Black Hole Binary Formation through Stellar Dynamics in Galactic Nuclei

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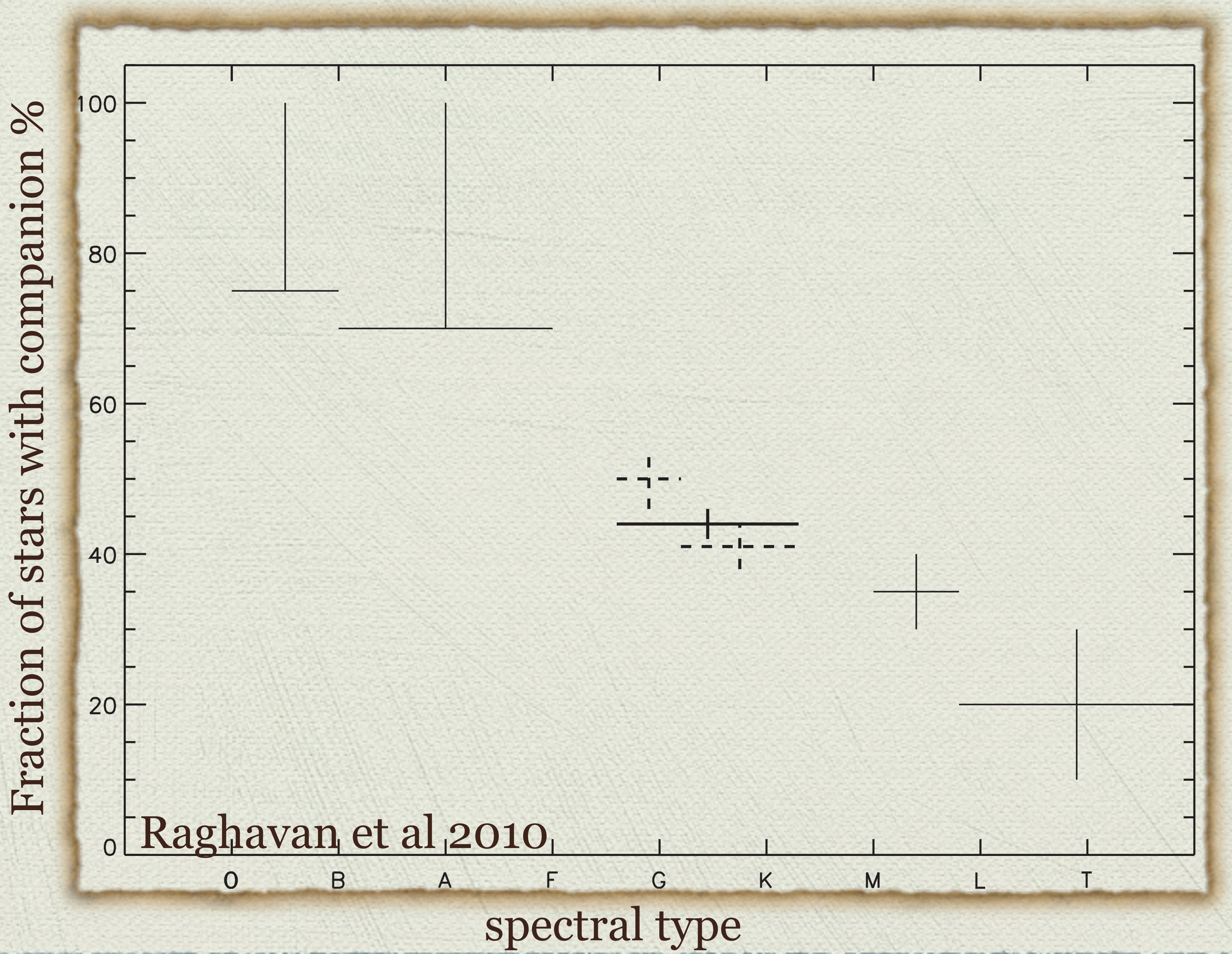
Extreme G environment

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

credit: spaceinfo.com

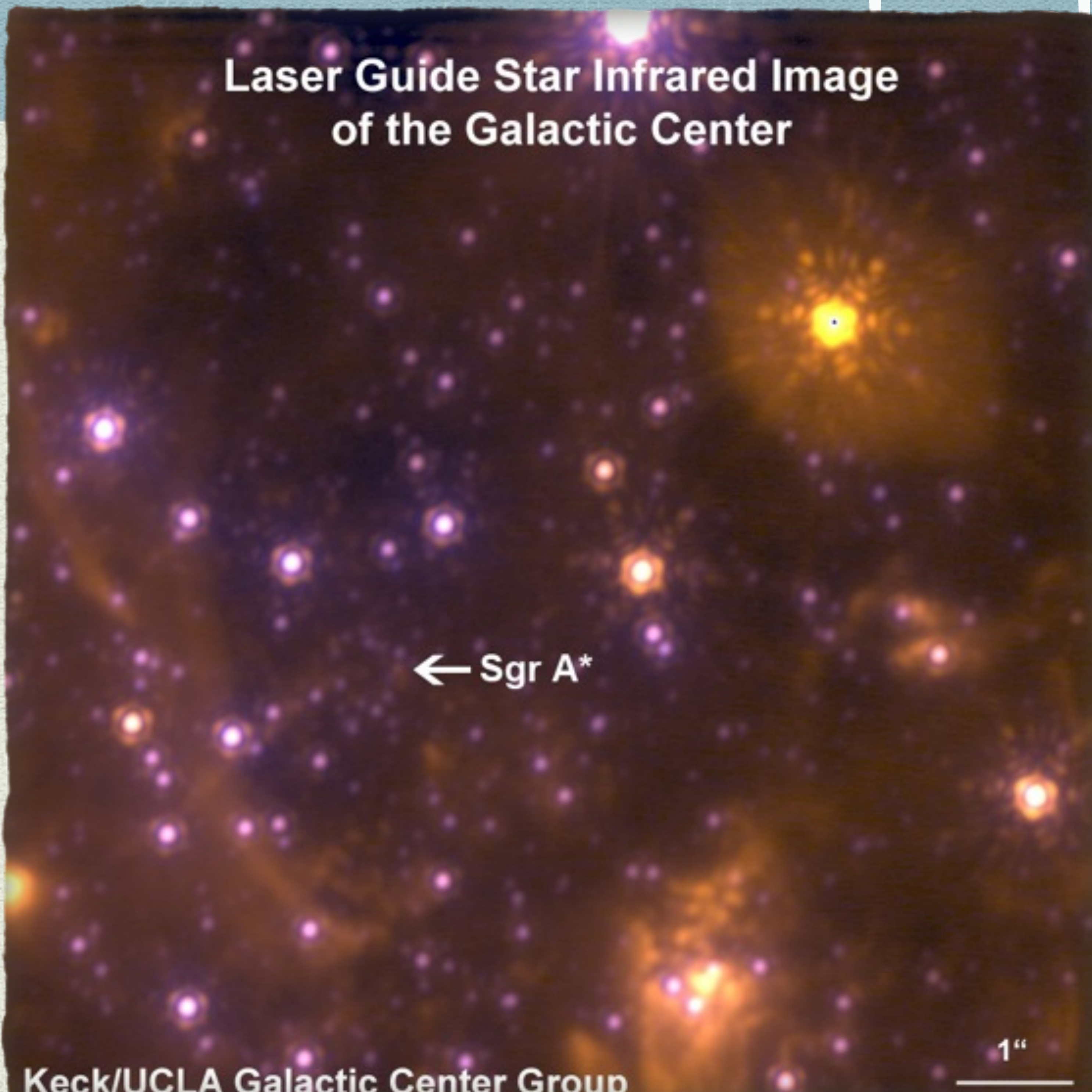
Binaries in Galactic Nuclei

The majority of stars in *the field and clusters* are born in binaries or higher multiples, e.g., Sana et al 2012



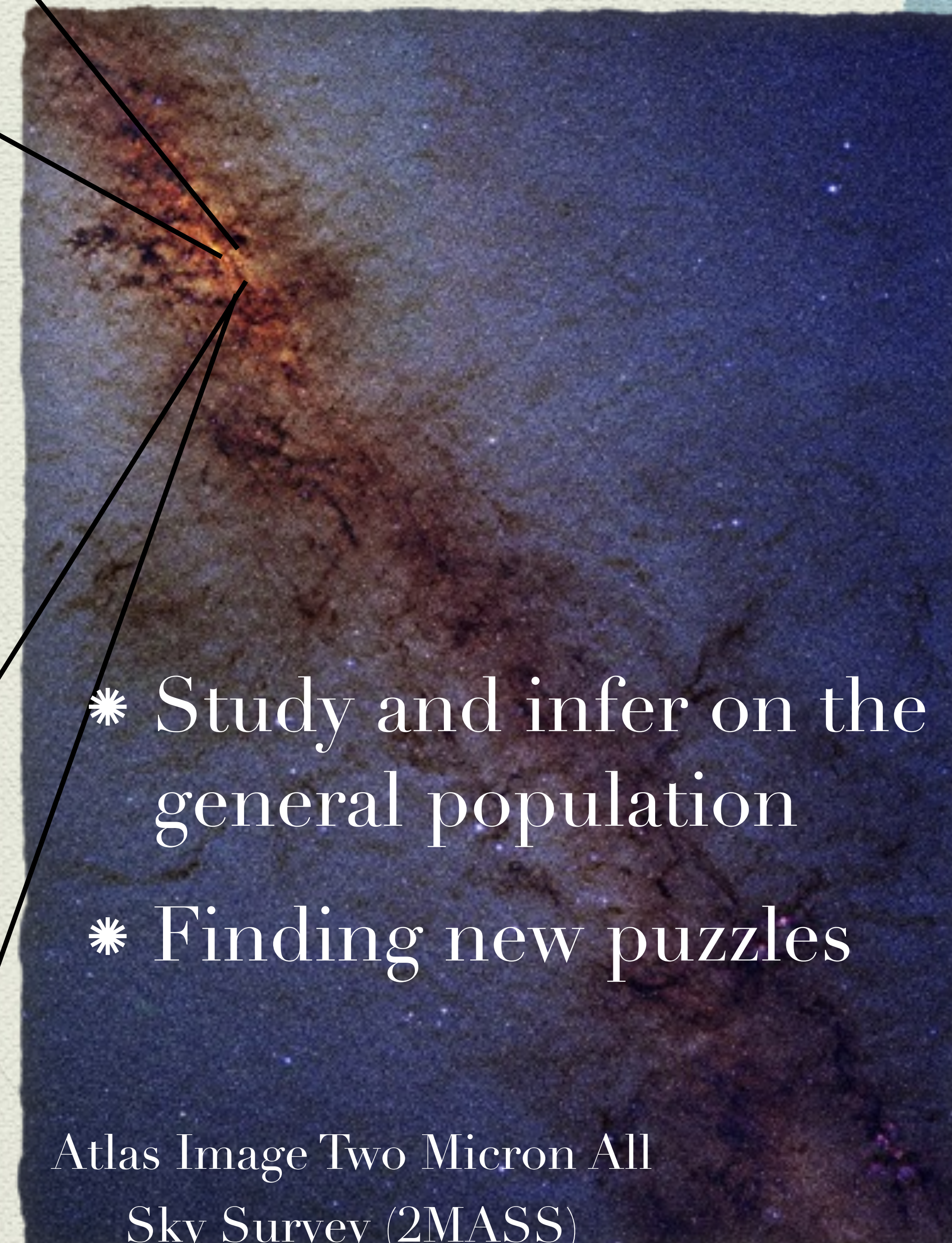
Extreme G environment

kyard



The central 10 arcsec ~ 0.4pc

Ghez et al 2005



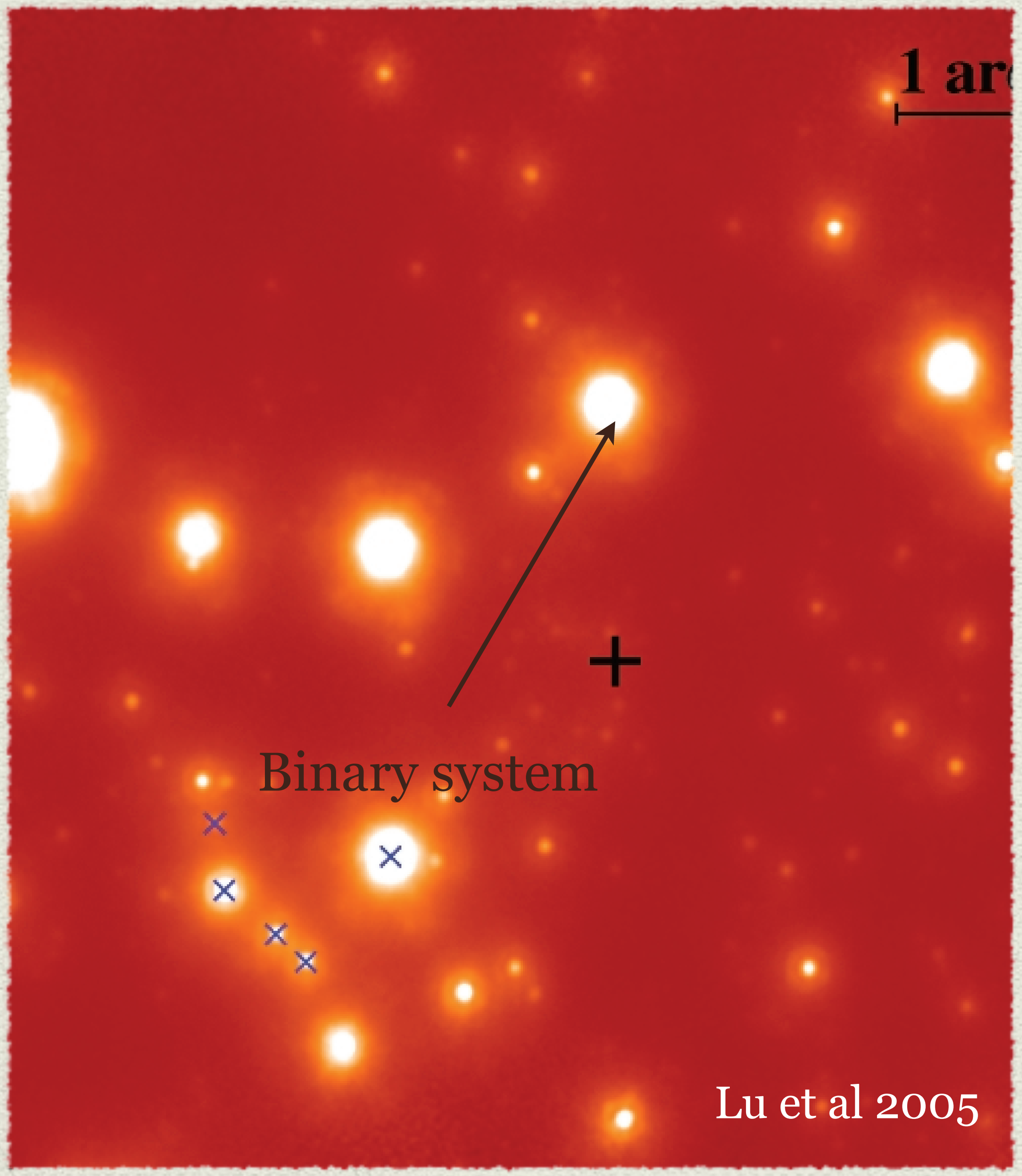
- Study and infer on the general population
- Finding new puzzles

Atlas Image Two Micron All Sky Survey (2MASS)

Binaries in Galactic Nuclei

Galactic Center - Observational evidence

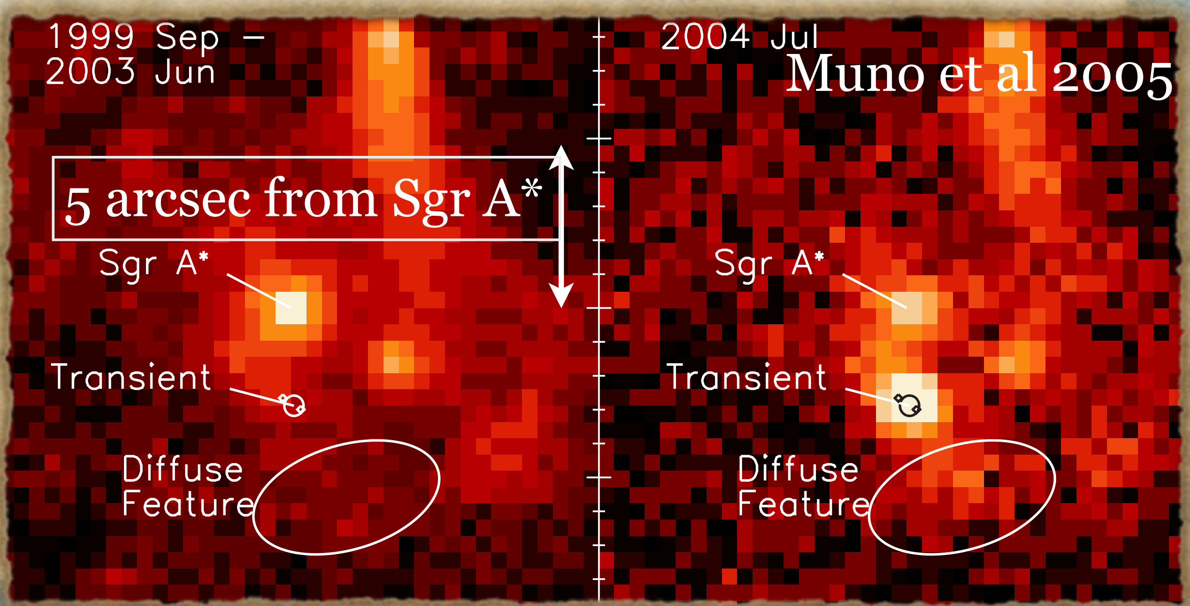
- 3 Known Binaries: IRS 16SW, ~19.5d, 50M⊙ @ 0.05pc (Ott et al. 1999; Martins et al. 2006); IRS 16NE @~0.1pc, 224d, e~0.3 (Pfuhl et al. 2014); E60 @~0.1pc, 2.3d, 30M⊙ (Pfuhl et al. 2014)
- Binary fraction of massive stars **may be** comparable to young clusters (e.g., Ott et al. 1999; Rafelski et al. 2007;Pfuhl et al. 2014) or larger (Alexander et al 2008)



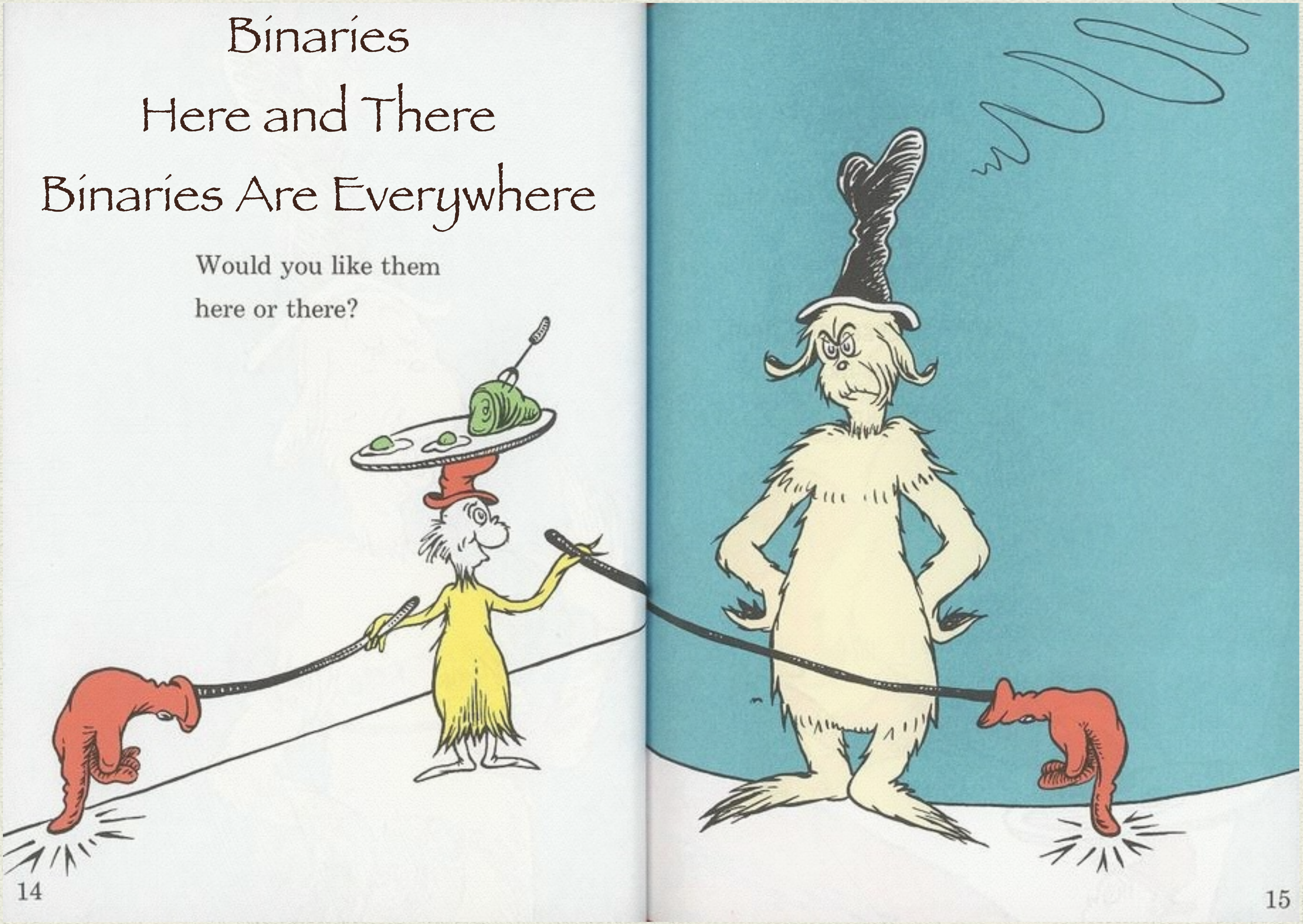
Binaries in Galactic Nuclei

Galactic Center - Observational evidence

- X-ray Binaries; Many in the inner 1pc (e.g., Muno et al 2005a,b,Hailey et al 2018)
- Hypervelocity stars (Brown et al 2005,2006,2007,2008, Hills 1988; Miralda-Escude & Gould 2000; Quillen & Gould 2003; Yu and Tremaine 2003; O'Leary & Loeb 2007, Perets et al. 2009; Perets 2009)
- *Stellar disk properties = Large binary fraction (**Naoz** et al 2018)



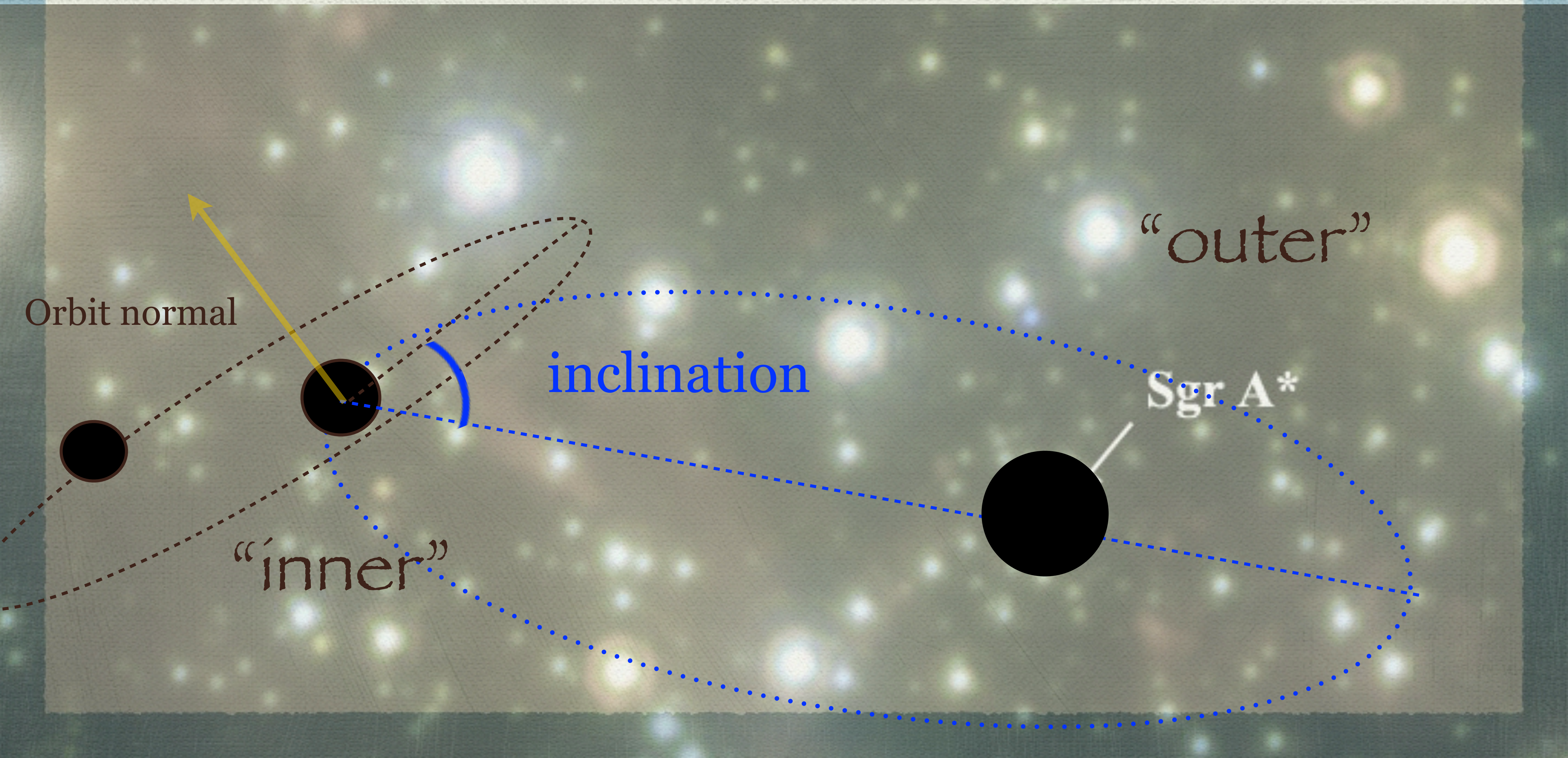
Binaries
Here and There
Binaries Are Everywhere



Binaries in Galactic Nuclei

Hierarchical triple system

Not to scale!



Binaries in Galactic Nuclei

Hierarchical triple system

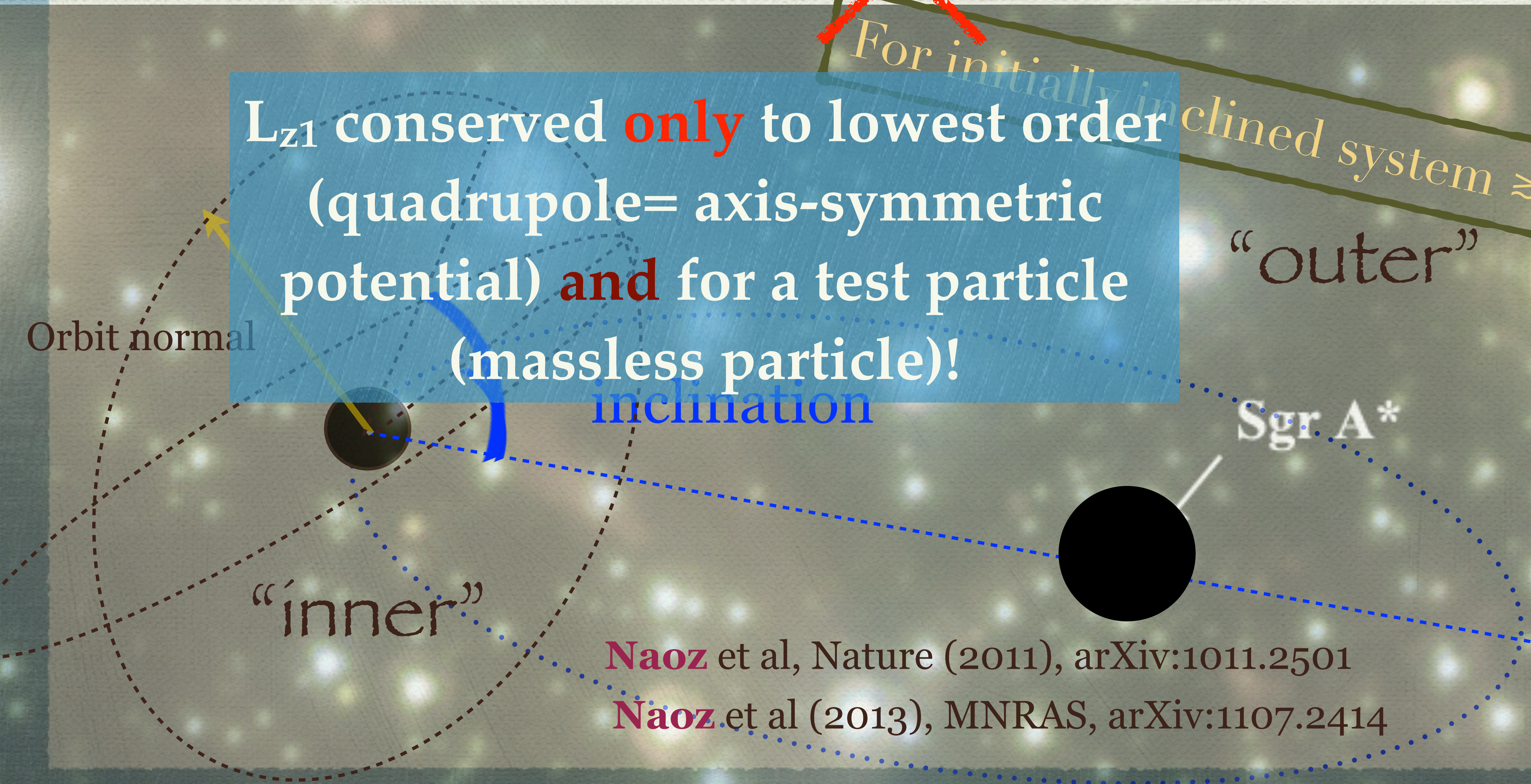
Kozai 1962, Lidov 1962

$$L_z \sim \sqrt{1-e^2}\cos i = \mathrm{const}$$

Not to scale!

For initially inclined system ≳ 40°

L_{z1} conserved only to lowest order (quadrupole= axis-symmetric potential) and for a test particle (massless particle)!



Naoz et al, Nature (2011), arXiv:1011.2501

Naoz et al (2013), MNRAS, arXiv:1107.2414

The Eccentric Kozai-Lidov Mechanism

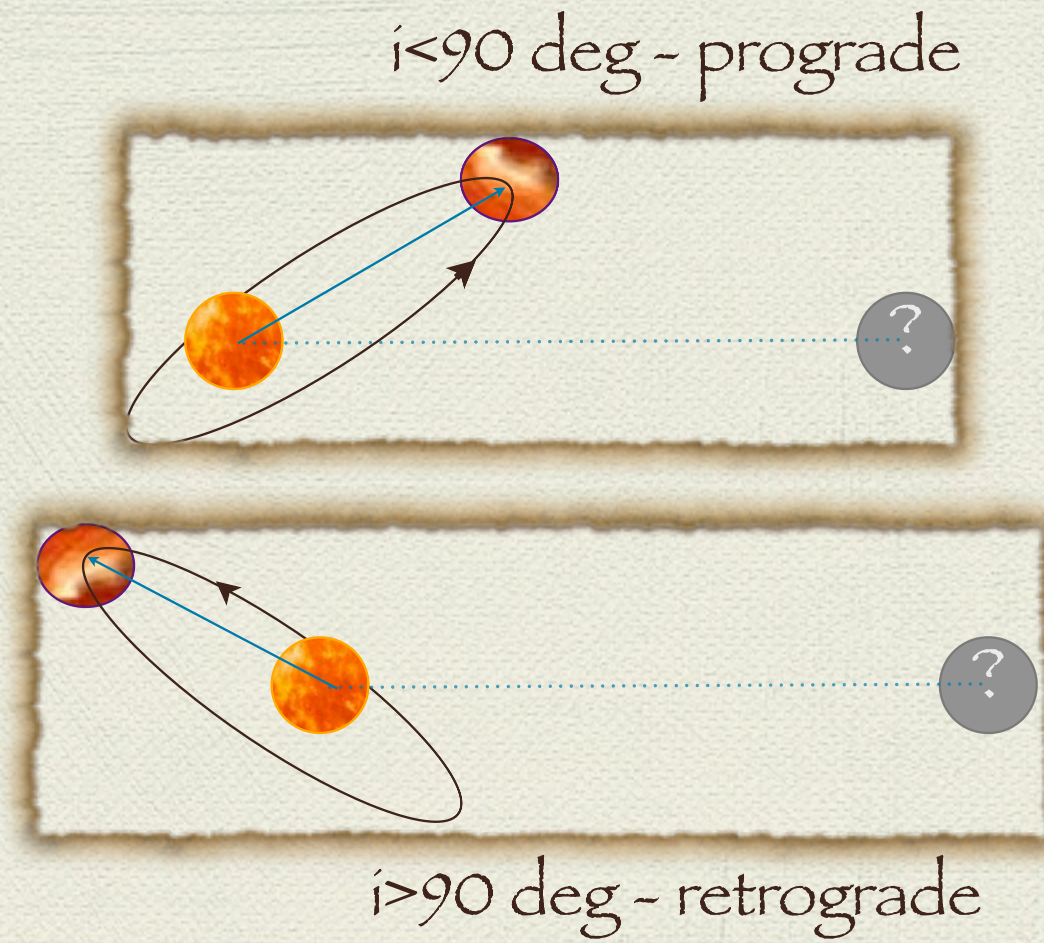
EKL:

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

- Allow for the z-component of the angular momenta of the inner and outer orbit to change - already at the quadrupole level

- Expanding the approximation to the octupole level ***(e.g., Ford et al 2000, Blaes et al 2002 - already done before us!!!)***

- Both the magnitude and orientation of the angular momentum can change



larger parts of the parameter space

Naoz et al, Nature (2011), arXiv:1011.2501

Naoz et al (2013), MNRAS, arXiv:1107.2414

Extreme eccentricities!

Binaries in Galactic Nuclei

GR effects: e.g., Ford et al 2000,
Naoz, Kocsis, Loeb, Yunes 2013

$m_1 = 10 M_\odot$

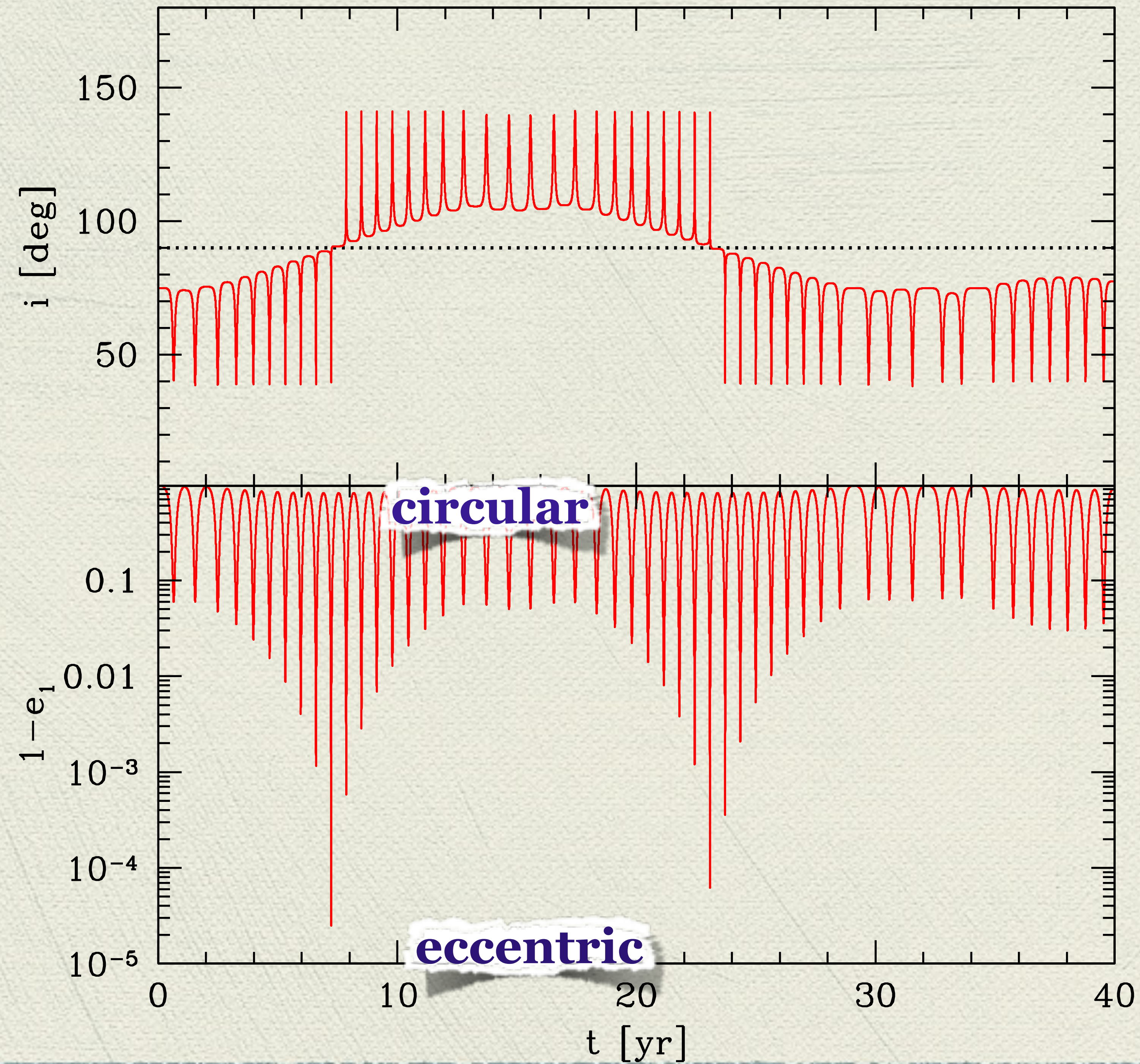
$m_2 = 1 M_\odot$

$M_{SMBH} = 4 \times 10^6 M_\odot$

$a_1 = 10 AU$

$a_2 = 0.003 pc$

$e_2 = 0.8$



Naoz (2016) ARA&A arXiv:1601.07175

Binaries in Galactic Nuclei

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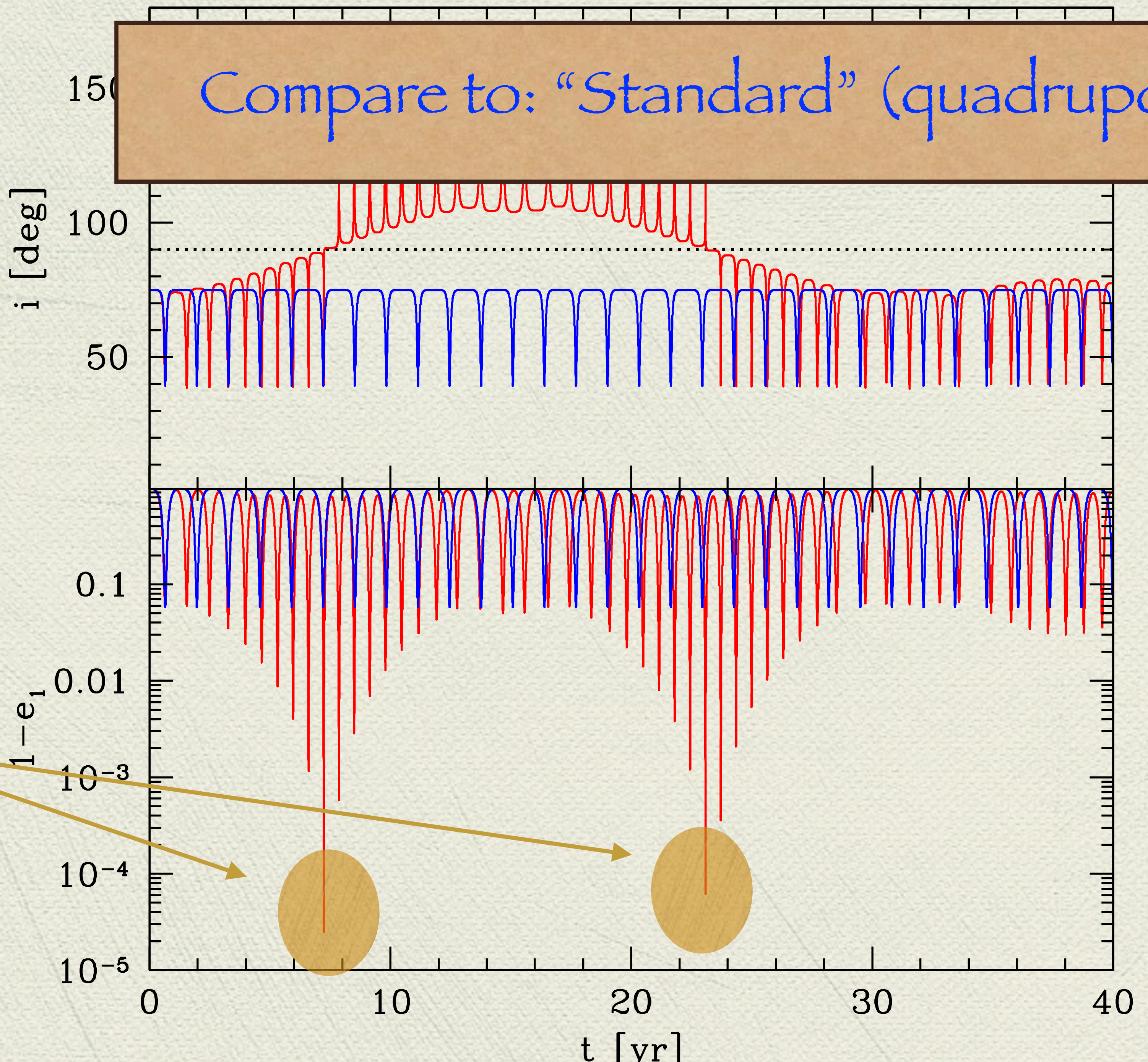
extreme eccentricity peaks



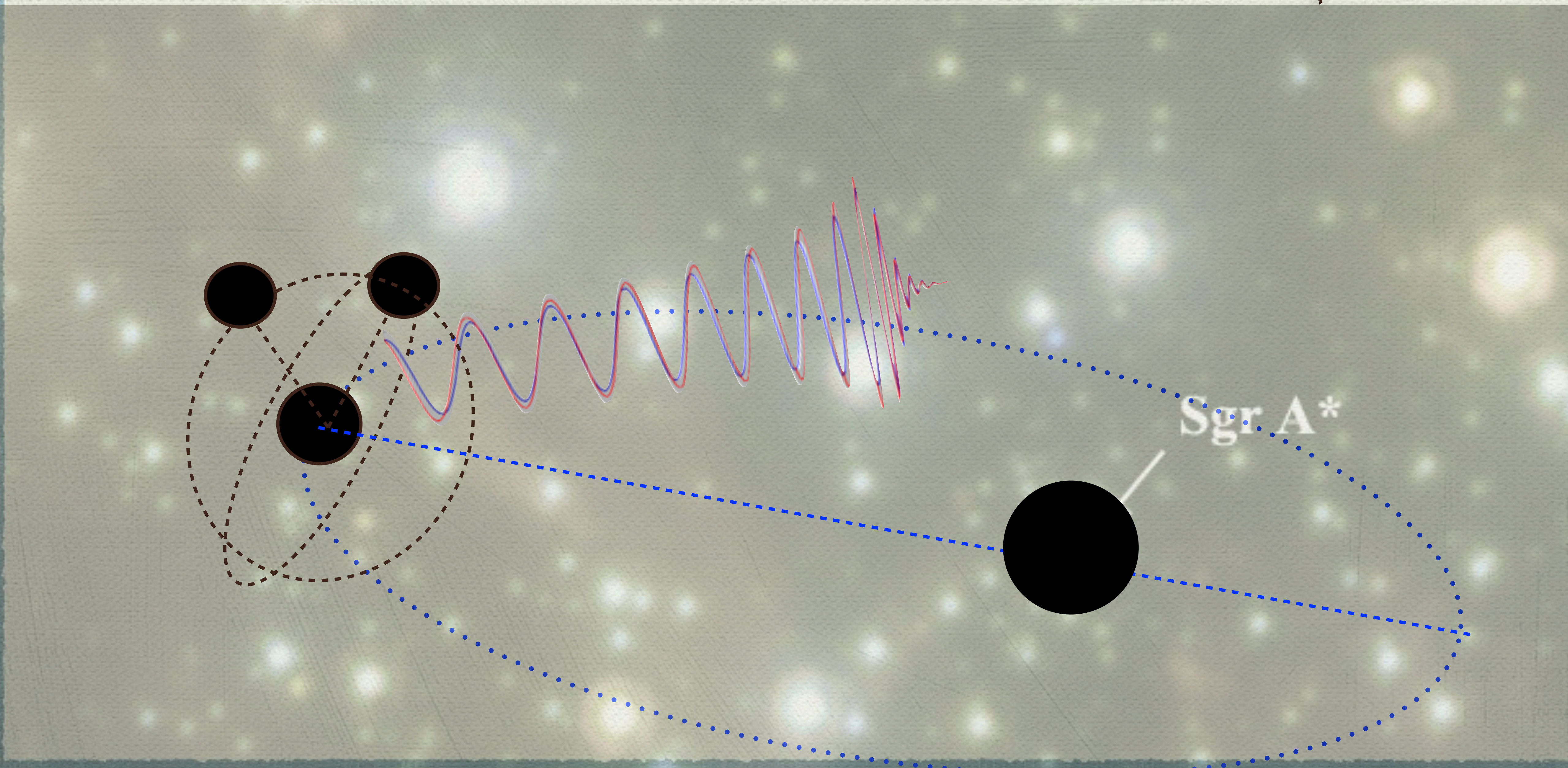
Compare to: "Standard" (quadrupole) Kozai

Naoz (2016) ARA&A arXiv:1601.07175

Binaries in Galactic Nuclei

EKL

Not to scale!

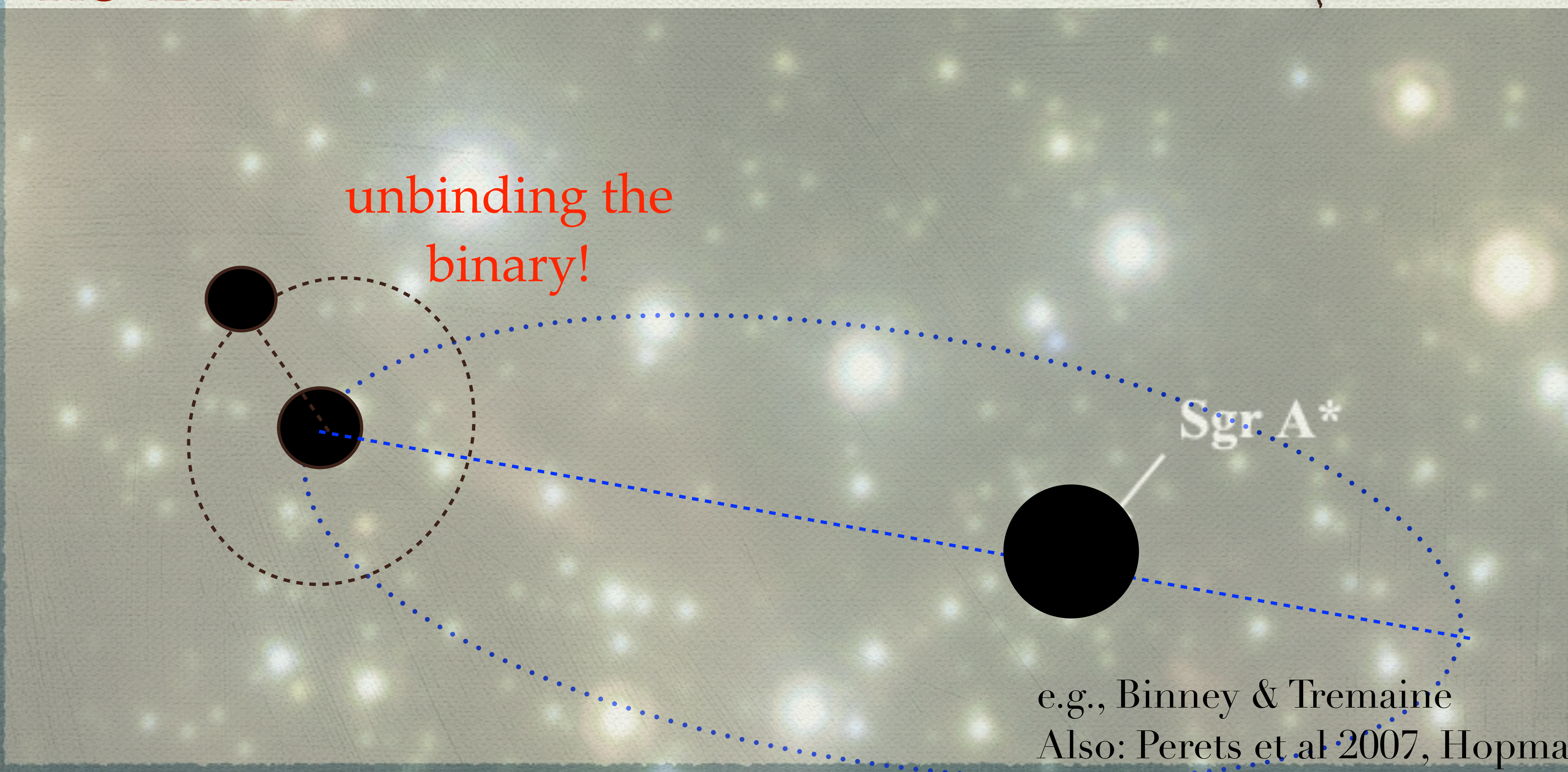


Binaries in Galactic Nuclei

and their neighbors

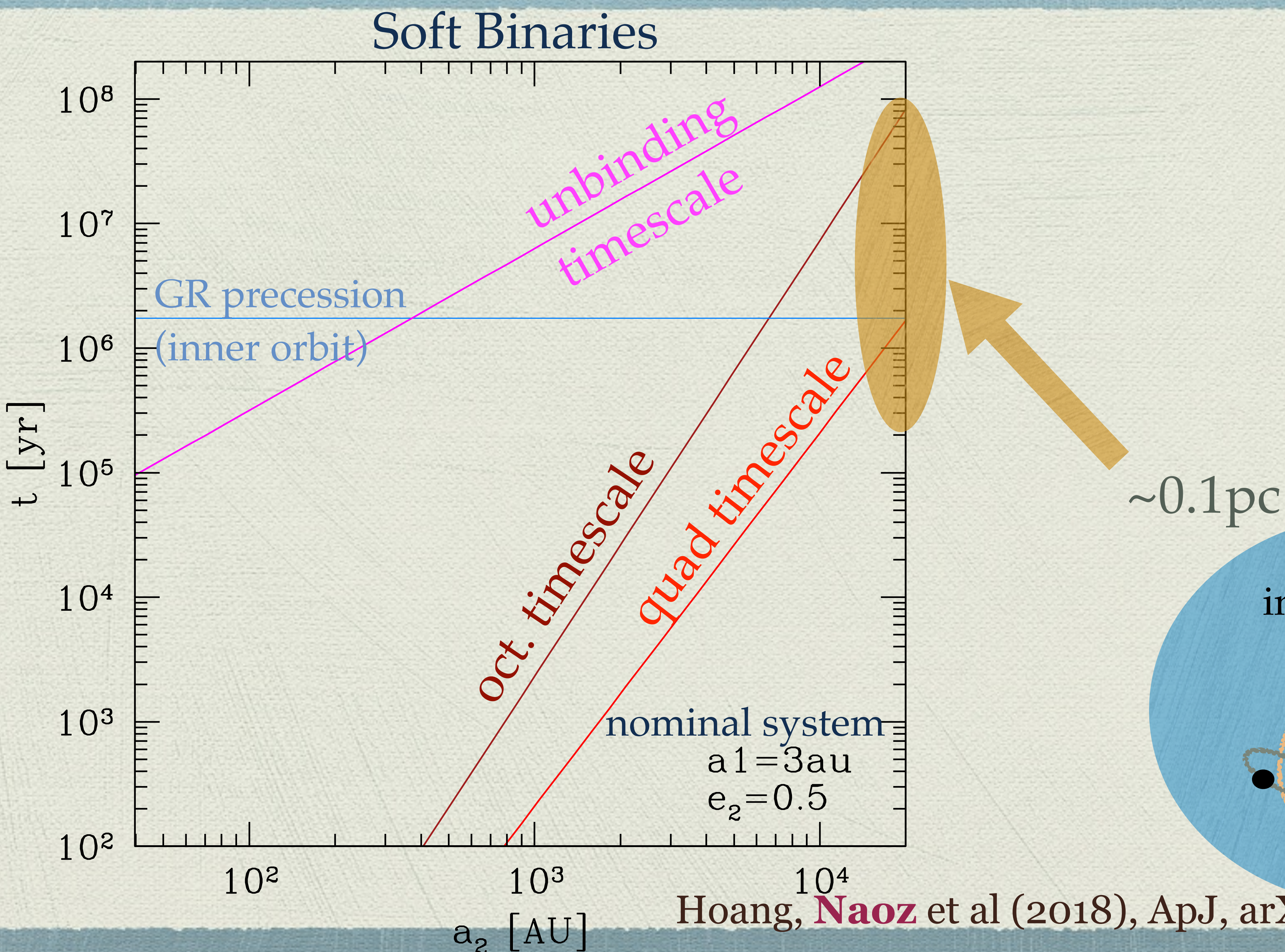
no EKL

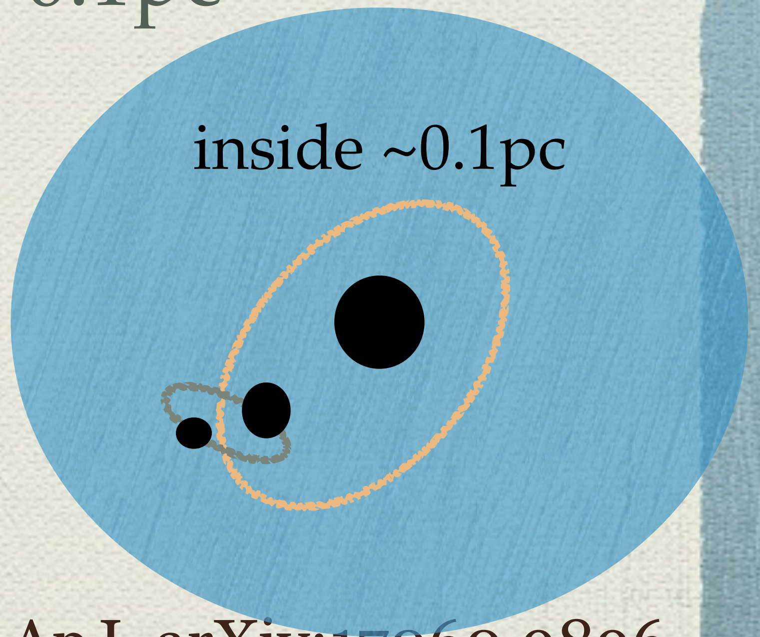
Not to scale!



e.g., Binney & Tremaine
Also: Perets et al 2007, Hopman 2009, Antonini et al 2010

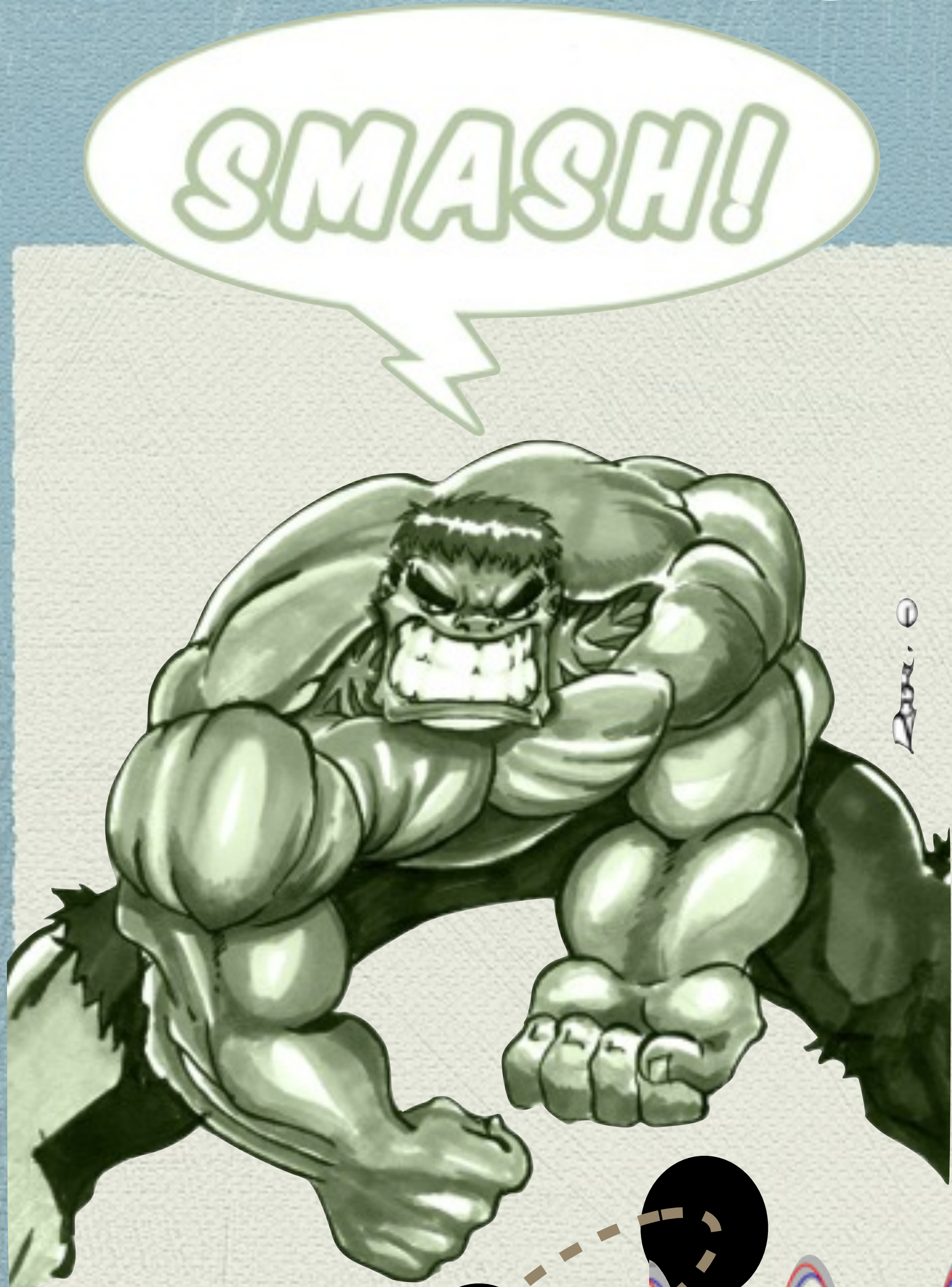
Binaries in Galactic Nuclei
^ and their neighbors





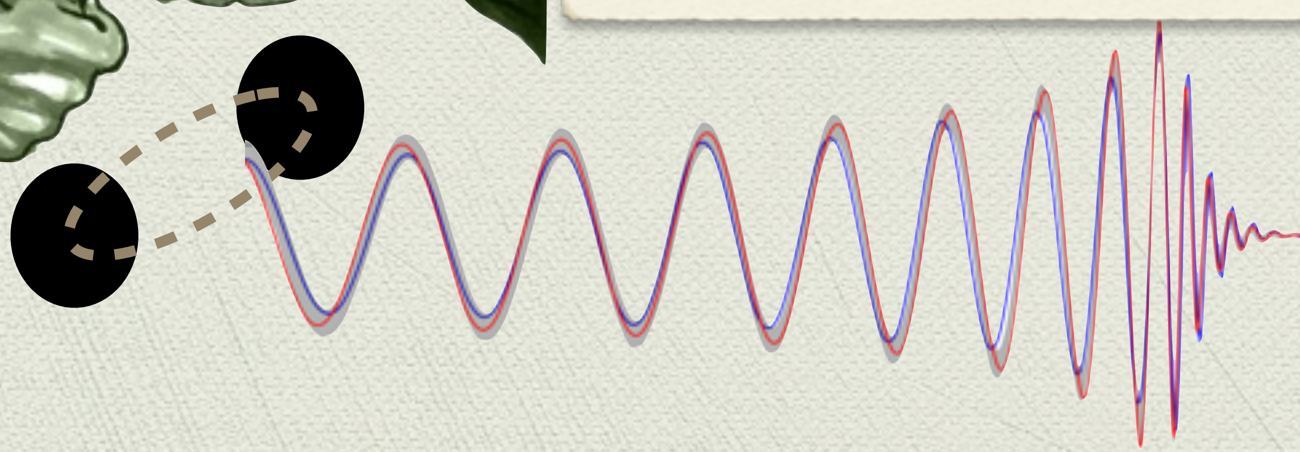
Hoang, **Naoz** et al (2018), ApJ, arXiv:17060.9896

Binaries in Galactic Nuclei



Looking at soft binaries

- EKL
- 1PN
- GW
- Unbinding
- Disruption
- Newtonian precession



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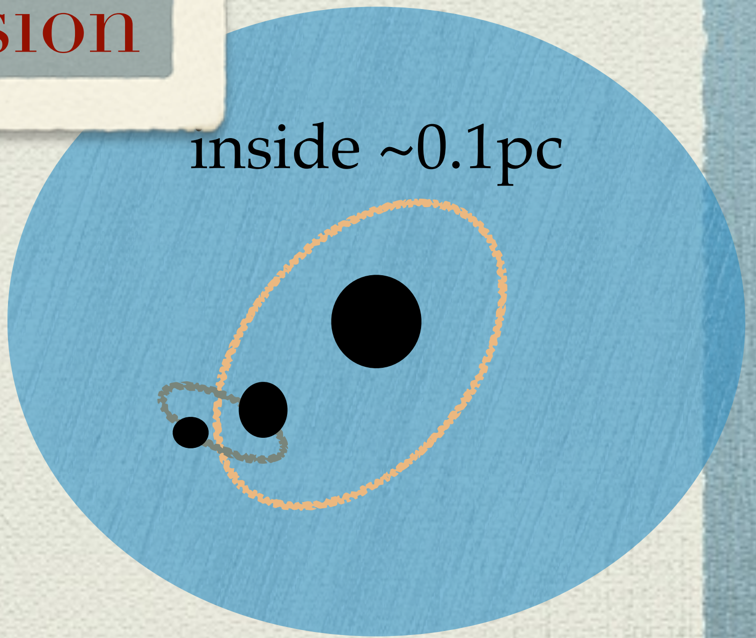
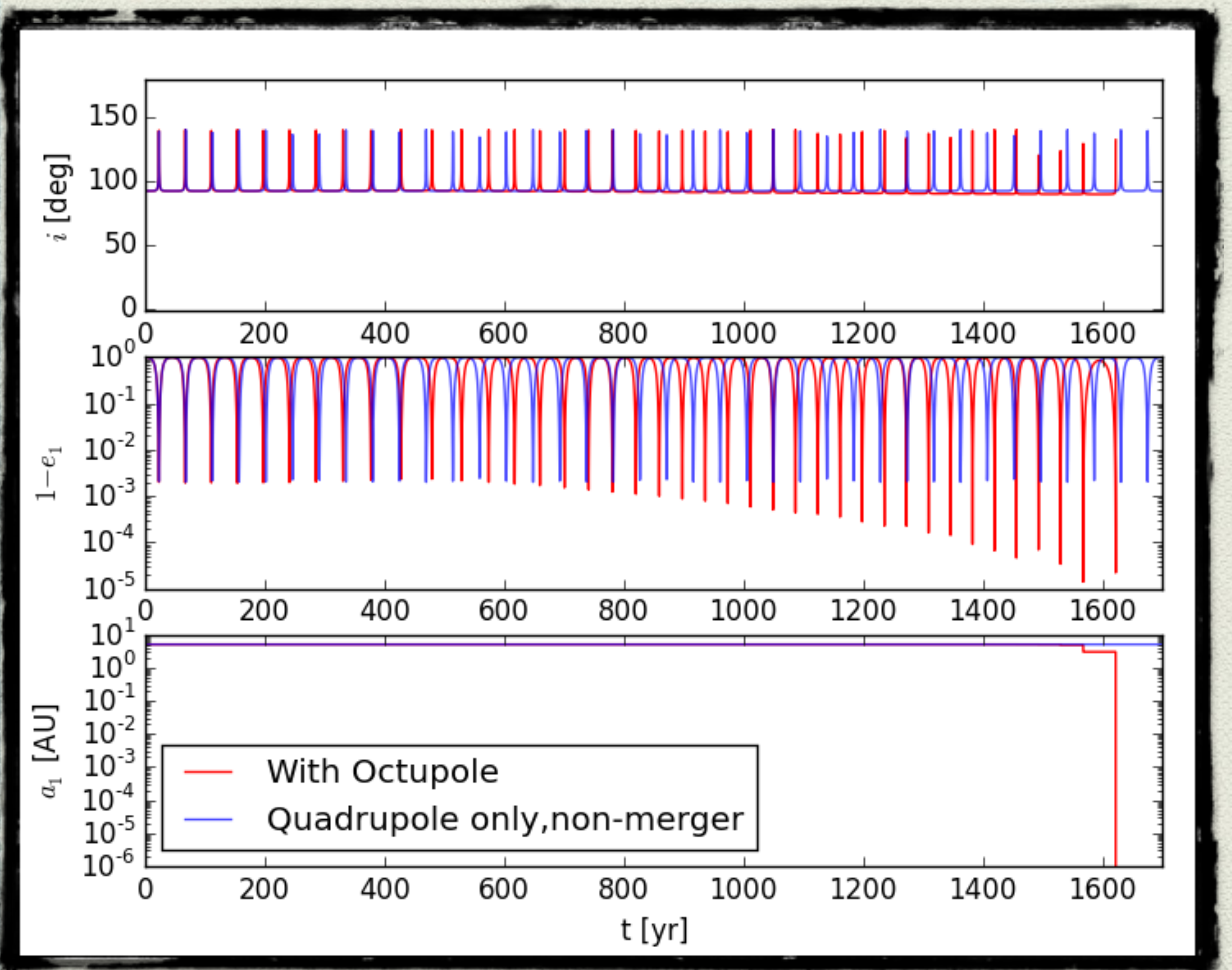


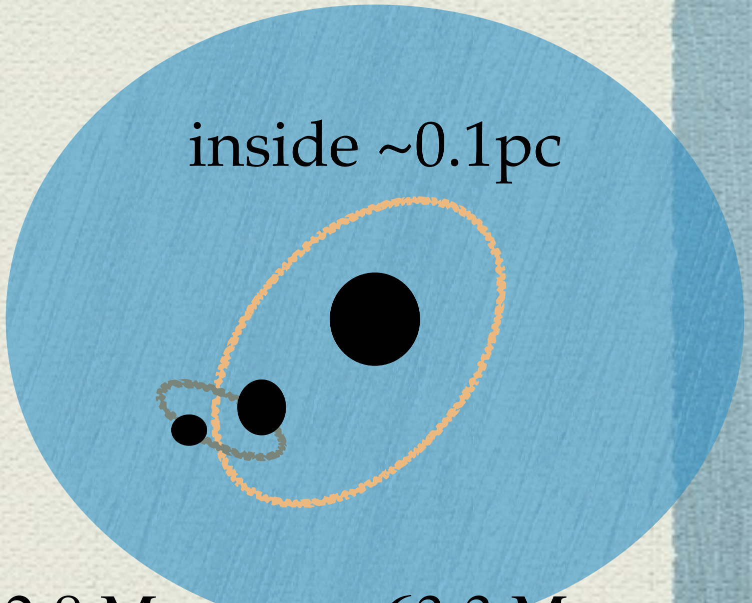
For hard binaries see: Antonini et al. 2010; Antonini & Perets 2012

Hoang, **Naoz** et al (2018), ApJ, arXiv:17060.9896

Binaries in Galactic Nuclei



Bao-Minh Hoang



$m_1 = 12.8\ M_\odot$, $m_2 = 63.3\ M_\odot$
$m_{MBH} = 1 \times 10^7\ M_\odot$
$a_1 = 5.1$ AU, $a_2 = 936$ AU,
$e_1 = 0.014$, $e_2 = 0.4$, $i = 92.8$

see Randall & Xianyu (2018) for quad level

Hoang, **Naoz** et al (2018), ApJ, arXiv:17060.9896

Binaries in Galactic Nuclei

Monte-Carlo simulations

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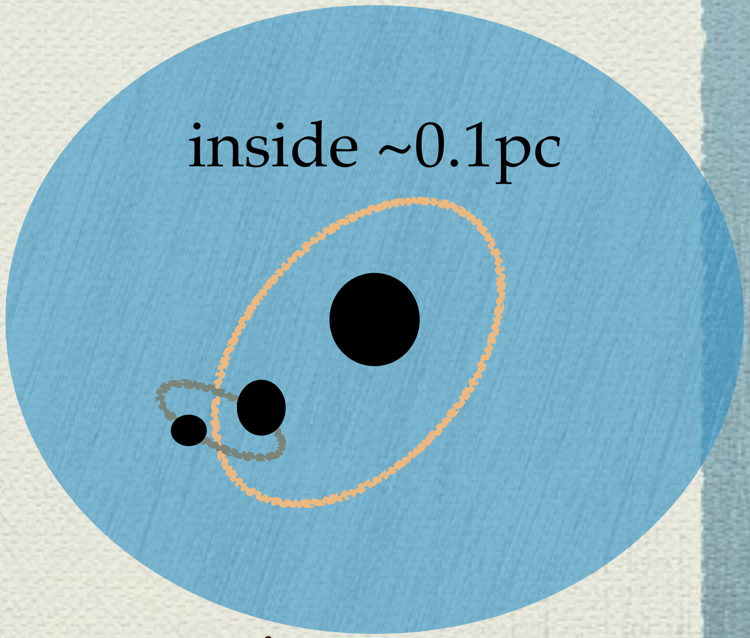

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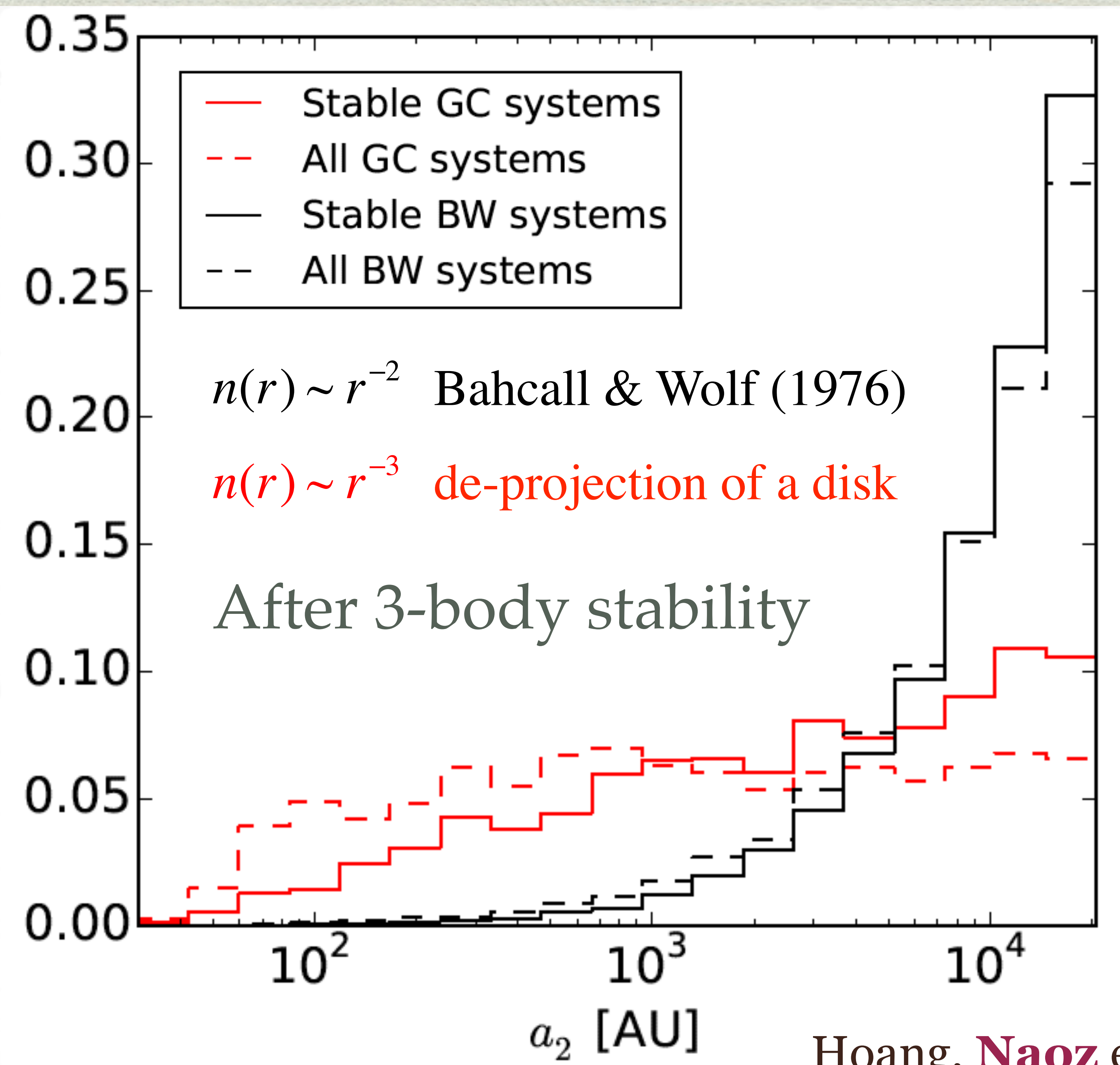
Binaries in Galactic Nuclei

Monte-Carlo simulations



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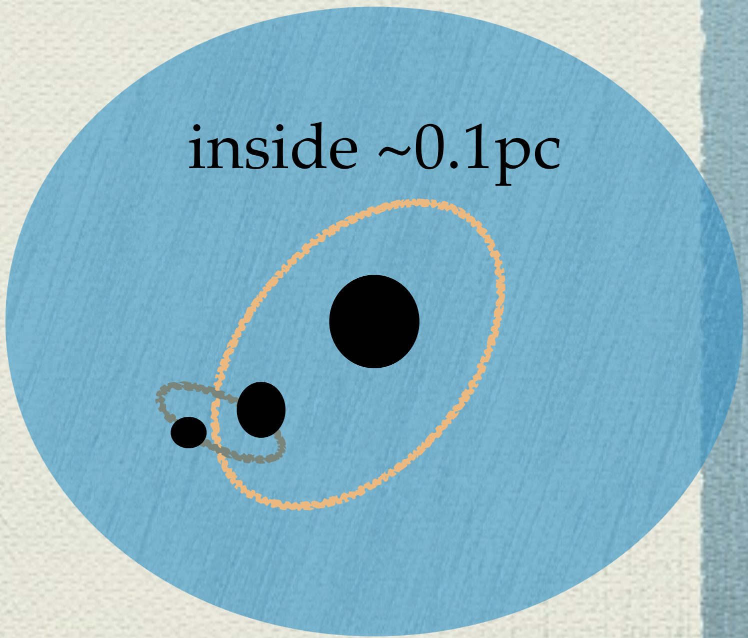

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Binaries in Galactic Nuclei

BH merger rate

$$\Gamma_{tot} = n_g f_{SMBH} \Gamma$$

$$\Gamma = N_{bin} f_{merge} \gamma_{EKL}$$

Insensitive to distribution

Galaxies # density:

$n_g = 0.02\ \mathrm{Mpc}^{-3}$ e.g., Conselice et al. (2005)

And: $f_{SMBH} \sim 0.5$

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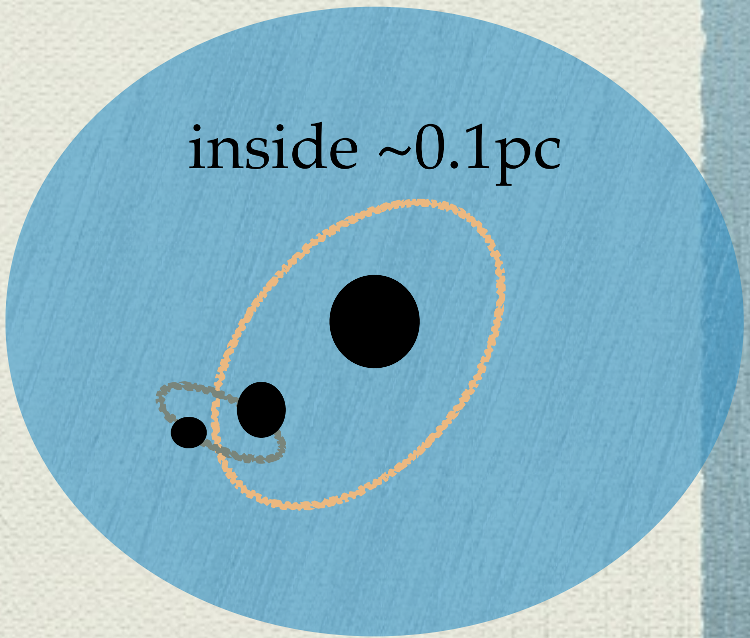

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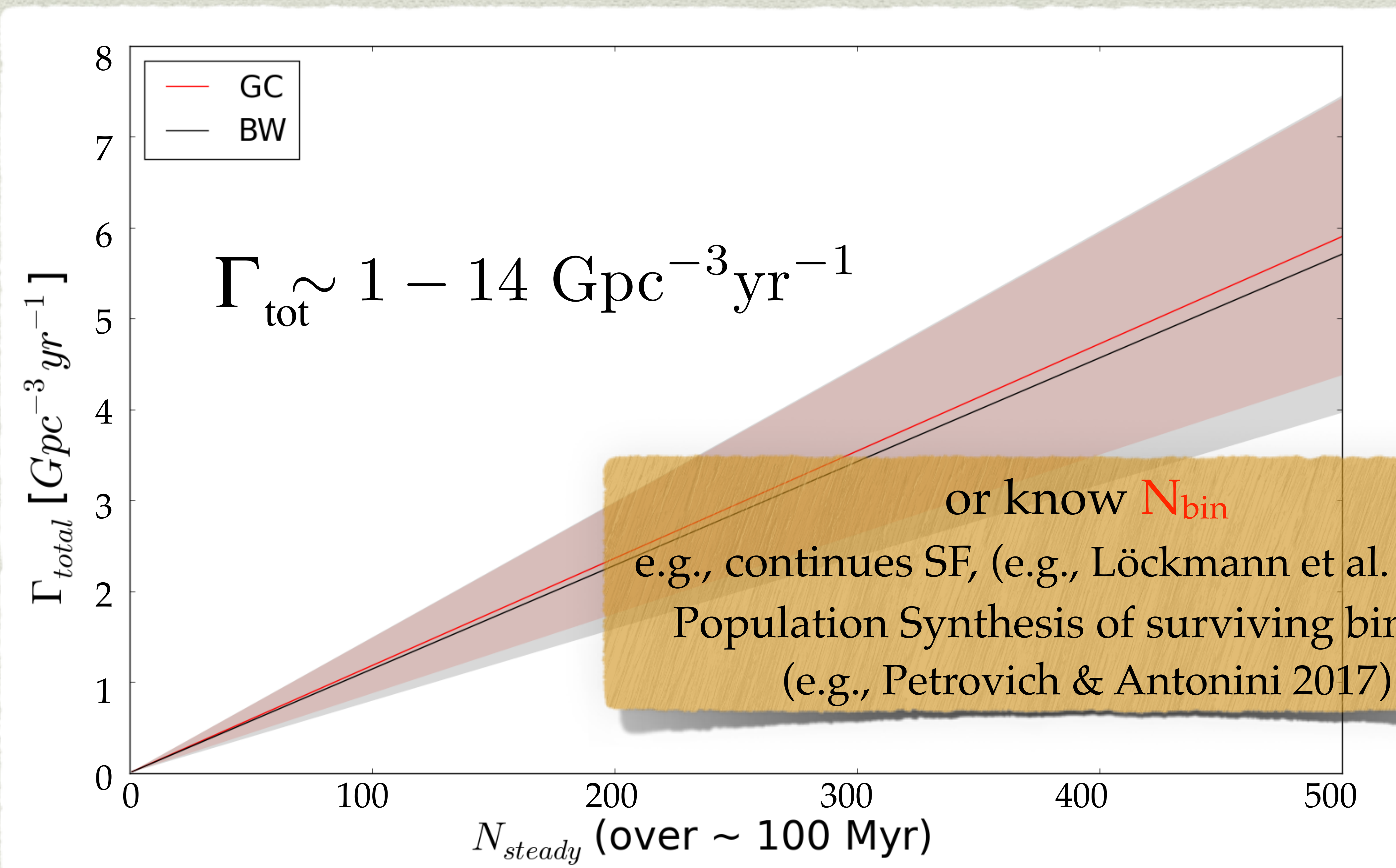
Binaries in Galactic Nuclei

BH merger rate



or know N_{bin}

e.g., continues SF, (e.g., Löckmann et al. 2010) +
Population Synthesis of surviving binaries
(e.g., Petrovich & Antonini 2017)

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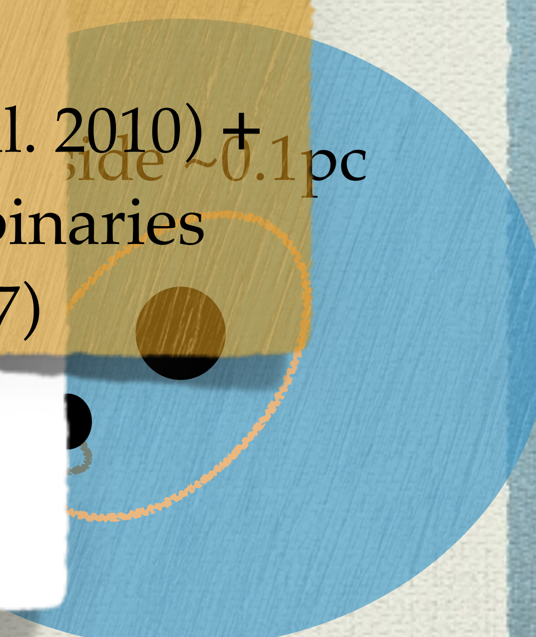


Hoang, **Naoz** et al (2018), ApJ, arXiv:17060.9896

BH merger rate - Dynamical Channels

$\Gamma \sim 1-14\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ Hoang, **Naoz** et al (2018)

+

$\Gamma \sim 1.5\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ O'Leary et al (2009)
Gondan et al (2018)

+

$\Gamma \sim 0.5-15\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ Petrovich & Antonini (2017)
EKL derivative

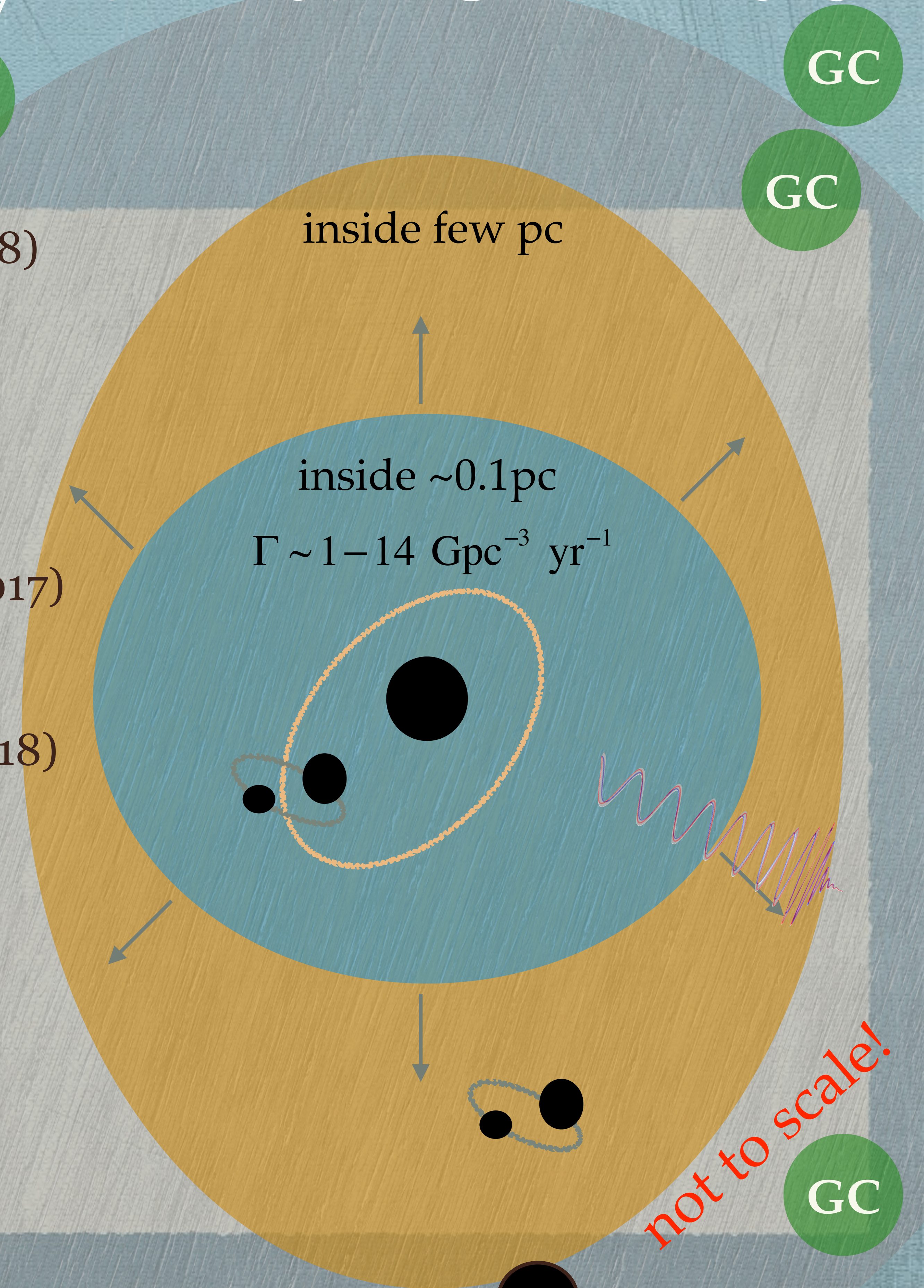
+

$\Gamma \sim 5-50\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ Rodriguez et al (2016,2018)
see Fred Rasio's talk

=

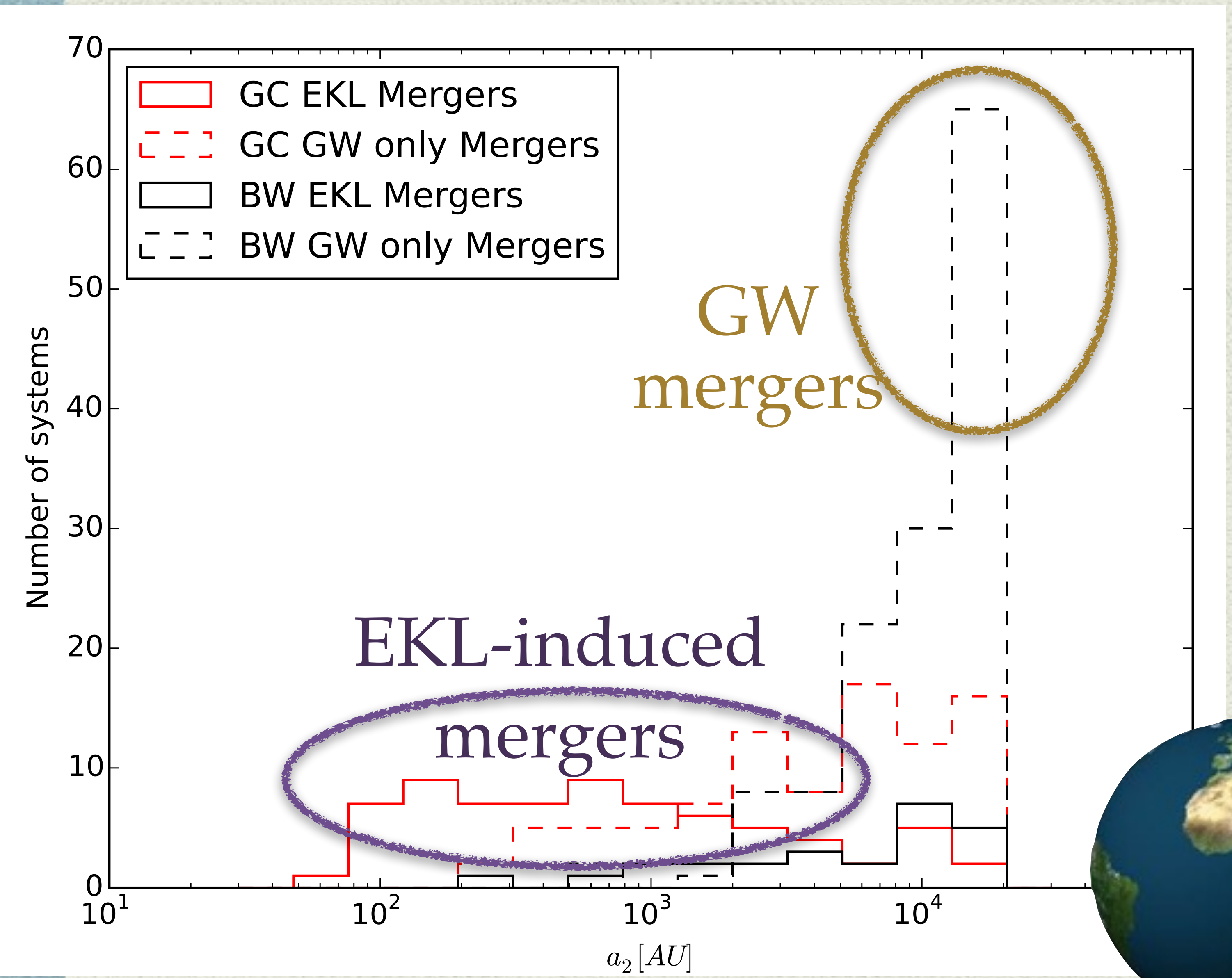
$\Gamma \sim 8-80.5\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

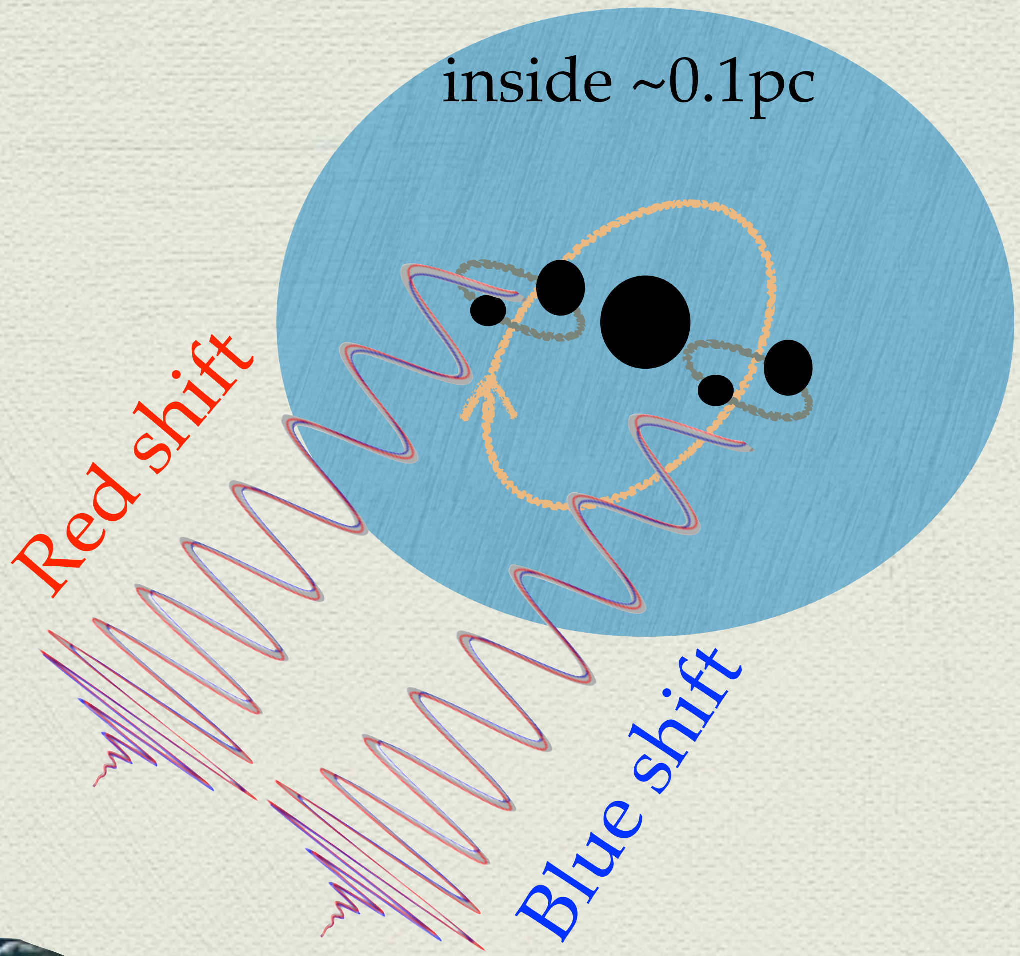
+ see Bartos et al (2018) for
binaries near AGN accretion disk



Can we disentangle between them?

Binaries in Galactic Nuclei

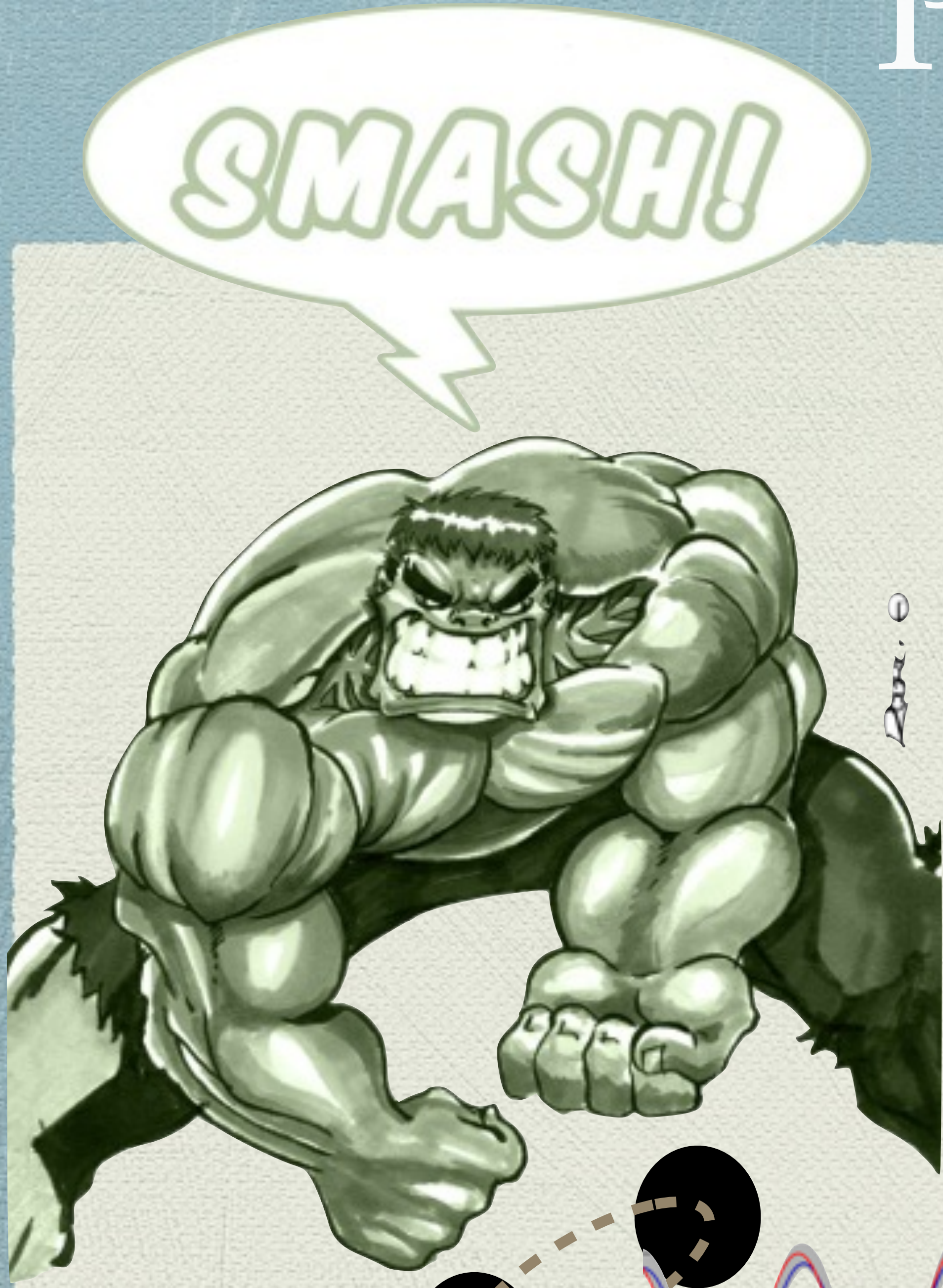




e.g., Meiron, et al (2017); Inayoshi et al. (2017)

Hoang, **Naoz** et al (2018), ApJ, arXiv:17060.9896

Punchline



- SMBH at the galactic nuclei can lead to BH merger
- Insensitive to $n \sim r^{-\alpha}$ or other outer orbit precession
- Rates comparable to other dynamical channels
- Possible distinguishable