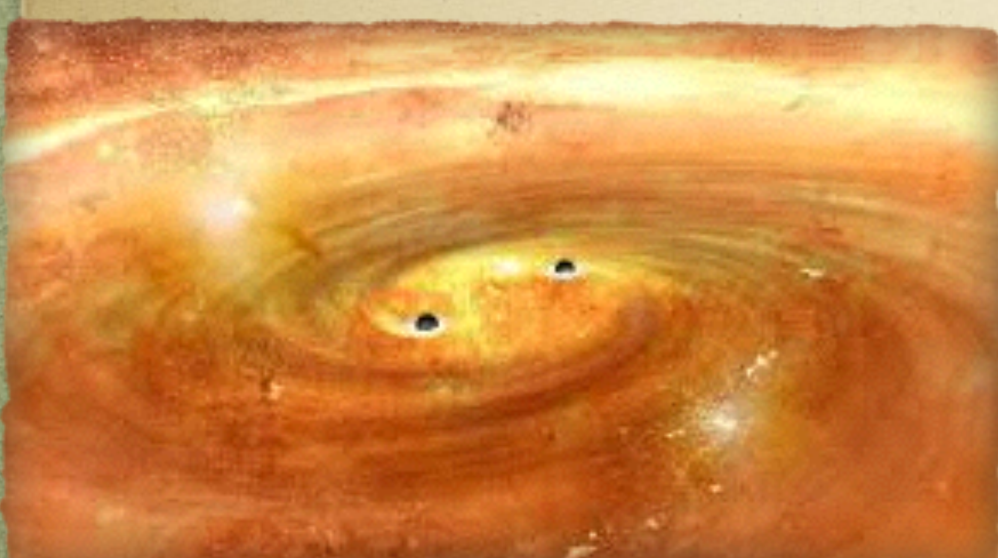
Formation of Dark Matter Donuts Around Supermassive Black Hole Binaries

Smadar Naoz
UCLA

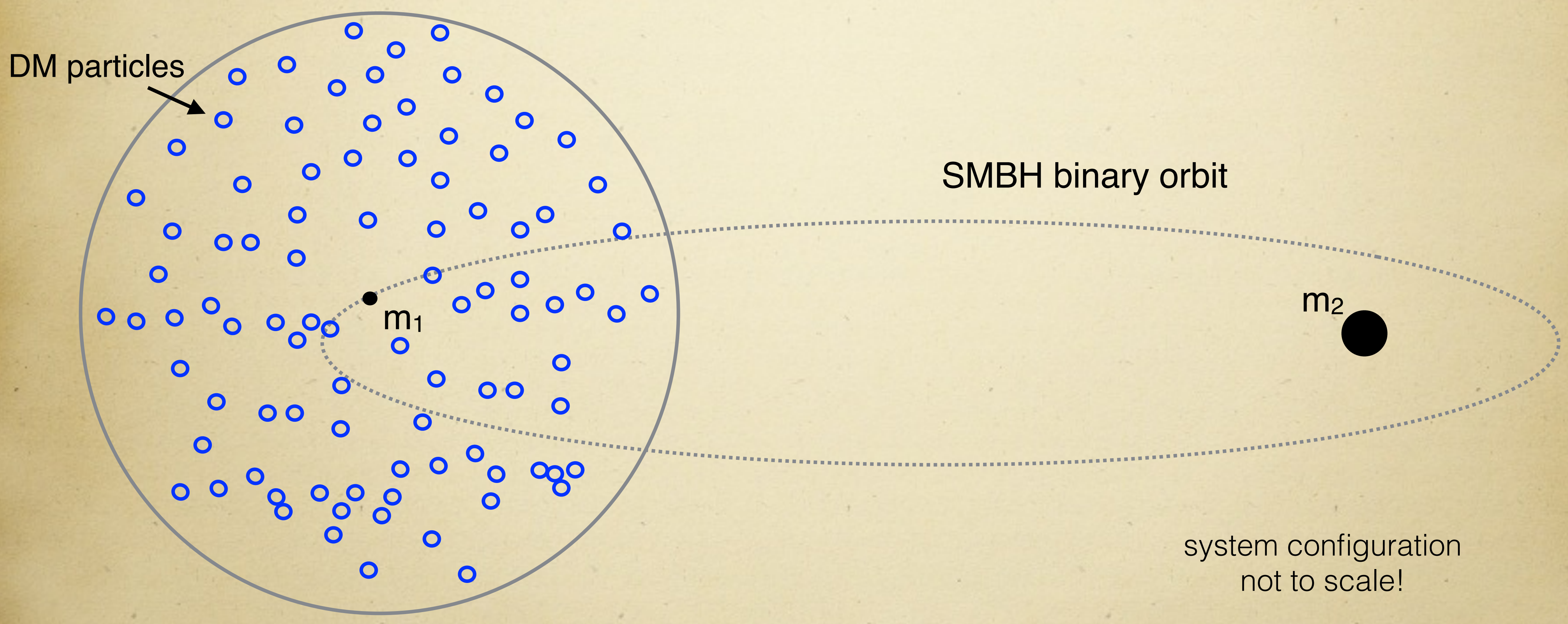
Collaborators:

Will Farr, Yoram Lithwick, Fred Rasio, Jean Teyssandier ,Gongjie Li, Avi Loeb, Bence Kocsis, Matt Holman,Joe Silk

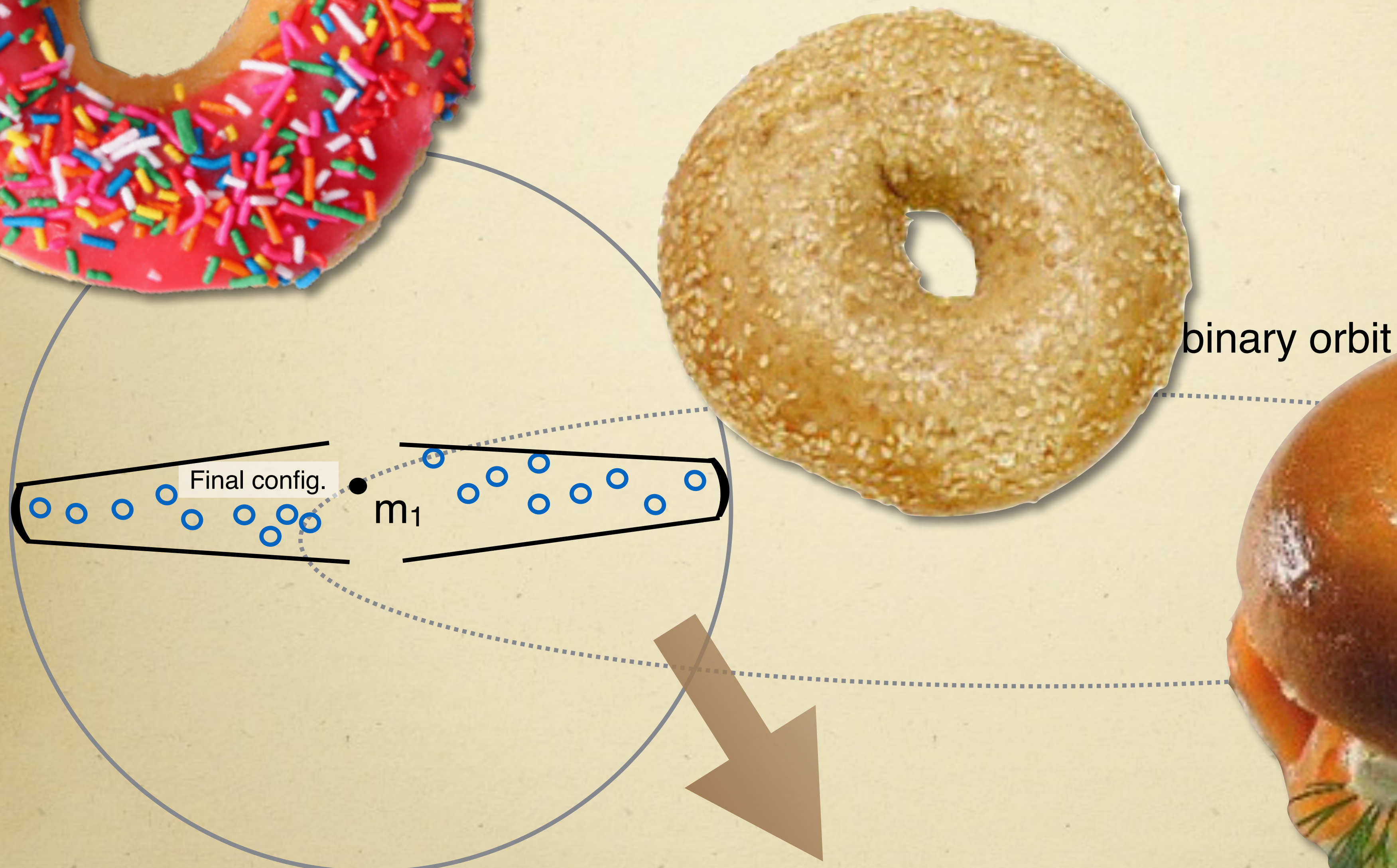


Rennan Barkana, Naoki Yoshida, Nick Gnedin,Ramesh Narayan, Cristina Popa, Mark Vogelsberger

Dark Matter Donuts



Dark Matter Donuts



DM - baryon interactions
@ high redshift

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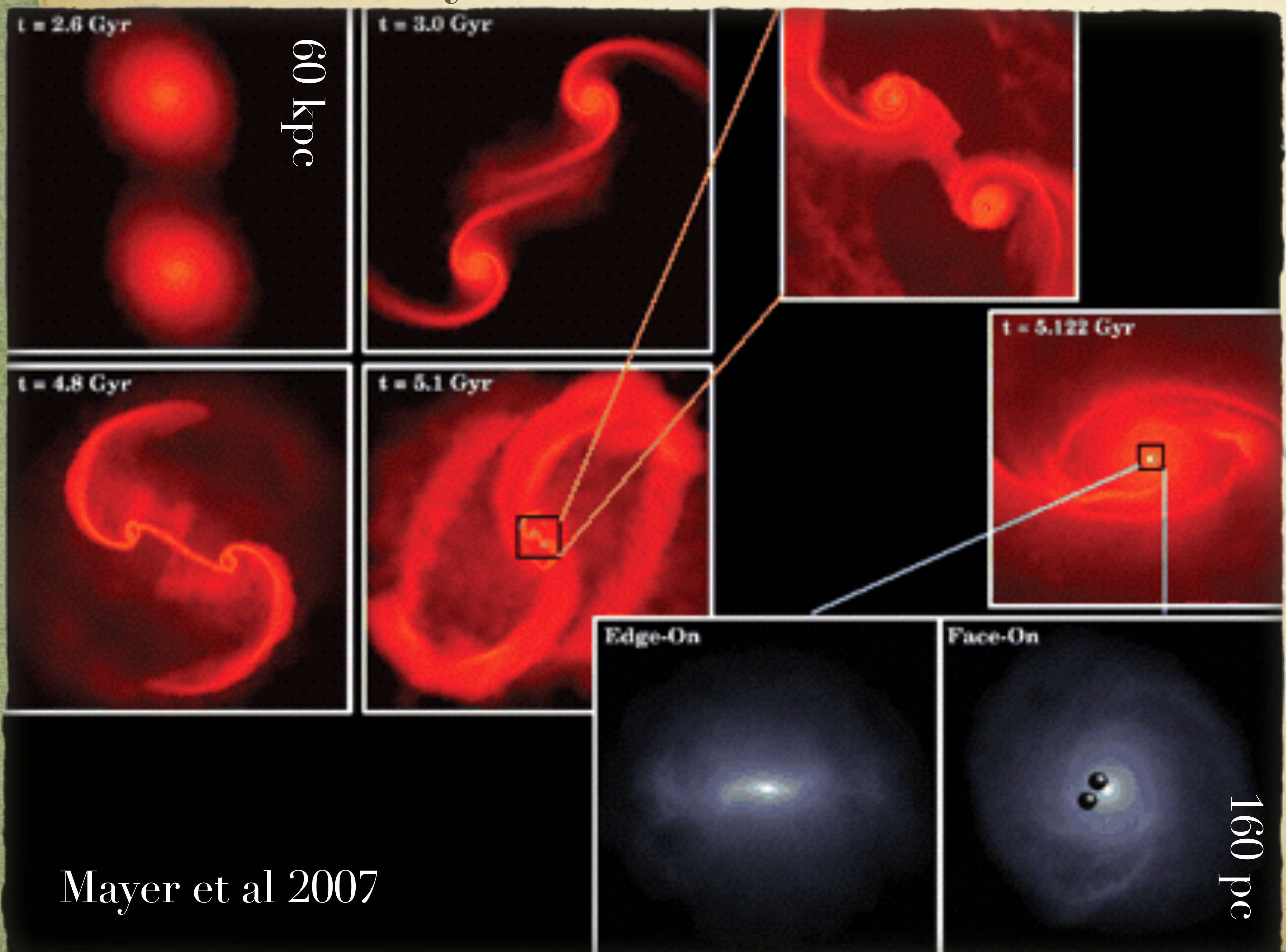
Supermassive Black Hole Binaries

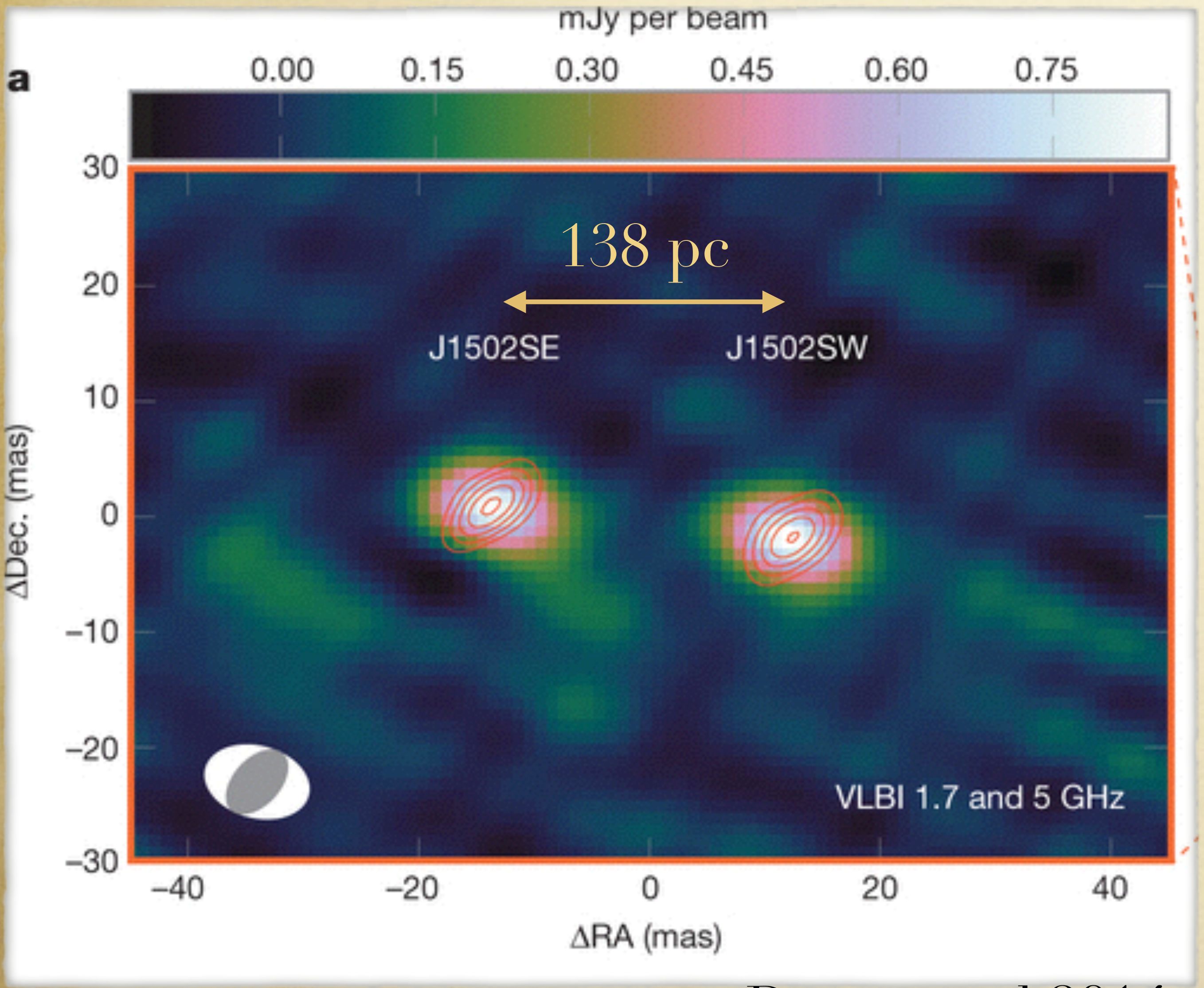
Theoretically:



Mayer et al 2007

Supermassive Black Hole Binaries

Observationally:



Deane et al 2014

VLBI observations

and see also: Dotti et al. 2009; Batcheldor et al. 2010; Liu et al. 2014

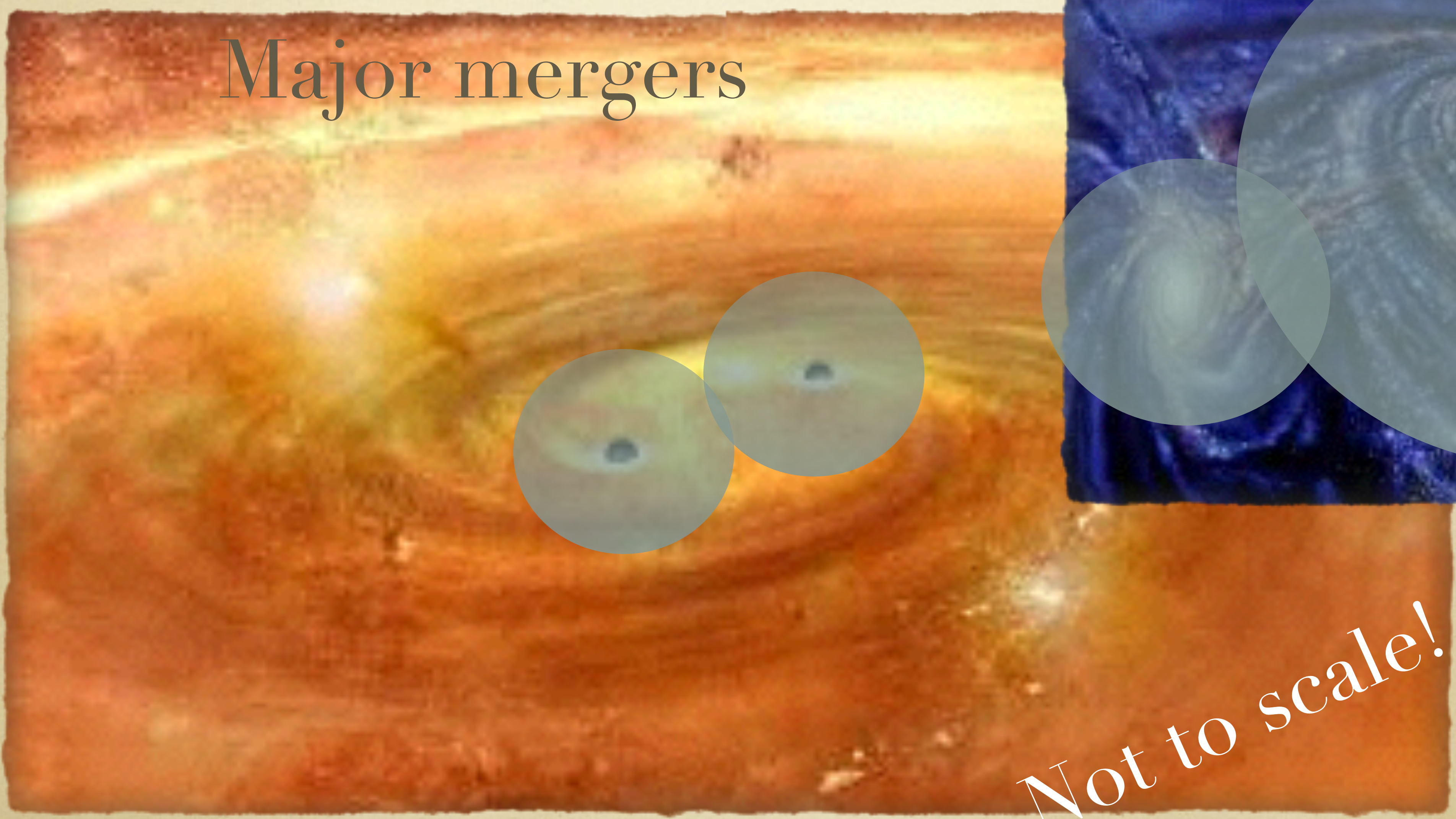
Supermassive Black Hole Binaries

What is happening to the dark matter?

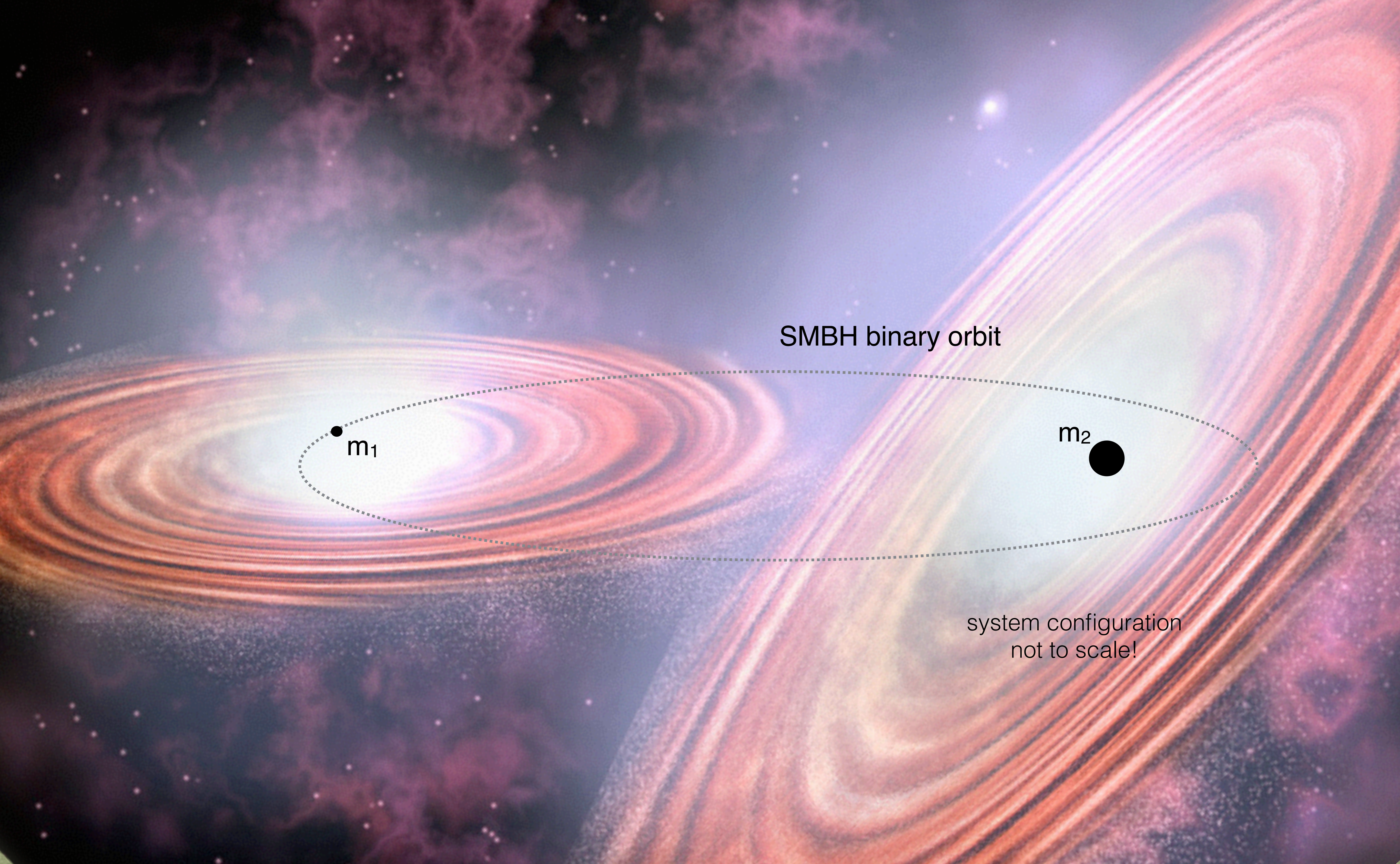
Supermassive Black Hole Binaries

What is happening to the dark matter?

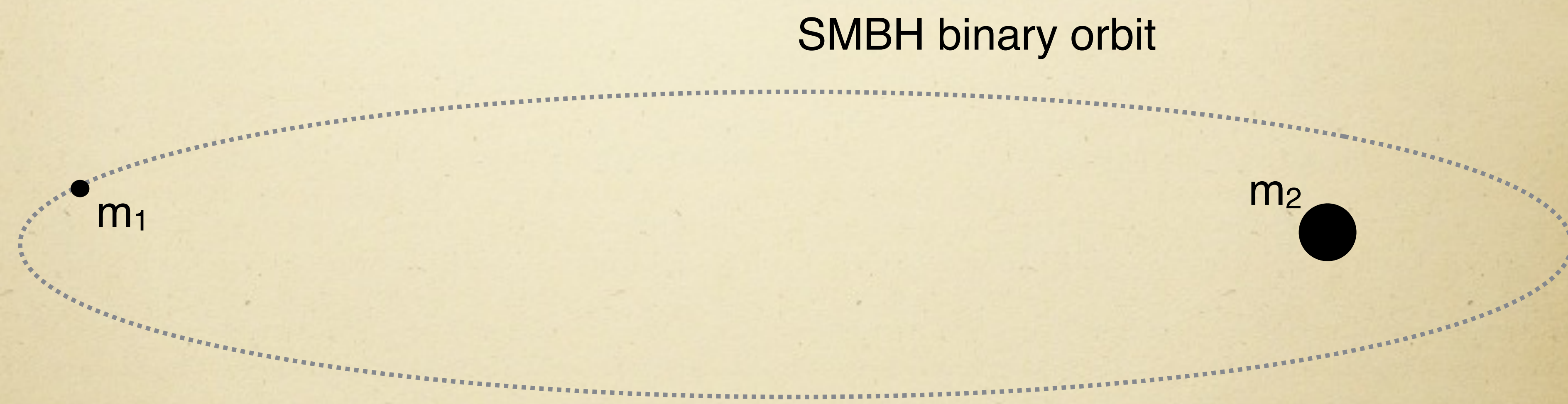
e.g., Rashkov & Madau 2013



SMBH Binaries and DM

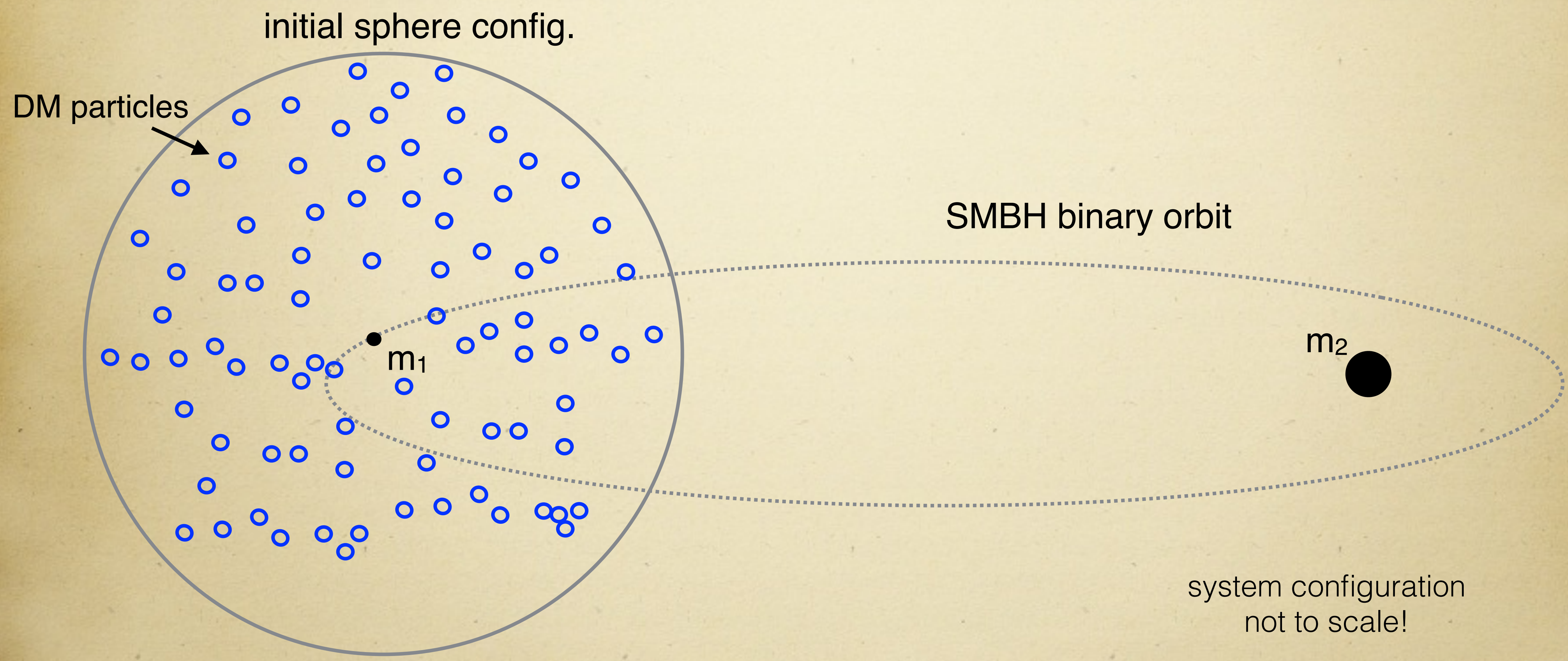


SMBH Binaries and DM



system configuration
not to scale!

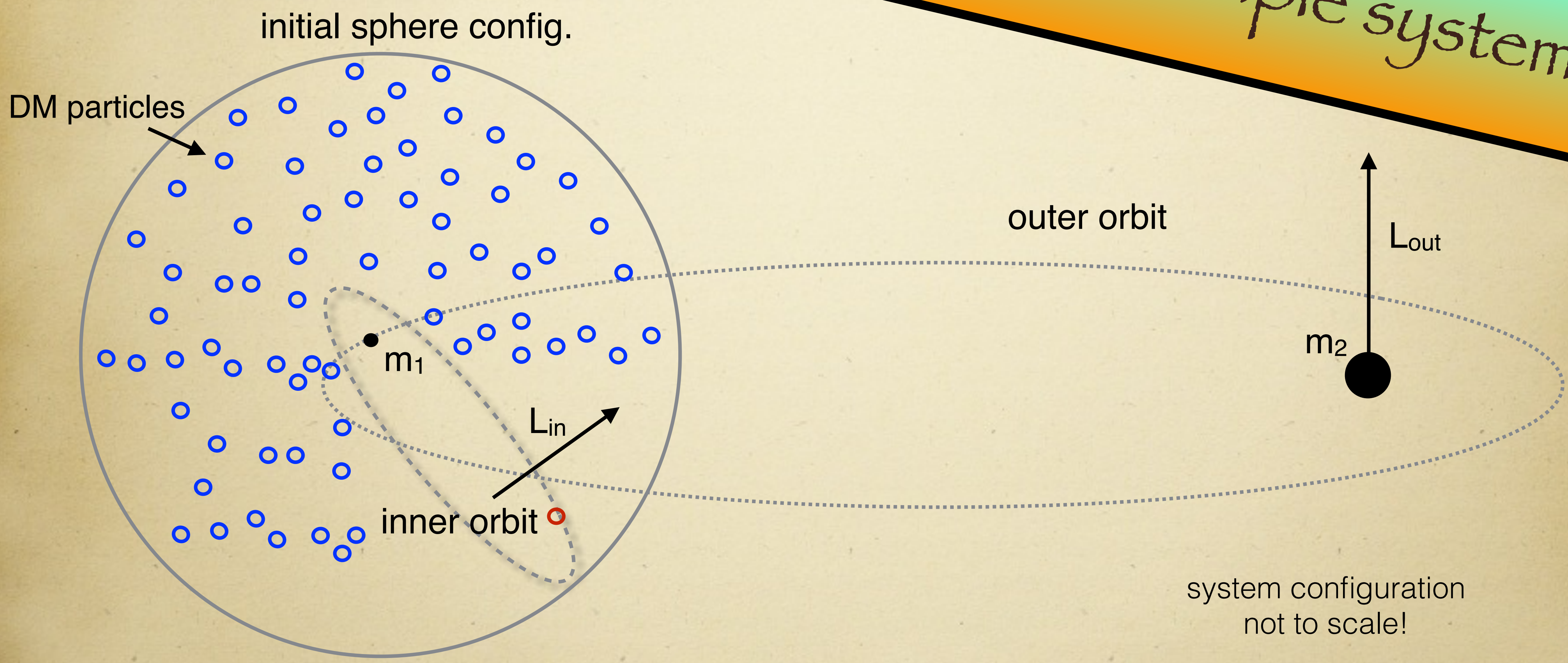
SMBH Binaries and DM



system configuration
not to scale!

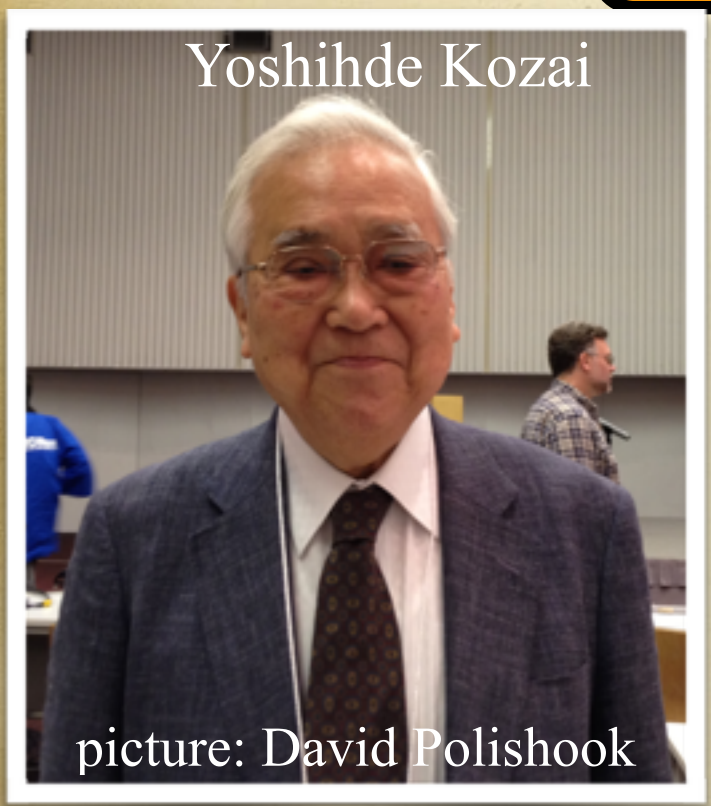
SMBH Binaries and DM

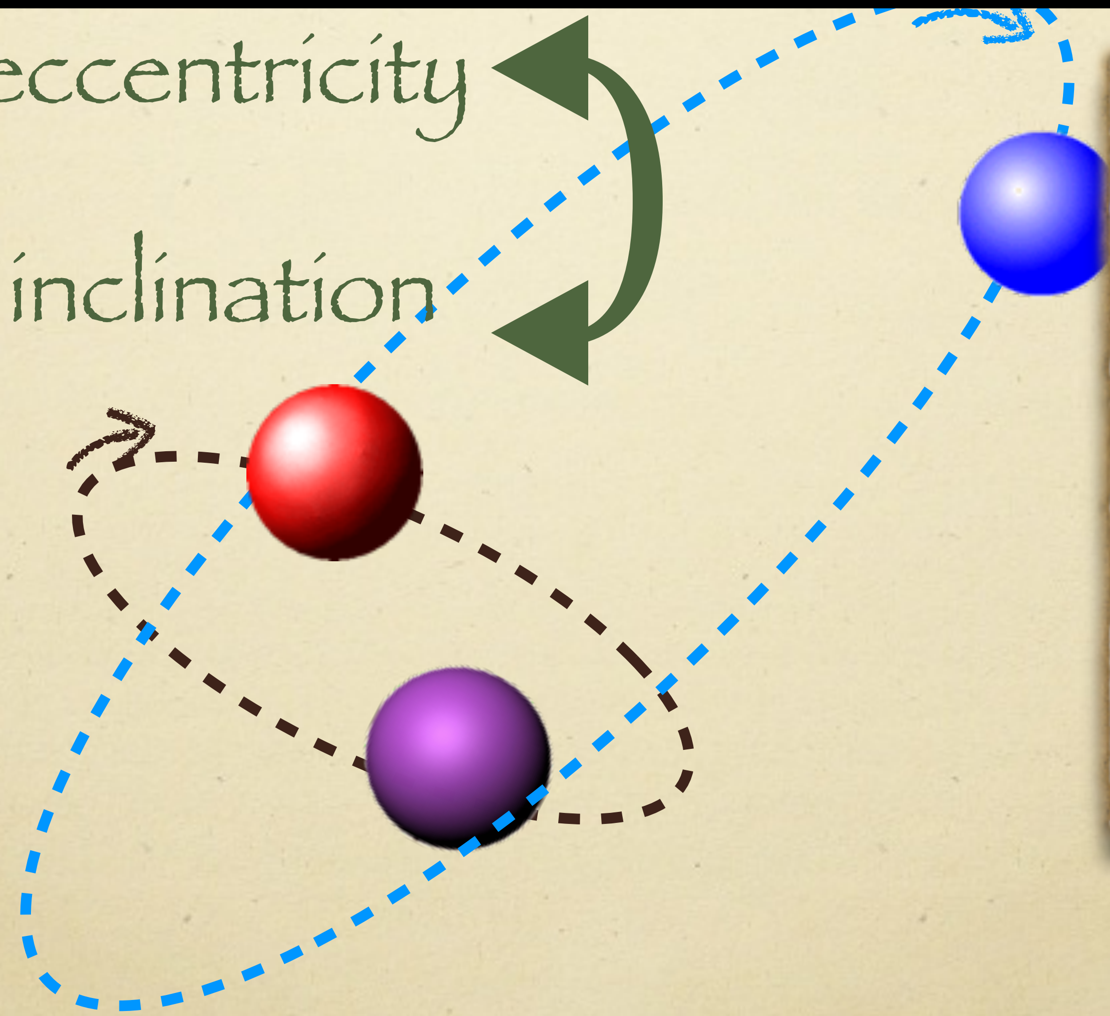
Hierarchical triple system

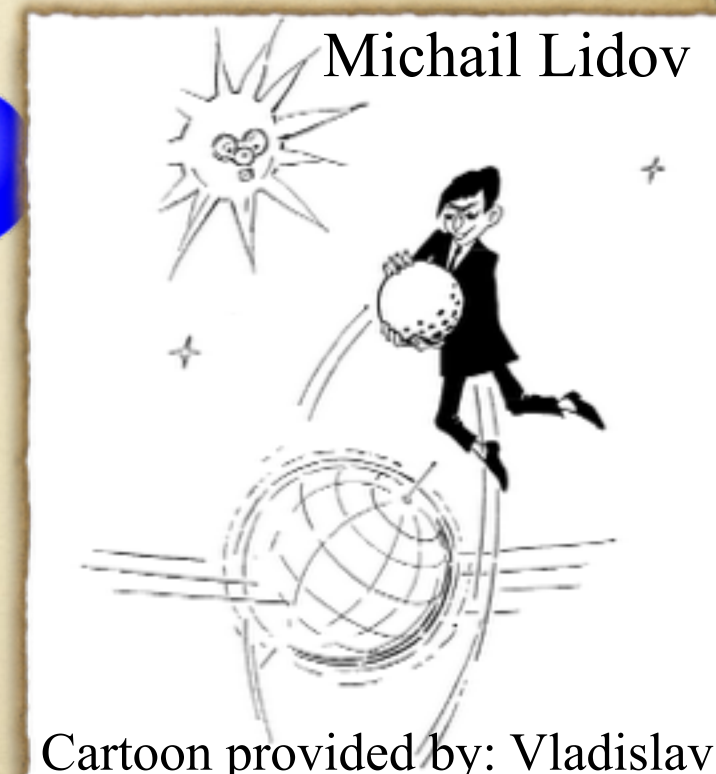


system configuration
not to scale!

Hierarchical triple system







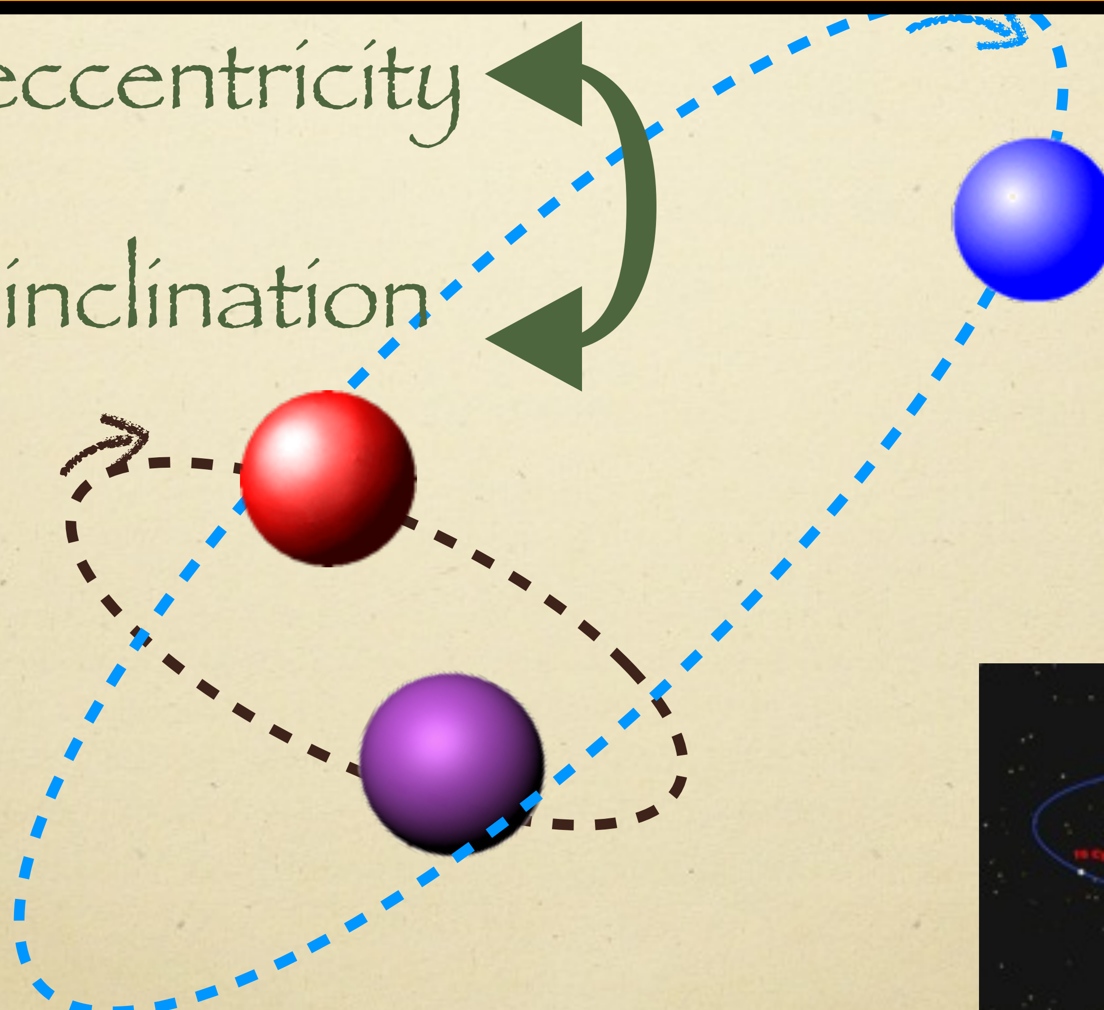
Cartoon provided by: Vladislav Sidorenko

Kozai 1962, Lidov 1962

Hierarchical triple system

eccentricity

inclination



Kozai 1962, Lidov 1962

Triples are everywhere:

Hierarchical triple system

initial @ different scales

New developments

Many applications

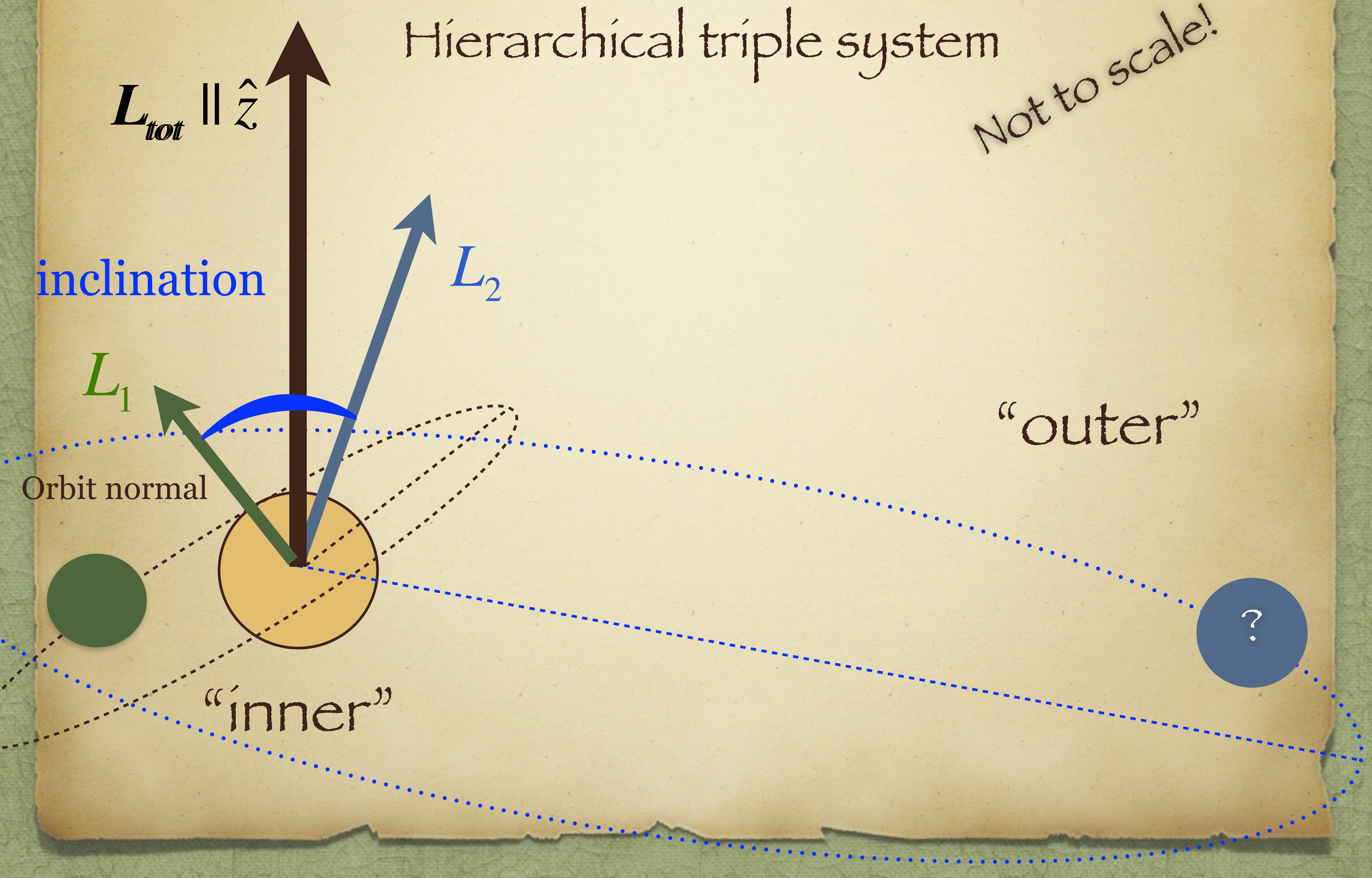
larger parameter space

BH systems

Triple stars

Planetary systems

The Kozai-Lidov Formalism

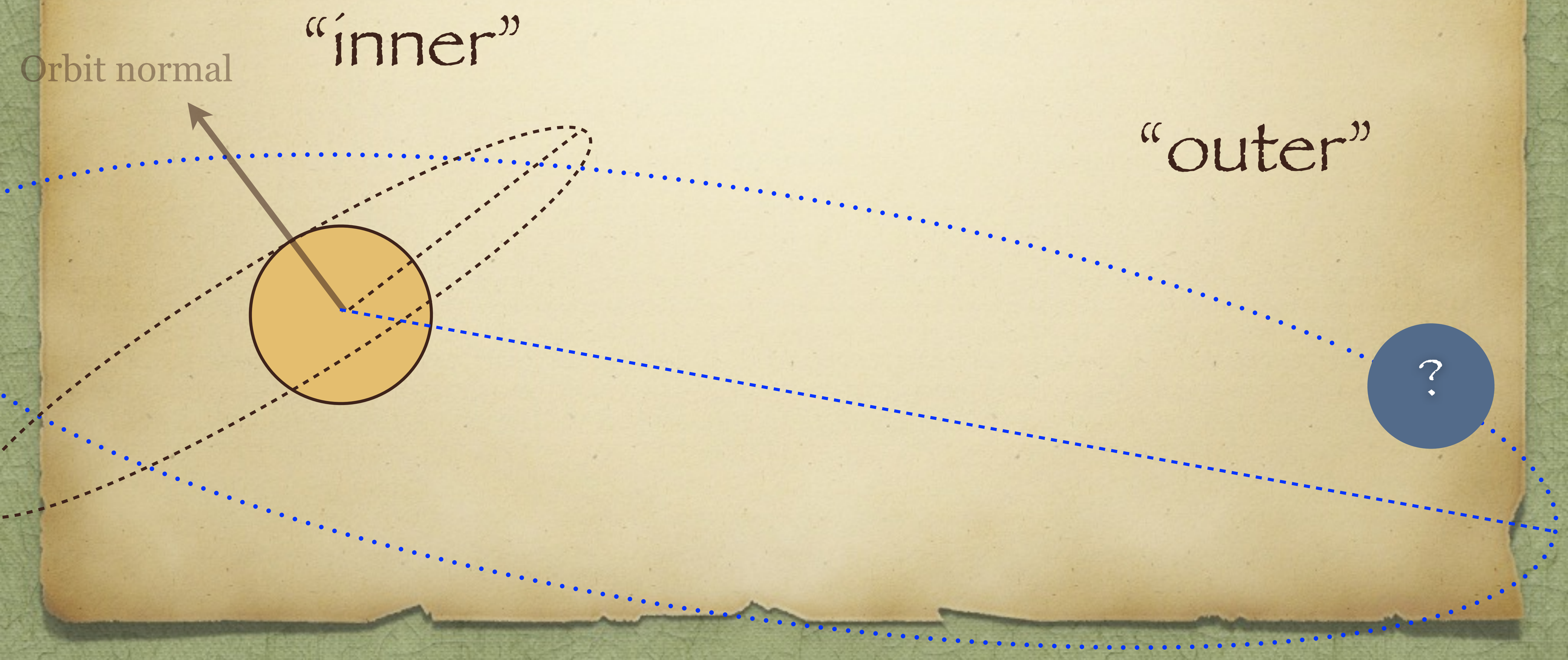


The Kozai-Lidov Formalism

Hierarchical triple system

Not to scale!

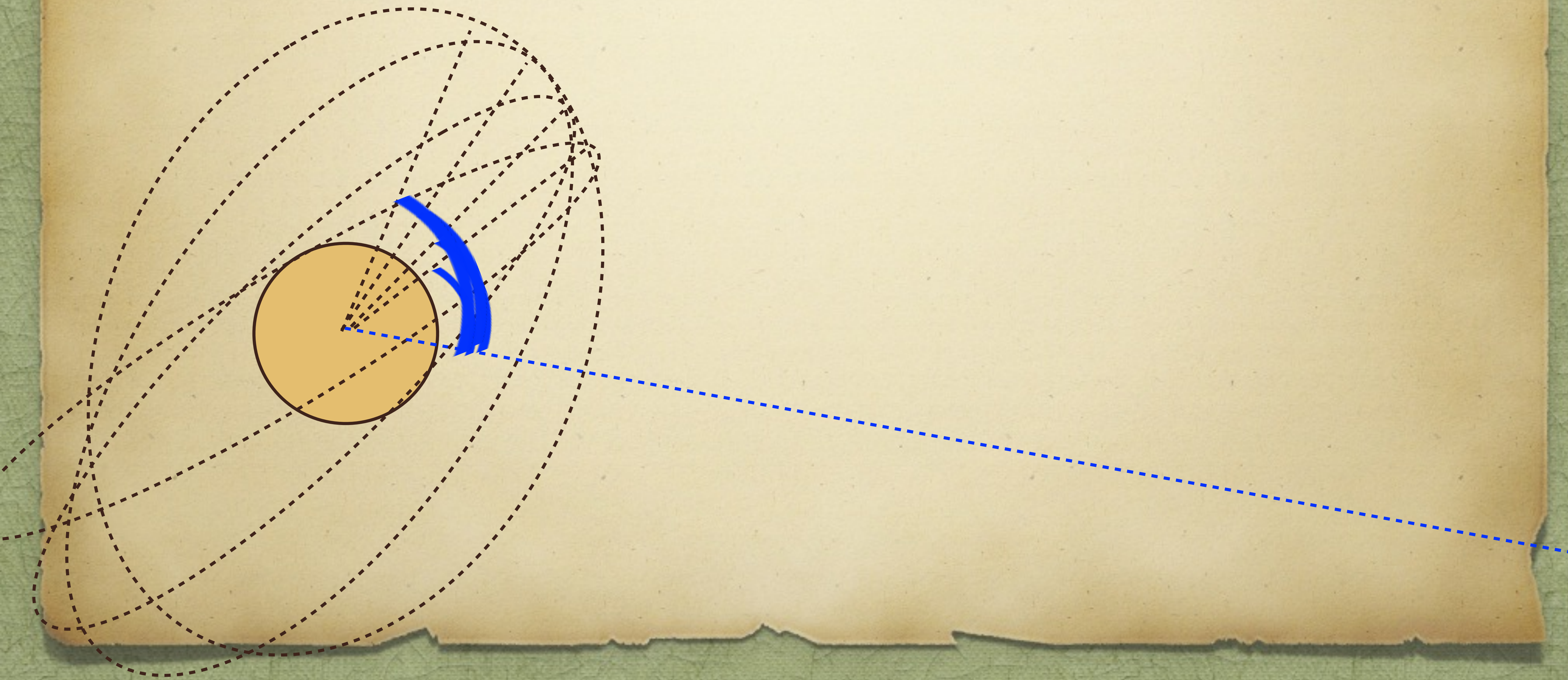
Kozai 1962, Lidov 1962



The Kozai-Lidov Formalism

The eccentricity and inclination oscillate

Kozai 1962, Lidov 1962



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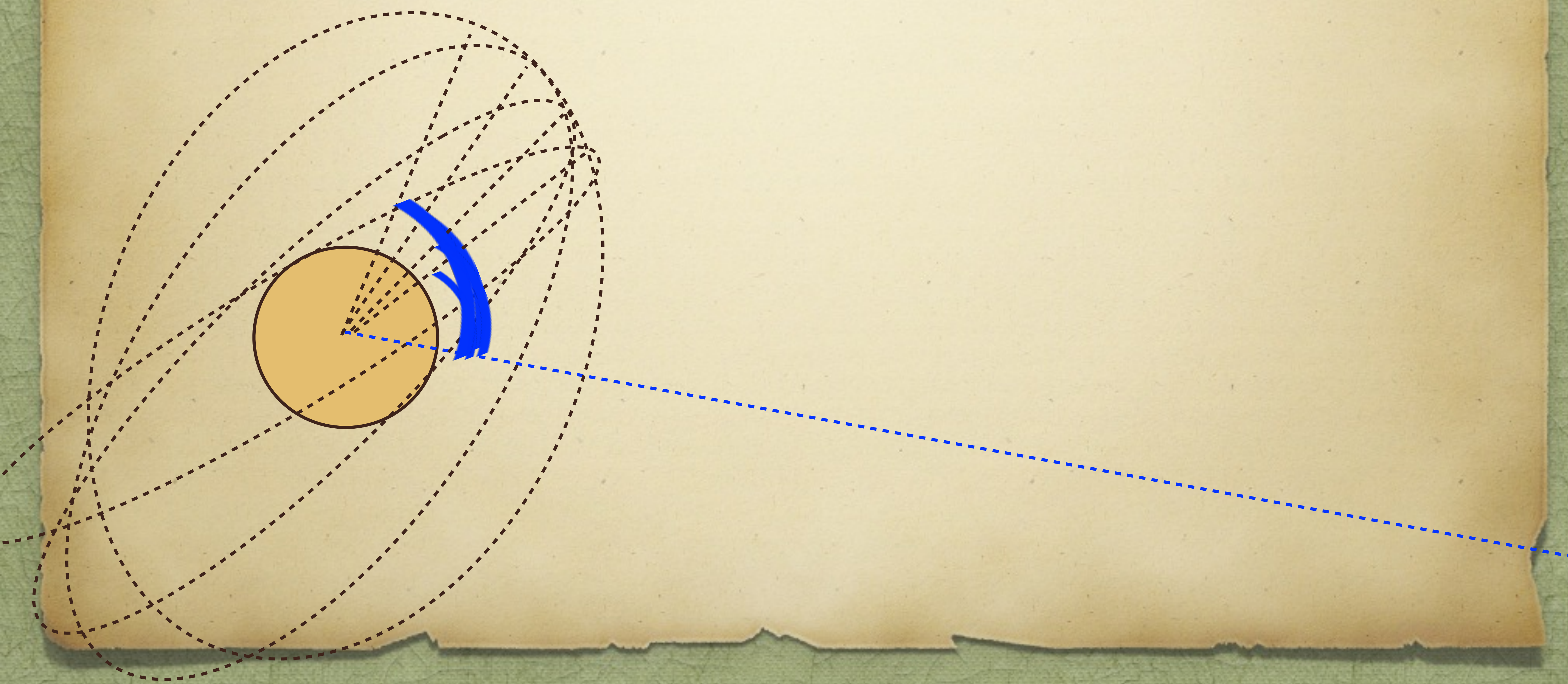

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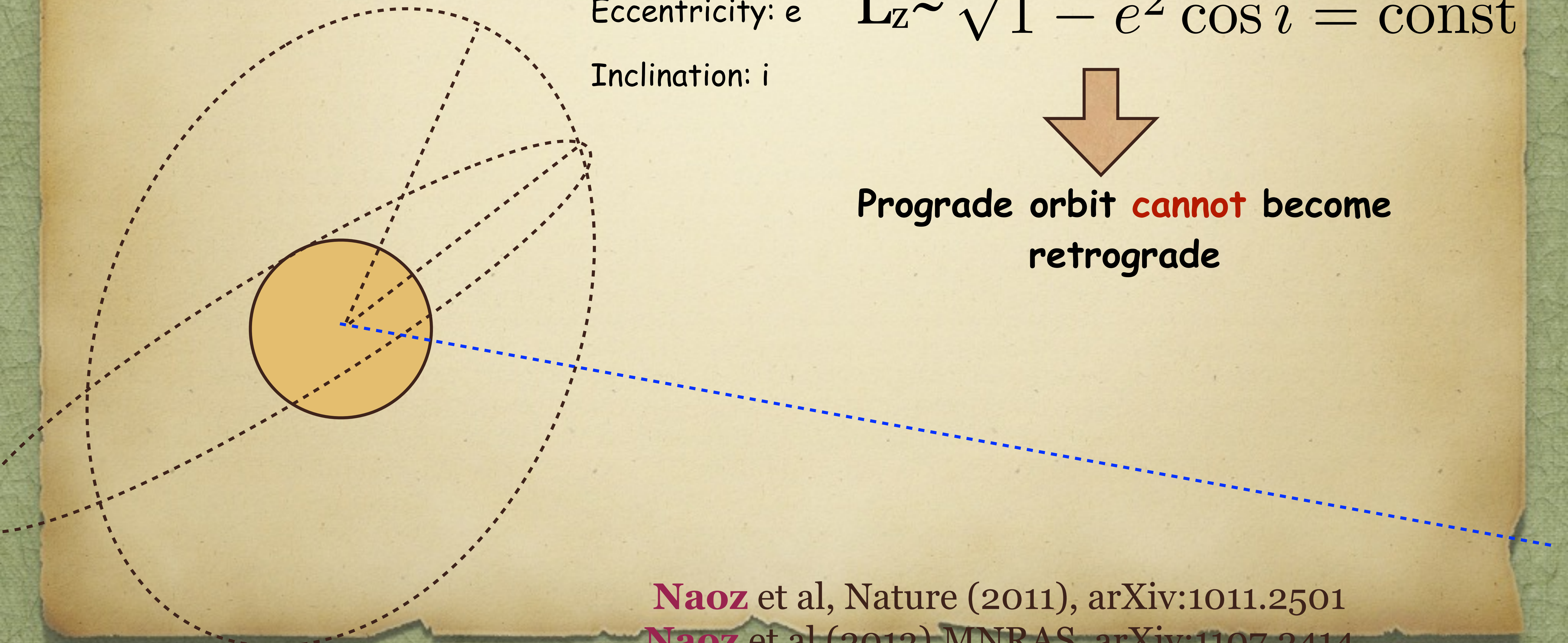
Kozai 1962, Lidov 1962



Conservation of the z component of angular momentum for both the inner outer orbits

The orbital elements:

Eccentricity: e

Inclination: i

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

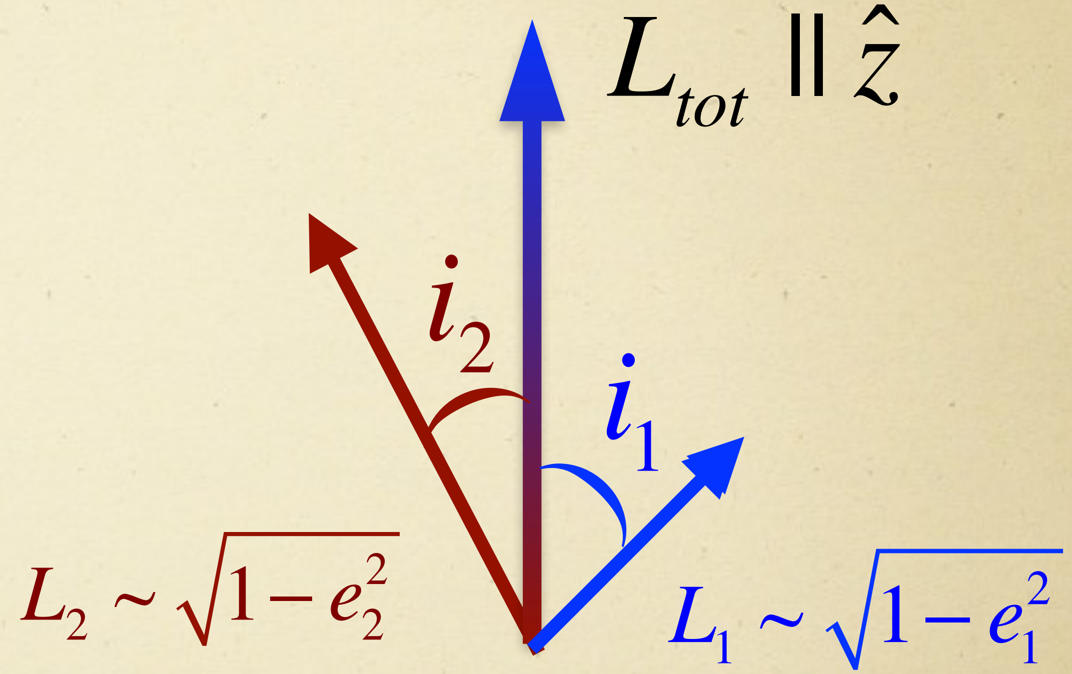
Prograde orbit cannot become retrograde

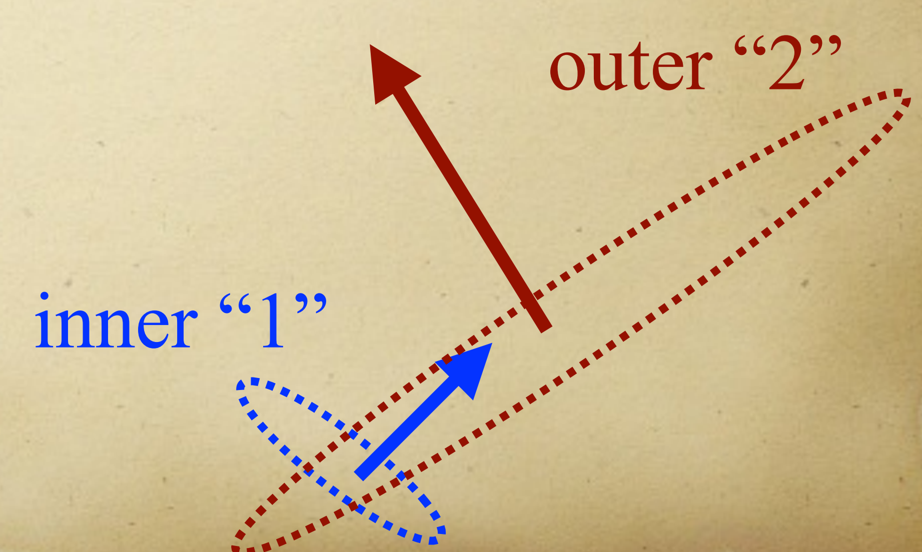
Naoz et al, Nature (2011), arXiv:1011.2501
Naoz et al (2013),MNRAS, arXiv:1107.2414

Is it constant?

Adding vector ...

$$\vec{L}_{tot} = \vec{L}_1 + \vec{L}_2$$





Is it constant?

Adding vector ...

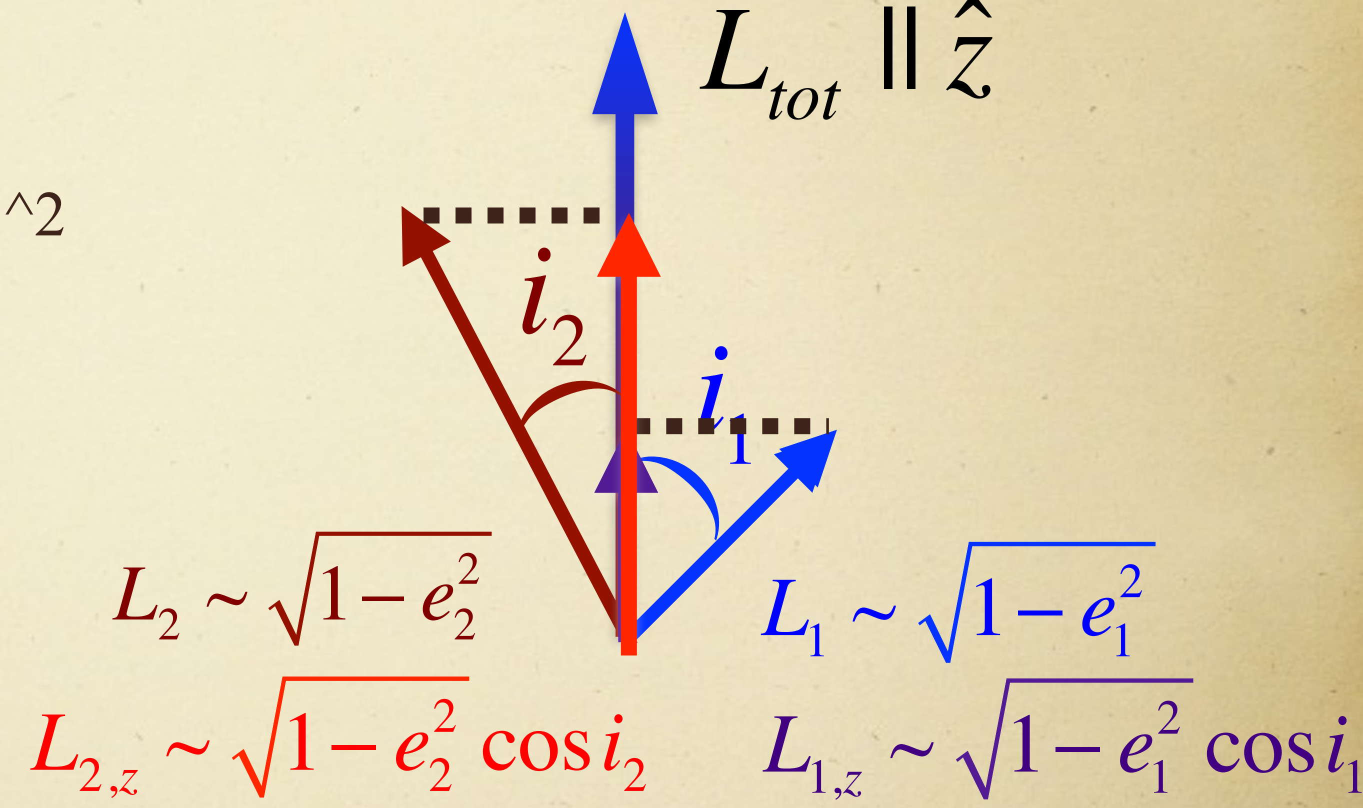
$$\vec{L}_{tot} = \vec{L}_1 + \vec{L}_2$$

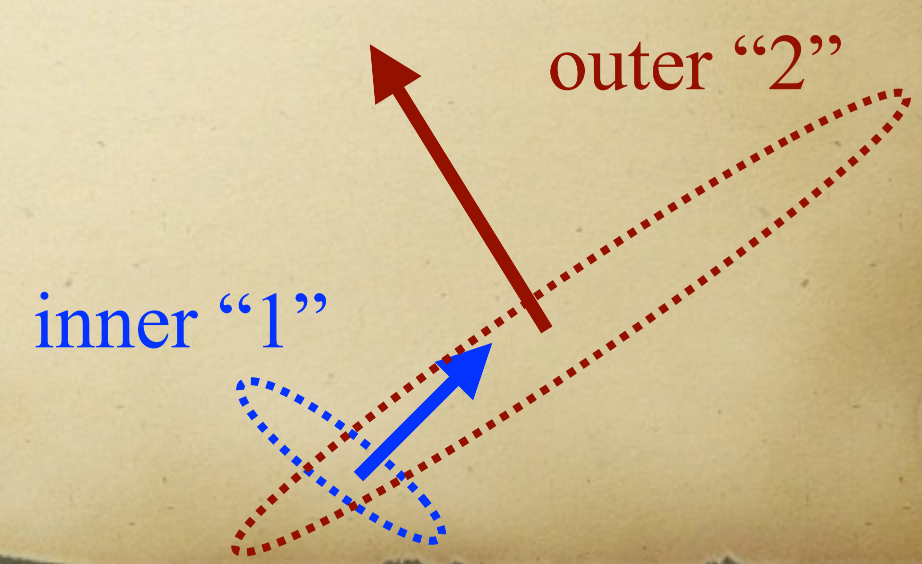
rearrange

$$\vec{L}_2 = \vec{L}_{tot} - \vec{L}_1$$

^2

$$L_2^2 = L_{tot}^2 + L_1^2 - 2L_{tot}\underbrace{L_1 \cos i_1}_{L_{1,z}}$$





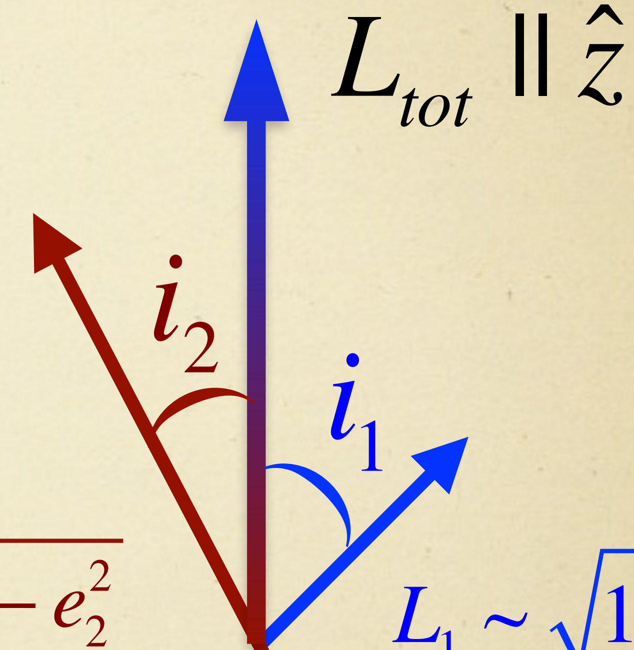
Is it constant?

Adding vector …

$$\vec{L}_{tot} = \vec{L}_1 + \vec{L}_2$$

$$\vec{L}_2 = \vec{L}_{tot} - \vec{L}_1$$

$$\boxed{L_2^2} = \boxed{L_{tot}^2} + L_1^2 - 2\boxed{L_{tot}}\boxed{\underbrace{L_1 \cos i_1}_{L_{1,z}}}$$

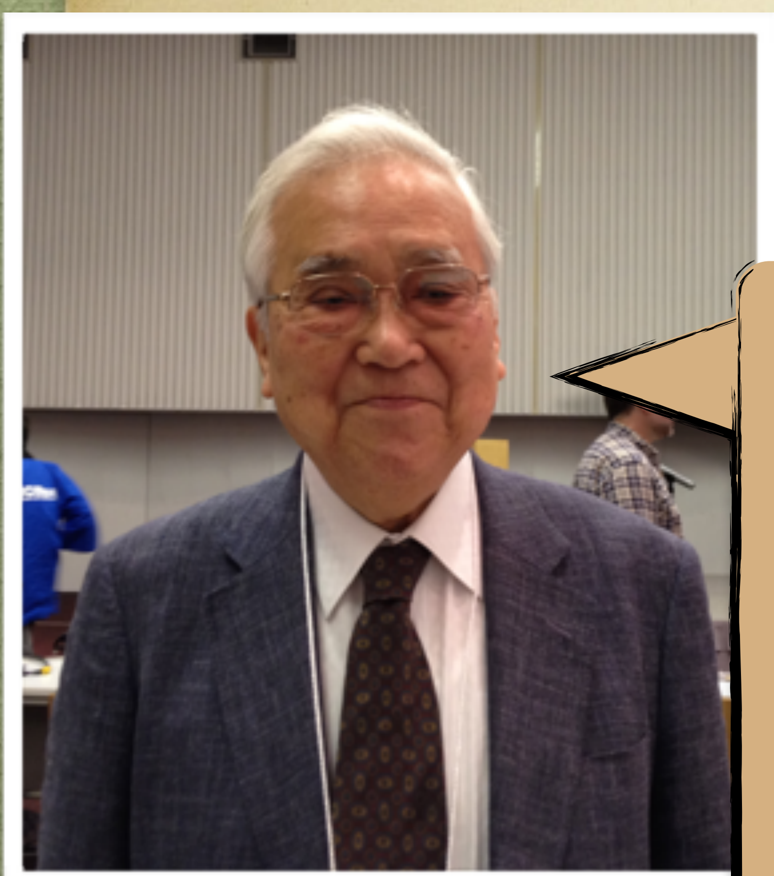


$L_2 \sim \sqrt{1-e_2^2}$

$L_1 \sim \sqrt{1-e_1^2}$

$L_{2,z} \sim \sqrt{1-e_2^2}\cos i_2$

$L_{1,z} \sim \sqrt{1-e_1^2}\cos i_1$



Yoshihde Kozai

for the quadrupole approx. ~ $(a_1/a_2)^2$:

$L_2 = Const.$

$L_{1,z} \cancel{=} Const.$

$L_{2,z} \cancel{=} Const.$

$L_1 \neq Const.$ $\mathcal{H}_{quad}(\omega_1)$

outer “2”

symmetry for rotation of the outer orbit

$\mathcal{H}_{quad}(\omega_1, \underbrace{\Omega_1 - \Omega_2}_{\pi})$

inner “1”

$$\left.\frac{df}{dx}\right|_{x=2} \neq \frac{df(x=2)}{dx}$$

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

The Kozai-Lidov Formalism

The eccentricity and inclination oscillate

Kozai 1962, Lidov 1962

~~**Conservation of the z component of angular momentum for both the inner outer orbits**~~

The orbital elements:

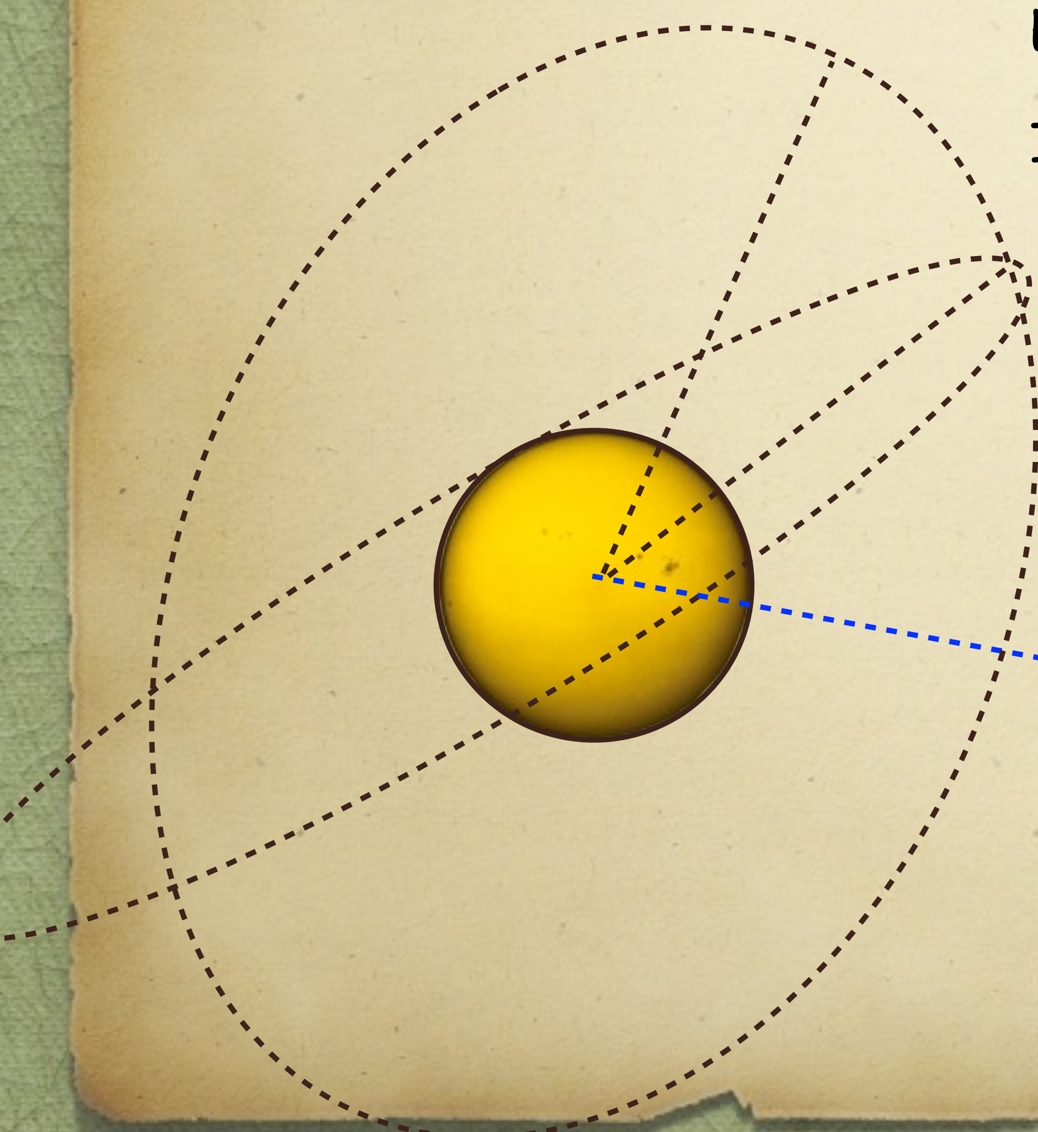
Eccentricity: e

Inclination: i

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

Prograde orbit cannot become retrograde

L_{z1} conserved only to lowest order (quadrupole) and for a test particle (massless planet)!



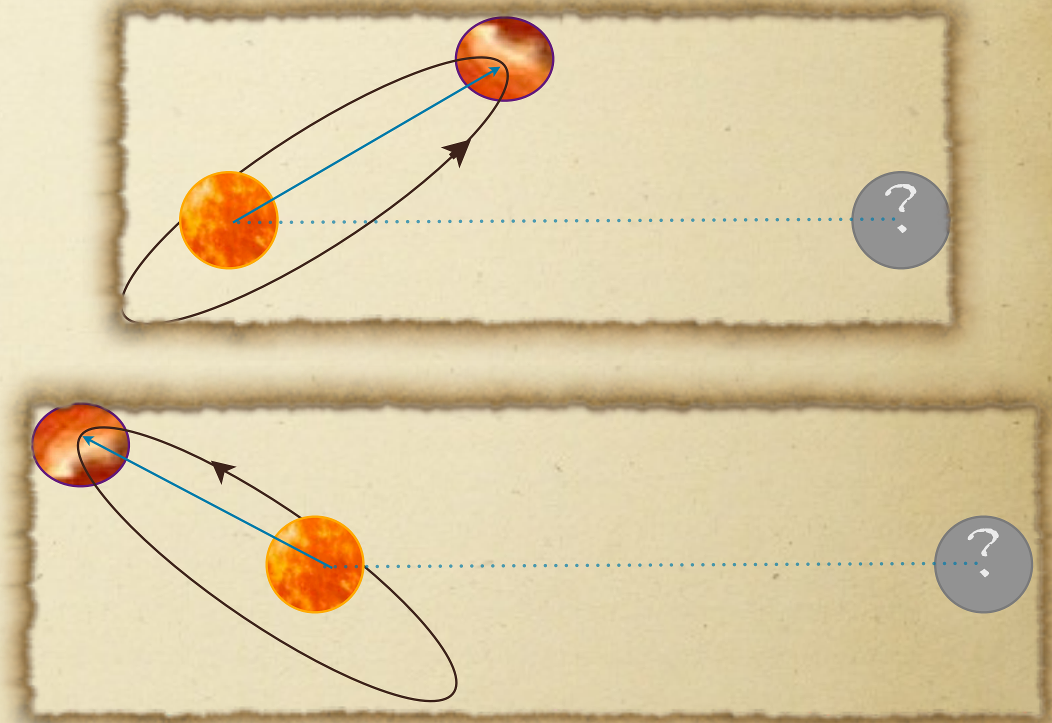
Naoz et al, Nature (2011), arXiv:1011.2501
Naoz et al (2013),MNRAS, arXiv:1107.2414

Our treatment

The eccentric Kozai-Lidov mechanism EKL

- 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** - **<u>already done before us</u>!!!**)
- Both the magnitude and orientation of the angular momentum can change

i<90 deg - prograde



i>90 deg - retrograde

larger parts of the parameter space

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

Naoz et al (2013), MNRAS, arXiv:1107.2414
Naoz (2016) review

for test particle approx. see:
Lithwick & **Naoz** (2011), ApJ, arXiv: 1106.3329
Katz at al (2011), arXiv:1106.3340

Lets…flip the planet

point mass limit

Lets…flip the planet

Example system: a_1=6AU, a_2=100AU, m_1=1.M_{sun} M_2=1M_j, M_3=40M_j i=65 deg secular dynamics + GR

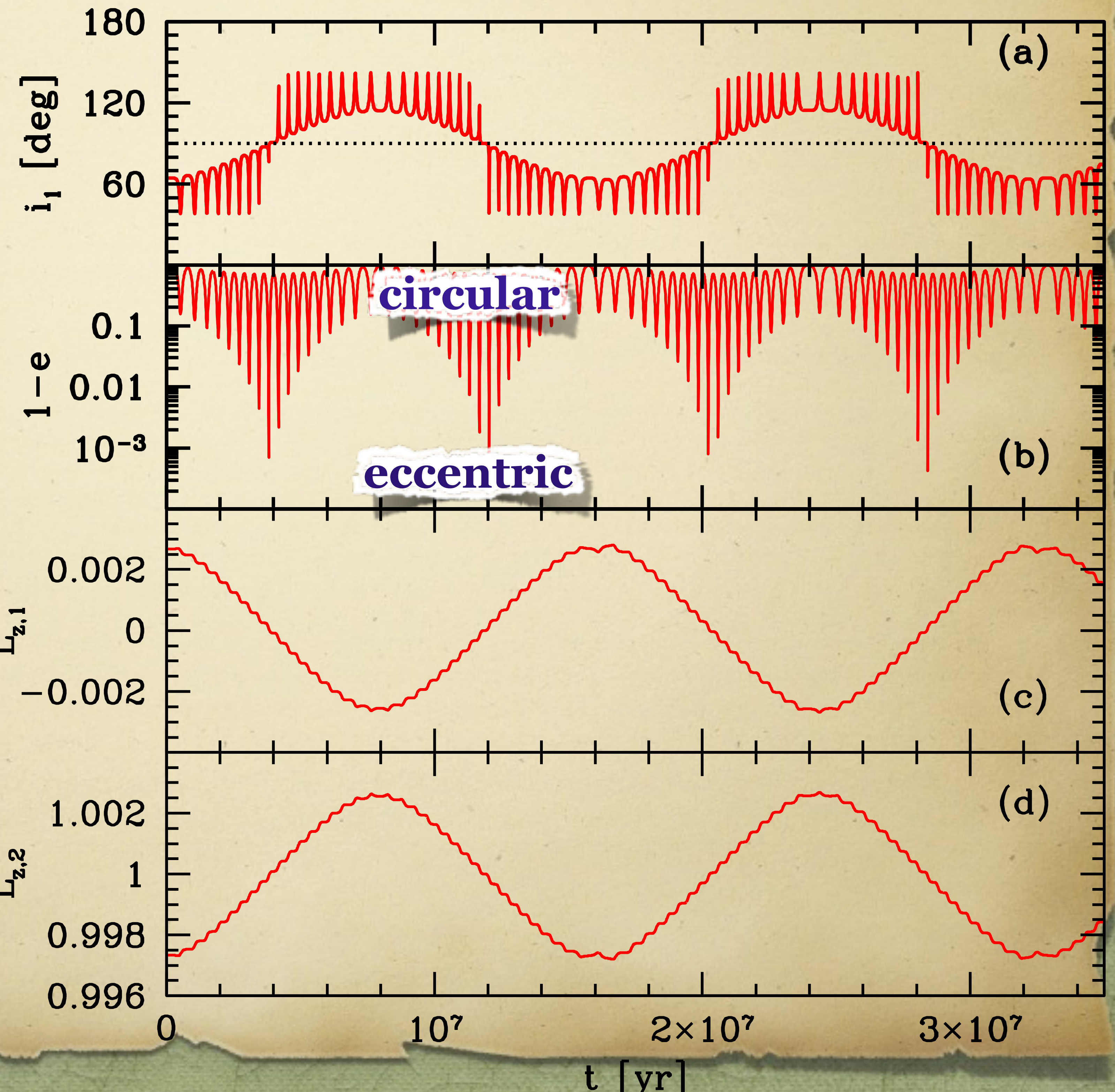
GR effects: e.g., Ford et al 2000, Naoz, Kocsis, Loeb, Yunes 2013

(a) inner orbit inclination

(b) inner orbit eccentricity

(c) inner orbit z-com. angular momentum

(d) inner orbit z-com. angular momentum



Naoz et al, Nature (2011), arXiv:1011.2501 point mass limit

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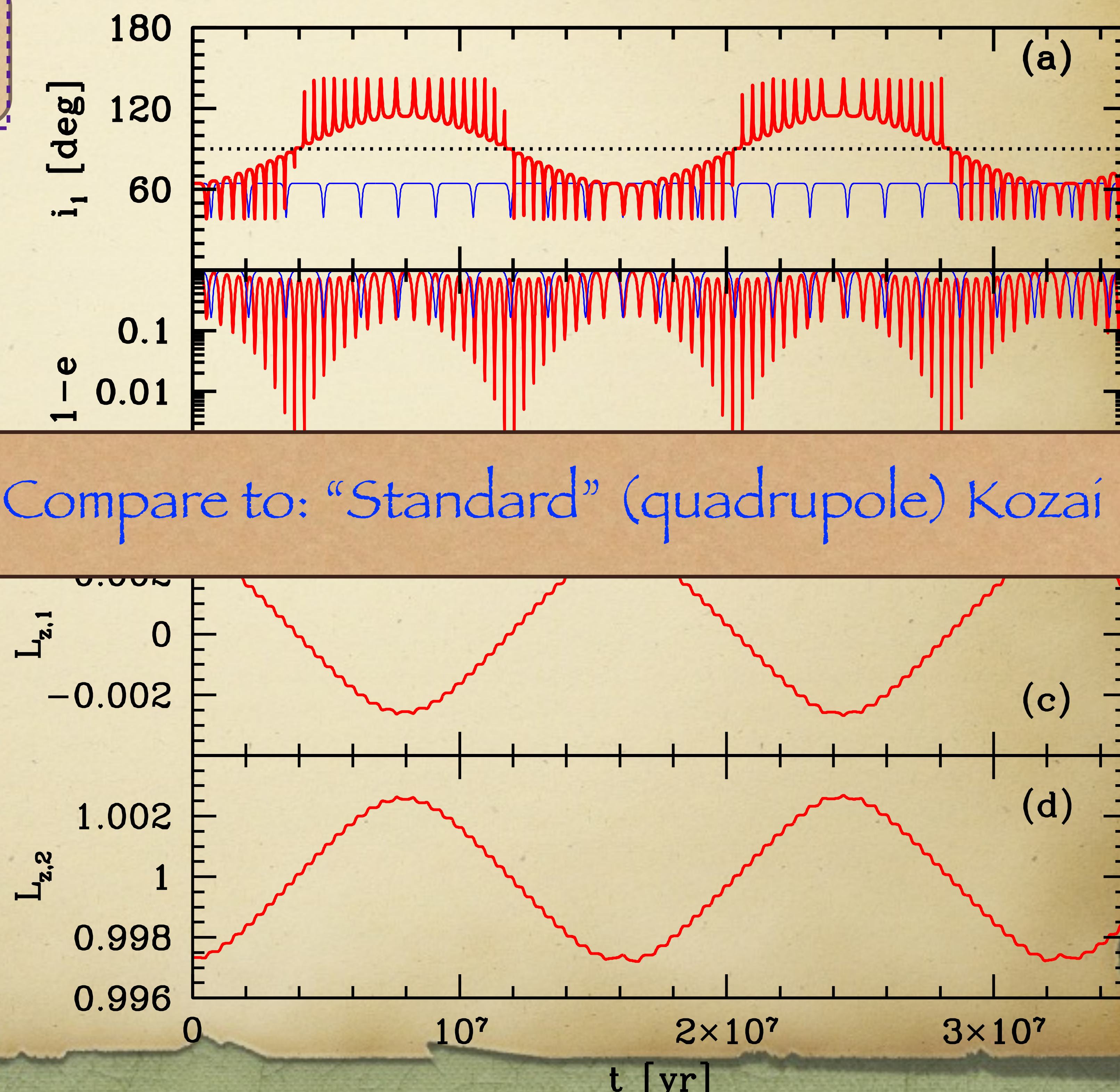


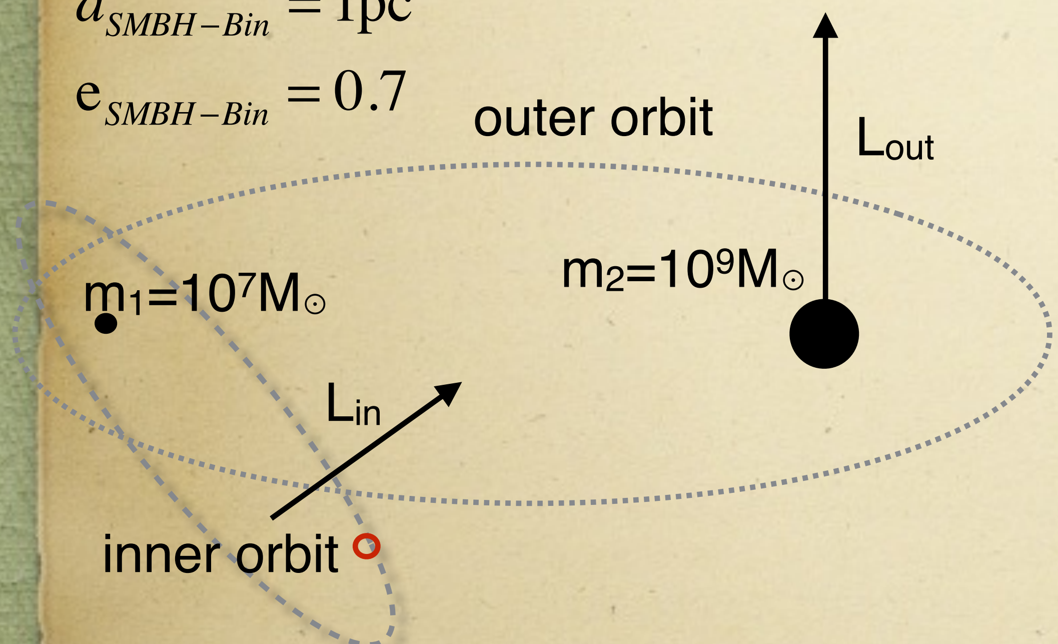
Compare to: “Standard” (quadrupole) Kozai

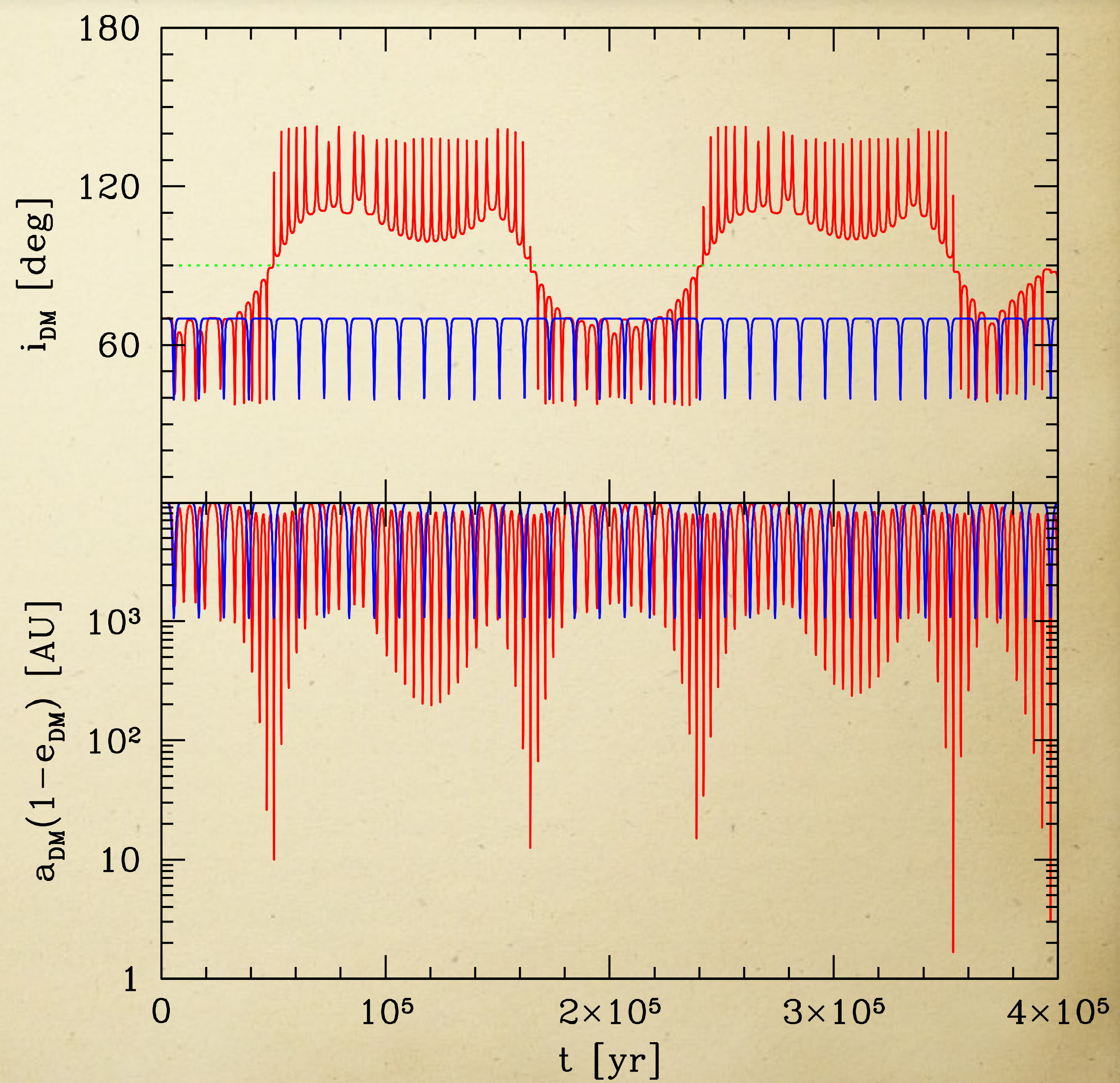
DM in SMBH binary

$a_{DM} = 0.06\text{pc} \approx 1237.6$ AU

$a_{SMBH-Bin} = 1\text{pc}$

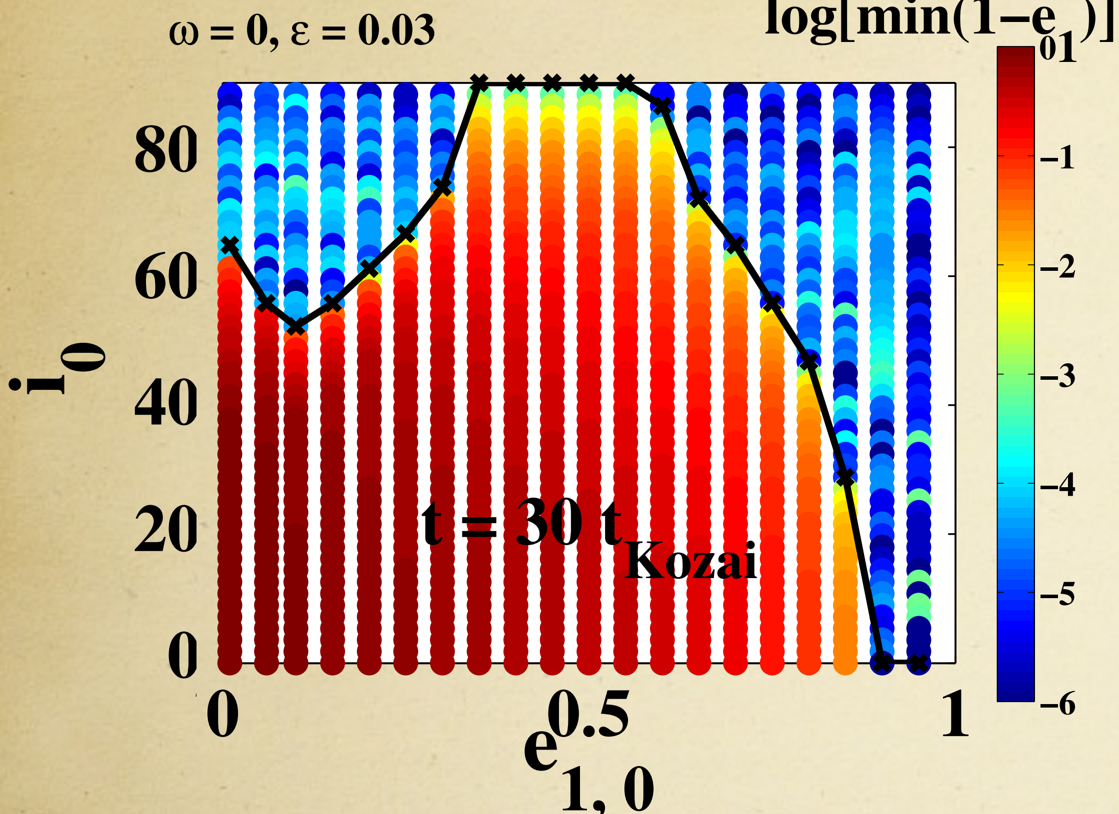
$e_{SMBH-Bin} = 0.7$





Naoz (2016), review

Eccentricity spikes



Maximum eccentricity at the test particle regime

Li, **Naoz** et al, (2014), ApJ 785, 116 + ApJ 791, 86

Gongjie Li

And even higher….

Maximum eccentricity outside the test particle regime

Teyssandier, **Naoz**, Lizarraga Rasio (2013), ApJ 779, 166

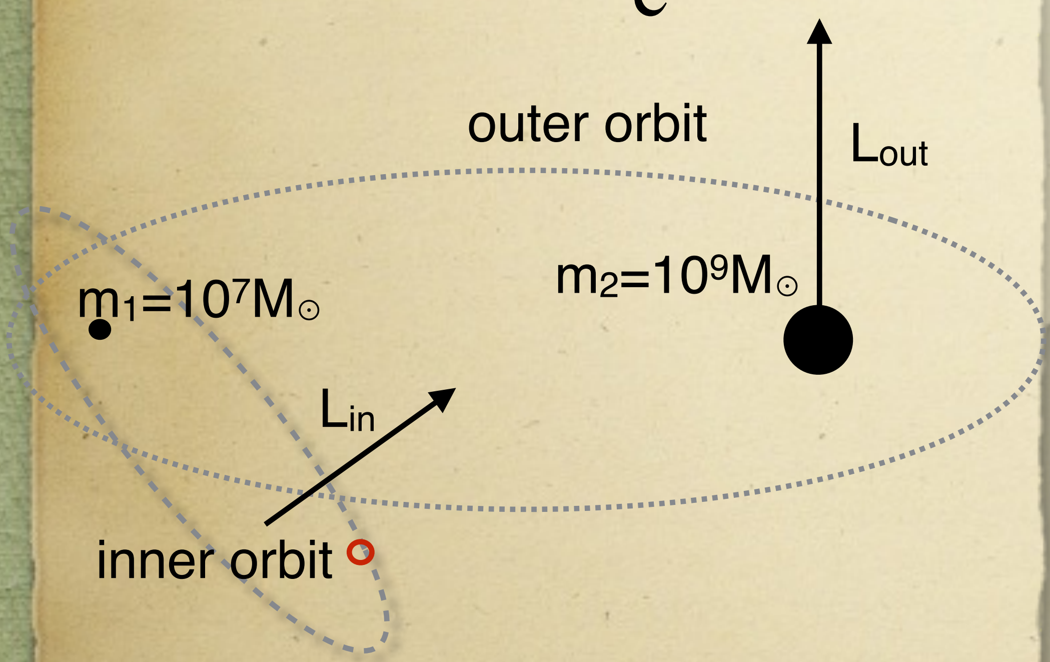
Ian Lizarraga

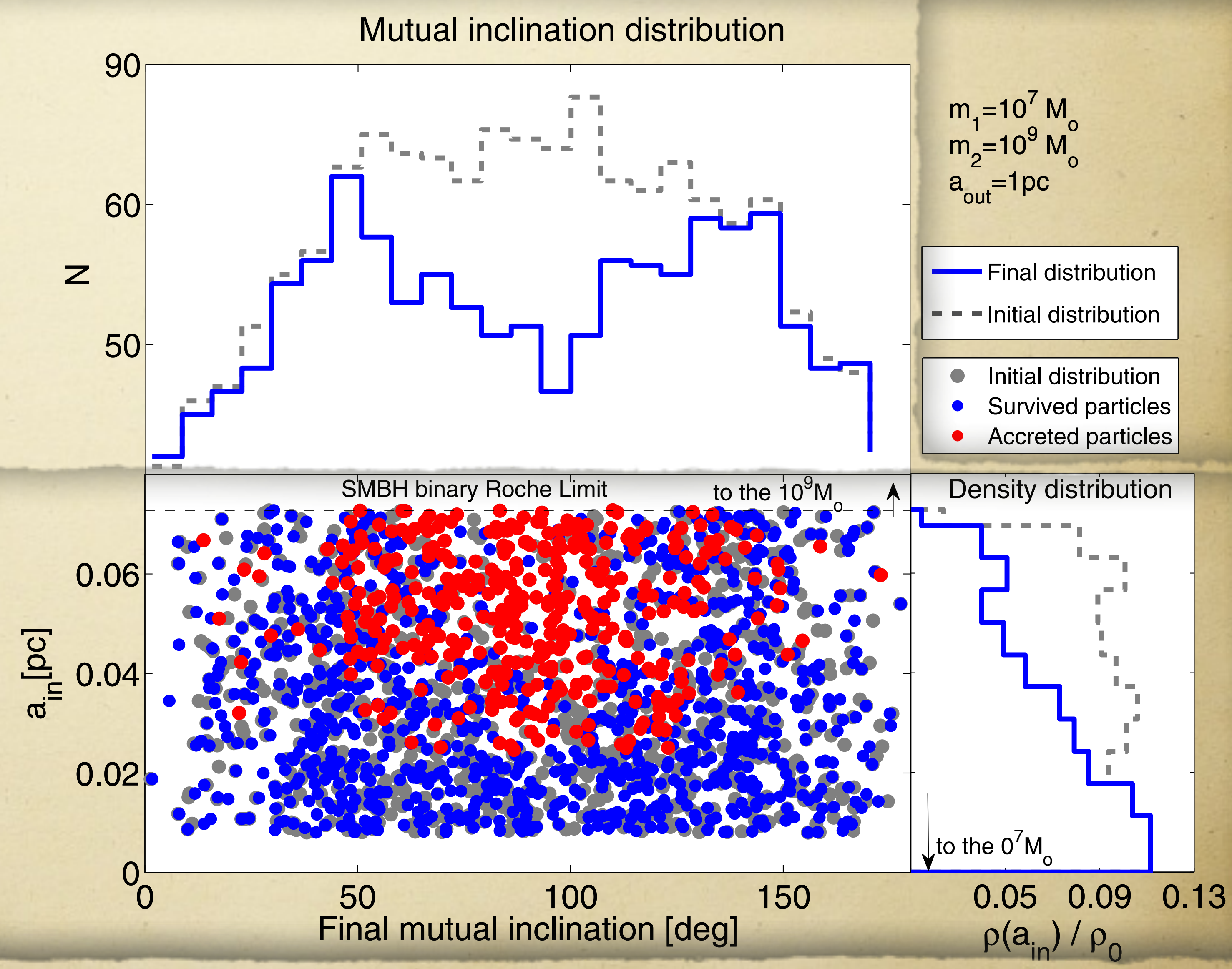
Jean Teyssandier

DM in SMBH binary

High eccentricity spike can drive the DM particle all the way to the BH

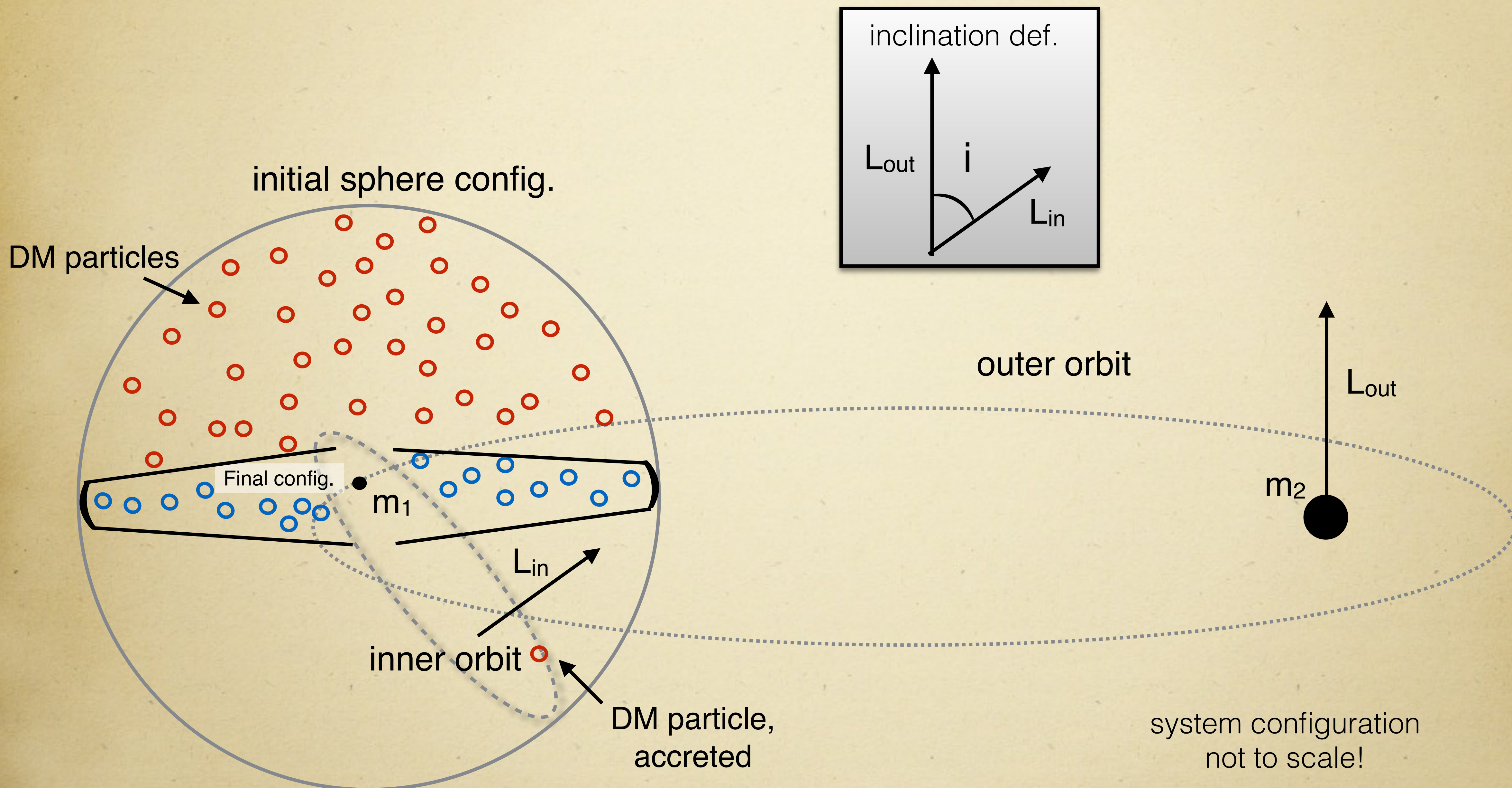
$$\text{Crossing} \sim \frac{G m_{BH}}{c^2}$$



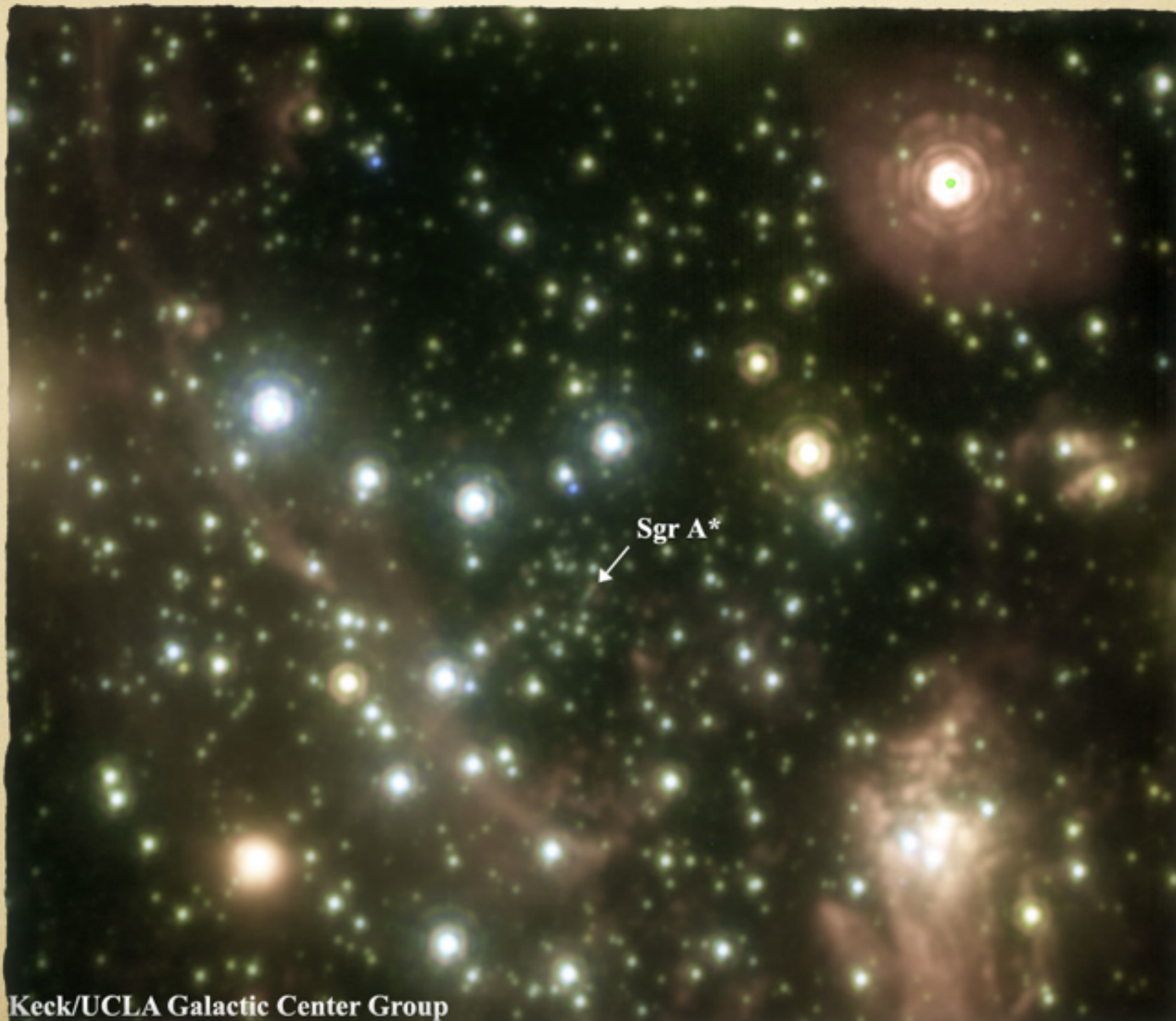


Naoz & Silk (2014) ApJ

SMBH Binaries and DM



IMBH at the Galactic Center

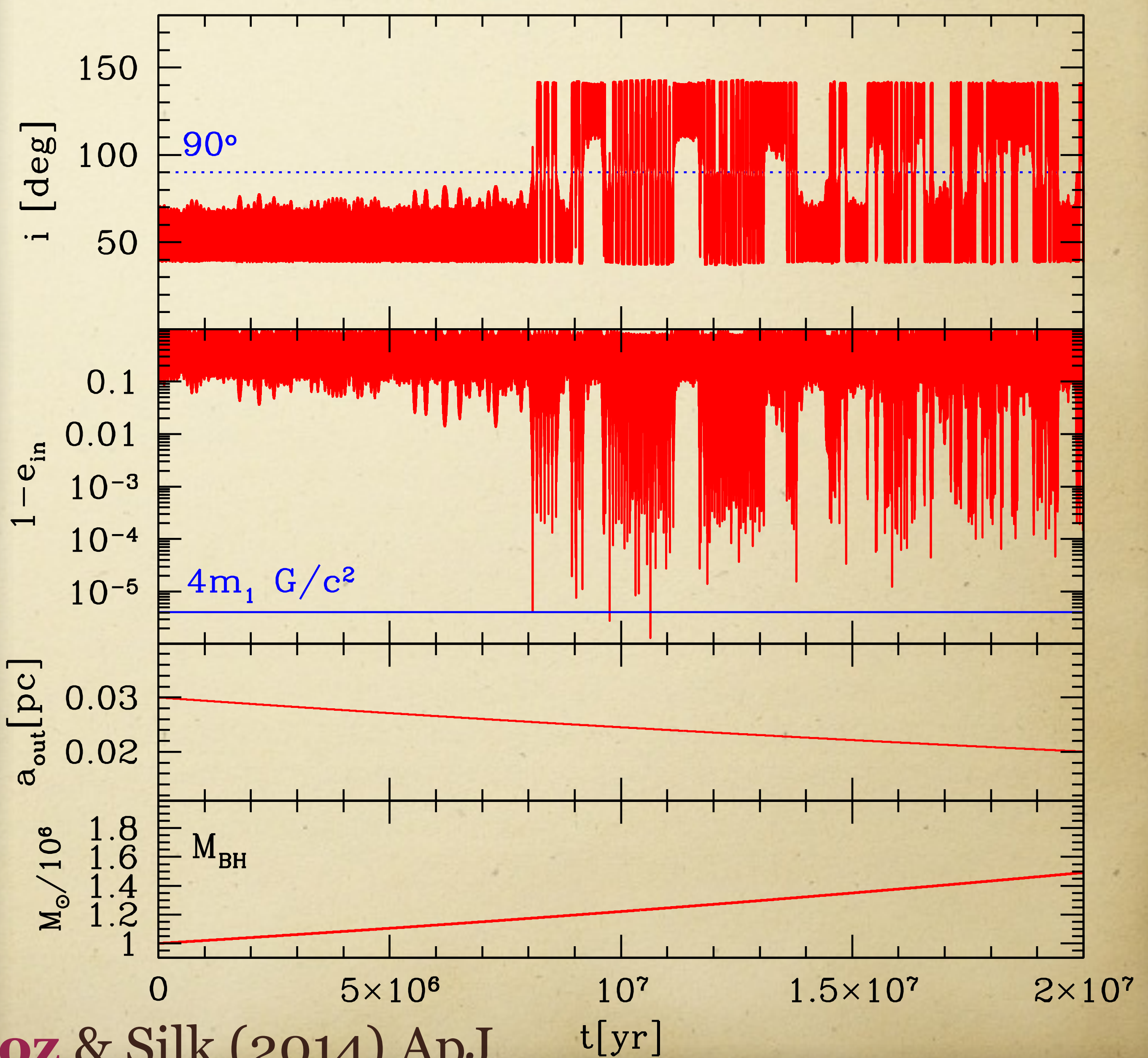


What happens if the BH eats?

High eccentricity spike can drive the DM particle all the way to the BH

$$\text{Crossing} \sim \frac{Gm_{BH}}{c^2}$$

Growing massive black hole (Gondolo & Silk 1999)



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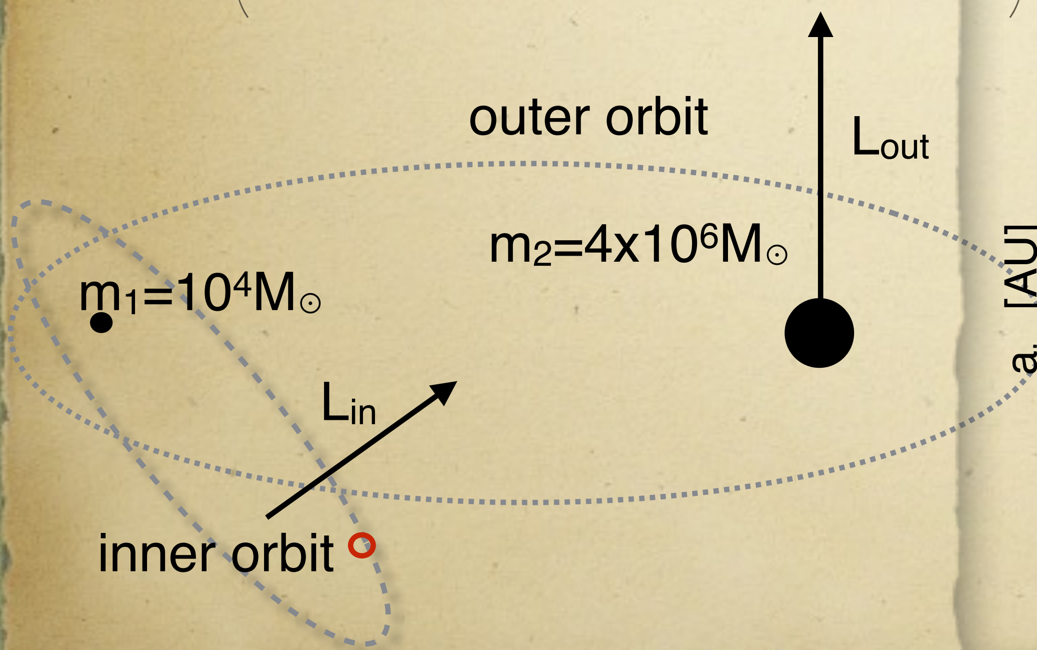
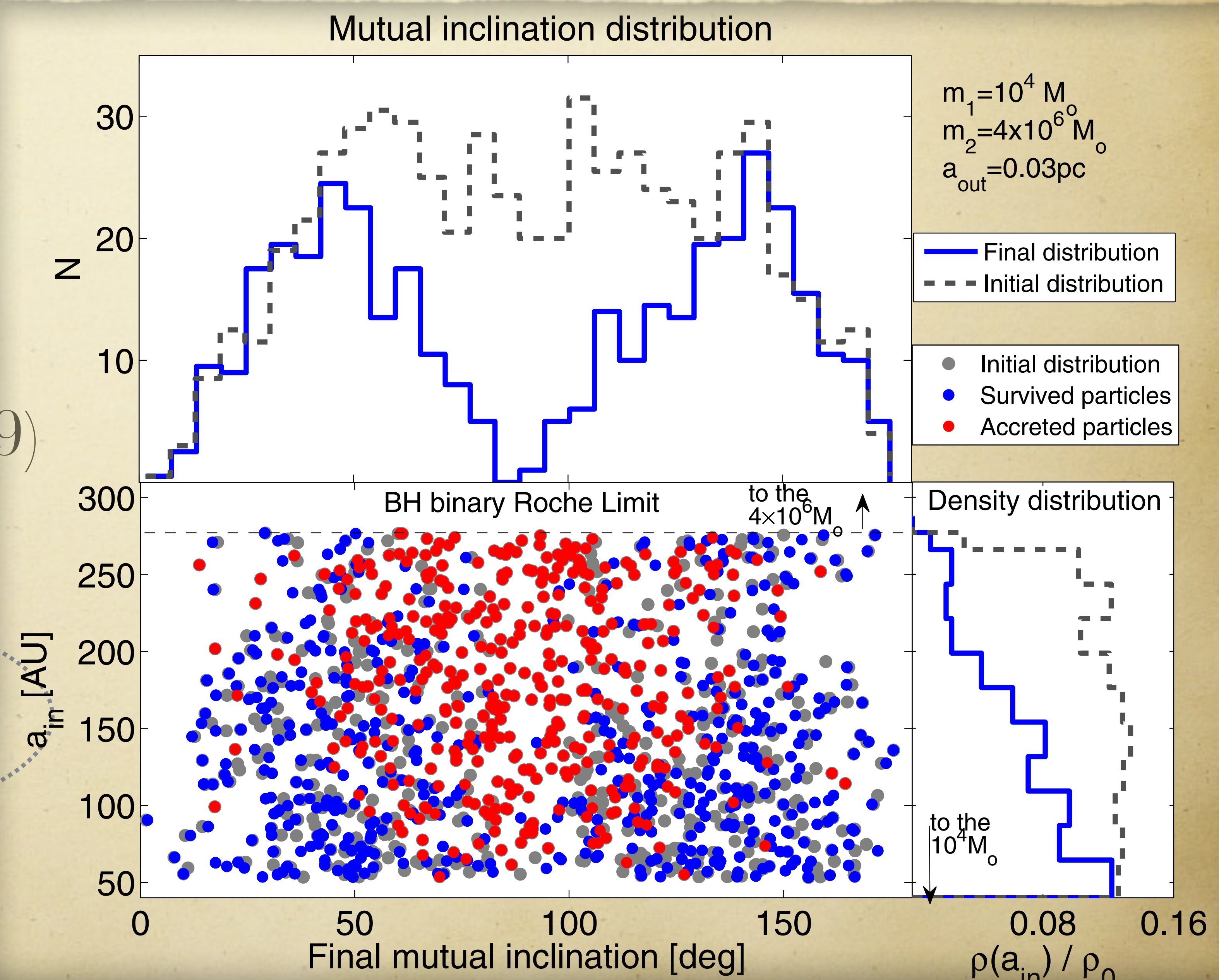
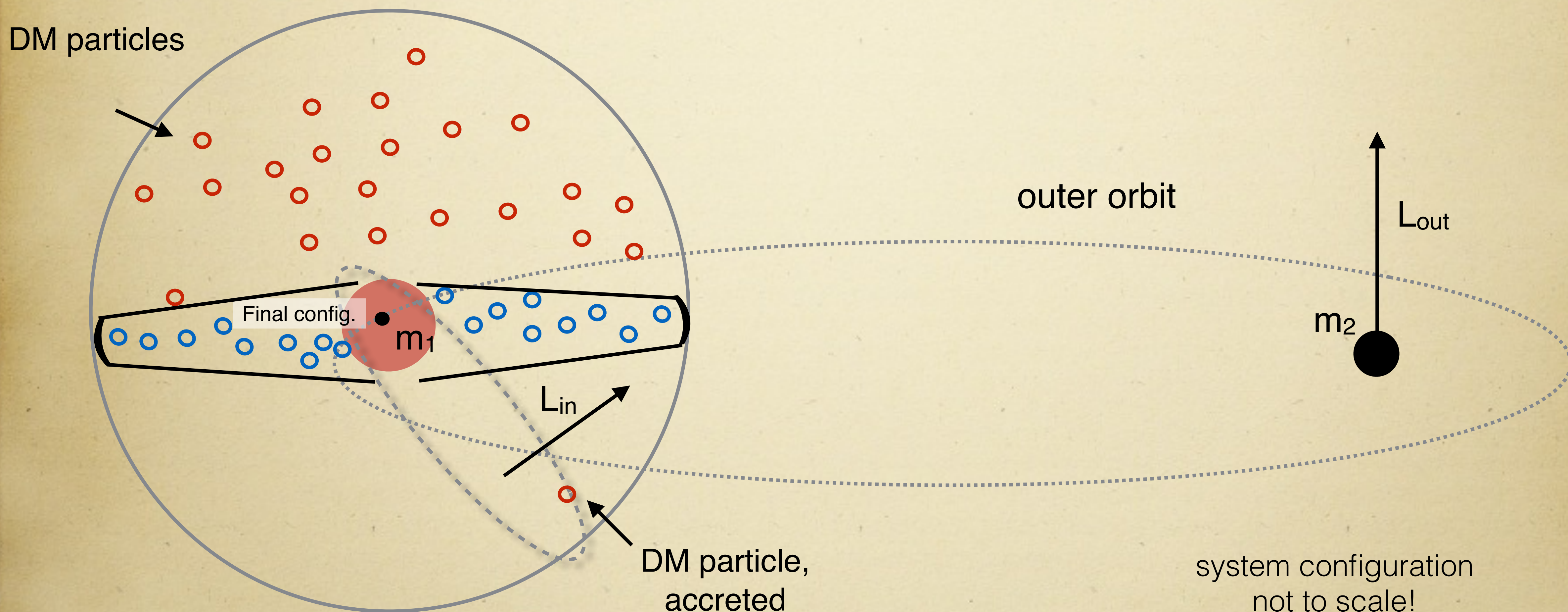




Naoz & Silk (2014) ApJ

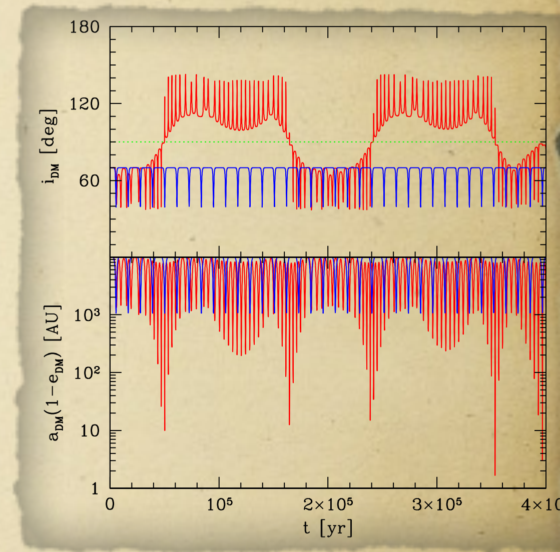
Speculation:

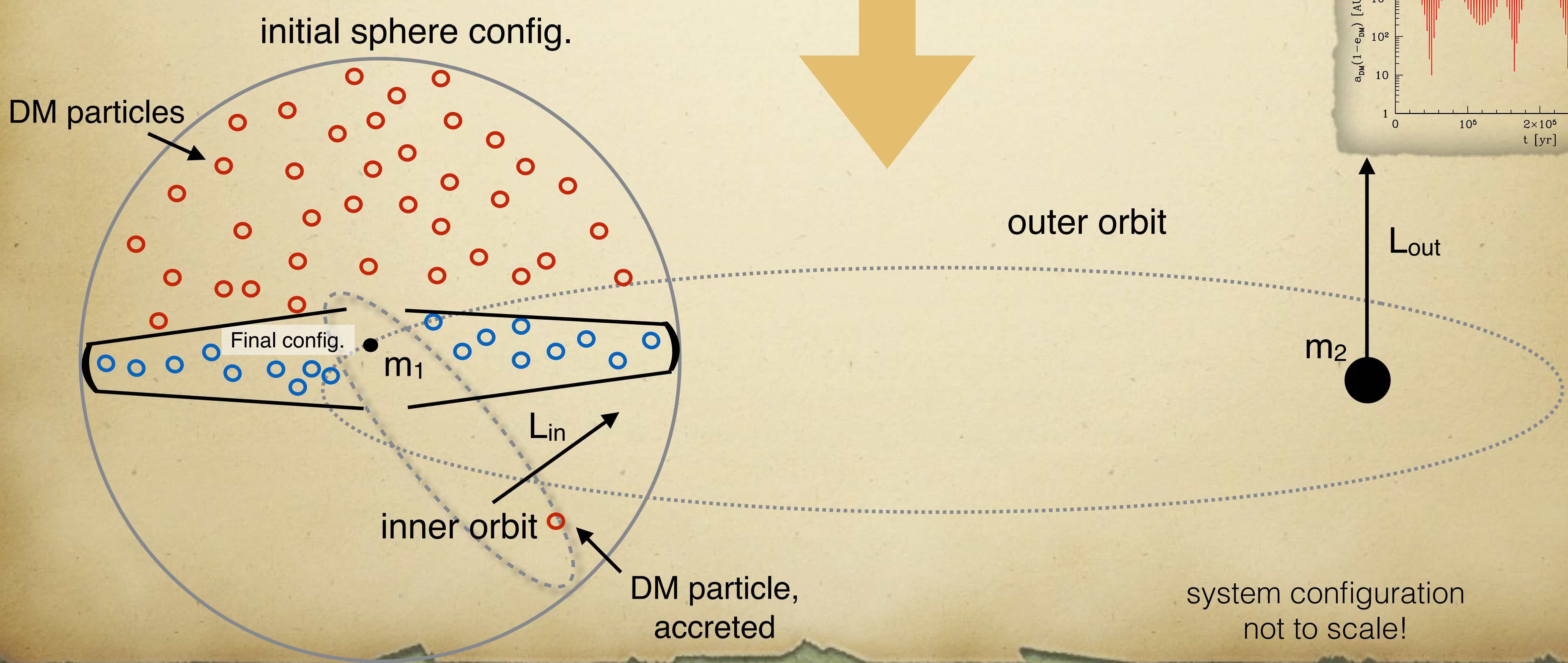
In the case of rotating BH, may linger in the ergosphere, e.g.,Banados et al. 2011; Zaslavskii 2012



DM Bagel (or Donuts)

New developments in triple dynamics
Richer behavior, over larger part of the parameter space





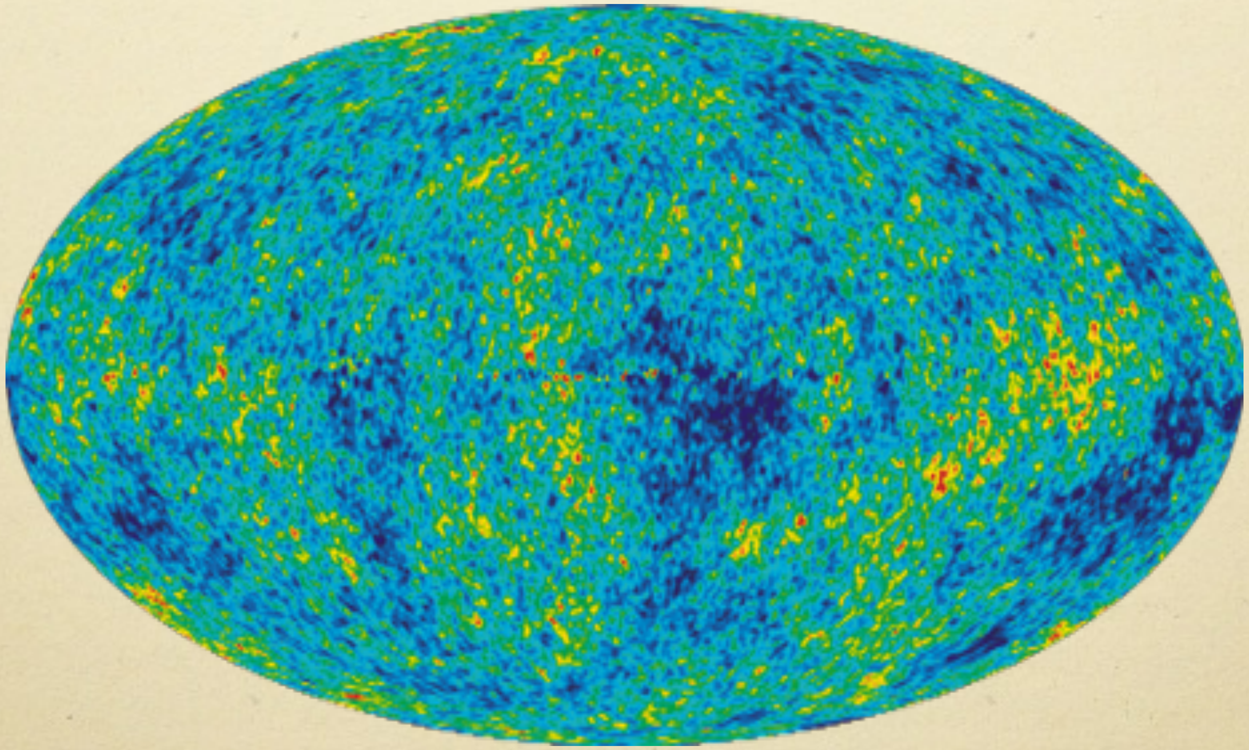
Question: why would an IMBH keep its DM?

Answer: (yet another cool effect from DM)

Have the first galaxies involve

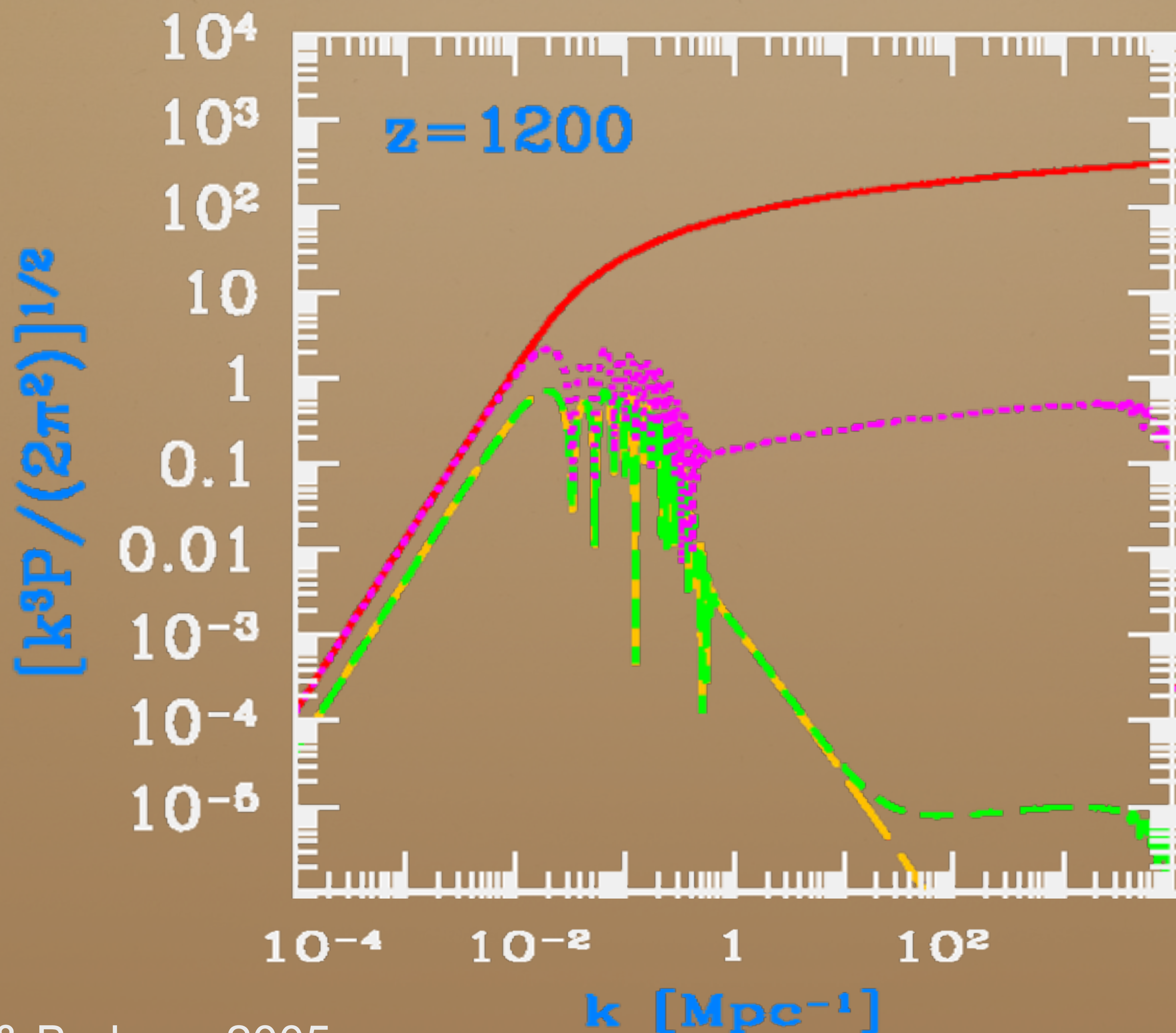
First Galaxies - Gas rich or gas poor?

DM baryon interactions



Suppressing the baryons

$|\delta| =$



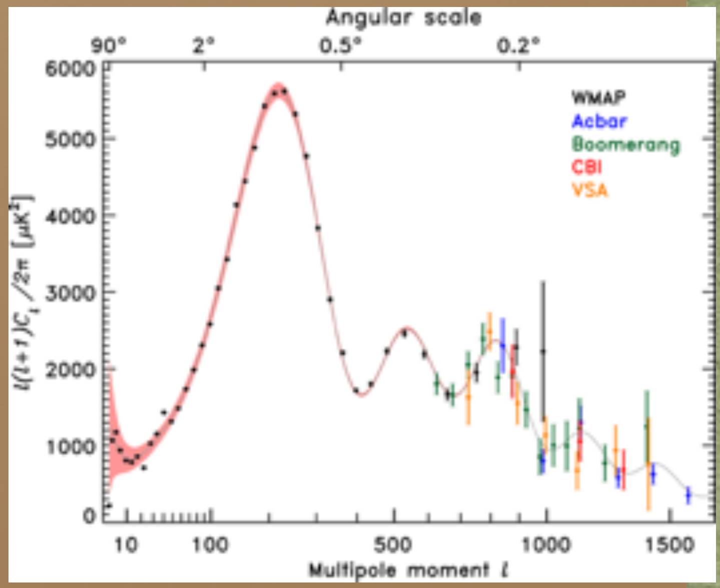
δ

Dark Matter

Gas

Gas temp

Radiation temp



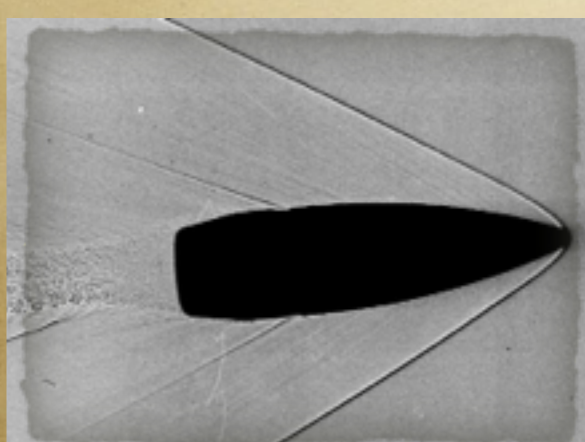
Naoz & Barkana 2005

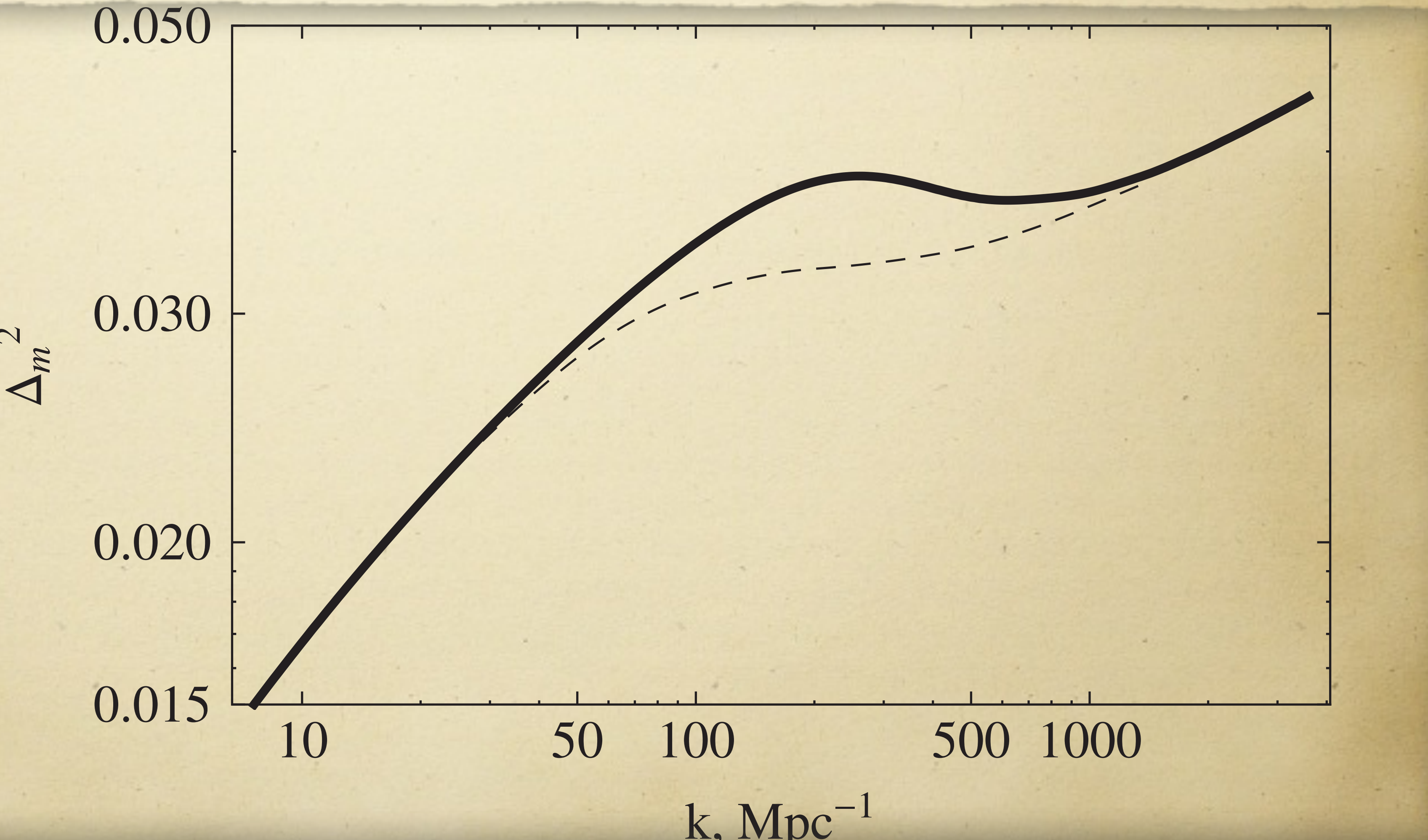
The stream velocity (v_{bc})

- $|v_b - v_{dm}| \approx 30$ km/sec at Recombination time =Mach 5
- scales as 1/a

$$[k^3/(2\pi^2)]P_m(k)$$

e.g.,effects on structure formation
Greif et al 2011,
Stacy et al 2011,
Naoz et al 2012,2013,
Visbal et al 2012….

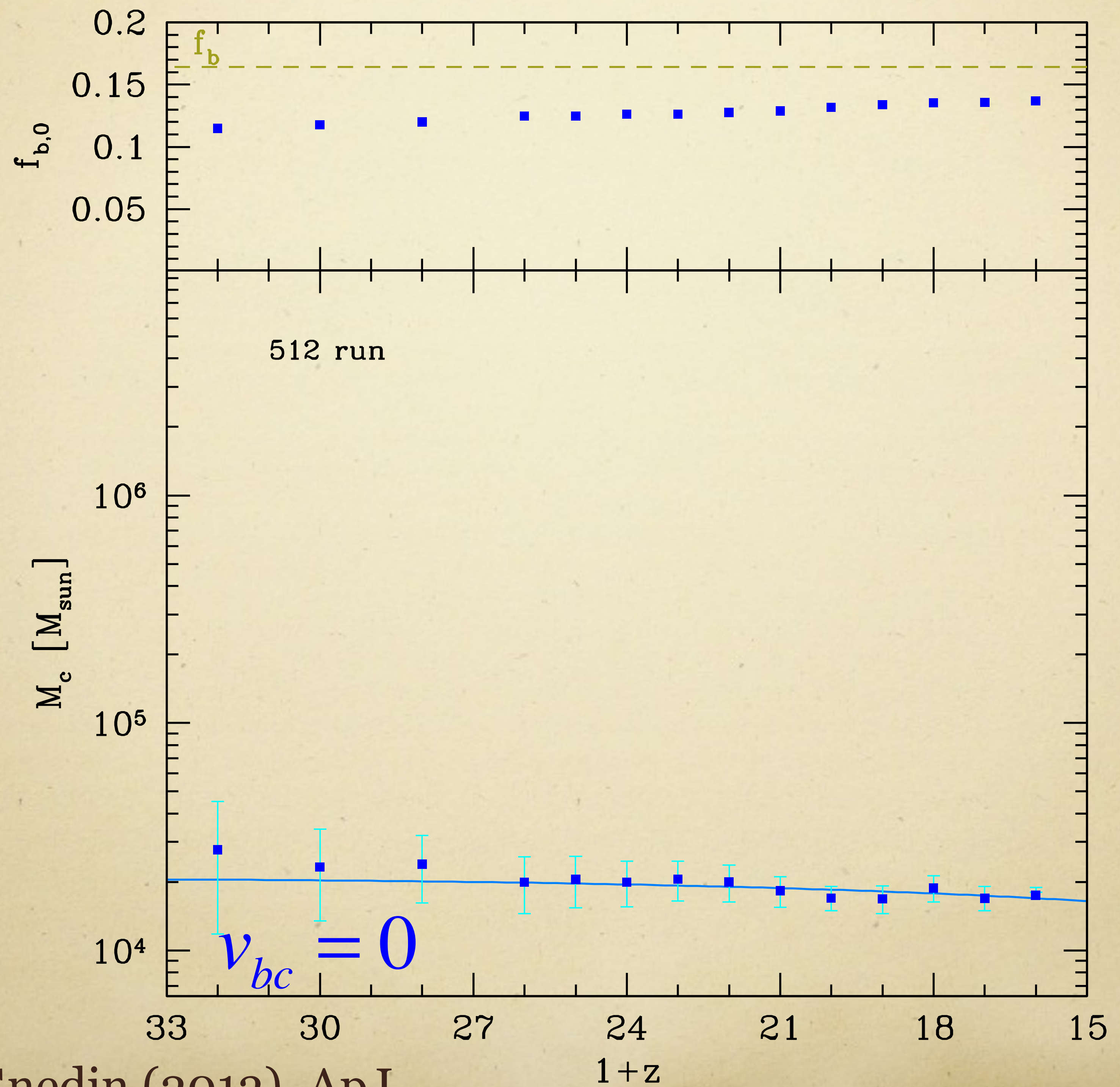




Tseliakhovich & Hirata 2010

Gas depletion

Minimum gas rich halo



Naoz Yoshida & Gnedin (2013), ApJ

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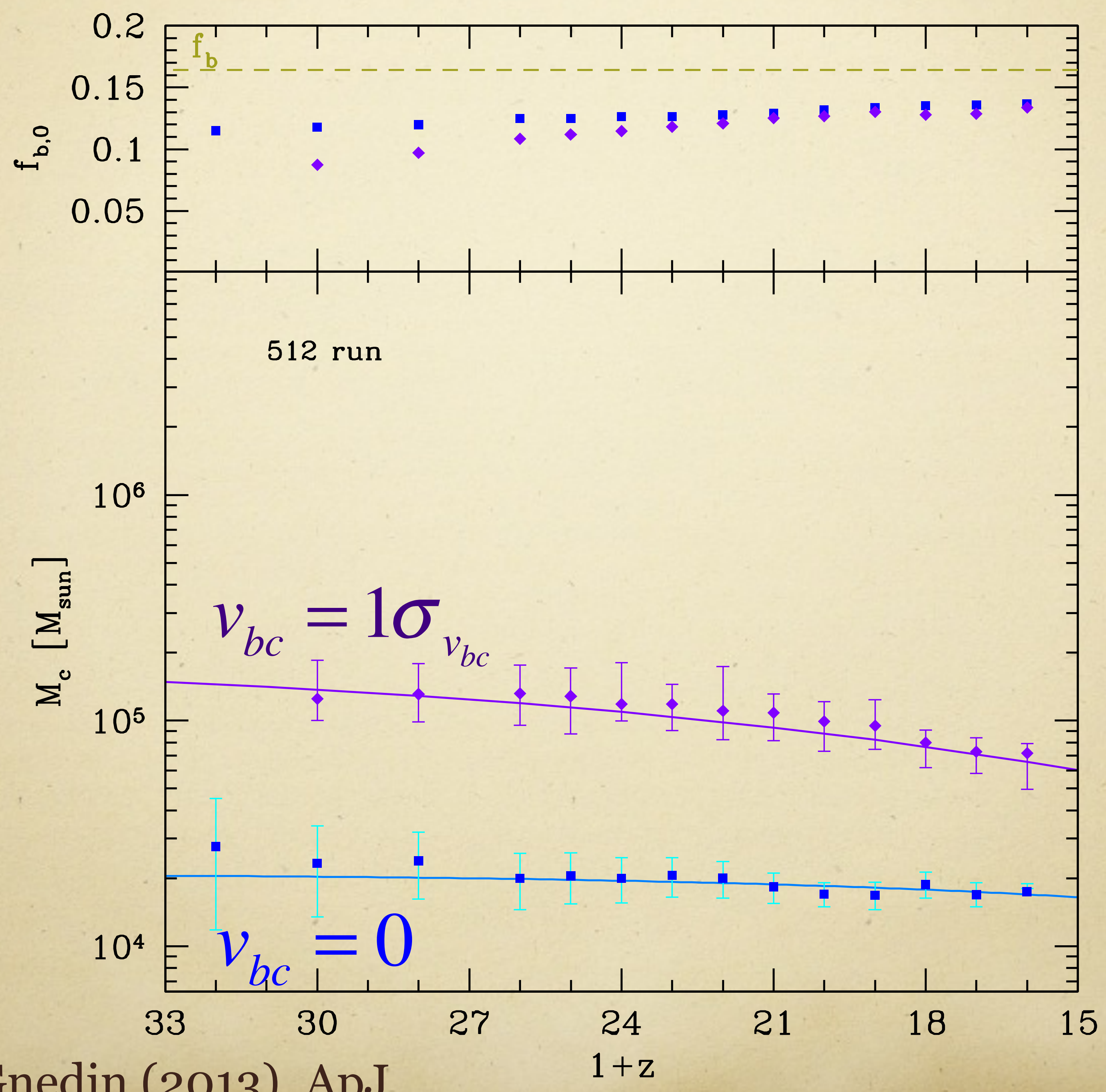

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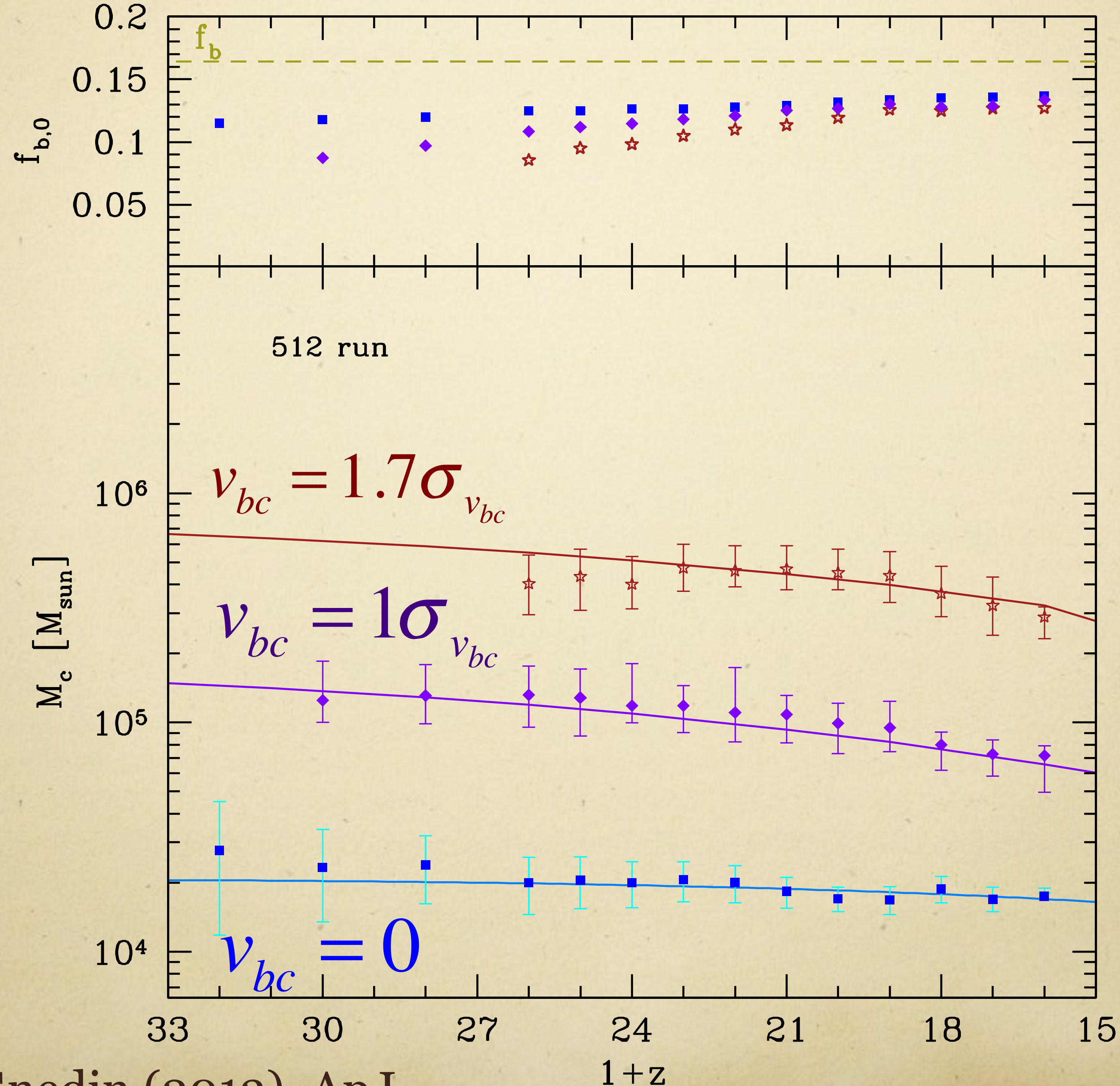

Naoz Yoshida & Gnedin (2013), ApJ

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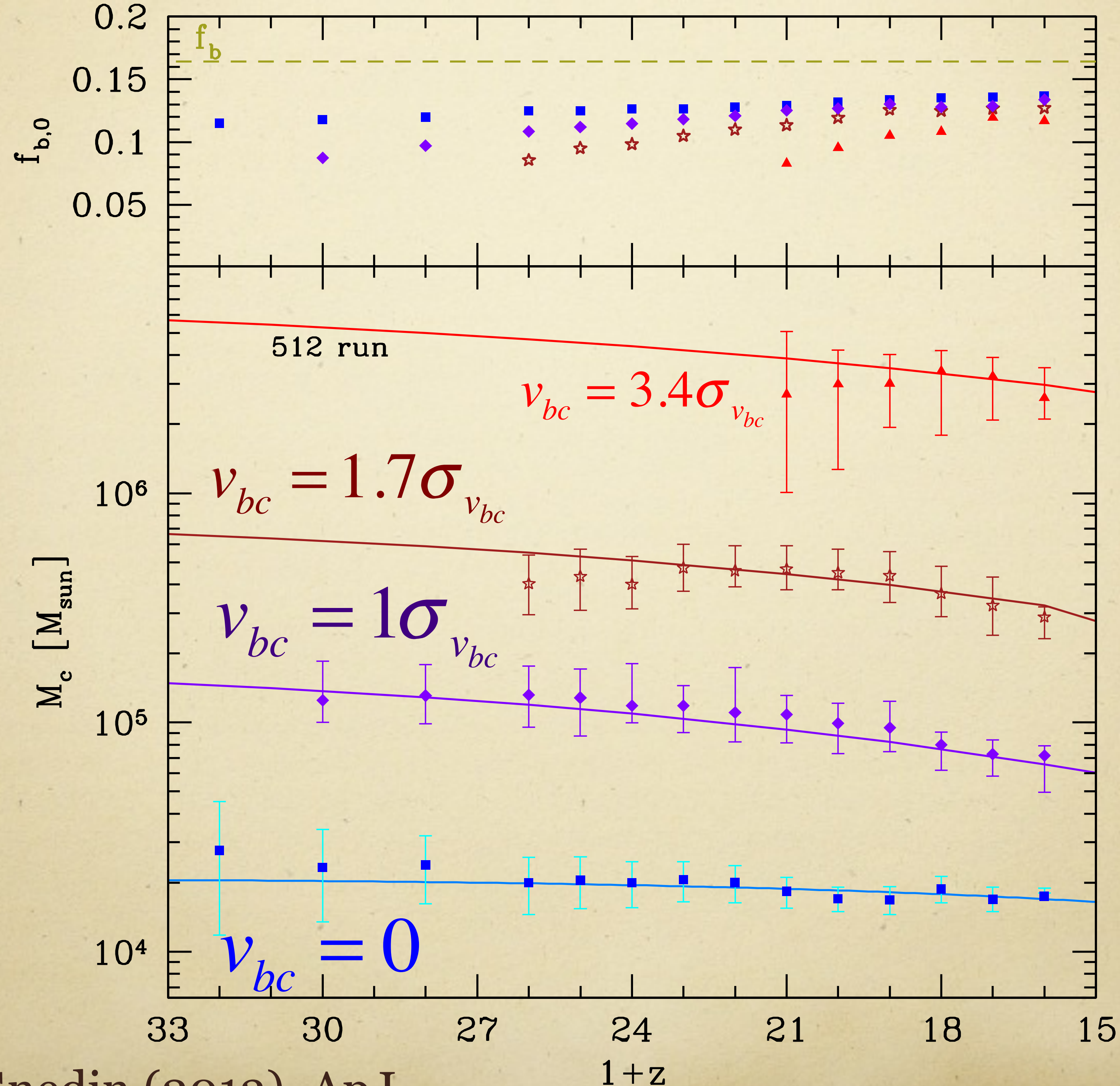
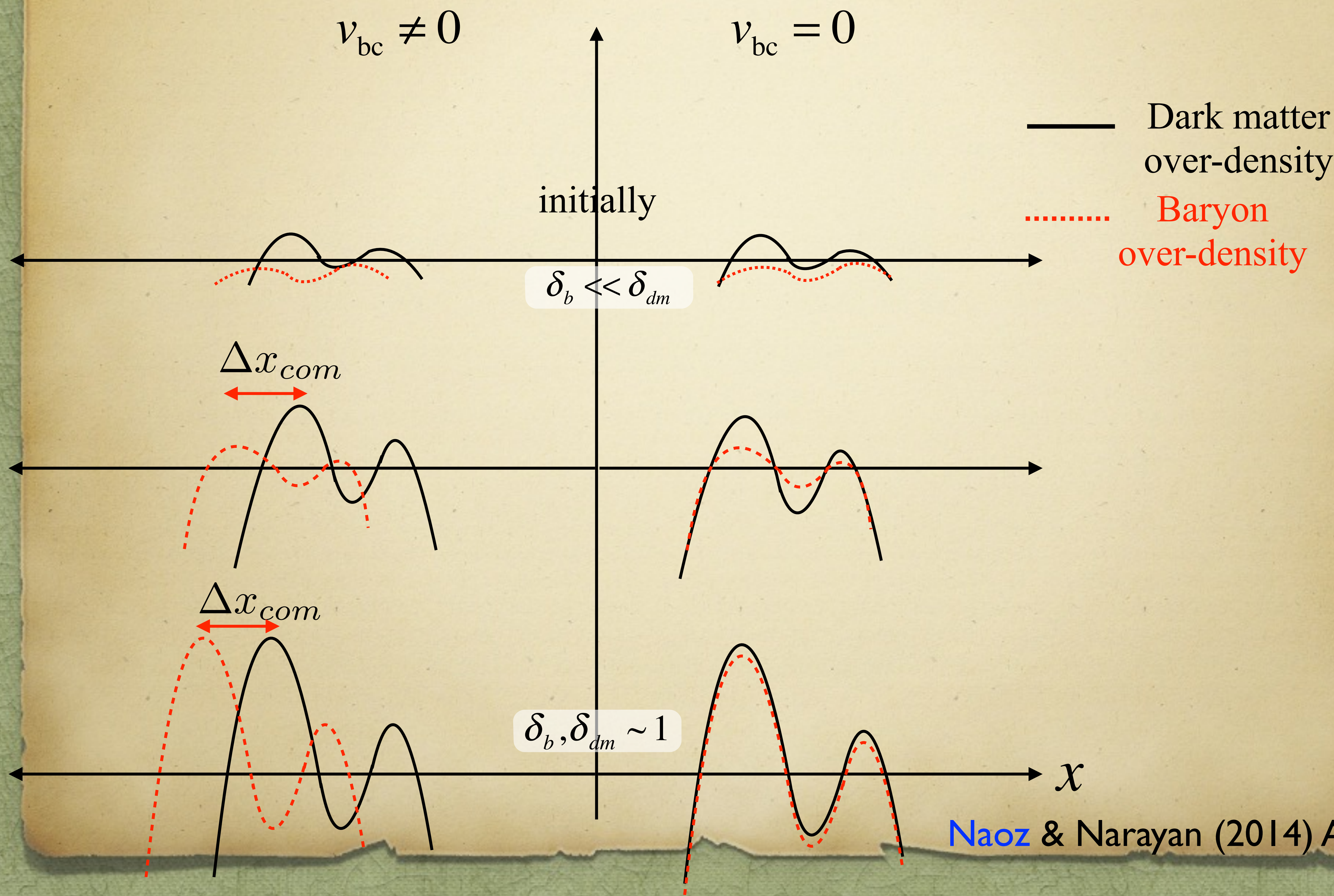


Naoz Yoshida & Gnedin (2013), ApJ

And what about the gas?

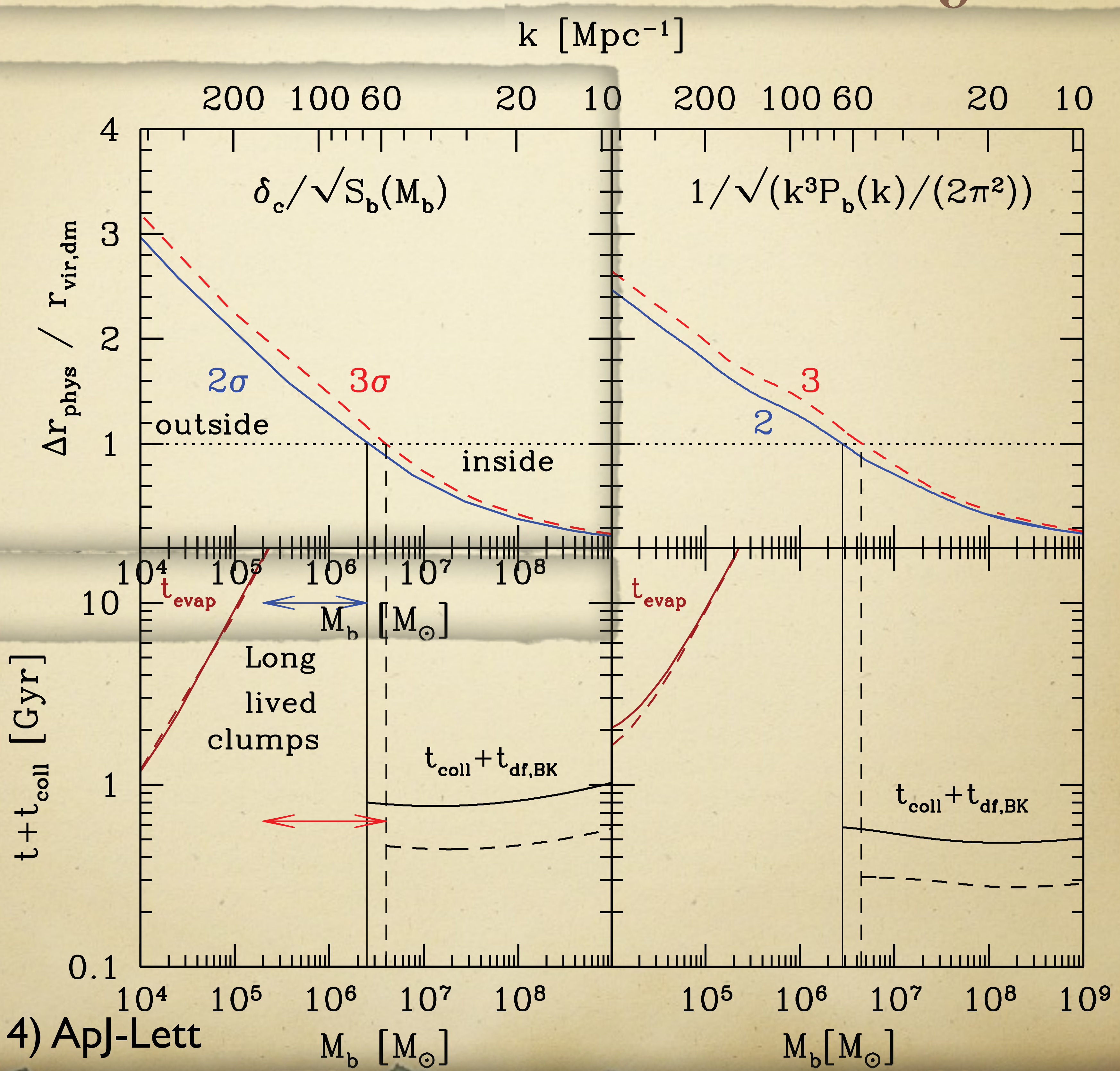
Growth of Perturbations

Different stages of collapse (represent different times)



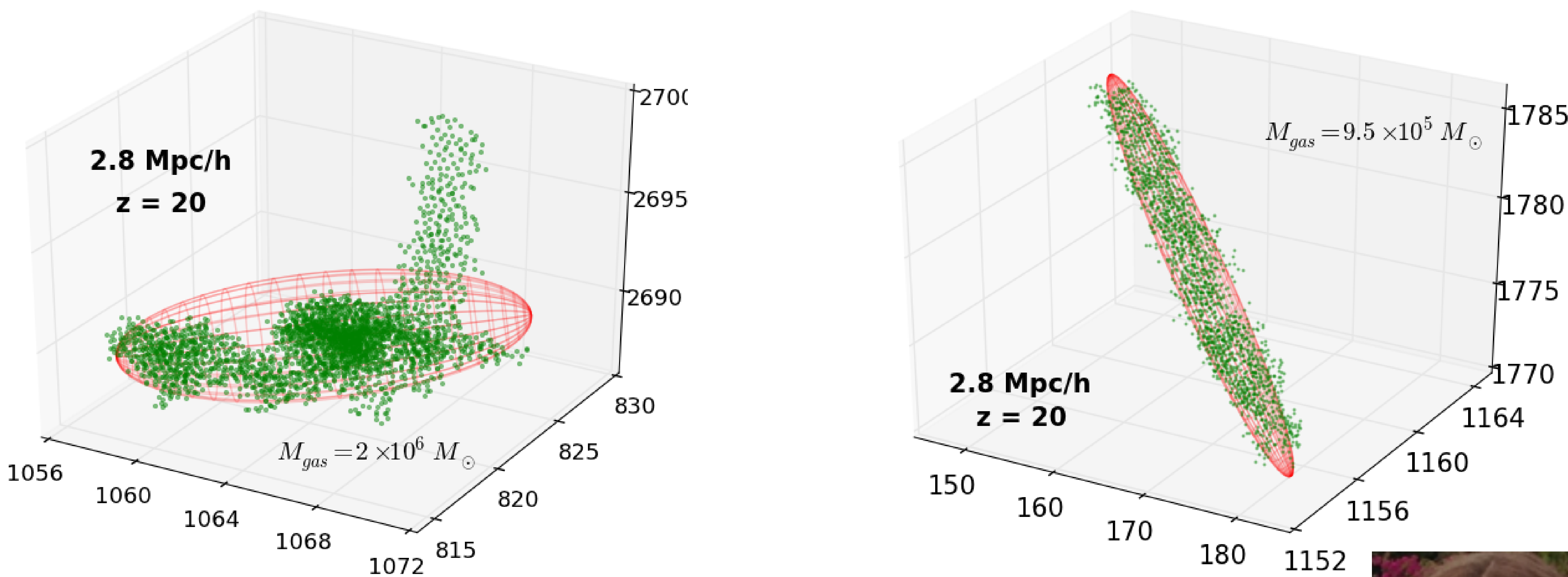
Naoz & Narayan (2014) ApJ-Lett

Gas rich-dominated objects



Naoz & Narayan (2014) ApJ-Lett

Gas rich-dominated objects

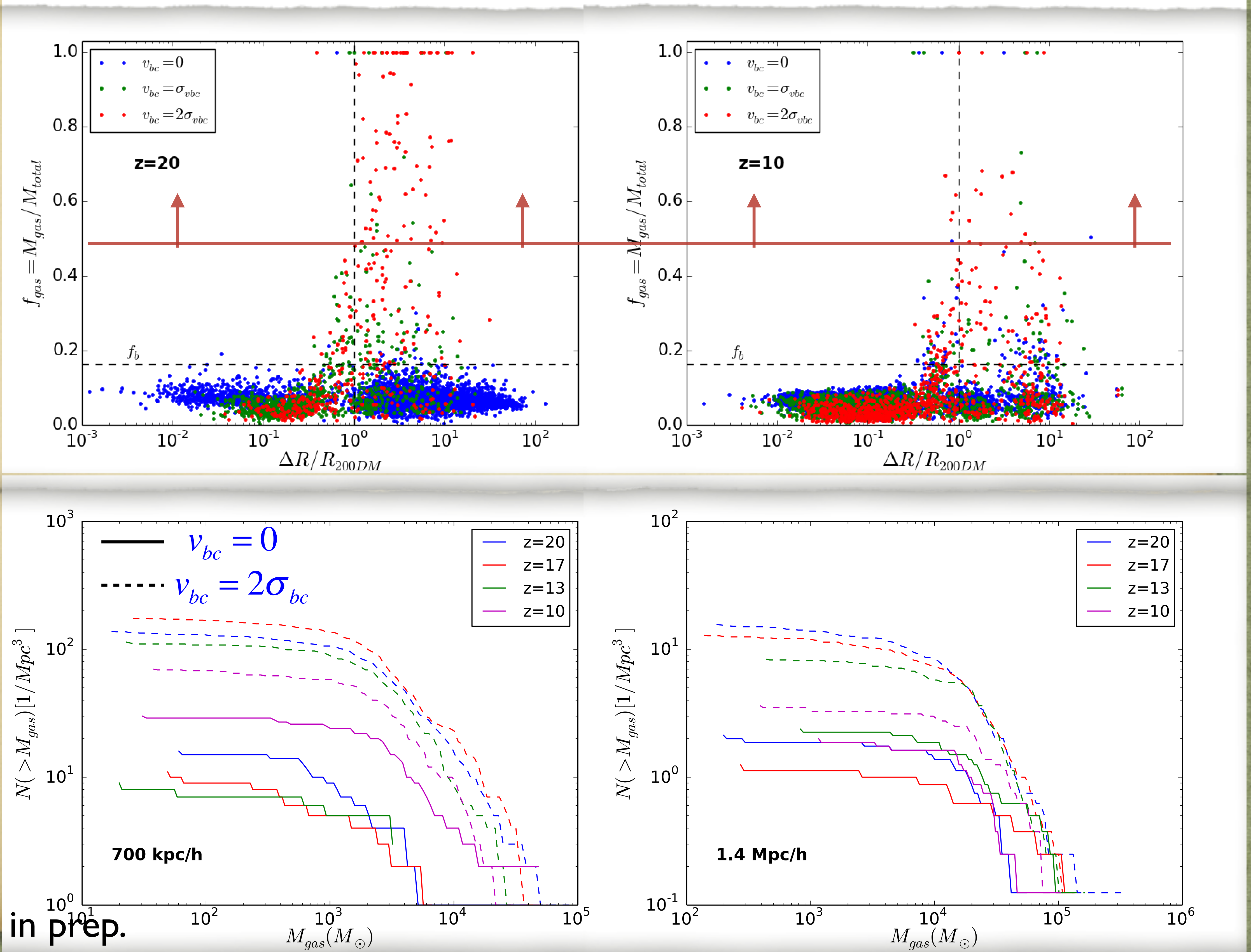



Cristina Popa

Popa, Naoz et al in prep.
Naoz & Narayan (2014) ApJ-Lett

Gas rich-dominated objects

Cristina Popa



Popa, Naoz et al in prep.

Gas rich and gas poor

The gas that didn't accrete onto the DM halos gone nonlinear

Exciting dynamics