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Gravitational Wave Astrophysics

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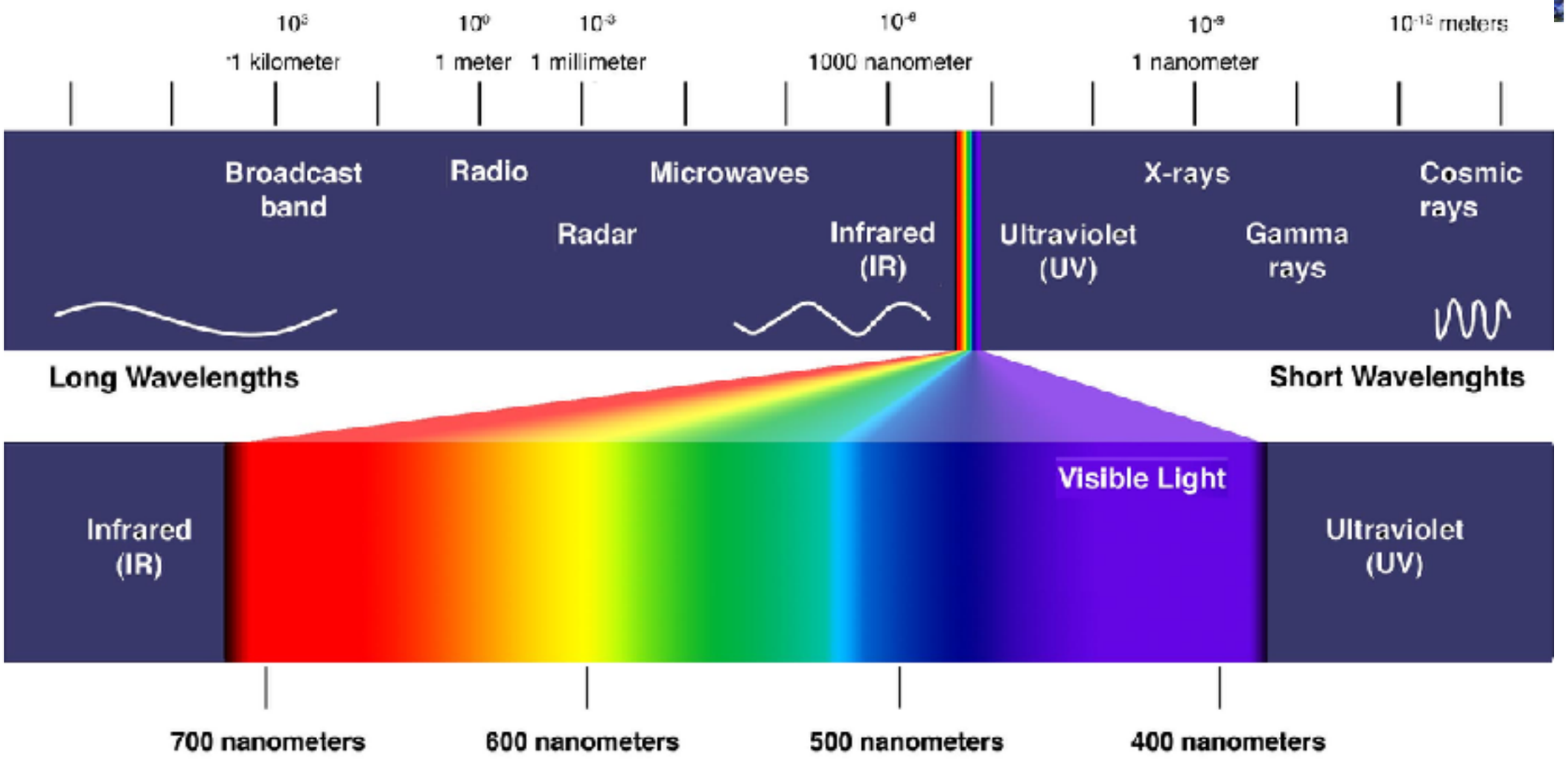
Outline

- Why do astronomers care about GWs?
- What kind of sources are out there?
- How do they form? (It is not obvious)
- What’s next? (My own work)

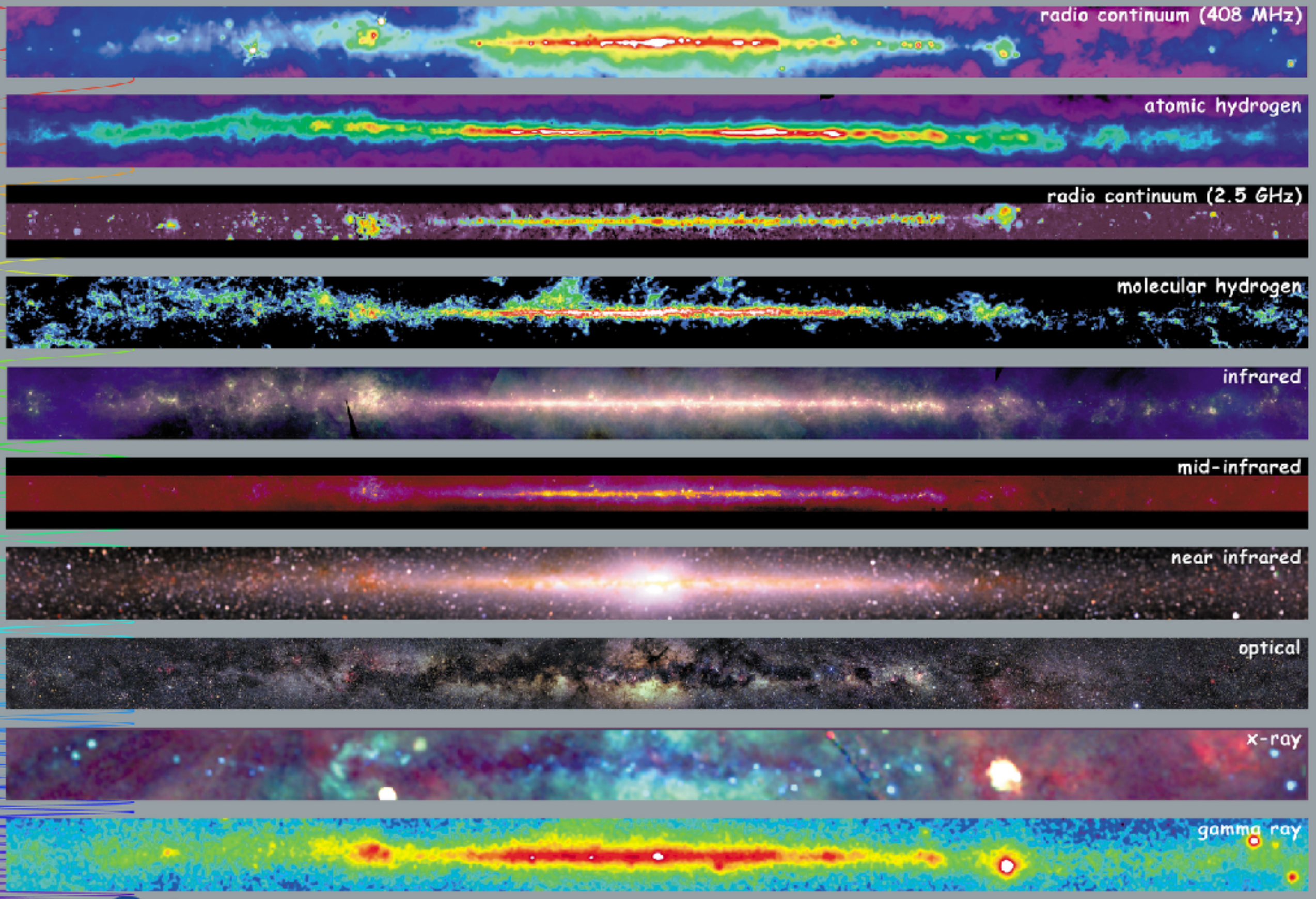
Why do we care: New Window

- Astronomers love new bands
  - For centuries: optical, stars



Why do we care: New Window

- Astronomers love new bands
  - **1910: electrometers, cosmic rays
  - **1930s: radio, quasars, pulsars
  - **1940: X-ray, X-ray binaries (neutron stars, black holes)
  - **1960s: microwave, comic microwave background
  - late 1960: gamma-ray, gamma-ray bursts (massive collapse, neutron star mergers)
  - **1970: neutrino, fundamental forces
  - 1990: infrared, Sgr A* is a supermassive black hole

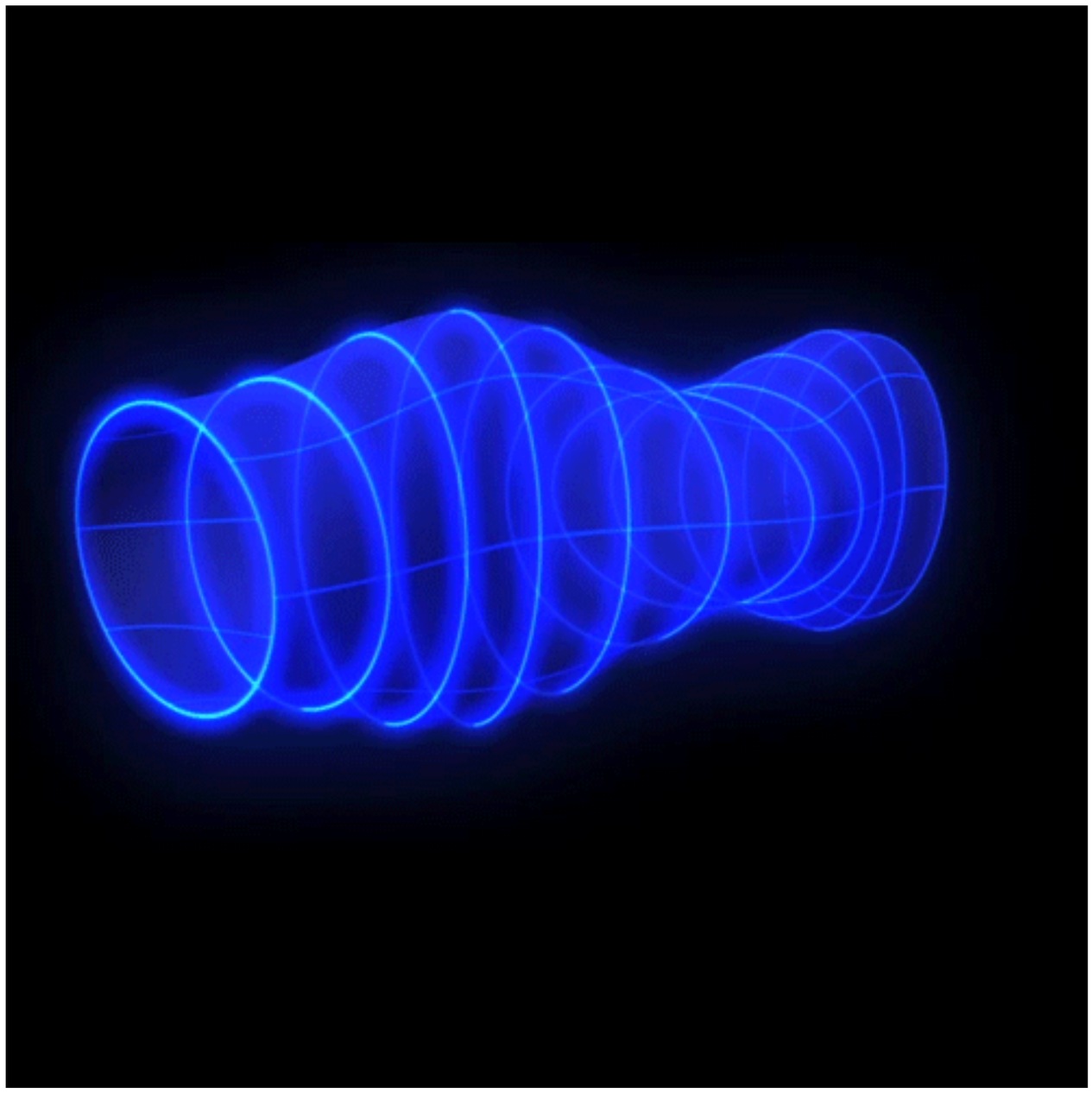


Multiwavelength Milky Way

http://antwrp.gsfc.nasa.gov/mw

Gravitational Waves

- Acceleration
  - Charge dipole: EM radiation
  - Mass quadrupole: GW



Why do we care: Advantages

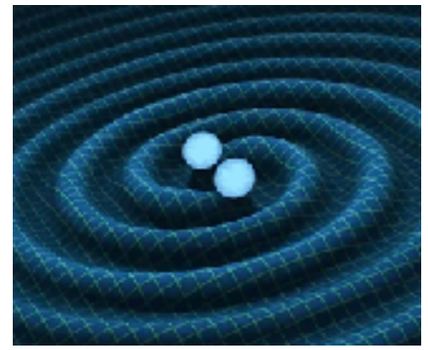
(K. Thorne 1995)

- GWs are not absorbed:
  - Light waves easily interact with atoms
  - GWs couple very weakly with matter (deep and far)
- GWs reveal matter in ACTION:
  - Acceleration of quadruple moment $h \sim \frac{G}{c^4}\frac{\ddot{\mathcal{I}}}{D}$
  - While light waves reflect thermal dynamical state of matter
  - Photos v.s. movies

Why do we care: Surprises?

(Credit: Pau Amaro-Seoane)

What are out there: Sources?



$$h \sim \frac{G}{c^4}\frac{\ddot{\mathcal{I}}}{D}$$

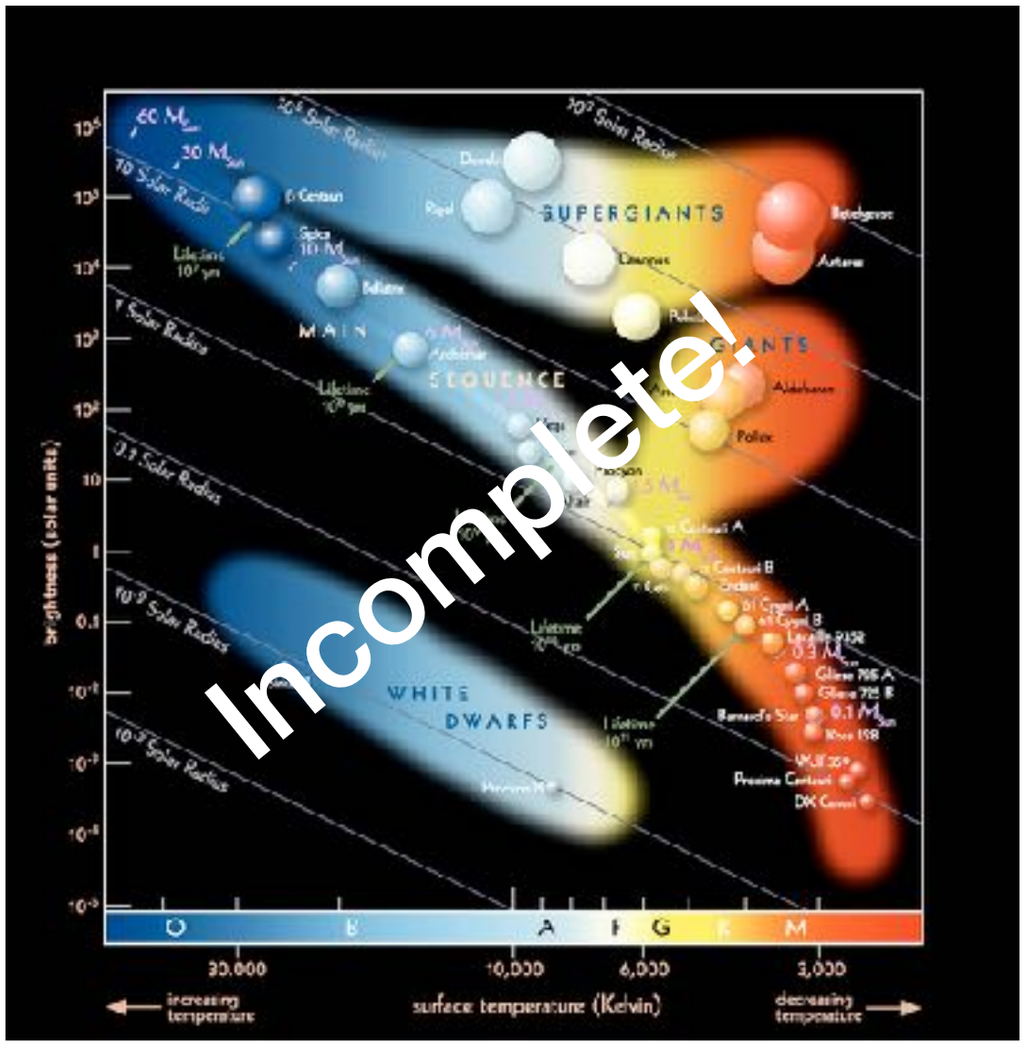
$$h \sim \frac{m_1}{D}\frac{m_2}{a}$$

$G \simeq 6.67 \times 10^{-8}\,\mathrm{cm}^3\,\mathrm{g}^{-1}\,\mathrm{s}^{-2}$

$c \simeq 3 \times 10^{10}\,\mathrm{cm\,s}^{-1}$

$\mathrm{Imagin:\ Two\ test\ mass\ 10\,m\ apart,\ each\ of\ 1\ ton,}$

$h \sim 10^{-40}$



Astronomers know massive bodies

$$M_{\mathrm{sun}} \simeq 2 \times 10^{33}\,\mathrm{g}$$

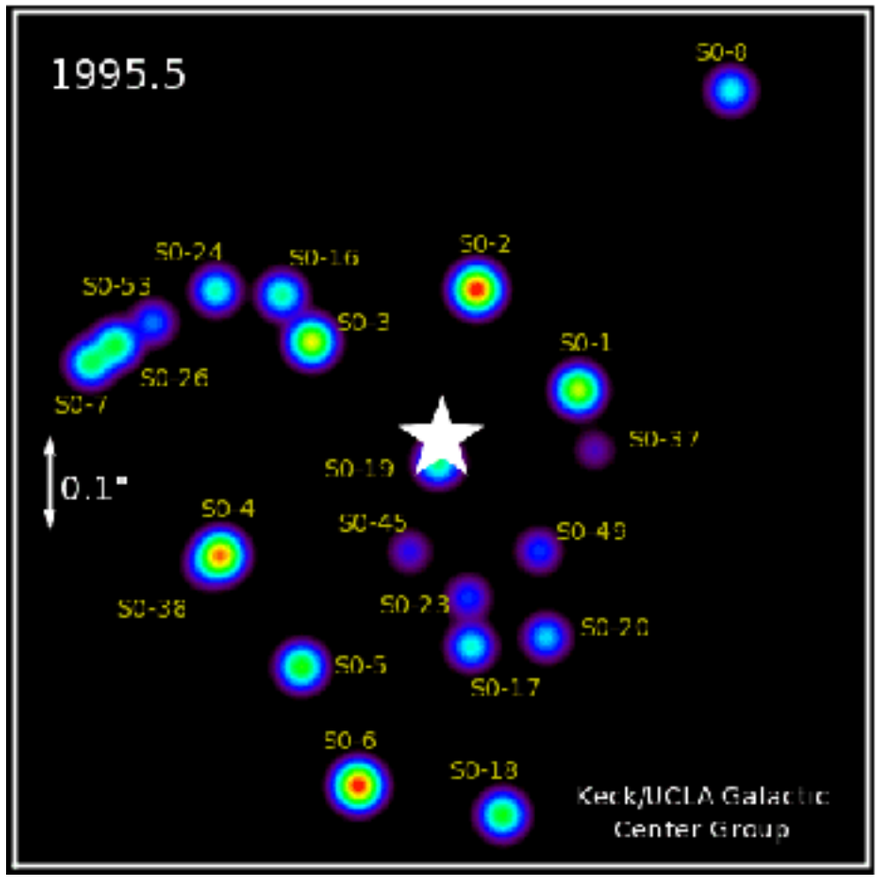
	Sun	White Dwarf	Neutron Star	Black Hole
Mass (Msun)	1	1	2	10
Radius (km)	7E+05	6E+03	10.0	30
M/R	1.4E-06	1.7E-04	2.0E-01	3.3E-01

Compactness of stellar objects

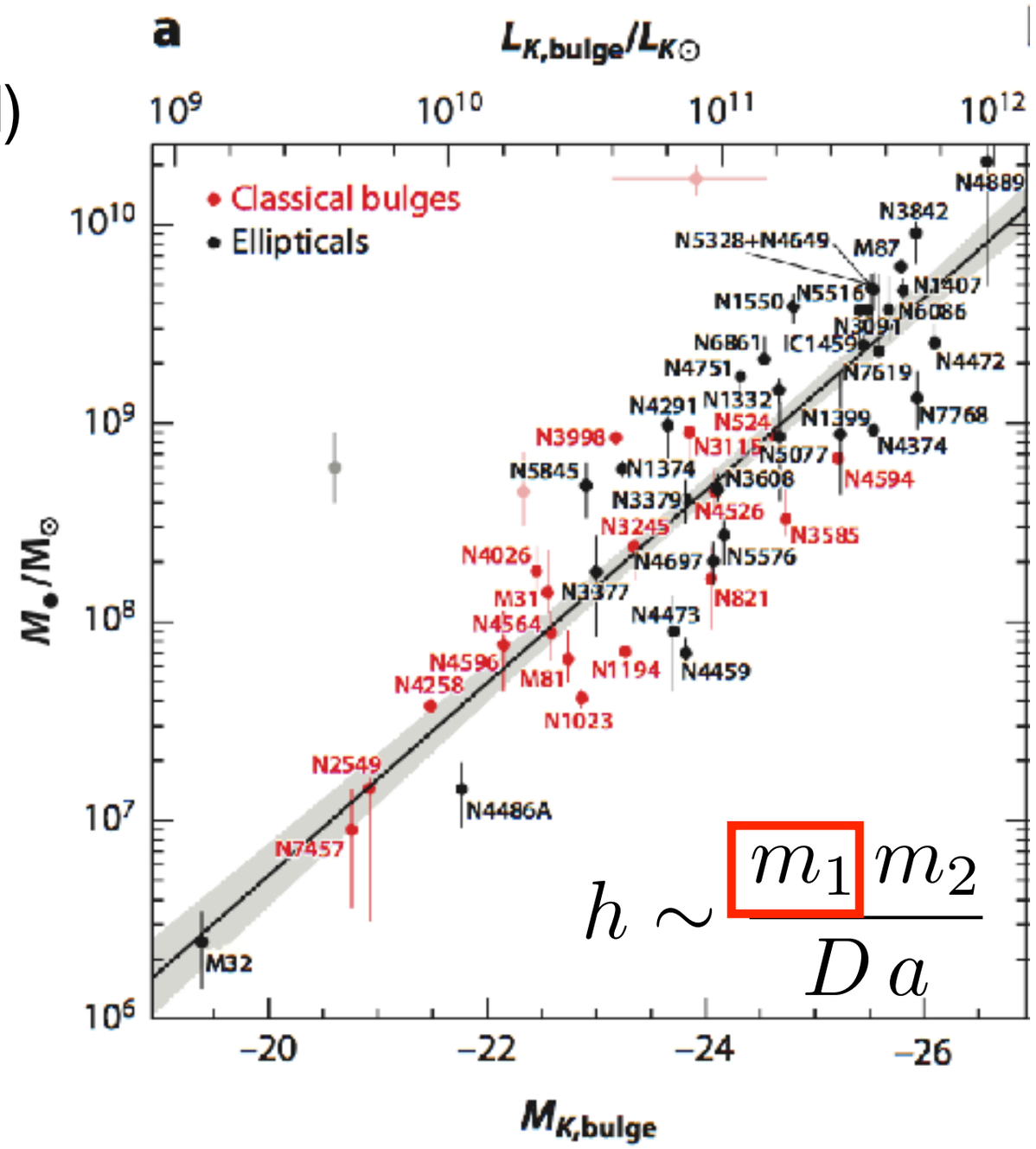
What are out there: Compact Objects

Supermassive black hole (SMBH)

$$10^6 \sim 10^9\, M_\odot$$



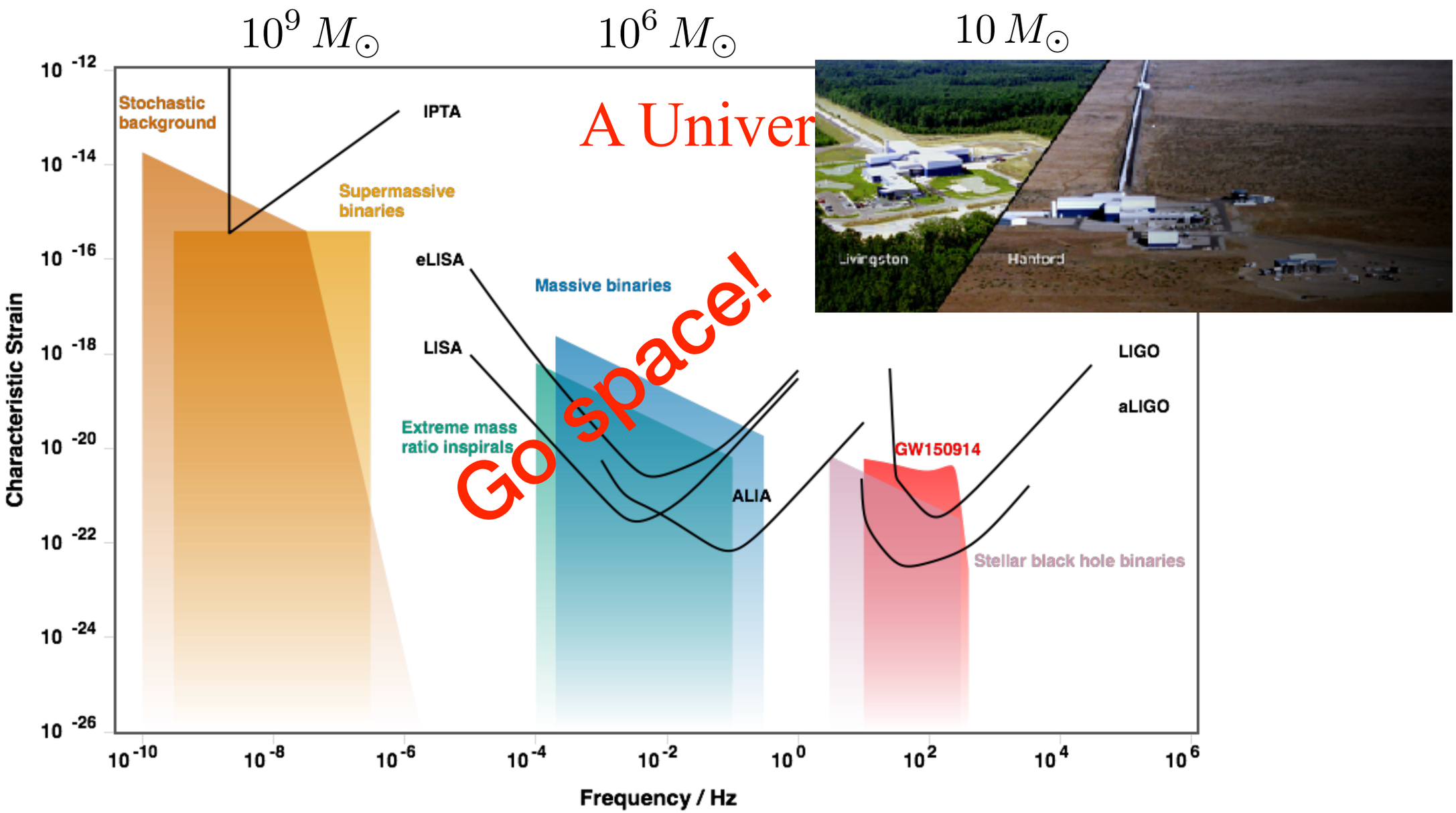
$$v = \sqrt{G(m_1 + m_2)/r}$$



(Kormendy & Ho 2013)

How do they sound?

$$f = \frac{1}{\pi}\sqrt{\frac{GM}{a^3}} \propto \frac{1}{M} \quad \text{because } a_{\min} \sim GM/c^2$$



Laser Interferometer Space Antenna

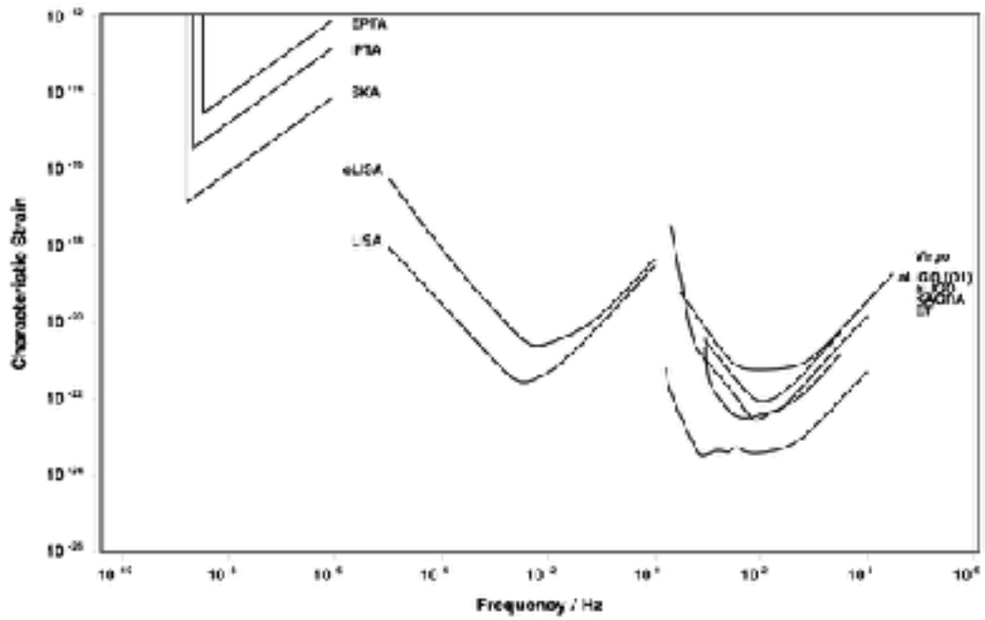
LISA

We are “Gravitational wave astronomy-Beijing”

LISA associate group

What's in LISA: Compact Binaries

- WDs, NSs, SBHs, SMBHs
- Keplerian frequency ~ mHz



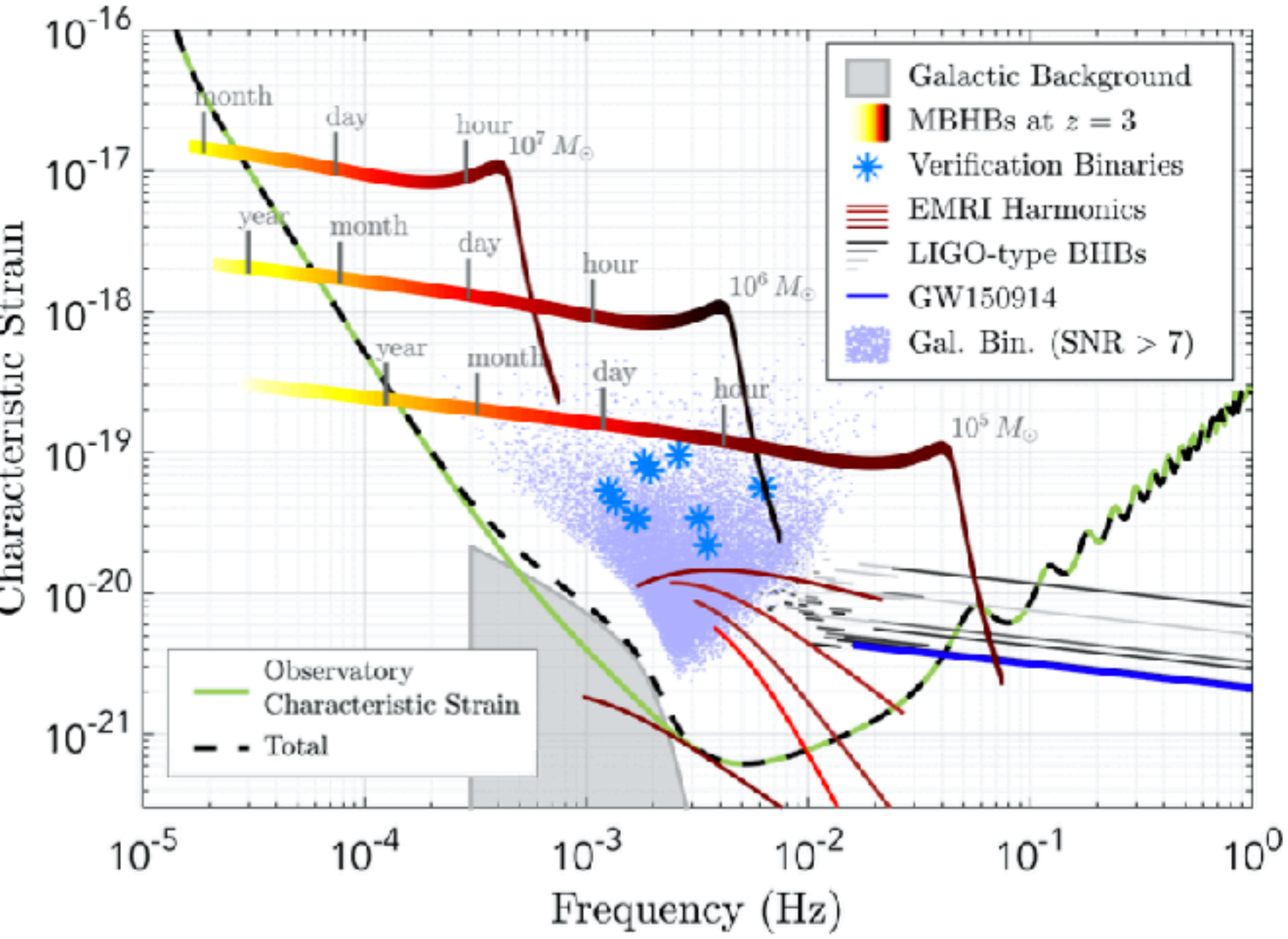
$$f = \frac{1}{\pi}\sqrt{\frac{G(m_1+m_2)}{a^3}}$$

$$\text{WD/NS} \quad \simeq 2.00\times10^{-3}\left(\frac{m_1+m_2}{1\,M_\odot}\right)^{1/2}\left(\frac{a}{10^{-3}\ \text{AU}}\right)^{-3/2}\ \text{Hz}$$

$$\text{SBH} \quad \simeq 3.17\times10^{-3}\left(\frac{m_1+m_2}{20\,M_\odot}\right)^{-1}\left(\frac{a}{10^{4}\,r_S}\right)^{-3/2}\ \text{Hz}$$

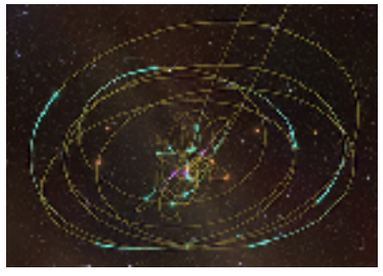
$$\text{SMBH} \quad \simeq 2.00\times10^{-3}\left(\frac{m_1+m_2}{10^{6}\,M_\odot}\right)^{-1}\left(\frac{a}{10\,r_S}\right)^{-3/2}\ \text{Hz}$$

What are out there: A Bucket of Binaries



- Stellar binaries
  - WD-WD
  - SBH-SBH
  - NS-NS
- Supermassive Black Hole Binaries (SMBHBs)
- Extreme Mass Ratio Inspirals (EMRIs)

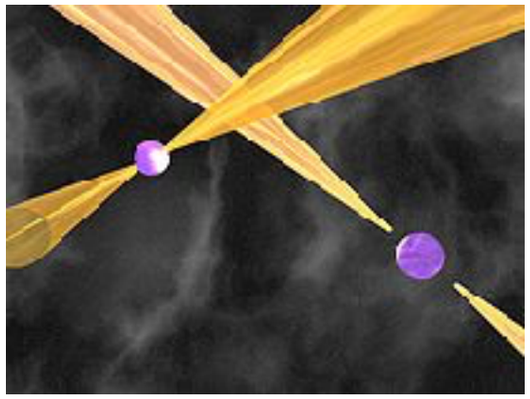
Formation: General Picture

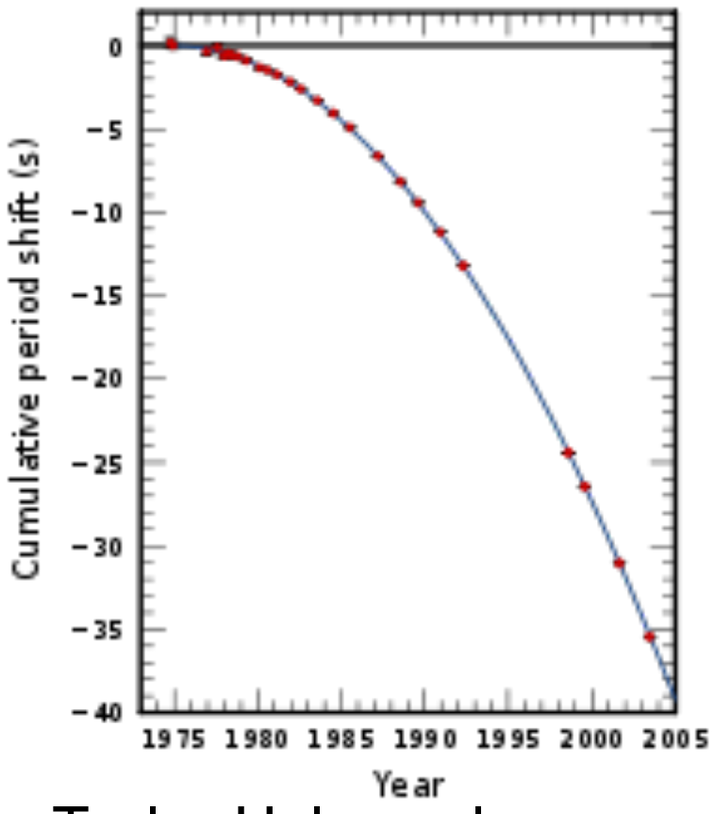


- Scales (in km)
  - WD: 6000, NS: 10; SBH: 30, SMBH: 3e6
  - Galaxy: 3e17; Mean stellar distance: 3e13
  - Globular cluster: 1e14; Mean stellar distance: 3e11
  - Galaxy center: 3e13; Closest distance (S2 star): 1e11

- 10^{10}:Imagine two 1mm dust particles in Earth atmosphere
- Two bodies form close enough+lose energy efficiently (not GW rad.)

Formation: Stellar Binaries



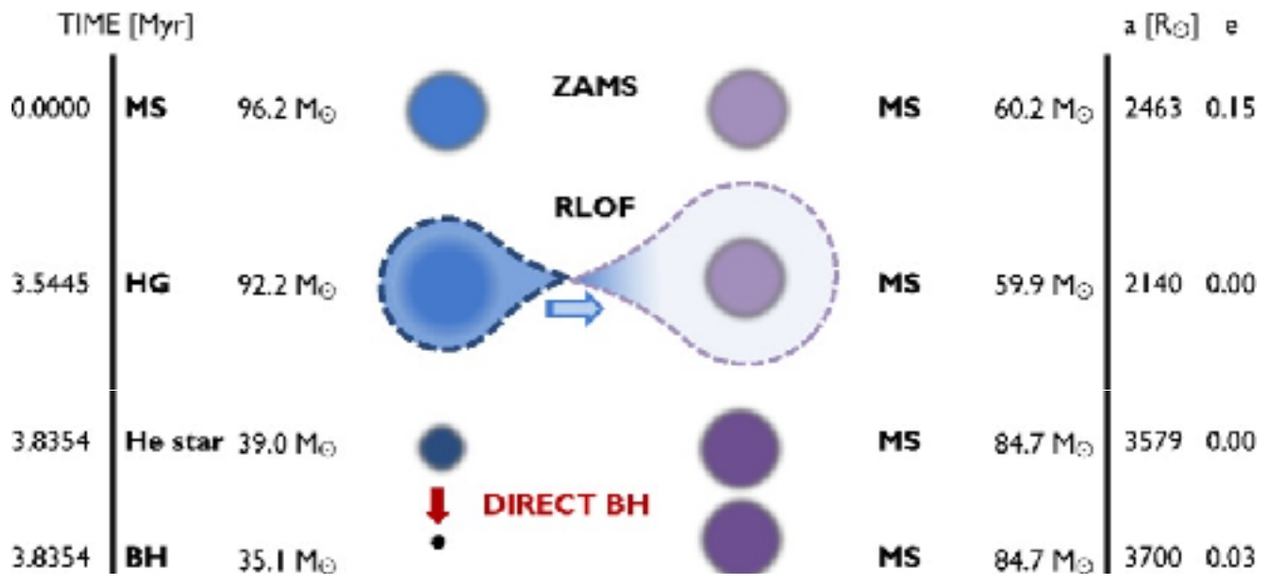


Taylor-Hulse pulsar

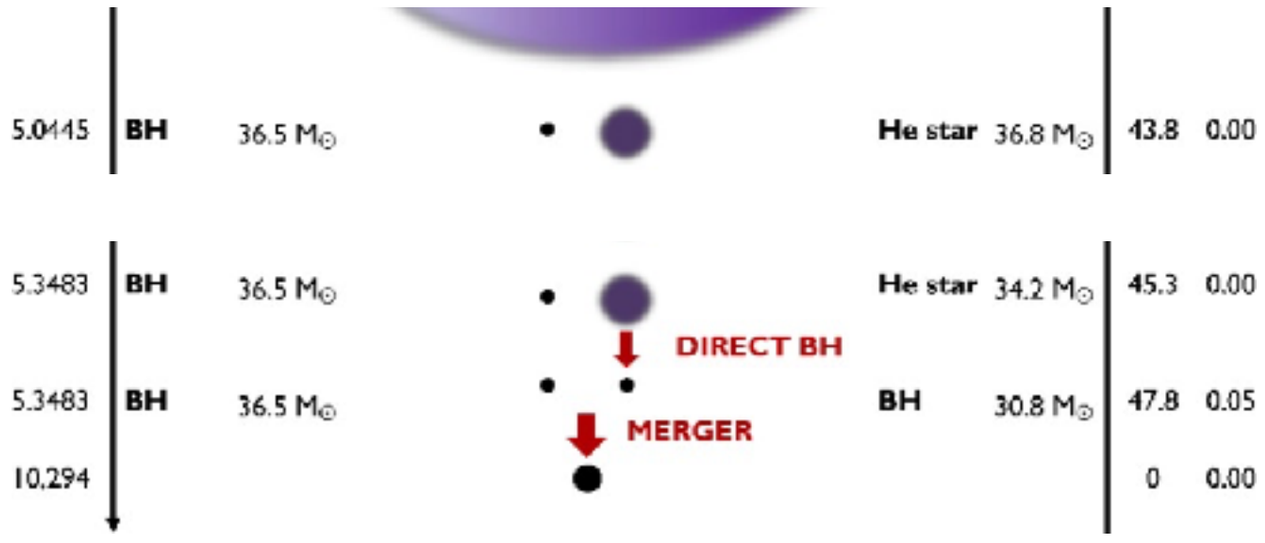
1993 Nobel Prize

Semi-major axis: 2e5 km

Decay time: 3e8 yrs



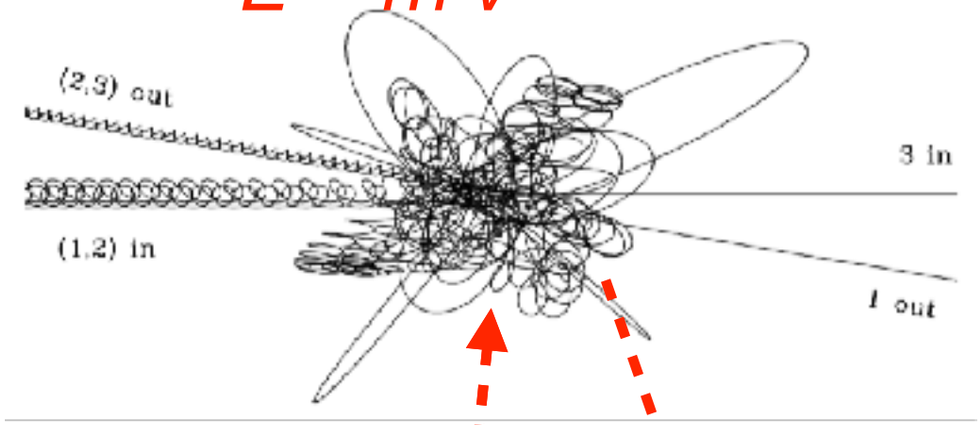
50% of massive stars were born in binaries

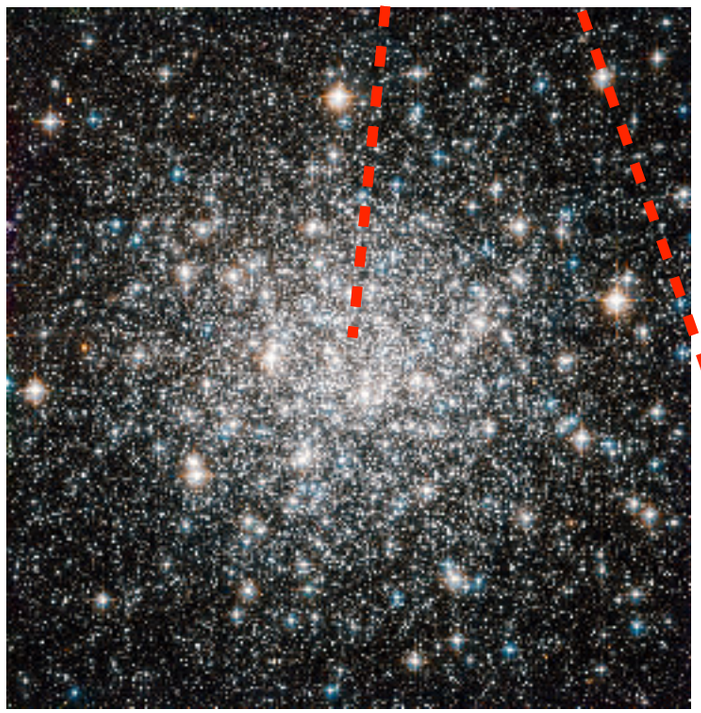


(Field binaries. e.g. Belczynski et al. 16)

Formation: Stellar Binaries

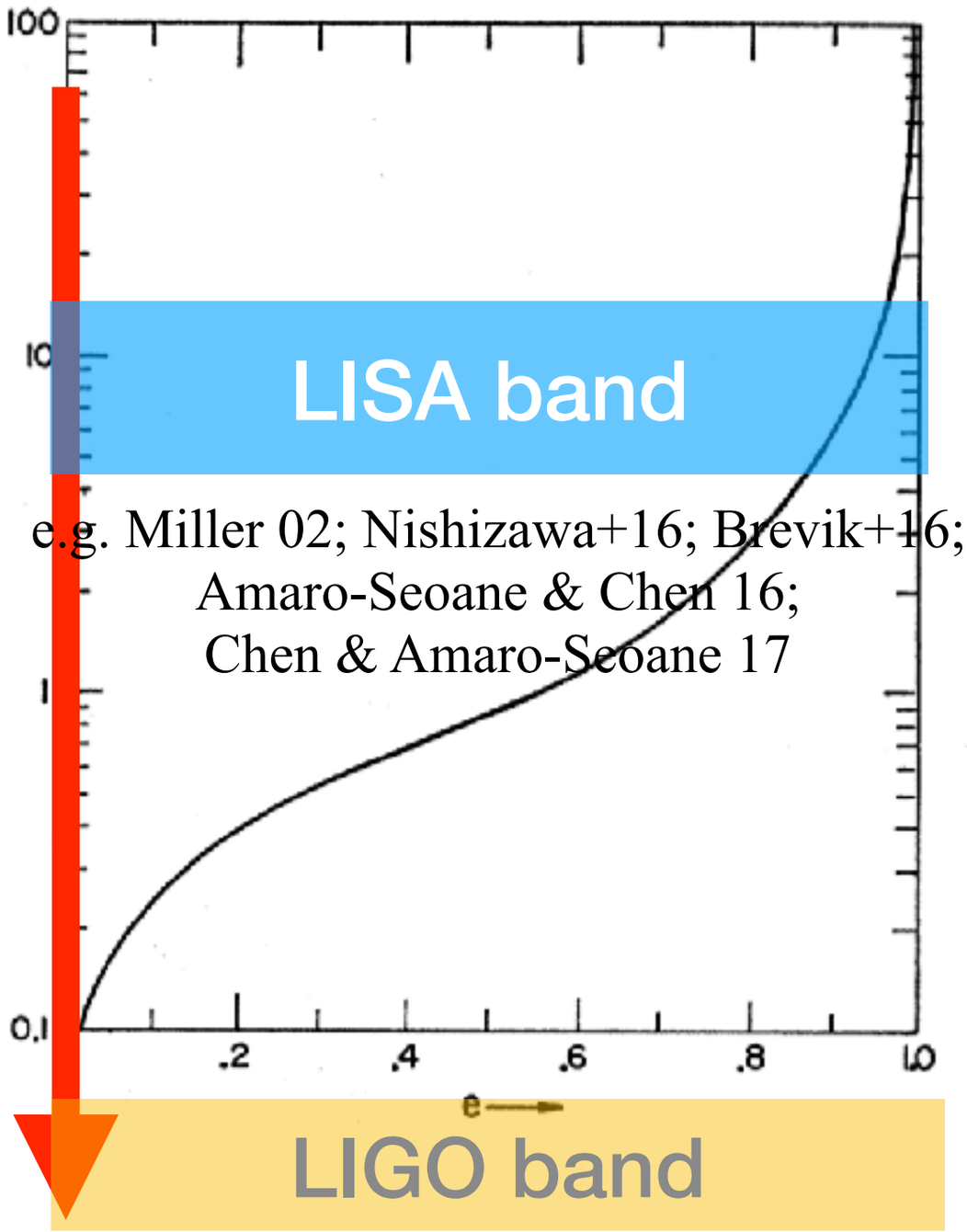
$E \sim m\, v^2$





(Dynamical binaries.
e.g. Rodriguez et al. 16)

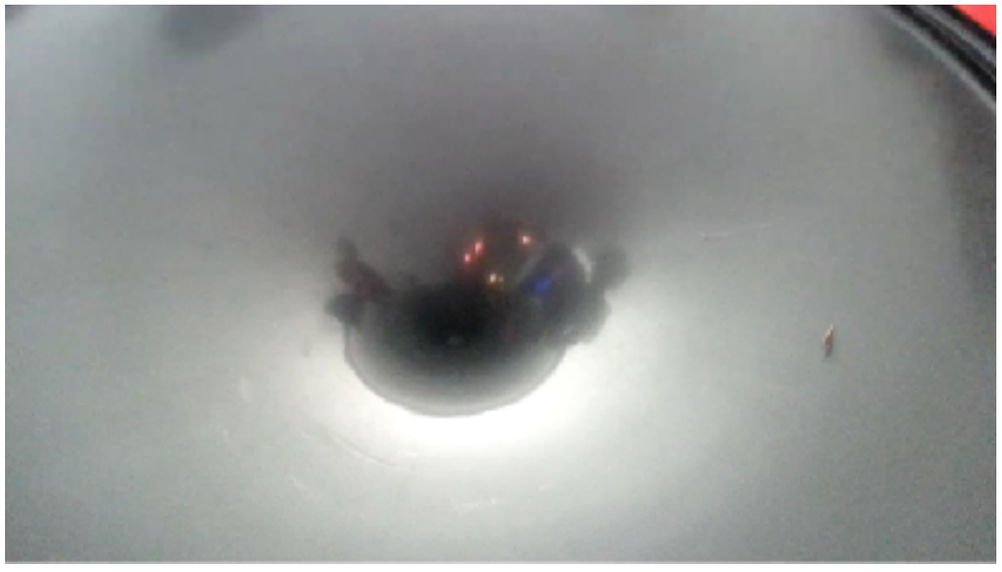
Distinguish different binaries



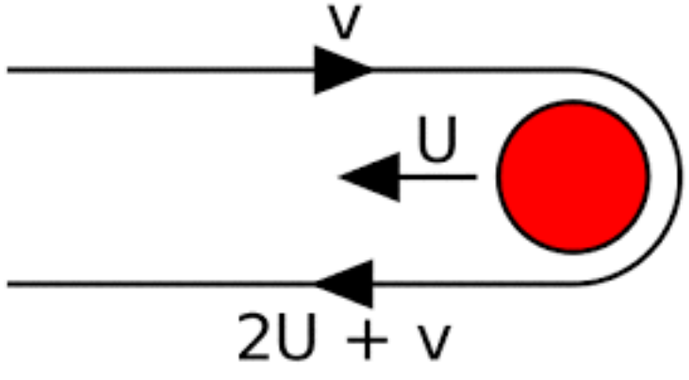
e.g. Miller 02; Nishizawa+16; Brevik+16;
Amaro-Seoane & Chen 16;
Chen & Amaro-Seoane 17

Formation: SMBH Binaries

- Scales (in km)
  - SMBH: 3e6 km; Galaxy: 3e17; Mean Galaxy distance: 3e19



- Galaxies merge

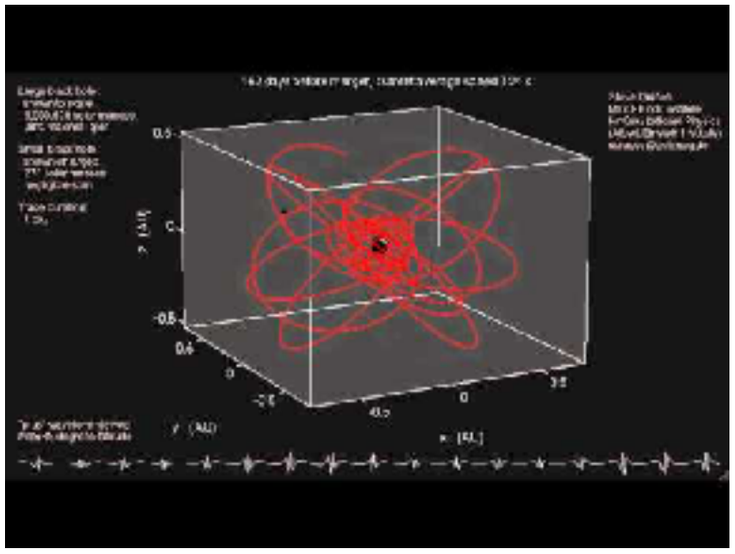


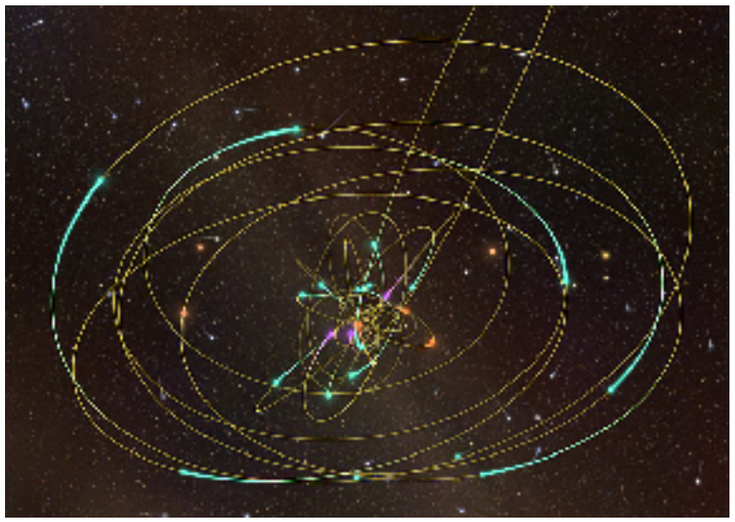
- Dynamical friction

- The “final parsec (3e13 km)” problem (e.g. Begelman+1980, Merritt & Milosavljevic 05; Berczik+05,06; Chen+08,09,11)

Formation: EMRIs

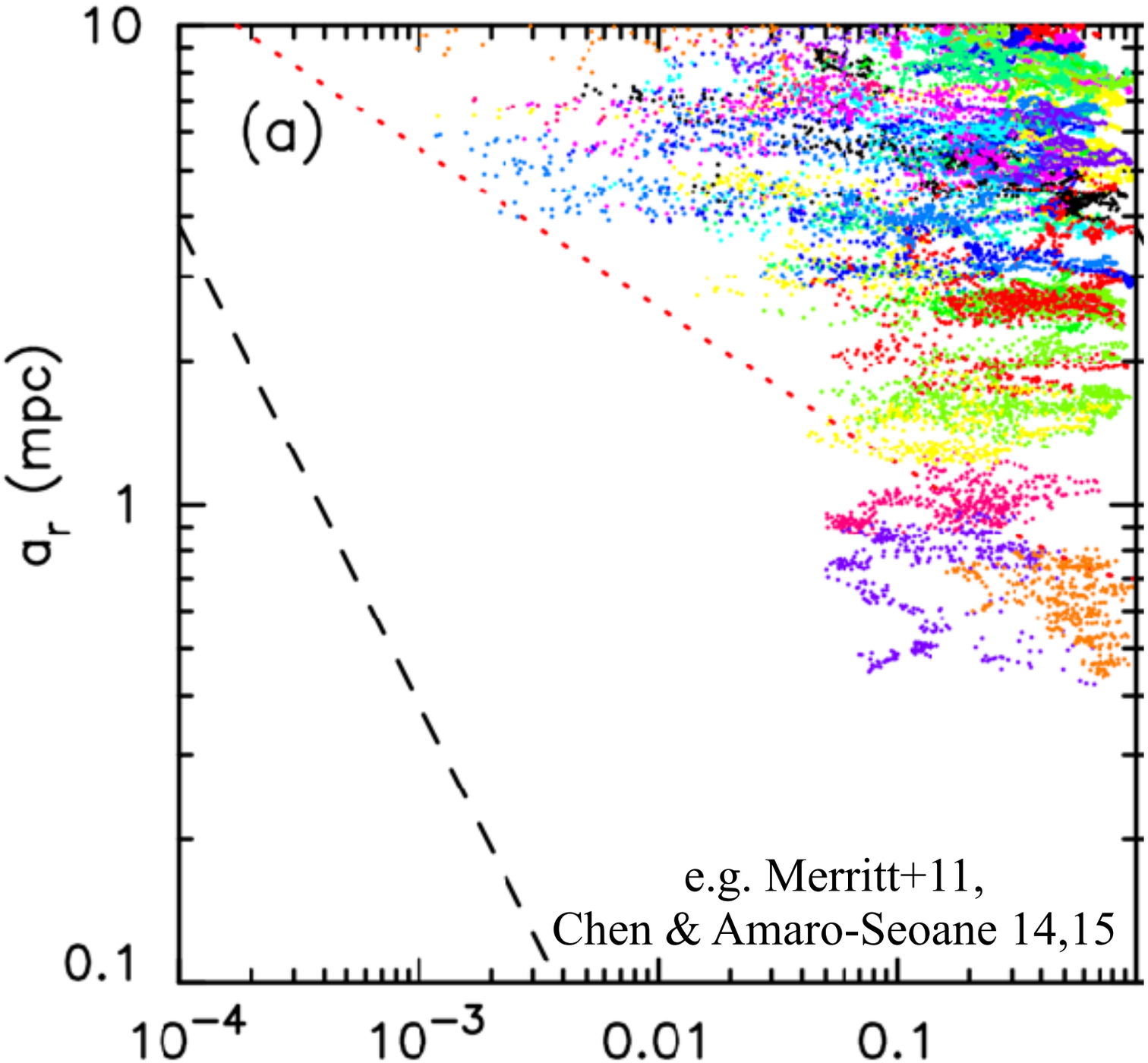
Credit: S. Drasco



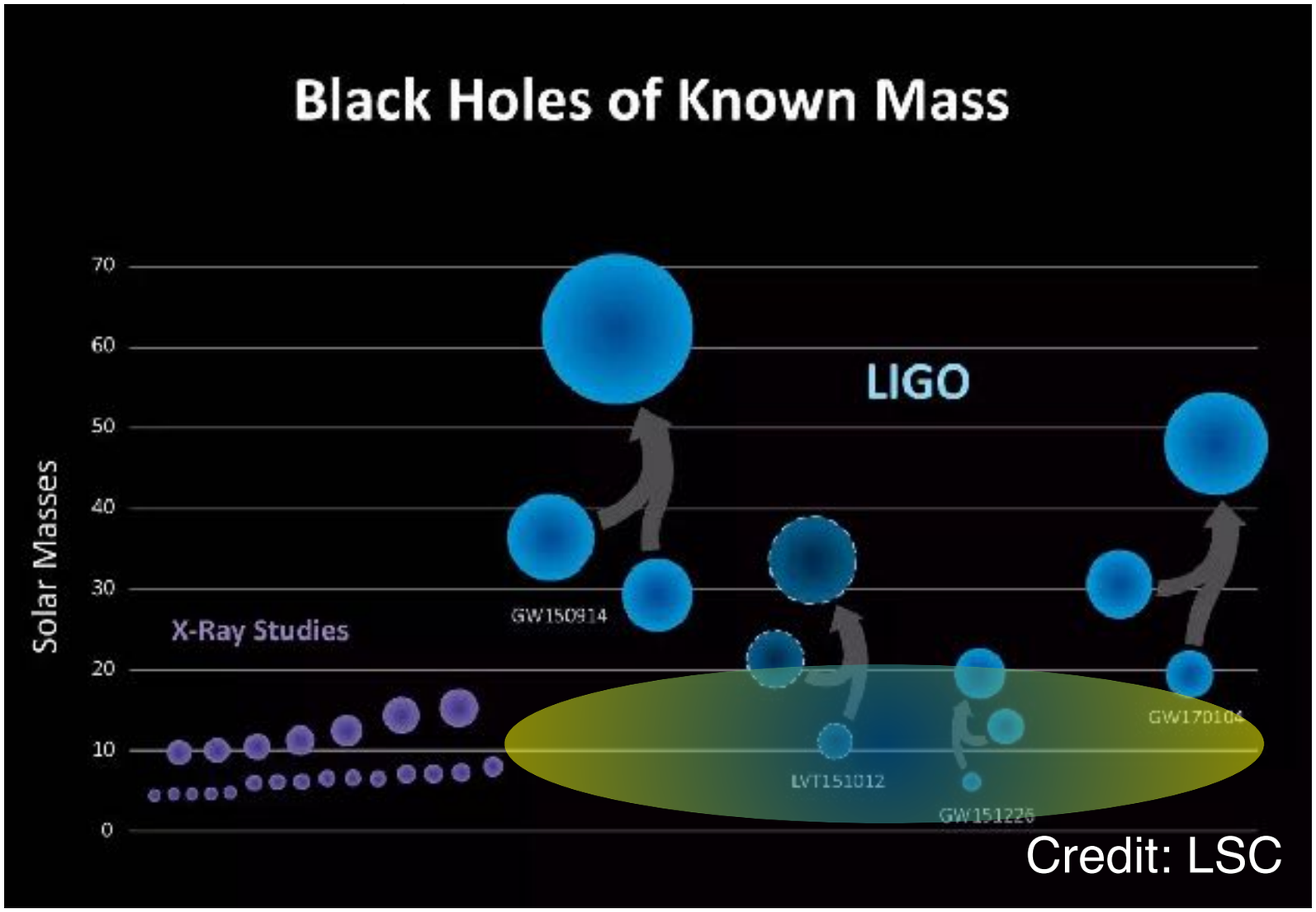


Credit: UCLA Galactic Center Group

SMBH: 1e7 km; SBH: 30 km

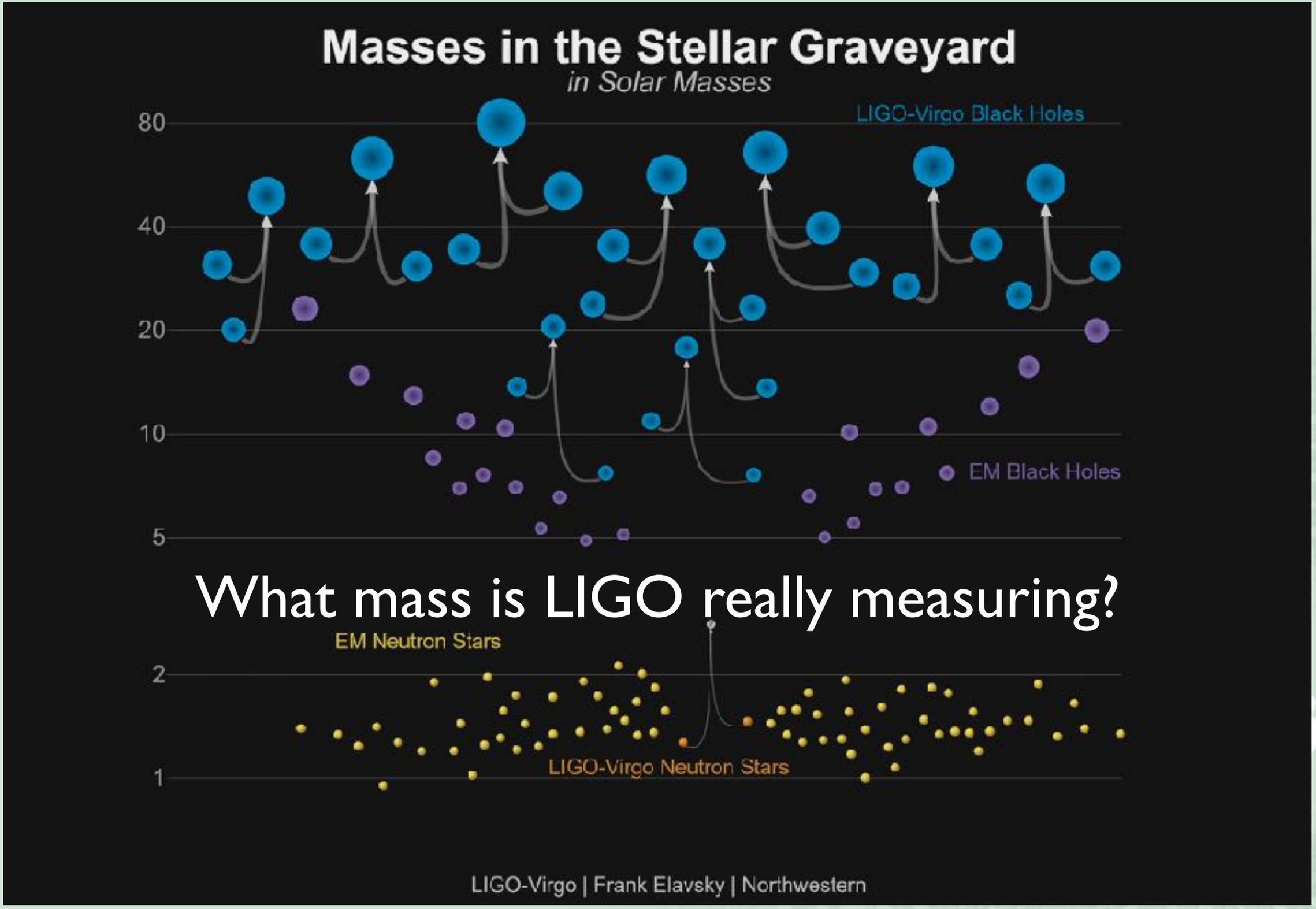


What's Next: Let's make a prediction

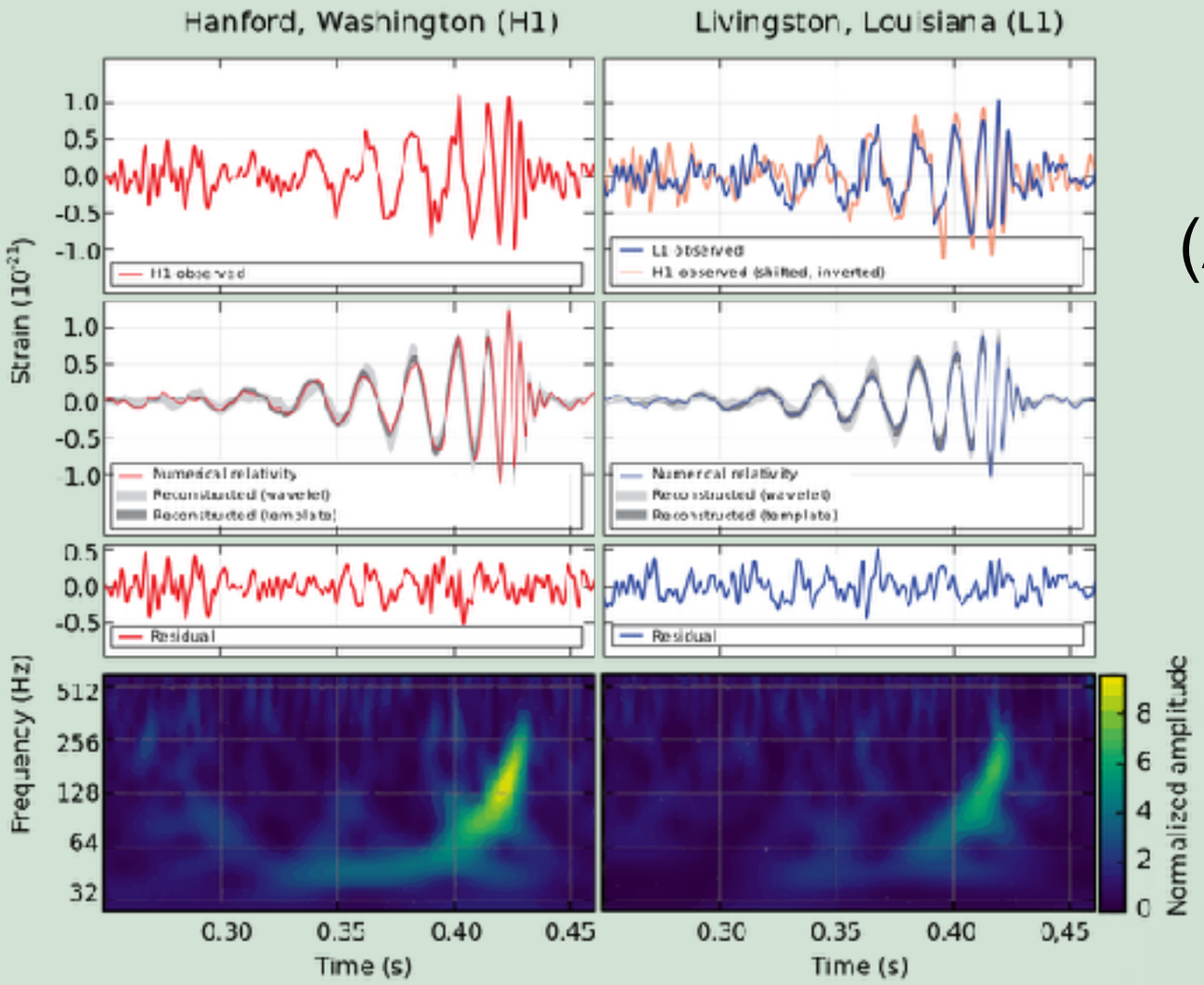


- Explanations: Low metallicity, primordial black hole, redshift (Chen+17)…

LIGO/Virgo detected GWs, but…



Measurement



Observables: the chirp

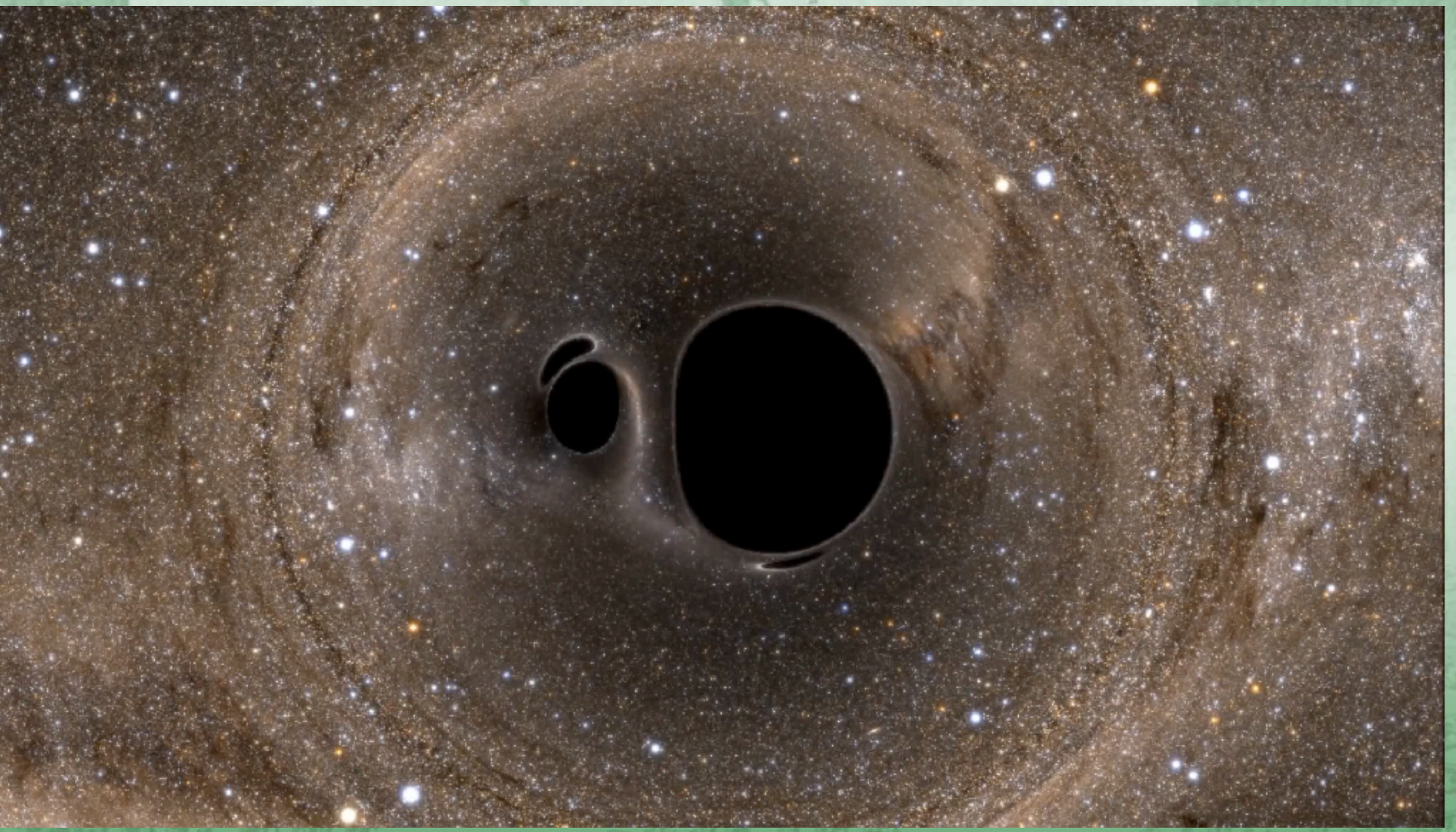
(Abbott et al. 2016, THE paper)

- $h(m1, m2, a)$
- $f(m1, m2, a)$
- df/dt (m1, m2, a)

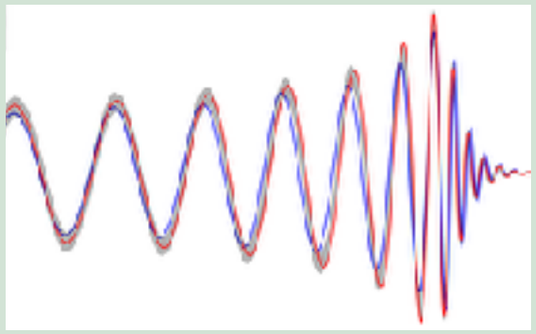
$$\mathcal{M} := \left(\frac{5 f^{-11/3} \dot{f}}{96 \pi^{8/3}} \right)^{3/5} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

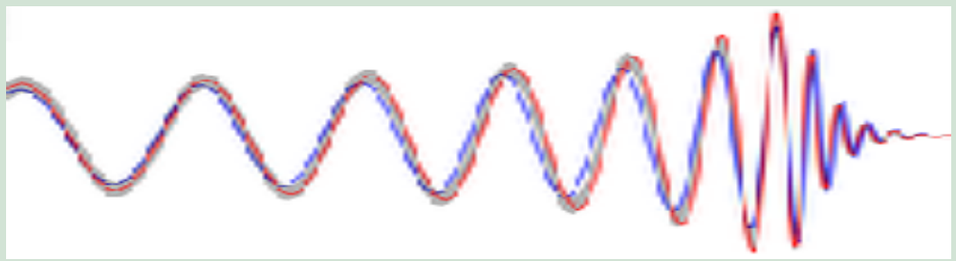
$$d = (4\mathcal{M}/h) \, (\pi f \mathcal{M})^{2/3}$$

The sound of black hole collision



Mass-redshift degeneracy





- All types of redshift:

$$f_o = f(1+z)^{-1}$$

$$\dot{f}_o = \dot{f}(1+z)^{-2}$$

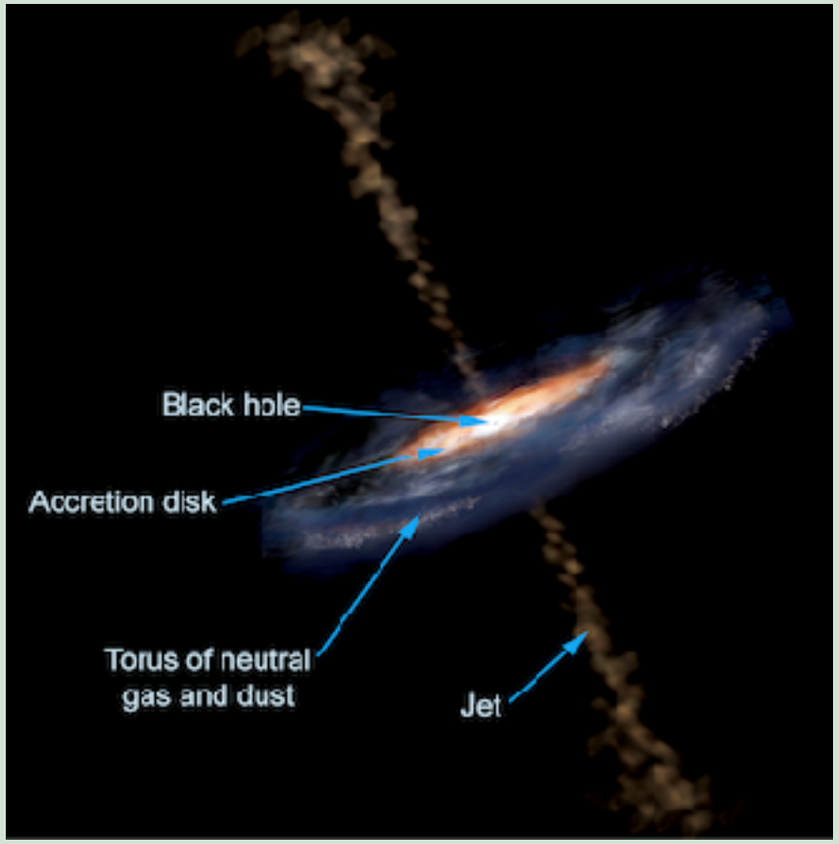
$$\mathcal{M}_o := \left(\frac{5 f_o^{-11/3}\dot{f}_o}{96\pi^{8/3}}\right)^{3/5} = \mathcal{M}(1+z)$$

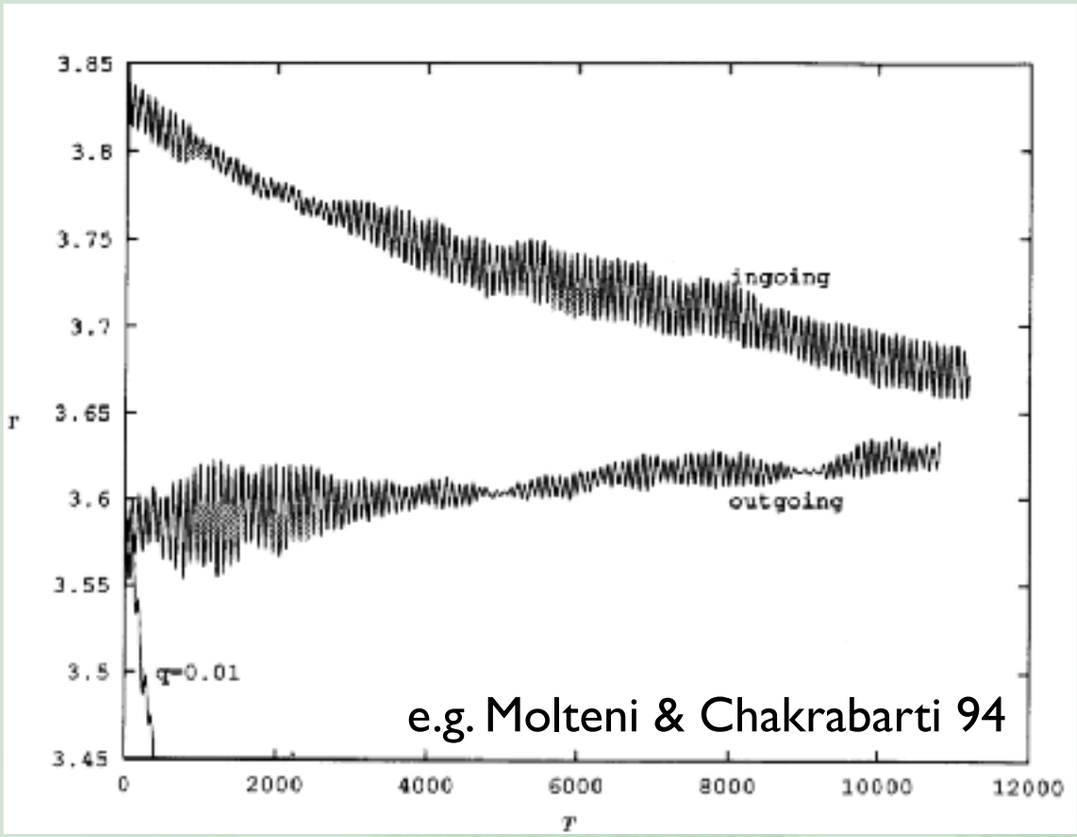
Why haven't people considered redshifts??

- Types of redshift:
  - Cosmological
  - Doppler (need a velocity close to *c*)
  - Gravitational (have to be close to the Schwarzschild radius)

- Formation channels:
  - Conventional: Galaxy disk/bulge or globular clusters —> Low velocity and shallow potential
  - Recent view: Enhancement of mergers close to a supermassive black hole (>10^6 Msun) because
    - Large escape velocity for compact objects
    - Mass segregation effect
    - Tidal perturbation of binaries by the supermassive black hole
    - Hydrodynamical drag if inside an active galactic nucleus (AGN)
    - See Chen, Li & Cao 2017 arXiv:1703.10543, for a brief review

Astrophysical scenarios





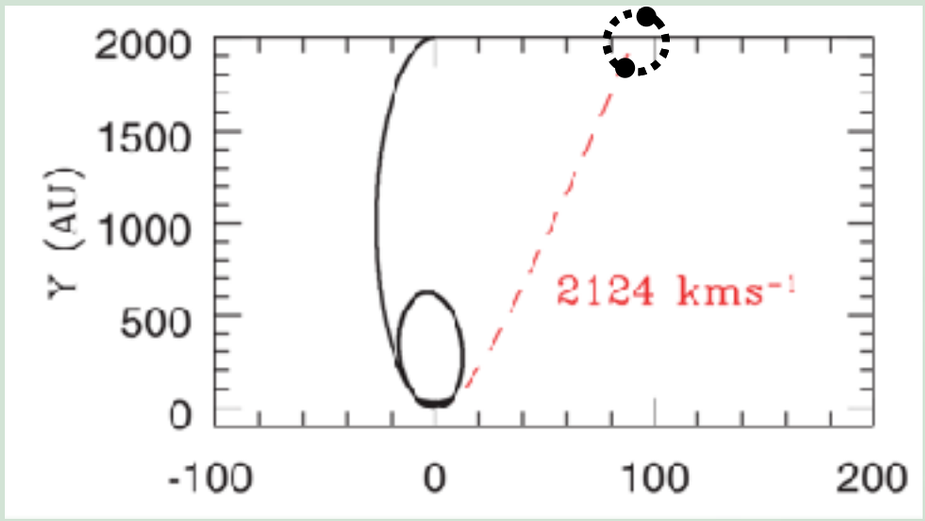
- One scenario: Trapped in AGN disks:
  - Star capture and growth in disk leads to BH formation (e.g. Syer 91, Goodman04)
  - Event rate: 1-10^4 per Gpc^3 per year? (Bartos+17, Stone+17, McKernan+18, Antoni+19)
  - Trapping radius:

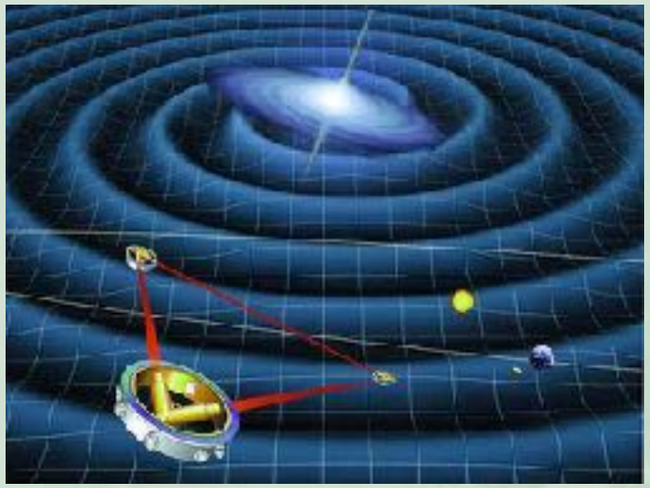
$$\frac{r}{R_S} \simeq 15\,\dot{m}^{-2/7}\left(\frac{M_3}{10^9\,M_\odot}\right)^{-4/7}\left(\frac{m}{20\,M_\odot}\right)^{4/7}$$

Another scenario: Tidal capture

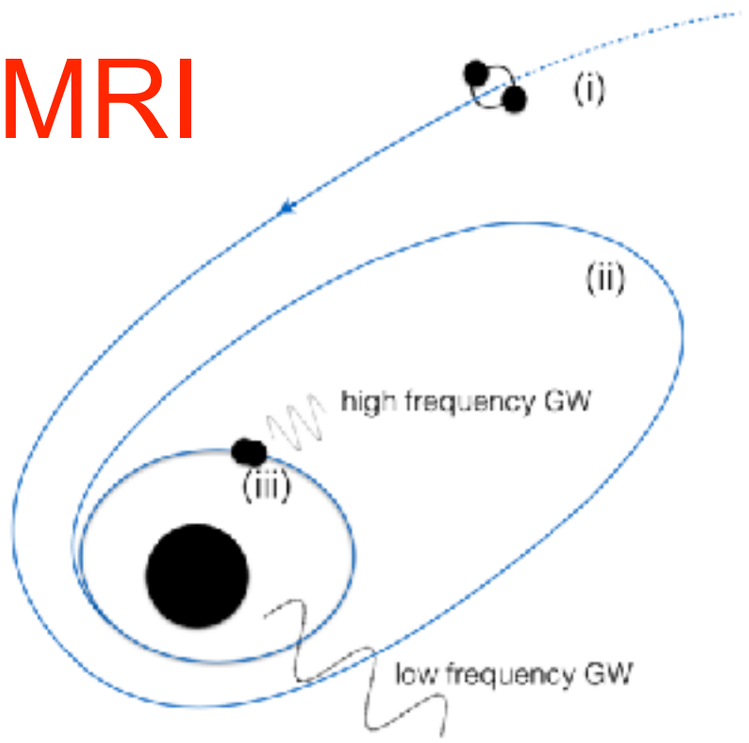
(XC & Han 2018 CommsPhy)

- Extreme-mass-ratio inspiral (EMRI)
  - Form at tidal radius, GW mHz, LISA/TaiJi/TianQin source





b-EMRI

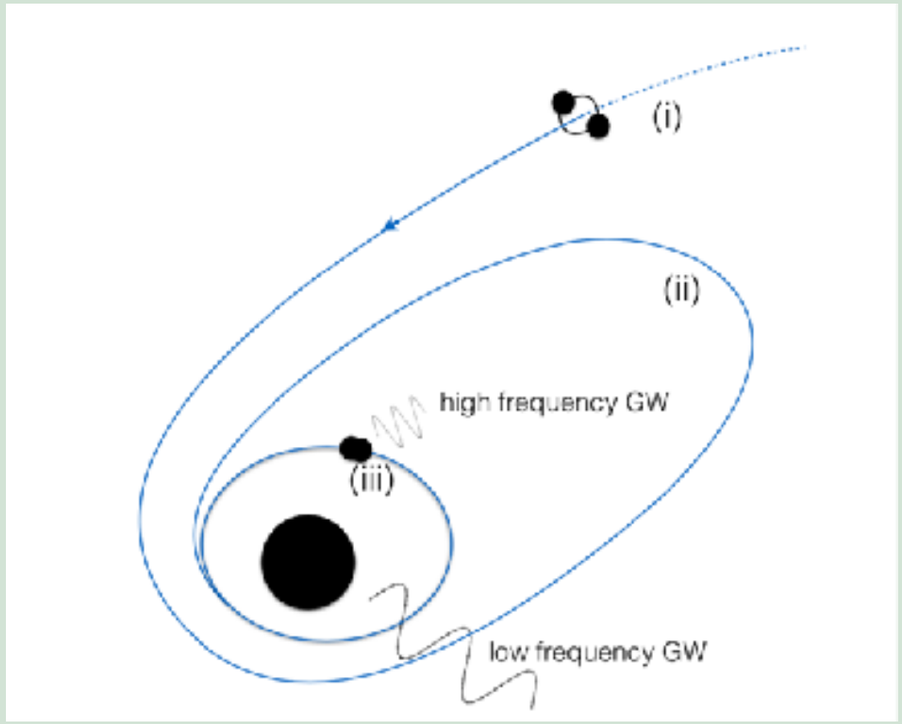


- Tidal capture of BBHs:
  - according to Hills 91, Addison, Laguna, Larson 2015

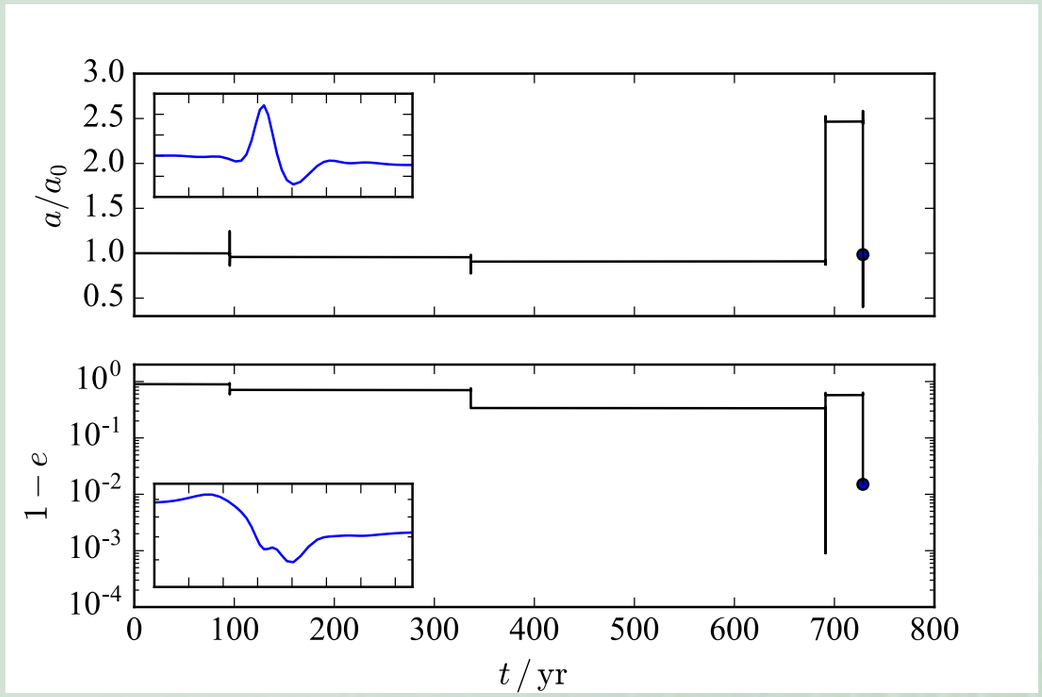
$$R_p \lesssim 21\, R_g \left(\frac{T_{\rm rlx}}{10^9\,{\rm yr}}\right)^{1/4} \frac{q^{3/8}}{(1+q)^{1/4}} \times \left(\frac{\eta}{0.1}\right)^{3/8} \left(\frac{m_1}{10\,M_\odot}\right)^{1/2} \left(\frac{M_3}{10^6\,M_\odot}\right)^{-3/4}.$$

  - Verified by our numerical scattering experiments

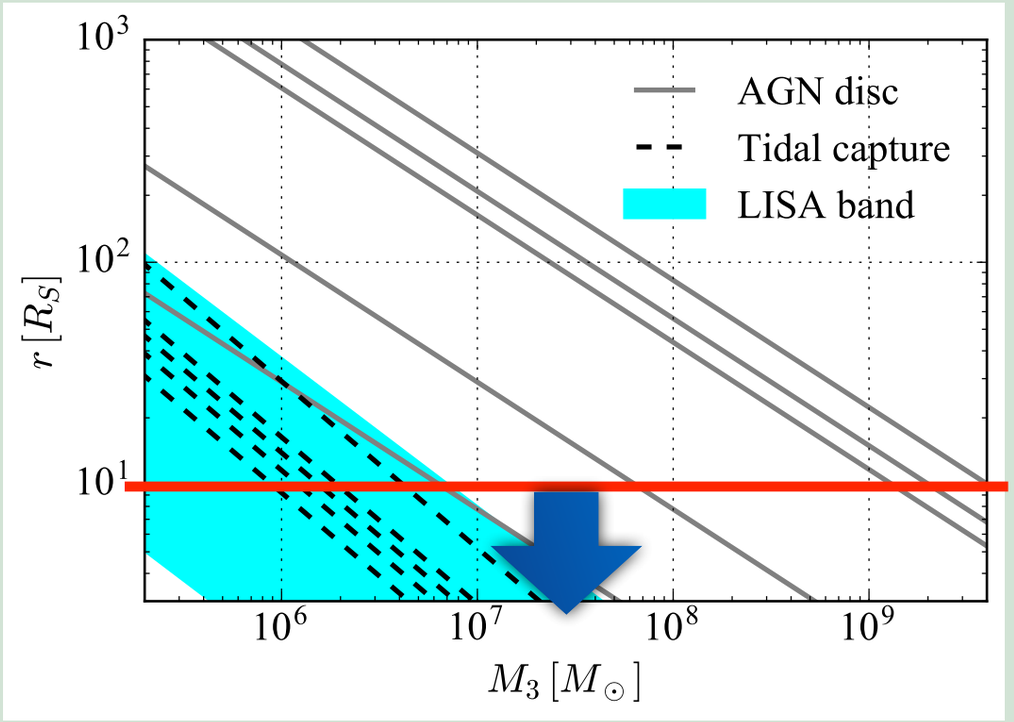
Long-term evolution of b-EMRIs



(XC & Han 2018 CommsPhy)



Capture radii (XC, Li & Cao, 2017)



- New features:
  - Eccentricity of the binary gets excited
  - Merger happens close to pericenter passage
  - 0.03 per Gpc^3 per year unless efficient loss cone filling

Multi-band GW astronomy

New sourc stronomy?

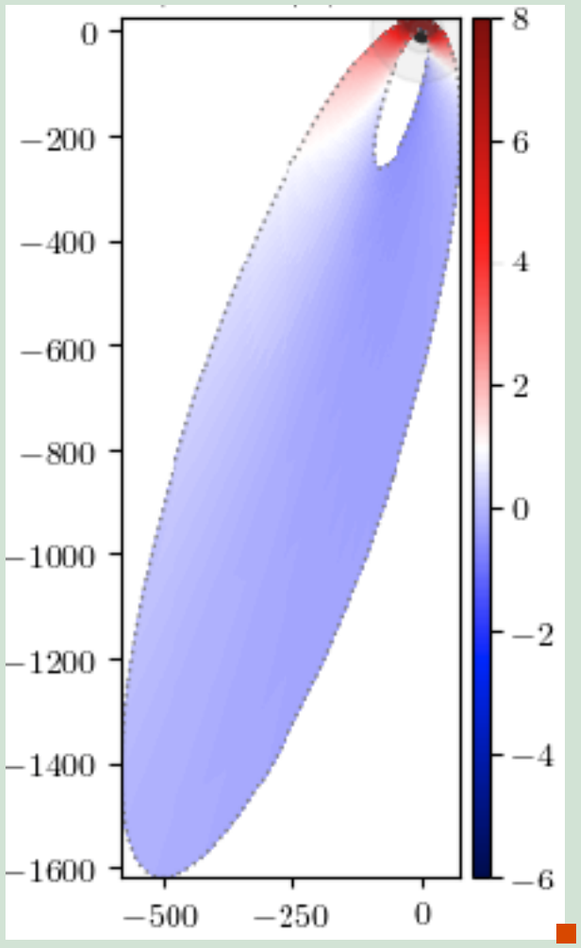
b-EMRI:b io Inspiral

Magnitude of this effect

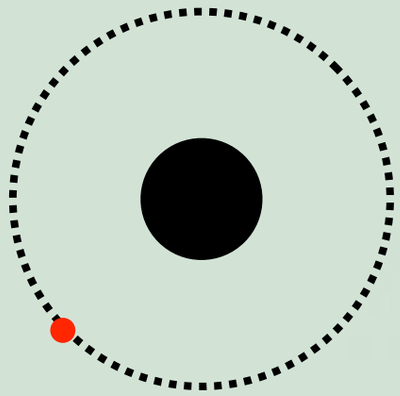
(Chen, Li, Cao, arXiv:1703.10543)

Redshift velocity

in unit of 10^4 km/s



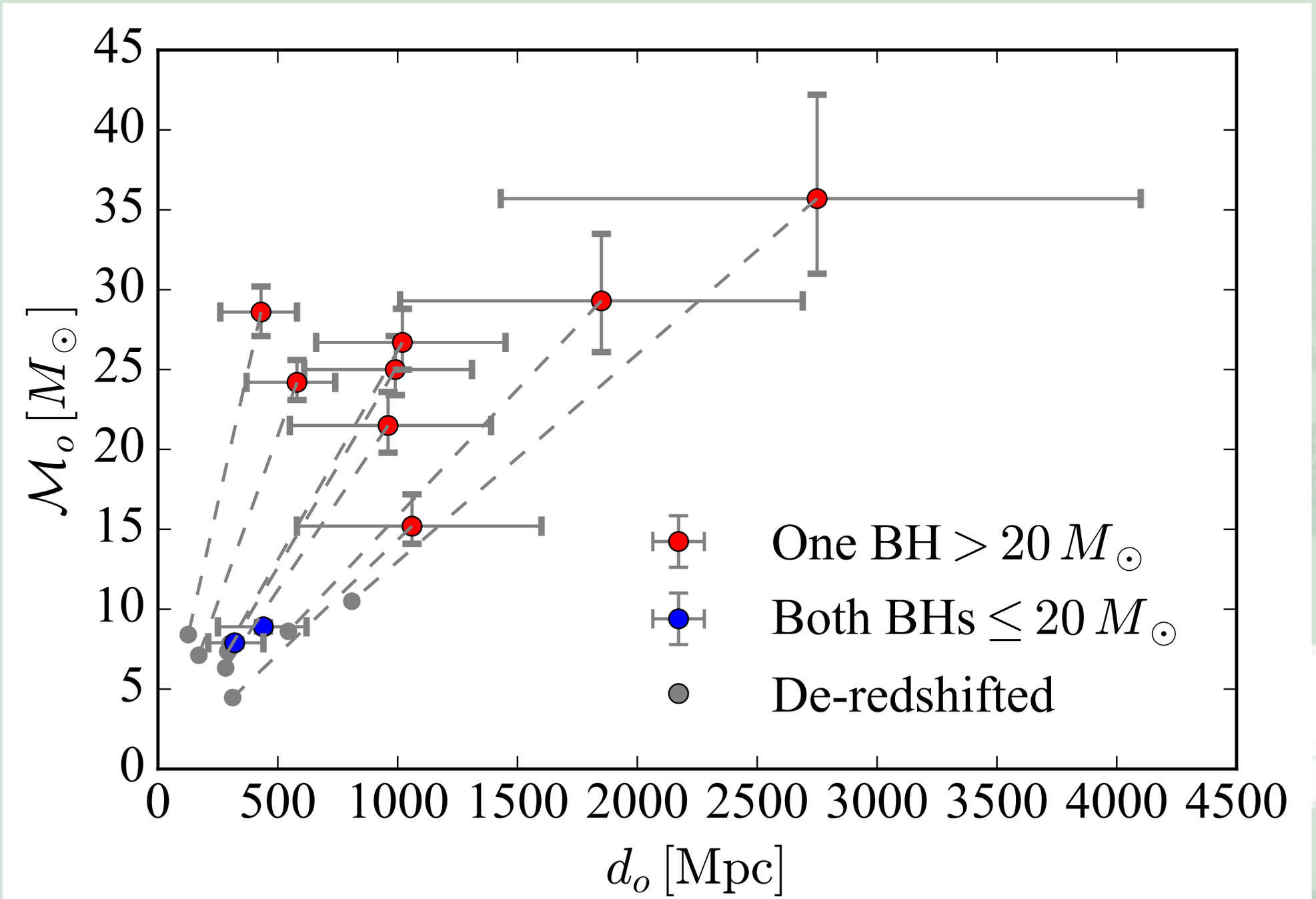
- $M_o=M(1+z_{cos})(1+z_{dop})(1+z_{gra})$
- $d_o=d_A(1+z_{cos})(1+z_{dop})(1+z_{gra})$



- Innermost stable circular orbit:
  - 3 Schwarzschild radii
  - v~0.408c
  - 1+z in total:1.89
- Innermost bound orbit:
  - 2 Schwarzschild radii
  - v~0.707c
  - 1+z in total: 3.41

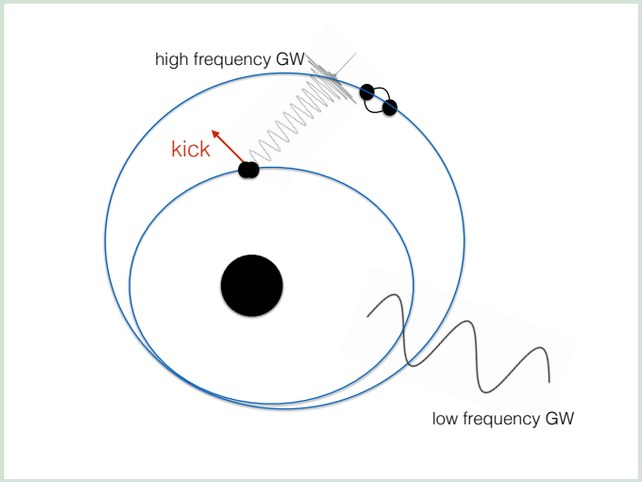
Compare with observations

- $M_o=M(1+z_{cos})(1+z_{dop})(1+z_{gra})$
- $d_o=d_A(1+z_{cos})(1+z_{dop})(1+z_{gra})$

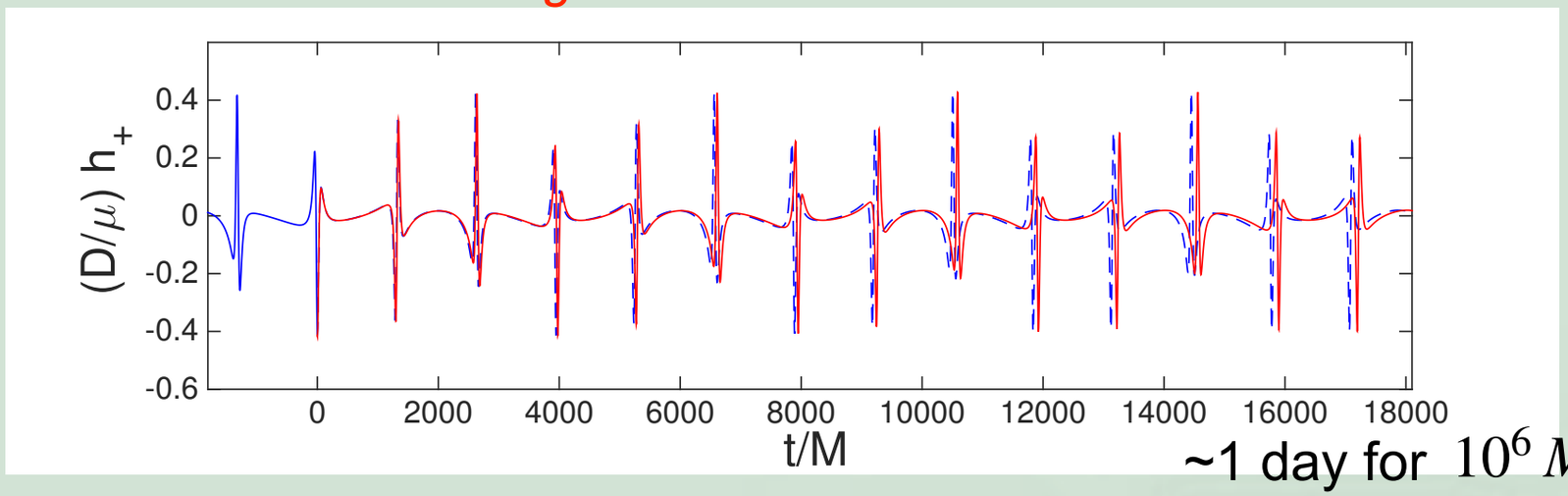


Why important?

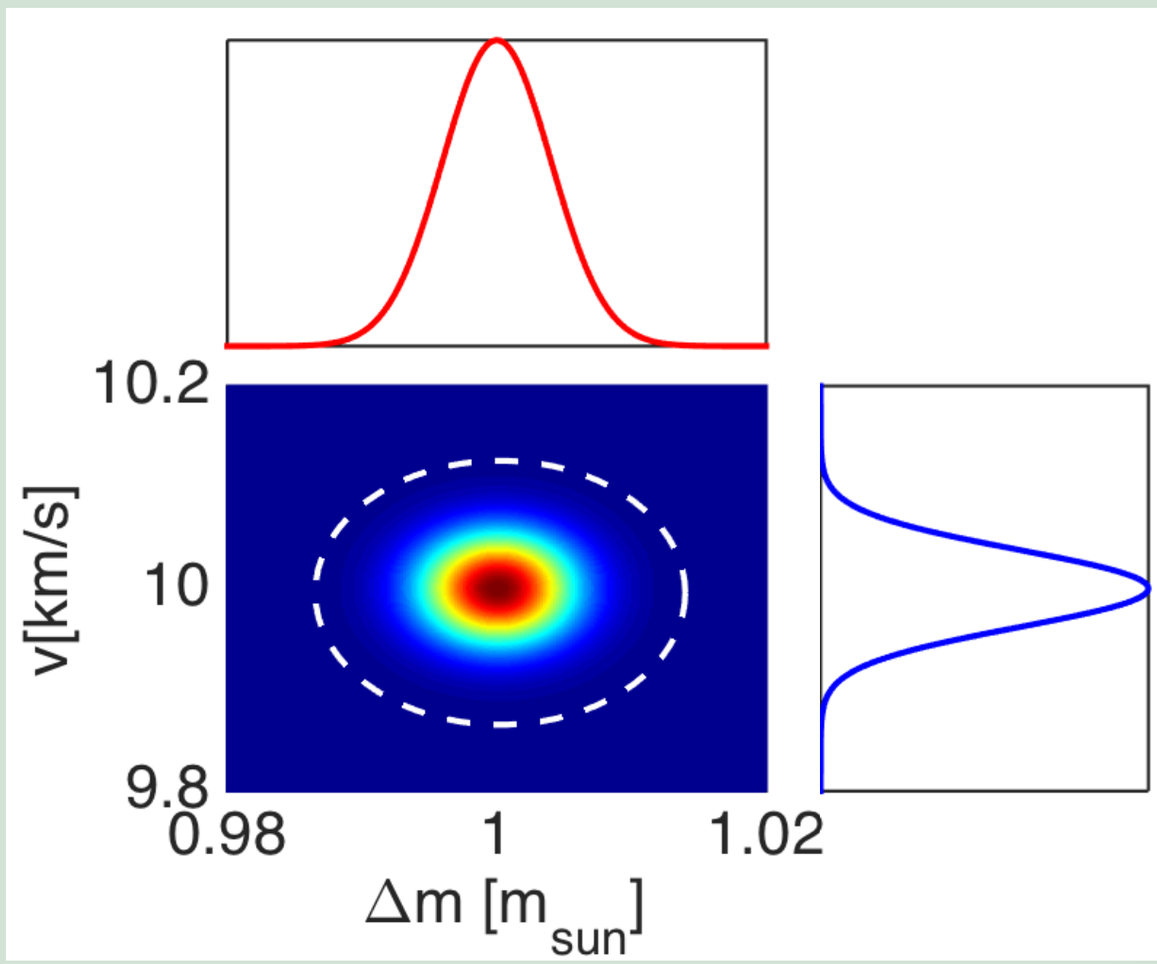
(Han & Chen 2019, submitted)



A *glitch* in EMRI waveform



~1 day for $10^6\,M_\odot$



LISA waveform tells us v and δv

$\delta v/v \approx 1\,\%$ when $v = 10\,\mathrm{km\,s^{-1}}$

For comparison (Gerosa+16):

200km/s using quasi normal mode

LISA waveform tells us Δm and δm

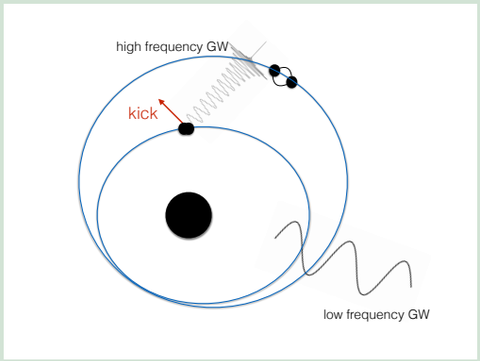
$\delta m/\Delta m \approx 2\,\%$ when $\mathrm{SNR} > 30$ in LISA

For comparison (LVC 16,17,18):

(10-30)% fromLIGO/Virgo

Measure GW dispersion (Han & Chen 2019 MNRAS)

Dispersion relationship for gravitational waves:



$$\Delta t = (1+Z)\frac{D_0}{2\lambda_g^2}\left(\frac{1}{f_{\rm low}^2} - \frac{1}{f_{\rm hight}^2}\right)$$

From LIGO/Virgo measurement (Abbott et al. 2017):

$$\text{Currently allowed region} : \lambda_g > 1.6\times10^{13}\,\text{km}$$

If we detect no dispersion, i.e.

$$\text{If } \Delta t < 0.5\,\text{day, then}$$

$$\lambda_g > 1.4\times10^{14}(D/100\,\text{Mpc})^{1/2}\,\text{km}$$

Summary

- Astrophysical models allow binary black holes to form inside 10 Rs of SMBHs (Chen & Han 18)

- Gravitational-wave forms affected by redshift (Chen, Li, & Cao17)

- Multi-band gravitational wave sources

- Test recoil, mass loss, and alternative gravity models (Han & Chen 19)