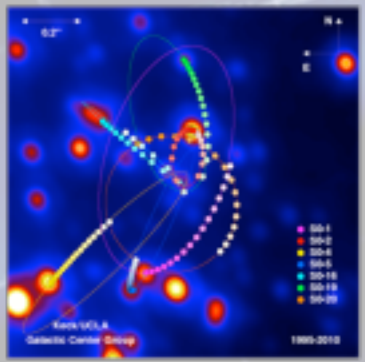
Finding the First Black Holes in the Milky Way's Backyard

Ryan O'Leary

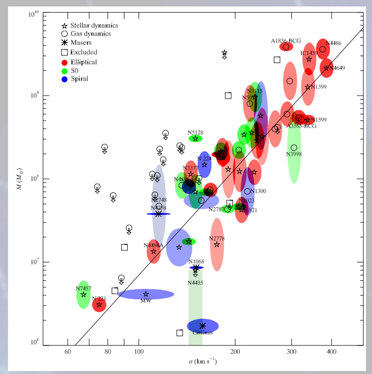
University of California, Berkeley

Motivation

Supermassive black holes at high z $\gtrsim 7$



Black holes in the centers of galaxies

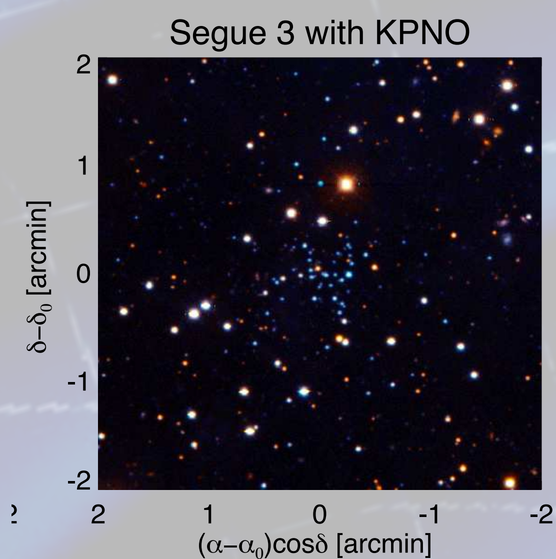


Black holes coevolve with host galaxy

Happy Accidents: Looking at the Smallest Clusters

Part I:
Recoiled Star Clusters in the Milky Way

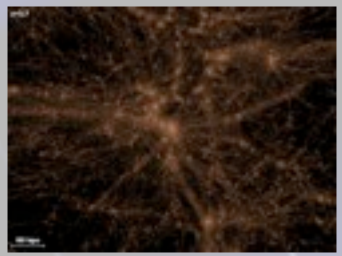
O'Leary & Loeb 2009,2011



Part II:
Black Holes in Tidally Stripped Clusters in the Milky Way

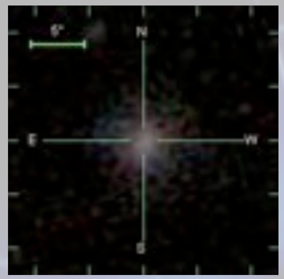
O'Leary 2011 (prep)

Recoiled Star Clusters in the Milky Way



- Hierarchical Galaxy Formation

- Properties and Evolution of Recoiling Star Clusters

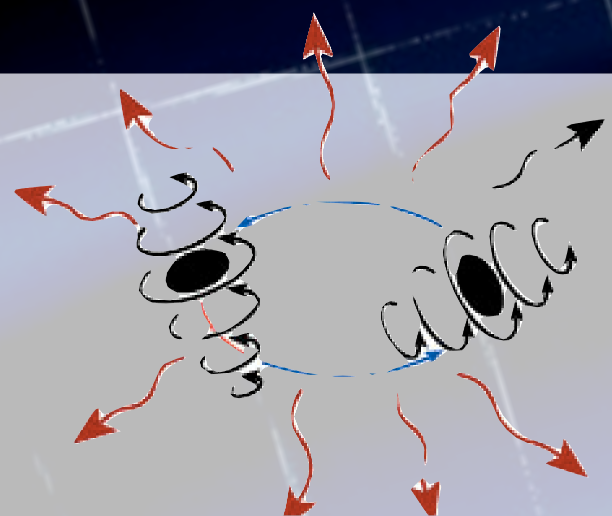


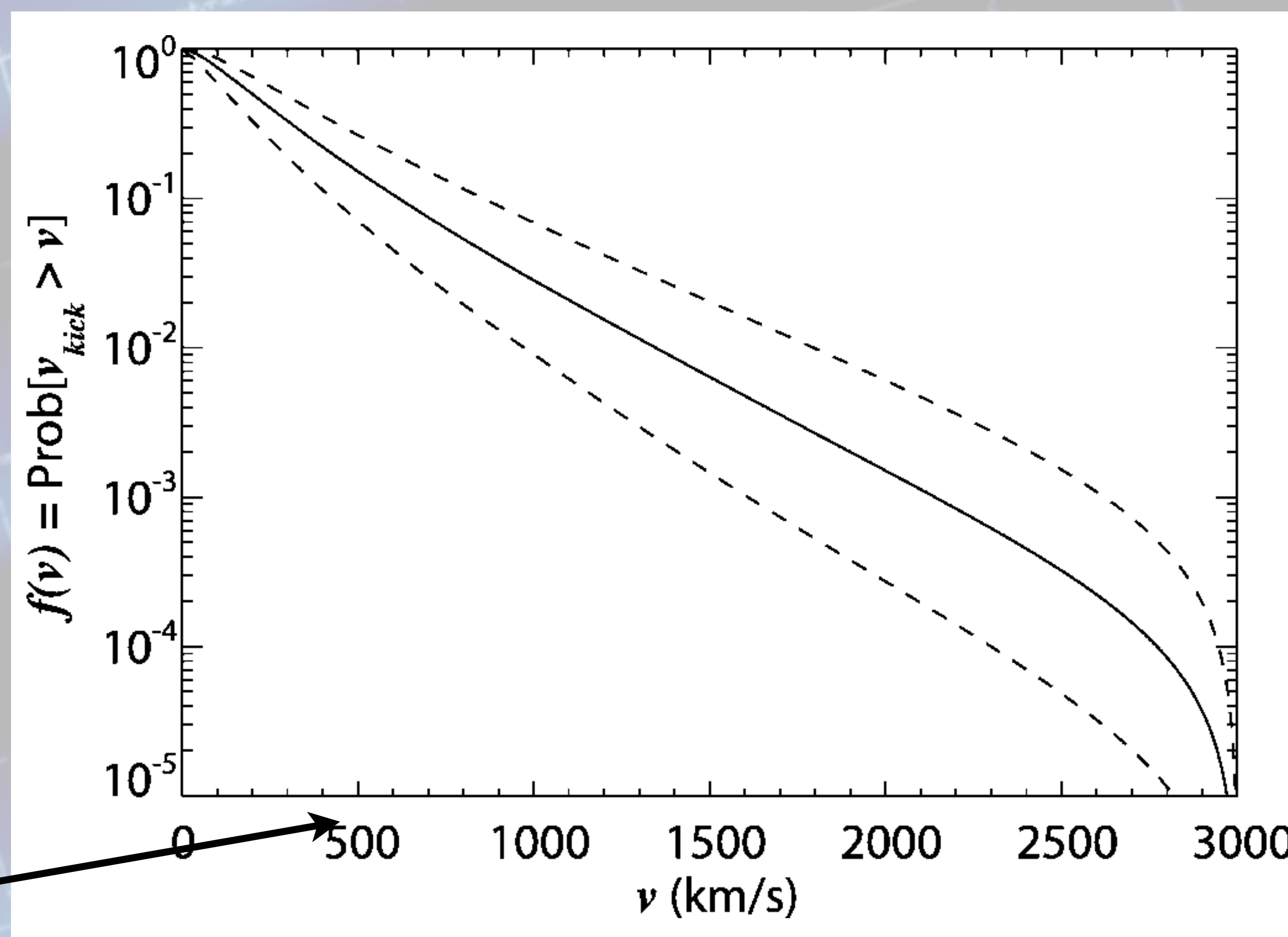
- Search Strategies and Progress

O'Leary & Loeb 2009,2011

Gravitational Wave Recoil

GWs



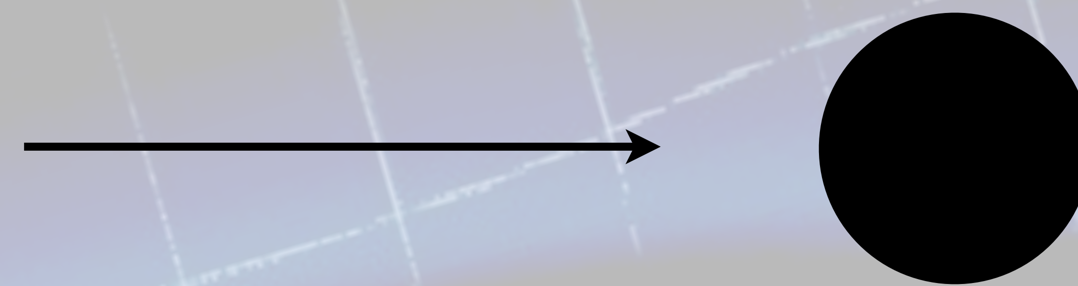


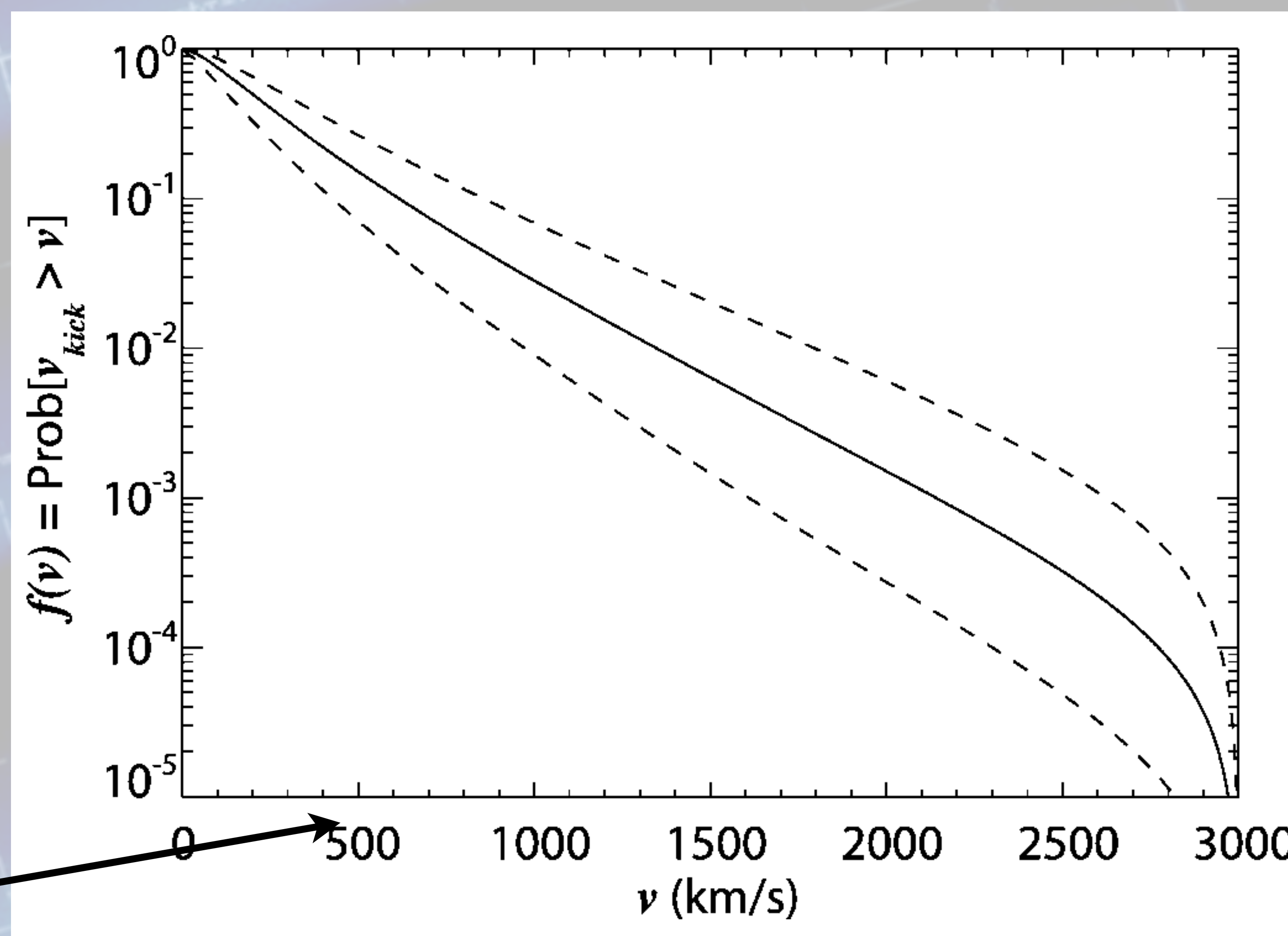
Milky Way
Escape Velocity

Schnittman & Buonanno 2007

Gravitational Wave Recoil

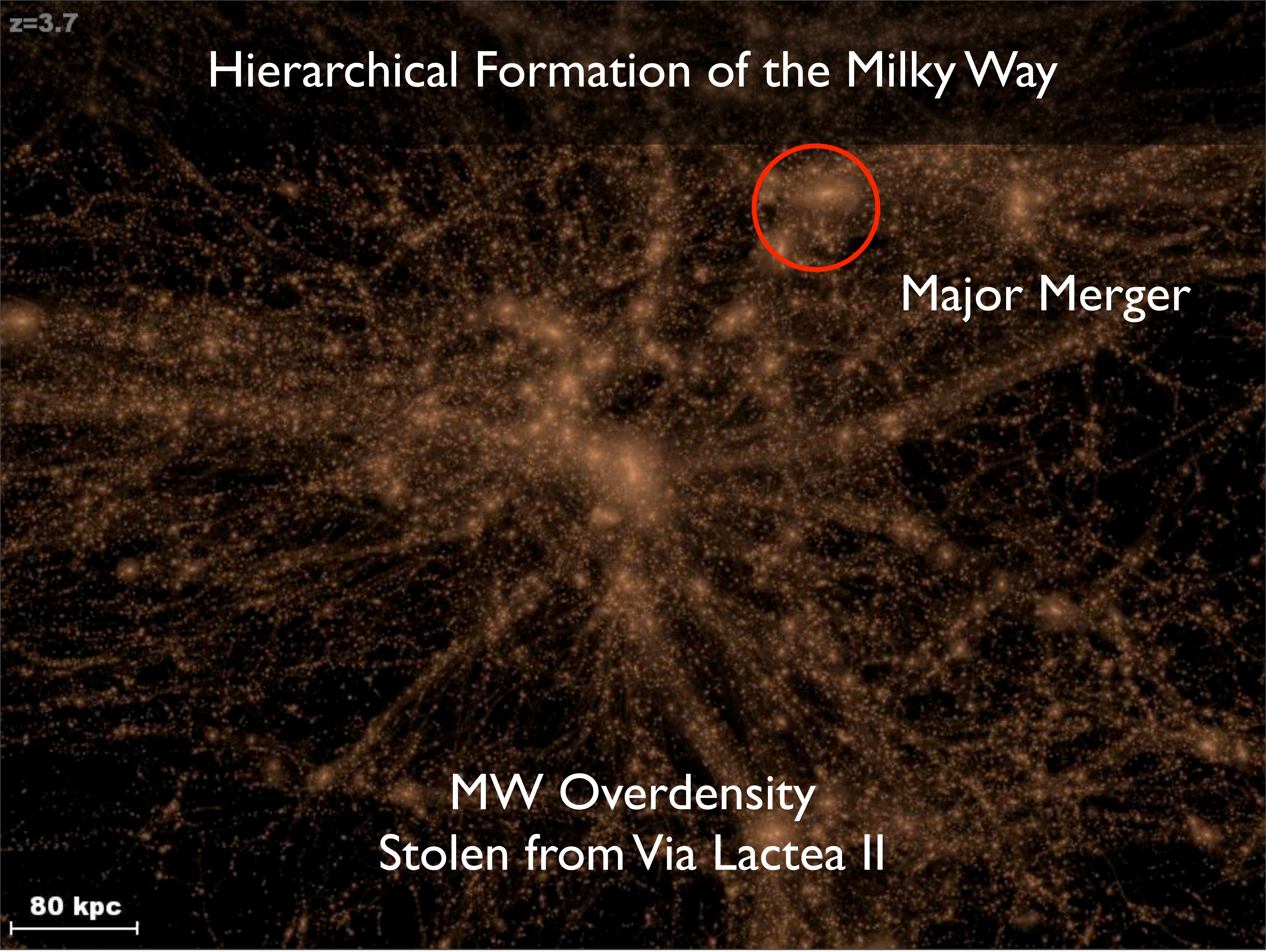
GWs

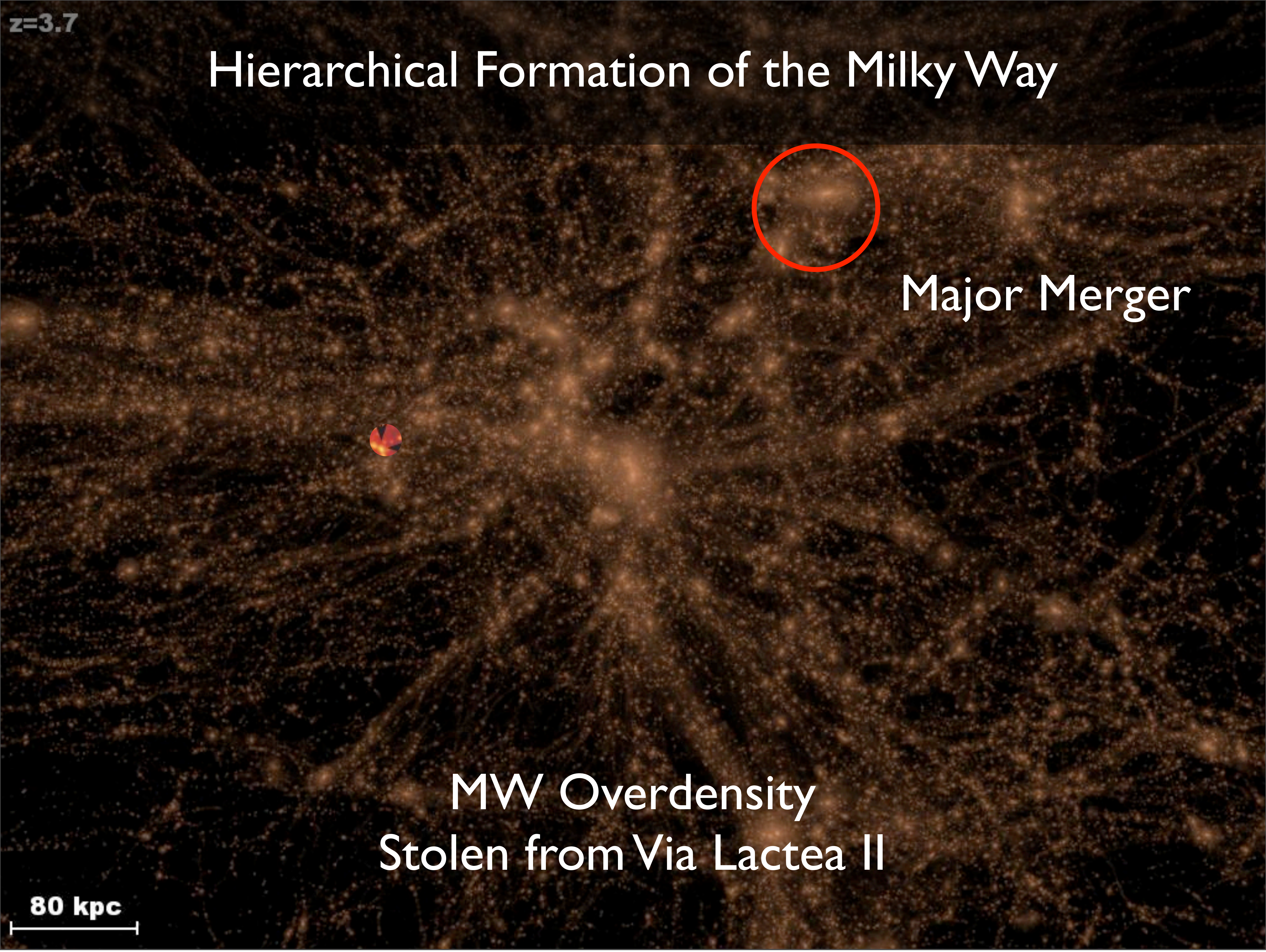




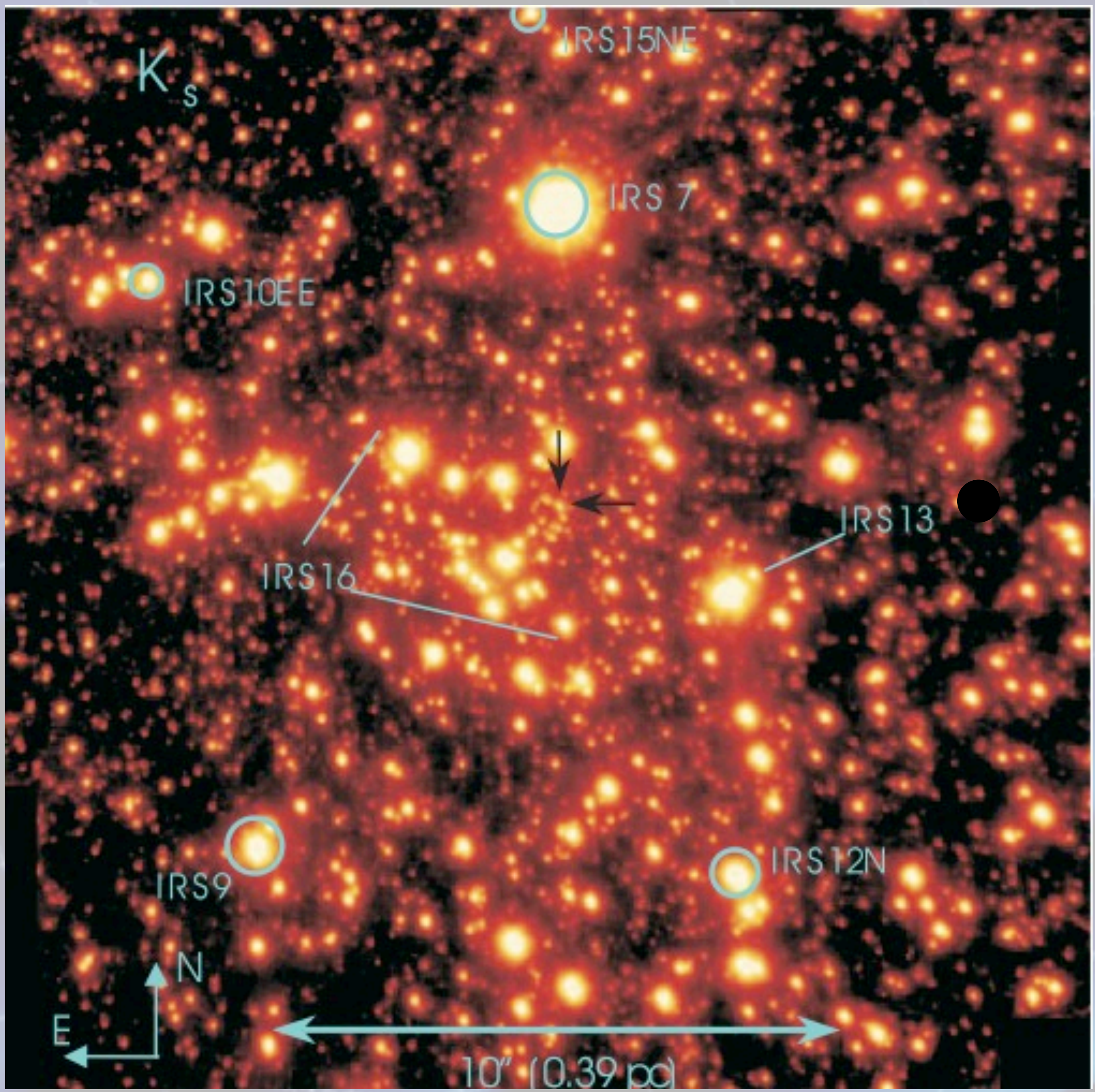
Milky Way Escape Velocity

Schnittman & Buonanno 2007


z=3.7
Hierarchical Formation of the Milky Way
Major Merger
MW Overdensity
Stolen from Via Lactea II
80 kpc


z=3.7
Hierarchical Formation of the Milky Way
Major Merger
MW Overdensity
Stolen from Via Lactea II
80 kpc

Cluster of Stars



Number of stars in cluster

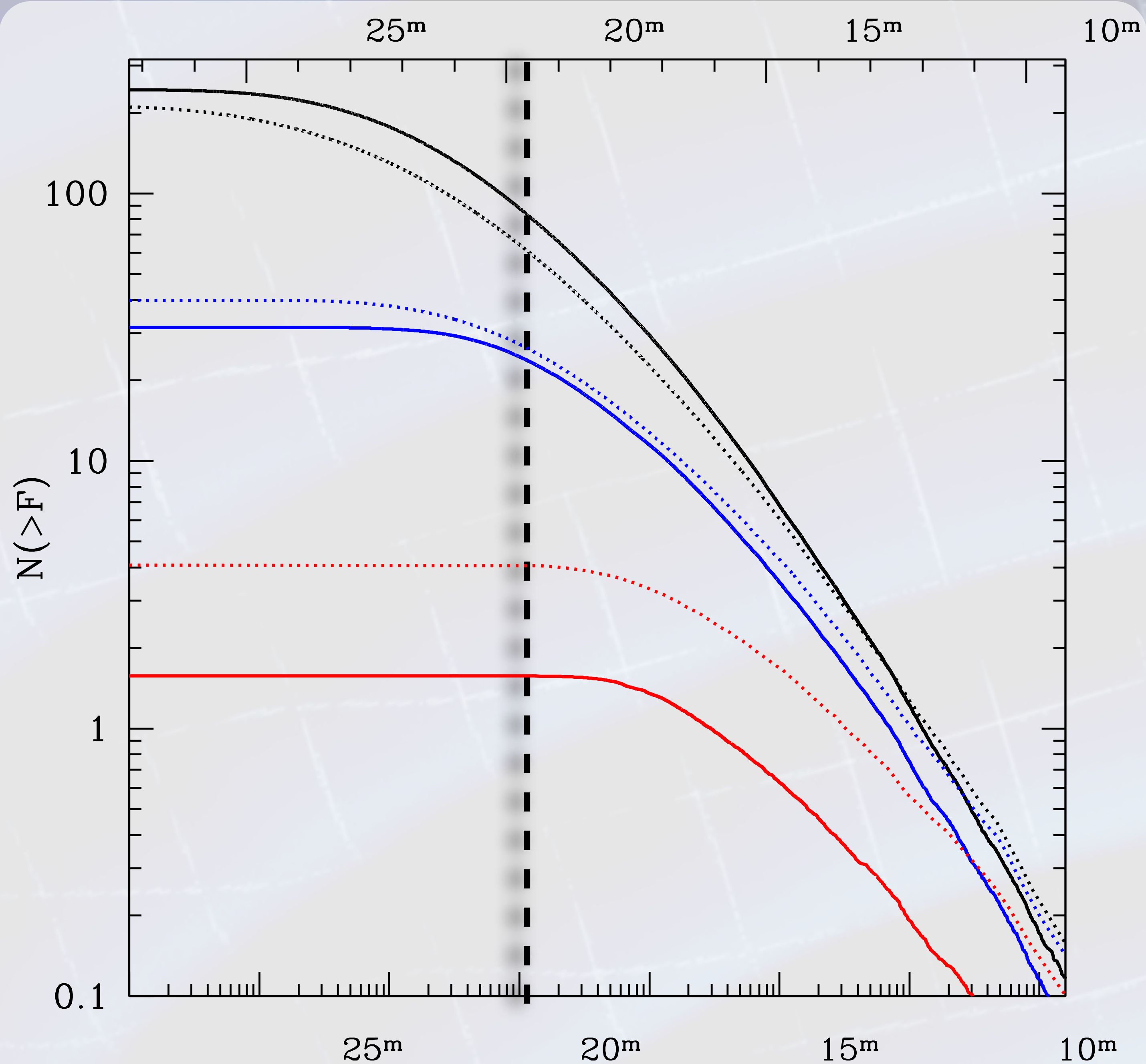
$$N_{\rm cl} \approx \frac{2M_\bullet}{m_*}\left(\frac{v_k}{\sigma_*}\right)^{2\alpha-6}$$

$$N_{\rm cl} \approx .04\frac{M_\bullet}{m_*}$$

If cusp regeneration is efficient

SMBH Fossils in our Backyard

SDSS Limit



Method:

Generate Monte-Carlo Merger tree models

(Parkinson et al. 2008)

Assume M-σ relation for galaxy M > $10^8 M_\odot$

(Tremaine et al. 2002)

Assign random kicks to the mergers

(Schnittman & Buonanno 2007)

Distribution of the BHs roughly follows the dark matter halo.

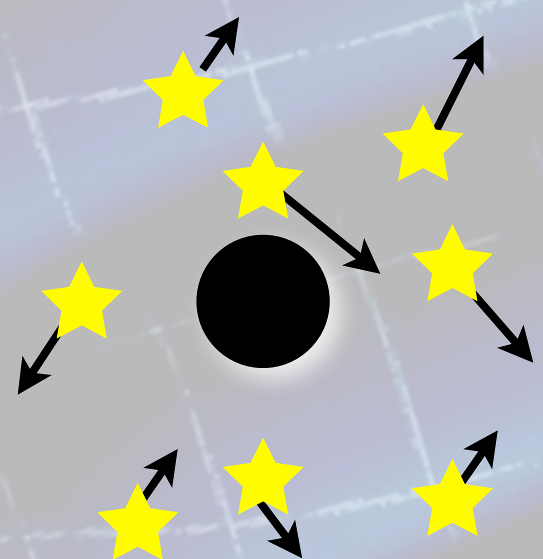
Comparable Number of BHs to:

Volonteri & Perna 2006
Libeskind et al. 2006
Islam et al. 2004

Long Term Evolution

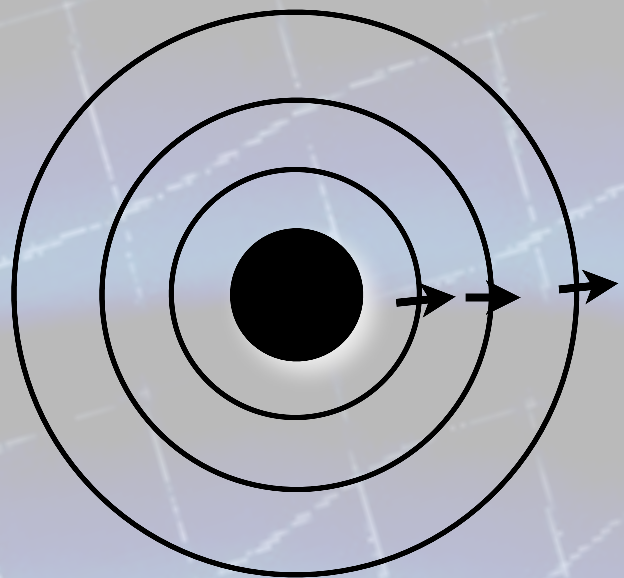
N-body Simulations with BHint

Ulf Löckmann, Holger Baumgardt



Includes all dynamics
Accurate
Slow

Fokker-Planck Simulations



Add non-diffusive effects
Many Approximations
Very Fast

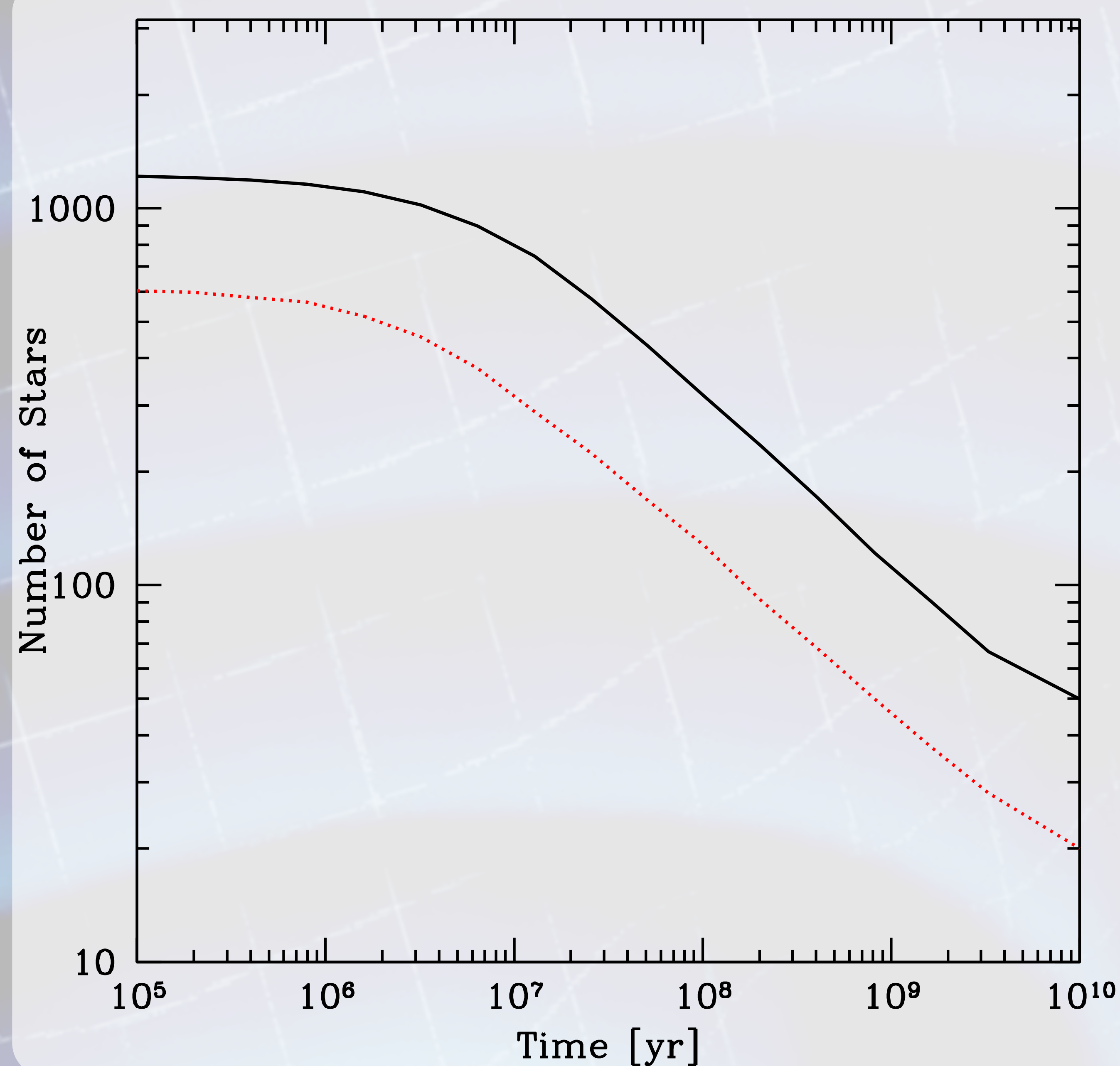
Cluster Decay

Perform N-body simulations of stars around a massive object (BHint).
Ulf Löckmann, Holger Baumgardt

40% of Stars Ejected for 10^4 Msun
(40% are Disrupted)

Break depends on M

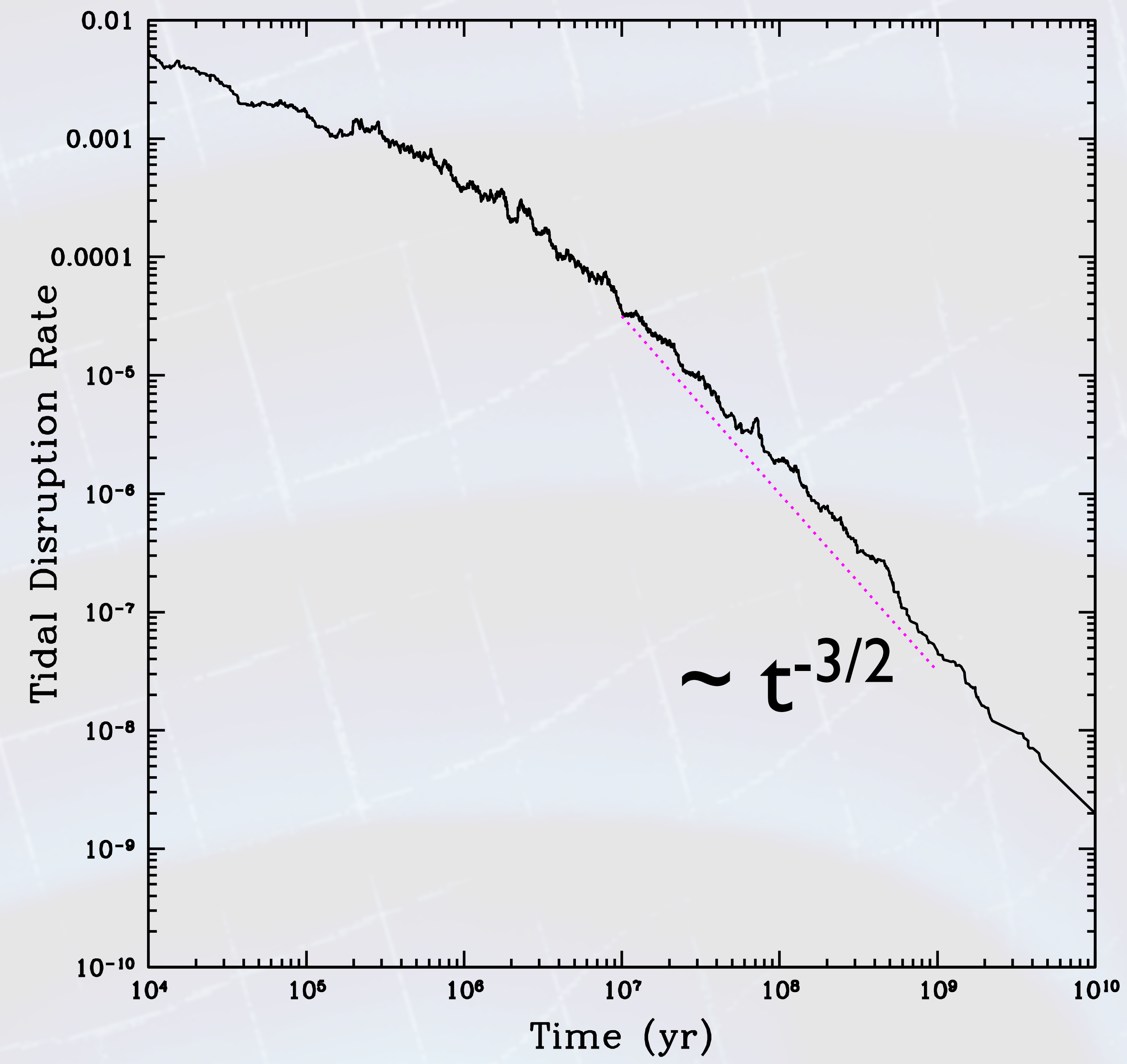
$$N_{\rm cl} \approx 800 M_5^{13/8} t_{10}^{-1/2}$$



Tidal Disruptions

Perform N-body simulations of stars around a massive object (BHint).

Ulf Löckmann, Holger Baumgardt



40% of Stars Ejected

40% of Stars Disrupted

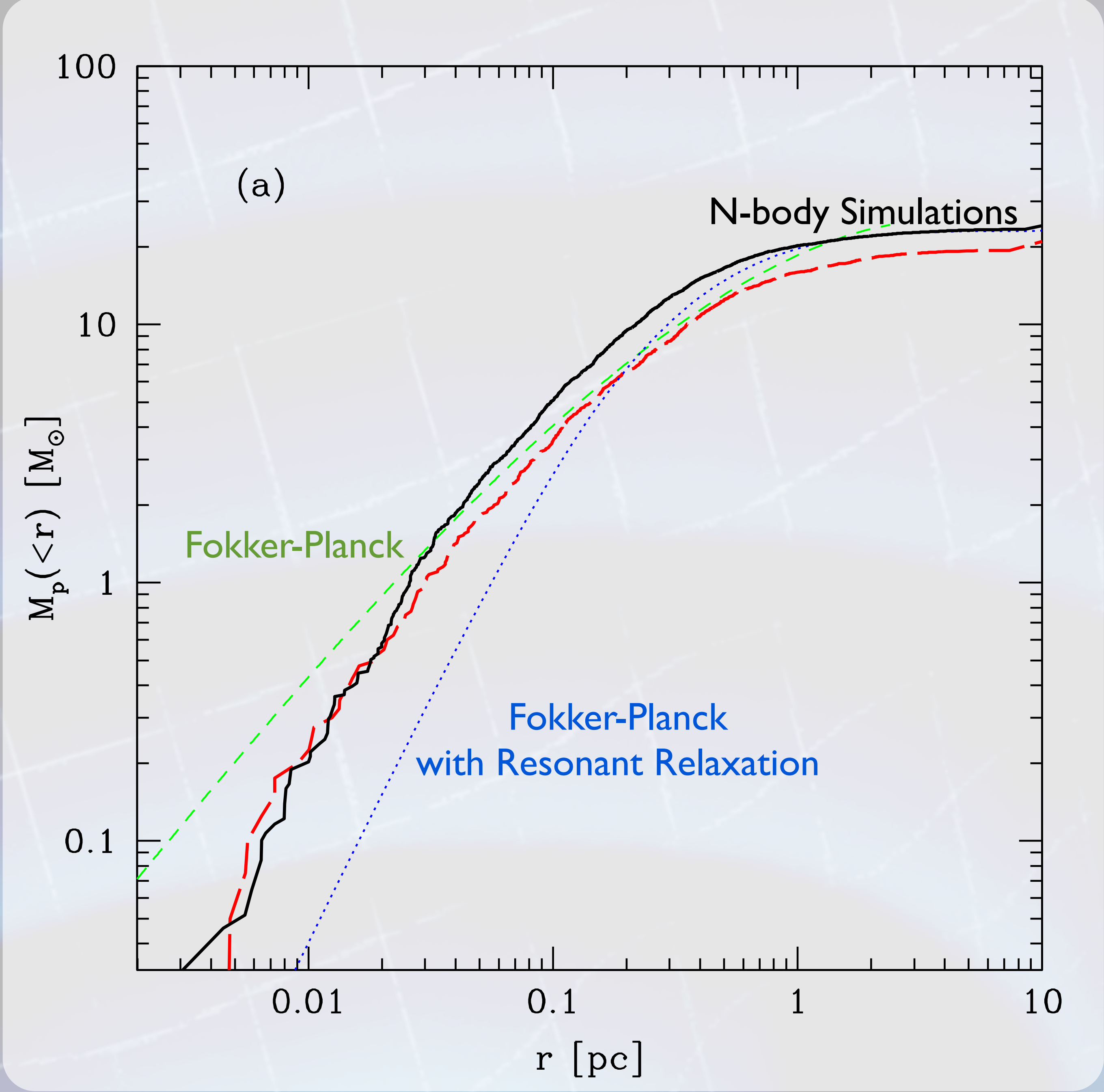
Results

Power-law slope from regular relaxation

Normalization from large angle scattering & resonant relaxation/tidal disruption

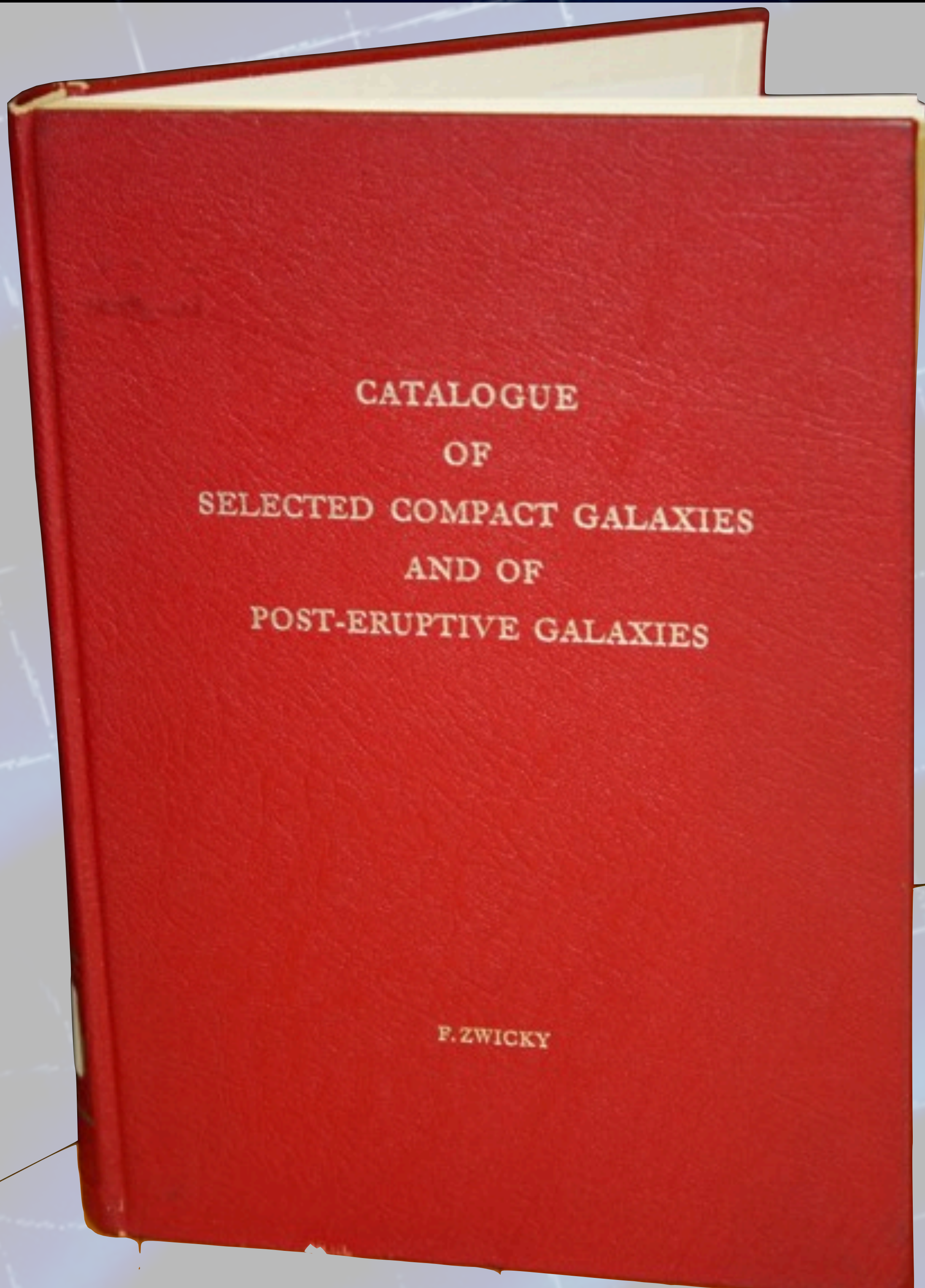
Henon '69, Lin & Tremaine '80

Robust Density Profile $\sim r^{-2.15}$



Cluster around a 10^4 $M_\odot$ ejected BH

Zwicky’s Catalog



Zwicky Cataloged Compact Galaxies

Wal Sargent found 14 objects had z=0 (1970)

Visually Identified 12 as galaxies

Getting My Hands Dirty

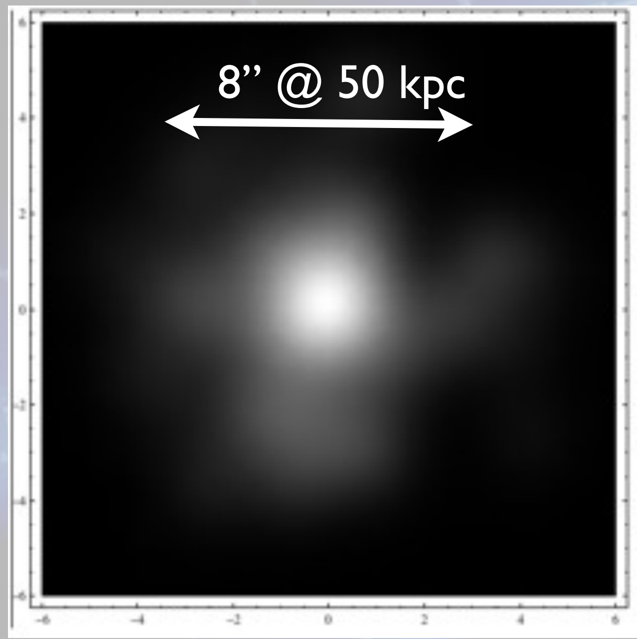
A Search Through SDSS

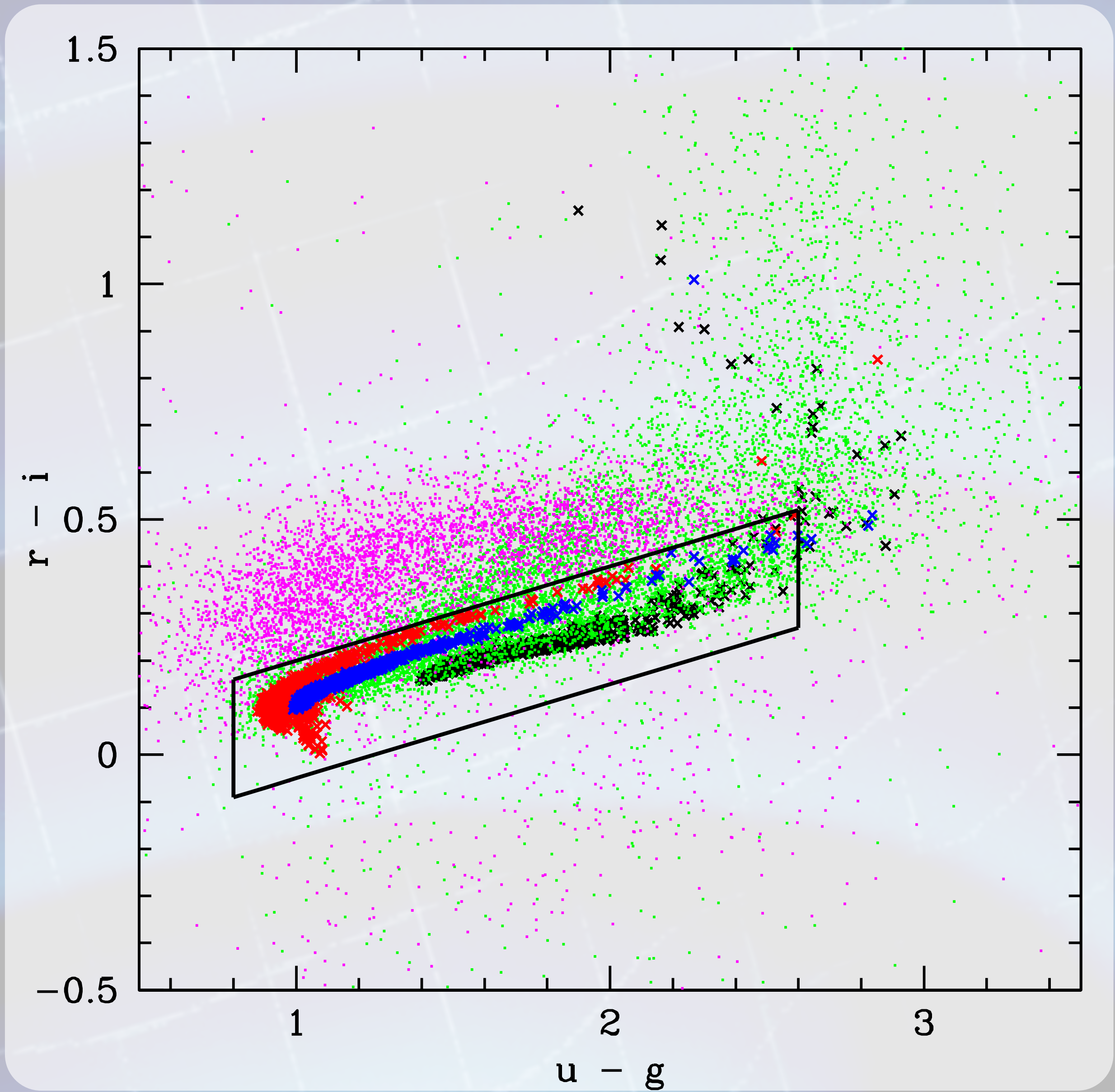
Many Objects have sizes > 3”

Colors more like stars than galaxies (see Merritt et al. 2009 as well) and highly stochastic.

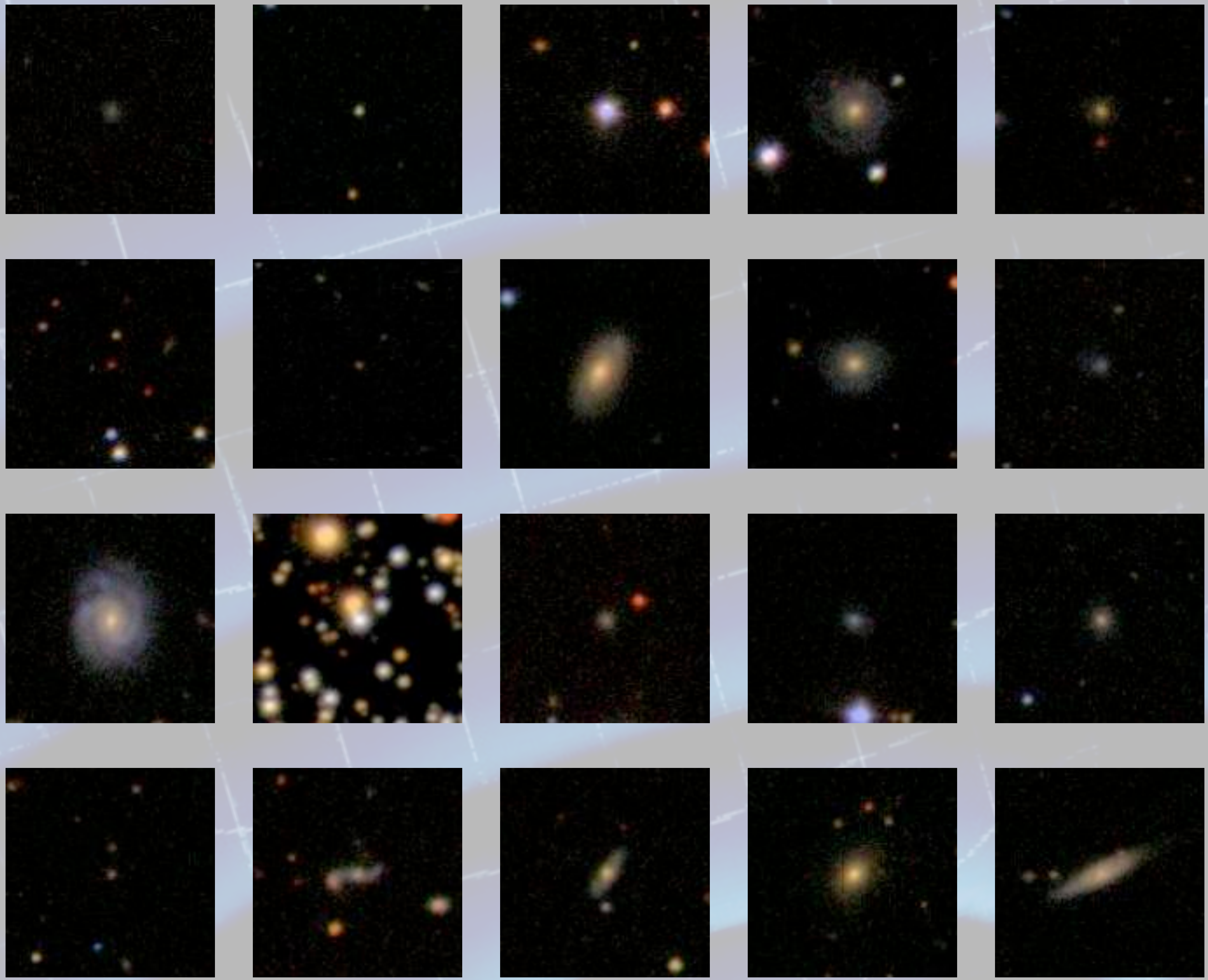
Different density profile than galaxies

Spectroscopic followup can confirm/ disprove candidates





Getting My Hands Dirty

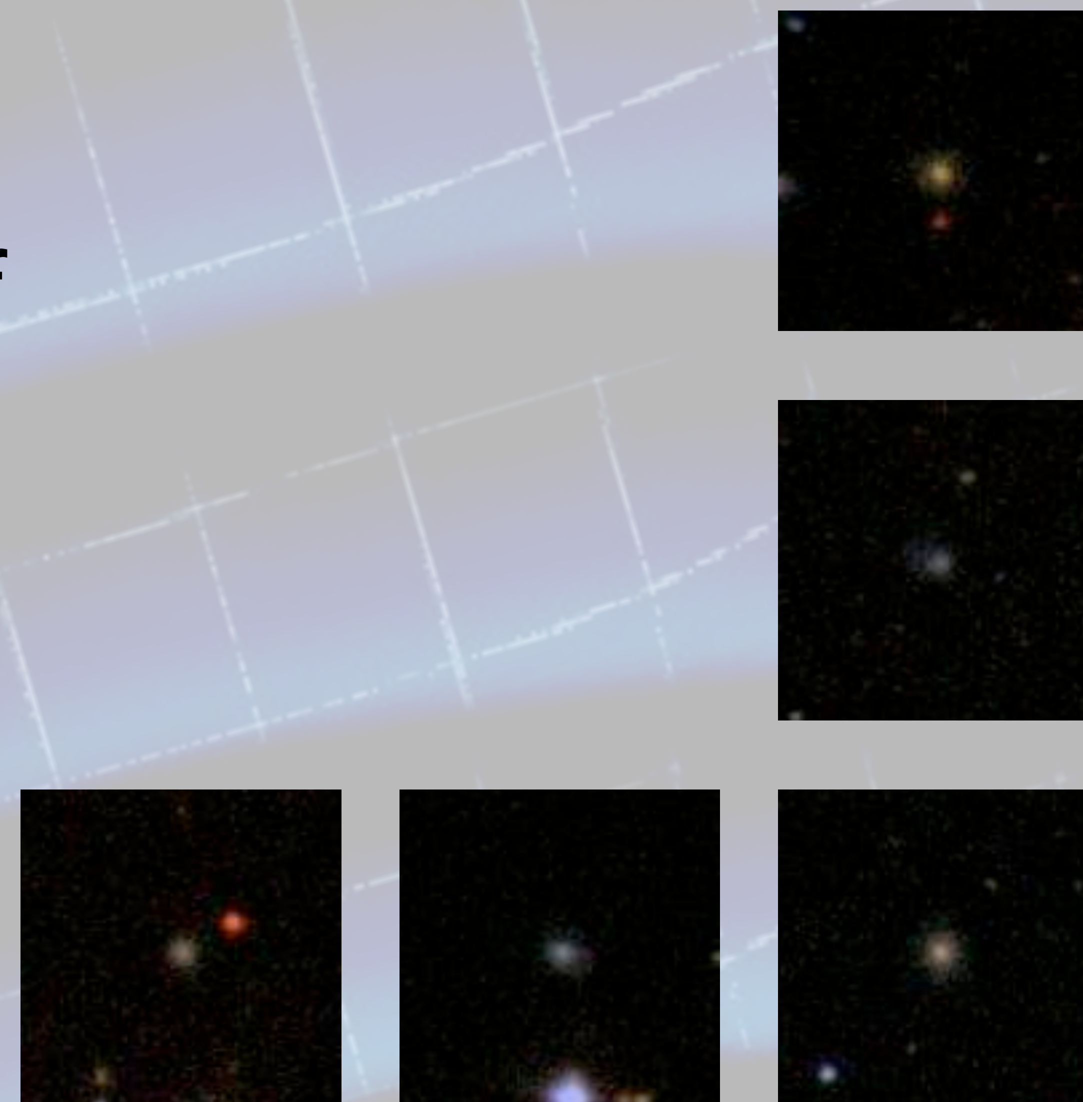


SDSS DR 7

Getting My Hands Dirty

Look for:

- ✓larger than 3” to get rid of partially resolved binaries
- ✓Stellar Colors
- ✓Round Shape
- ✓Correct Light Profile
- ✓Visually Inspect Objects



SDSS DR 7

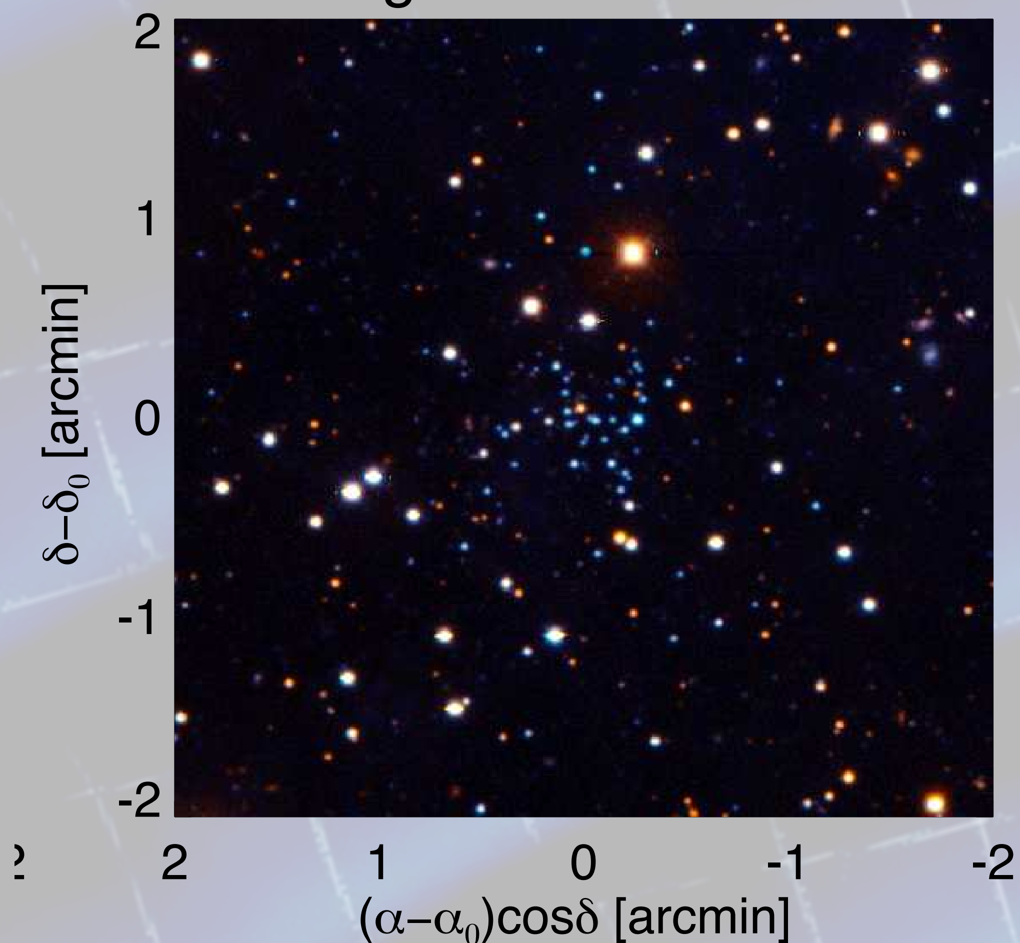
~100 candidates remain
Can follow up with spectroscopy

Part I: SMBH Fossils in our Backyard

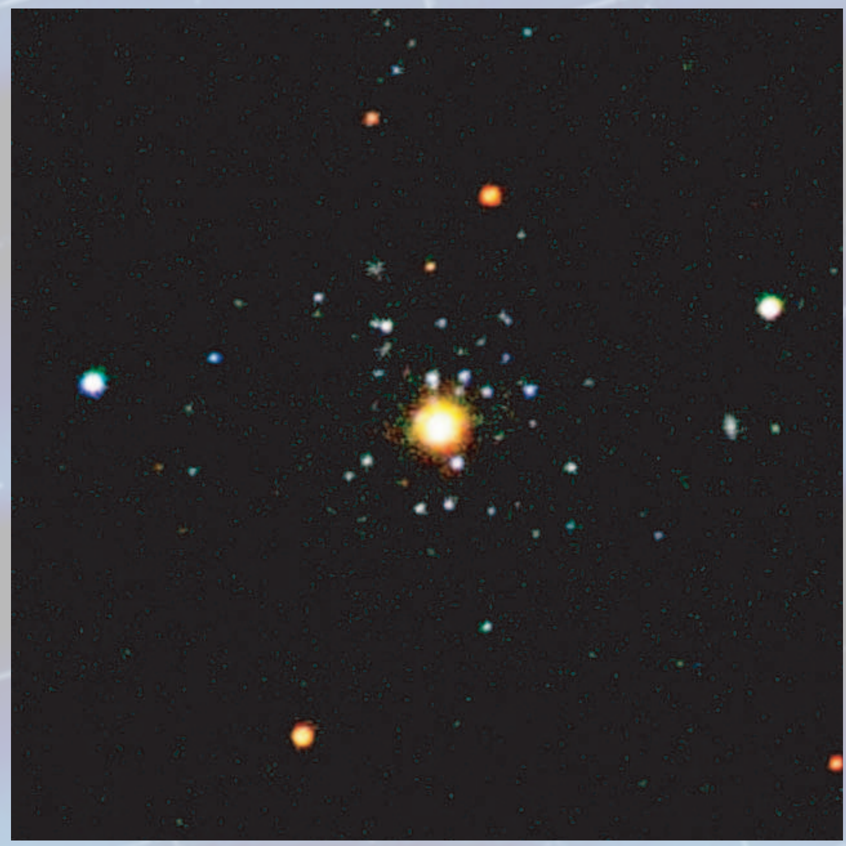
- Inevitable Process
- Cluster Rapidly Expands ~ 1pc
- Have high Keplerian dispersions, and not point like
- Extragalactic Tidal Disruptions are common
- Can also look in local group around M31, M33, etc.
- Larger BHs may be found in the Virgo cluster as well

(Merritt et al. 2009)

Part II: Black Holes in tidally Stripped Clusters



Belokurov et al. 2010

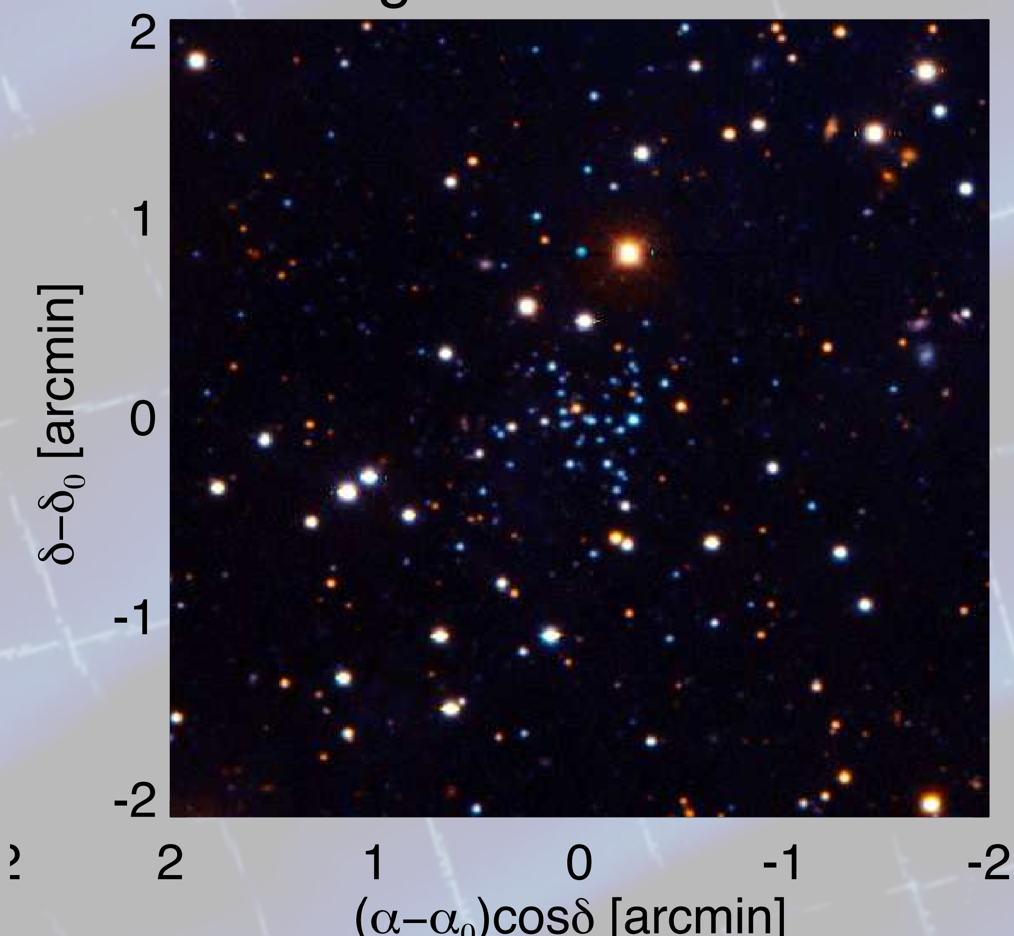


Koposov I

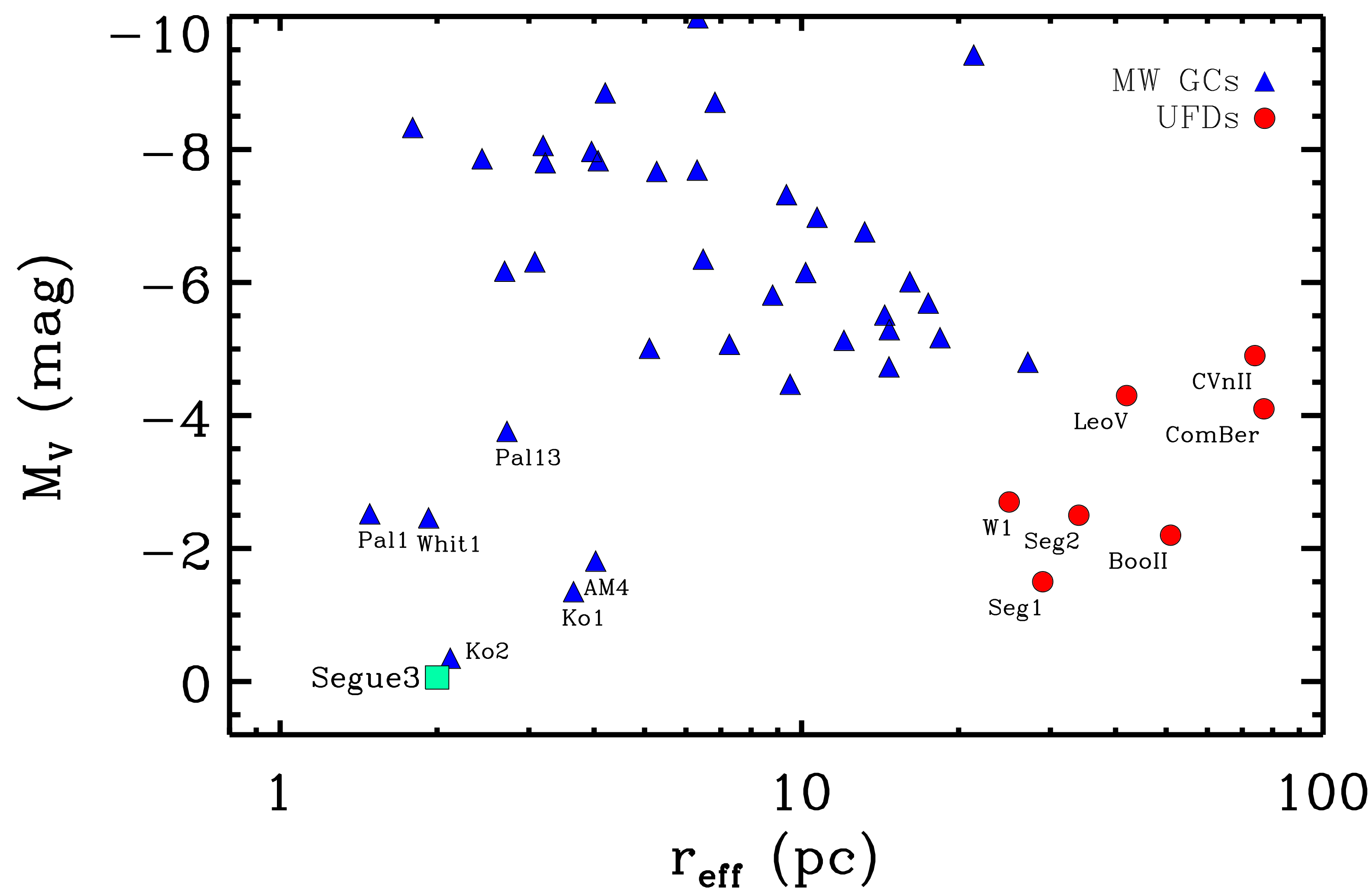
Koposov et al. 2007

Segue 3

Segue 3 with KPNO

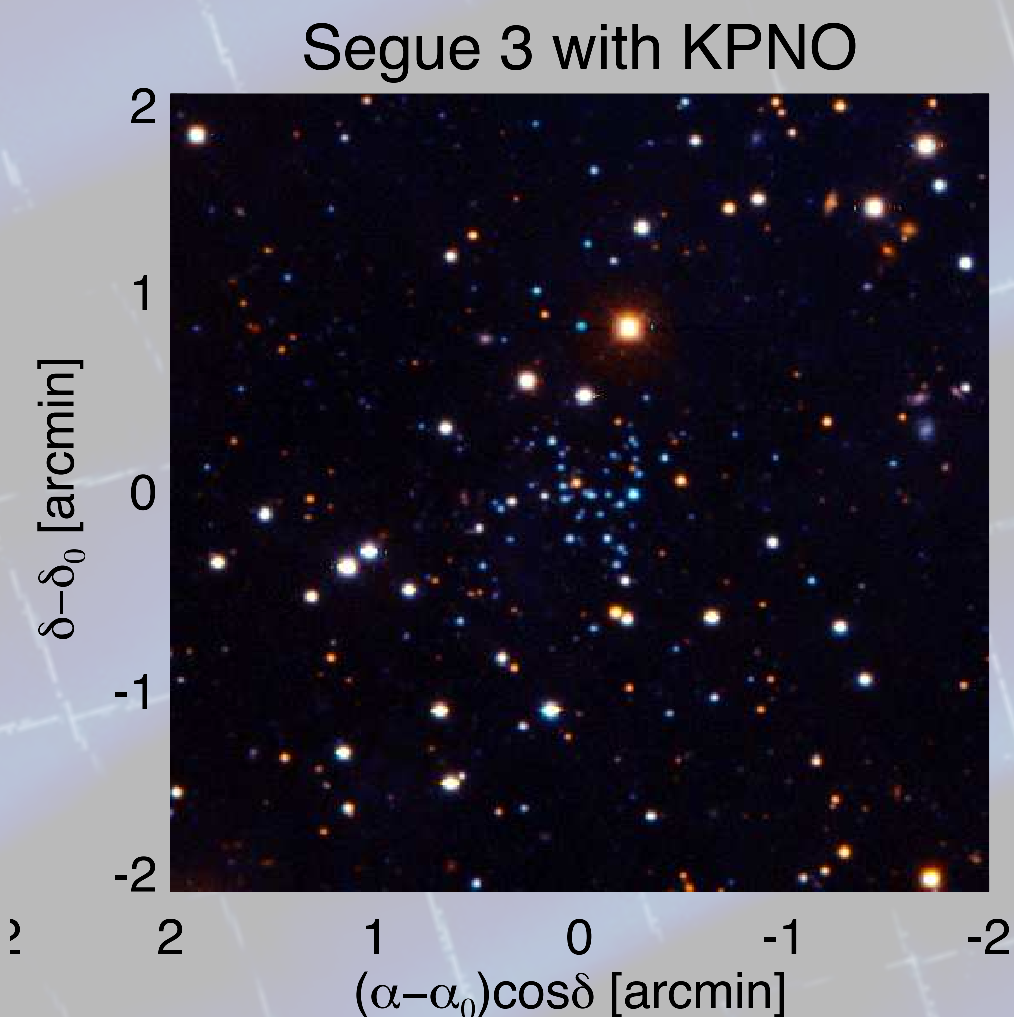


Belokurov et al. 2010

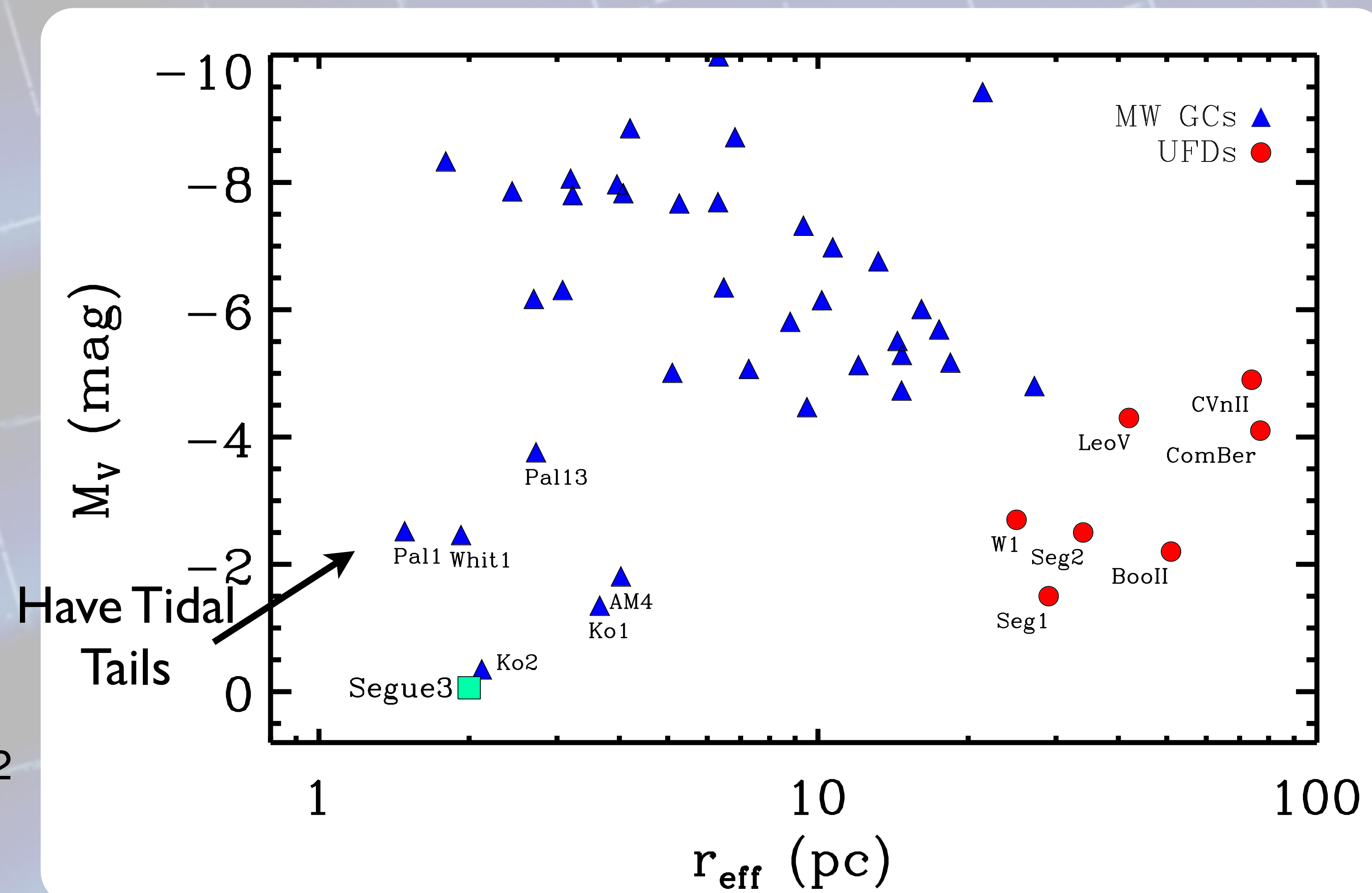


Fadely et al. 2011

Segue 3



Belokurov et al. 2010



Fadely et al. 2011

BHs in Tidally Stripped Clusters?

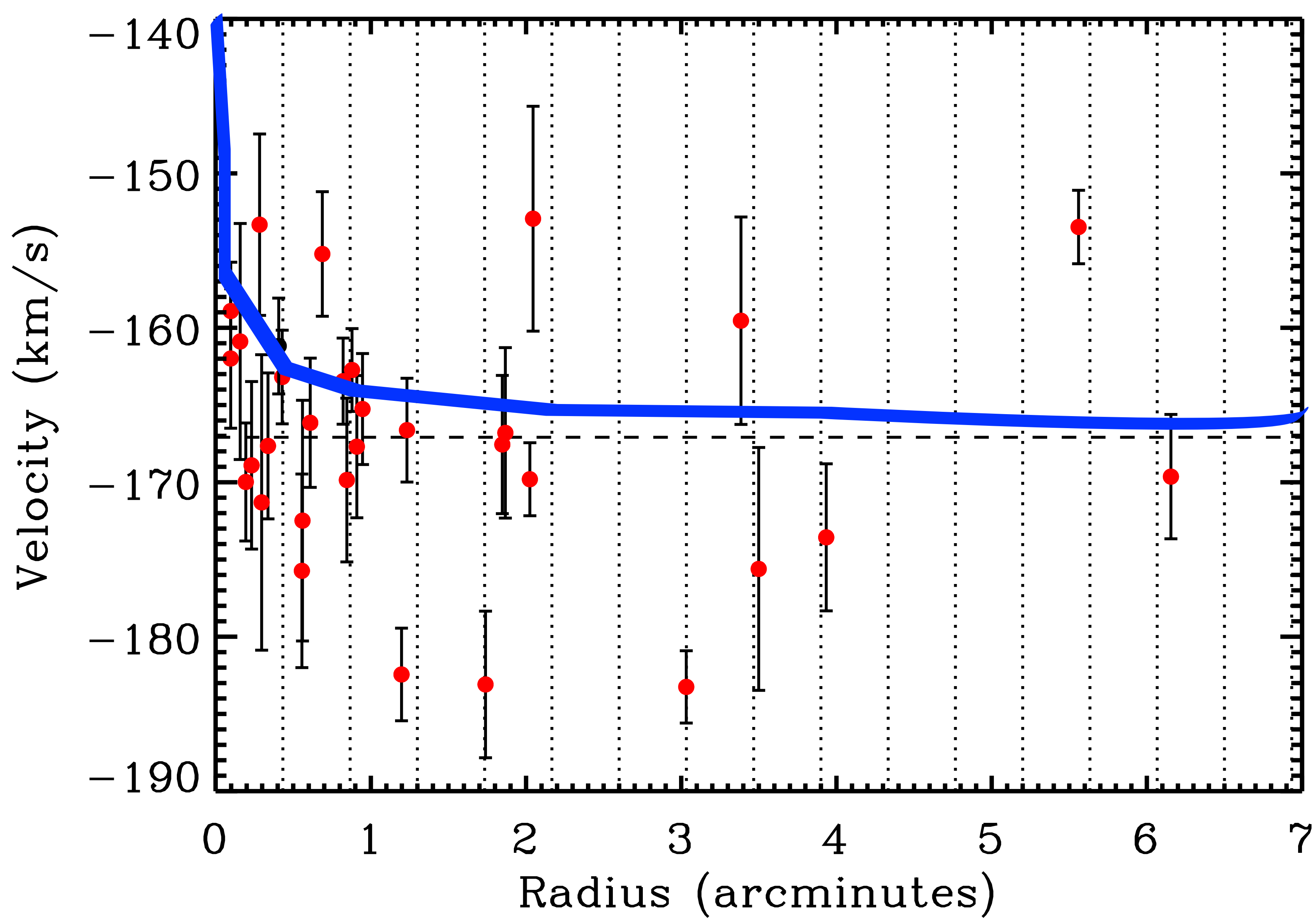
I) Originally $M_{\rm cluster} >> M_\bullet$

II) Cluster expands and is stripped of stars

III) When $M_{\rm cluster} \approx M_\bullet$ the black hole protects the cluster from complete disruption.

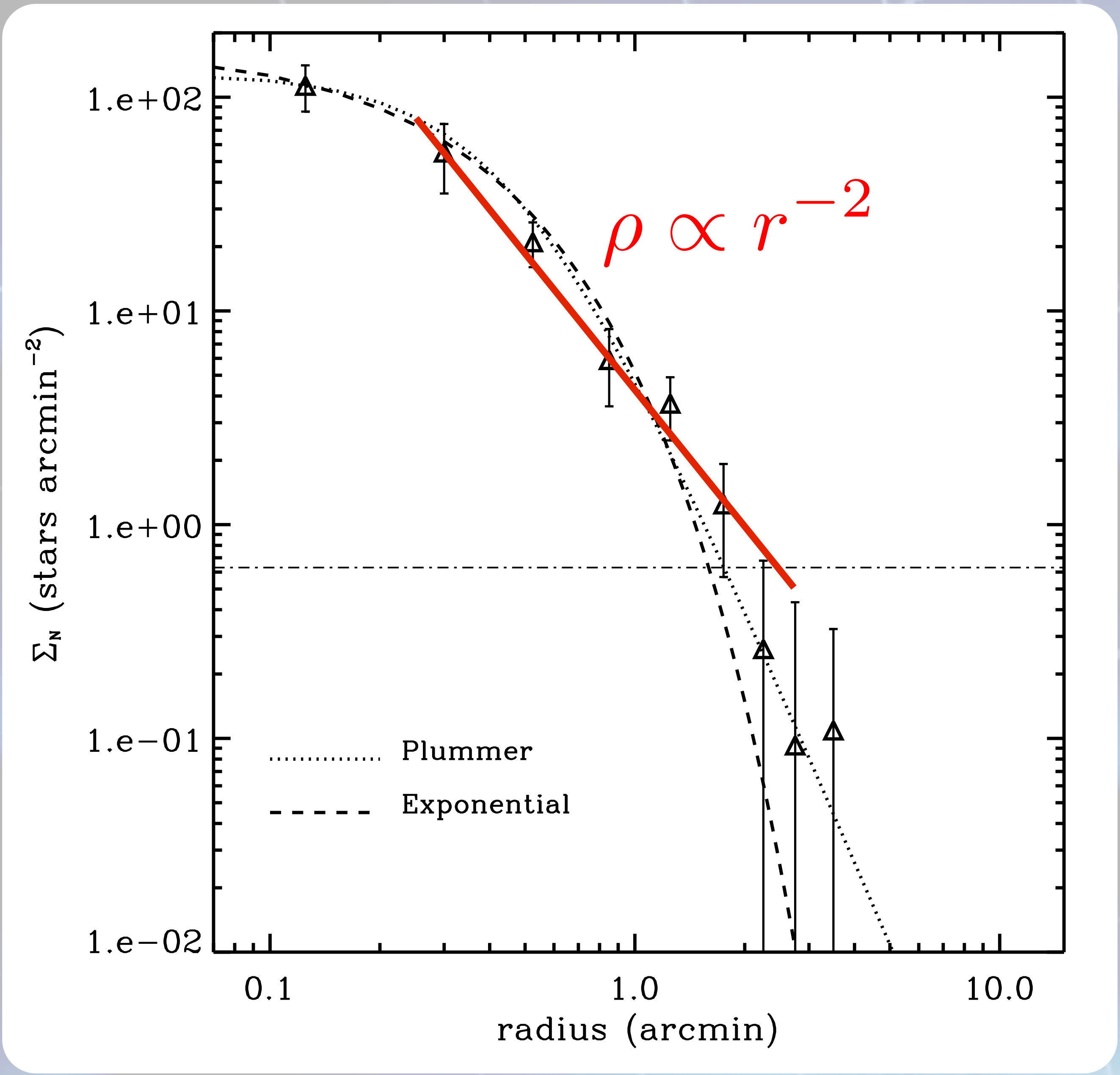
IV) Should appear like recoiled clusters with more stars

Segue 3



Fadely et al. 2011

Segue 3 with Black Hole?



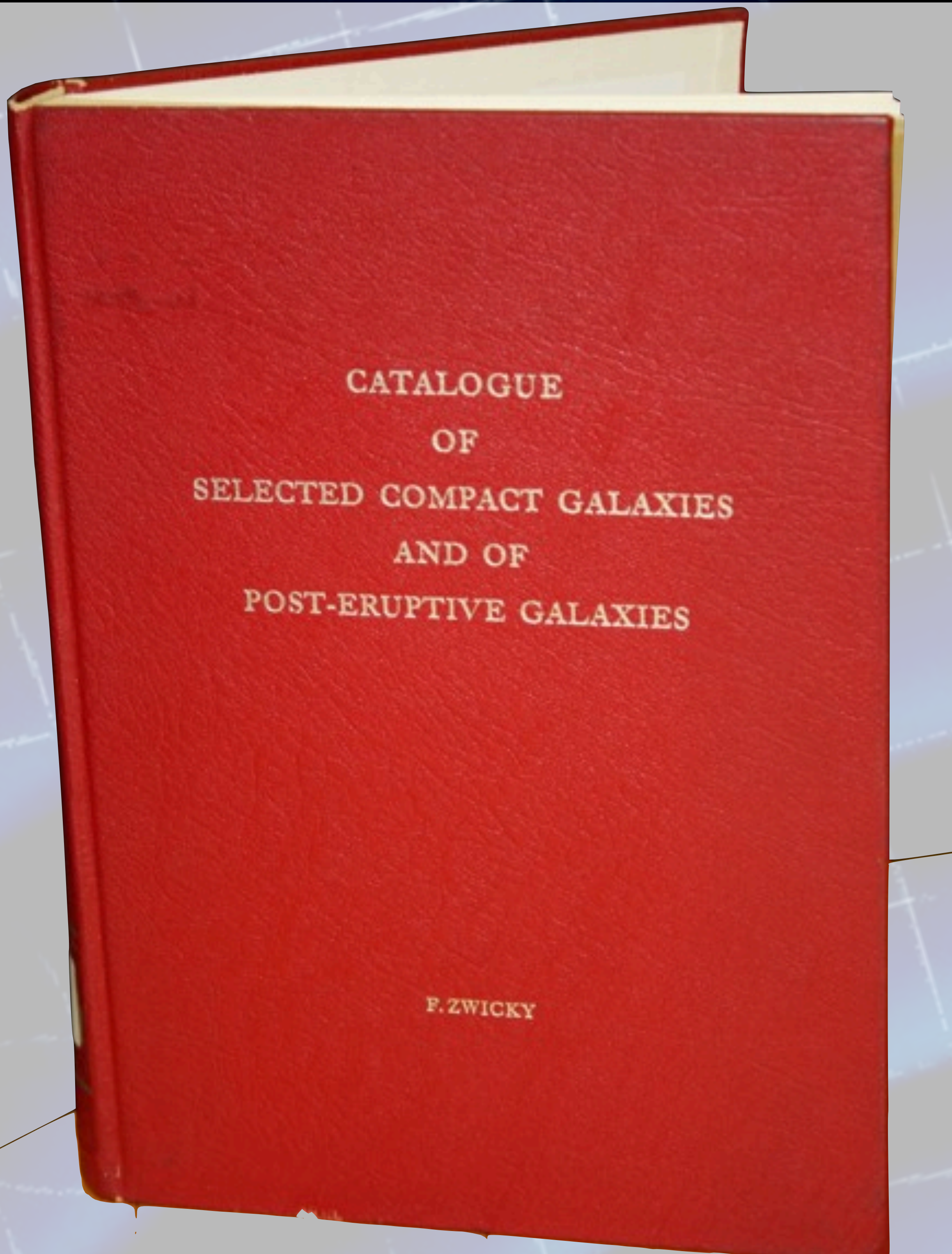
Fadely et al. 2011

Part II: BHs in Tidally Disrupted Clusters

- Easy to find the dynamical center of cluster
- Only a few stars have anomalous velocity $\gtrsim 10\,\mathrm{km\,s^{-1}}$
- BHs protect clusters from further disruption

  $\rightarrow$ Increases chances smallest clusters have BHs
- Can take individual spectra of the most central stars

Zwicky's Catalog

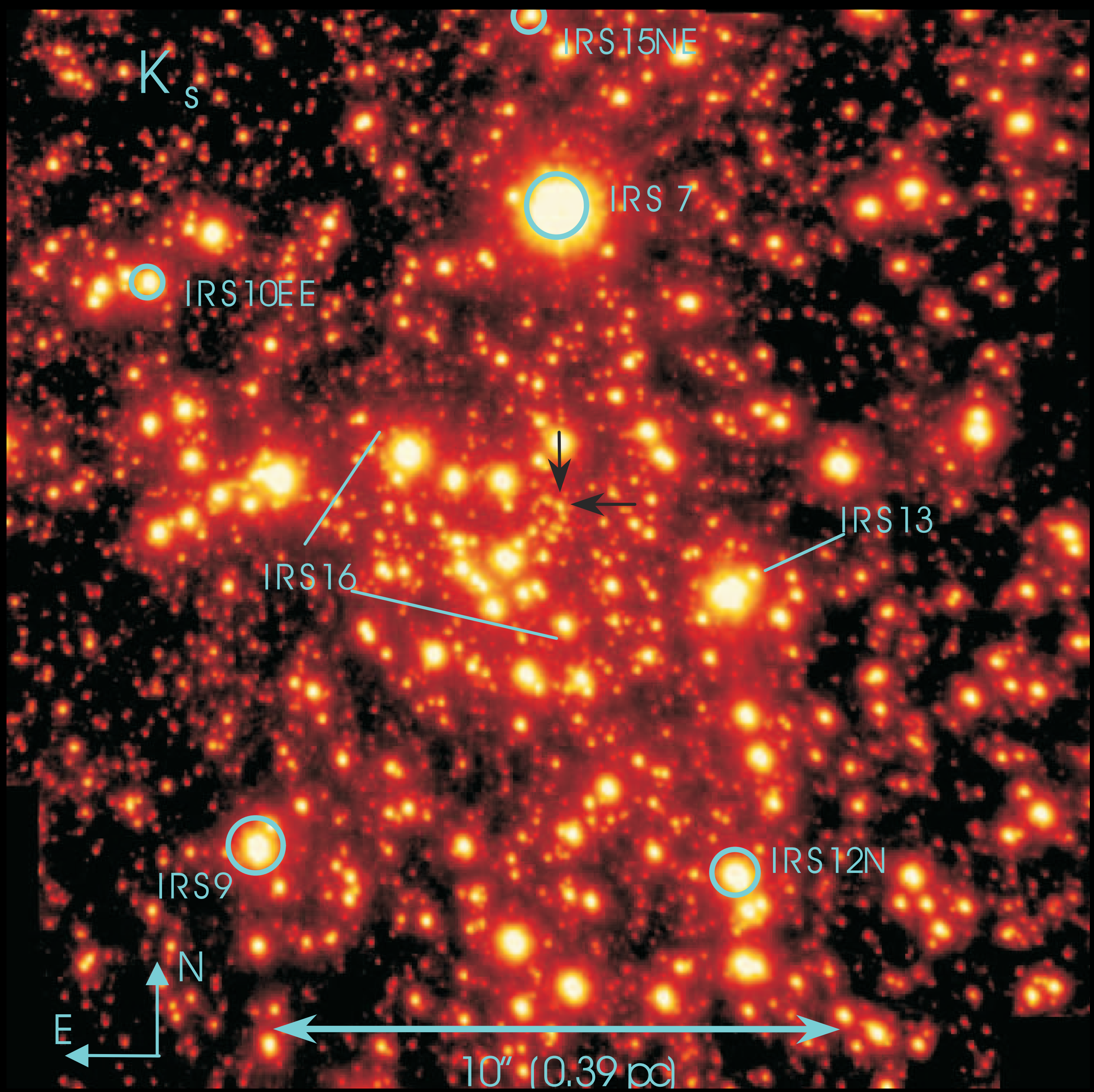


"to the High Priests of American Astronomy and to their Sycophants"

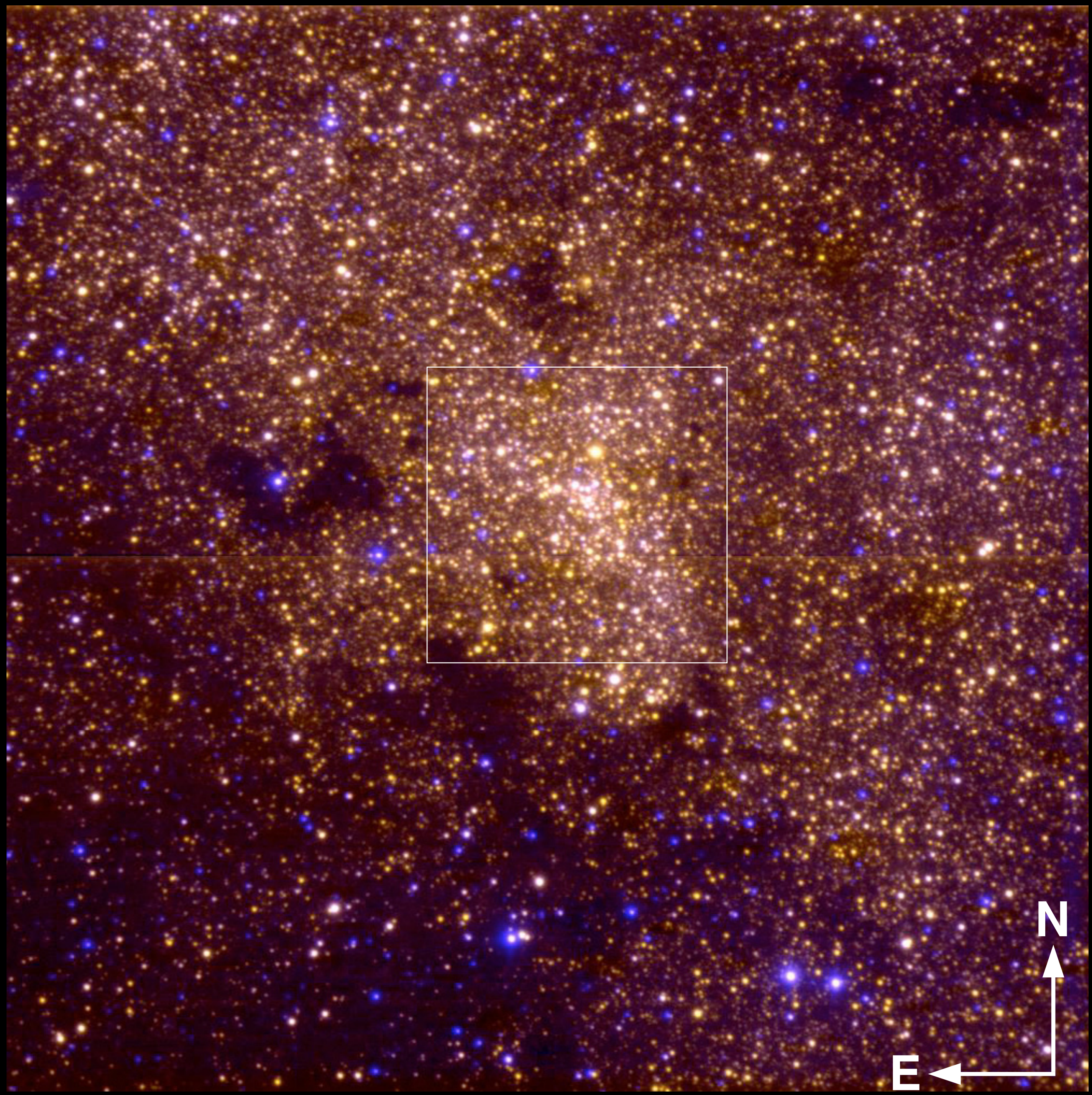
"high pope of American Astronomy, one Henry Norris Russell"

"Hubble, Bade, and the sycophants among their assistants..."

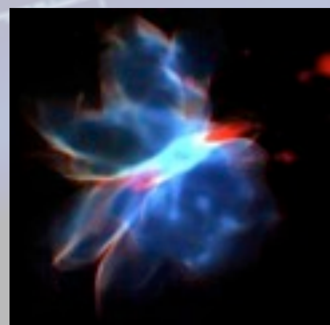
"in 1964, A. Sandage ... attempted one of the most astounding feats of plagiarism"



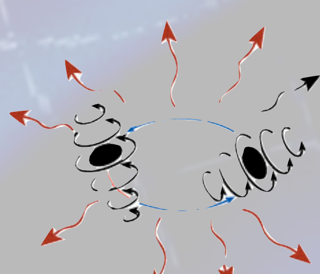
Genzel et al. 2003 ~20”x20”


N
E

Getting Black Holes into the Milky Way Halo



Abel's Group



Remnants of first massive stars

Islam et al. 2003,2004; Zhao & SIlk 2005

Direct Collapse / Recoil

Bertone et al. 2005; Mapelli et al. 2006; Micic et al. 2006

Dynamical Ejection

Volonteri & Perna 2005

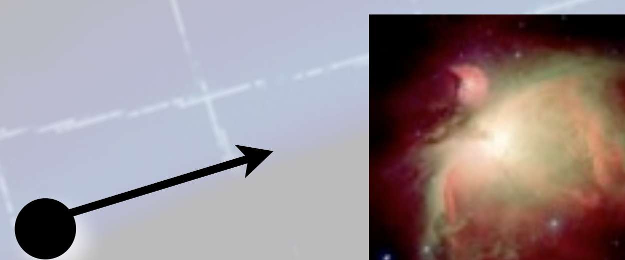
Gravitational Wave Recoil

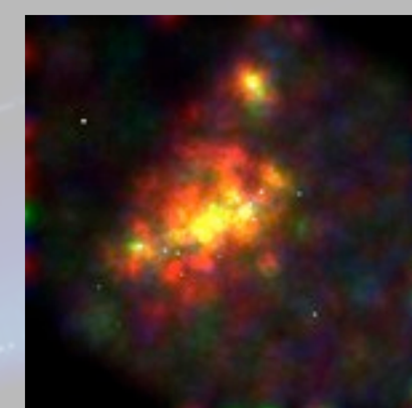
Madau & Quataert 2004;Volonteri & Perna 2005; Libeskind et al. 2006; Micic et al. 2006; Holley-Bockelmann et al. 2008; O'Leary & Loeb 2009,2010

Limits in the Halo

Bondi-Hoyle-Litttleton Accretion

Islam et al. 2004; Mii et al. 2005; Mapelli et al. 2006





ULX?

Poor Constraints: < .1% of baryons

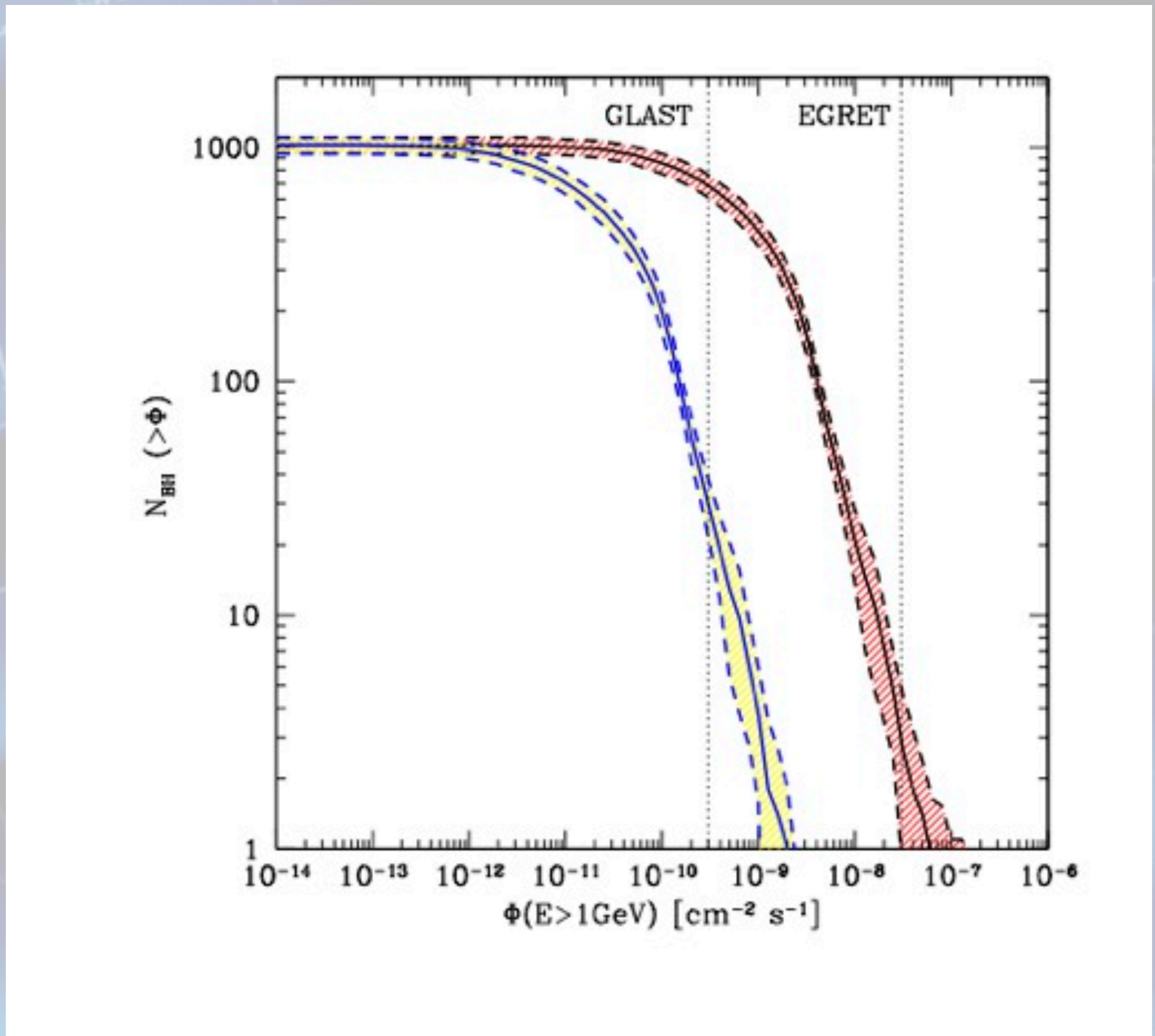
Limits in the Halo

Dark Matter Annihilation

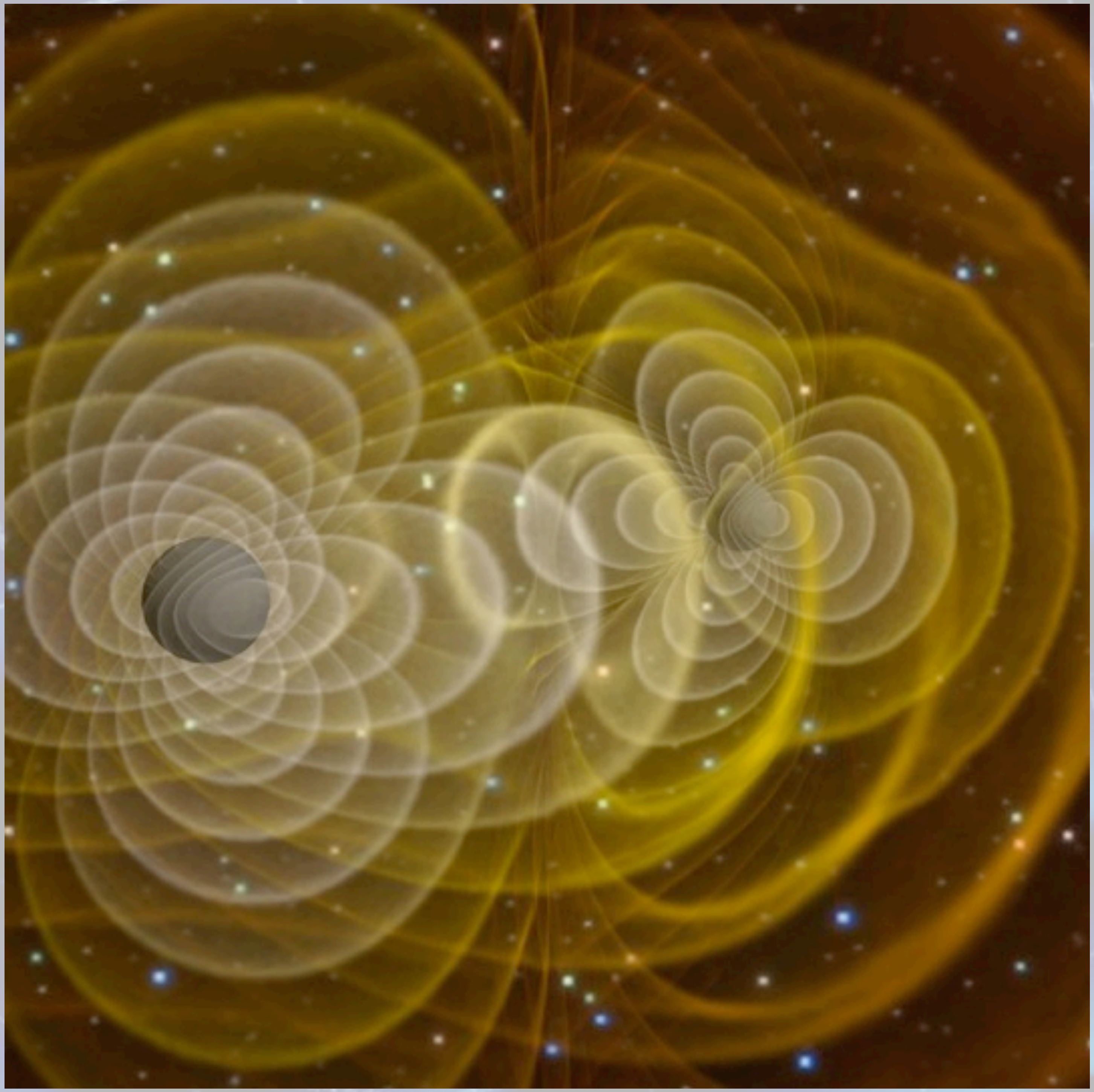
Bertone et al. 2005;

Assume BHs form in centers of dark matter halos

DM annihilates in cusp



Most ‘Luminous’ Events



$$E_{\rm GW} \sim .1 M c^2$$

$$\Delta t \sim 10 \frac{GM}{c^3}$$

$$L_{\rm GW} \sim 10^{-2} \frac{c^5}{G}$$

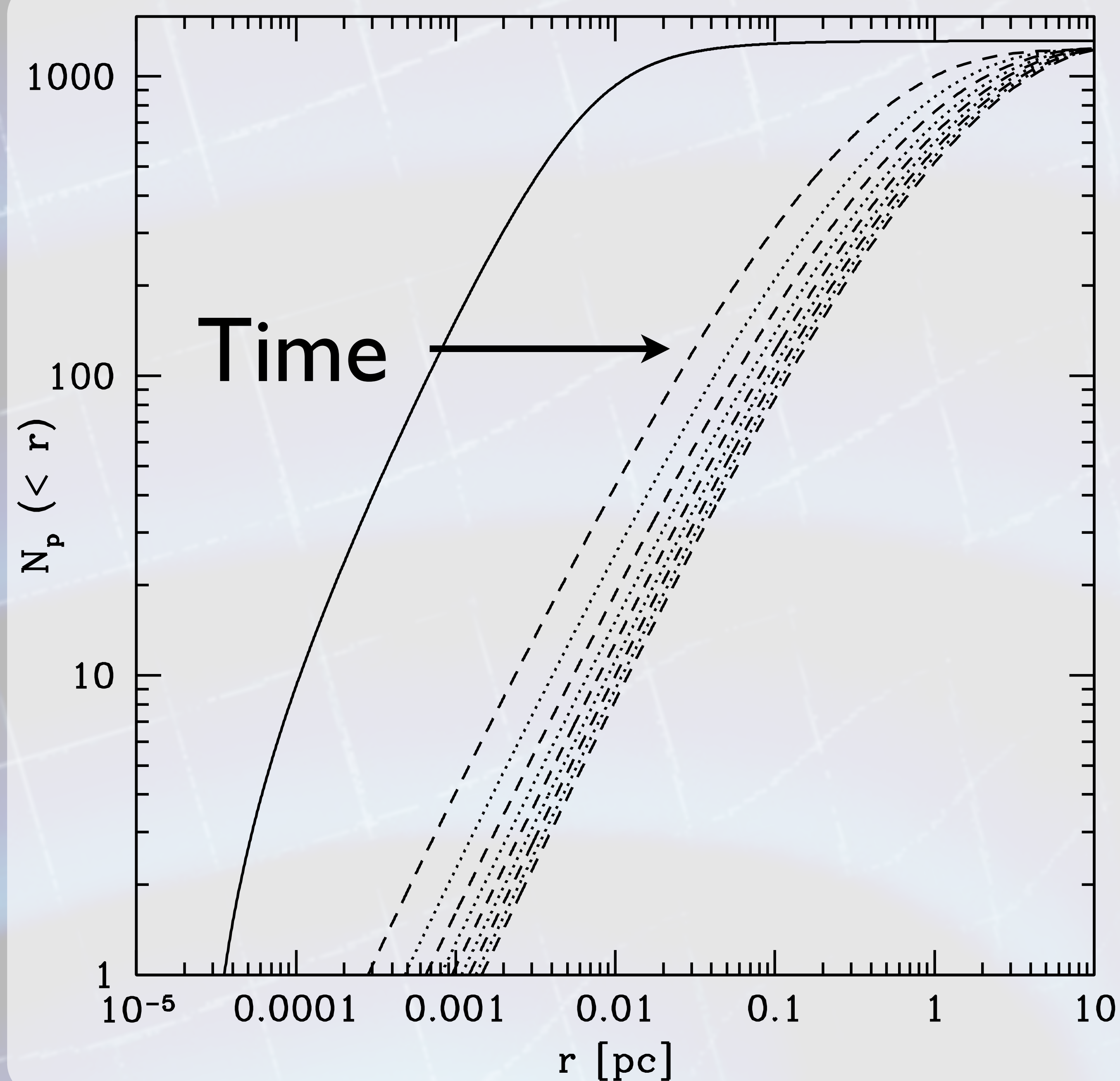
$$\gtrsim 10^{57}\,{\rm erg\ s}^{-1}$$

Cluster Expansion

Numerically Solve Time Dependent Fokker-Planck Equations with Loss Cone
(Bahcall & Wolf 1976/1977)

Cluster Rapidly Expands

Relaxation Time ~ Time since ejection



Cluster around a $10^5\ M_\odot$ ejected BH

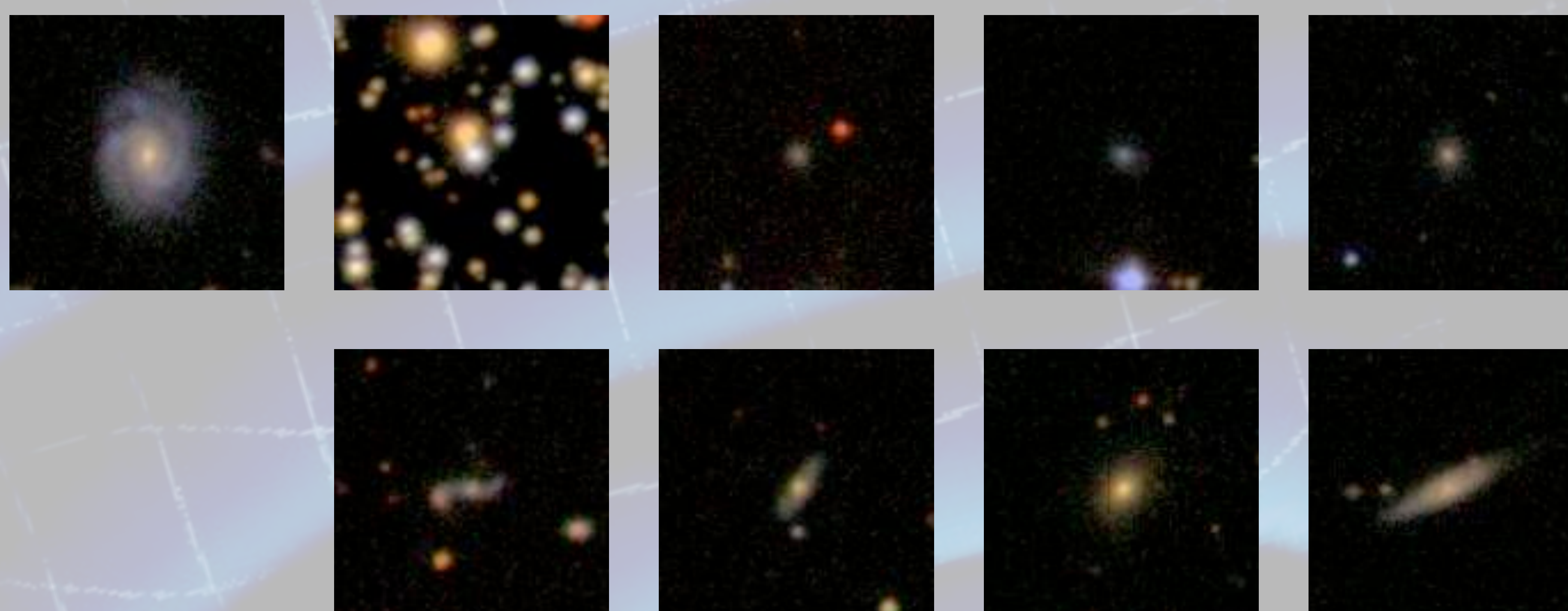
Thursday, September 1, 2011

Observations: Getting My Hands Dirty

Getting My Hands Dirty

Look for:

✓larger than 3" to get rid of partially resolved binaries



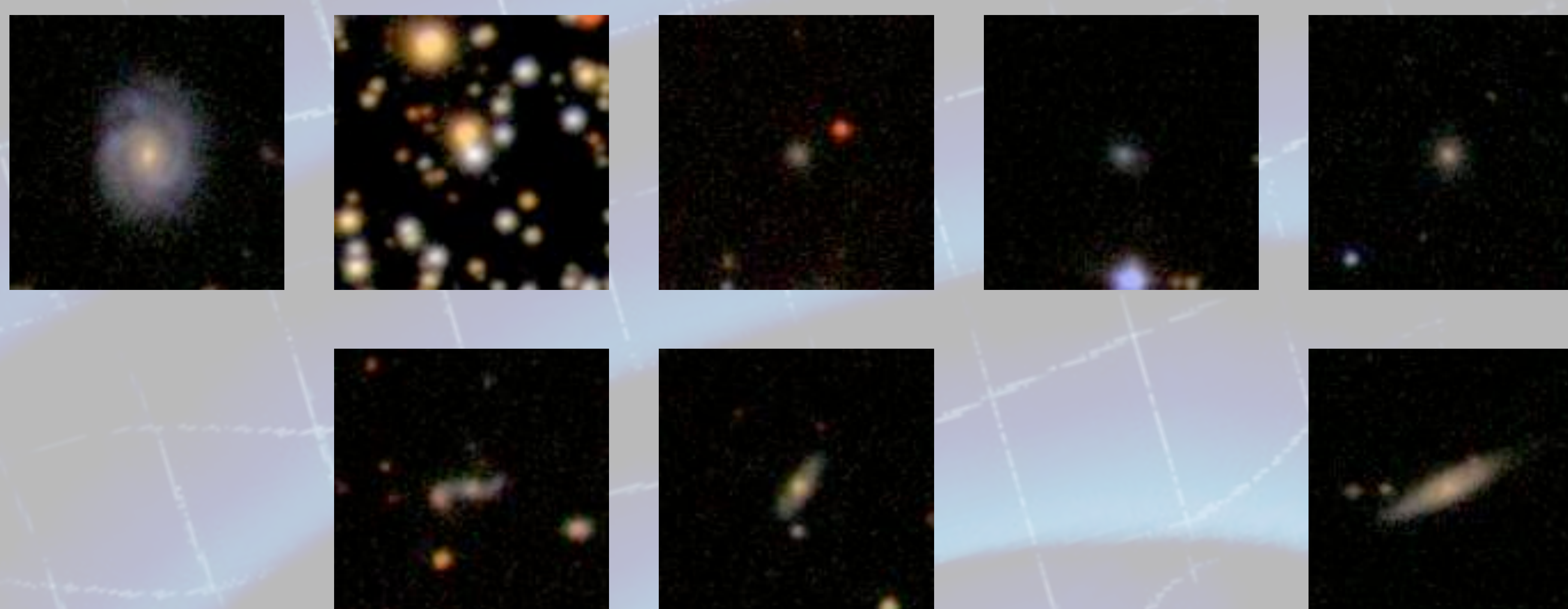
SDSS DR 7

Getting My Hands Dirty

Look for:

✓larger than 3” to get rid of partially resolved binaries

✓Stellar Colors



SDSS DR 7

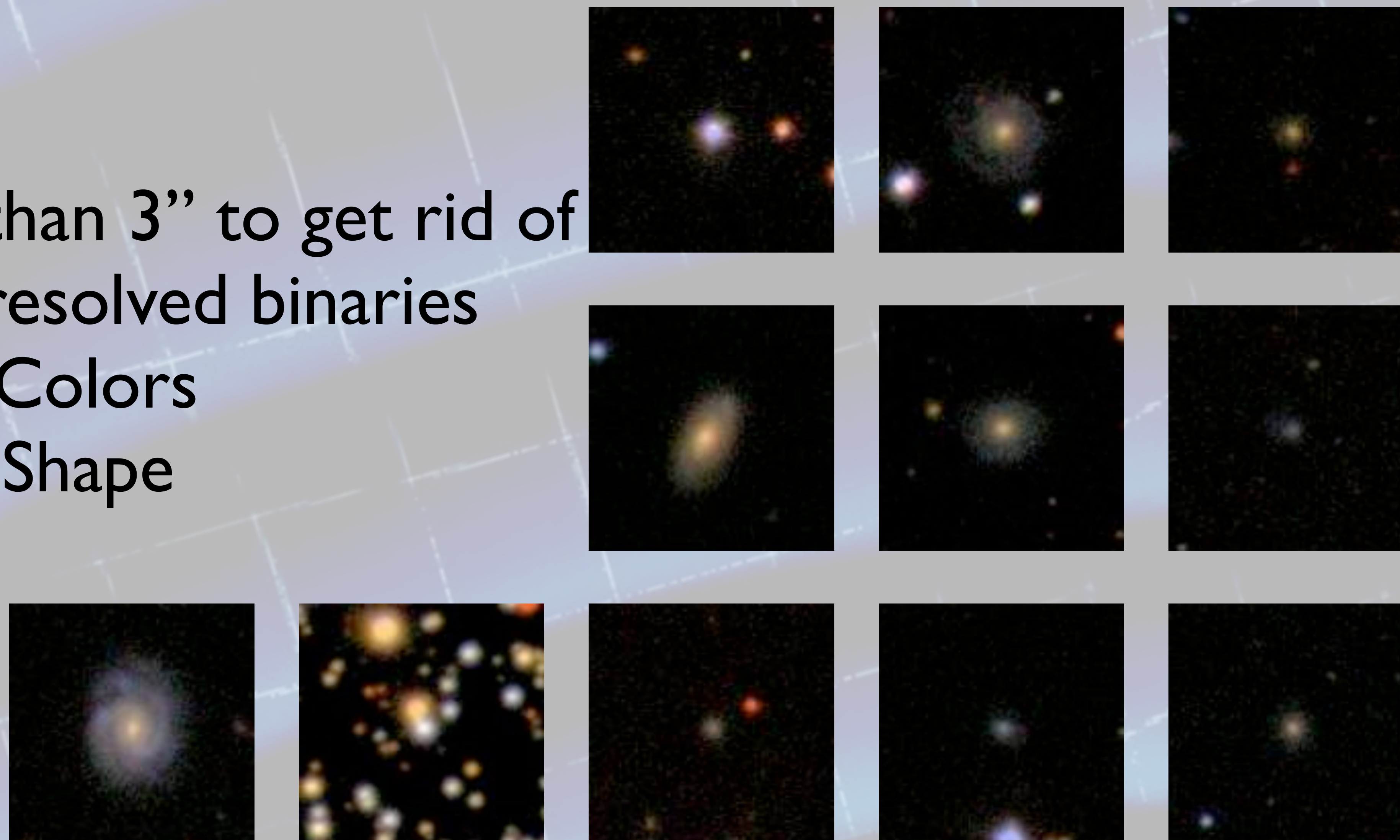
Getting My Hands Dirty

Look for:

✓larger than 3” to get rid of partially resolved binaries

✓Stellar Colors

✓Round Shape



SDSS DR 7

Getting My Hands Dirty

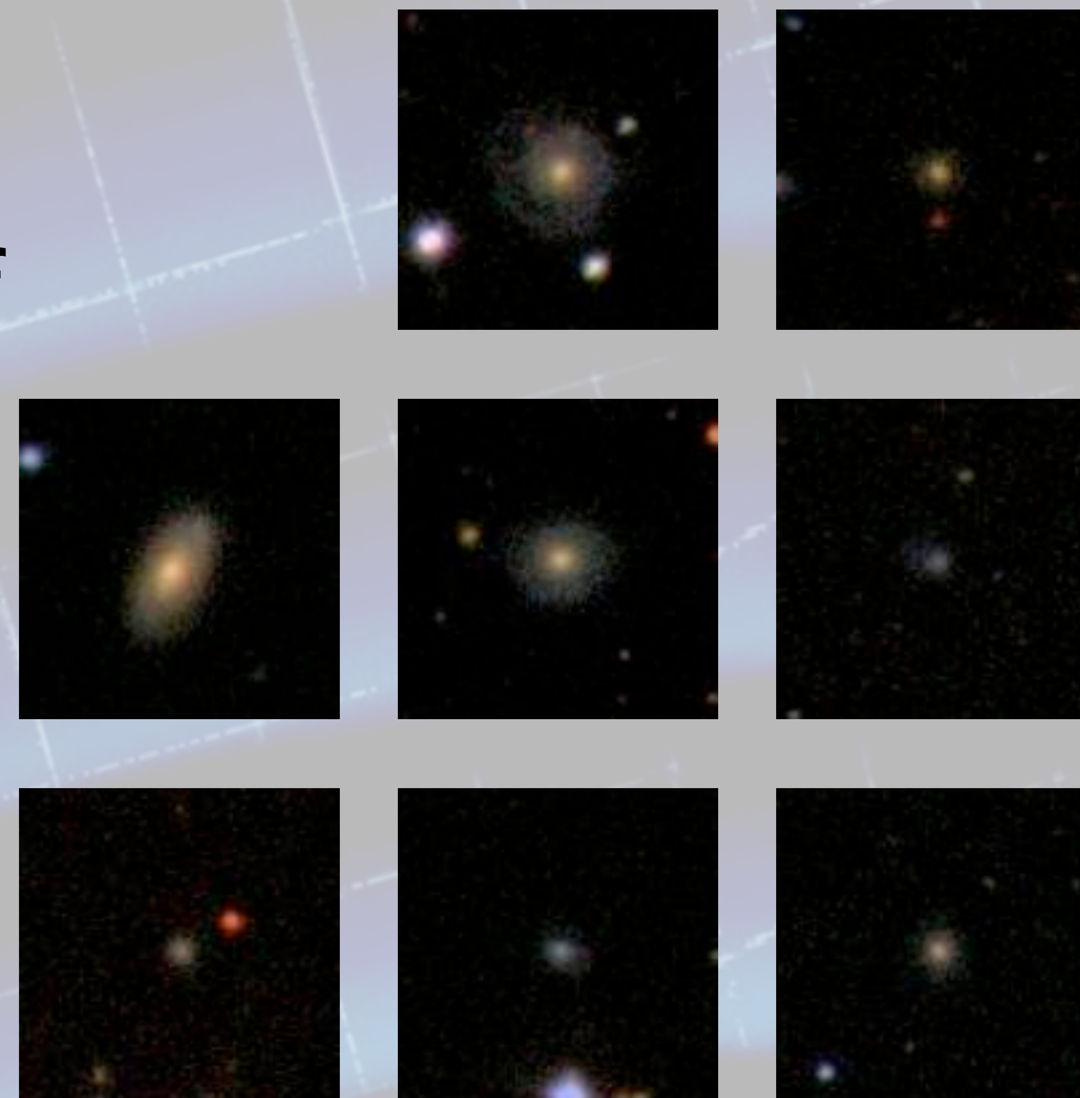
Look for:

✓ larger than 3” to get rid of partially resolved binaries

✓ Stellar Colors

✓ Round Shape

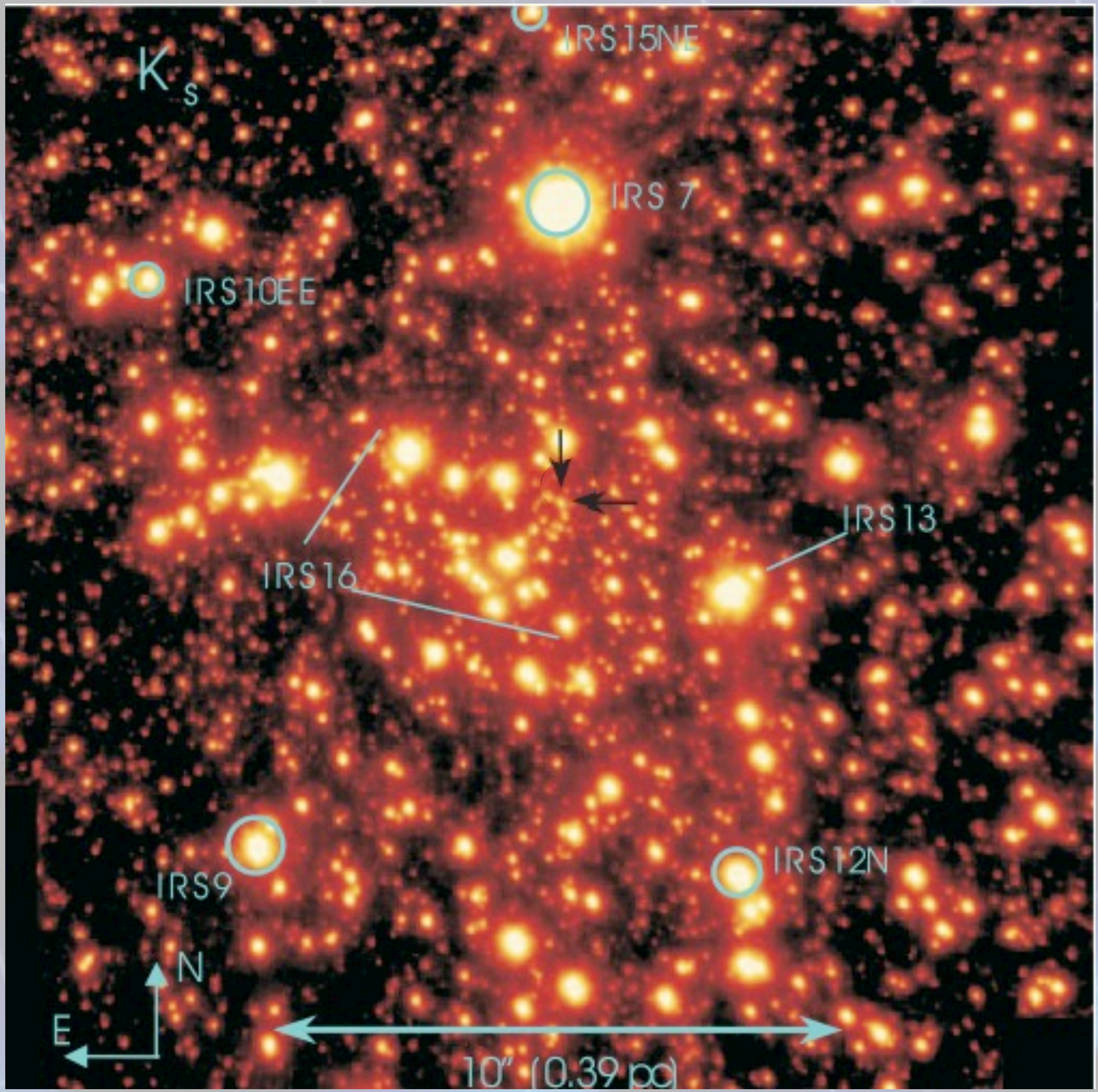
✓ Correct Light Profile



SDSS DR 7

Cluster of Stars

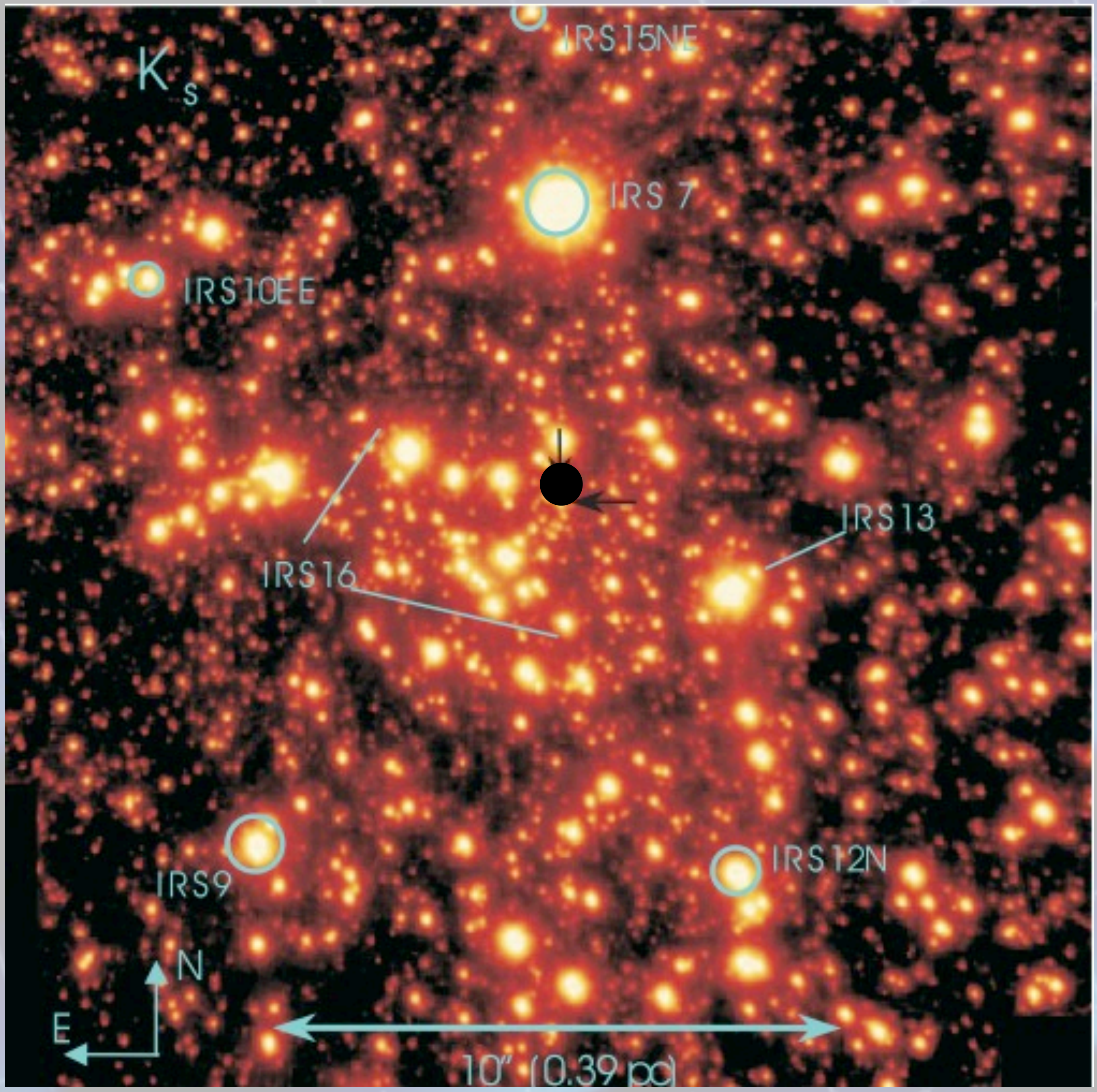
$$r \lesssim \frac{GM_\bullet}{v_k^2}$$



Genzel et al. 2003

Cluster of Stars

$$r \lesssim \frac{GM_\bullet}{v_k^2}$$



Genzel et al. 2003