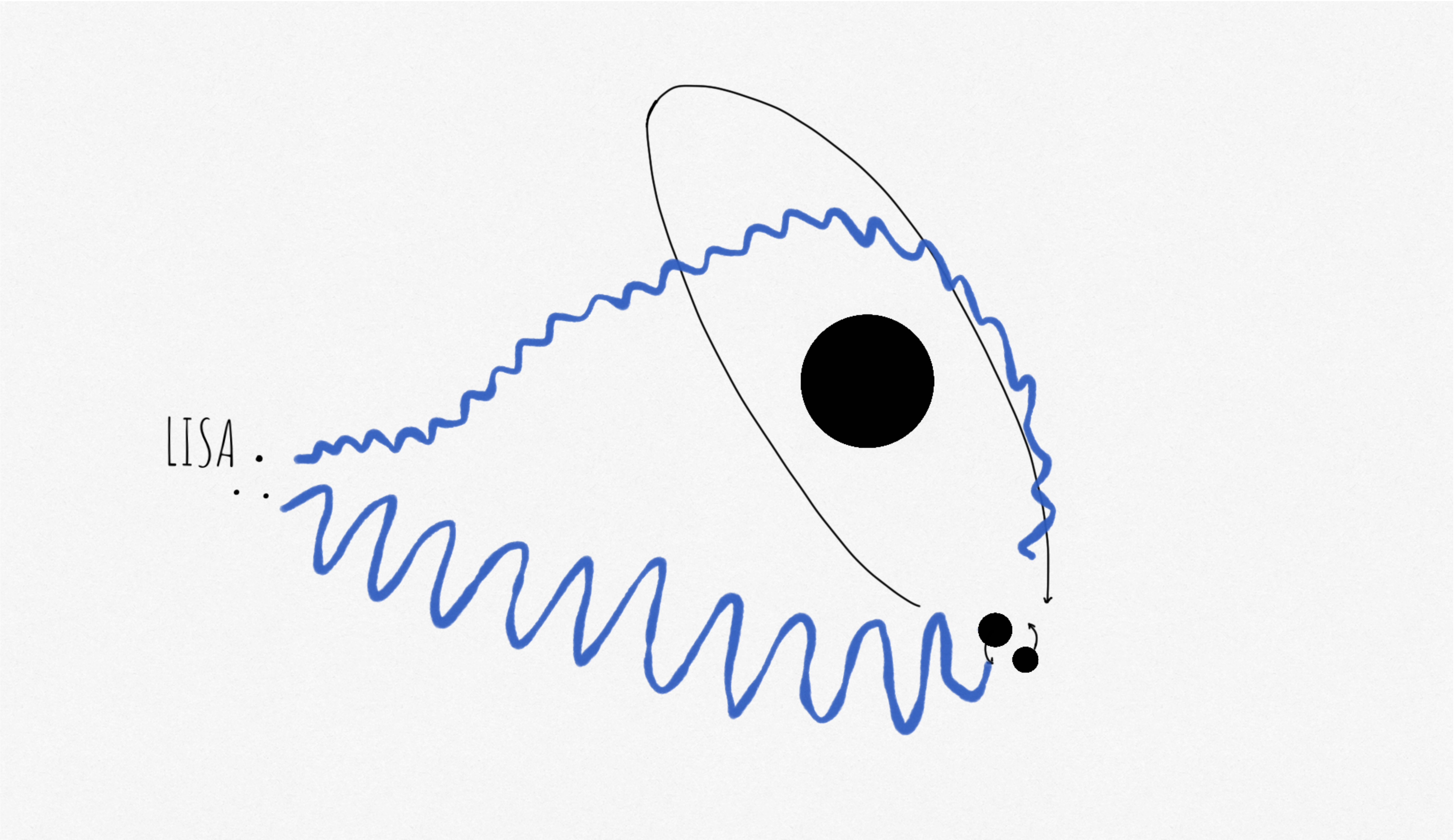
LISA data analysis in the presence of environmental effects



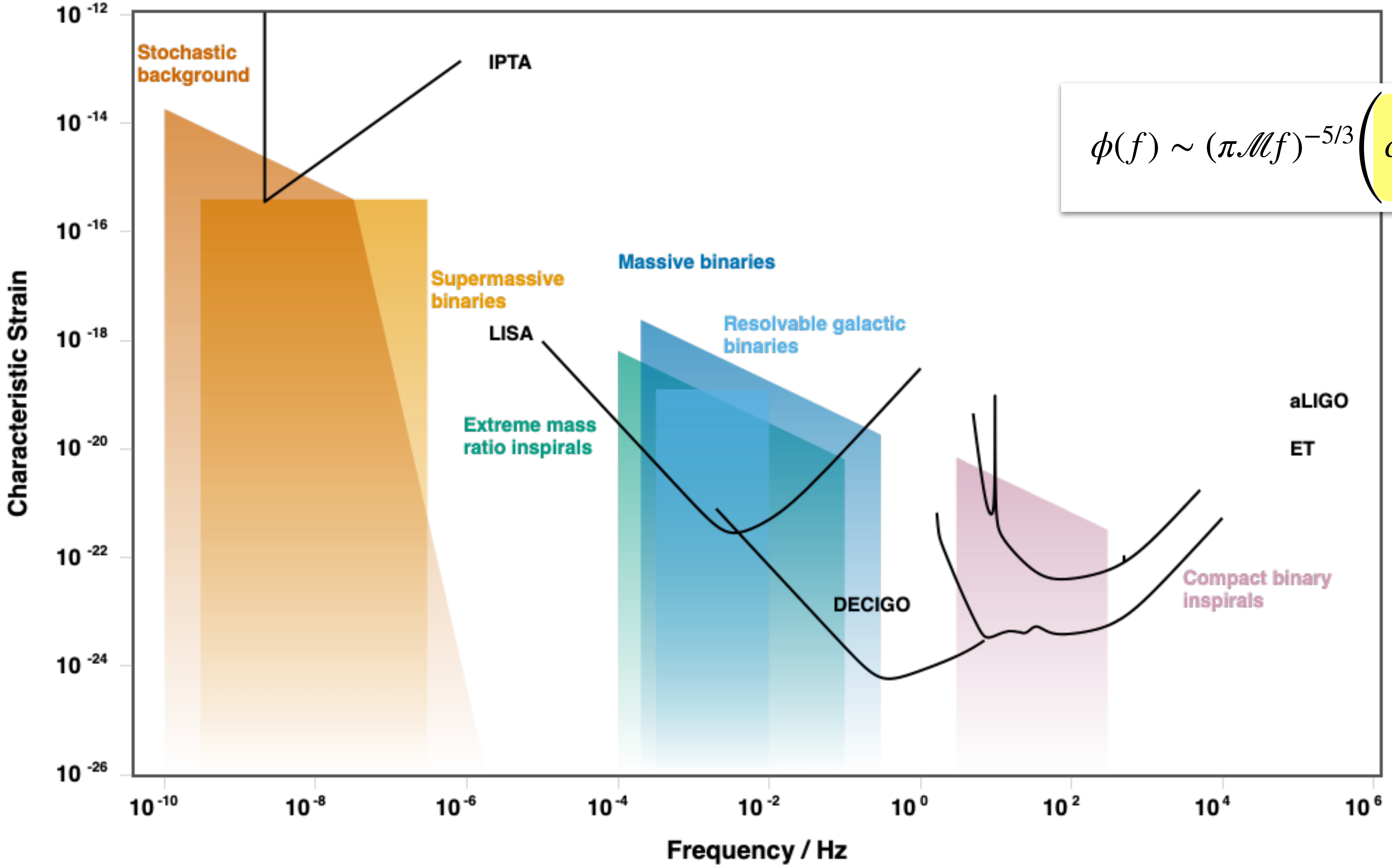
Laura Sberna (Max Planck Institute for Gravitational Physics, Potsdam)

with Toubiana, Caputo, Speri, Antonelli, Marsat, Babak, Cusin, Barausse, Pani, Tamanini, Caprini, Sesana, Dal Canton, Katz

arXiv:2001.03620, arXiv:2010.06056, arXiv:2205.08550, arXiv: 2207.10086

LIDA workshop, Toulouse 2022

LISA'S SPECIAL POWER: ENVIRONMENTAL EFFECTS



$$\phi(f) \sim (\pi \mathcal{M} f)^{-5/3} \left(c_n (\pi \mathcal{M} f)^{n_{\rm env}} + \sum_{n=0} a_n (\pi \mathcal{M} f)^{n/3} \right)$$

negative

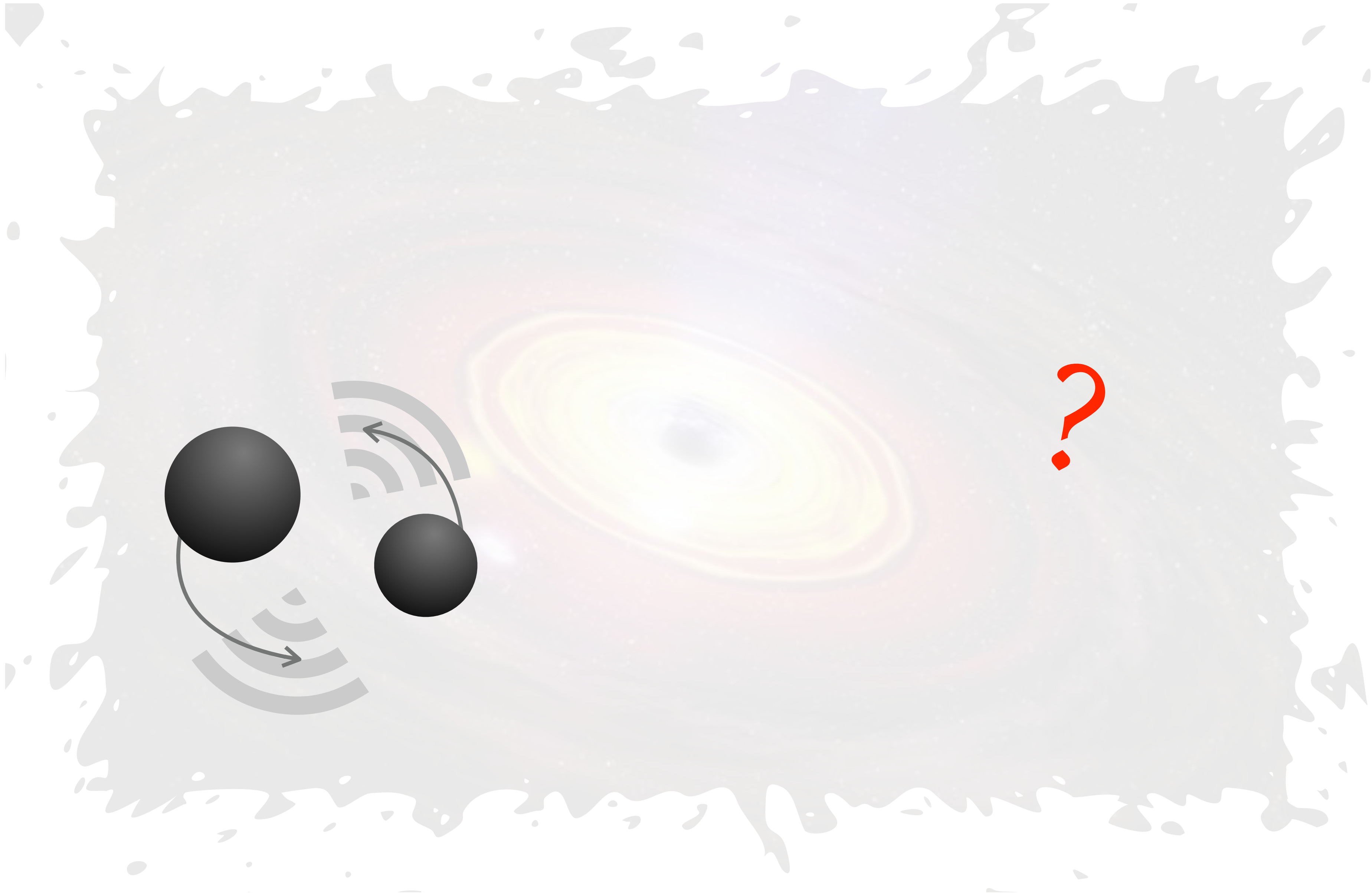
Laura Sberna (MPI for Gravitational Physics, Potsdam)

ENVIRONMENTAL EFFECTS: WHY CARE?

A **blessing** and a **curse**.

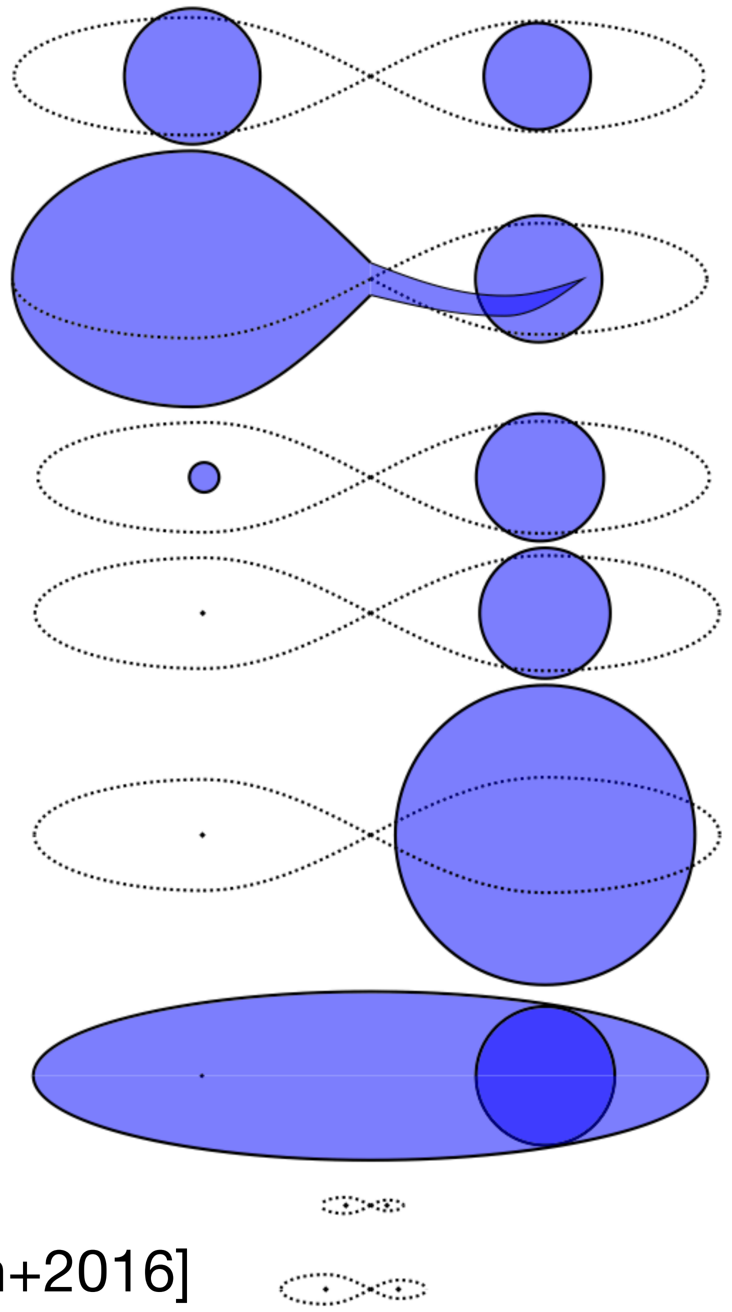
Blessing: Astrophysical insights!

1. **Black hole formation** scenarios
2. **Galactic nuclei**
3. **Accretion disk** phenomena
4. **Multimessenger** astronomy…



Blessing:

Isolated



[Stevenson+2016]

vs

AGN

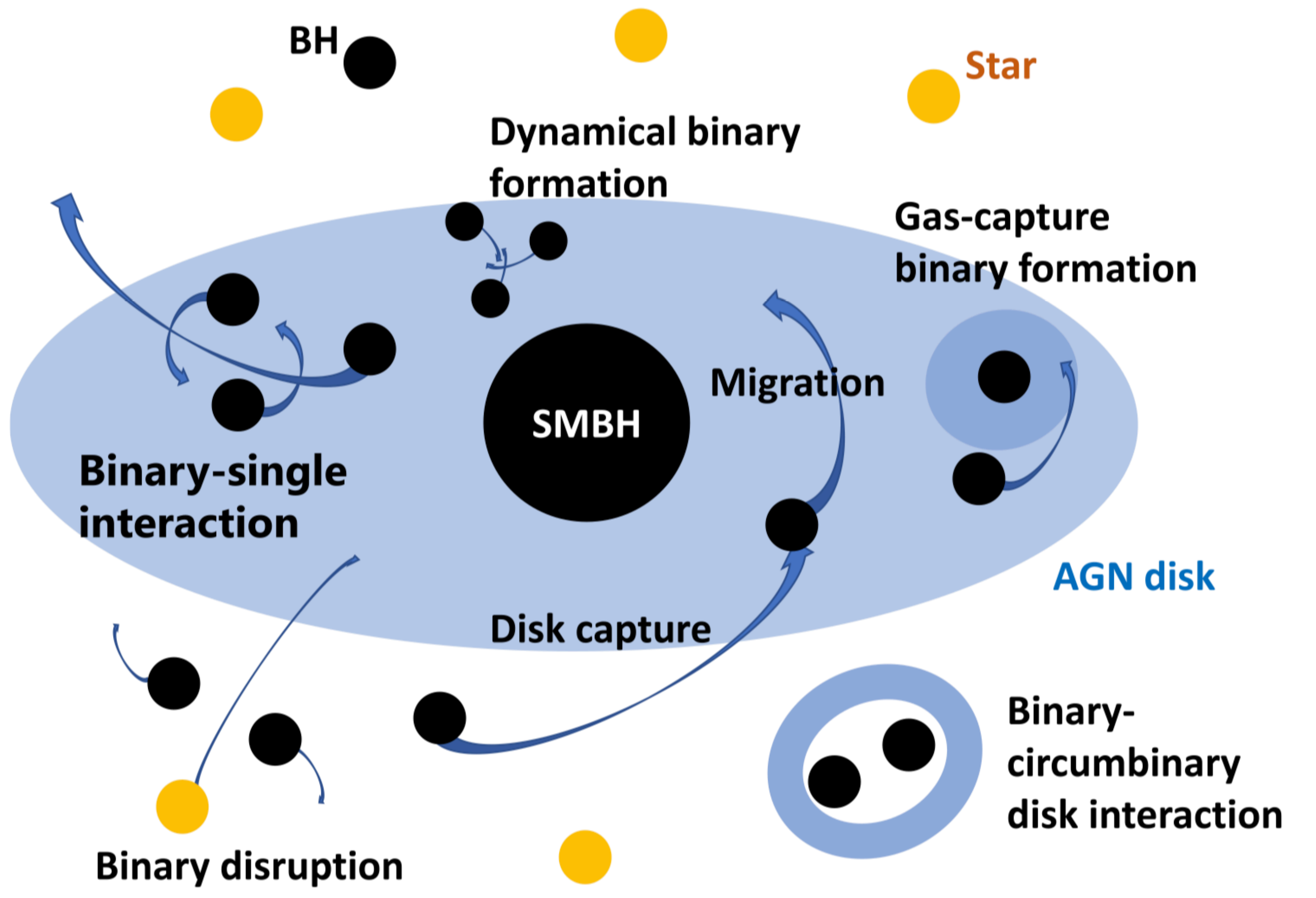


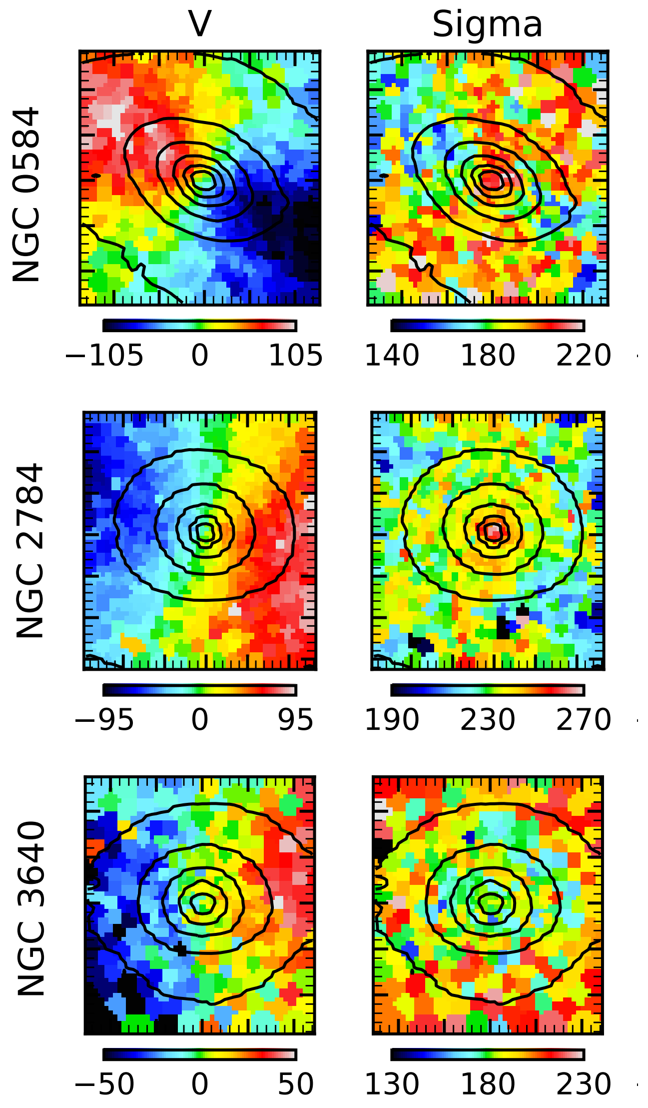
Figure 3. Schematic diagram illustrating the mechanisms affecting the BH population and driving binary formation and evolution. See Section 2 and Figure 2 for an overview and Section 3 for numerical details.

[Tagawa+2020]

1. **Understand the origin of LIGO binaries.**

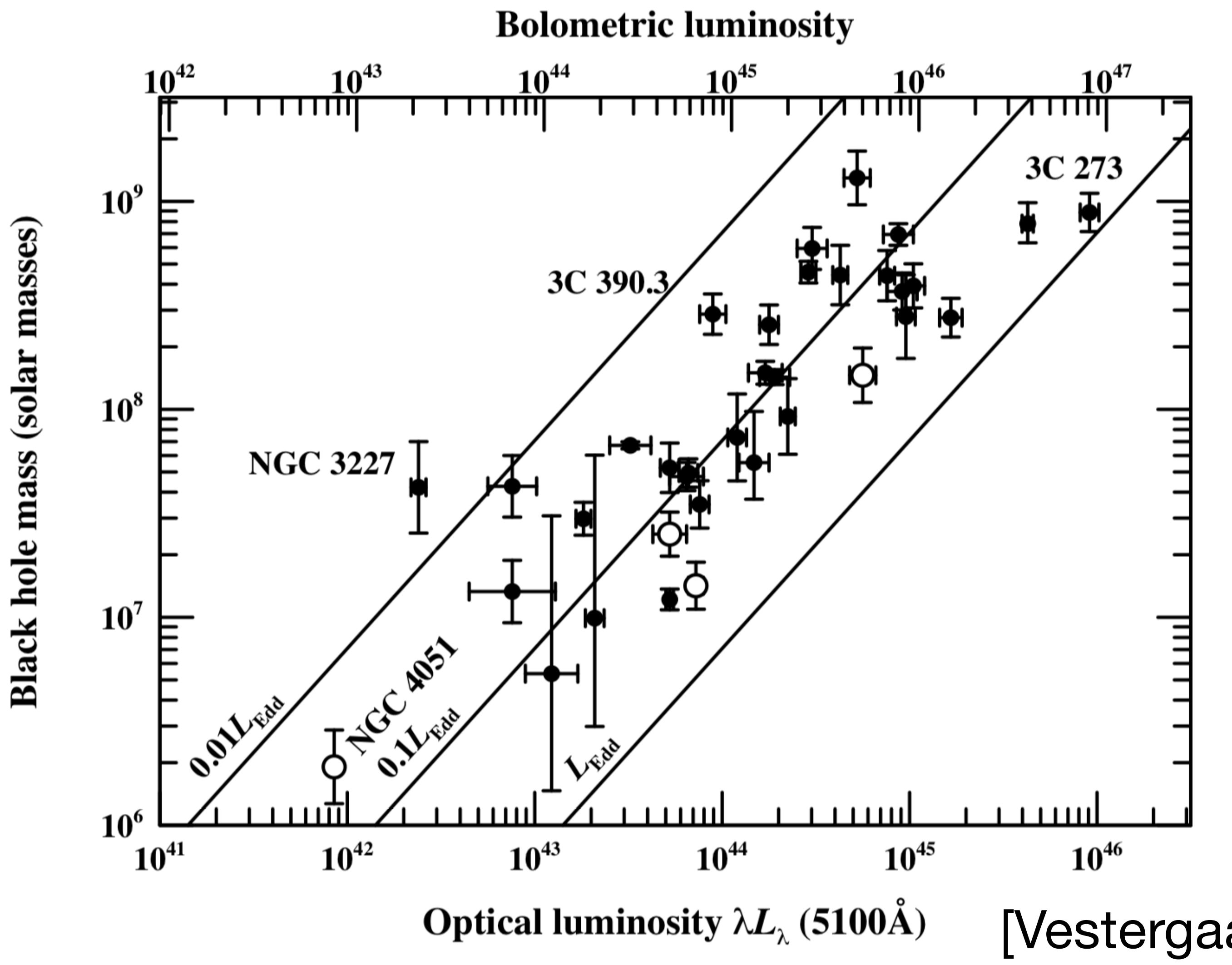
Blessing:

1) Kinematic of stars and gas



[Thater+ 2019]

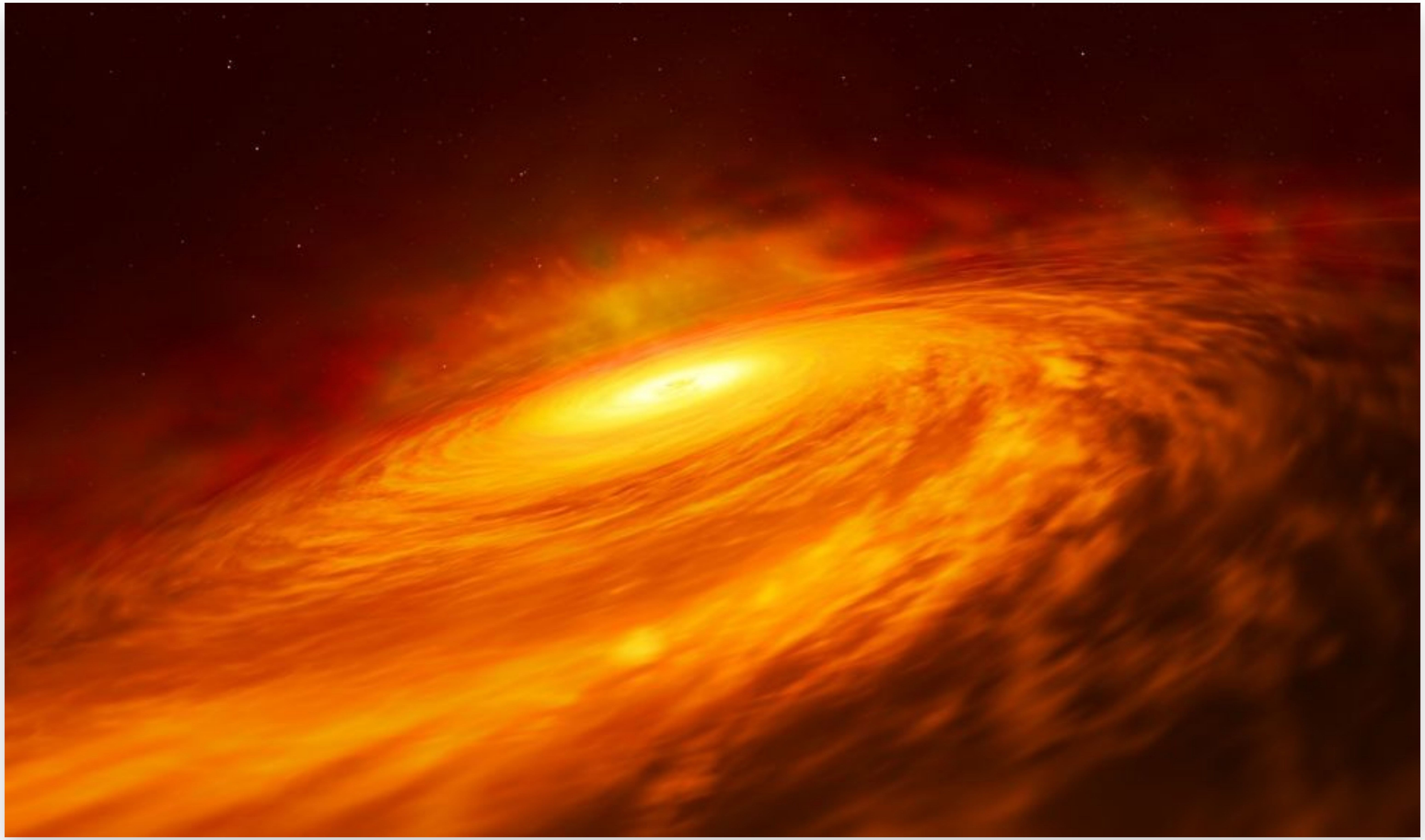
2) Reverberation mapping



[Vestergaard 2019]

2. Study supermassive BHs. (…in yet another way, with LISA)

Blessing:



3. **Study accretion disks and Active Galactic Nuclei.**

ENVIRONMENTAL EFFECTS: WHY CARE?

A **blessing** and a **curse**.

Curse 1 : Distinguish matter effects and **modified gravity**. [Barausse, Pani, Cardoso 2014]

$$h \sim h_{\rm GR} e^{i\delta(f)}$$

Varying G (and constant-rate accretion)

$$\delta = c(\pi \mathcal{M} f)^{-13/3}$$

vs

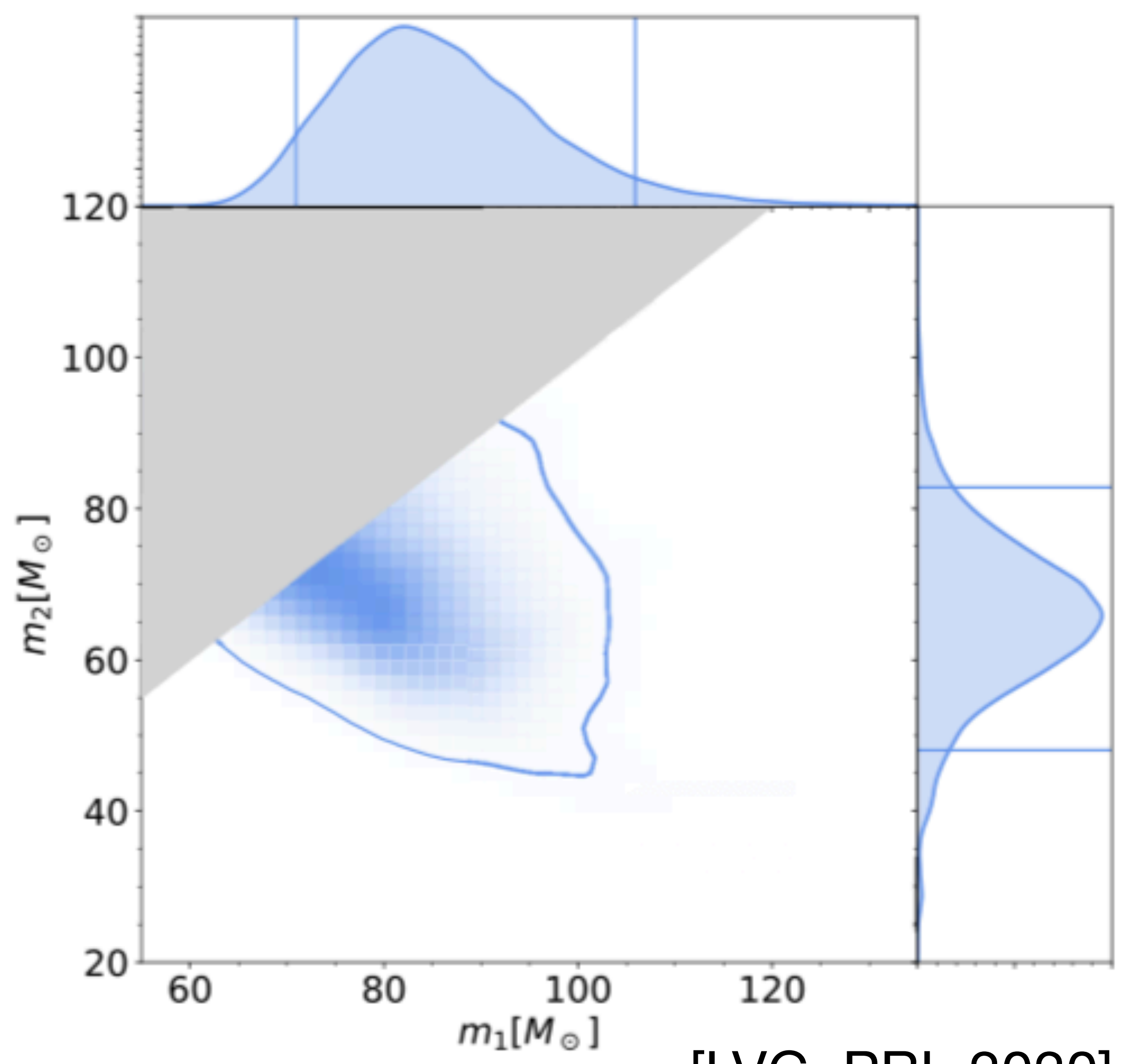
Curse 2: Models are still far from being realistic.

Curse 3: Data analysis/detection challenges.

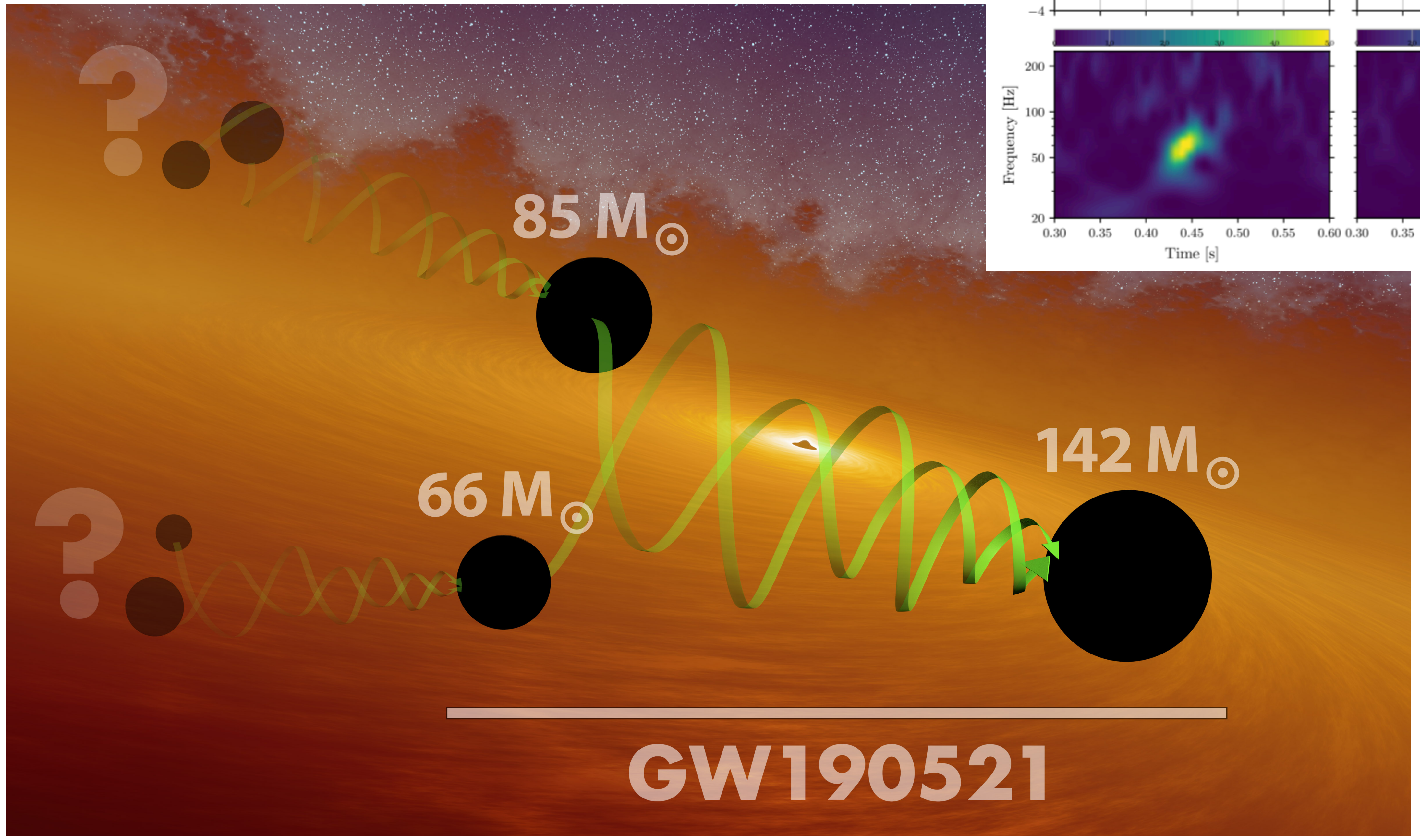
A (BIASED) SELECTION:

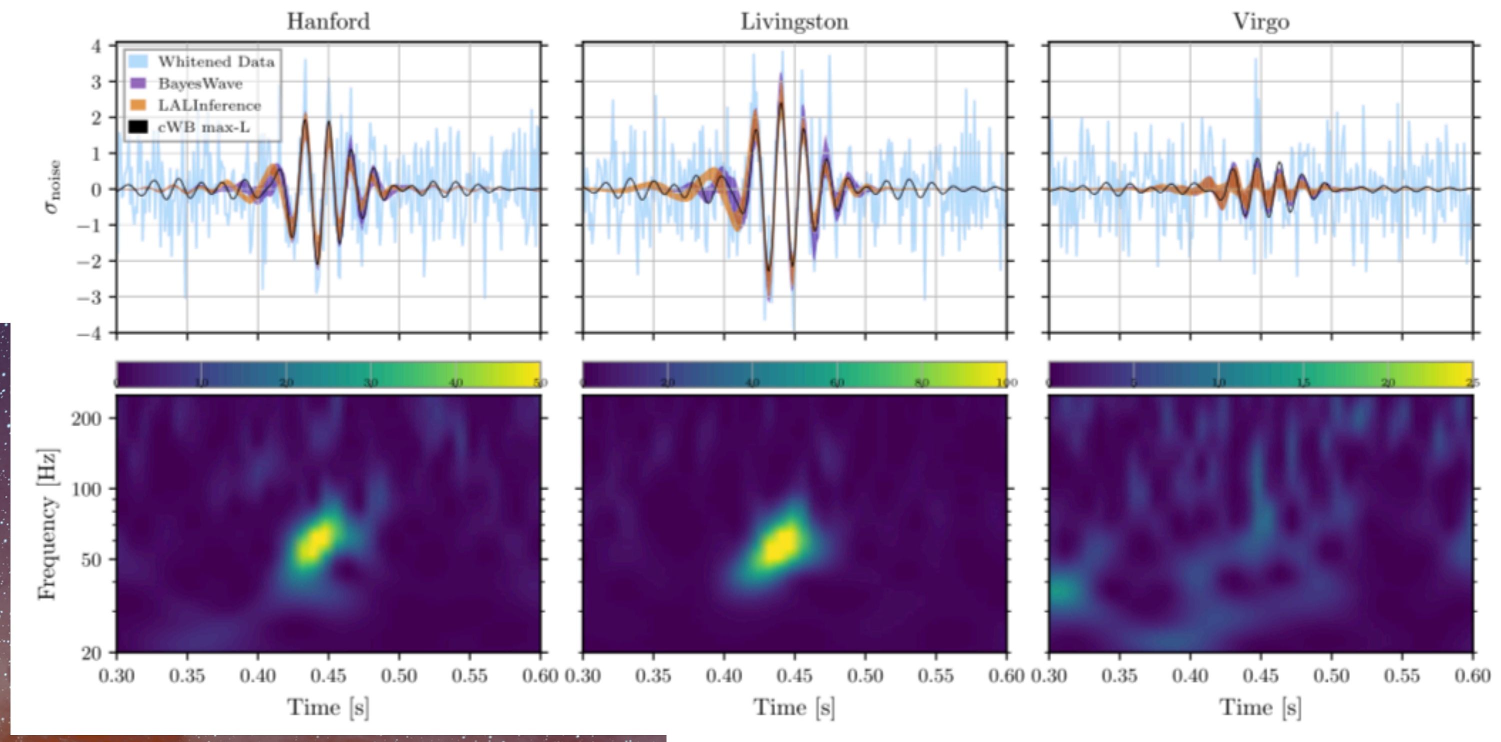
1. STELLAR MASS BINARIES IN ACCRETION DISKS/NUCLEAR REGIONS

OUR MODEL SOURCE: GW190521



[LVC, PRL 2020]

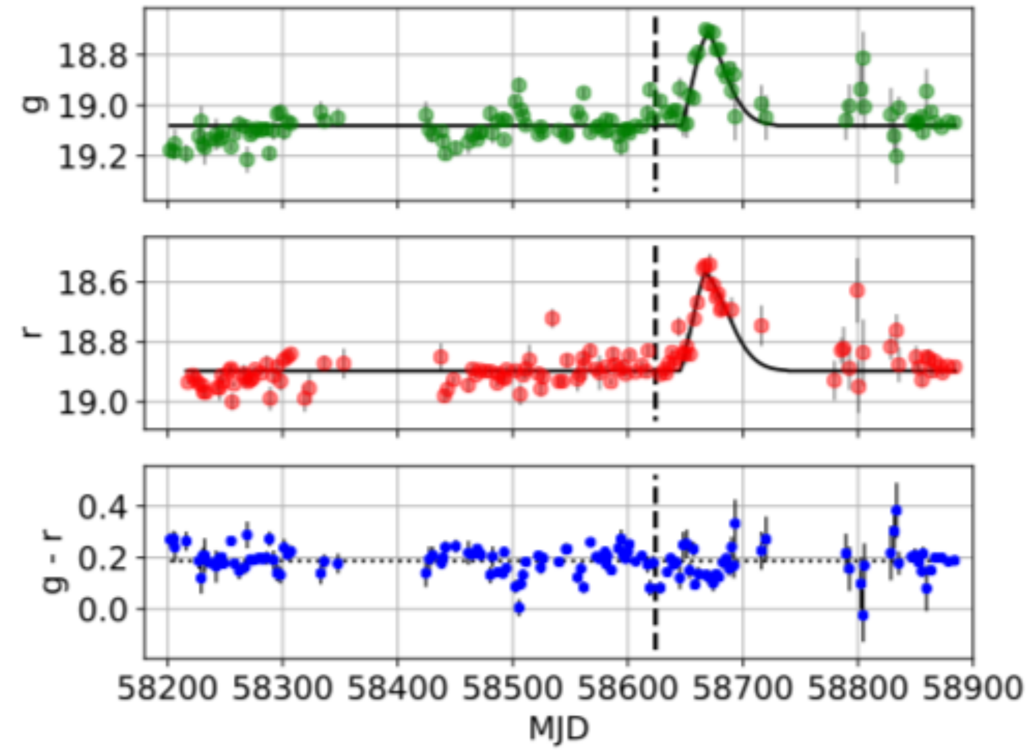




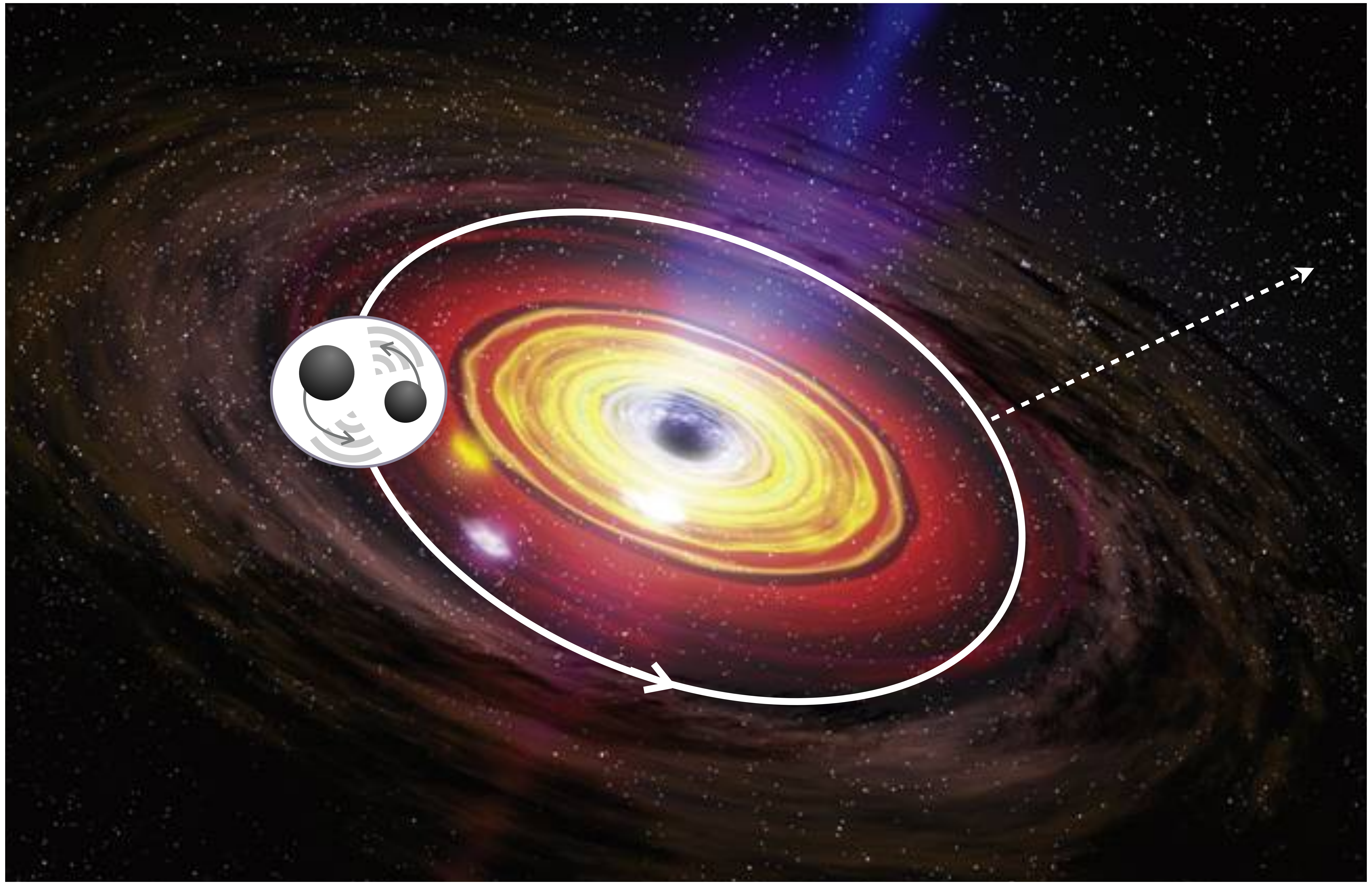
LIGO/Caltech/MIT/R. Hurt (IPAC).

+ Optical flare detected by the Zwicky Transient Facility

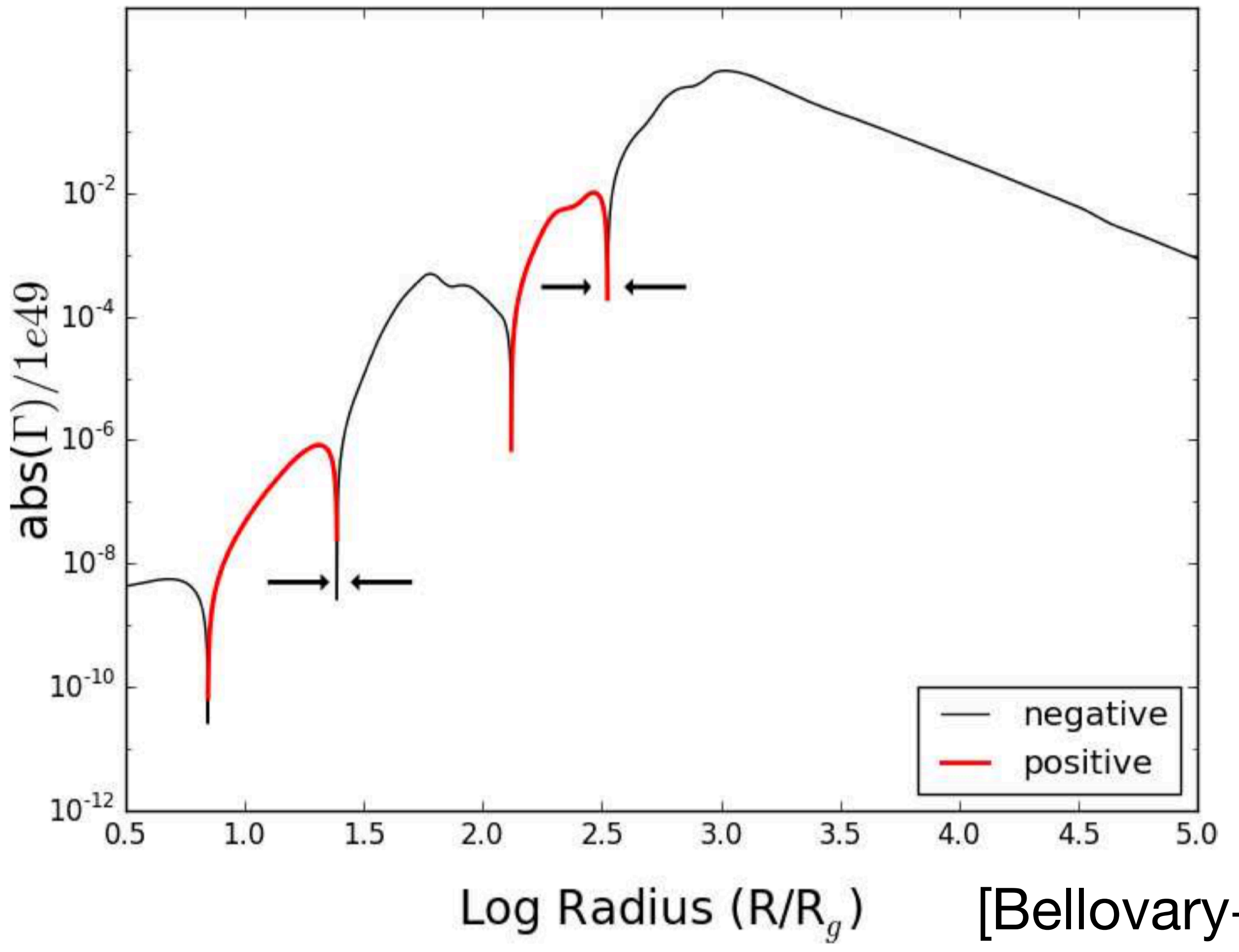
[Graham et al. 2020]



STELLAR-MASS BINARIES IN ACTIVE GALACTIC NUCLEI



Migration traps

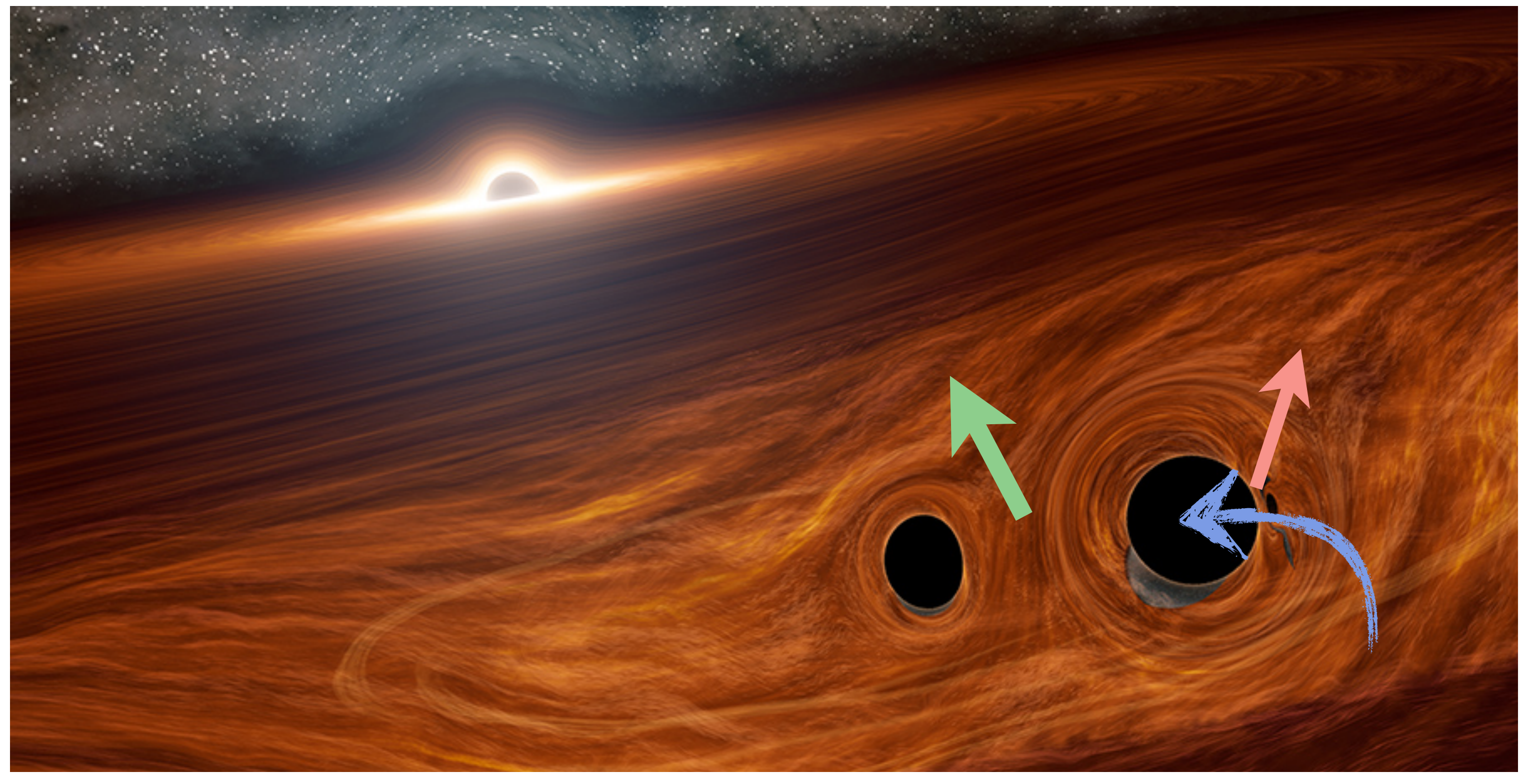


[Bellovary+ 2016]

$$a_\bullet \sim 700\, M_\bullet \sim 10^{-3}\,\mathrm{pc}\left(\frac{M_\bullet}{10^8 M_\odot}\right)$$

STELLAR-MASS BINARIES IN ACTIVE GALACTIC NUCLEI

Detectability of accretion, friction, constant peculiar acceleration

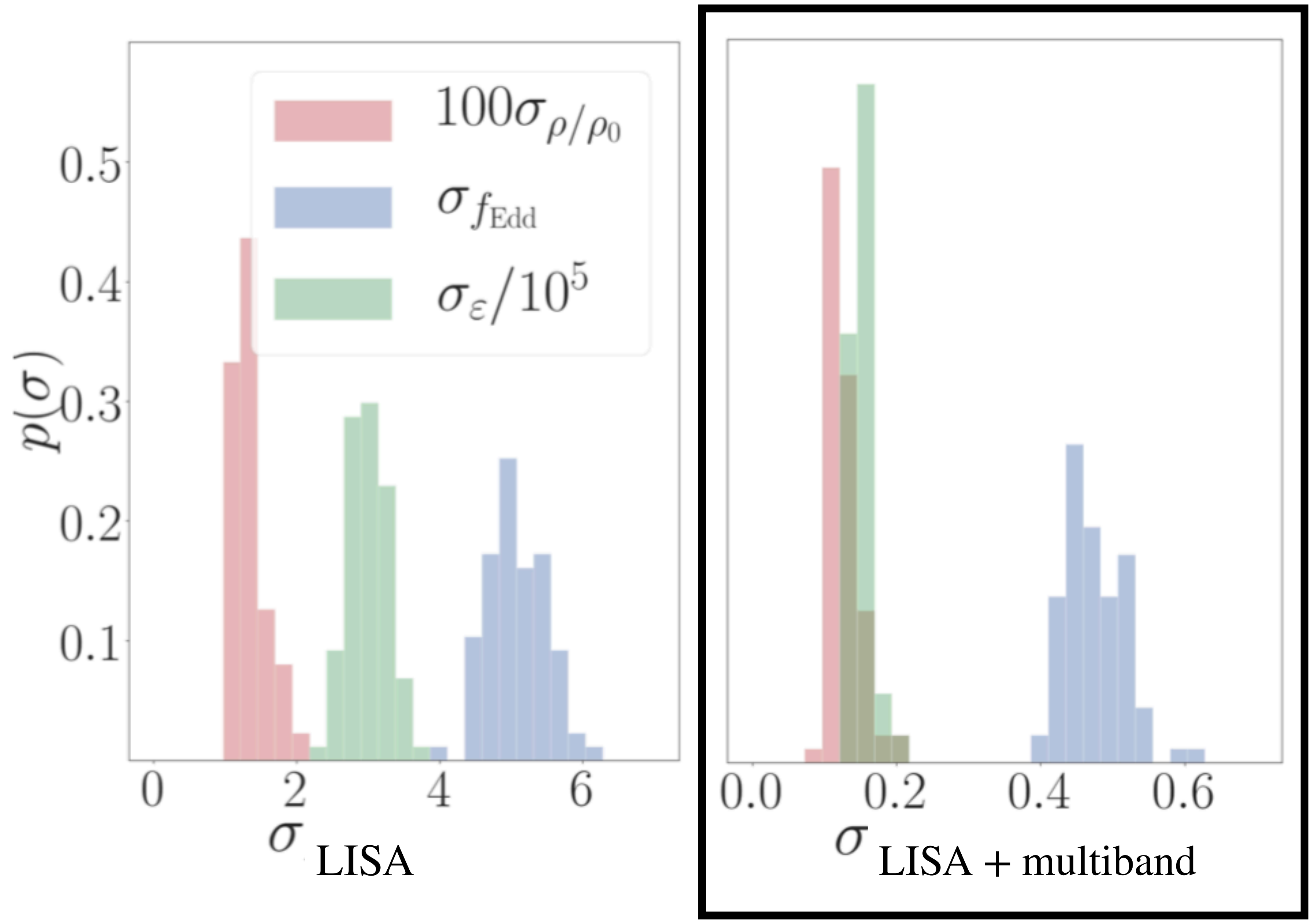


$$\tilde{\phi}_{\rm accretion} \sim -f_{\rm Edd}\left[\pi f \mathcal{M}(1+z)\right]^{-13/3}$$

$$\tilde{\phi}_{\rm acceleration} \sim \epsilon\left[\pi f \mathcal{M}(1+z)\right]^{-13/3}$$

$$\tilde{\phi}_{\rm dyn\,fr} \sim \rho\left[\pi f \mathcal{M}(1+z)\right]^{-16/3}$$

$\rho_0 \simeq 10^{-10} g/cm^3$
$f_{\rm Edd} \simeq 1$
$\epsilon : a \simeq 1\,{\rm pc}$



Easily captured by (negative) parametrised PN, small SNR loss in detection

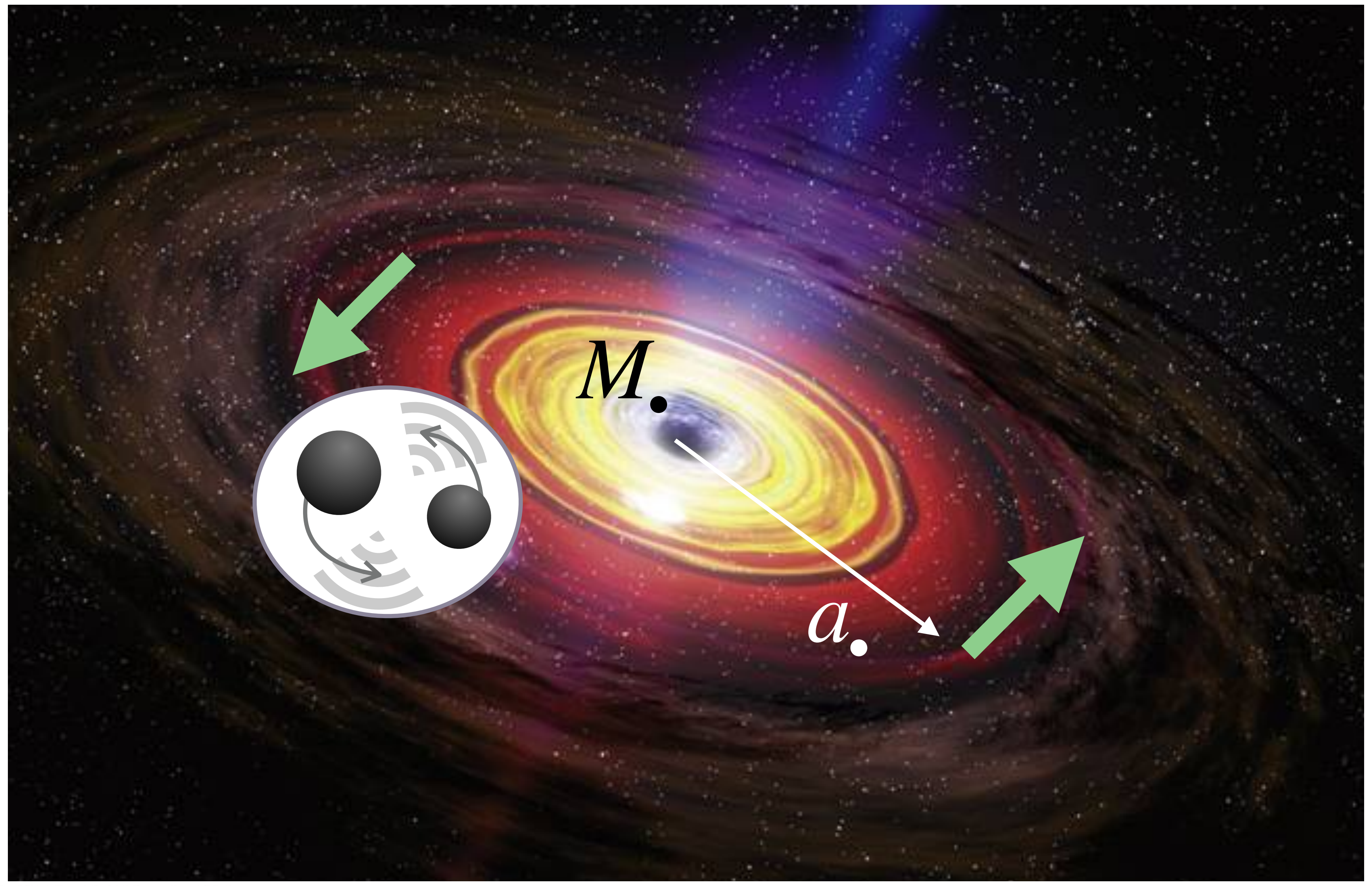
[Toubiana, LS et al. 2010.06056]

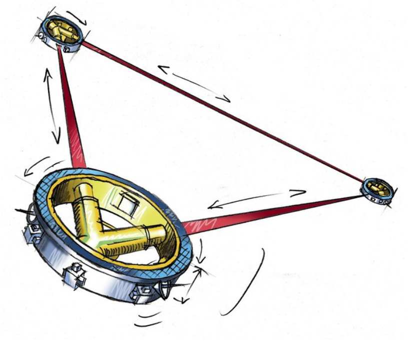
GW190521-LIKE BINARIES SEEN BY LISA

The problem:

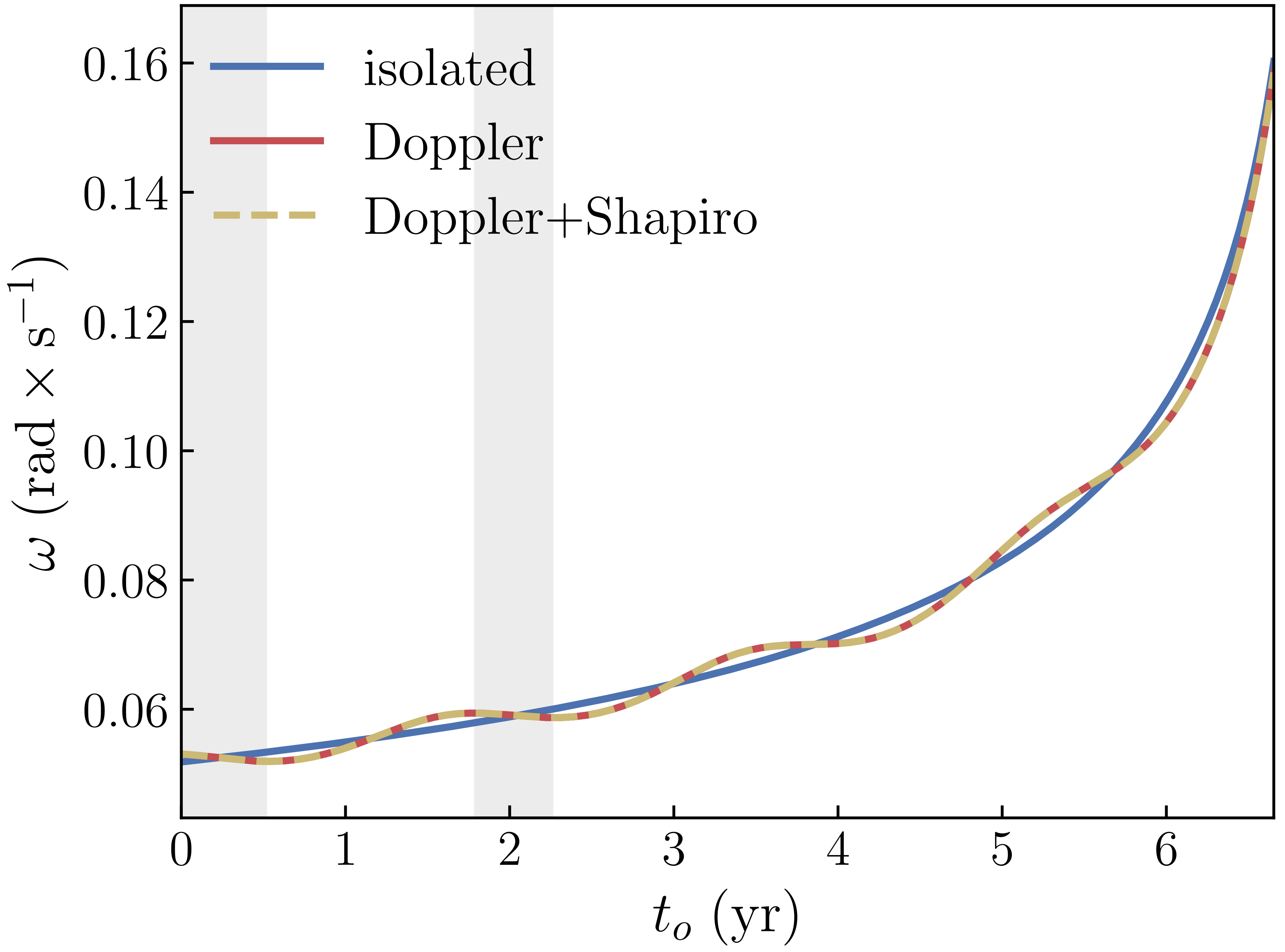
$$T = 2\,\mathrm{yr}\left(\frac{a_\bullet}{700\,M_\bullet}\right)^{3/2}\left(\frac{M_\bullet}{10^8 M_\odot}\right)$$

Doppler (and Shapiro) effect





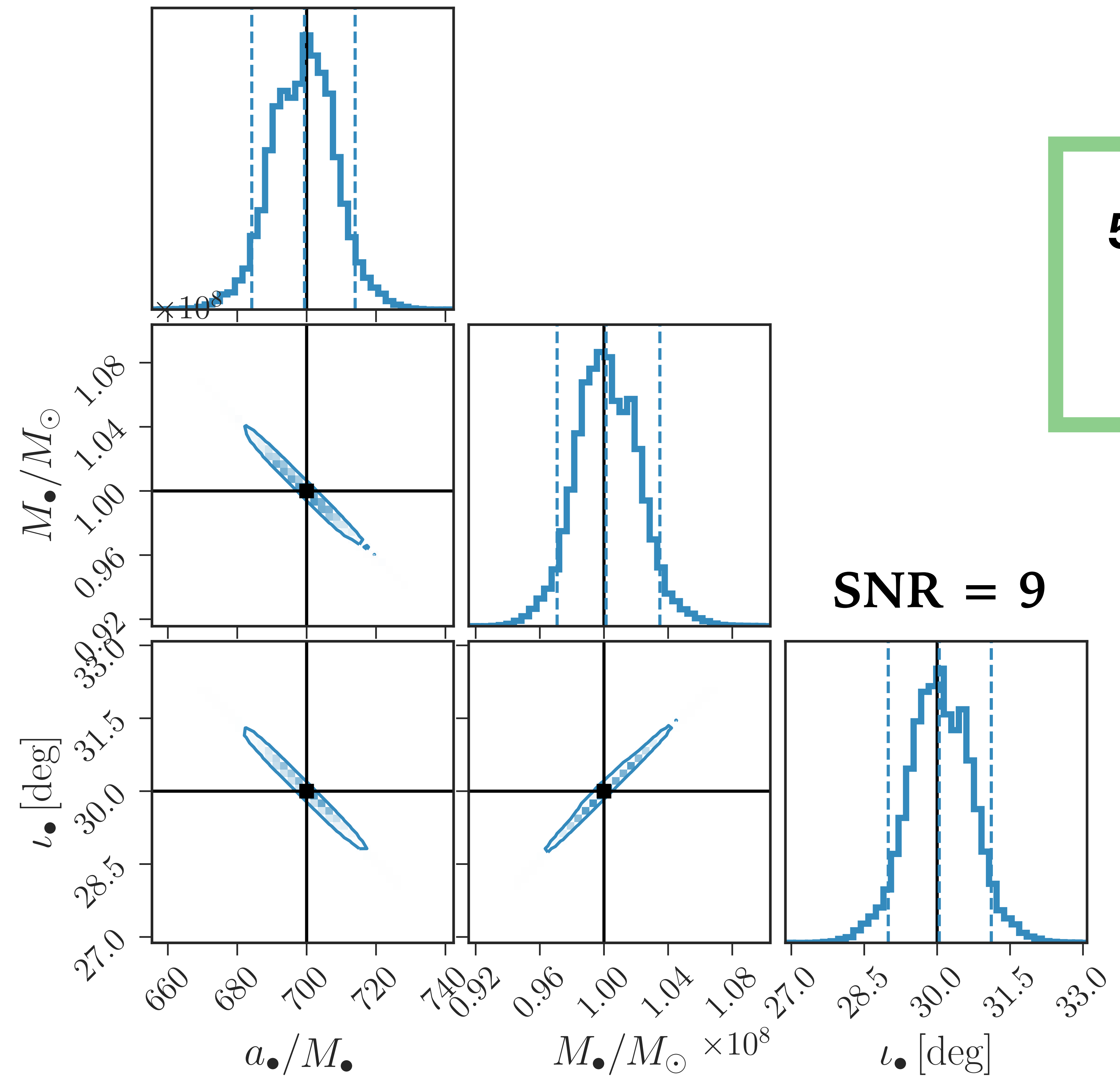
$$s(t) = h(t + d^{\|}(t) + d^S(t))$$



[LS et al. 2205.08550]

GW190521-LIKE BINARIES SEEN BY LISA

Doppler + Shapiro parameter estimation



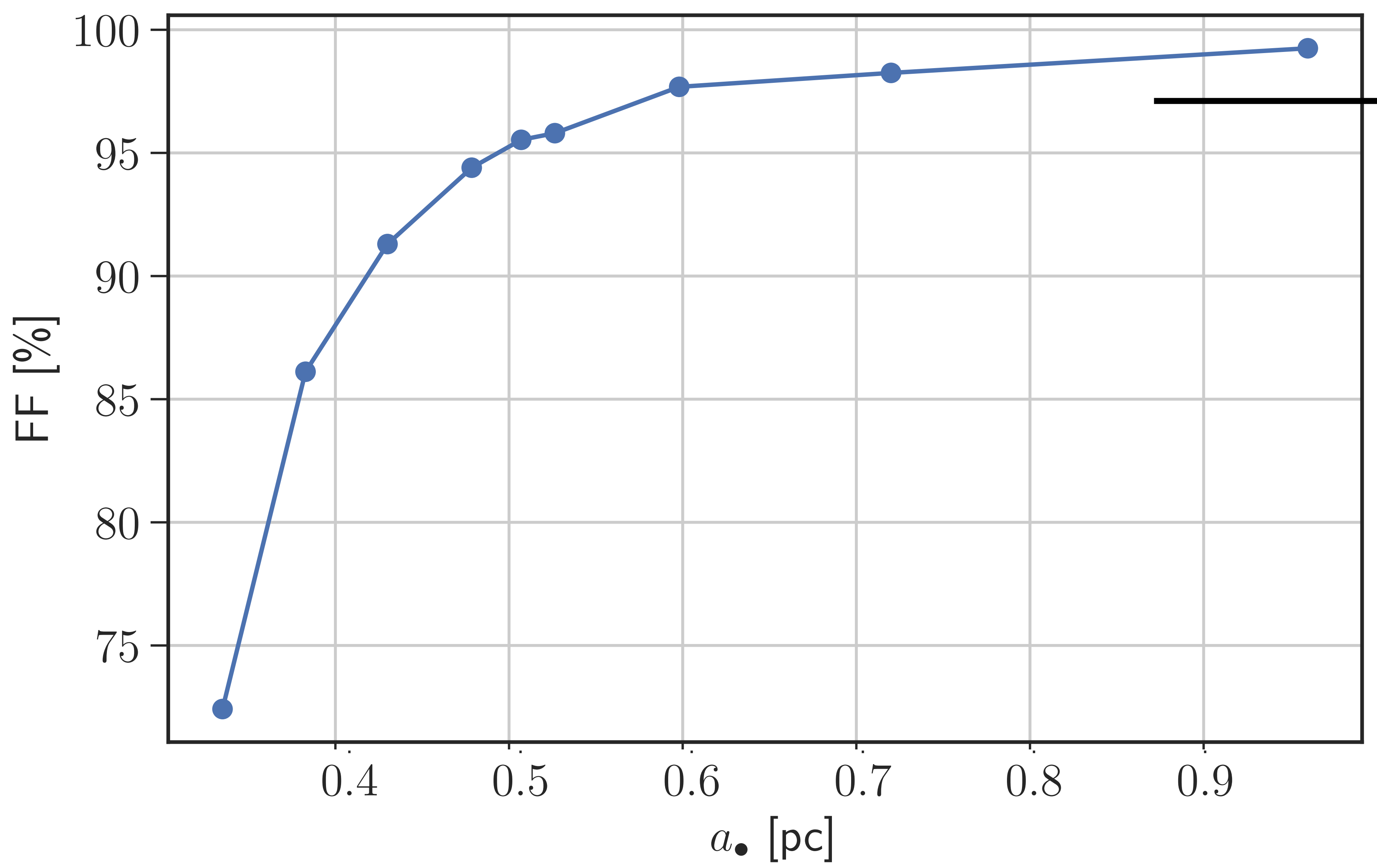
5 % central BH mass

3 % orbit radius

[LS et al. 2205.08550]

GW190521-LIKE BINARIES SEEN BY LISA

Doppler + Shapiro, detection (FF: fitting factor)

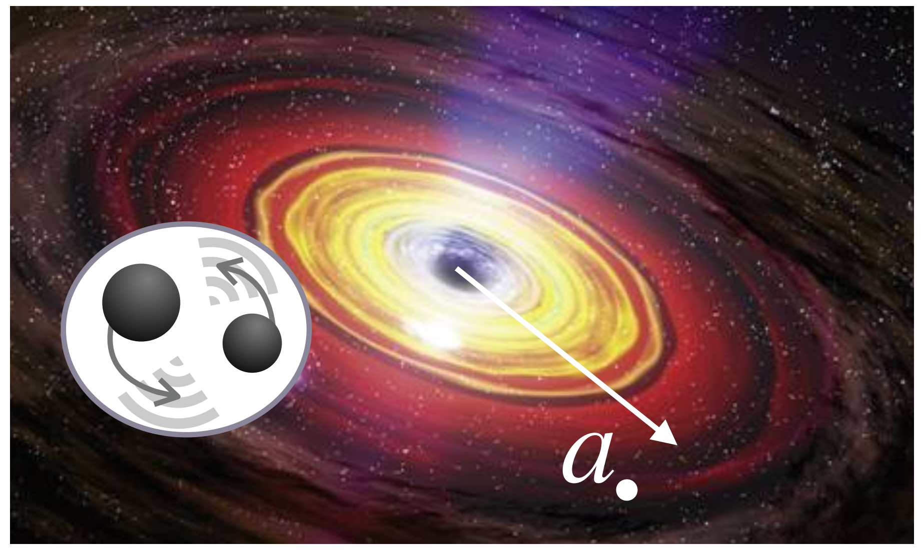


peculiar velocity limit

Could prevent detection with vacuum templates and matched filtering

remember?

$$a_\bullet \sim 700\, M_\bullet \sim 10^{-3}\,\mathrm{pc}\left(\frac{M_\bullet}{10^8 M_\odot}\right)$$



A (BIASED) SELECTION:

2. EXTREME MASS RATIO INSPIRALS IN ACCRETION DISKS

EMRIS IN ACCRETION DISKS

(Unknown) fraction of all EMRIs detectable by LISA

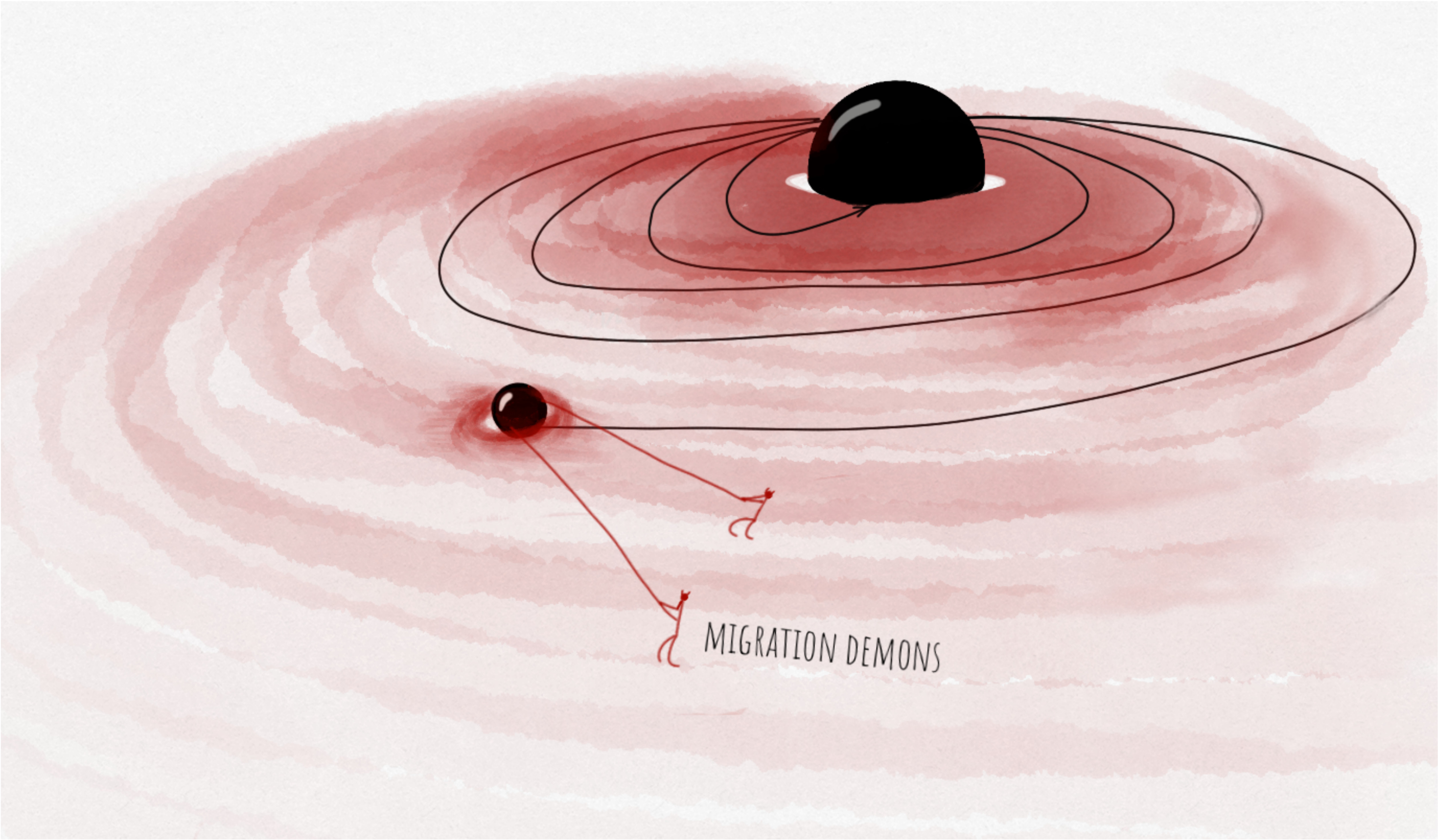
[Dittmann, Miller 2019, Pan+ 2021]

Main effect: planetary-like migration

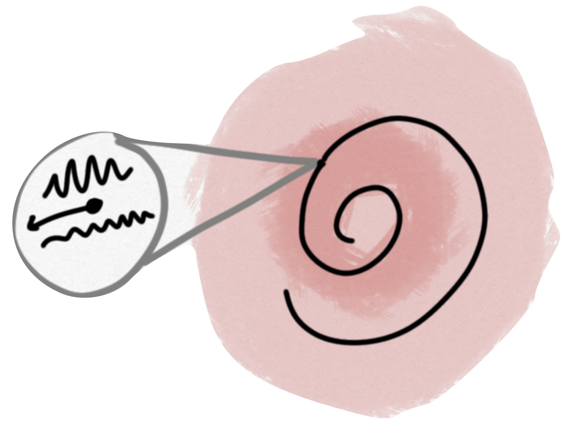
[Goodman, Rafikov 2001; GWs: Kocsis+ 2011, Yunes+ 2011,]

Previous estimates: detectable ✔

[Yunes+ 2011, Kocsis+ 2011, Barausse+ 2014, Derdzinski+ 2020]



EMRIS IN ACCRETION DISKS



Our model:

$$\frac{\dot{L}_{\text{environment}}}{\dot{L}_{\text{GW}}} = A(f_{\text{edd}}, \alpha; M_i)\, r^{n_r}$$

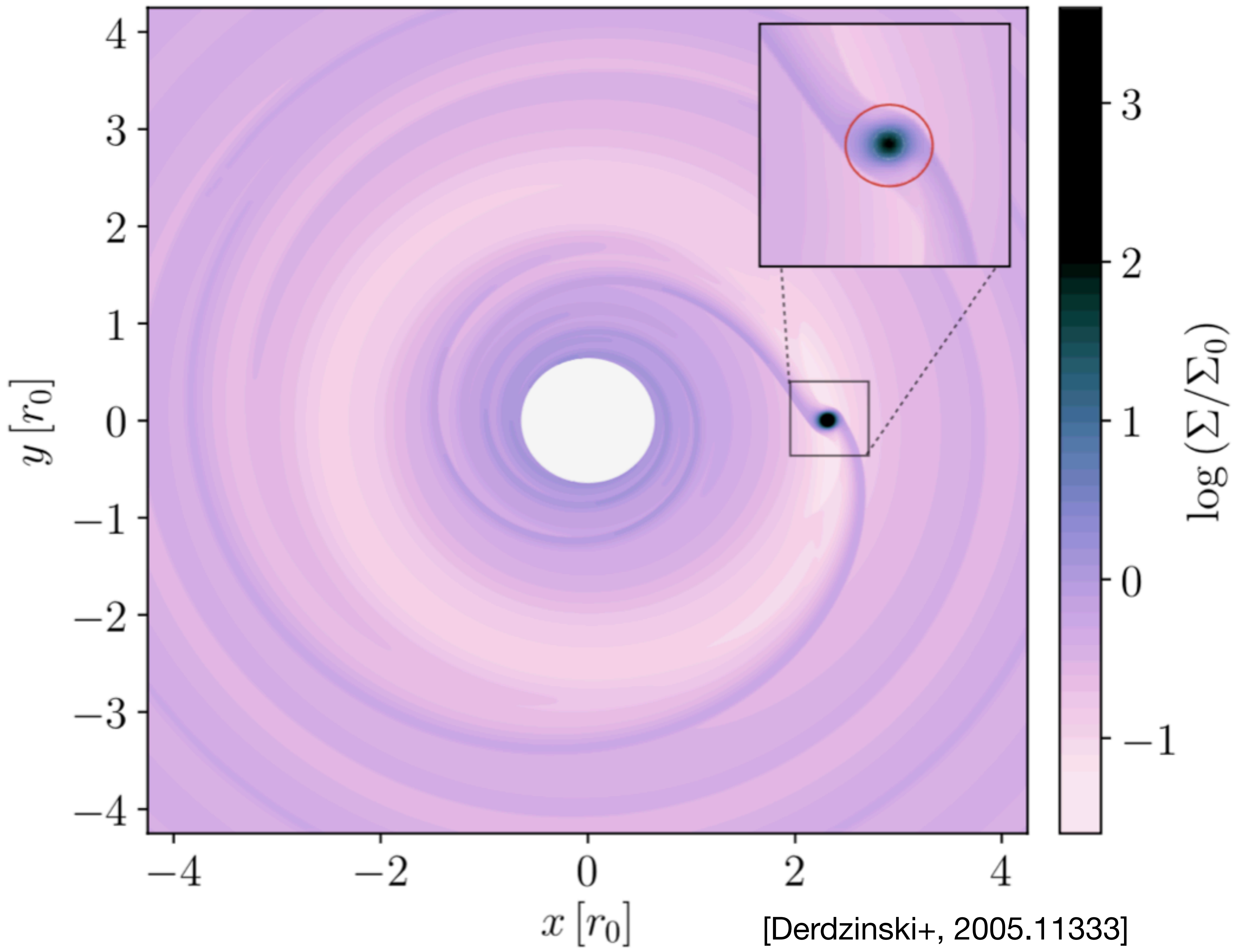
disk viscosity

disk accretion rate

Our waveform model:

FastEMRIWaveforms (FEW)

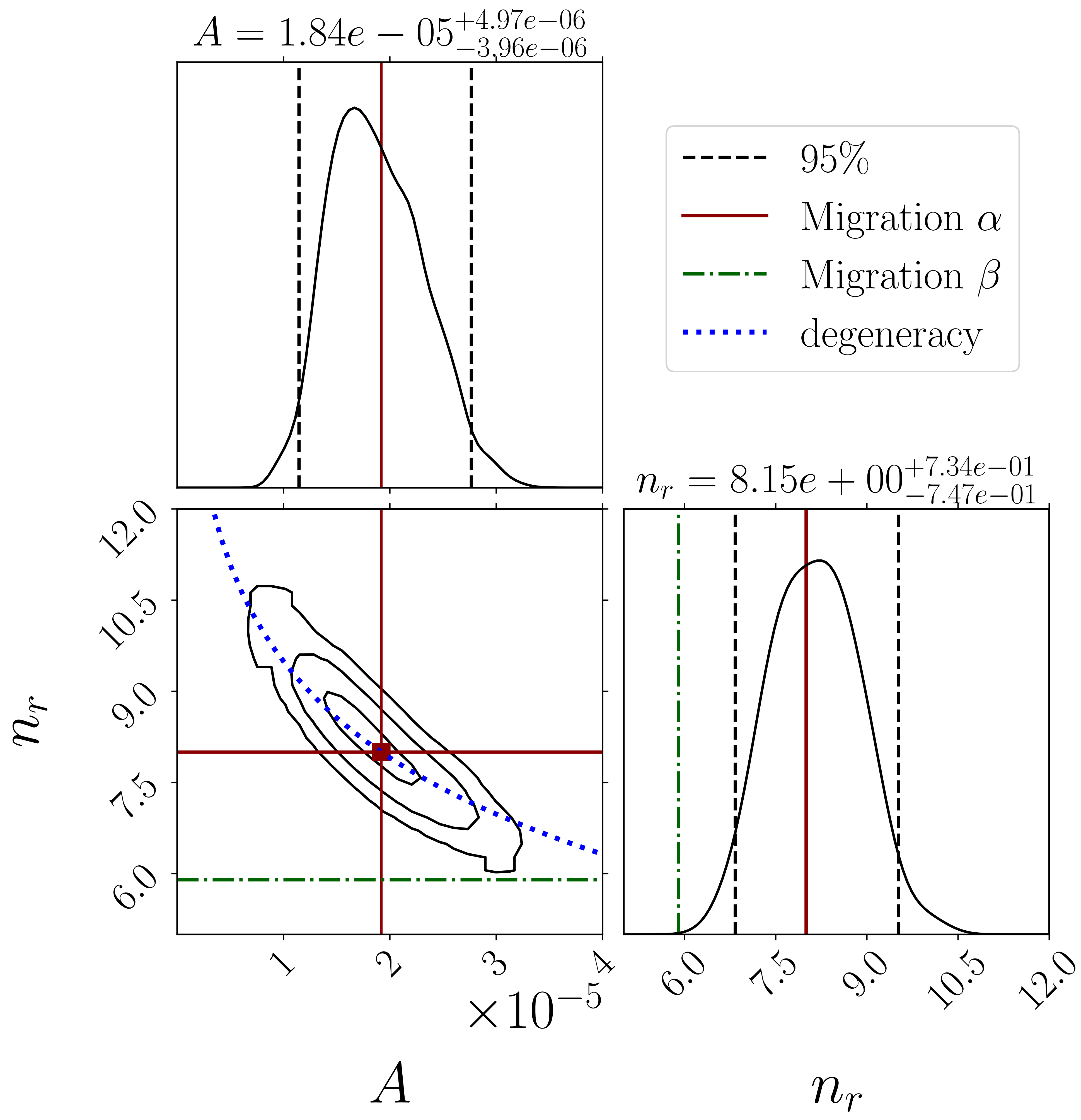
[GPU accelerated by M. Katz!
See https://bhptoolkit.org and L. Speri's talk (Friday morning)]



[Derdzinski+, 2005.11333]

[Speri, LS et al. 2207.10086]

EMRIS IN ACCRETION DISKS

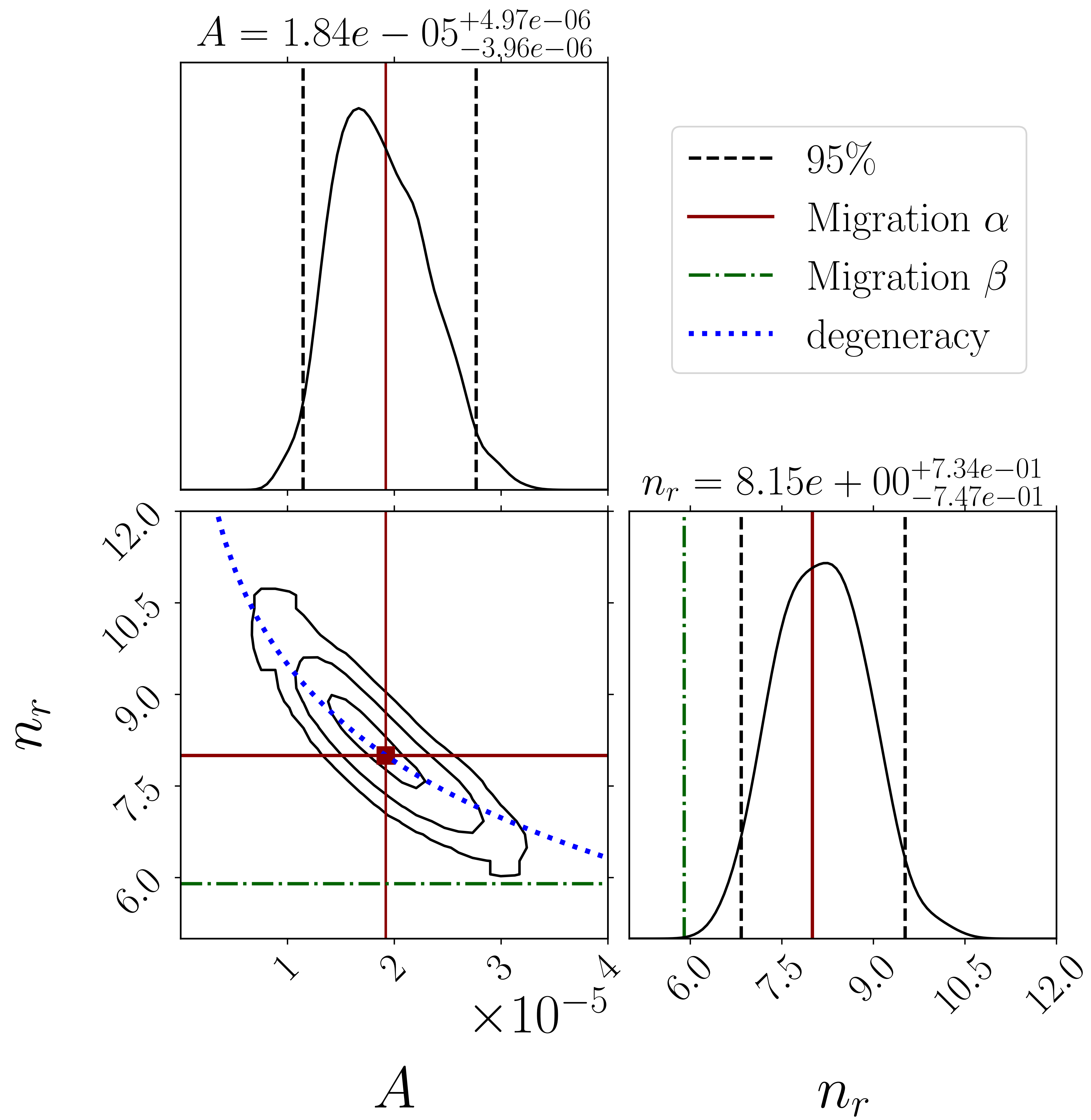


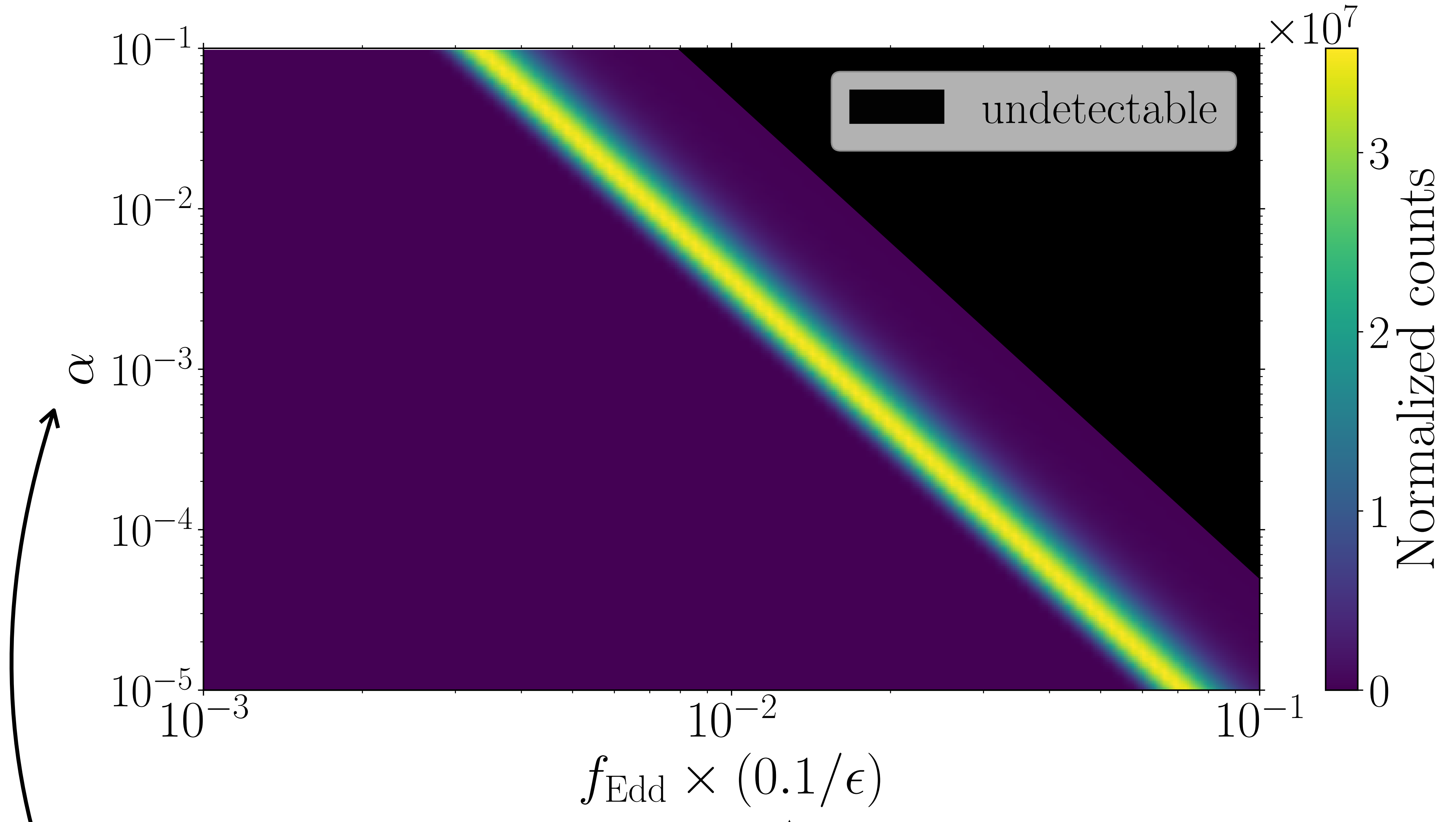
$$\frac{\dot{L}_{\rm environment}}{\dot{L}_{\rm GW}} = A\, r^{n_r}$$

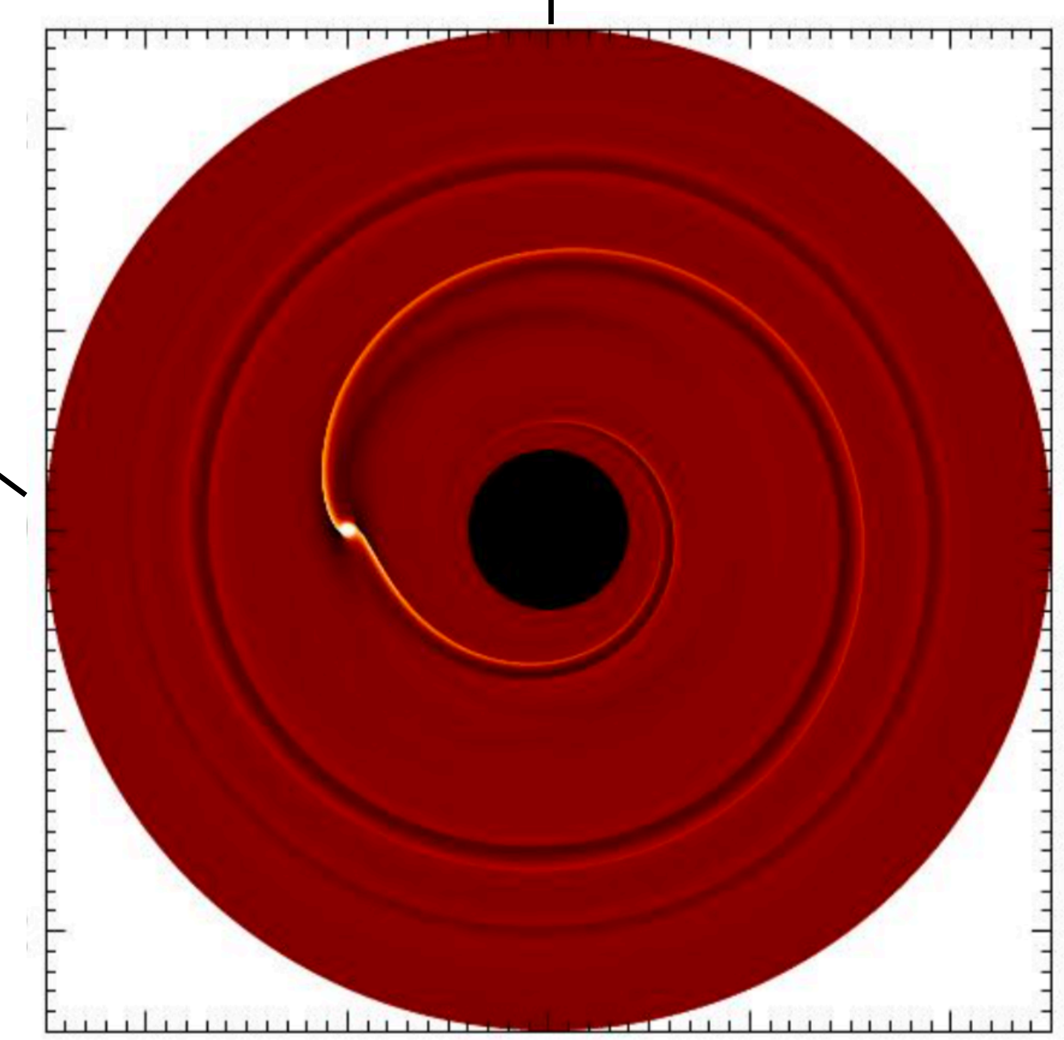
Not captured by parametrised PN, captured by our generalised waveform model

[Speri, LS et al. 2207.10086]

EMRIS IN ACCRETION DISKS





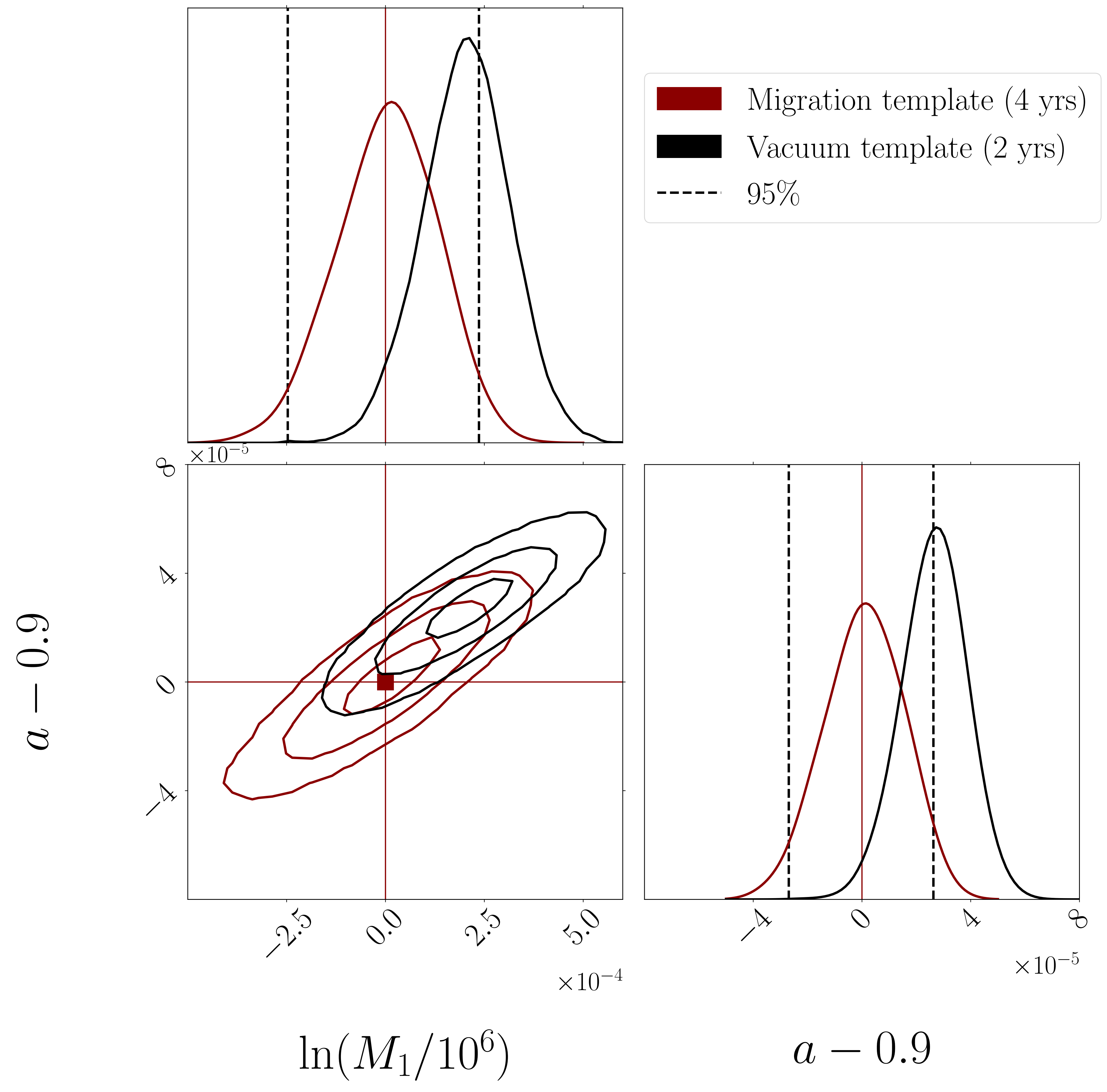


[Nelson 2018]

[Speri, LS et al. 2207.10086]

EMRIS IN ACCRETION DISKS

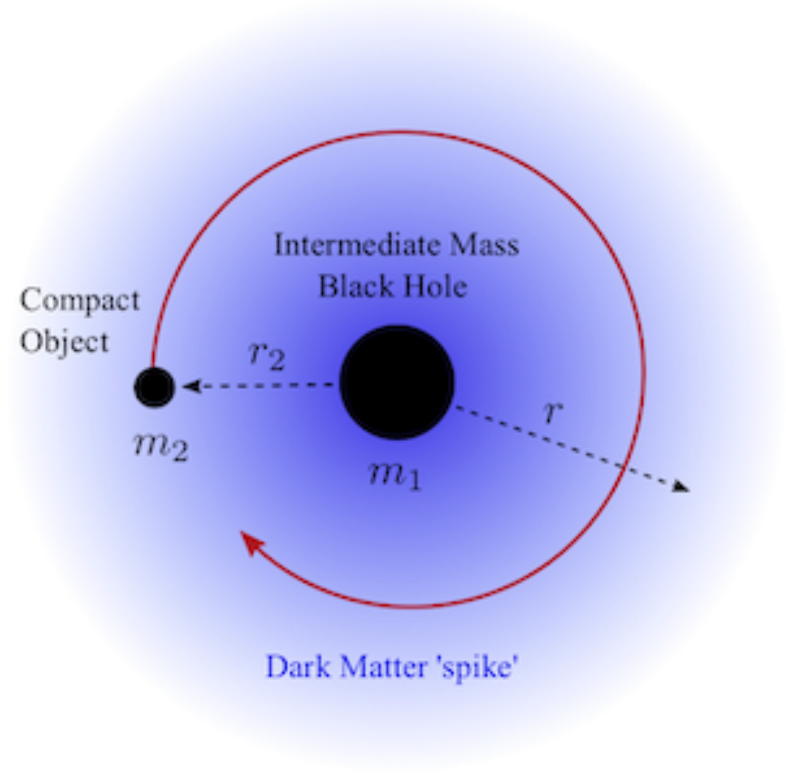
Detection challenge
(on top of standard EMRI challenge)
with vacuum templates

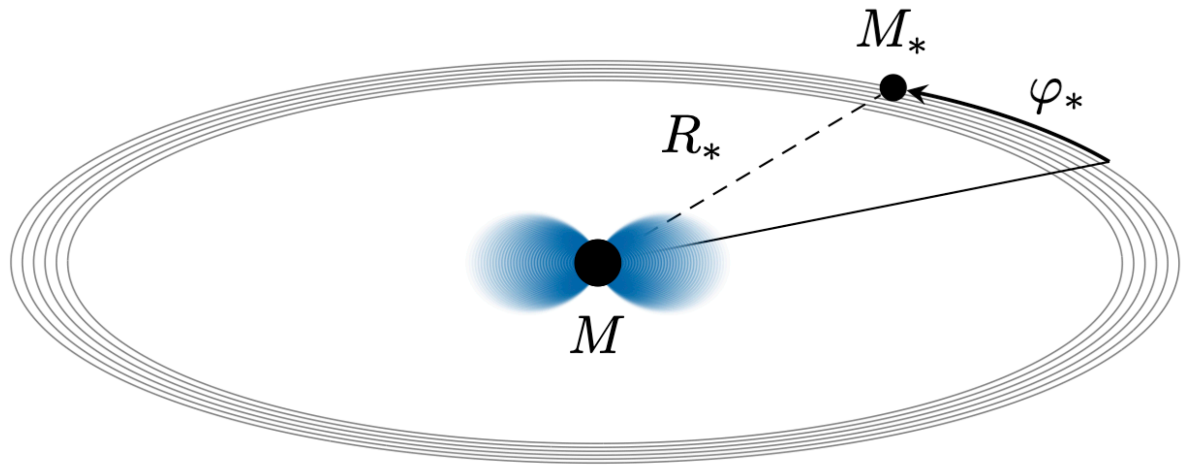


[Speri, LS et al. 2207.10086]

OTHER EXAMPLES

[Kavanagh+ 2021]



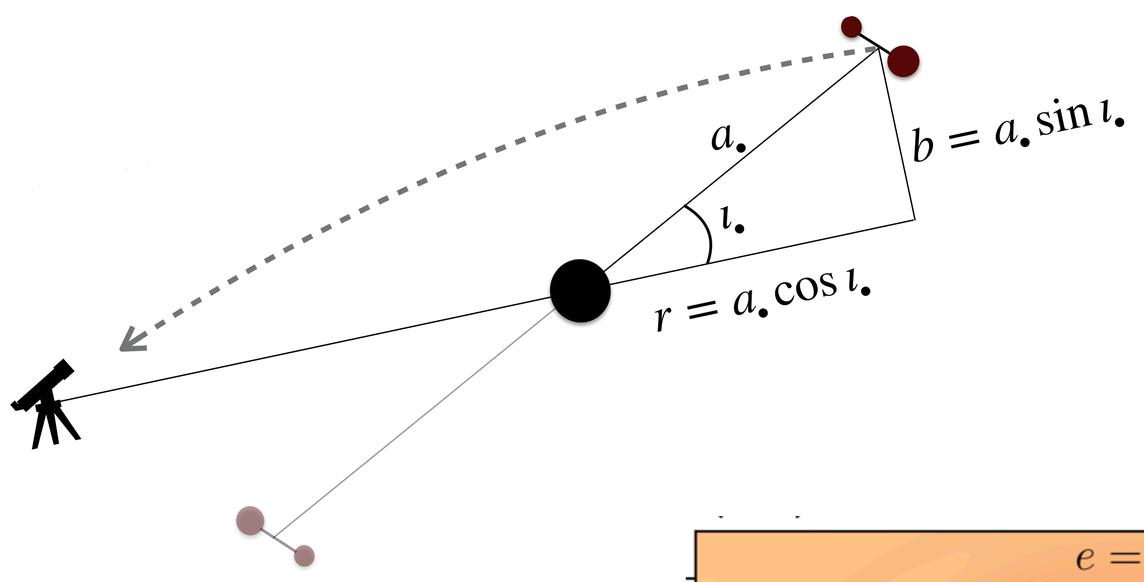


[Baumann+ 2021]

EMRIs and exotic matter:

dark matter “spikes” [Cole+ 2022, Becker, Sagunski 2022, …]

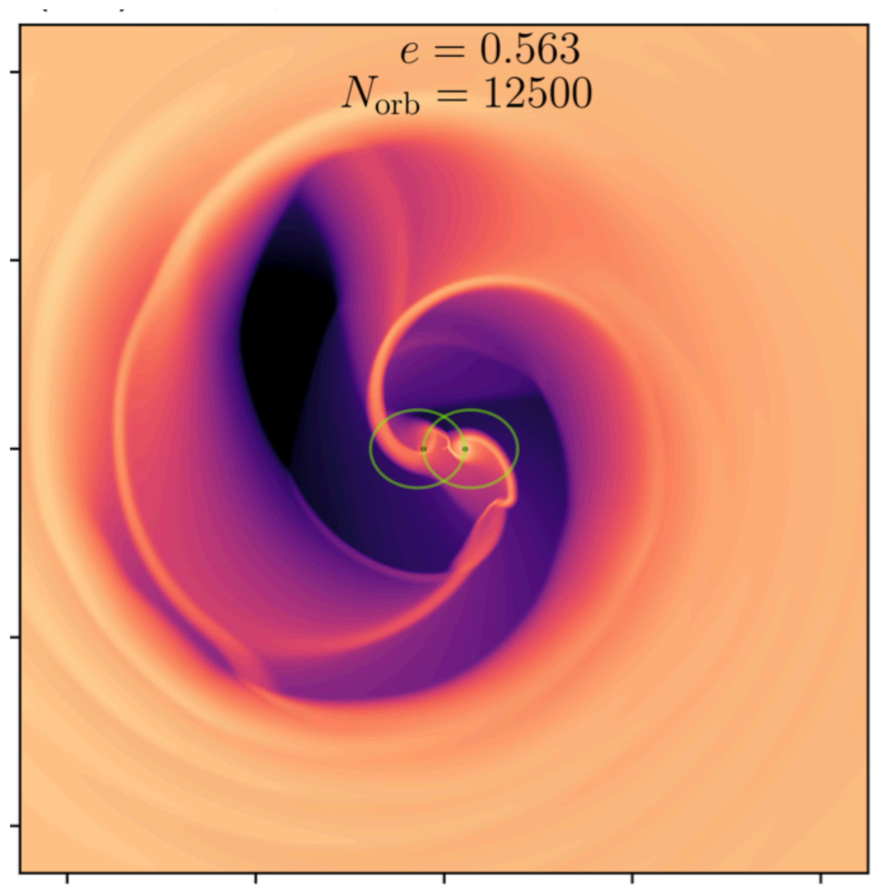
bosonic clouds [Baumann+ 2021, Cole+ 2022, …]



Lensing by local lens [D’Orazio, Loeb 2019, Toubiana, LS et al. 2020]

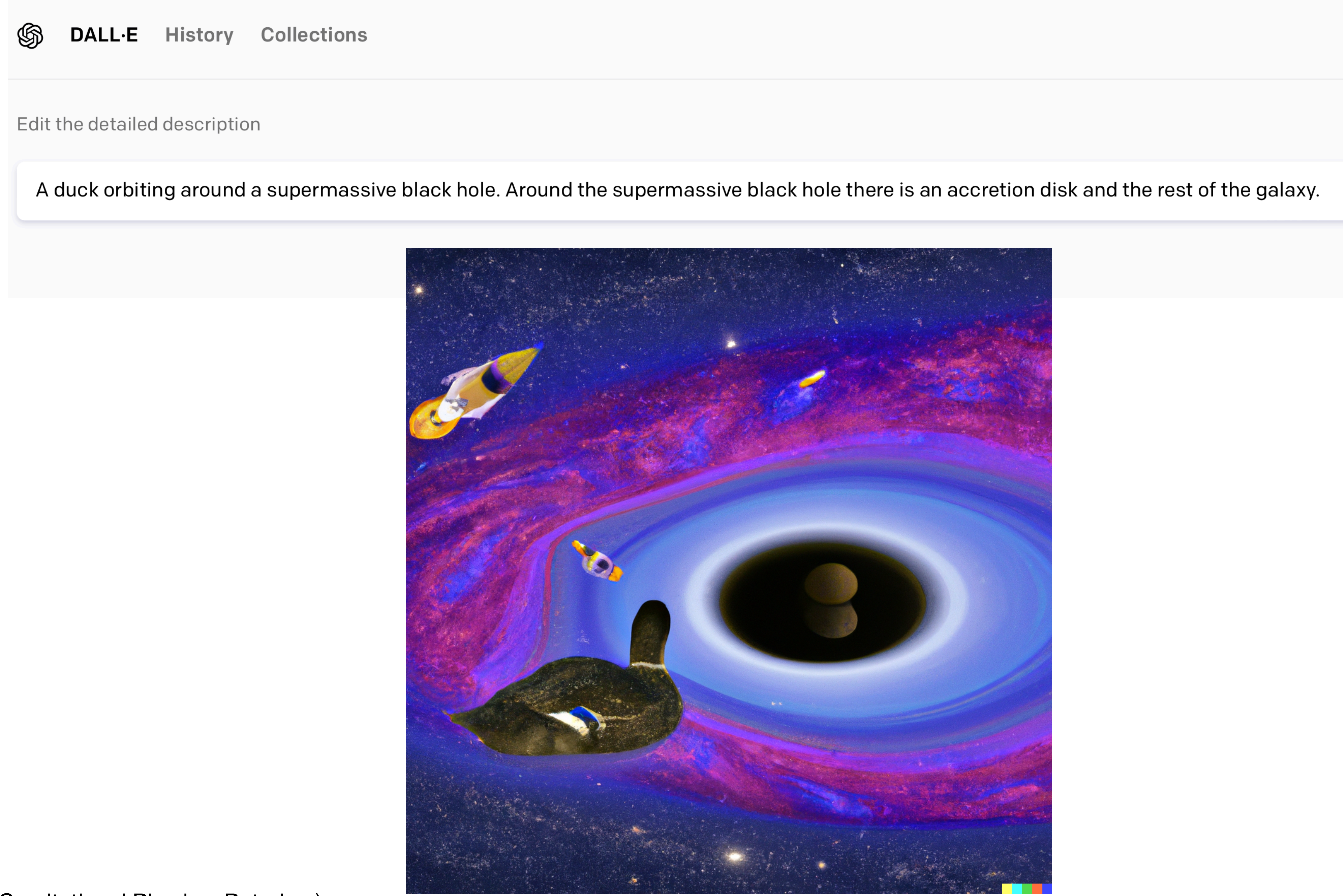
Adding eccentricity

[see talk by M. Garg or D’Orazio, Duffell 2021]

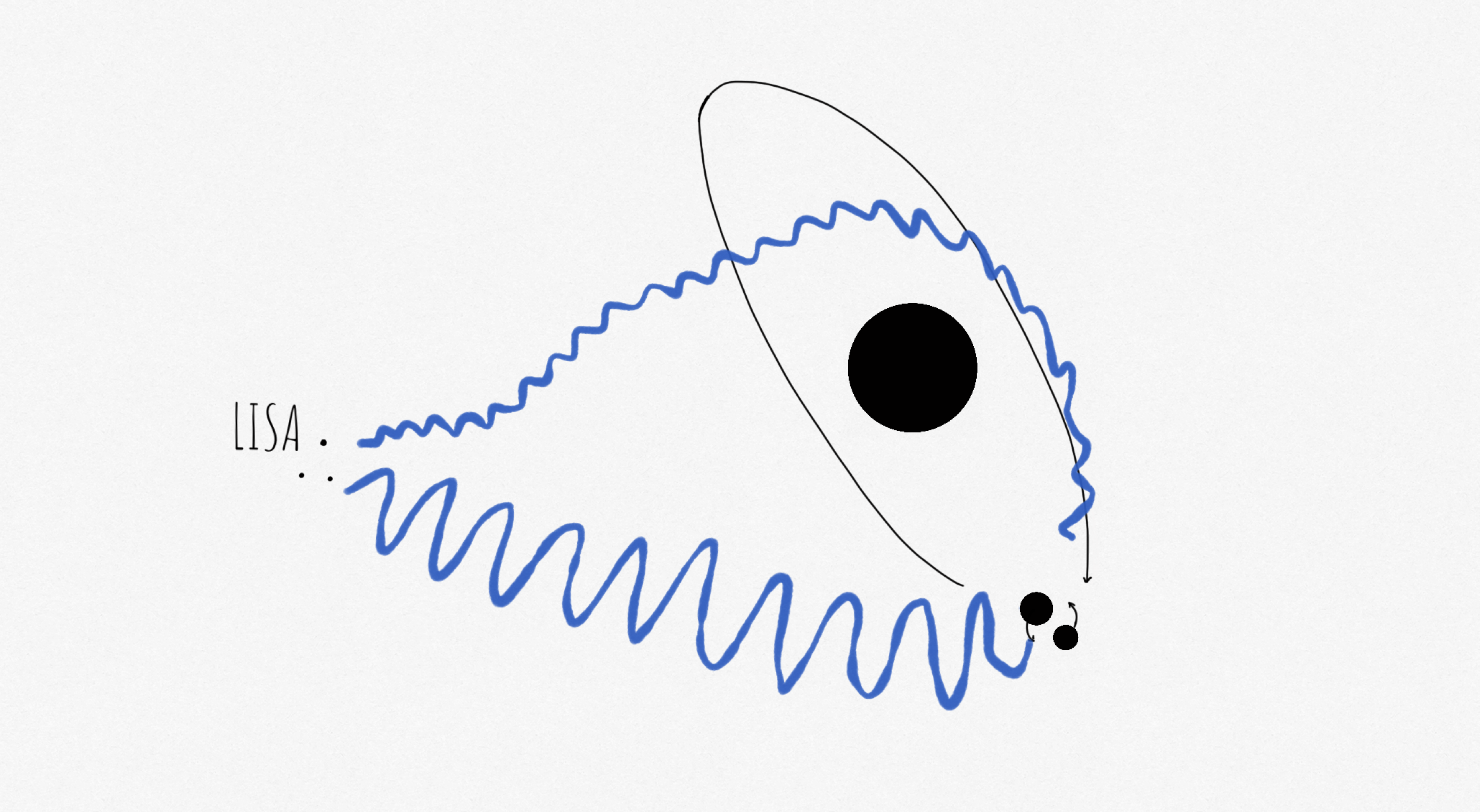


[D’Orazio, Duffell 2021]

CONCLUSIONS: MACHINE LEARNING IN TOULOUSE



Thank you!



Laura Sberna (Max Planck Institute for Gravitational Physics, Potsdam)

LIDA workshop, Toulouse 2022