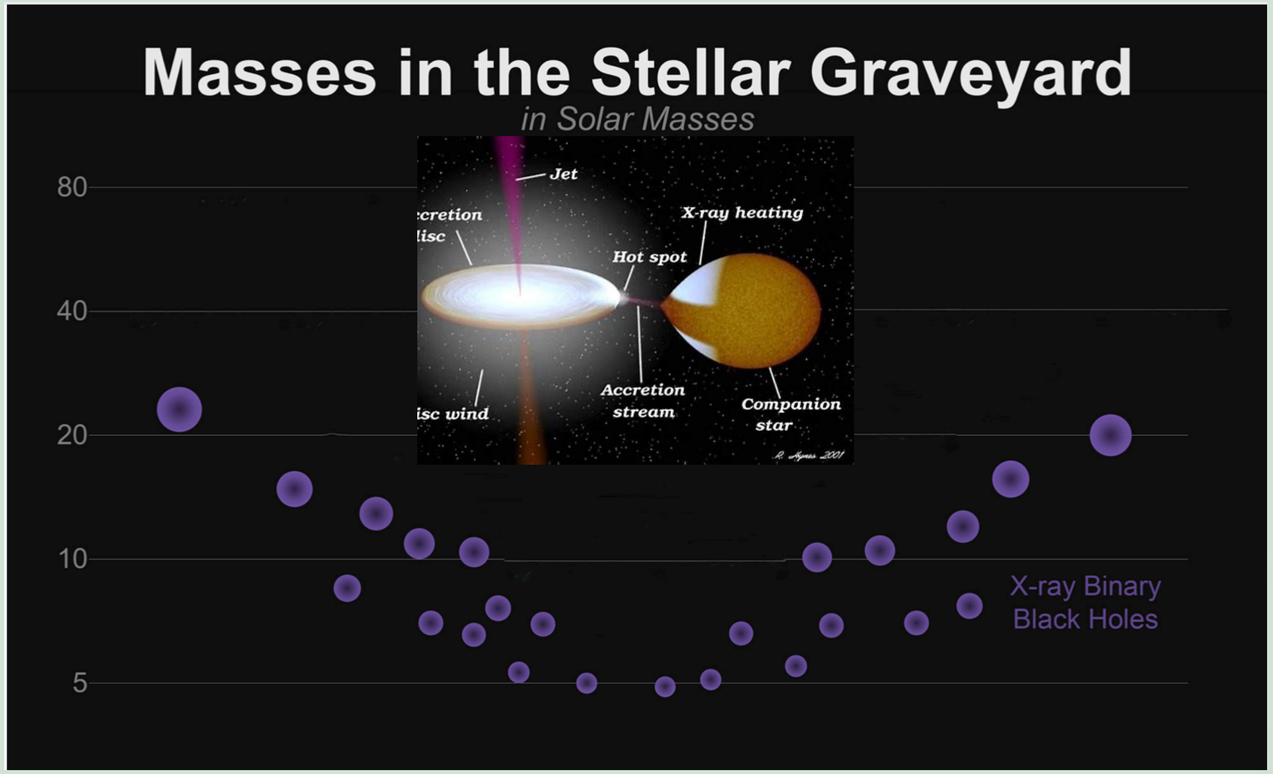
Massive black holes detected by LIGO/Virgo



- Stellar-mass black holes we knew by 2015
- Around 5-20 Msun
- Not observational bias but result from stellar evolution
- (McClintock et al. 2014; Corral-Santana et al. 2016; Ozel et al. 2010; Farr et al. 2011)

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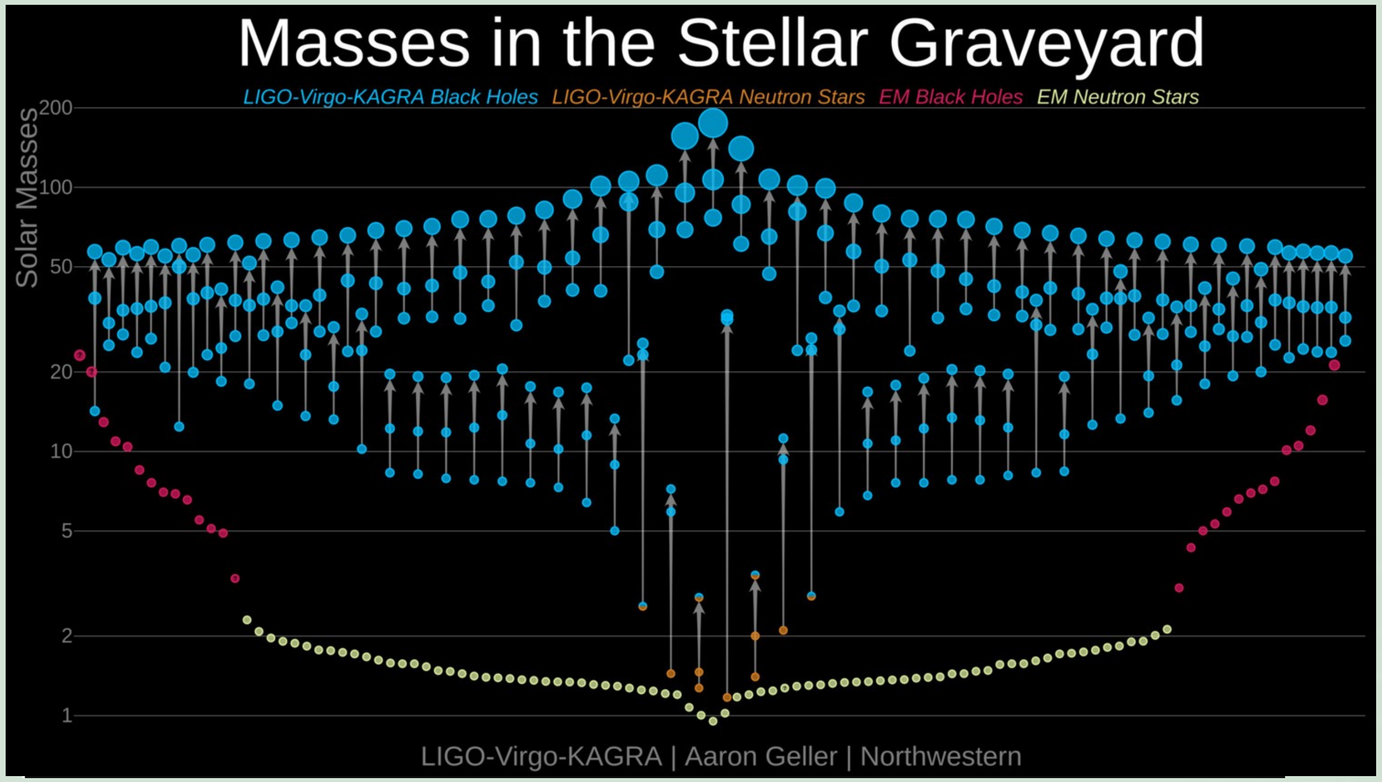

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GW BHs 3-10 times more massive than X-ray BHs

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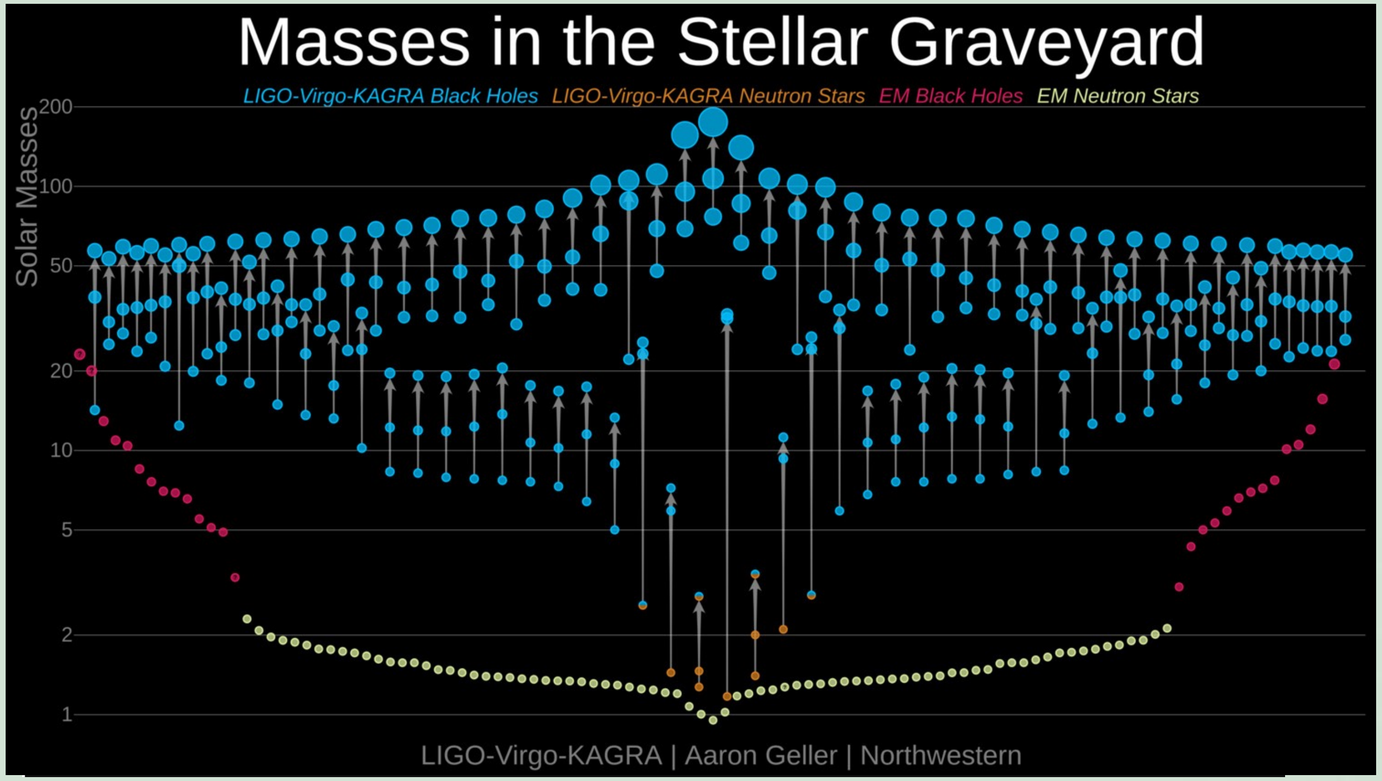
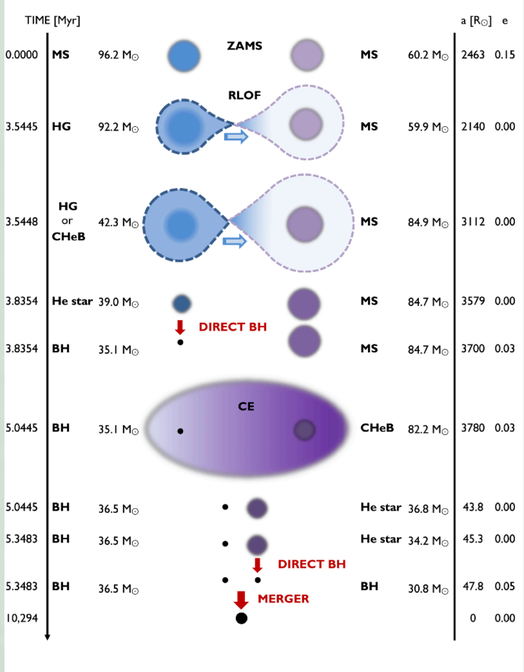


Binary stars (e.g. Belczynski+16)



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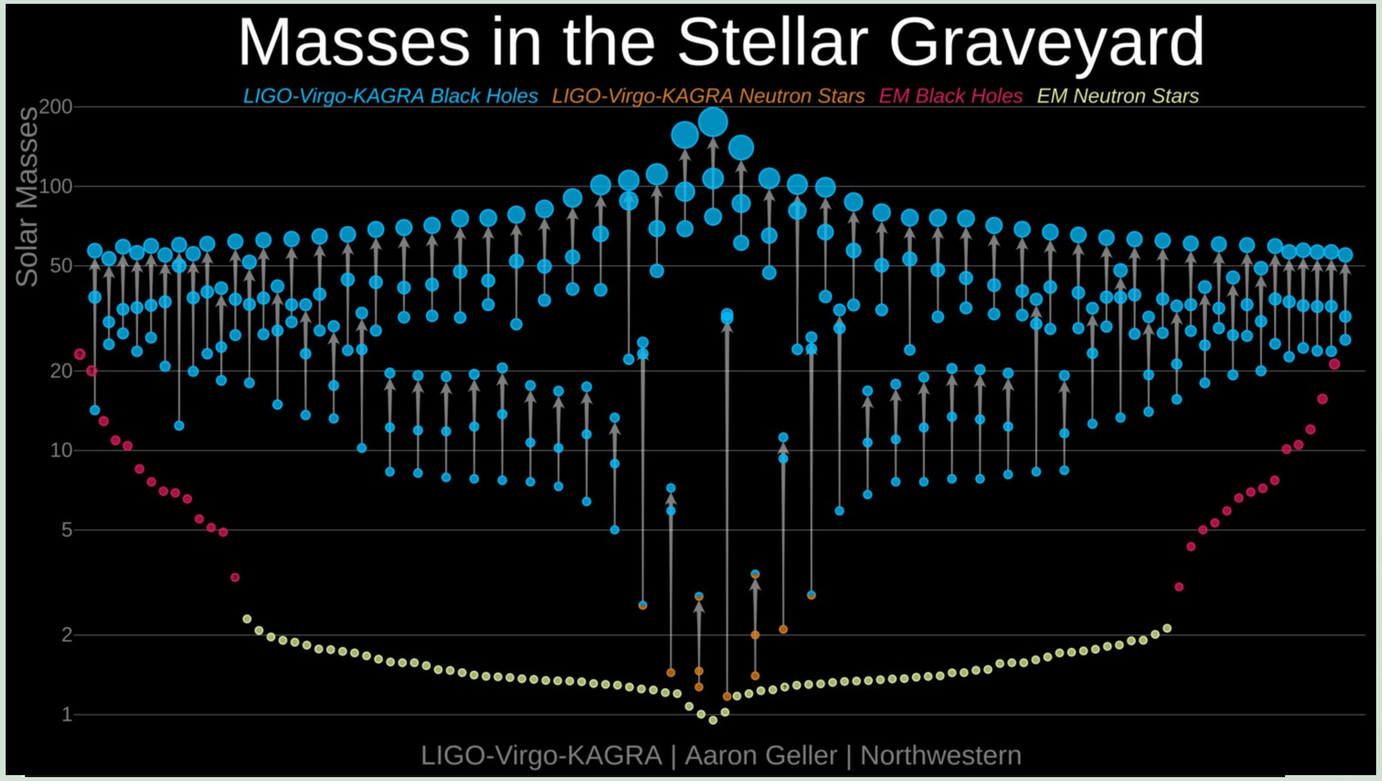

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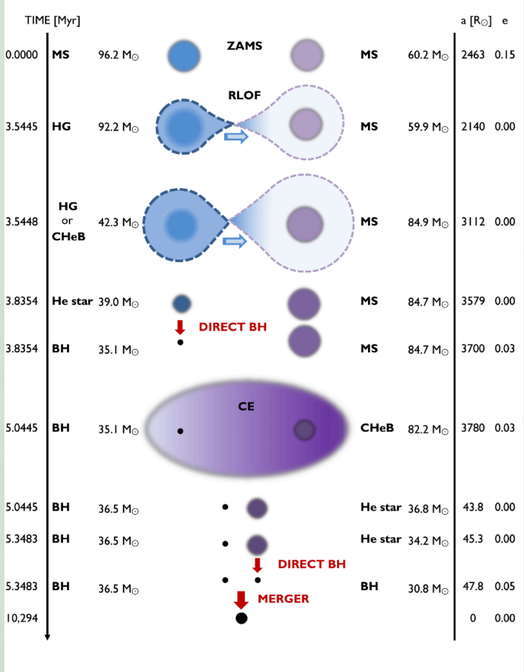

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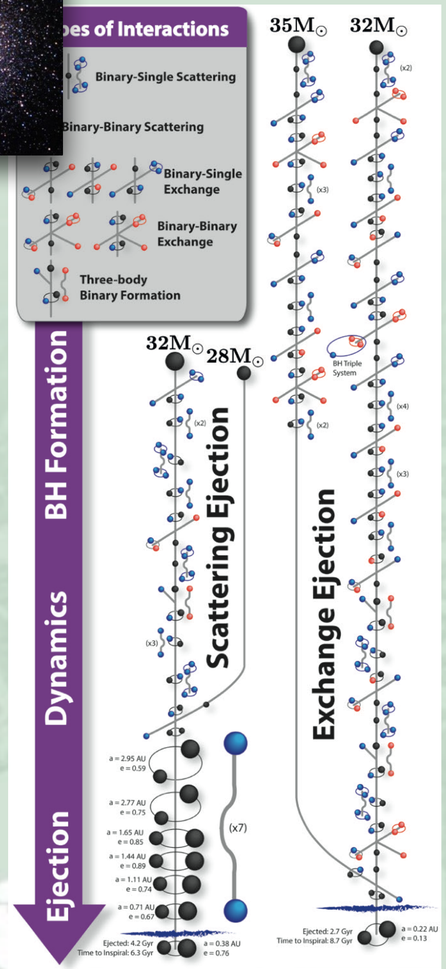
Dynamical binary
(Fig. From Rodriguez+16)



- **Multi-body interaction**
- **Repeated merger**

How is mass measured?

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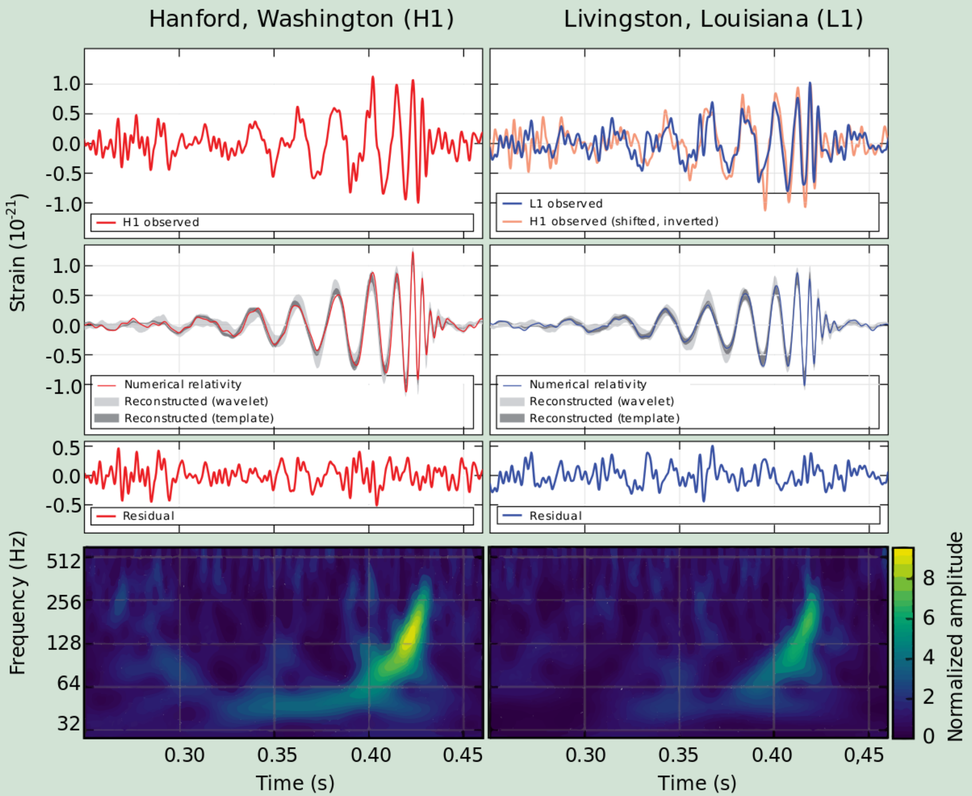
Observable: the chirp signal



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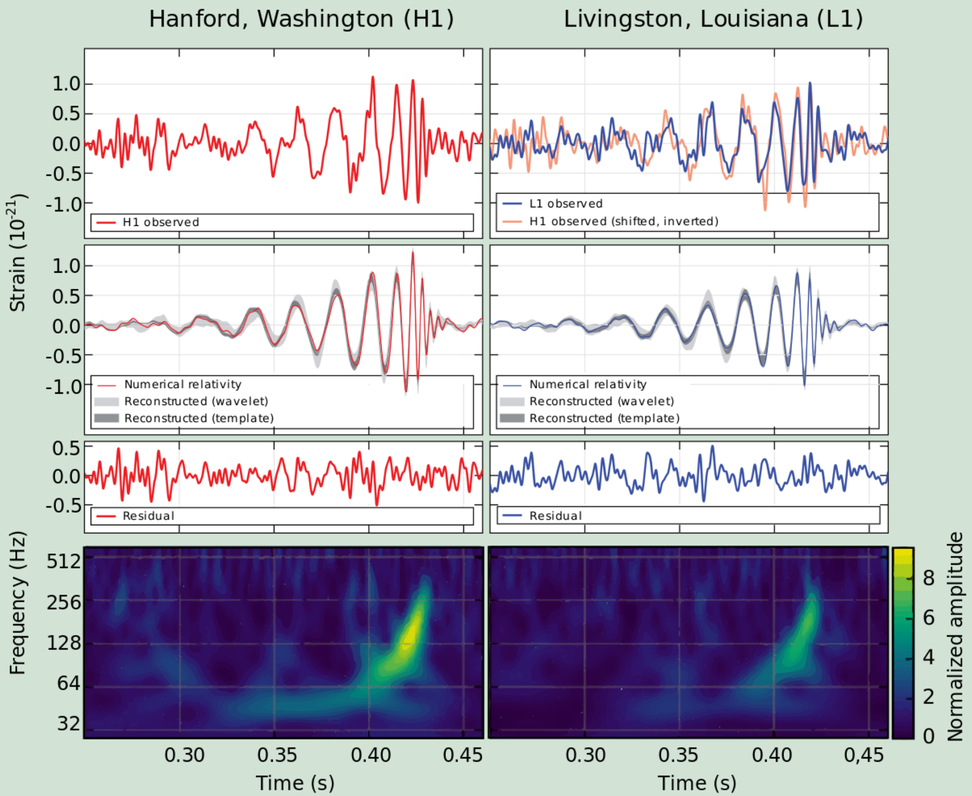

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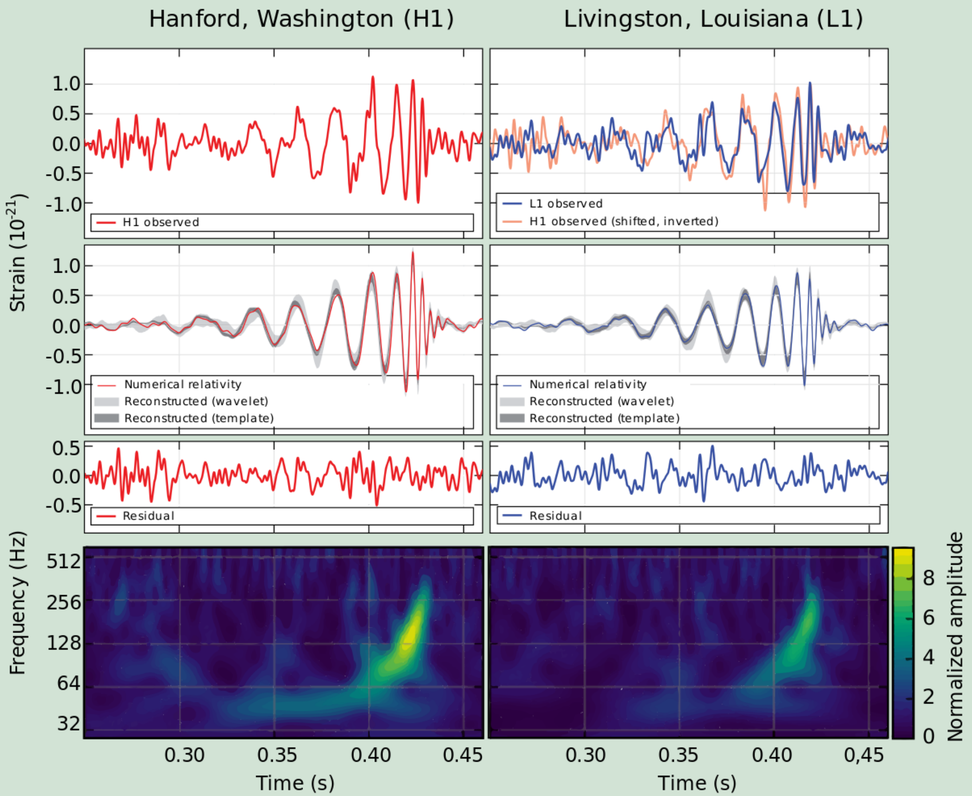

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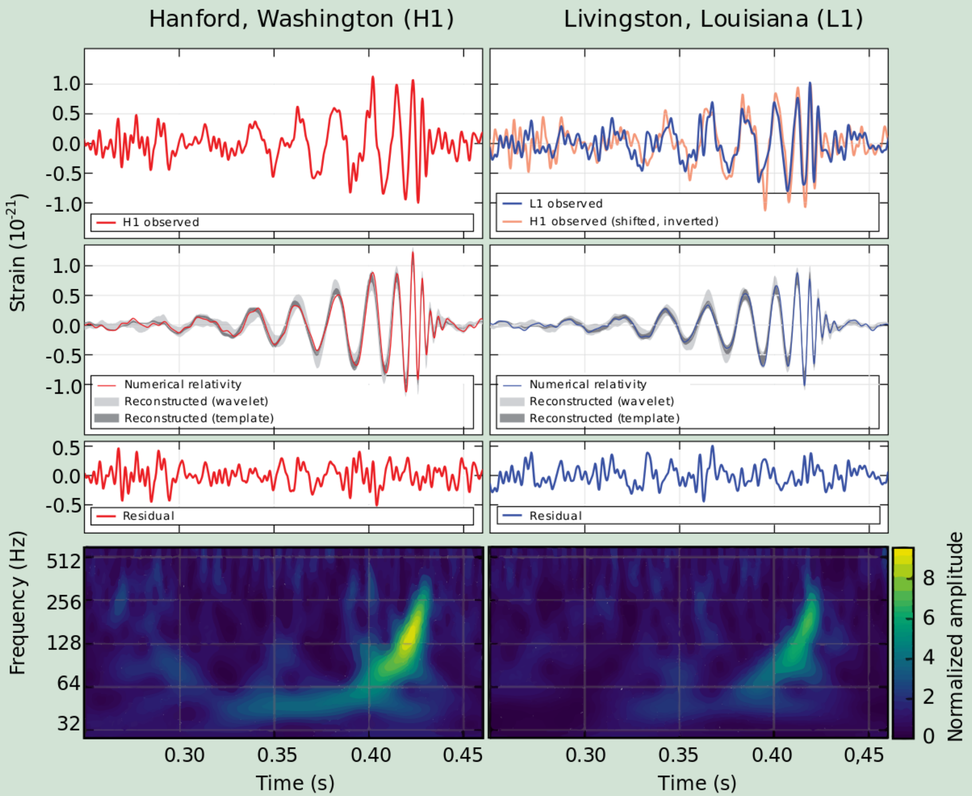

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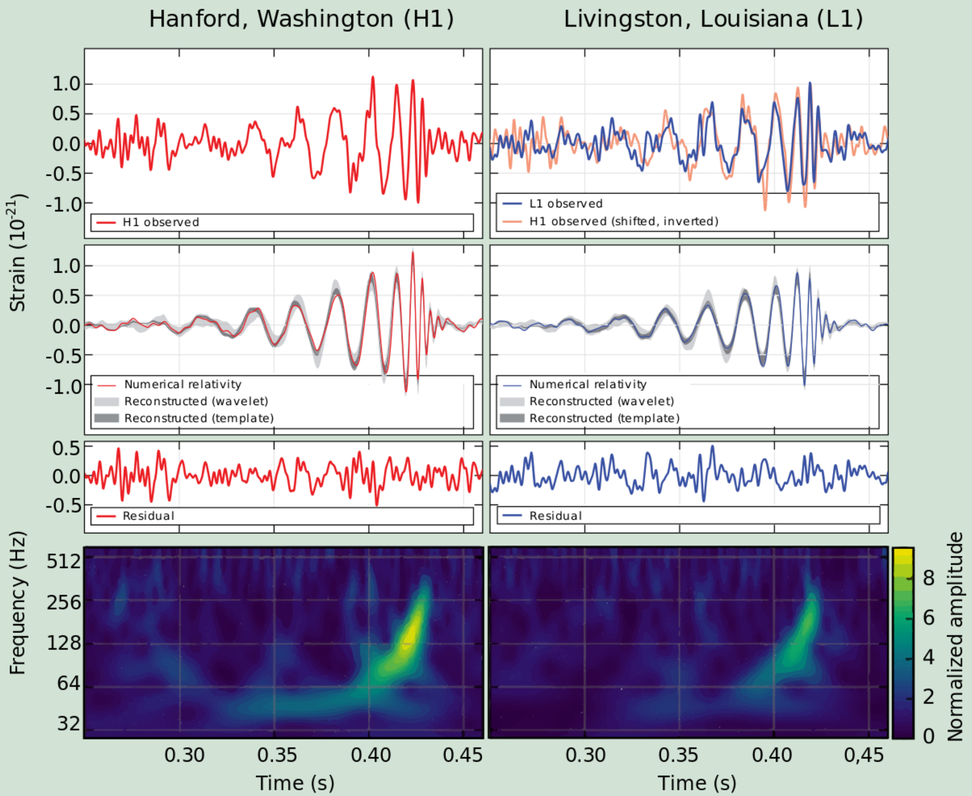

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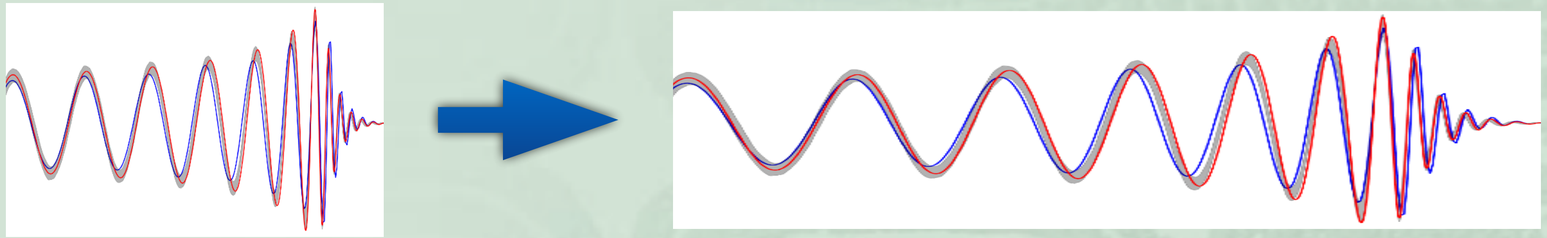

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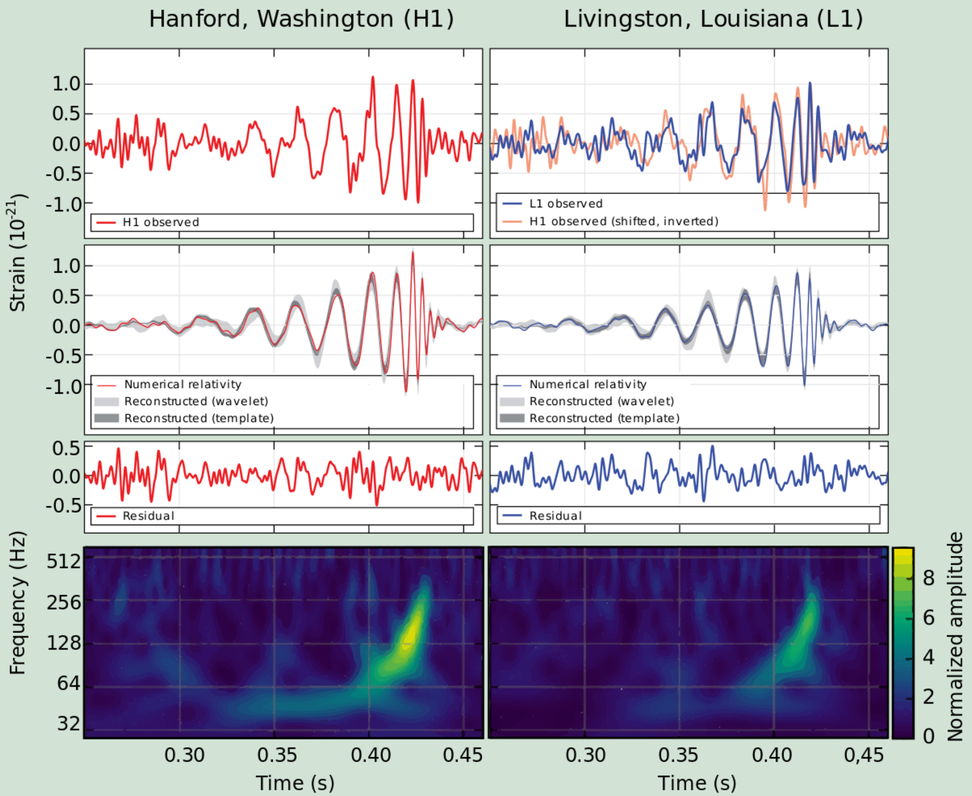

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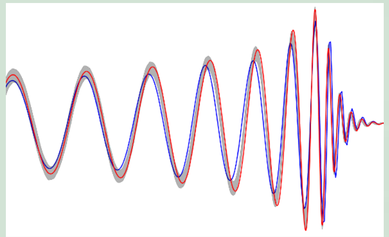

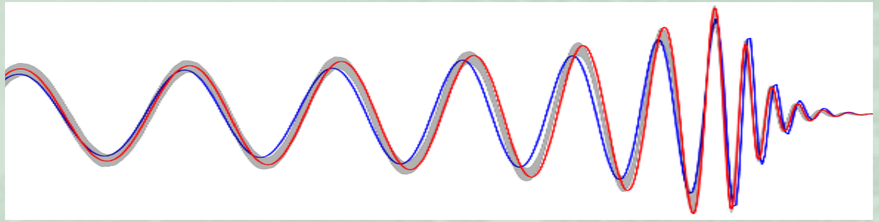

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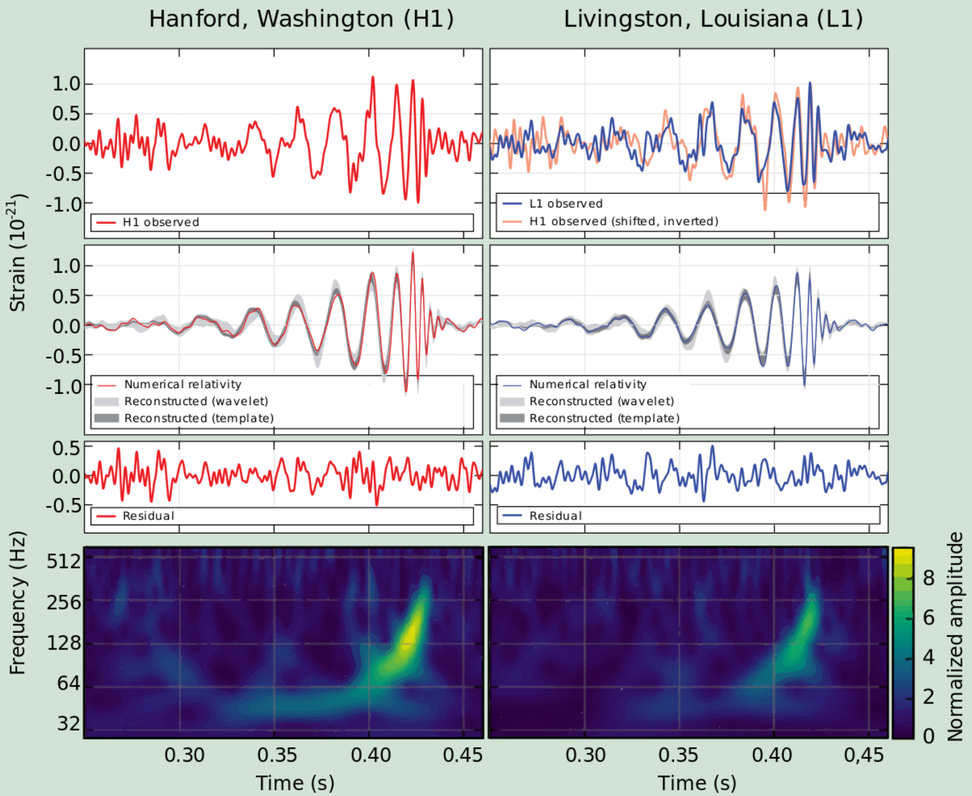

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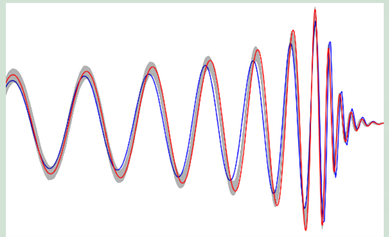

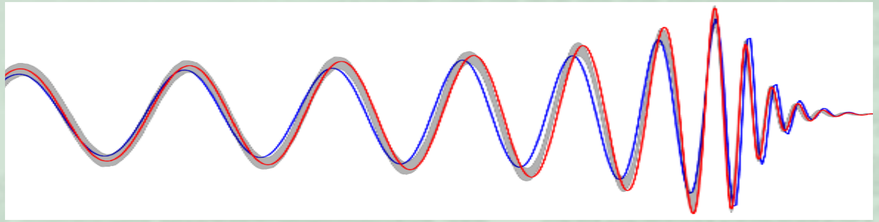

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More about redshift

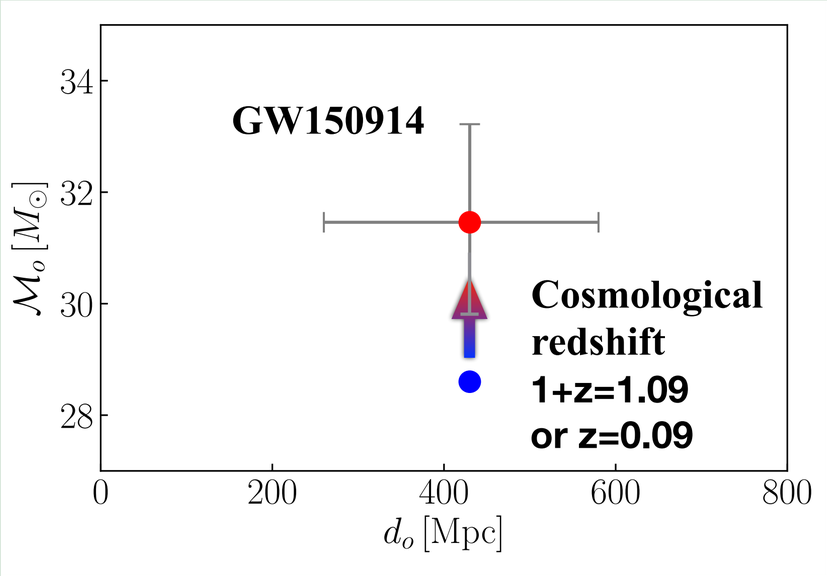

Fig. from Chen 2020, invited Chapter for Handbook of GW Astronomy

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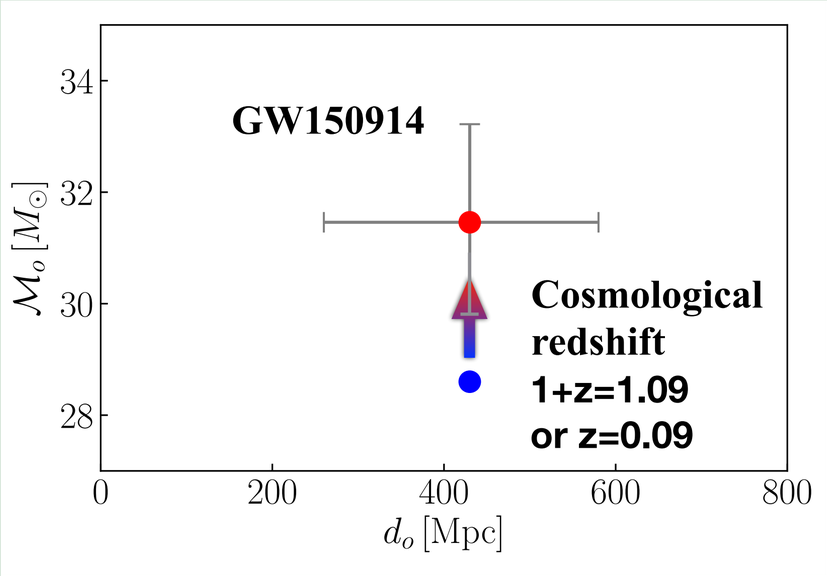

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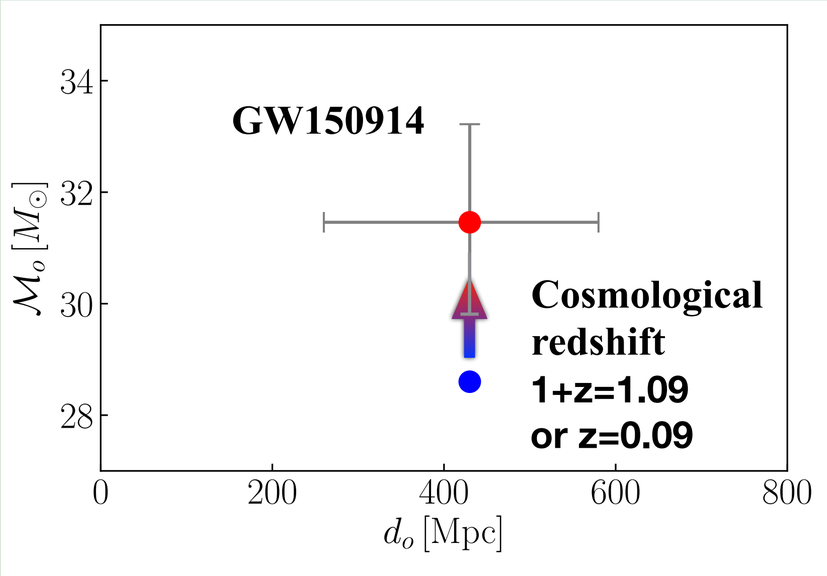

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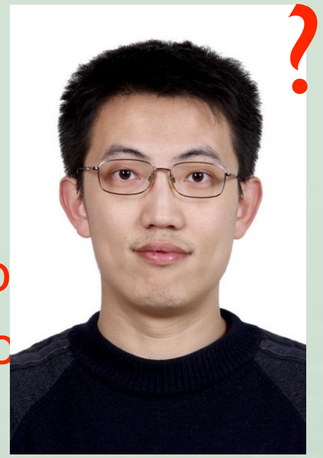

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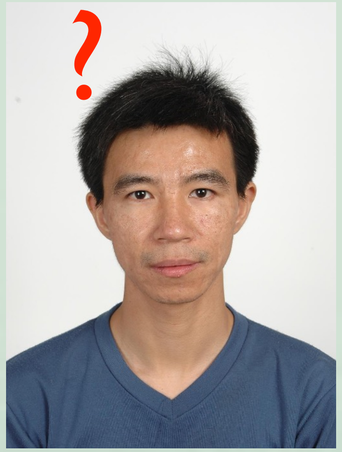
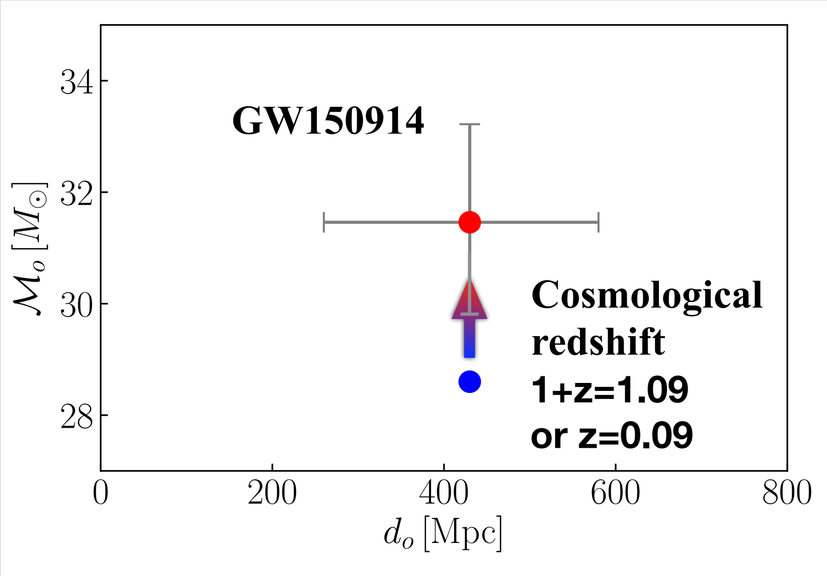


Zhoujian Cao (BNU)

More about redshift



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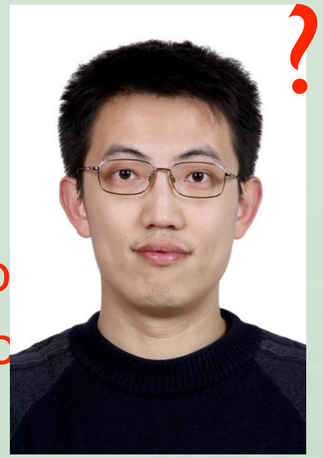

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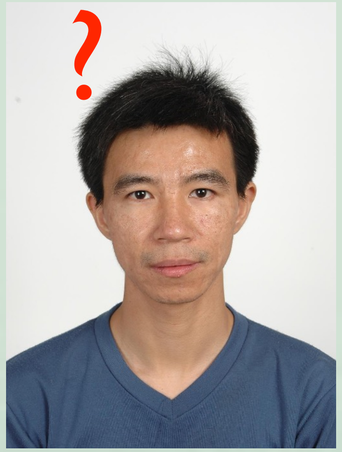

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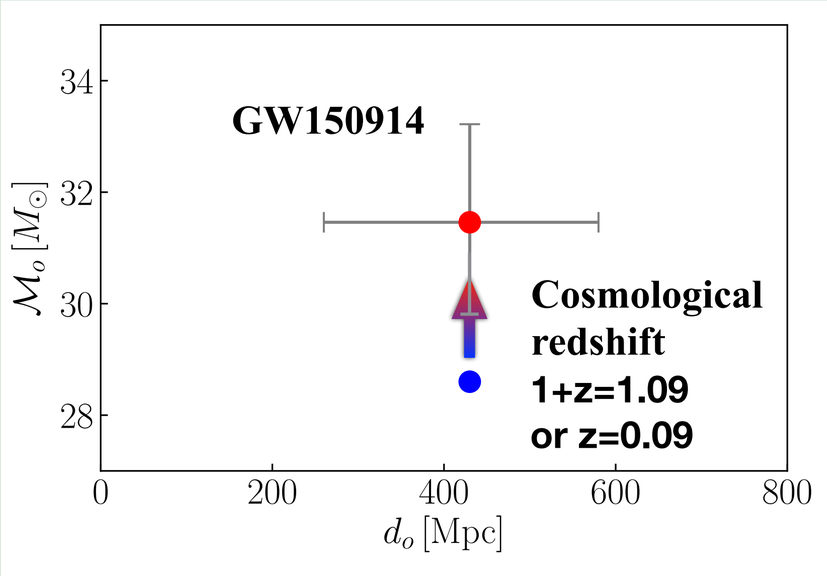

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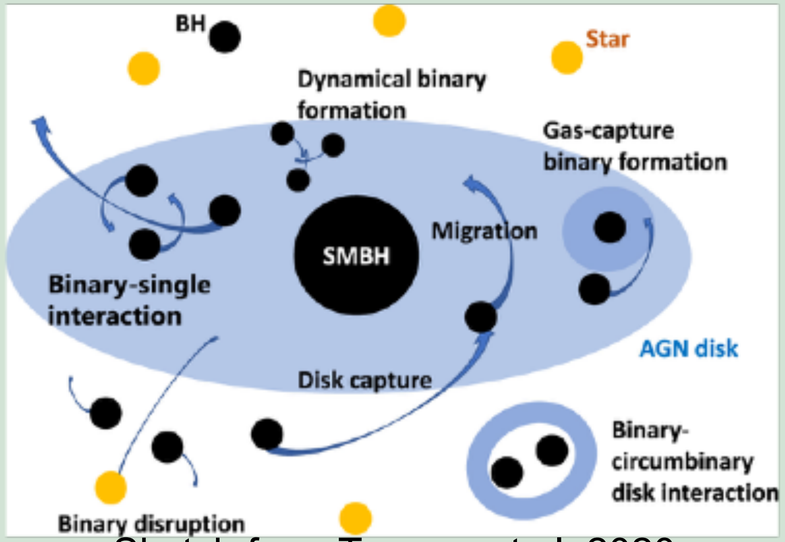

Sketch from Tagawa et al. 2020

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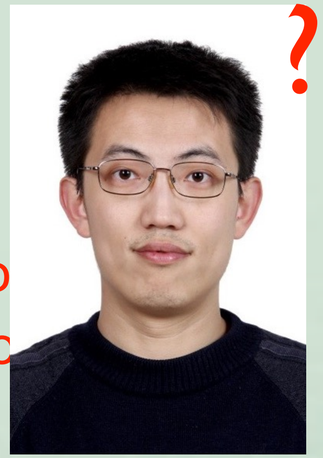

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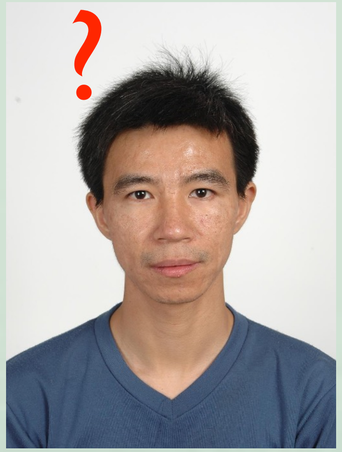

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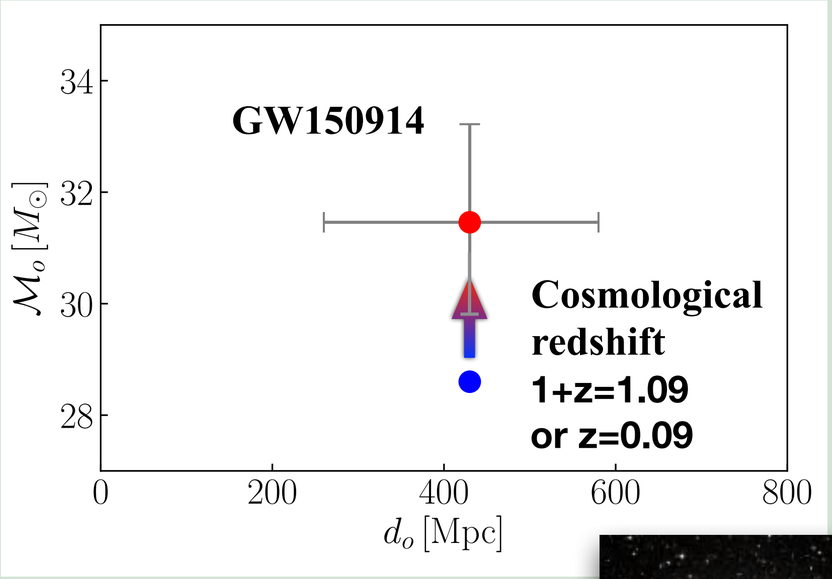

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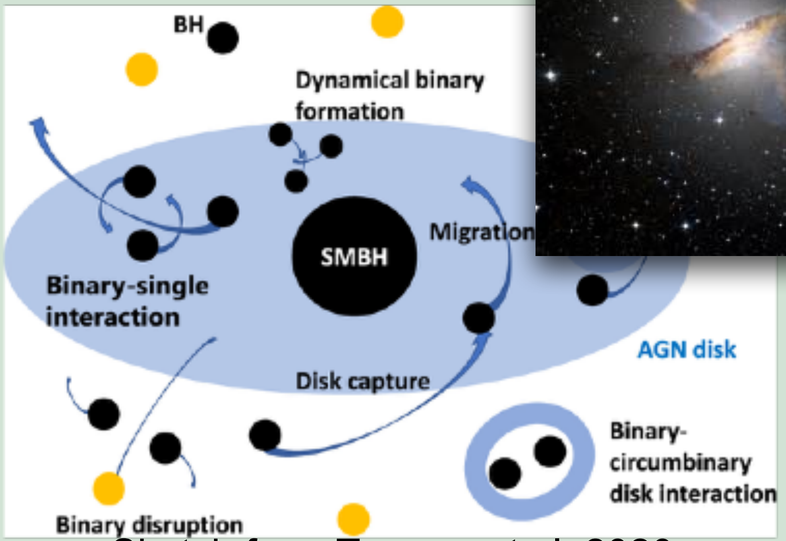

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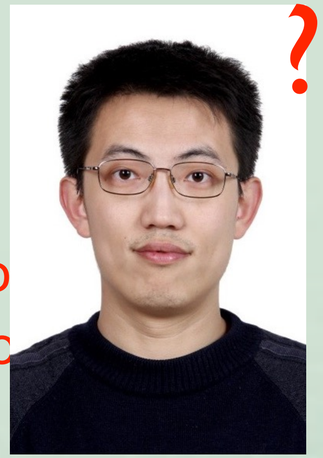

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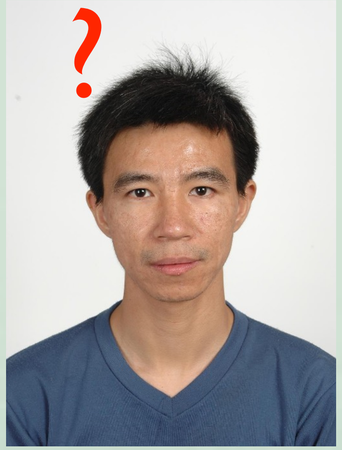

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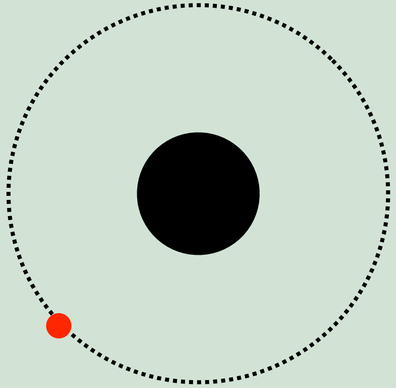

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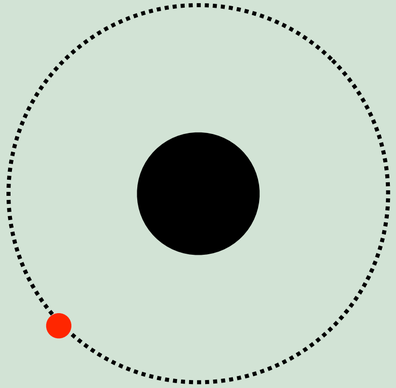
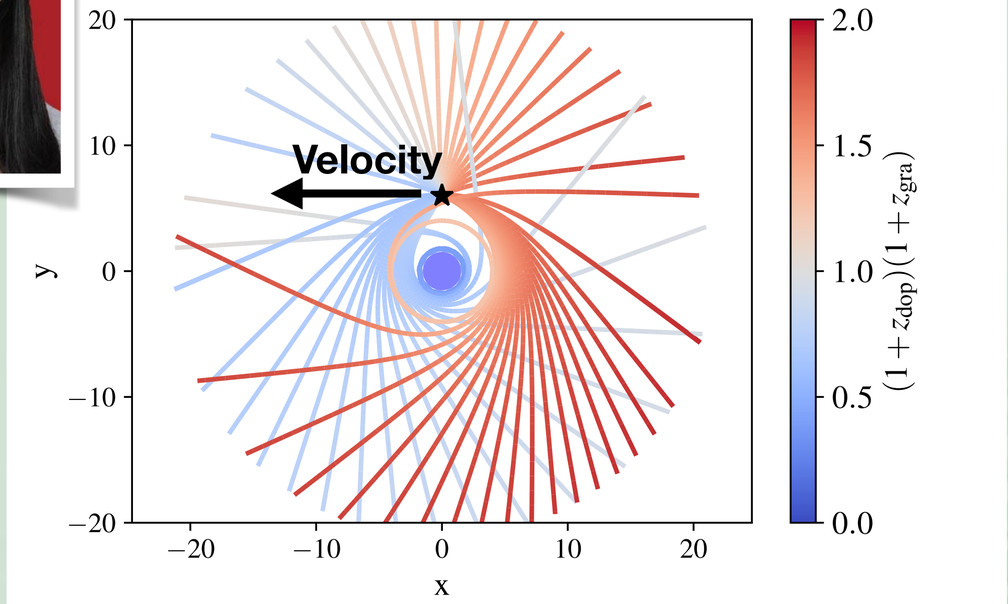


Kerr SMBH *a*=0.9

(Zhang & Chen 2023 MNRAS)



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- At 6 gravitational radii (6M)
- Both blueshift and redshift: both heavy and light BHs
- Asymmetric: dark red v.s. light blue
- Light bending: focused and de-focused rays
- Affect amplitude and distance measurement

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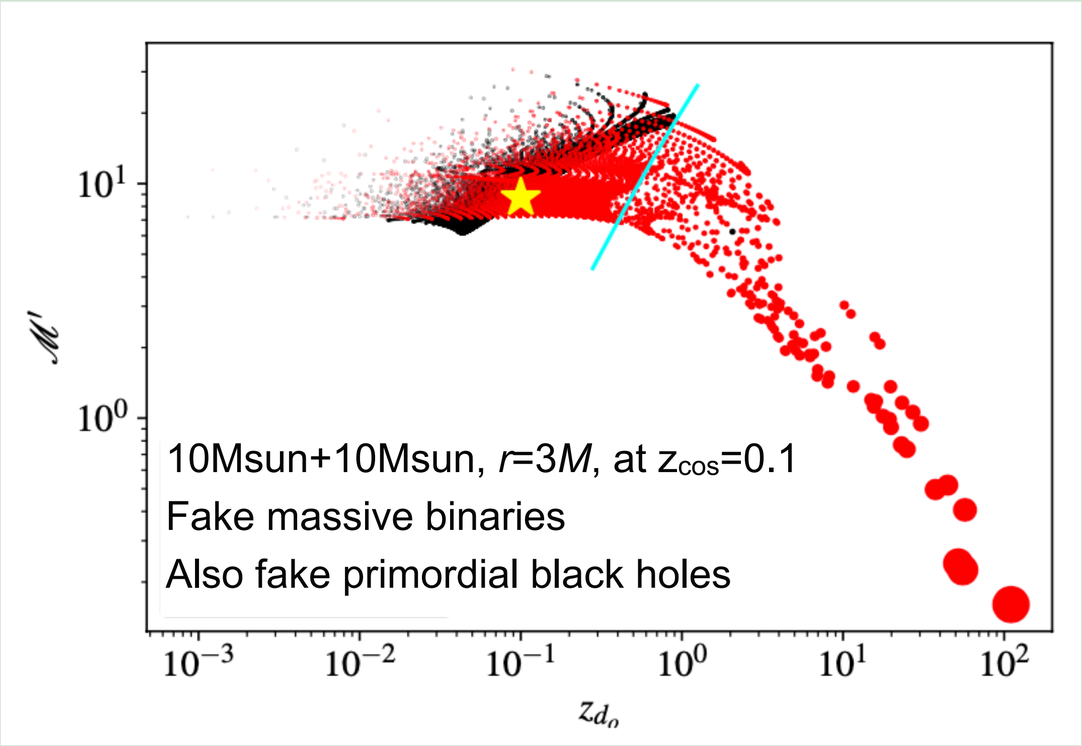

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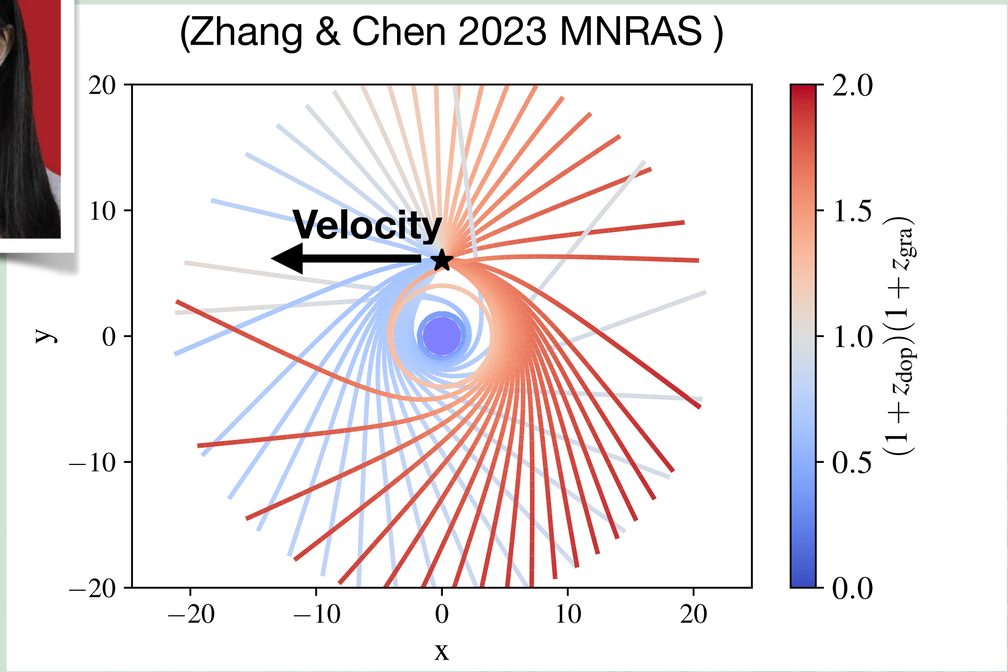

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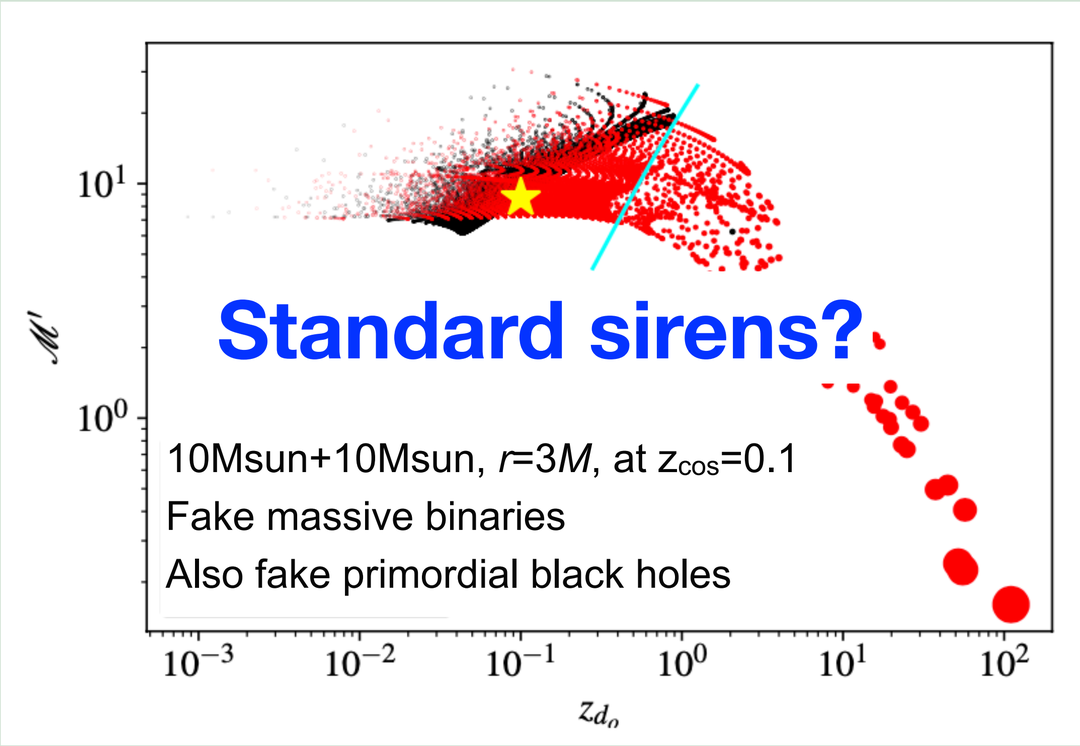
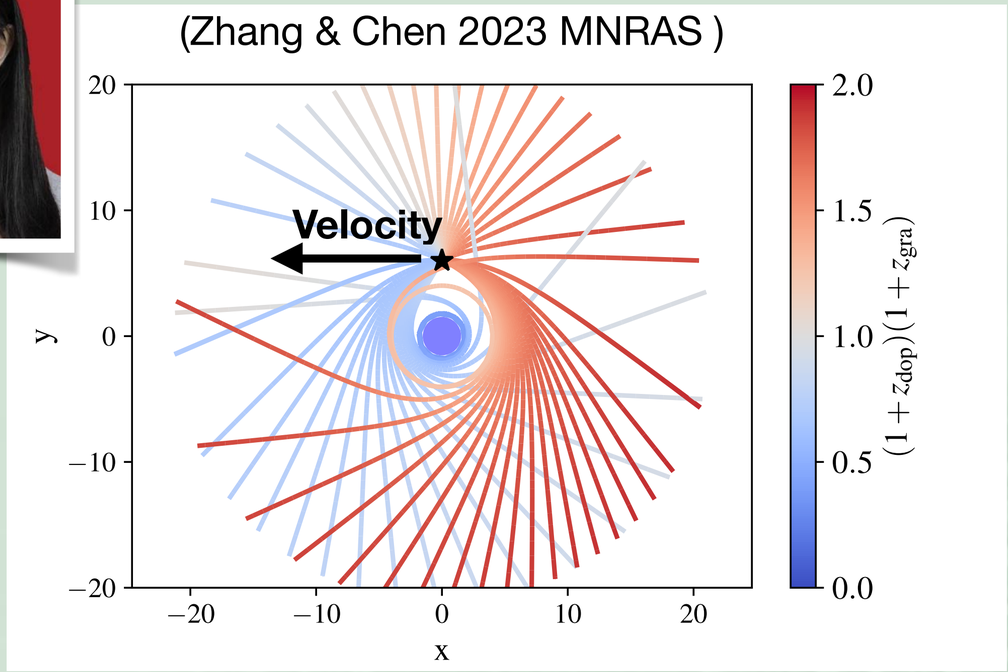
- Both blueshift and redshift: both heavy and light BHs
- Asymmetric: dark red v.s. light blue
- Light bending: focused and de-focused rays
- Affect amplitude and distance measurement

What does the binary black hole look like?



Kerr SMBH *a*=0.9

(Zhang & Chen 2023 MNRAS)



- Innermost stable circular orbit:
  - 3 Schwarzschild radii
  - v~0.408c
  - 1+z in total:1.89
  - (Chen, Li, Cao 2019 MNRAS)

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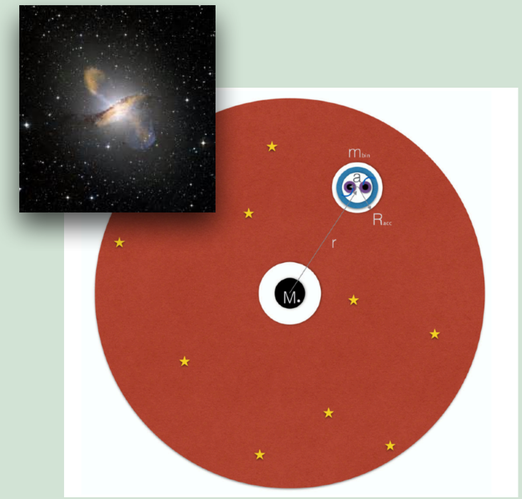
Formation channel: AGN accretion disk

(Peng & Chen 2021)



AGN disk (Bartos+17; Stone+17)

- Stellar-mass black holes in AGN disks:
  - 10^2-10^3 BHs captured or form in AGN disks (Syer 91, Artymowicz+93, Goodman 04, Wang+10, Bellovary+16, Paramarev+18)
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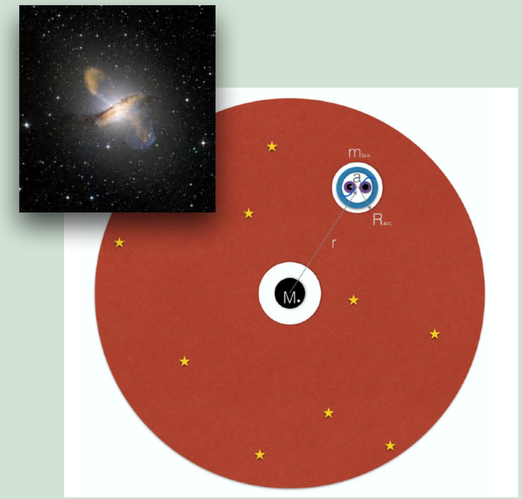

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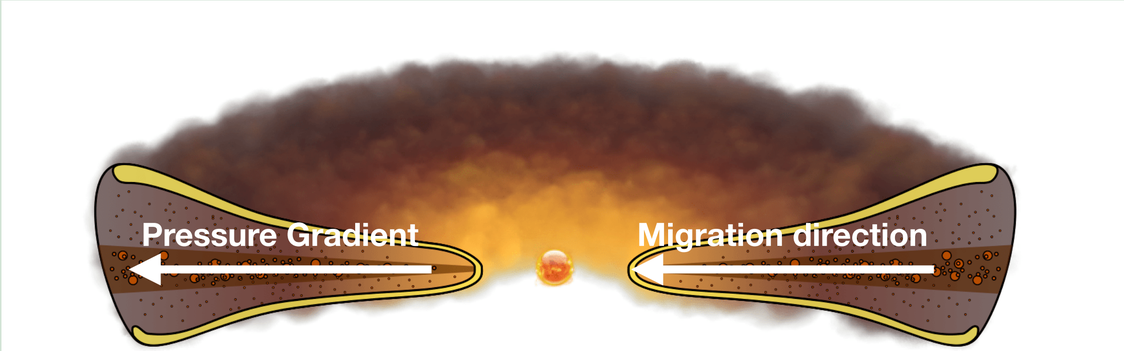

- Type-I migration in AGN disks:
  - Disk thickness: Large pressure
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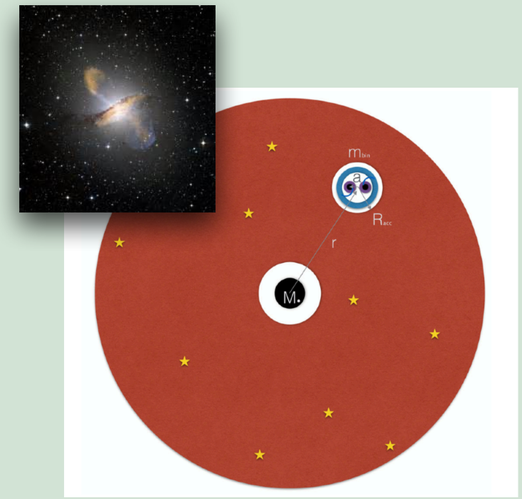

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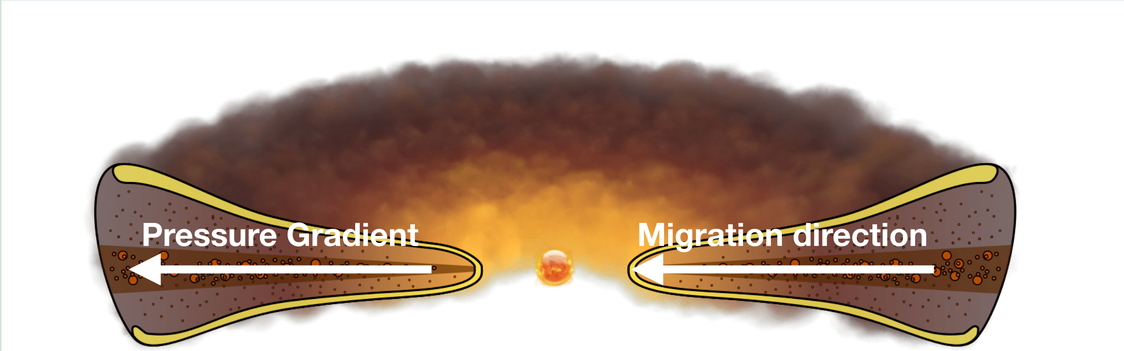
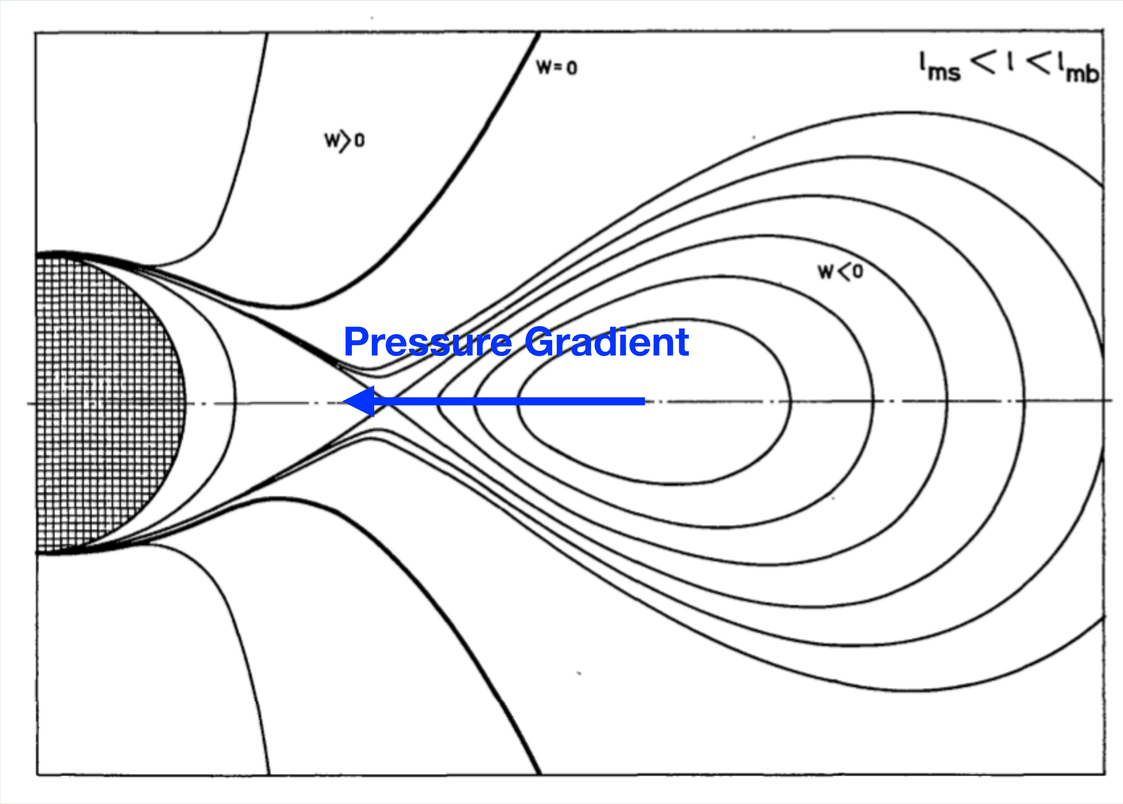


- Type-I migration in AGN disks:
  - Disk thickness: Large pressure
  - Gravity = Centrifugal + Pressure gradient
  - Sub-Keplerian: headwind (Kocsis et al. 2011)
  - Stop from falling into the central SMBH?

Formation channel II: AGN accretion disk



- Equipotential in GR (Abramowicz+78)
- Gravity + Pressure gradient = Centrifugal
- Super-Keplerian motion = Tailwind
- BHs gain angular momentum

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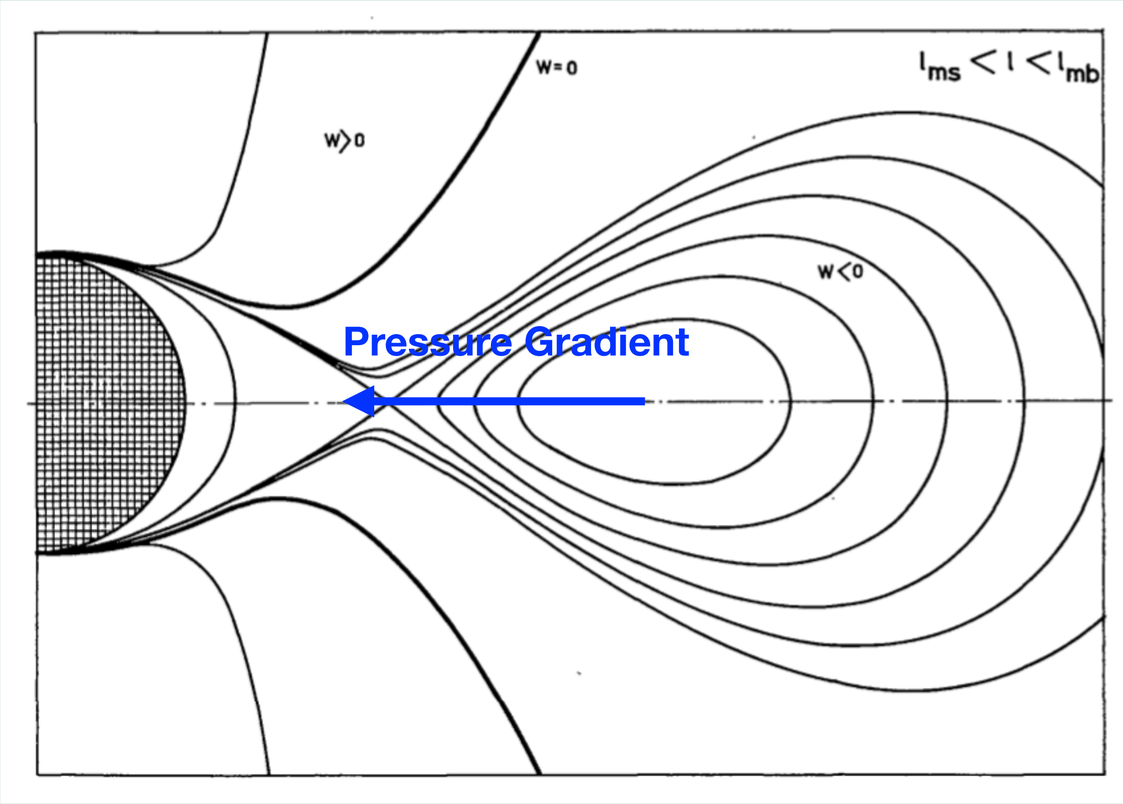

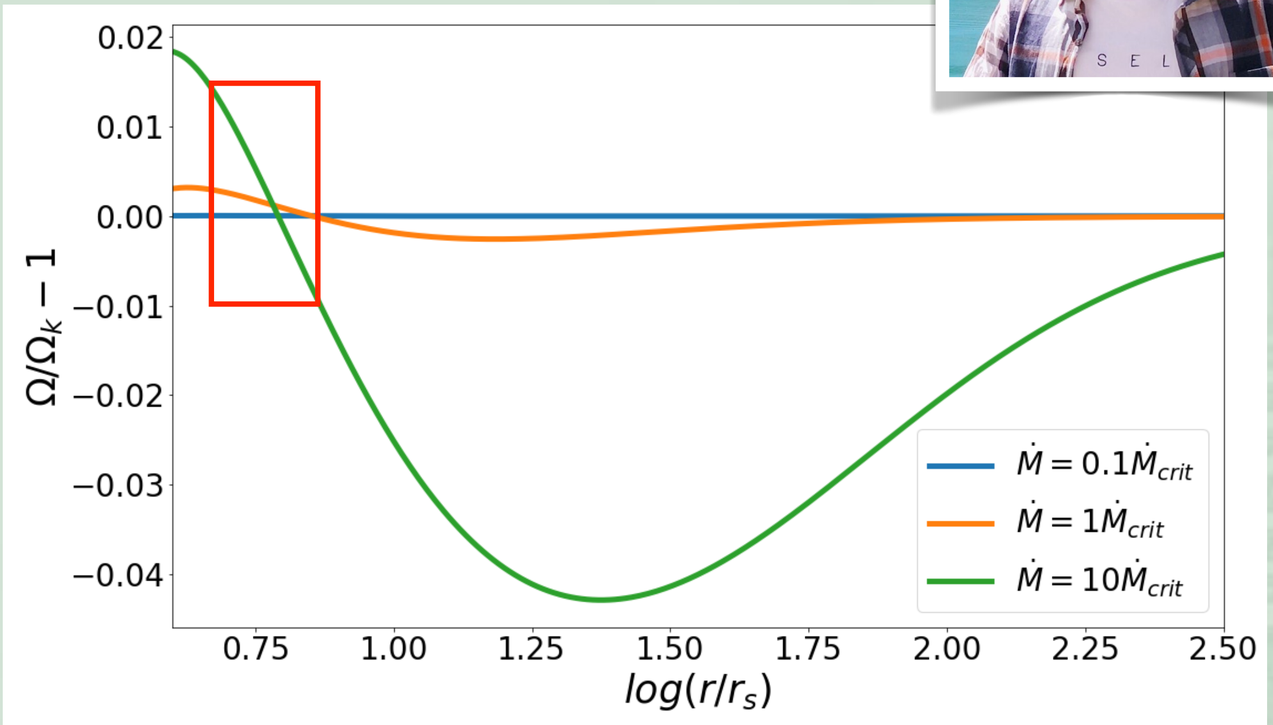

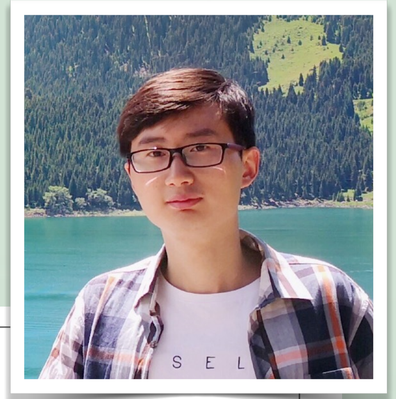

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Slim disk has a super- to sub-Keplerian transition region

(Peng & Chen 2021 ApJ)

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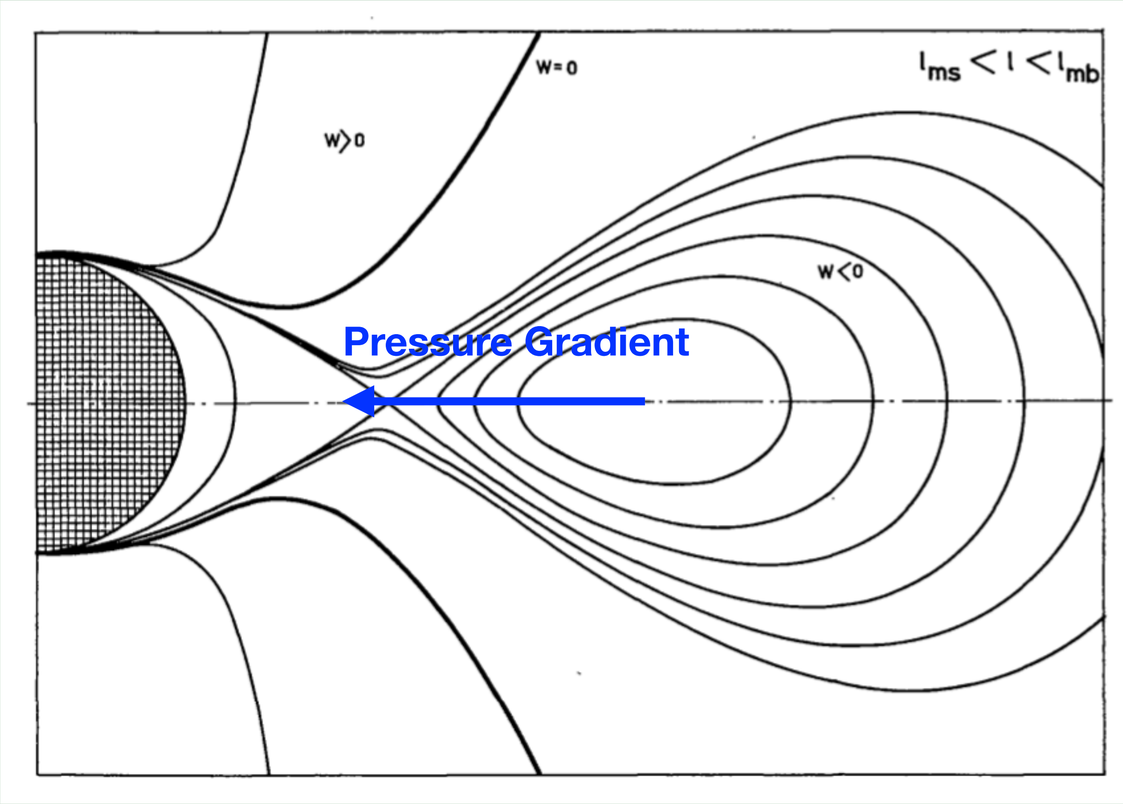

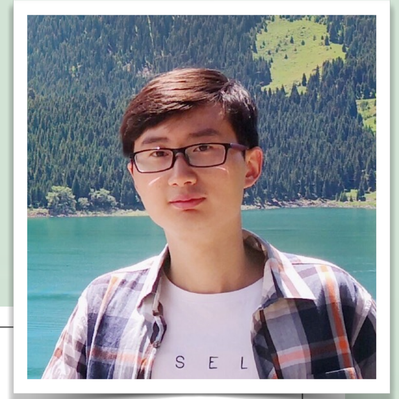

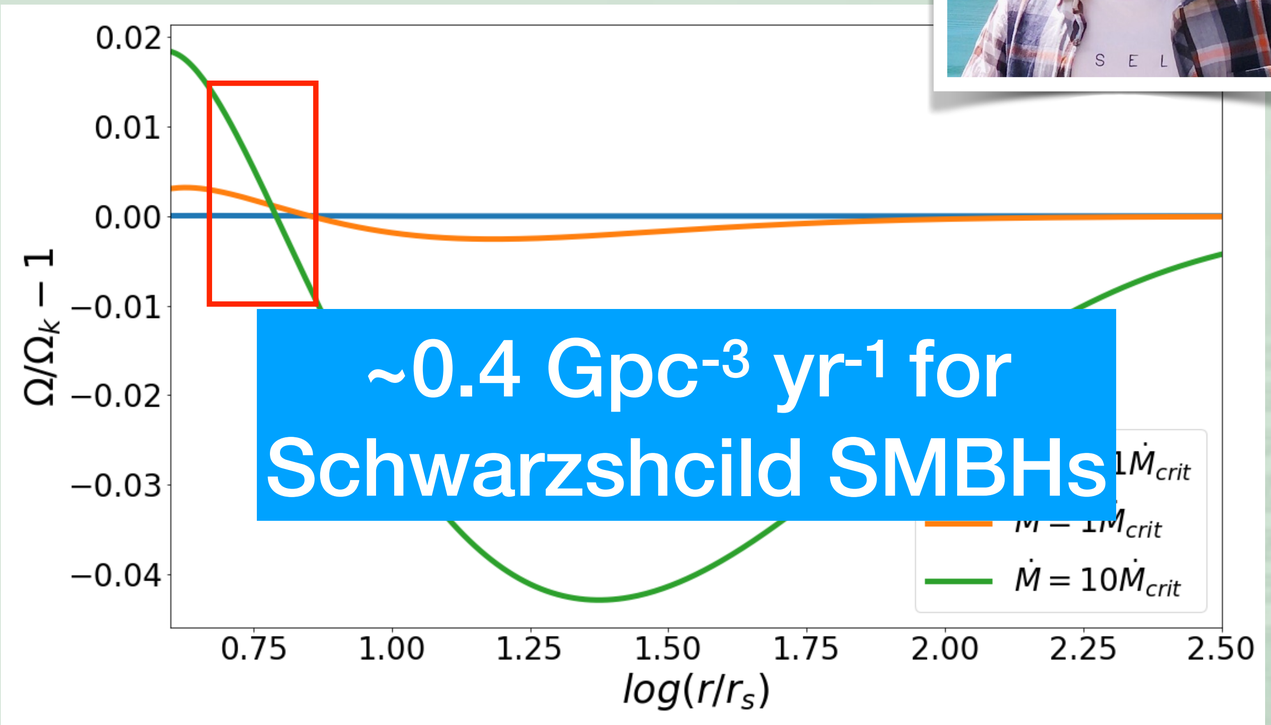

~0.4 Gpc^{-3} yr^{-1} for Schwarzshcild SMBHs

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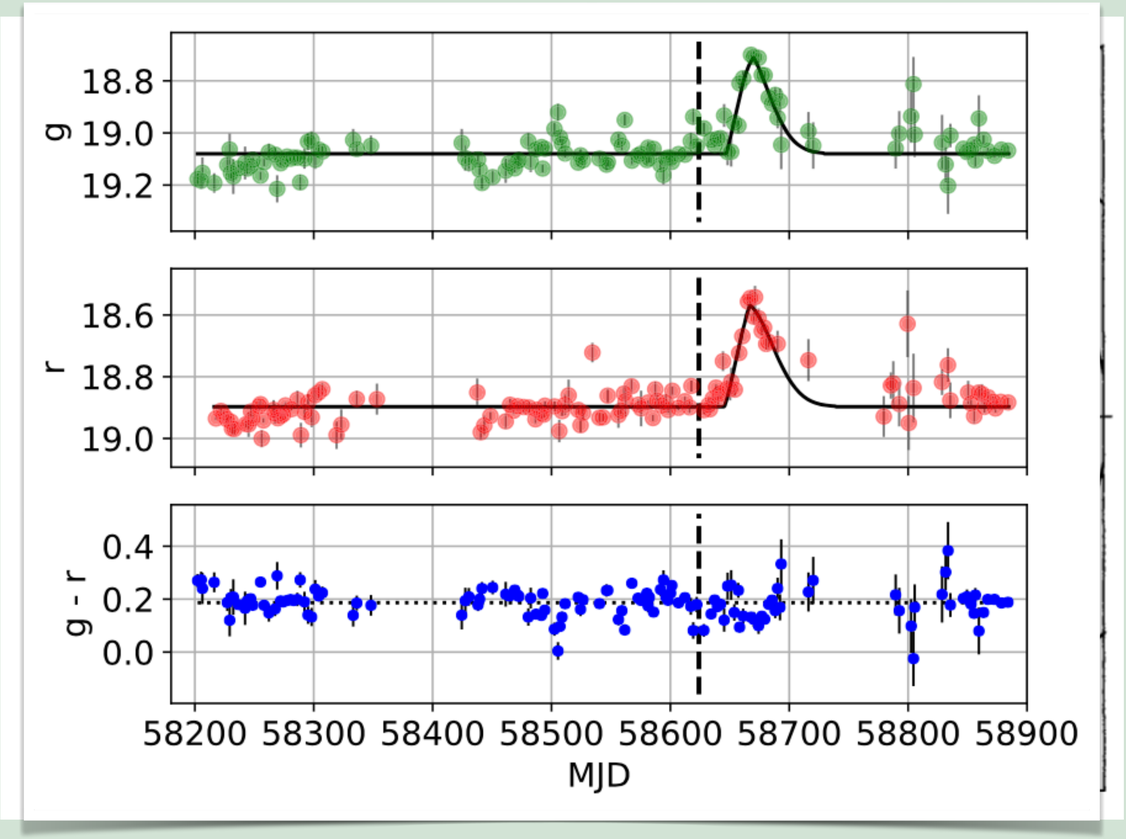

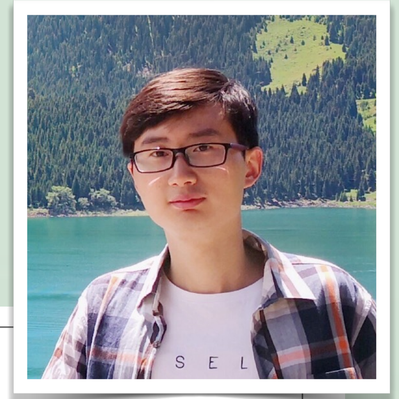

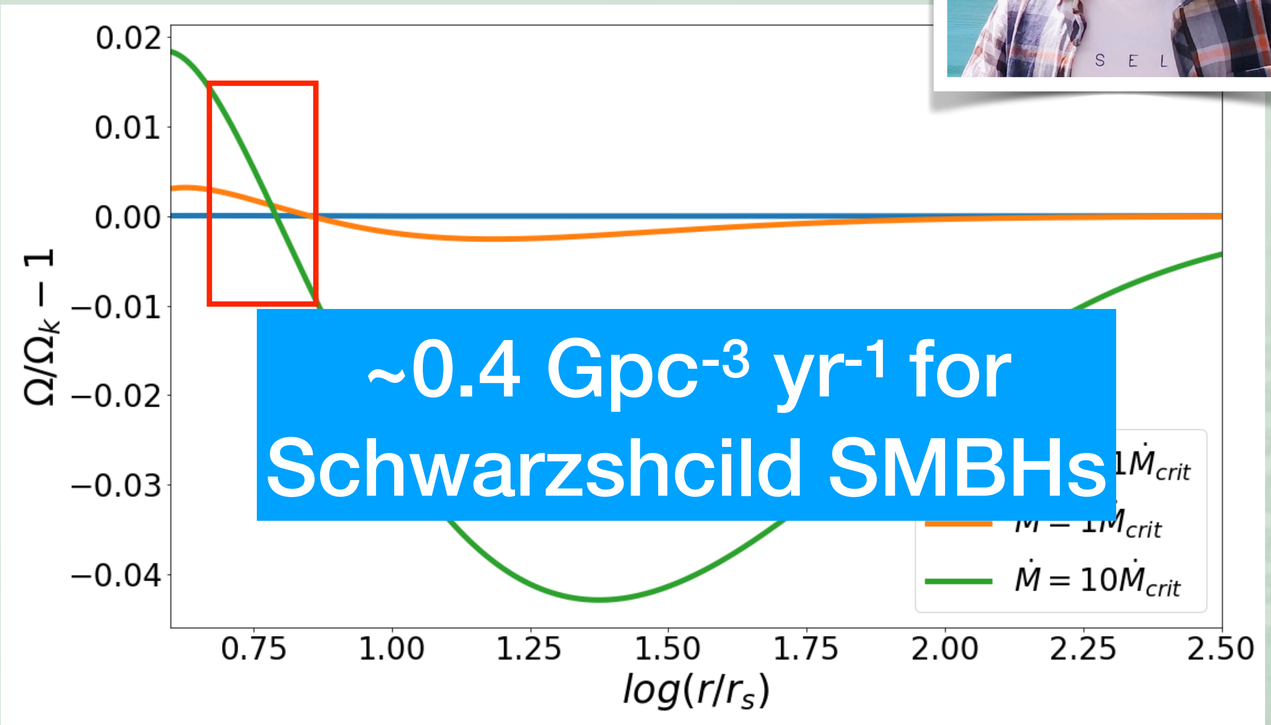

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GW190521: 91+67 Msun

- d_{GW}=4.5 Gpc (Abbott+20)
- d_{EM}=2.2 Gpc (S190521g, Graham+20)
- $(1+z_{dop})(1+z_{gra})=2$
- Also see Graham+22 for ZTF results

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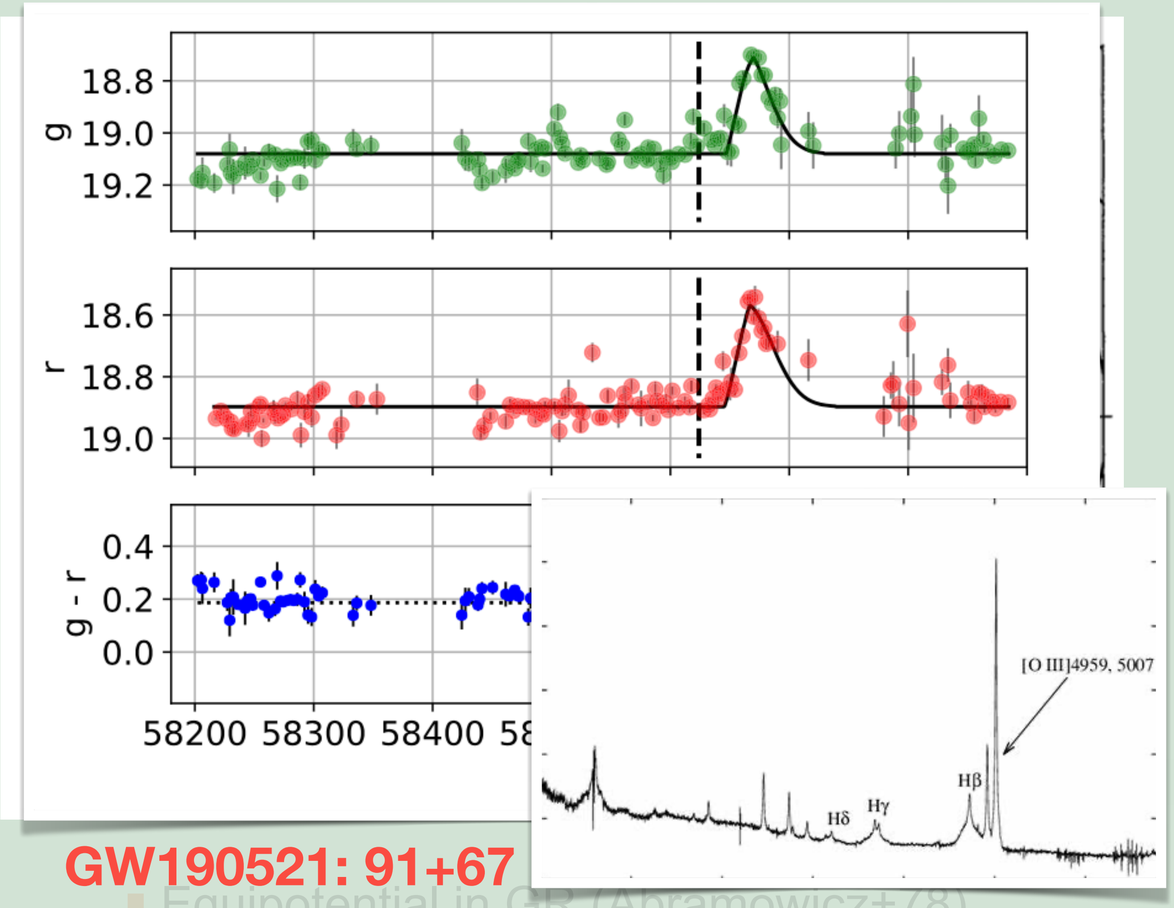

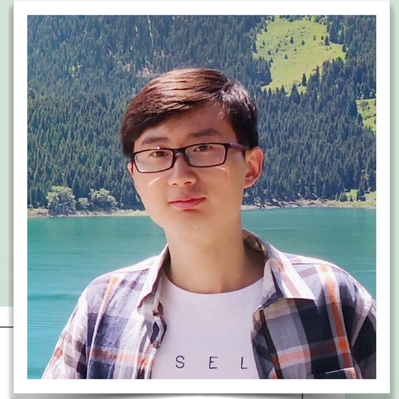

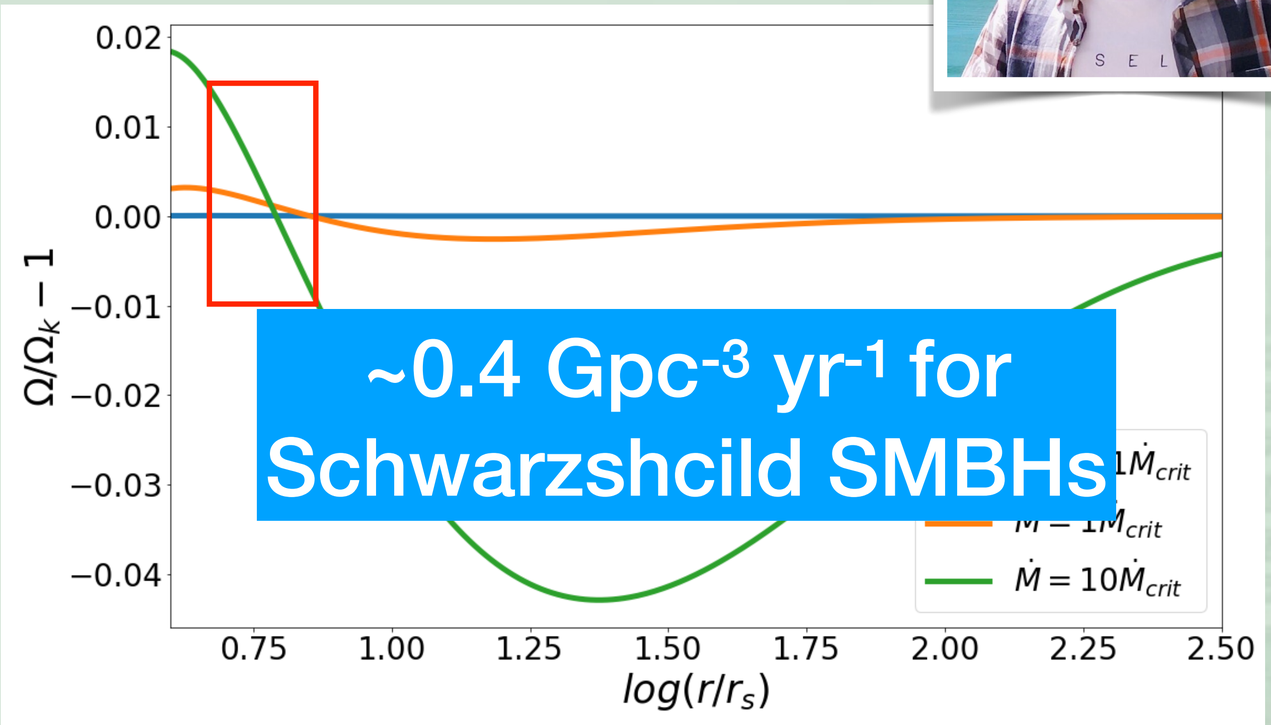

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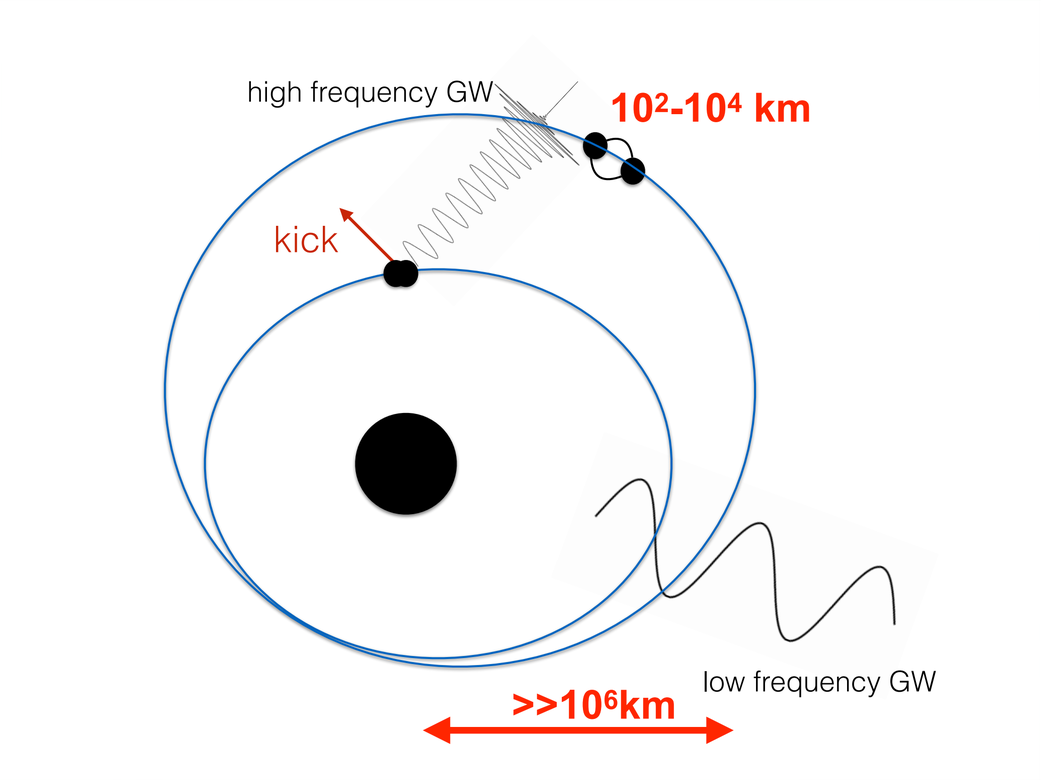
Binary Extreme-mass-ratio Inspiral (b-EMRI)



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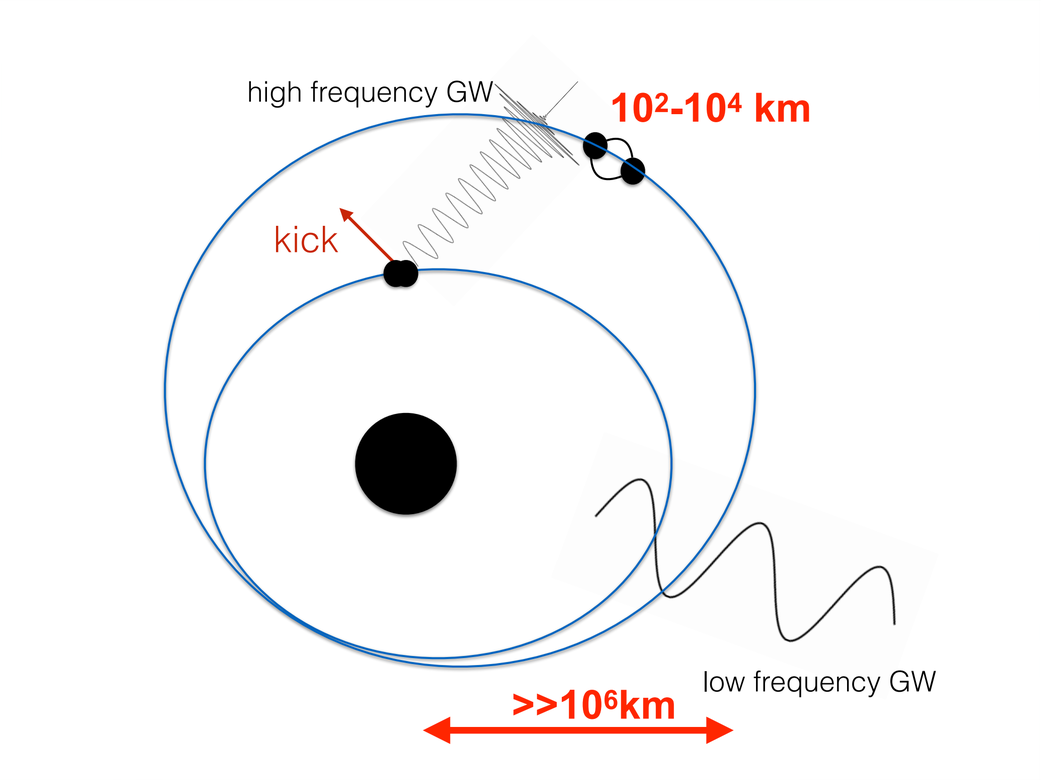
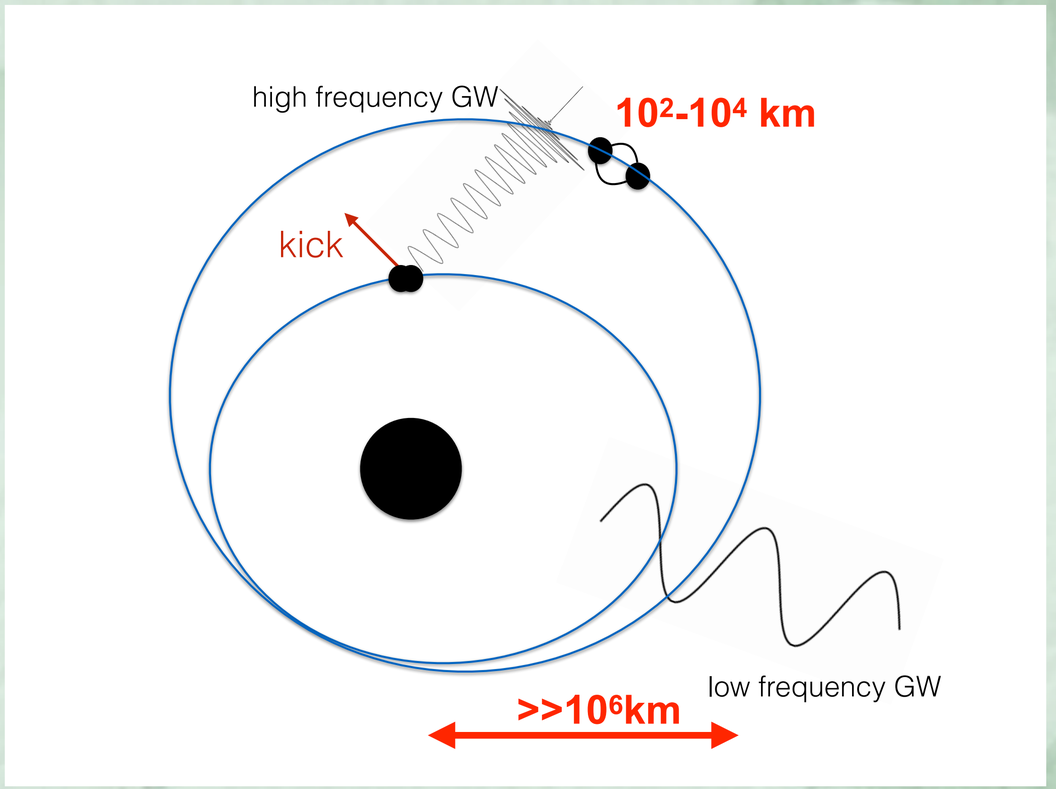


Binary Extreme-mass-ratio Inspiral (b-EMRI)

LIGO (USA)

Virgo (Italy)



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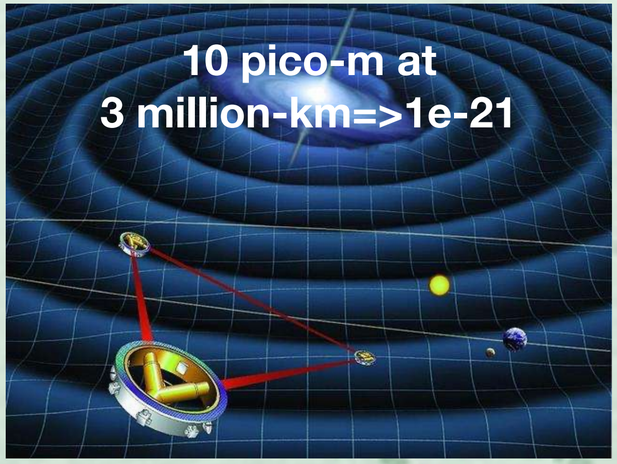

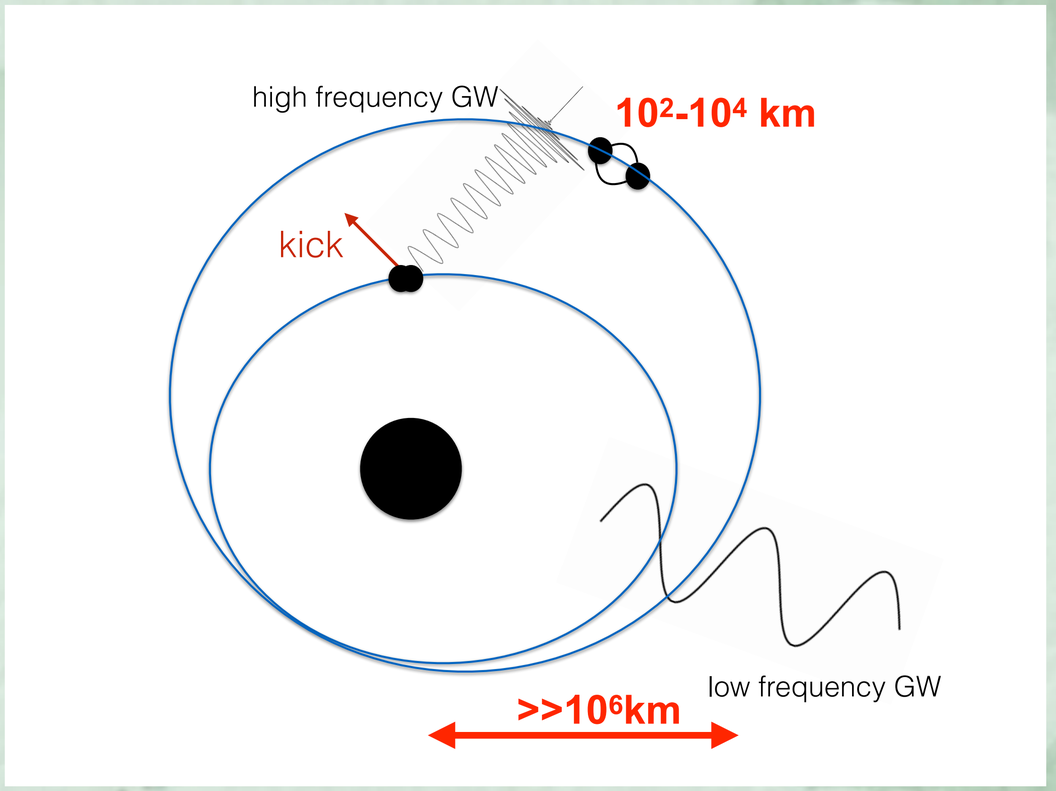

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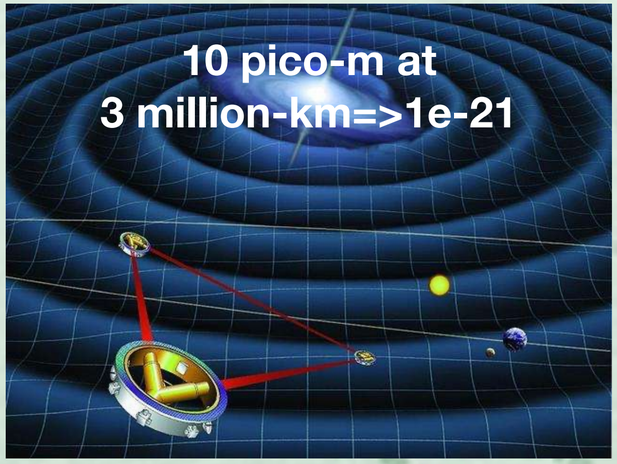

GW

Conclusion

- GW observations bring new phenomena/theories/models.
- Observation/interpretation affected astrophysical environments (SMBH/gas/motion/tertiary stars).
- E.g. Fake massive BHs.
- Wrong formation channel or cosmology if not properly accounted for.

Distinguish b-EMRI from normal binary BHs?

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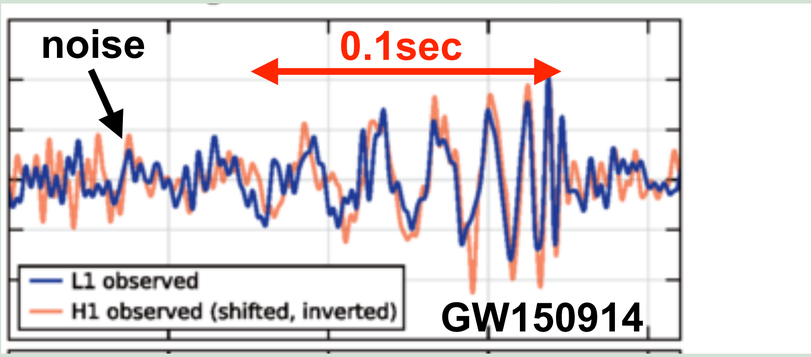

- Difficult with LIGO/Virgo
  - 0.1sec x 0.1c ~ 3e3 km
  - Curvature radius M>1e6 km
  - Constant redshift, degenerate with mass

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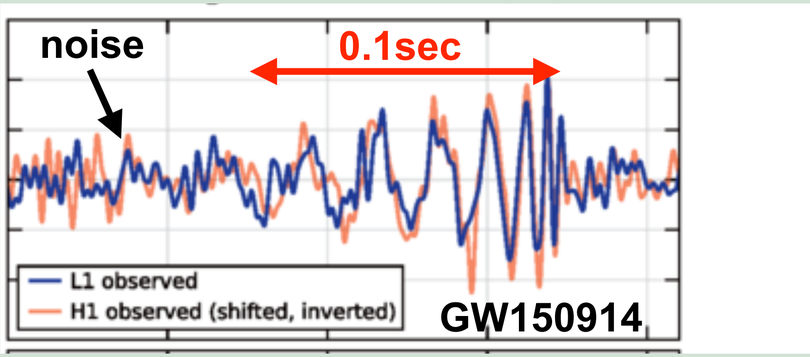

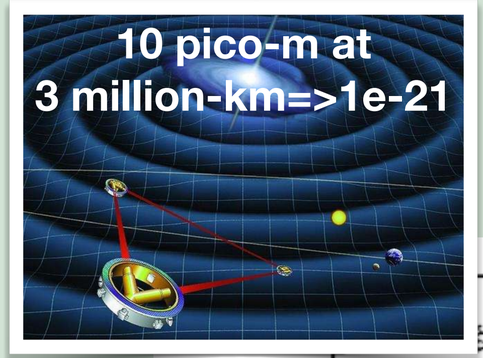

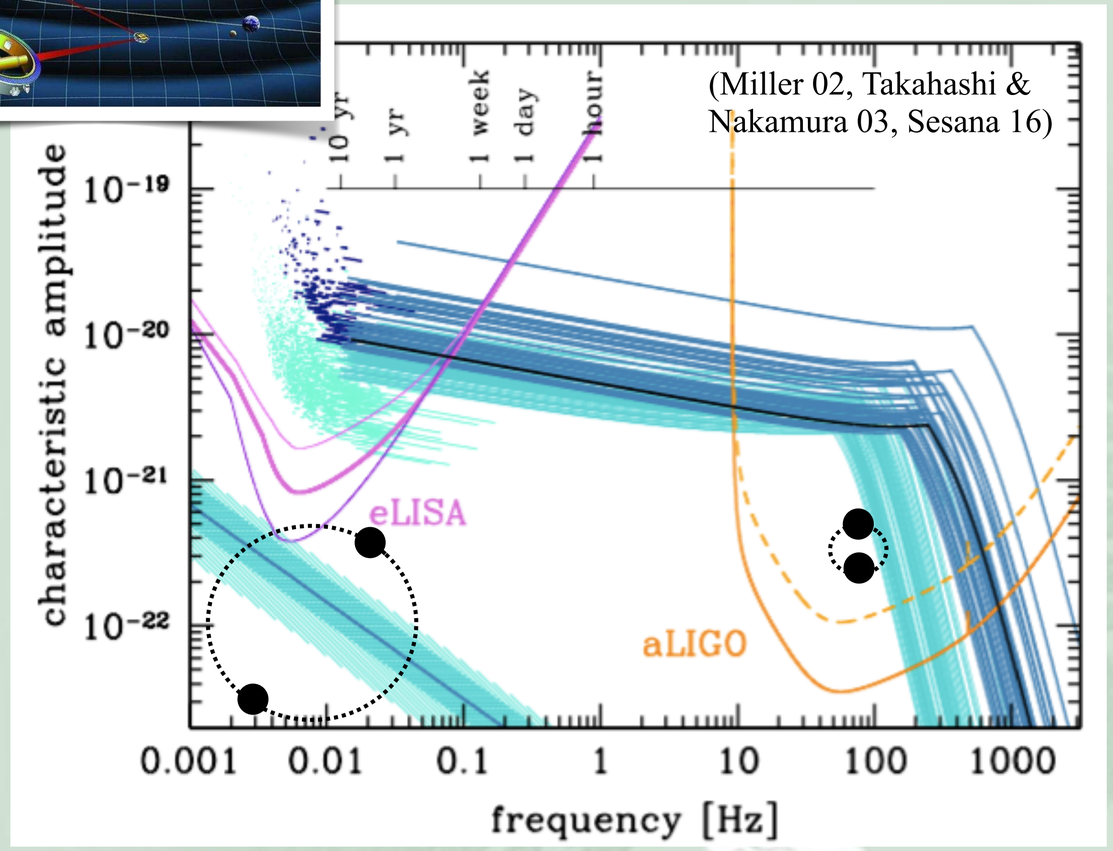

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- Months to years before merger in LISA band
- Track it for months to years
- Reveal motion around the SMBH!

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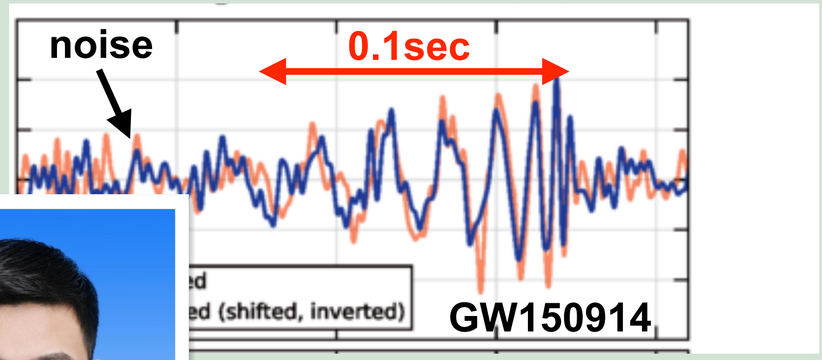

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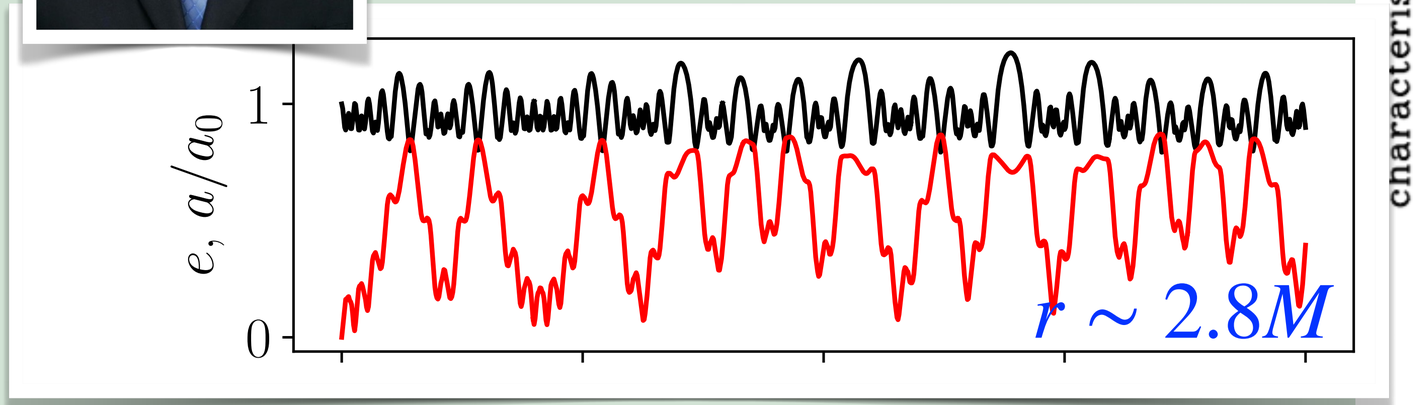
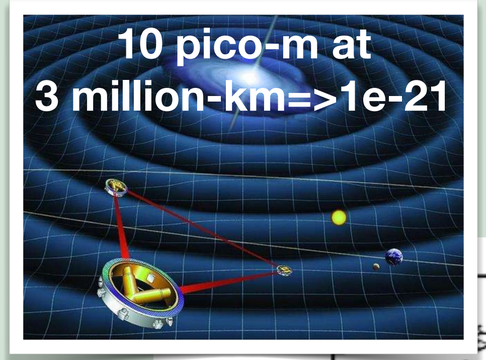
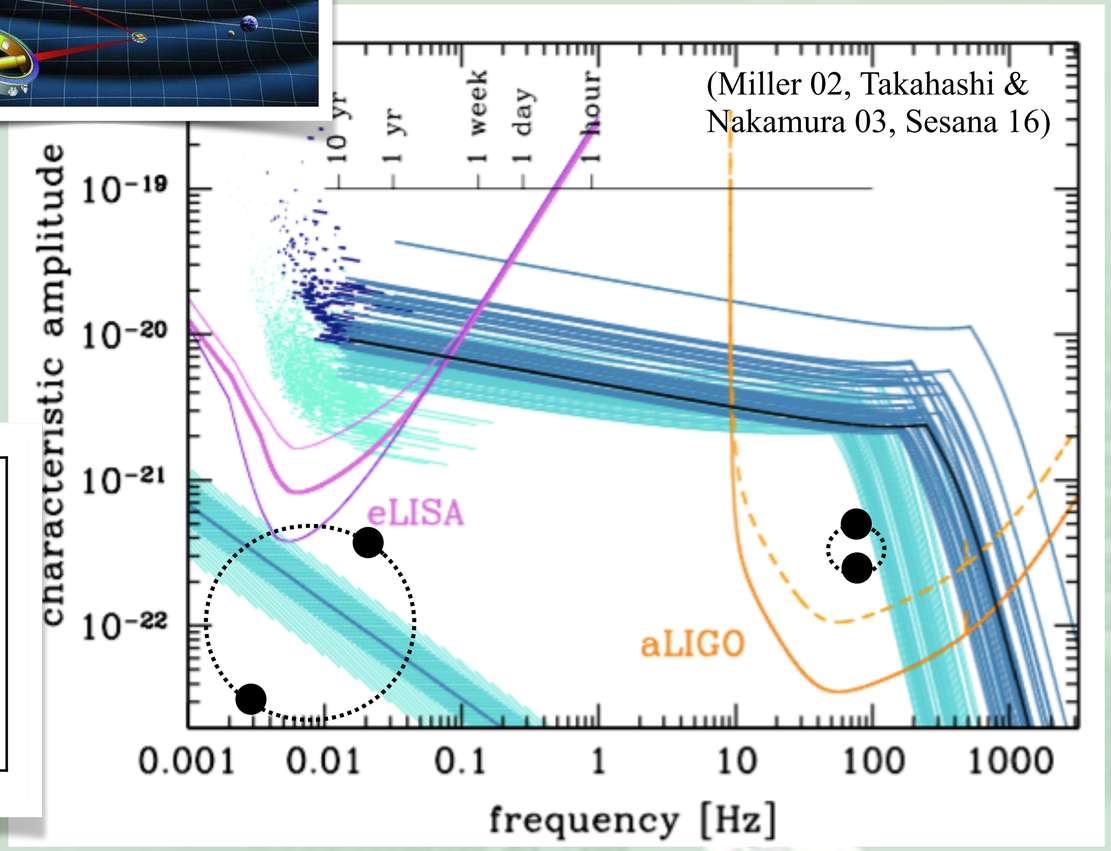


- Significant eccentricity evolution
- Some binary black holes merge!
- "Coincidence" between smaller distance and merger
- Chen & Zhang 2022 PRD





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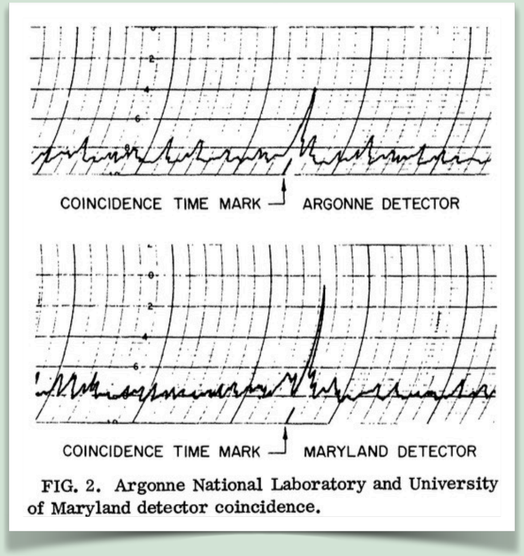
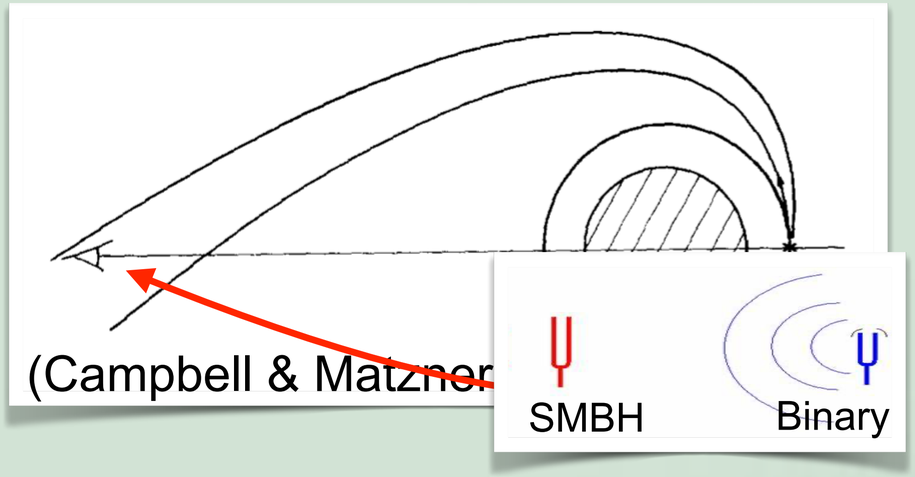
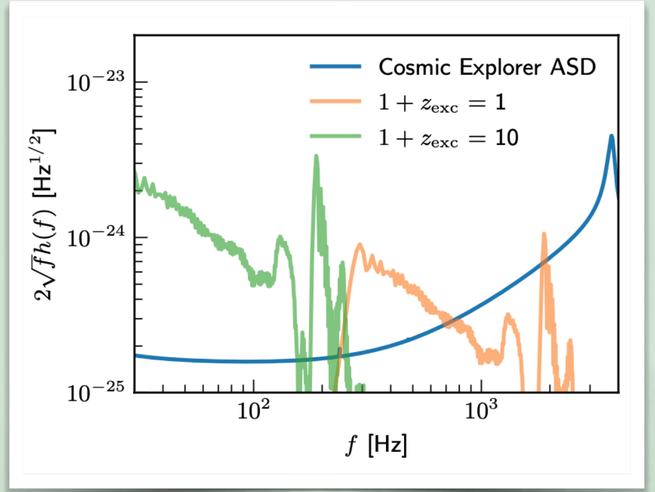
国外b-EMRI研究进展







- **The Weber events** (Weber 1969 PRL)
  - Repeated signal from the Galactic Center
  - 1000 times more powerful than binary black hole mergers
  - Lensing: Campbell & Matzner 73, Lawrence 73, Ohanian 73
- **GW bursts and echoes**
  - Lensing: Kocsis 13; D'Orazio & Loeb 20; Yu+21; Gondán & Kocsis 21
  - Shapiro delay (Sberna+22) and Graviton spin (Oanance+22)
  - Penrose process (Gong, Cao, XC, 21)
- **Neutron star equation of state**
  - Position and strength of the peaks inform structure
  - Redshifted signal (Vijaykumar+22)
- **Joint observation with LISA?**
  - GW dispersion, constrain graviton mass (Han & Chen 19)
  - SMBH resonates with binary (Cardoso+21)