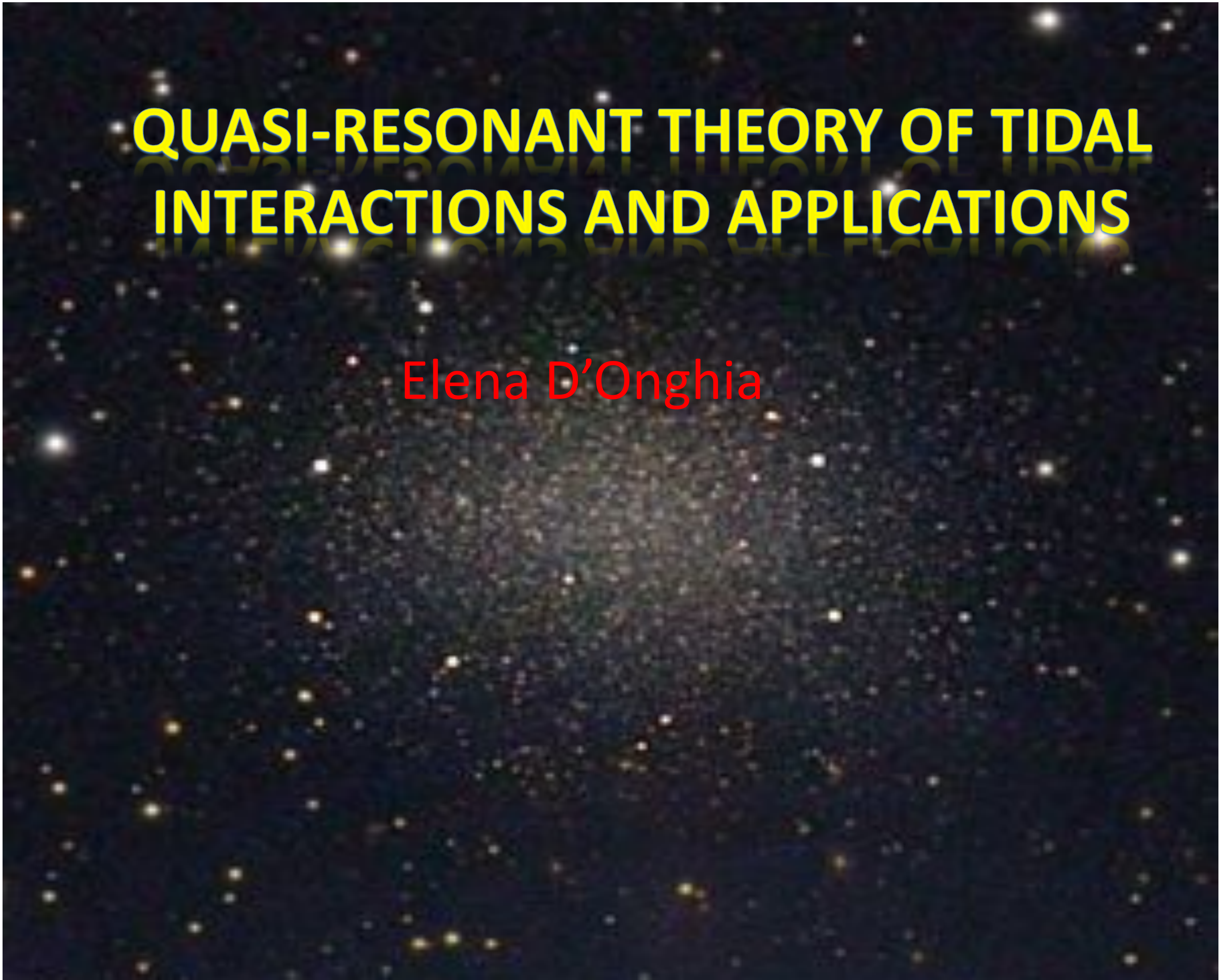
QUASI-RESONANT THEORY OF TIDAL INTERACTIONS AND APPLICATIONS

Elena D'Onghia



✧ Dwarf spheroidals (dSphs) challenge our understanding of galaxy formation and evolution because:

- dSphs are gas poor and have few stars (Mateo 1998)
- found in galaxy clusters and groups (Fergusson & Binggeli 1994)
- the most dark matter dominated galaxies (M/L~ 30-100)
- the ultra-faint dwarf galaxies have L~ 1000 Lsun

(Willman et al. 2005, Zucker et al. 2006;Belokurov et al.2009; Walker et al.2008)

We need a mechanism to separate gas & stars from DM to explain high M/L ratio

✧ Previous Theories:

✓ Gas photoheated during reionization or blown out by feedback, but:

- few signatures of reionization in dSphs (Gallagher et al. 2003)

✓ Tidal shocking can convert a disk of stars into a spheroid but requires:

- ram pressure to remove the gas (Mayer et al. 2007)
- that dwarfs orbit close to Milky Way or Andromeda

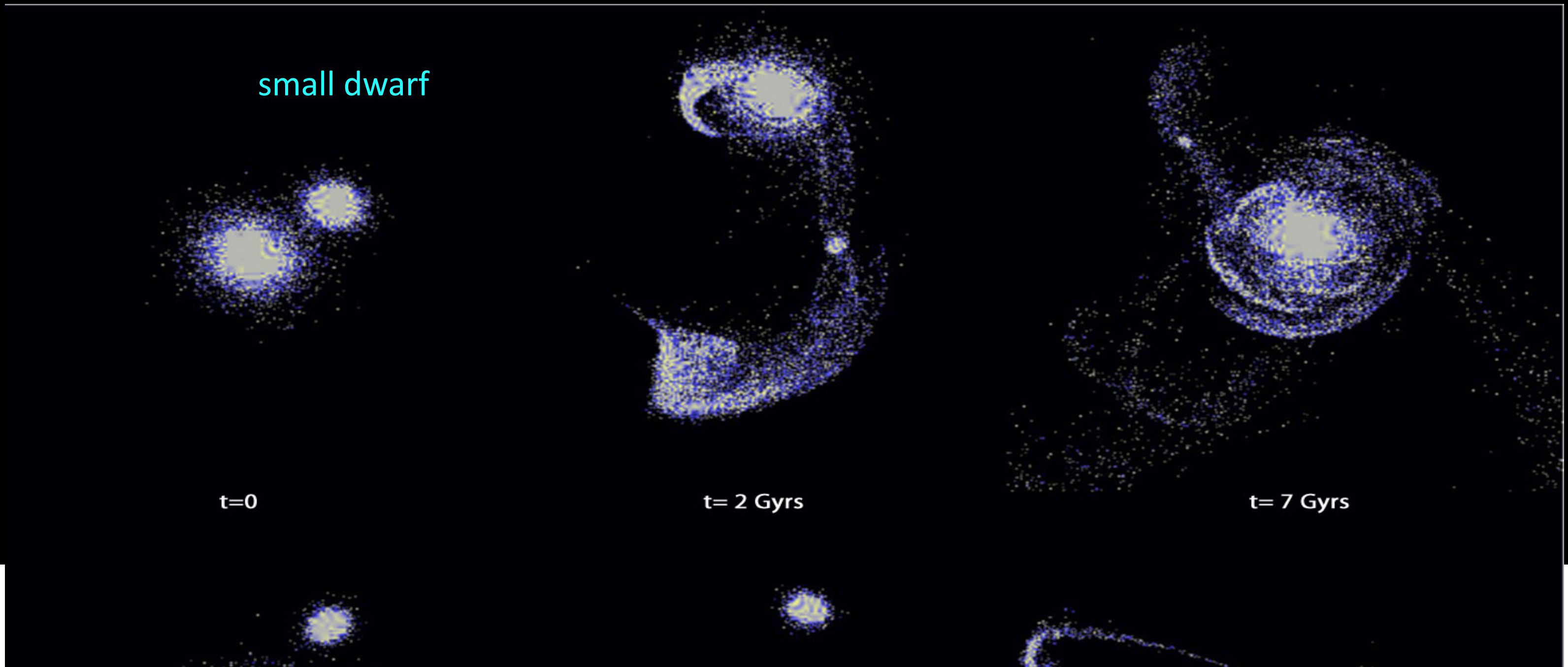
A small dwarf orbiting inside a larger system

(D'Onghia et al., 2009, Nature, 460, 605)

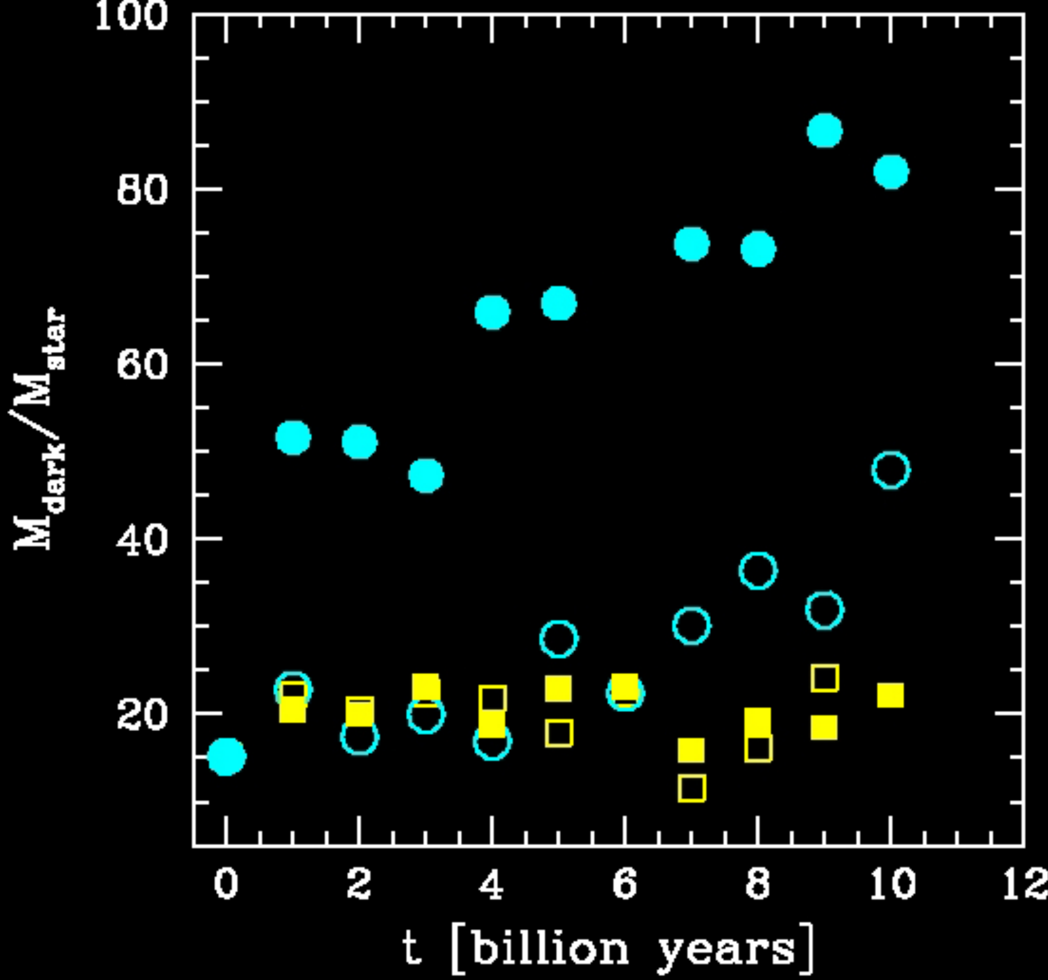
The stripping of stars is caused by a gravitational process: "*Resonant Stripping*": stars and gas in the victim are removed by a resonance between the spin frequency of its disk and the angular frequency of its orbit around the perturber.

Former Milky Way at high z

Former MW



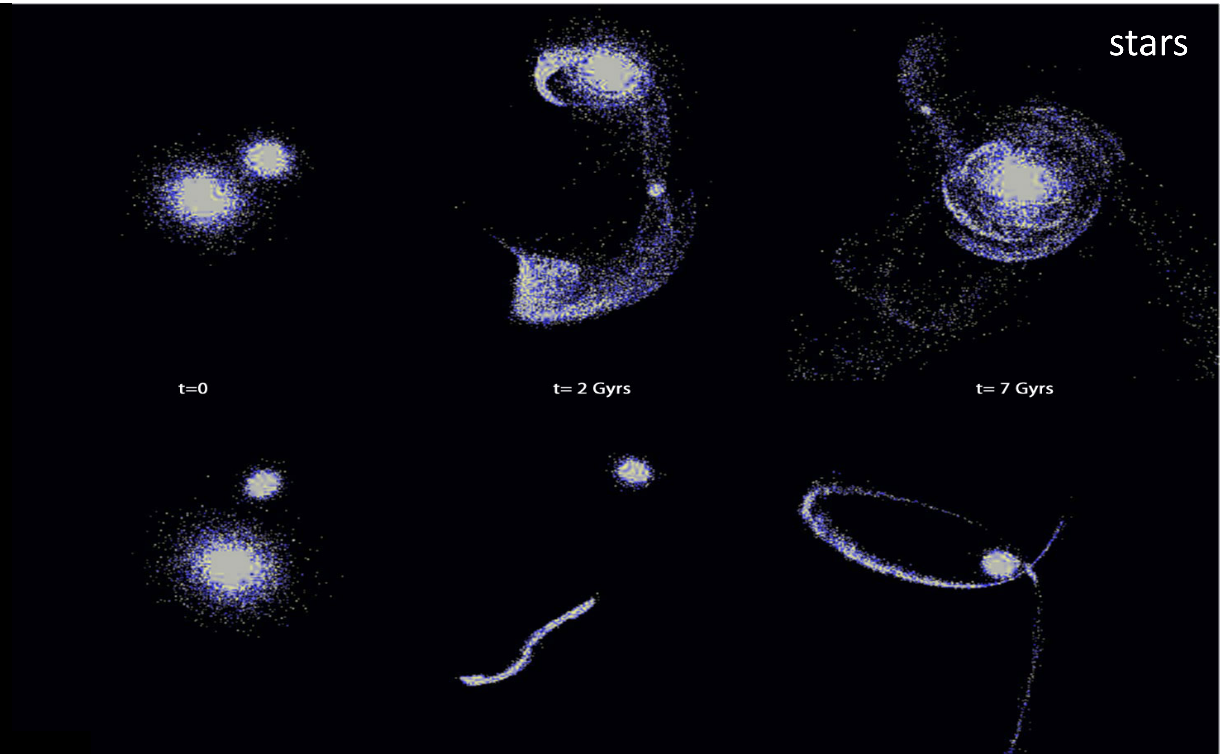
Surprising outcome: baryons at the bottom of the potential well are removed !

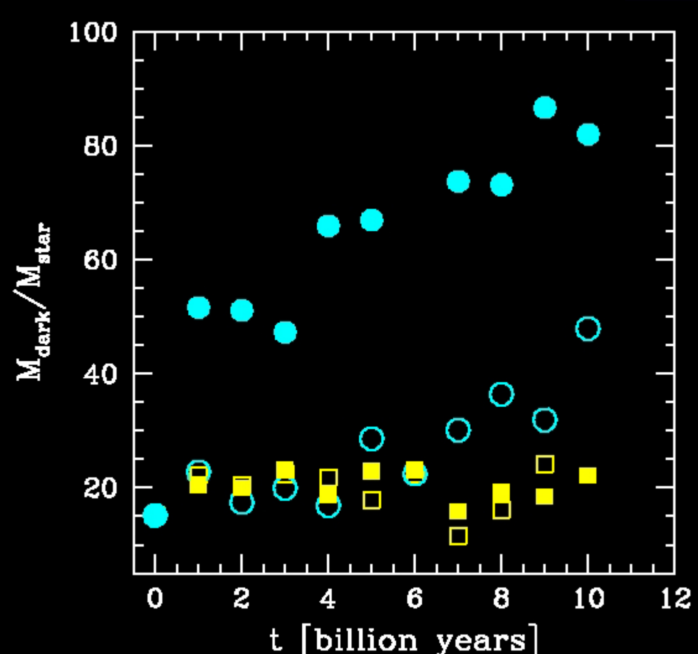


NEW: "*Resonant Stripping*" alters the M/L ratio in galaxies because stars and gas are removed more efficiently than the dark matter

Resonant Stripping

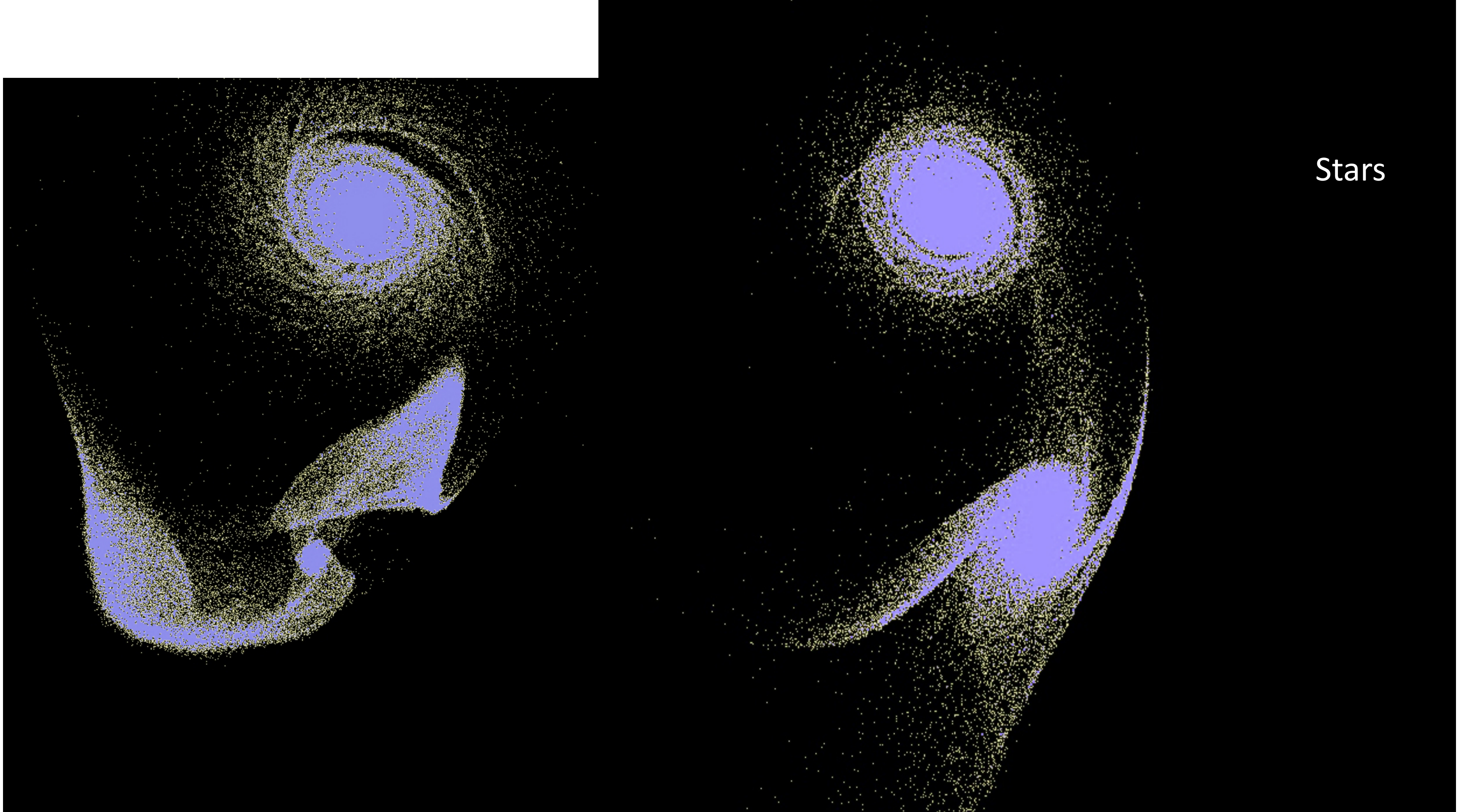
Tidal Stripping





Resonant Stripping

Tidal Stripping

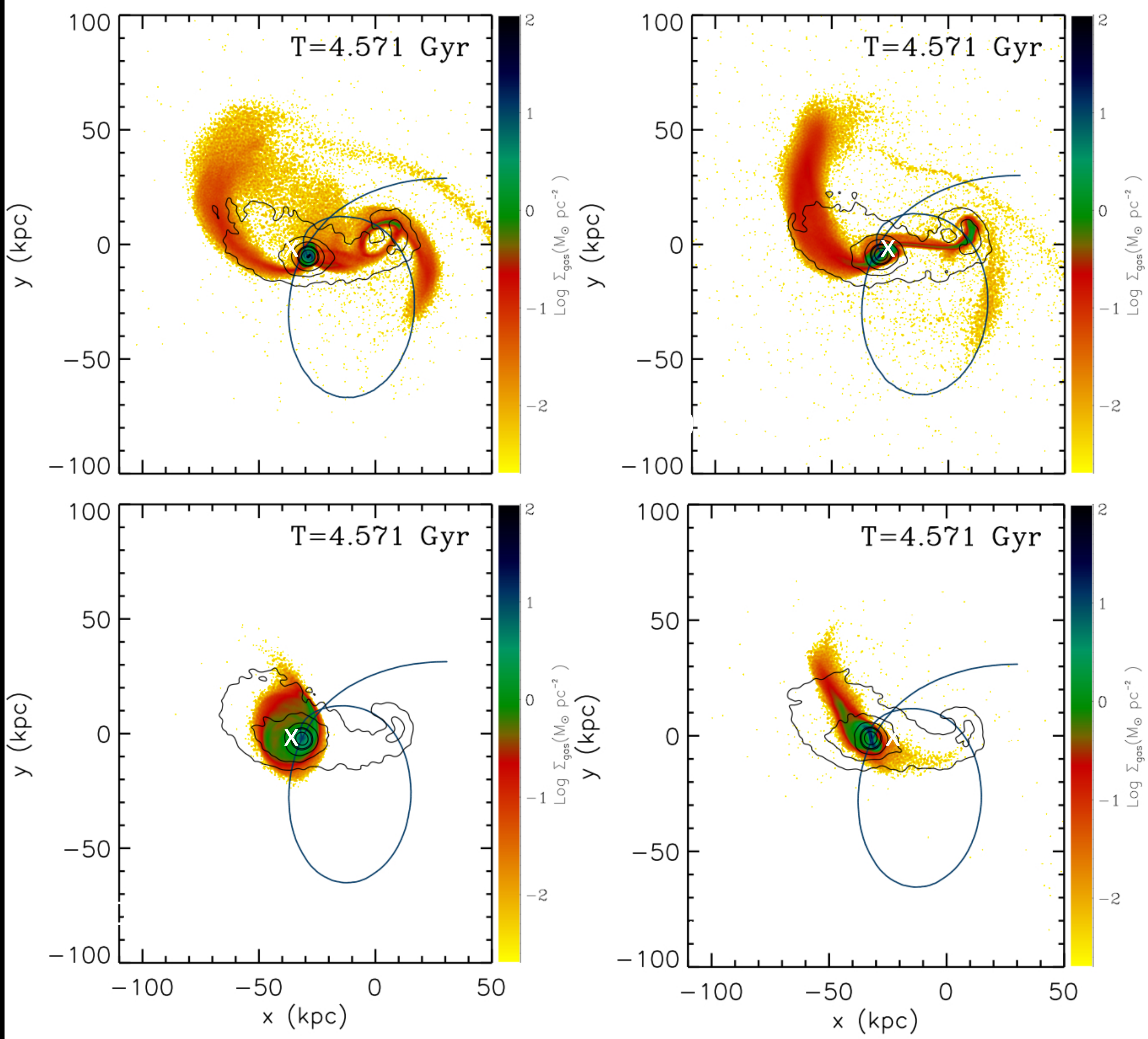


Nearly Prograde Encounter

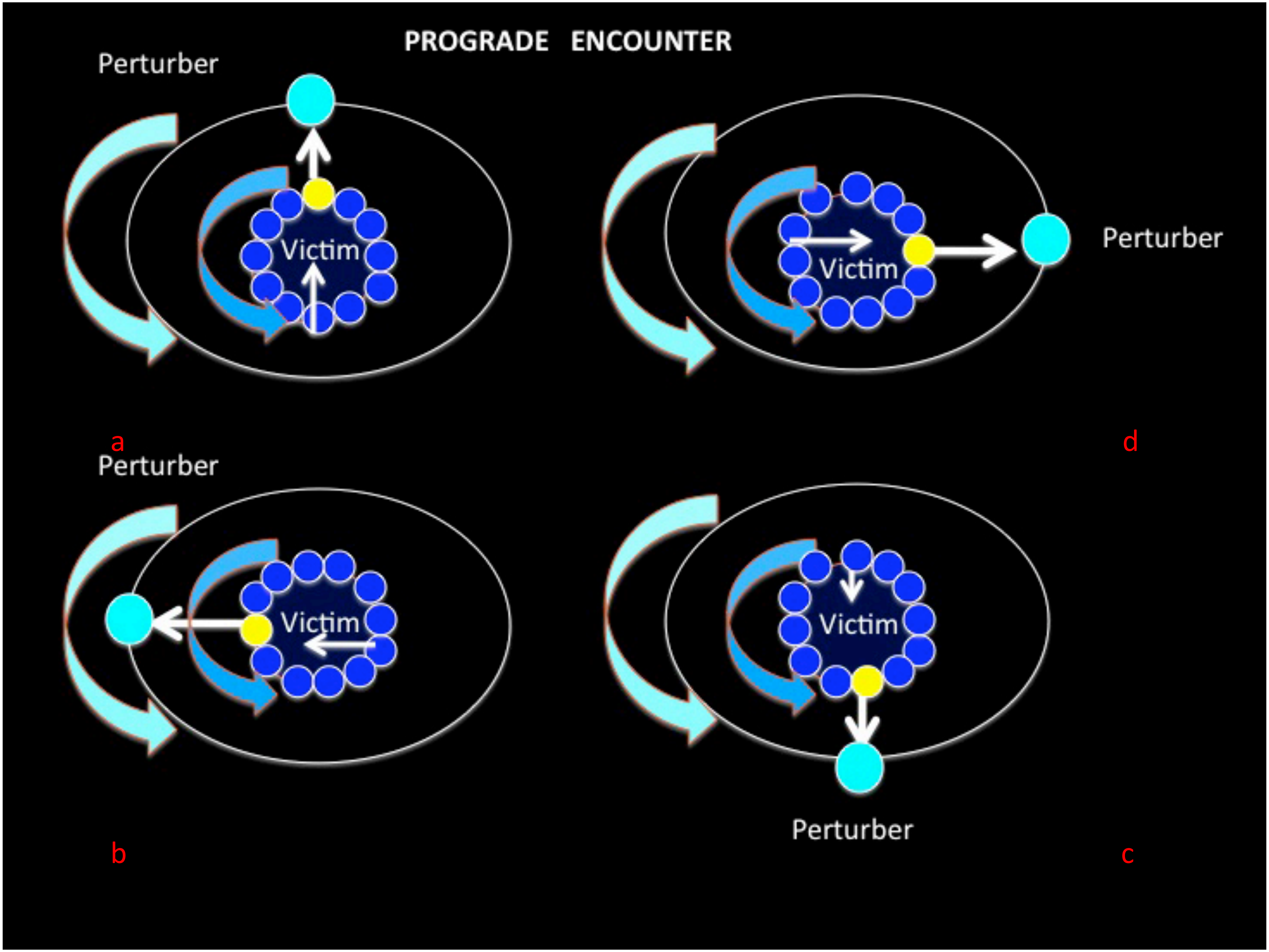
Nearly Retrograde Encounter

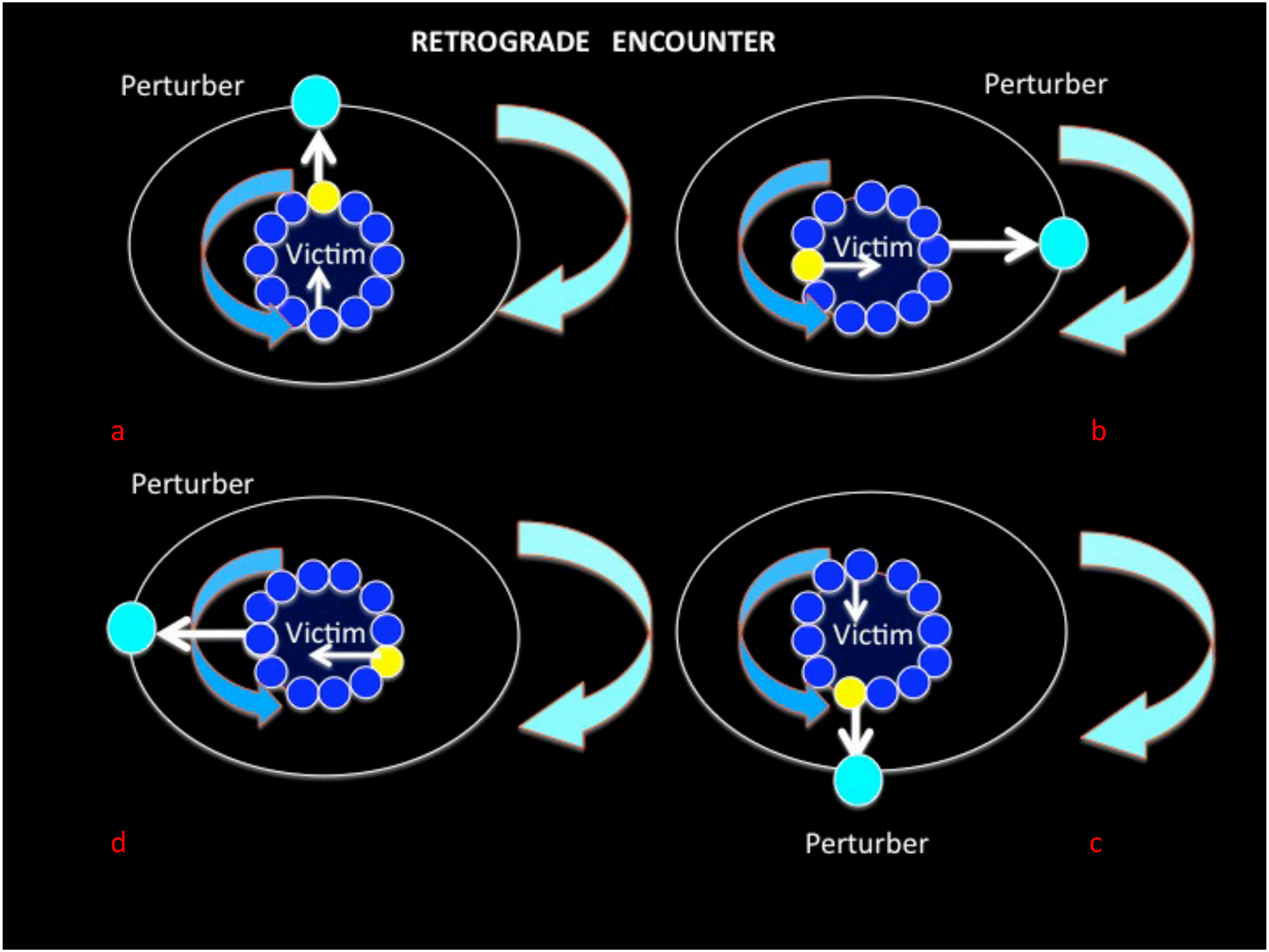
Prograde
CCW orbit
CCW rotation

Retrograde
CCW orbit
CW rotation



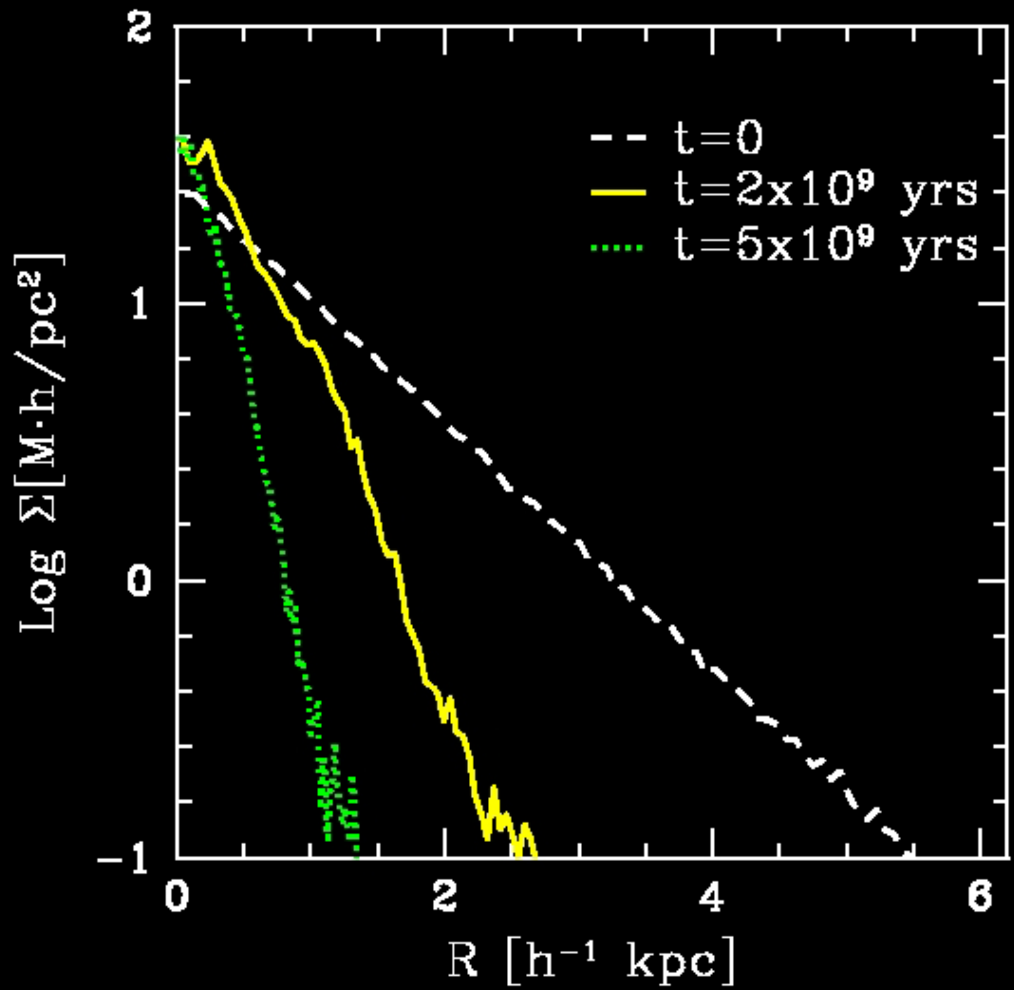
Courtesy of
G. Besla


PROGRADE ENCOUNTER
Perturber
Victim
Perturber
a
d
Perturber
Victim
Victim
Victim
Perturber
b
c



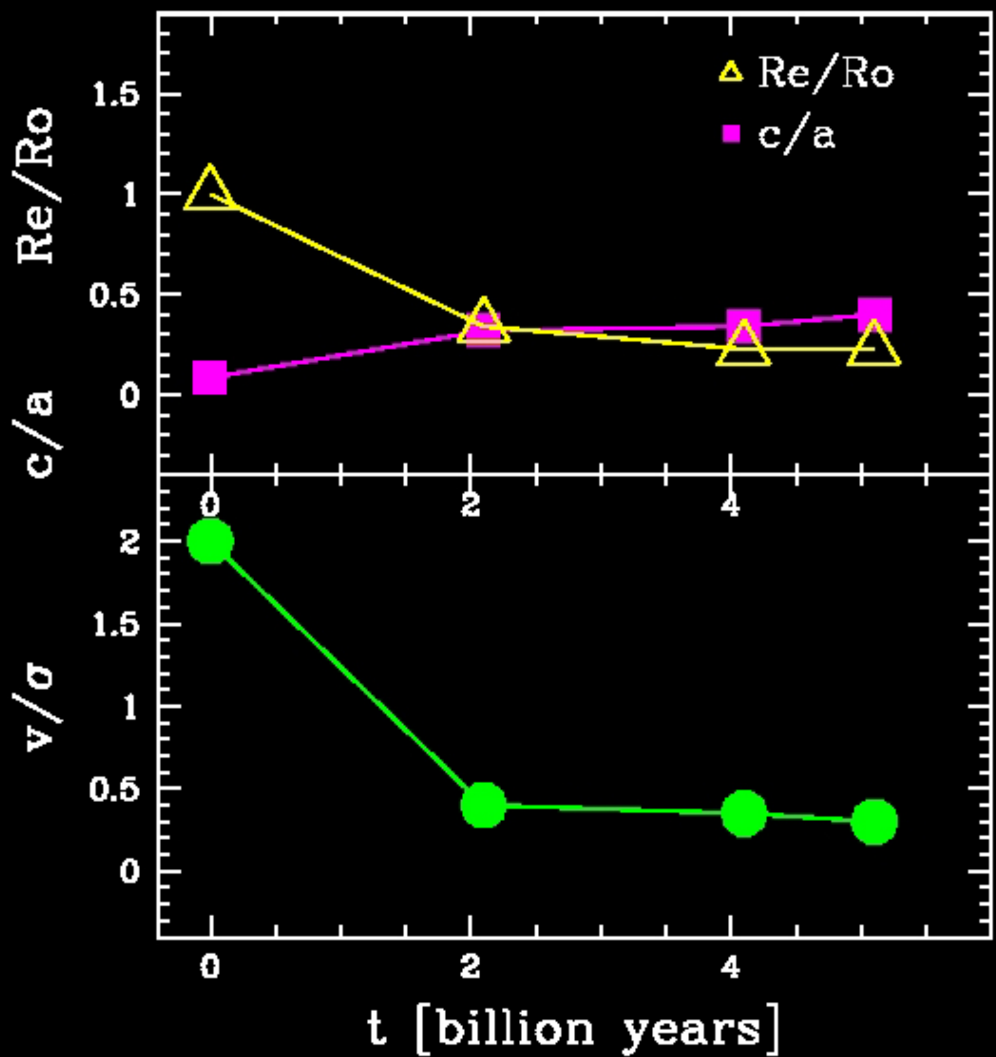
RETROGRADE ENCOUNTER
Perturber
Victim
a
Perturber
Victim
b
Perturber
Victim
d
Victim
Perturber
c

Evolution of mass surface density profile



D’Onghia et al., 2009, Nature, 460, 605

Evolution of kinematic and structural properties



D'Onghia et al., 2009, Nature, 460, 605

Predictions

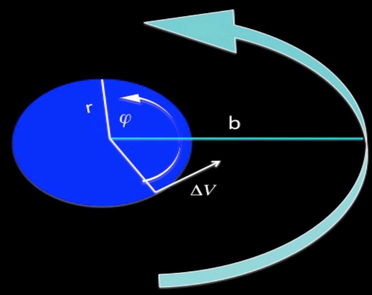
- ✓ *"Resonant Stripping"* should be visible in situ in groups of dwarfs nearby.
- ✓ Many dSphs should be found in groups of dwarfs along with detectable stellar tails and shells.

tadpole galaxy

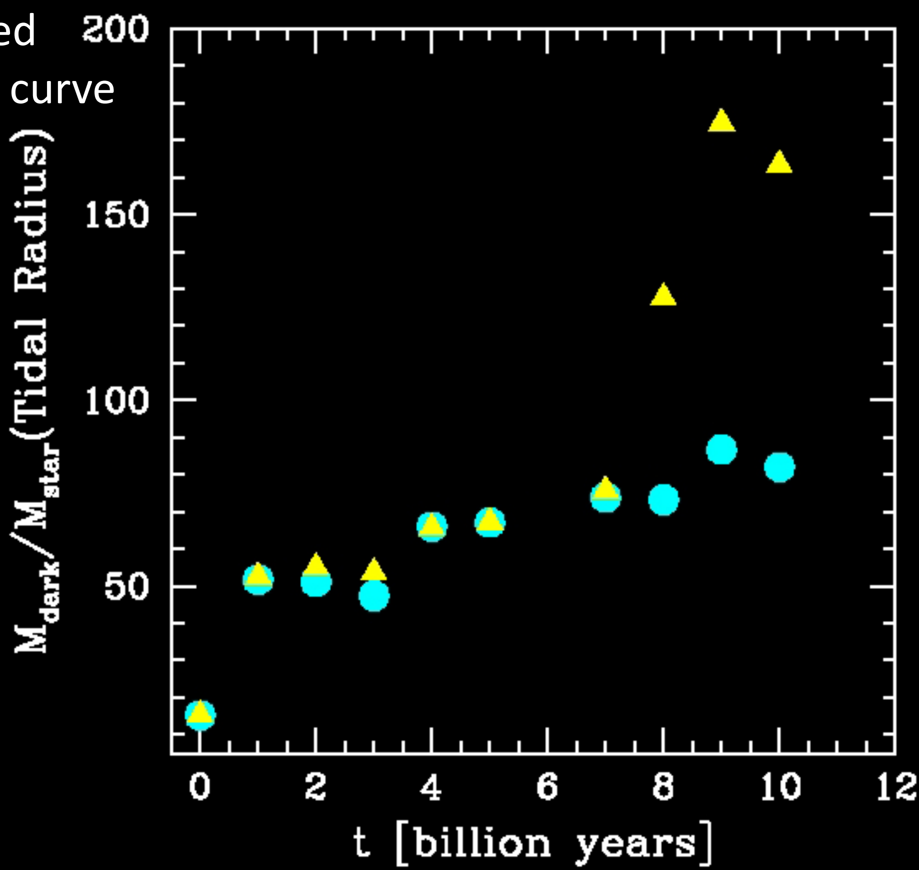
NGC 2782

NOTE: Resonant Stripping depends on a combination of the rotation curve and orbital parameters

$$\Omega_{dwarf} \approx \Omega_{Pert} \Rightarrow \frac{v}{r} \approx \frac{V}{R}\sqrt{1+e}$$



Fainter Dwarfs may be reproduced assuming a slowly rising rotation curve



fainter dwarfs

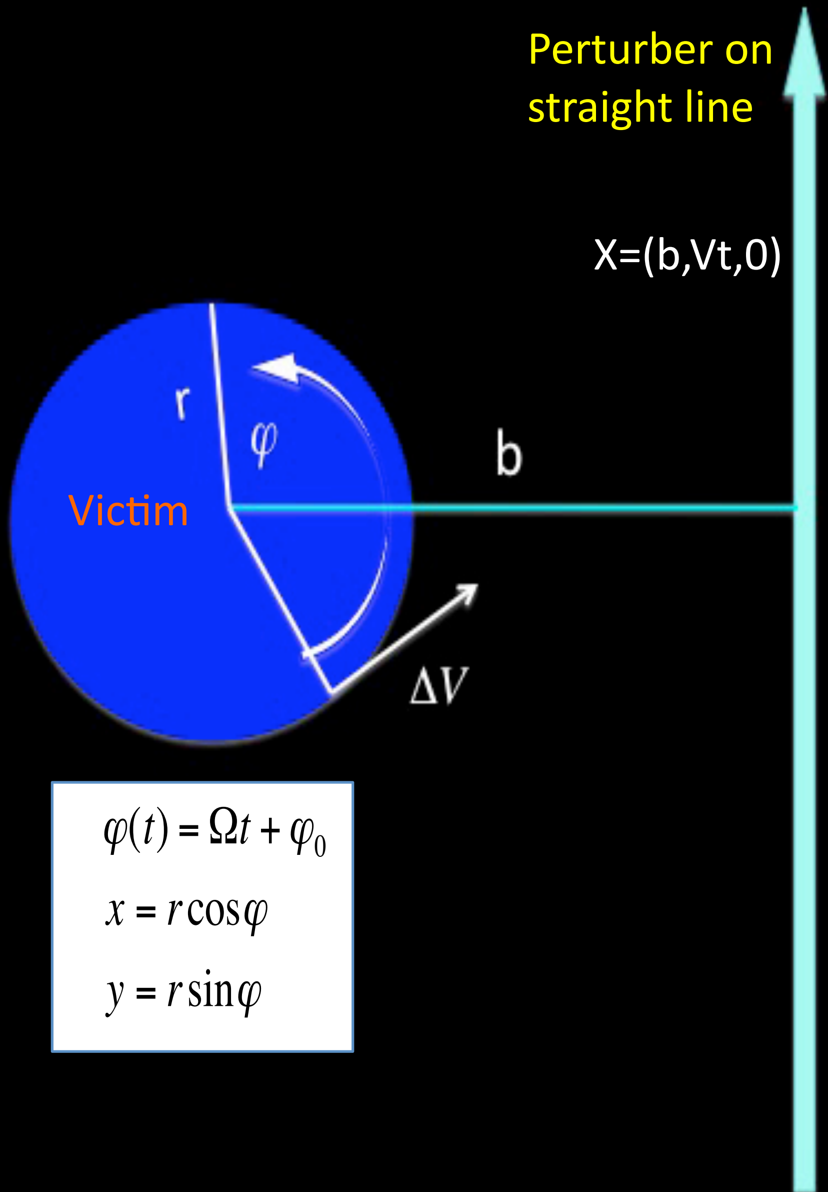
TIDAL RESONANCES DURING MAJOR MERGERS

- ✓ The tails and bridges of stars in major mergers are caused by a tidal resonance (Toomre & Toomre 1972)

- ✓ Simulations have shown that 10% of stars are removed
- during major mergers

"Quasi-Resonance theory of tidal Interaction

Ω



$$\varphi(t) = \Omega t + \varphi_0$$
$$x = r\cos\varphi$$
$$y = r\sin\varphi$$

$$\Delta v(x) = -GM_{pert}\int\left[\frac{x}{|X|^3} - \frac{X(x\cdot X)}{|X|^5}\right]dt$$

$$\Delta v_x = -2\frac{GM_{pert}}{b^2V} r\cos\phi_0(-\alpha^2K_0 - \alpha(1\pm\alpha)K_1)$$
$$\Delta v_y = -2\frac{GM_{pert}}{b^2V} r\sin\phi_0(\alpha^2K_0 \pm \alpha^2K_1)$$

$$\alpha = \frac{|\Omega| b}{V}$$

angular frequency

D'Onghia et al. 2010, ApJ, 725, 353

Limits of "Tidal Quasi-Resonance approximation"

✓ For angular frequency=0 $\boxed{\alpha = 0}$

Tidal near-resonance → Impulse Approximation

$$\Delta v_x = -2\frac{GM_{pert}}{b^2V} r\cos\phi_0(-\alpha^2K_0 - \alpha(1\pm\alpha)K_1)$$
$$\Delta v_y = -2\frac{GM_{pert}}{b^2V} r\sin\phi_0(\alpha^2K_0 \pm \alpha^2K_1)$$

$$\Delta v_x = -2\frac{GM_{pert}}{b^2V} r\cos\phi_0$$
$$\Delta v_y = -2\frac{GM_{pert}}{b^2V} r\sin\phi_0$$

✓ For Infinite angular frequency $\boxed{\alpha = \infty}$

Tidal near-resonance → Adiabatic Invariant

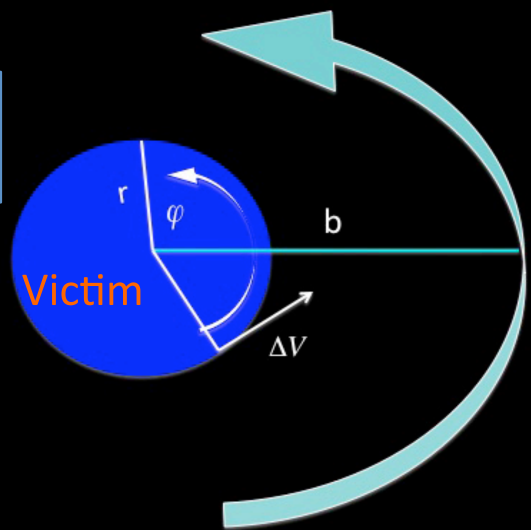
$$\Delta v_x = -2\frac{GM_{pert}}{b^2V} r\cos\phi_0(-\alpha^2K_0 - \alpha(1\pm\alpha)K_1)$$
$$\Delta v_y = -2\frac{GM_{pert}}{b^2V} r\sin\phi_0(\alpha^2K_0 \pm \alpha^2K_1)$$

$$\Delta v_x = -2\frac{GM_{pert}}{b^2V} x\alpha e^{-\alpha}\sqrt{\frac{\pi}{2\alpha}}(1-\alpha\pm\alpha) \to 0$$
$$\Delta v_y = 2\frac{GM_{pert}}{b^2V} y\alpha e^{-\alpha}\sqrt{\frac{\pi}{2\alpha}}(1-\alpha) \to 0$$

Perturber
on parabolic orbit

"Tidal Quasi-Resonance approximation"

Ω

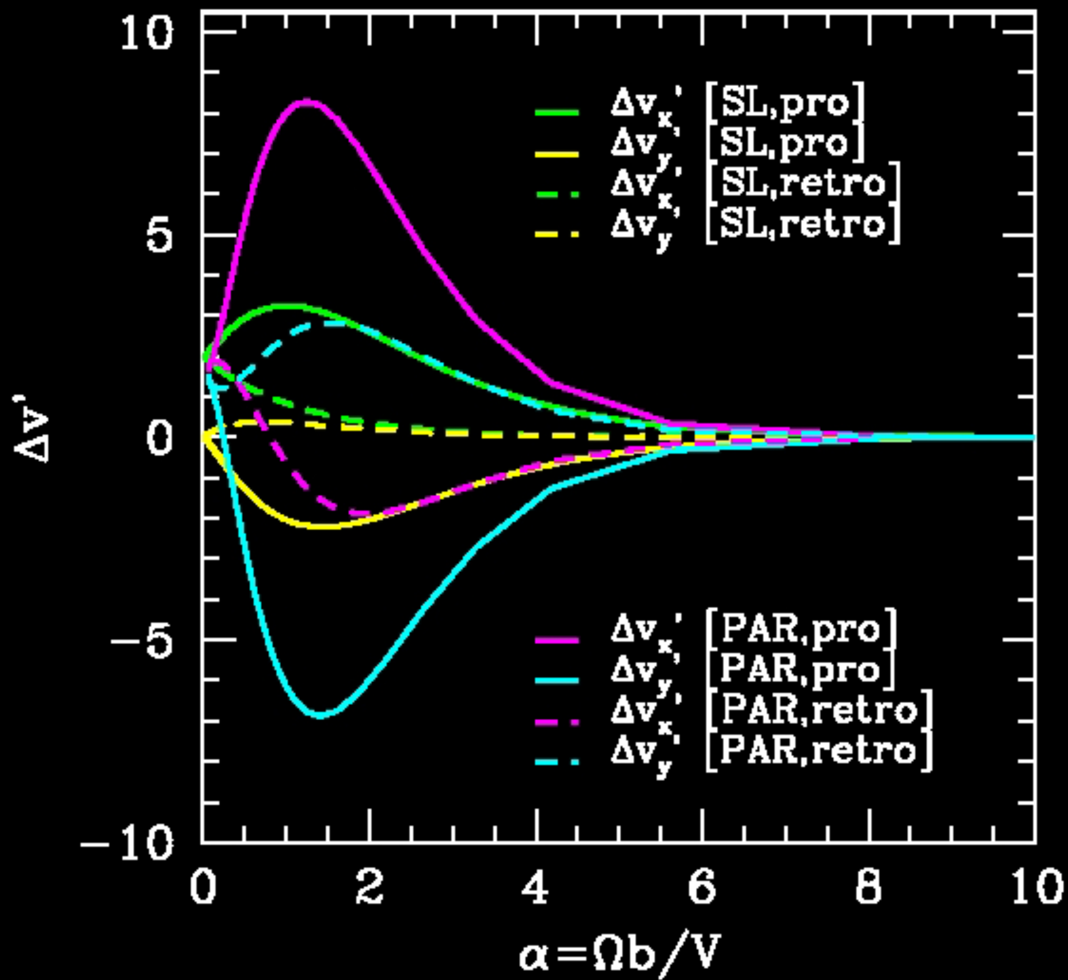


$$\Delta v_x = -4\frac{GM_{pert}}{b^2 V} r\cos\phi_0 (2I_{30} - 2(1 \pm 2\alpha)I_{20} \pm 3\alpha I_{10} - 4\alpha^2 I_{00}$$

$$\Delta v_y = 4\frac{GM_{pert}}{b^2 V} r\sin\phi_0 (2I_{30} - (1 \pm 4\alpha)I_{20} \pm 3\alpha I_{10} - 4\alpha^2 I_{00})$$

$$\alpha = \frac{|\Omega| b}{V}$$

The Tidal Quasi-Resonance approximation is more efficient than the impulse approximation



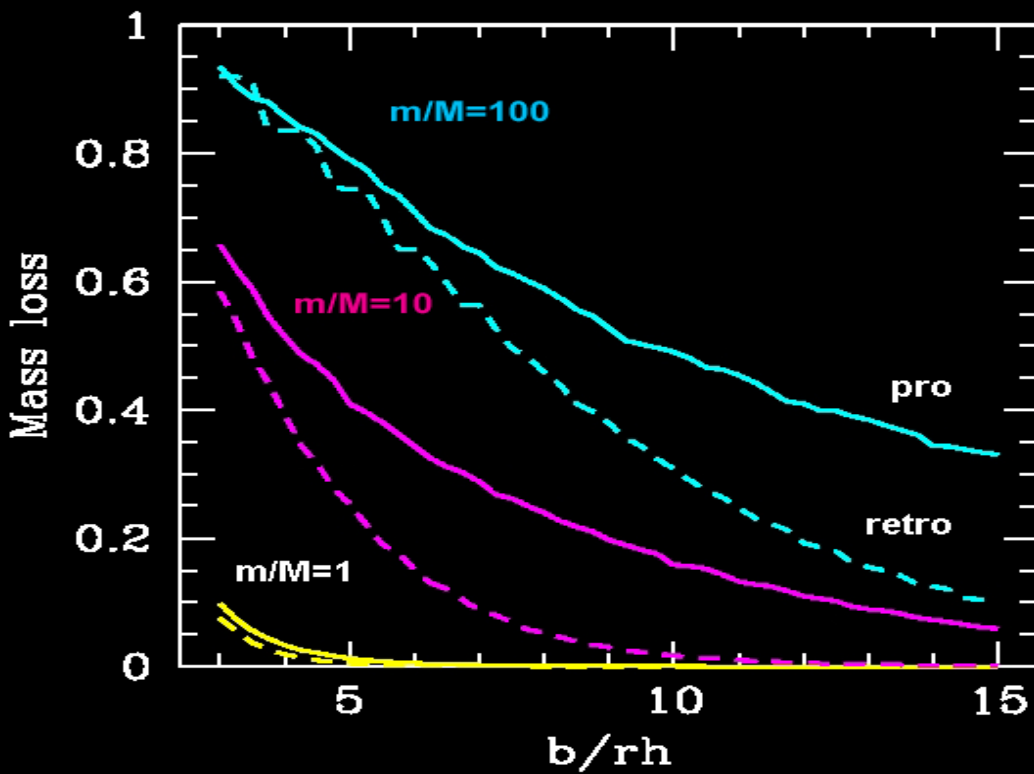
angular frequency

The resonance is broad

$$\Omega_{dwarf} \approx \Omega_{Pert} \Rightarrow \frac{v}{r} \approx \frac{V}{R}\sqrt{1+e}$$

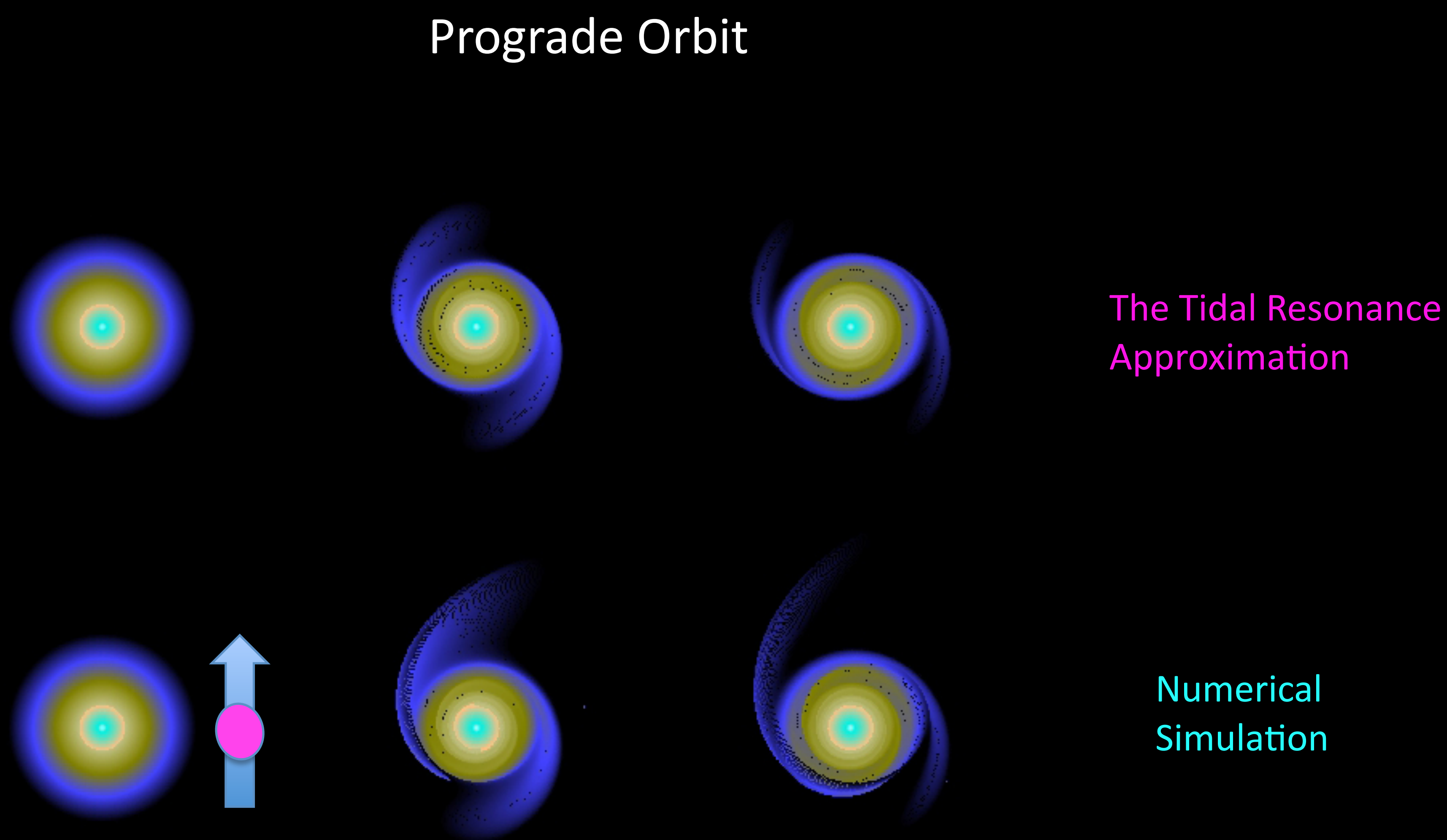
D'Onghia et al. 2010, ApJ, 725, 353

Efficiency of Resonant Stripping



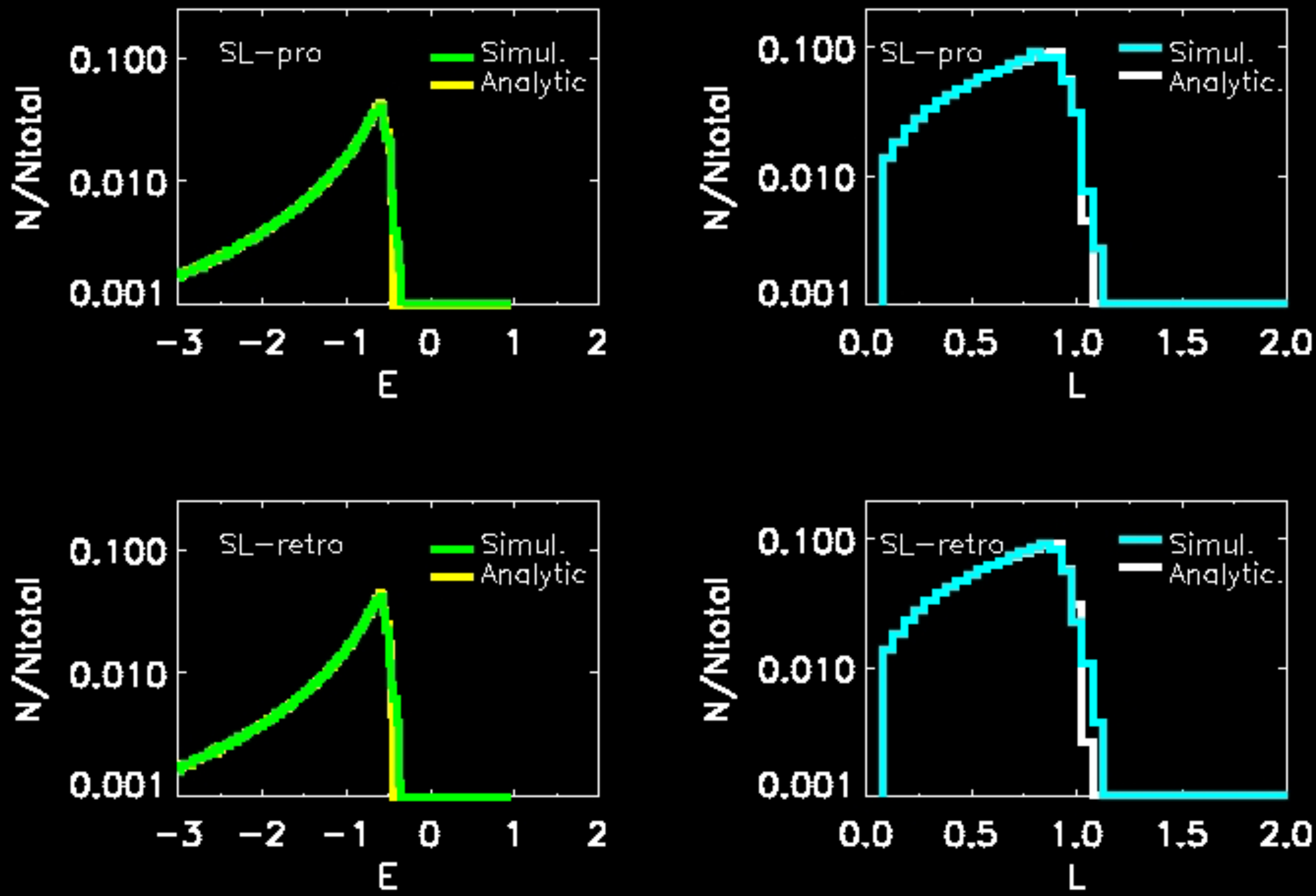
The efficiency depends on:
mass ratio (m/M) and
impact parameter b

Comparison between the quasi-resonance theory and simulations

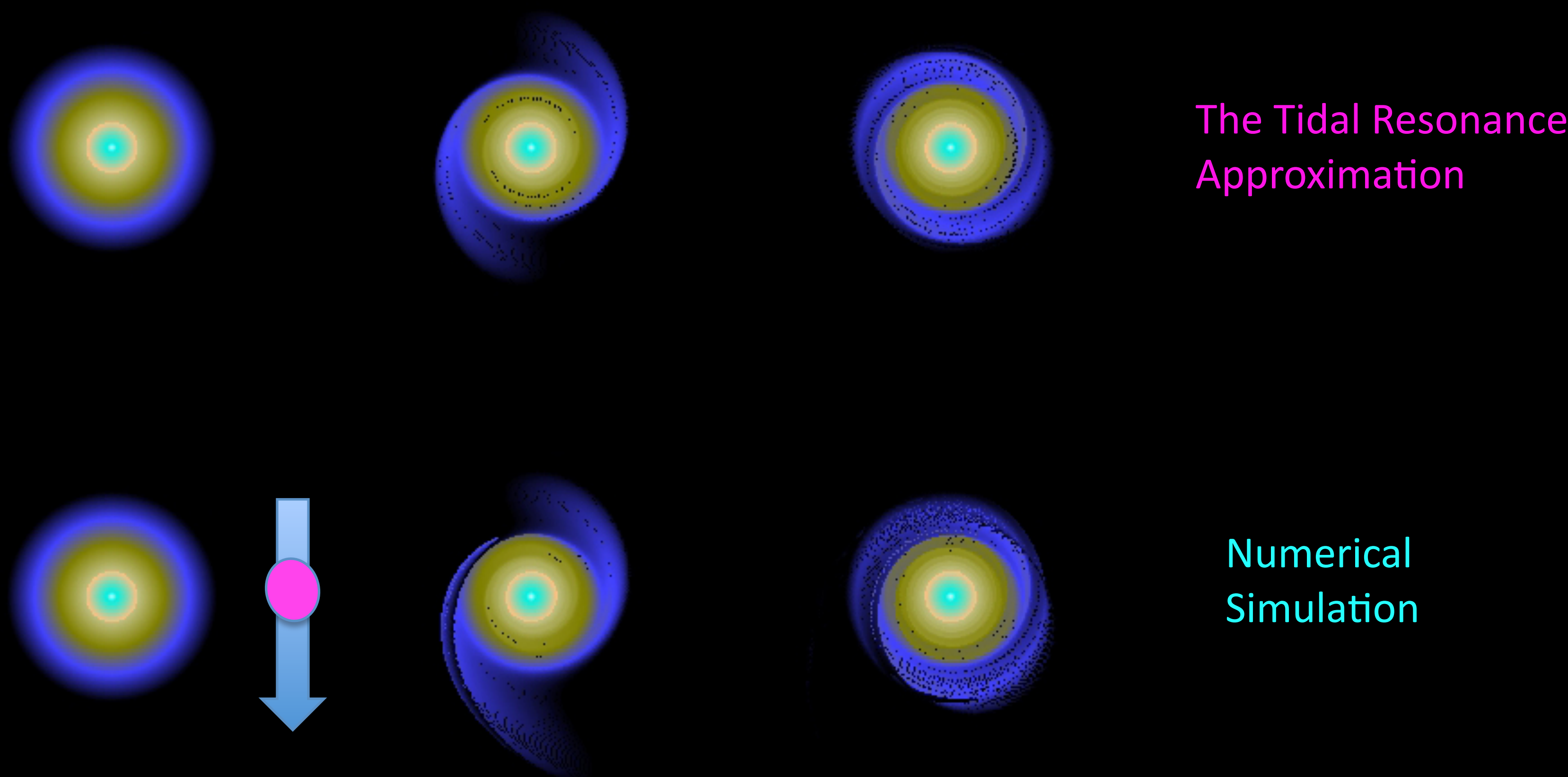


D'Onghia et al. 2010, ApJ, 725, 353

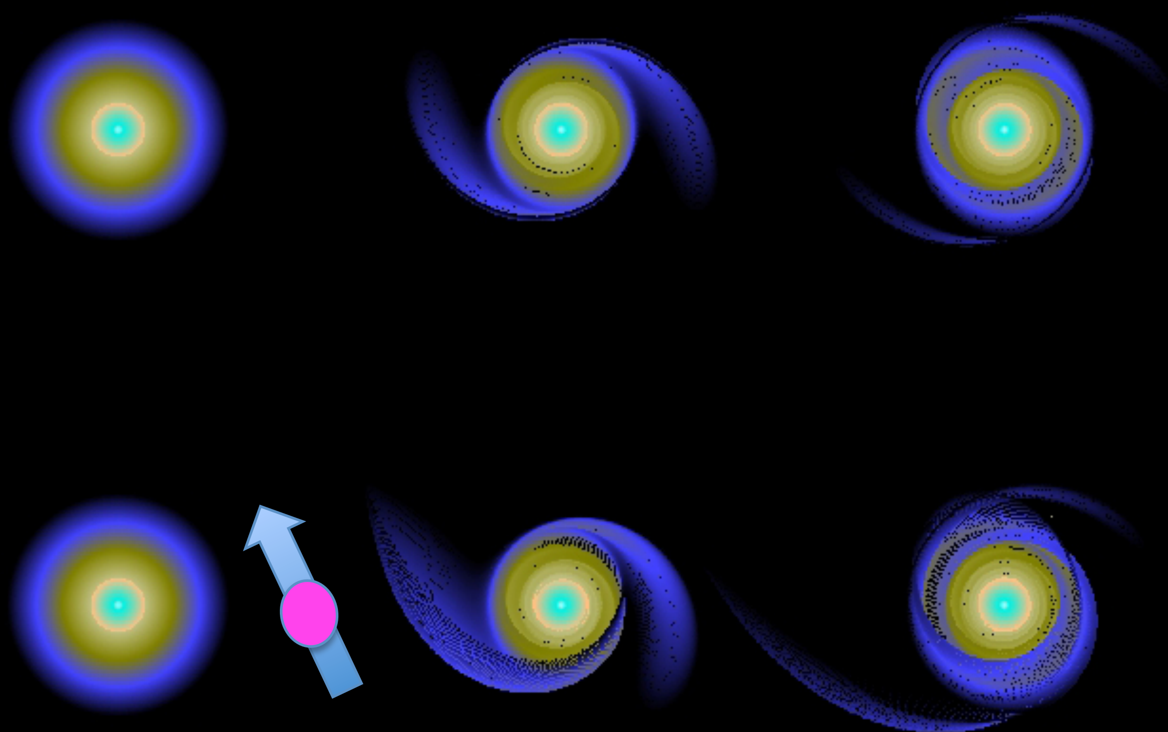
The energy and angular momentum distributions match !



Retrograde Orbit



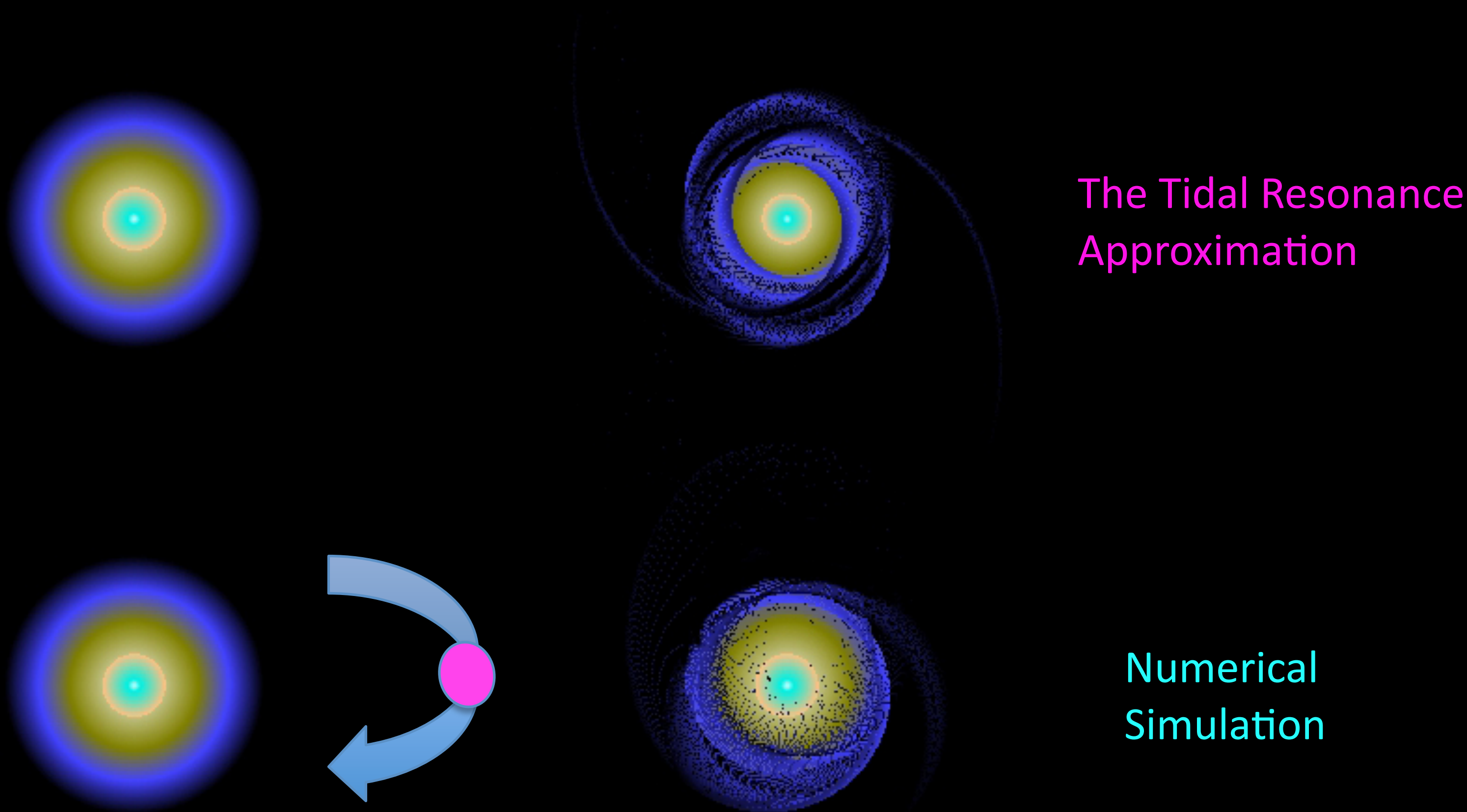
Non Coplanar Orbit

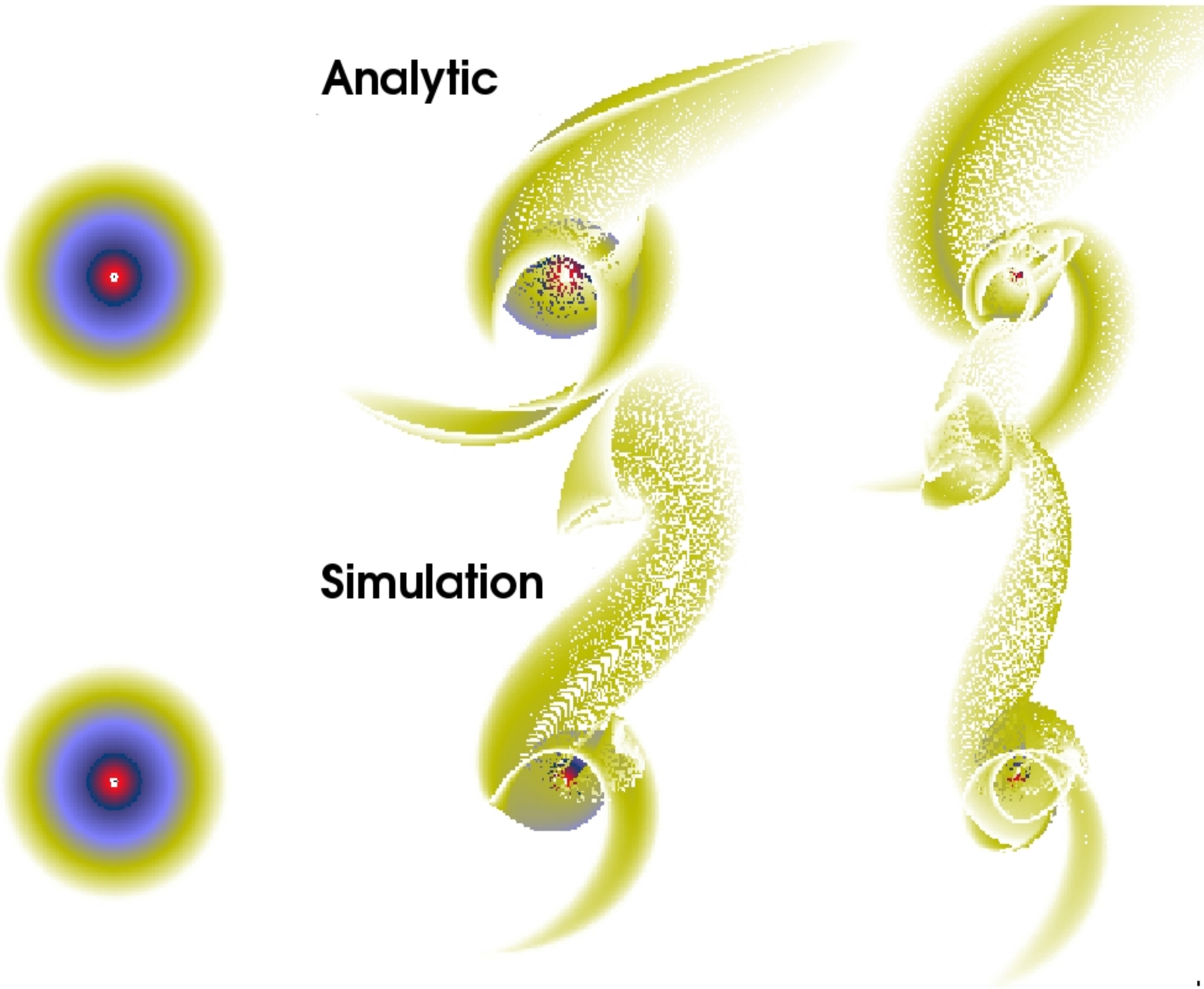


The Tidal Resonance Approximation

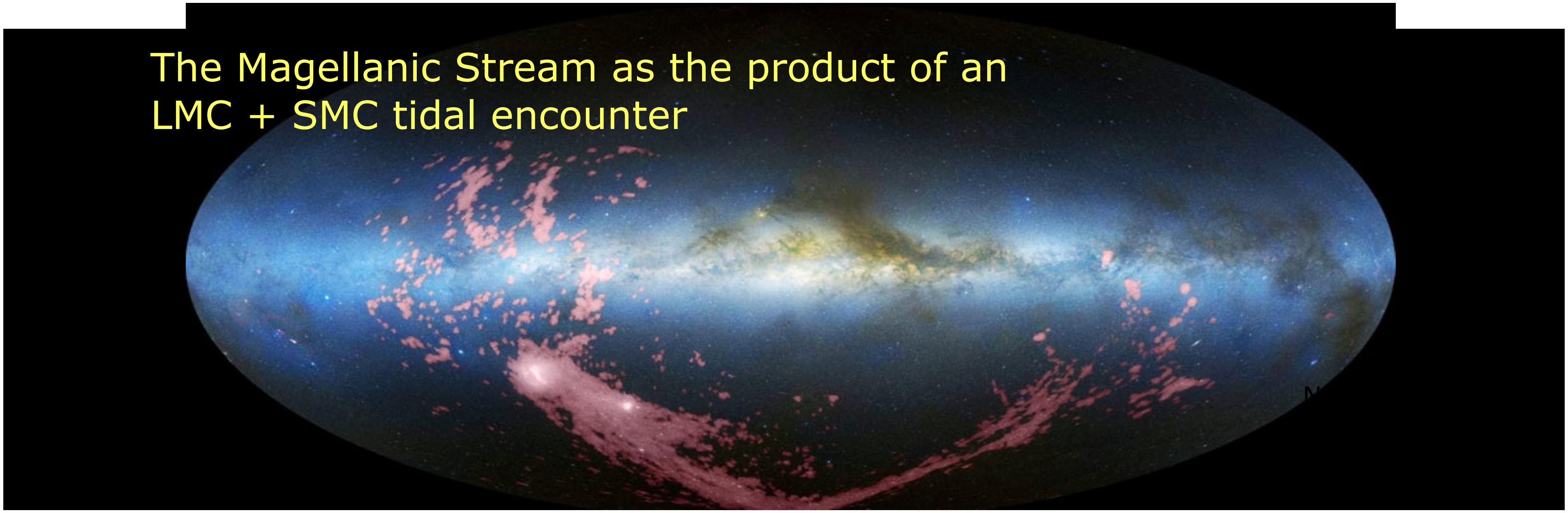
Numerical Simulation

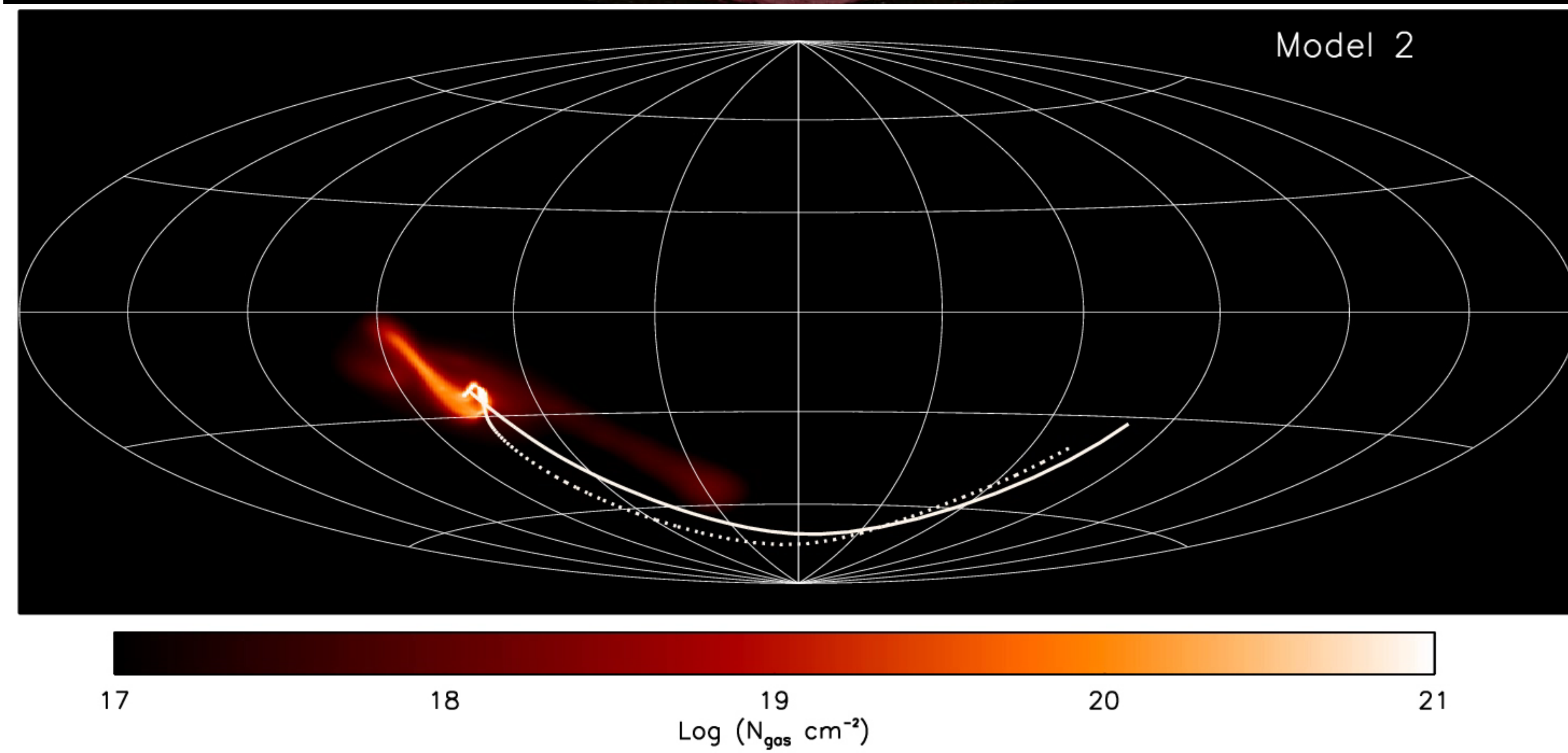
Parabolic Orbit




Analytic
Simulation

The Magellanic Stream as the product of an LMC + SMC tidal encounter

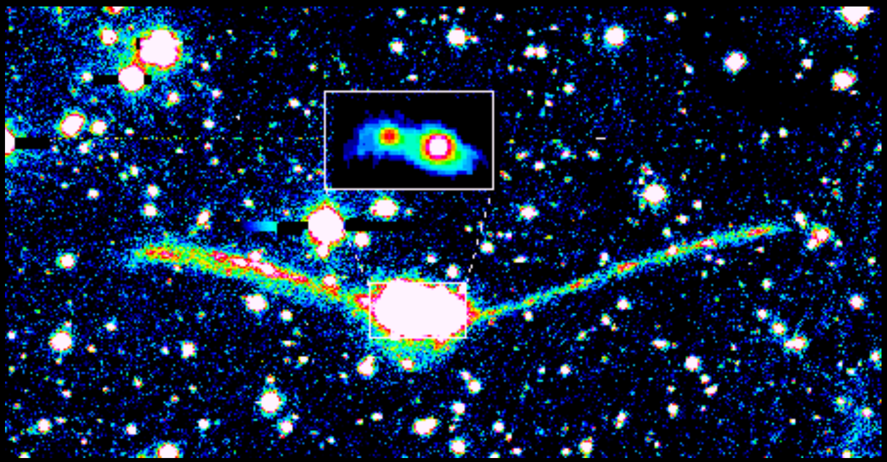




APPLICATIONS OF TIDAL RESONANCE THEORY

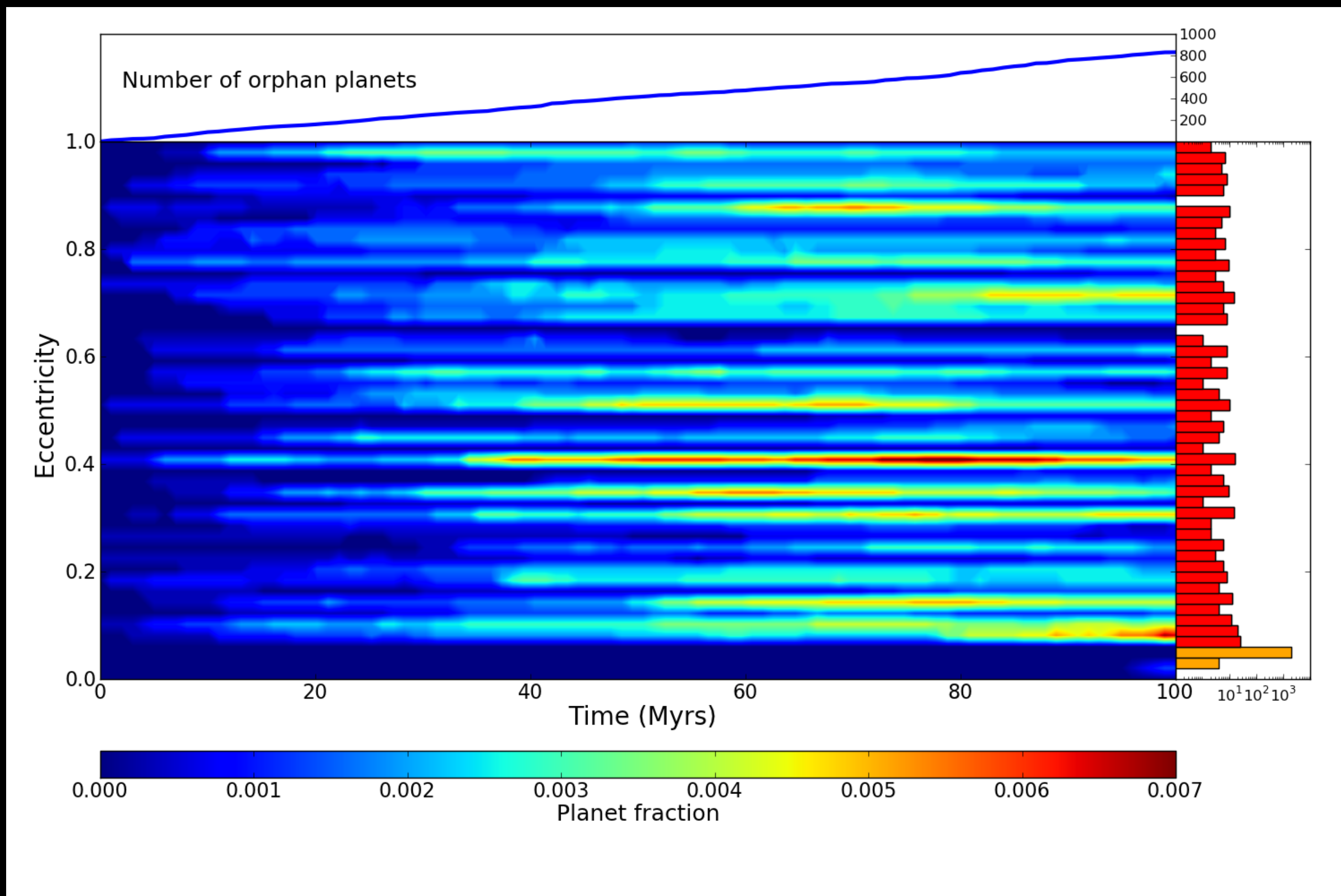
- ✓ Resonant stripping is a gravitational process that removes gas & stars in a disk but affects less DM and is interesting for the dSph formation

- ✓ To study tails and bridges of stars: e.g. Superantennae and the shape of the dark matter potential



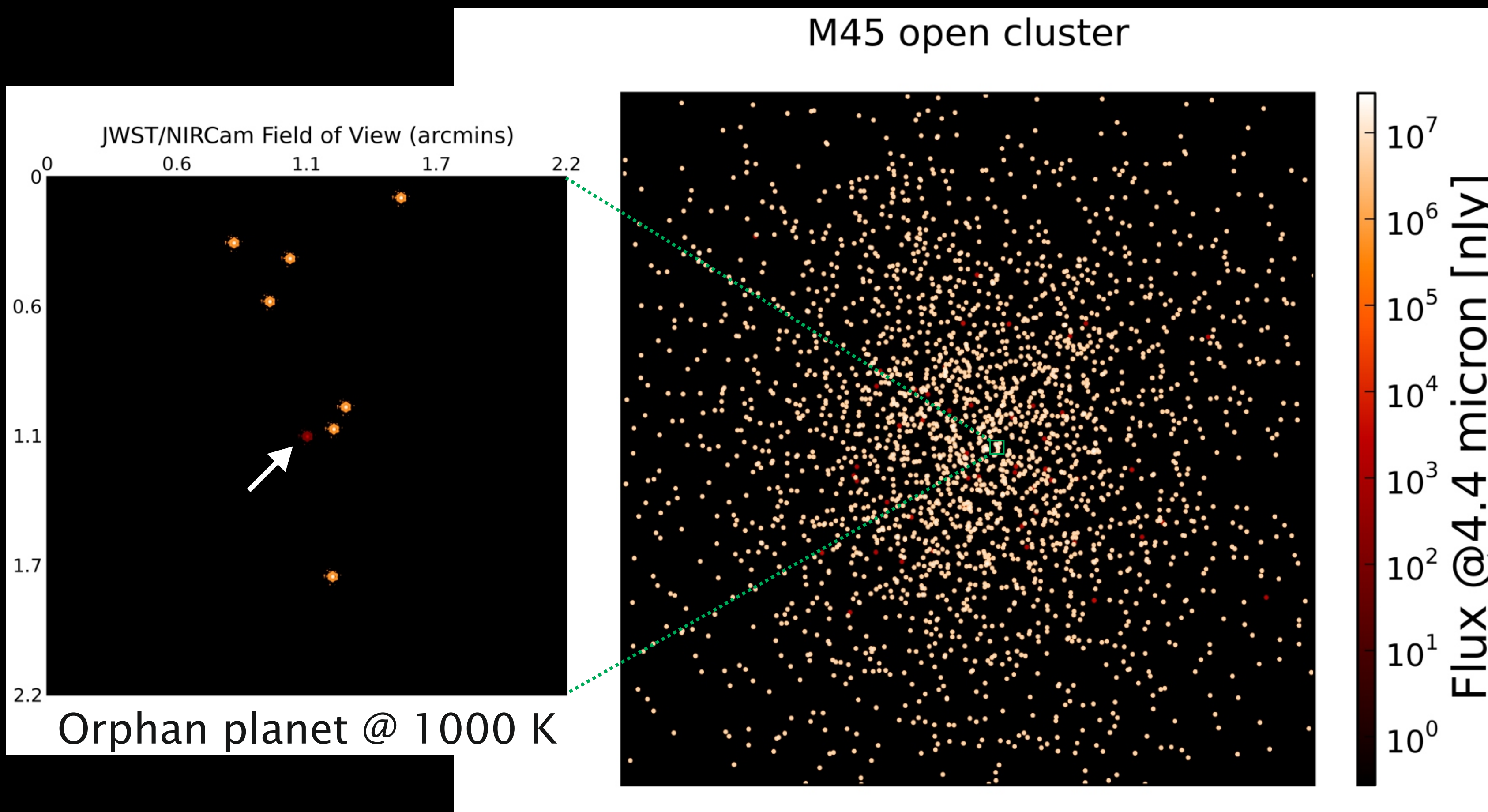
- ✓ Planetary systems

Free Floating Planets in Open Clusters



Pacucci, Ferrara, D'Onghia 2013, ApJ,778, L42

Free-Floating planets as seen from JWST



Pacucci, Ferrara, D'Onghia 2013, ApJ,778, L42

Conclusion

- ✓ Interactions between dwarf galaxies in small groups excite a resonant response: *"Resonant Stripping"* that rapidly transforms disks into dSphs.

- ✓ Resonant stripping is a gravitational process that removes gas & stars in a disk but affects less DM and can be described by tidal Quasi-Resonance Theory

- ✓ TEST: -- rotational velocity of the stars in data

  -- subhalo angular momentum in cosmological simulations and if they are preferentially retrograde