Supermassive Black Holes

Lecture for Advanced Cosmology
May 15, 2014
Colin DeGraf


http://www.spacetelescope.org/images/heic0409a/


http://www.universetoday.com/100336/nustar-puts-new-spin-on-supermassive-black-holes/

Outline

- Black hole background
- Growth of black holes
- Black hole feedback
- How black holes are studied

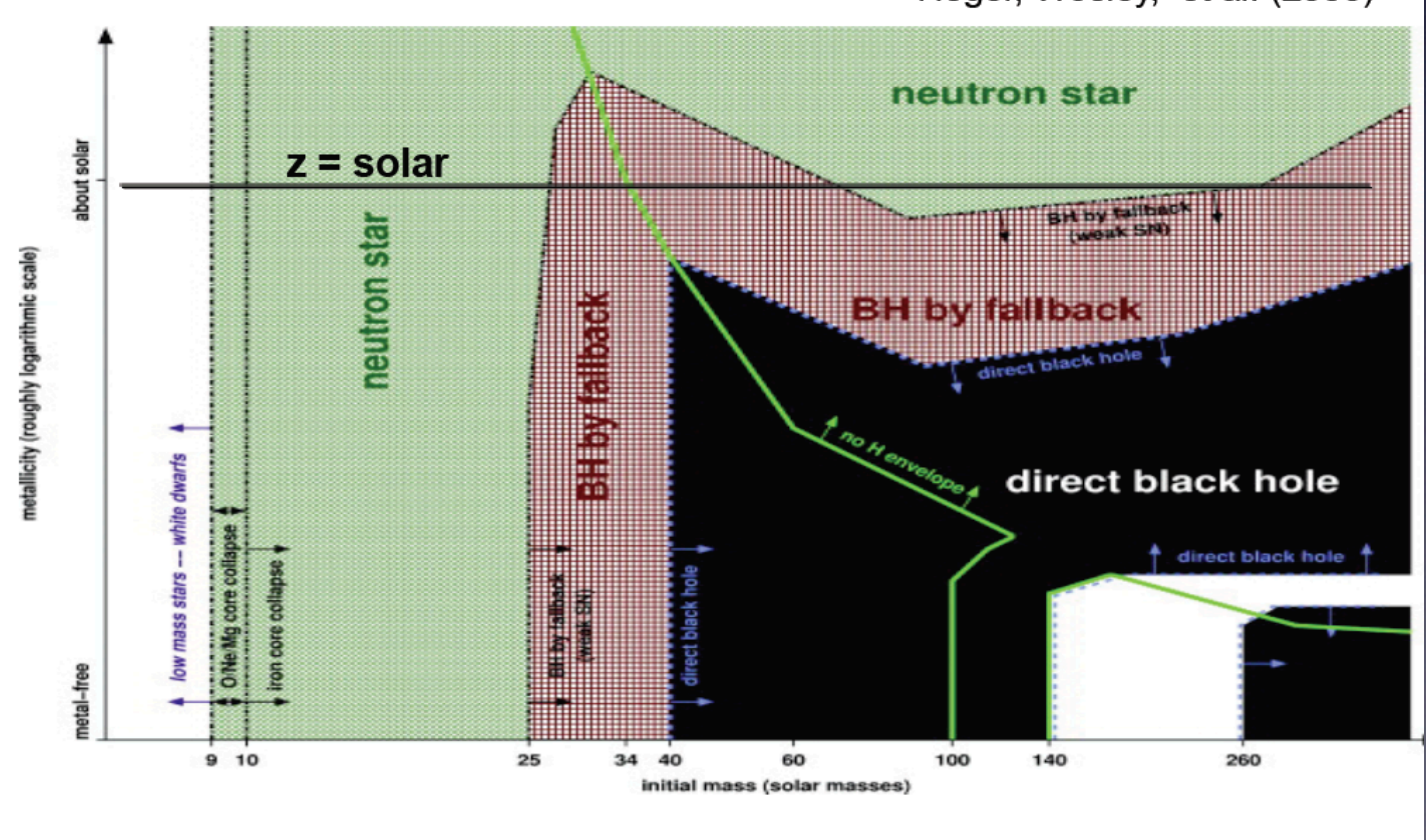
Why do we care about black holes?

- Black holes can probe the distant/old universe
- Black holes correlate with host properties

What is a black hole?

- Gravitationally-collapsed singularity
- Can form from massive dead stars (or massive gas clouds)
- Light cannot escape event horizon
- Can range from stellar-mass to supermassive (up to 10^{10} M_{sun})

Heger, Wosley, et al. (2003)



Observational Evidence

- First quasar detections looked like *very* bright, distant stars
- Difficult to explain except as a black hole
  - Too much energy being emitted for anything else

Direct Observation of AGN Impact

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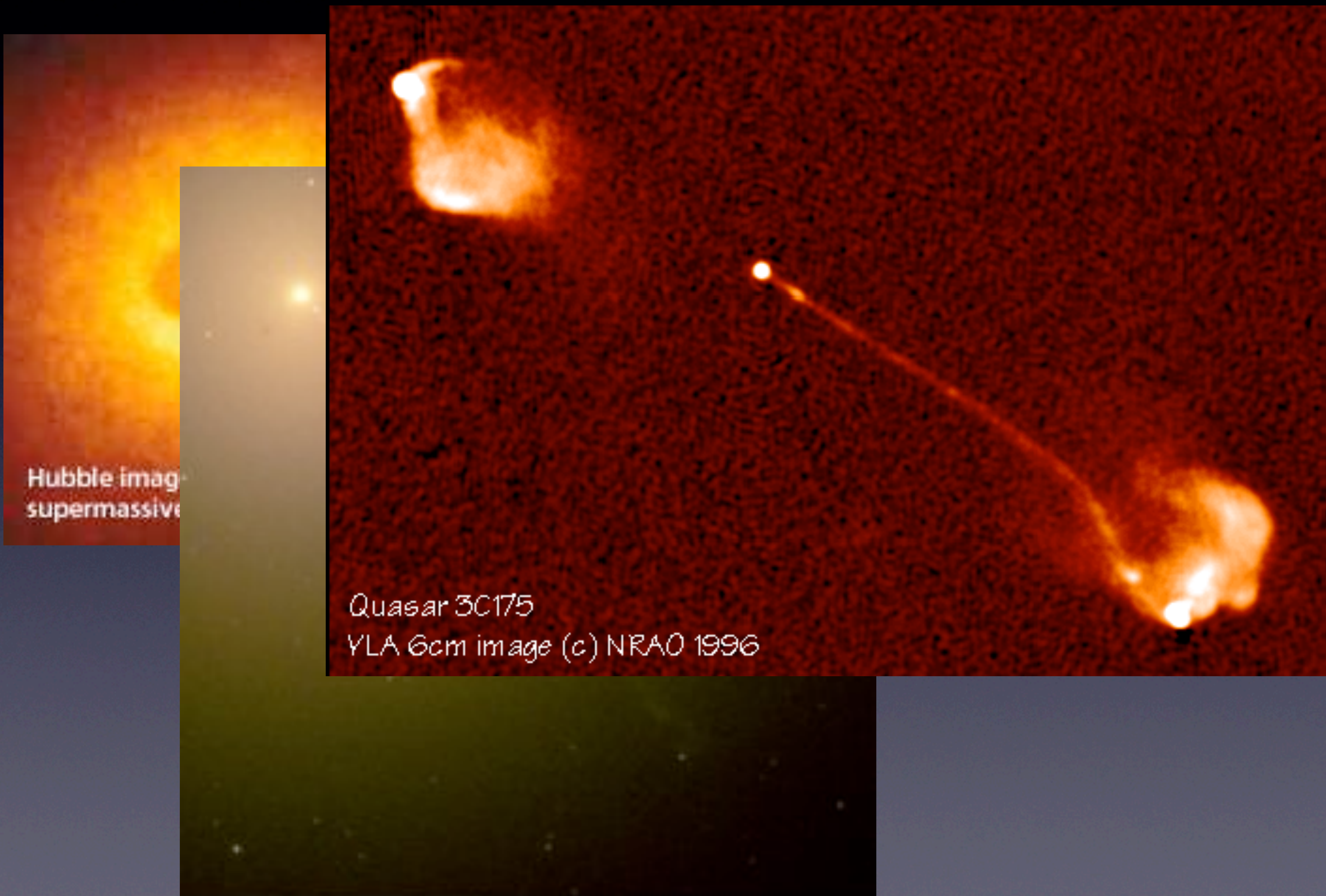
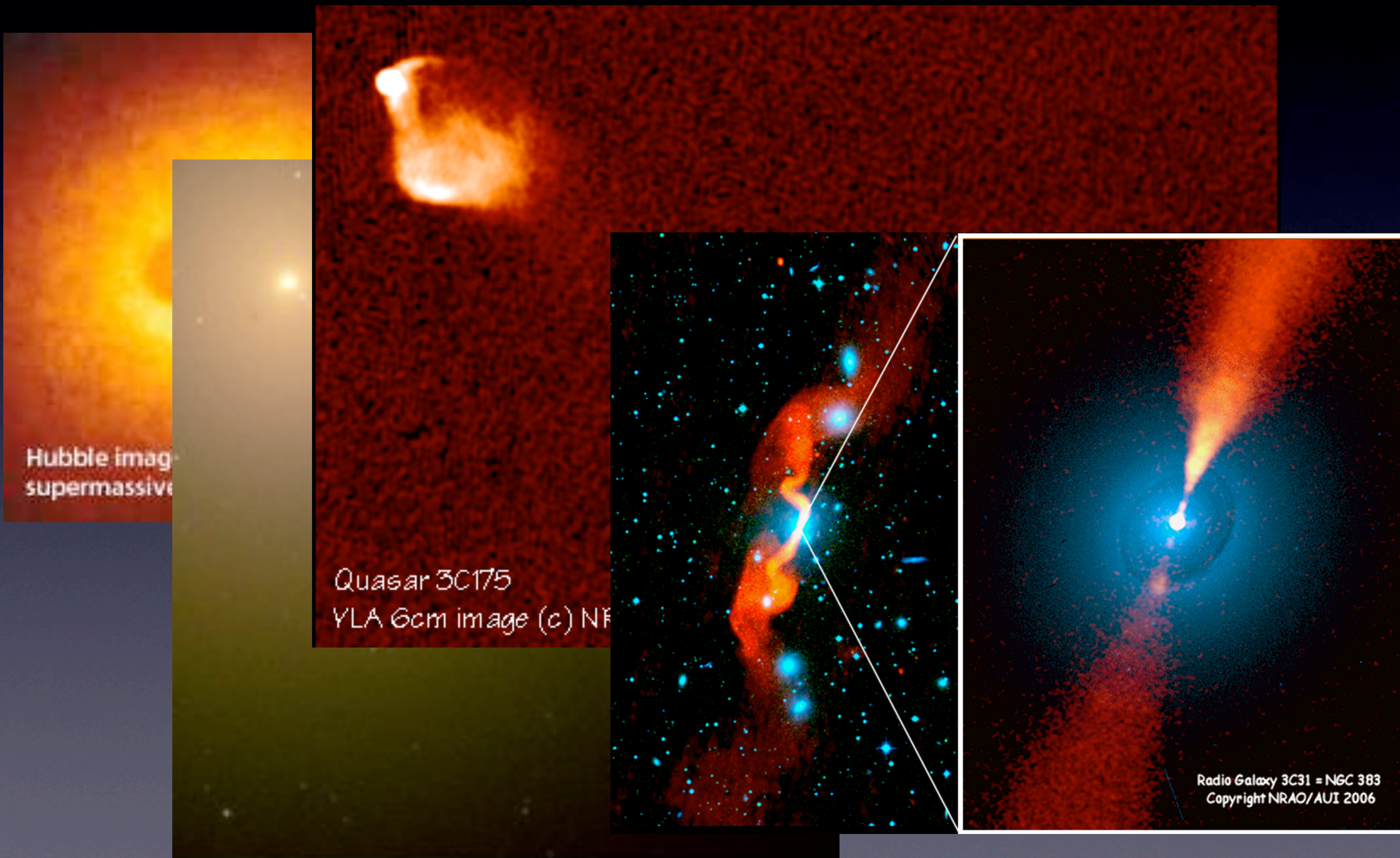


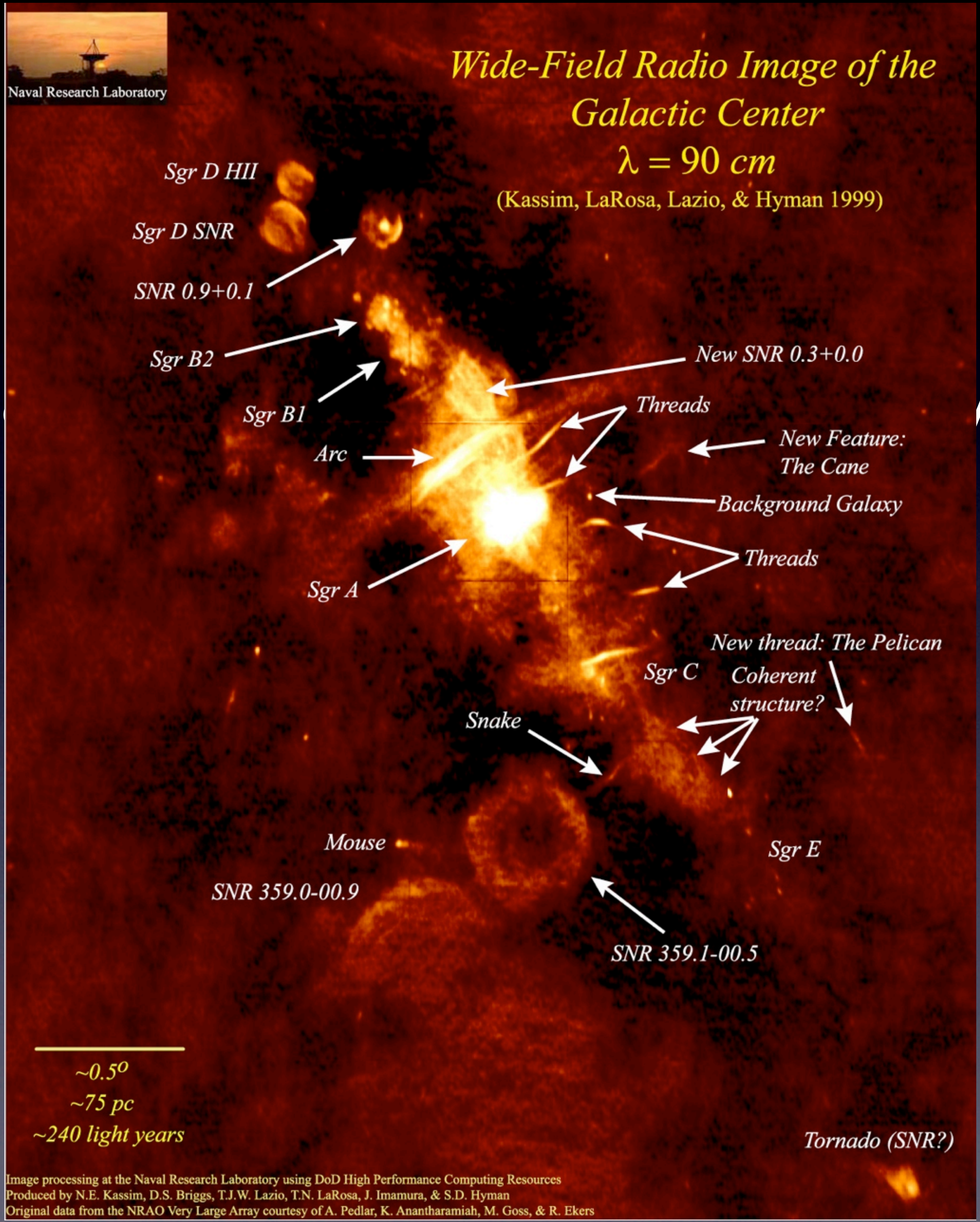
Direct Observation of AGN Impact



Sgr A*

- Black hole at the center of the Milky Way

• Bla… …Way



Naval Research Laboratory
Wide-Field Radio Image of the Galactic Center
λ = 90 cm
(Kassim, LaRosa, Lazio, & Hyman 1999)
Sgr D HII
Sgr D SNR
SNR 0.9+0.1
Sgr B2
Sgr B1
New SNR 0.3+0.0
Threads
New Feature: The Cane
Arc
Background Galaxy
Threads
Sgr A
New thread: The Pelican
Sgr C
Coherent structure?
Snake
Mouse
Sgr E
SNR 359.0-00.9
SNR 359.1-00.5
~0.5°
~75 pc
~240 light years
Tornado (SNR?)
Image processing at the Naval Research Laboratory using DoD High Performance Computing Resources
Produced by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, J. Imamura, & S.D. Hyman
Original data from the NRAO Very Large Array courtesy of A. Pedlar, K. Anantharamiah, M. Goss, & R. Ekers

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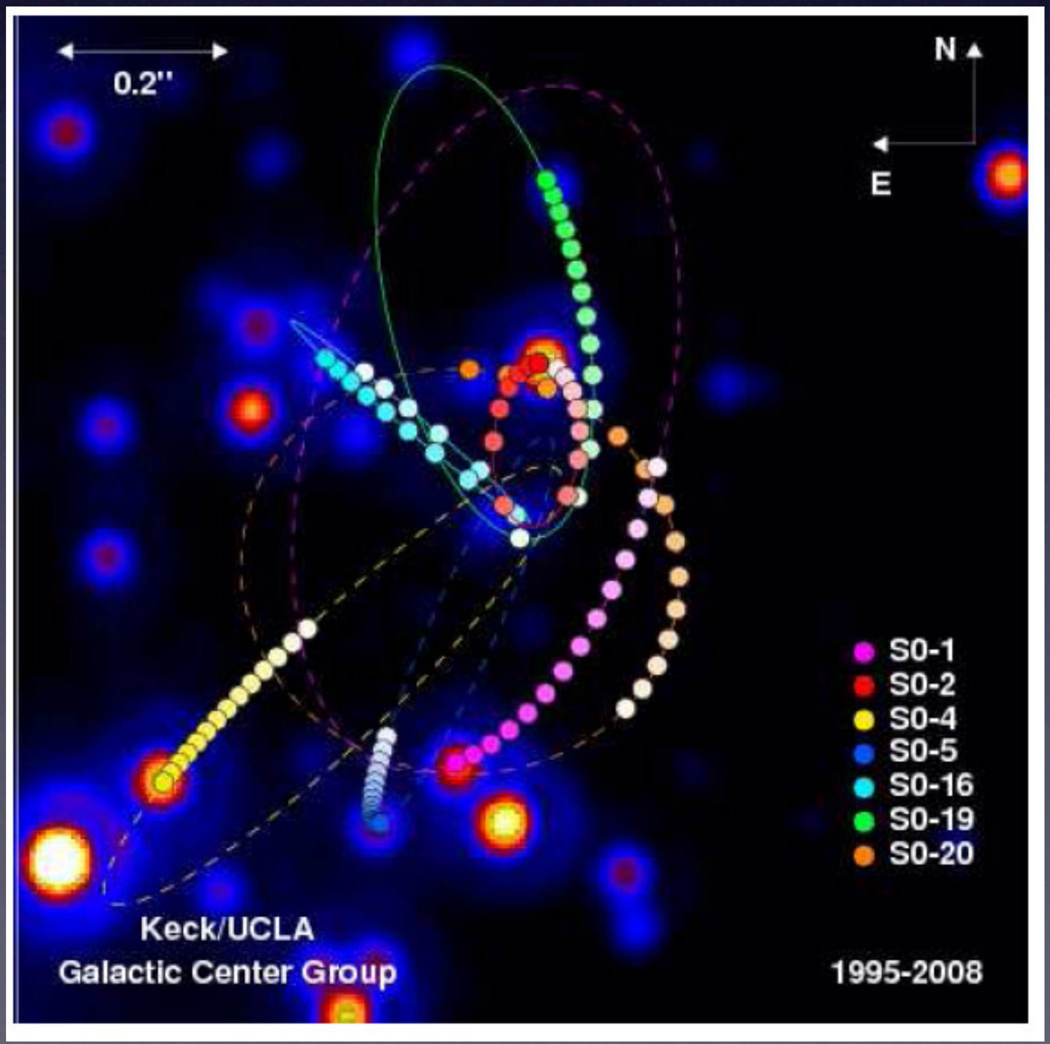

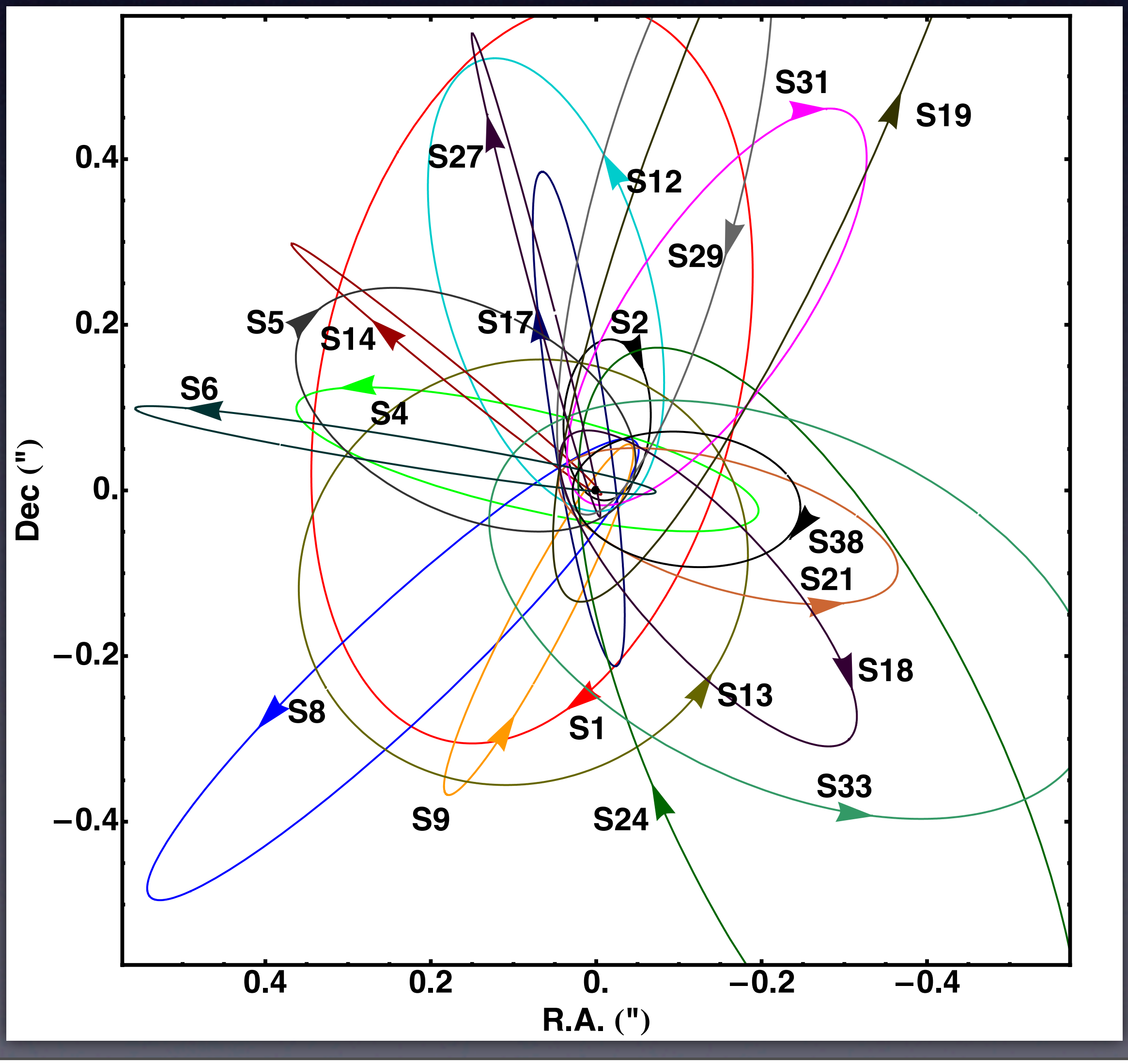

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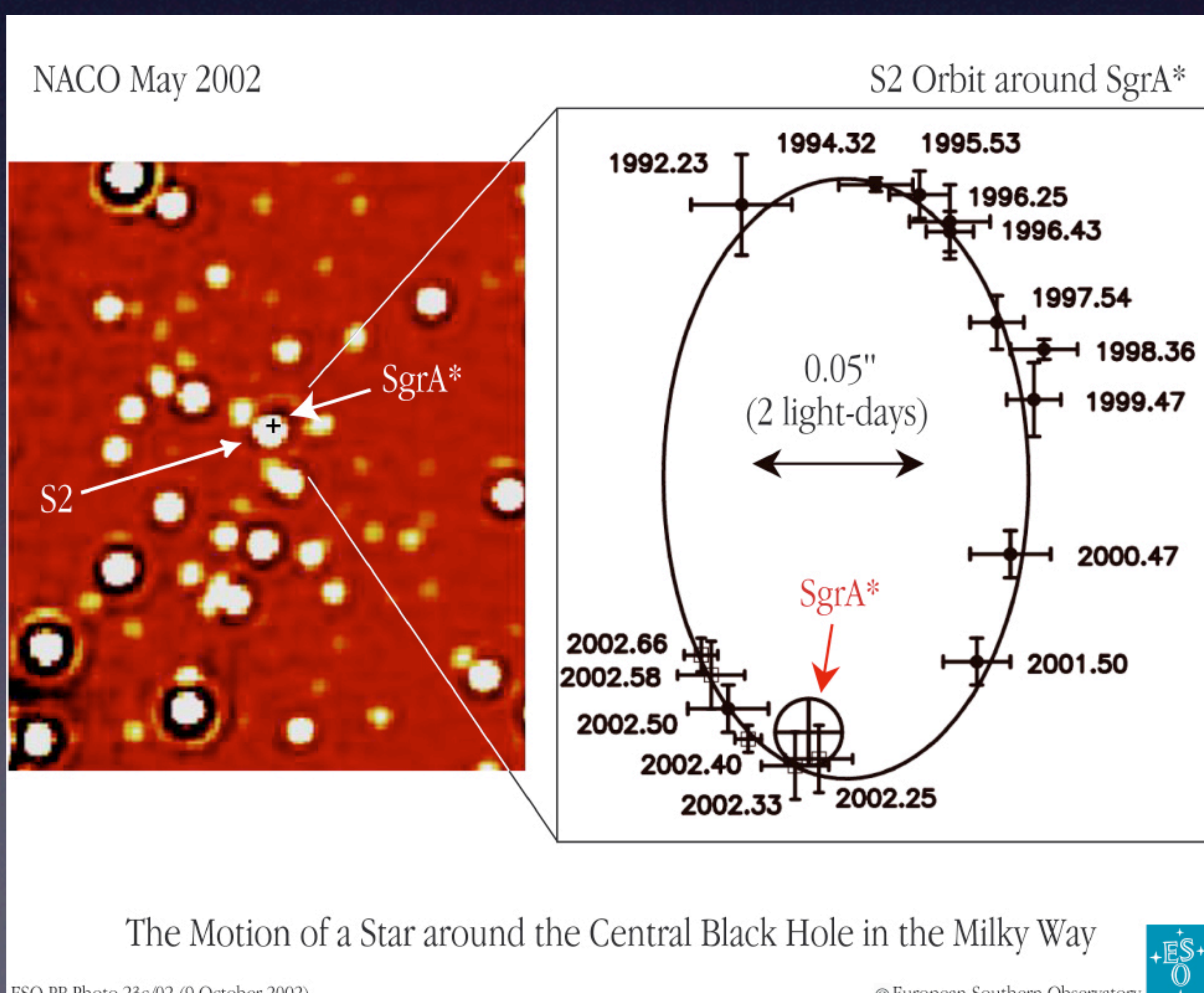

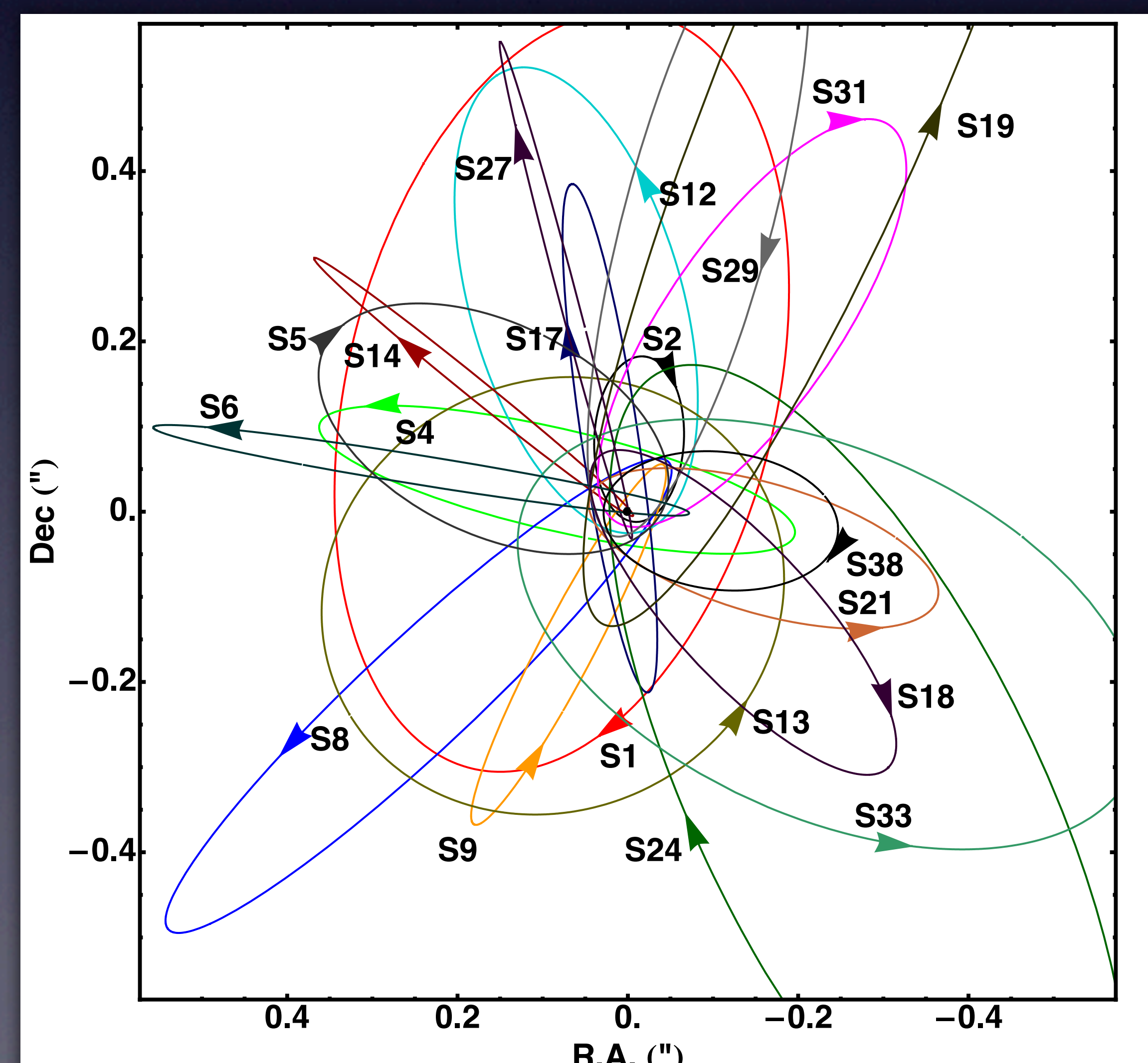

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- Stellar orbits require immense mass within *very* small scales

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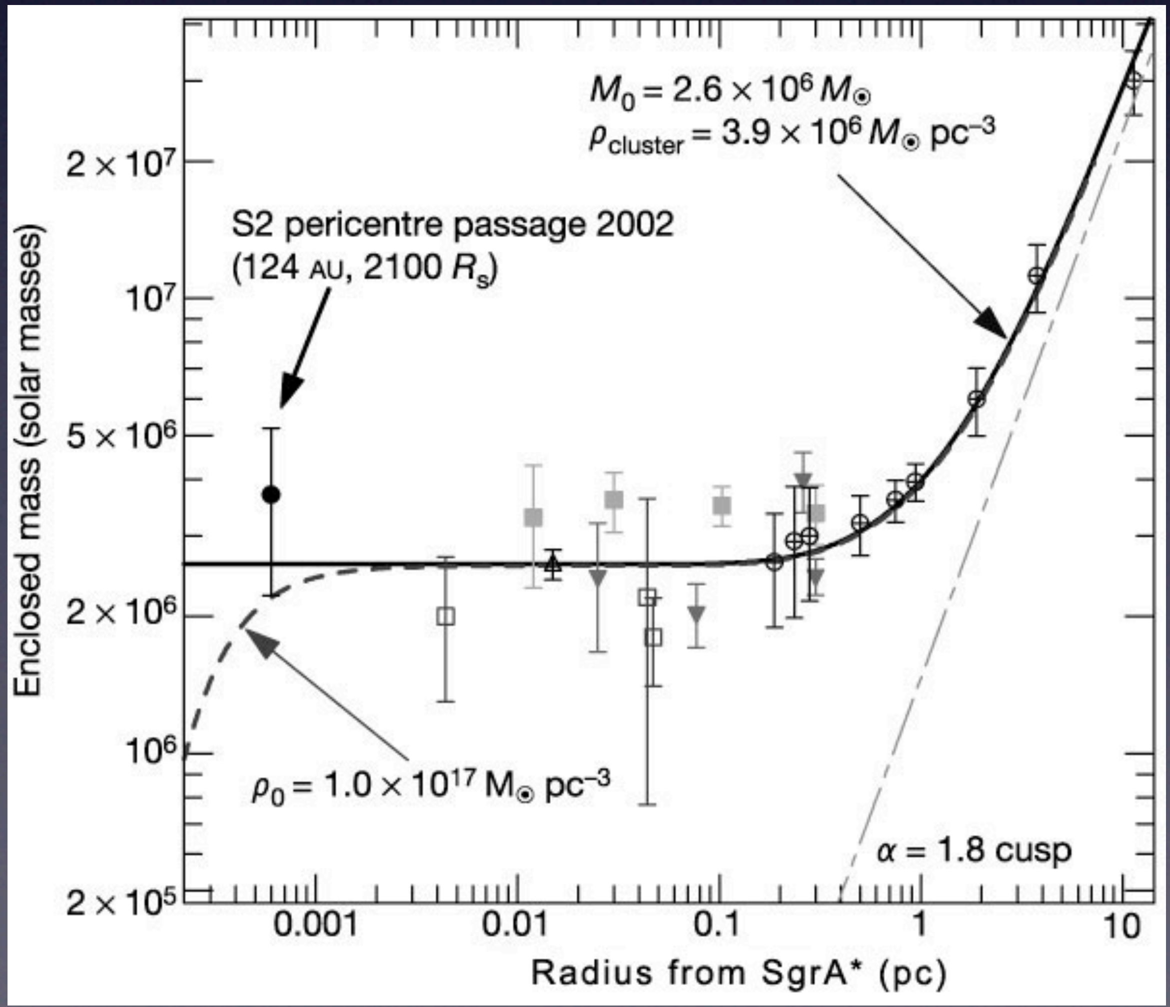
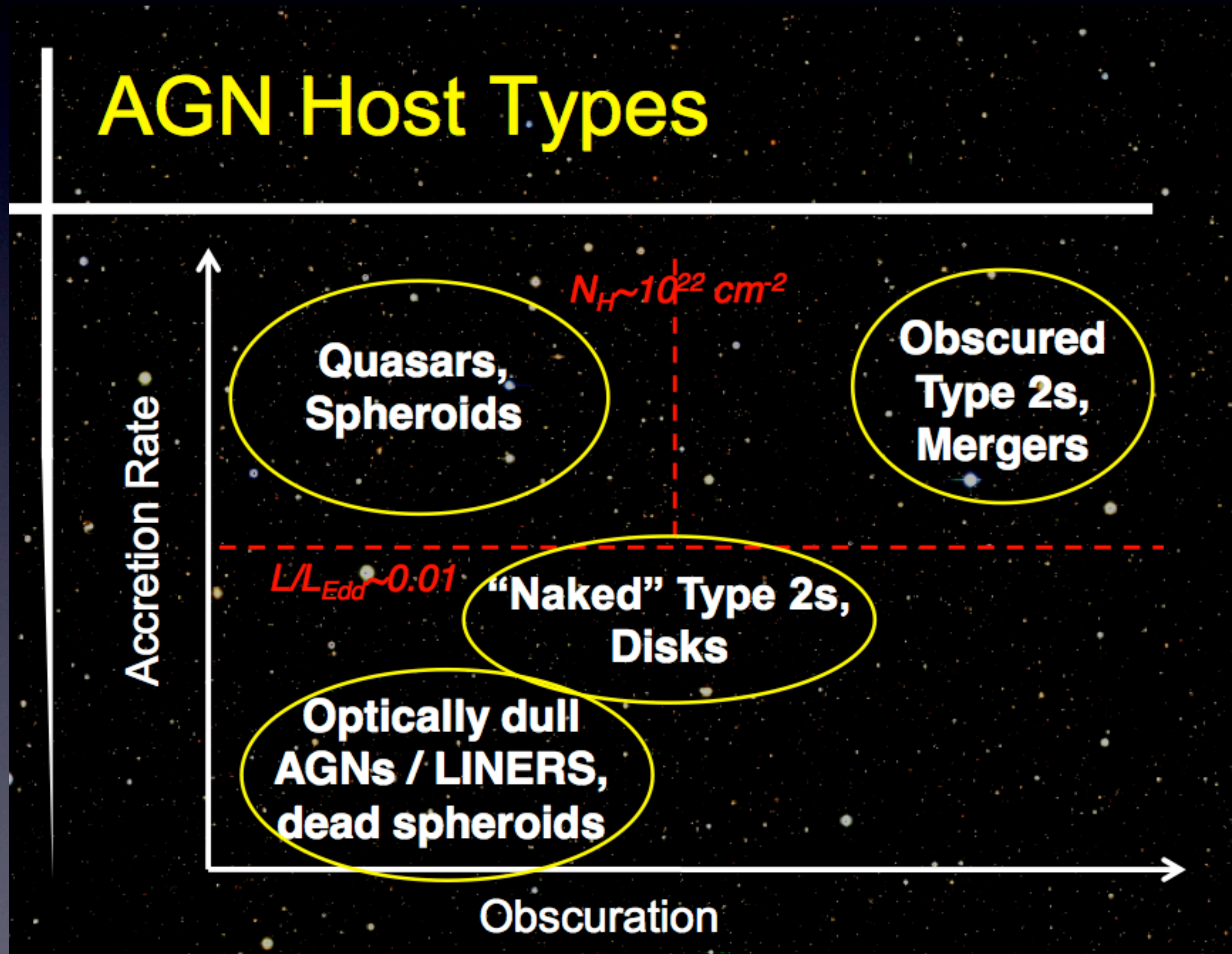


Types of AGN

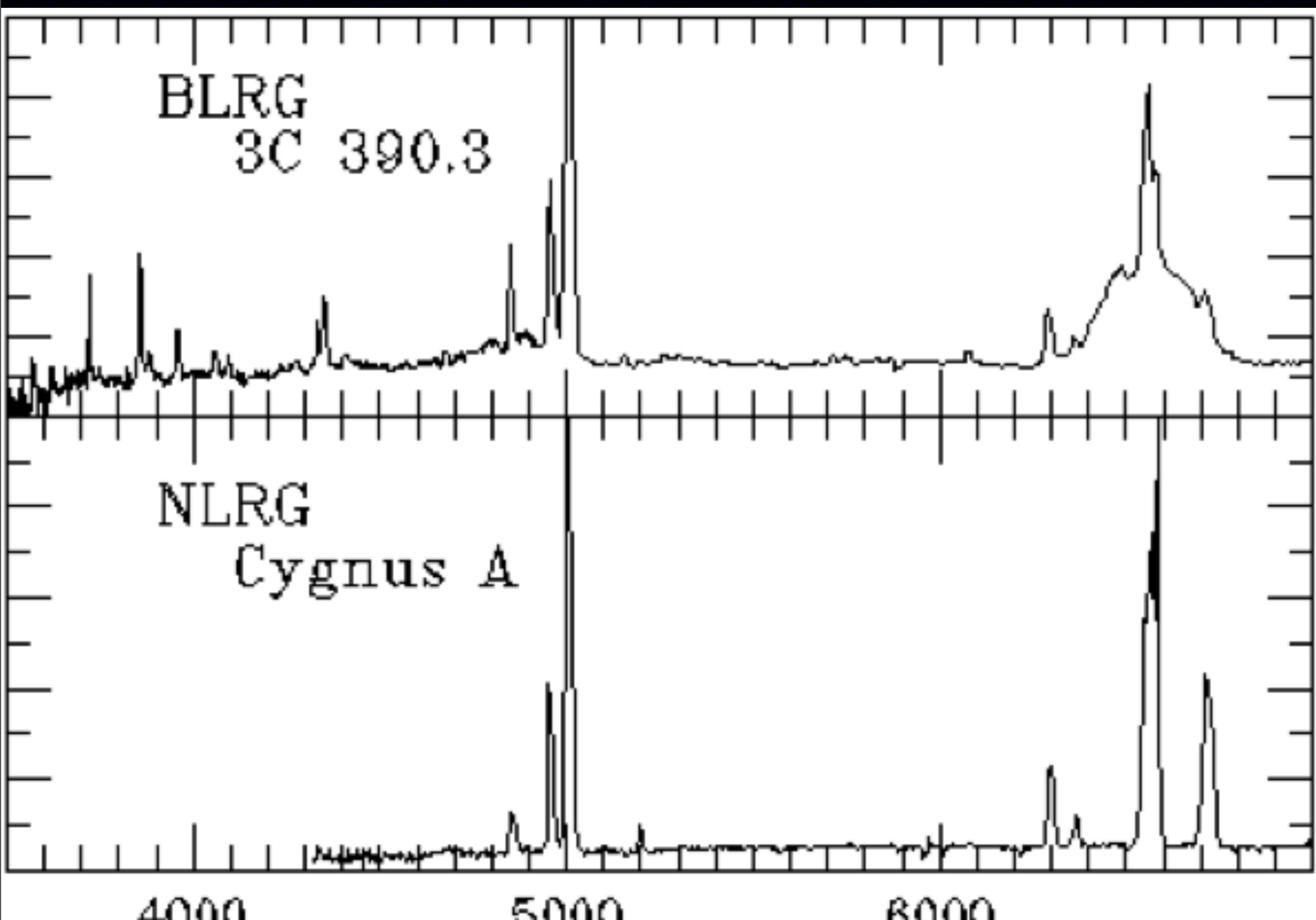
- Lots of different types of AGN:
  - Bright vs. faint
  - Obscured vs. unobscured
  - Broad line vs. narrow line
  - etc.

Types of AGN - Lum & Obscuration

- Quasar: Very luminous objects
- AGN: Less luminous
- Both powered by SMBH



Types of AGN - Line Emission



- Broad Line Quasar
- Narrow Line Quasar

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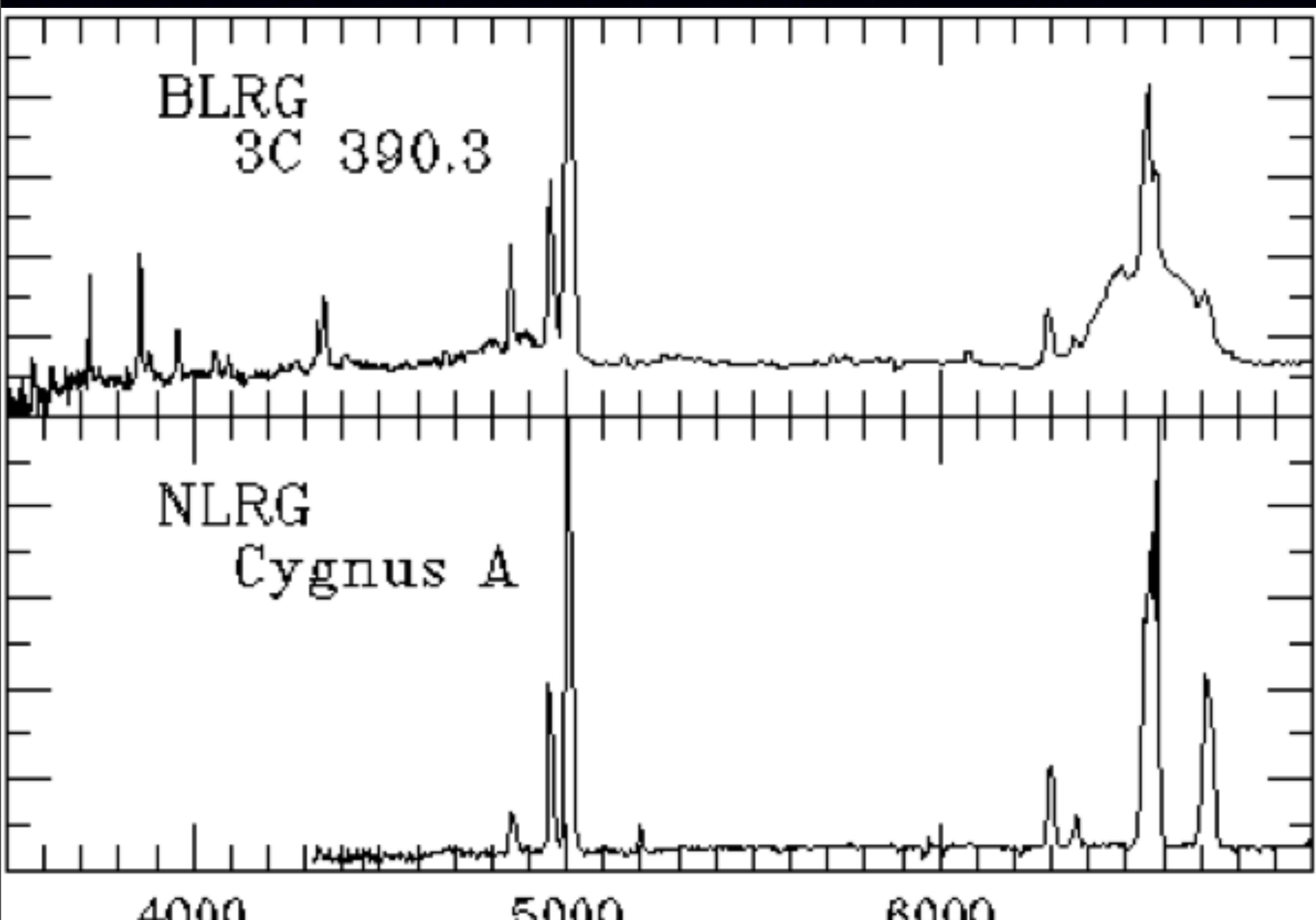


- Broad Line Quasar
- Narrow Line Quasar

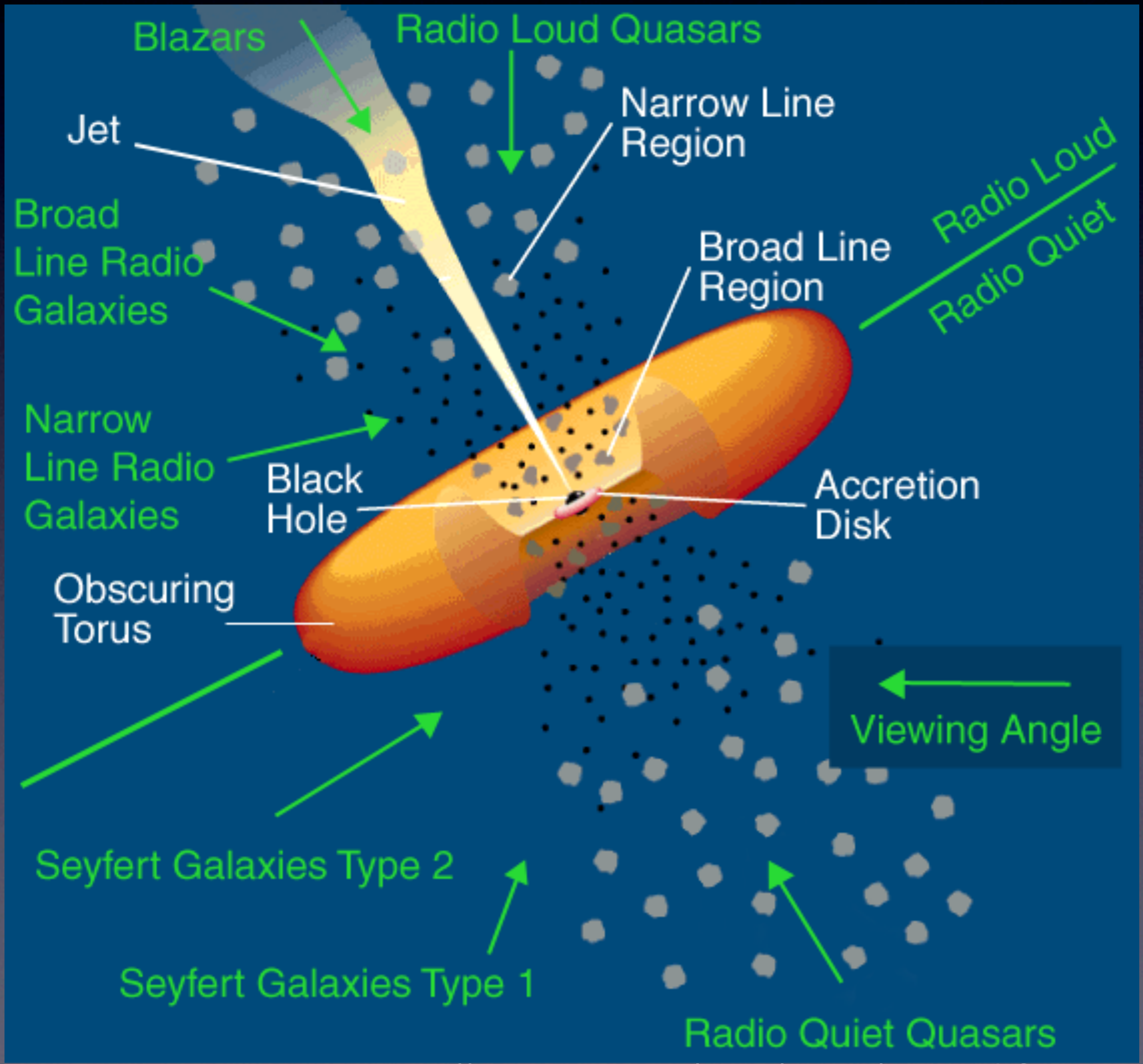
Similar objects, or fundamentally different?

Unified Model

- Explanation for different AGN types via geometry
- Fundamentally the same population, merely different orientation

Unified Model

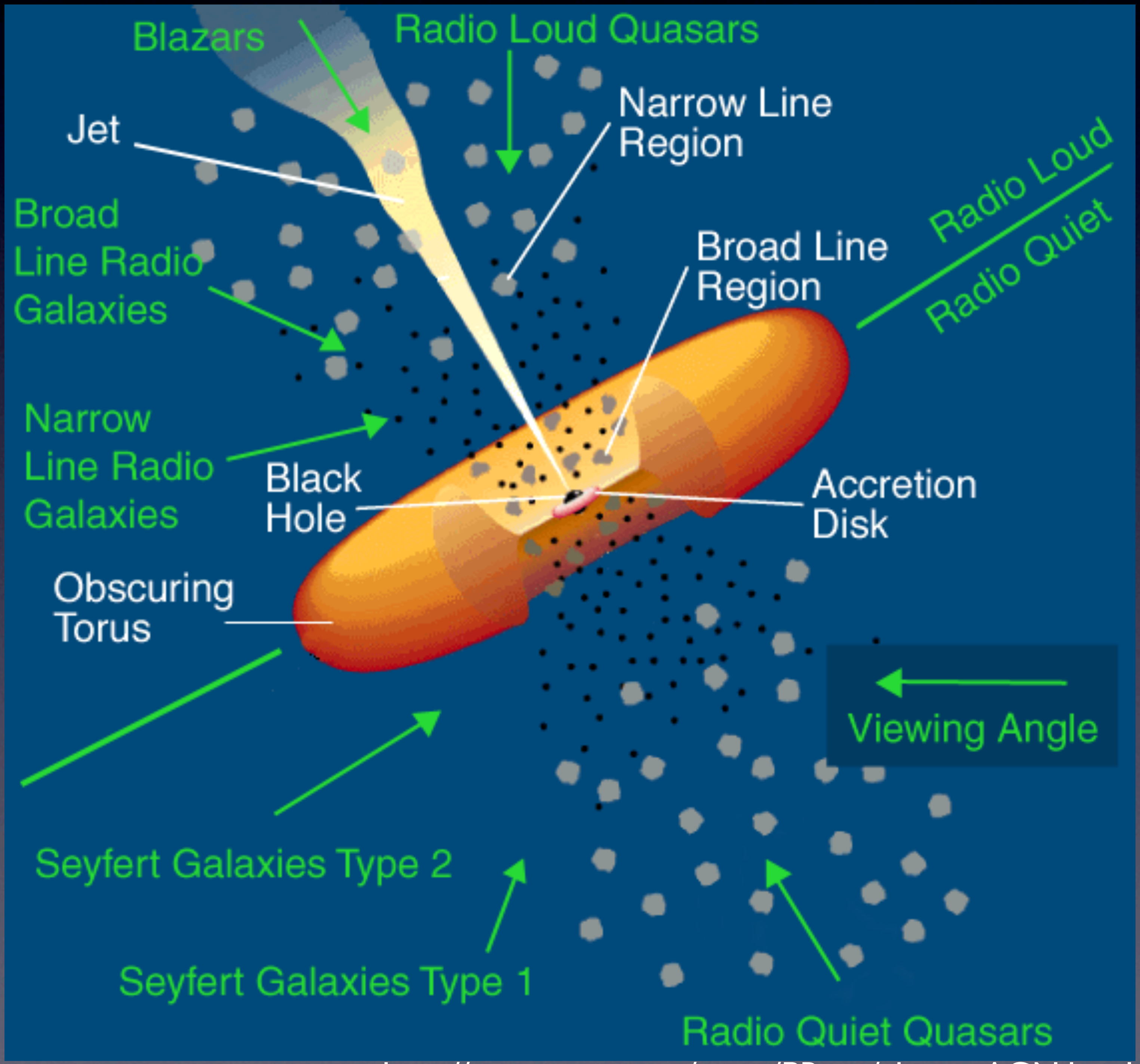
- BLR: Clouds rapidly orbiting central BH
  - High-v ➛ Broad doppler lines



http://www.auger.org/news/PRagn/about_AGN.html

Unified Model

- BLR: Clouds rapidly orbiting central BH
  - High-v ➛ Broad doppler lines
- NLR: Lower-v, lower-density clouds
  - Forbidden lines allowed
    - Unlikely transitions only occur in low-density where electrons can survive in higher orbits without collisions



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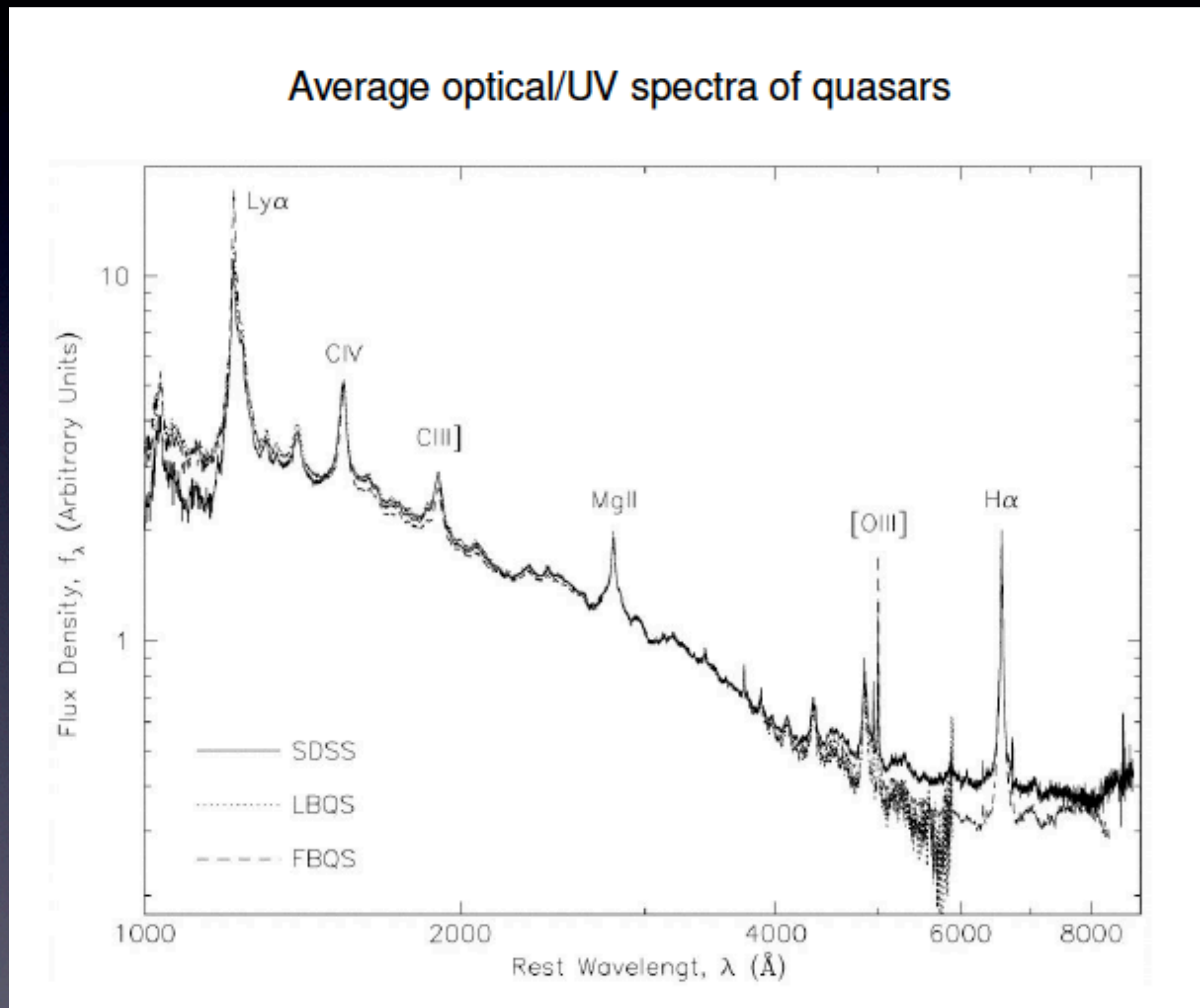
Quasar Spectra



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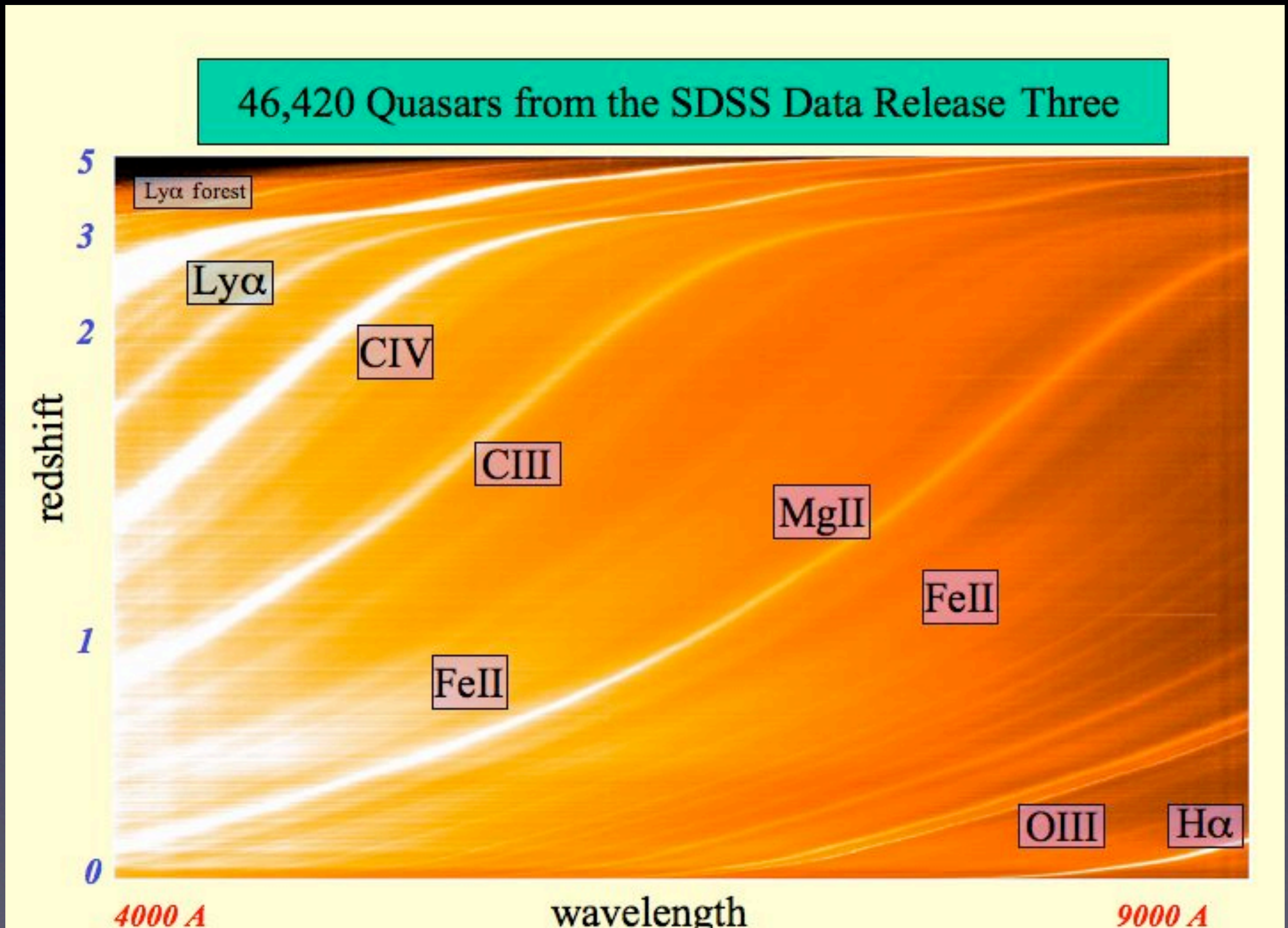

X. Fan & SDSS group

Supermassive Black Hole Model

Supermassive Black Hole Model

- Where do they come from?
- How do they get so large?
- How do they interact with their hosts?

SMBH Origins

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PopIII stellar remnants

Form from massive metal-free stars in early universe

$M_{seed} \sim 100\text{-}500\ M_{sun}$

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Collapse model

Massive gas cloud

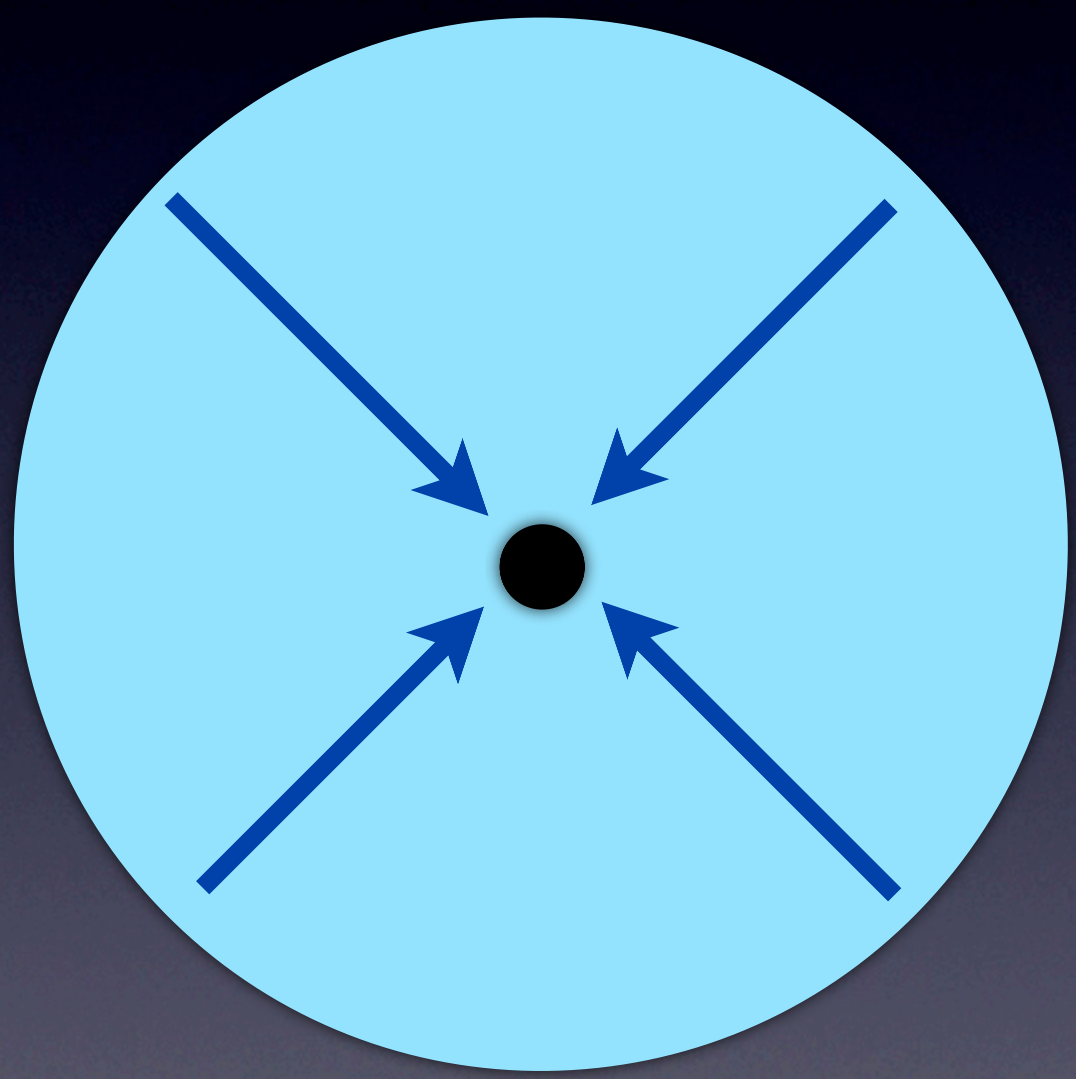
- High inflow rate ➝ unstable system ➝ direct collapse to BH
- Low inflow rate ➝ mild unstable system ➝ fragmentation to stars ➝ black hole formation

$M_{seed} \sim 10^3\text{-}10^5\ M_{sun}$

But can they grow enough?

- Upper limit on growth rate of black holes
  - Eddington limit

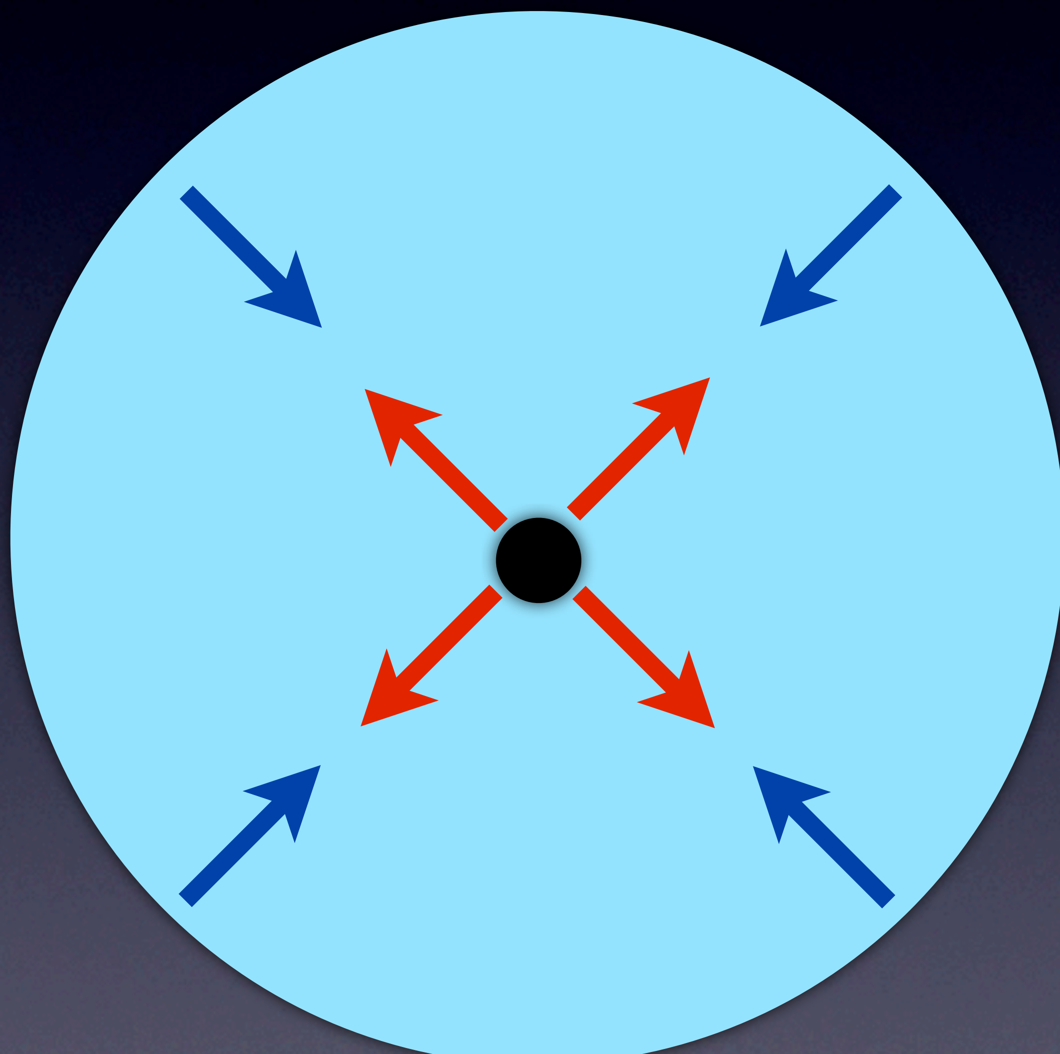
Eddington limit



Gravitational infall:

$$F_{grav} = \frac{GMm}{r^2}$$

Eddington limit



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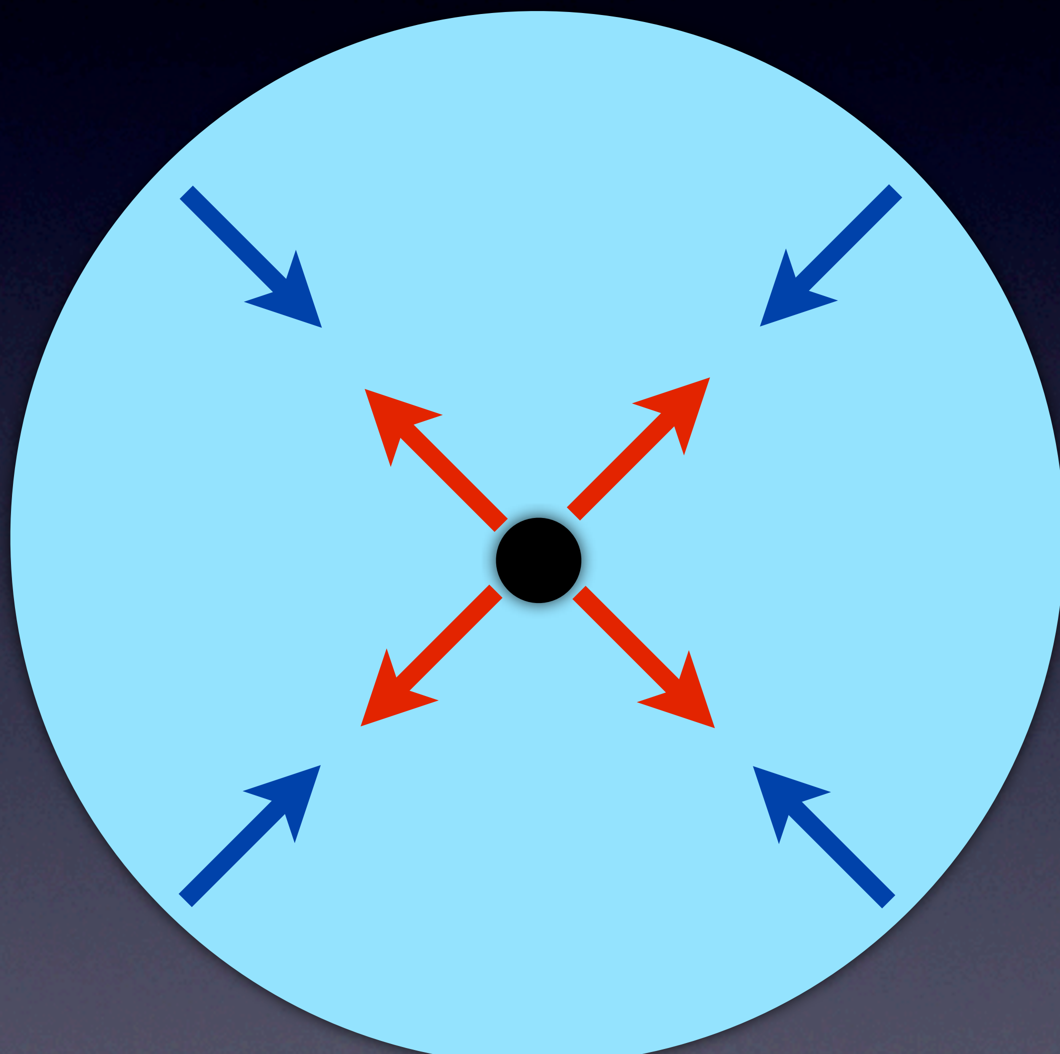

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$$\frac{dE}{dtdA} = \frac{L}{4\pi r^2} \rightarrow \frac{dp}{dtdA} = \frac{L}{4\pi r^2 c}$$

Eddington Limit

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$$\frac{dE}{dtdA} = \frac{L}{4\pi r^2} \rightarrow \frac{dp}{dtdA} = \frac{L}{4\pi r^2 c} \rightarrow \frac{dp}{dt} = \sigma_T \frac{dp}{dtdA} = \sigma_T \frac{L}{4\pi r^2 c}$$

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$$\rightarrow \frac{L_{edd}\,\sigma_T}{4\pi r^2 c} = \frac{GMm}{r^2}$$

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Eddington Limit

Eddington luminosity: $$L_{edd} = \frac{4\pi G M m_p c}{\sigma_T}$$

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Approx. upper limit on BH growth rate!

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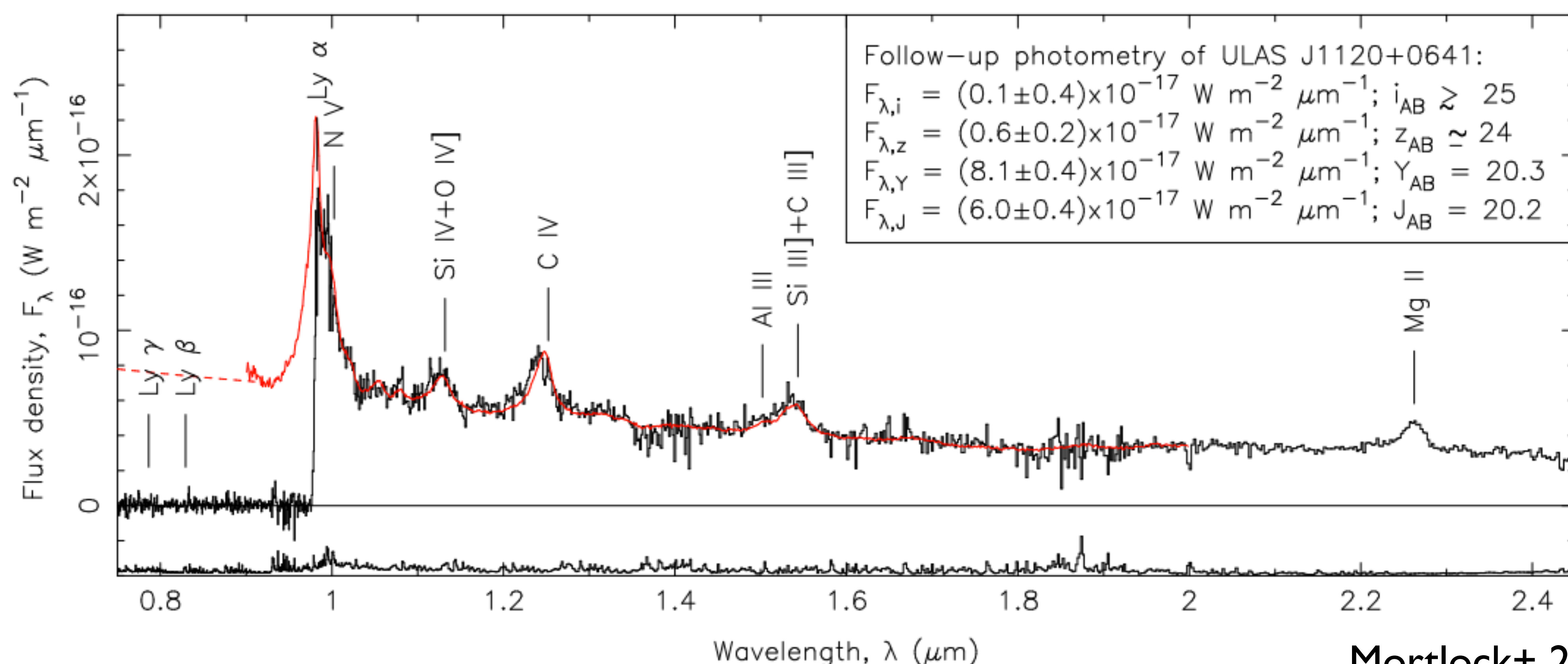
Approx. upper limit on BH growth rate!

Is it fast enough?

So can they grow enough?

Highest redshift observation:

$M_{BH} \sim 2 \times 10^9\ M_{sun}$ at z=7.085



Mortlock+ 2011

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Even with exponential growth, this is challenging

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$$\rightarrow M(t) = M_0 e^{t/t_{edd}}$$

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$$M_{BH} = M_{seed}\, e^{t/t_{edd}}$$
$$t_{edd} \approx 50\ Myr$$

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$M_{seed} = 100\text{-}10^5\ M_\odot$

➢ 10-16 e-foldings to $10^9\ M_\odot$

➢ 0.5-0.8 Gyr

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Age of universe at z=7.085: ~0.75 Gyr

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Gyr

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Is that feasible?

How is it maintained?

Black Hole Growth

Black Hole Growth

- Two modes of growth
  - Black hole mergers
  - Gas accretion

Black hole mergers

- Growth not limited to Eddington
- Major mergers can double M_{BH}
- BUT major mergers aren't too common

Gas Accretion

- Gas falls in to be swallowed by BH
- Simplest model: Bondi accretion
  - Spherical symmetry

$$\dot{M}_{BH} = \frac{4\pi G^2 M_{BH}^2 \rho}{(c_s^2 + v_{rel}^2)^{3/2}}$$

Thin Accretion Discs

- Thin disc accretion
- $c_s << v_{rot}$ (small pressure gradients)
- Simple viscosity approximation allows for solution to hydrodynamic equations (α-disc model) $\nu = \alpha c_s H$
- Radiatively efficient

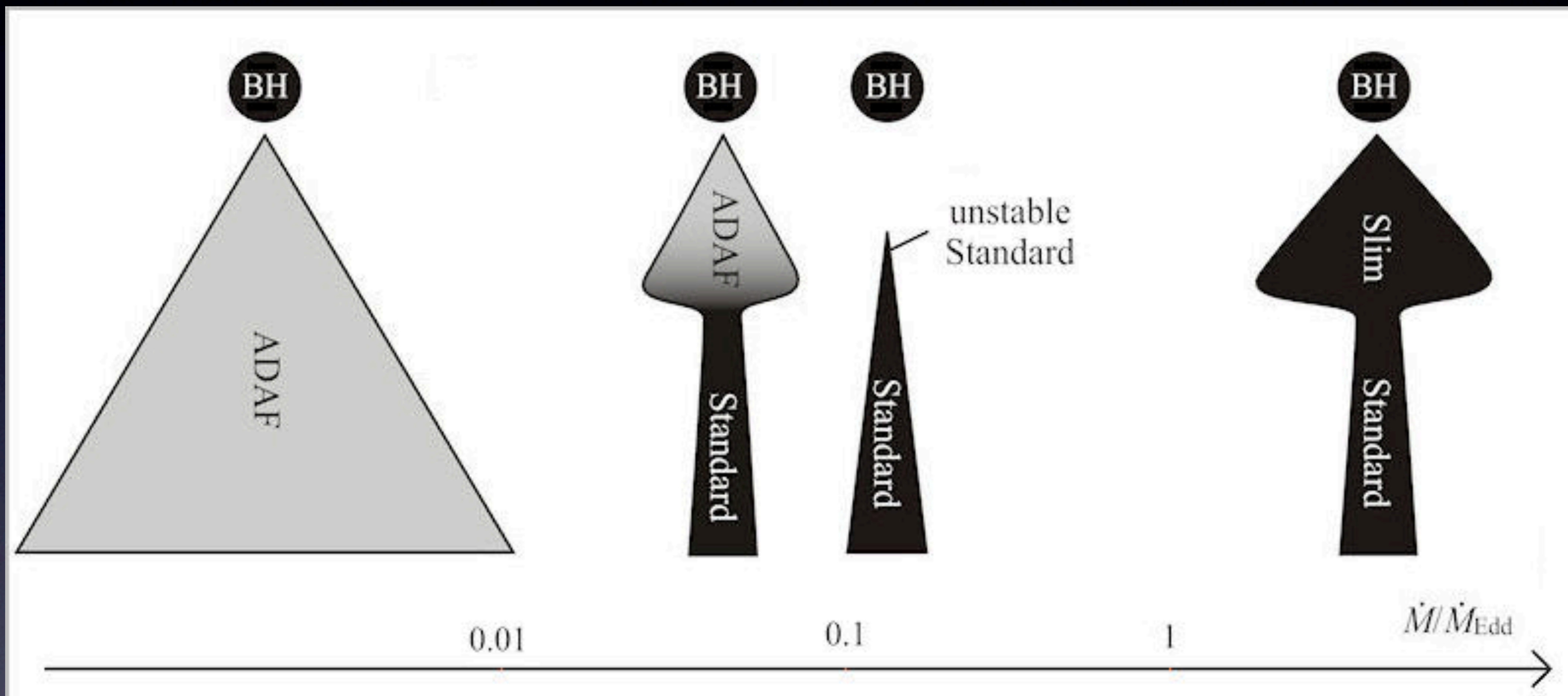
Slim Accretion Discs

- Consider thin disk with more efficient accretion ($L > \sim 0.3\ L_{edd}$)
- Energy no longer radiated away efficiently
- Causes disk to get a bit thicker

Thick Disc Accretion

- Low gas density ➛ low radiative power
- Viscous heating unbalanced by radiative loss
- Heat advected rapidly toward center
- Hotter gas puffs up ➛ thick disc (quasi-spherical)

Accretion Discs



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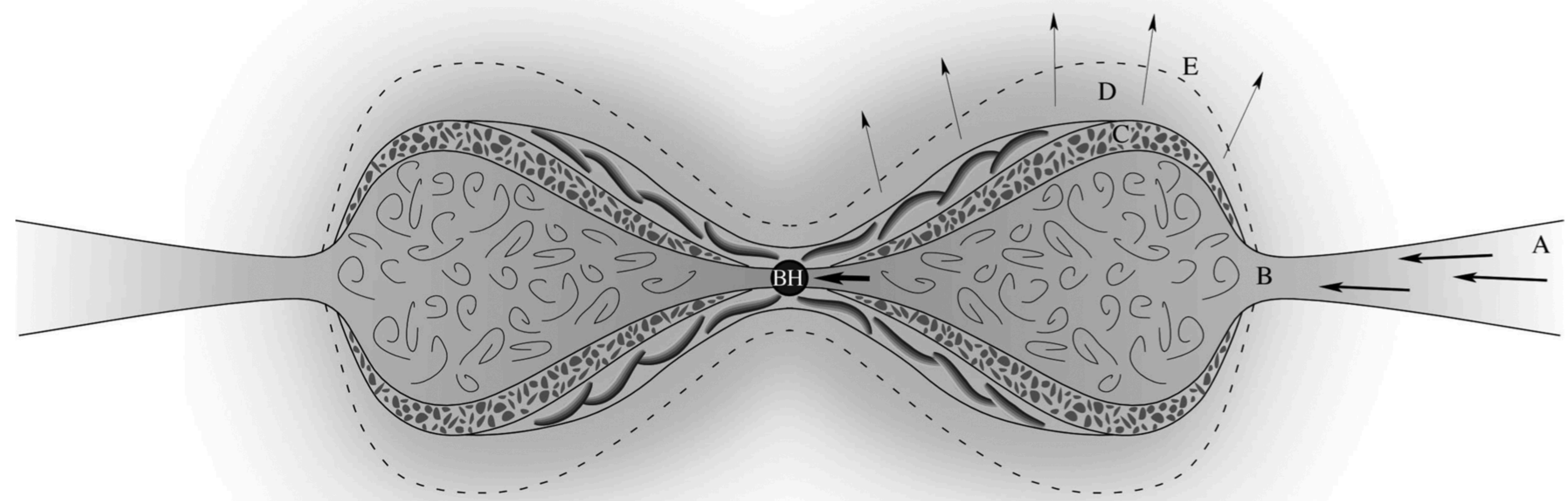
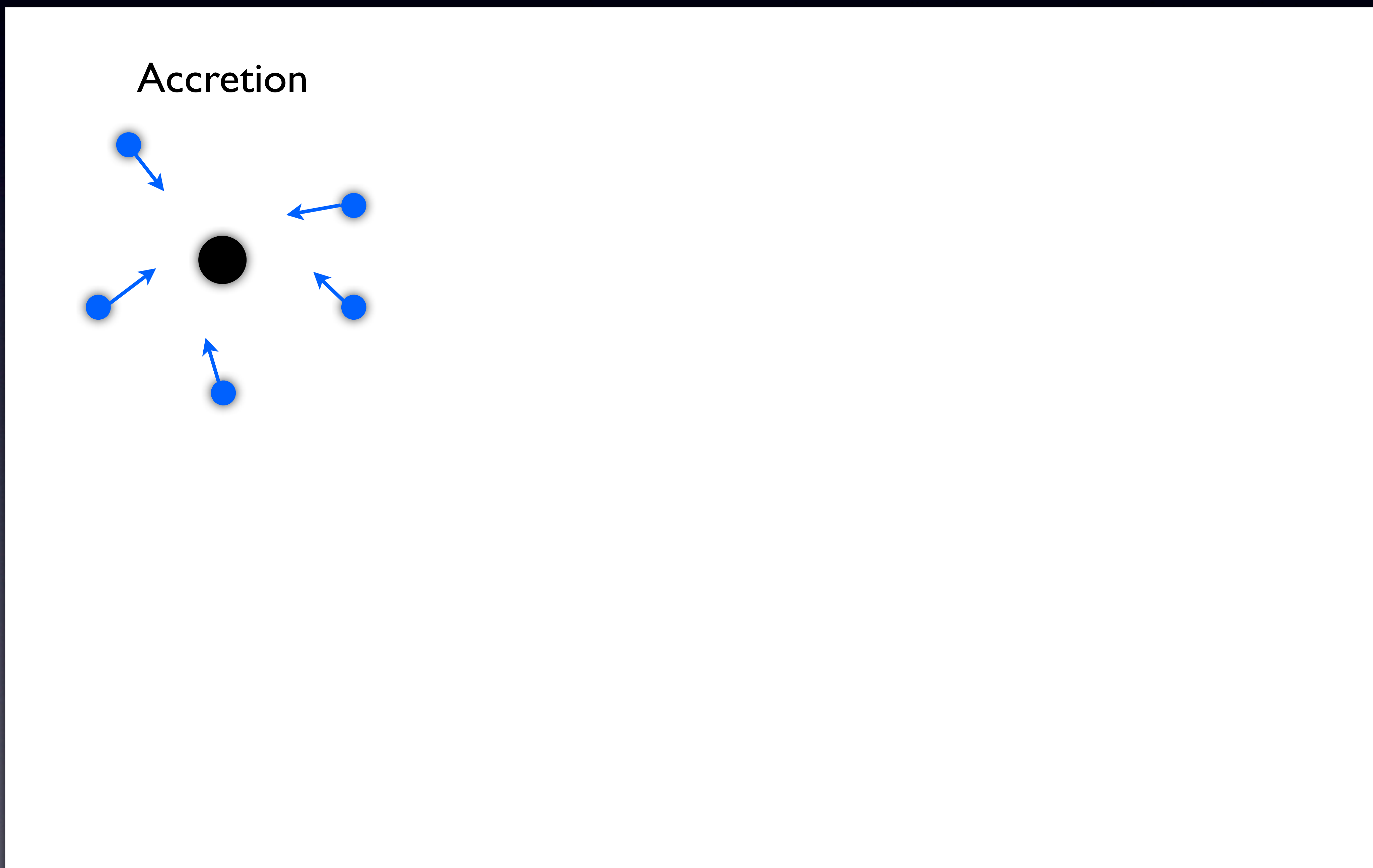


Dotan & Shaviv 2011

Black Hole Feedback

Black Hole Feedback - Basic Picture



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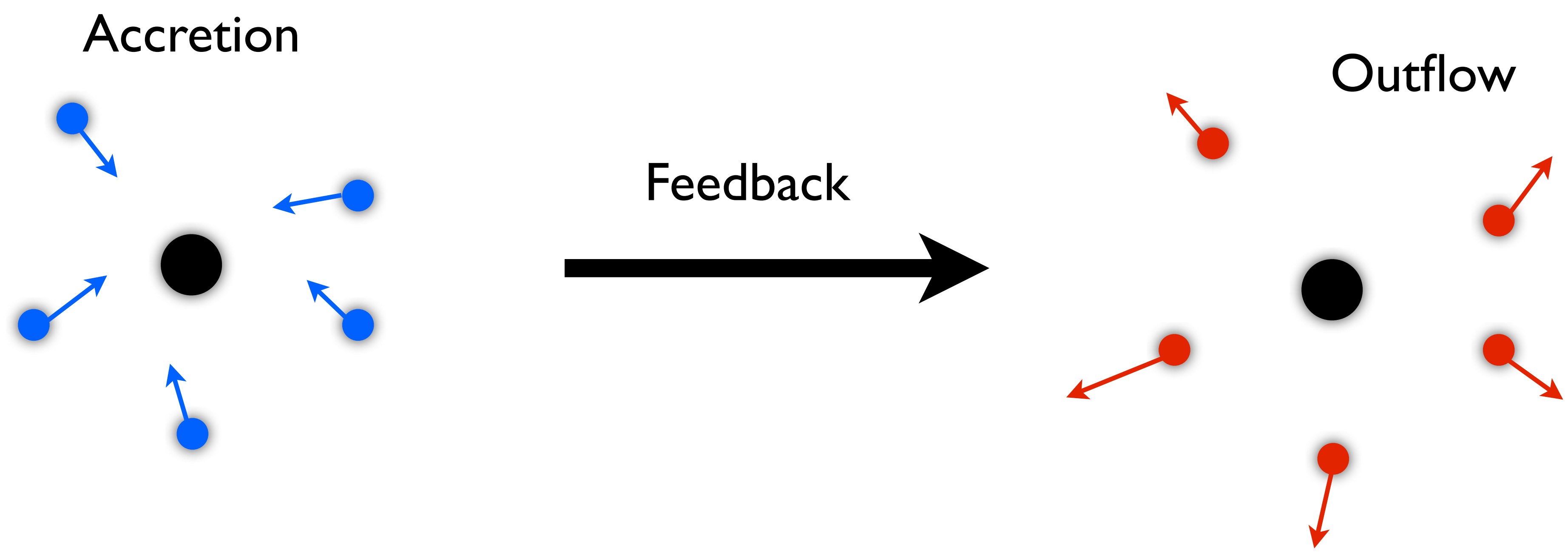

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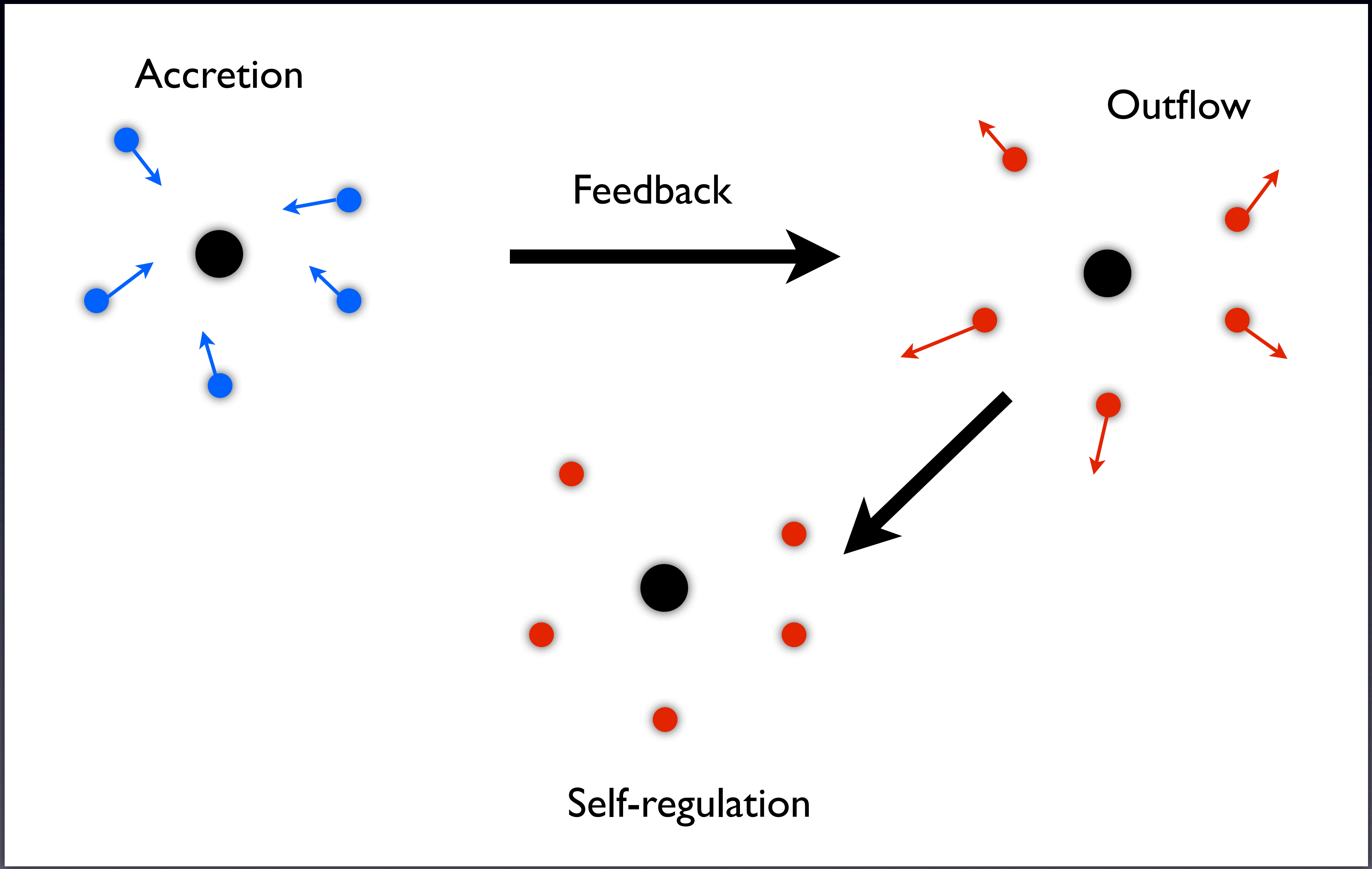

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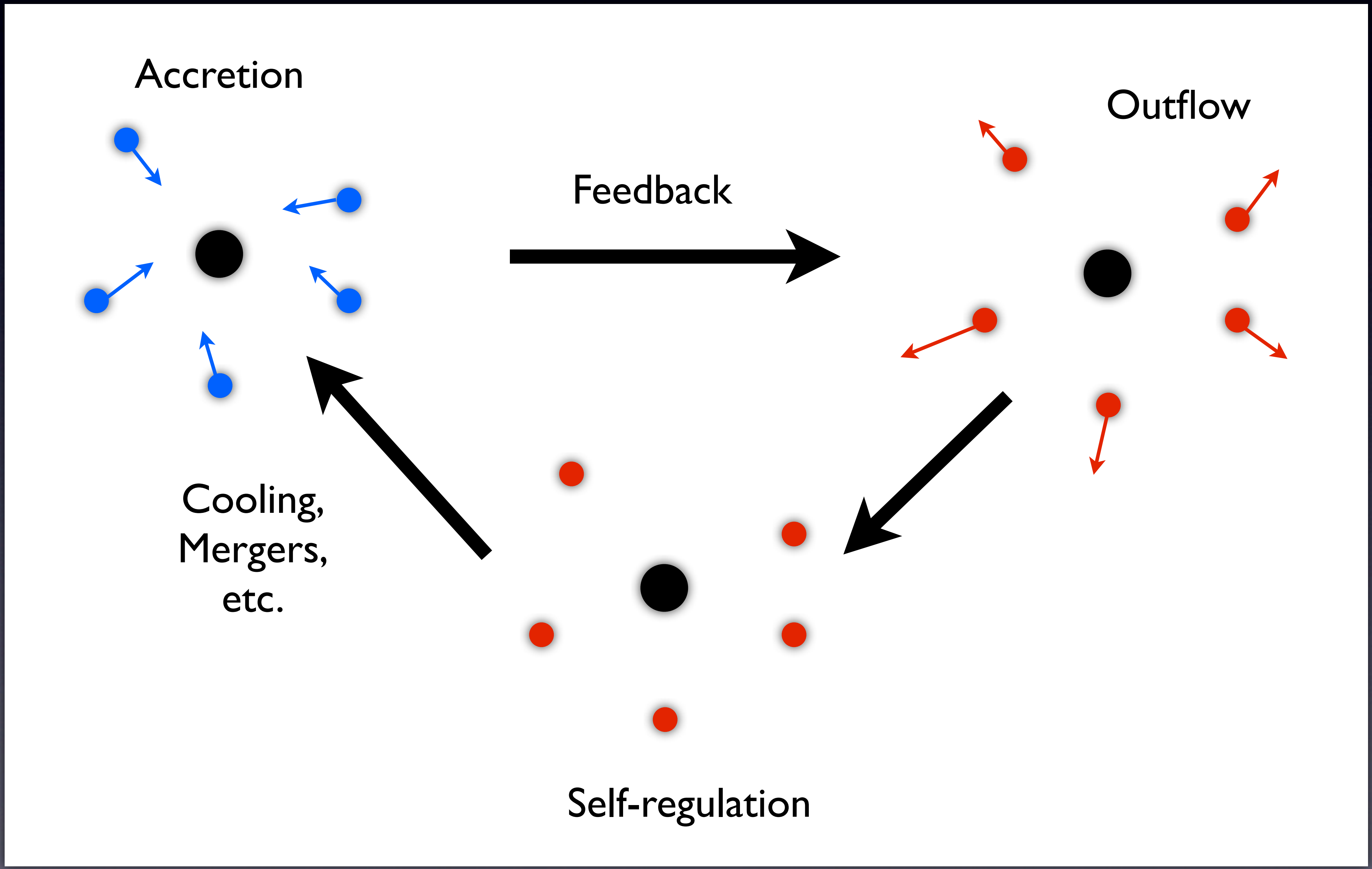

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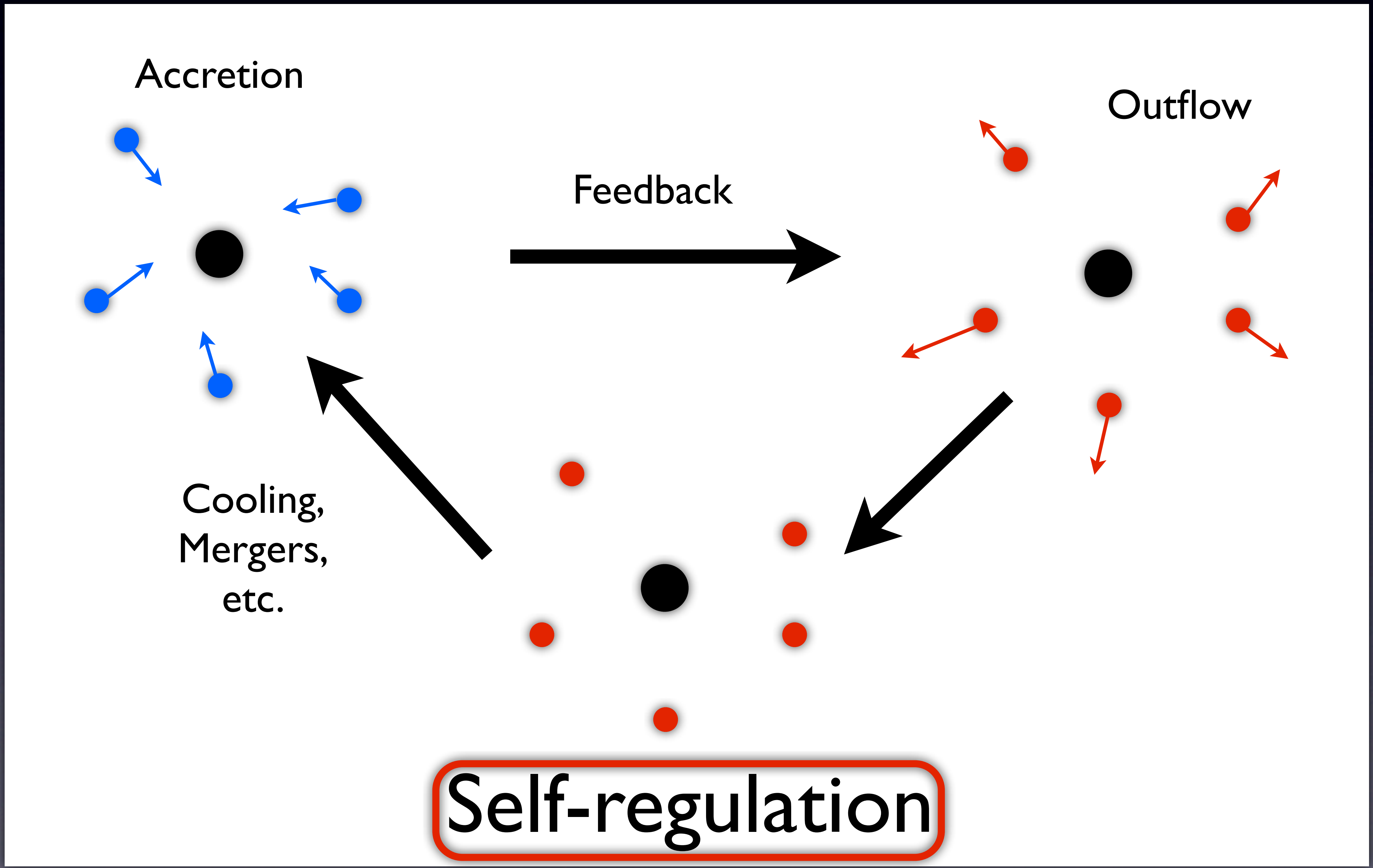


Feedback Mechanisms

- Accretion energy of BH:
  $\sim 10^{62}$ erg for 10^9 M_{sun} BH
- Feedback definitely has the potential for strong effects

Feedback Mechanisms

- Rapid heating of gas ➛ strong gas outflow
  - 'Quasar' mode
- BH powers radio jet ➛ prevents nearby gas from cooling ➛ suppresses further infall
  - 'Radio' mode

Quasar Mode vs. Radio Mode

Quasar Mode

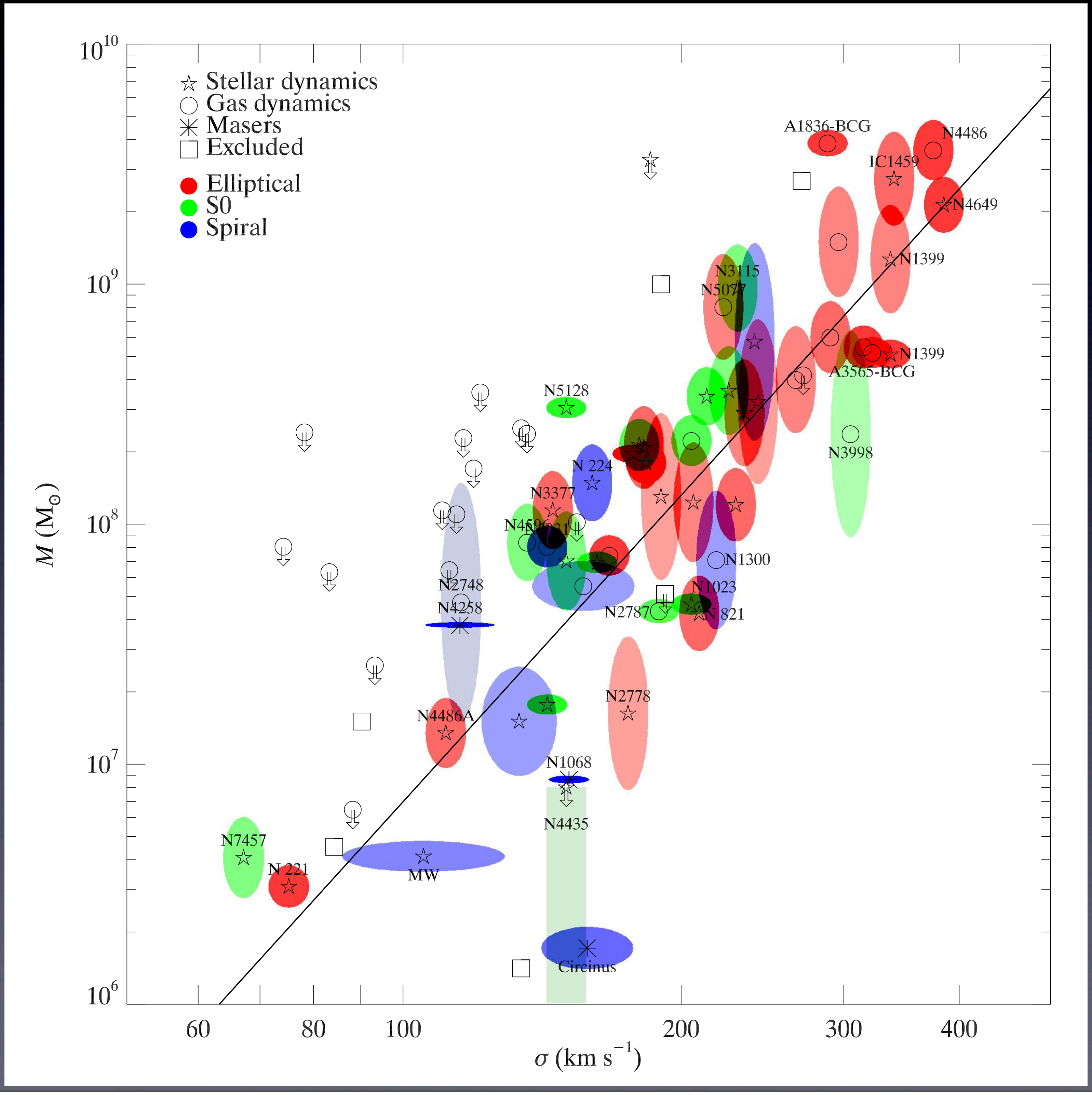
- Cold gas accretion
- High accretion efficiency
- Triggered by mergers/ cold streams
- Feedback:
  - Thermal
  - Isotropic

Radio Mode

- Hot gas?
- Low accretion efficiency
- Suppresses gas cooling, SF
- Feedback:
  - Kinetic
  - Highly directed (jets)

Scaling Relations

- Black hole mass strongly correlates with host properties
  - σ
  - M_{bulge}
  - L_{gal}



Scaling Relations

- Lets us use black hole as direct probe of host properties
- Suggests a direct link between black hole growth and galaxy evolution

Scaling Relations - Problem of Scale

- Black hole scale:

  <parsec

$$\boxed{\begin{array}{c} R_{Sch}=2GM_{BH}/c^2 \\ R_{grav}=2GM_{BH}/\sigma^2 \end{array}}$$

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- Galaxy scale:
  kiloparsec

$$\boxed{R=2GM_{*}/\sigma^2}$$

Scaling Relations - Problem of Scale

- Black hole scale:
  <parsec

  $R_{Sch}=2GM_{BH}/c^2$

  $R_{grav}=2GM_{BH}/\sigma^2$

- Galaxy scale:
  kiloparsec

  $R=2GM_{*}/\sigma^2$

- Halo scale:
  megaparsec

  $R=2GM_{halo}/\sigma^2$

Scaling Relations

- Outside-in:
  - Properties of the host determine the mass scale of the black hole
- Inside-out:
  - Properties of the black hole impact the host evolution

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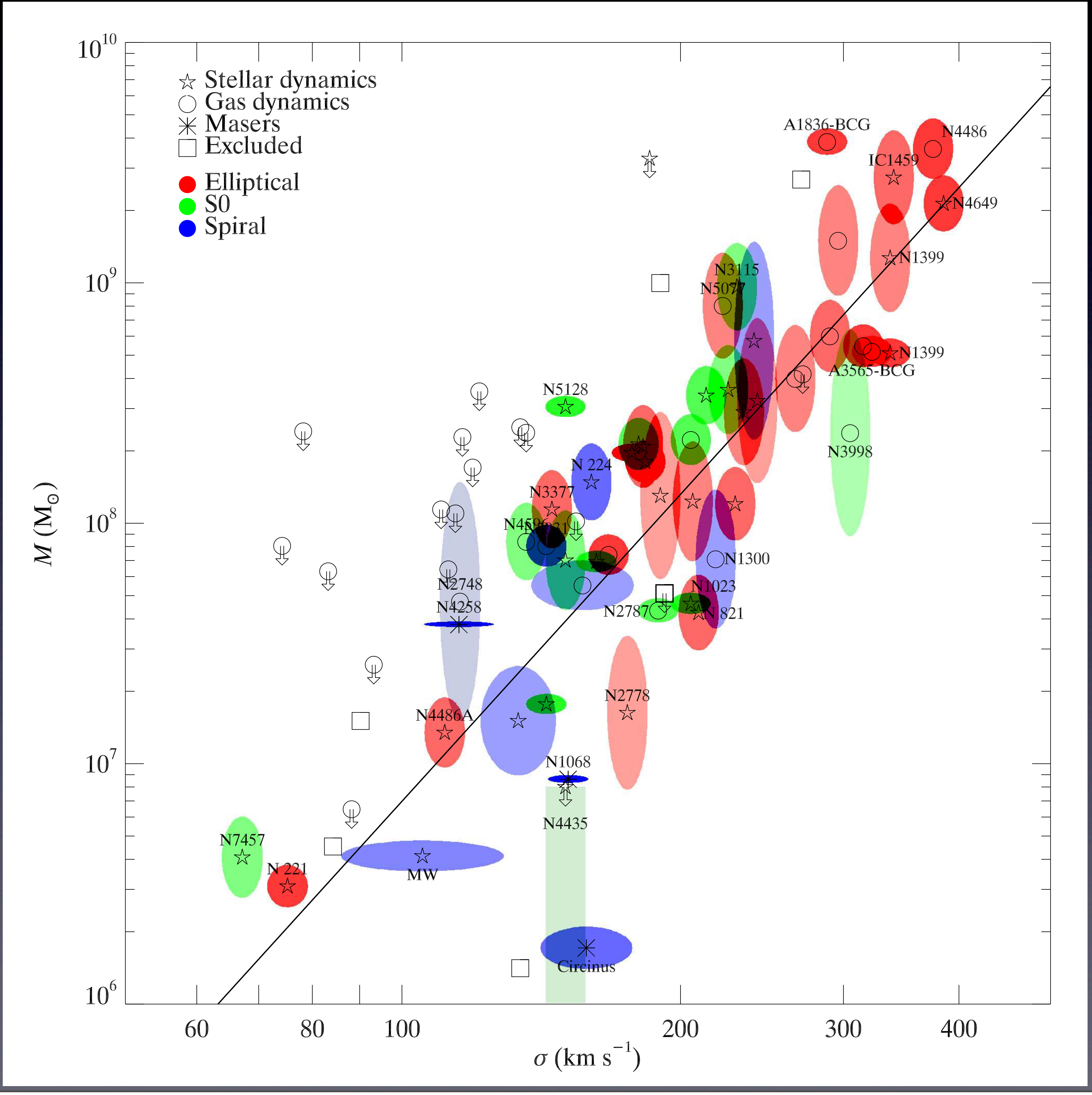

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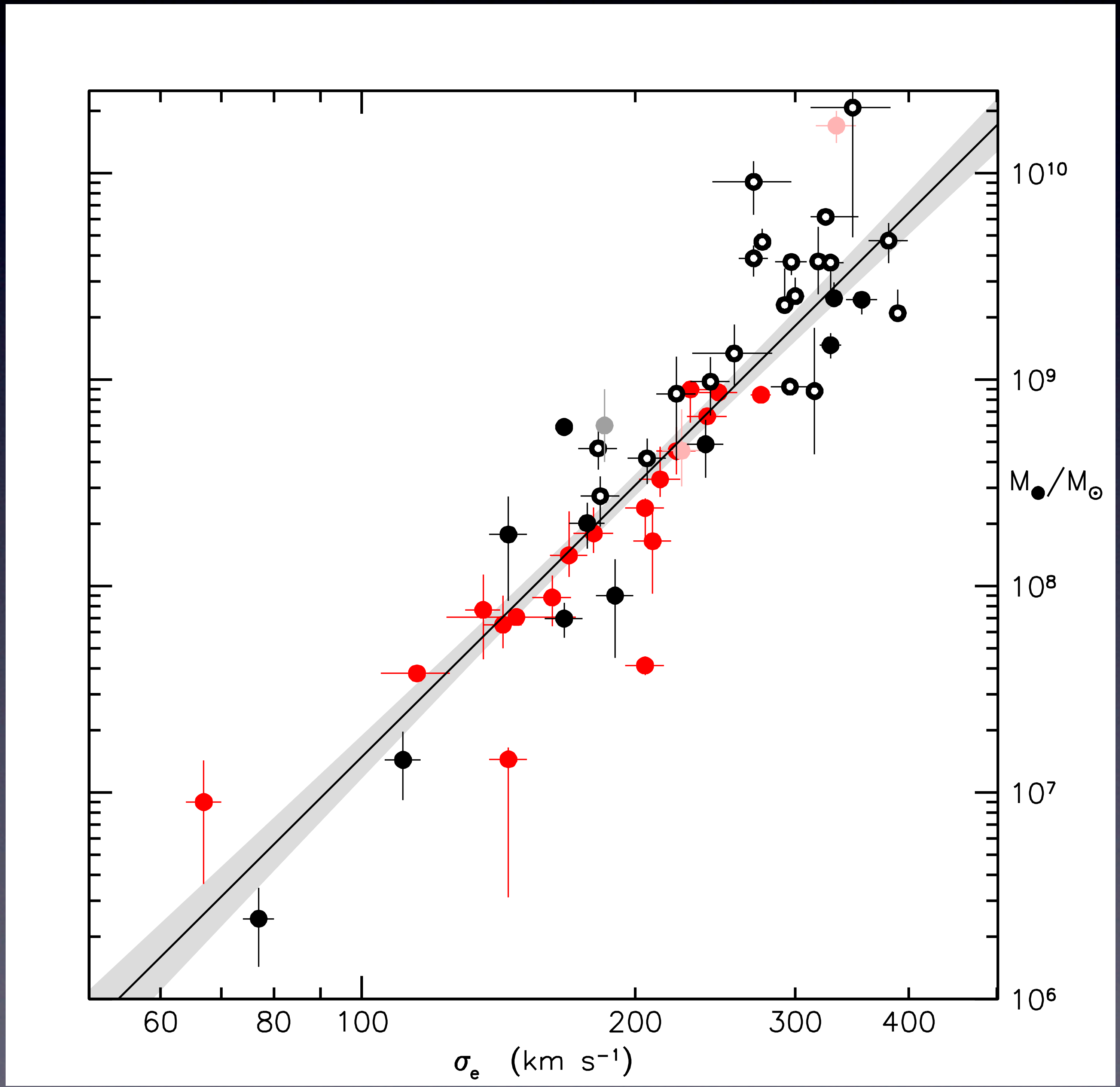

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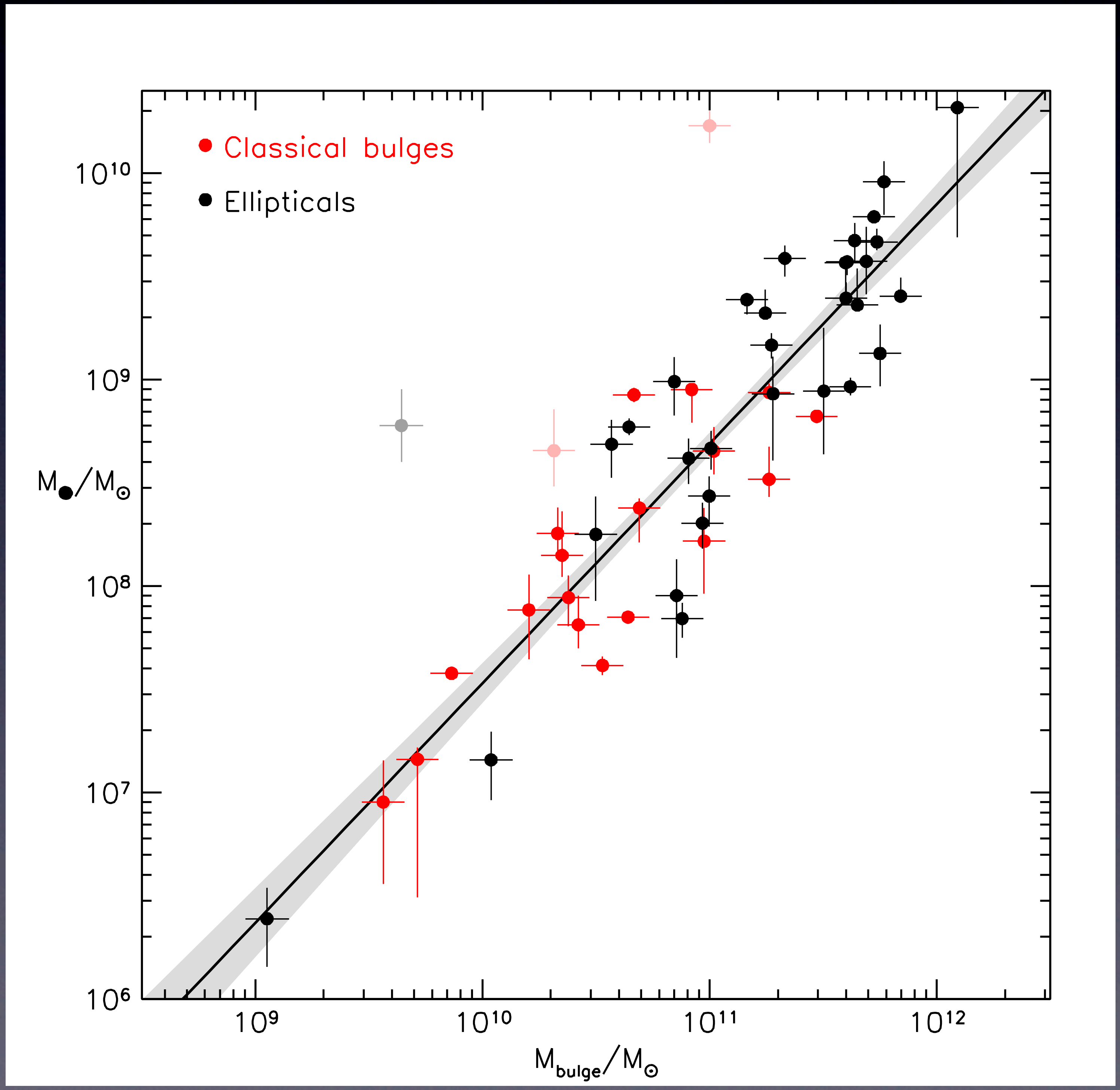
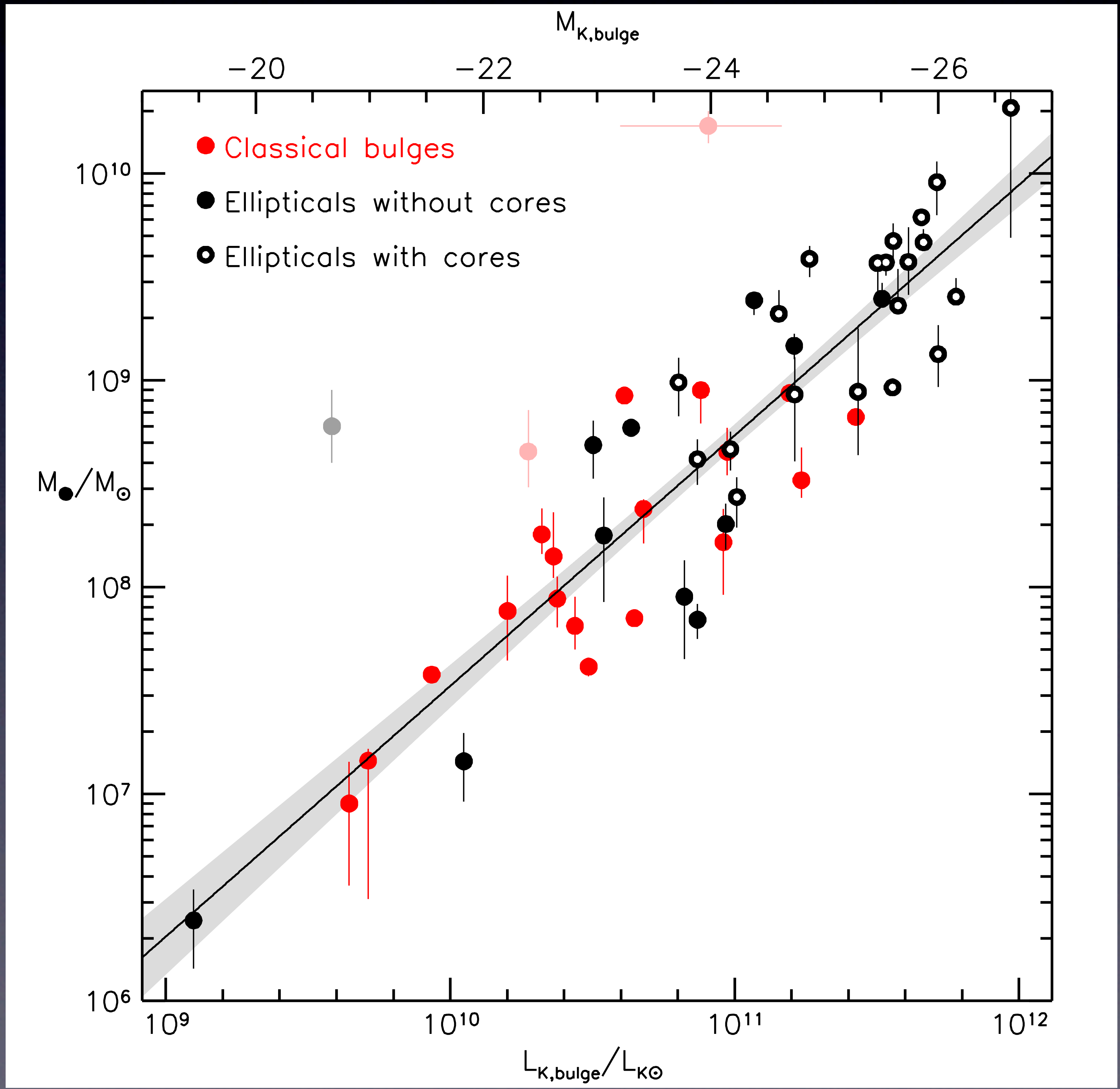


Scaling Relations

- Black hole mass strongly correlates with host properties
  - σ
  - M_{bulge}
  - L_{bulge}



Scaling Relation - Rough Derivation

Original matter distribution: $\frac{GM_{total}}{R}=2\sigma^2$ $\frac{GM_{gas}}{R}=2f_{gas}\sigma^2$

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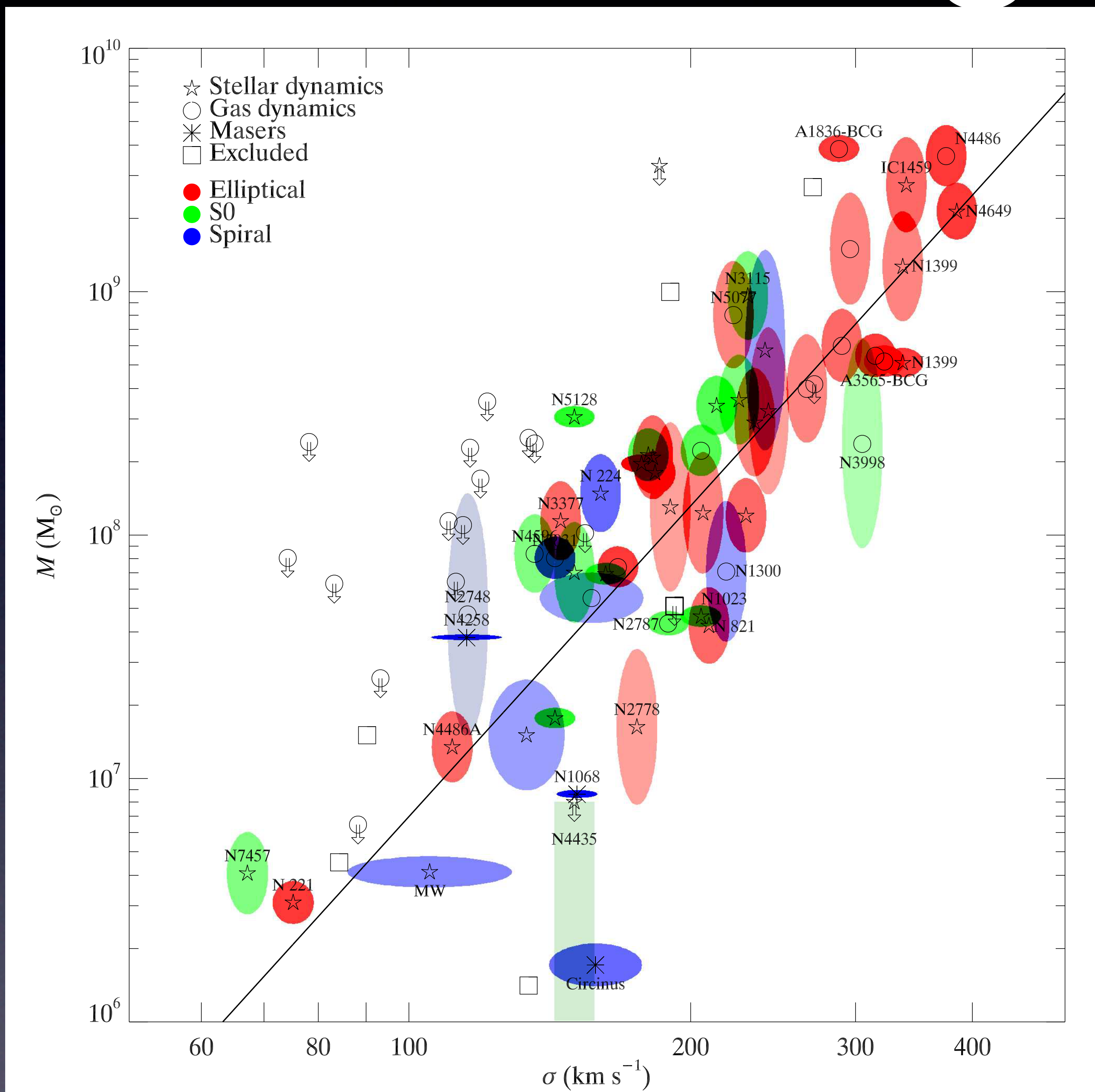
Equating to weight:

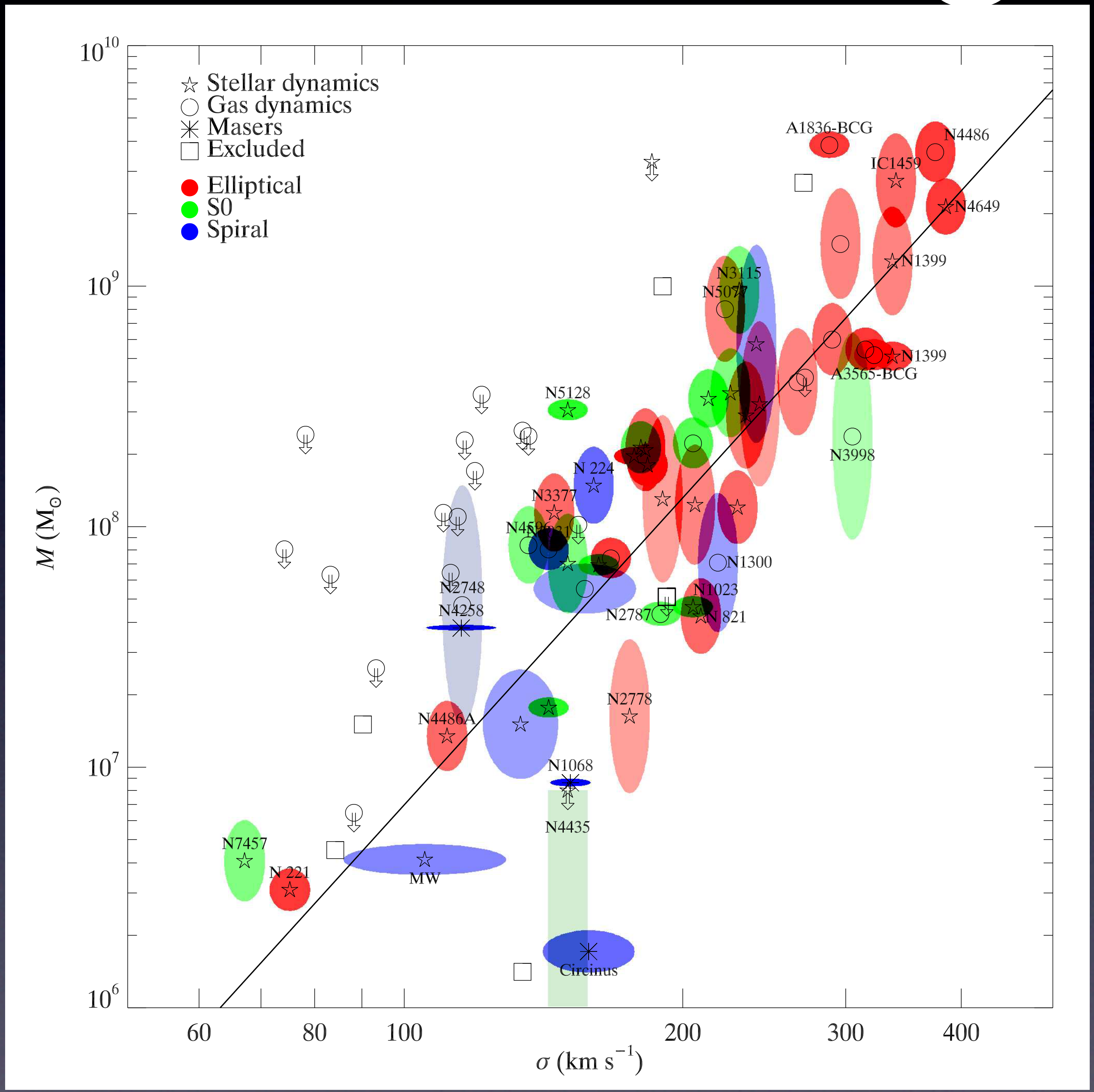
$$\frac{4\pi G M_{BH} m_p}{\sigma_T} = \frac{4 f_{gas} \sigma^4}{G} \rightarrow M_{BH} \propto \sigma^4$$

Scaling Relations



$$M_{BH} \propto \sigma^4$$

Scaling Relations



$$M_{BH} \propto \sigma^4$$

Gultekin+ 2009: $\log(M_\bullet/M_\odot) = (8.12 \pm 0.08) + (\boxed{4.24} \pm 0.41)\log(\frac{\sigma}{200\ \mathrm{km\ s^{-1}}})$

Scaling Relations

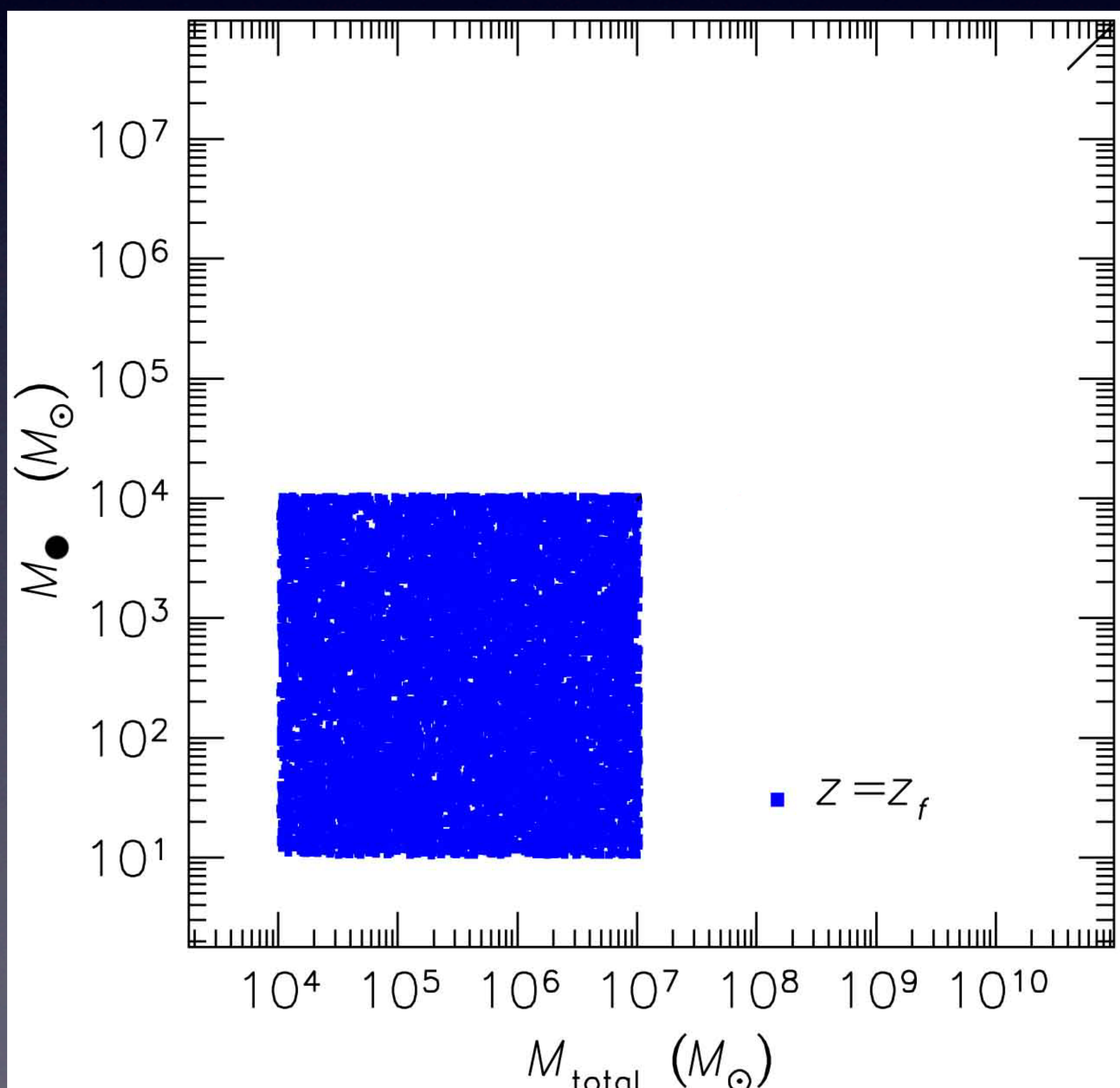
However: More recent calculations suggest it may be as steep as σ^5

$$M_{BH} \propto \sigma^4$$

Gultekin+ 2009: $\log(M_\bullet/M_\odot) = (8.12 \pm 0.08) + (\boxed{4.24} \pm 0.41)\log(\frac{\sigma}{200 \text{ km s}^{-1}})$

Alternatives to Self-Regulation

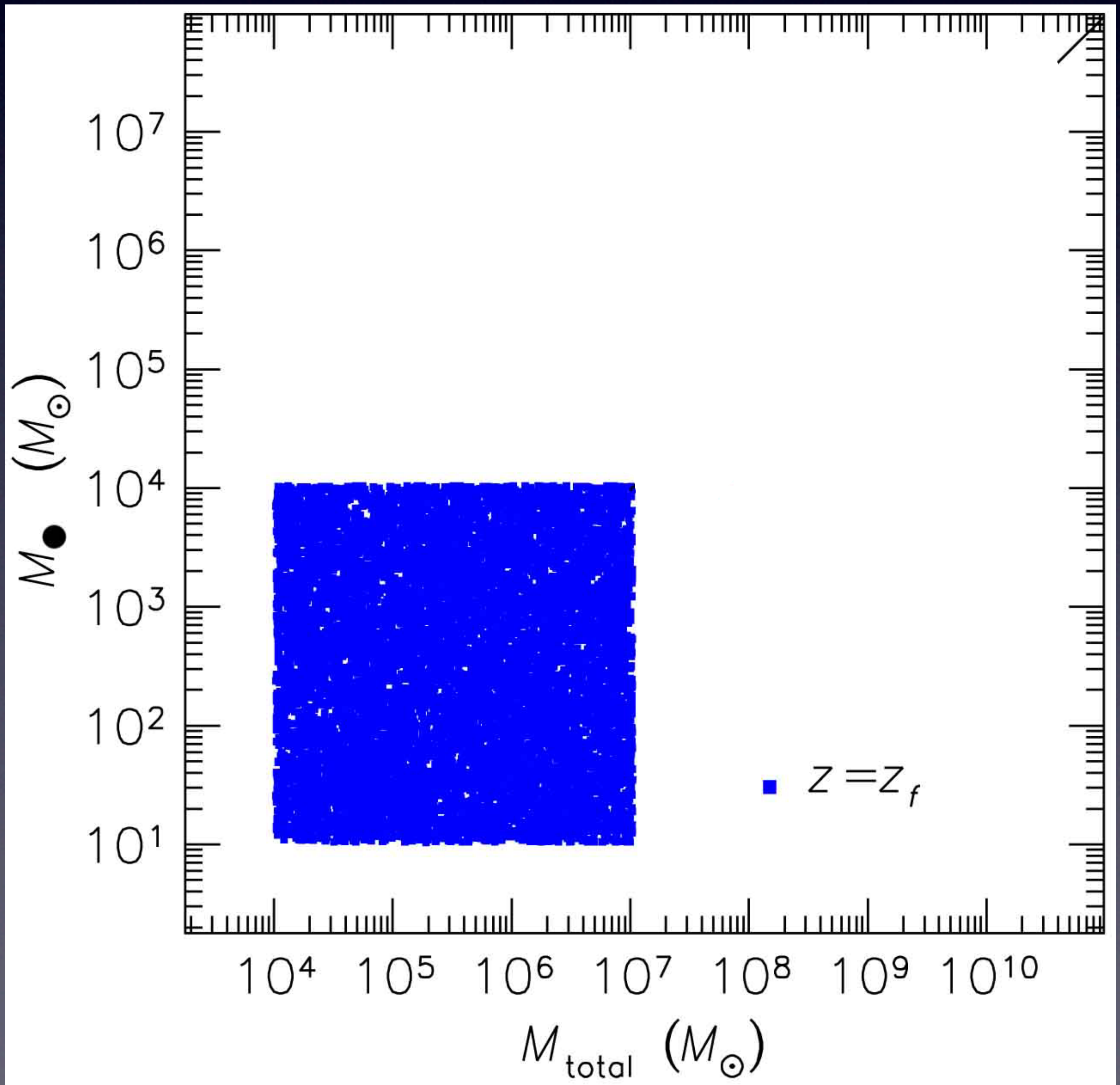
- Merger-induced averaging



Initial Relation Uncorrelated

Alternatives to Self-Regulation

- Merger-induced averaging



Initial Relation Uncorrelated

Many gas-poor mergers bring everything progressively closer to average

Alternatives to Self-Regulation

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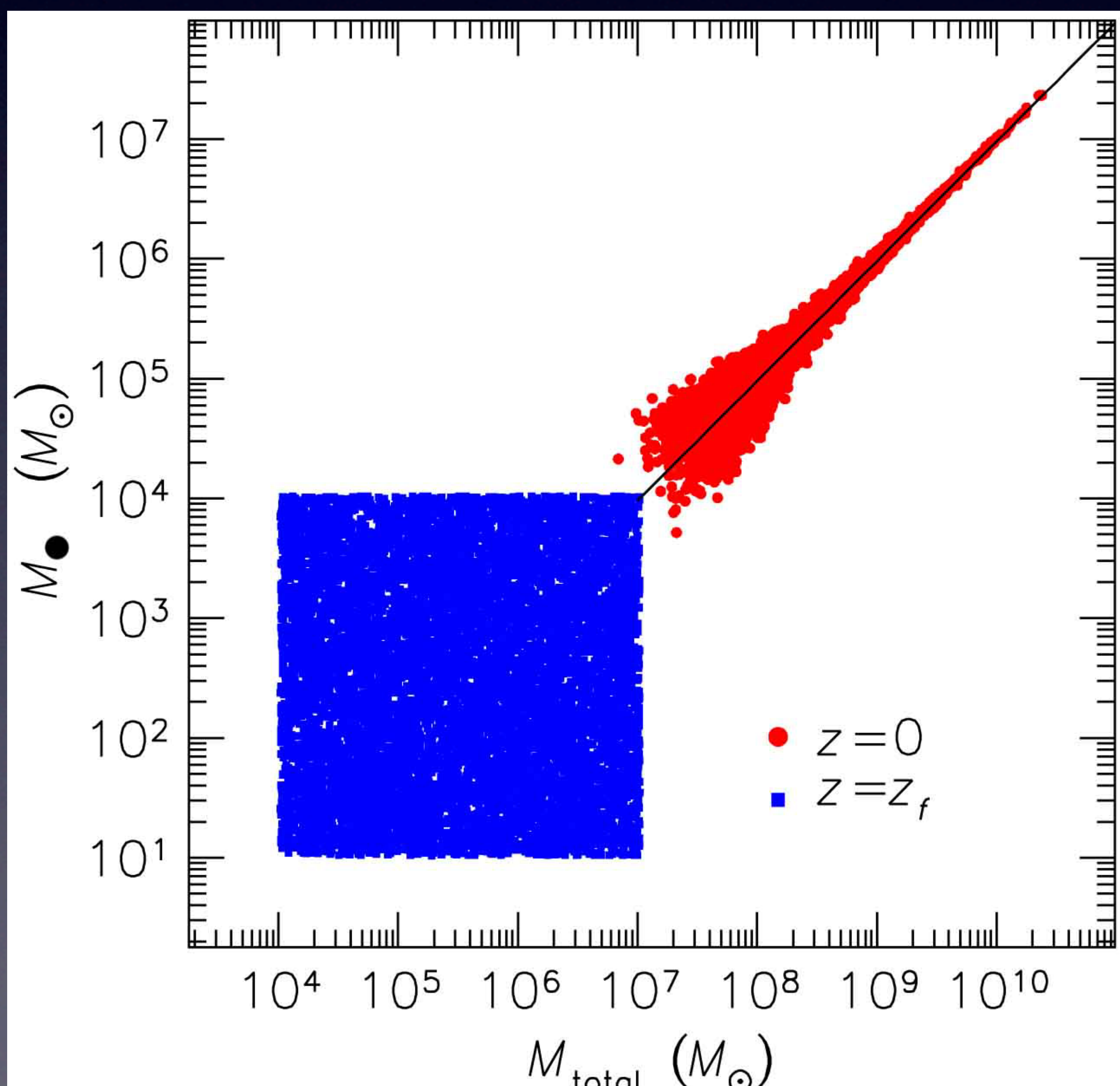


Initial Relation Uncorrelated

Many gas-poor mergers bring everything progressively closer to average

Alternatives to Self-Regulation

- Torque-driven fueling
- Gas driven to black hole dependent on galaxy size
- Black hole and host grow together

Studying SMBHs

What do we study?

- How many are there?
  - For different sub-populations
- Where are they found?
- How do they correlate with hosts?

How to study black holes

- Direct observation
- Computer simulations
- Semi-analytic models

Observational Studies

- Earlier figures show observational studies
- Crucial to make direct observations to see what is *actually* there

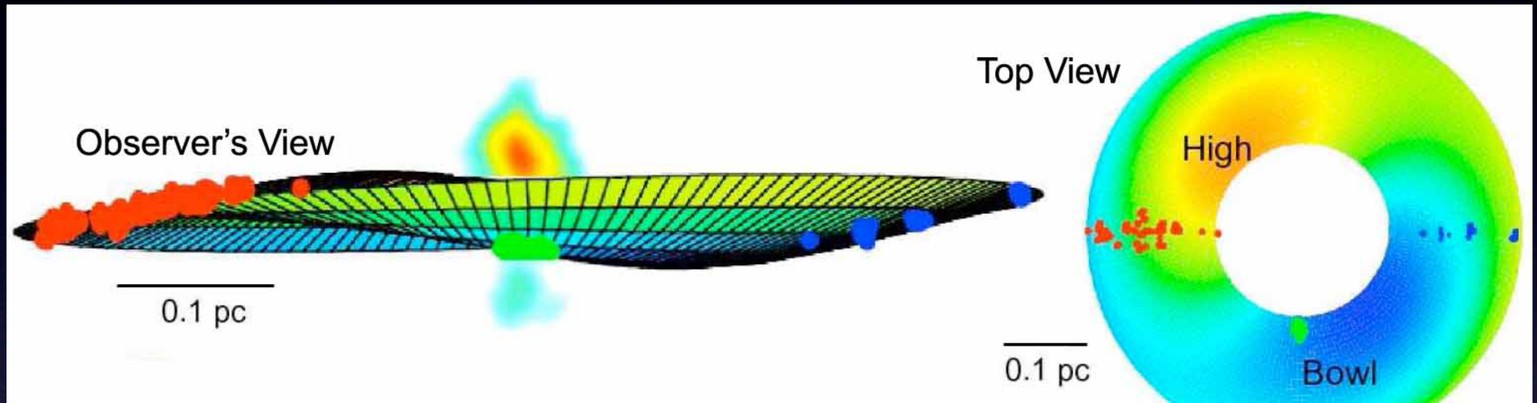
Observational Studies - Difficulties

- Only have single universe to study
- Cannot study evolution of individual objects - Only have single snapshot in time
- Many properties of difficult to measure
    - e.g. Measuring BH mass

Mass determination

- AGN spectrum
- Megamasers
  - Uses acceleration & velocity of water masers orbiting BH
- Reverberation mapping
  - Measure delay between continuum source (i.e. BH) and emission lines in BLR to get radius of Innermost Stable Circular Orbit

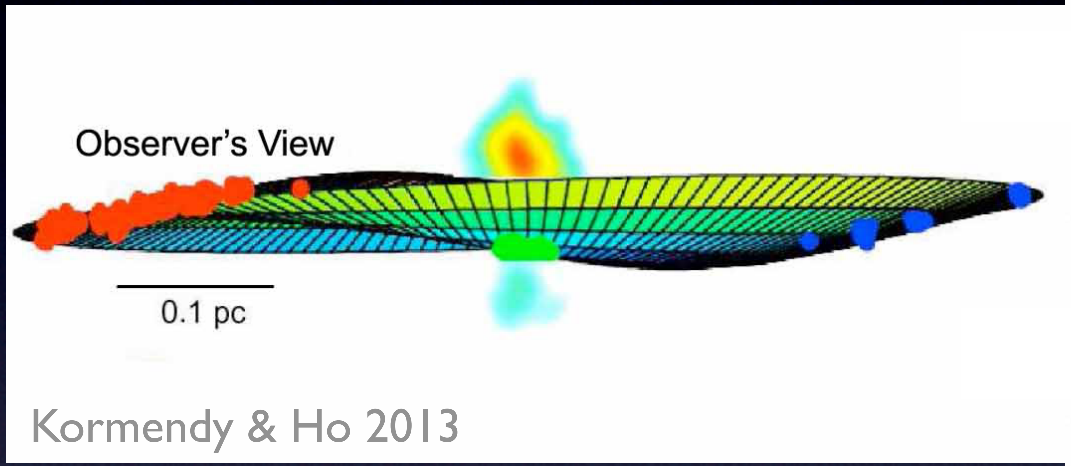
Mass determination - Megamasers



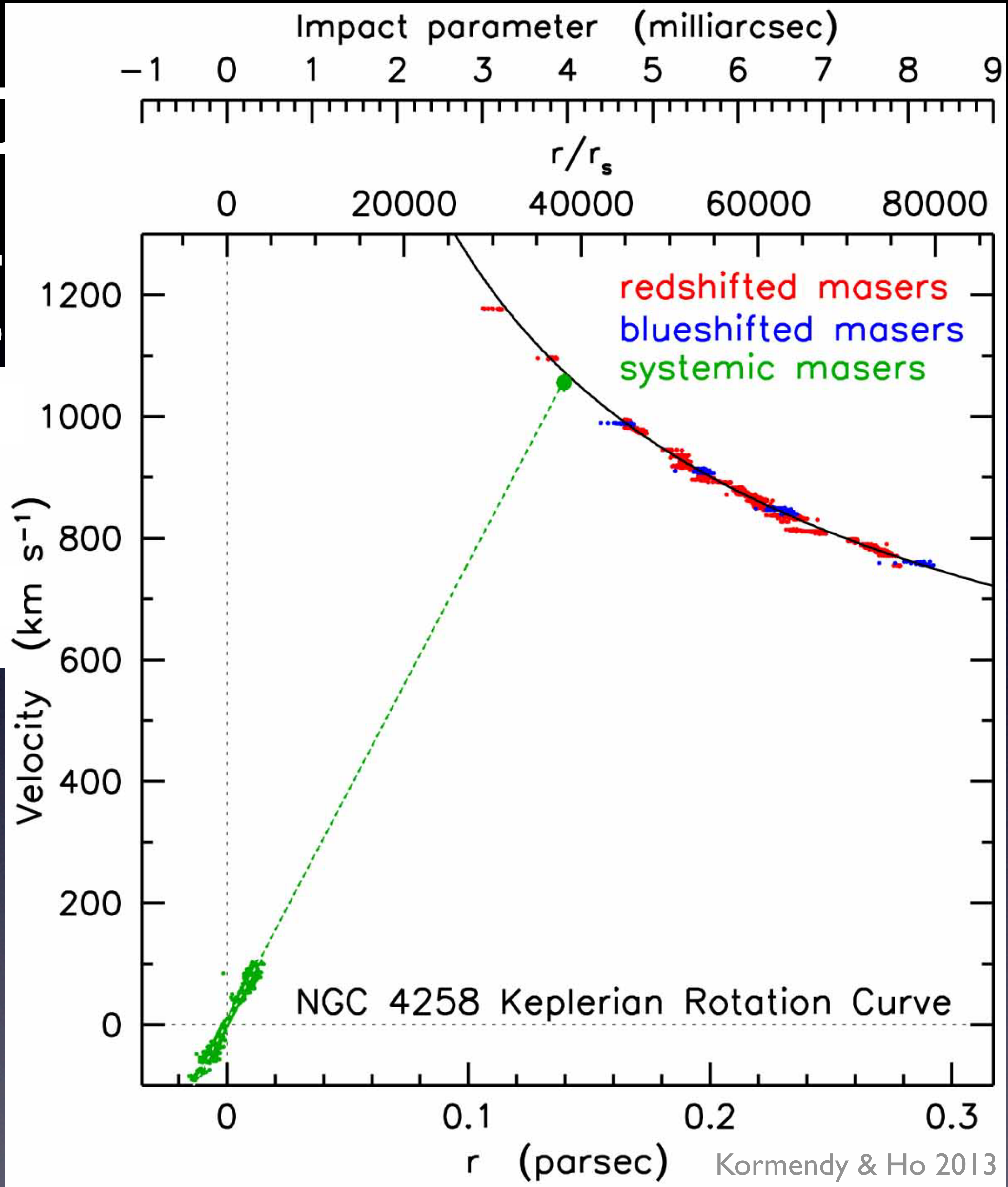
Kormendy & Ho 2013

- Disk around black hole
- Measured observations of masers moving toward us (blue), away from us (red), and near the central position (green)

Mass det… Meg…

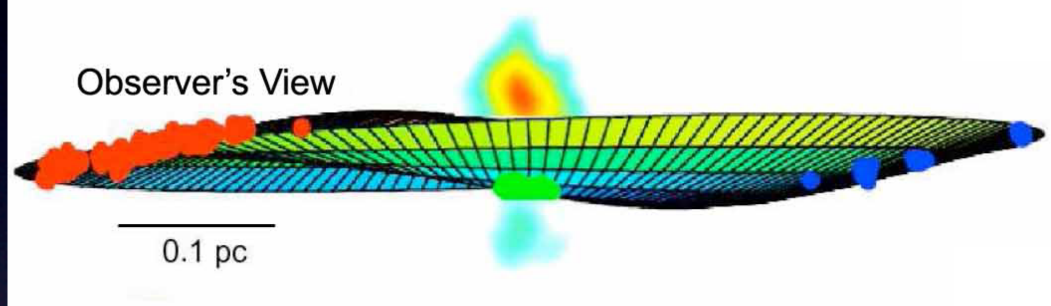


Observer's View
0.1 pc
Kormendy & Ho 2013

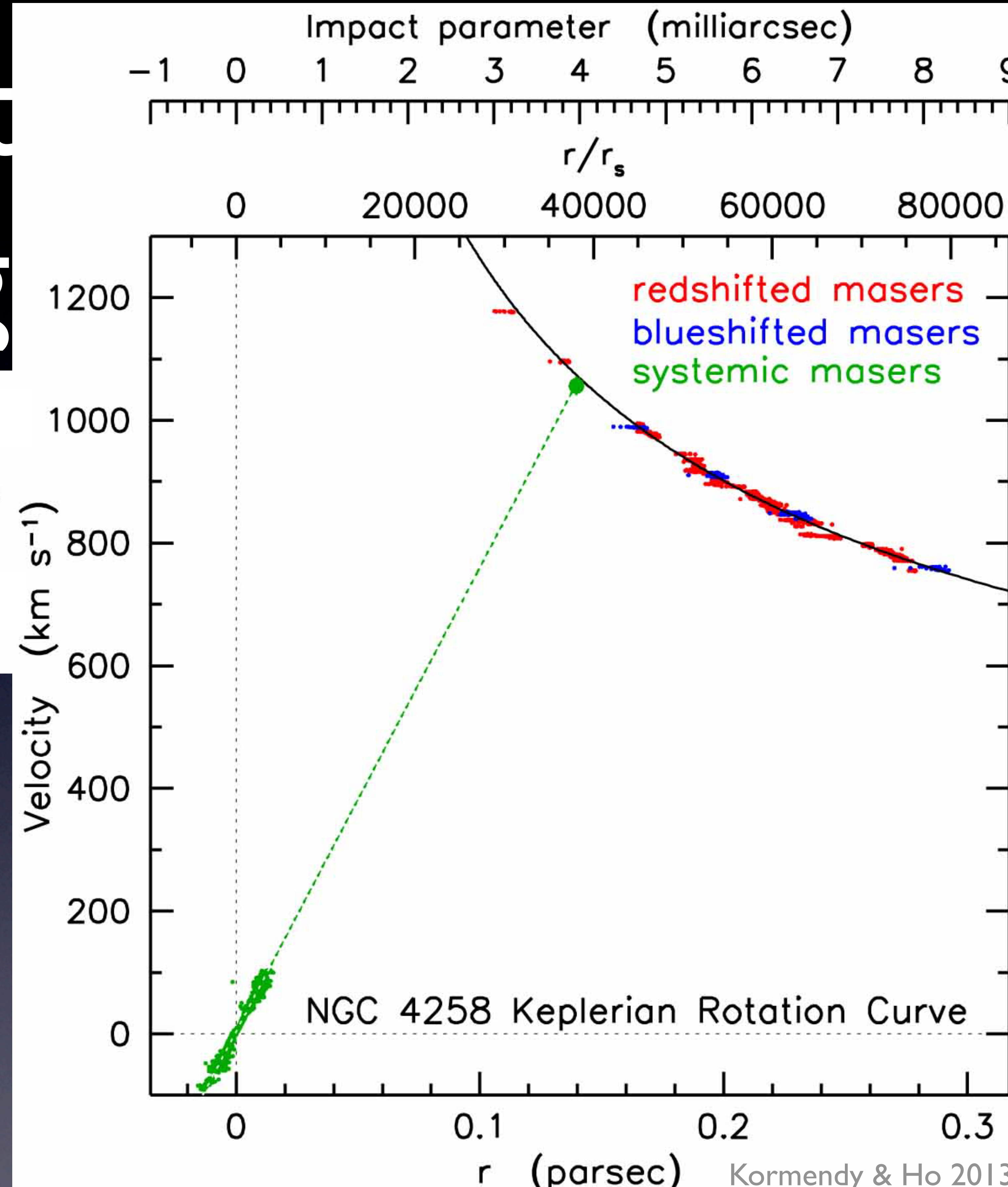


Impact parameter (milliarcsec)
−1 0 1 2 3 4 5 6 7 8 9
r/r_s
0 20000 40000 60000 80000
redshifted masers
blueshifted masers
systemic masers
Velocity (km s⁻¹)
1200 1000 800 600 400 200 0
NGC 4258 Keplerian Rotation Curve
0 0.1 0.2 0.3
r (parsec)
Kormendy & Ho 2013

Mass det
Meg



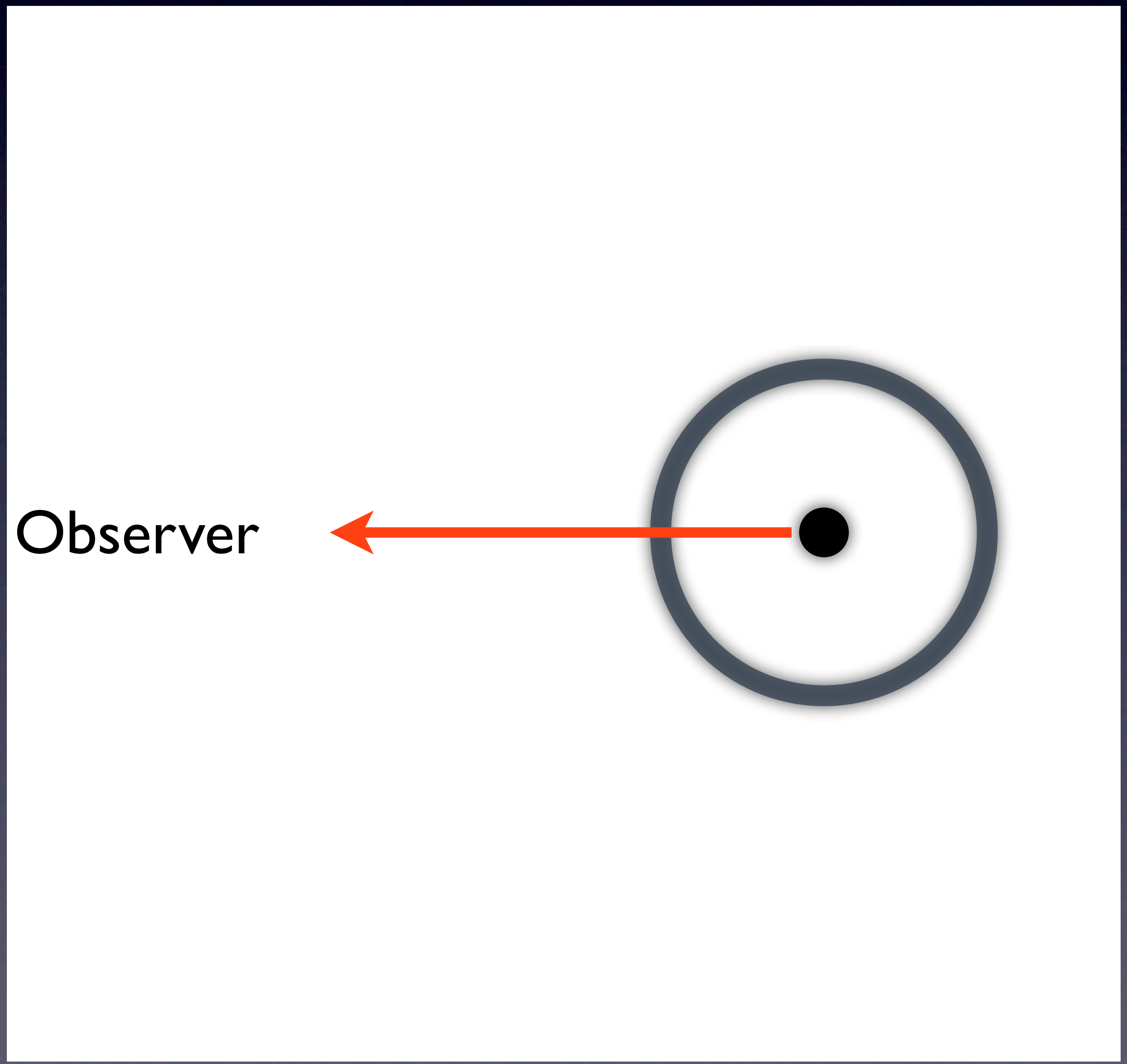
Kormendy & Ho 2013



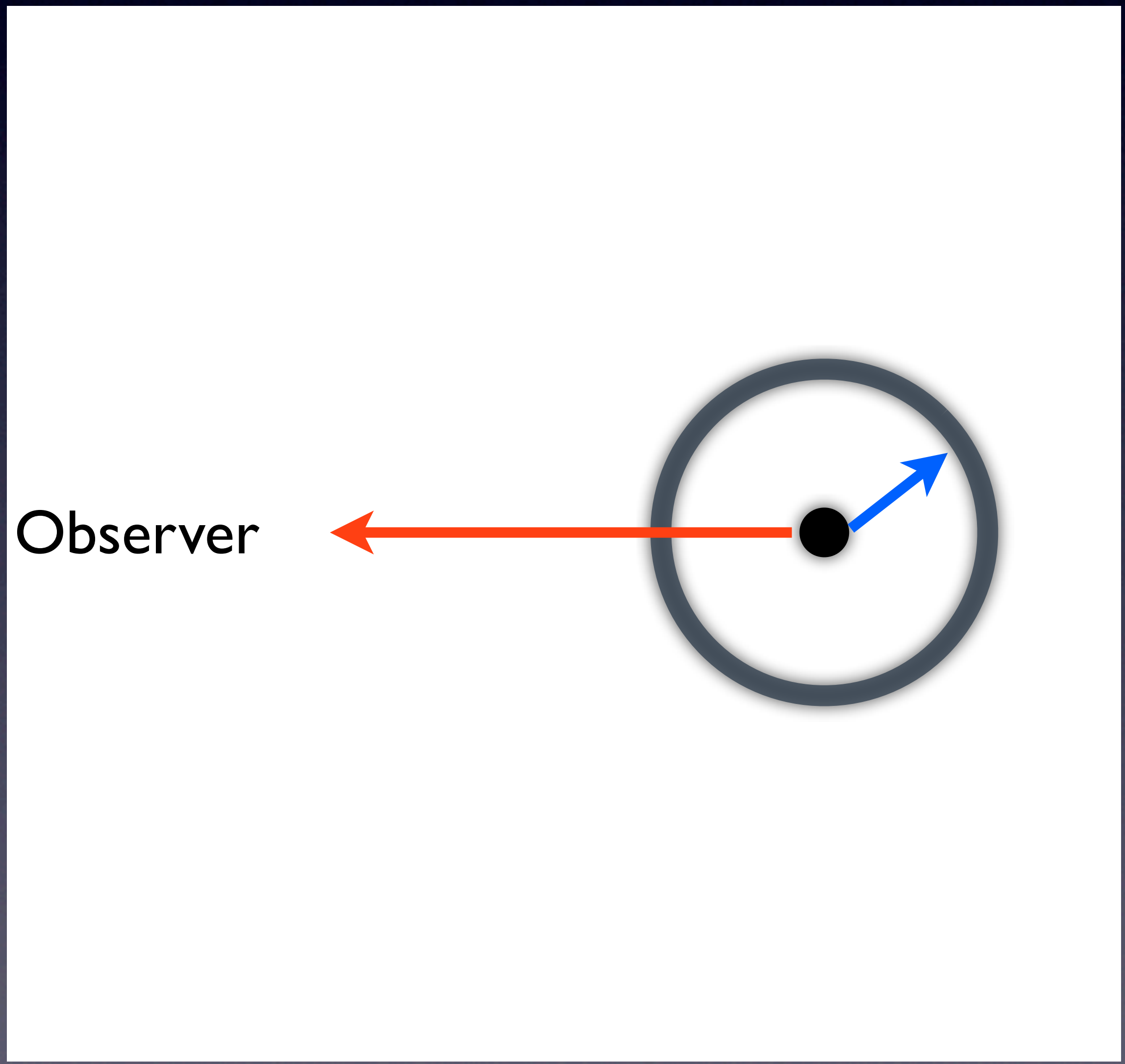
- Nearly perfect Keplerian orbiting
  - Mass of disk insignificant

    -Provides excellent mass estimate for BH

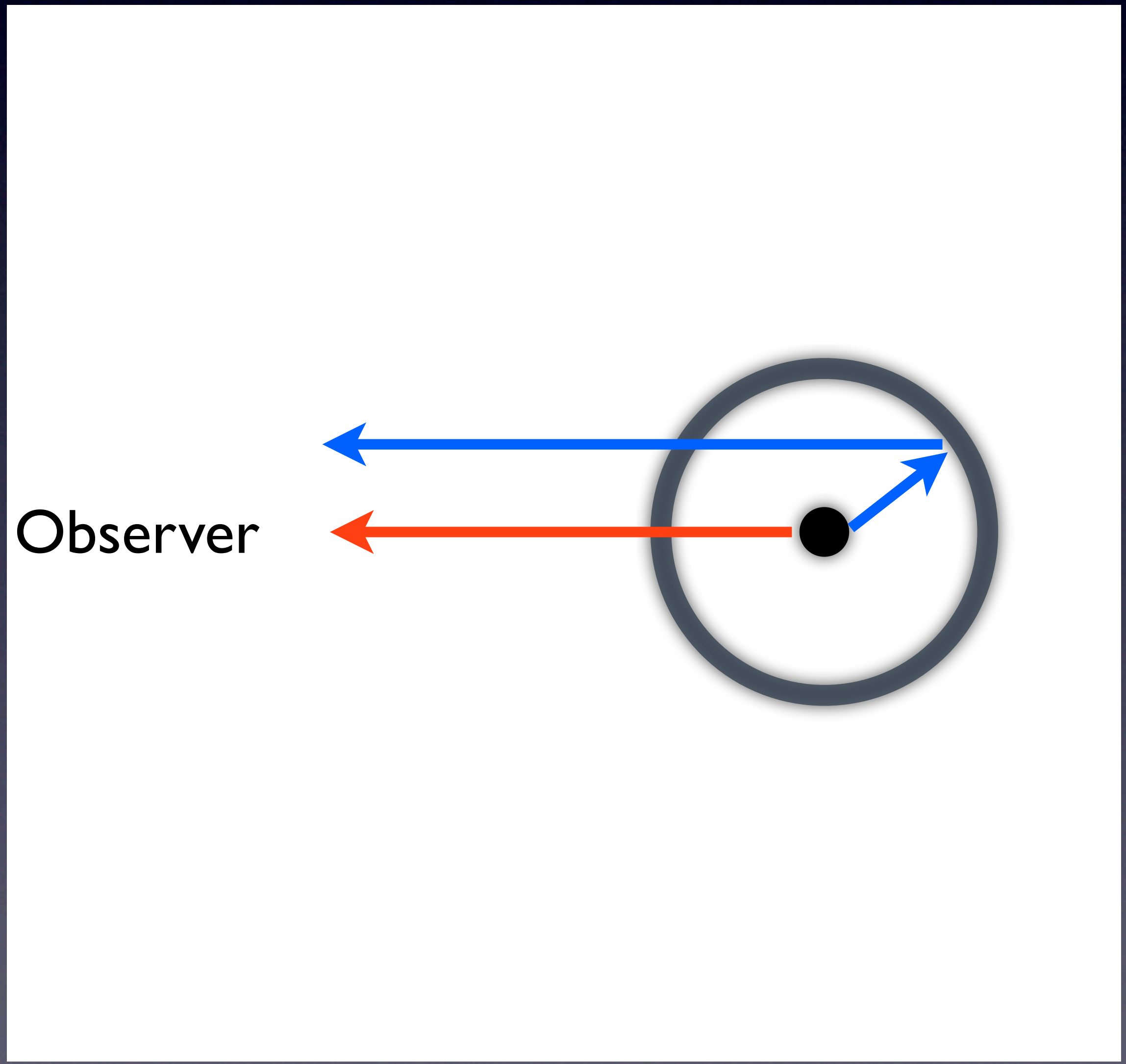
Mass determination - Reverberation Mapping



Mass determination - Reverberation Mapping

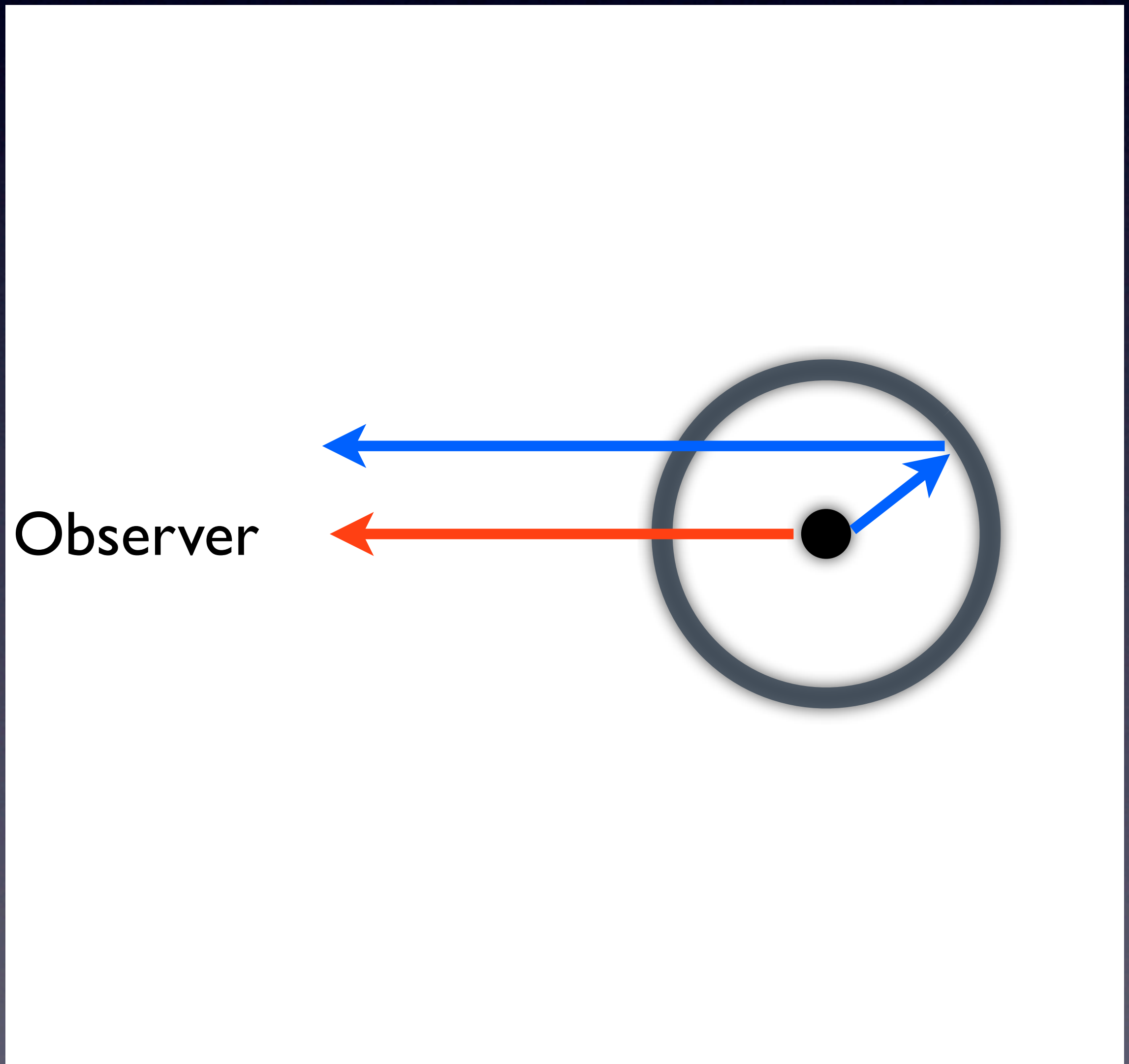


Mass determination - Reverberation Mapping



Mass determination - Reverberation Mapping

- Look for time delay in luminosity signal
- Time delay ➛ Distance traveled $[R_{BLR} \sim ct]$
- Distance ➛ Mass estimate $[M=f \cdot R_{BLR}\, \Delta V^2/G]$



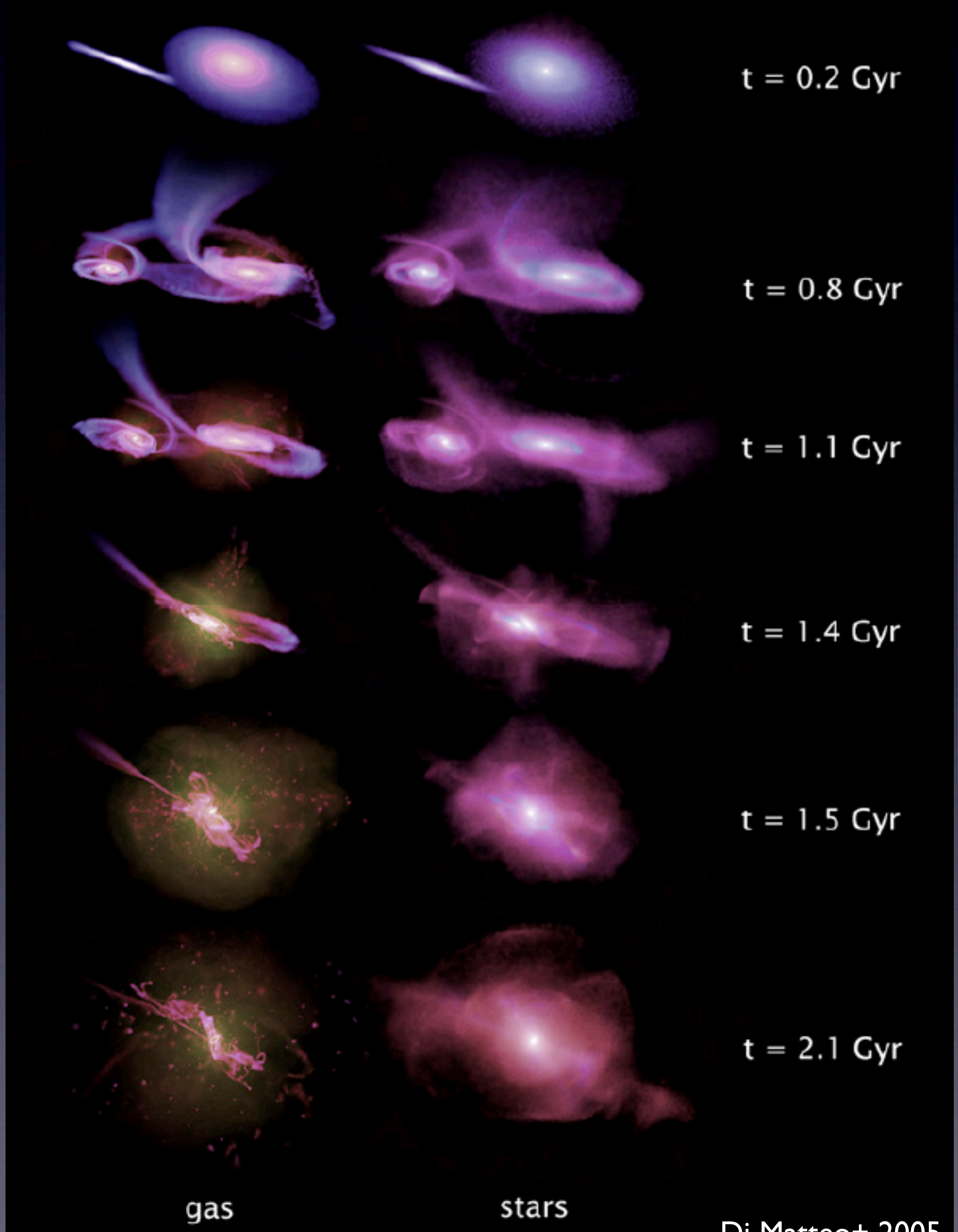
Simulations - Advantages

- No measurement difficulties
- Time-evolution inherent to simulation
- Can run as many as needed
- Physical models included can be changed
  - Lets us see what processes are important, and which have no effect

Simulations

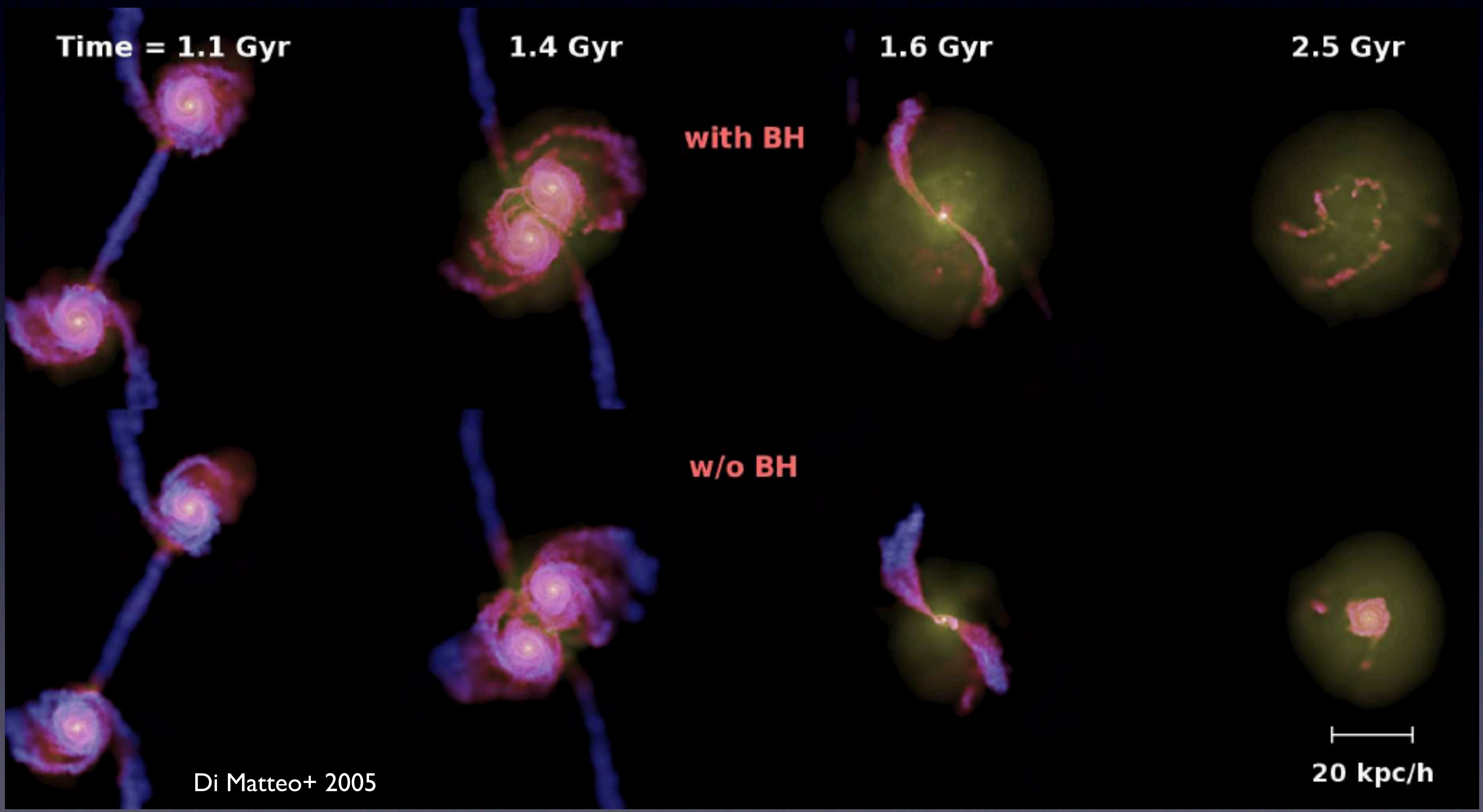
- Isolated galaxies
  - High resolution
  - Excellent details
- Cosmological Simulations
  - Large volume
  - Good statistics
  - Cosmological behavior (mergers, gas flows, etc.)

Galaxy simulation

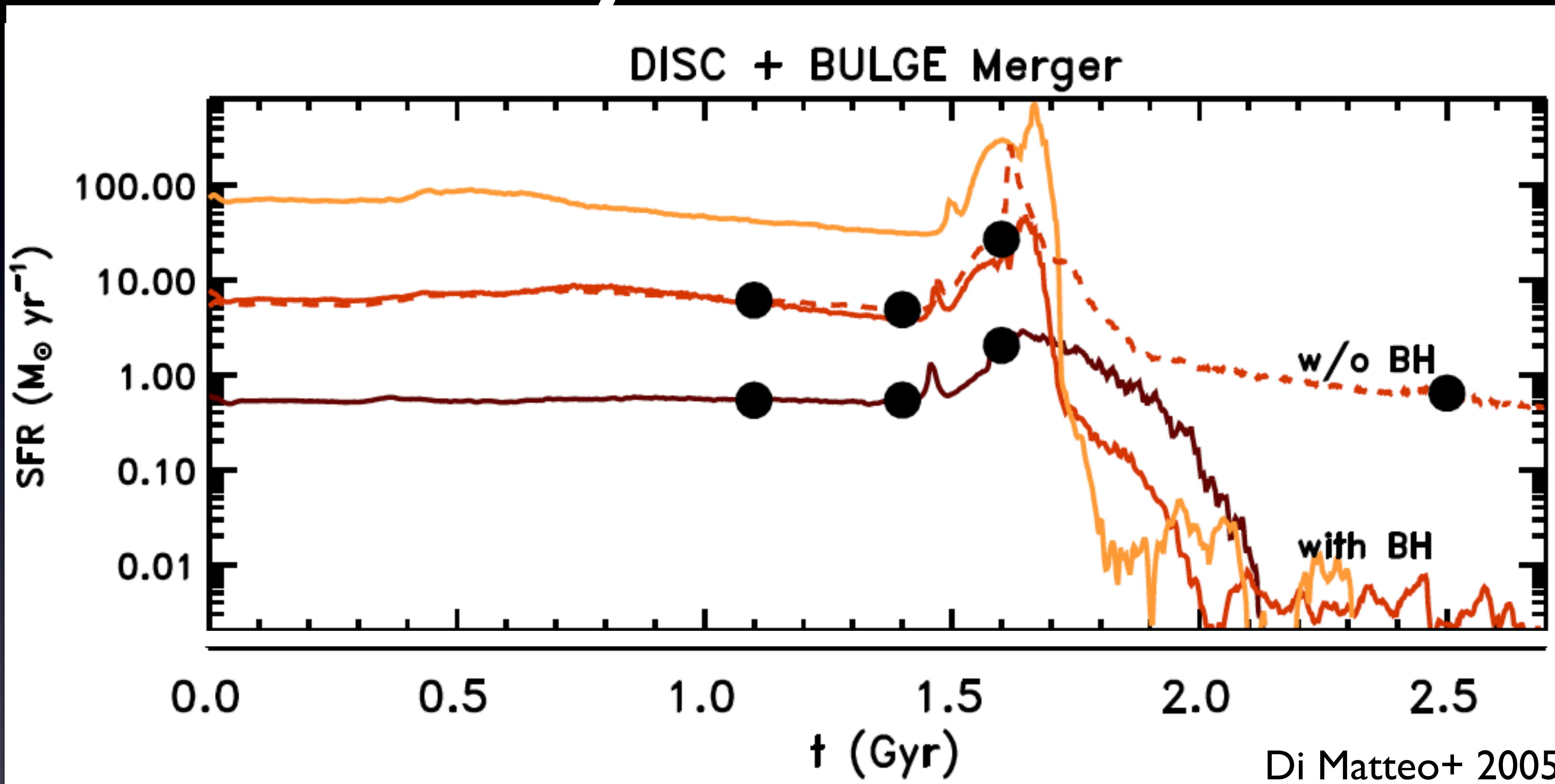


Di Matteo+ 2005

Galaxy simulation

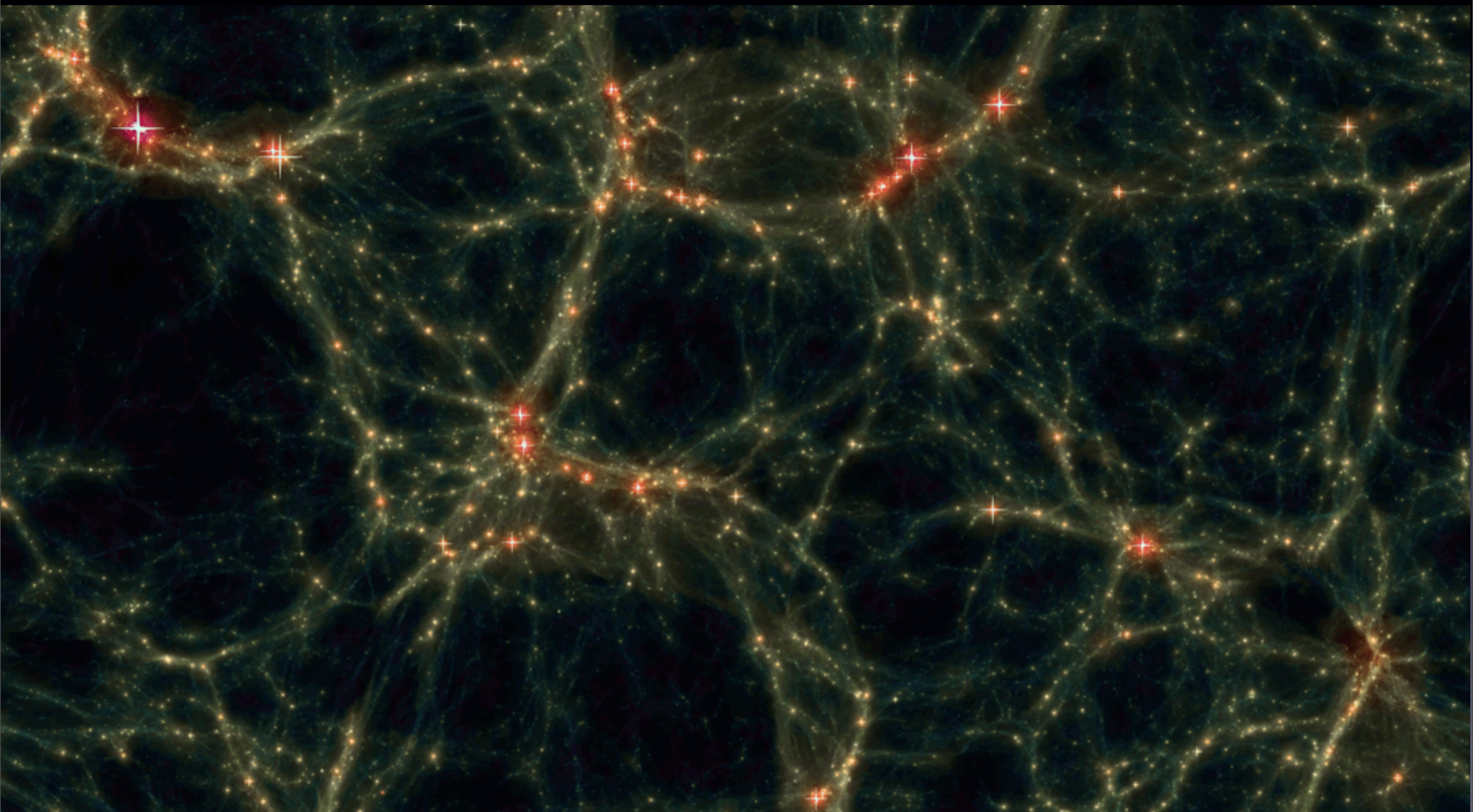


Galaxy simulation



- Without BH, star formation is much too high

Cosmological Simulation



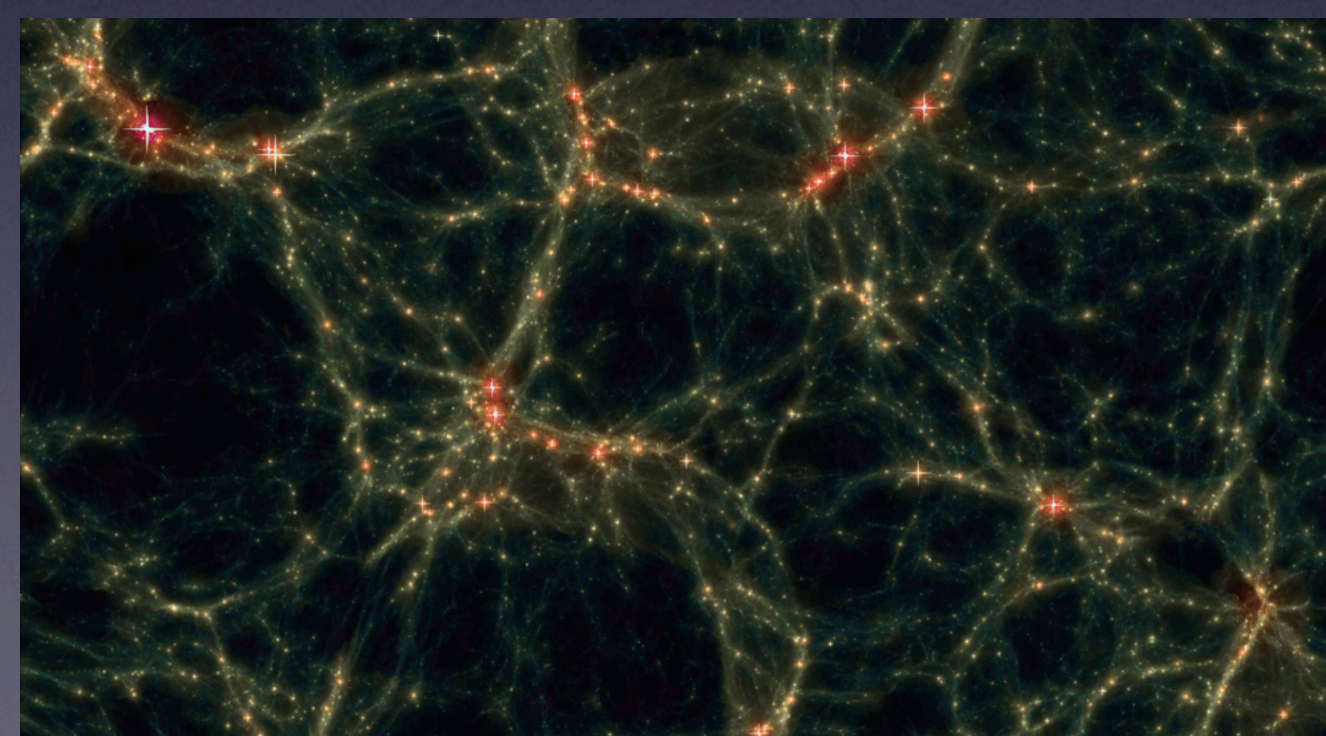
Cosmological Simulation

Simulation - *MassiveBlack*

- Code: PetaGADGET
  - SPH, cooling, SF, feedback, BHs
- Particle Number: $2*3200^3$ ~ 64 billion
- Box Size: 533 h^{-1} Mpc
- Resolution:
  - 5 h^{-1} kpc
  - $m_{dm} = 2.8*10^8\ M_\odot$, $m_{gas} = 5.6*10^7\ M_\odot$
- Run on ~ 100K compute cores on Kraken at NICS

Simulation - BH implementation

- Halo-based seeding: $5*10^5 M_\odot$ BH seeded into $5*10^{10} M_\odot$ halo



Simulation - BH implementation

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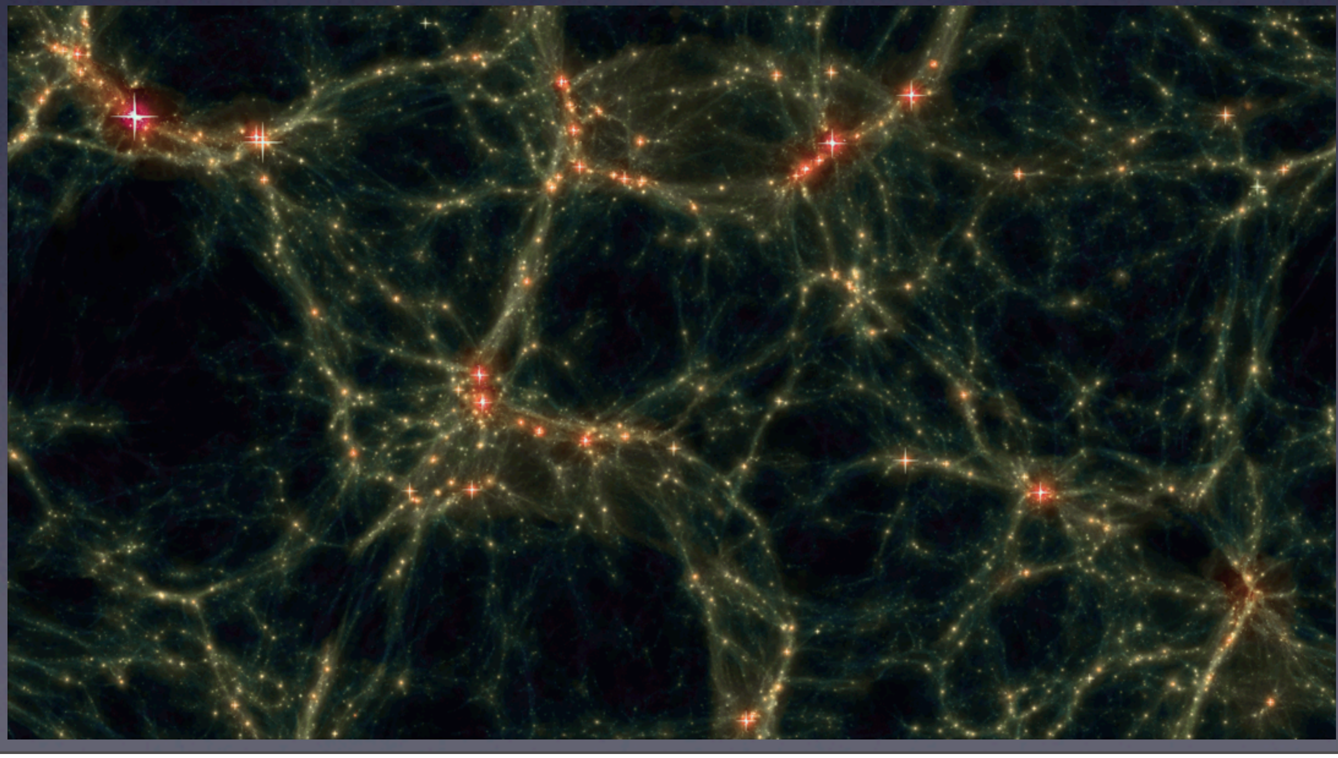
- BH growth follows (with imposed eddington limit)

$$\dot{M}_B = 4\pi \frac{(GM_{BH})^2}{(c_s{}^2 + V_{rel}^2)^{3/2}} \rho$$



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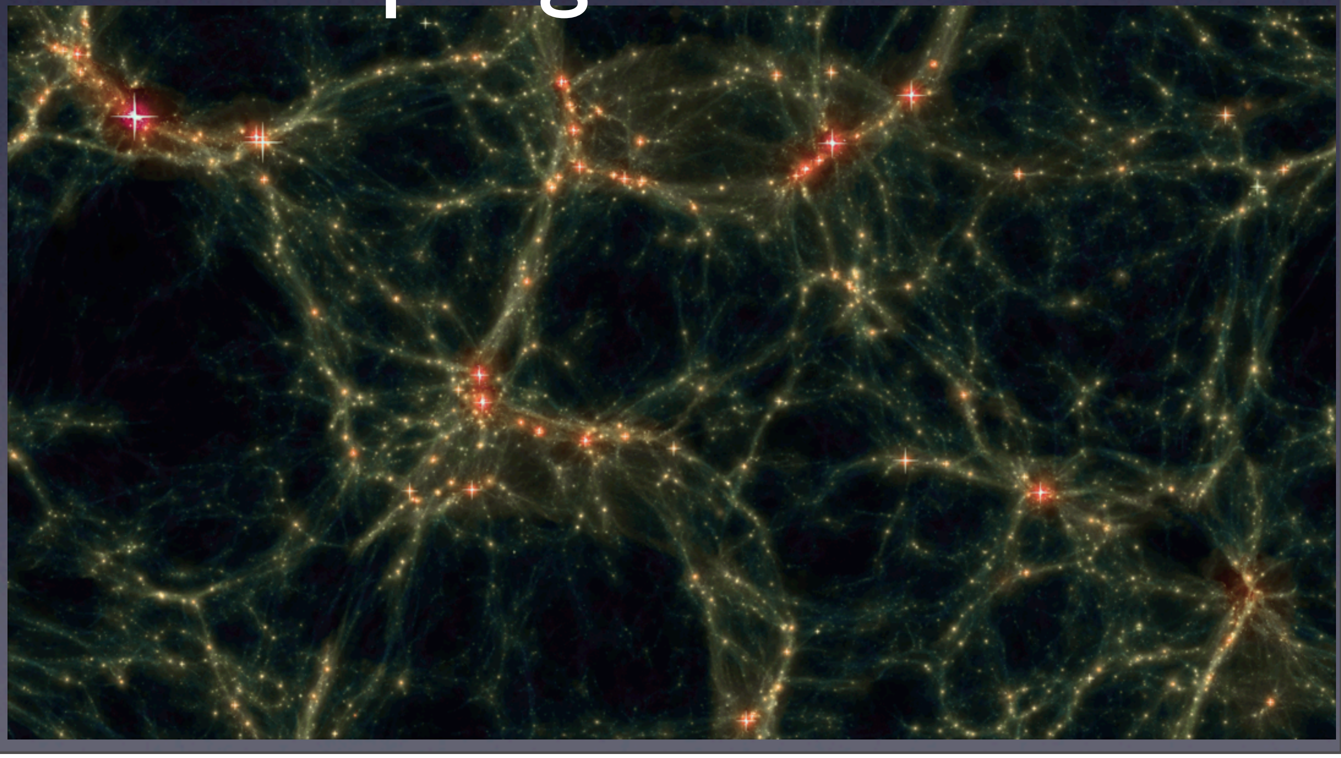
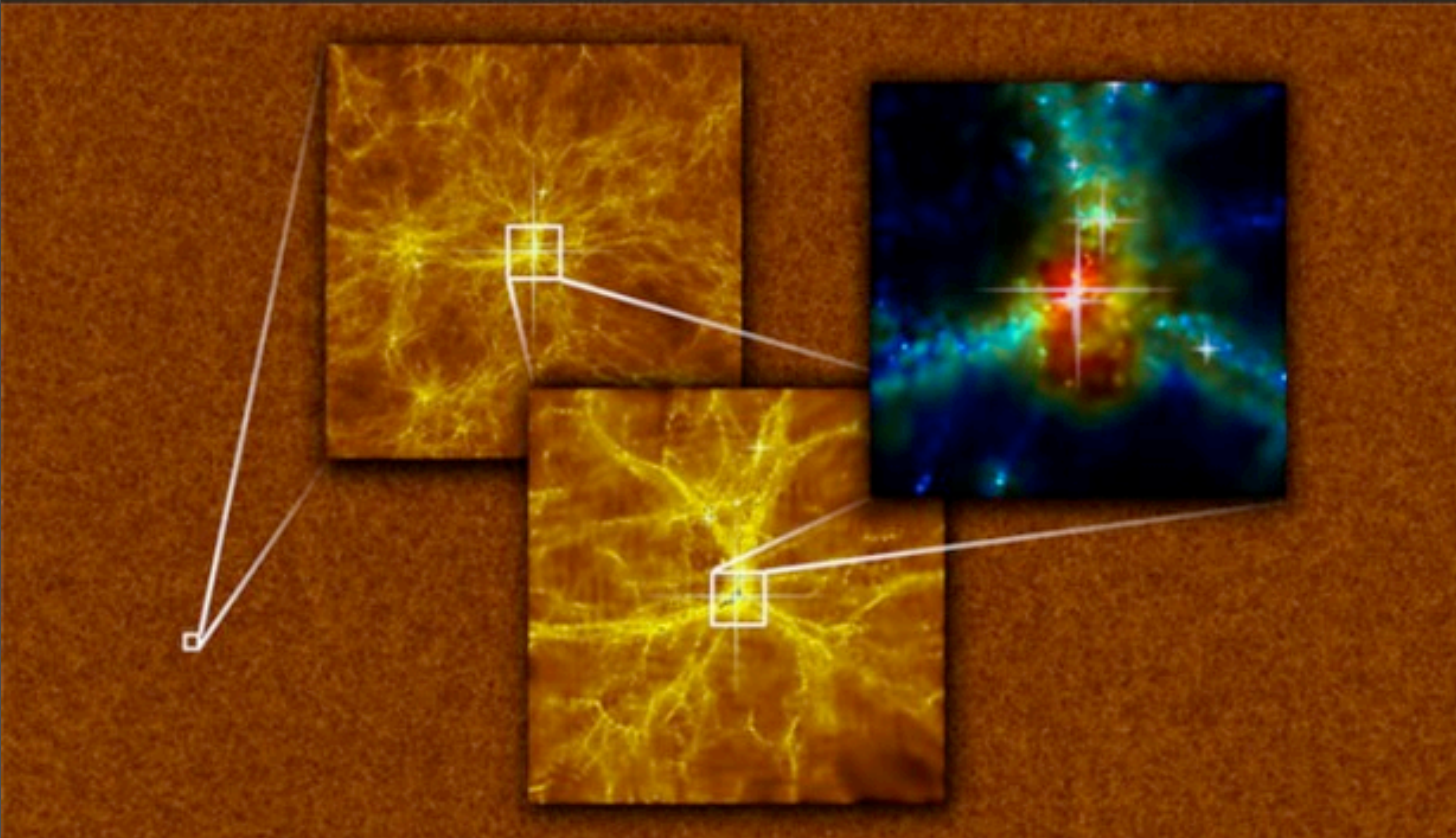
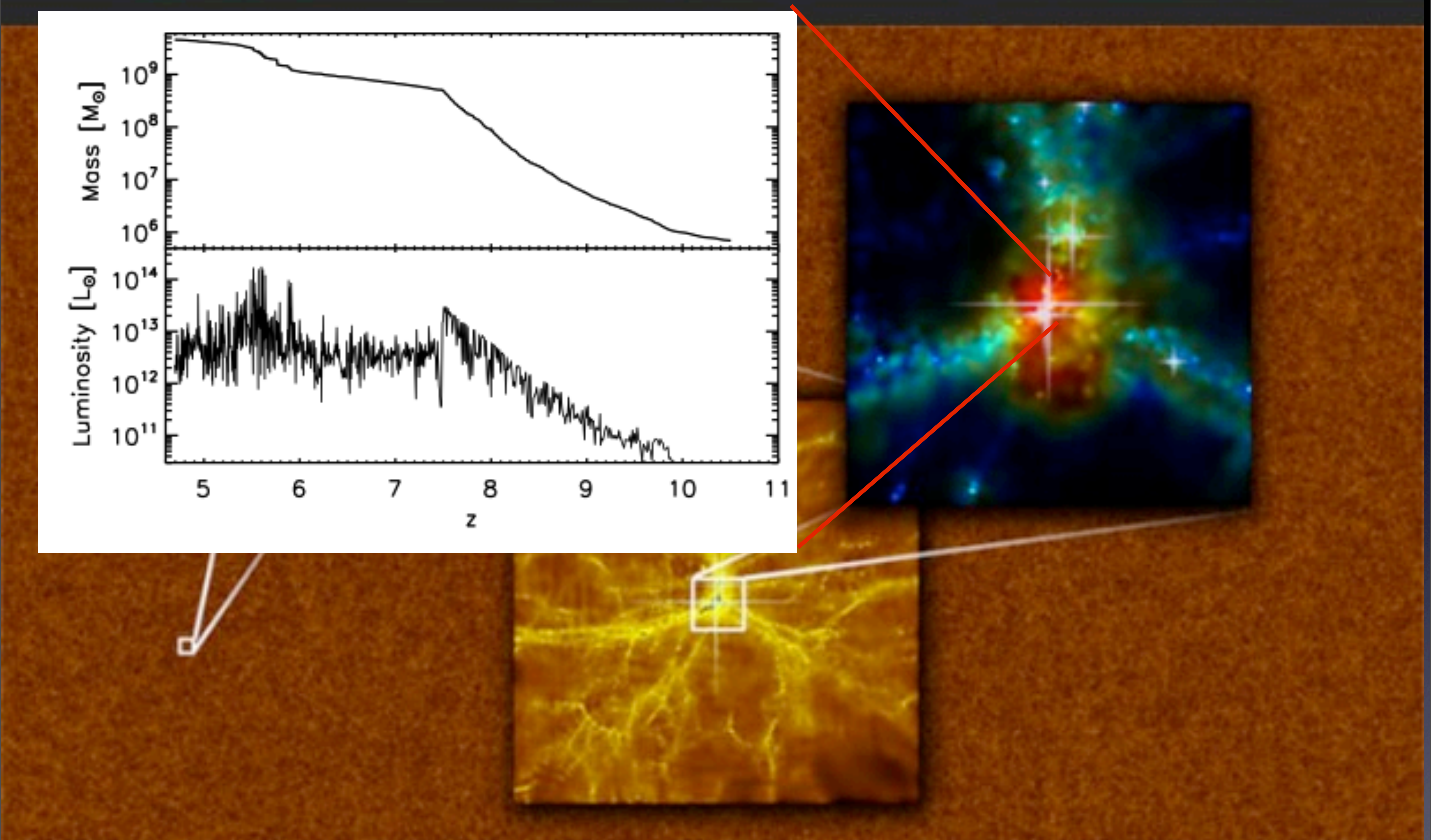
- BH feedback via thermal coupling:
  - $E_{feedback} = f(\eta M c^2)$
    - f=5%, η=10%



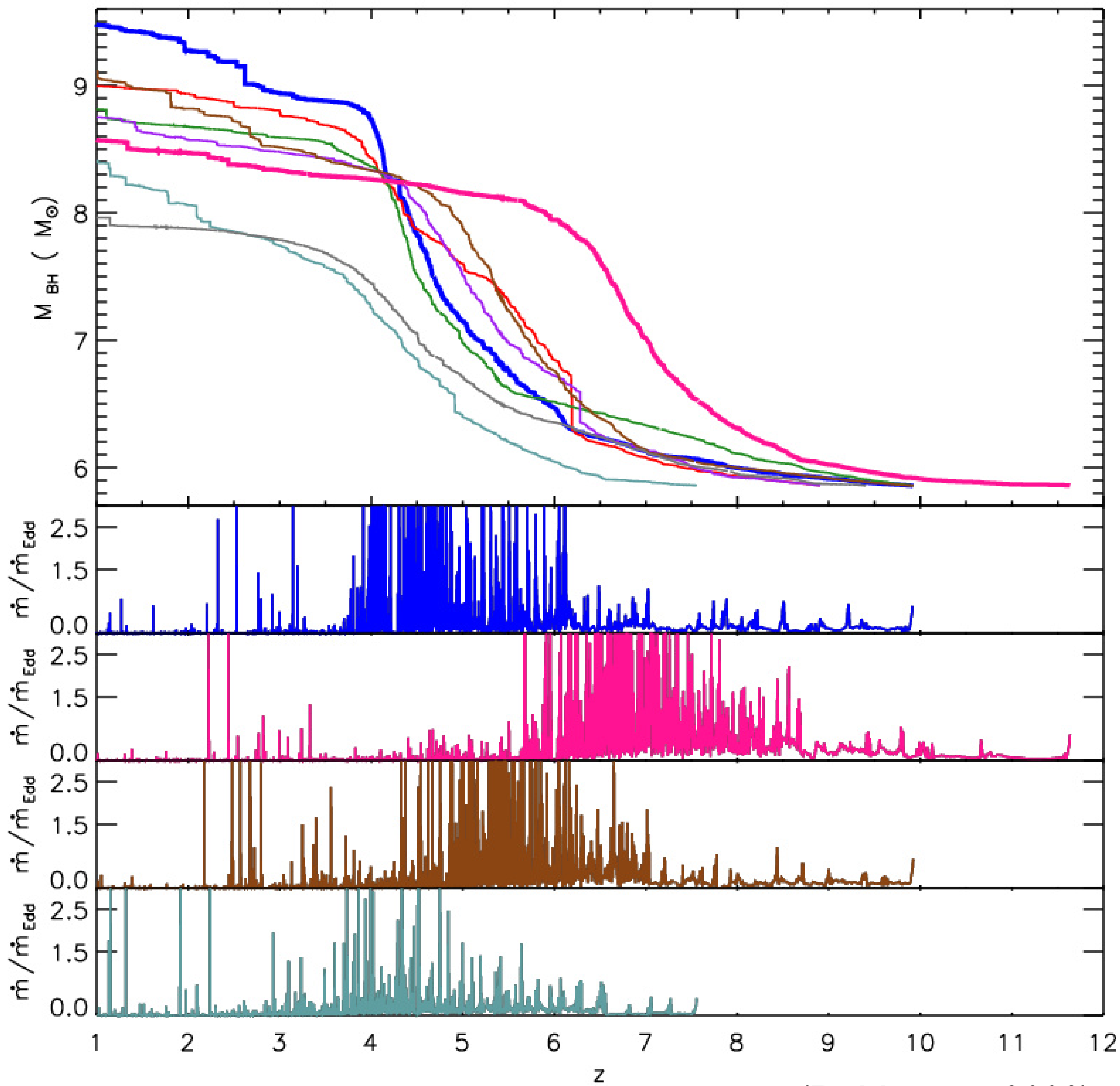


(Image by Y. Feng)

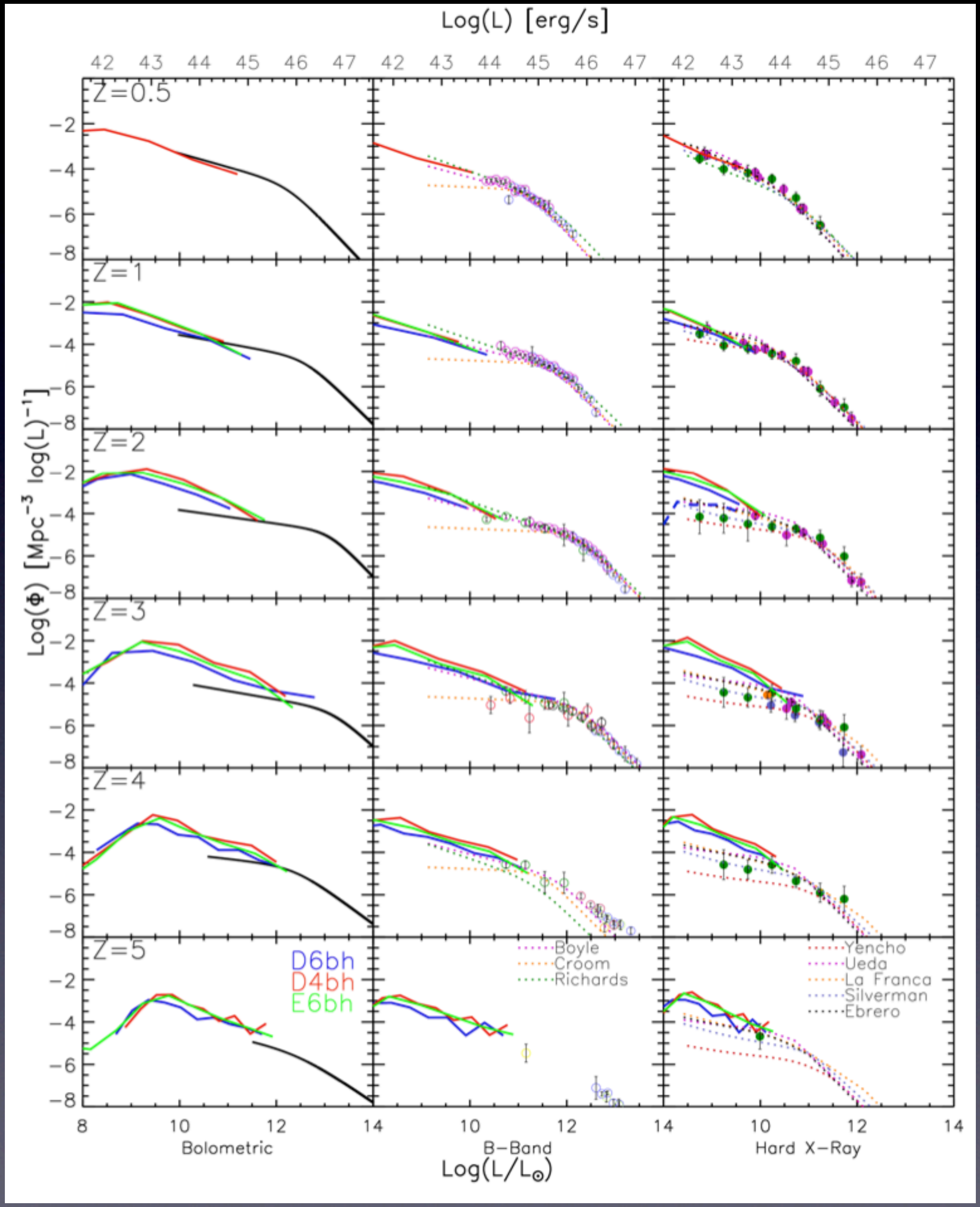


(Image by Y. Feng)

Sample accretion histories

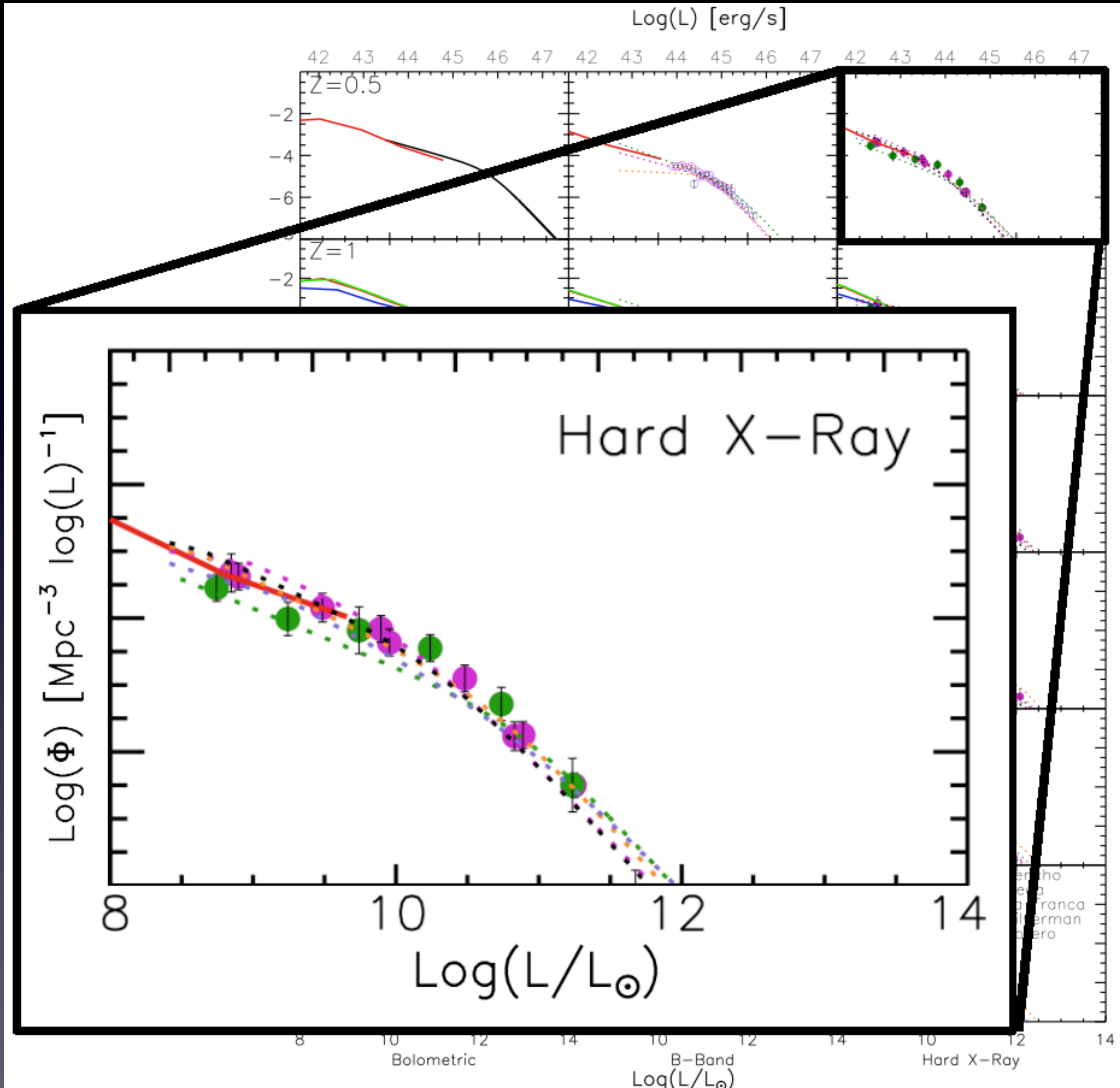


(Di Matteo+ 2008)

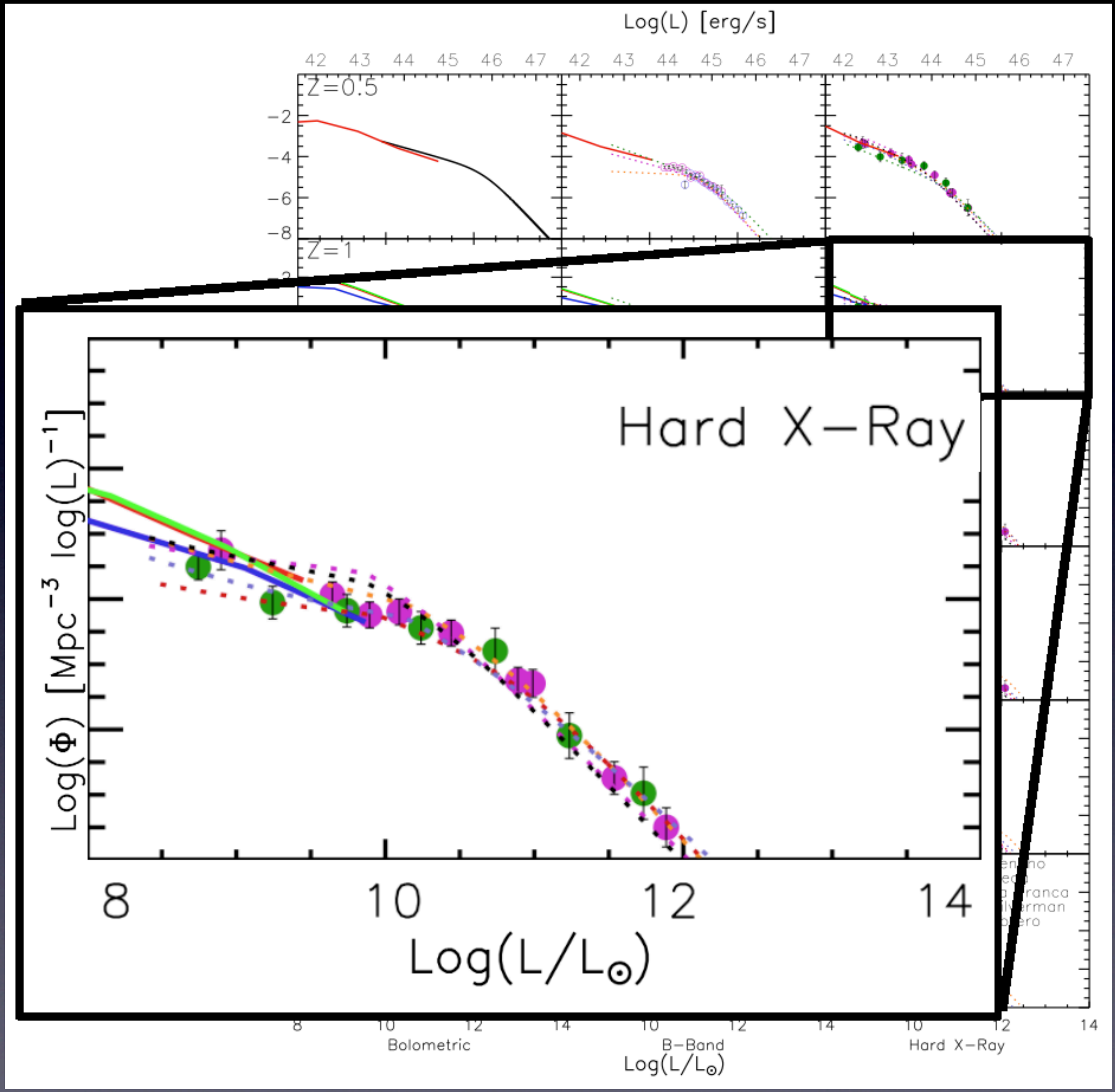


Log(L) [erg/s]
42 43 44 45 46 47
Z=0.5
Z=1
Z=2
Z=3
Z=4
Z=5
Log(Φ) [Mpc⁻³ log(L)⁻¹]
D6bh
D4bh
E6bh
Boyle
Croom
Richards
Yencho
Ueda
La Franca
Silverman
Ebrero
Bolometric
B-Band
Hard X-Ray
Log(L/L⊙)

(DeGraf+ 2010)


Log(L) [erg/s]
42 43 44 45 46 47
Z=0.5
Z=1
−2
−4
−6
Hard X−Ray
Log(Φ) [Mpc^{-3} log(L)$^{-1}$]
8 10 12 14
Log(L/L$_\odot$)
Bolometric
B−Band
Hard X−Ray
Log(L/L$_\odot$)

(DeGraf+ 2010)



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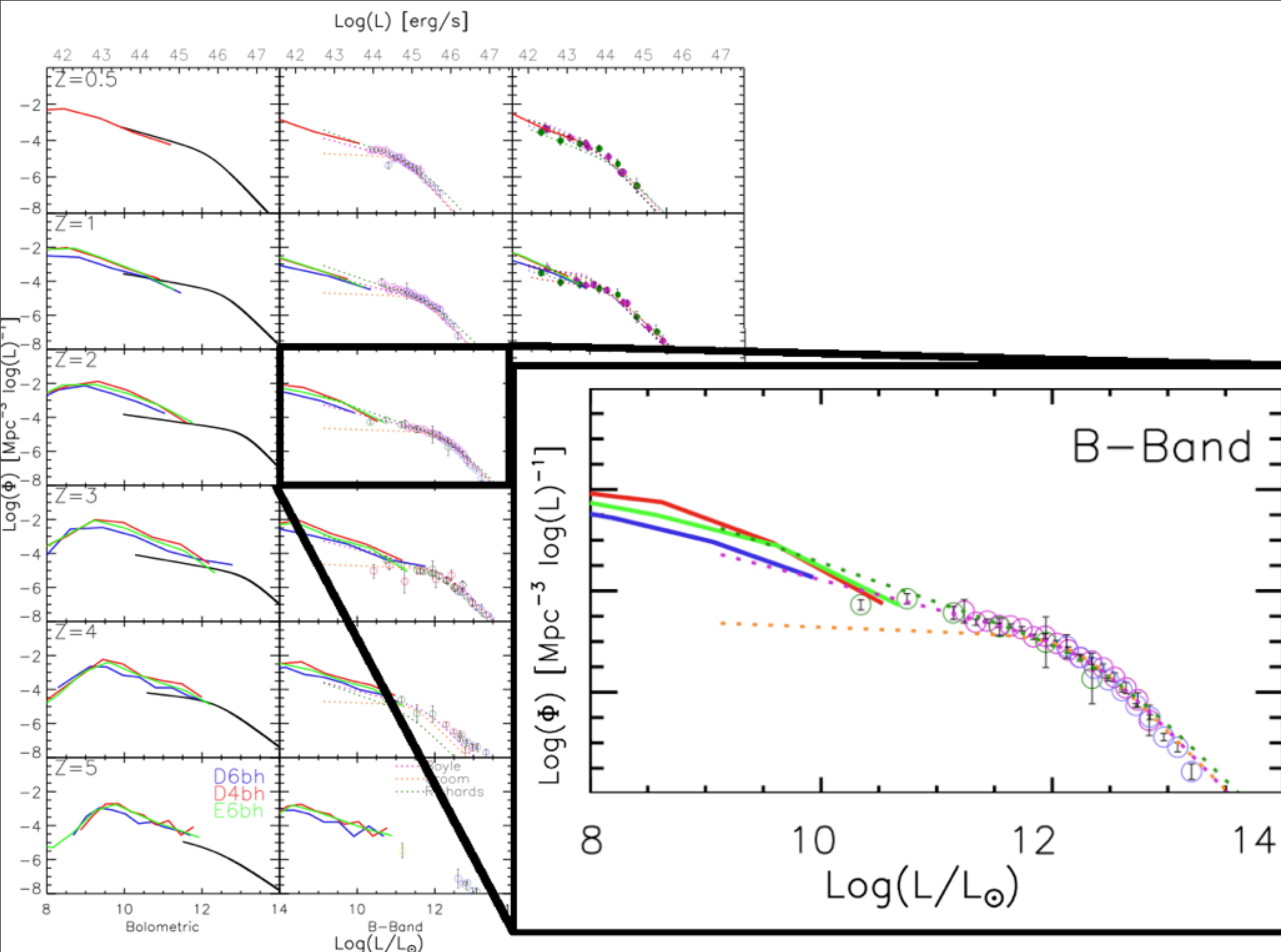

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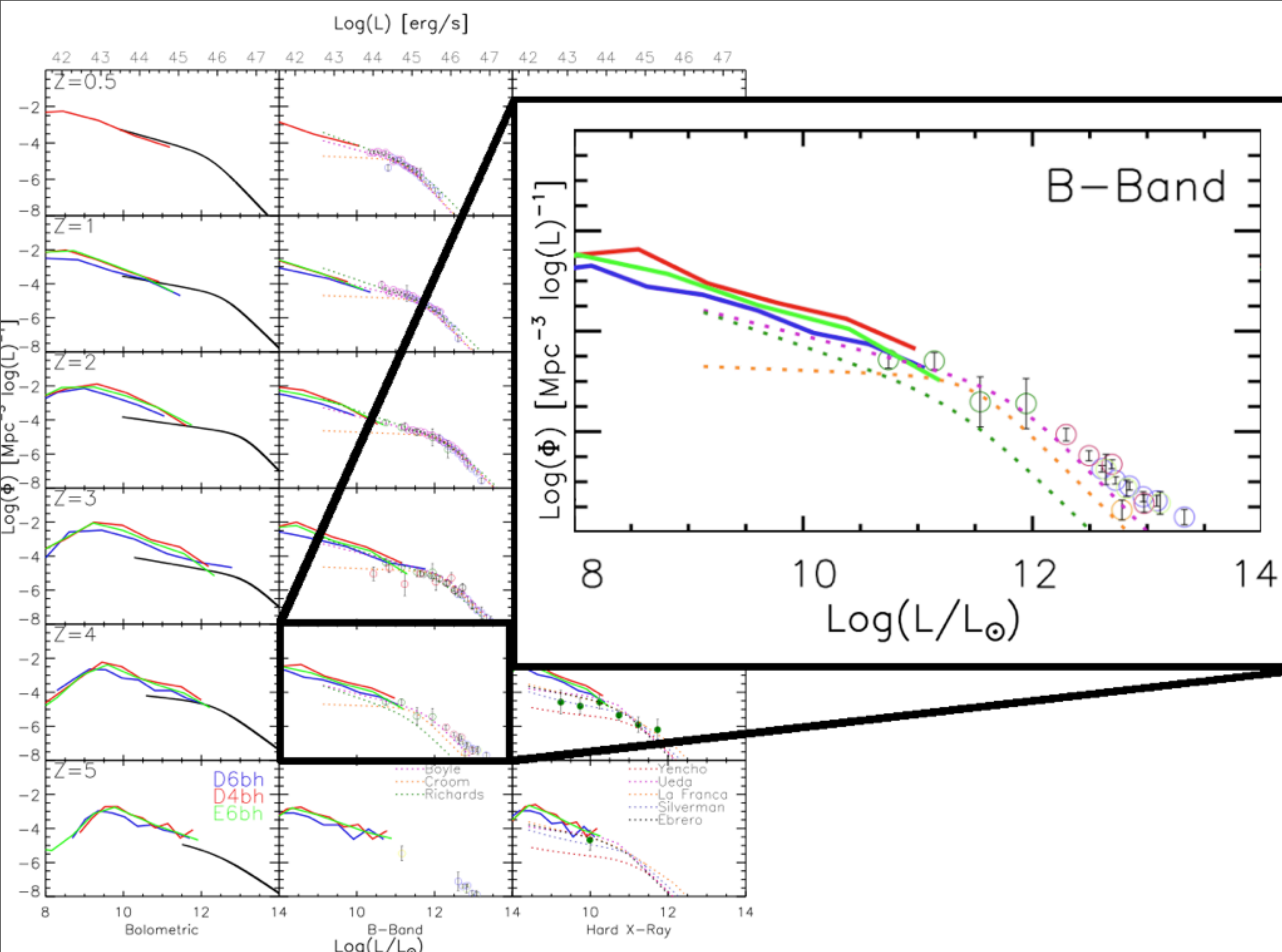
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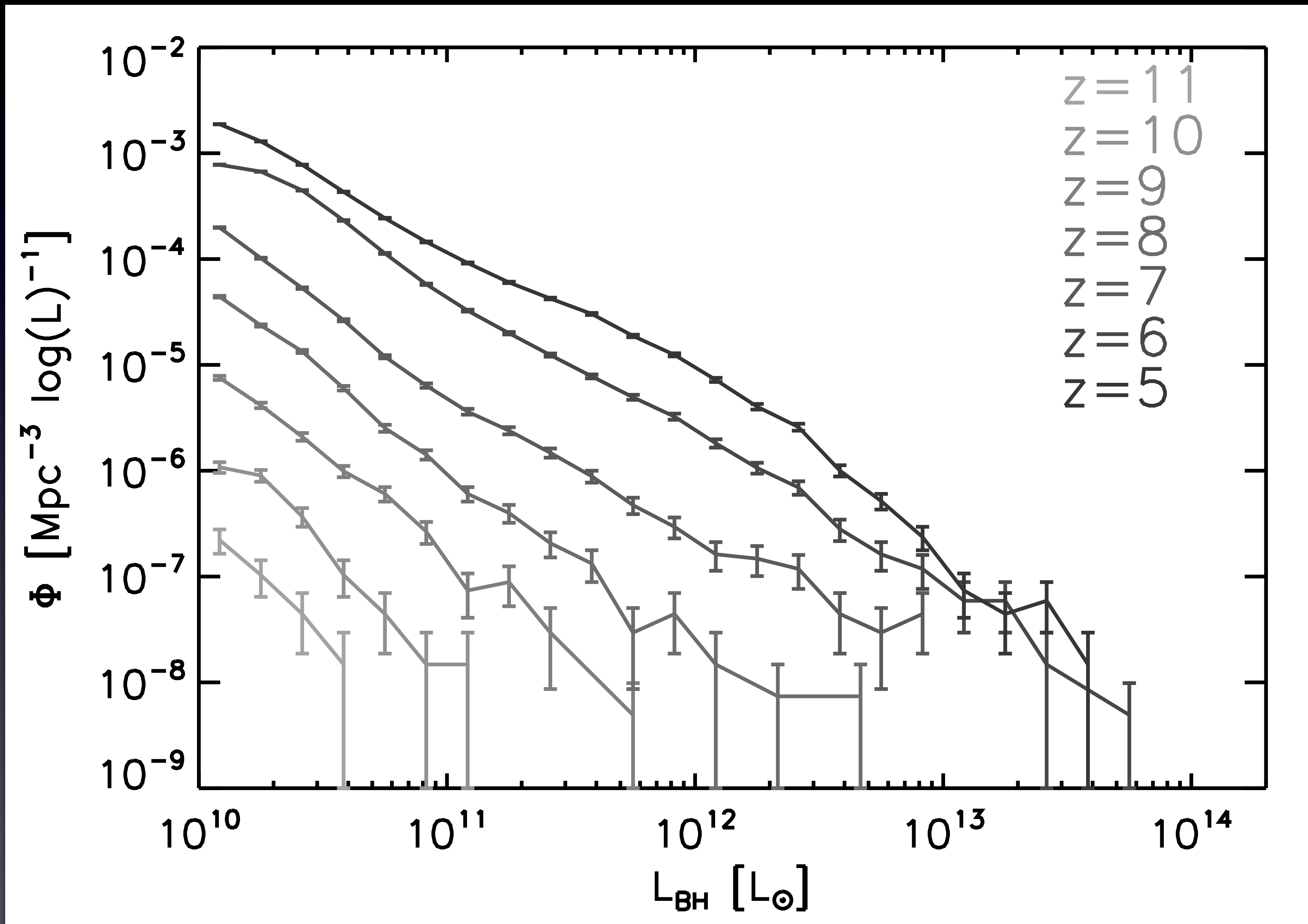
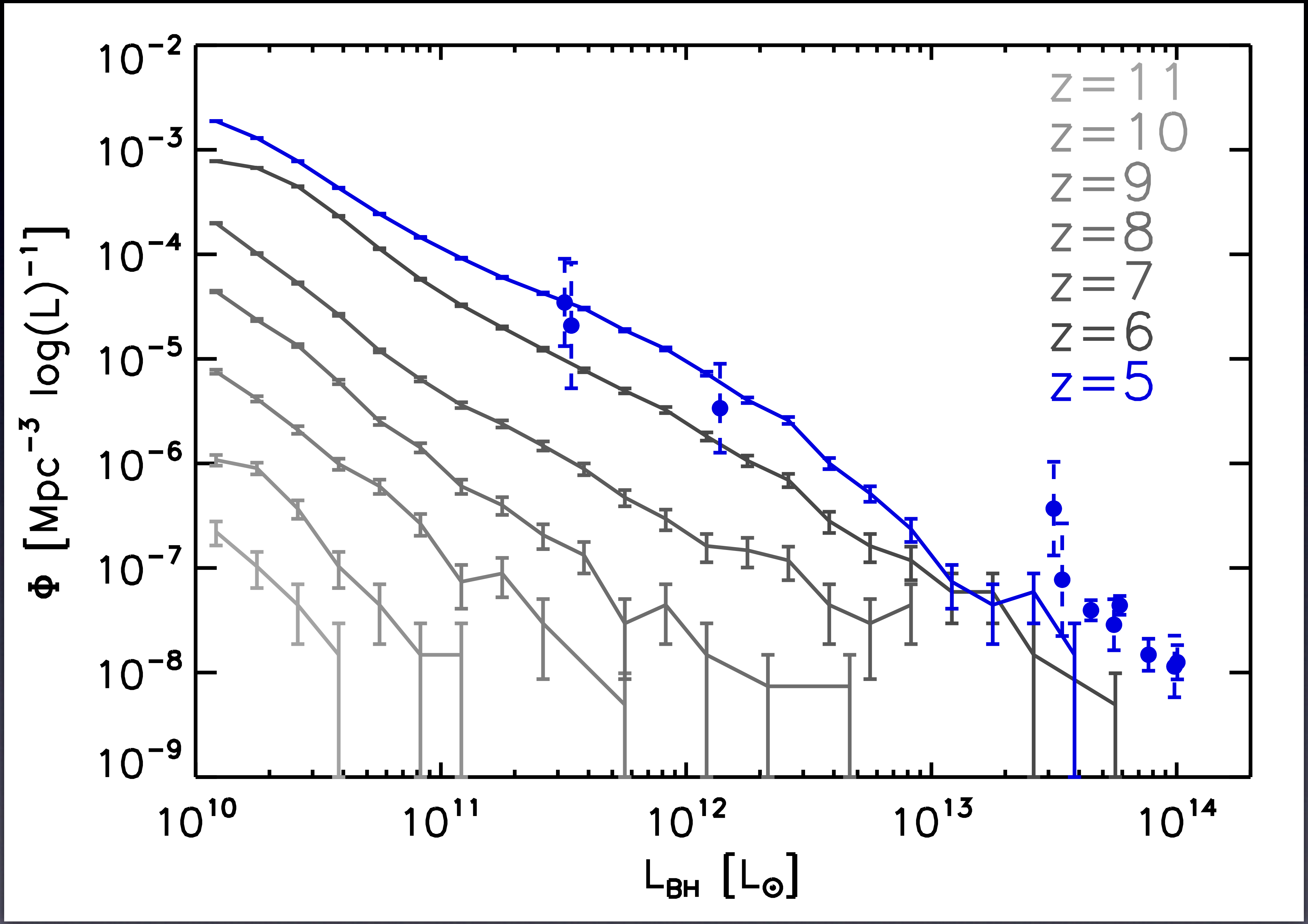
(DeGraf+ 2010)

Quasar Luminosity Function



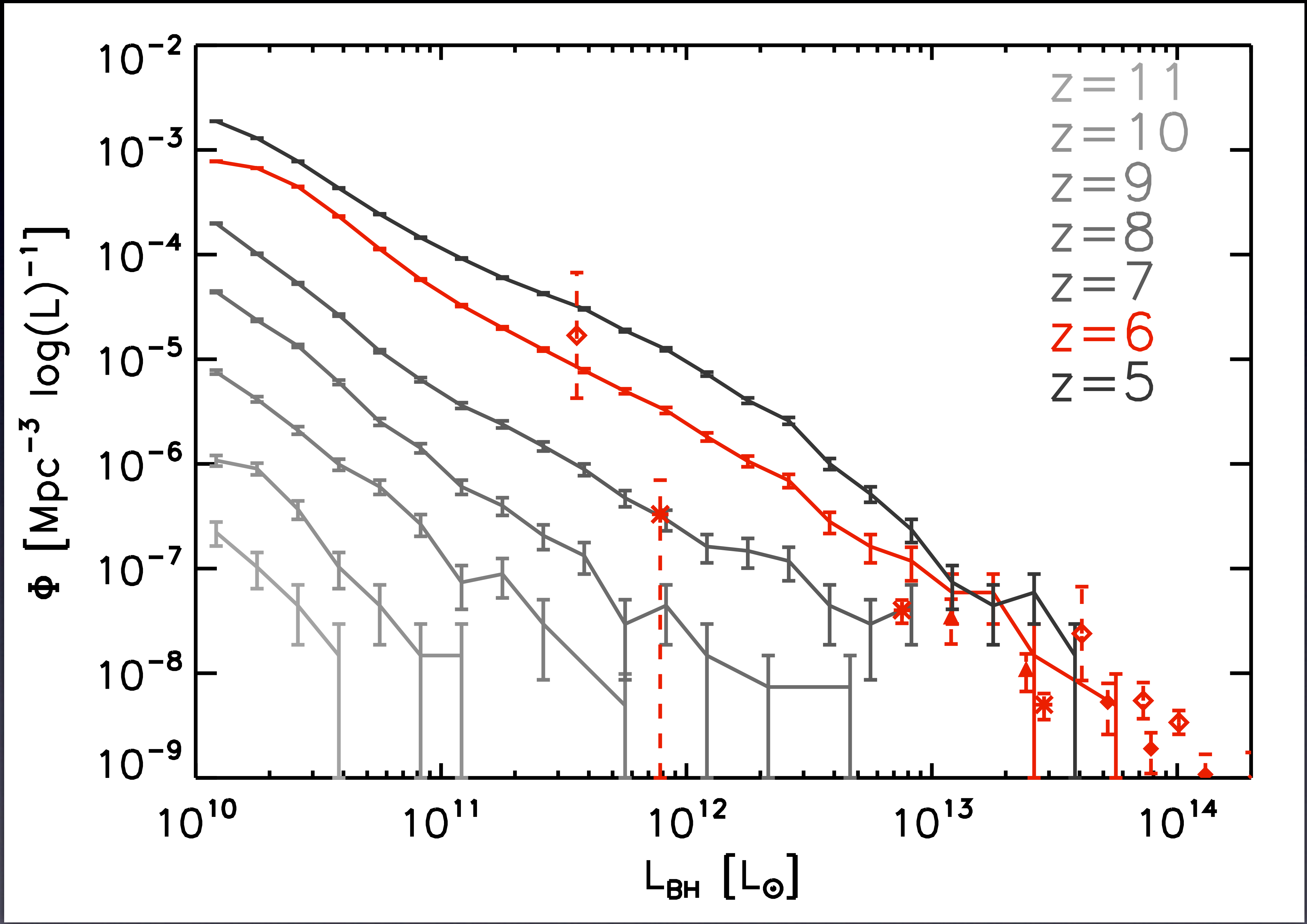
(DeGraf+ 2012)

Quasar Luminosity Function



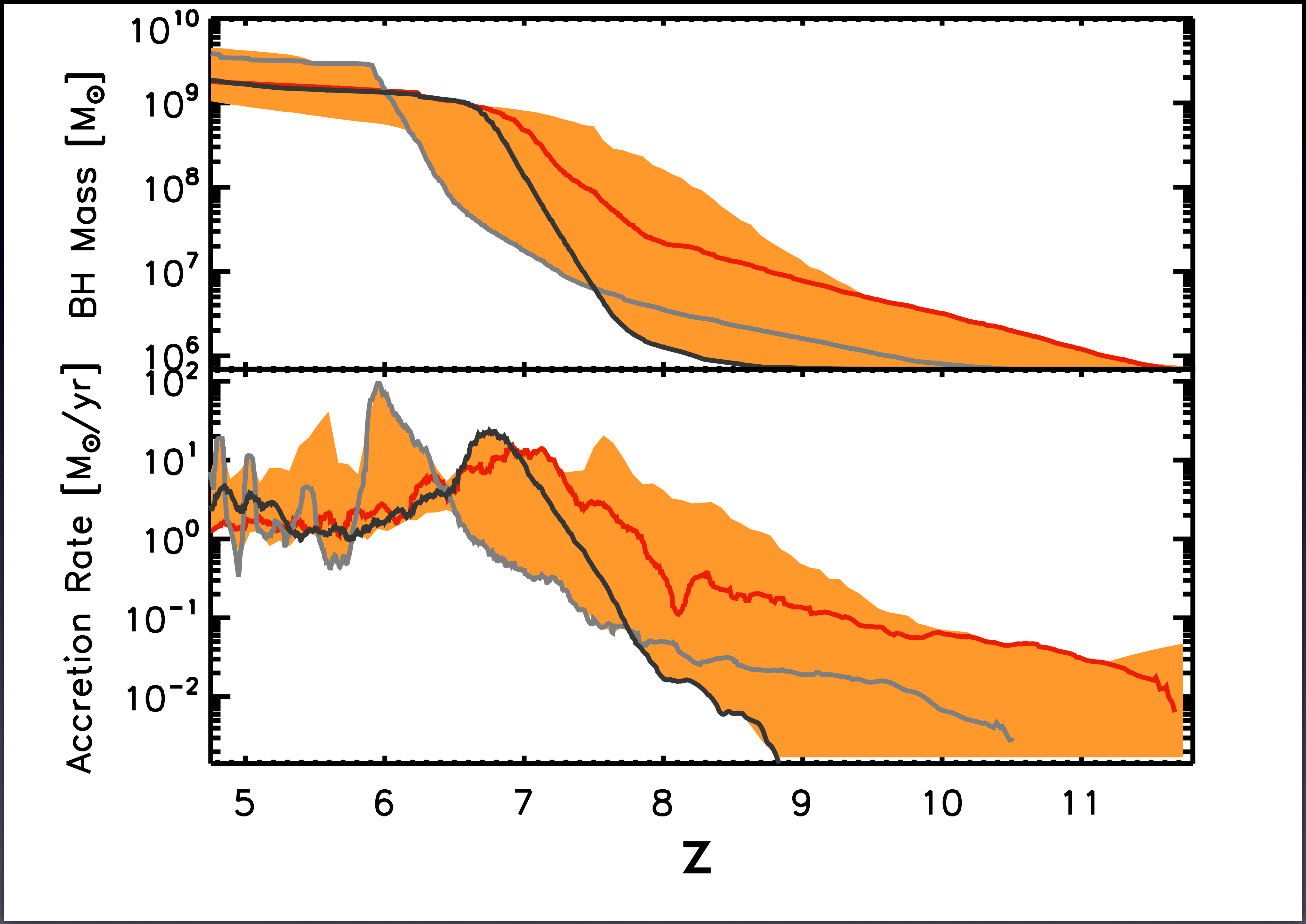
(DeGraf+ 2012)

Quasar Luminosity Function



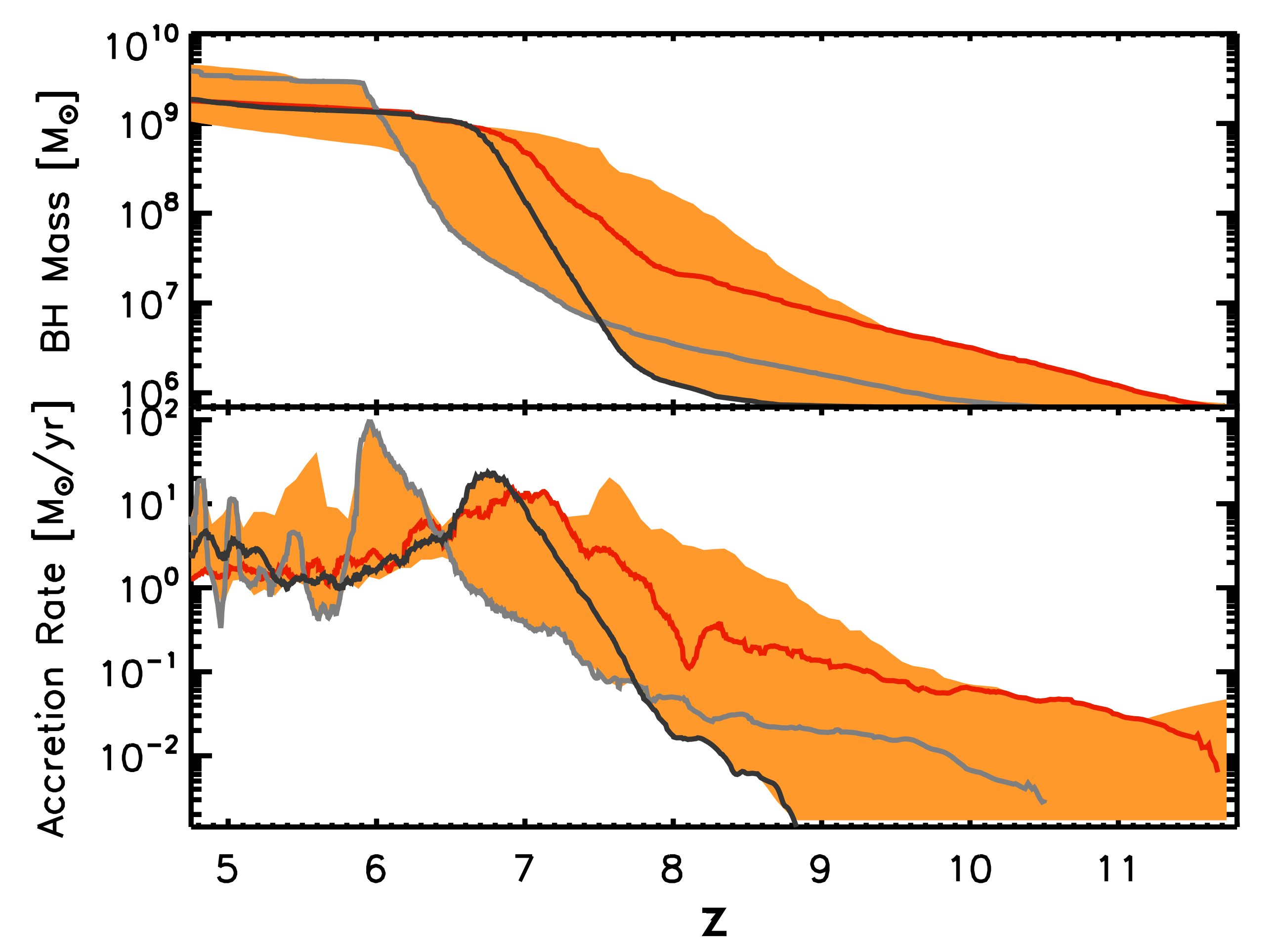
(DeGraf+ 2012)

Black Hole Growth



(Di Matteo+ 2012)

Black Hole Growth



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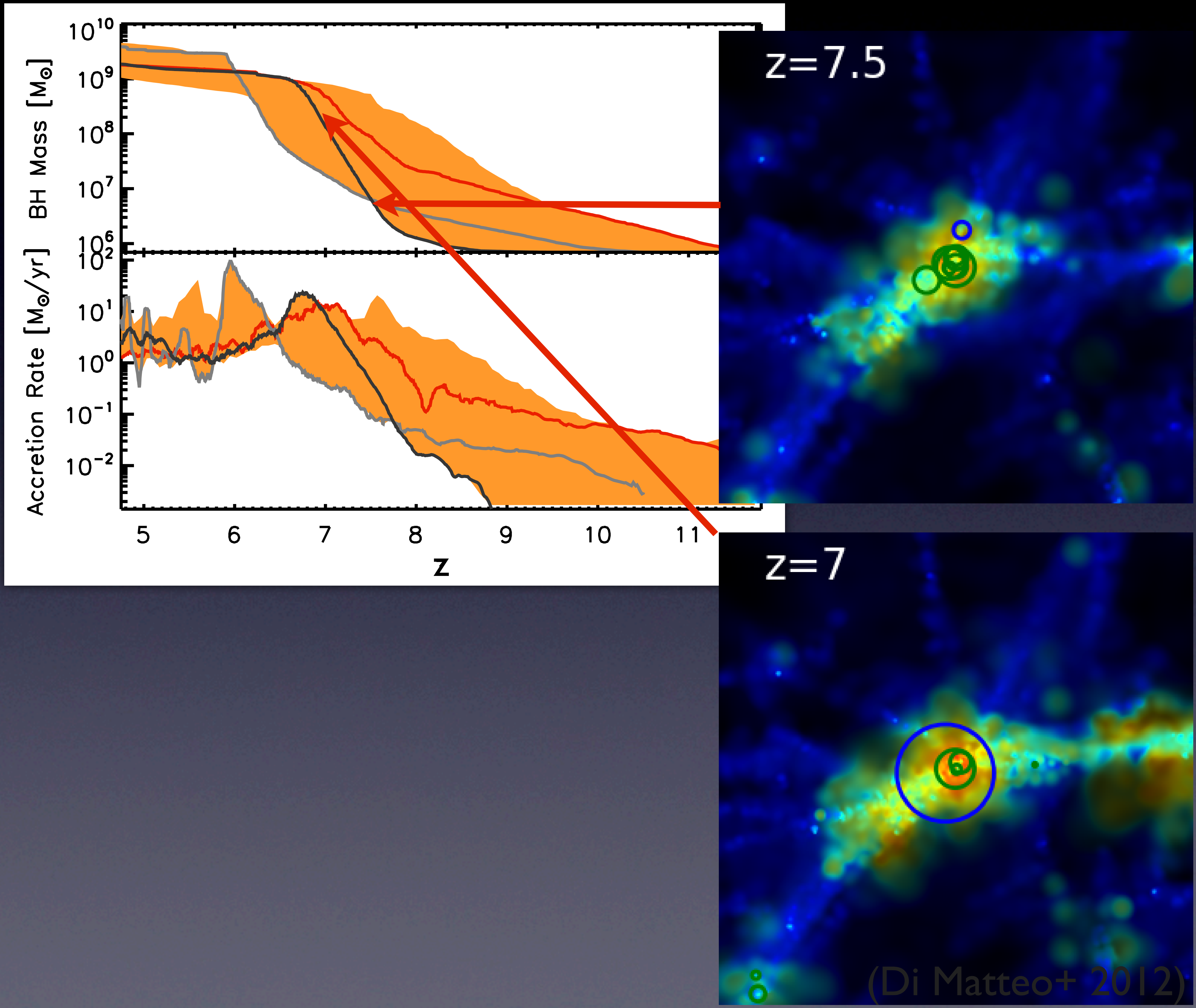

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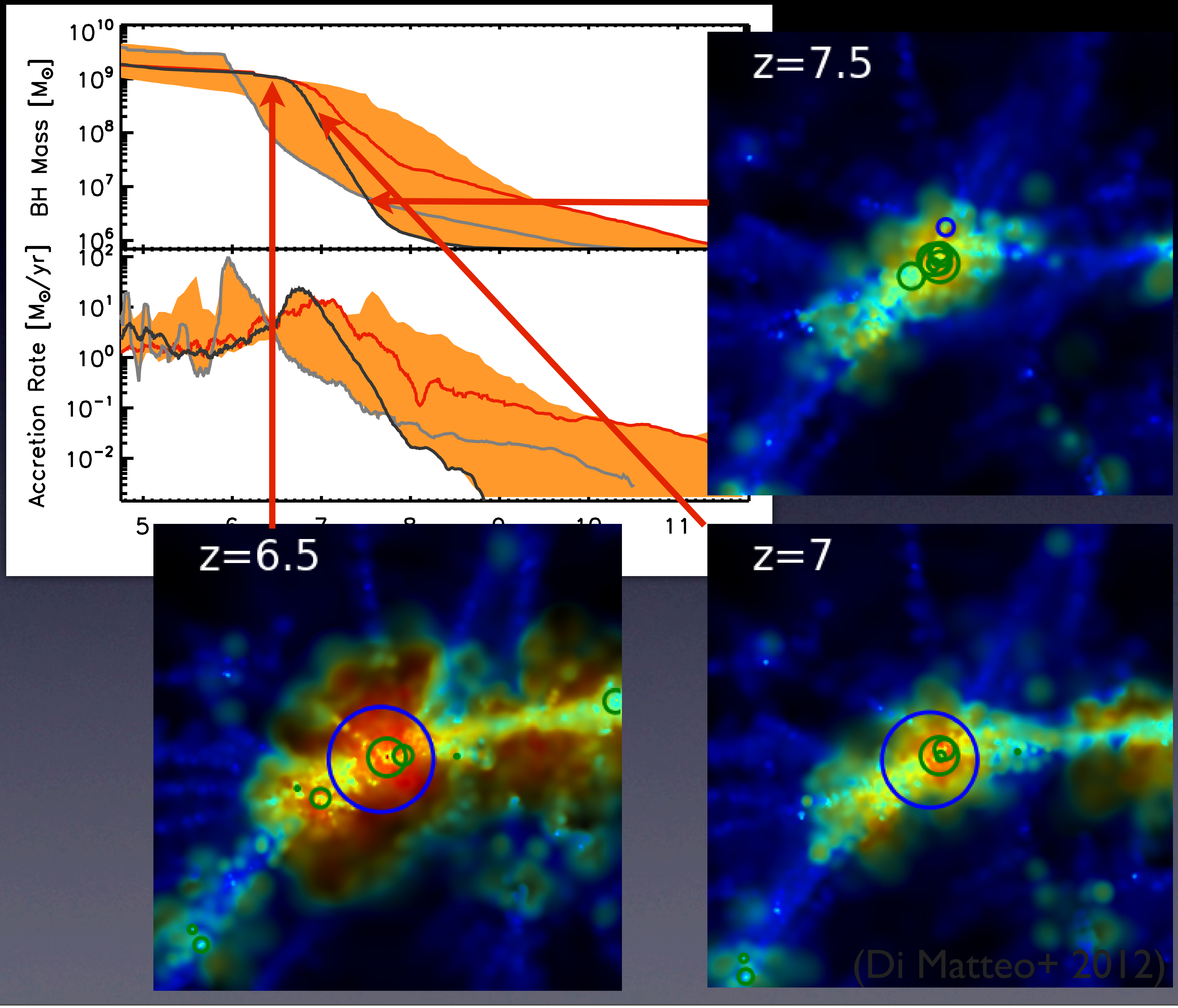

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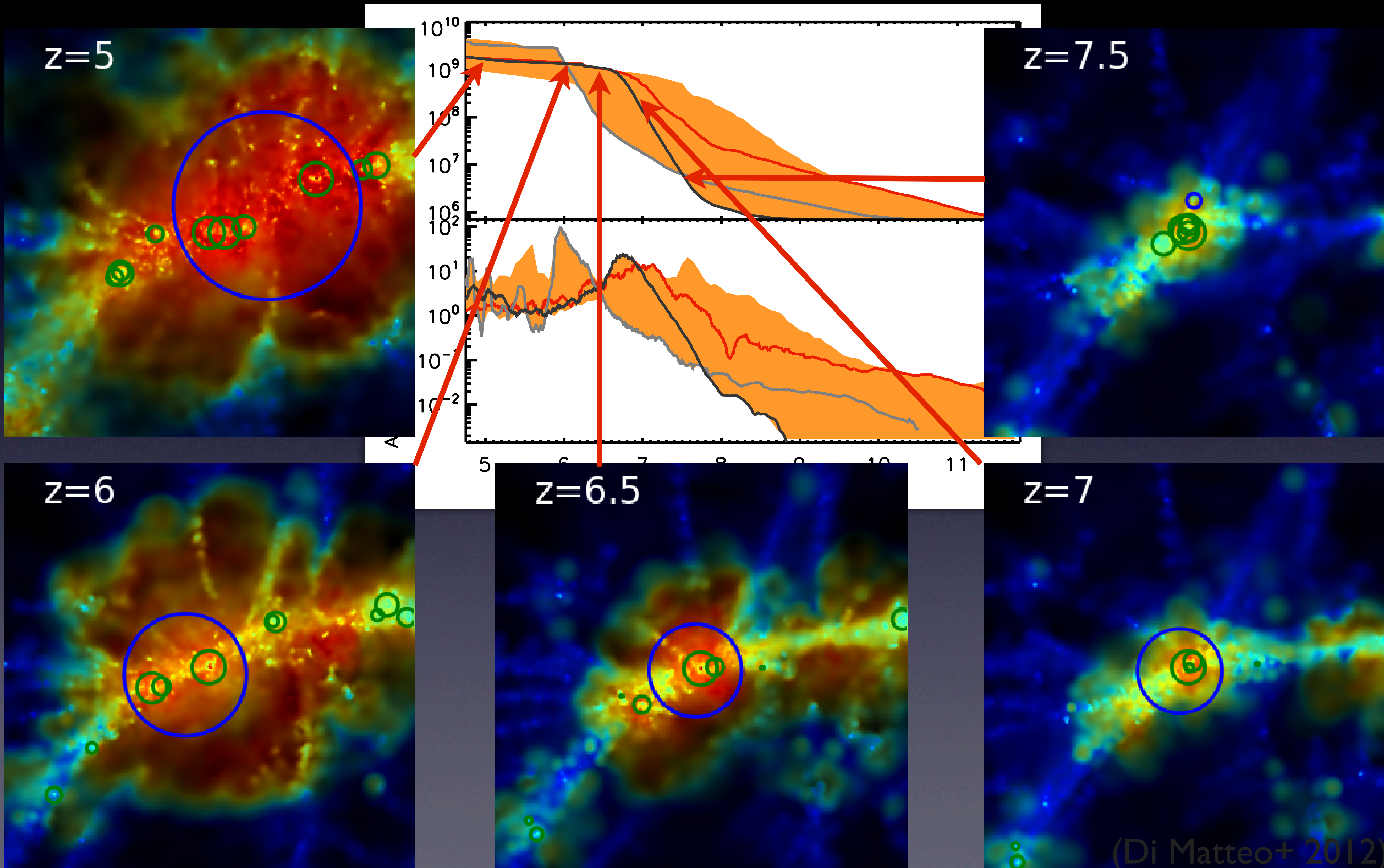
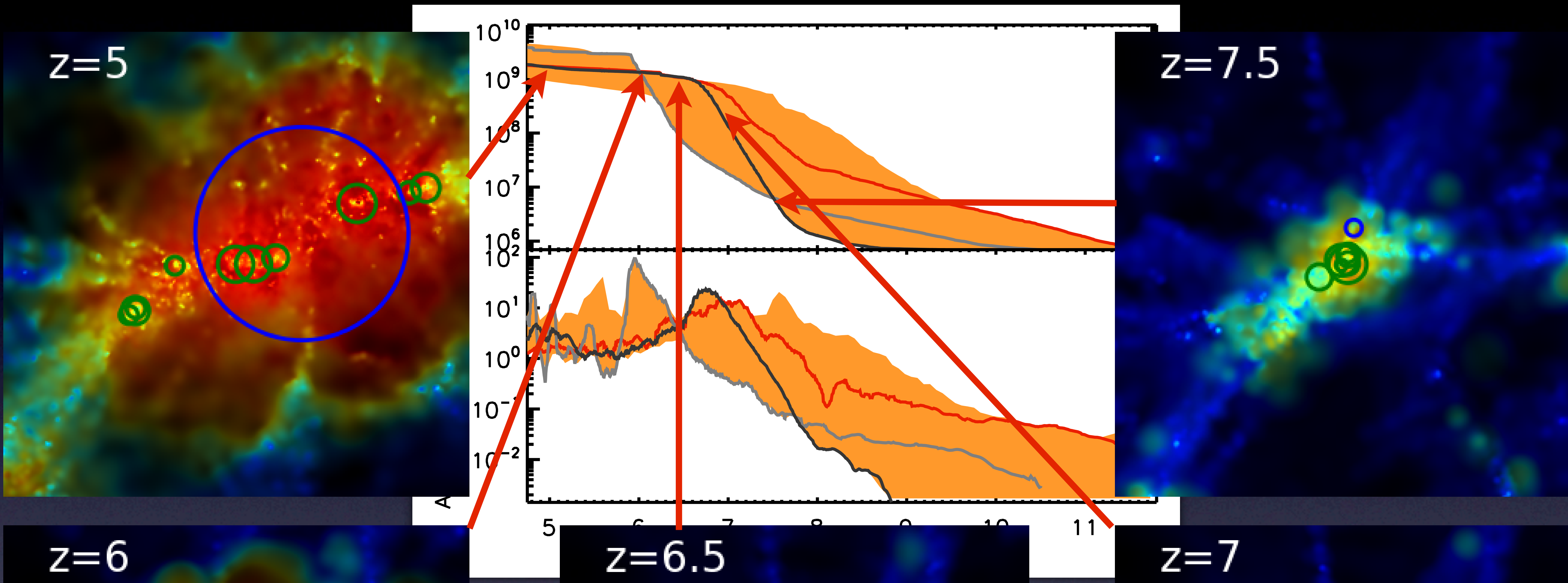


Black Hole Growth



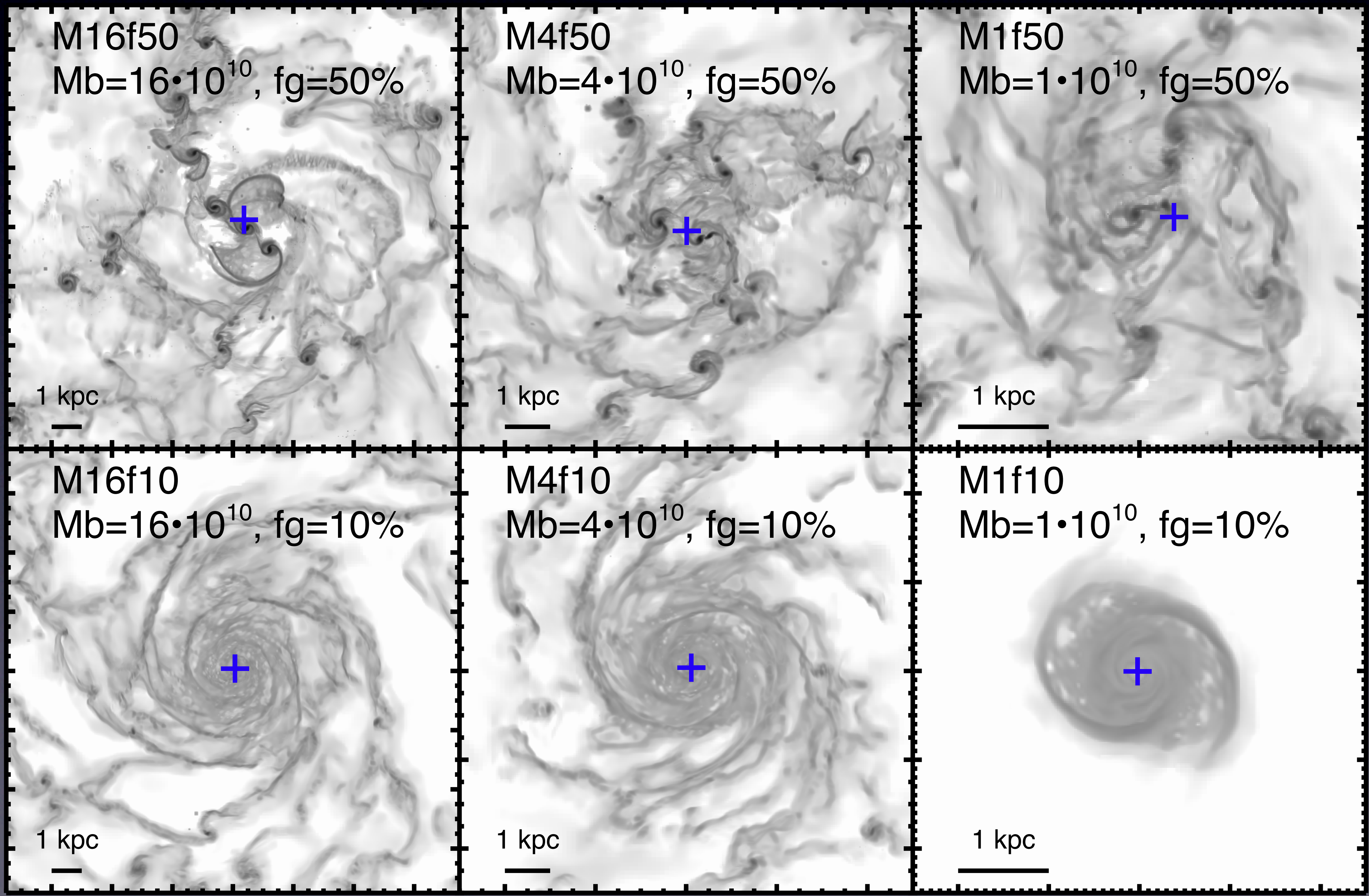
- Can sustain near-Eddington growth to produce large BHs
- Gas provided by long-term cold streams of gas penetrating galaxy to fuel accretion

(Di Matteo+ 2012)

Black Hole Growth - Alternate Fuel Source

- Internal, rather than external, source
- Gravitational instabilities within galaxy produces high-density gas clouds

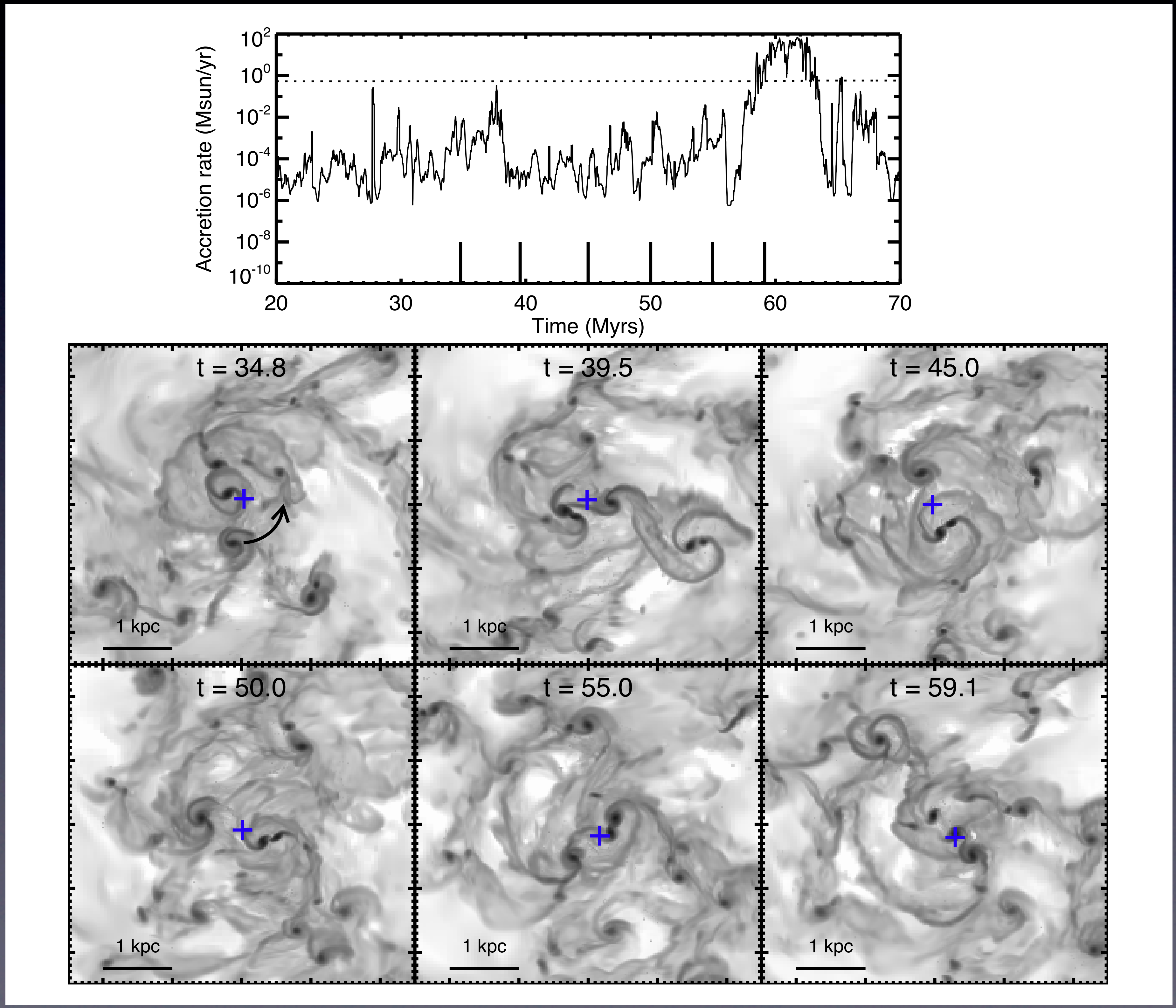
Black Hole Growth - Alternate Fuel Source



Black Hole Growth - Alternate Fuel Source

- Internal, rather than external, source
- Gravitational instabilities within galaxy produces high-density gas clouds
- Gas clouds fall to center of galaxy, where they fuel the BH

Black Hole Growth - Alternate Fuel Source



Summary

- Supermassive Black Holes are found in most galaxies
- SMBHs can have strong impact on the evolution of their host galaxy

  (and vice versa)
- Can learn about host galaxies/halos by studying the black holes

Open Questions

- Which track is source for SMBH seeds?
- Importance of Quasar vs. Radio feedback
  - Thermal vs. kinetic
- Importance of merger- vs. secular-driven accretion
- Self-regulation dominant driver for scaling relations?
  - Inside-out vs. outside-in

Black hole mergers - final parsec problem

- How to lose angular momentum?
  - Gas
  - Stars
  - Gravity waves