Title: It's Raining Black Holes... Hallelujah!

Speakers: Smadar Naoz

Collection/Series: Strong Gravity

Subject: Strong Gravity

Date: December 05, 2024 - 1:00 PM

URL: https://pirsa.org/24120017

Abstract:

The groundbreaking detection of gravitational waves from merging black holes has forever changed how we observe the Universe. Upcoming detectors, like the Laser Interferometer Space Antenna (LISA), will unlock new opportunities by allowing us to detect mergers between stellar-mass black holes (tens of solar masses) and supermassive black holes (SMBHs, millions to billions of solar masses). These fascinating events, known as extreme-mass-ratio inspirals (EMRIs), provide a wealth of information about the dynamics near SMBHs. A key formation channel for EMRIs involves weak gravitational interactions—two-body kicks—from surrounding stars and compact objects that gradually alter the small black hole's orbit, eventually driving it into the SMBH. However, the picture changes when we consider the presence of SMBH companions, which can induce high orbital eccentricities, further enhancing EMRI formation. In this talk, I will show that combining these two processes is crucial for understanding the progenitors of EMRIs. Moreover, I will demonstrate that SMBH binaries create EMRIs more efficiently than either process alone, making it truly rain black holes! This scenario results in a substantial stochastic gravitational wave background for future detectors like LISA. Finally, I will also discuss how this mechanism affects tidal disruption events and address the tantalizing question: Is it raining stars, too?

It's Raining Black Holes... Hallelujah!

Smadar Naoz
UCLA

December
2024
Perimeter Institute

Collaborators: Andrea Ghez, Mike Grudić , Anna Ciurlo, Avi Loeb, Bence Kocsis, Blakesley Burkhart, Cliff Will, Enrico Ramirez-Ruiz, Federico Marinacci, Fred Rasio, Gongjie Li, Jess McIver, Joe Silk, Katie Breivik, Mark Morris, Mark Vogelsberger, Naoki Yoshida, Tommaso Treu, Tuan Do, Vicky Kalogera, Will Farr, Yoram Lithwick, Zoltan Haiman… + My group

Special thanks to Howard and Astrid Preston for their generous support

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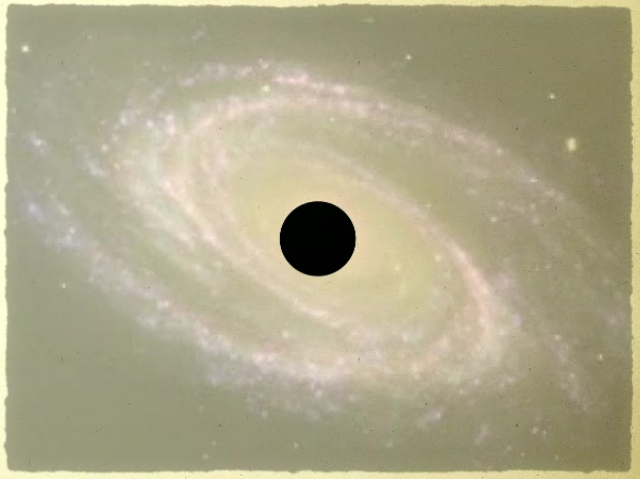

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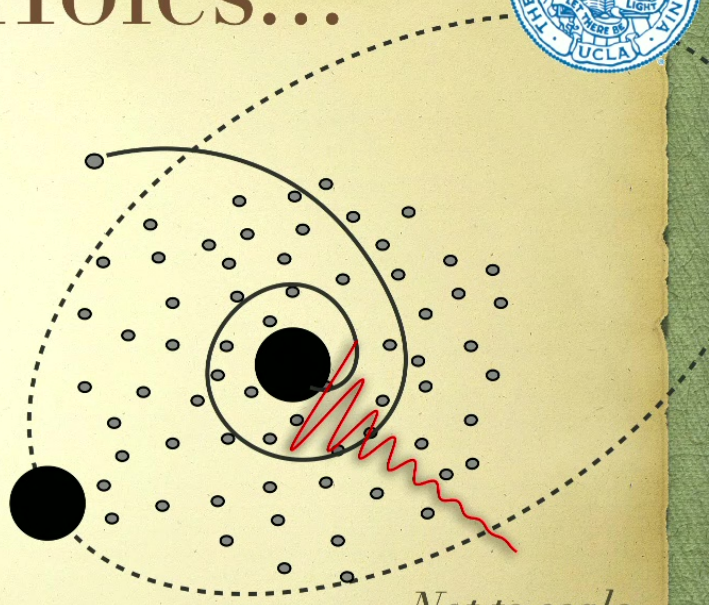

Not to scale

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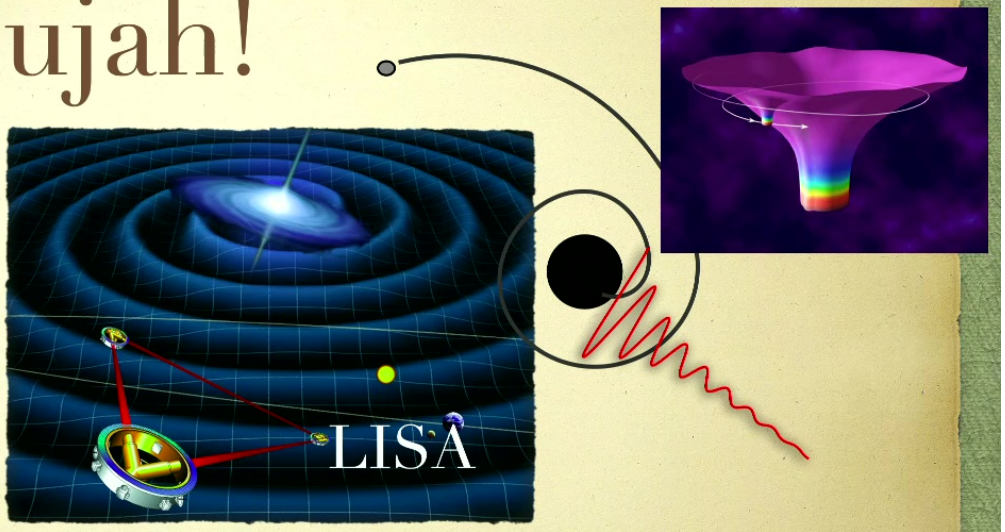
It's Raining Black Holes... Hallelujah!

What will LISA detect, and what can we learn about SMBH astrophysics?



e.g., Hughes 2001; Amaro-Seoane et al. 2007,2012; Hopman & Alexander 2005; Bode & Wegg 2014; Haster et al. 2016;Aharon & Perets 2016; Ryu et al. 2016; Sari & Fragione 2019 Mazzolari et al. 2022; Pan et al. 2021,2023

EMRI = Extreme mass ratio inspiral

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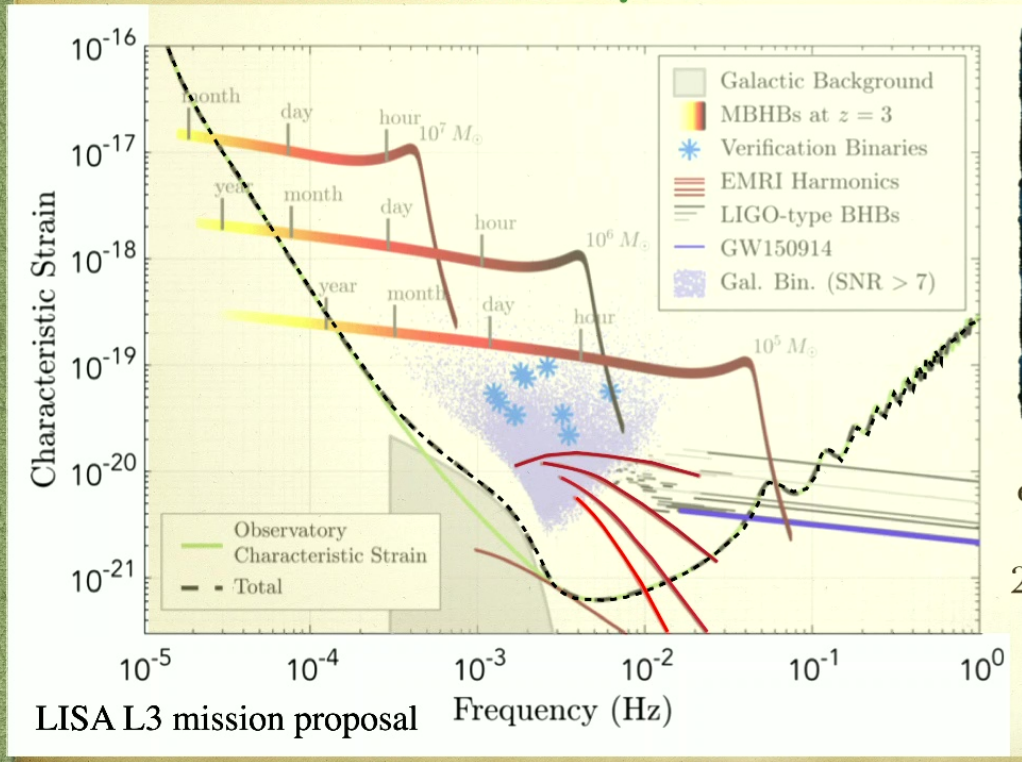
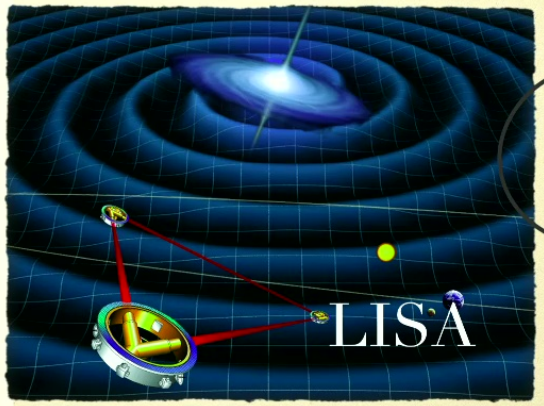
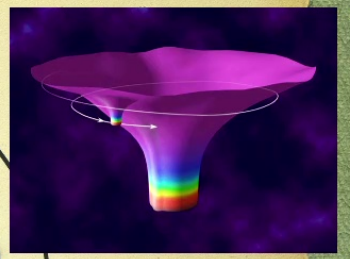
EMRI = Extreme mass ratio inspiral



LISA L3 mission proposal





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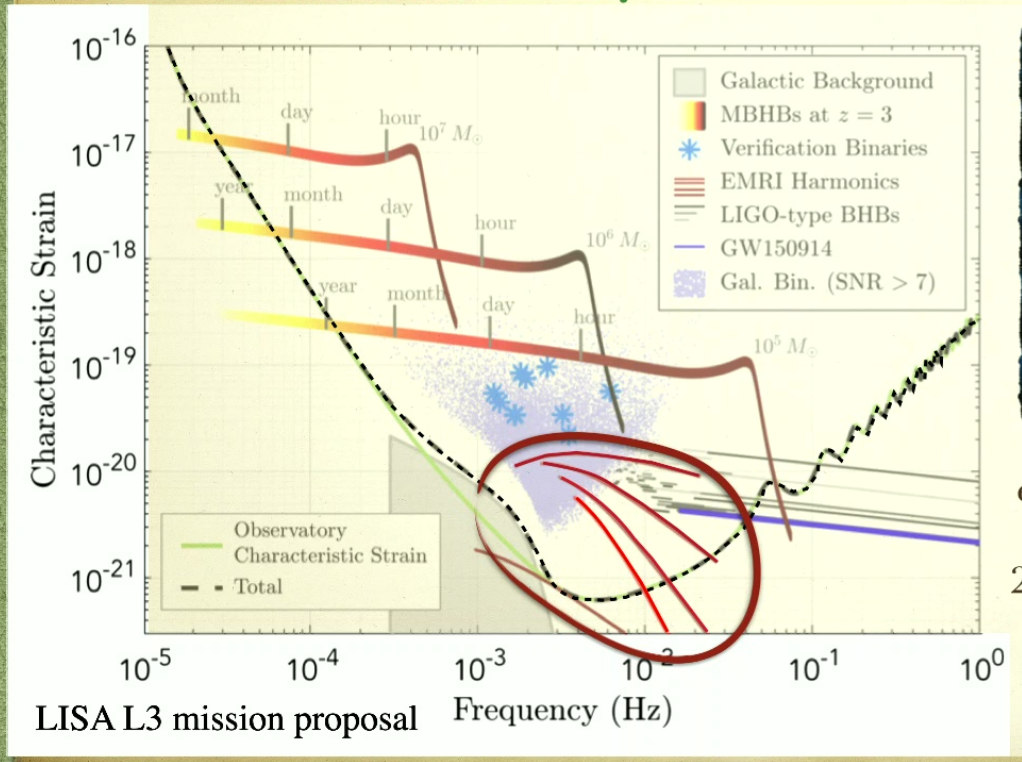

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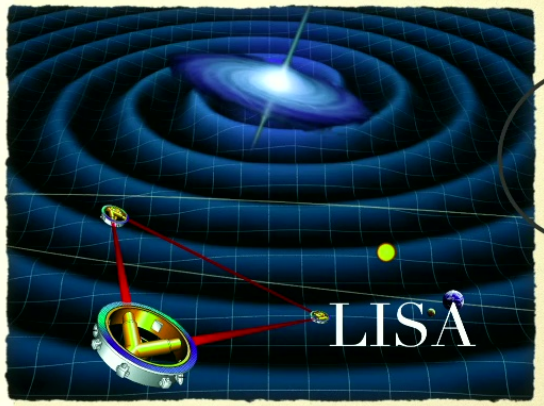

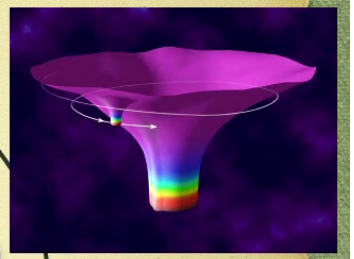

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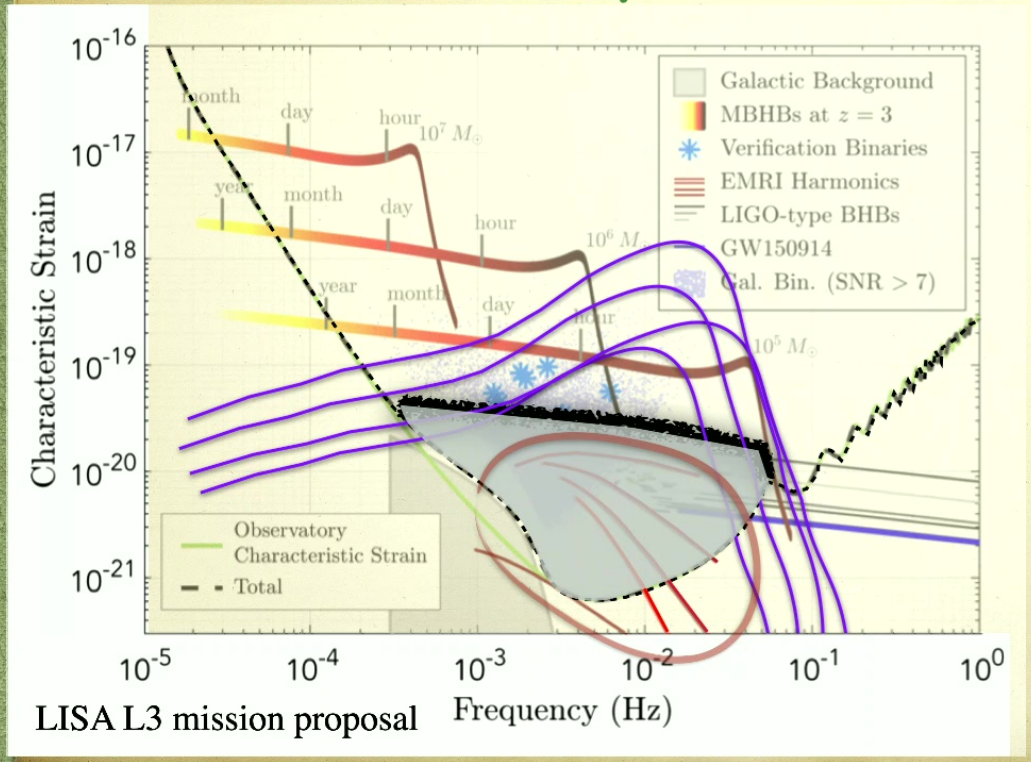


LISA L3 mission proposal

Punchline:

EMRIs in SMBH binaries yield a stochastic background

It's Raining Black Holes... Hallelujah!

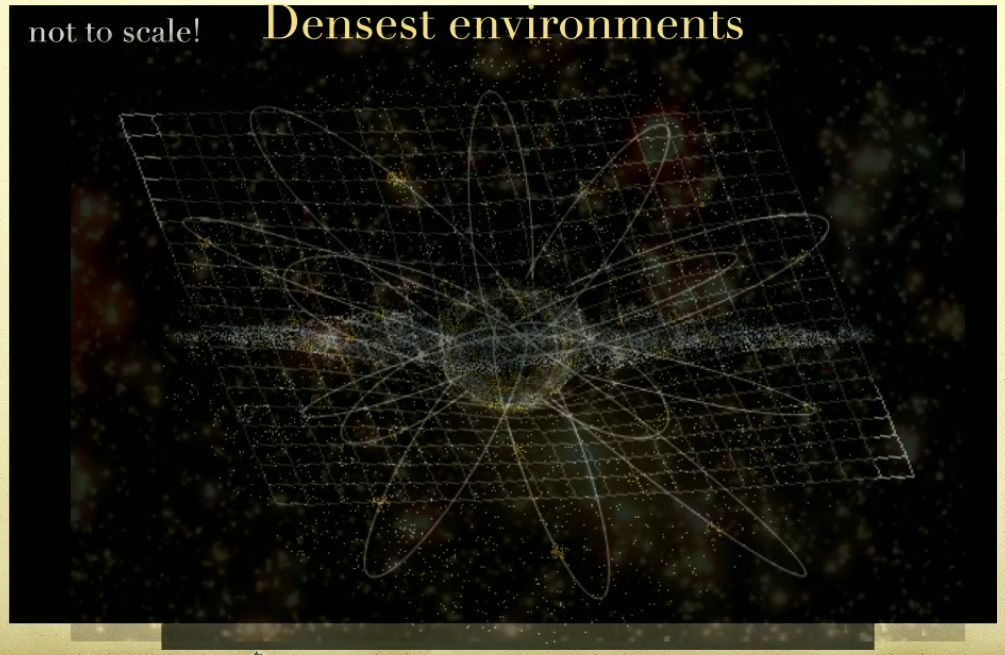
- How to form an EMRI?
  - "Classic approach"
  - SMBH binaries
- Something is missing…
- Prediction of raining back holes
- Implications for tidal disruption events (TDEs)


SPICE
GIRLS

How to form an EMRI?

We first need a Supermassive black hole (SMBH)

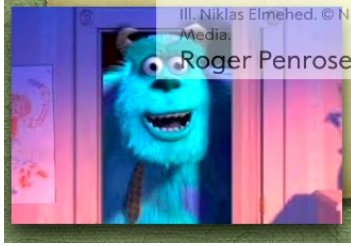
~Every galaxy has a Supermassive Black Hole $10^{6\text{-}9} M_\odot$



A monster in our backyard

Ghez et al. 2003

The central 10 arcsec … year



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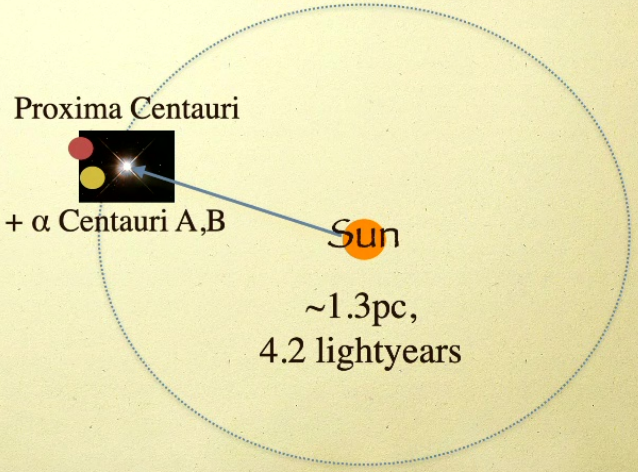
A monster in our backyard



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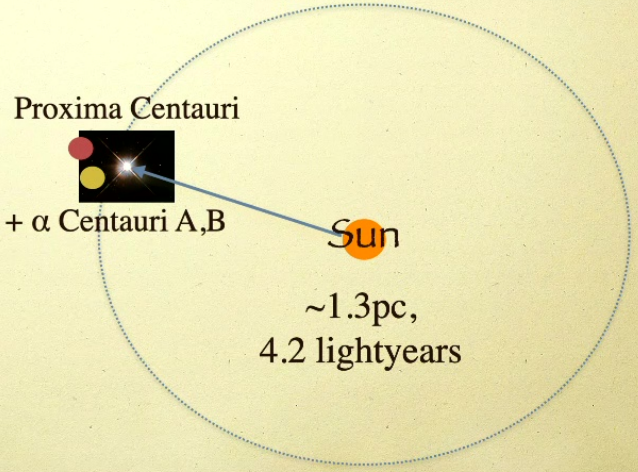
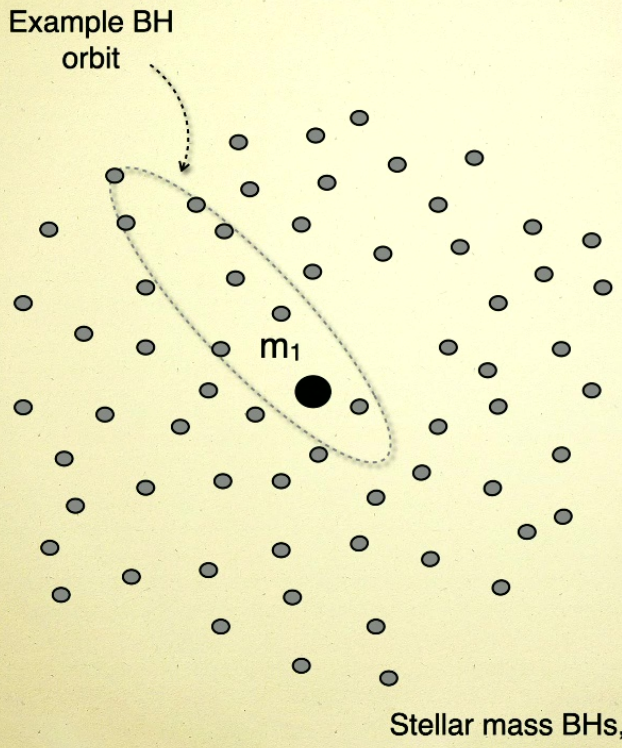


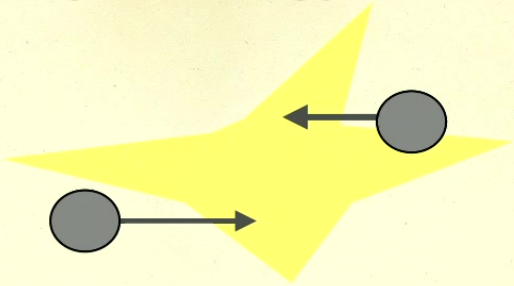
How to form an EMRI?



#1

How to form an EMRI?

Changes for E or L by order of themselves: $\Delta L \sim L$



Weak kicks
⇛ two body relaxation

The number of interactions: $N \sim t_{rlx}/P$

So: $\delta L/L \sim \sqrt{P/t_{rlx}}$ or $t_{rlx}/P \sim (L/\delta L)^2$

#1

The velocity changes are like a one-dimensional random walk (on average, the kicks cancel out).

$$\Delta L \sim \sqrt{N}\ \delta L_n$$

Change in L after N interactions

L change per-interaction

(e.g., Magorrian & Tremaine 1999; Hopman & Alexander 2005; Freitag et al. 2006; Fregeau & Rasio 2009; O'Leary et al.2009; Kocsis et al. 2011; Aharon & Perets 2016; Amaro-Seoane 2018; Sari & Fragione 2019; Emami & Loeb 2021).

How to form an EMRI?

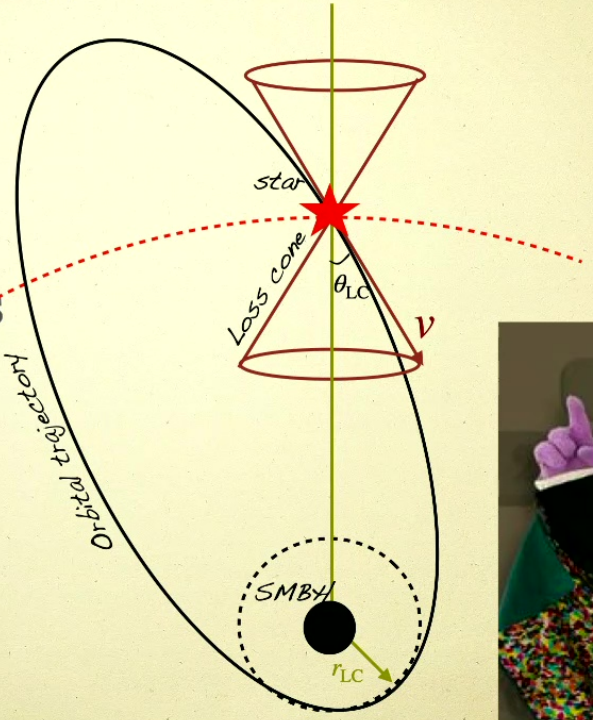
EMRI rate is set by passage of BHs into loss cone

EMRI rate ~ few 10s /Gyr/galaxy

e.g., Magorrian & Tremaine 1999; Hopman & Alexander 2005; Aharon & Perets 2016; Amaro-Seoane 2018; Sari & Fragione 2019

Example orbit

Critical radius



#1

Weak kicks ⇛ two body relaxation

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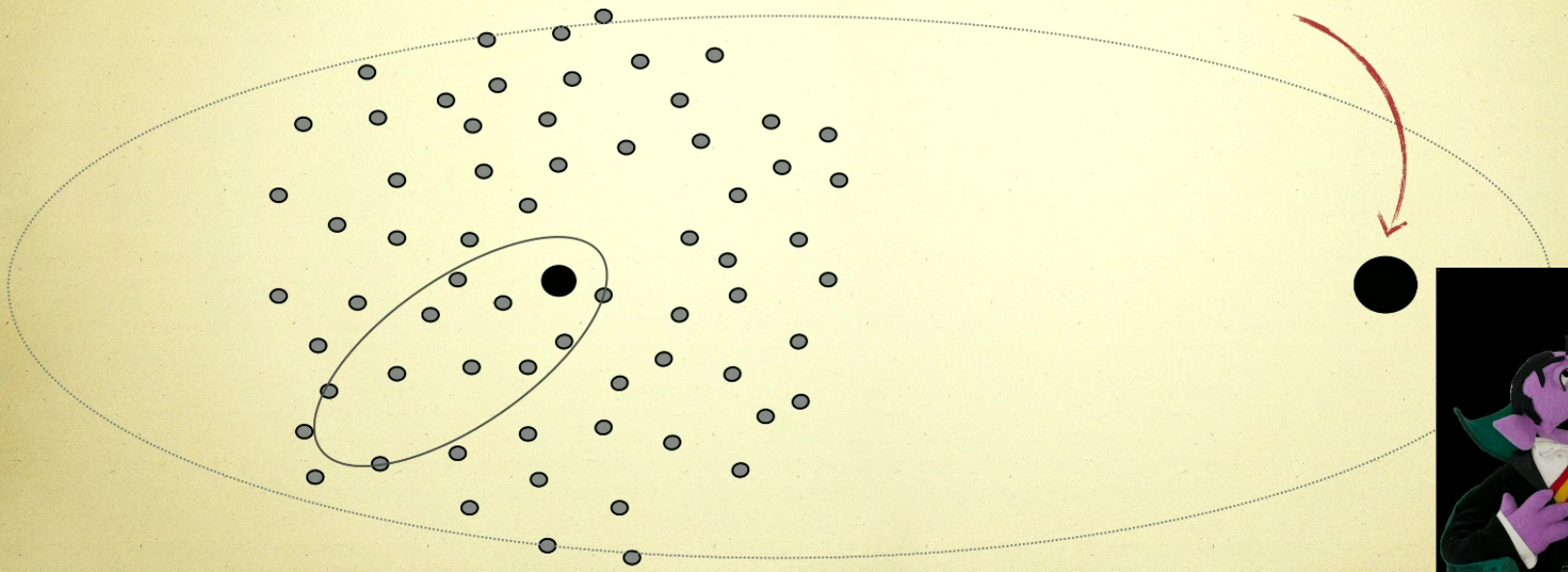
How to form an EMRI?

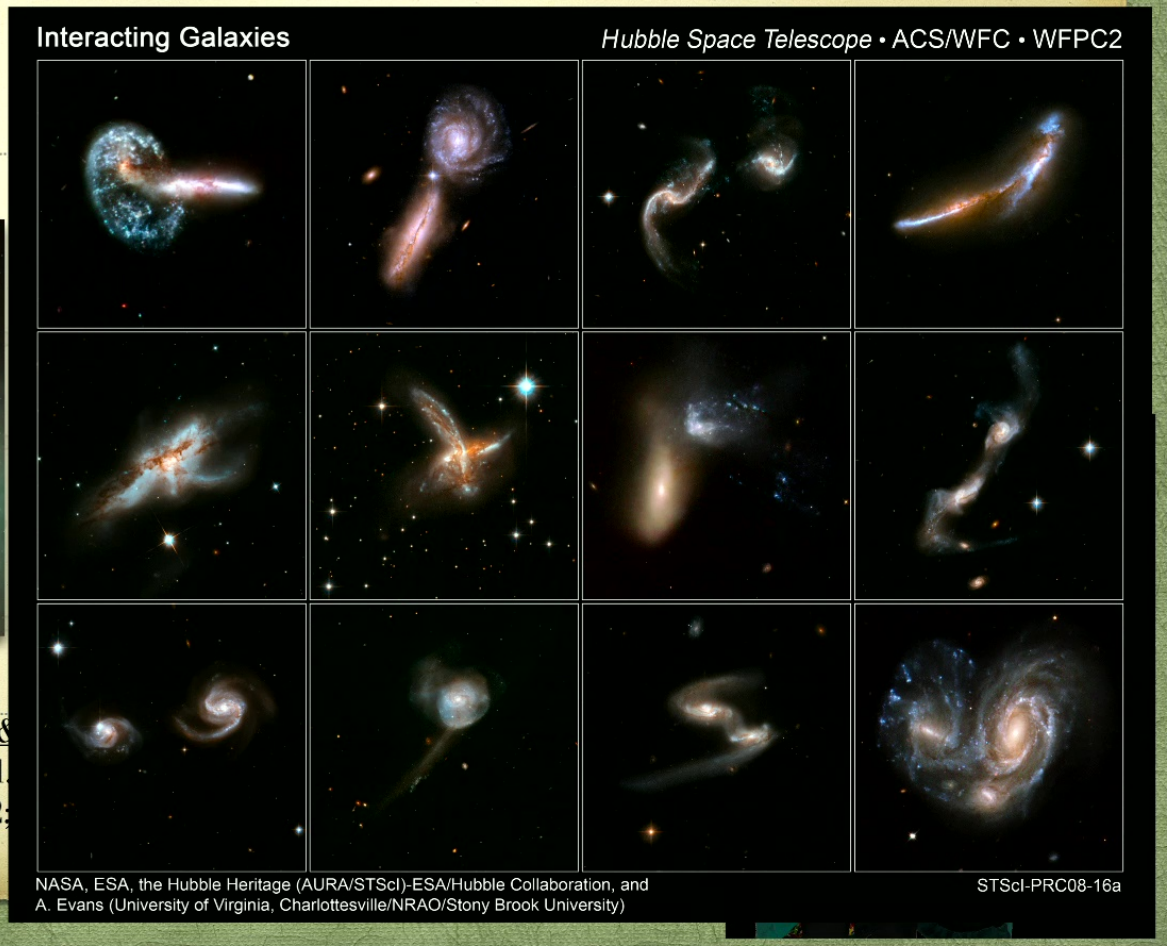
Add another SMBH



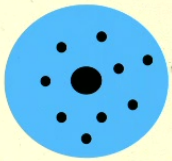
#2

Why pair of SMBHs?

Di Matteo et al. 2005; Hopkins et al. 2006; Robertson et al. 2006; Callegari et al. 2009; Blecha et al. 2011, 2013; Meiron & Laor 2013; Bogdanović 2015; Runnoe et al. 2017; Wise et al. 2019; Zine & Salim 2022; Li et al. 2020; De Rosa et al. 2022; Masterson et al. 2024; Pasham et al. 2024; Kelley et al. 2019;2021



Galactic Cannibalism



Dwarf galaxy or a globular cluster, merging, hosting a lighter SMBH

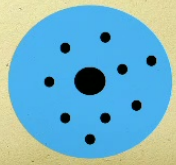
Massive SMBH

~pc

Galaxy, not to scale

Hierarchical limit

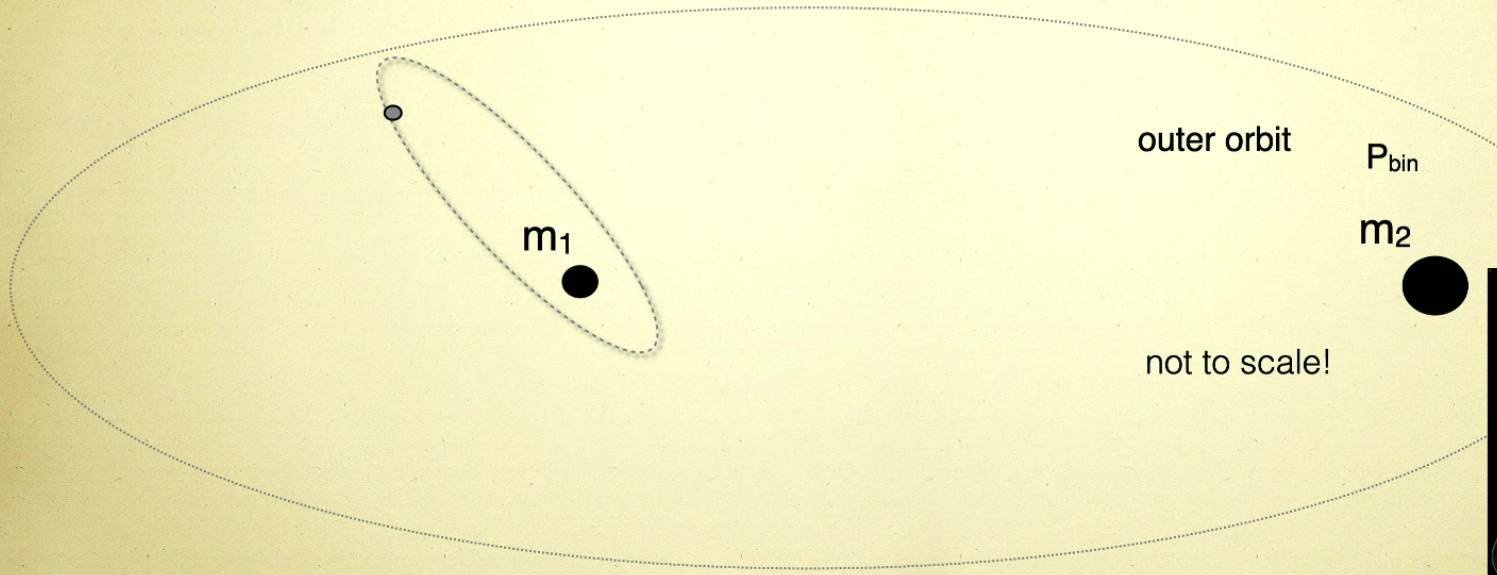
Sphere of influence of the massive SMBH



Naoz & Haiman (2023)

e.g., Volonteri et al. 2003a; Rodriguez-Gomez et al. 2015; Pillepich et al. 2018; Paudel et al. 2018; Mićić et al. 2023; Madau & Rees 2001; Volonteri et al. 2003b; Rashkov & Madau 2014; Ricarte et al. 2016

How to form an EMRI?



#2

Kozai 1962, Lidov 1962

Naoz et al, (2011,2013)

See for review: **Naoz** (2016) ARA&A
arXiv:1601.07175

How to form an EMRI?

The three body problem

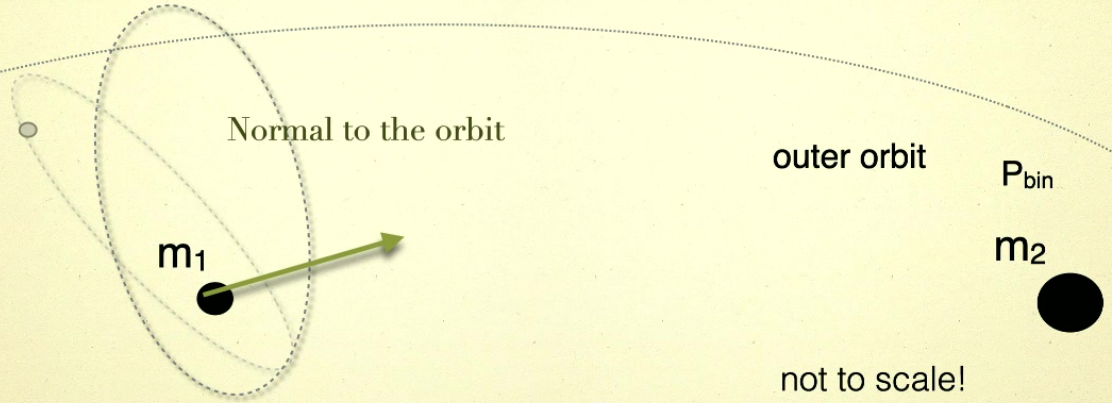
Kozai 1962, Lidov 1962

Naoz et al, (2011,2013)

See for review: **Naoz** (2016) ARA&A
arXiv:1601.07175

#2

How to form an EMRI?



#2

The hierarchical three body problem

Kozai 1962, Lidov 1962

Naoz et al, (2011,2013)

See for review: **Naoz** (2016) ARA&A
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The Eccentric Kozai-Lidov (EKL) Mechanism

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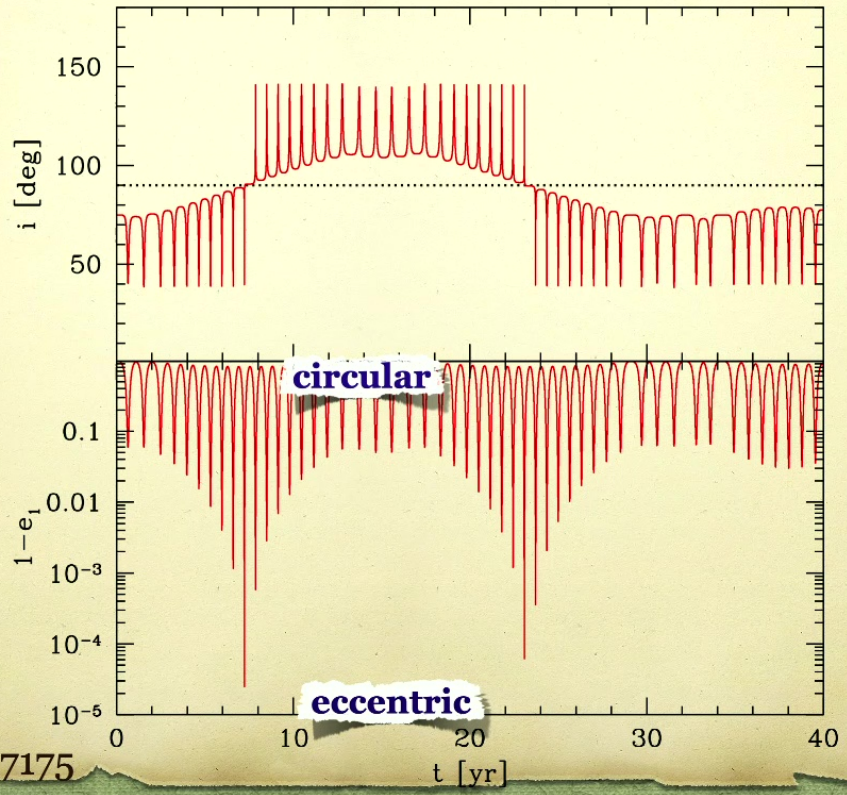
GR effects: Naoz et al (2013)



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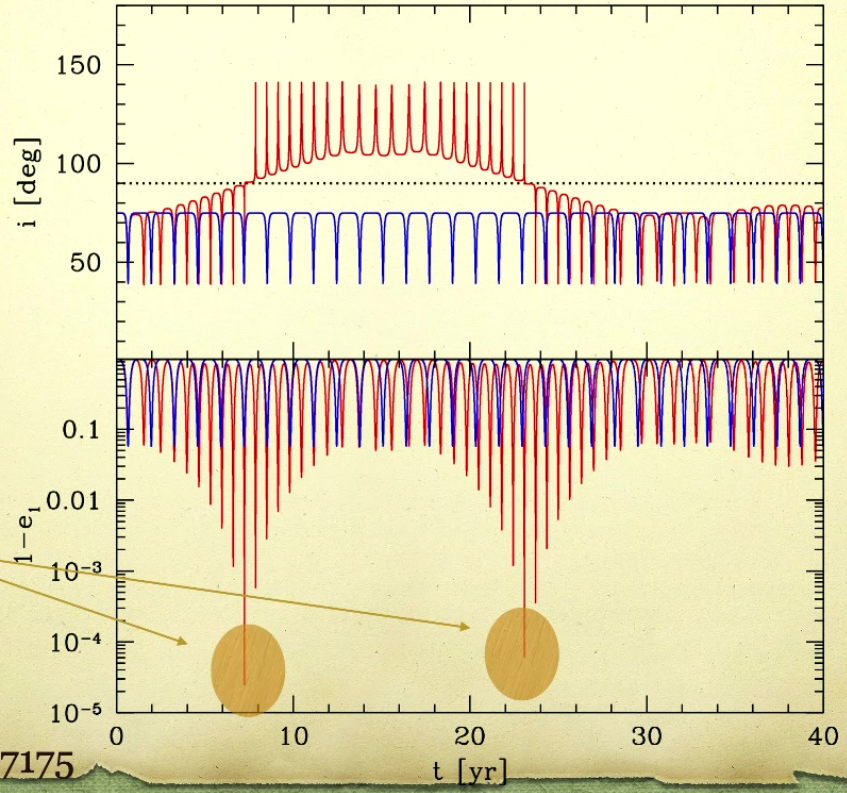

extreme eccentricity peaks cause mergers!

Naoz (2016) ARA&A arXiv:1601.07175

The Eccentric Kozai-Lidov (EKL) Mechanism

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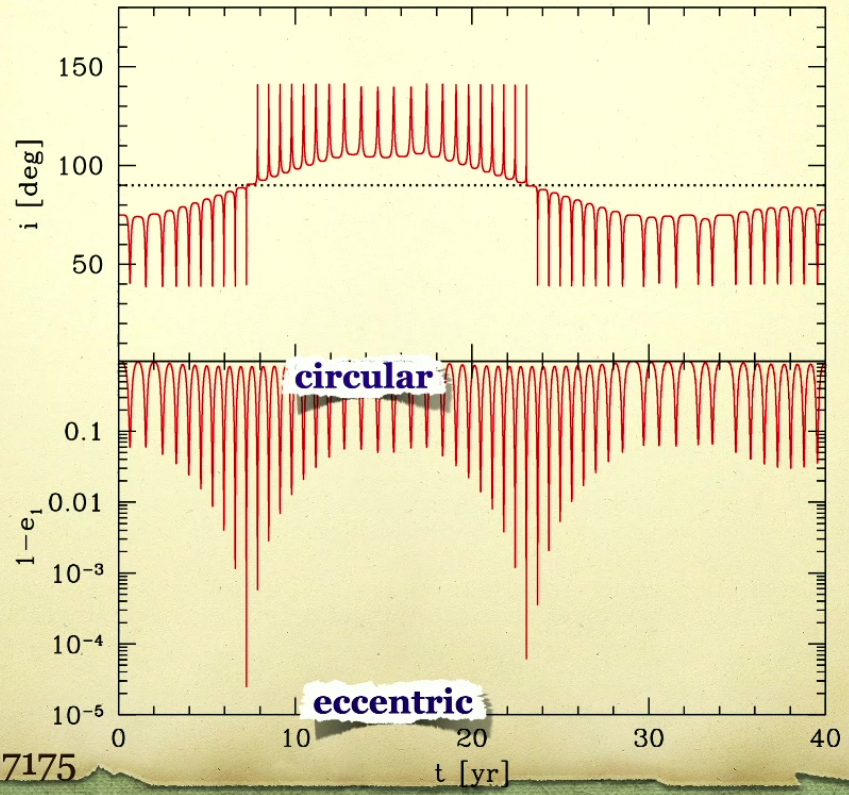


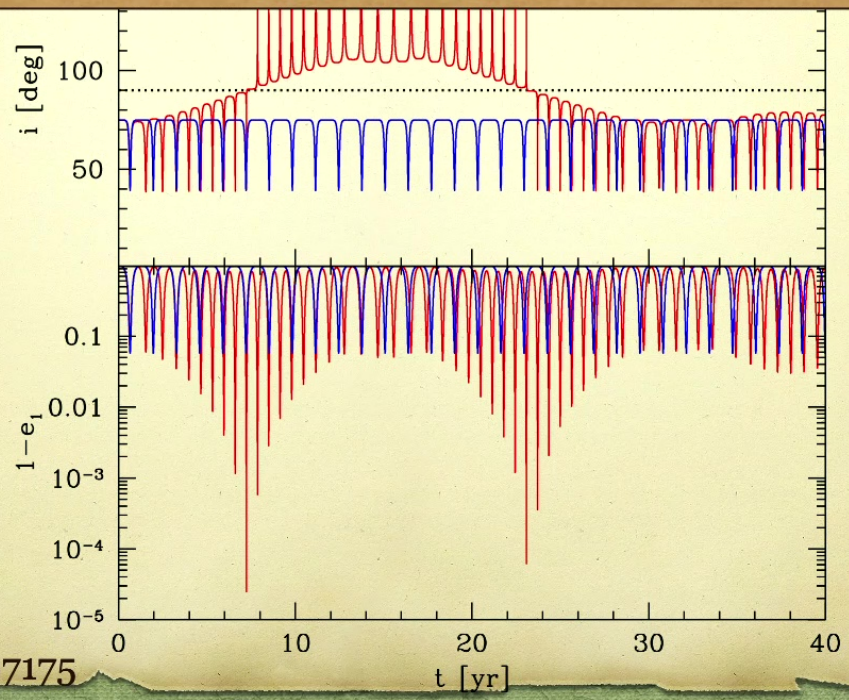
Naoz (2016) ARA&A arXiv:1601.07175

The Eccentric Kozai-Lidov (EKL) Mechanism

The Eccentric Kozai-Lidov (EKL) mechanism

GR effects: Naoz et al (2013)

Compare to: "Standard" (quadrupole) Kozai



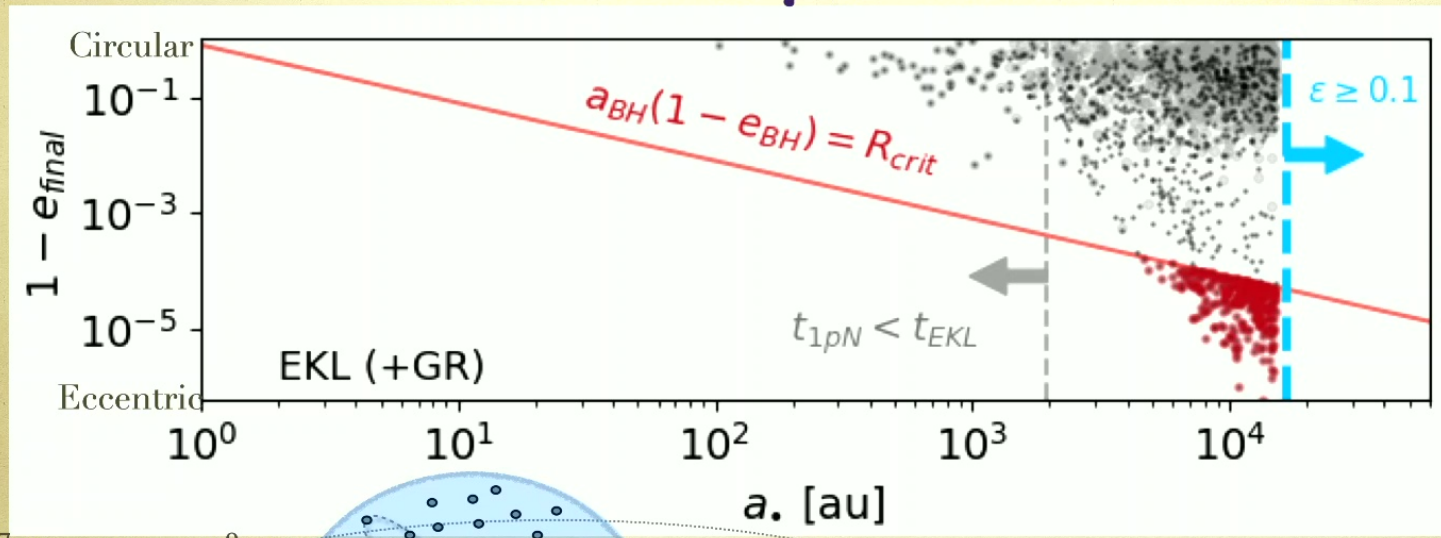
Naoz (2016) ARA&A arXiv:1601.07175

How to form an EMRI?

The Eccentric Kozai Lidov (EKL) mechanism drive high eccentricity in SMBH binaries

GR effects follow **Naoz** et al (2013)

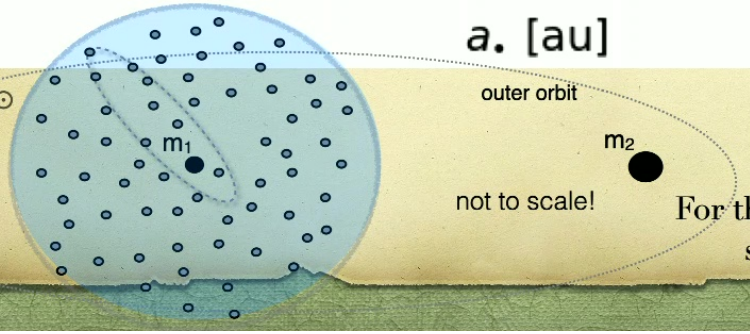
#2



$m_1 = 10^7 M_\odot$ $m_c = 10^9 M_\odot$

$m_c = 1\ pc$ $e_c = 0.7$

Naoz et al (2022)

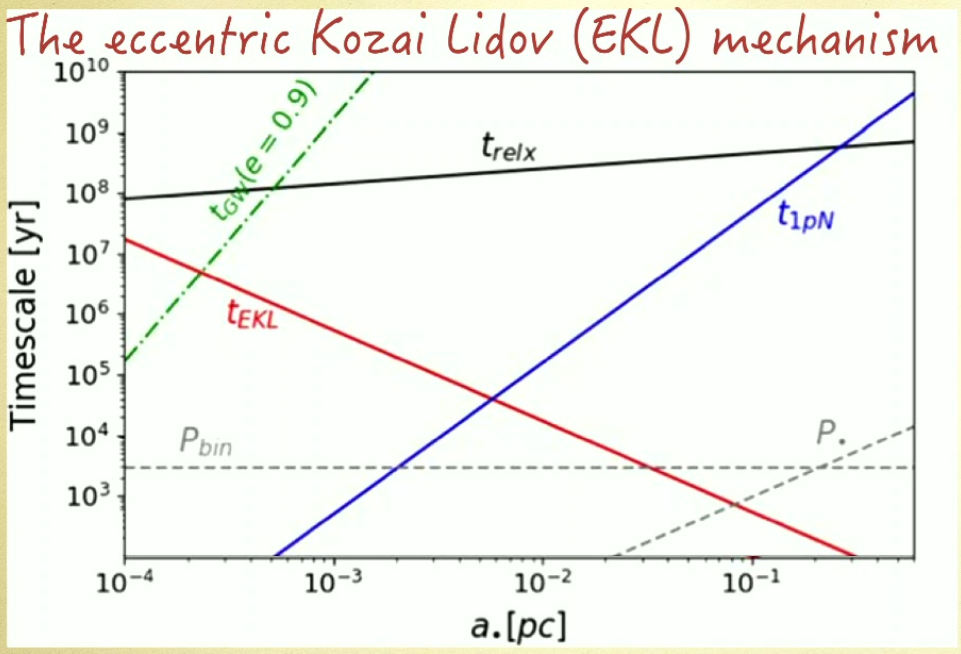


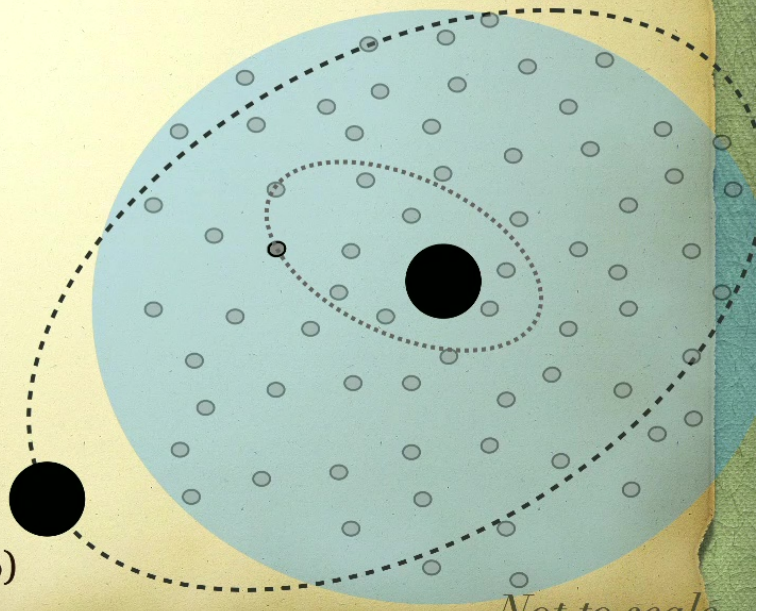
See also: Bode & Wegg 2014; Haster et al. 2016

For the effect of merging binaries, see: Mazzolari et al. 2022

Should we include two body relaxation + EKL?

The eccentric Kozai Lidov (EKL) mechanism





Not to scale

Naoz et al (2022)

See for review on EKL: **Naoz** (2016)
ARA&A arXiv:1601.07175

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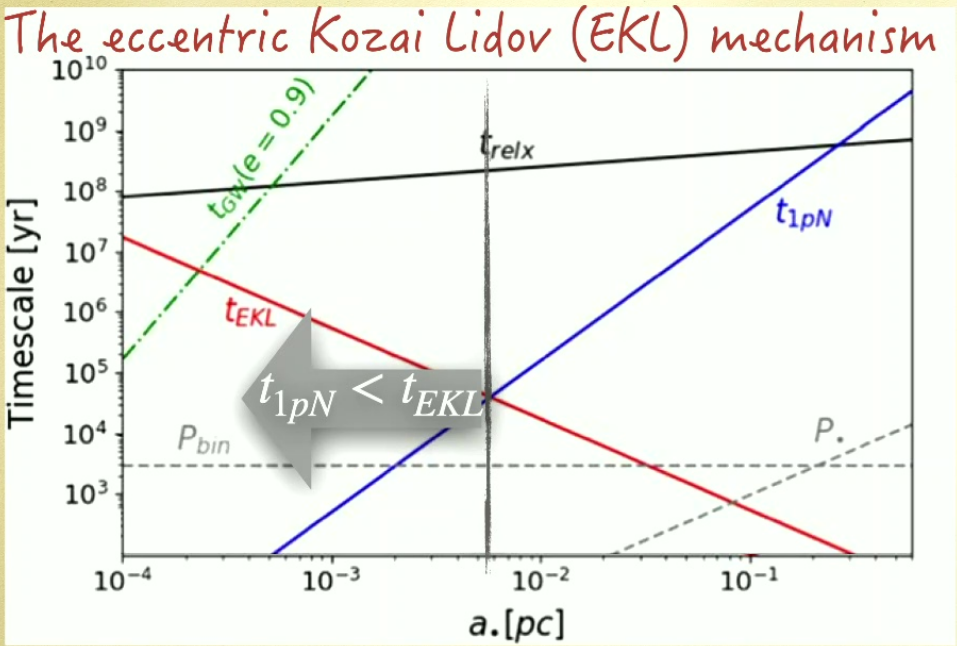
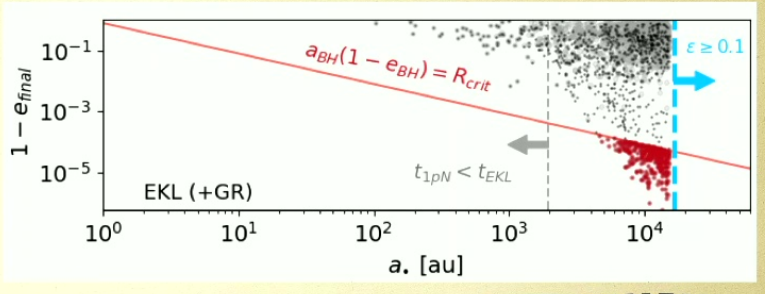
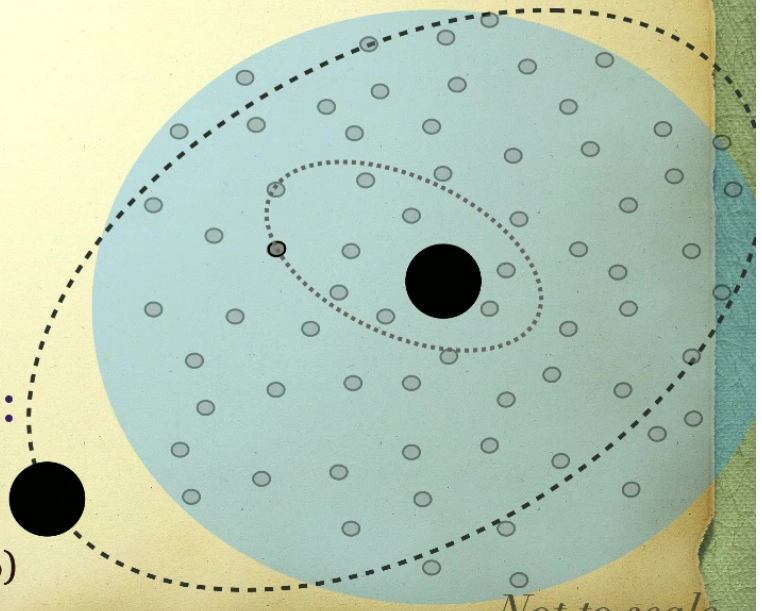






Changes to the angular momentum (two body relx.):

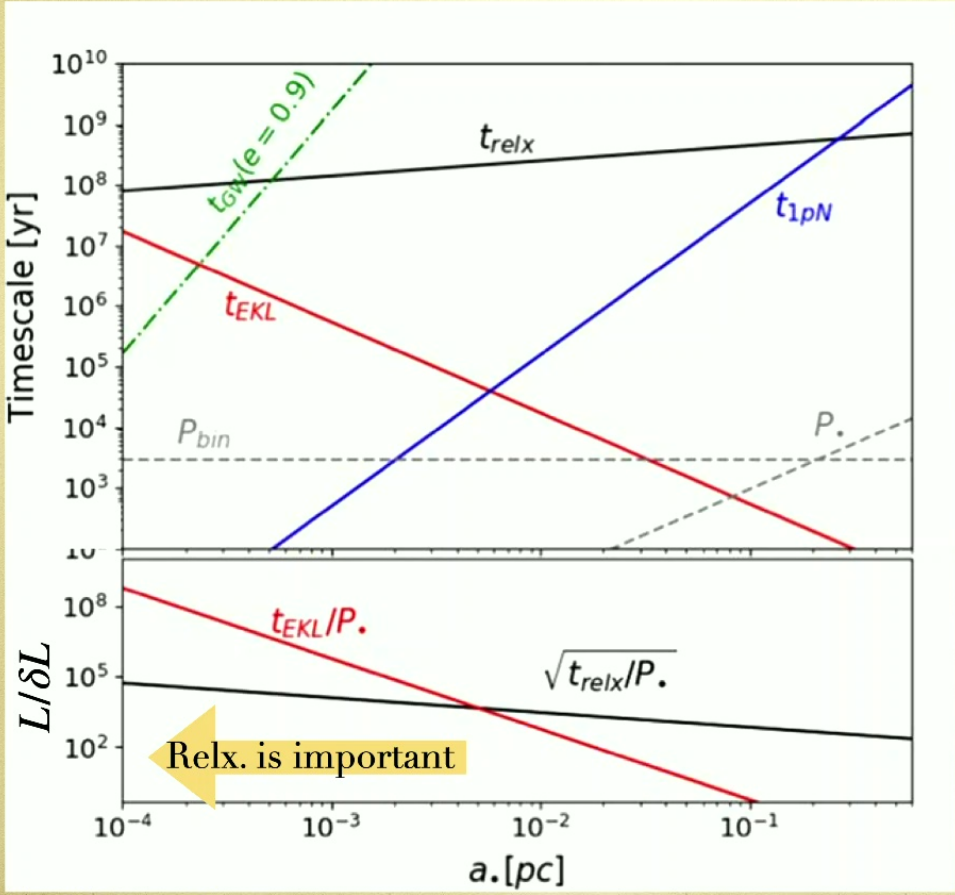
$$\delta L/L \sim \sqrt{P/t_{rlx}}$$

Naoz et al (2022)

See for review on EKL: **Naoz** (2016)
ARA&A arXiv:1601.07175

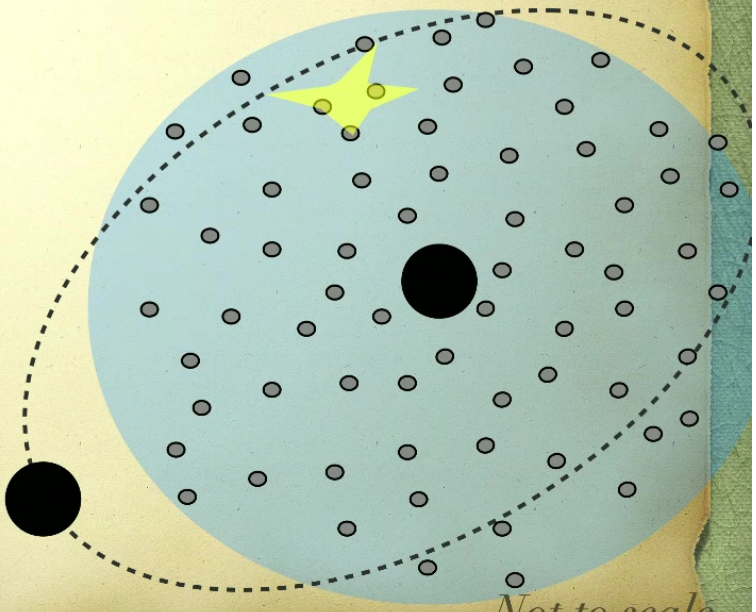
Not to scale

Should we include two body relaxation + EKL?



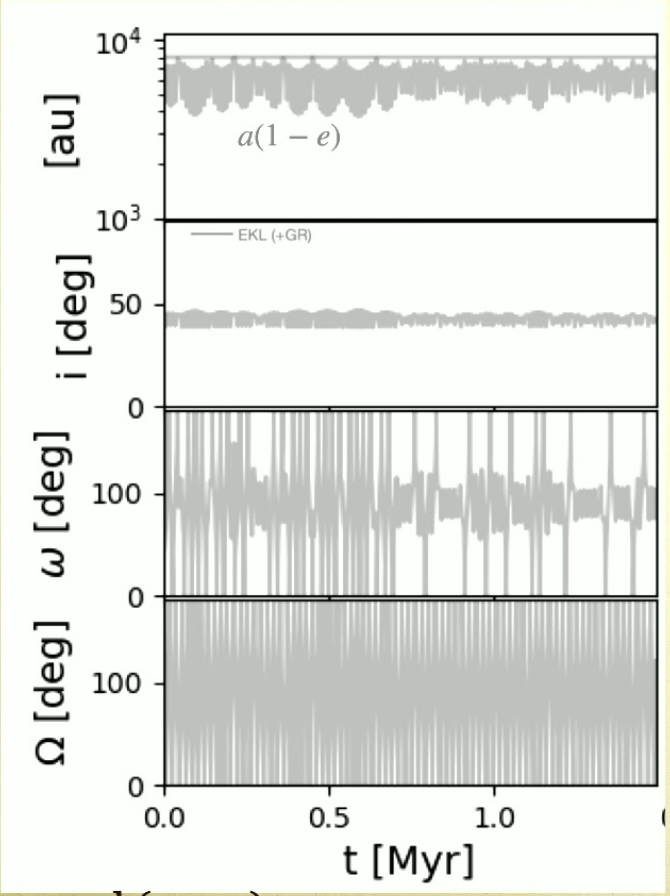
Naoz et al (2022)

Changes to the angular momentum: $\delta L/L \sim \sqrt{P/t_{rlx}}$



Not to scale

On the combined effects of 2-body relx. and EKL



Naoz et al (2022)

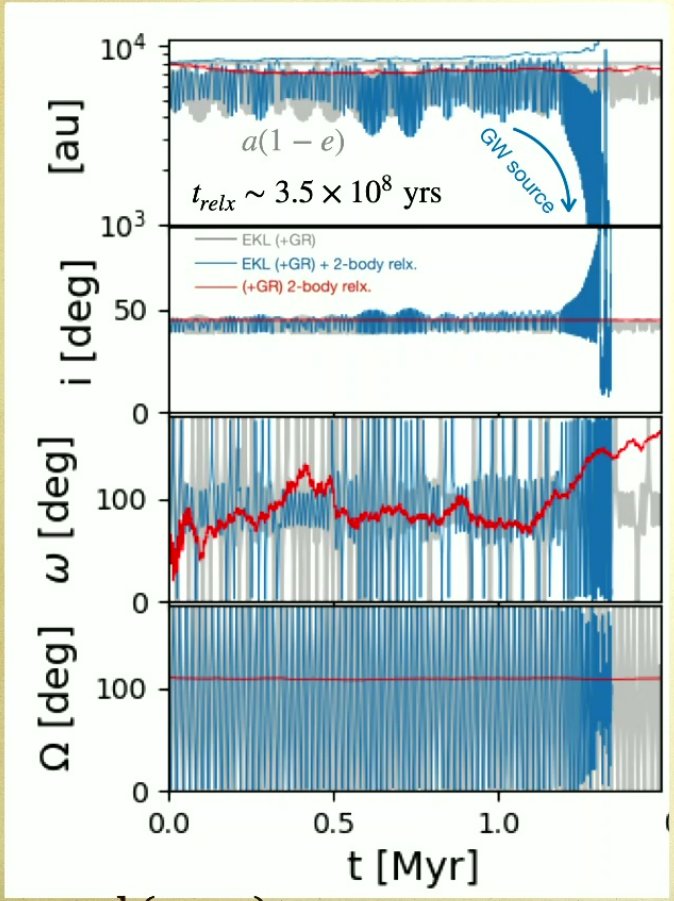
#2

GR effects follow
Naoz et al (2013)

$m_1 = 10^7 M_\odot \quad m_c = 10^9 M_\odot$

$a_c = 1\ pc \quad e_c = 0.7$

On the combined effects of 2-body relx. and EKL



Naoz et al (2022)

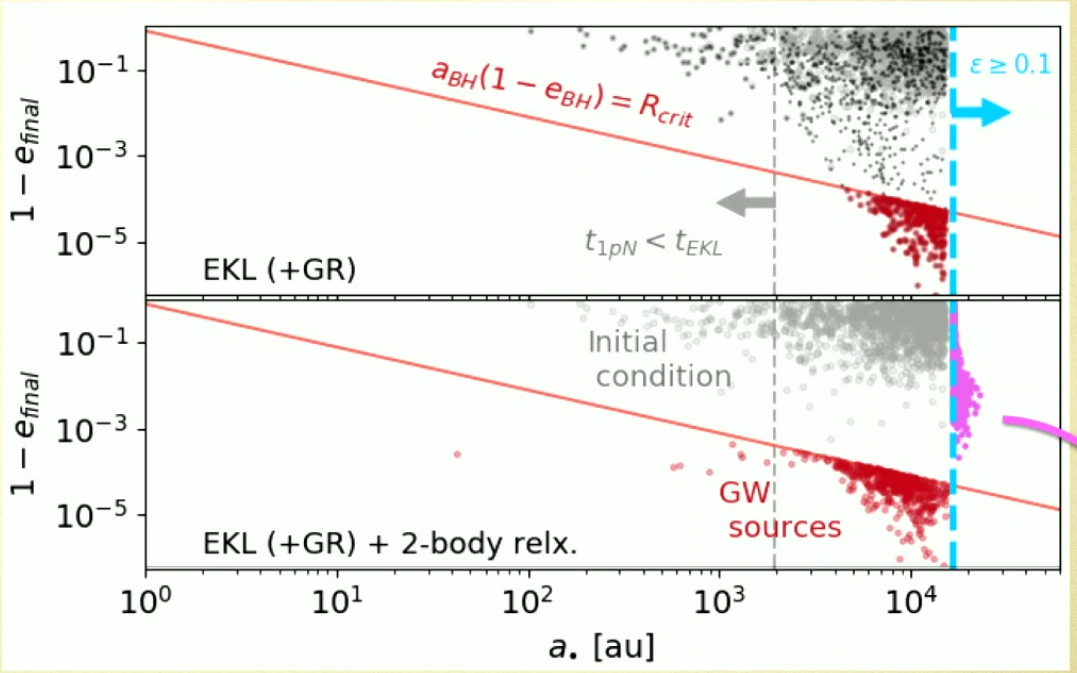
GR effects follow
Naoz et al (2013)

#1

$m_1 = 10^7 M_\odot \quad m_c = 10^9 M_\odot$

$a_c = 1\ pc \quad e_c = 0.7$

On the combined effects of 2-body relx. and EKL



Their eccentricity can be excited to even larger eccentricities

Bhaskar et al. 2021

Naoz et al (2022)

On the combined effects of 2-body relx. and EKL

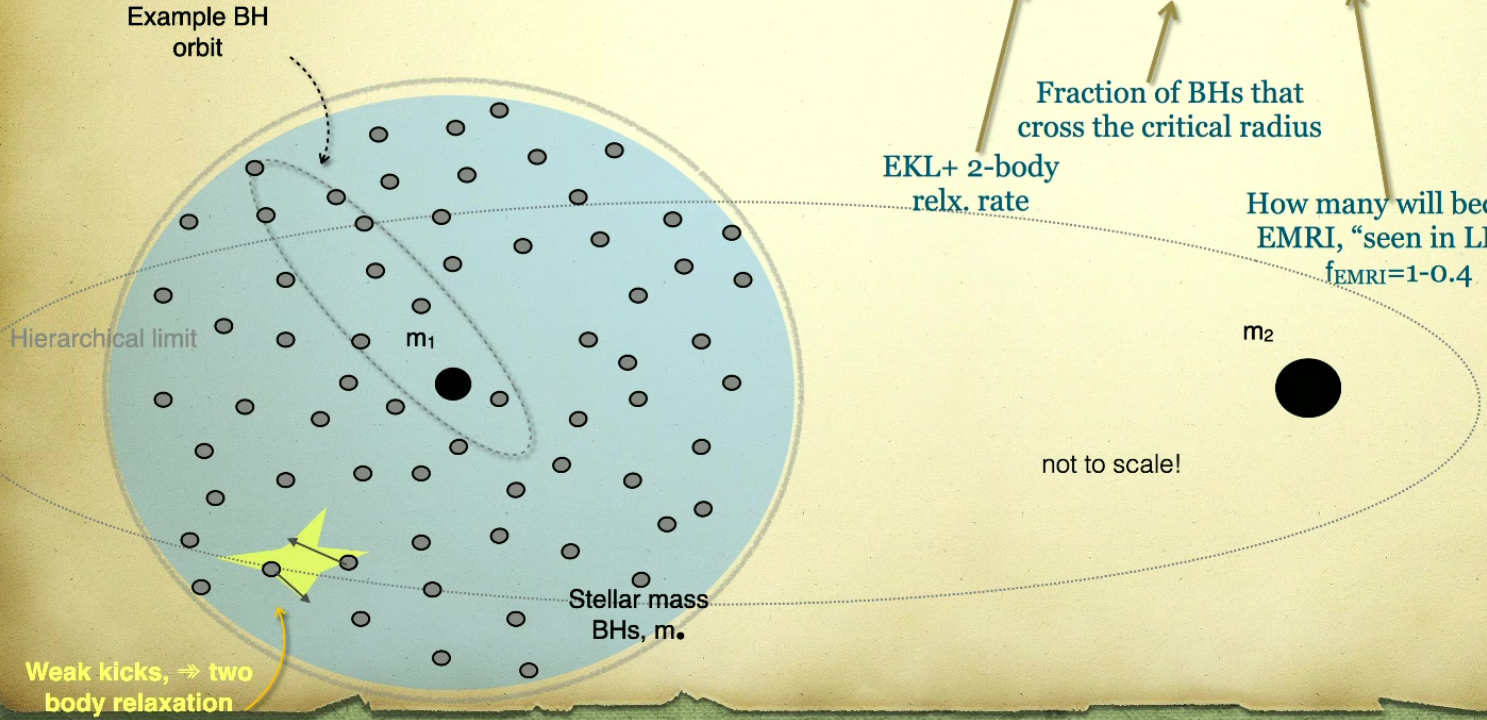
EMRI rate:

$$\Gamma \approx \Gamma_{\rm EKL} \times f_{\rm EKL} \times f_{\rm EMRI} \times n_{\rm BH}(\leqslant r_{\rm max})$$

EKL+ 2-body relx. rate

Fraction of BHs that cross the critical radius

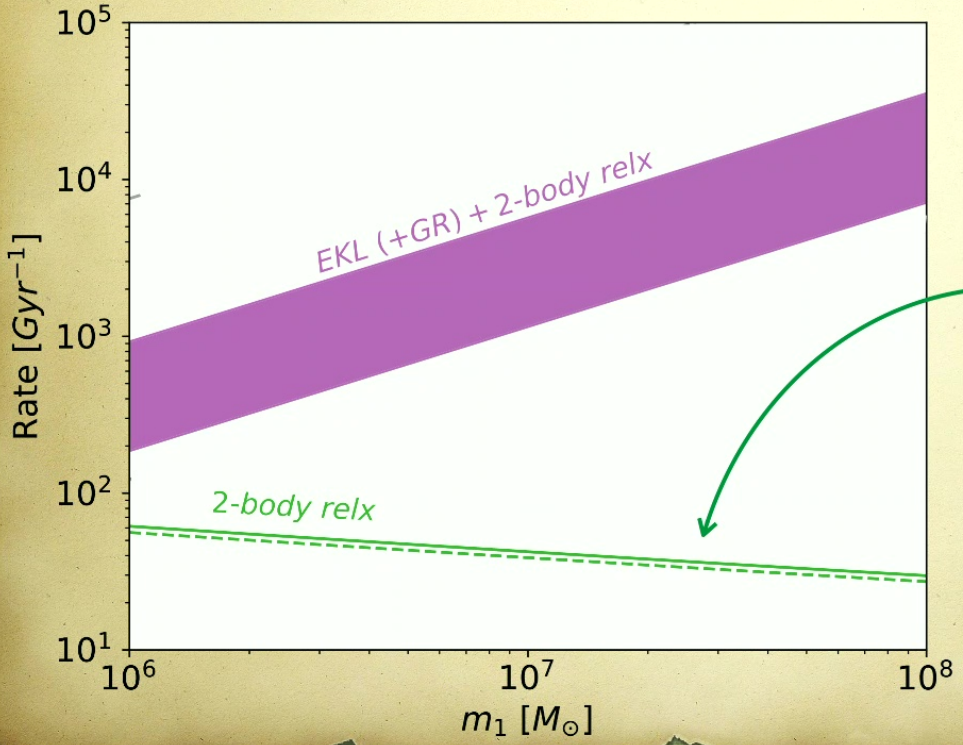
How many will become EMRI, "seen in LISA" $f_{\rm EMRI}$=1-0.4



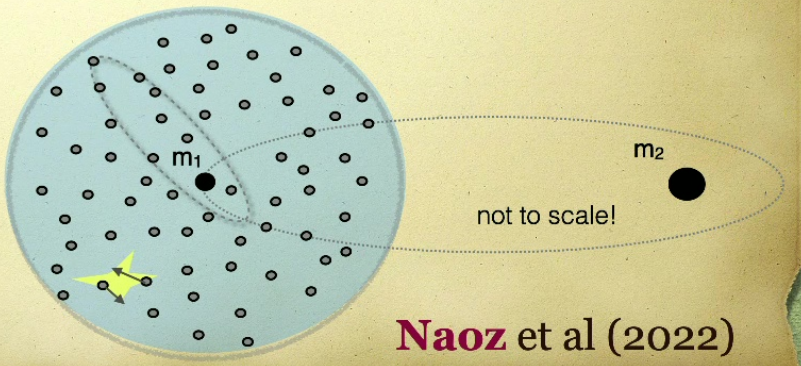
Naoz et al (2022)

On the combined effects of 2-body relx. and EKL

EMRI rate: per (little) SMBH



e.g., Hopman & Alexander 2005



Naoz et al (2022)

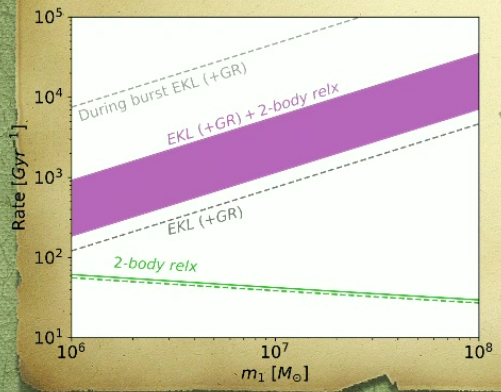
On the combined effects of 2-body relx. and EKL

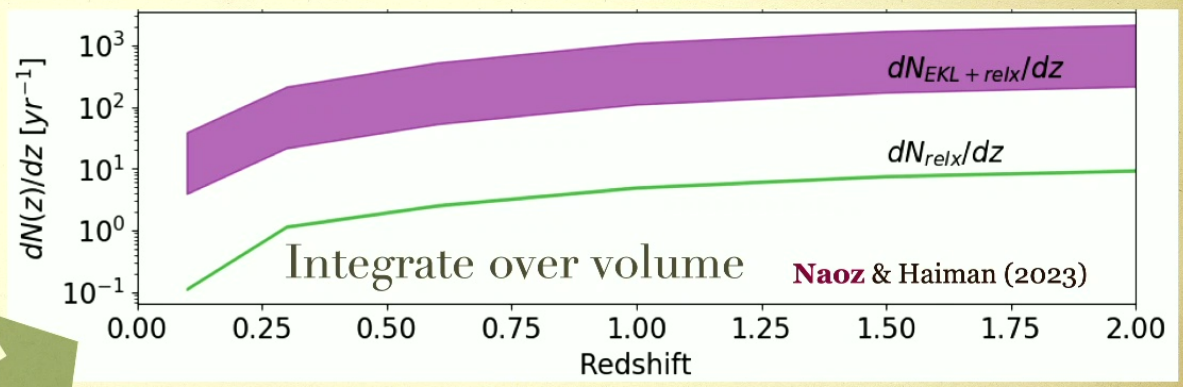
EMRI rate:

Rate per (lit) SMBH

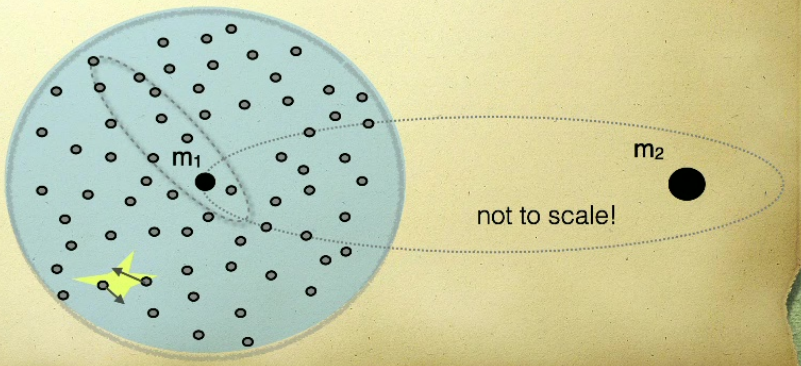
$$\Gamma(z) = \int \frac{d^2N}{dV\, d\ln M}\gamma(M) d\ln M$$

Convolve with SMBH mass function (e.g., Merloni & Heinz 2008)



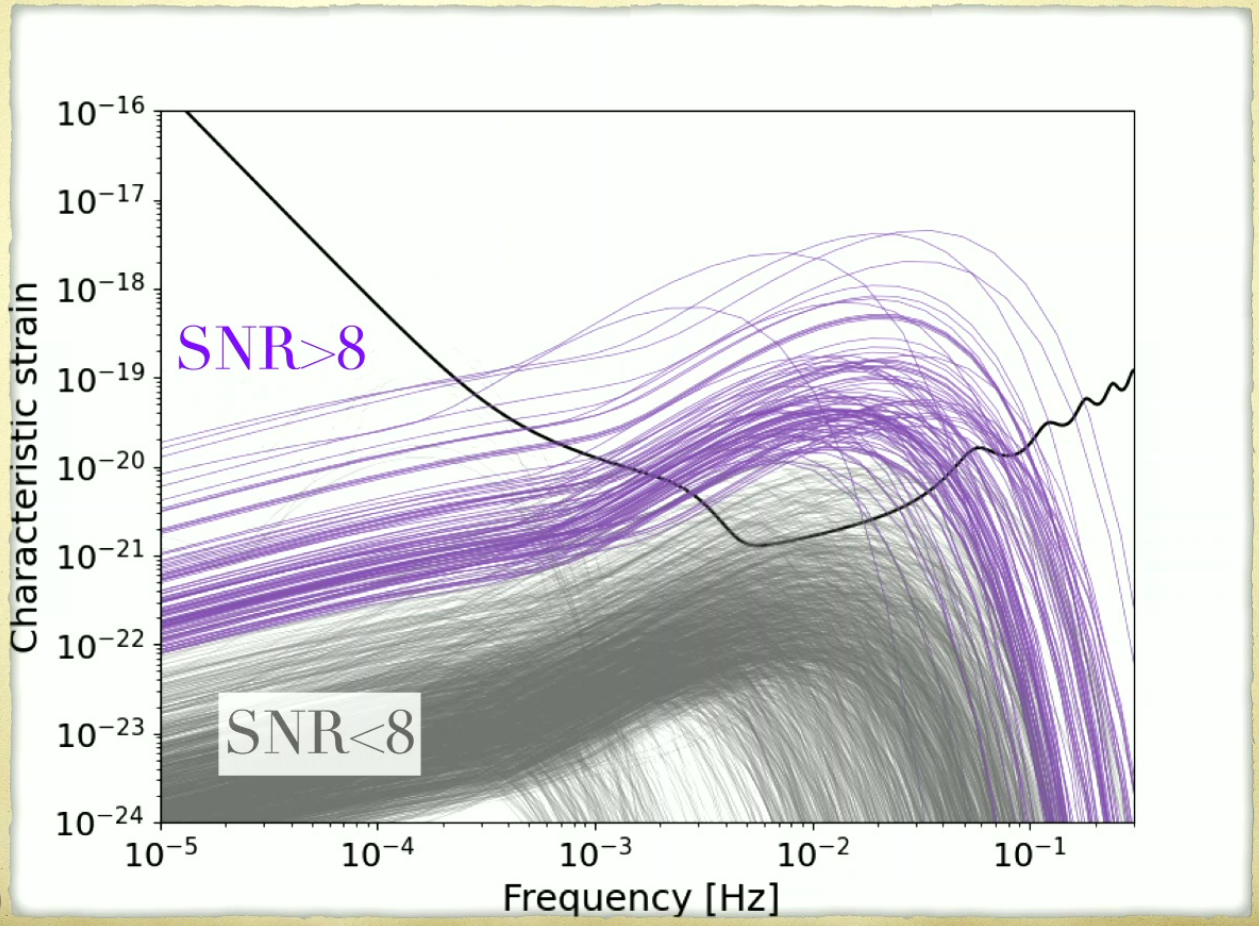


$$\frac{dN}{dz}(z) = T_{\rm obs} \times \int \frac{\Gamma(z)}{1+z}\frac{dV}{dz}$$



What will LISA see?

Within z~1.5



Naoz & Haiman (2023)

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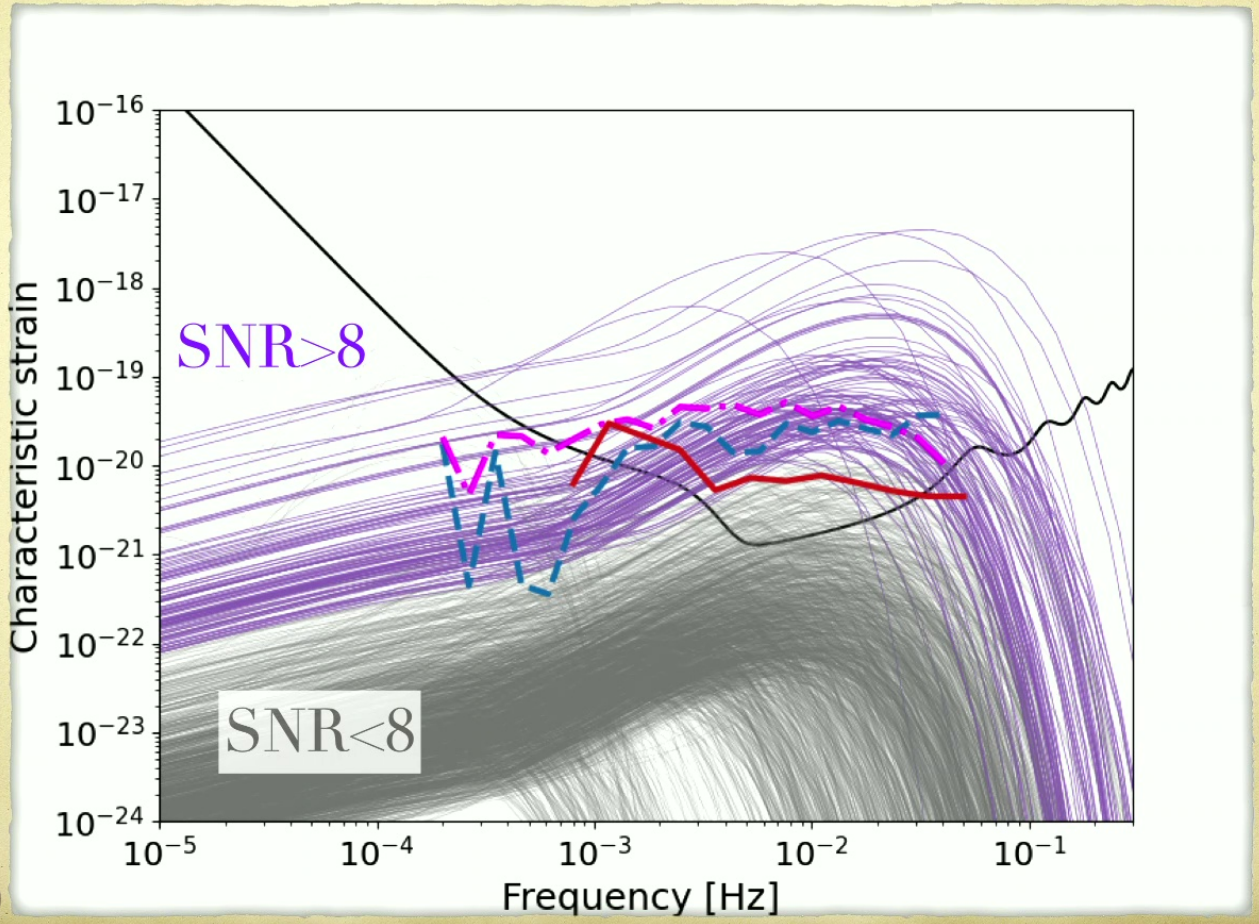


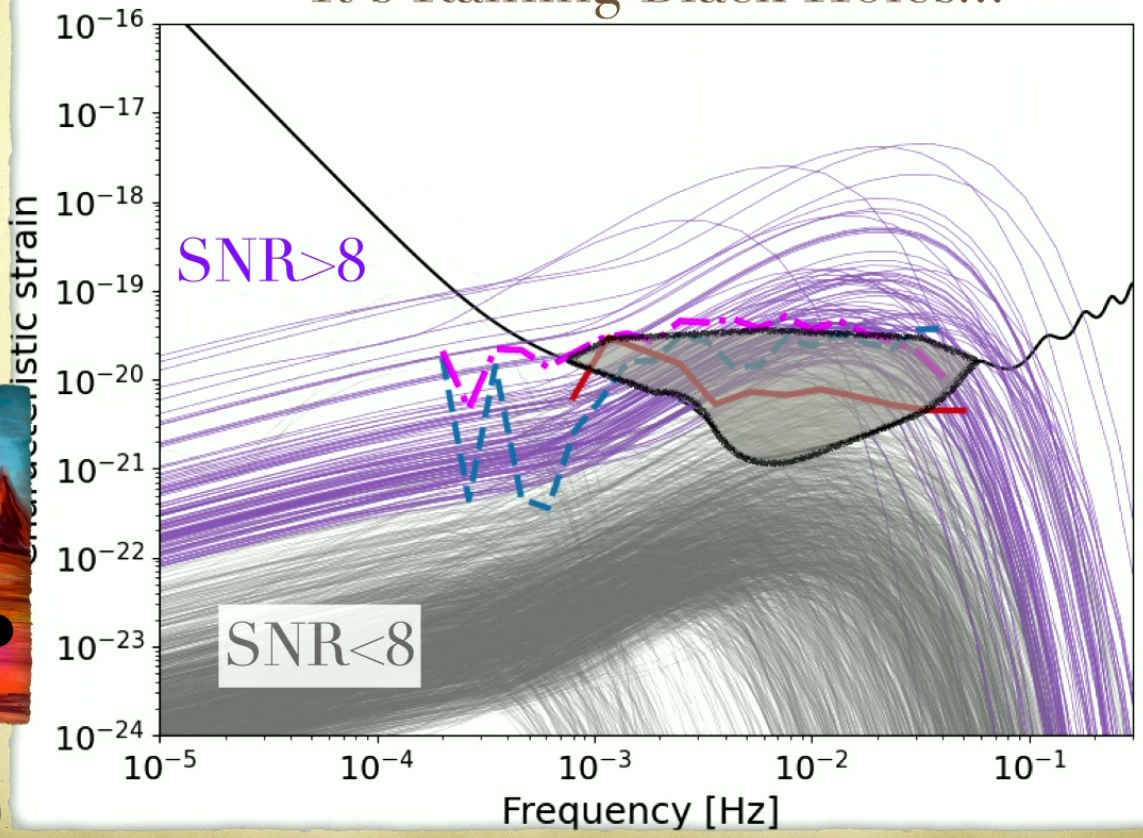
Naoz & Haiman (2023)

What will LISA see?

Within z~1.5

Naoz & Haiman (2023)

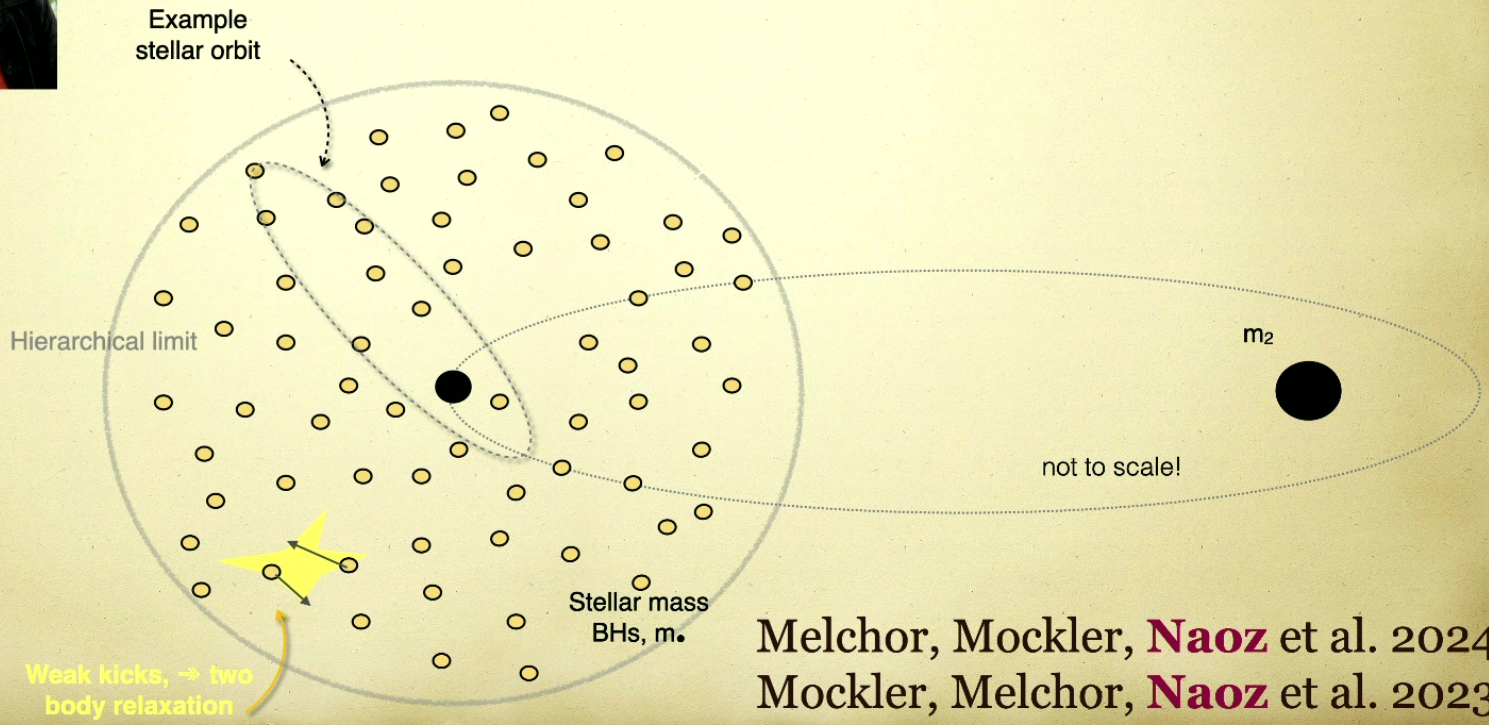
It's Raining Black Holes...



Is it raining stars…Hallelujah(?!)

Denyz Melchor

Brenna Mockler



Melchor, Mockler, **Naoz** et al. 2024
Mockler, Melchor, **Naoz** et al. 2023

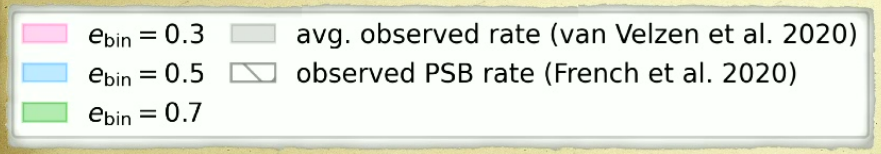
Is it raining stars…Hallelujah(?!)

Denyz Melchor

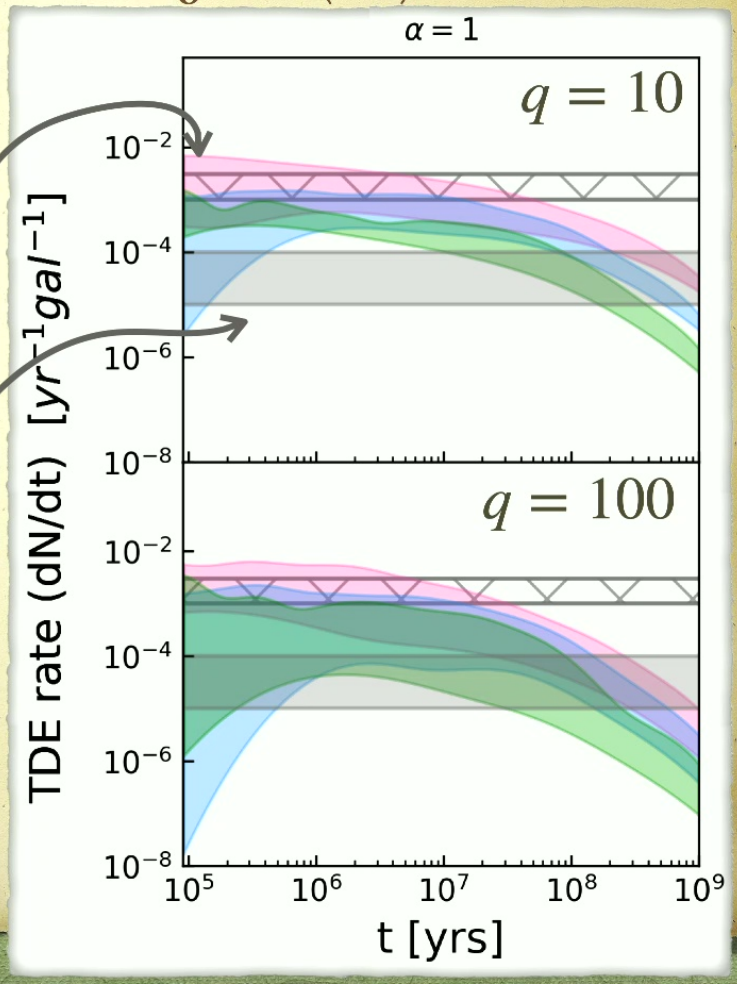
Brenna Mockler

Observed post-starburst (E+A) galaxies TDE rate
(French et al. 2020)

Average observed TDE rate
(van Velzen et al. 2020)



Melchor, Mockler, **Naoz** et al. 2024



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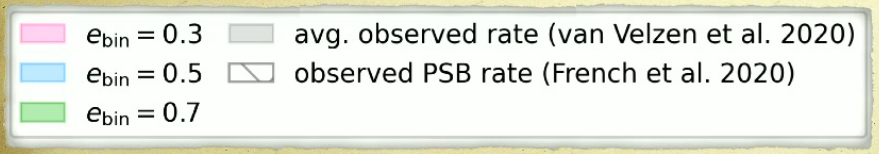
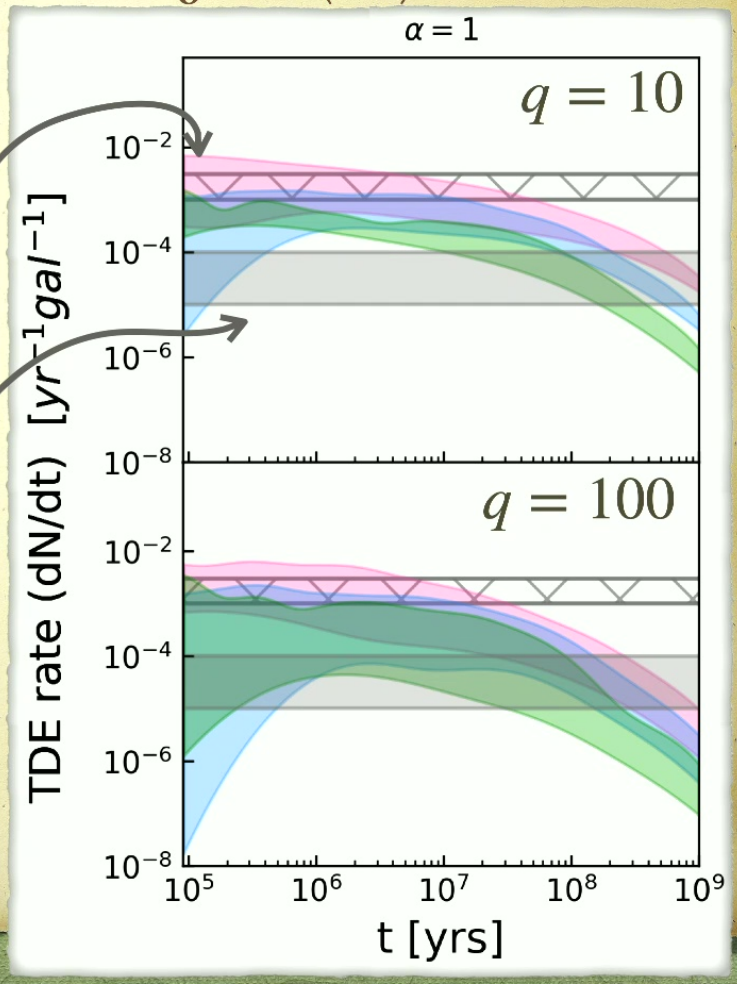
Observed post-starburst (E+A) galaxies TDE rate
(French et al. 2020)

Suggesting E+A (PSB) galaxies may host SMBH binaries

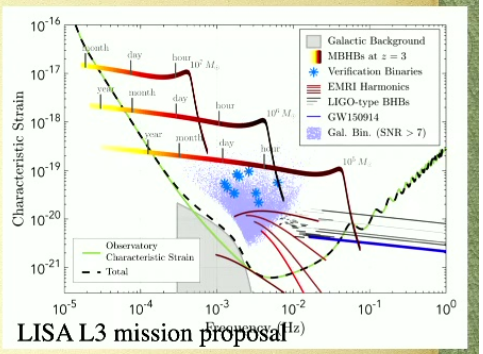
Average observed TDE rate
(van Velzen et al. 2020)



Melchor, Mockler, **Naoz** et al. 2024



How is that connected to EMRIs?



LISA L3 mission proposal

Noise level

10^{-19}

10^{-20}

10^{-21}

The fraction of little SMBHs with big friends

LISA sensitivity

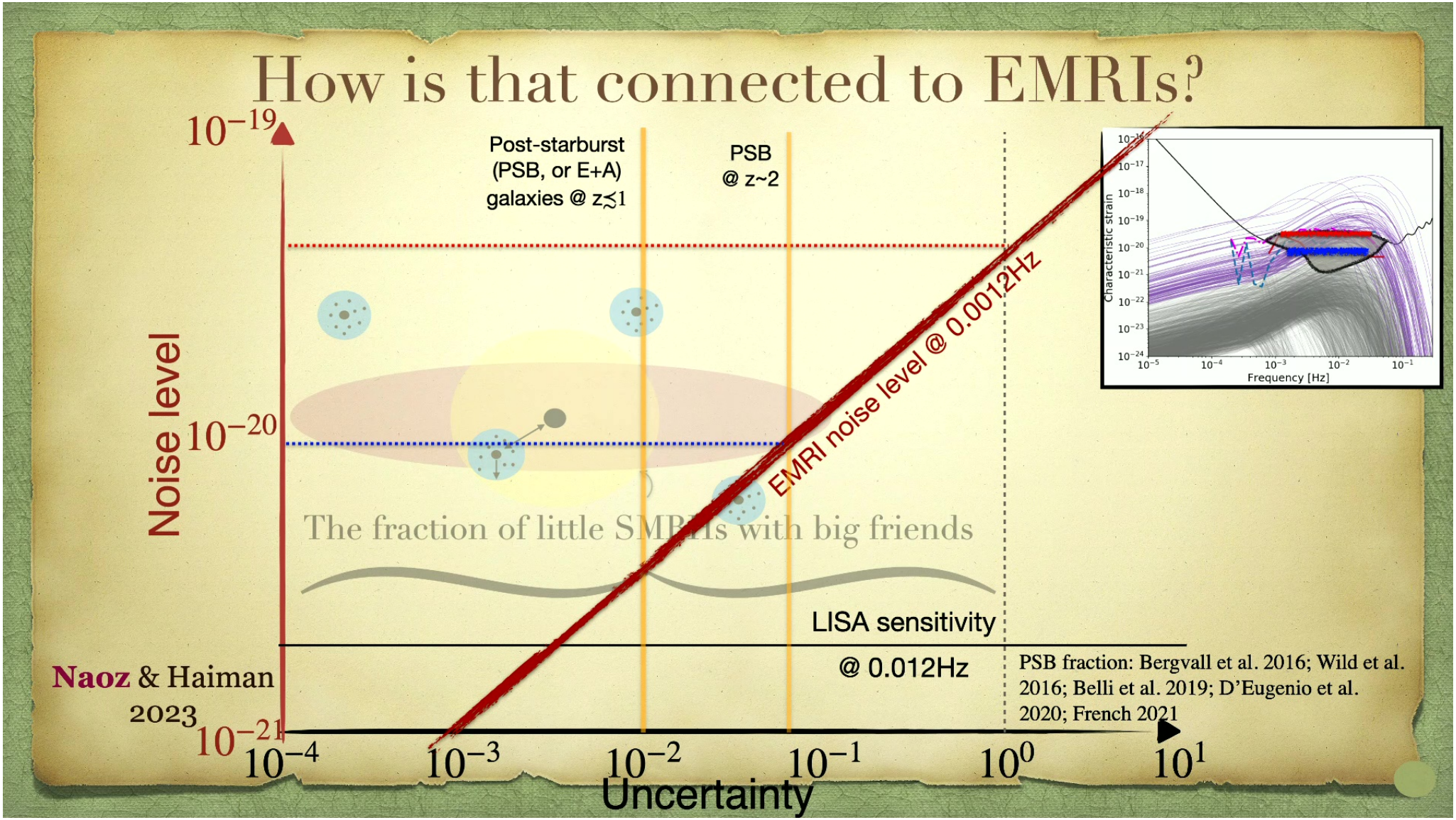
@ 0.012Hz

Naoz & Haiman 2023

10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}

Uncertainty

How is that connected to EMRIs?



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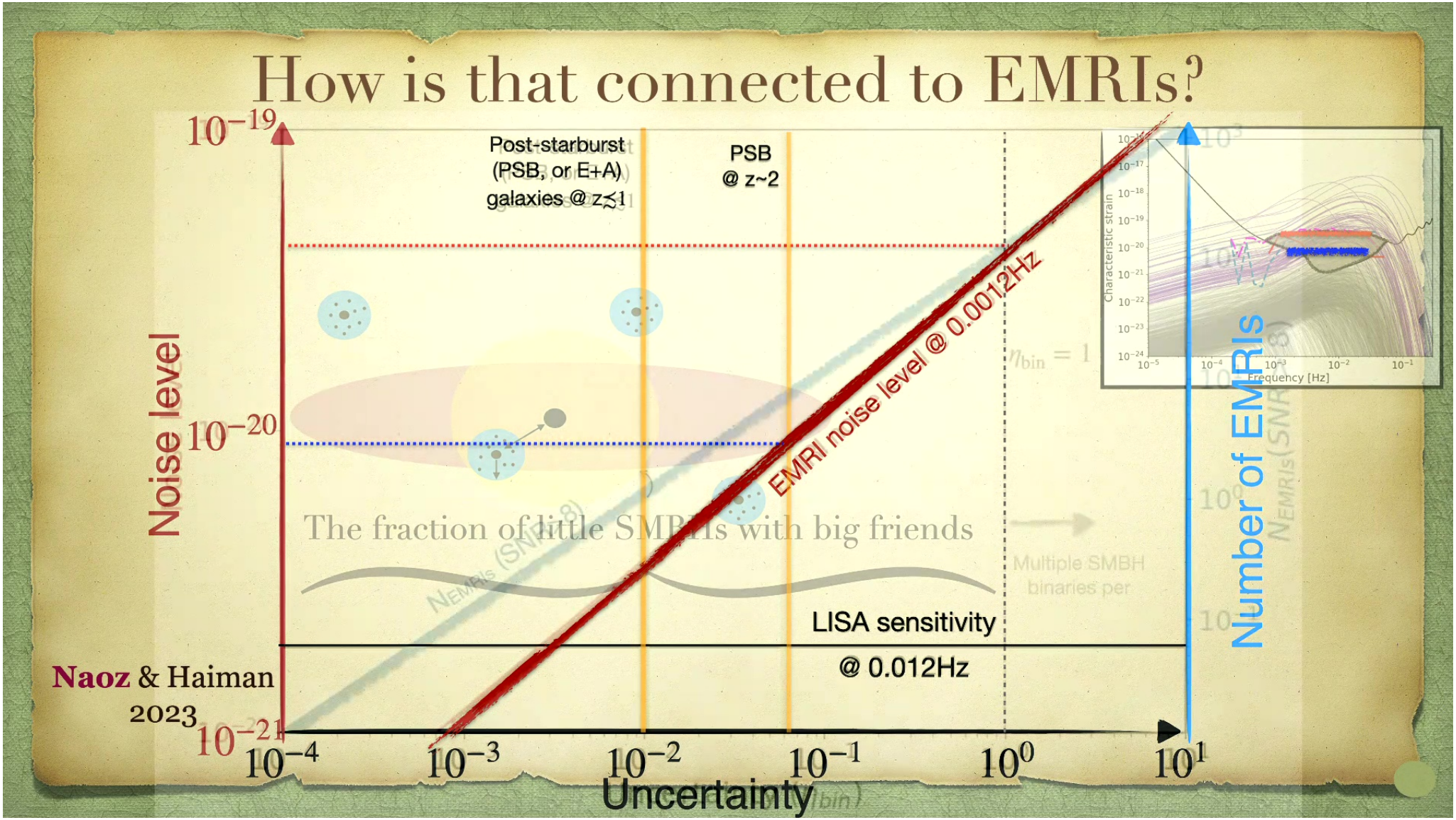

Naoz & Haiman
2023

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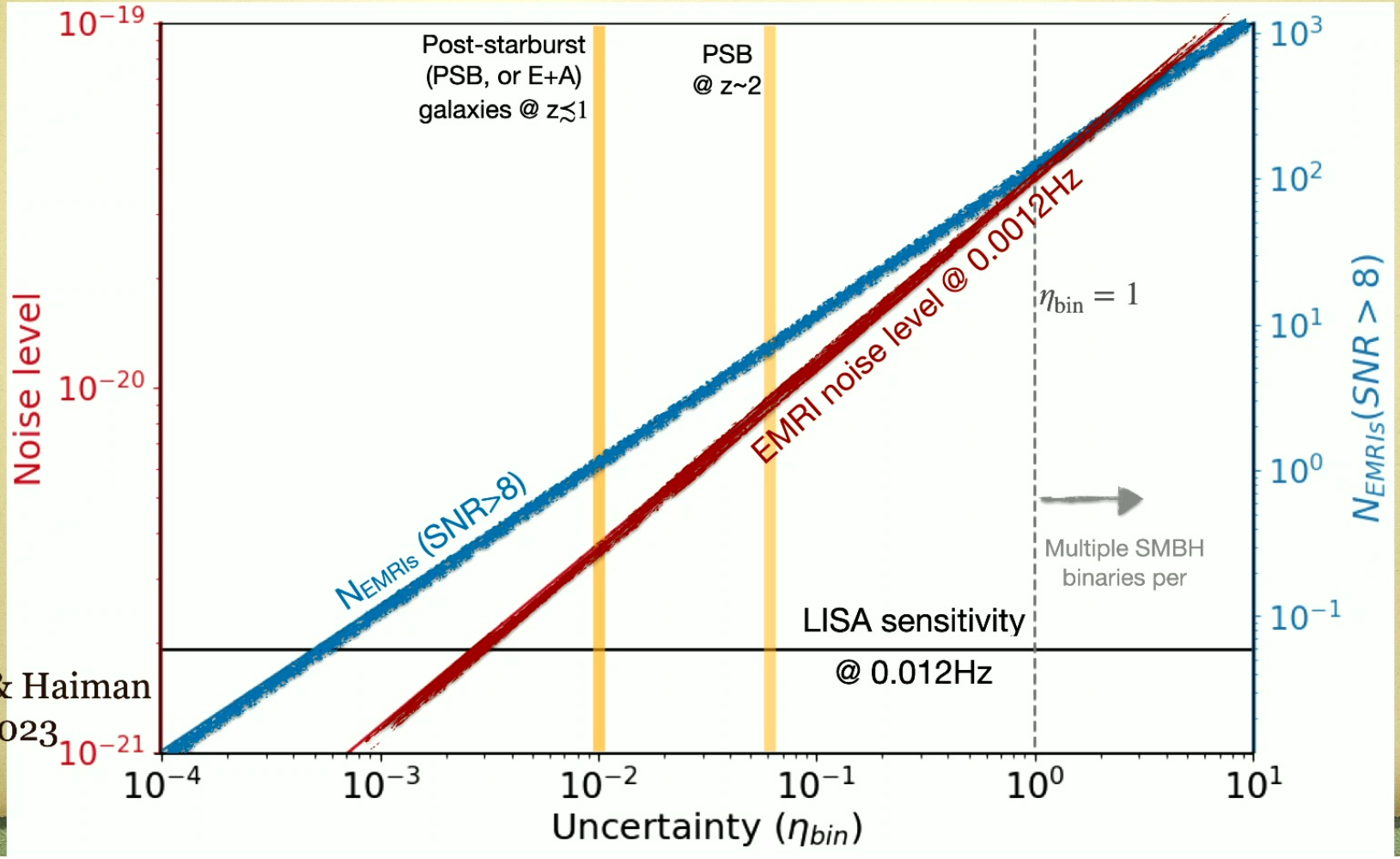

Naoz & Haiman 2023

It's Raining Black holes and Stars… Hallelujah!

- EMRI rate in SMBH binaries is orders of magnitude higher than around a single SMBH and has a different trend with SMBH mass
- Yields a background stochastic noise source in LISA (possibly an order(s) of magnitude higher than LISA's sensitivity curve)
- This can be used to constrain the fraction of SMBH binaries
- Observed TDE rates suggest that E+A galaxies host SMBH binaries