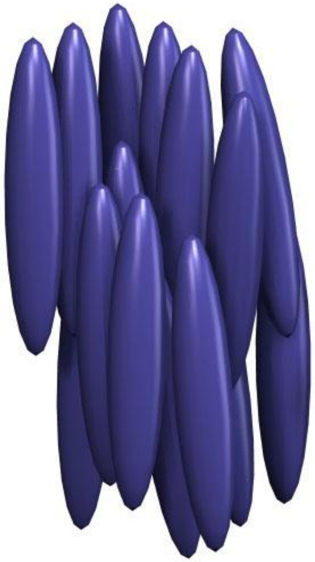
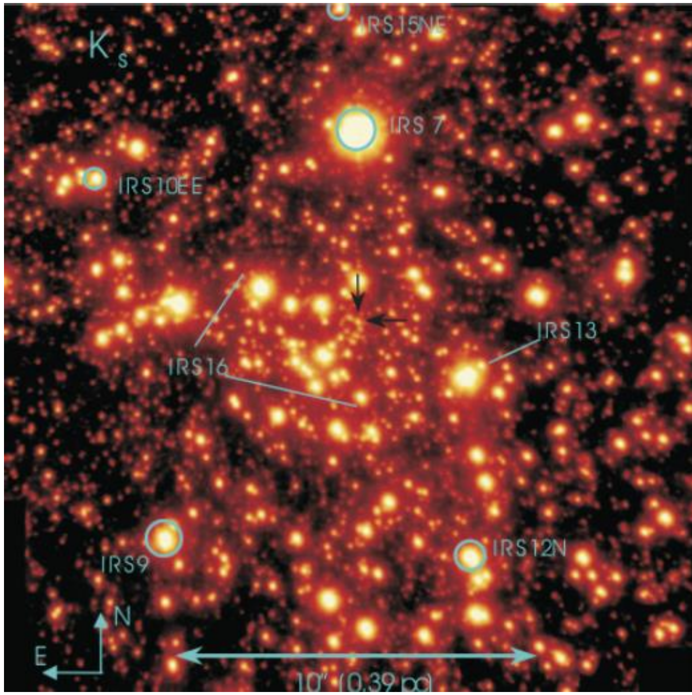


Liquid crystals of stars and black holes at the centers of galaxies

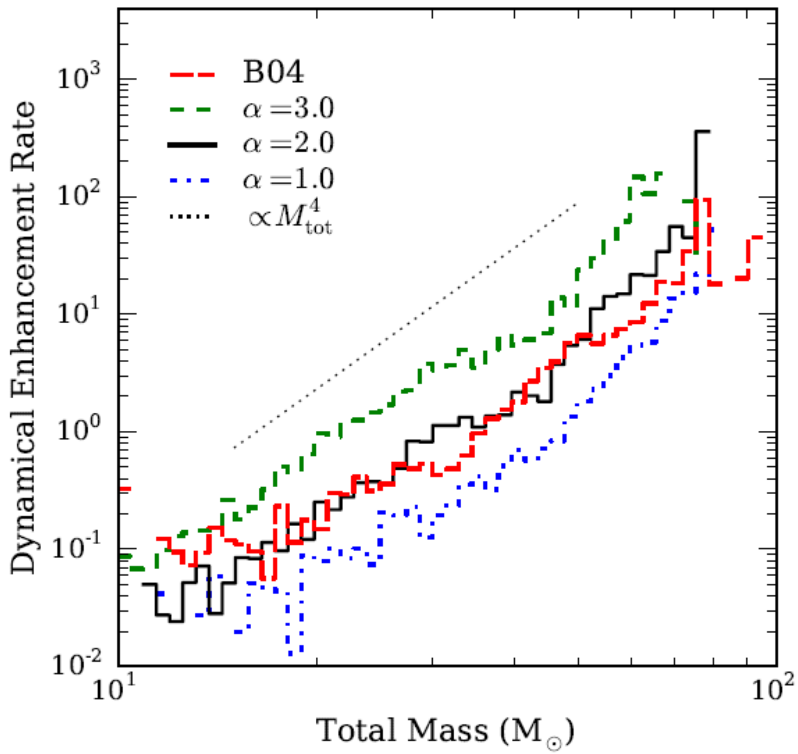
Bence Kocsis
ERC Starting Grant group leader
Eotvos University

In collaboration with
Yohai Meiron, Zacharias Roupas,
and Tim Brandt, Ryan O'Leary, Scott Tremaine

Dynamics and accretion at the Galactic Center
Februrary 9, 2016



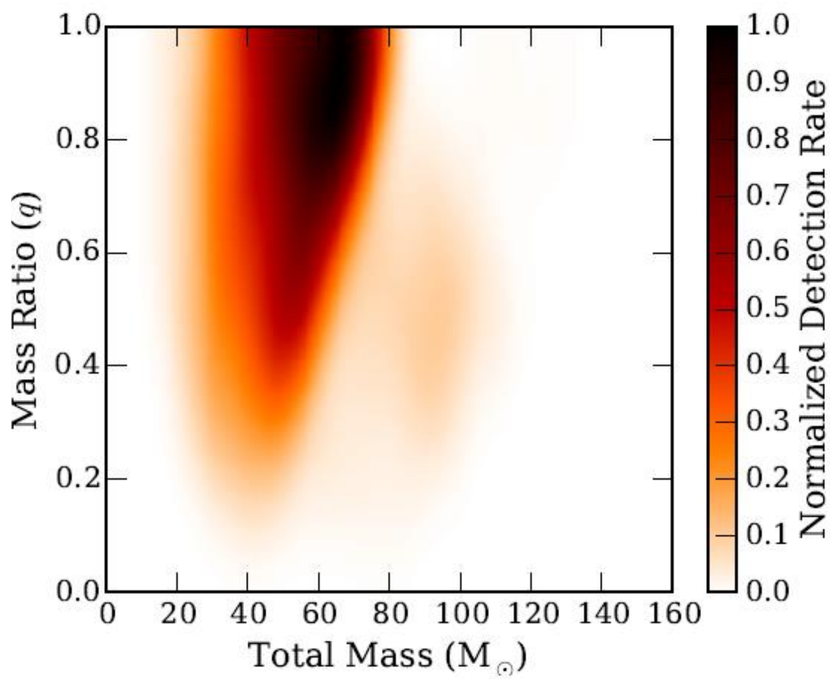
Dynamical Formation Signatures
of black hole binaries
in future gravitational wave detections



Monte Carlo and Nbody simulations

Advanced LIGO will measure GWs soon!

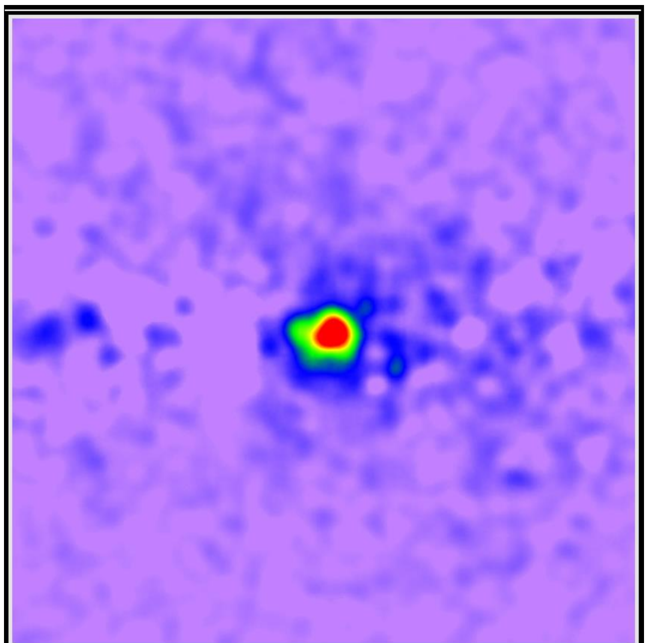
- dynamical encounters lead to black hole mergers
- higher mass objects merge more often by M^4
- GW detections can tell us about the BH IMF



O'Leary, Meiron, & Kocsis (2016 – arXiv tonight)

Evidence for disrupted globular clusters?

A fraction of stars was delivered by infalling globular clusters

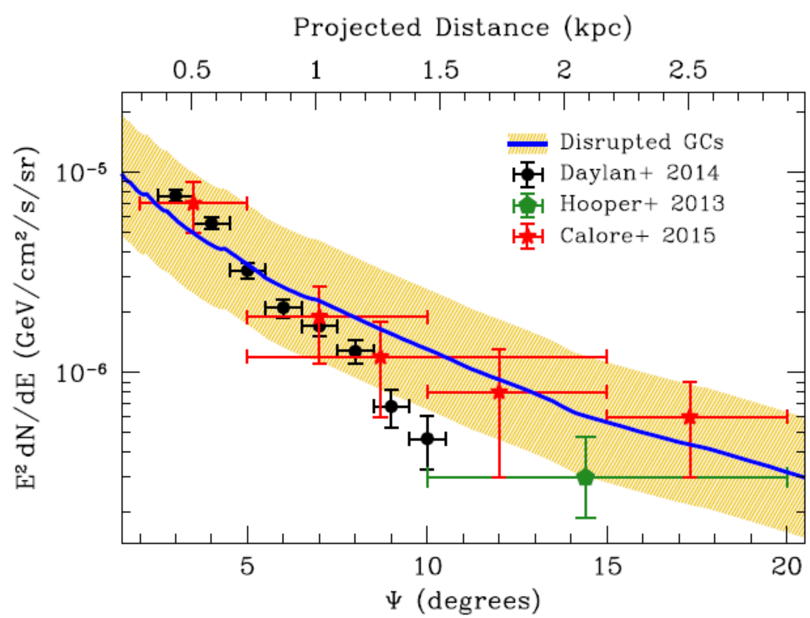


Known sources removed

Fermi measured excess gamma ray emission from the Galactic bulge

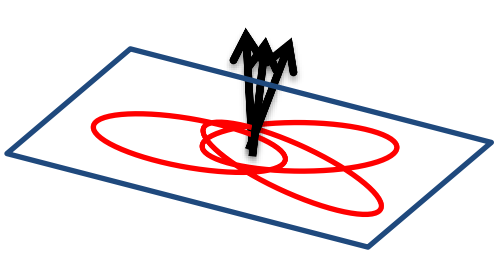
- Millisecond pulsars match the observed spectrum
- Millisecond pulsars do not form in the bulge
- Infalling globular clusters delivered the needed population

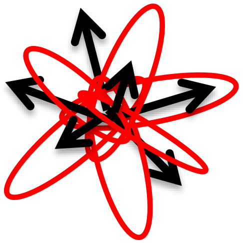
(No need to invoke dark matter annihilation to explain the gamma ray excess, just ordinary MSPs)



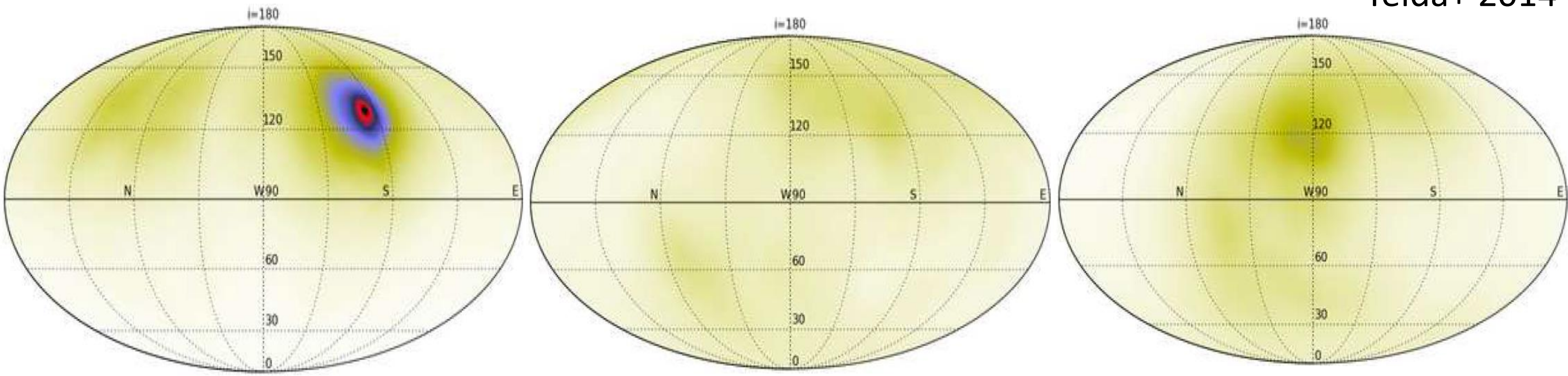
Brandt & Kocsis (2015)

Liquid crystals of stars to explain
Anisotropy of massive stars





Yelda+ 2014

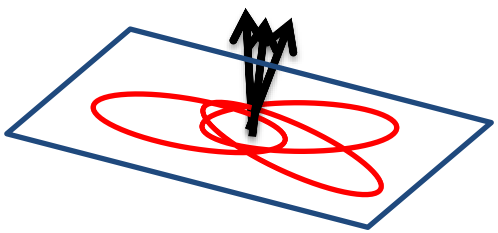


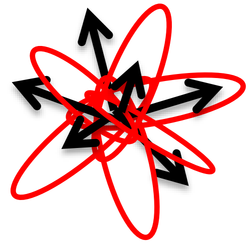
Inside 0.03-0.13 pc   Middle 0.13-0.27 pc   Outside 0.27-0.47 pc

Density map of angular momentum vector **directions** for massive stars **at three different locations**

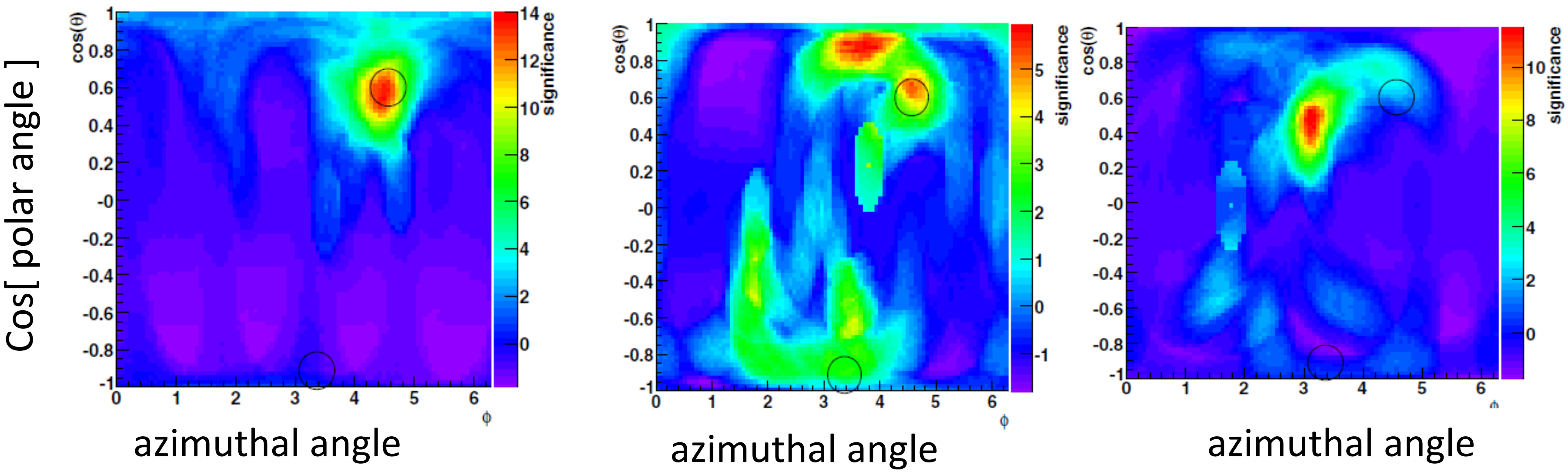
Liquid crystals of stars to explain

Anisotropy of massive stars





Bartko+ 2009



Inside 0.03-0.13 pc   Middle 0.13-0.27 pc   Outside 0.27-0.47 pc

Density map of angular momentum vector **directions** for massive stars **at three different locations**

Liquid crystals of stars at the centers of galaxies

orbital period << in-plane precession << reorientation << semimajor axis change

[1—10^4 yr] **[10^{4-5} yr]** **[10^{5-7} yr]** **[10^9 yr]**

Persistent ("resonant") torques between smeared orbits cause rapid reorientation

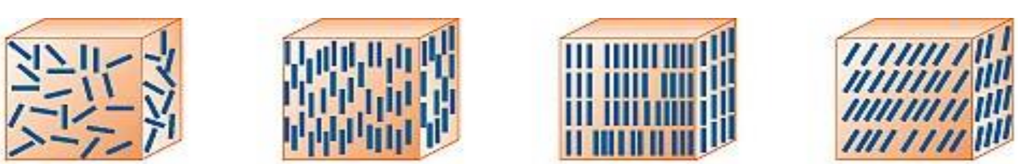
(Rauch & Tremaine 1996, Hopman & Alexander 2006, Eilon, Kupi, Alexander 2009, ...)

Hamiltonian of resonant relaxation

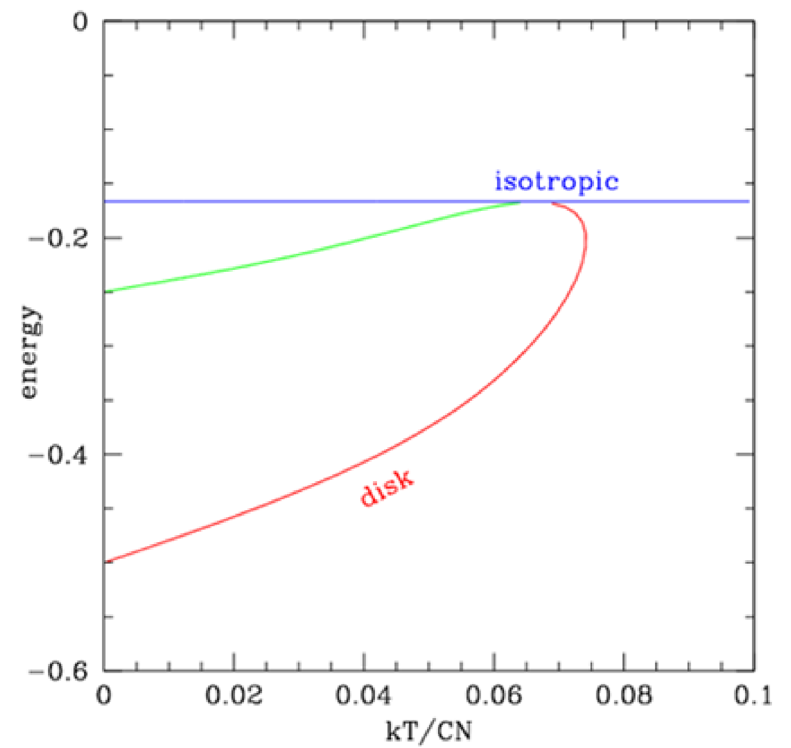
Kocsis & Tremaine 2014

- Multipole expansion
- Leading order is the Hamiltonian of a liquid crystal

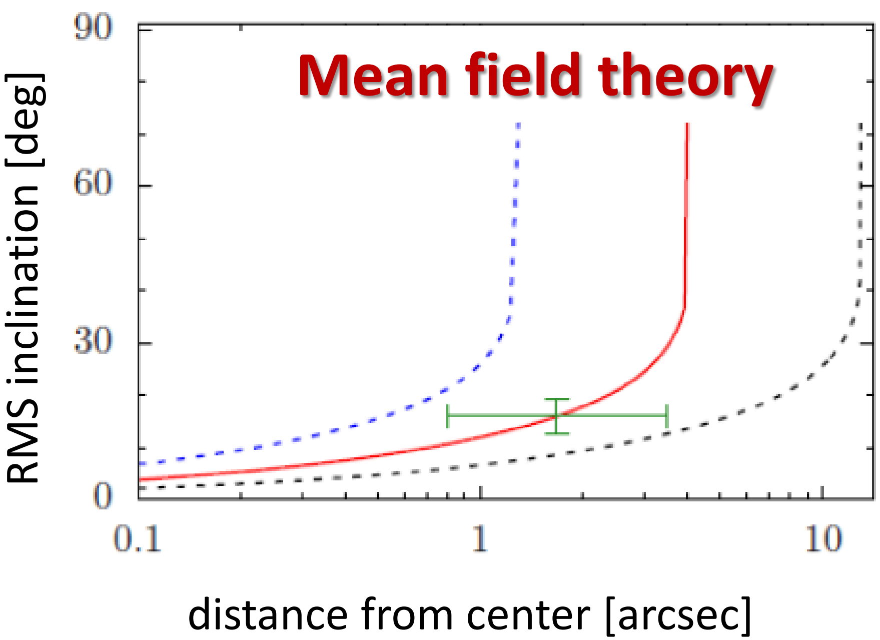
Interesting analogy: Liquid crystals

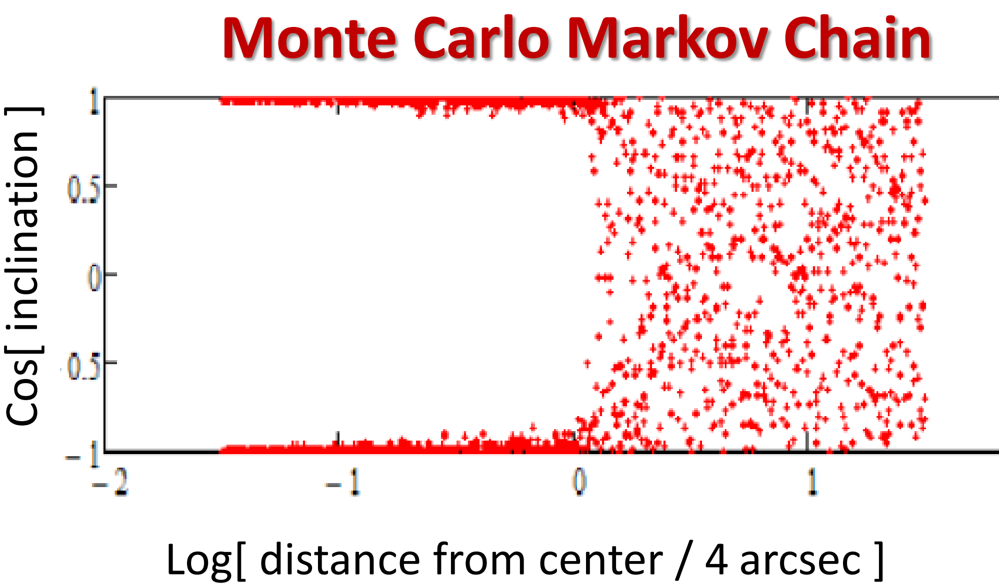


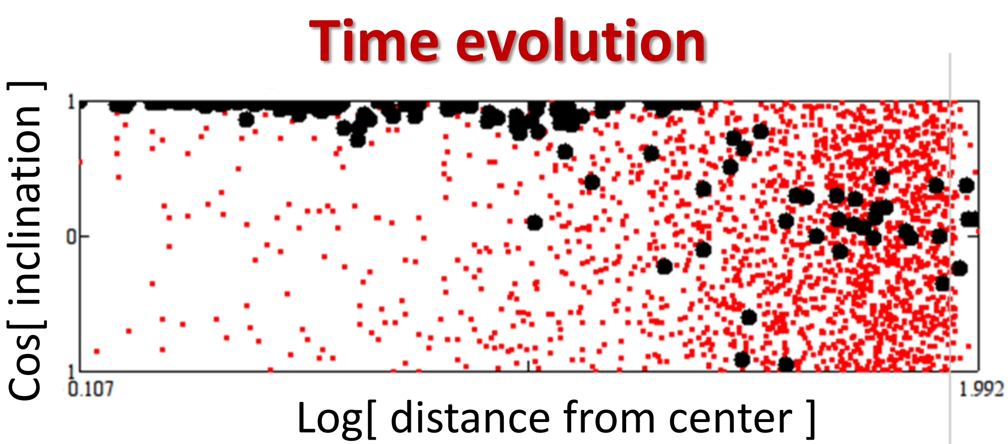
(a) Normal liquid (b) Nematic liquid crystal (c) Smectic A liquid crystal (d) Smectic C liquid crystal

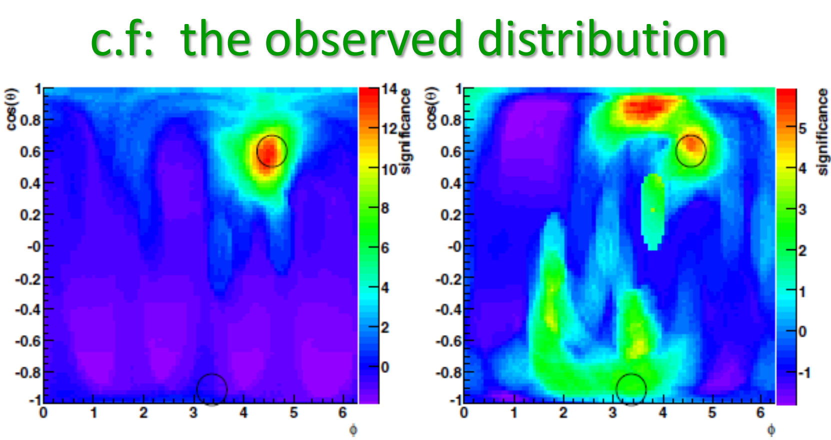


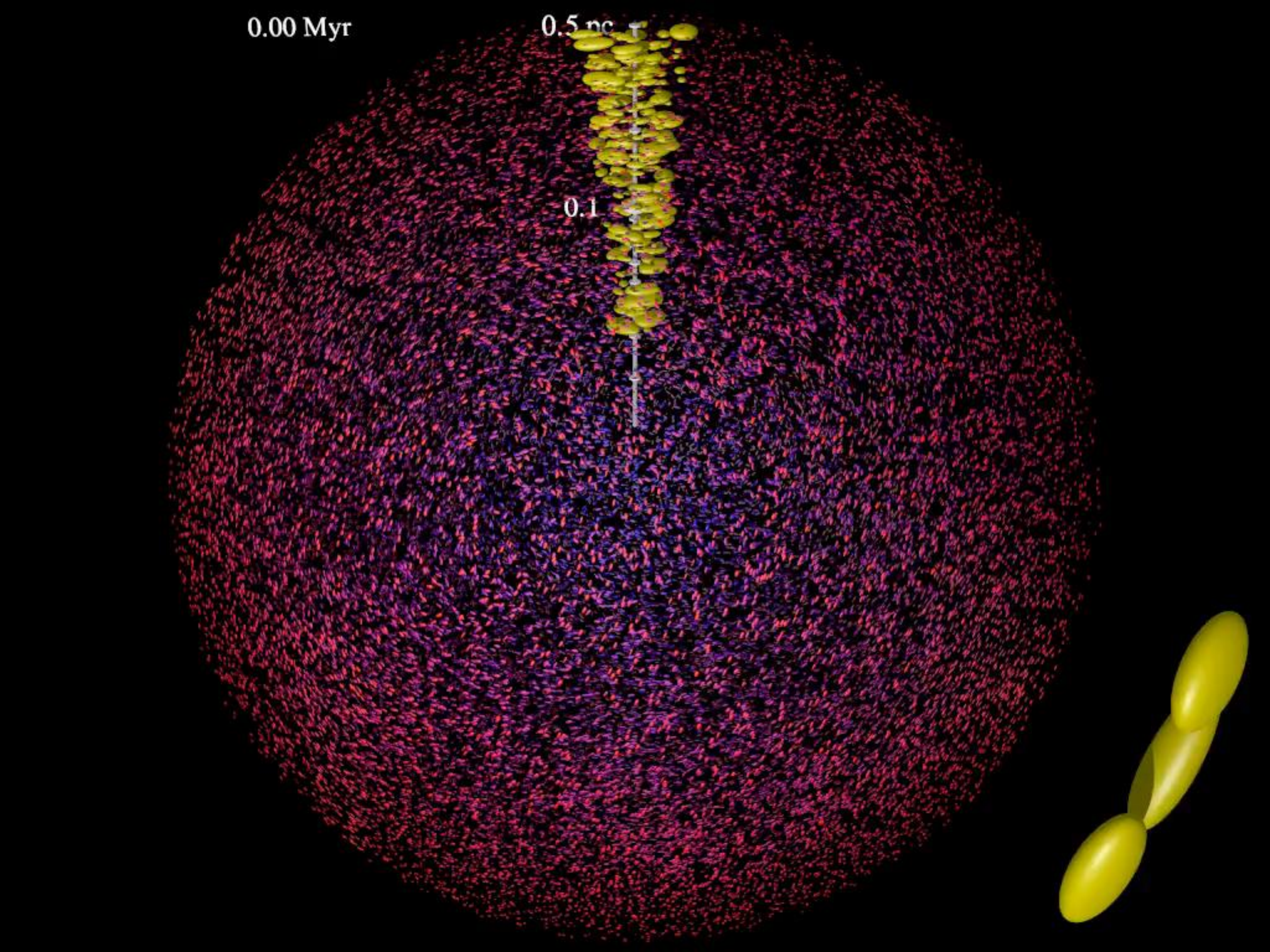
Results


Mean field theory
90
60
30
0
RMS inclination [deg]
0.1
1
10
distance from center [arcsec]

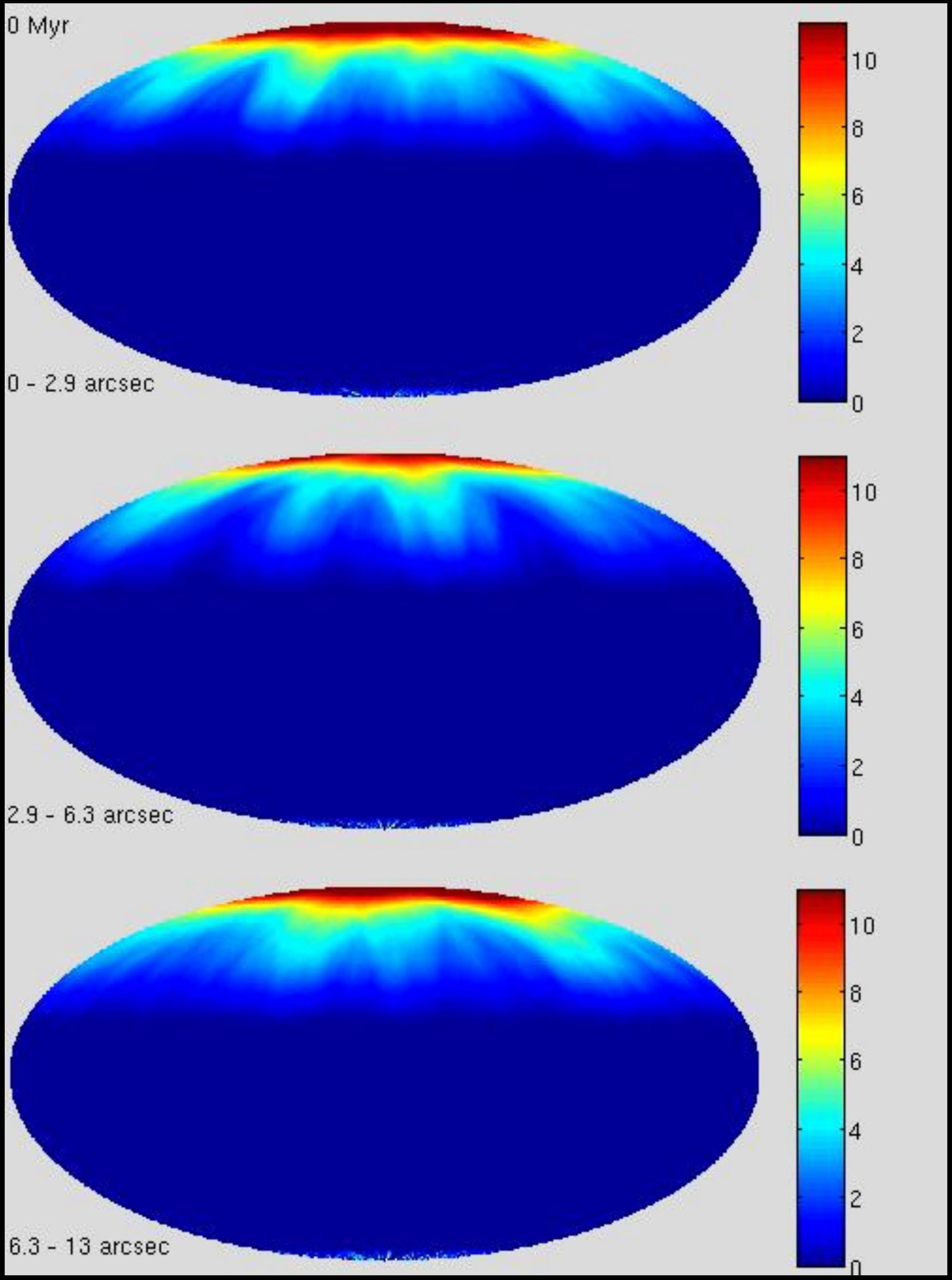

Monte Carlo Markov Chain
1
0.5
0
-0.5
-1
Cos[inclination]
-2
-1
0
1
Log[distance from center / 4 arcsec]


Time evolution
1
0
Cos[inclination]
0.107
1.992
Log[distance from center]


c.f: the observed distribution
cos(θ)
significance
φ

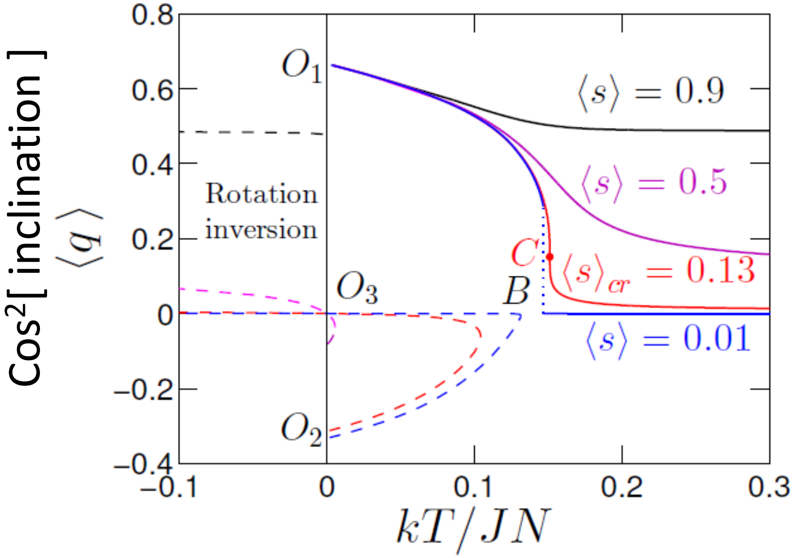


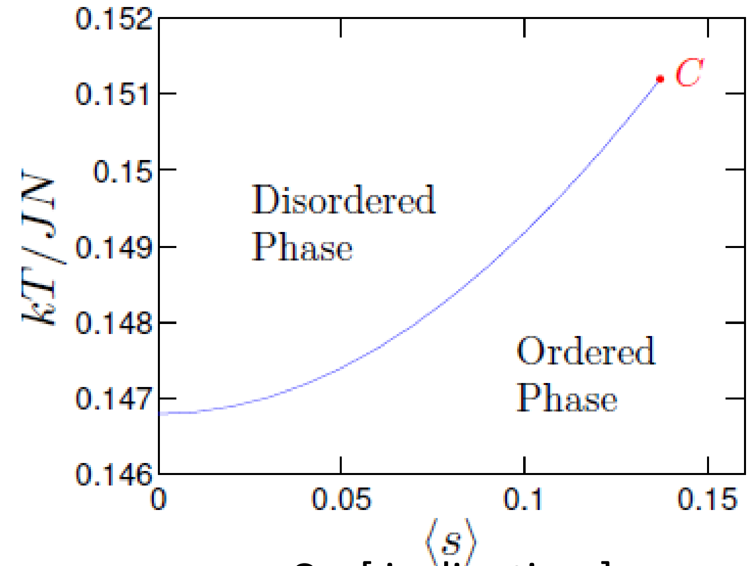
0.00 Myr
0.5 pc
0.1



0 Myr
0 - 2.9 arcsec
2.9 - 6.3 arcsec
6.3 - 13 arcsec
10
8
6
4
2
0

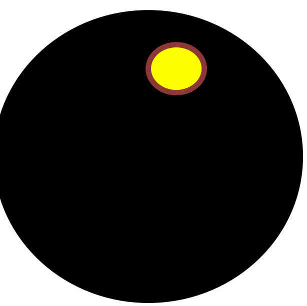
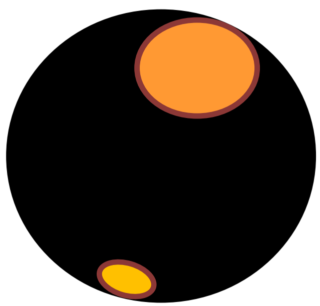
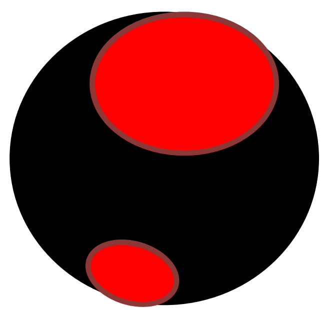
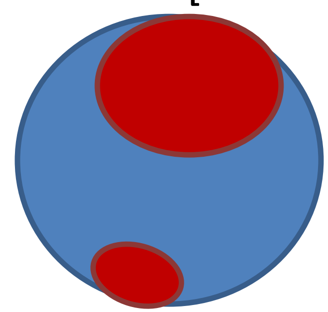
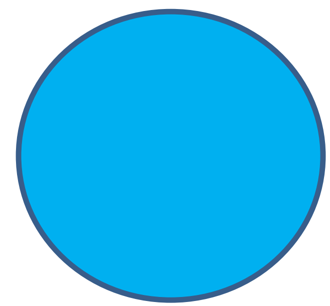
Statistical equilibria





Cos[inclination]

Distribtion of angular momentum directions:

-20 C / -4 F

-10 C / 14 F

0 C / 32 F

0 C / 32 F

5 C / 41 F

Summary

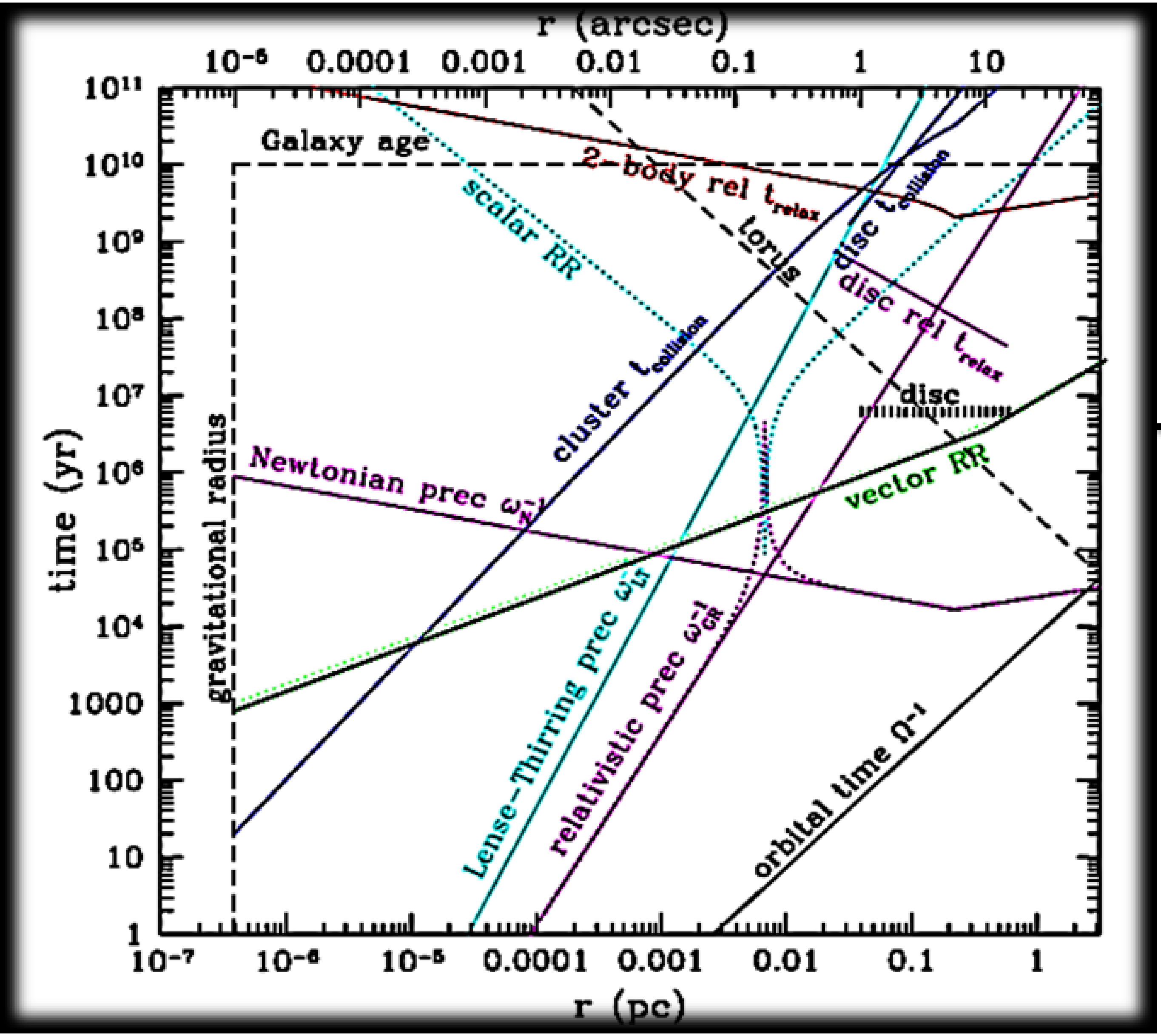
- **LIGO** will constrain the **high-mass end** of the **BH mass function** in dense star clusters

- **Fermi** detected remains of **disrupted globular clusters**

- Orbital planes of stars **reorient resonantly** (~Myr)
  - **Liquid crystals** have a similar Hamiltonian
  - First order phase transition → mixed phase (disk + spherical)
  - Young stars in the Galactic center show a similar structure

- Use this to
  - model the inclination distribution of different stellar types
  - predict the distribution of black holes

Hierarchy of Interaction Timescales vs. radius



Semimajor axis change

Eccentricity change

Disk age

Re-orientation of orbital plane

Precession in plane

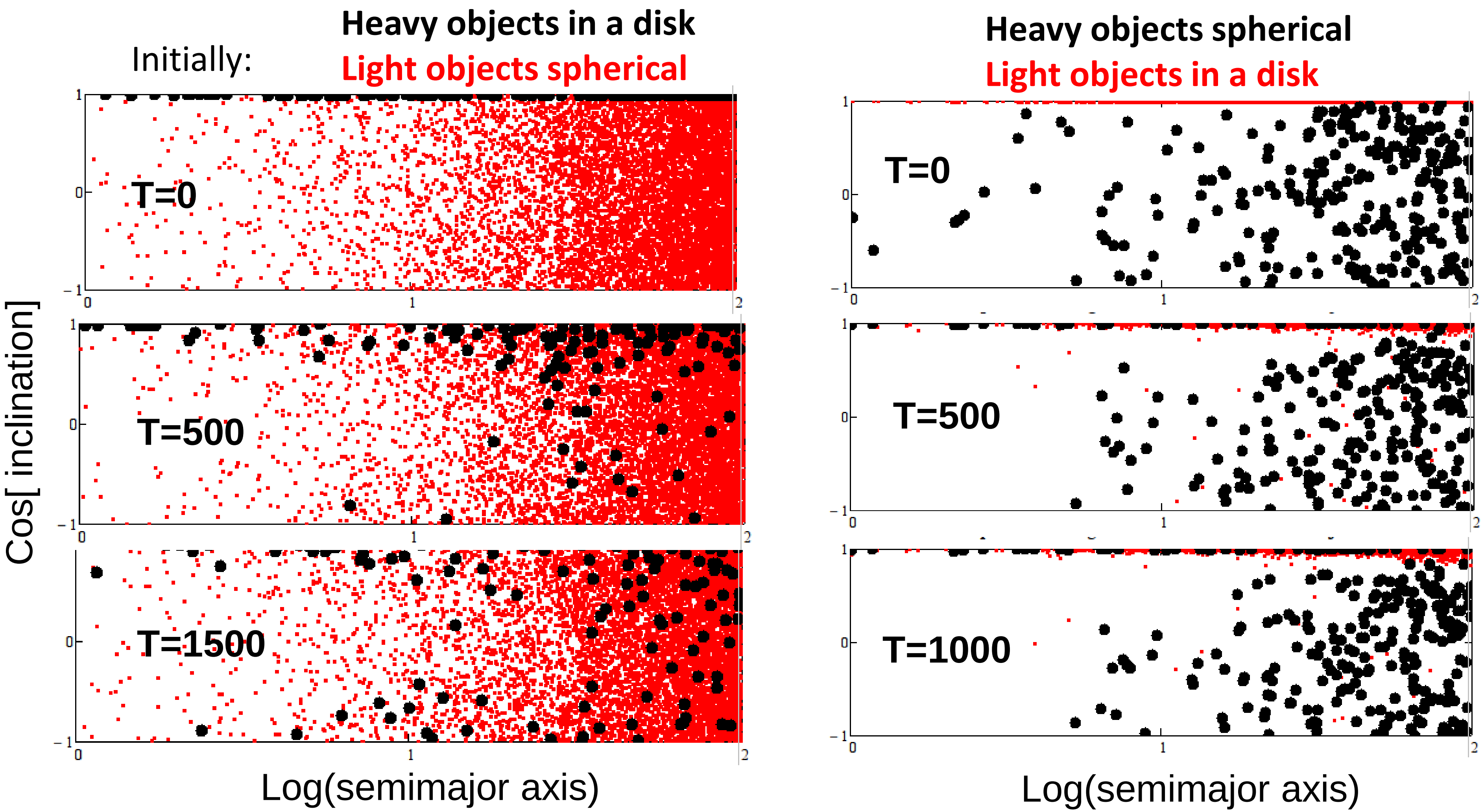
Keplerian orbit around SMBH

Time scale

Kocsis & Tremaine (2011)

Final state in the simulation

- Three snapshots in two simulations



Statistical equilibrium

- Objects fill up phase space uniformly

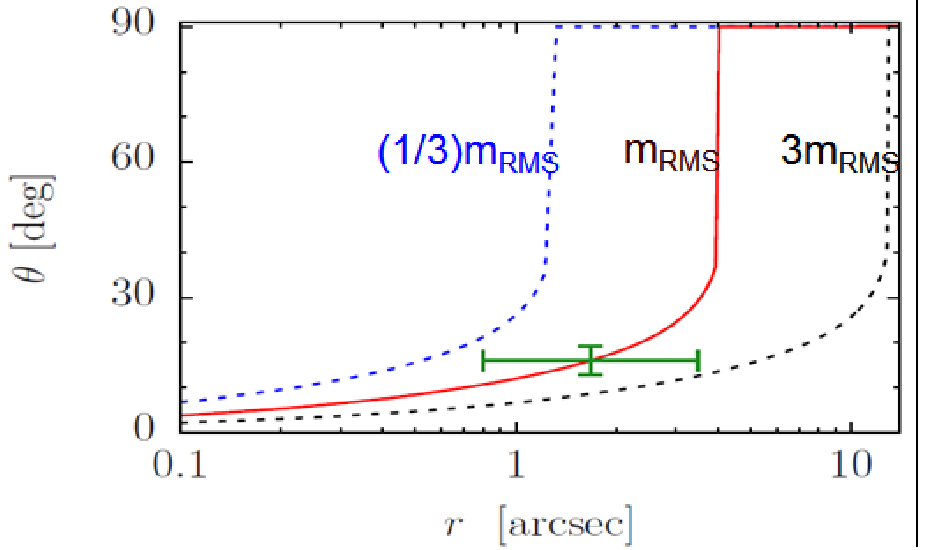
Find maximum entropy configuration under constraints $E_{tot} = \text{const}$

$$\mathbf{L}_{tot} = \text{const}$$

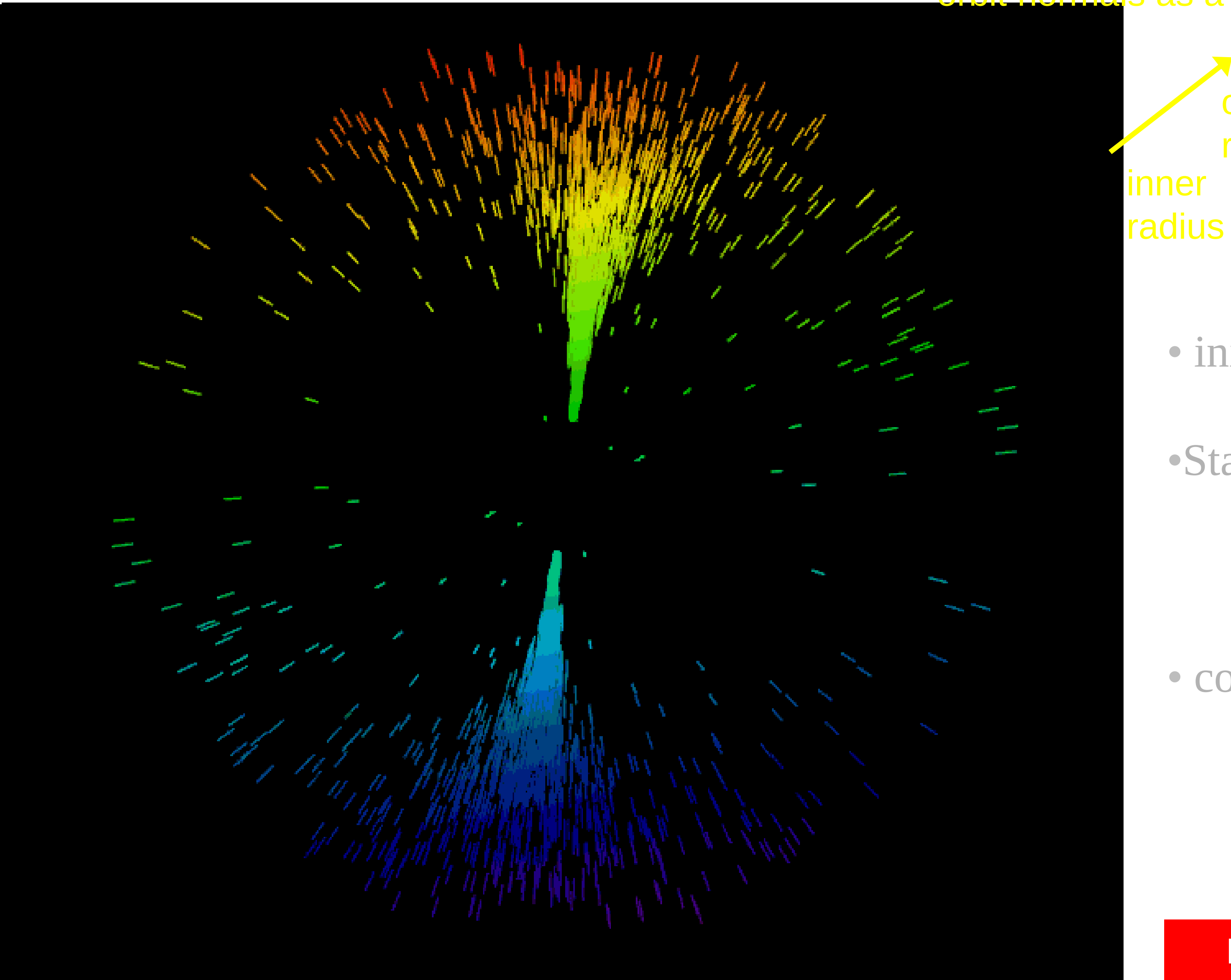
$$f(\mathbf{L}) = C \exp\left(-\frac{E(\mathbf{L})}{kT} \right)$$

Phase transition in inclination

- Mean field theory
  - Maier & Saupe (1959)
  - keep only the quadrupole term
  - assume interaction dominated by stars on same radius
  - self-consistency equation for quadrupole moment



Thermal equilibrium (maximum entropy)

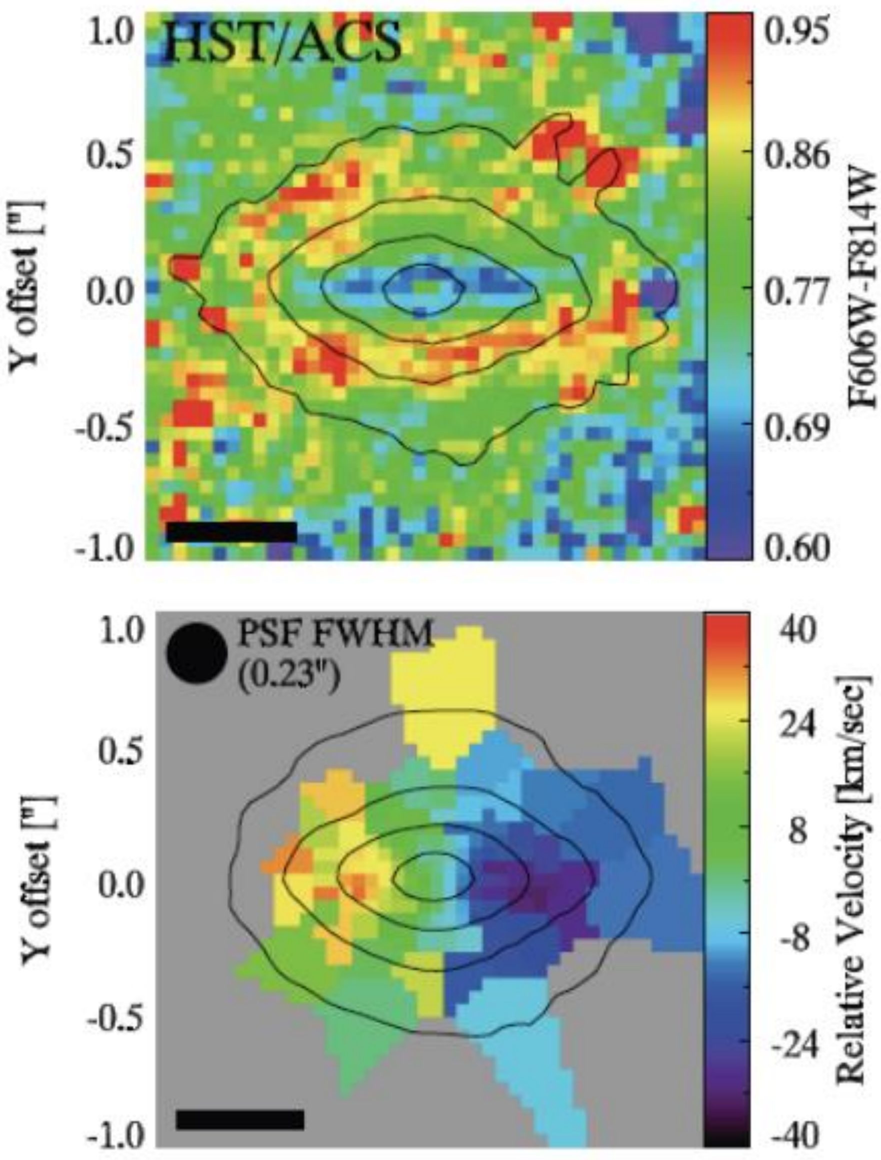


- initially warped disk
- Stars:
  - same mass, eccentricity
- conserve total energy "microcanonical ensemble"

Phase transition in inclination

Monte Carlo Markov Chain simulation

Nuclear Star Clusters



The densest stellar environments

Multiple stellar populations

Walcher+ ‘06, Rossa+ ‘06, Seth+ 06, 08, 10

- old, red spheroid
- young, blue disk

- Both rotate
- In many edge-on galaxies: counterrotating with respect to galaxy