STAR CLUSTERS

Lecture 4

Intermediate-Mass Black Holes

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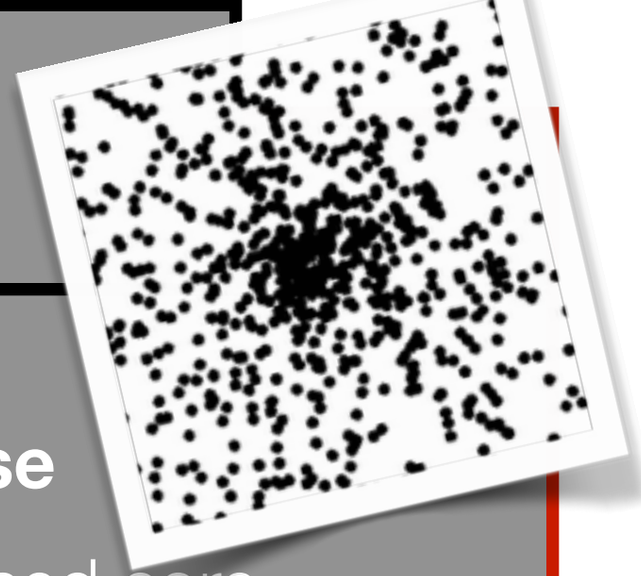
FIRST KATHMANDU ASTROPHYSICS SCHOOL KAS16

LECTURE 3



1. **The Gravitational N-body problem**
   - N=2: exactly solvable
   - N=3: approximately solvable
   - N>3: only numerical solvable
2. **Dynamic Equilibrium**
   - No EXPANSION or CONTRACTION of the system
3. **Negative Heat Capacity**
   - Remove energy —> hotter
   - Gain energy —> colder

4. **Core Collapse**
   - Very condensed core, steep light profile
5. **Equipartition of Energies**
   - All the stars (at radius R) have the same kinetic energy
   - High-mass stars: slow, low-mass stars: fast
6. **Mass Segregation**
   - Mass gradient from center to the outskirts

Outline

1. Introduction
   - What, How, Where?
2. Observations
   - Photometry
   - Spectroscopy
3. Simulations
4. Future

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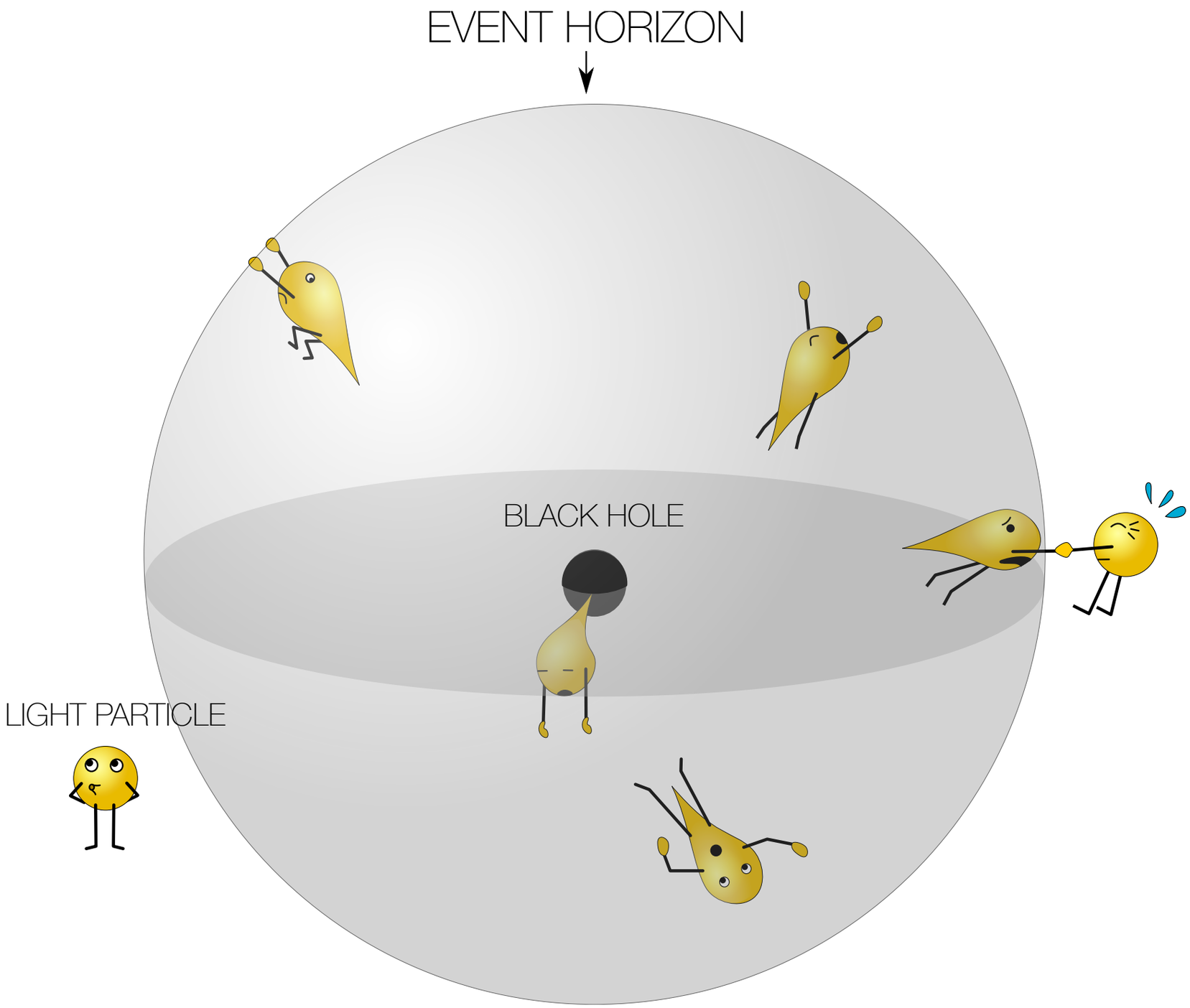
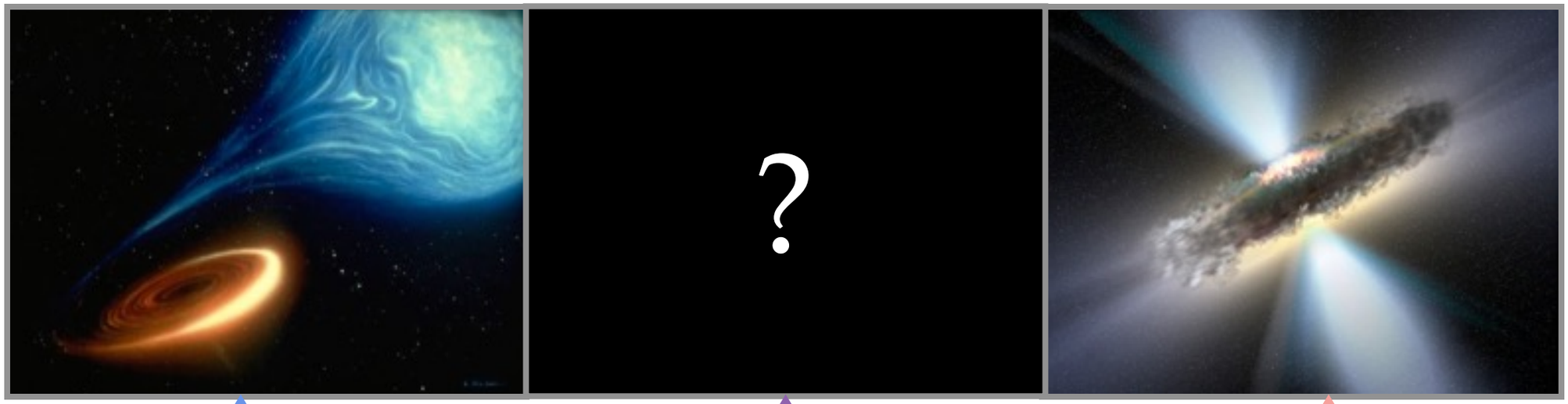
What is a Black Hole?



What are IMBHs?



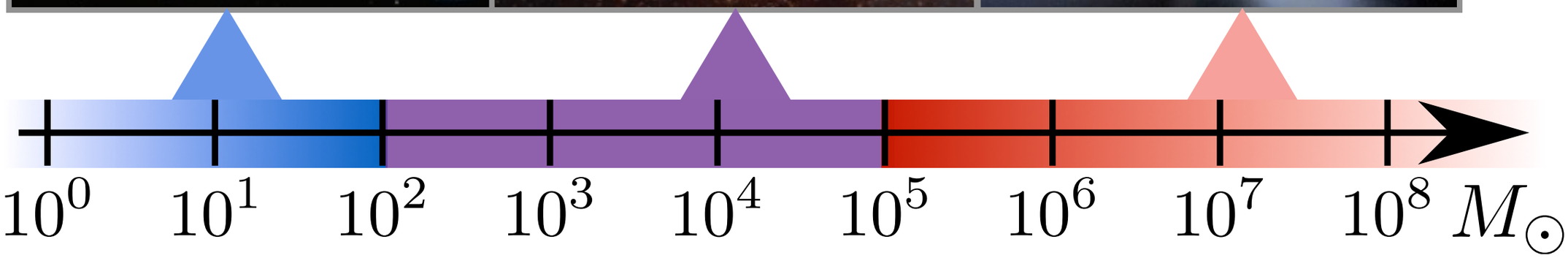
STELLAR

- Gravitational Collapse of Massive Star
- Supernovae
- Compact X-ray Binaries
- ...

SUPERMASSIVE

- Centers of Massive Galaxies
- Active Galactic Nuclei
- Quasars
- Center of the Milky Way
- ...

What are IMBHs?



STELLAR

- Gravitational Collapse of Massive Star
- Supernovae
- Compact X-ray Binaries
- ...

IMBH

SUPERMASSIVE

- Centers of Massive Galaxies
- Active Galactic Nuclei
- Quasars
- Center of the Milky Way
- ...

How do they form?

STELLAR | INTERMEDIATE | SUPERMASSIVE

STELLAR REMNANTS

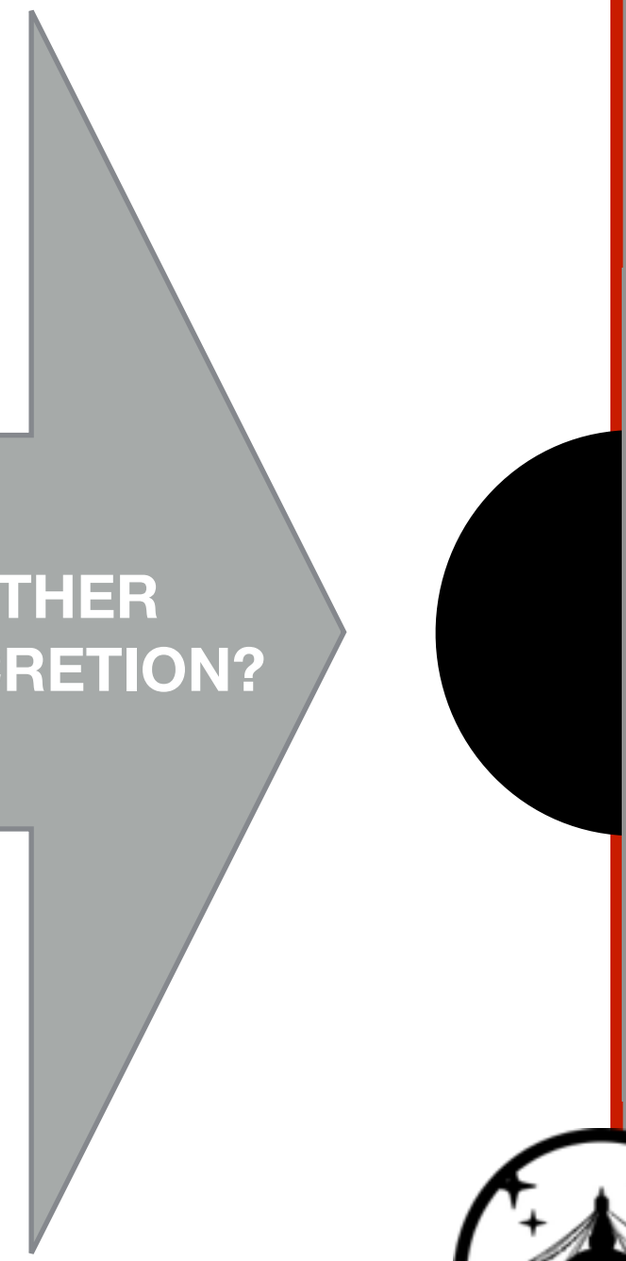
RUNAWAY MERGER

RUNAWAY COLLISIONS

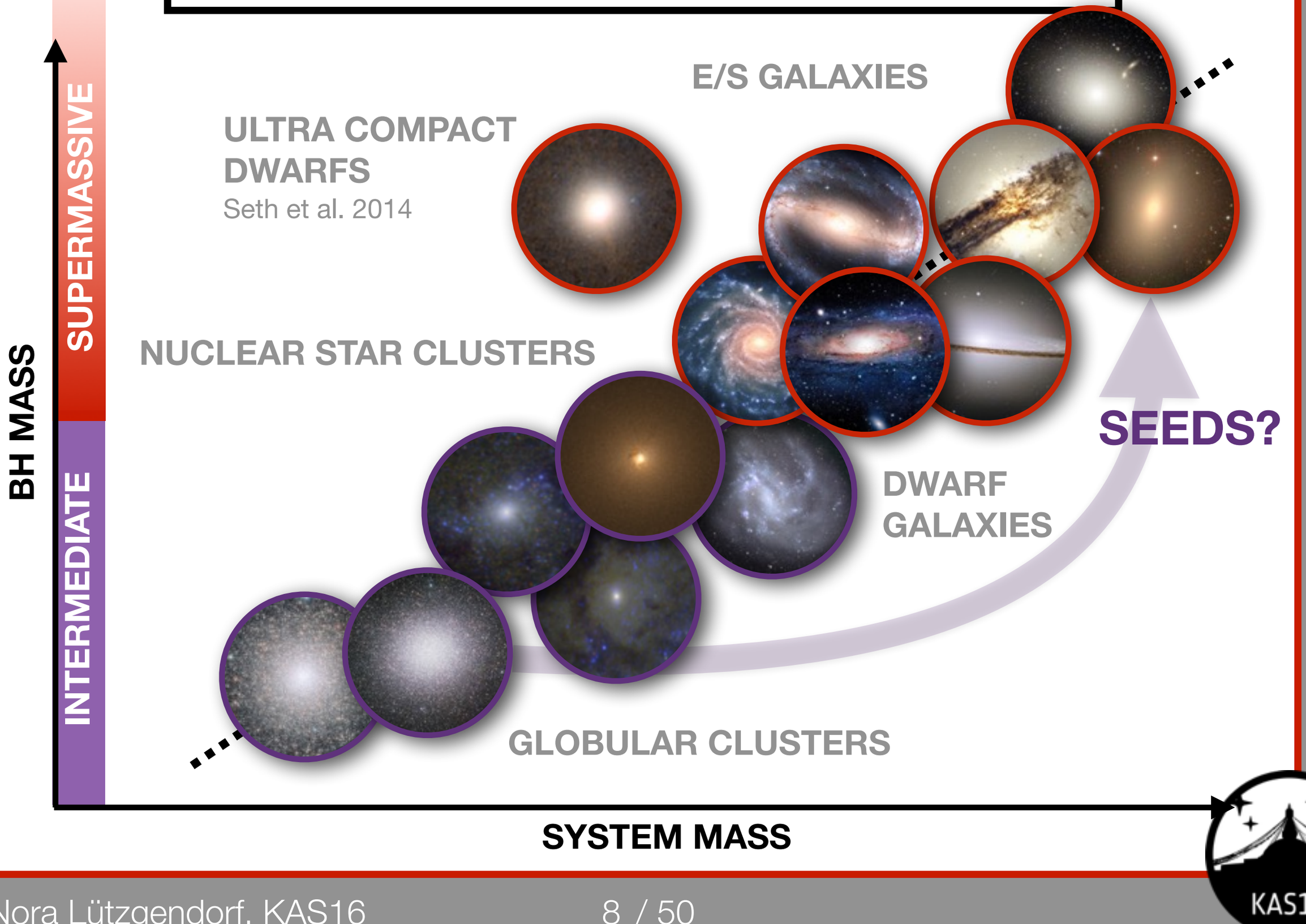
STELLAR GAS ACCRETION

BH GAS ACCRETION

DIRECT COLLAPSE



Where do we find them?



Outline

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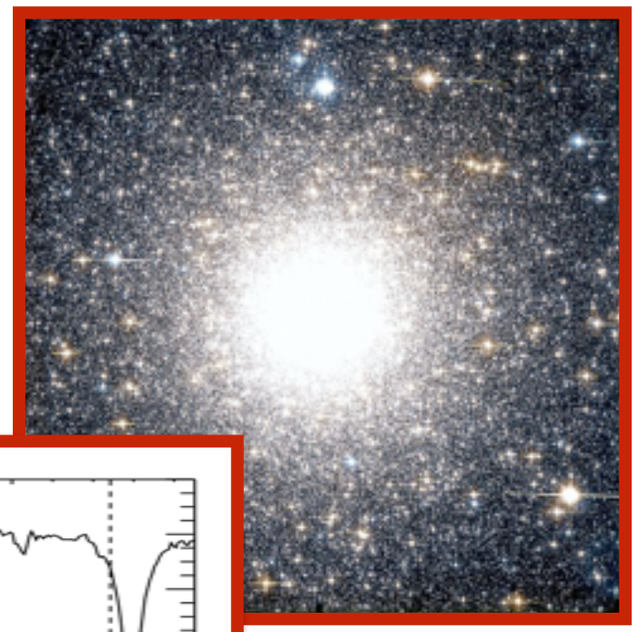
4. Future

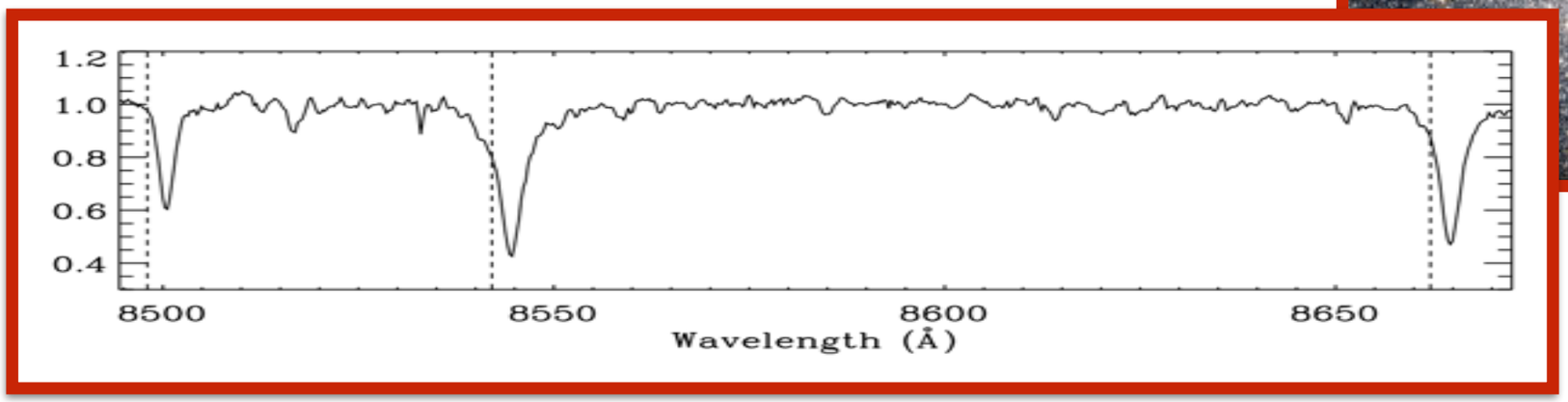
Observations

1. Measure the LIGHT

   ➡ **expected** velocities



2. Measure the KINEMATICS

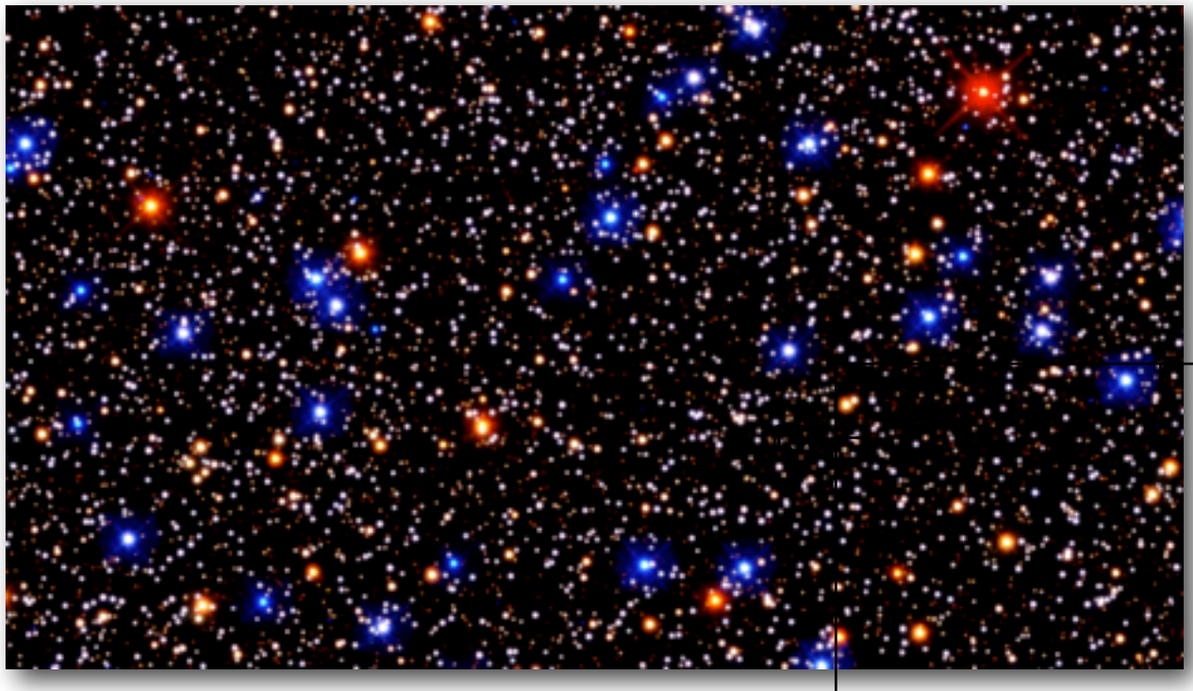


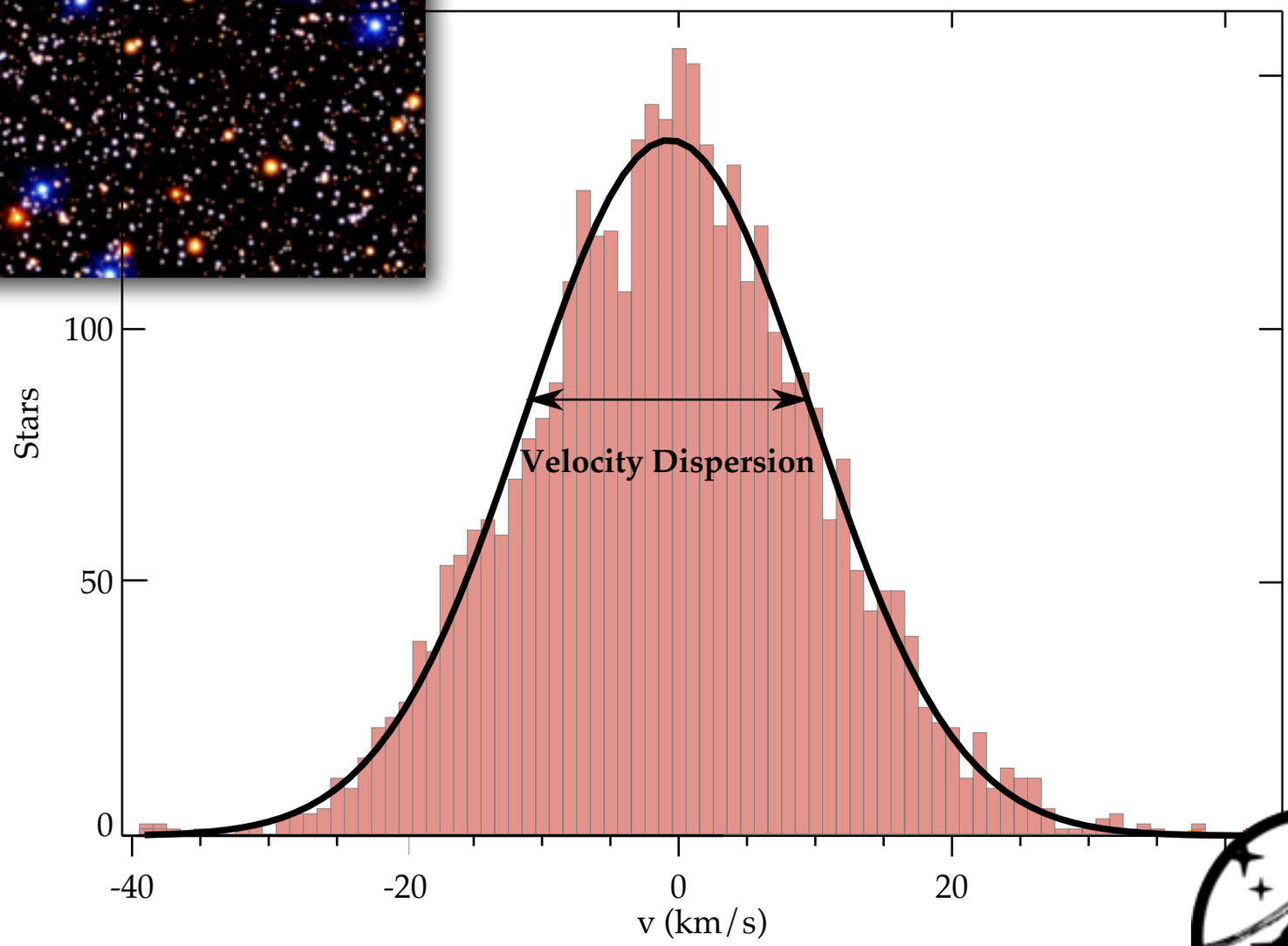
   ➡ **true** velocities

3. COMBINE the data
4. COMPARE to DYNAMICAL MODELS

   ➡ Missing dark mass?

Excursion: Velocity Dispersion





Excursion: Jeans Equations

Velocity Dispersion

Surface Brightness Profile

Potential+BH

$$\frac{\mathrm{d}(\nu\overline{v_r^2})}{\mathrm{d}r} + \frac{2\beta\nu\overline{v_r^2}}{r} = -\nu\frac{\mathrm{d}\Phi}{\mathrm{d}r}$$

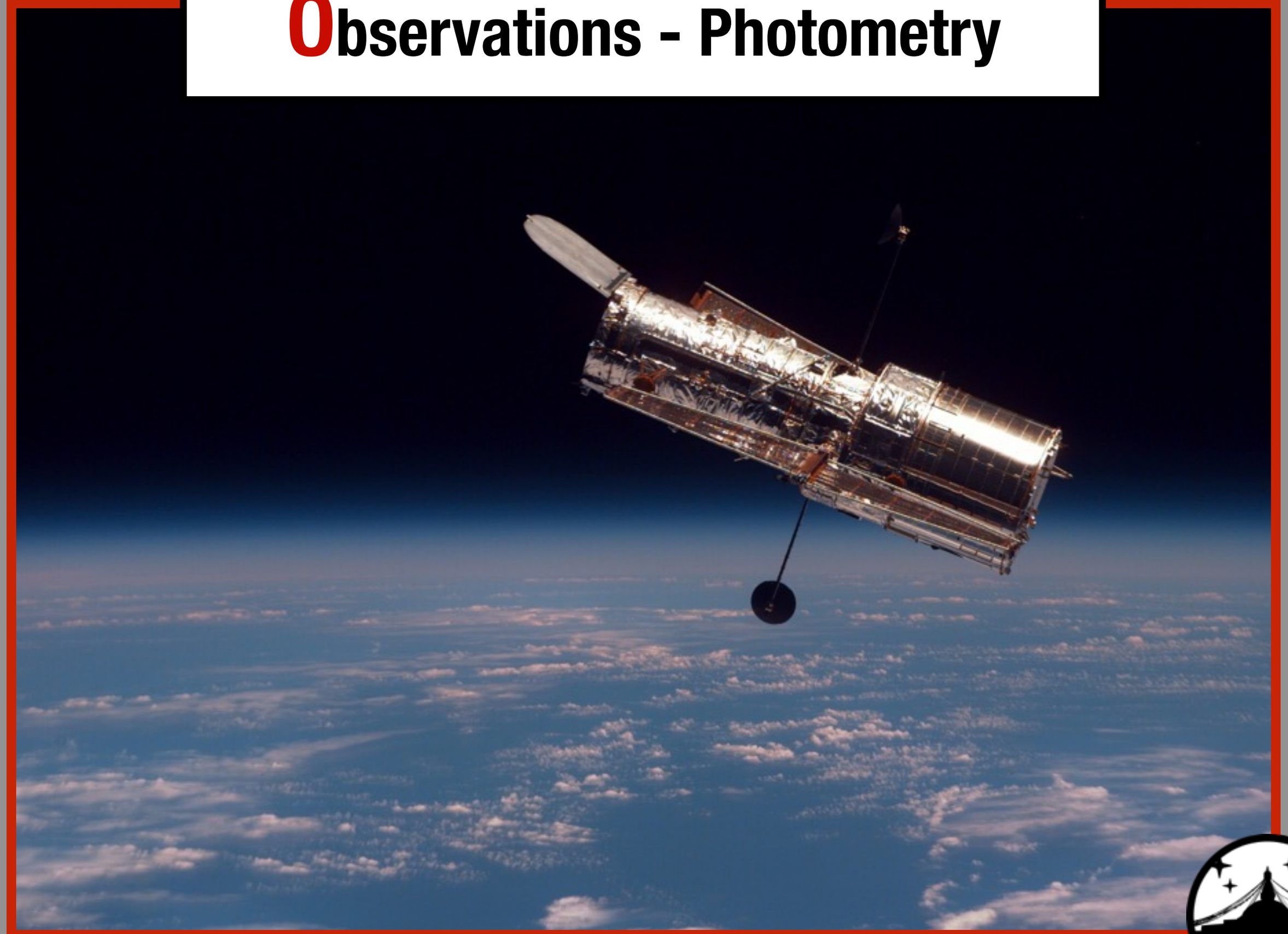
Anisotropy

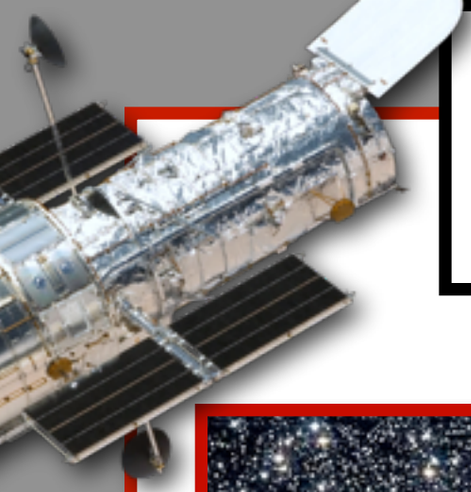
$(\beta = 1 - \overline{v_\theta^2}/\overline{v_r^2})$

SURFACE BRIGHTNESS PROFILE → VELOCITY DISPERSION PROFILE

LIGHT → KINEMATICS

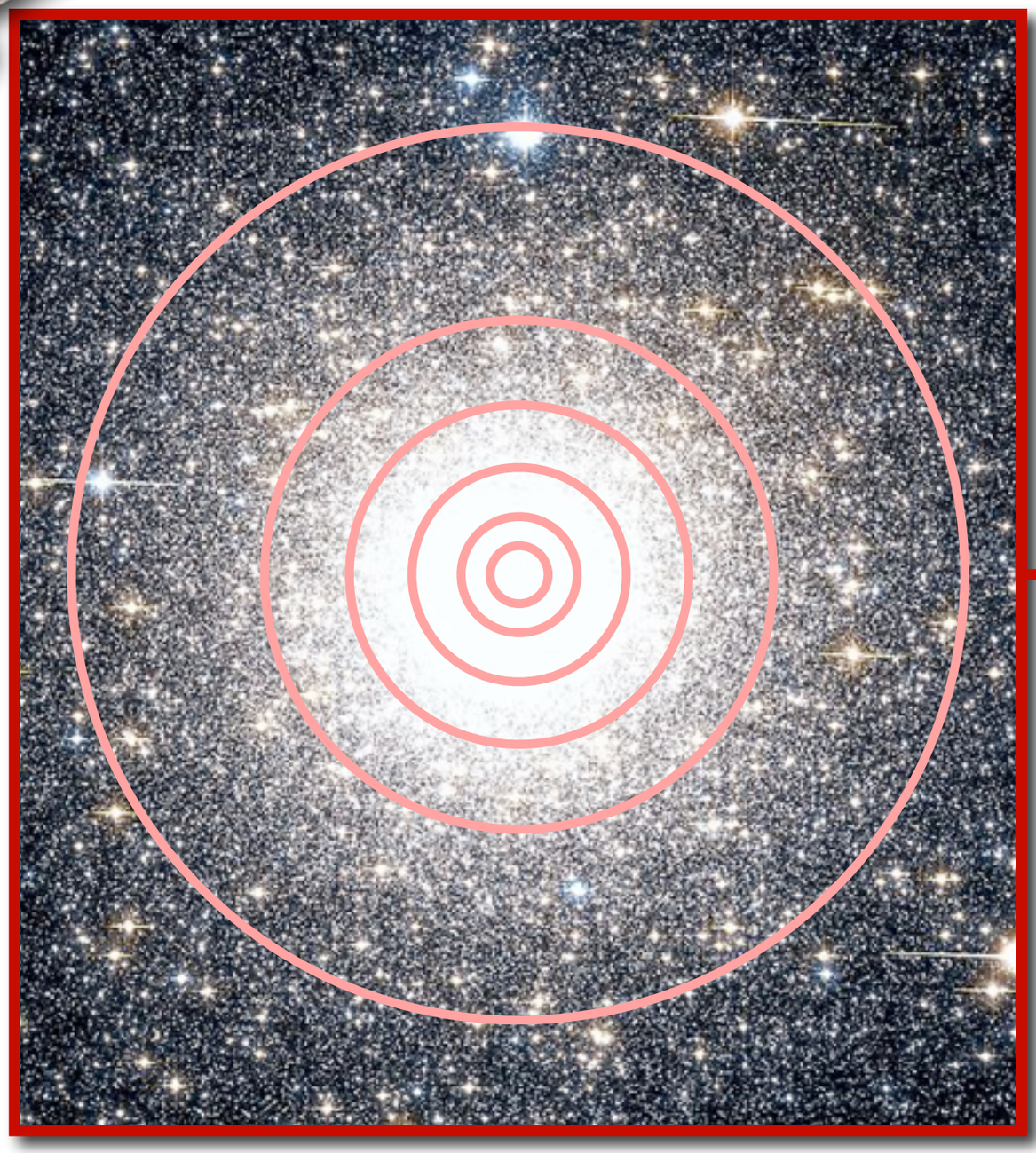
Observations - Photometry



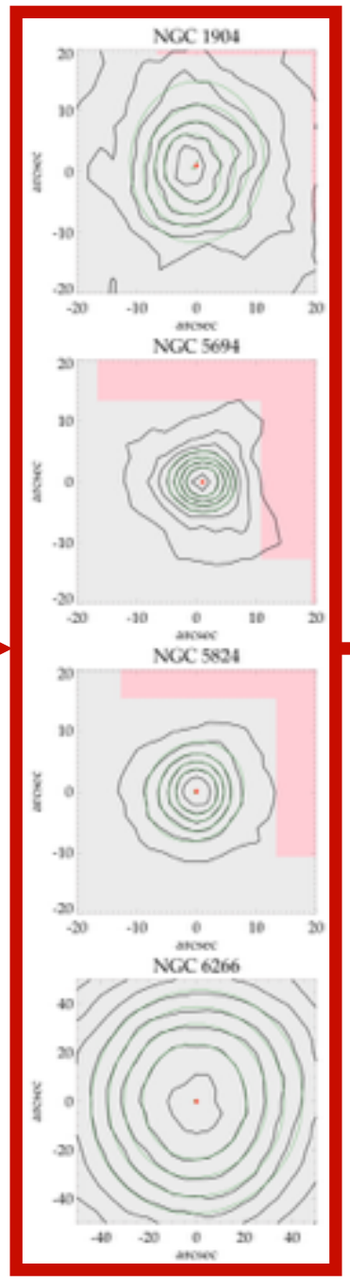


Observations - Photometry

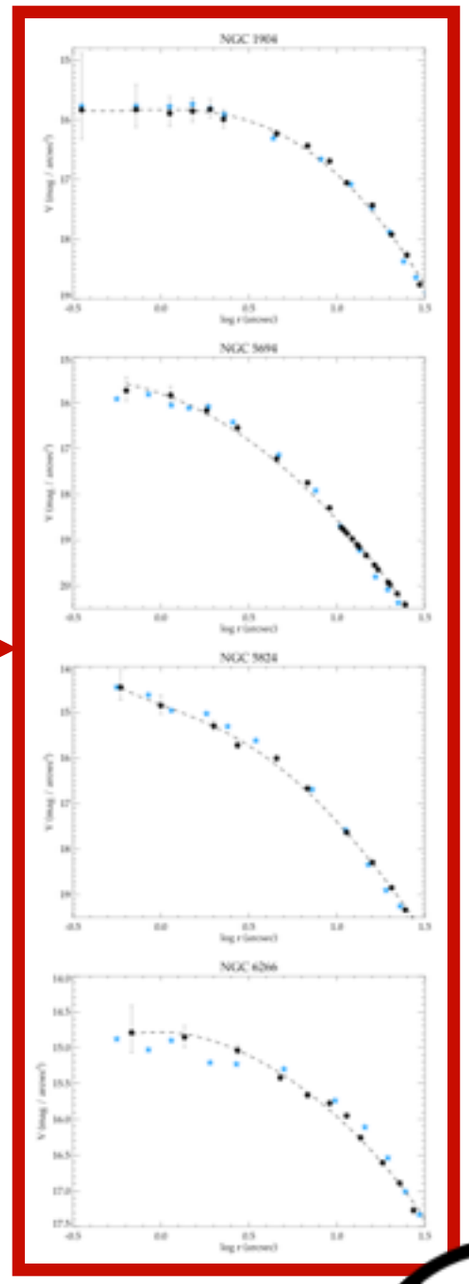
1. HST Image



2. Center

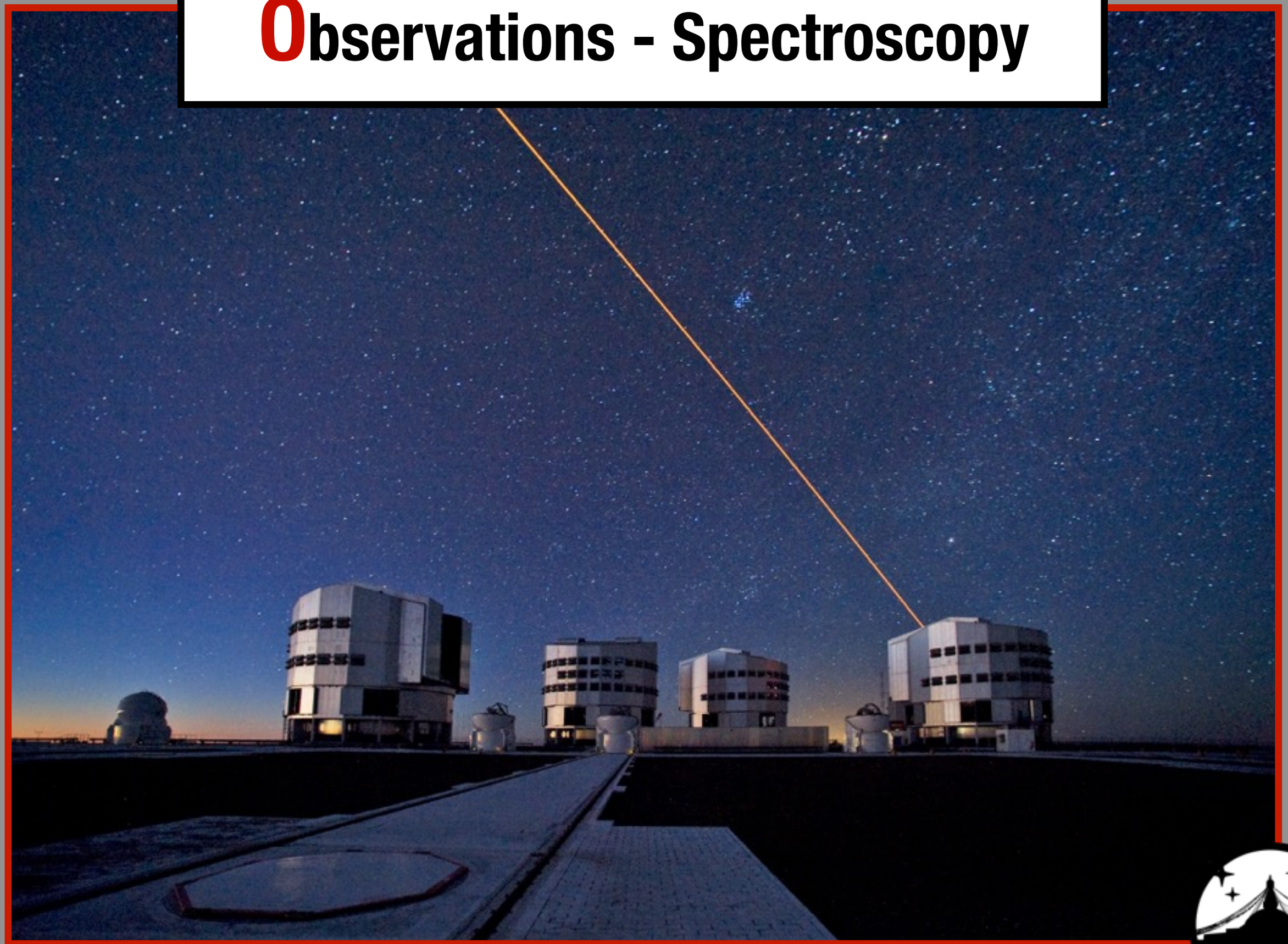


3. SB-Profile

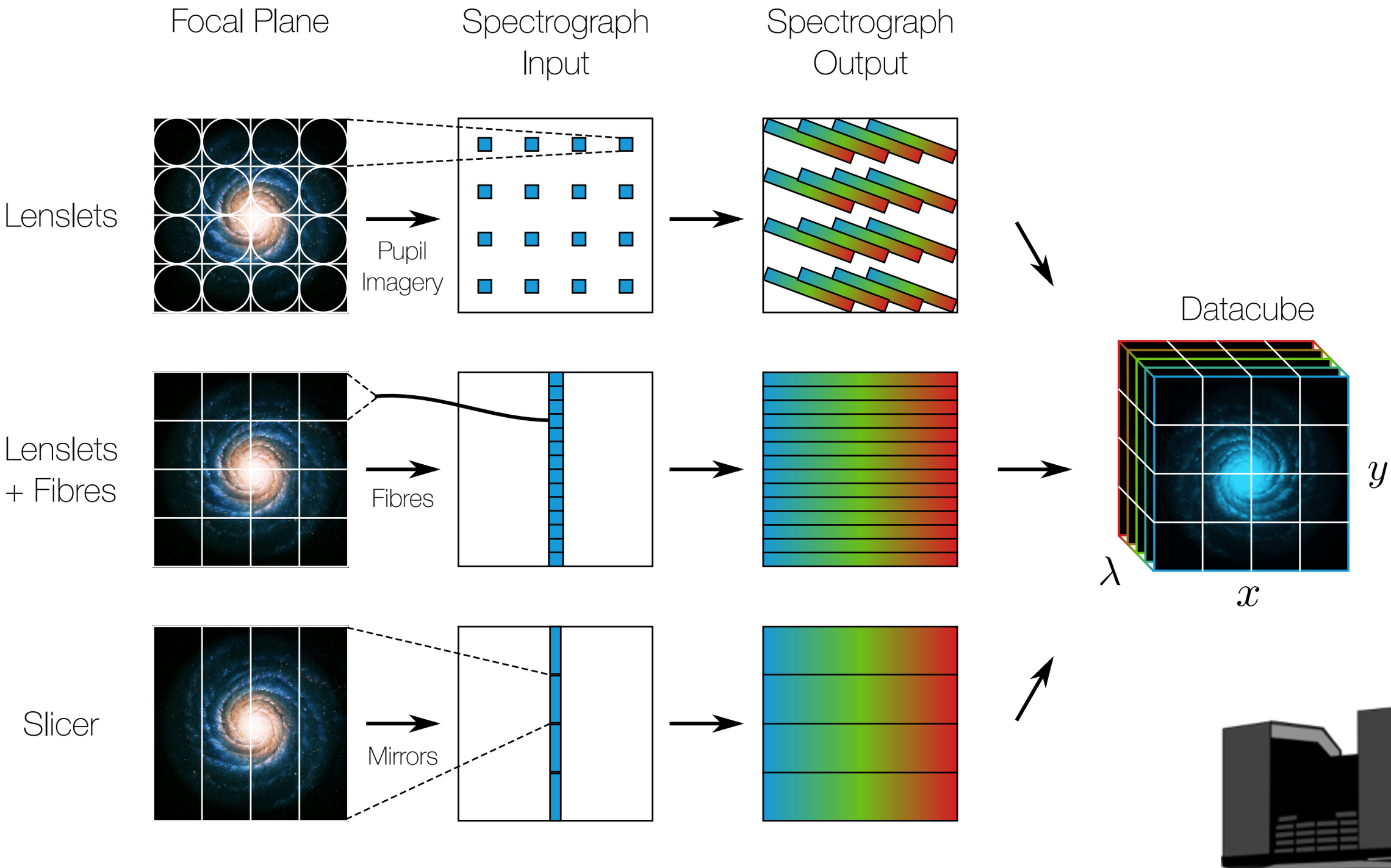


Lützgendorf et al., 2013a

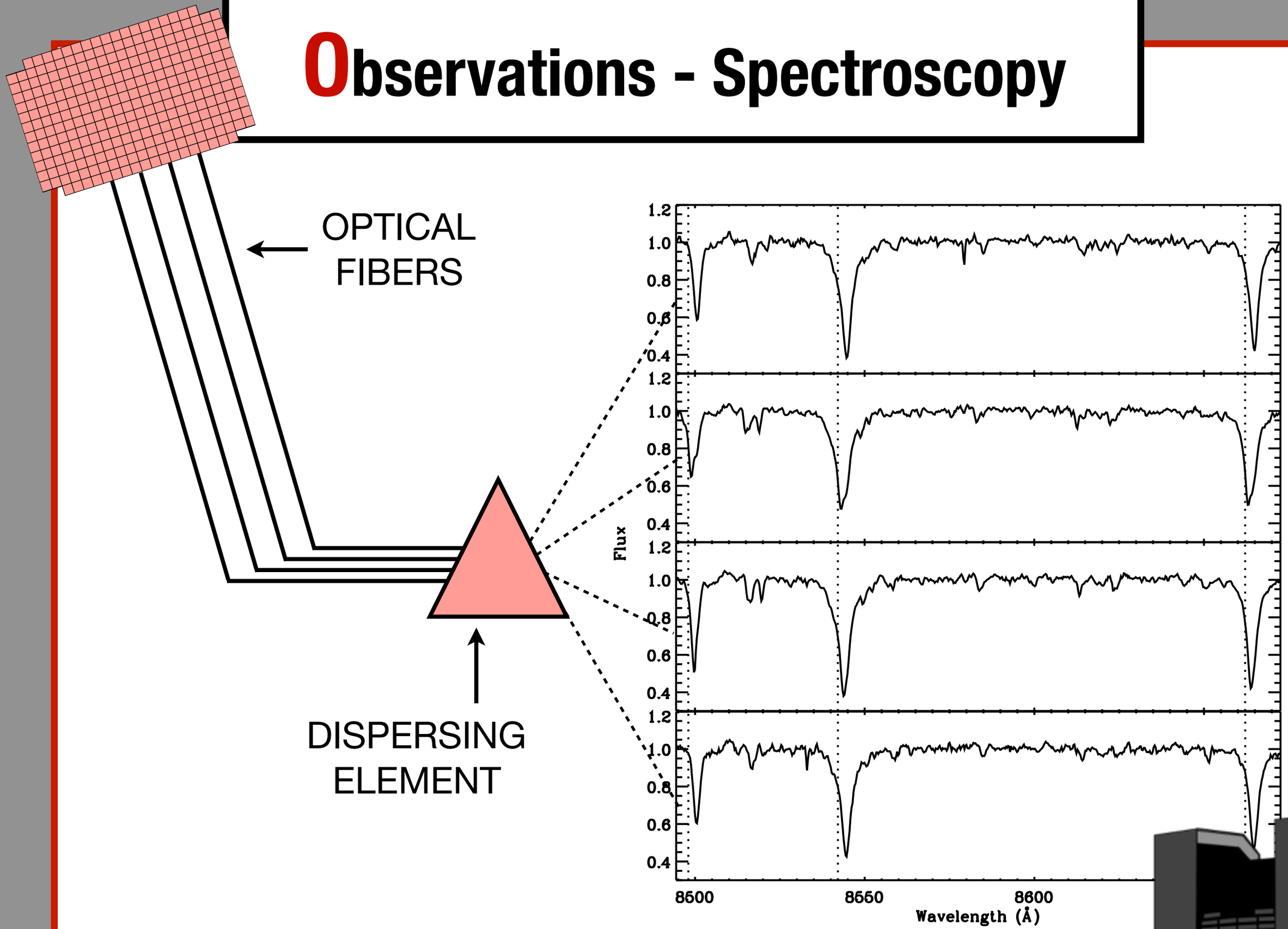
Observations - Spectroscopy



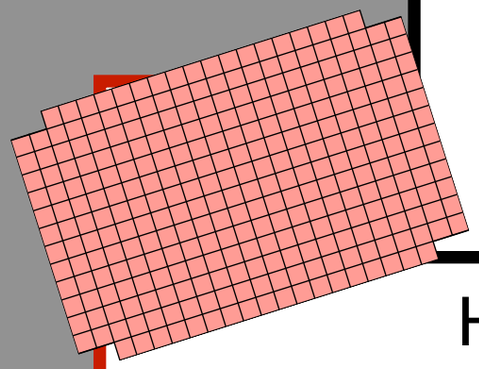
Observations - Spectroscopy



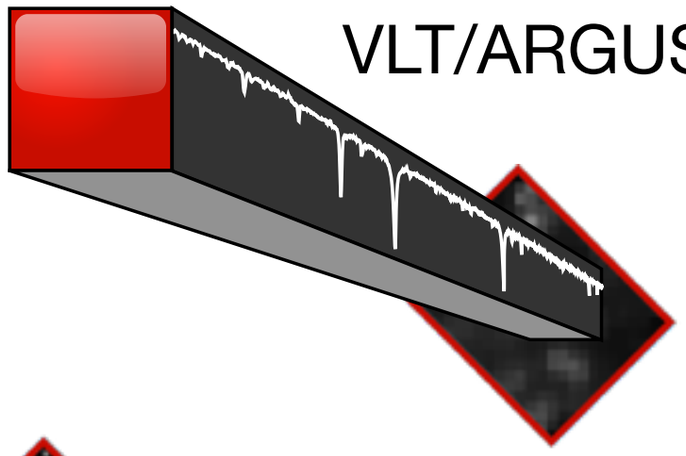
Observations - Spectroscopy



Observations - Spectroscopy

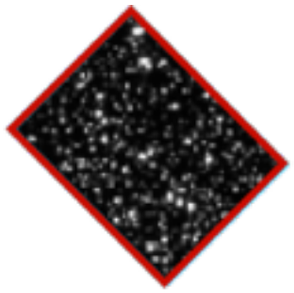


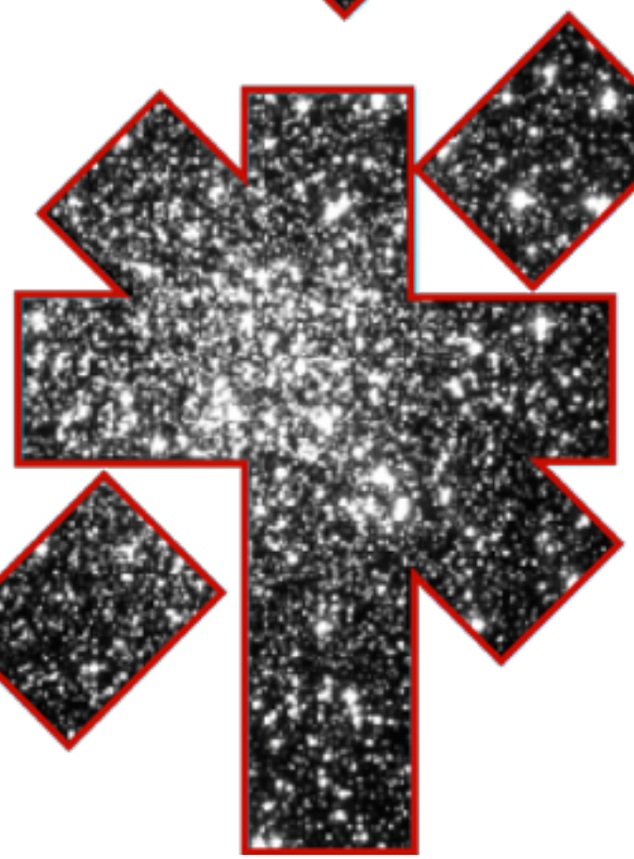
HST

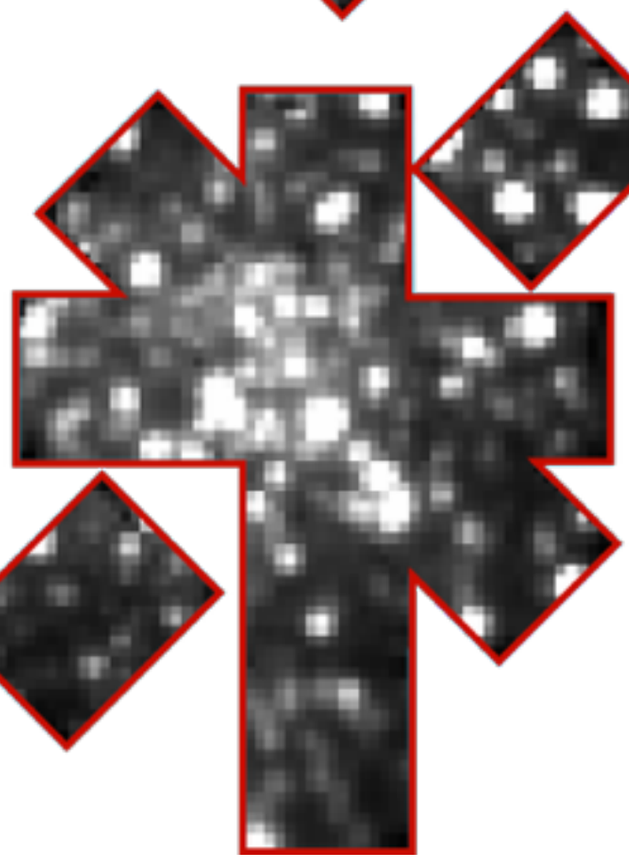


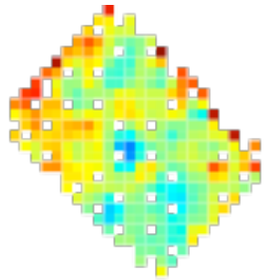
VLT/ARGUS

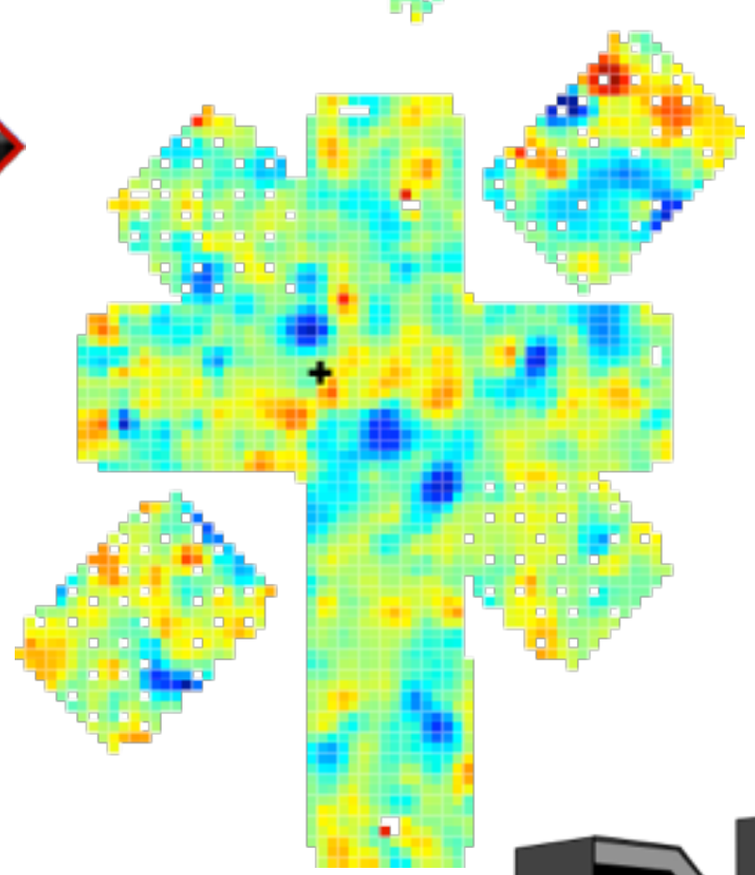
VELOCITY

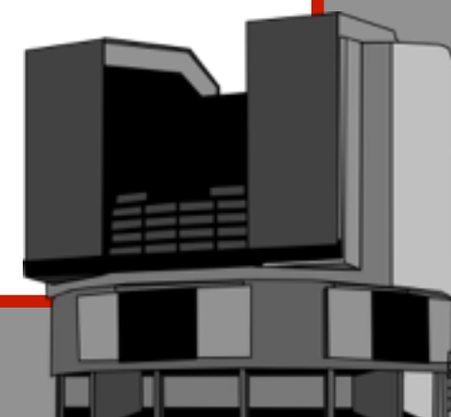




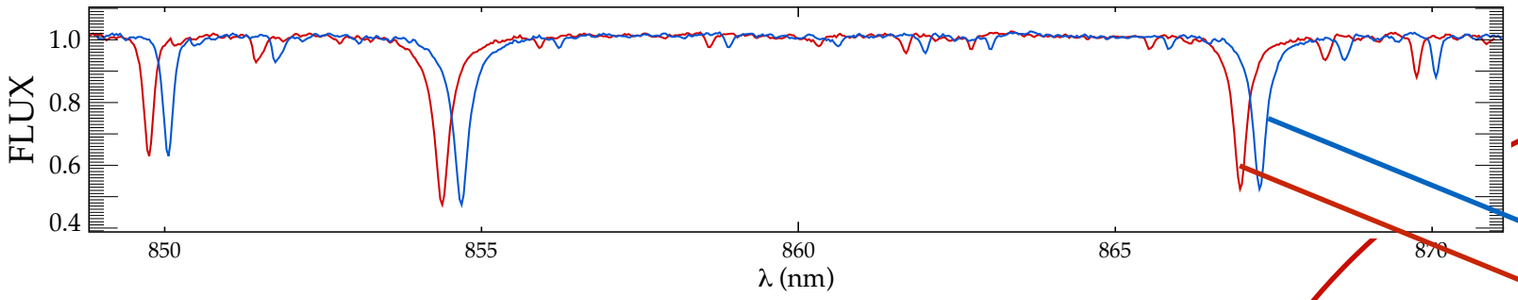


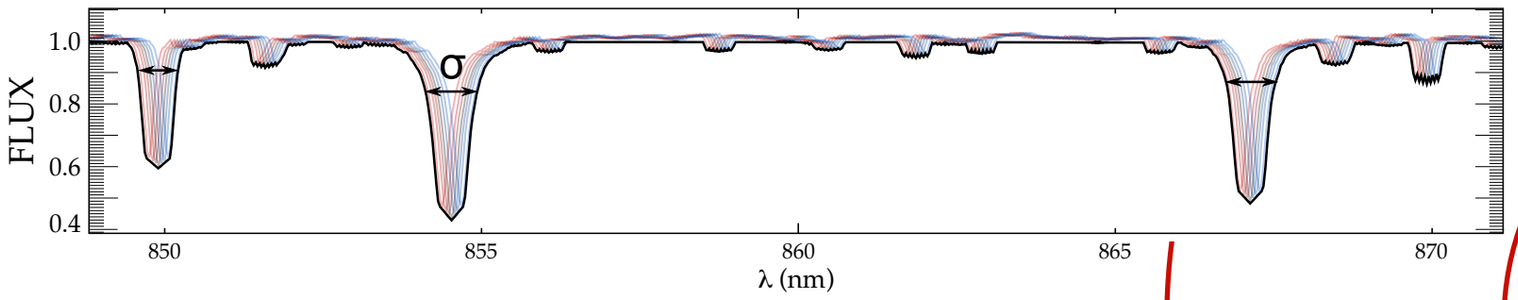


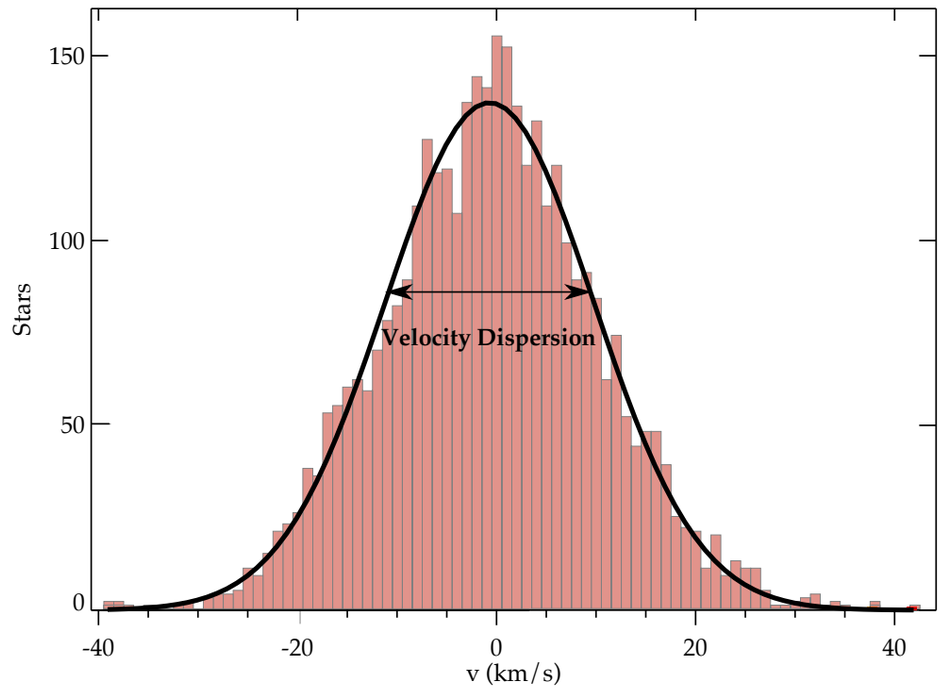


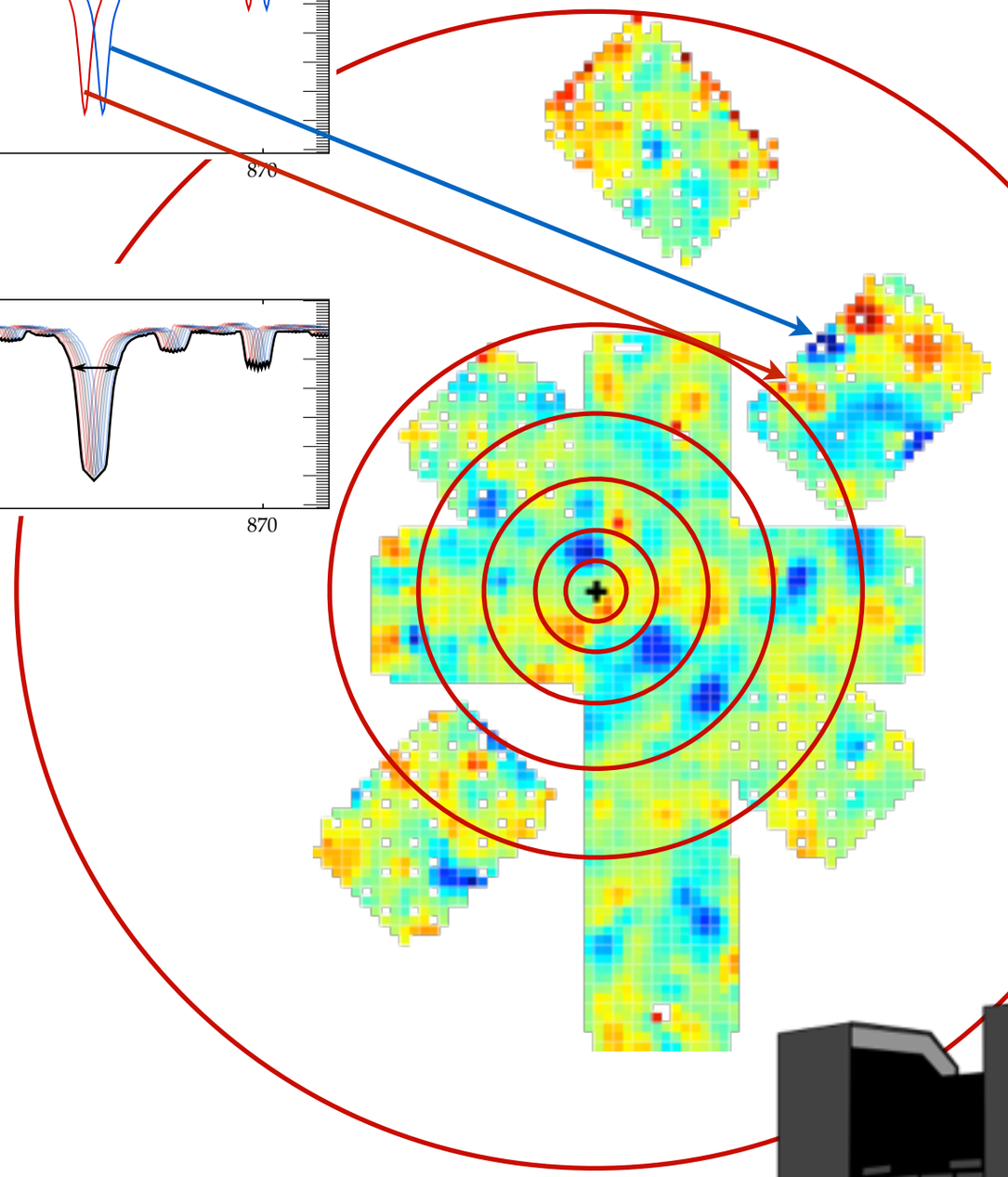


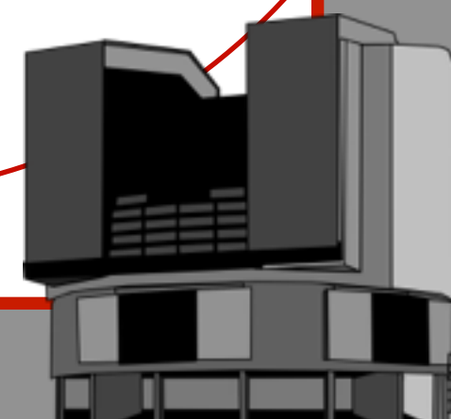
Observations - Spectroscopy





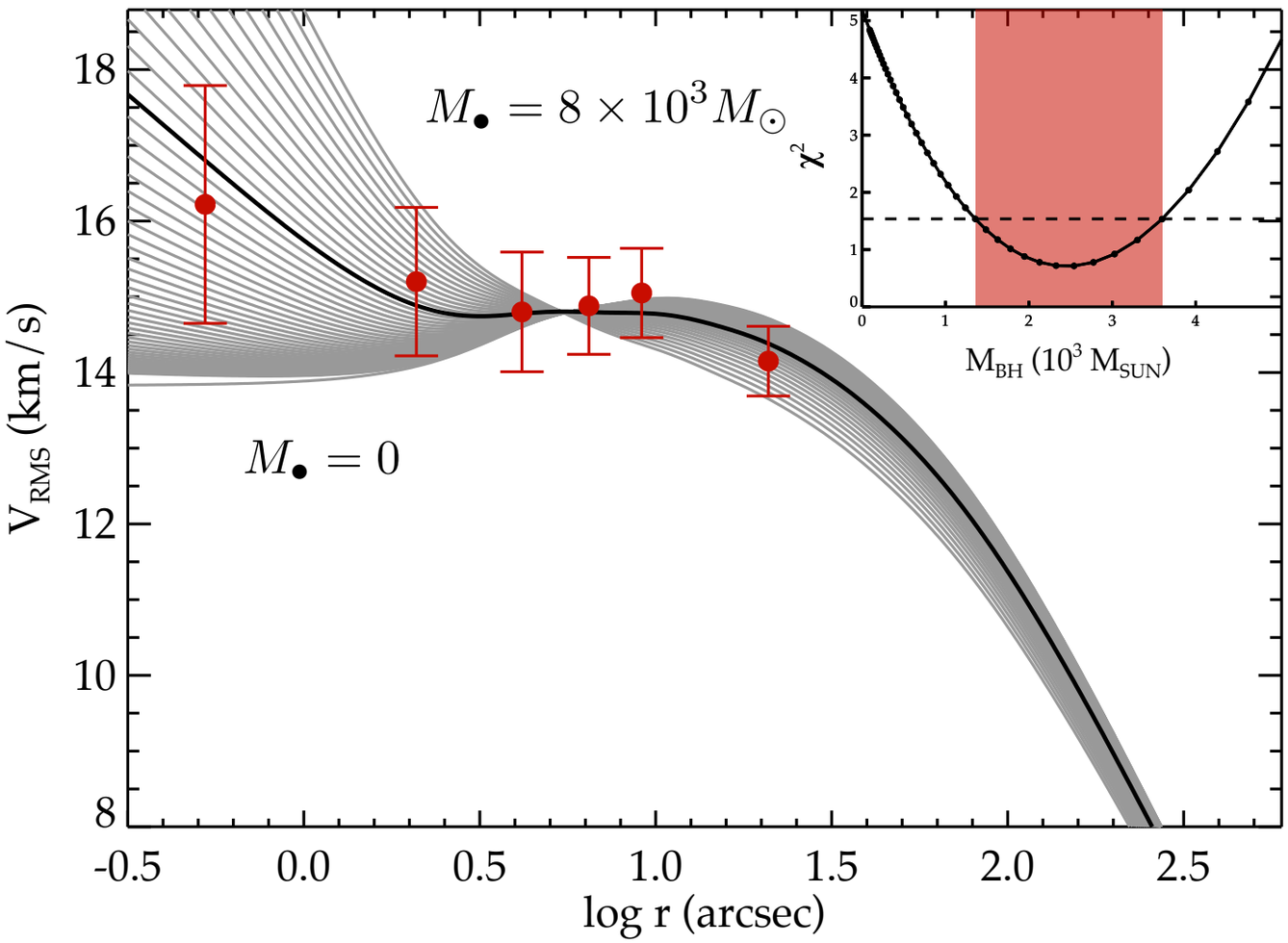


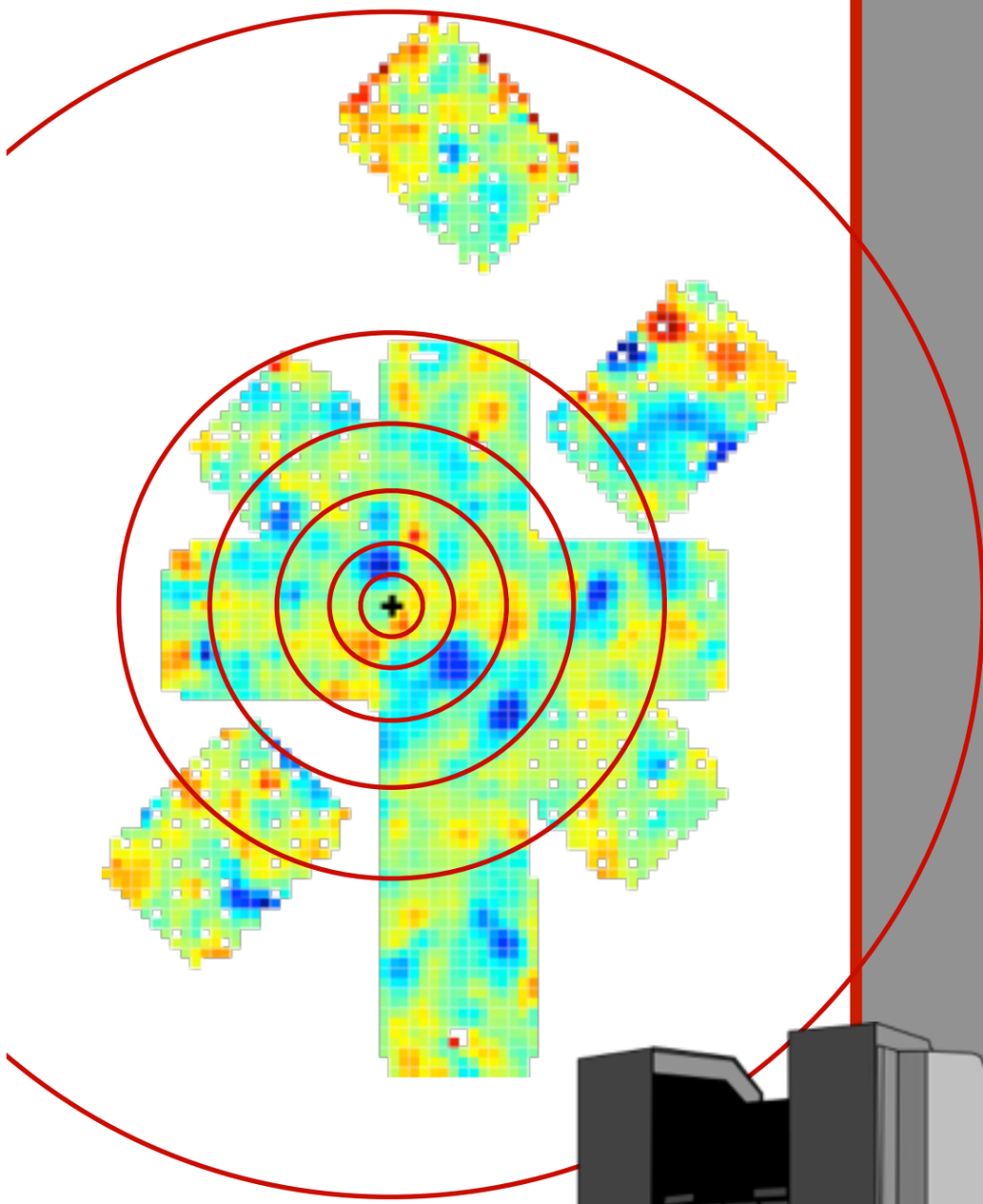




Observations - Spectroscopy

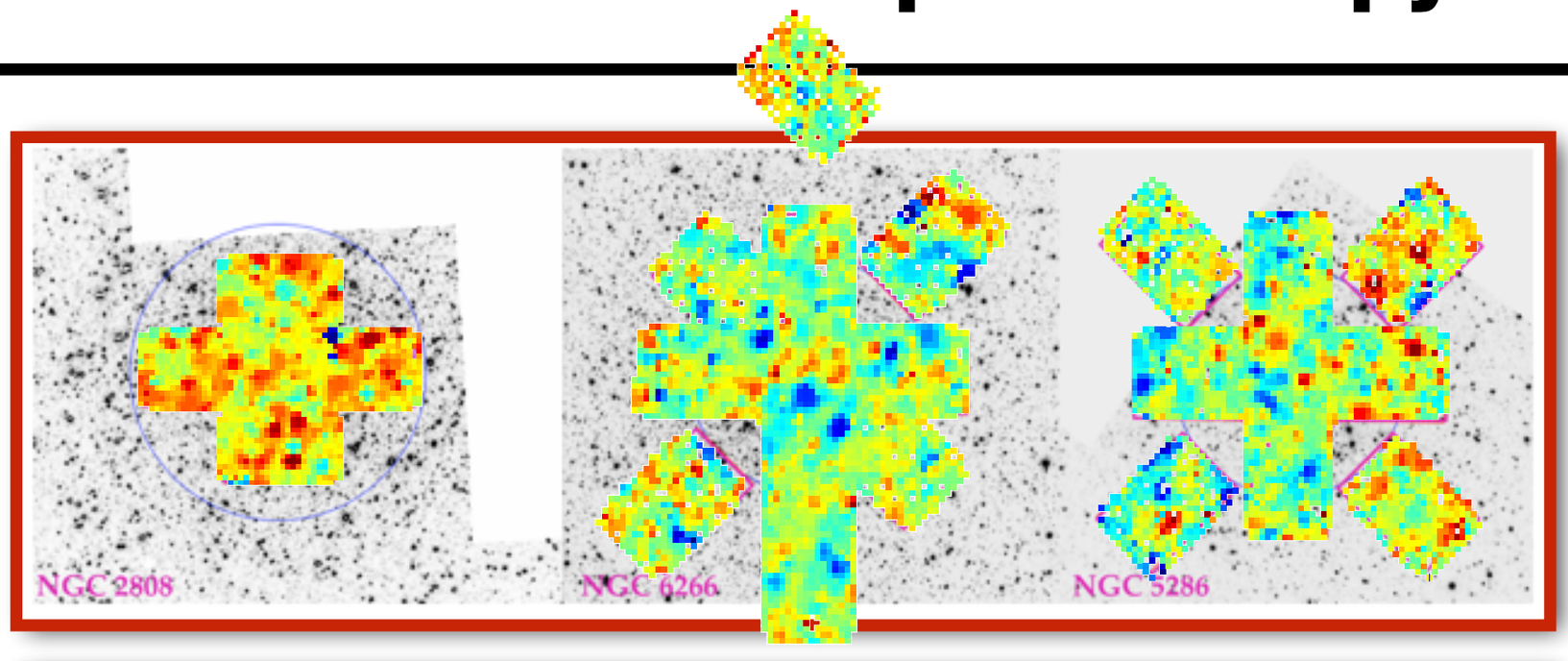
$$M_\bullet = (3 \pm 2) \times 10^3 M_\odot$$





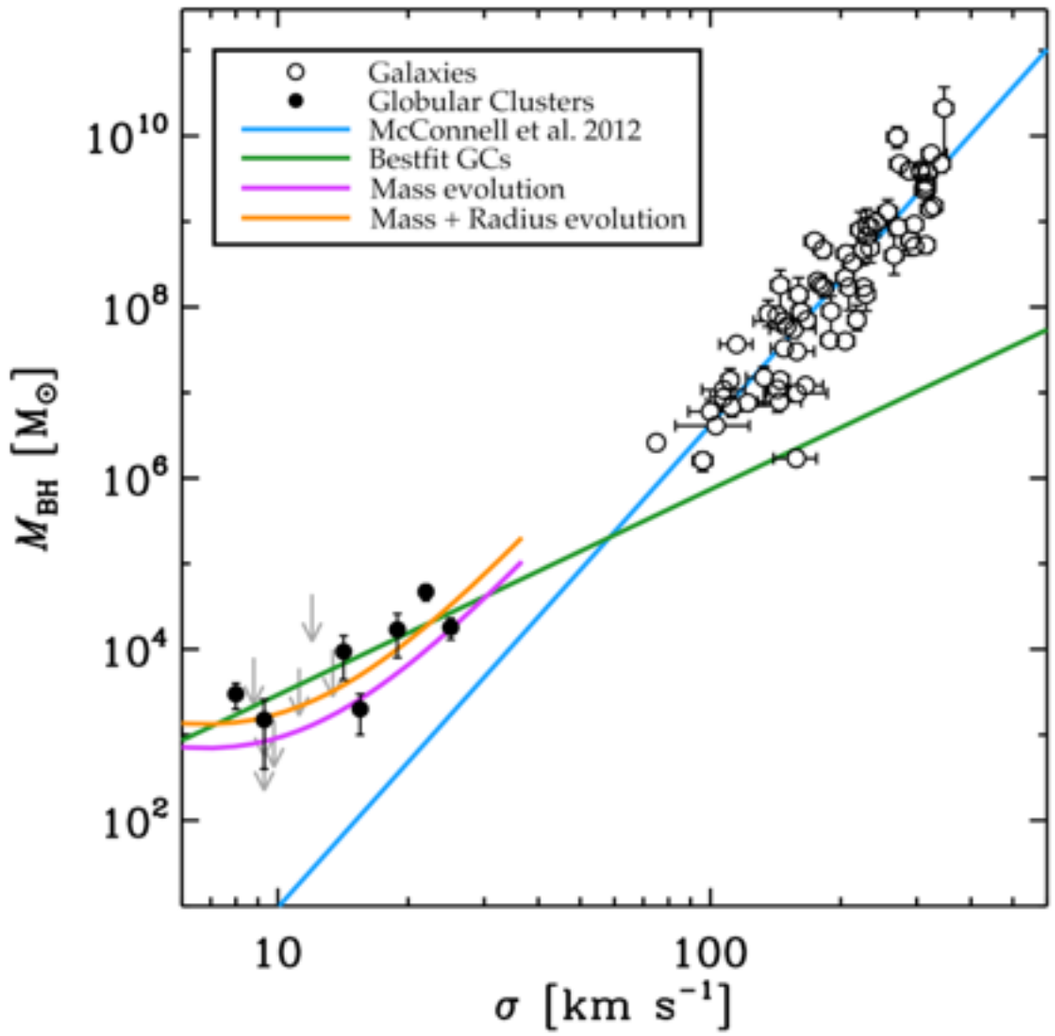
NGC 6266, Lützgendorf et al., 2013a

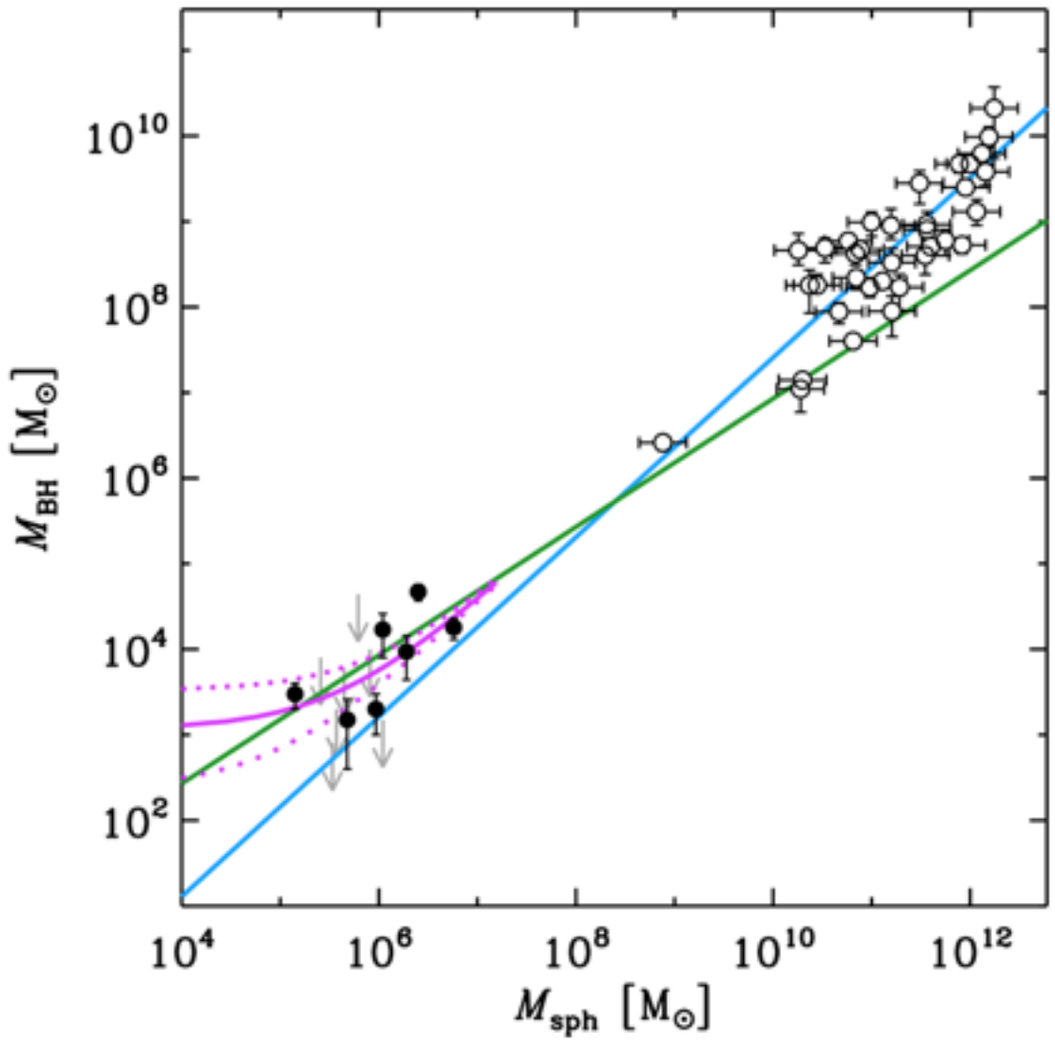
Observations - Spectroscopy



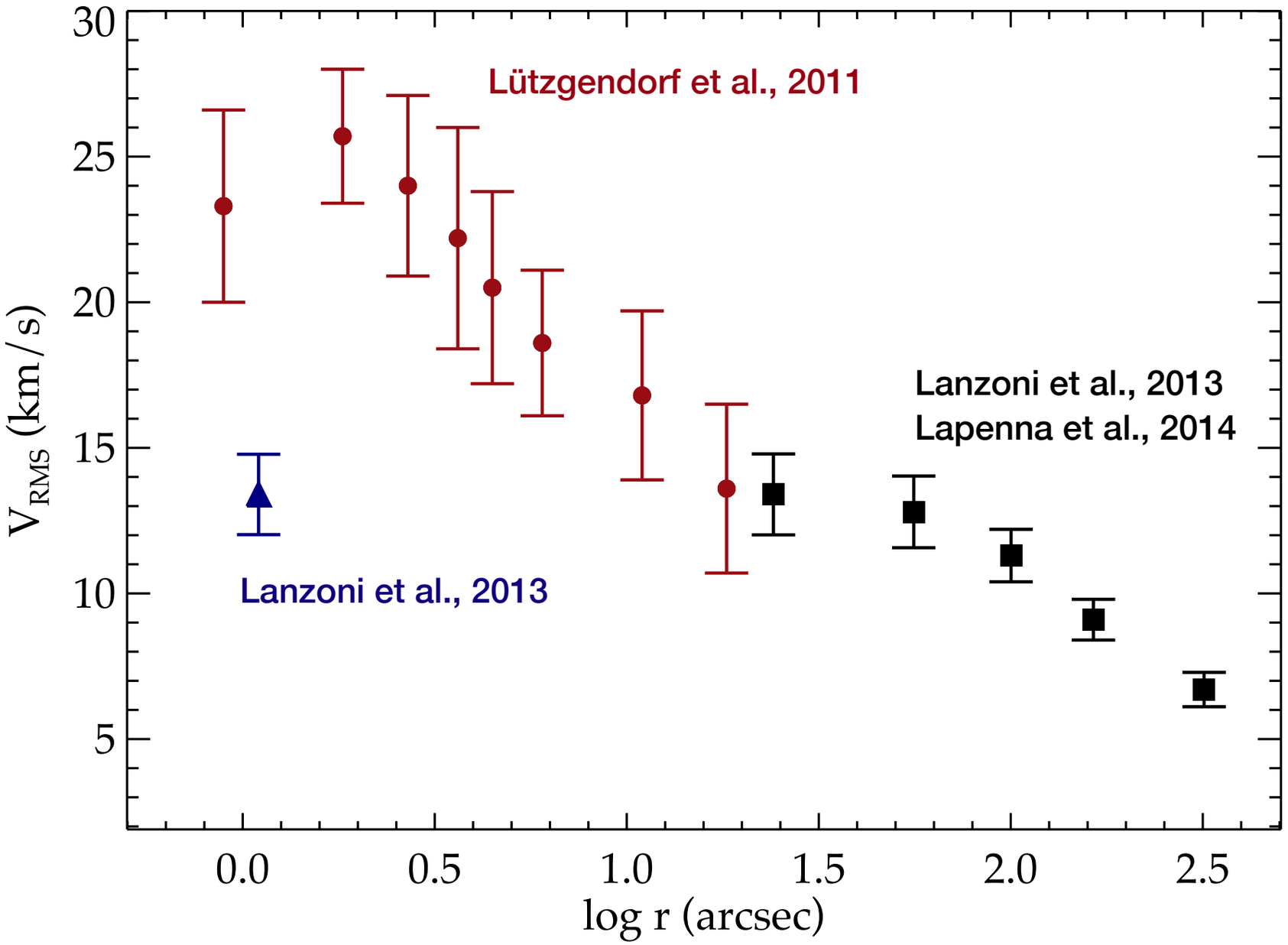
Observations - Spectroscopy

Lützgendorf et al., 2013b
Kruijssen & Lützgendorf, 2013





Observations - Spectroscopy



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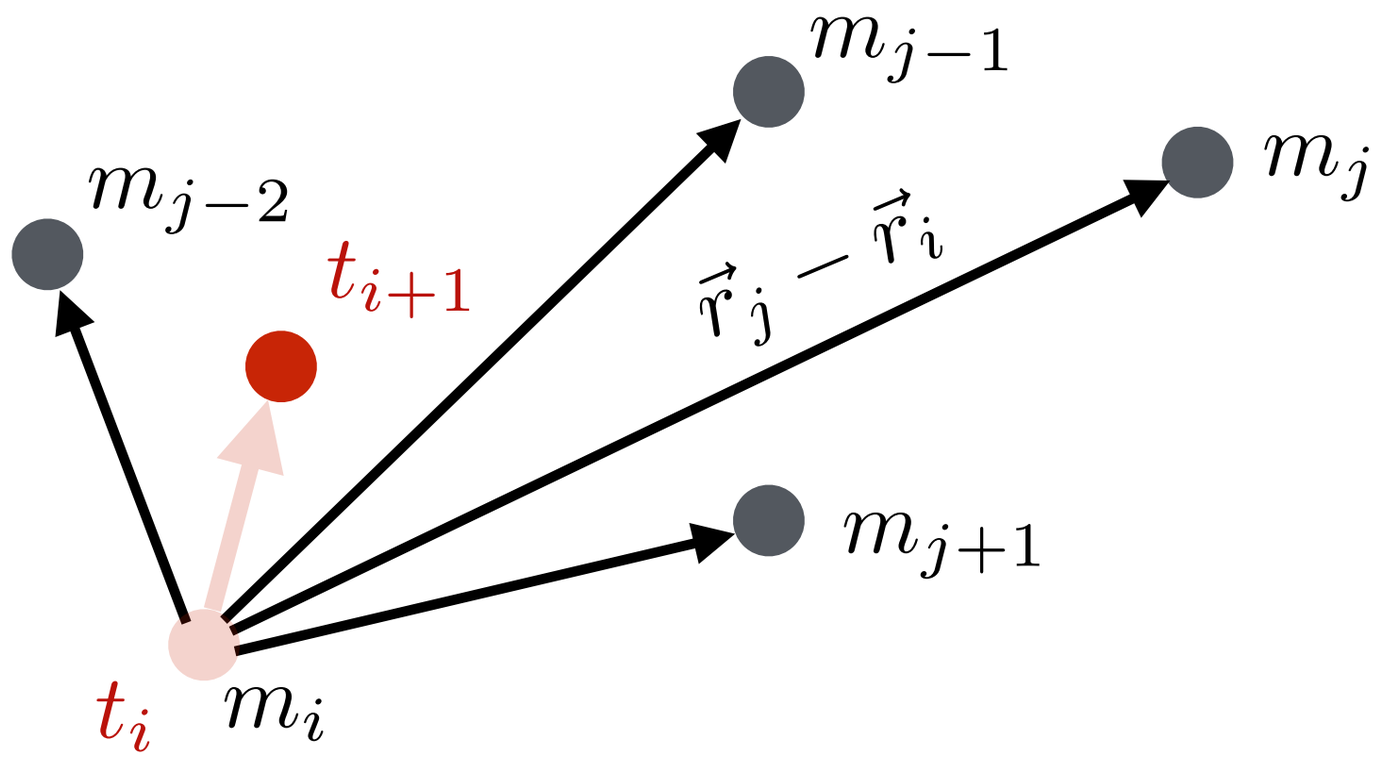
N-BODY Simulations

$$\ddot{\vec{r}}_i = -G \sum_{j=1, j\neq i}^{N} m_j \frac{\vec{r}_j - \vec{r}_i}{|\vec{r}_j - \vec{r}_i|^3}$$



N-BODY Simulations

$$\ddot{\vec{r}}_i = -G \sum_{j=1, j\neq i}^{N} m_j \frac{\vec{r}_j - \vec{r}_i}{|\vec{r}_j - \vec{r}_i|^3}$$

LEAPFROG INTEGRATION

$$x_{i+1} = x_i + v_i \Delta t + \frac{1}{2} a_i \Delta t$$

$$v_{i+1} = v_i + \frac{1}{2}(a_i + a_{i+1}) \Delta t$$

N-BODY Simulations

THE ASTROPHYSICAL JOURNAL

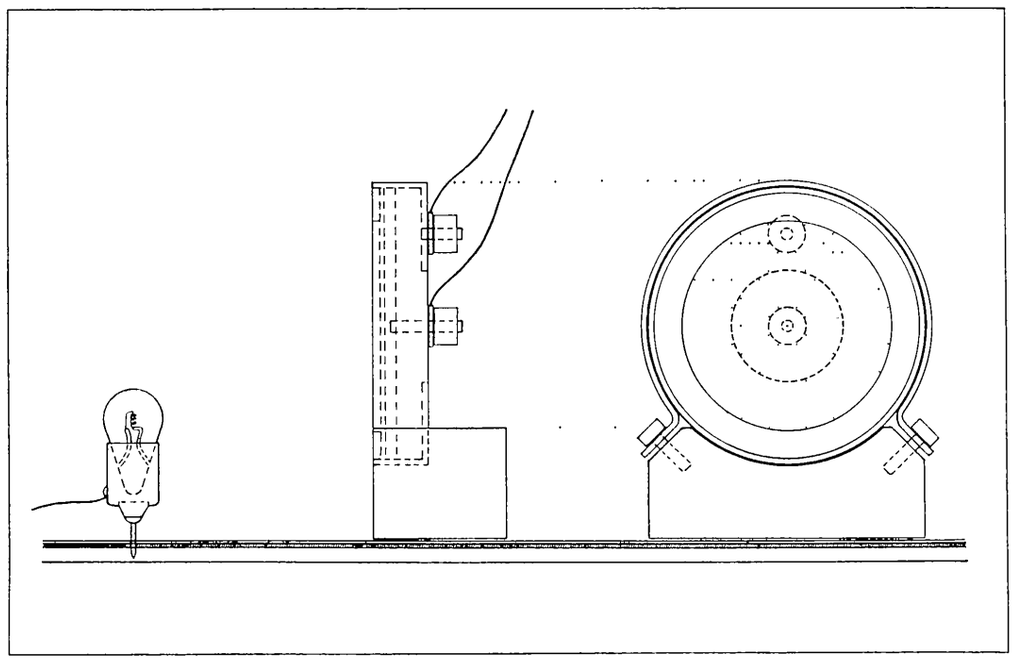
AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

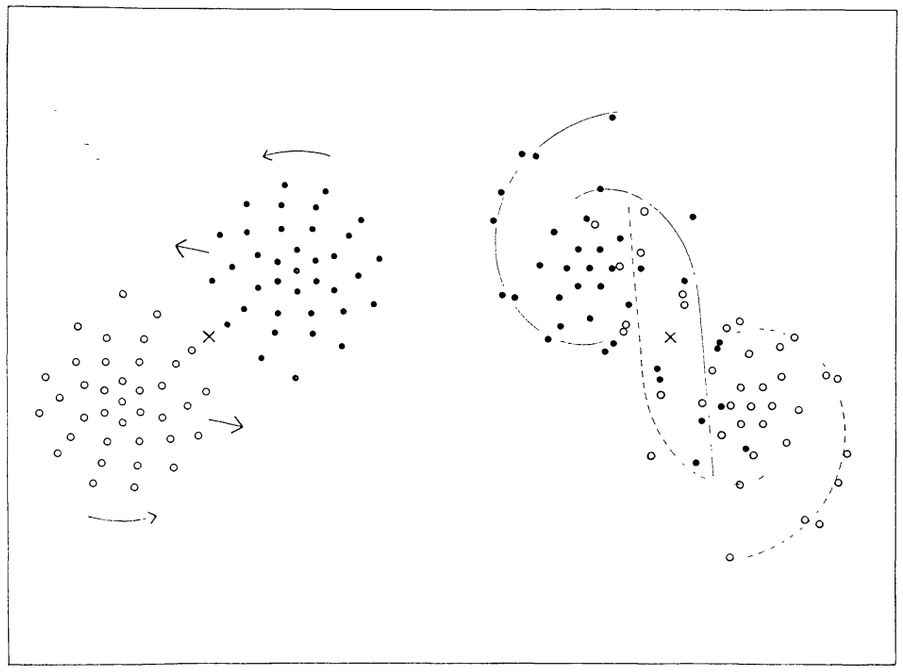
VOLUME 94 NOVEMBER 1941 NUMBER 3

ON THE CLUSTERING TENDENCIES AMONG THE NEBULAE

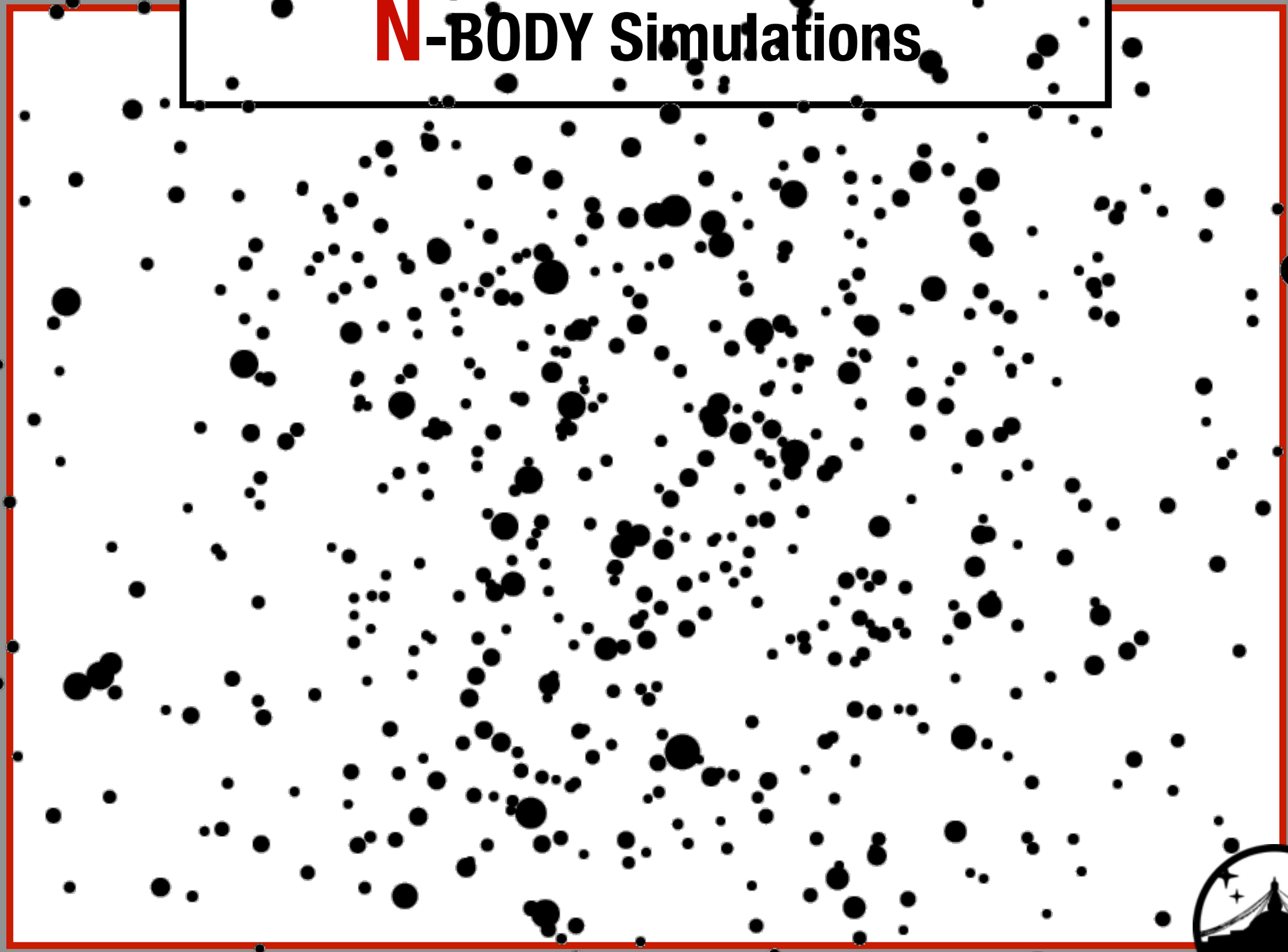
II. A STUDY OF ENCOUNTERS BETWEEN LABORATORY MODELS OF STELLAR SYSTEMS BY A NEW INTEGRATION PROCEDURE

ERIK HOLMBERG



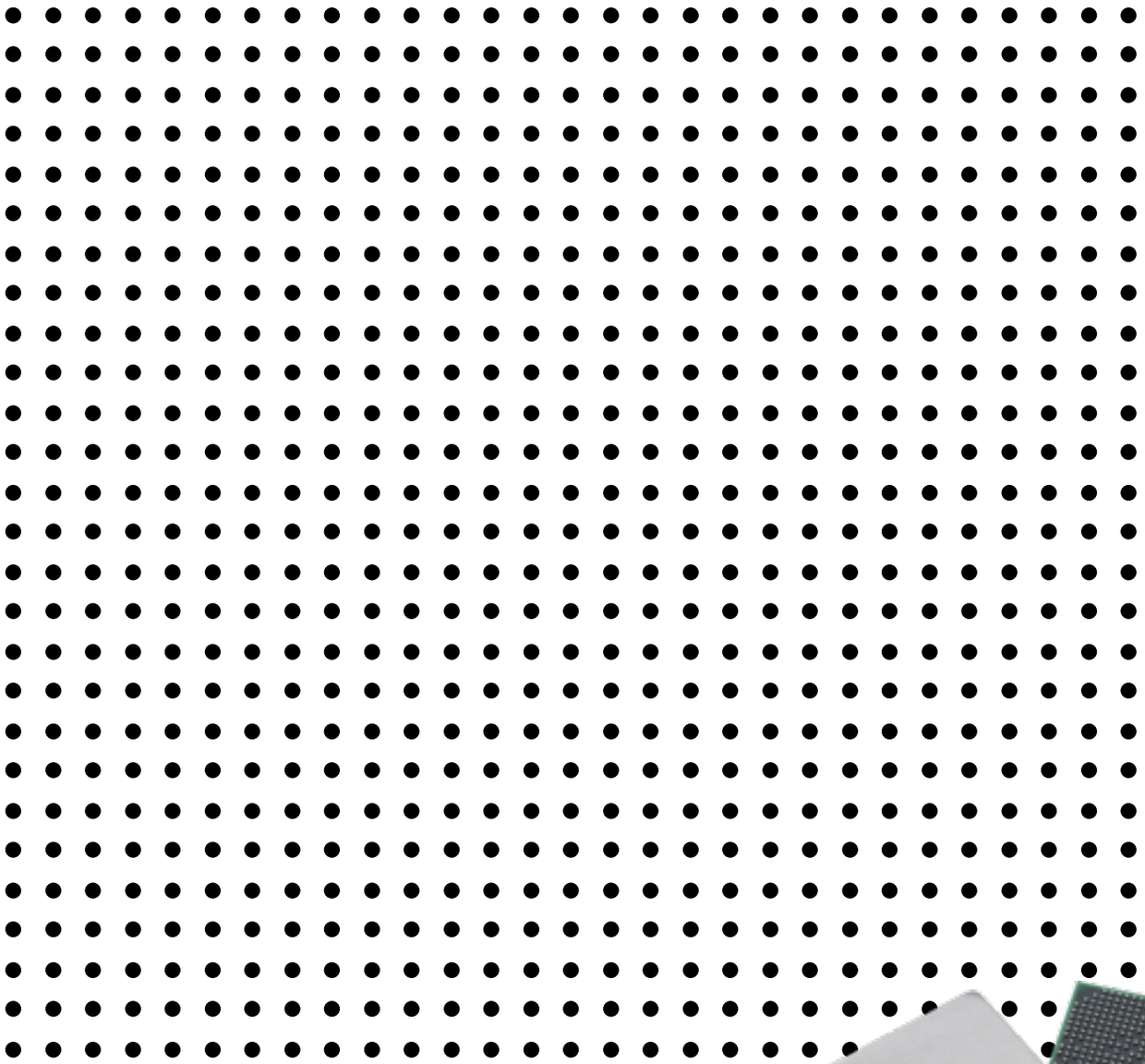


N-BODY Simulations



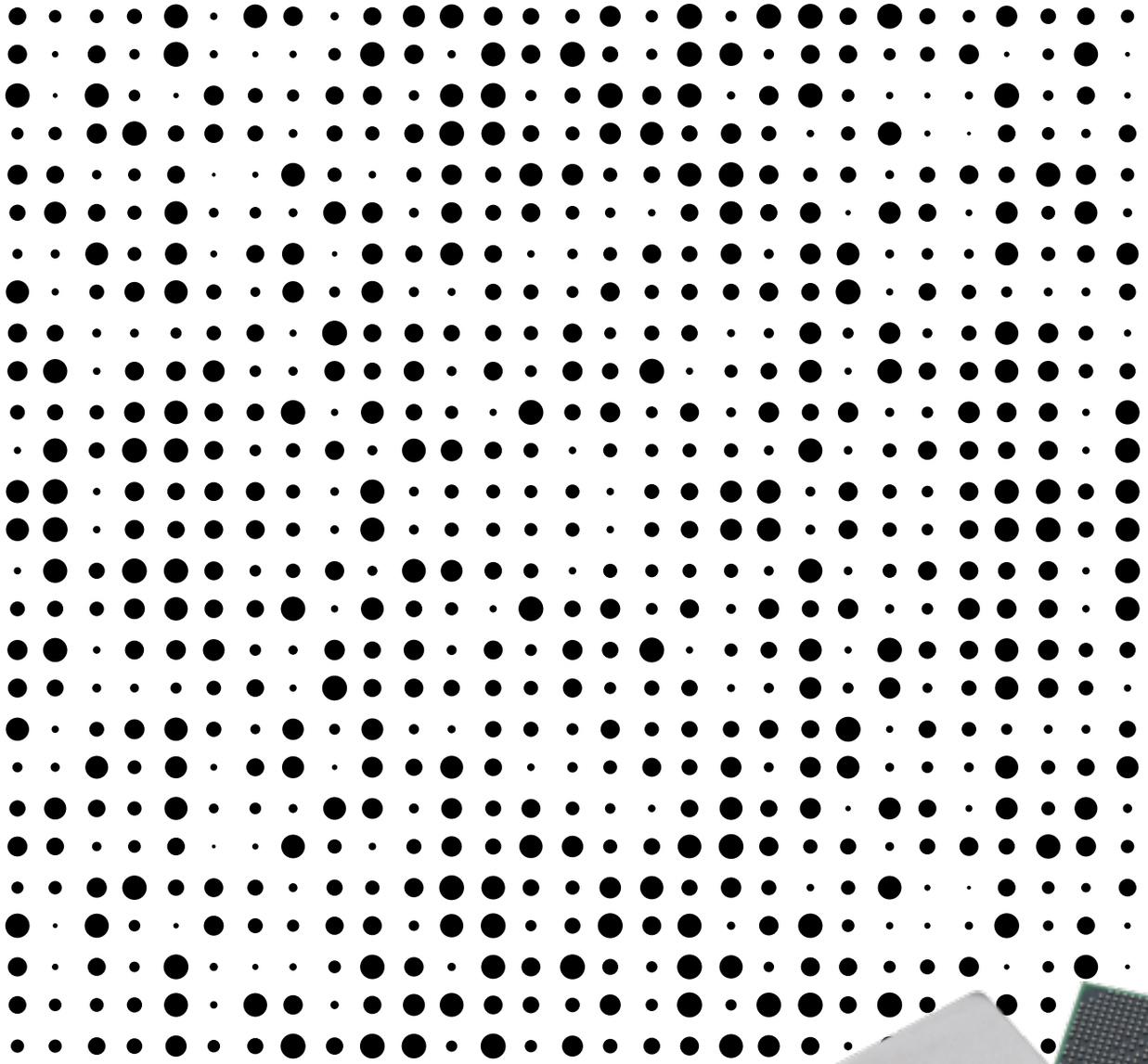
N-BODY Simulations

1. N Stars



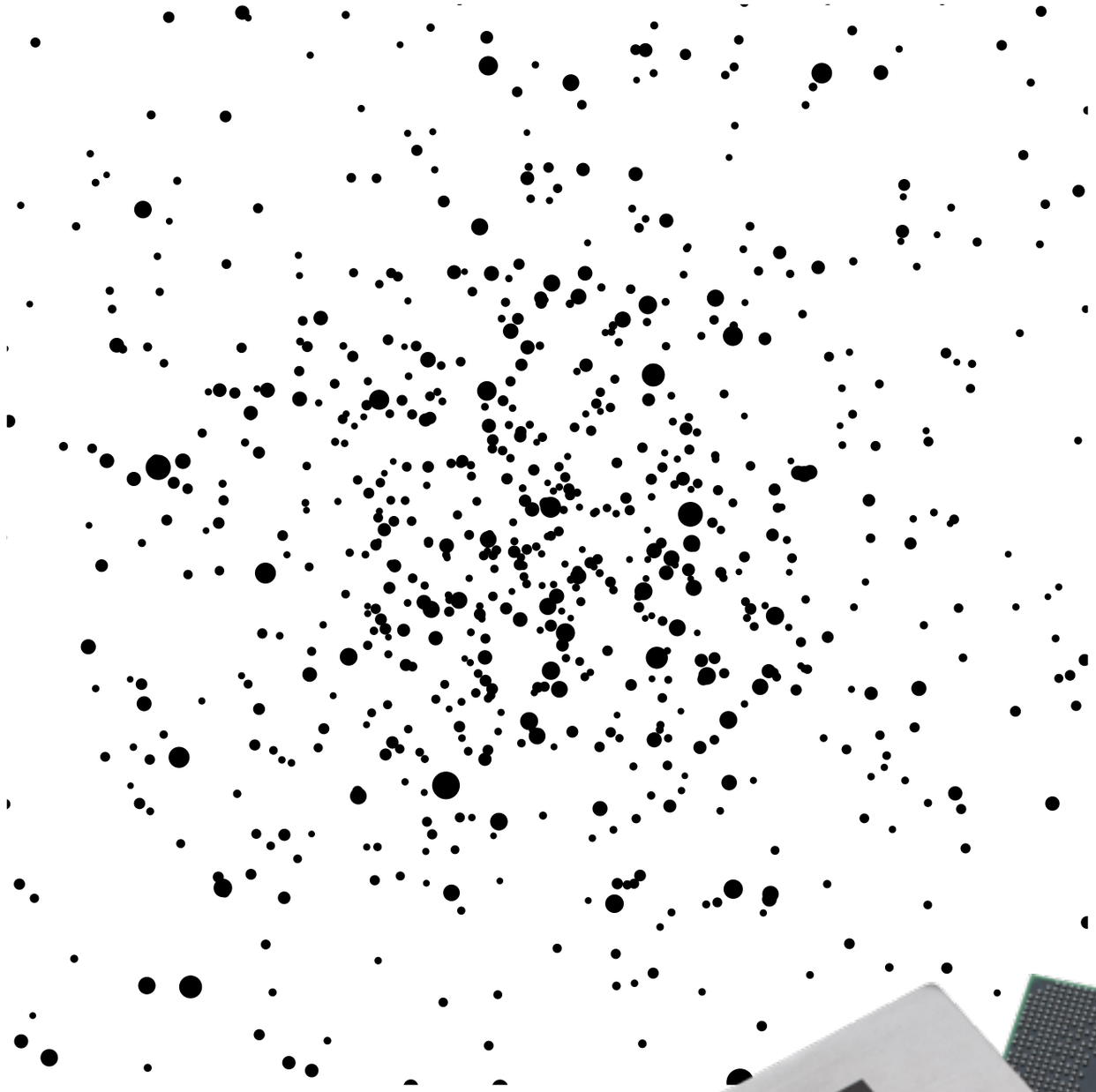
N-BODY Simulations

1. N Stars
2. Masses



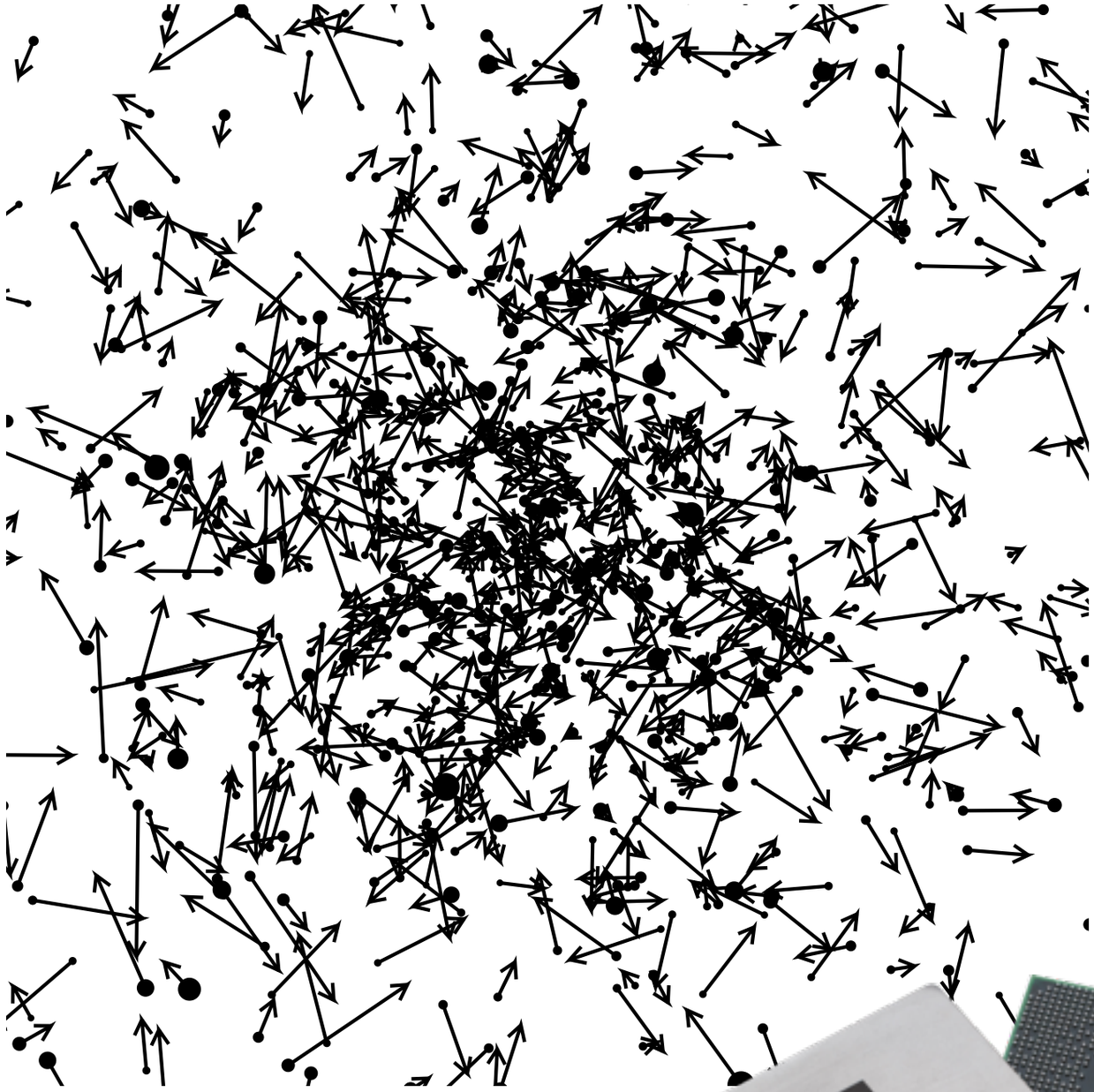
N-BODY Simulations

1. N Stars
2. Masses
3. Distribution



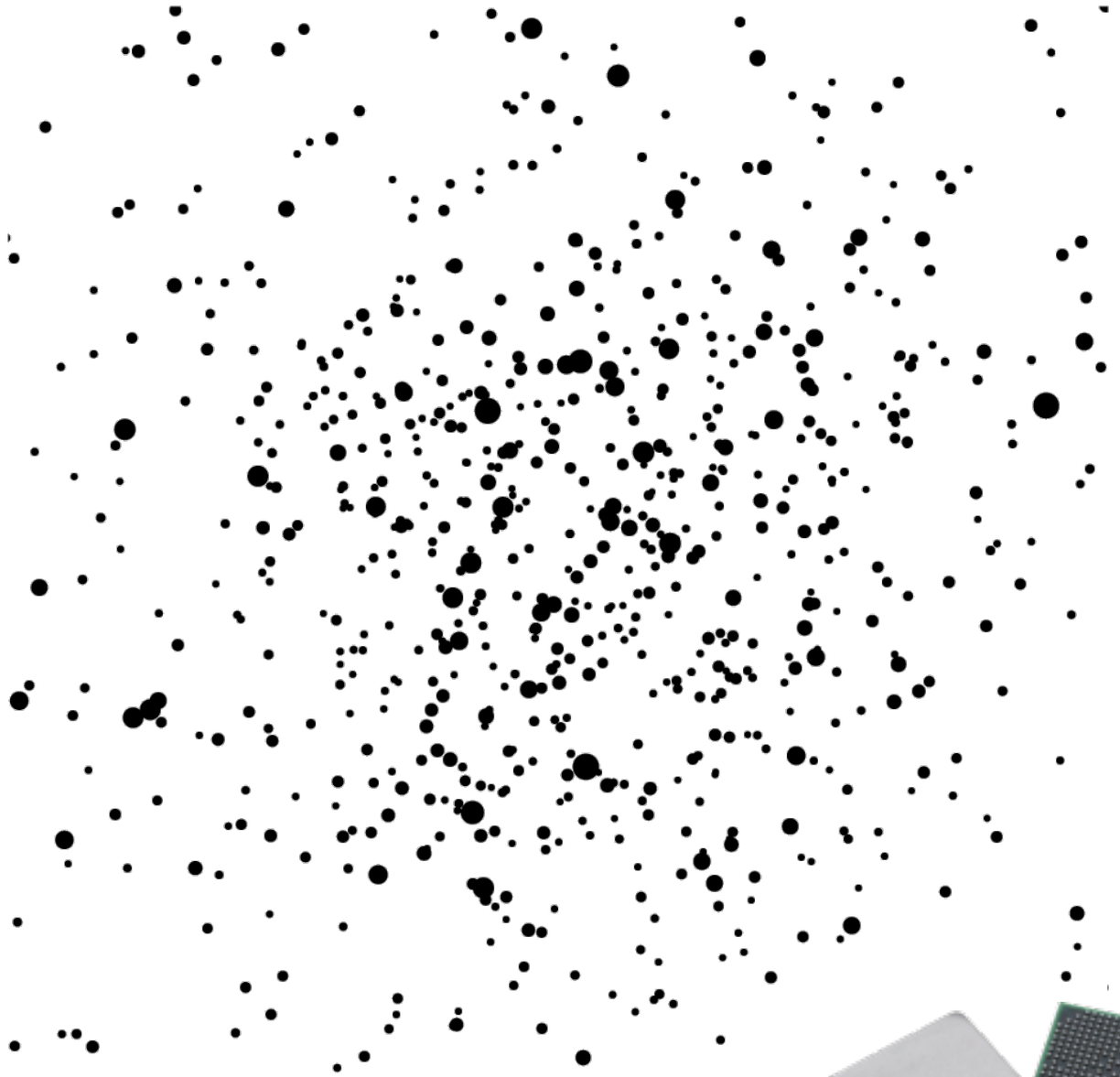
N-BODY Simulations

1. N Stars
2. Masses
3. Distribution
4. Velocities



N-BODY Simulations

1. N Stars
2. Masses
3. Distribution
4. Velocities
5. **GO**



N-BODY Simulations

Applications?

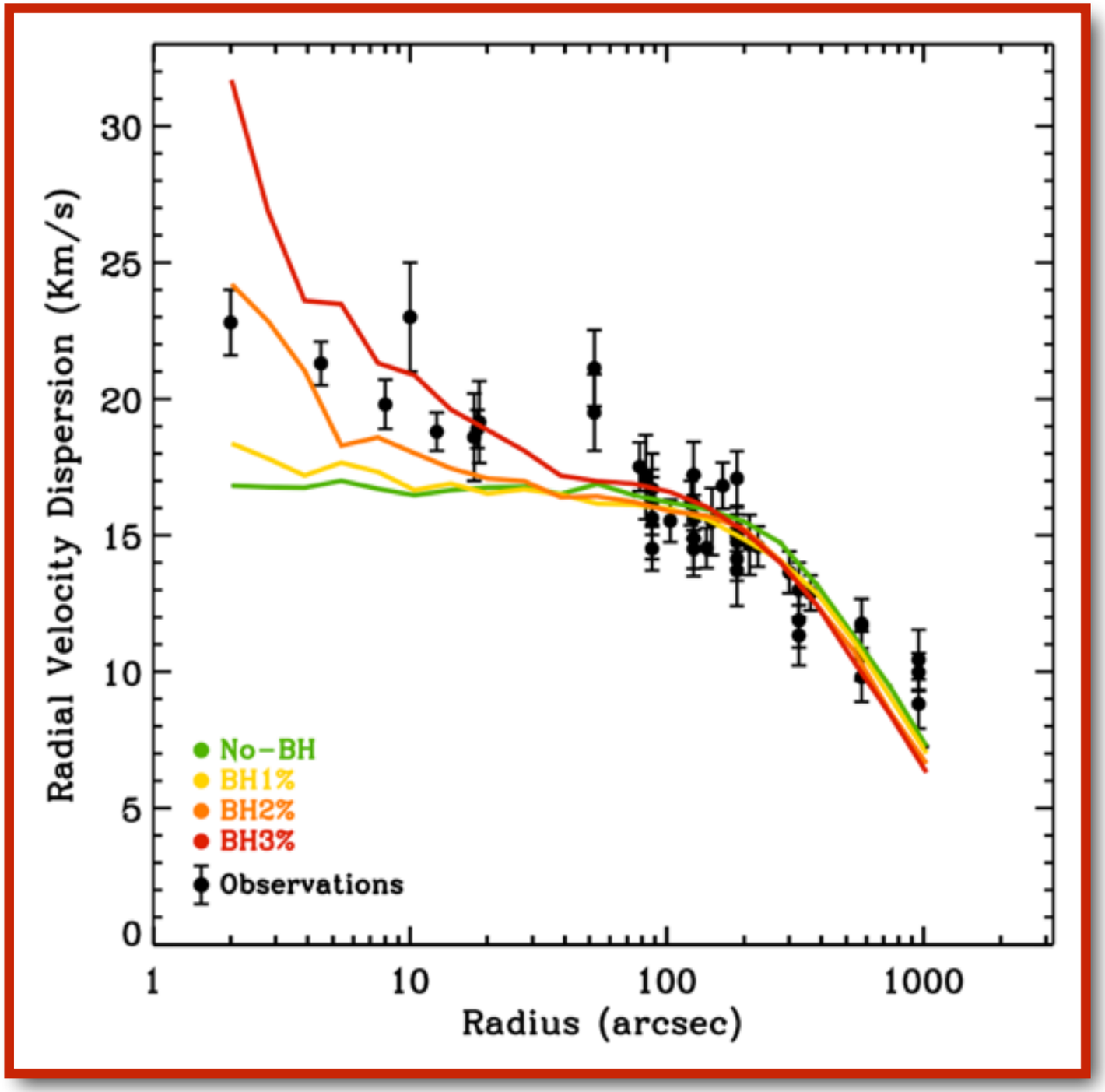
COMPARE TO DATA

SIMULATE DATA

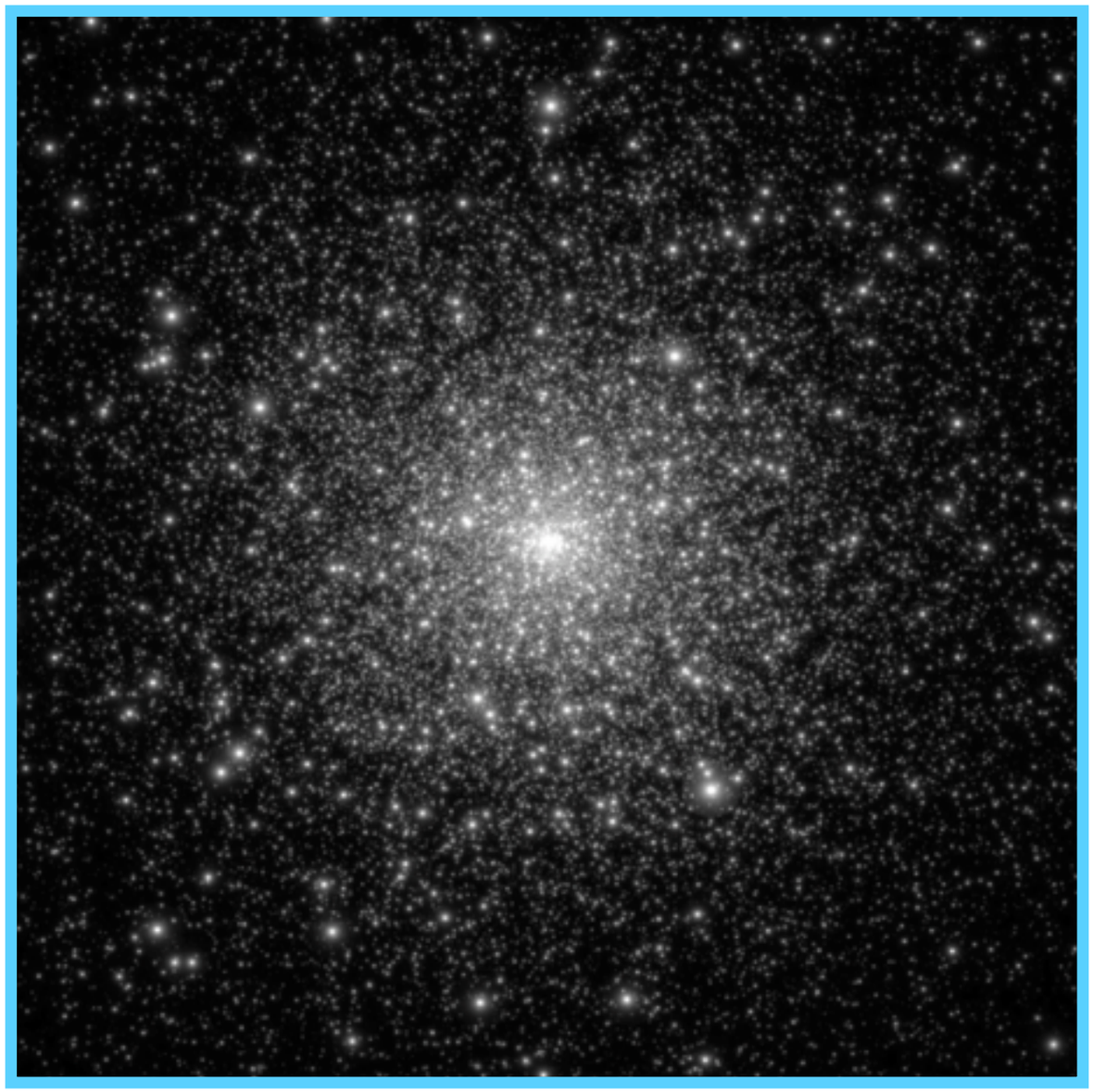
FIND NEW OBSERVABLES

N-BODY - COMPARE

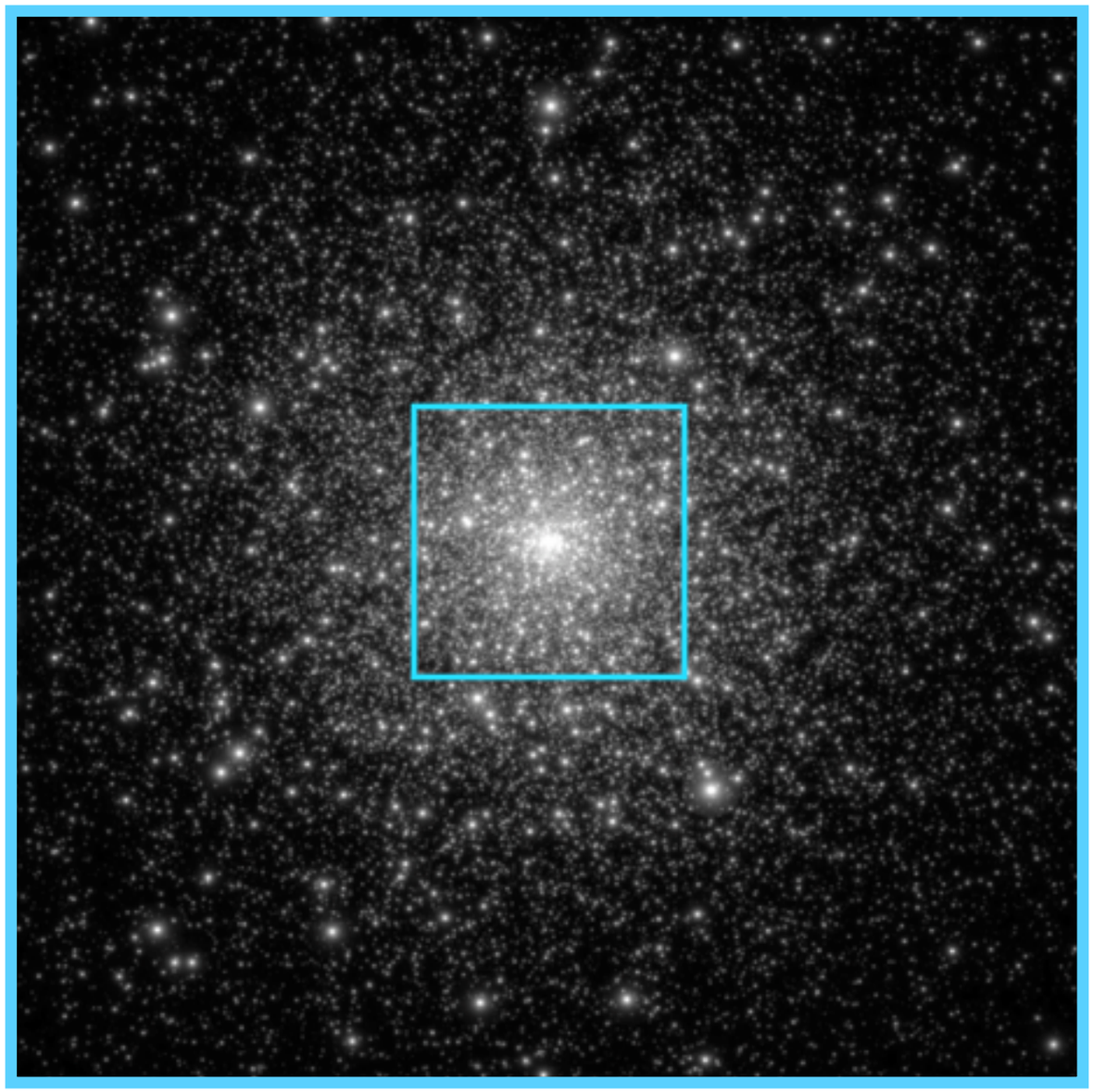
Jalali et al. 2012



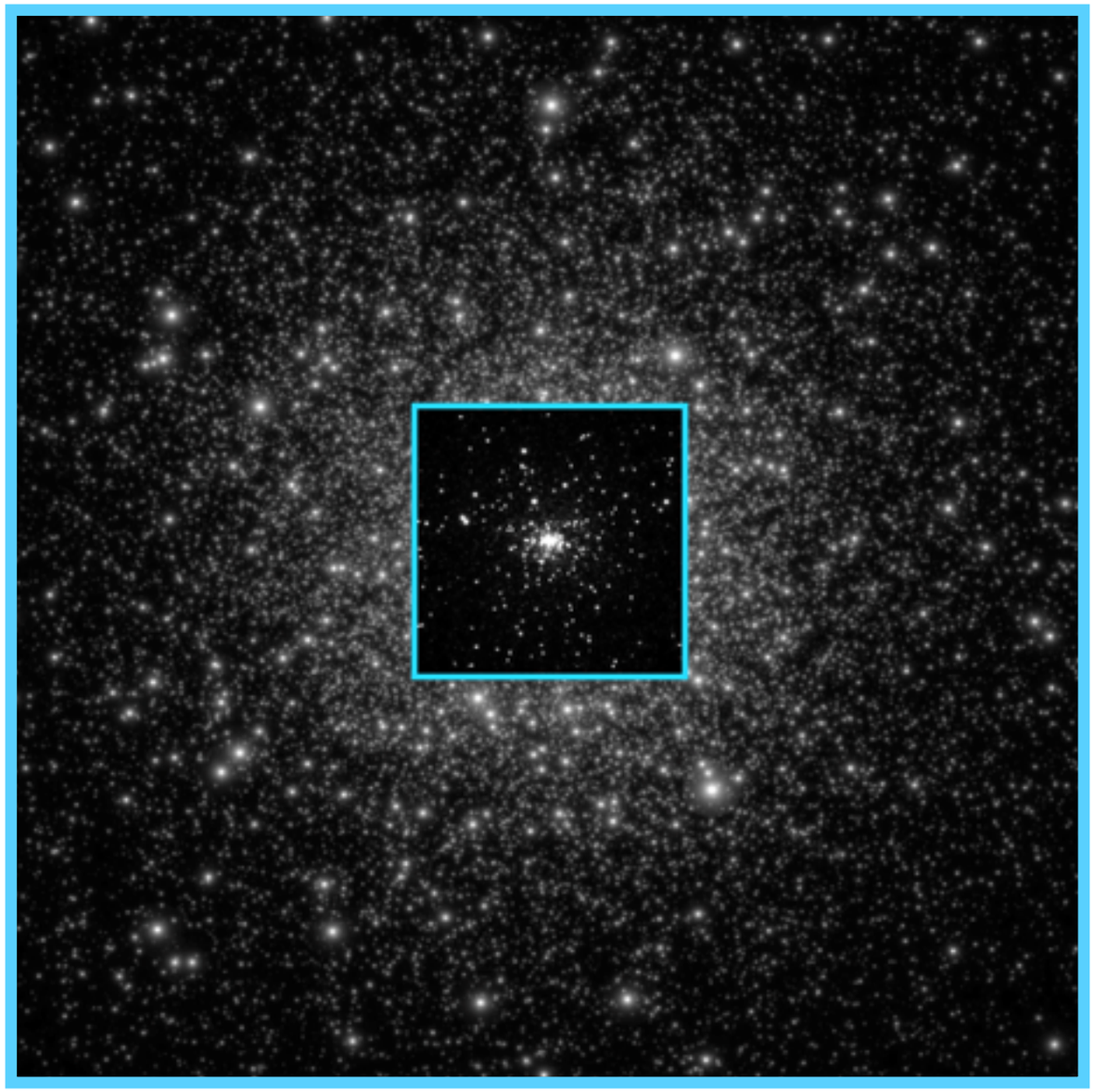
N-BODY - SIMULATE



N-BODY - SIMULATE

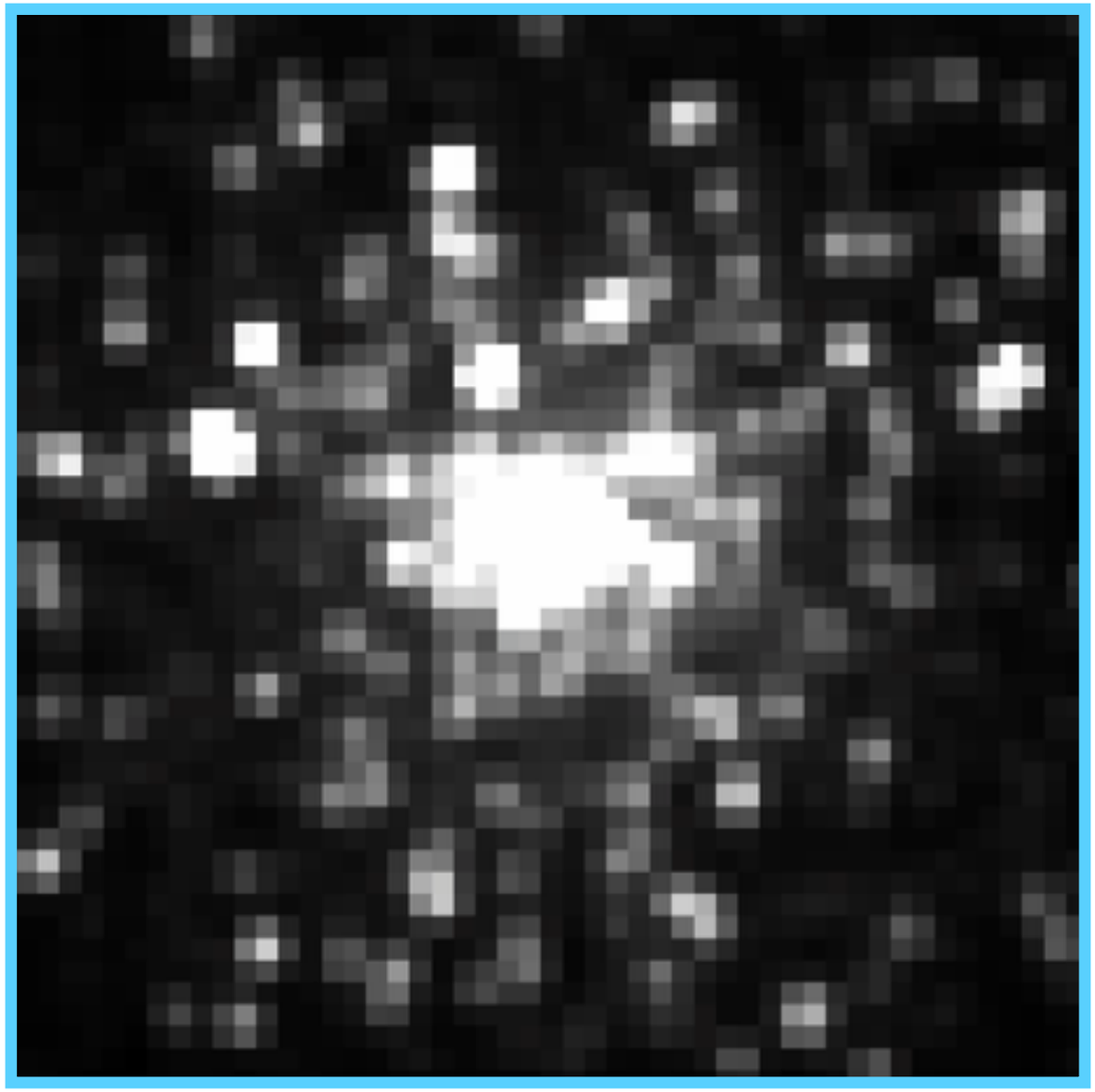


N-BODY - SIMULATE

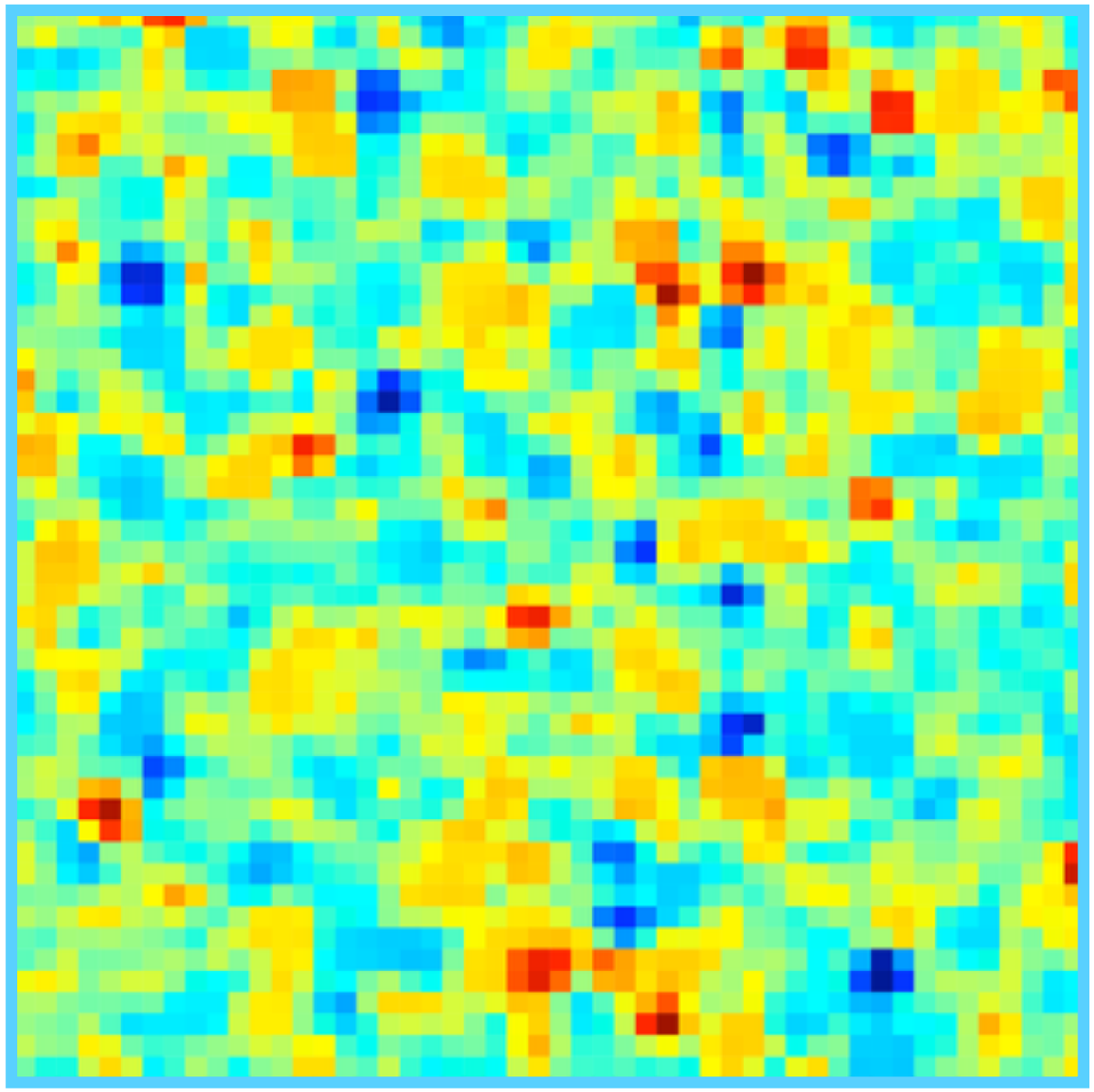


N-BODY - SIMULATE

N-BODY - SIMULATE

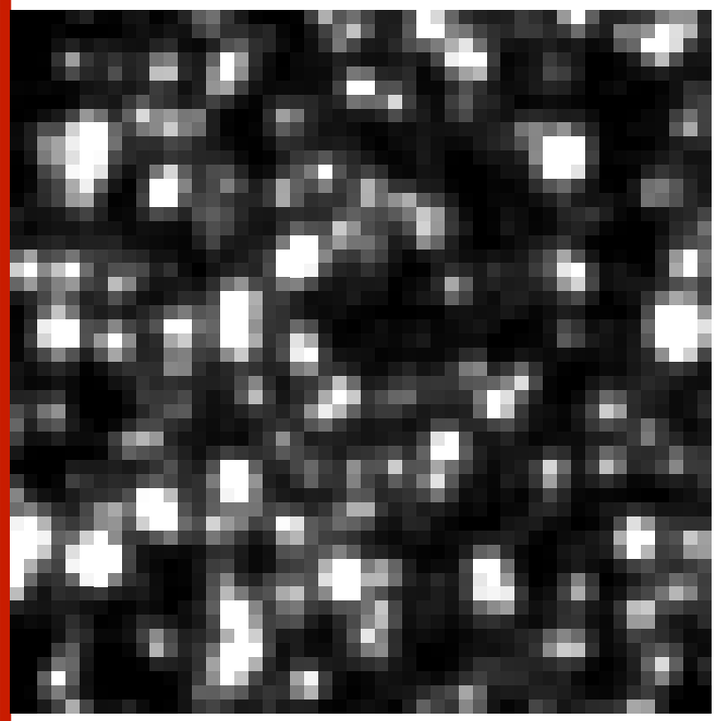


N-BODY - SIMULATE

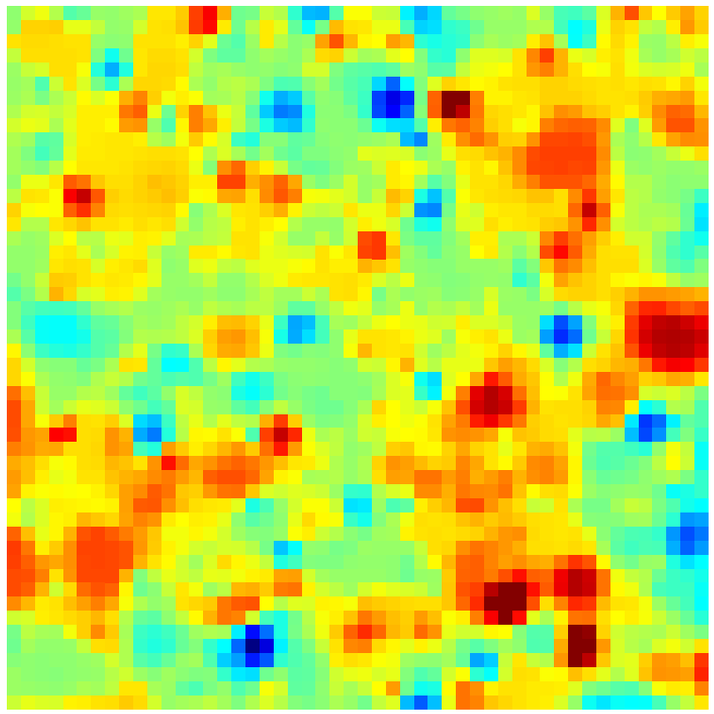


N-BODY - SIMULATE

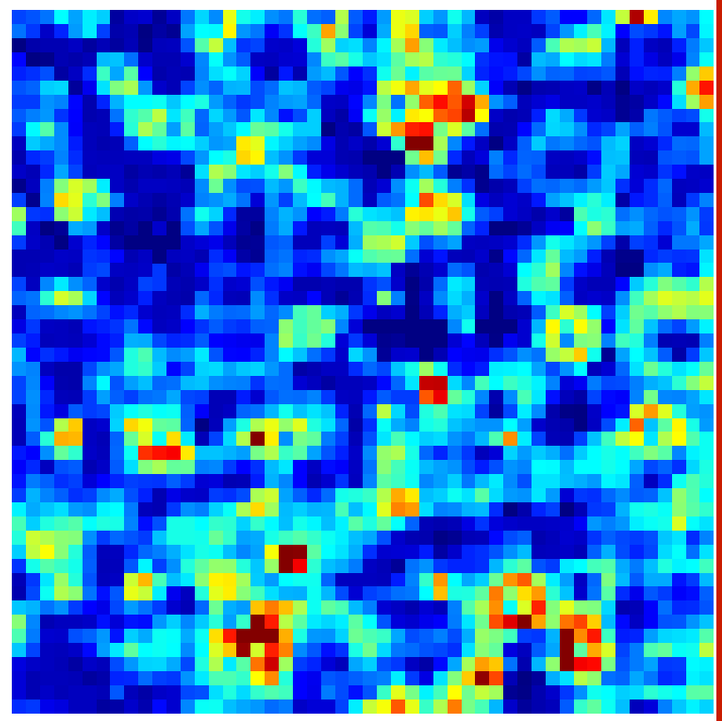
LIGHT



VELOCITY



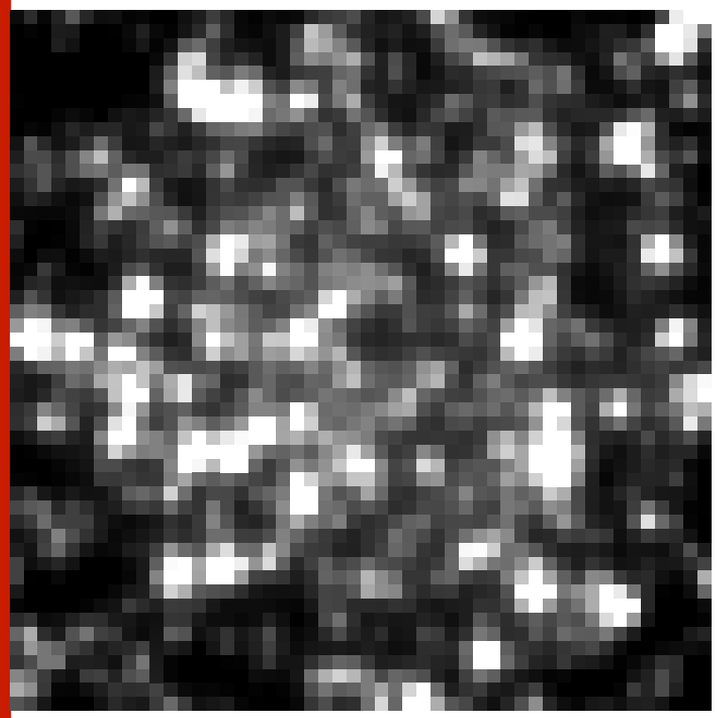
VELOCITY DISPERSION



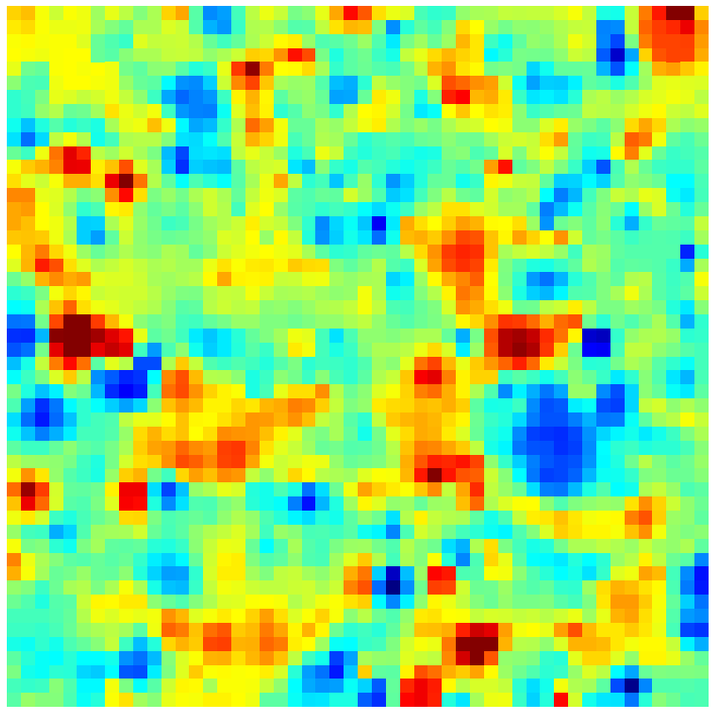
$$M_\bullet = 0, M = 10^6\, M_\odot, d = 5\,\mathrm{kpc}, s = 1.0''$$

N-BODY - SIMULATE

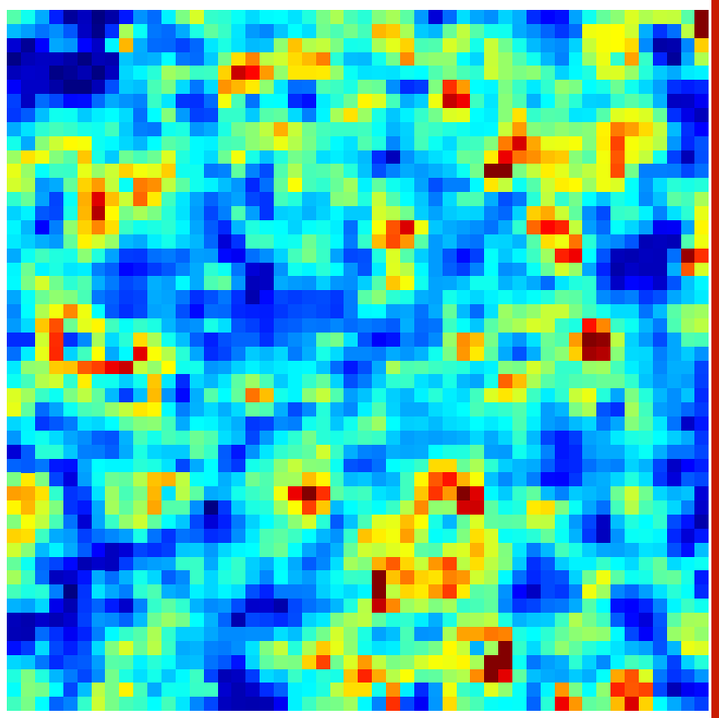
LIGHT



VELOCITY



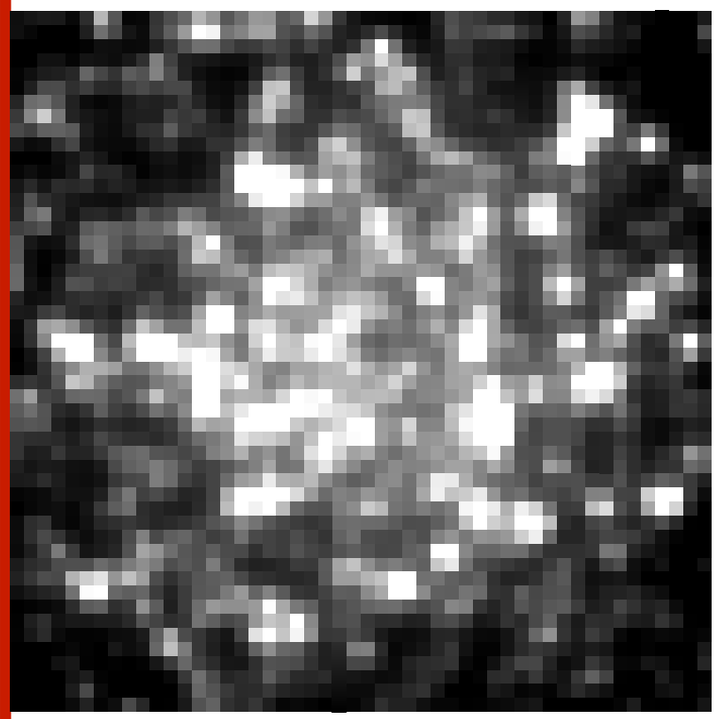
VELOCITY DISPERSION



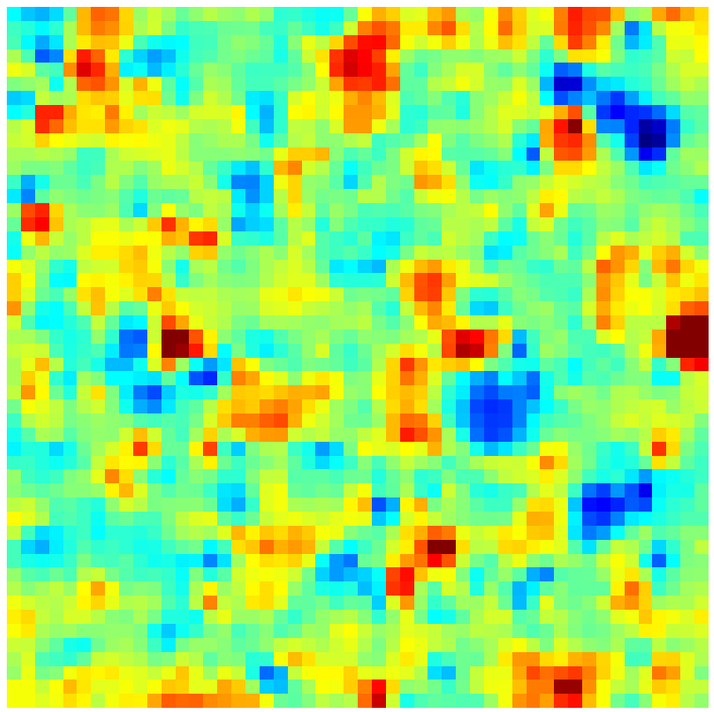
$$M_\bullet = 0, M = 10^6\, M_\odot, d = 10\,\mathrm{kpc}, s = 1.0''$$

N-BODY - SIMULATE

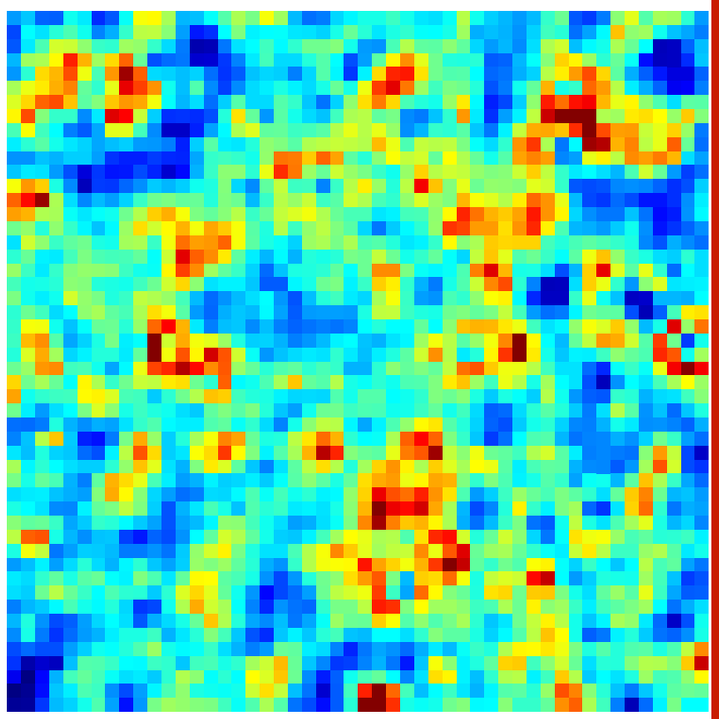
LIGHT



VELOCITY



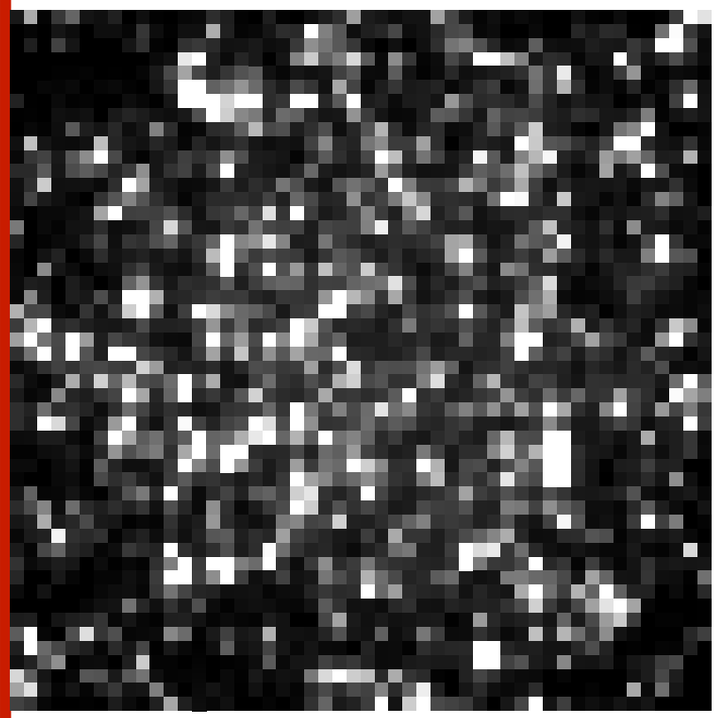
VELOCITY DISPERSION



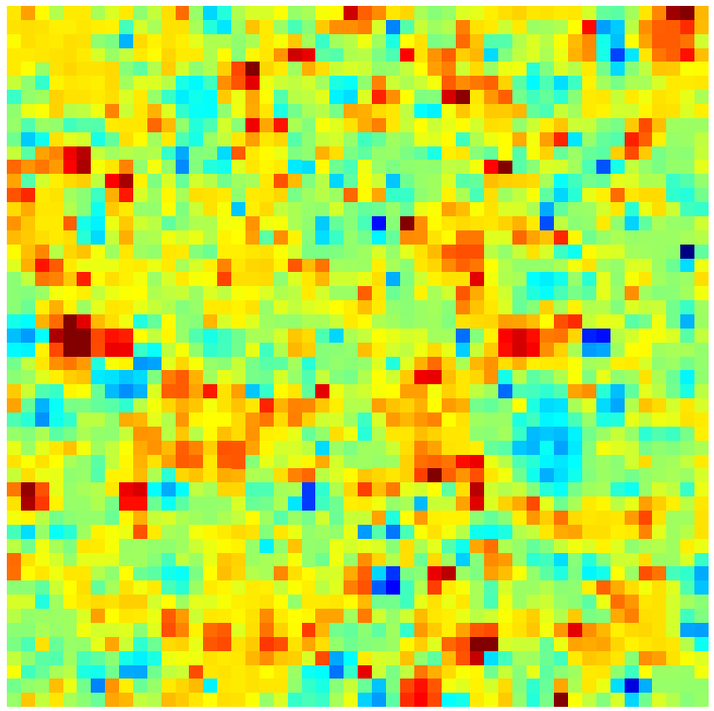
$$M_\bullet = 0, M = 10^6\, M_\odot, d = 15\,\mathrm{kpc}, s = 1.0''$$

N-BODY - SIMULATE

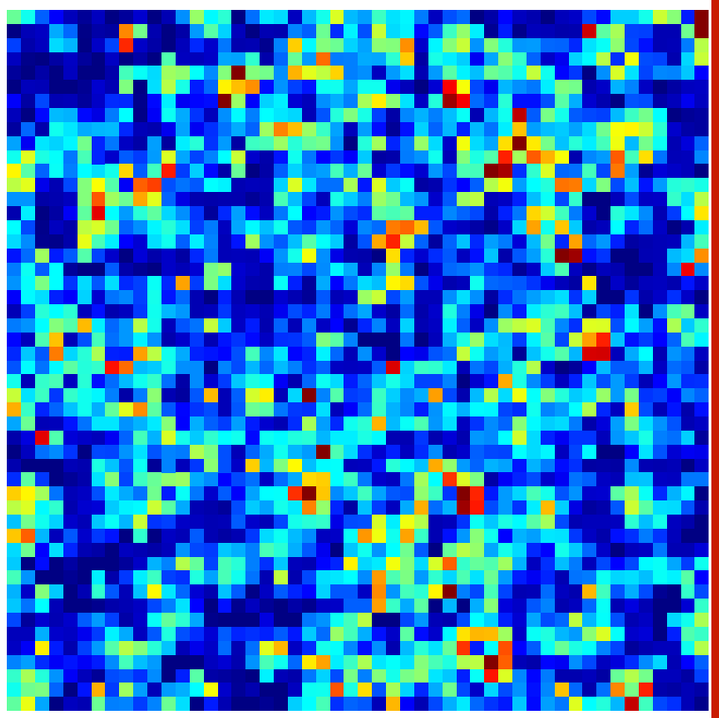
LIGHT



VELOCITY



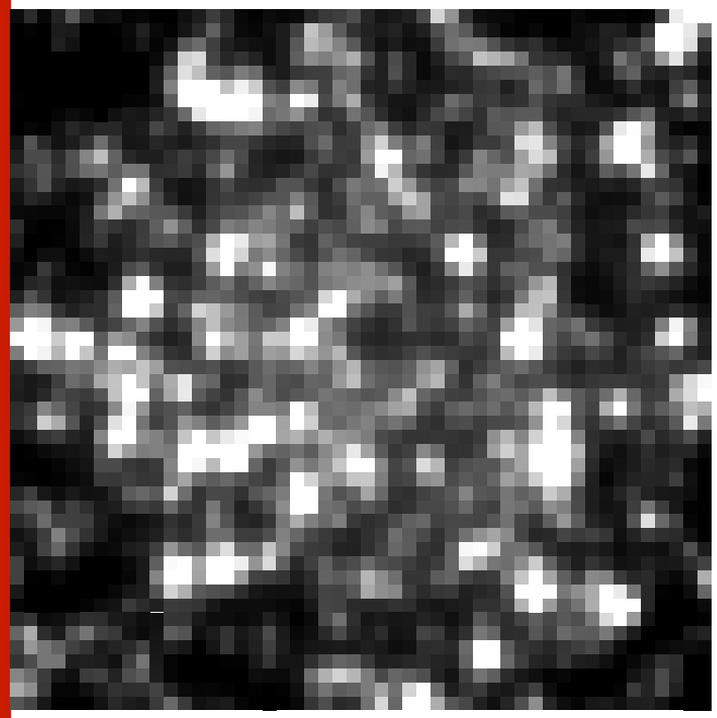
VELOCITY DISPERSION



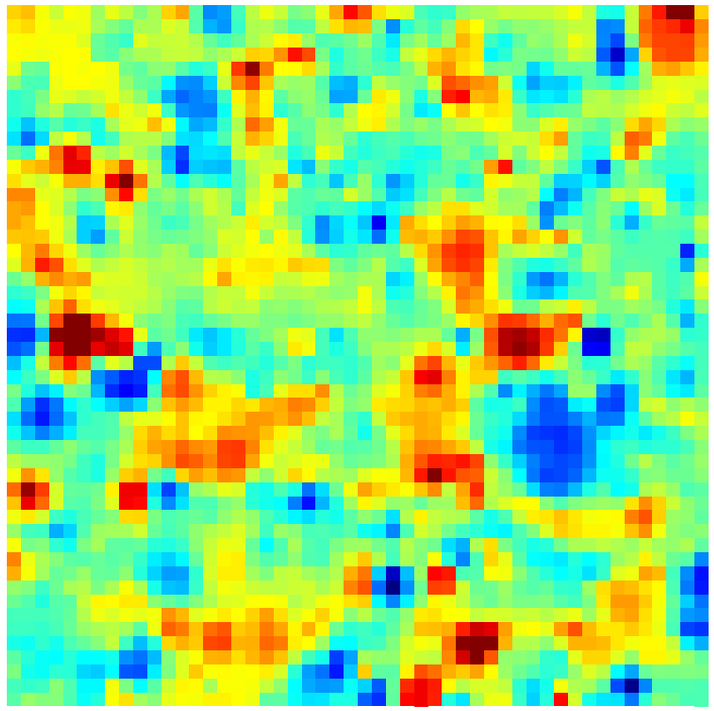
$$M_\bullet = 0, M = 10^6\, M_\odot, d = 10\,\mathrm{kpc}, s = 0.5''$$

N-BODY - SIMULATE

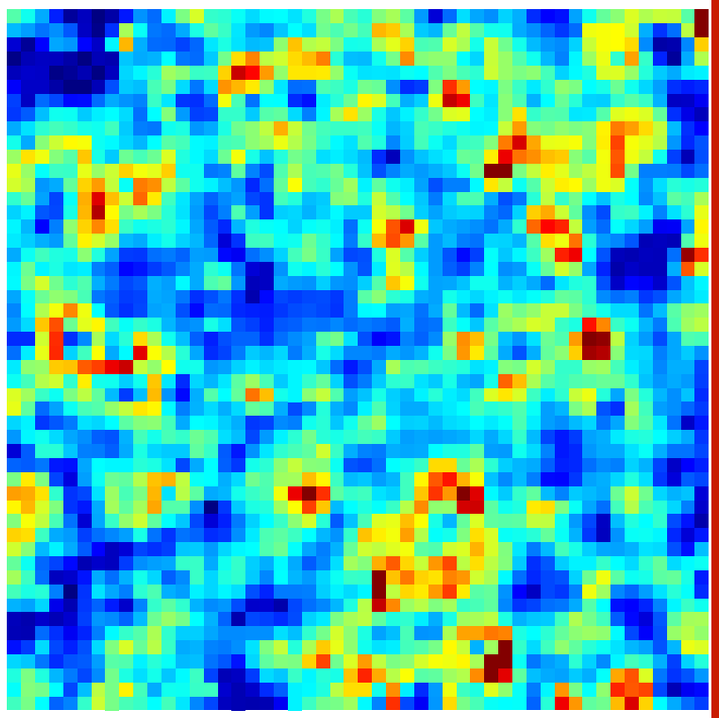
LIGHT



VELOCITY



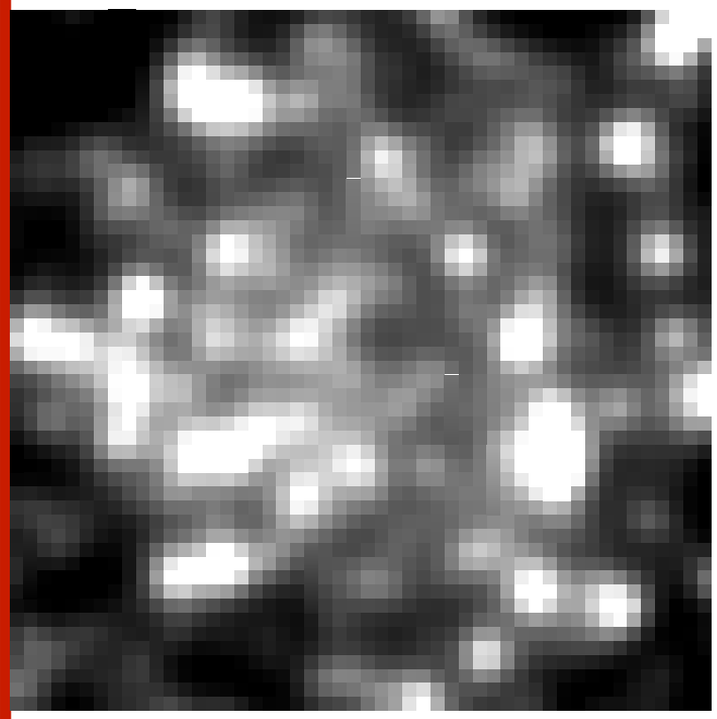
VELOCITY DISPERSION



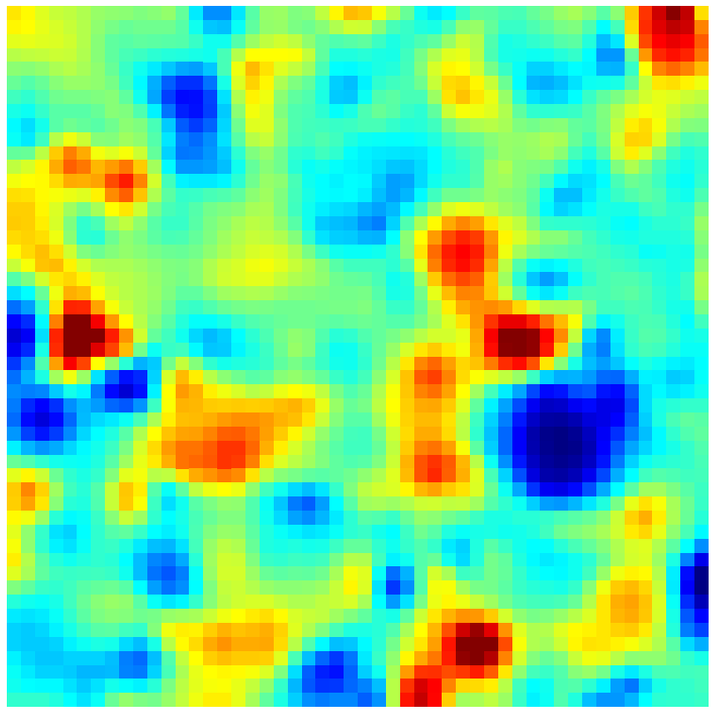
$$M_\bullet = 0, M = 10^6\, M_\odot, d = 10\,\mathrm{kpc}, s = 1.0''$$

N-BODY - SIMULATE

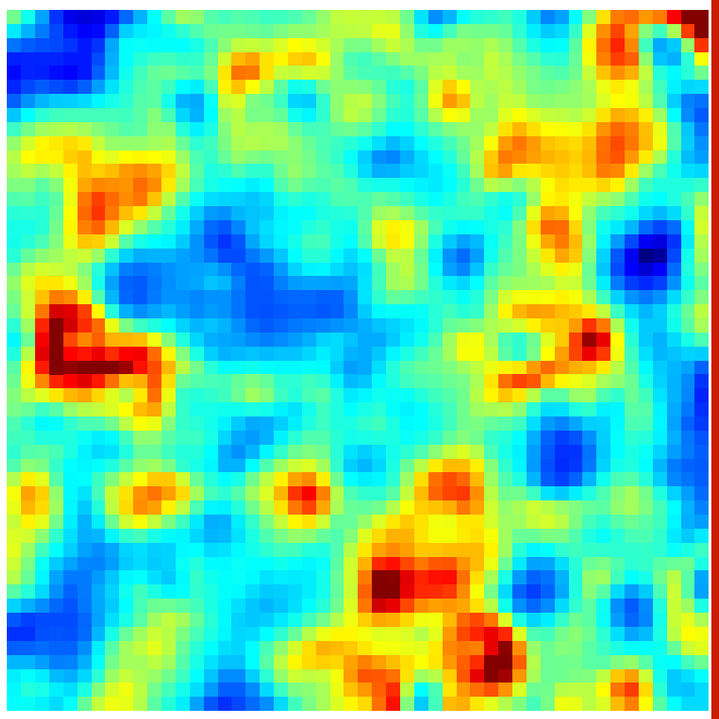
LIGHT



VELOCITY



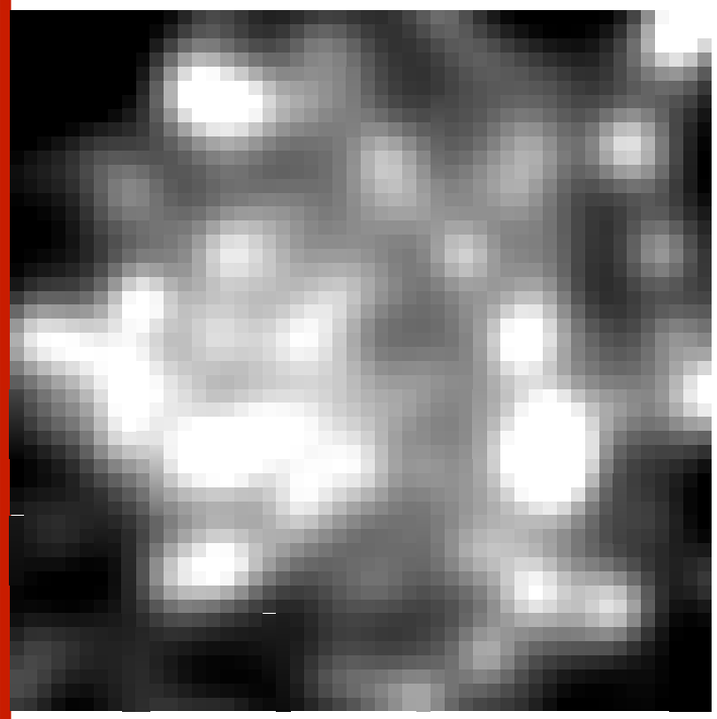
VELOCITY DISPERSION



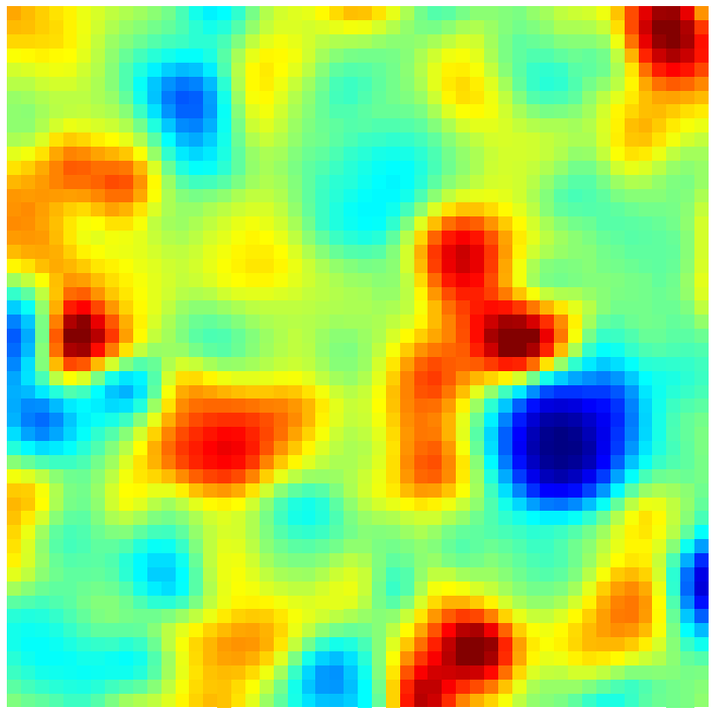
$$M_\bullet = 0, M = 10^6\, M_\odot, d = 10\,\mathrm{kpc}, s = 2.0''$$

N-BODY - SIMULATE

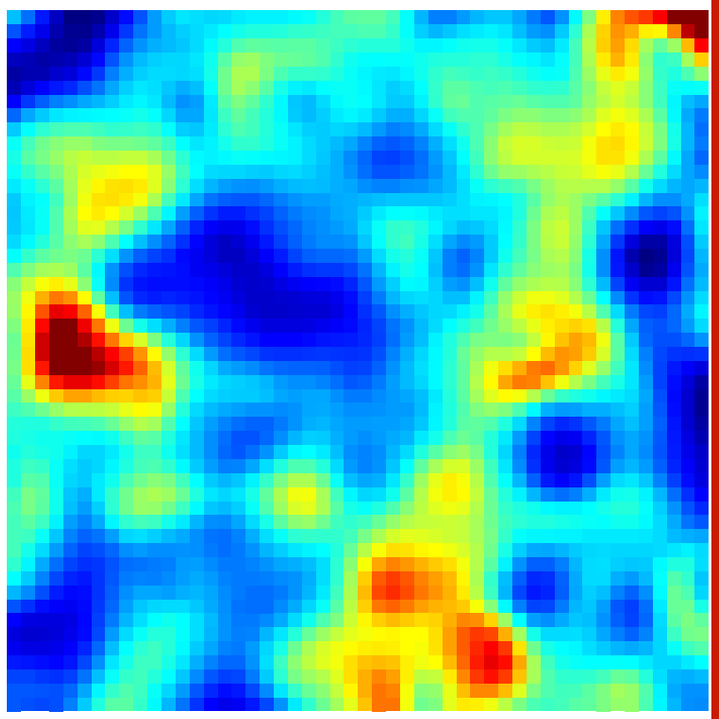
LIGHT



VELOCITY

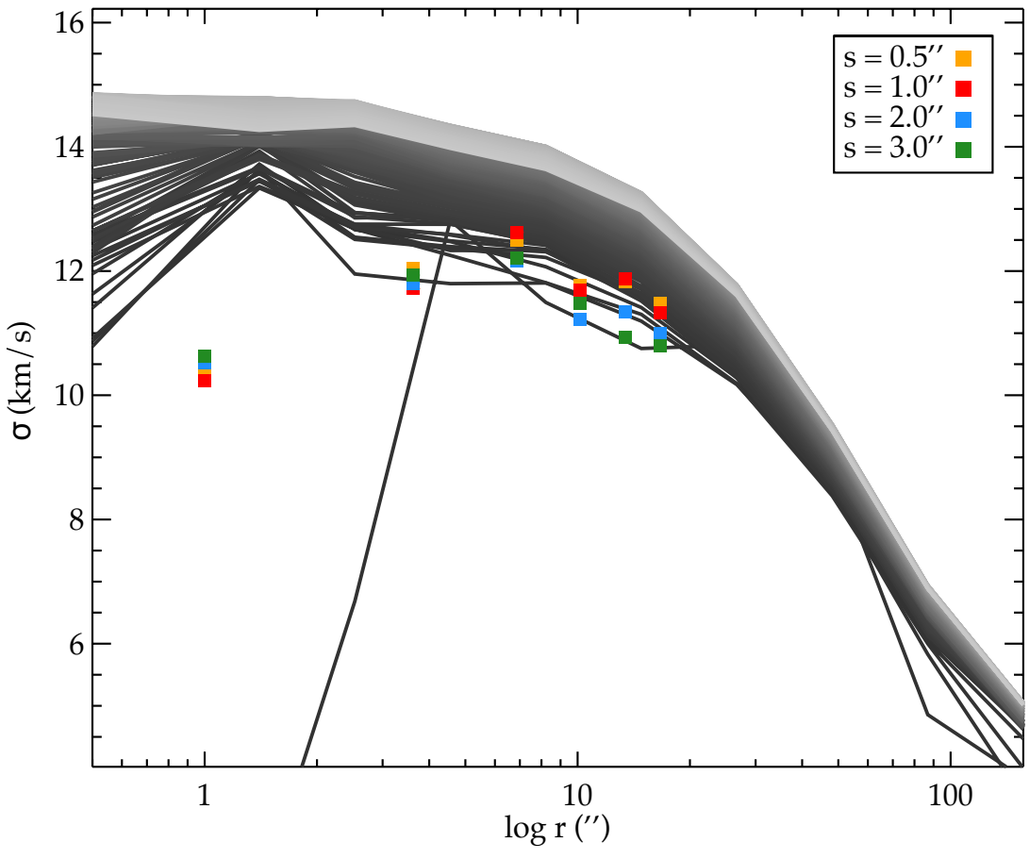


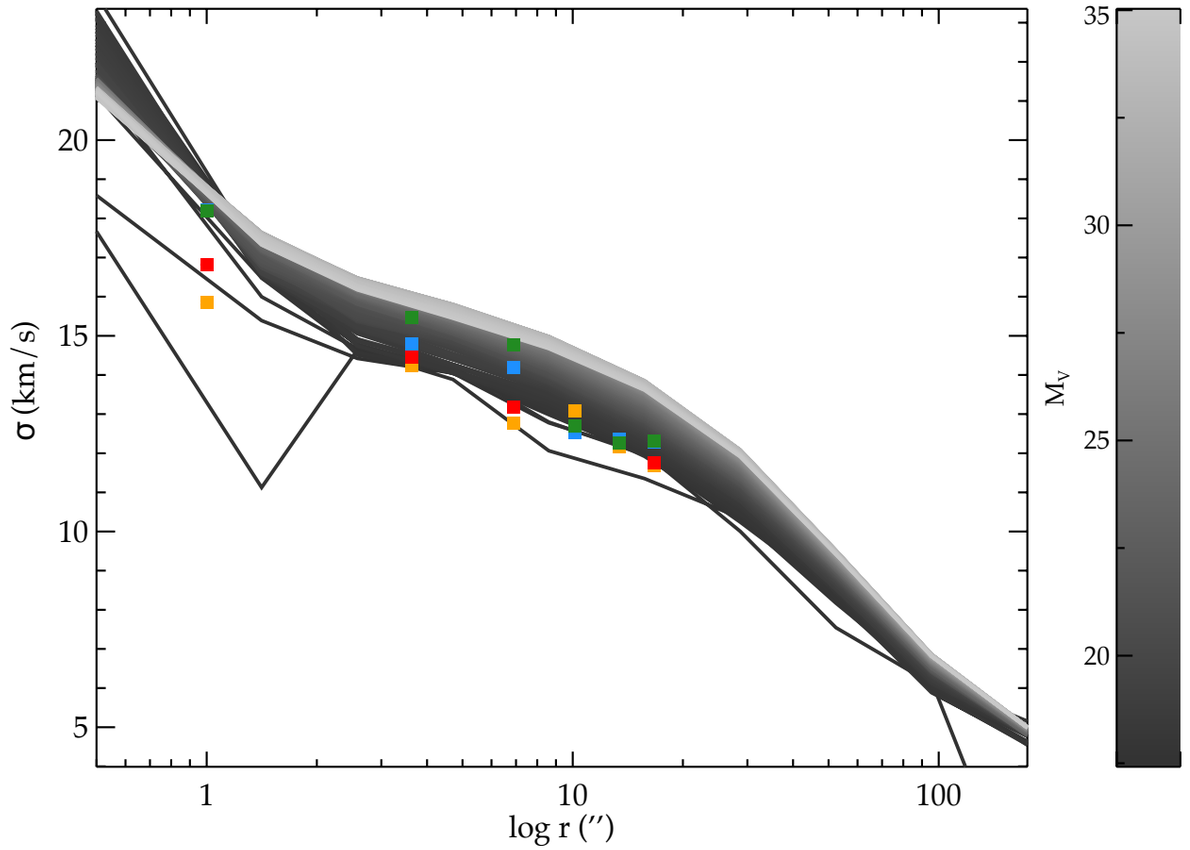
VELOCITY DISPERSION



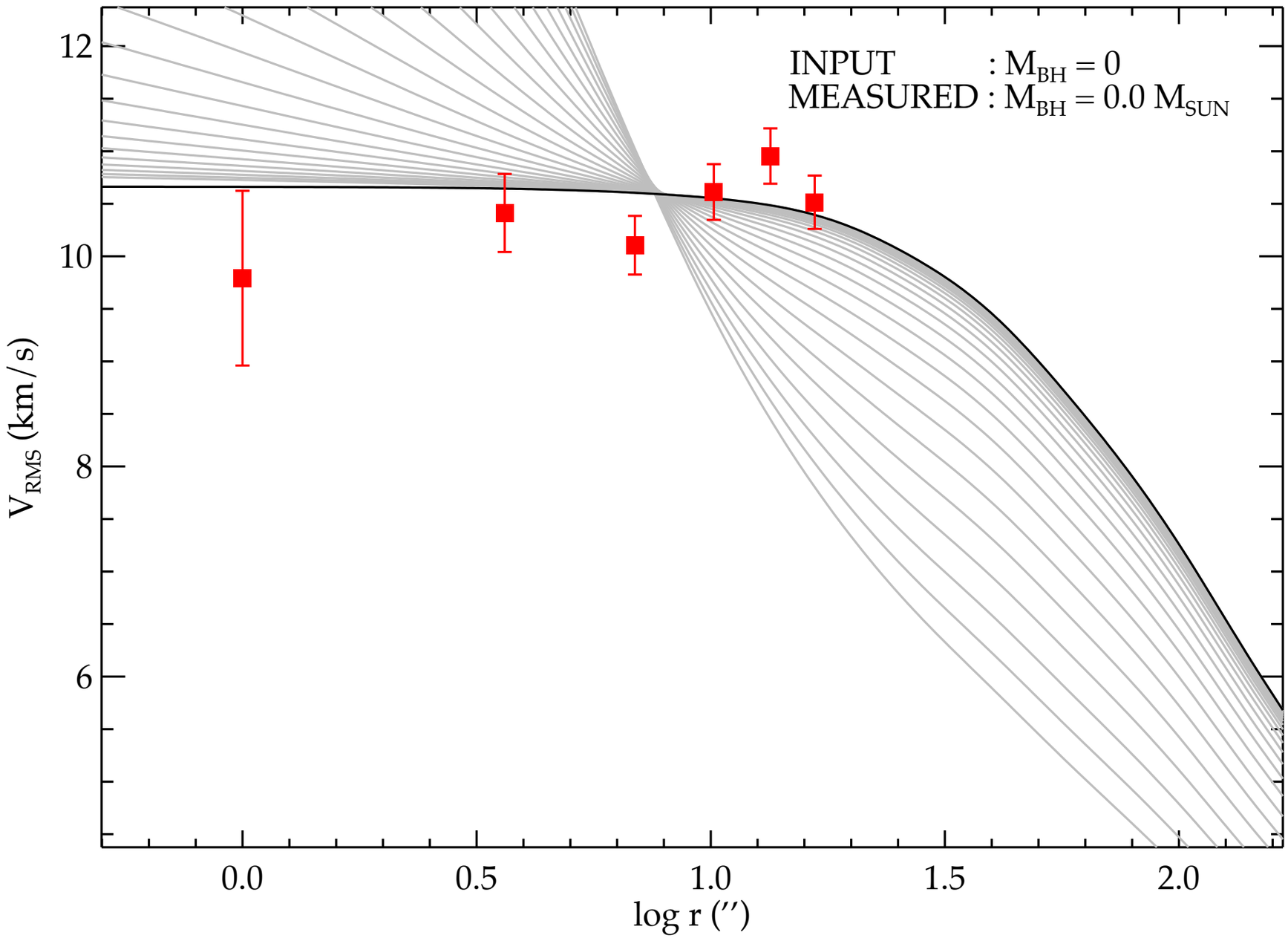
$$M_\bullet = 0, M = 10^6\, M_\odot, d = 10\,\mathrm{kpc}, s = 3.0''$$

N-BODY - SIMULATE

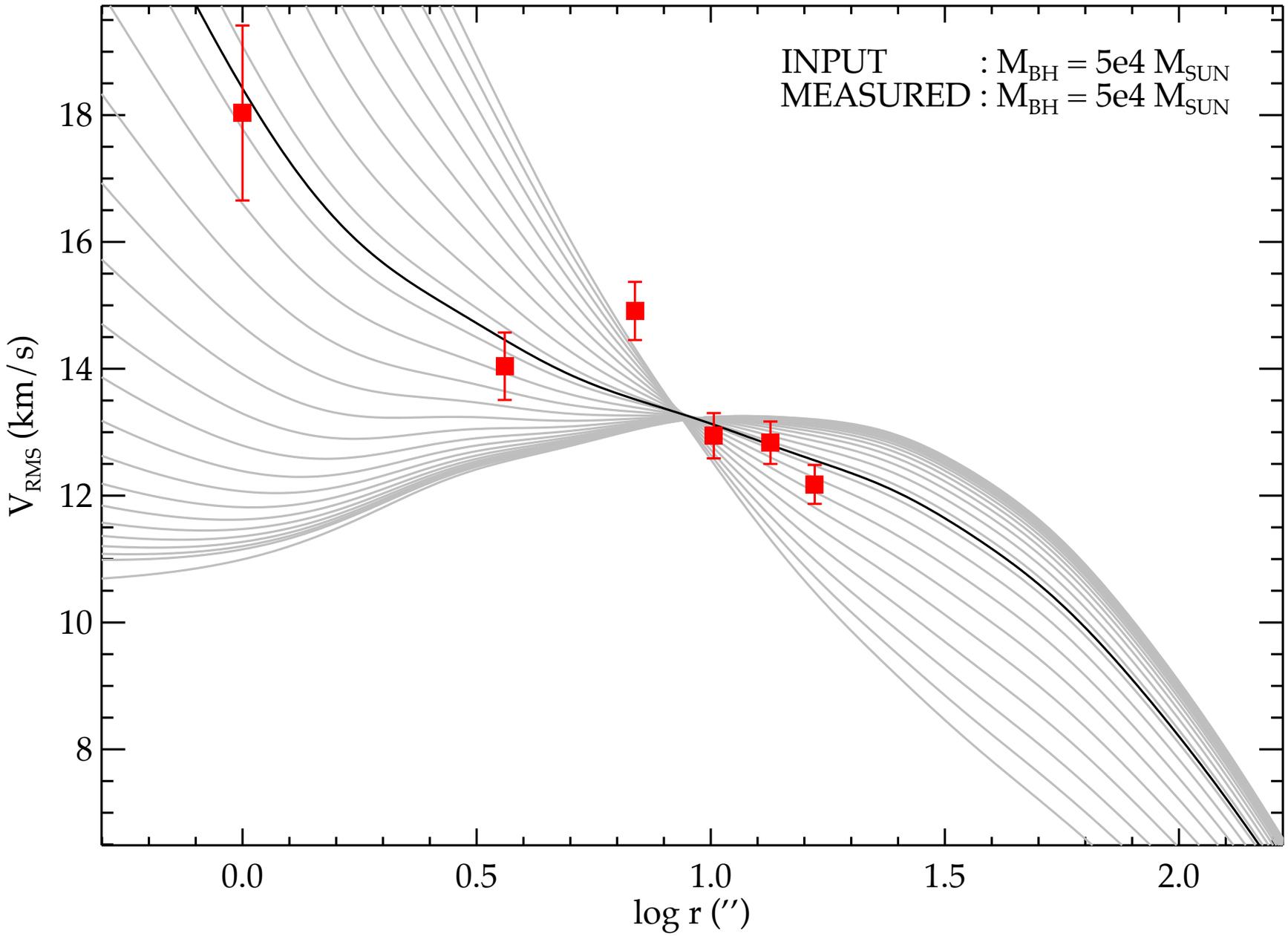




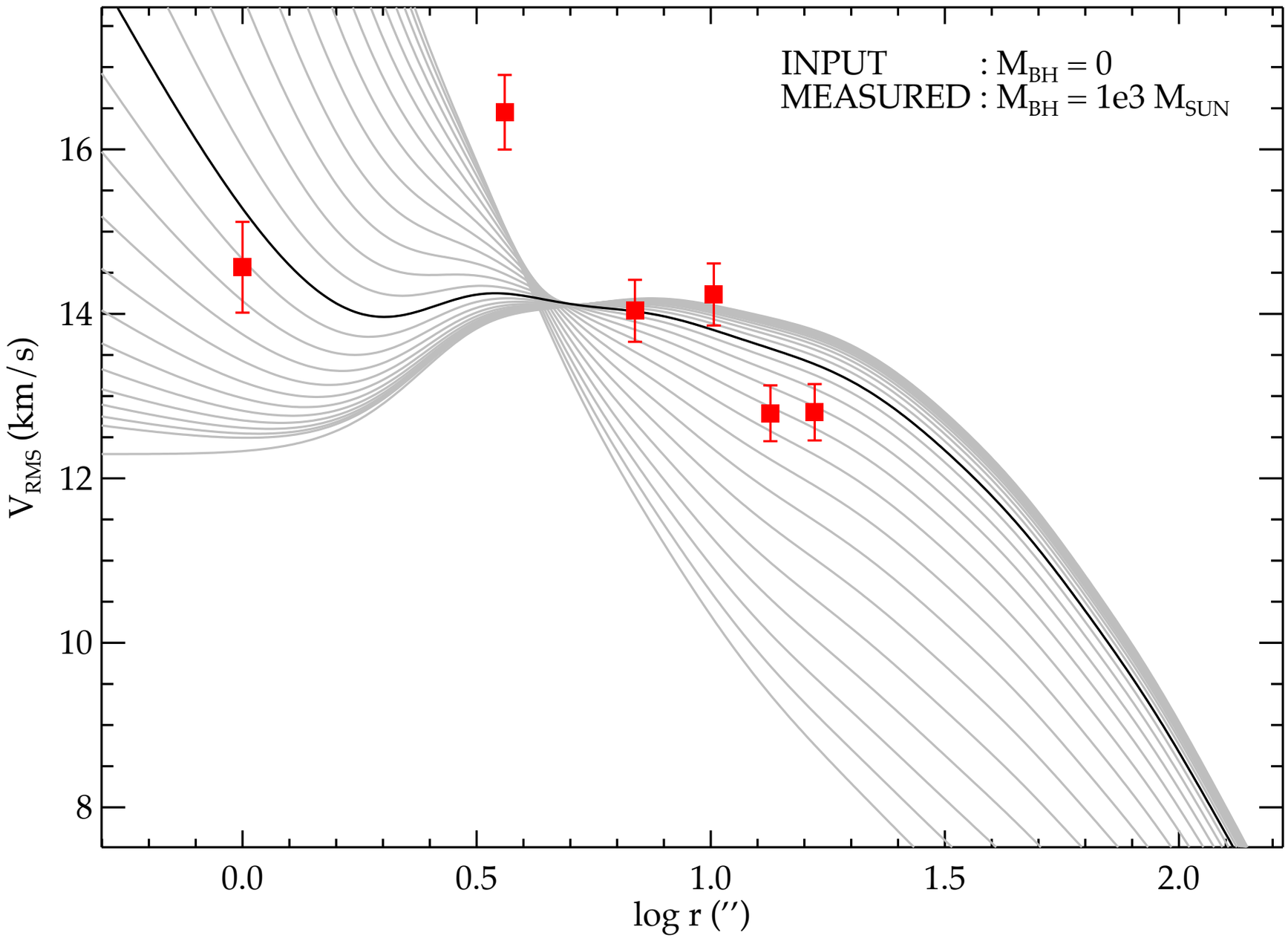
N-BODY - SIMULATE



N-BODY - SIMULATE



N-BODY - SIMULATE

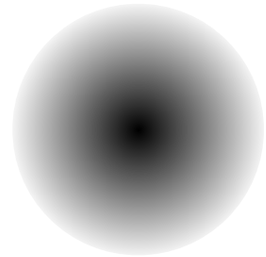


N-BODY - FIND

SMALLER

$r_{10\%}/r_{50\%}$

LARGER



IMBH

STELLAR-MASS BLACK HOLES

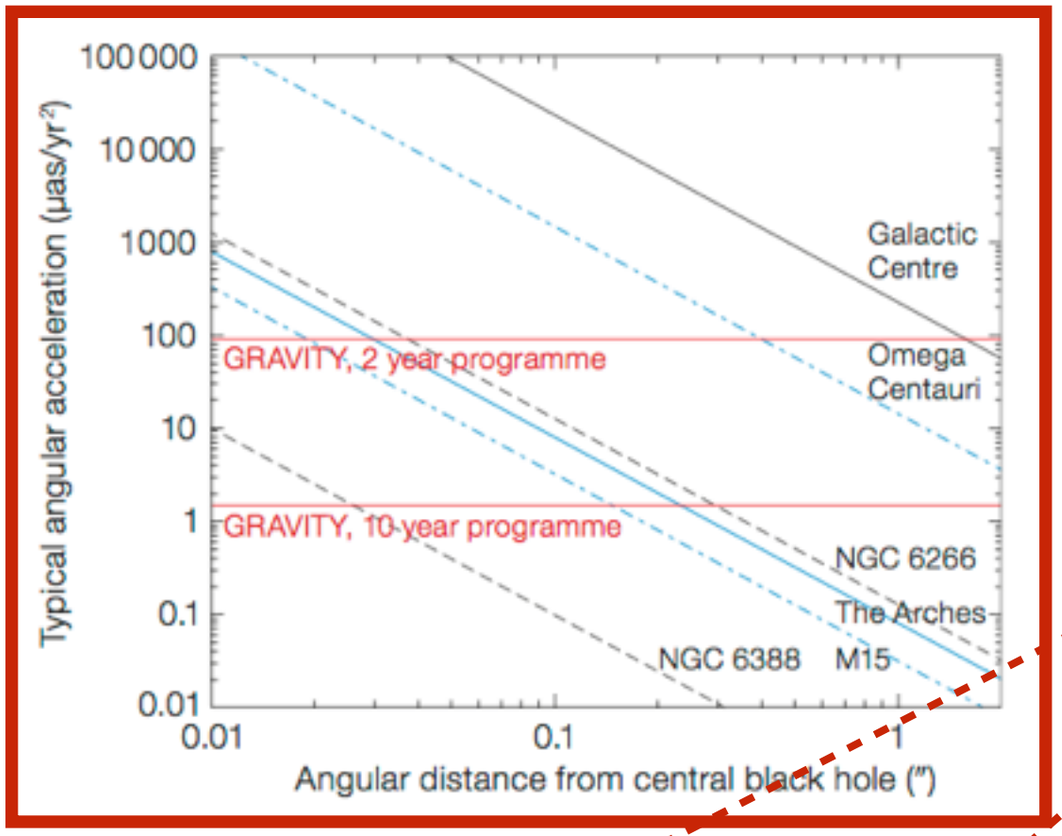
BINARIES

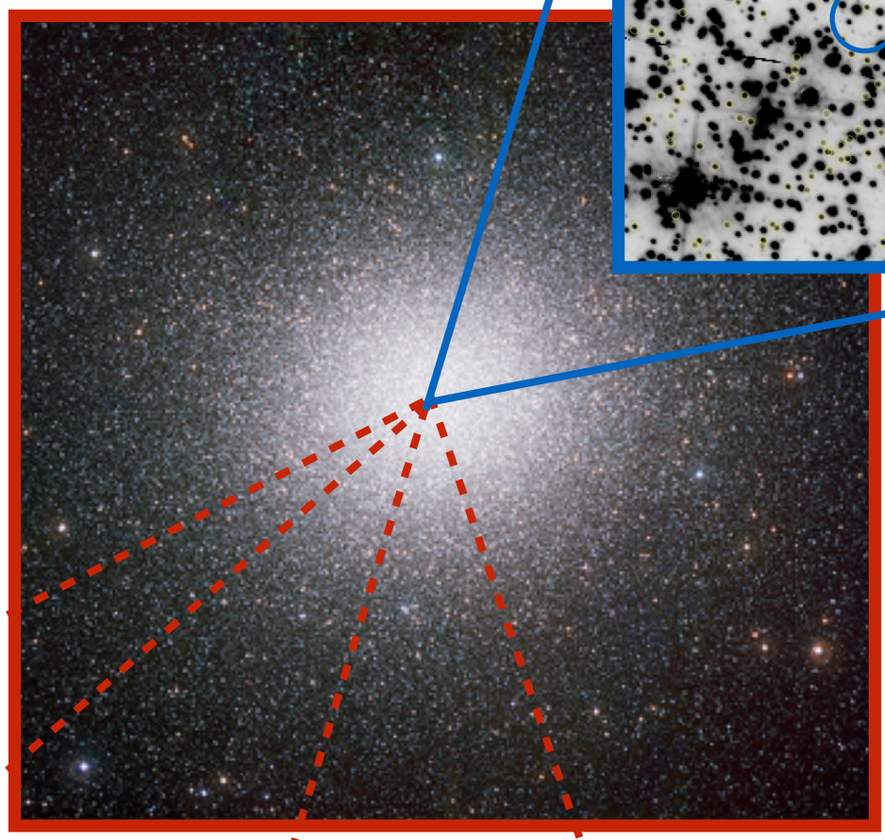
Lützgendorf et al., 2013a

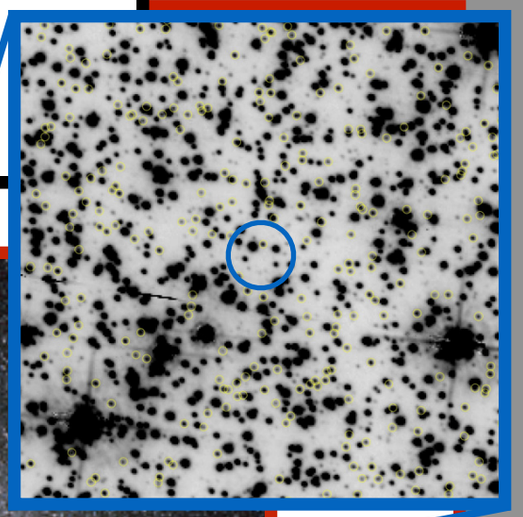
Outline

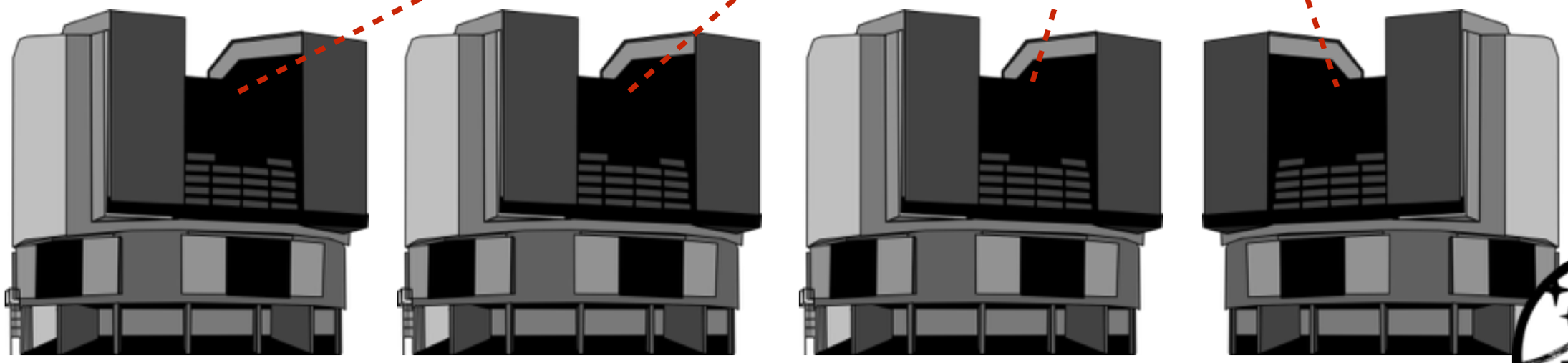
1. Introduction
   - What, How, Where?
2. Observations
   - Photometry
   - Spectroscopy
3. Simulations
4. Future

Future - GRAVITY









Future - Simulations

? How much accretion would we expect from an IMBH in a Globular Cluster?

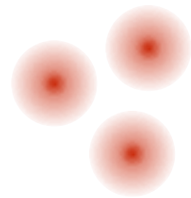
Simulate accretion from stellar winds onto the IMBH!

Future - Simulations

Simulate the Gravity → N-body Simulations

Simulate Stellar Evolution → Stellar Evolution Codes

Simulate the Gas → Smoothed Particle Hydrodynamics



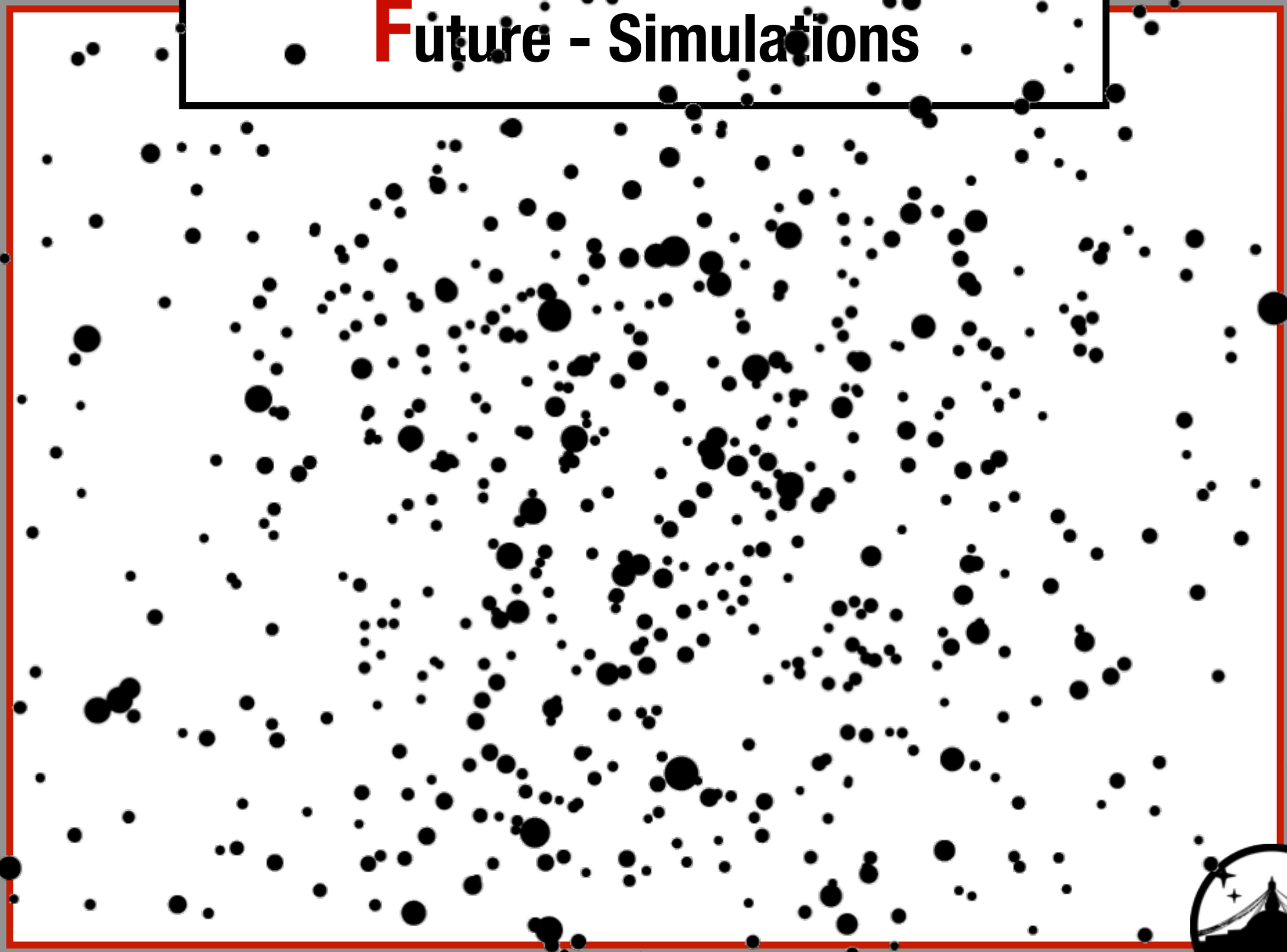
Future - Simulations

Simulate the Gravity → N-body Simulations

Simulate Stellar Evolution → Stellar Evolution Codes

Simulate the Gas → Smoothed Particle Hydrodynamics

Future - Simulations



Future - Simulations

Simulate the Gravity → N-body Simulations

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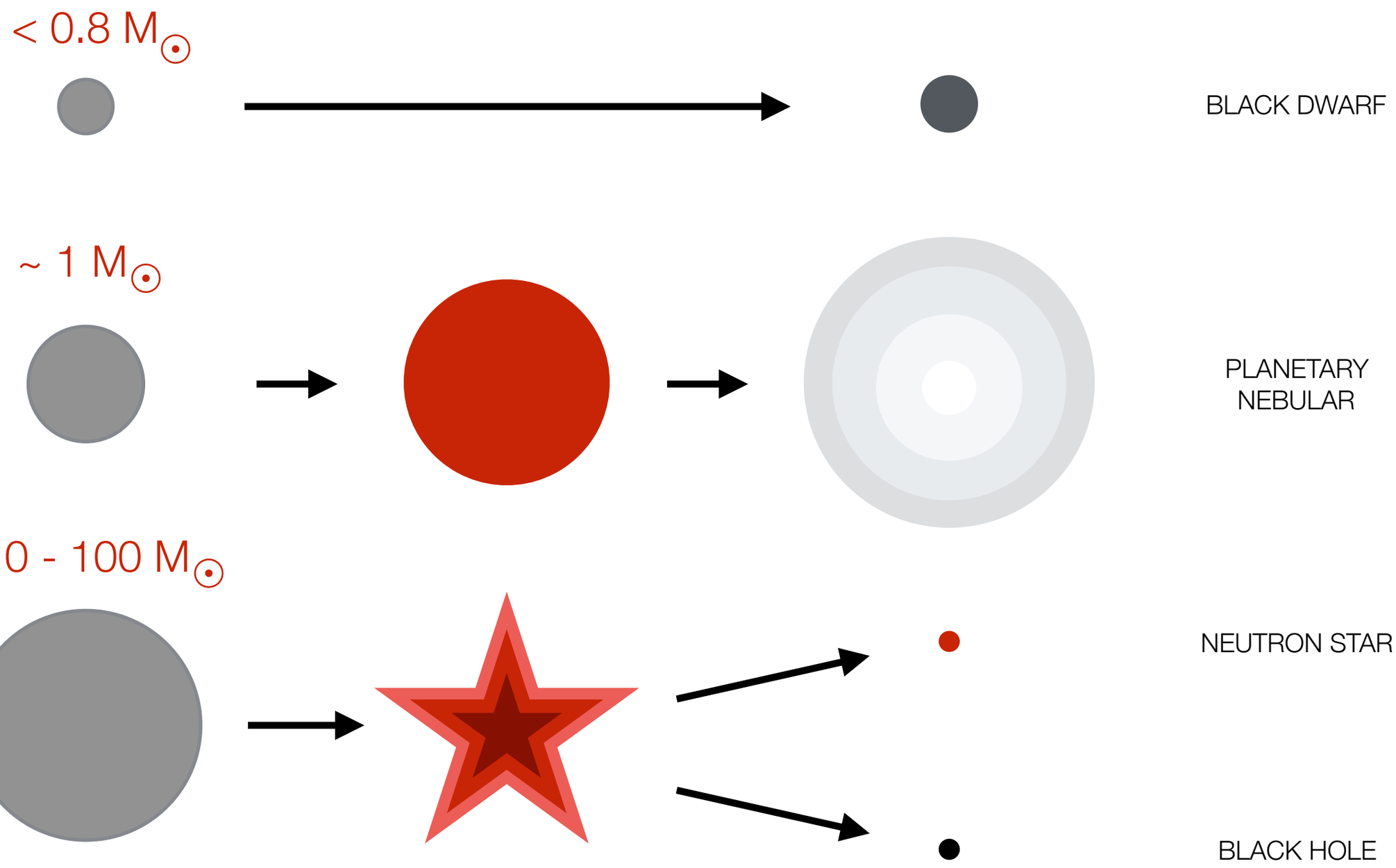
Future - Simulations



Future - Simulations

Simulate the Gravity → N-body Simulations

Simulate Stellar Evolution → Stellar Evolution Codes

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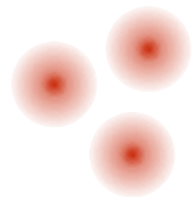
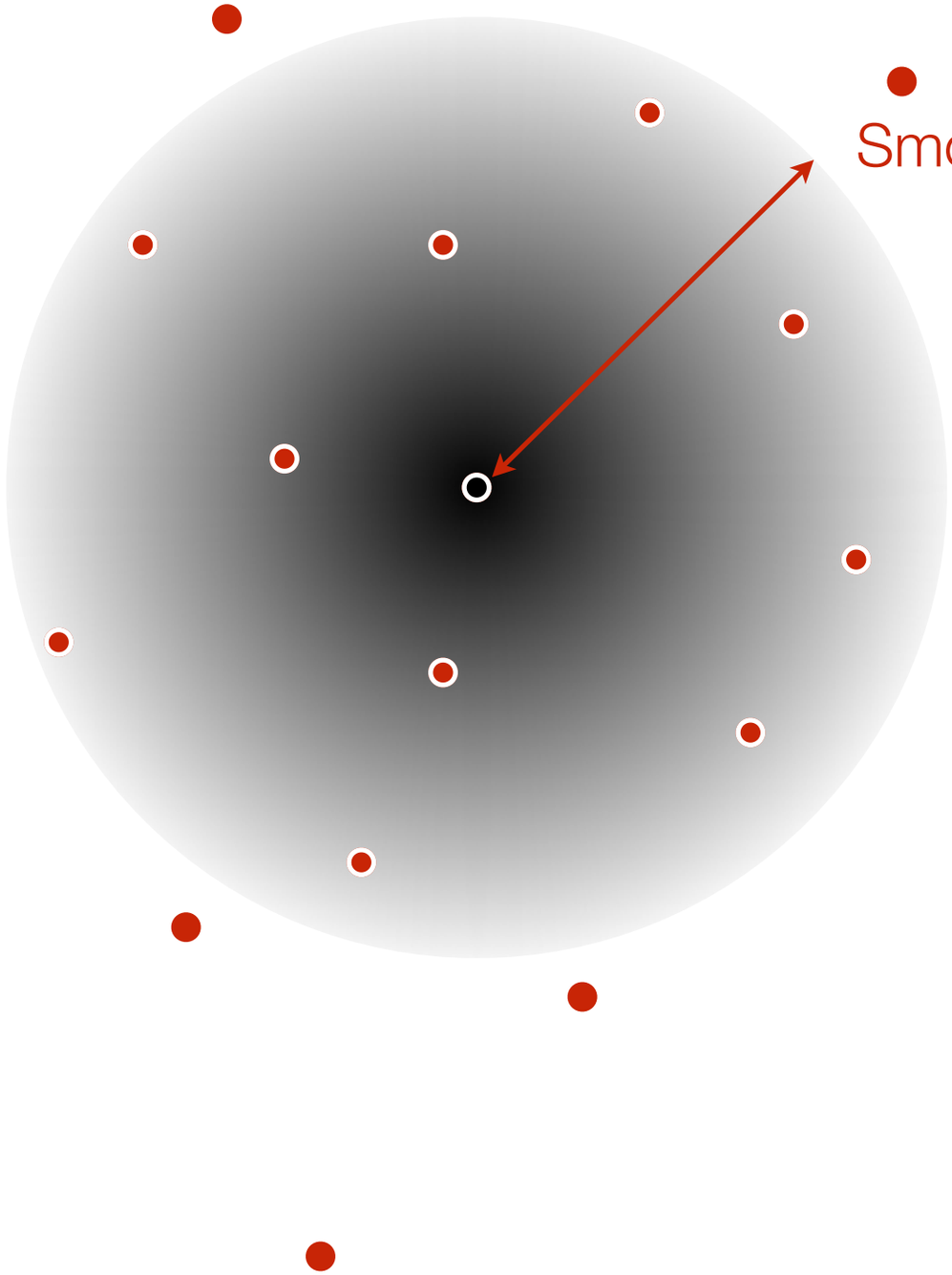
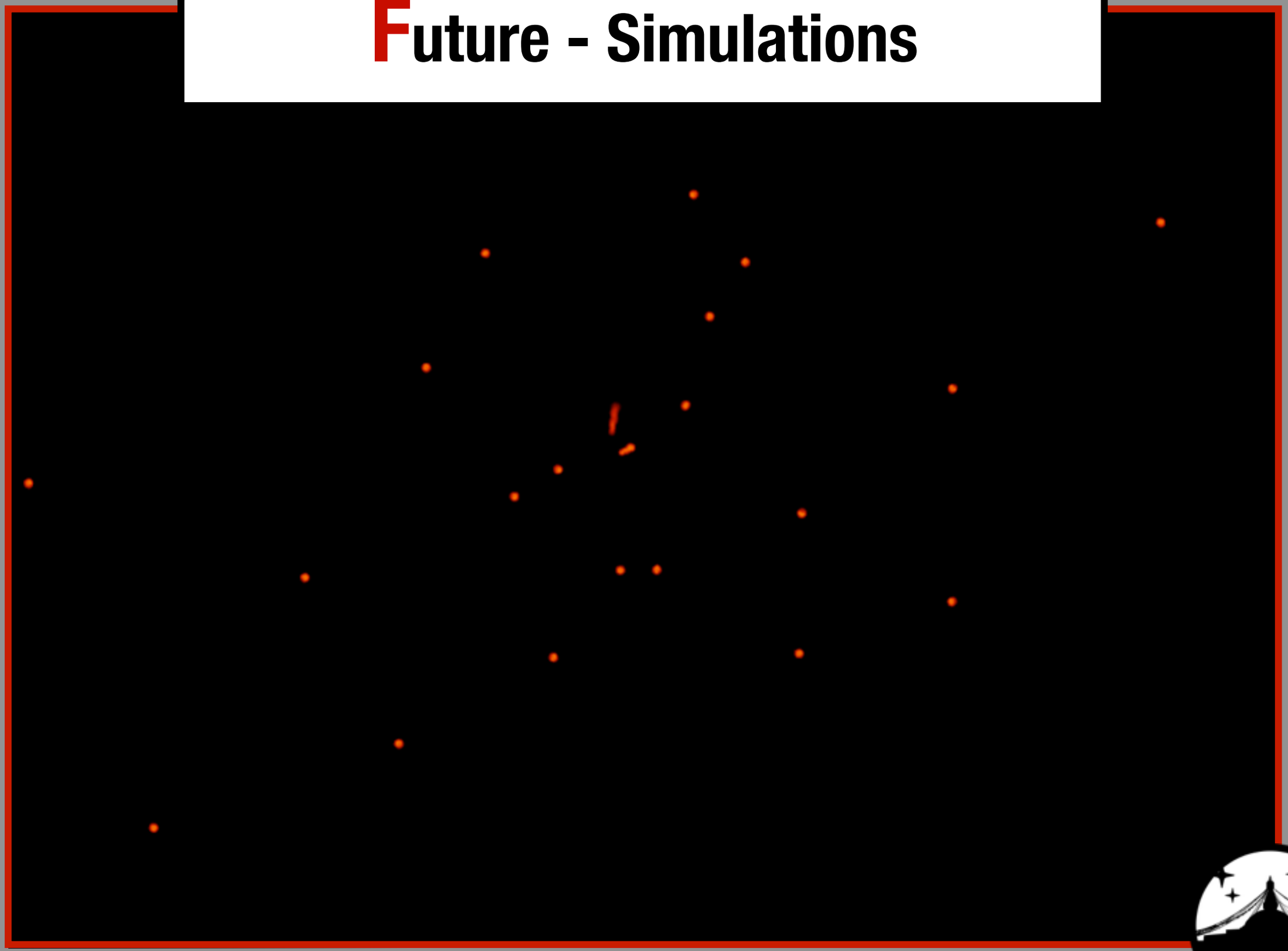


Future - Simulations



Future - Simulations



Summary

1. **Intermediate-mass black holes**
   - 10^2 - 10^4 M_{SUN}
   - could explain how SMBH grow
2. **Observations**
   - Photometry: —> get surface brightness profile
   - Spectroscopy: Integral Field Units (IFU) —> get velocities
   - Compare to Jeans models
3. **N-body Simulations**
   - compare to data, simulate data, find new observables
4. **Future**
   - GRAVITY - Interferometer to measure accelerations

FINAL SUMMARY

1. **Star Clusters**
   - OB associations, Embedded Clusters, Open Clusters, Globular Clusters, Nuclear Clusters
2. **Multiple Stellar Populations (MSP)**
   - Spectroscopic and photometric evidence for MSP
   - Explanations still flawed
3. **Kinematics**
   - Gravitational systems have negative heat capacity
   - Consequences: core collapse, mass segregation
4. **Intermediate-mass black holes**
   - Black hole hunt: Photometry and Spectroscopy
   - Simulations to understand observations