Unsolved Problems in Astrophysics and Cosmology:

Galaxy Formation

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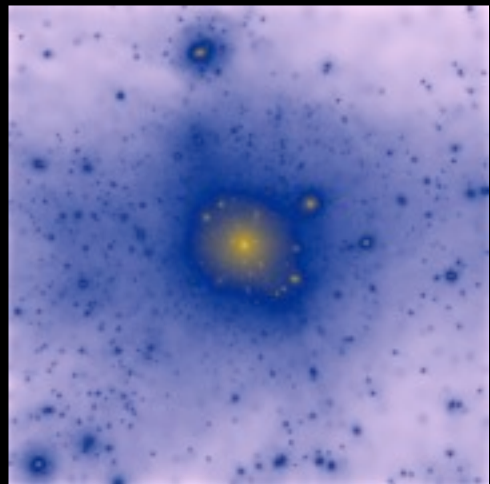
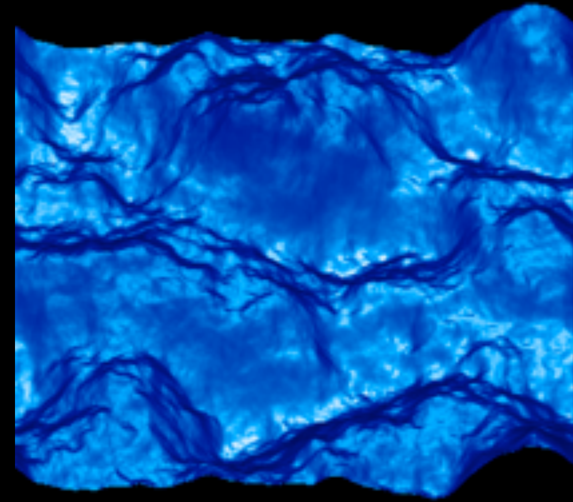
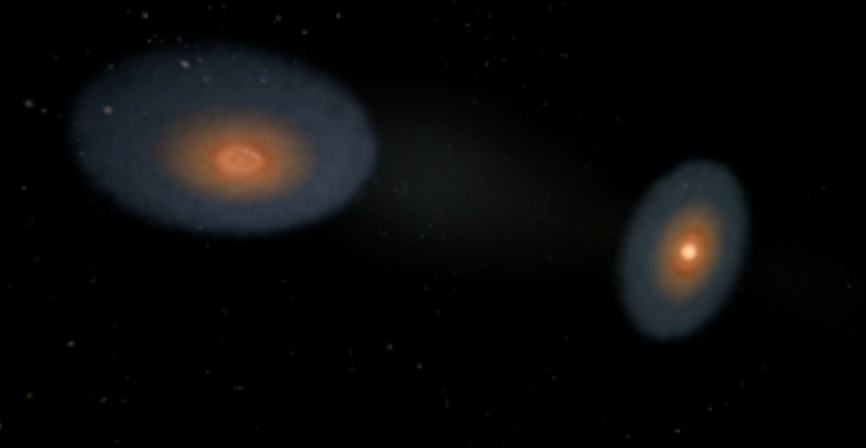


Nonlinear Dynamics

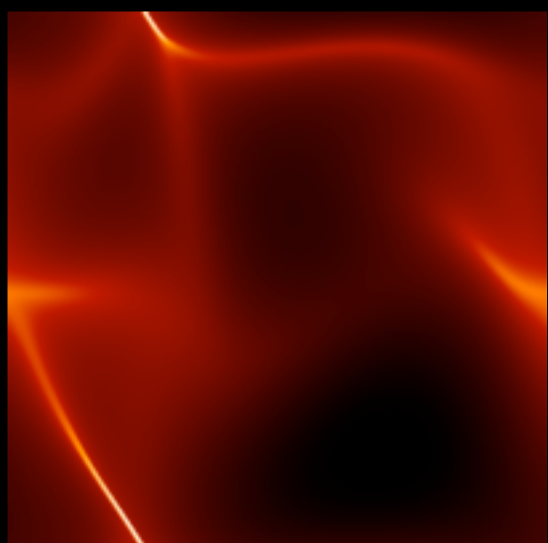


CDM Power Spectrum



AGN Feedback

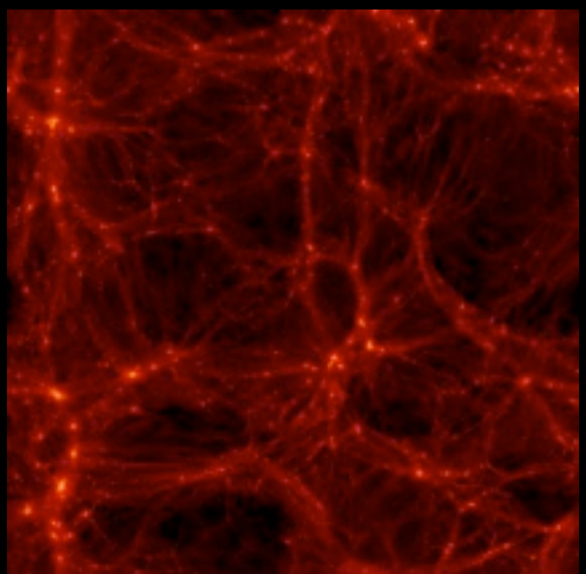
Reionization



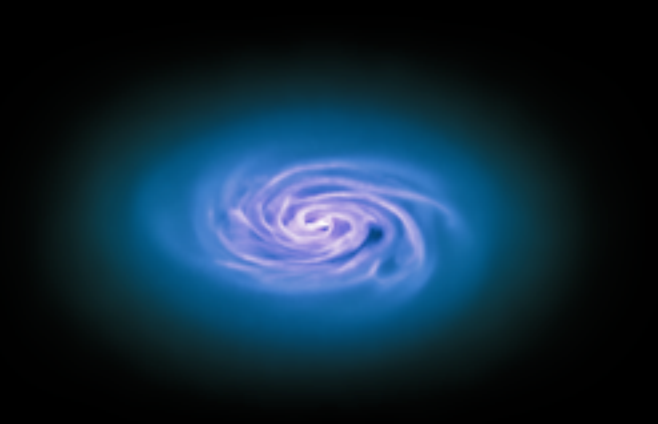
Supersonic
Turbulence

The modern theory of cosmological galaxy formation is a synthesis of many physical ideas; these are but a few salient examples.

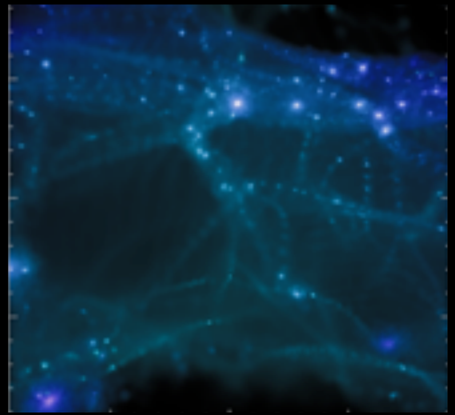
The array of operative physics makes galaxy formation a fun area to work in, but also presents a variety of unsolved problems....



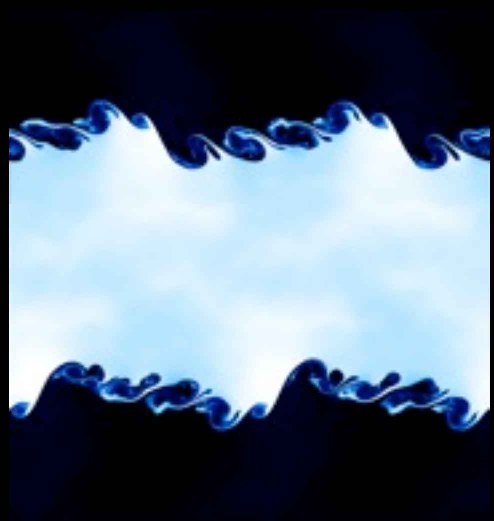
Hierarchical
Clustering



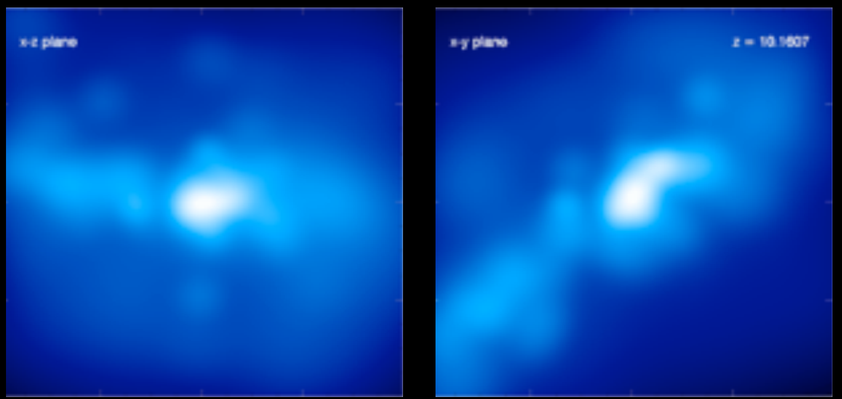
Star Formation +
Supernovae Feedback



DM Particle
Physics



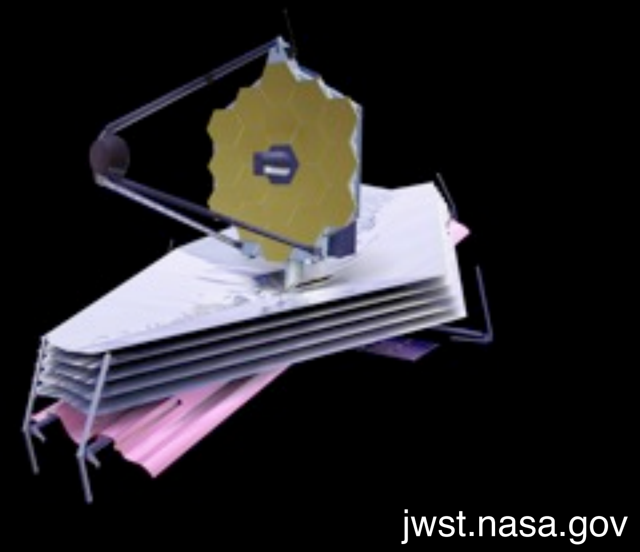
Hydrodynamics



Molecular, Atomic, &
Bremsstrahlung Cooling

A Transformative Decade(+) for Observational Astronomy

20-40m Ground-Based Telescopes



6m Space-Borne IR Telescopes

Large-Scale Radio Arrays

8m Telescope All-Sky Synoptic Surveys

The Theory of Galaxy Formation Also Needs Transformative Improvement!

"Tremendous progress has been made over the last decade in establishing a broad cosmological framework in which galaxies and large-scale structure develop hierarchically over time, as a result of gravitational instability of material dominated by dark matter. However, there remain many unanswered questions... most of this uncertainty relates to our poor understanding of the complex baryonic processes that must be included in any successful theory of galaxy formation: cooling, star formation, feedback, merging." - Thirty Meter Telescope Science Case

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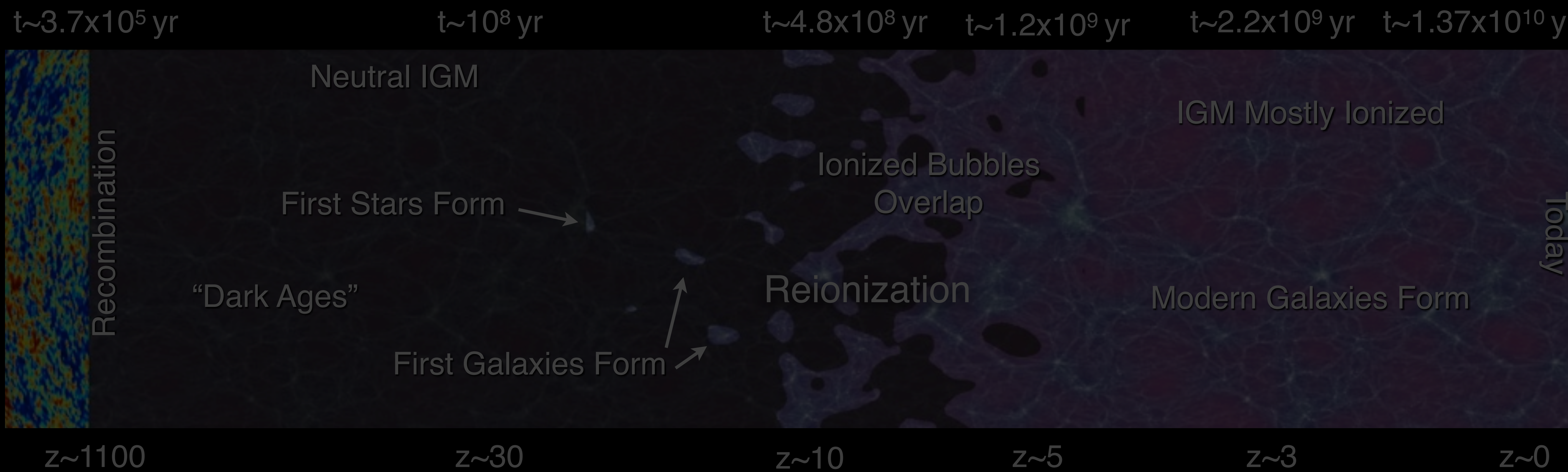
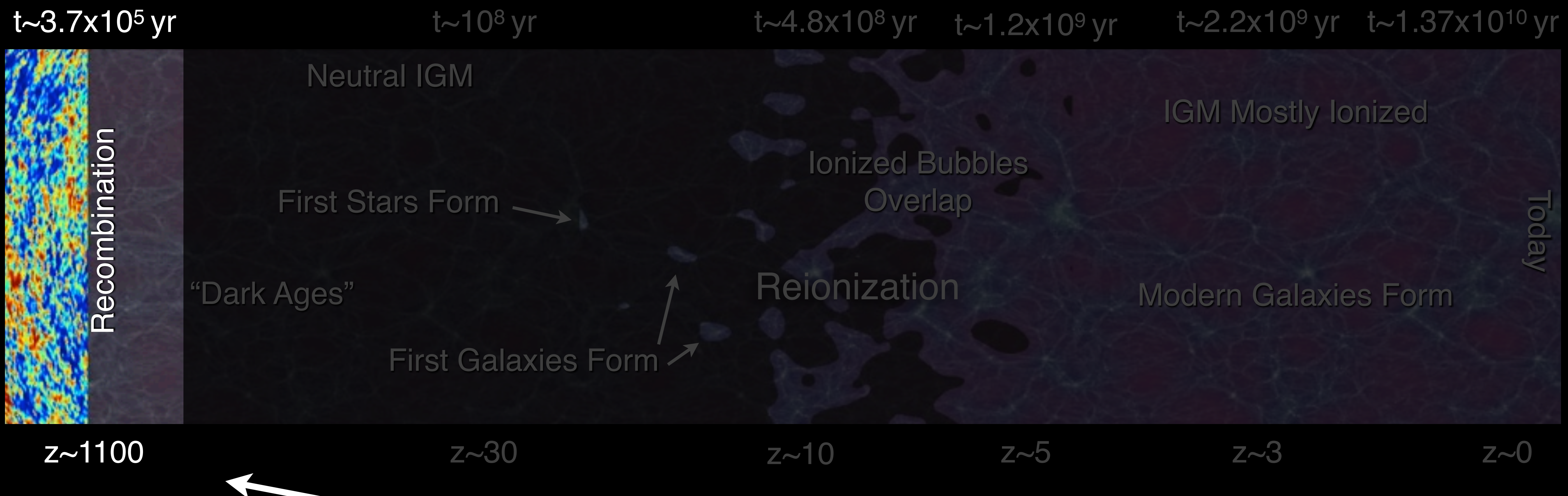
Observable Cosmological History



Robertson et al., *Nature*, **468,** 49 (2010d)

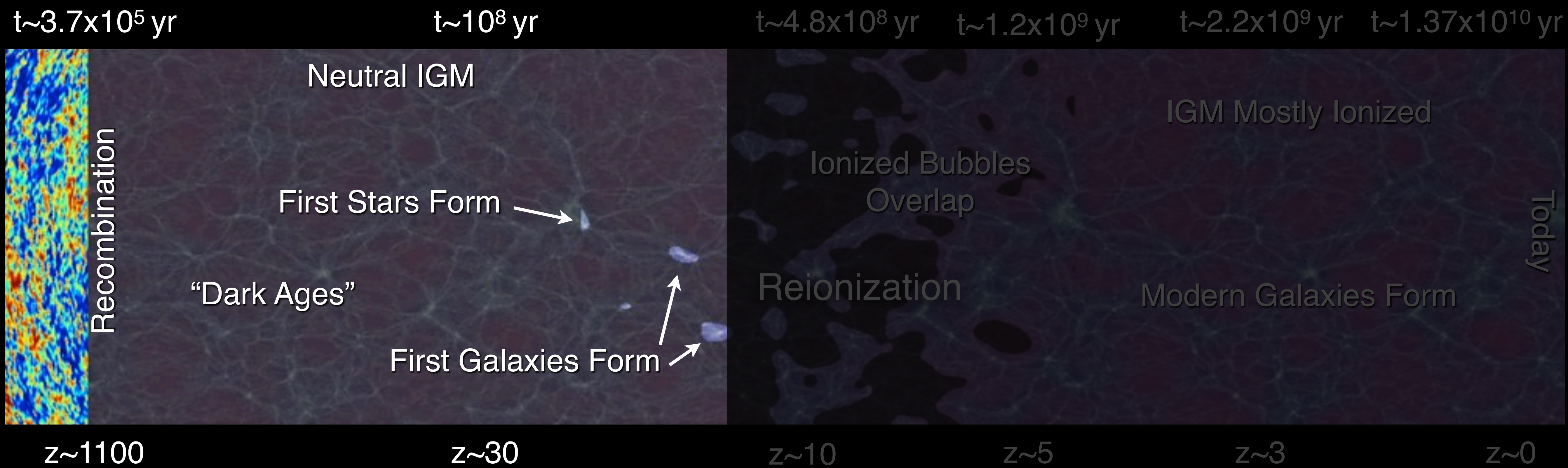
Observable Cosmological History



Recombination

Robertson et al., *Nature*, **468,** 49 (2010d)

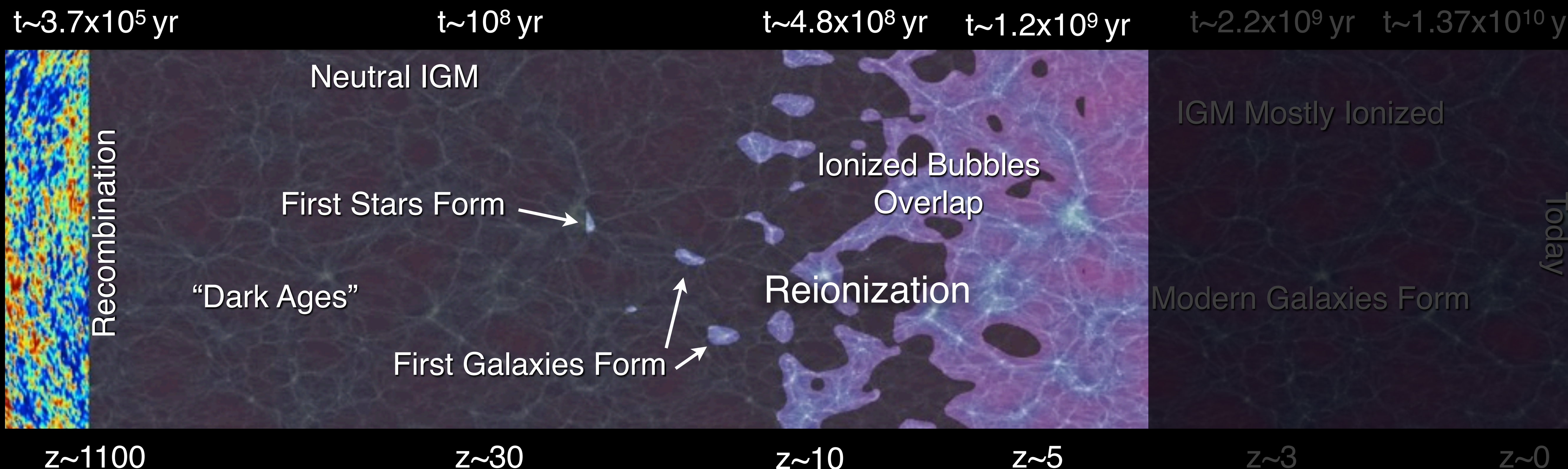
Observable Cosmological History



First Light / "Cosmic Dawn"

Robertson et al., *Nature*, **468,** 49 (2010d)

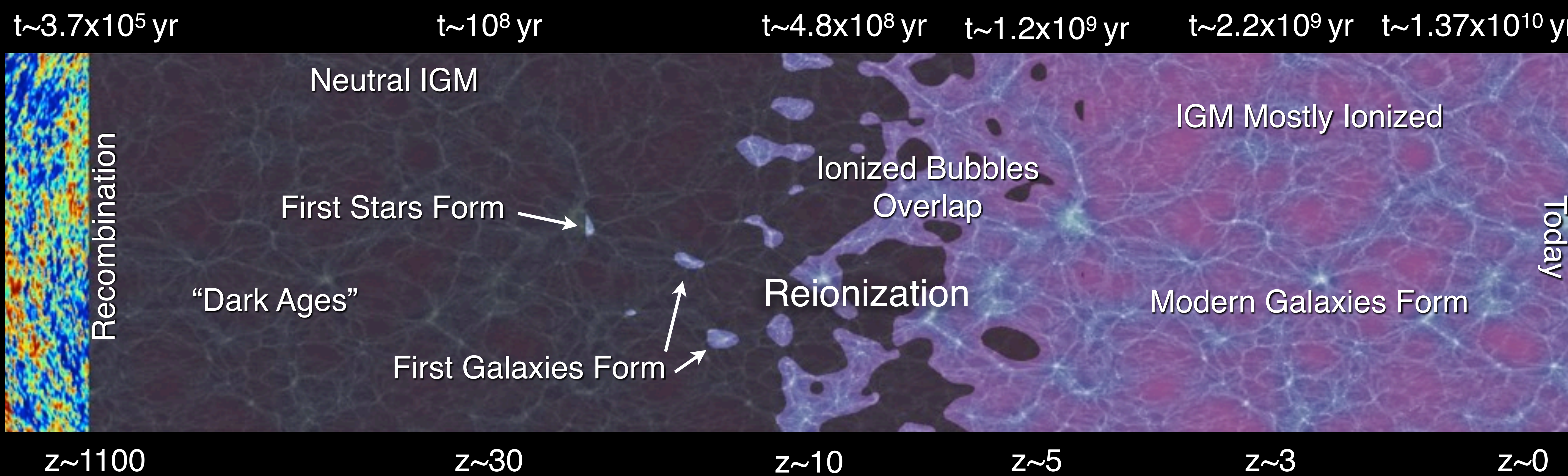
Observable Cosmological History



Reionization

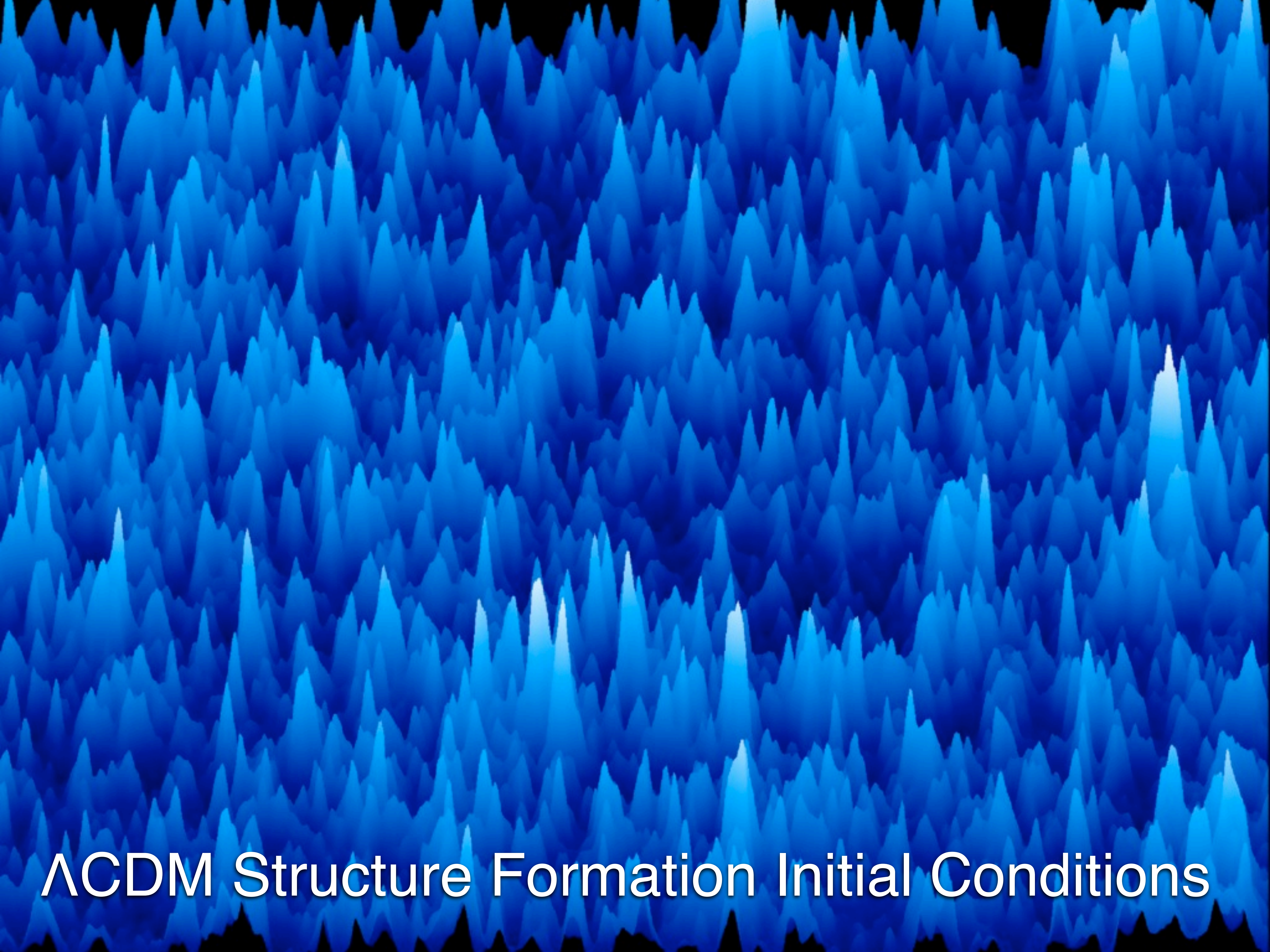
Robertson et al., *Nature*, **468,** 49 (2010d)

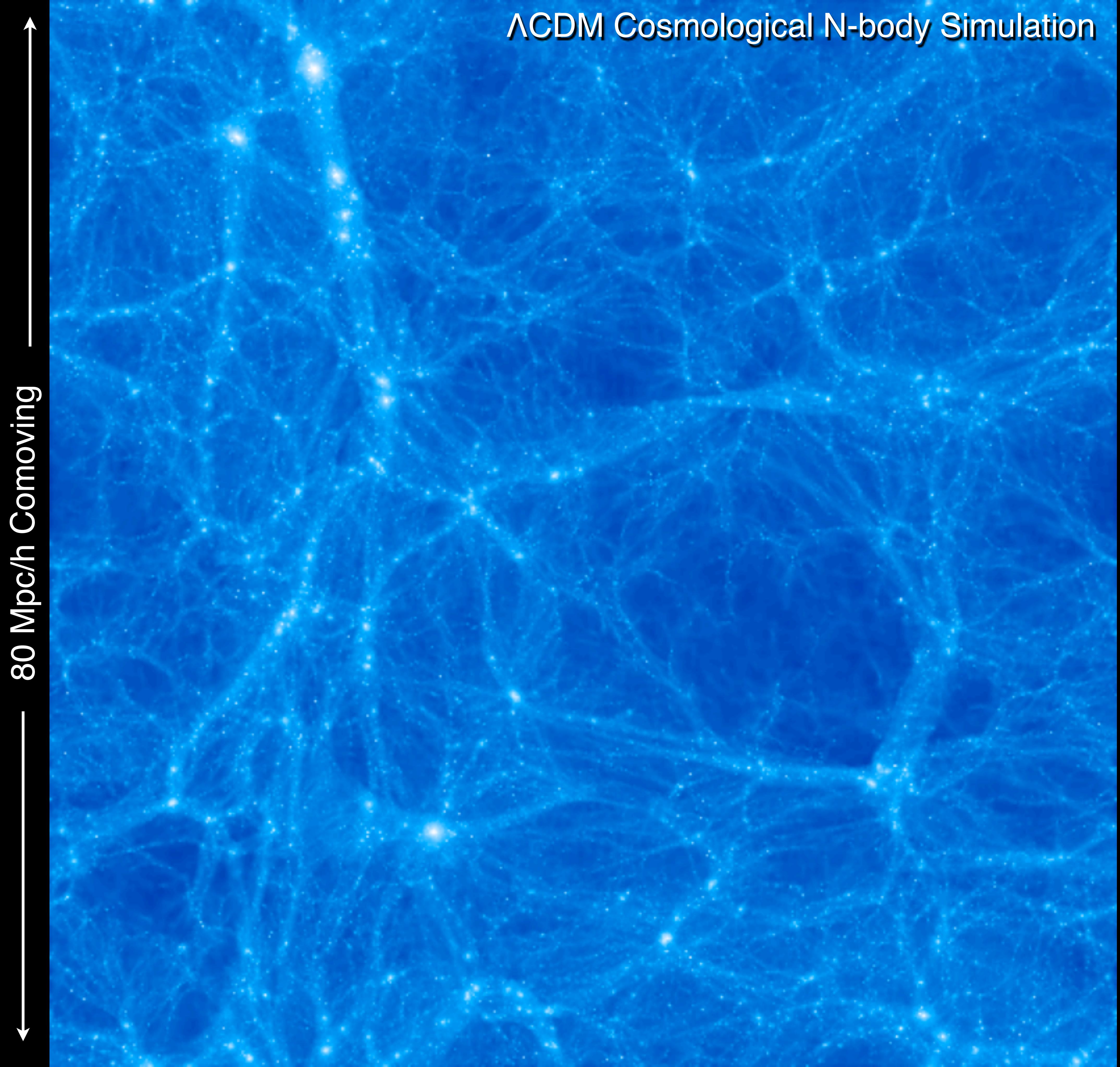
Observable Cosmological History



Epoch of Modern Galaxy Formation

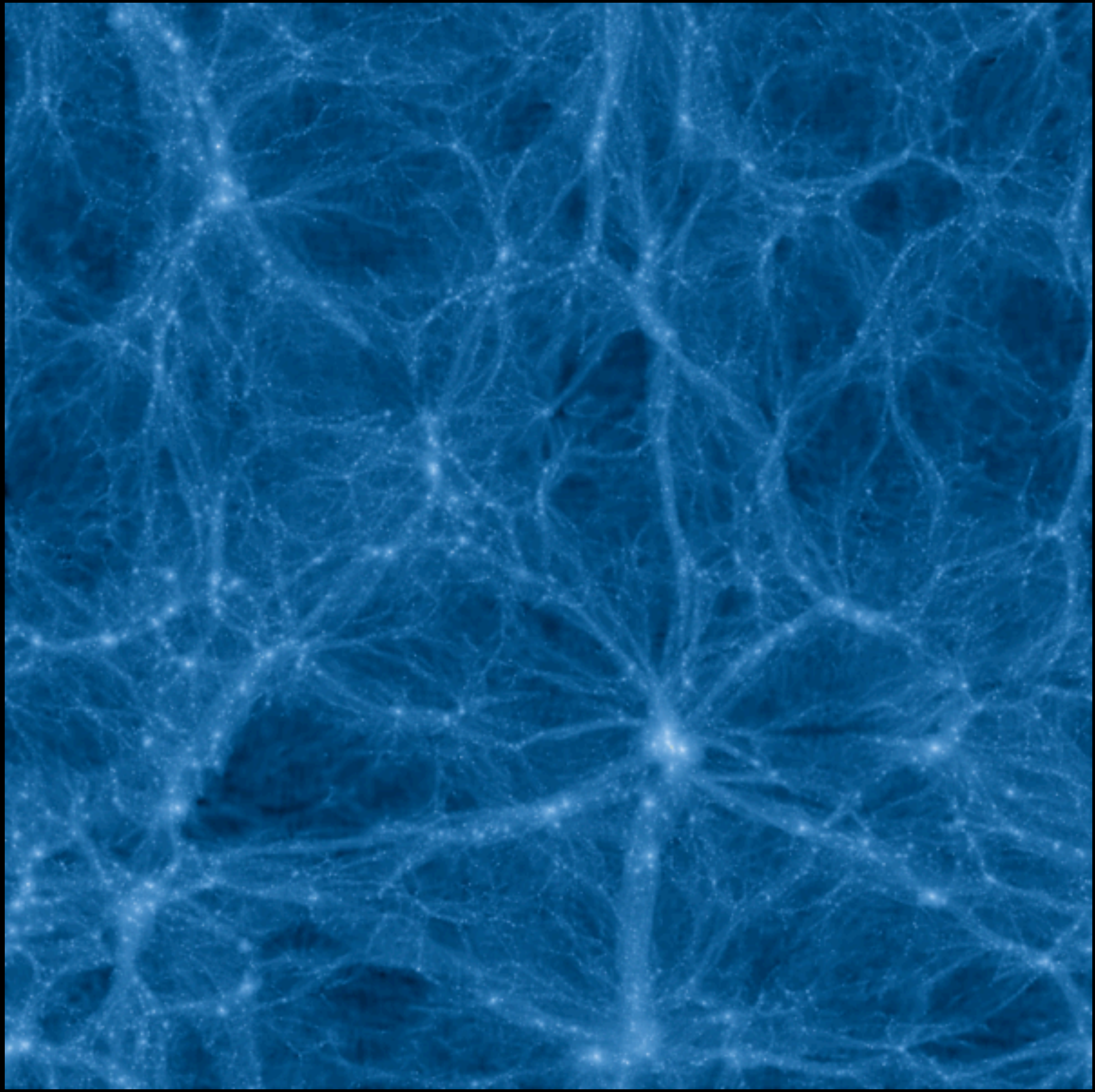
Robertson et al., *Nature*, **468,** 49 (2010d)


ΛCDM Structure Formation Initial Conditions


ΛCDM Cosmological N-body Simulation
80 Mpc/h Comoving

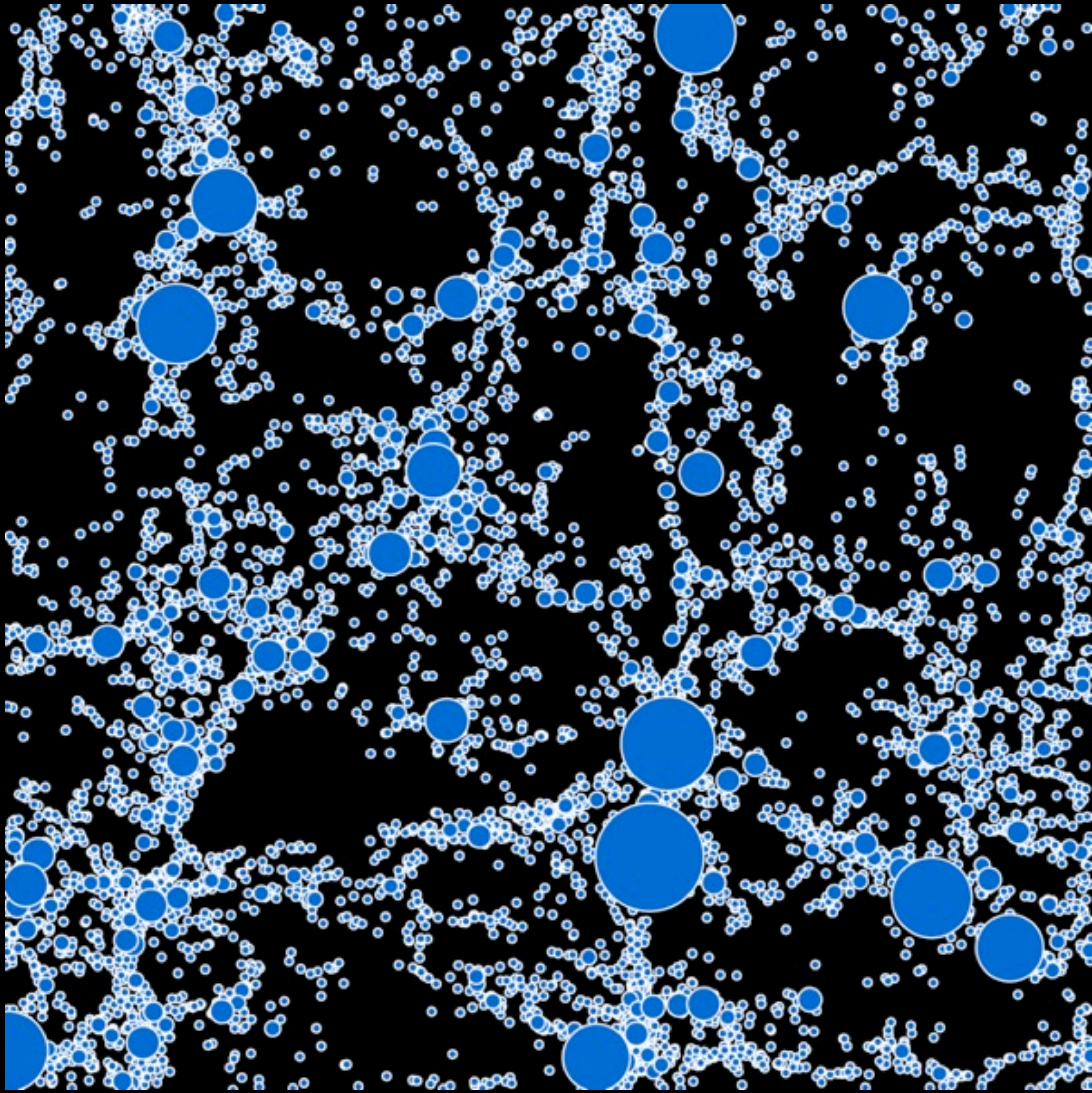
An Overview of Galaxy Formation

Large-scale structures form in dark matter overdensities



An Overview of Galaxy Formation

Gravitationally-bound dark matter halos (blue circles) form at the peaks of density field.



Gas Cooling Rates

High

Temperature

Low

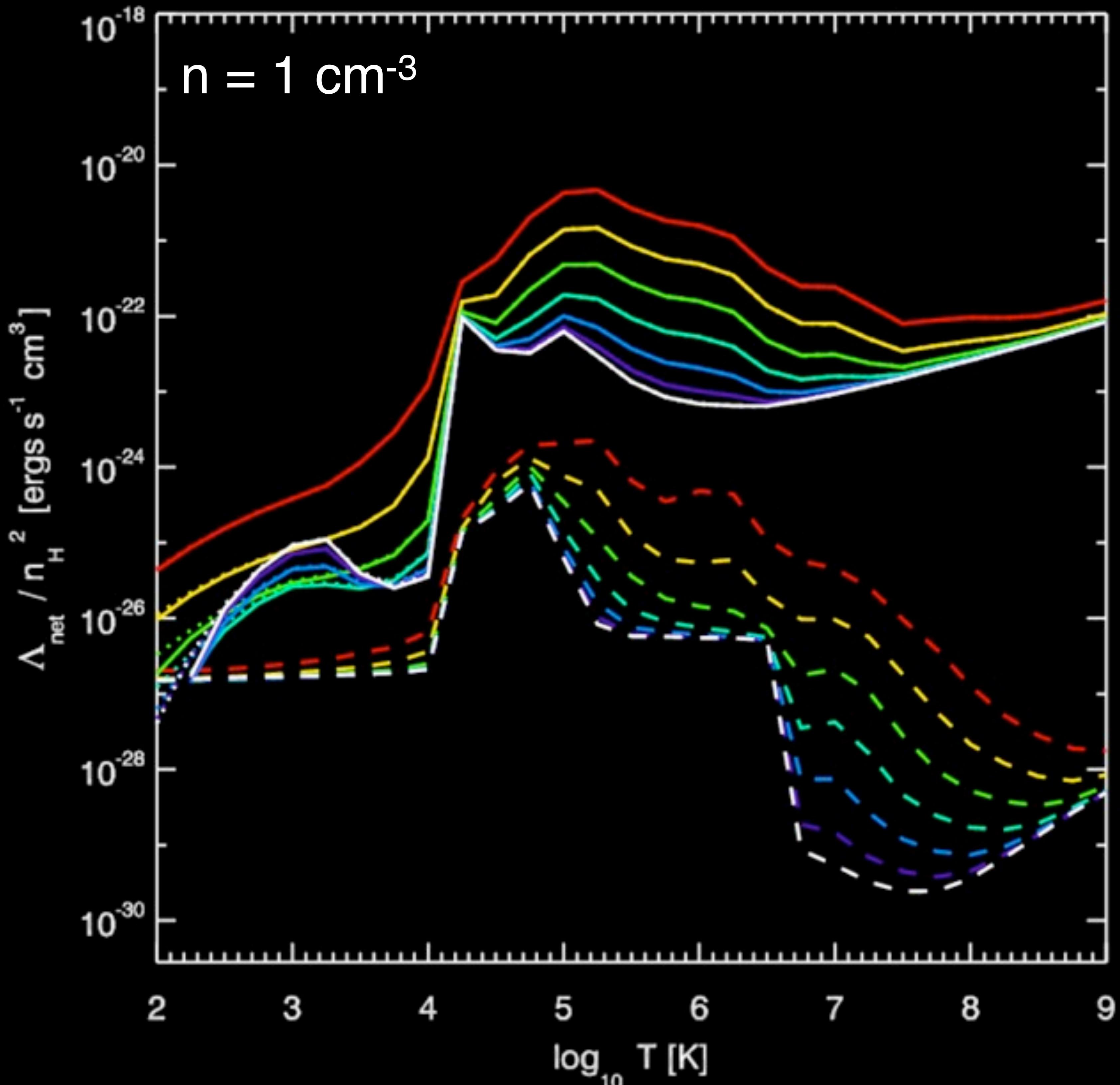
Bremsstrahlung

Metal line cooling

H+He collisional ionization + recombination

Atomic fine structure lines

Molecular coolants

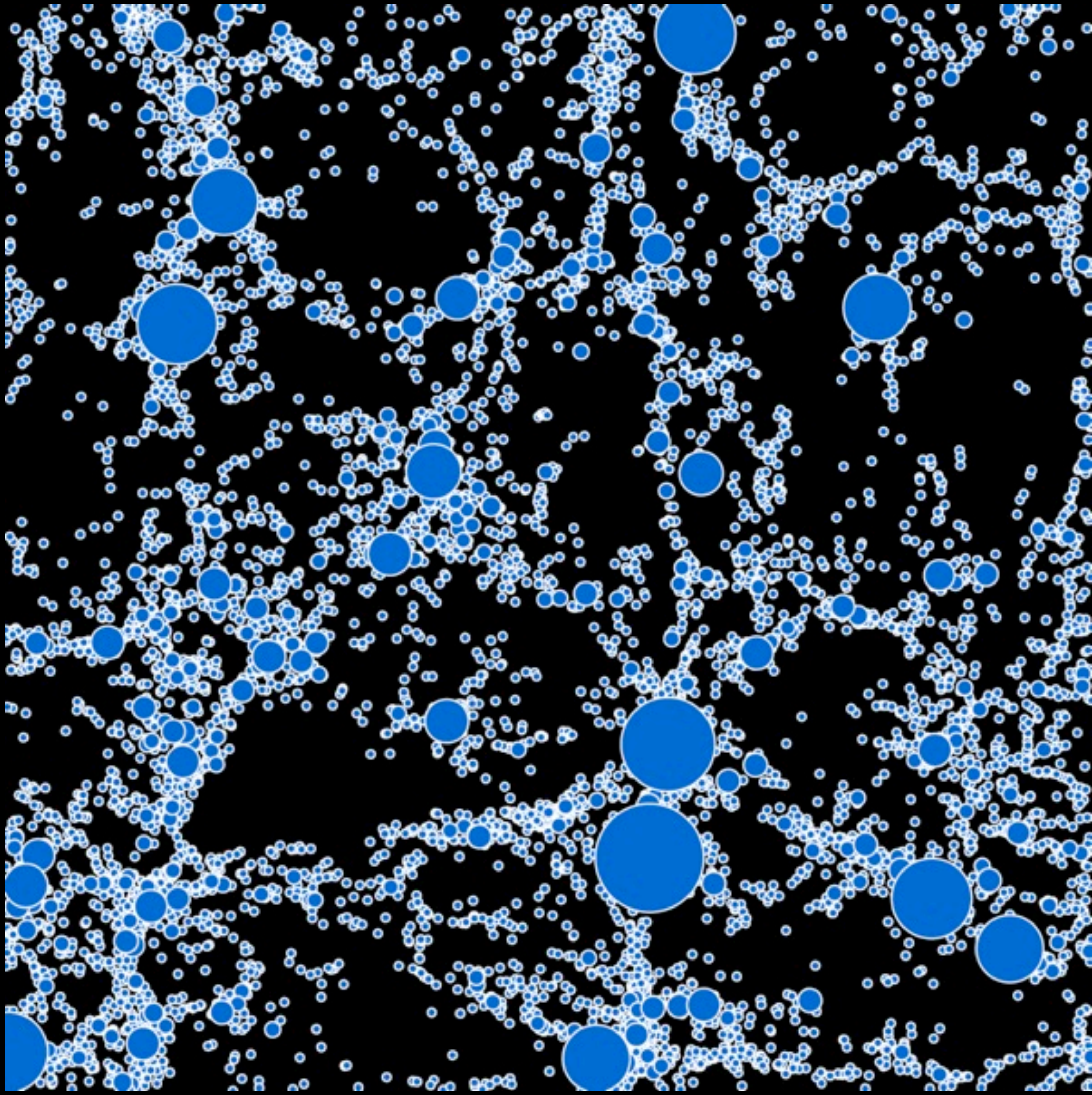


$\log_{10} Z/Z_{sun} = -2$ $\log_{10} Z/Z_{sun} = -1$ $\log_{10} Z/Z_{sun} = 0$ $\log_{10} Z/Z_{sun} = 1$

$\log_{10} Z/Z_{sun} = -1.5$ $\log_{10} Z/Z_{sun} = -0.5$ $\log_{10} Z/Z_{sun} = 0.5$

An Overview of Galaxy Formation

Gas cooling allows for the formation of dense baryonic components at the centers of dark matter halos.

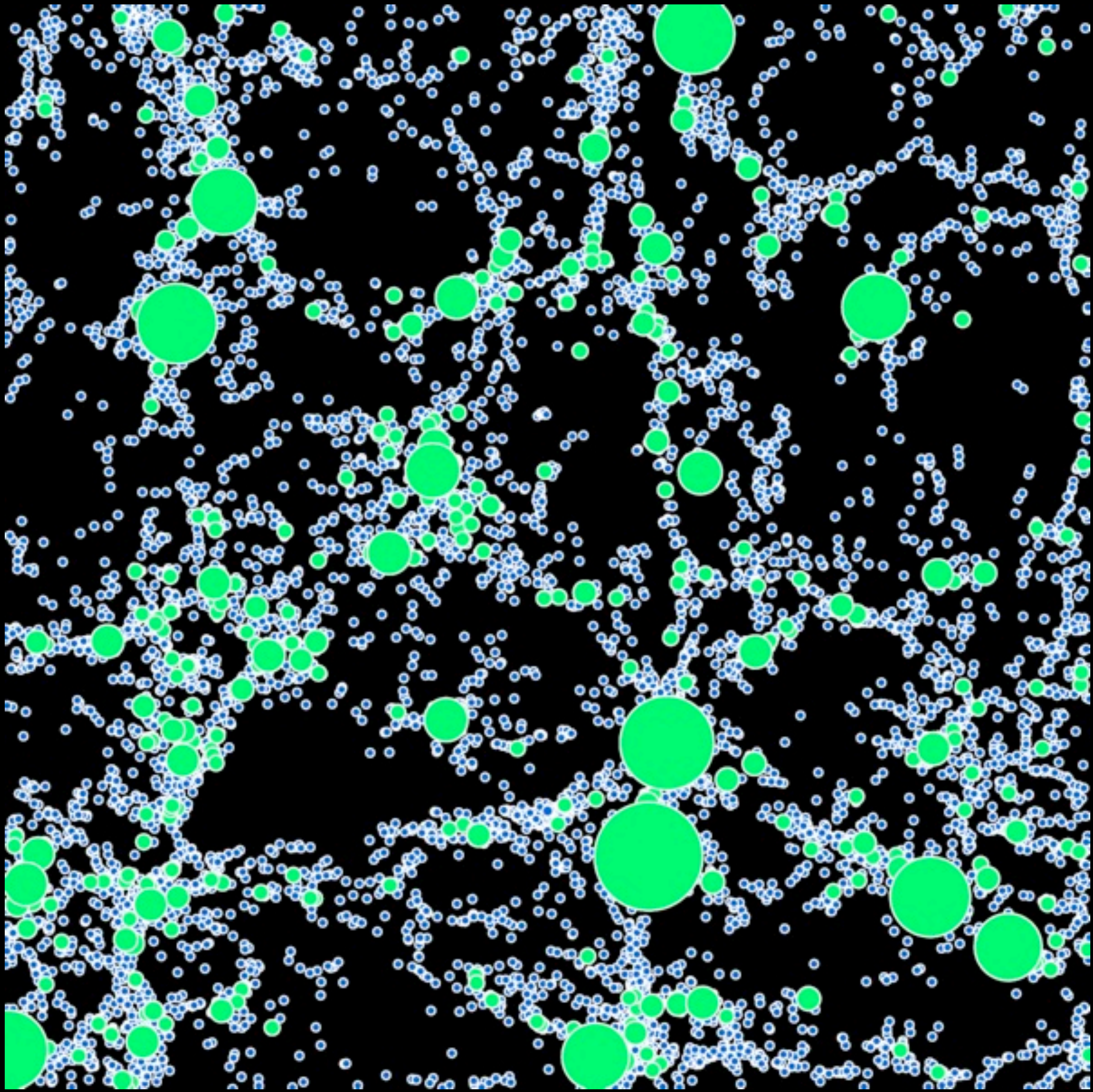


An Overview of Galaxy Formation

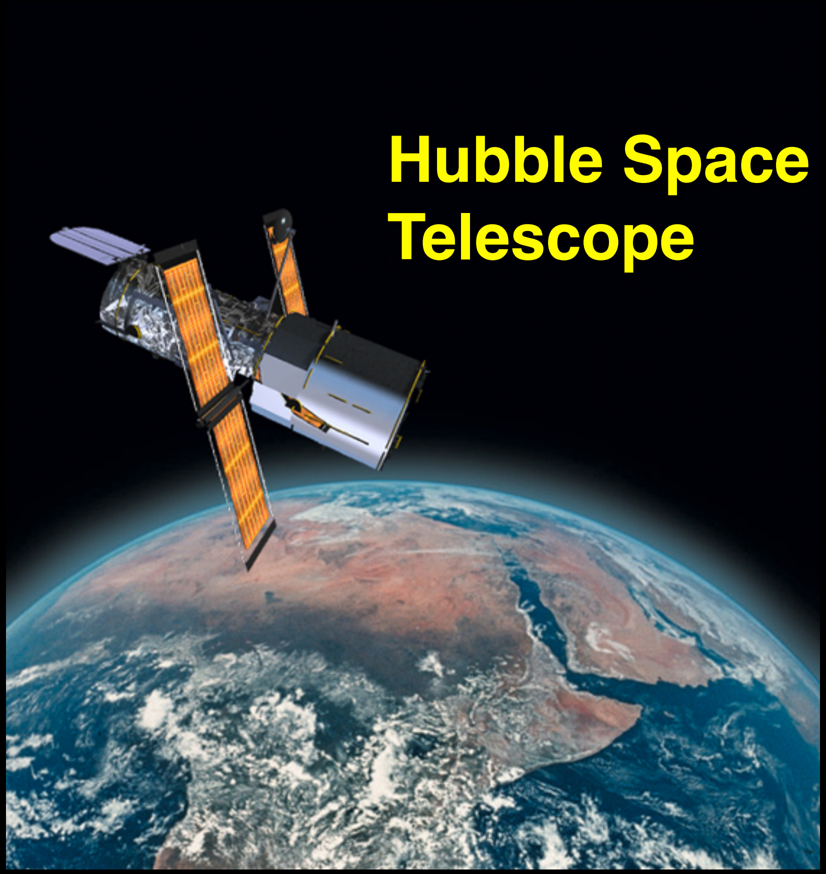
Gas cooling allows for the formation of dense baryonic components at the centers of dark matter halos.

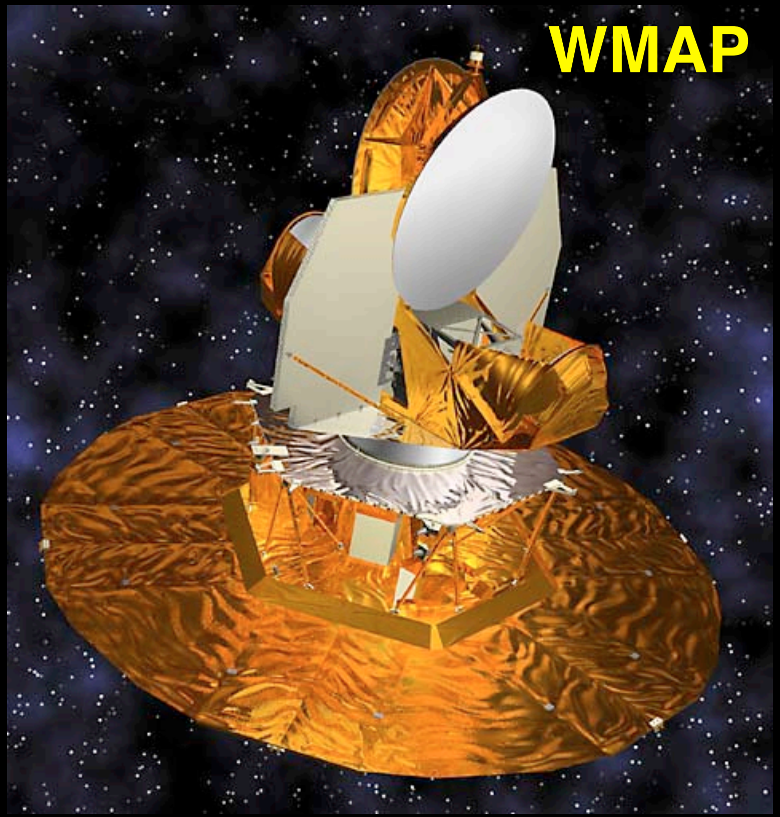
Massive dark matter halos can eventually form baryonic galaxies (green circles).

Low-mass galaxy formation suppressed → inefficient cooling / feedback?



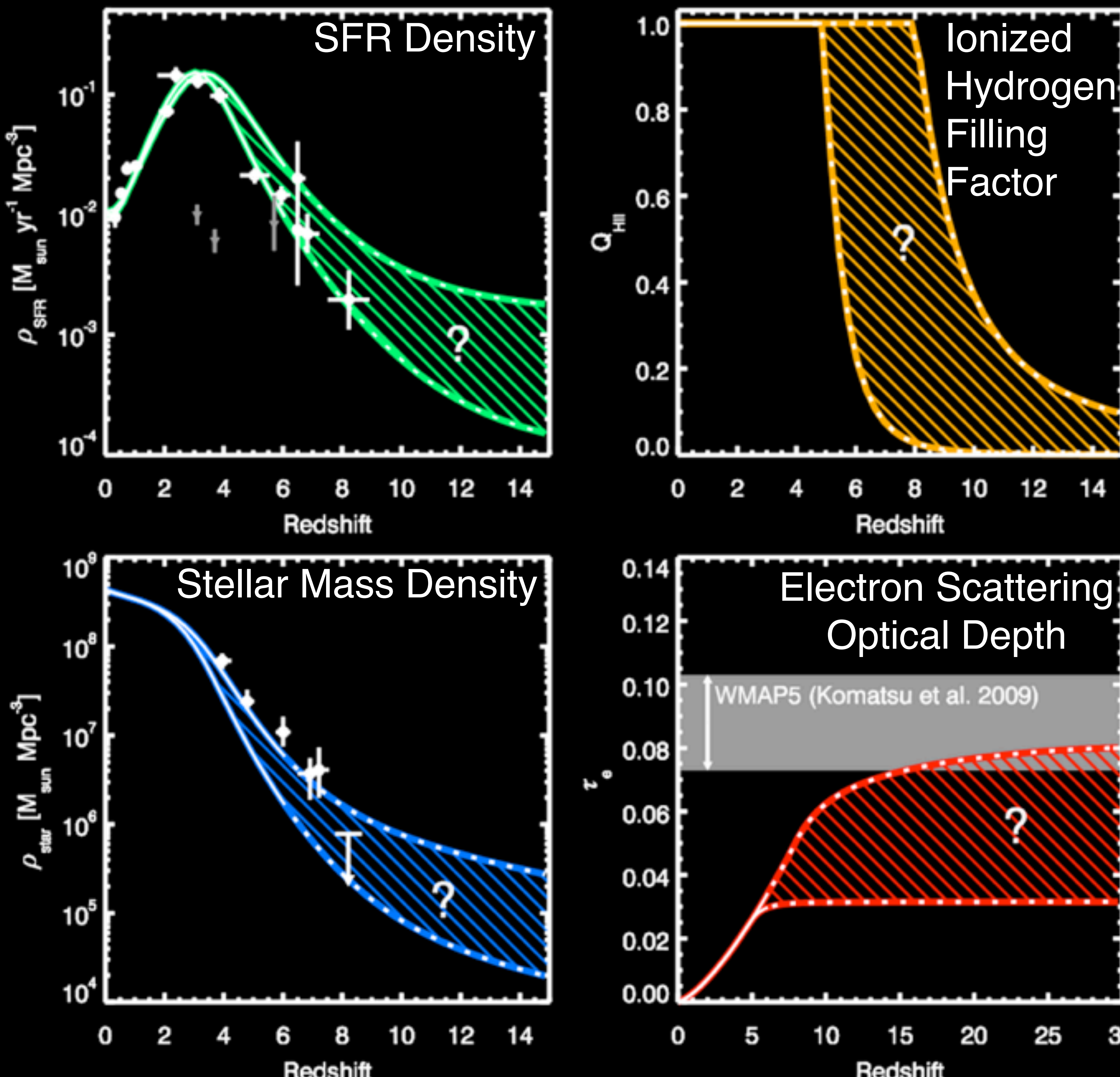
Current Space-Based Facilities For Learning About Galaxy Formation



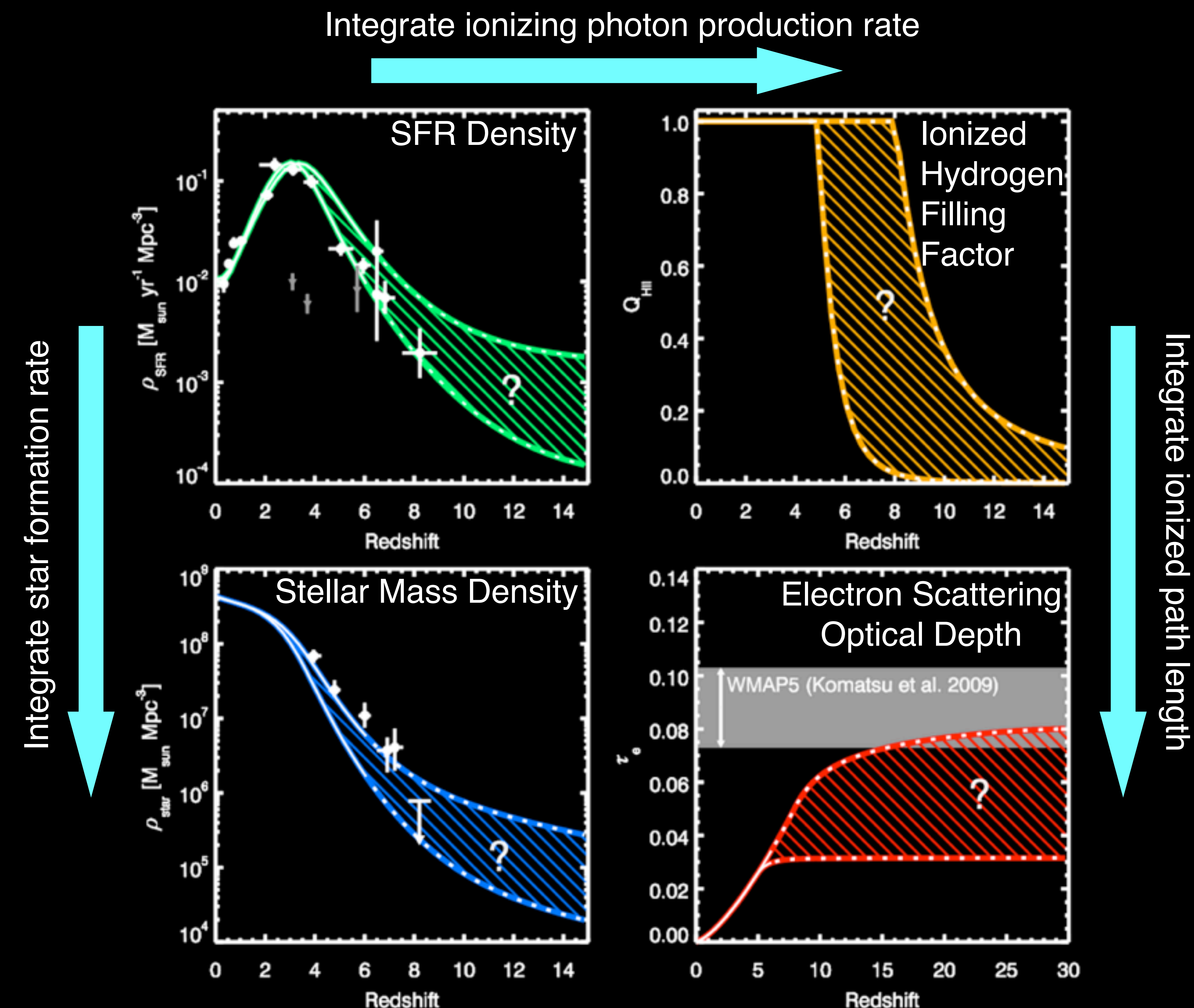


- *HST* - High-resolution imaging in near UV to near IR → discovery
- *SST* - 3.6 & 4.5 μm photometry → stellar mass constraints
- *WMAP* - Thomson optical depth → global reionization constraint

History of Galaxy Formation

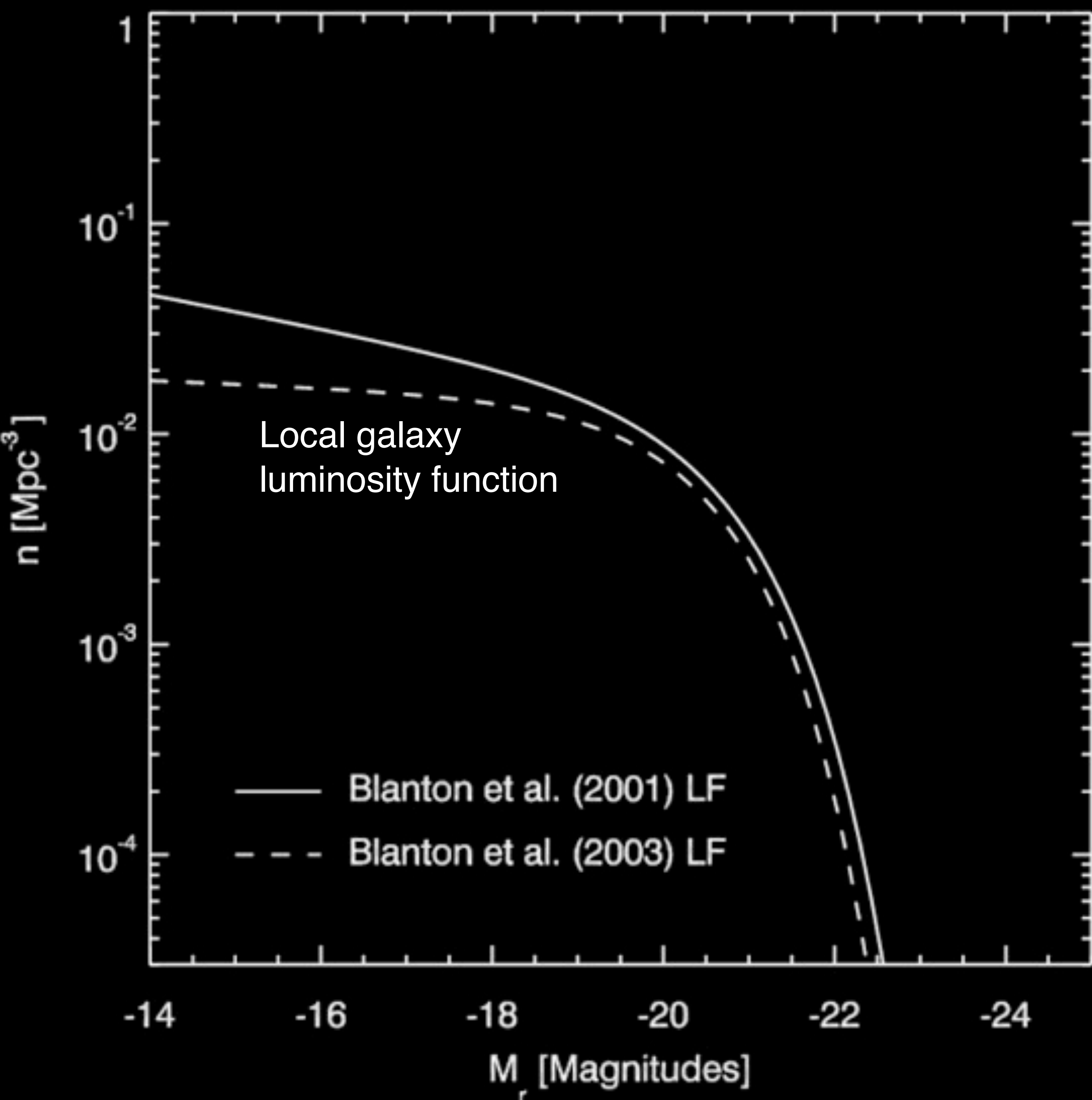


Robertson et al., *Nature*, **468**, 49 (2010d)

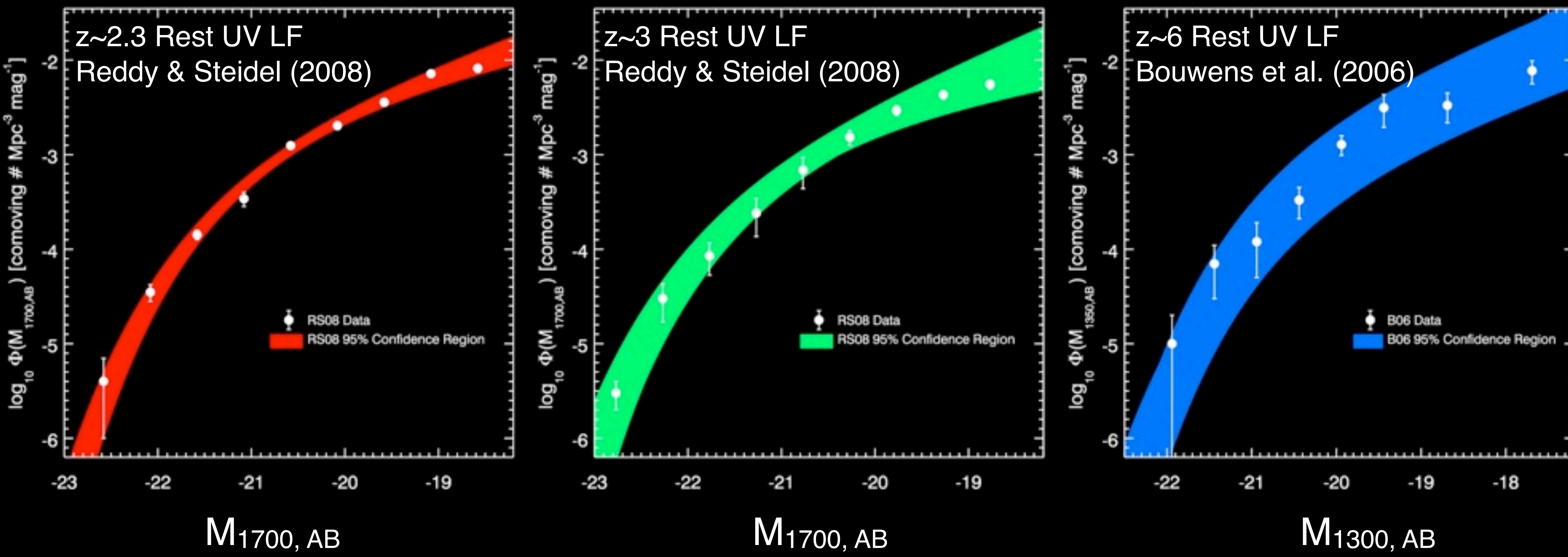


Integrate ionizing photon production rate
Integrate star formation rate
Integrate ionized path length
SFR Density
Ionized Hydrogen Filling Factor
Stellar Mass Density
Electron Scattering Optical Depth
WMAP5 (Komatsu et al. 2009)
Redshift
?

A Primary Challenge for the Theory of Galaxy Formation

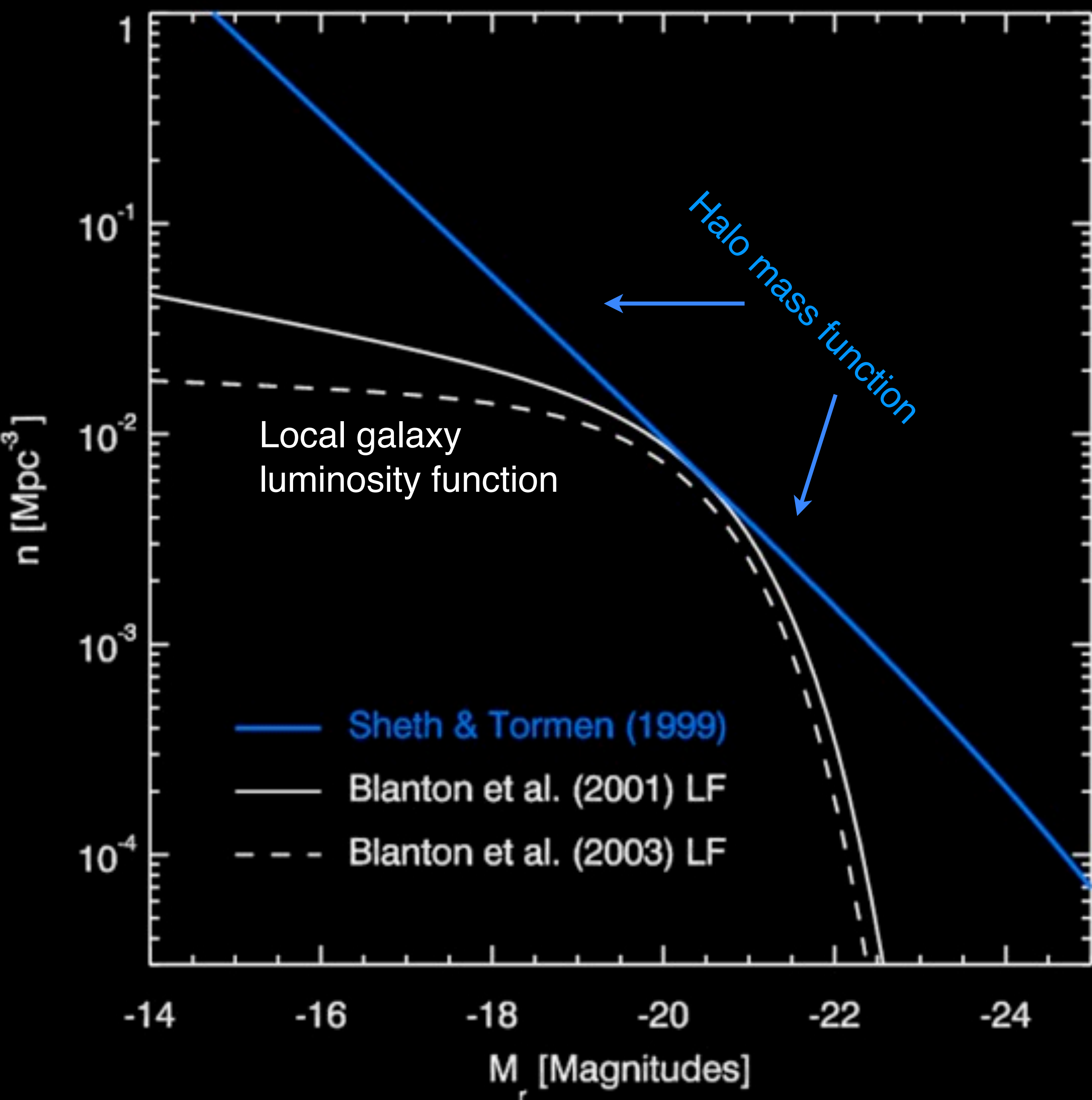


Evolution of the Galaxy Luminosity Function



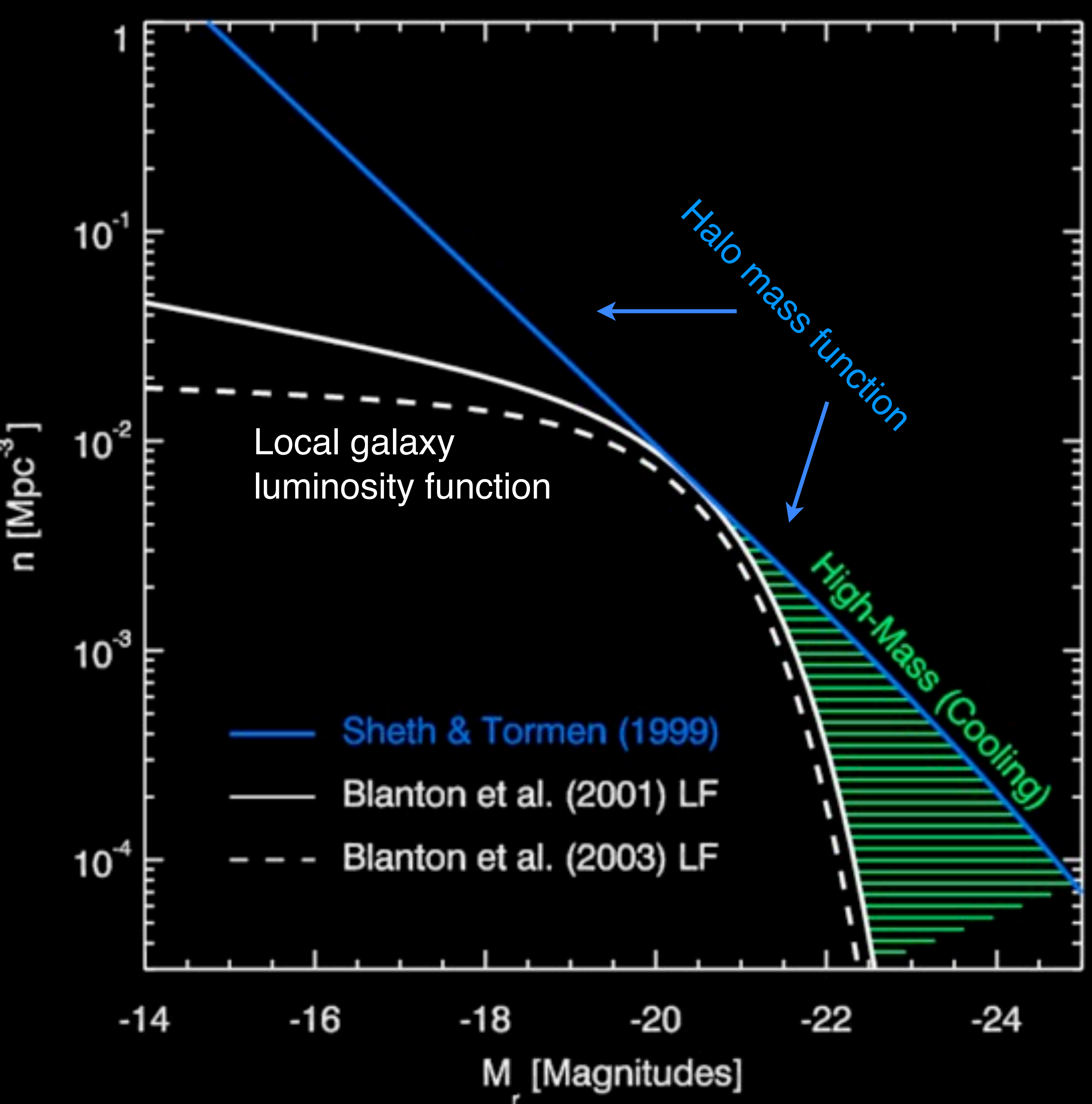
The faint-end slope gets steeper while the normalization and/or the characteristic luminosity declines.

A Primary Challenge for the Theory of Galaxy Formation



Mass function of dark matter halos, normalized to match abundance near L* with constant mass-to-light ratio.

A Primary Challenge for the Theory of Galaxy Formation

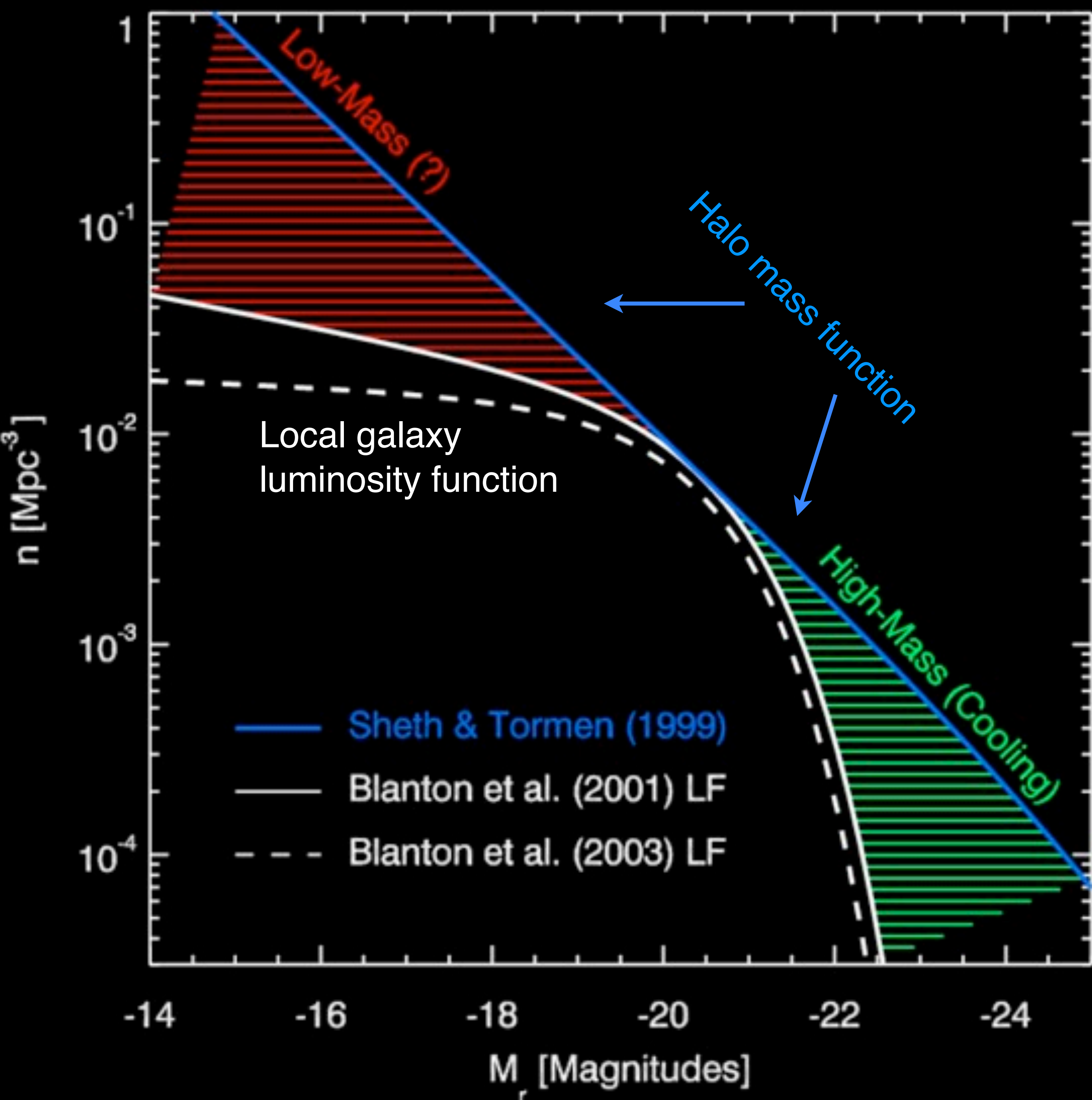


Deficit of bright galaxies relative to massive DM halos.

Suppress gas cooling:

AGN?
multiphase cooling?
hot accretion / shocks?
quenching?

A Primary Challenge for the Theory of Galaxy Formation



Deficit of faint galaxies relative to low-mass DM halos.

Supernova-driven winds?

Photoionization?

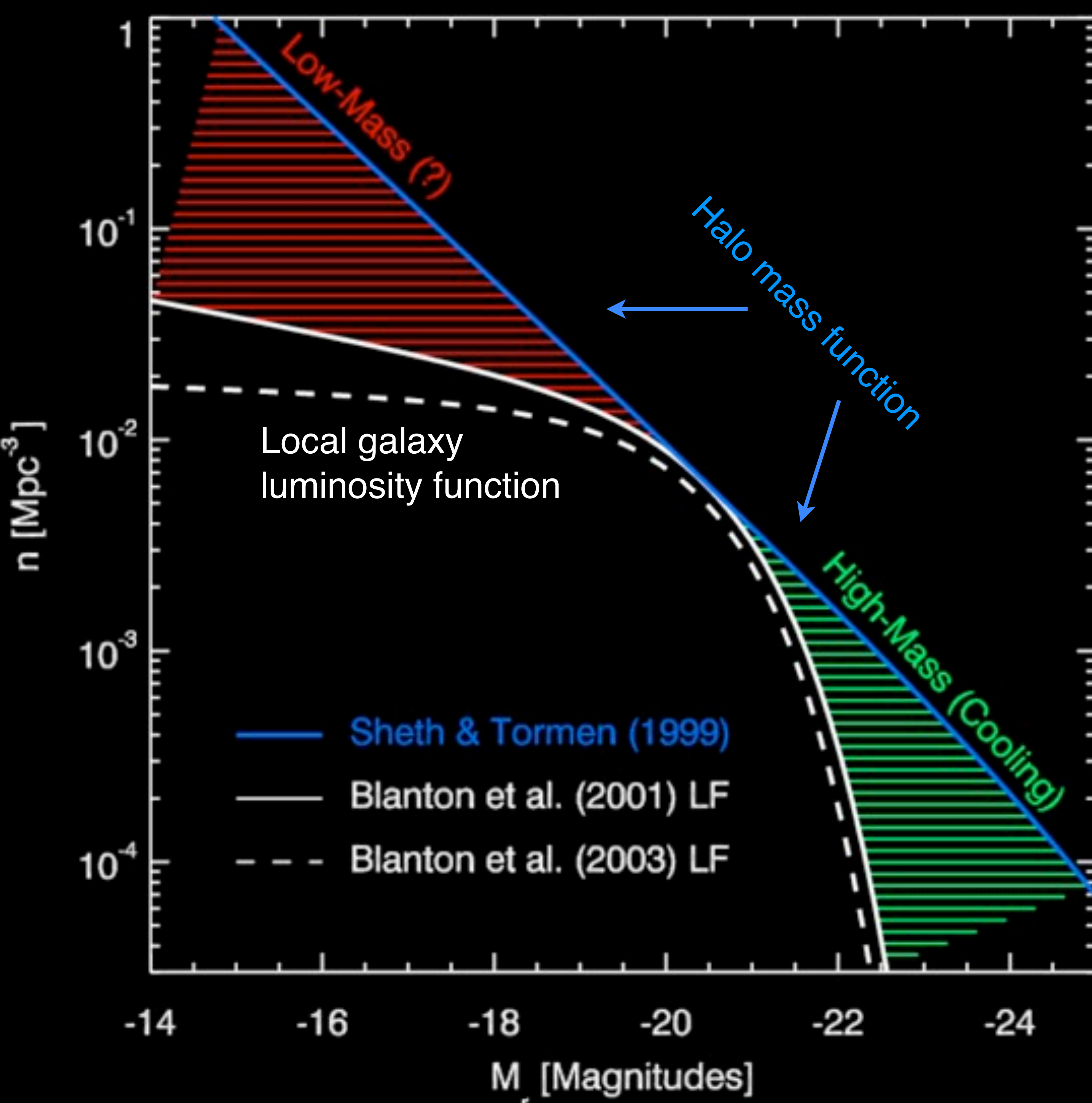
Suppression of small-scale power?

No current method provides a convincing solution.

Image Credit :
NOAO

Image Credit :
NASA/Hubble/Chandra/Spitzer/JPL-Caltech/CXC/UofA/ESA/AURA/JHU

A Primary Challenge for the Theory of Galaxy Formation



Deficit of faint galaxies relative to low-mass DM halos.

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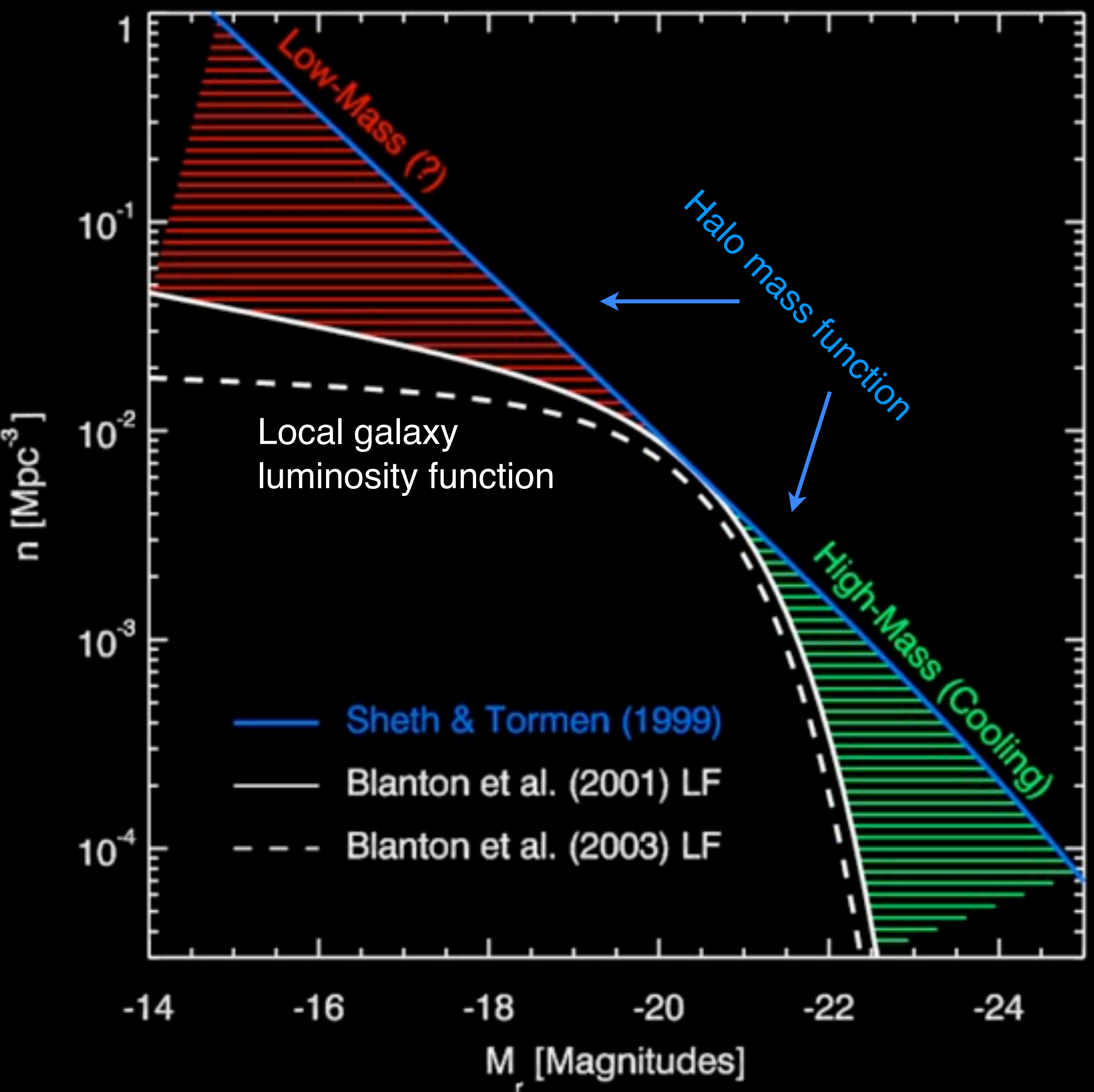
A Primary Challenge for the Theory of Galaxy Formation



Deficit of faint galaxies relative to low-mass DM halos.

Supernova-driven winds?

Photoionization?

Suppression of small-scale power?

No current method provides a convincing solution.

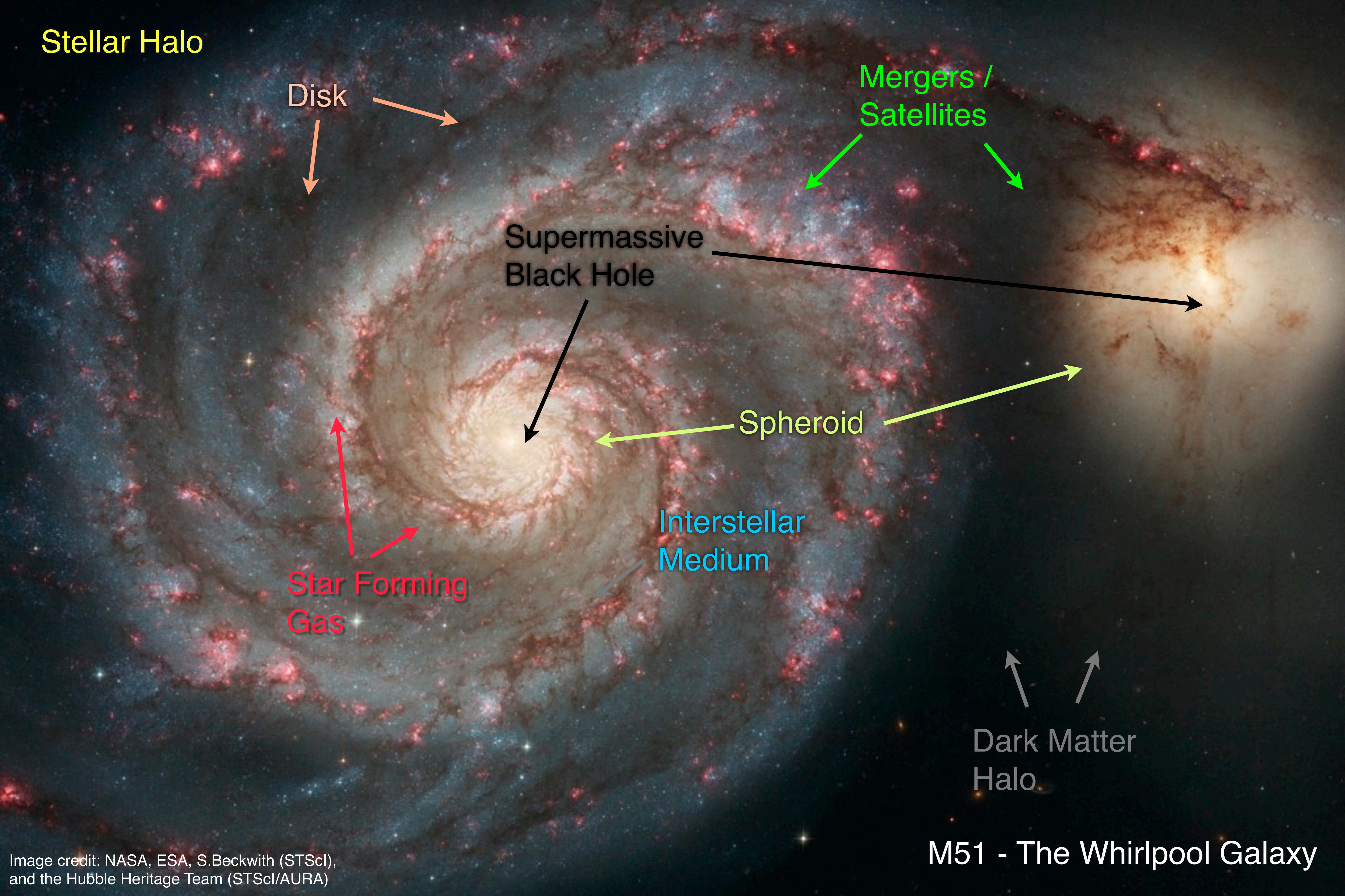
Possible Key: Low-mass galaxies are **gas rich.**

The Structural Components of Galaxies

M51 - The Whirlpool Galaxy

Image credit: NASA, ESA, S.Beckwith (STScI), and the Hubble Heritage Team (STScI/AURA)

The Structural Components of Galaxies

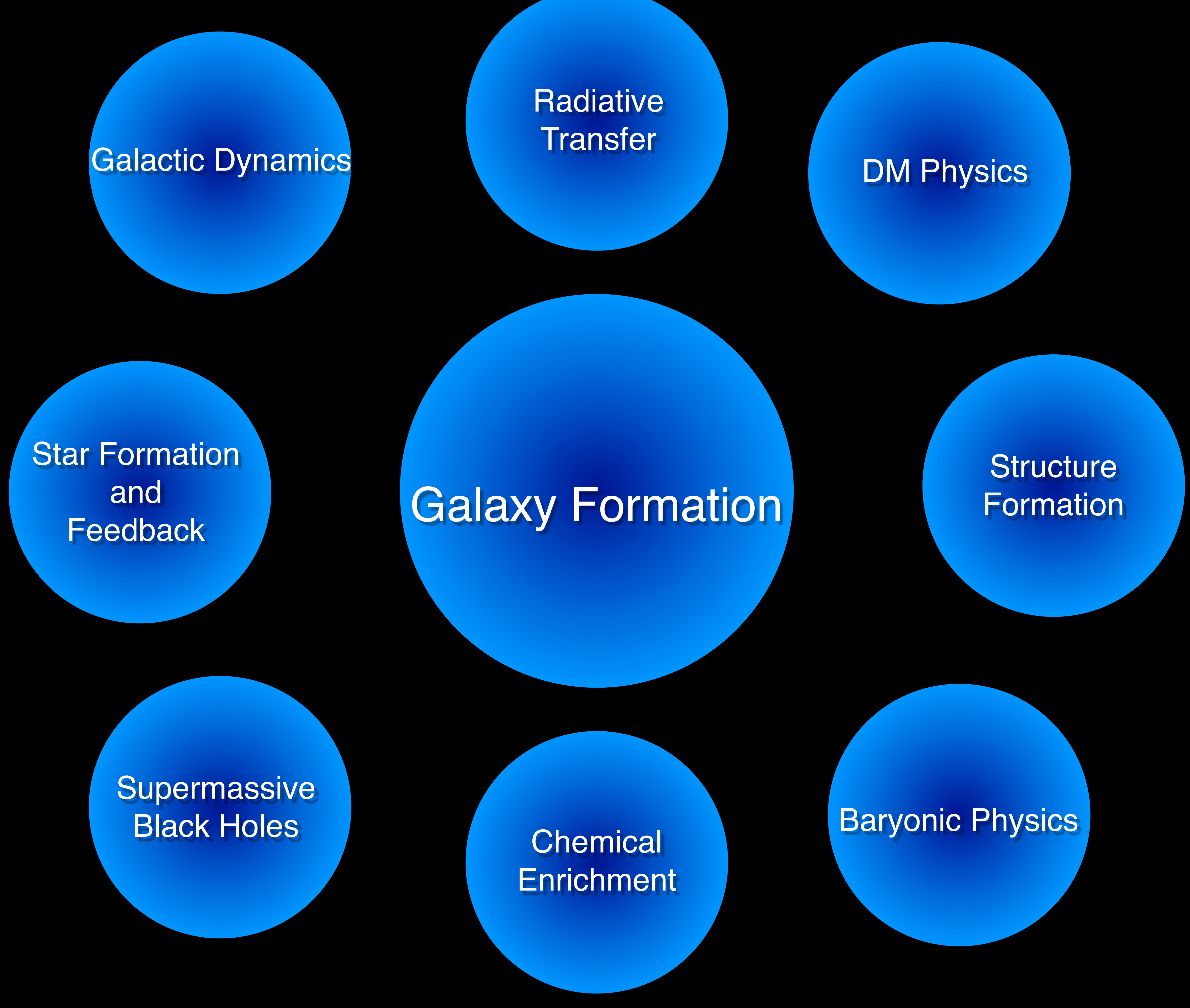


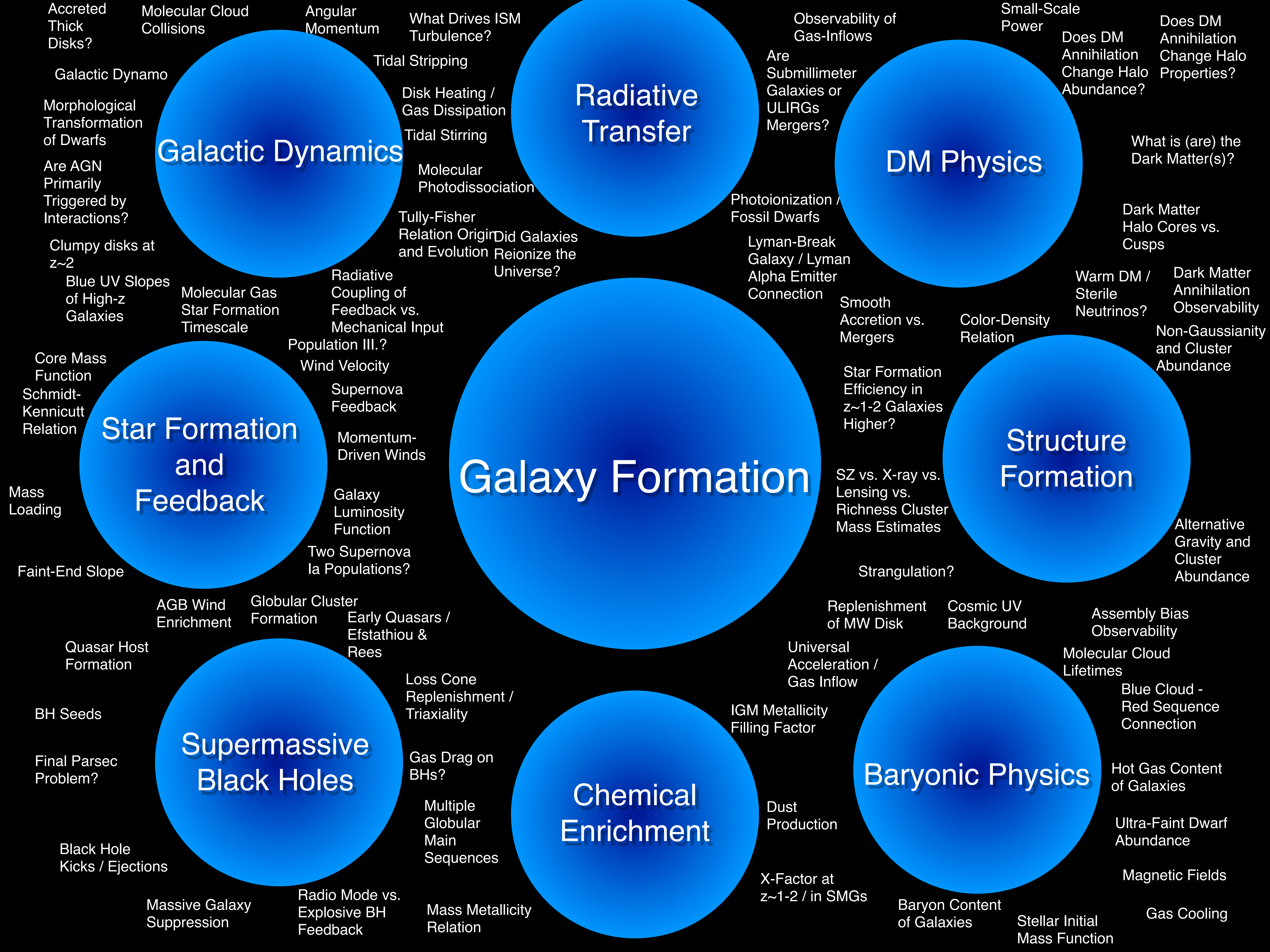
M51 - The Whirlpool Galaxy

Image credit: NASA, ESA, S.Beckwith (STScI), and the Hubble Heritage Team (STScI/AURA)

What are the outstanding problems?

Galaxy Formation


Galactic Dynamics
Radiative Transfer
DM Physics
Star Formation and Feedback
Galaxy Formation
Structure Formation
Supermassive Black Holes
Chemical Enrichment
Baryonic Physics


Galaxy Formation
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Accreted Thick Disks?
Molecular Cloud Collisions
Angular Momentum
What Drives ISM Turbulence?
Tidal Stripping
Galactic Dynamo
Morphological Transformation of Dwarfs
Disk Heating / Gas Dissipation
Tidal Stirring
Are AGN Primarily Triggered by Interactions?
Molecular Photodissociation
Clumpy disks at z~2
Tully-Fisher Relation Origin and Evolution
Did Galaxies Reionize the Universe?
Blue UV Slopes of High-z Galaxies
Molecular Gas Star Formation Timescale
Radiative Coupling of Feedback vs. Mechanical Input
Population III.?
Wind Velocity
Observability of Gas-Inflows
Are Submillimeter Galaxies or ULIRGs Mergers?
Small-Scale Power
Does DM Annihilation Change Halo Abundance?
Does DM Annihilation Change Halo Properties?
What is (are) the Dark Matter(s)?
Photoionization / Fossil Dwarfs
Dark Matter Halo Cores vs. Cusps
Lyman-Break Galaxy / Lyman Alpha Emitter Connection
Warm DM / Sterile Neutrinos?
Dark Matter Annihilation Observability
Smooth Accretion vs. Mergers
Color-Density Relation
Non-Gaussianity and Cluster Abundance
Core Mass Function
Schmidt-Kennicutt Relation
Supernova Feedback
Momentum-Driven Winds
Star Formation Efficiency in z~1-2 Galaxies Higher?
Mass Loading
Galaxy Luminosity Function
SZ vs. X-ray vs. Lensing vs. Richness Cluster Mass Estimates
Alternative Gravity and Cluster Abundance
Faint-End Slope
Two Supernova Ia Populations?
Strangulation?
AGB Wind Enrichment
Globular Cluster Formation
Early Quasars / Efstathiou & Rees
Replenishment of MW Disk
Cosmic UV Background
Assembly Bias Observability
Quasar Host Formation
Universal Acceleration / Gas Inflow
Molecular Cloud Lifetimes
Loss Cone Replenishment / Triaxiality
Blue Cloud - Red Sequence Connection
BH Seeds
IGM Metallicity Filling Factor
Final Parsec Problem?
Gas Drag on BHs?
Hot Gas Content of Galaxies
Multiple Globular Main Sequences
Dust Production
Ultra-Faint Dwarf Abundance
Black Hole Kicks / Ejections
X-Factor at z~1-2 / in SMGs
Magnetic Fields
Massive Galaxy Suppression
Radio Mode vs. Explosive BH Feedback
Mass Metallicity Relation
Baryon Content of Galaxies
Stellar Initial Mass Function
Gas Cooling

Where to begin?!?

You Tell Me!

The remarkable design of this meeting brings together brilliant people to solve problems.

Let me facilitate further discussions via five brief reviews of recent work by renown experts in the field:

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Risa Wechsler

Busha, Wechsler et al., arXiv:1011.6373

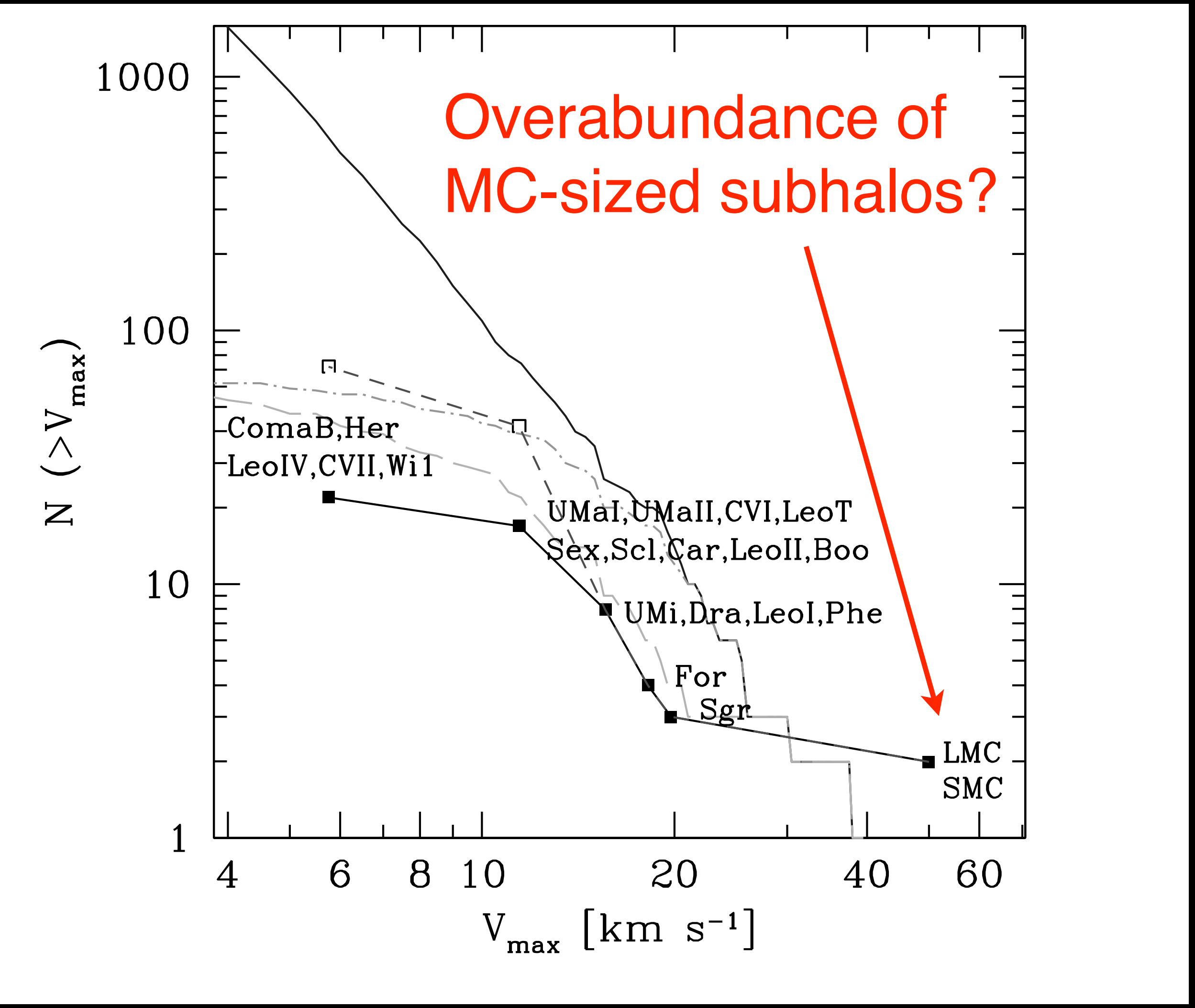
Problem:

Satellite galaxy populations about the Milky Way are direct evidence of hierarchical structure formation. In contrast to the “missing satellite” problem, do simulations of Galaxy-sized halos correctly predict the abundance of massive satellites compared to the Magellanic Clouds-Milky Way system.

How unusual is the MC-MW system in the context of ΛCDM structure formation?

Risa Wechsler

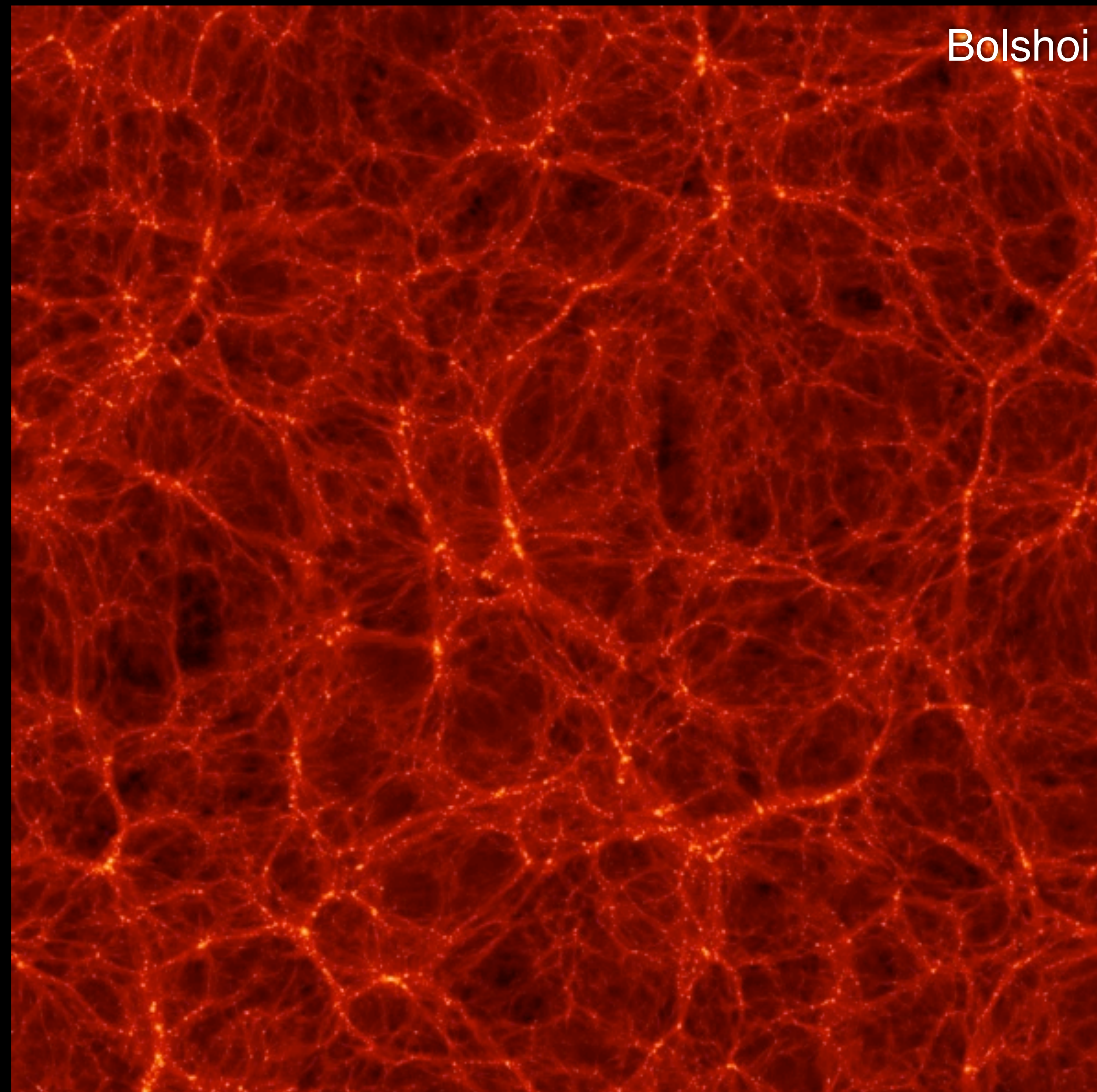
Busha, Wechsler et al., arXiv:1011.6373



Madau et al. 2008

Risa Wechsler

Busha, Wechsler et al., arXiv:1011.6373



Methodology:

Use the Bolshoi N-body simulation (250 h^{-1} Mpc, 2048^3 particles, σ_8=0.82) to study 36,000 MW analogues.

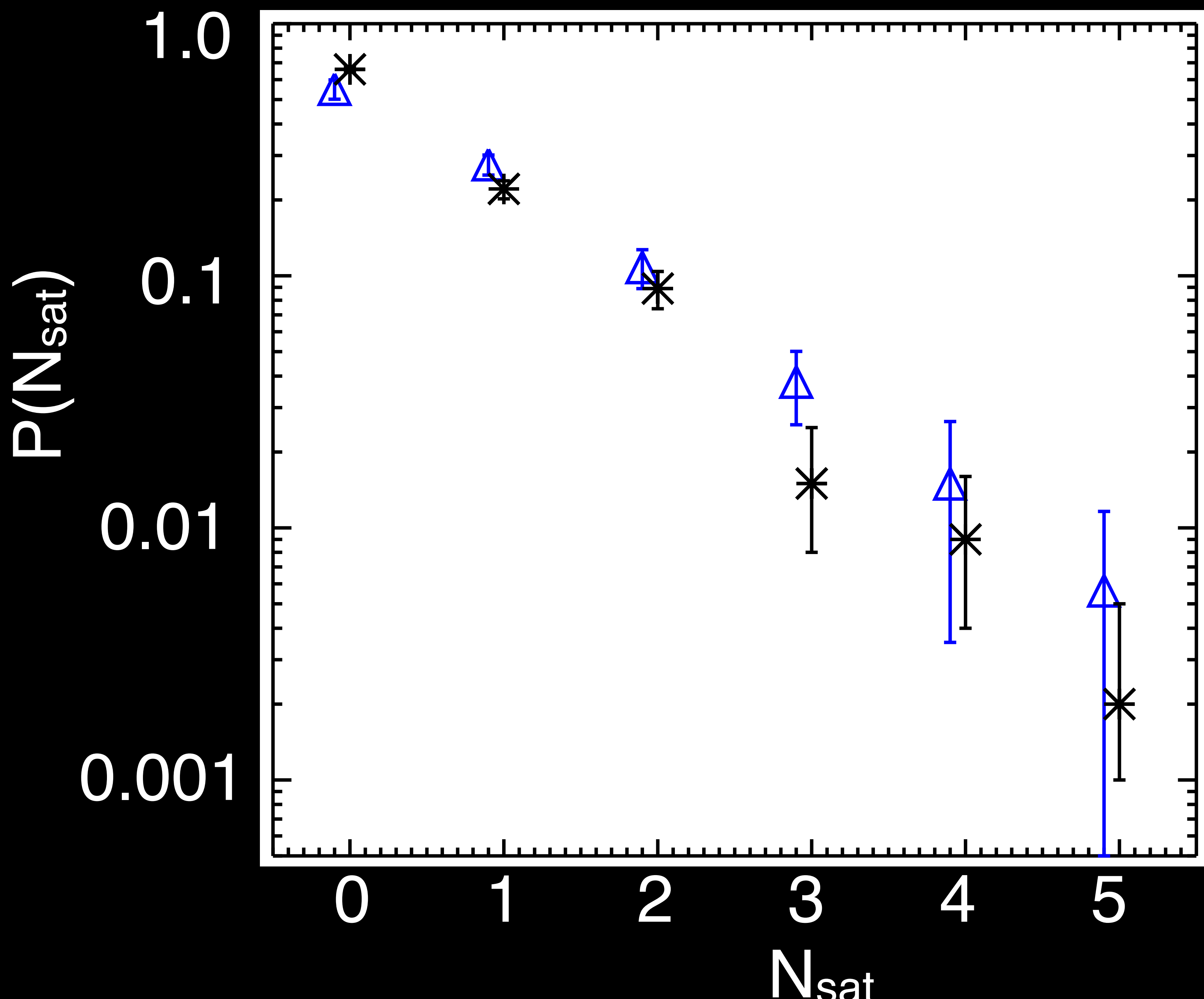
Apply Risa's subhalo abundance-matching (SHAM) method to assign luminosities to substructure and compare with the observed abundance of MC-MW analogues (Liu et al. 2010).

Risa Wechsler

Busha, Wechsler et al., arXiv:1011.6373

Results:

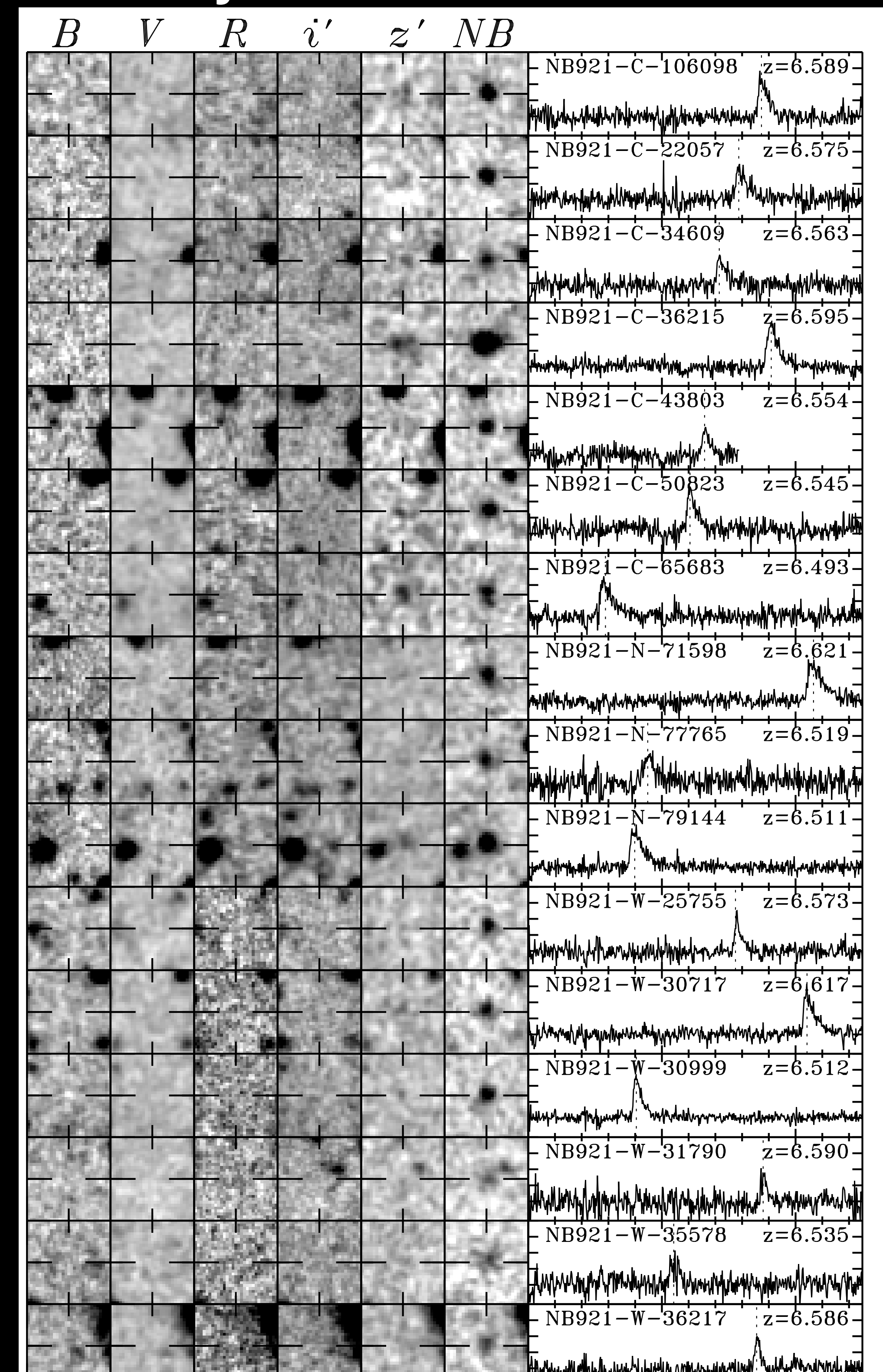
5-10% of simulated MW halos contains 2 SMC-luminous satellites (after SHAM; see also Boylan-Kolchin et al. 2010), in agreement with observations by Liu et al. 2010.



Andrea Ferrara

Dayal and Ferrara, arXiv:1102.1726

Lyman-α Emitters



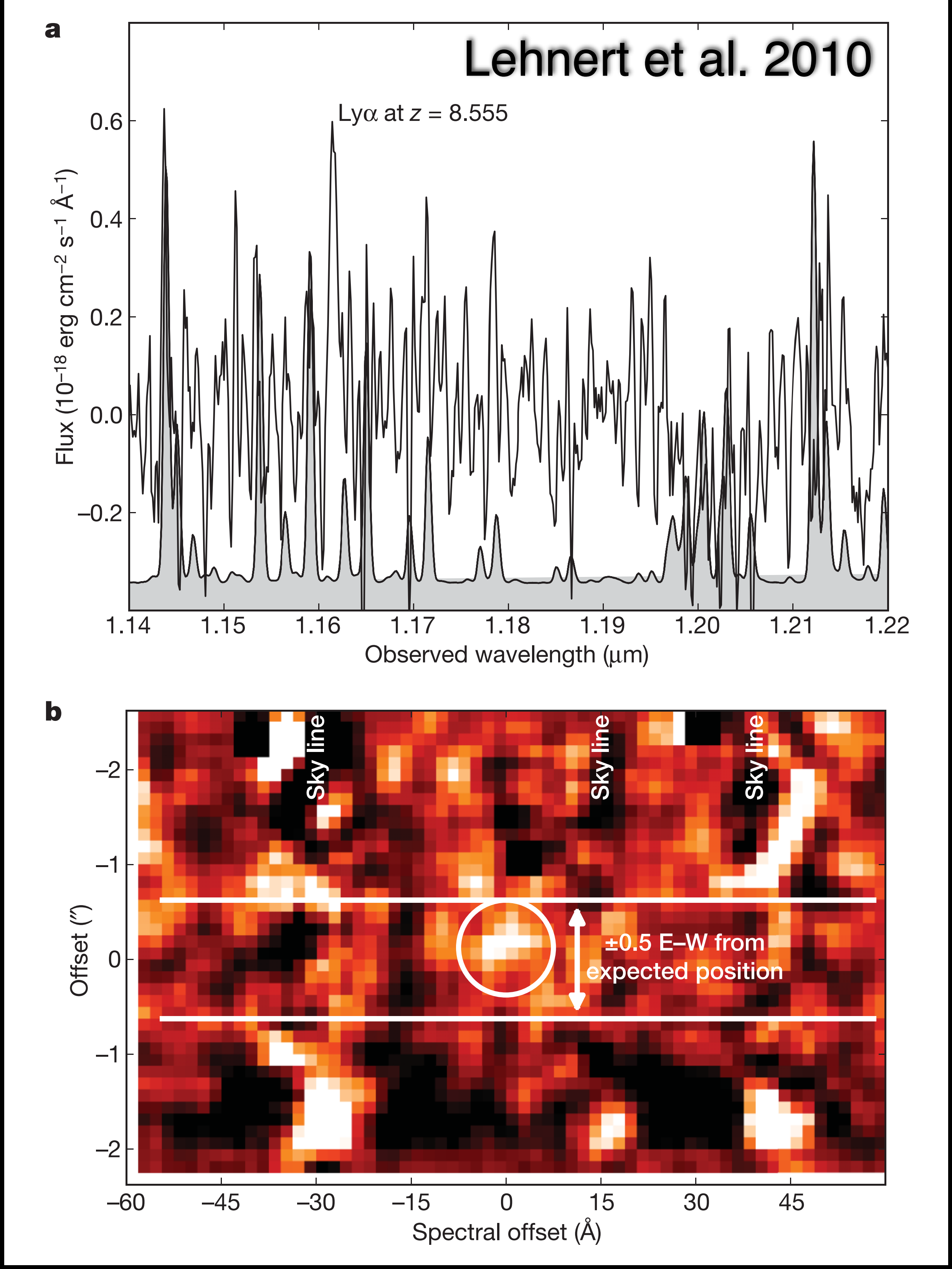
Ouchi et al. 2010

Problem:

How should we interpret the properties of the most distant known Lyman-α emitting galaxies, and can we use their properties to learn about the ionization state of the intergalactic medium?

Andrea Ferrara

Dayal and Ferrara, arXiv:1102.1726



Background:

Lehnert et al. 2010 claimed detection of Lyα emission from a LBG at z~8.6 previously discovered in the UDF.

What does the presence of Lyα emission in this galaxy imply about cosmological galaxy populations and the ionization state of the IGM?

Andrea Ferrara

Dayal and Ferrara, arXiv:1102.1726

Methodology:

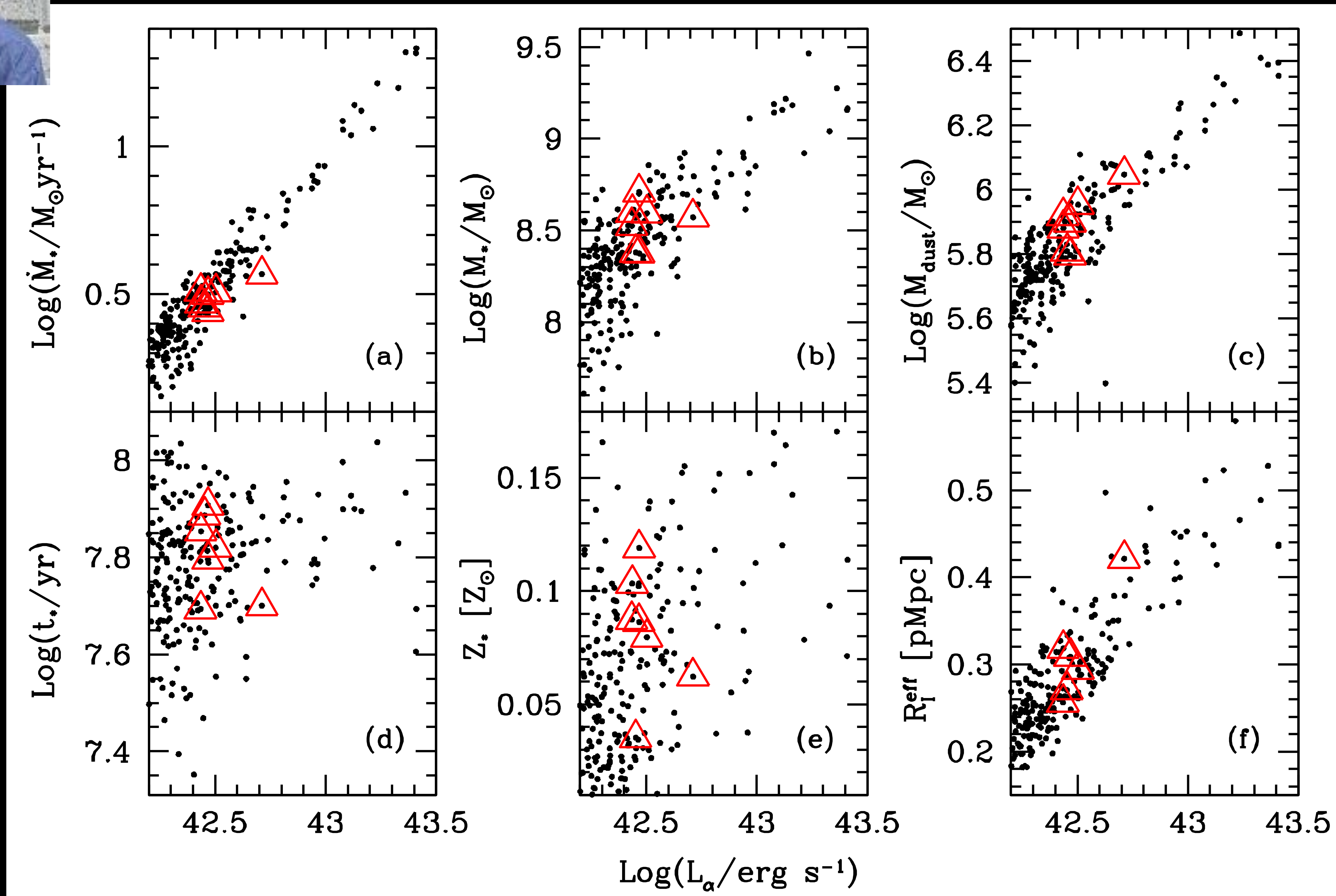
Perform a cosmological hydro simulation (75 h^{-1} Mpc, 512^3 DM + 512^3 gas particles), identify galaxies at $z = 8.6$.

Model the production and attenuation of Lyα emission, accounting for different average IGM neutral fractions and locally (at least partially) ionized regions around galaxies. Find the fraction of Lyα photons reaching the observer.

Compare the properties of simulated Lyα emitting galaxies with observed LAE galaxy properties.

Andrea Ferrara

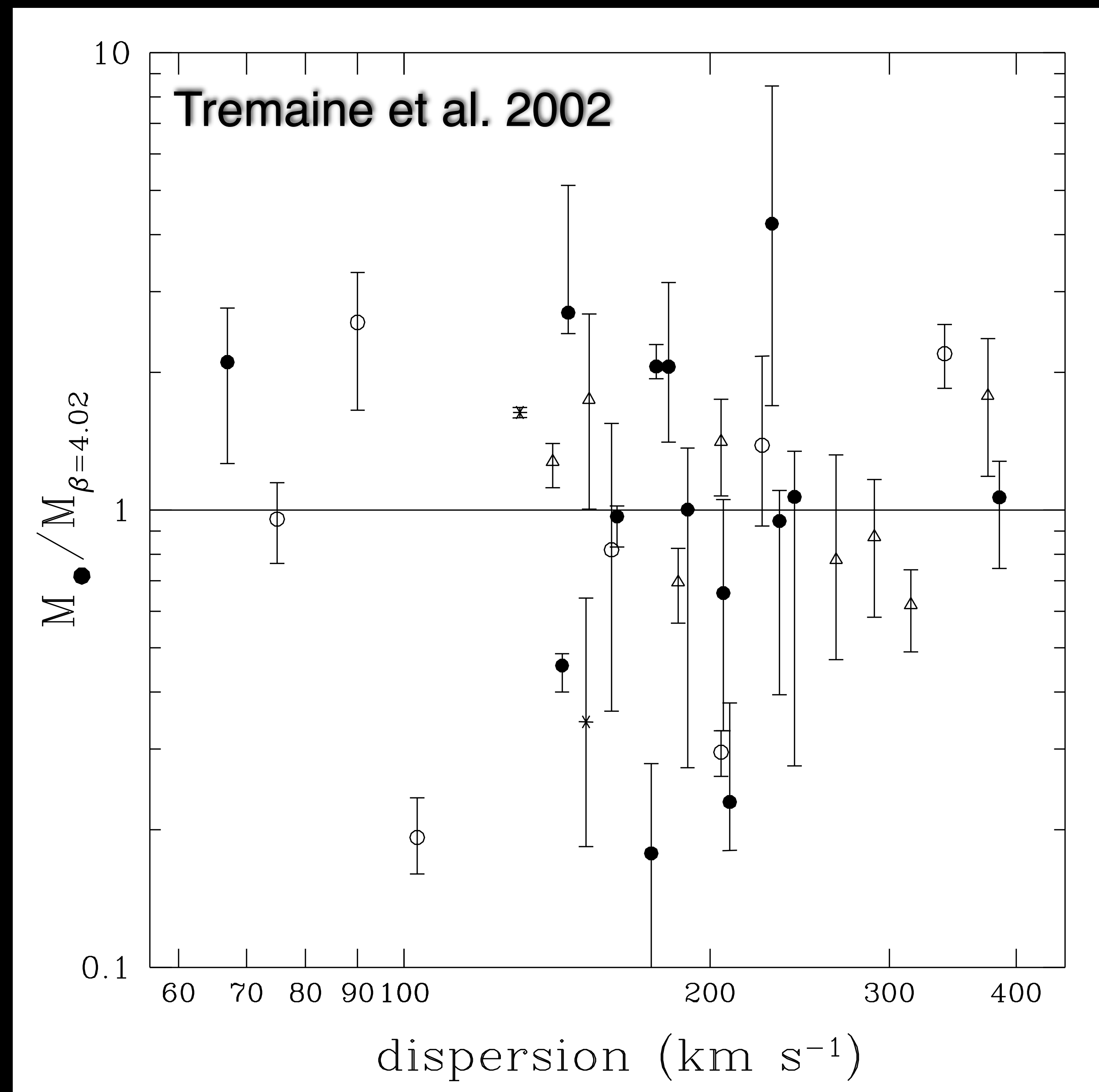
Dayal and Ferrara, arXiv:1102.1726



Red triangles: simulated LAE galaxy properties with UV and Lyα properties similar to observed z = 8.6 galaxies.

Rachel Somerville

Somerville, MNRAS, **399,** 1988 (2009)



Problem:

There are remarkable observed relationships between black hole mass, galaxy stellar mass, and velocity dispersion (Ferrarese & Merrit 2000, Gebhardt et al. 2000, Tremaine et al. 2002, Marconi & Hunt 2003, Haring and Rix 2004). The observed scatter is small (0.3 dex in m_{BH} at fixed σ, and 0.5 dex in m_{BH} at fixed L).

Do these relations evolve (e.g., Peng et al. 2006, Robertson et al. 2006)?

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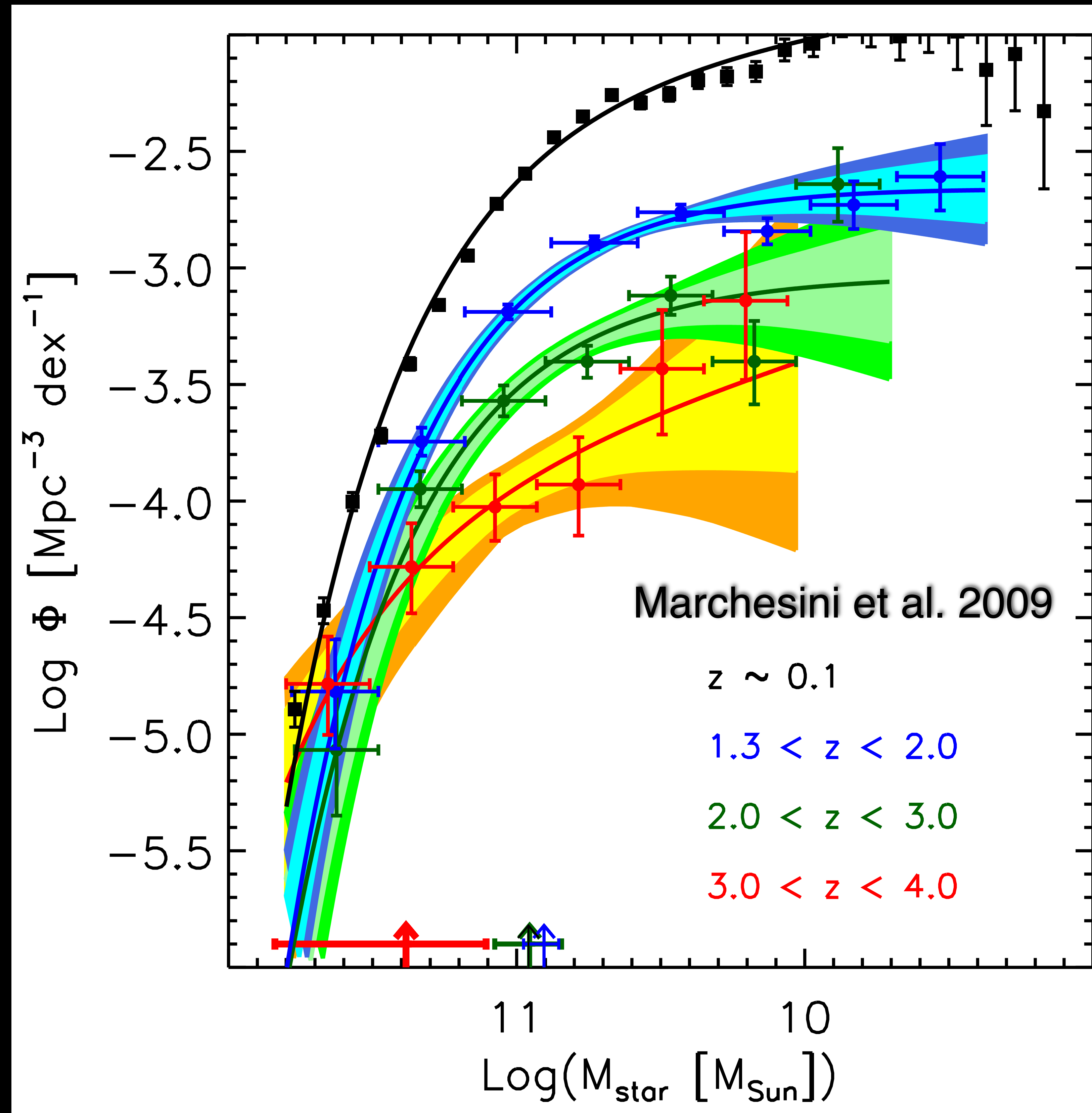


Methodology:

Assuming all galaxies contain BHs, combine the galaxy stellar mass function, a duty cycle, and average Eddington ratio to predict the QSO bolometric luminosity function, and compare with observations.

How much can the SMBH mass / stellar mass relation evolve without over-predicting the abundance of luminous QSOs given the observed scatter in the local relations?

Rachel Somerville

Somerville, MNRAS, **399,** 1988 (2009)

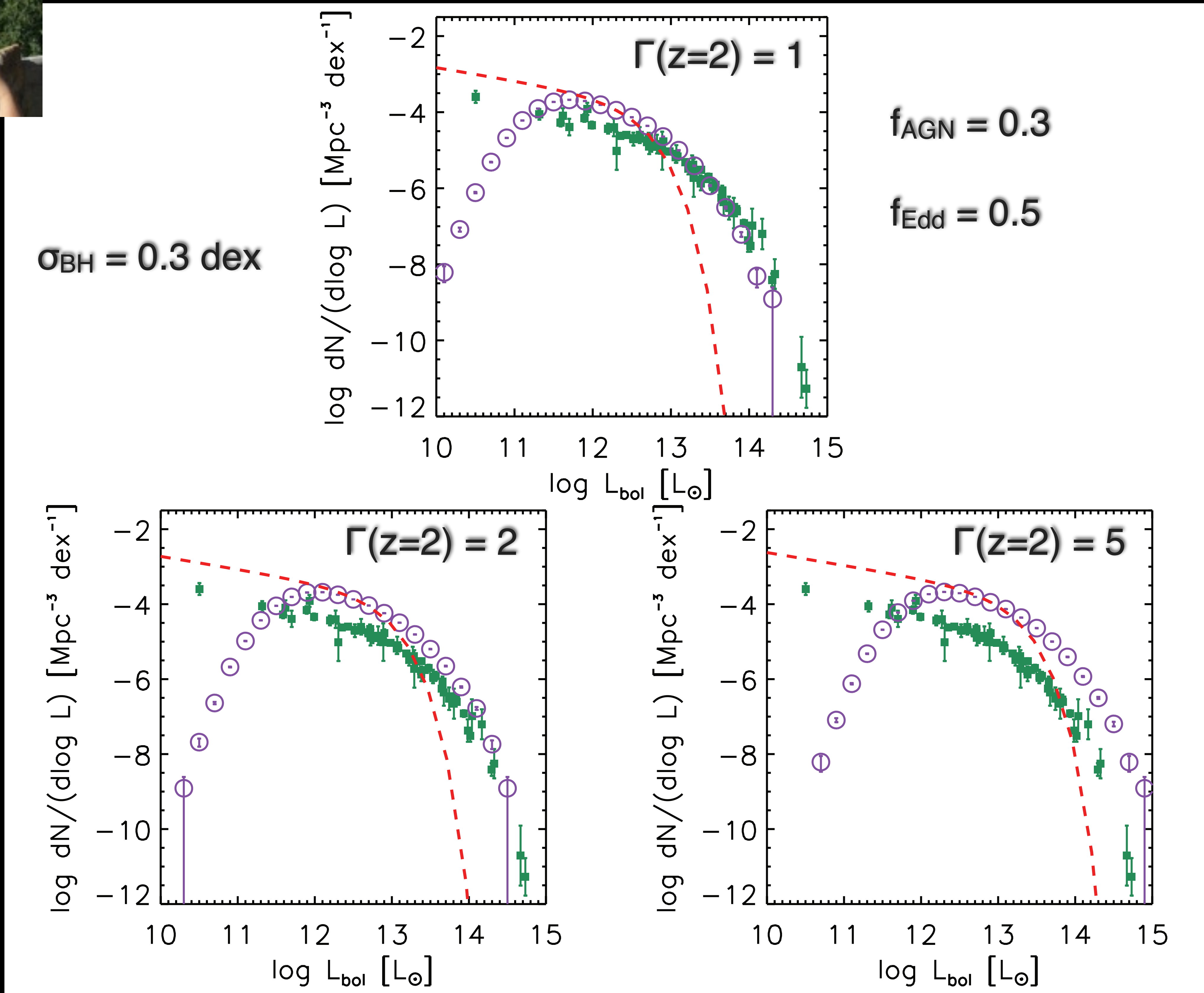
$$m_{\rm BH}(z, m_{\rm gal}) = \Gamma(z) m_{\rm BH}(z=0, m_{\rm gal}) = \Gamma(z) m_{\rm gal}^{1.1}$$

Black hole mass — Scaling factor — Galaxy mass

Γ(z=0), how large can Γ(z=2) be without over-producing luminous z=2 QSOs? -- bright quasars may be dominated by systems in the large-BH scatter of the distribution.

Rachel Somerville

Somerville, MNRAS, **399,** 1988 (2009)



Results:

With scatter in the m_{BH}/m_{gal} relation, strong evolution in the ratio m_{BH}/m_{gal} would over-produce the abundance of luminous z~2 QSOs.

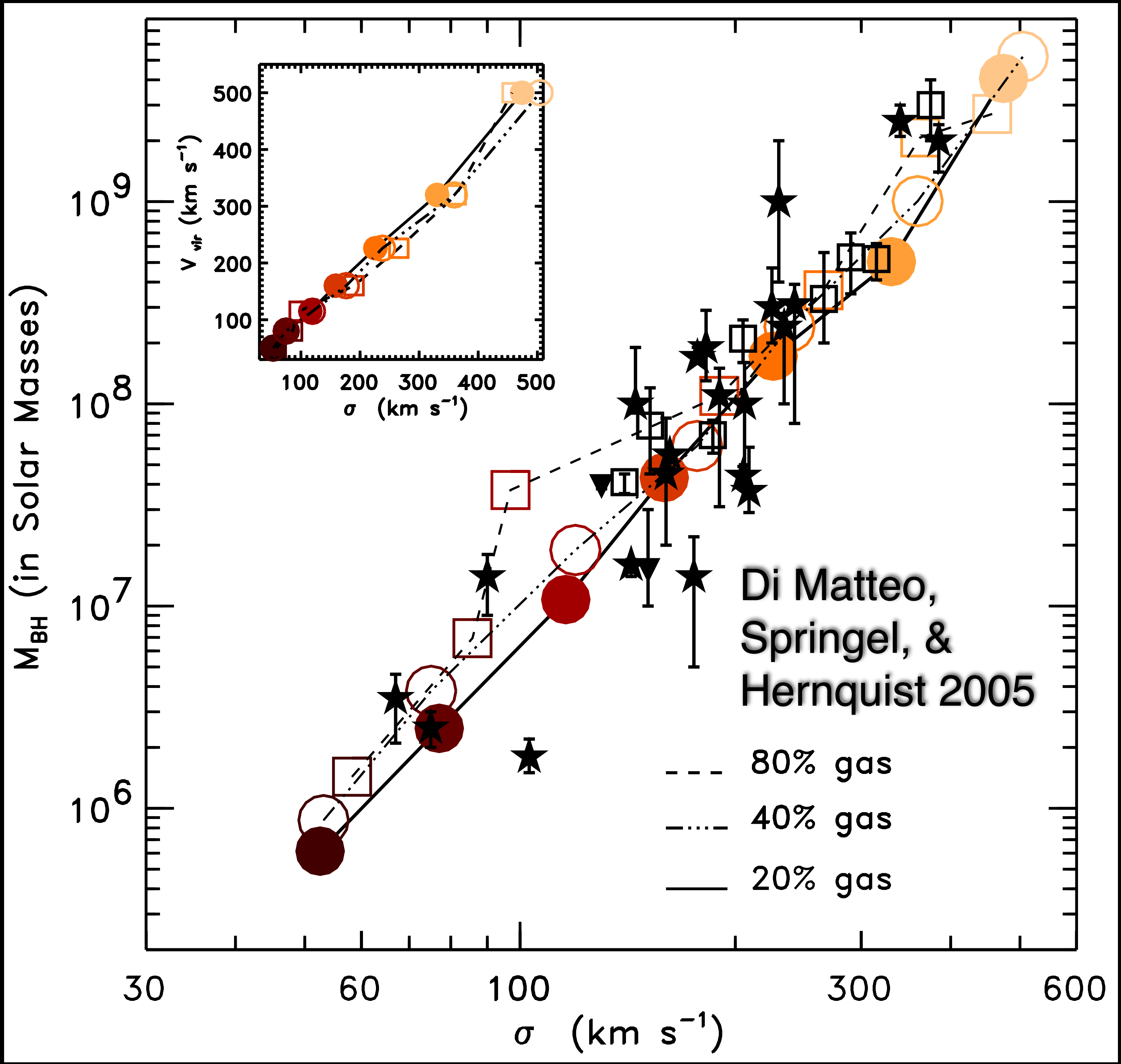
Tiziana Di Matteo

Di Matteo et al., ApJ, **676,** 33 (2008)

Problem:

Observations suggest that the galaxy stellar and black hole components are tightly coupled. Our collective picture for galaxy formation is therefore also a picture of supermassive black hole formation.

Tiziana's famous for calculating how this coupling might arise through gas-rich galaxy mergers. How do these relations develop in a fully cosmological context?



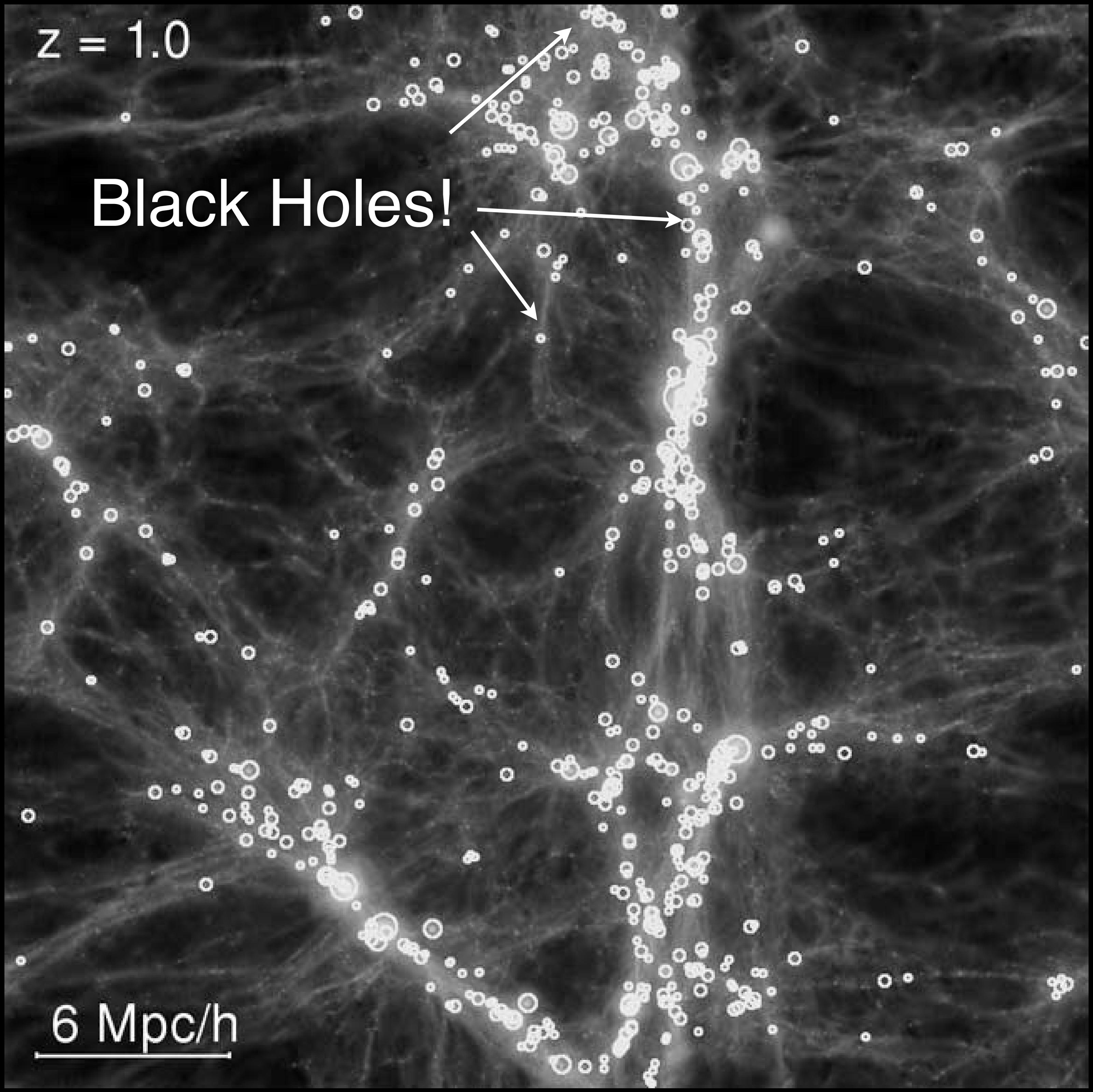
Tiziana Di Matteo

Di Matteo et al., ApJ, **676,** 33 (2008)

Methodology:

Cosmological hydro simulations (34-50 h^{-1} Mpc, $2x486^3$ particles) with galactic winds and a multiphase ISM model (Springel & Hernquist 2003), incorporating a model for growth and feedback from SMBHs (Springel et al. 2005, Di Matteo et al. 2005).

Populate growing halos above a threshold mass with a black hole seed, track the cosmological development of the SMBH population and the BH-galaxy connection.



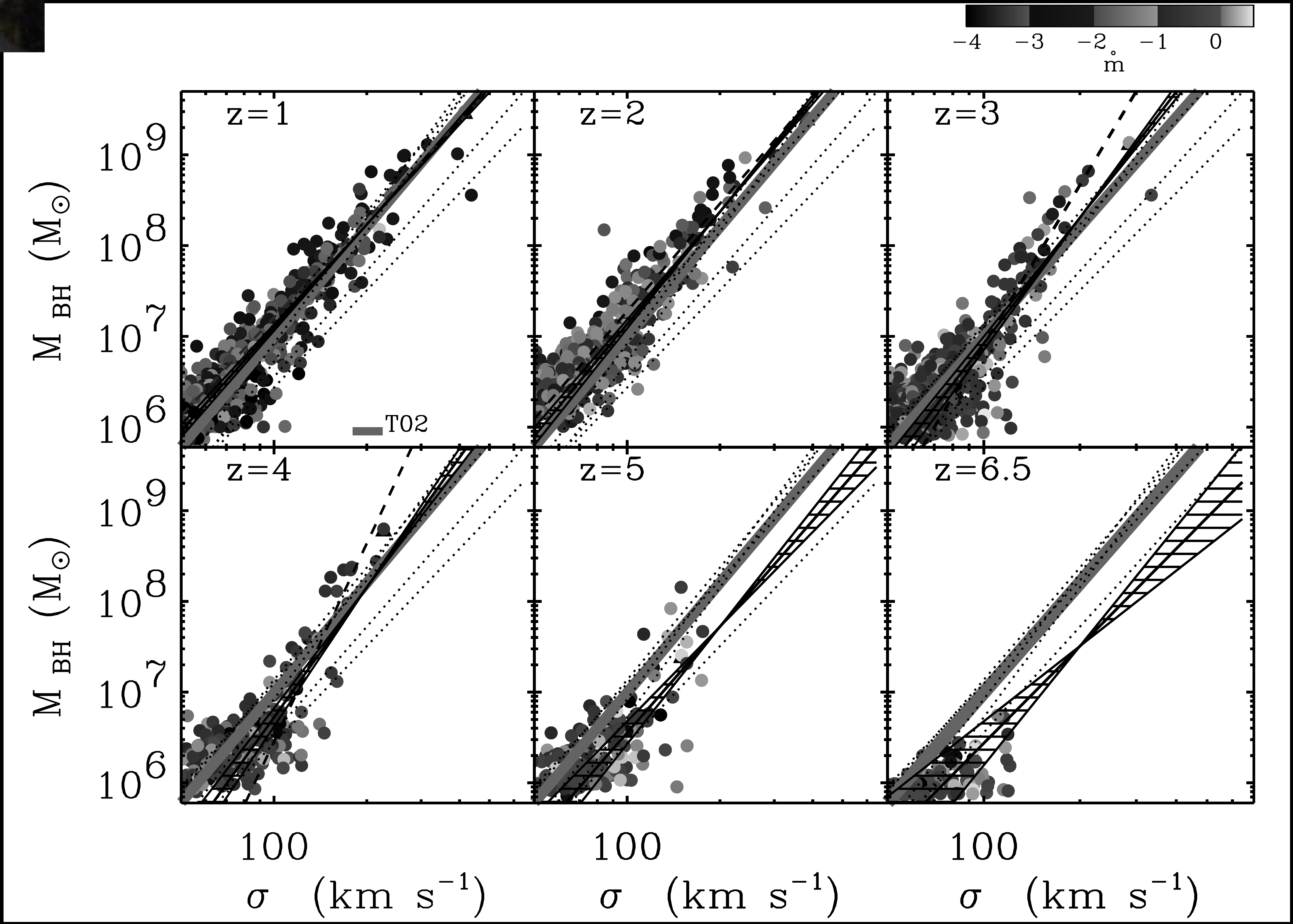
Tiziana Di Matteo

Di Matteo et al., ApJ, **676,** 33 (2008)

Results:

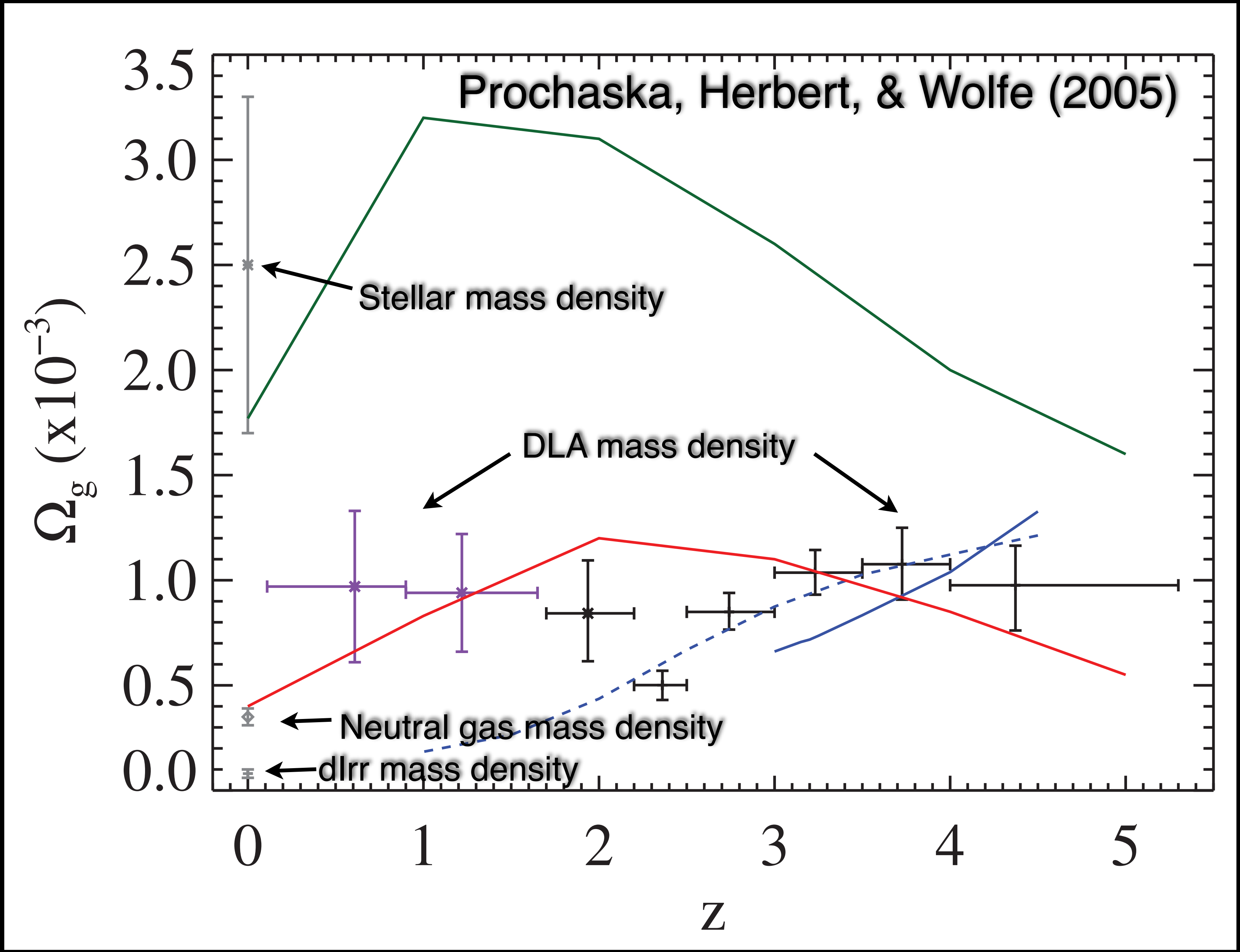
The black hole-galaxy mass relations are predicted to evolve gently with redshift (see also R06) -- at the massive end, systems lie above the mean M-σ relation.

Many others!



Andrew Pontzen

Pontzen et al., MNRAS, **390,** 1349 (2008)



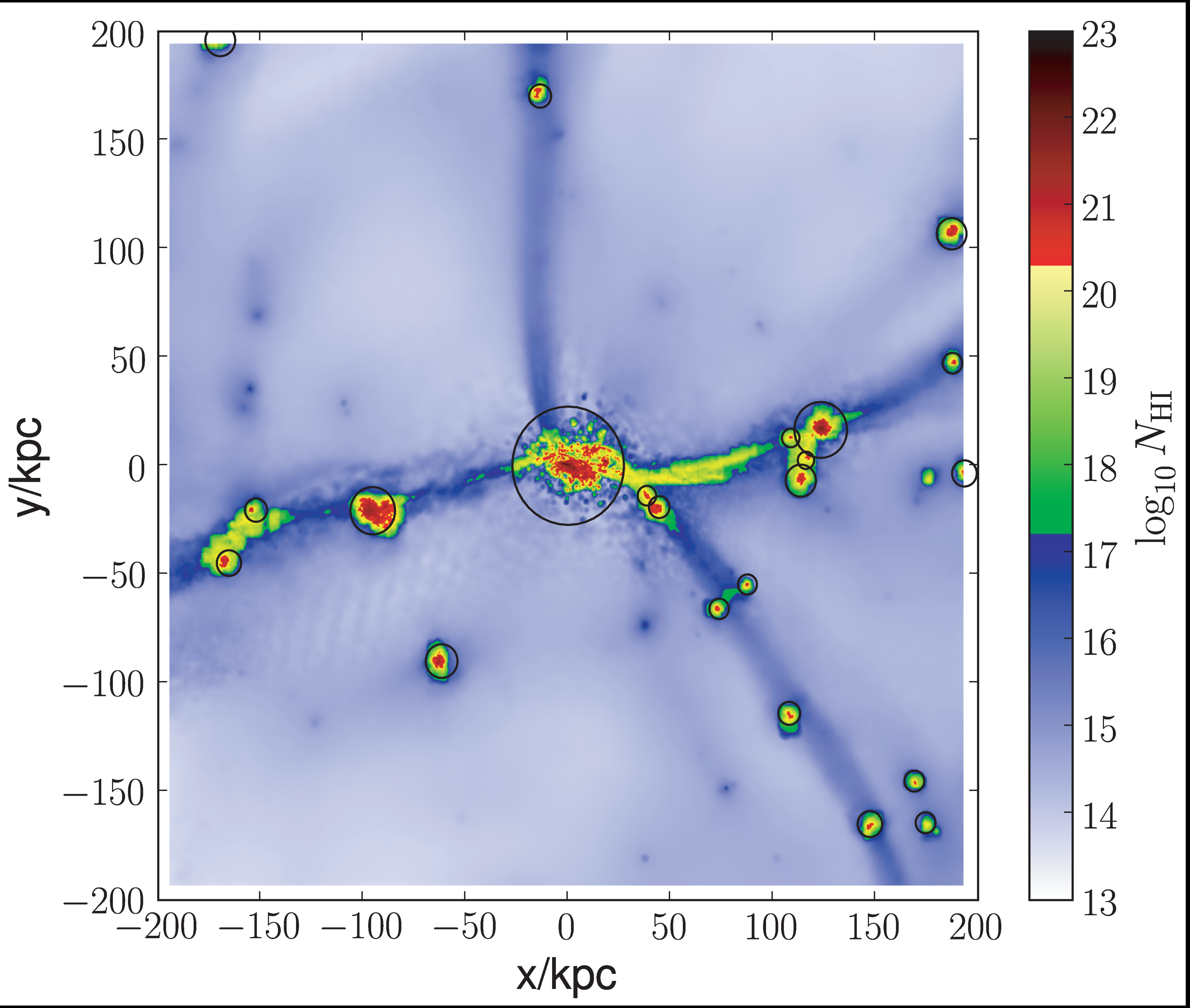
Problem:

A significant reservoir of the neutral baryonic mass density in the universe is observationally inferred to reside in damped Lyα absorbers (DLAs) at z~3 (e.g., Wolfe/Prochaska).

How are DLAs connected to the galaxy population?

Andrew Pontzen

Pontzen et al., MNRAS, **390,** 1349 (2008)

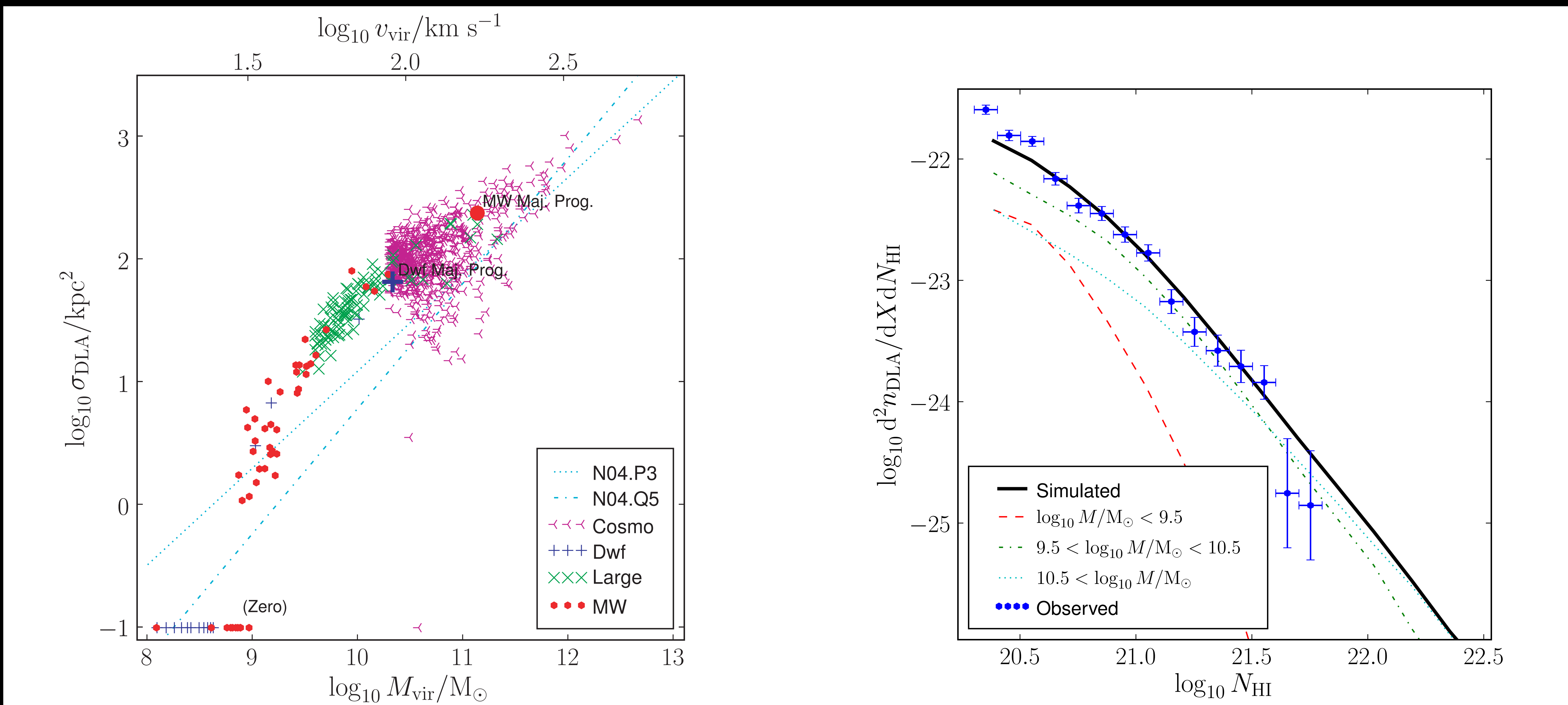


Methodology:

Use re-simulations of cosmological calculations to obtain high resolution (see Governato et al. 2007), then post-process the simulations using a radiative transfer scheme to capture self-shielding effects on the local ionization/neutrality state of gas.

Andrew Pontzen

Pontzen et al., MNRAS, **390,** 1349 (2008)

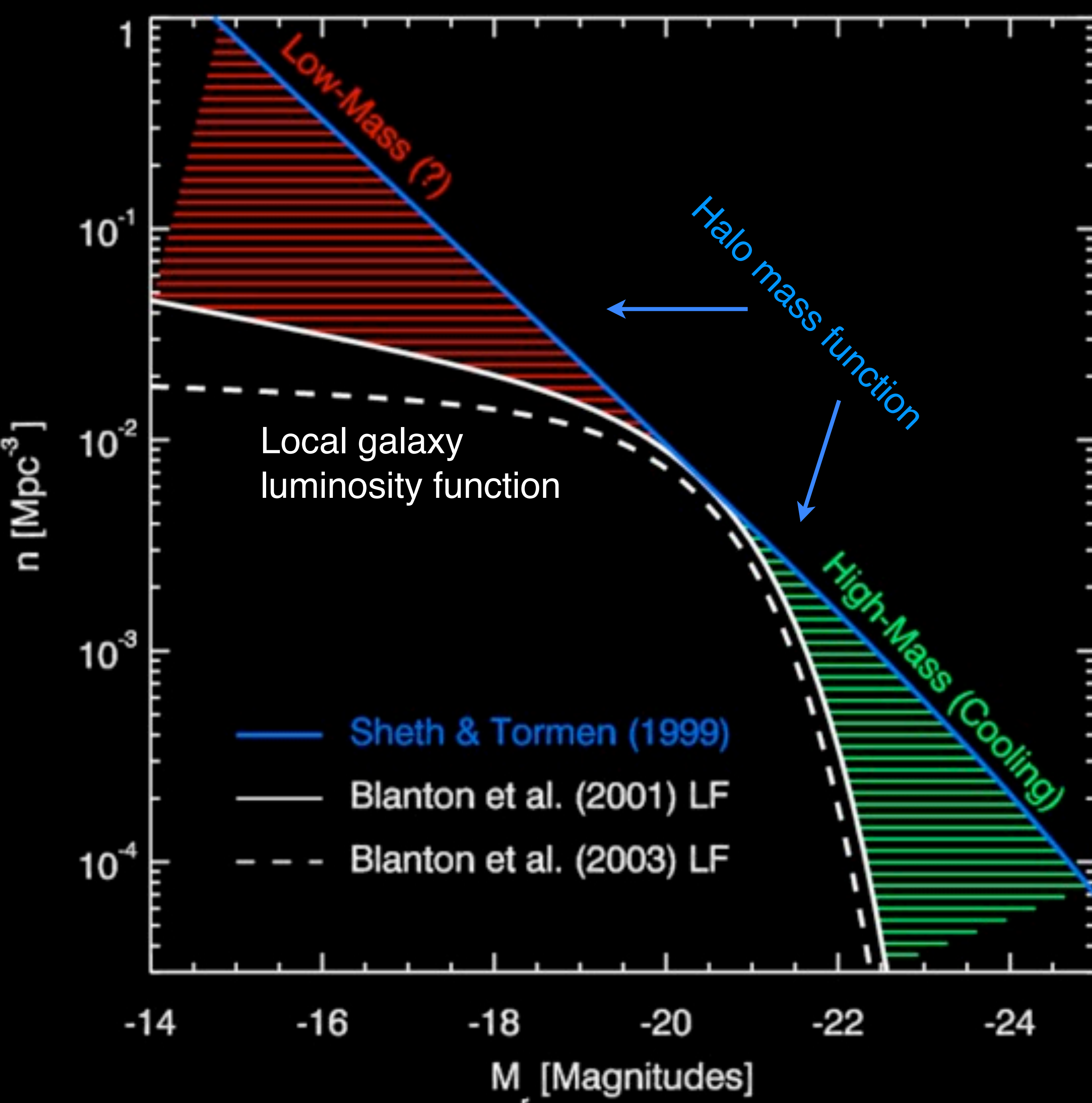


Results:

DLAs contributed by halos with $M_{vir}>10^9$ M_{sun}

DLA column densities reproduced!

A Primary Challenge for the Theory of Galaxy Formation



Deficit of faint galaxies relative to low-mass DM halos.

Supernova-driven winds?

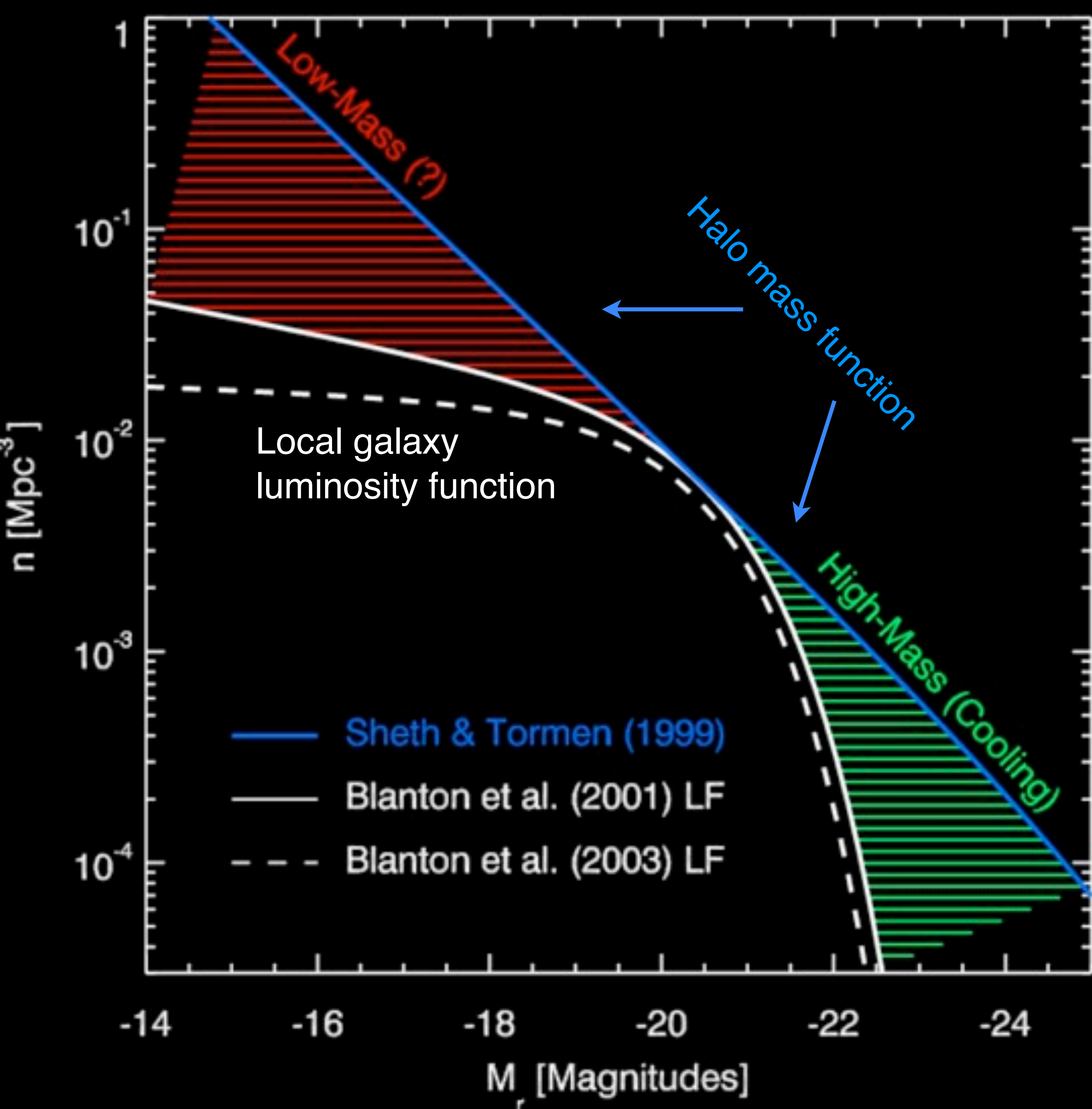
Photoionization?

Suppression of small-scale power?

No current method provides a convincing solution.

Possible Key: Low-mass galaxies are **gas rich.**

A Primary Challenge for the Theory of Galaxy Formation



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How can the physics of the ISM and star formation help solve this primary challenge for the theory of galaxy formation?

Star Formation Rates in Disks: The Standard Lore

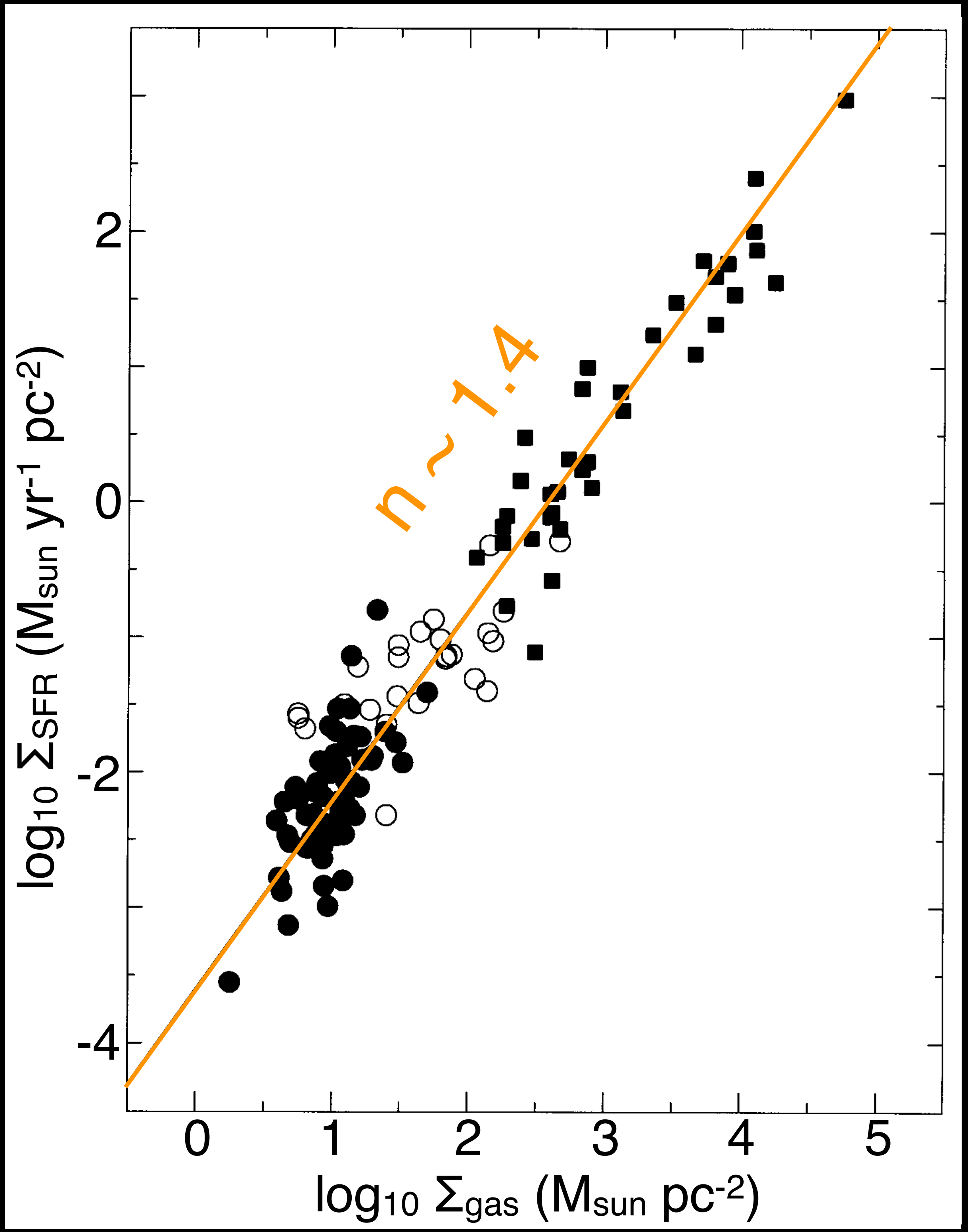
Schmidt (1959): Star formation rate scales with gas density

$$\dot{\rho}_\star \propto \rho_{\rm g}^n$$

Kennicutt (1989,1998): Star formation rate surface density scales with total gas mass surface density

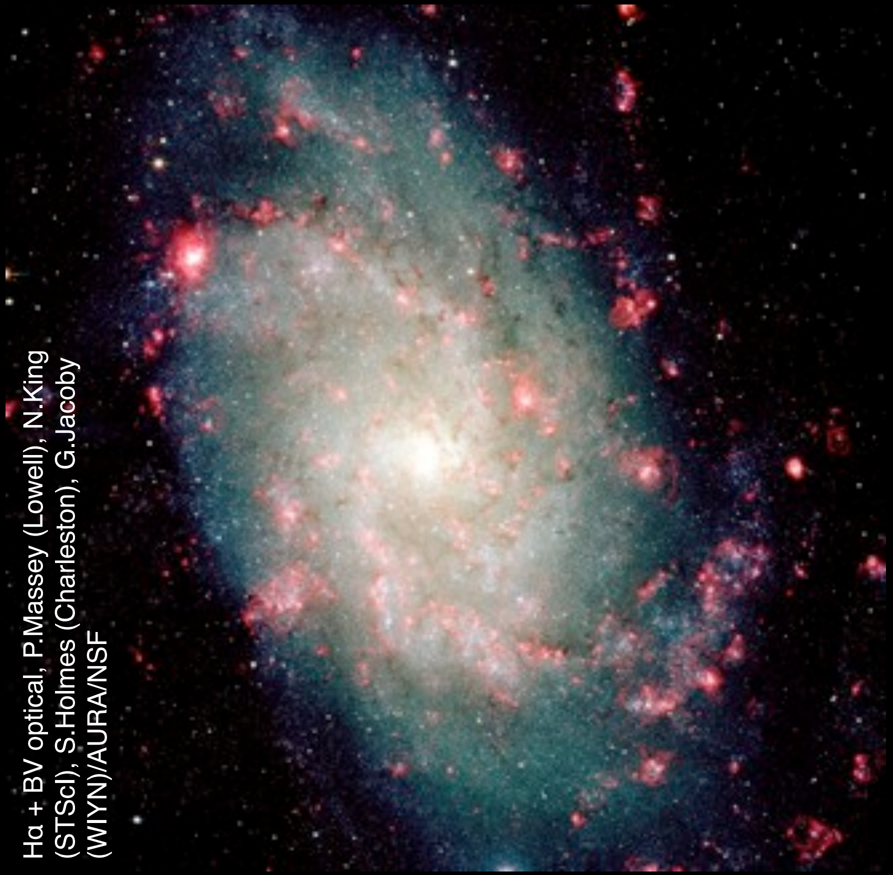
$$\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{1.4\pm0.15}$$

This scaling is the star formation prescription in almost all models of galaxy formation, starting with Larson (1969), Katz (1992), and Navarro & White (1993).



Kennicutt (1998)

Star formation vs. gas distribution: M33



Hα emission (red) traces areas of active star formation in the disk of M33.

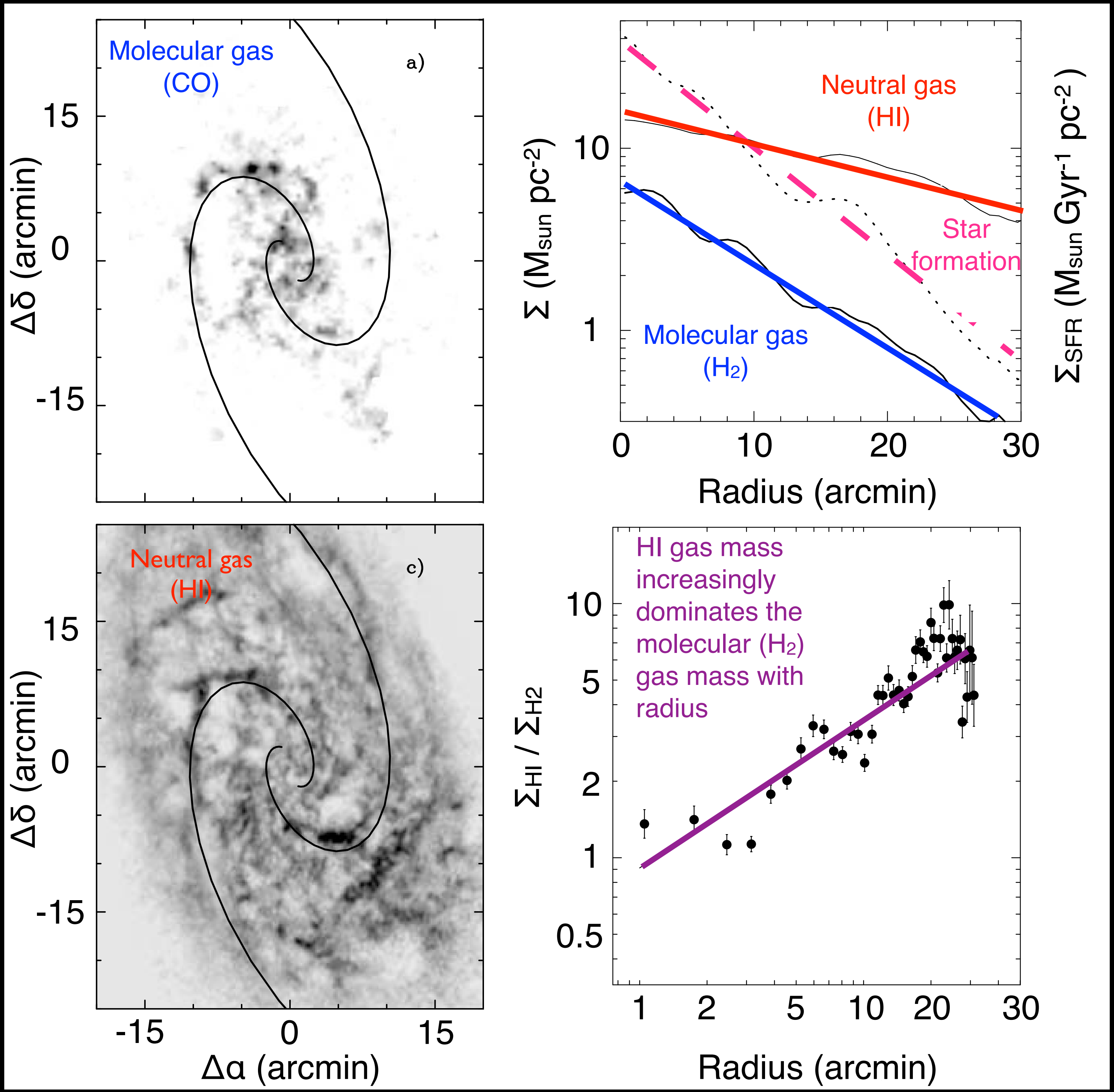
Star formation vs. gas distribution: M33

Hα emission (red) traces areas of active star formation in the disk of M33.

The neutral HI gas (blue) in M33 is much more extended than the star formation.

Why doesn't star formation track the gas distribution?

Star formation vs. gas distribution: M33



Heyer et al. (2004), ApJ, 602, 723

Star formation traces molecular gas better than atomic gas.

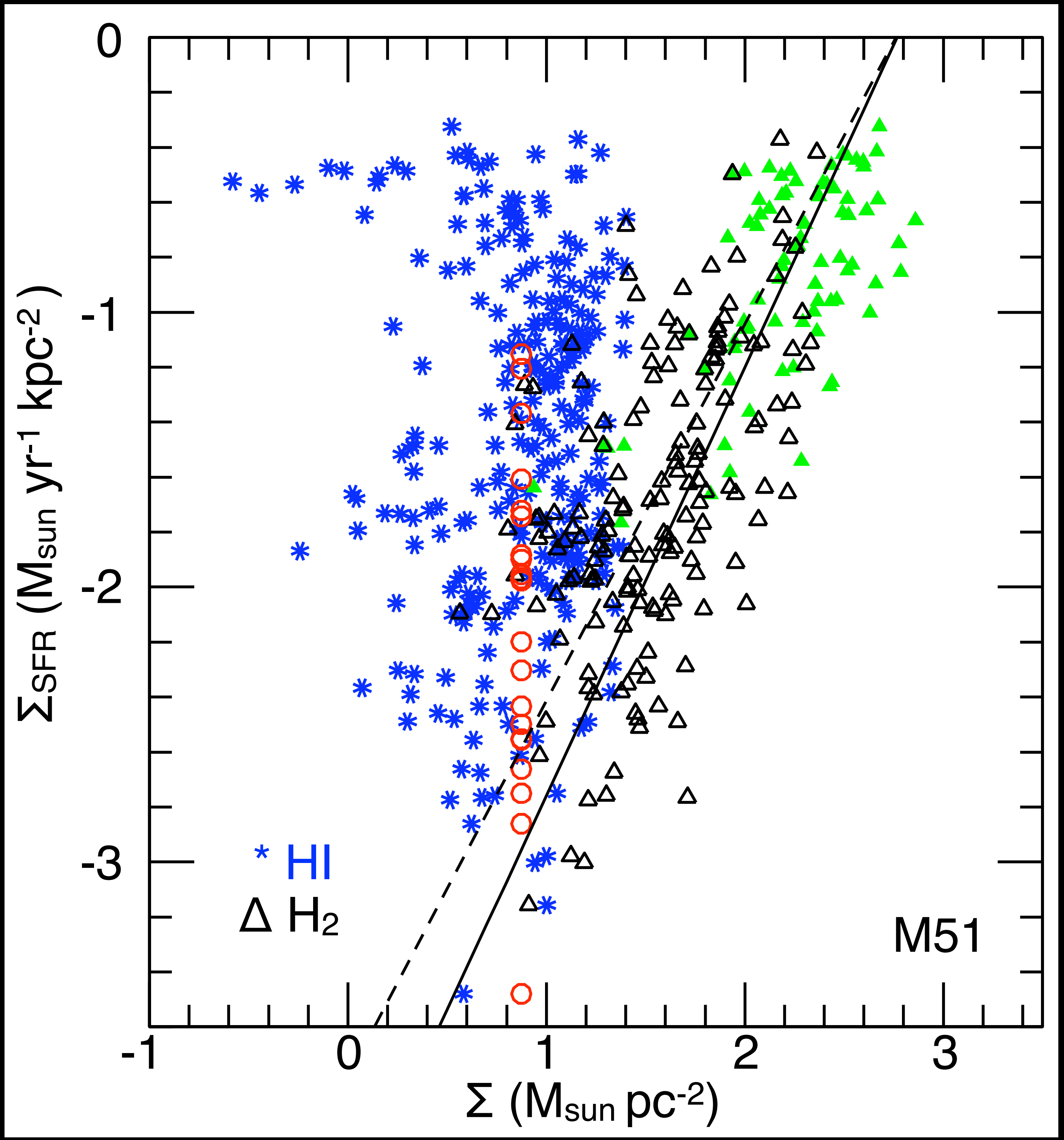
Neutral gas has a longer scale radius than molecular gas.

Is $\dot{\rho}_\star \propto \rho_{\mathrm{g}}/t_{\mathrm{dyn}}$ the Whole Story?

Time to consider a model for star forming gas in simulations that:

1) Treats the microphysics of the molecular ISM

2) Ties the SFR to the molecular gas properties.



Kennicutt et al. (2007)

Motivation for a new model of the molecular ISM:
Robertson & Kravtsov (2008), ApJ, 680, 1083

The “Standard” ISM Model

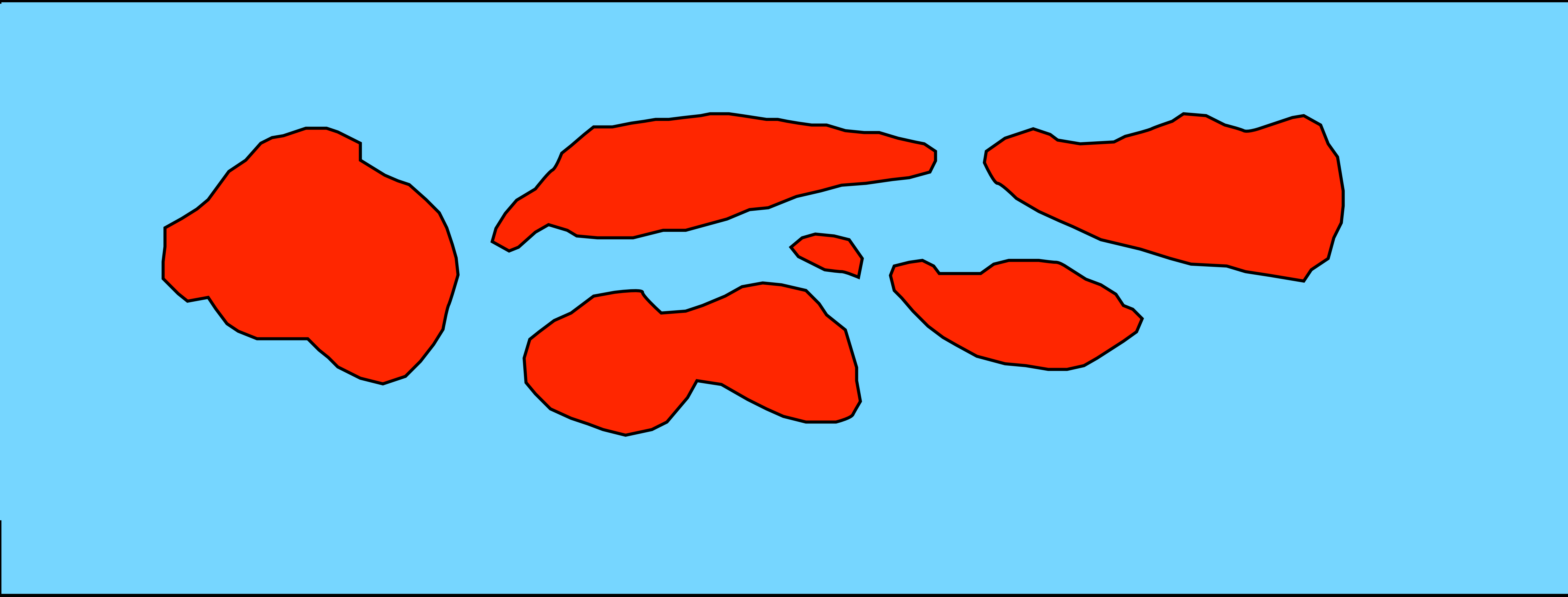
The “Standard” ISM Model

10^4 K

1) Gas can cool to a minimum temperature of 10^4 K.
2) Star formation occurs in “dense” (n_H >~ 0.1-1 cm^{-3}) regions.
3) The efficiency of star formation is normalized to match Kennicutt (1998).

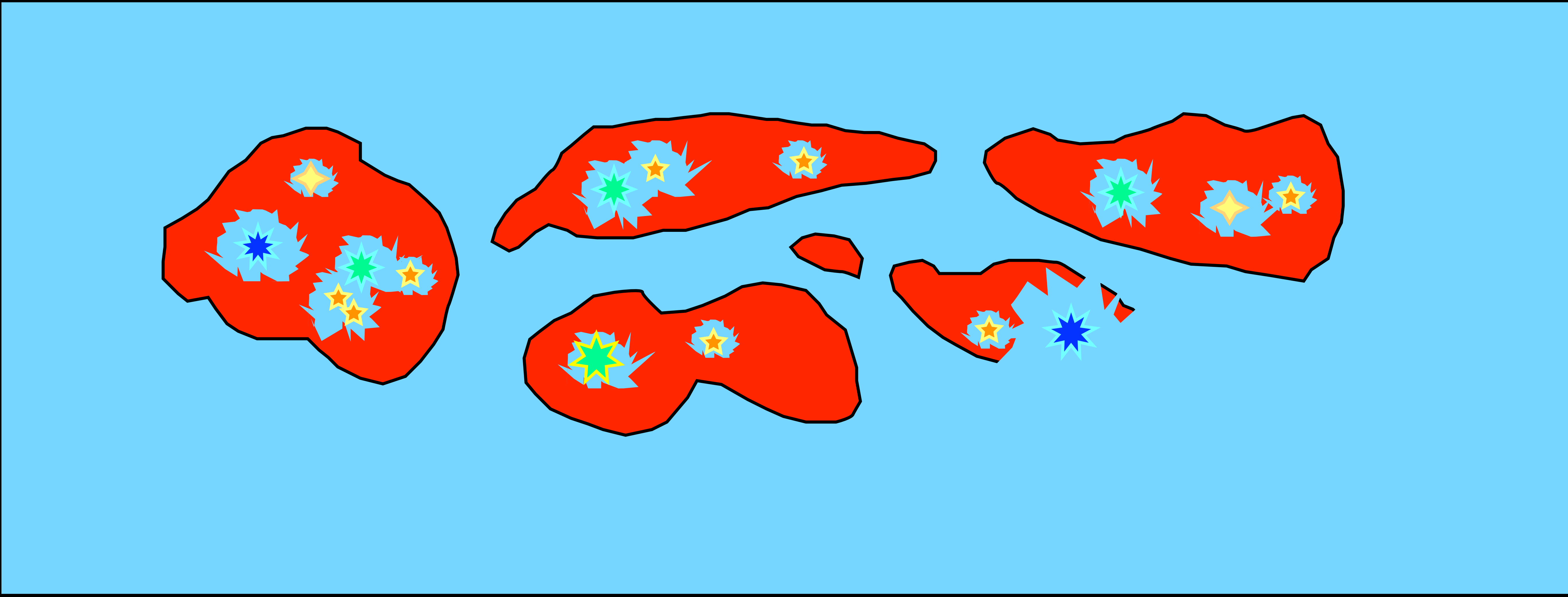
A Cartoon of Molecular ISM Processes

A Cartoon of Molecular ISM Processes



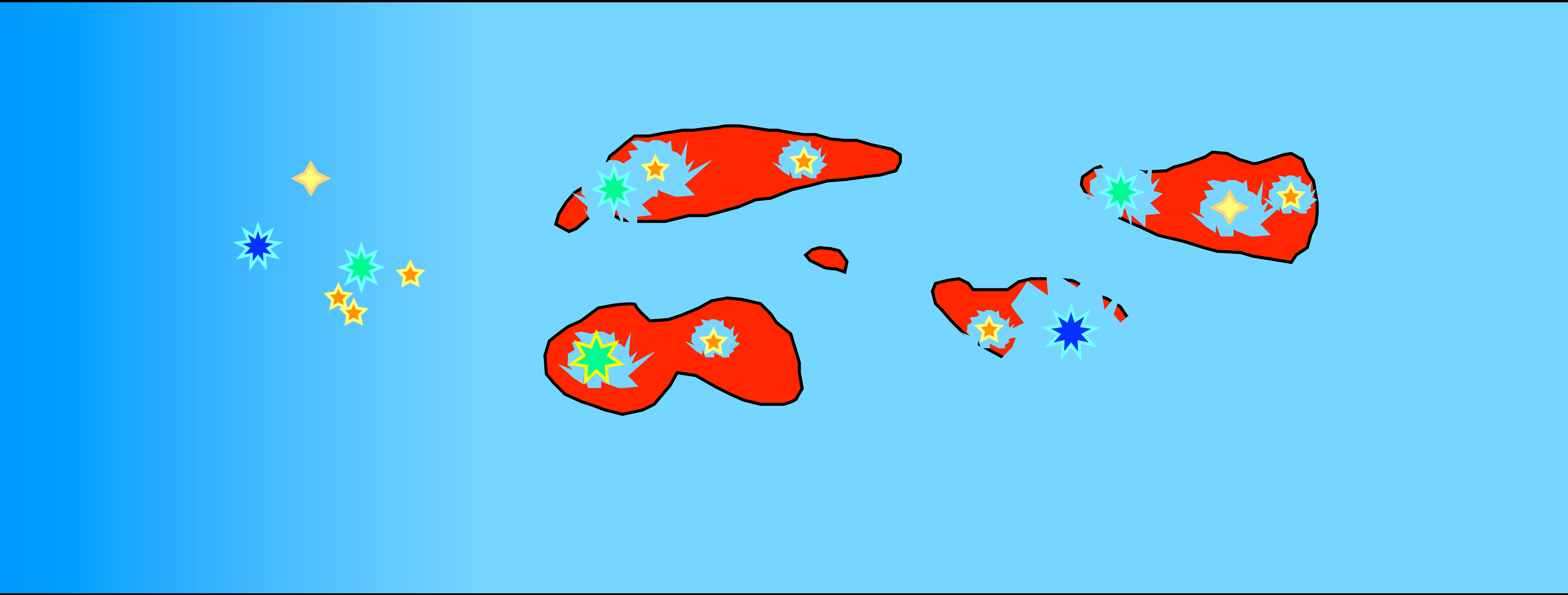
At sufficiently high gas densities, low-temperature coolants will allow molecular gas to condense from the hot ambient medium.

A Cartoon of Molecular ISM Processes



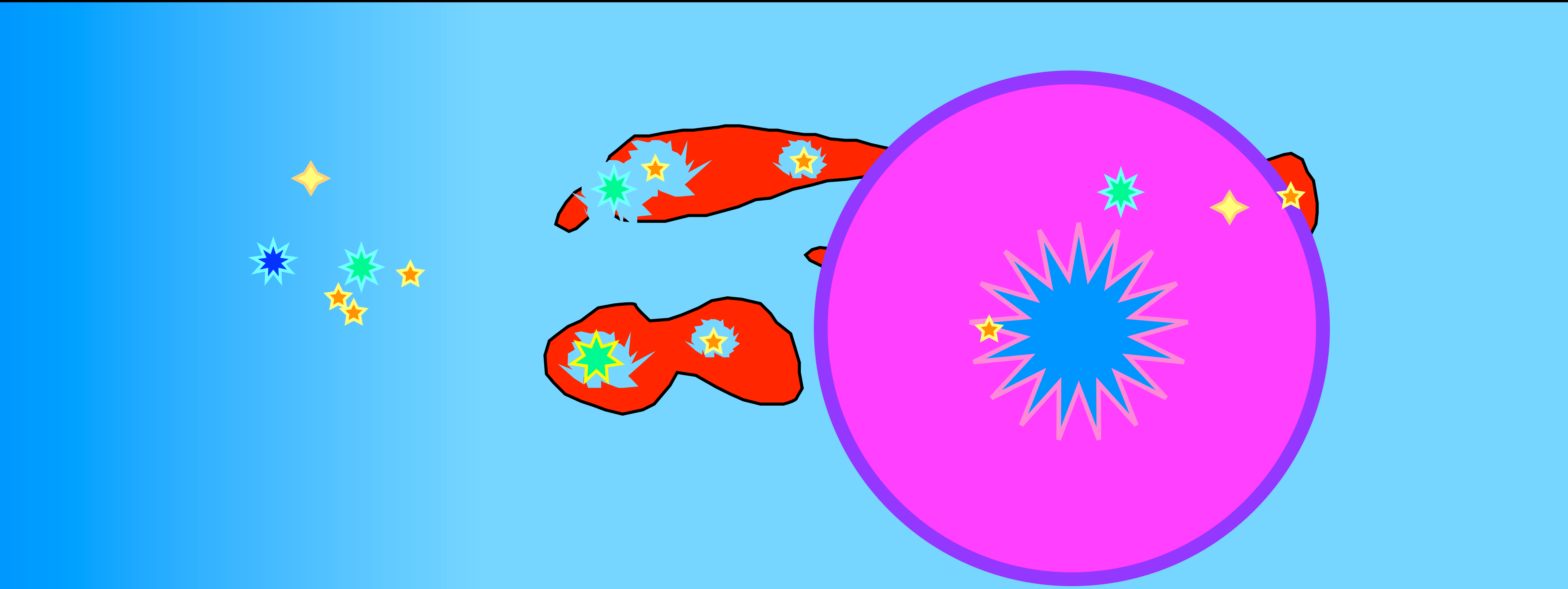
Stars form from the molecular clouds, and the local interstellar radiation field increases. Soft UV photons in the ISRF can begin to photodissociate and heat the molecular clouds.

A Cartoon of Molecular ISM Processes



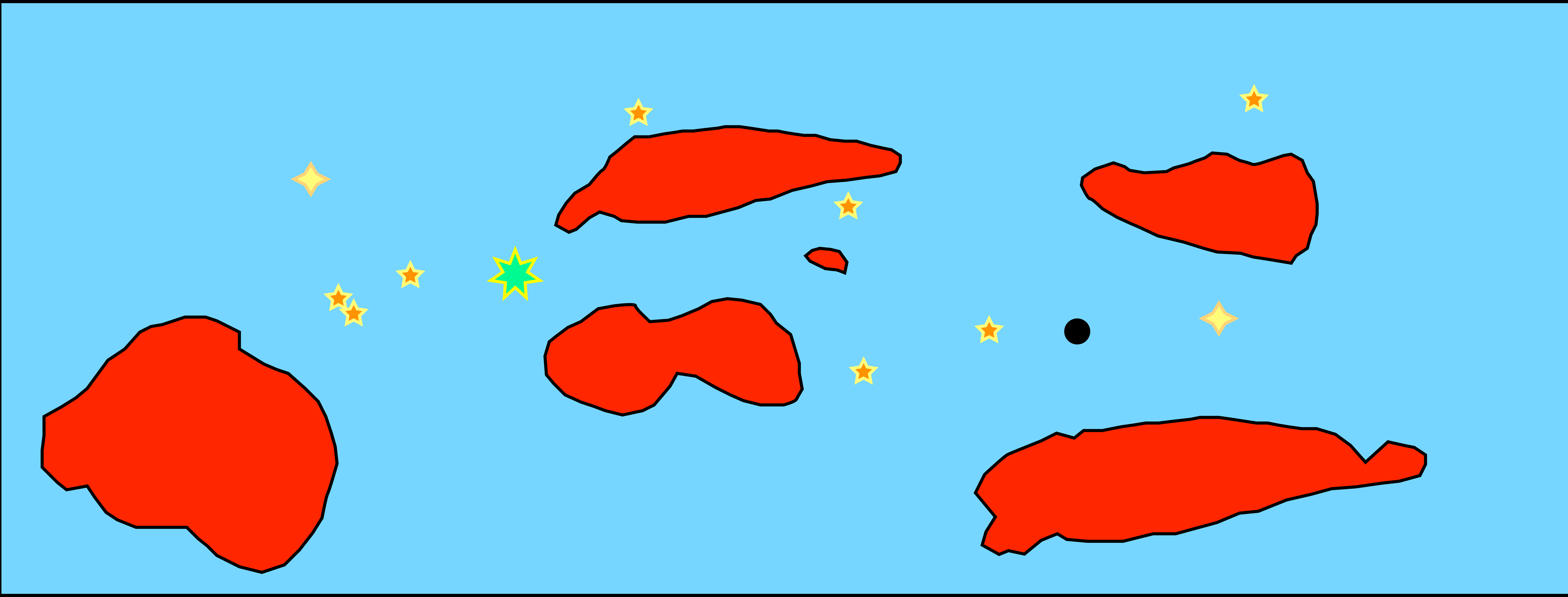
In the presence of an ISRF, the molecular density at moderate ISM densities is suppressed. In some regions of the ISM, the local ISRF can destroy all molecular gas, removing low-temperature coolants and increasing the gas temperature. The destruction of H_2 by the ISRF acts as a feedback mechanism to regulate star formation, and is efficient even as the local cooling time is short.

A Cartoon of Molecular ISM Processes



Additional feedback mechanisms, such as supernovae from massive stars, may still operate.

A Cartoon of Molecular ISM Processes



After the young stars die the ISRF may abate, allowing the molecular ISM to reform and the star formation cycle to start again.

A New Model for the Molecular ISM and Star Formation

SFR tied to molecular density and dynamical time

$$\dot{\rho}_\star = C_\star f_{\rm H2} (1-\beta) \rho_{\rm gas}^{1.5}$$

Molecular fraction vs.density, T, Z, and ISRF strength

$$f_{\rm H2} = f_{\rm H2}(\rho_{\rm gas}, T, Z, U_{\rm ISRF})$$

Interstellar radiation field strength tracks the local SFR density

$$U_{\rm ISRF} = U_\odot(\nu) \times \left(\frac{\Sigma_{\rm SFR}}{\Sigma_{\rm SFR,\odot}} \right)$$

ISM thermal evolution = supernovae heating - net atomic and molecular cooling rates

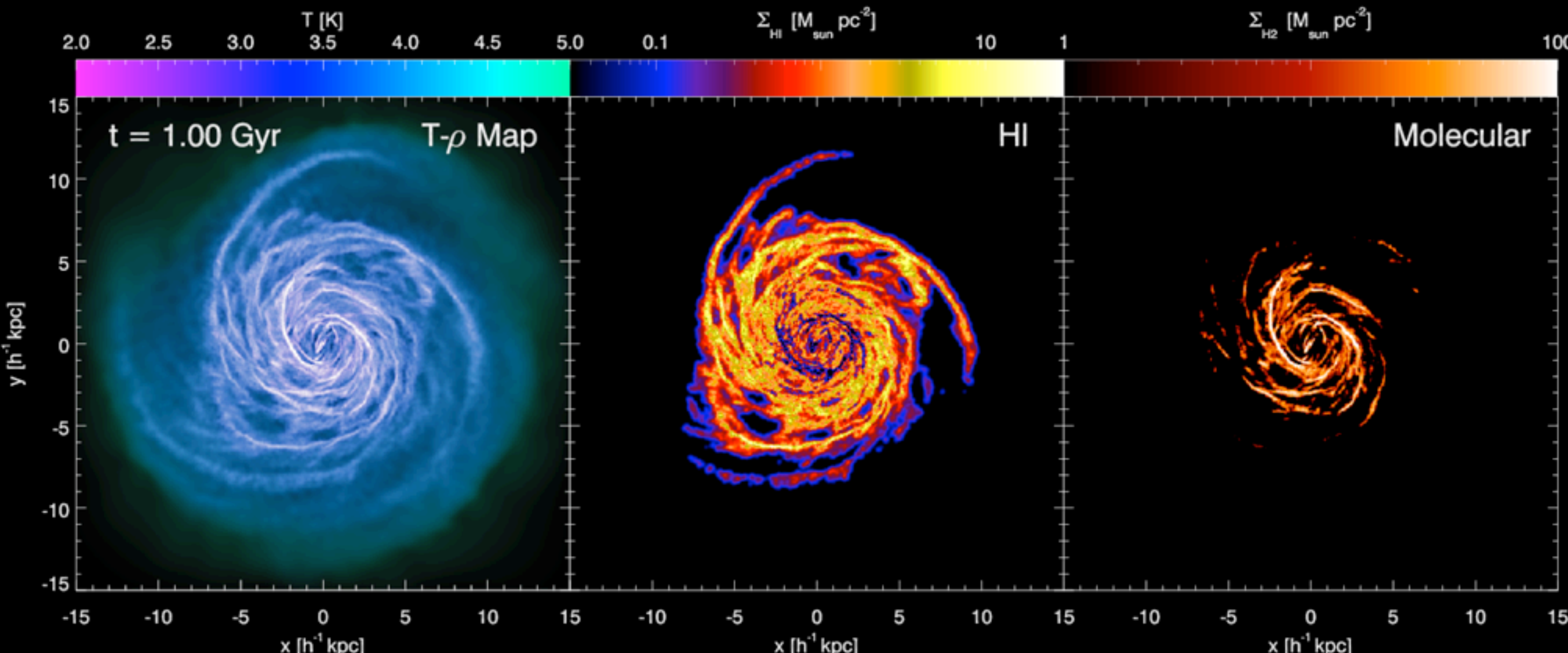
$$\rho_{\rm gas} \frac{{\rm d}u}{{\rm d}t} = \epsilon_{\rm SN} \dot{\rho}_\star - \Lambda_{\rm net}$$

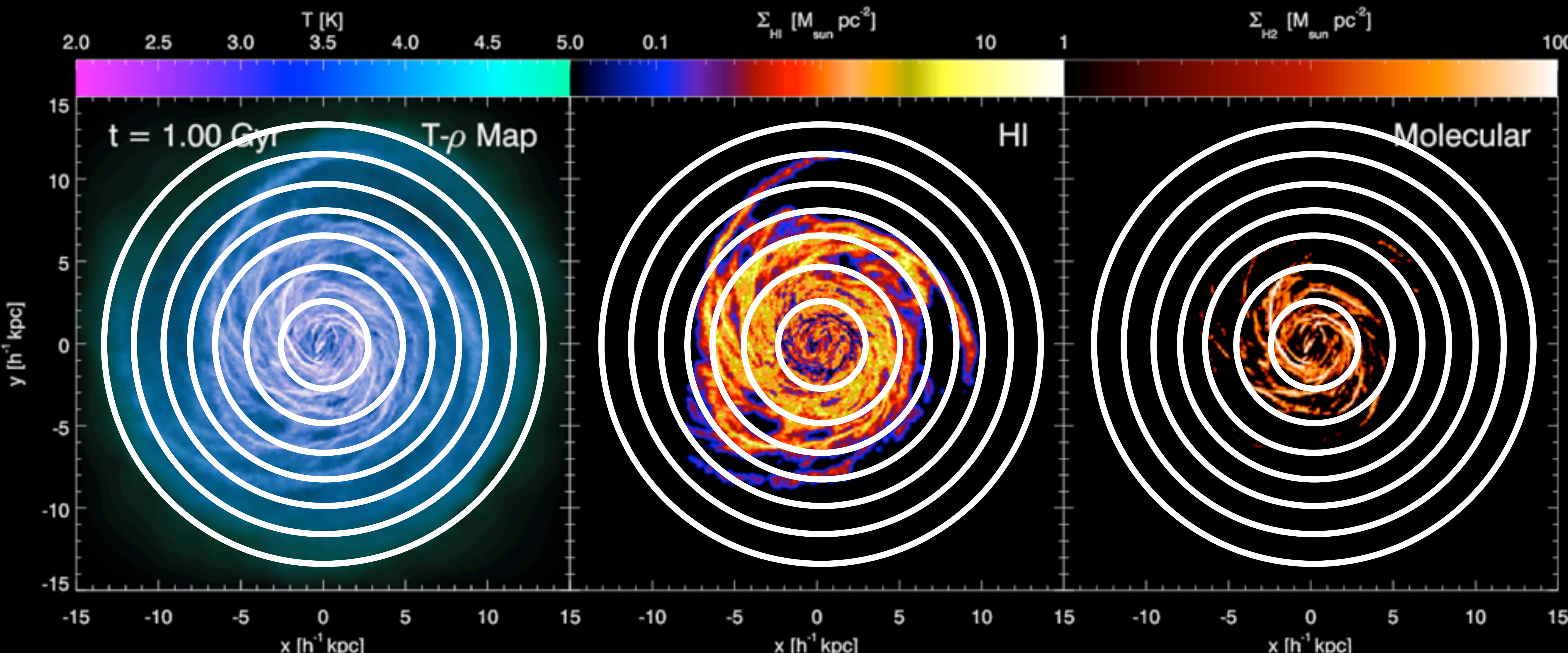
Net atomic and molecular cooling rates depend on density, T, Z, and ISRF strength

$$\Lambda_{\rm net} = \Lambda_{\rm net}(\rho_{\rm gas}, T, Z, U_{\rm ISRF})$$

Implemented in the N-body/SPH code GADGET2

Robertson & Kravtsov (2008), ApJ, 680, 1083

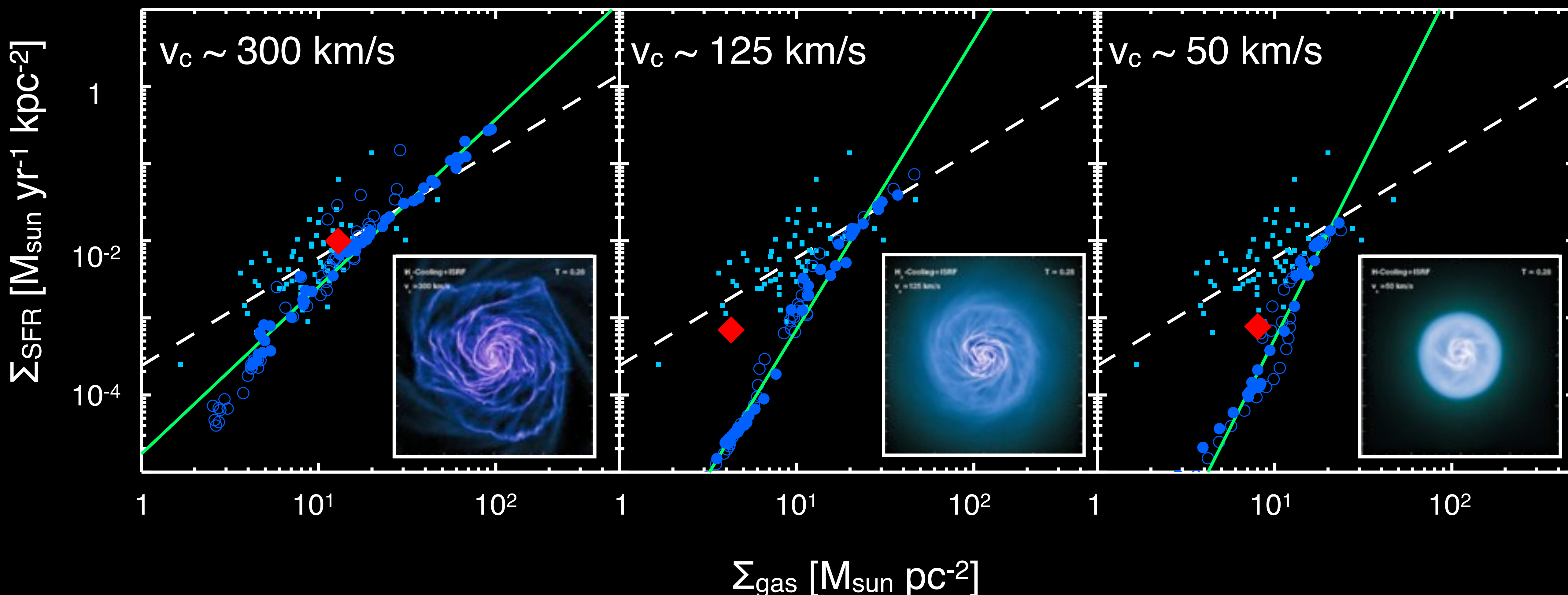

T [K]
2.0 2.5 3.0 3.5 4.0 4.5 5.0
Σ_{HI} [M_{sun} pc^{-2}]
0.1 10
Σ_{H2} [M_{sun} pc^{-2}]
1 100
t = 1.00 Gyr
T-ρ Map
HI
Molecular
y [h^{-1} kpc]
x [h^{-1} kpc]
15 10 5 0 -5 -10 -15



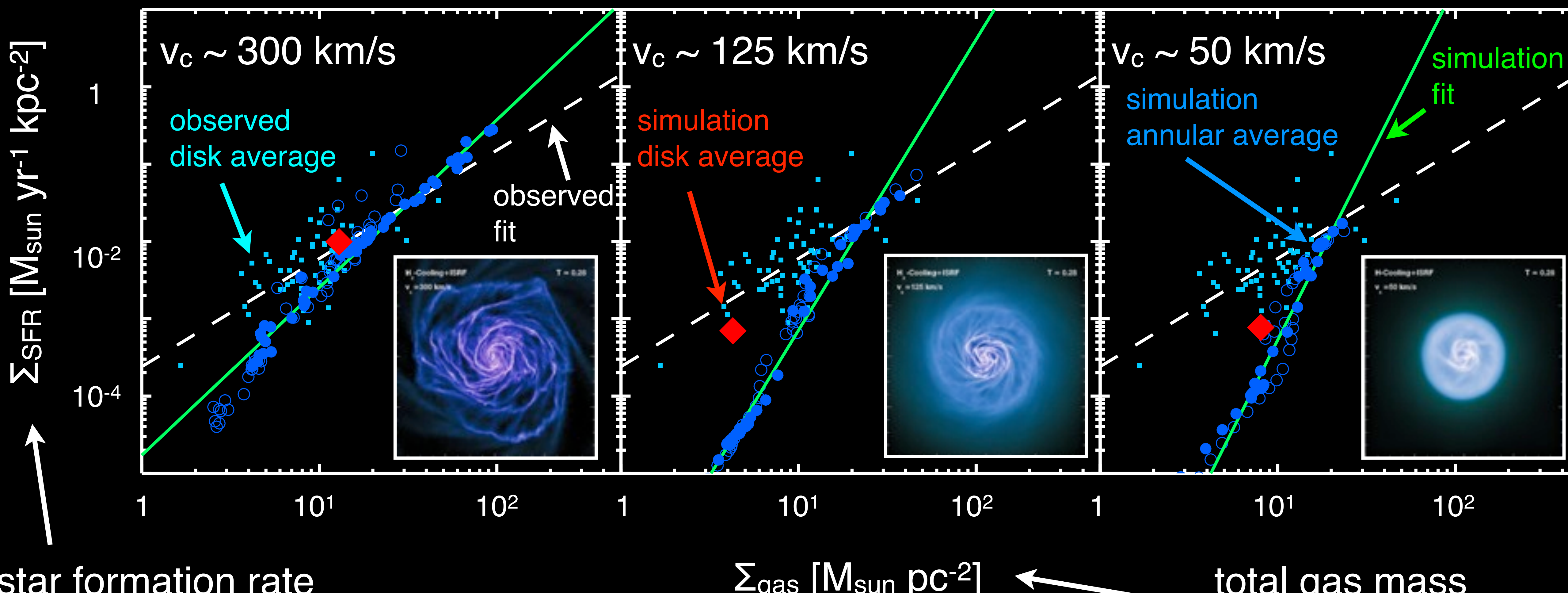
1) Measure gas and SFR properties in annuli.

2) Compare with observations.

Results: Star Formation Efficiency vs. Galaxy Mass



Results: Star Formation Efficiency vs. Galaxy Mass



star formation rate per unit area

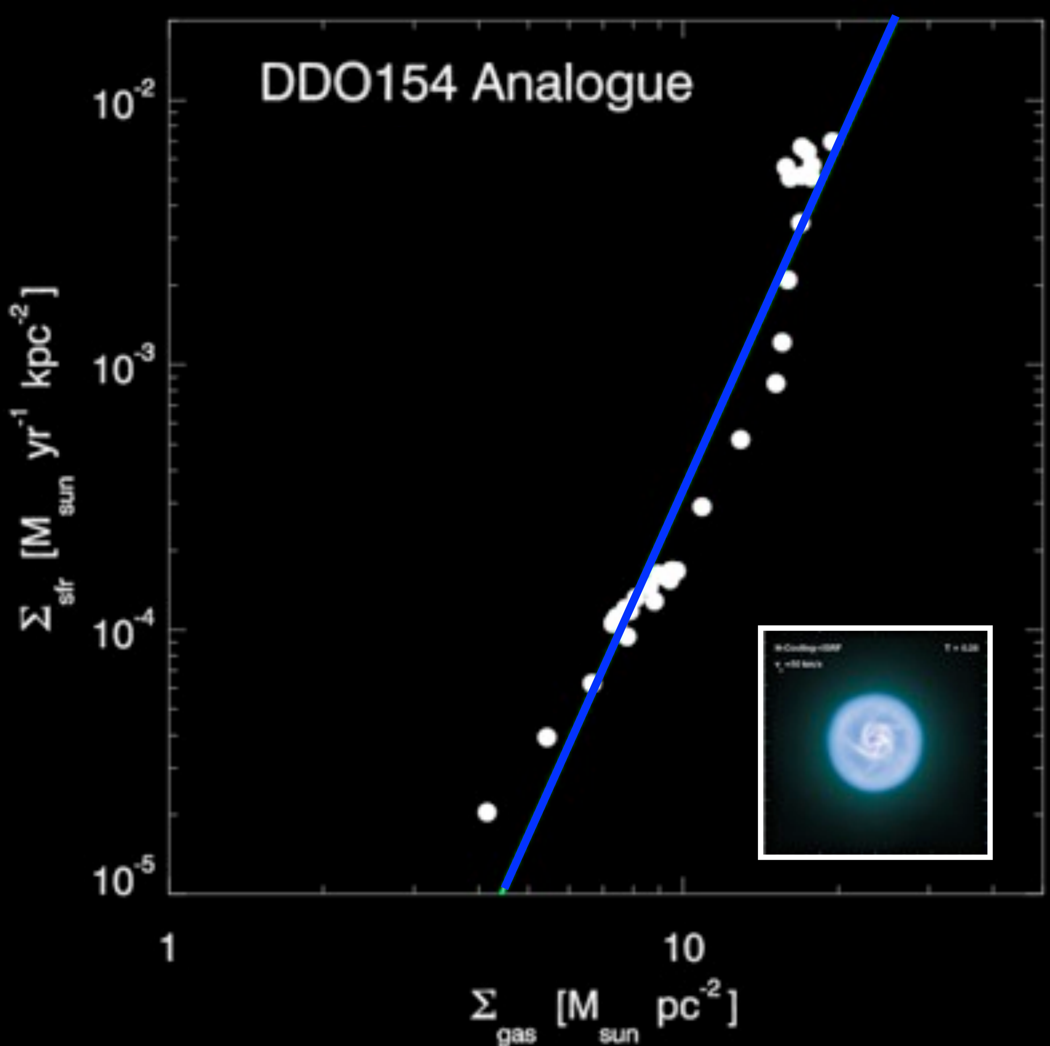
total gas mass per unit area

Galaxy mass

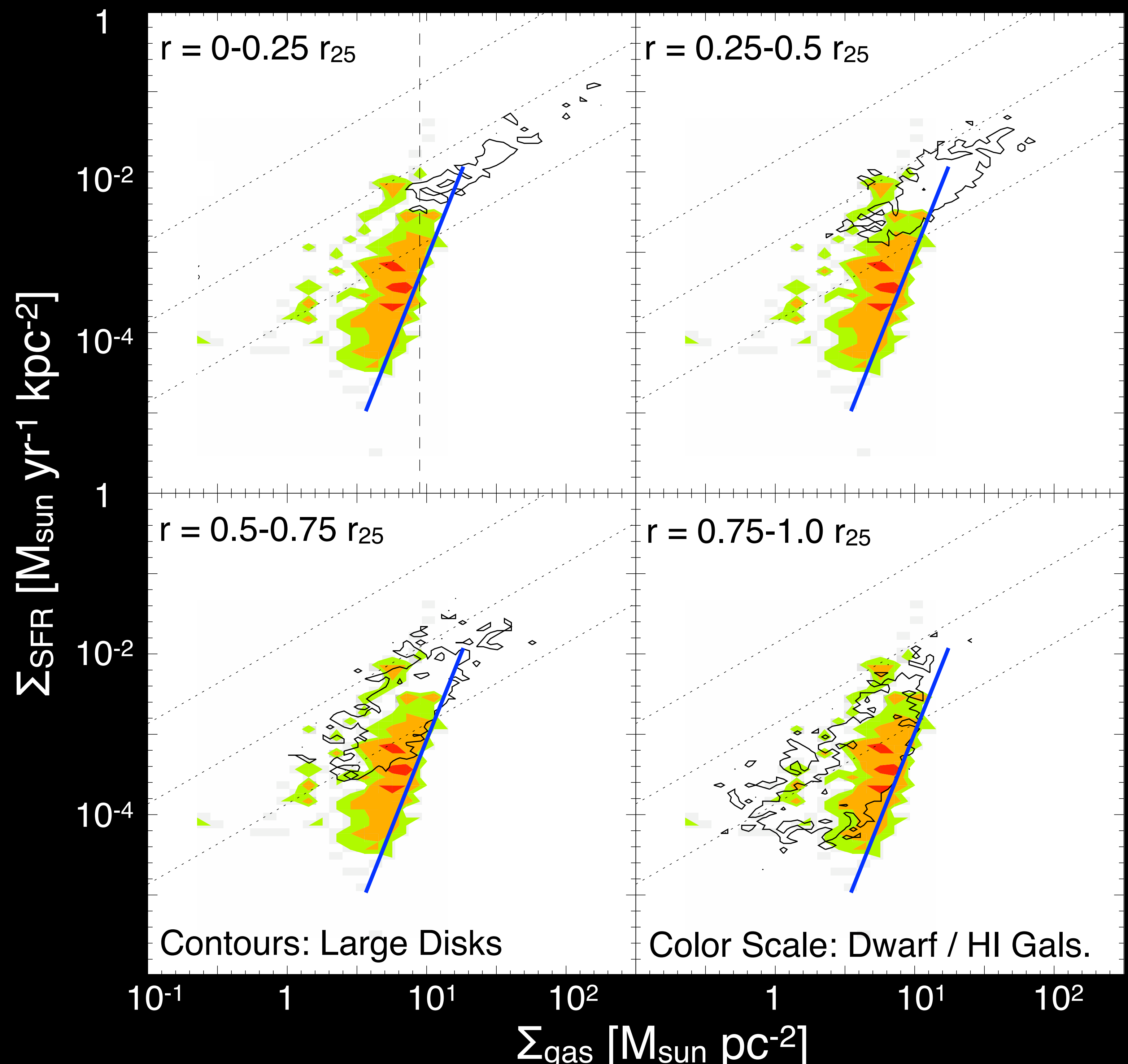
Large ← Small

Results: Star Formation Efficiency vs. Galaxy Mass

Quantitative agreement between simulations and THINGS survey.



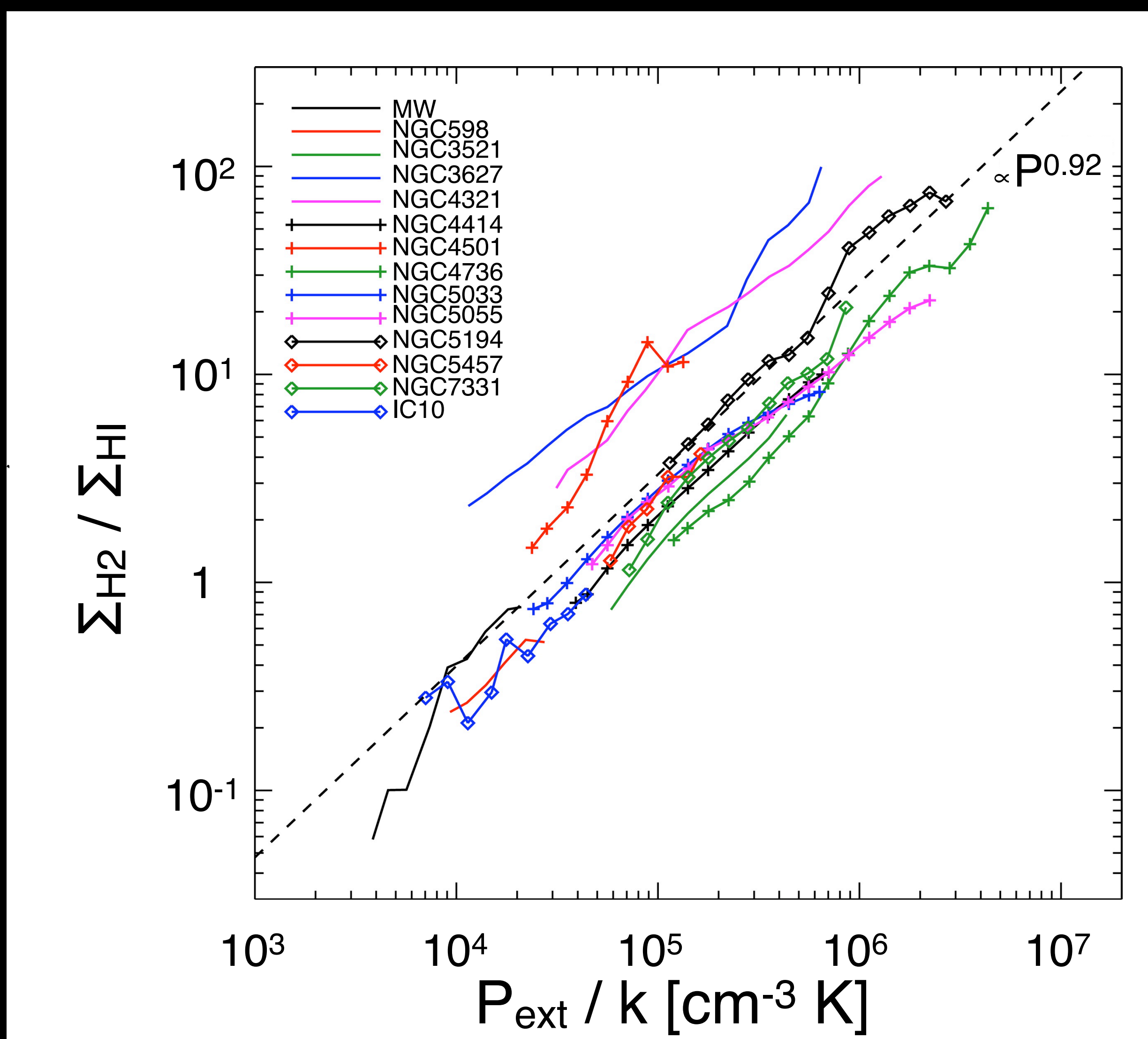
from THINGS



Robertson & Kravtsov (2008)

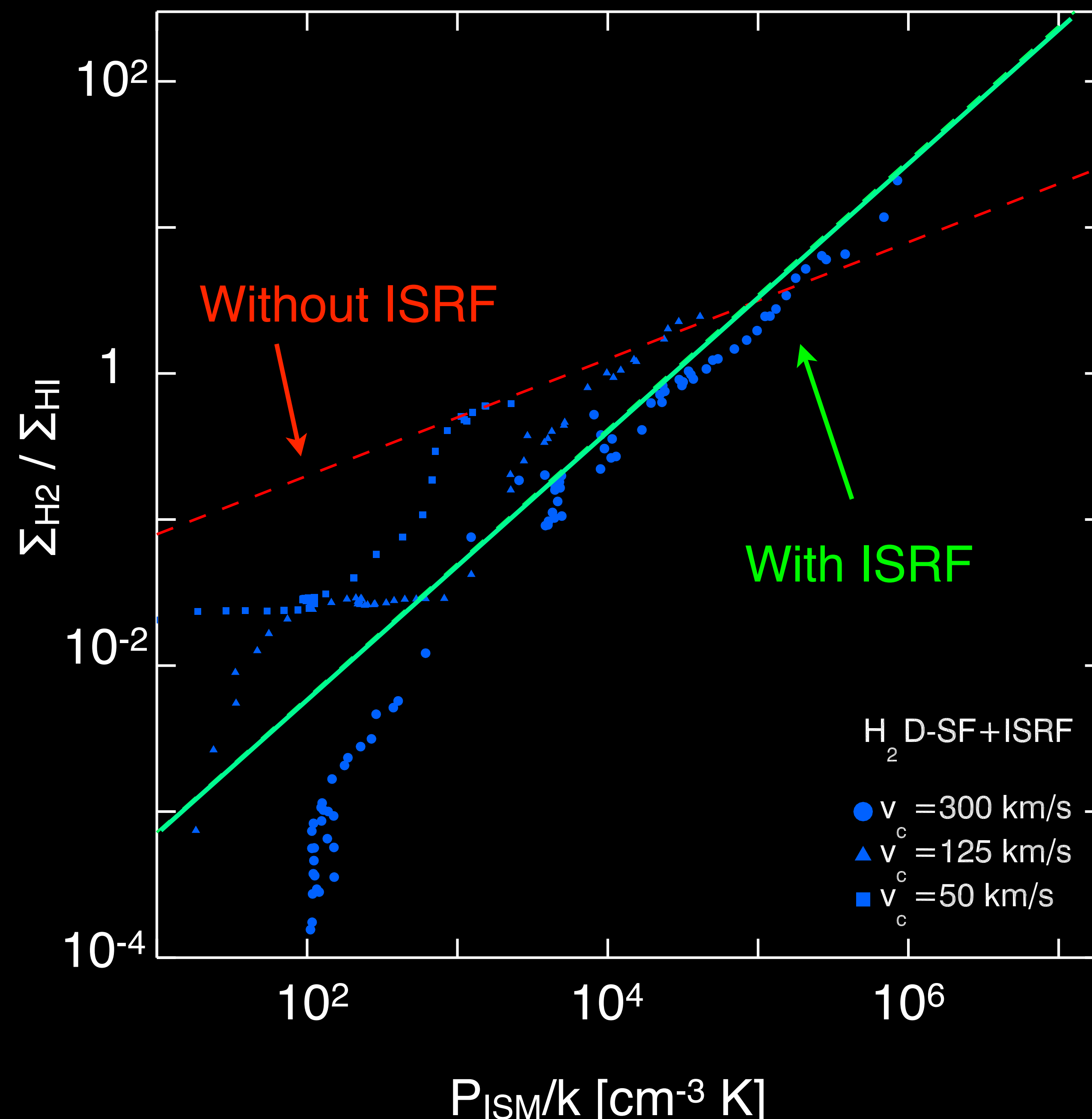
Bigiel et al. (2008)

Results:
f_{H2}-Pressure Correlation



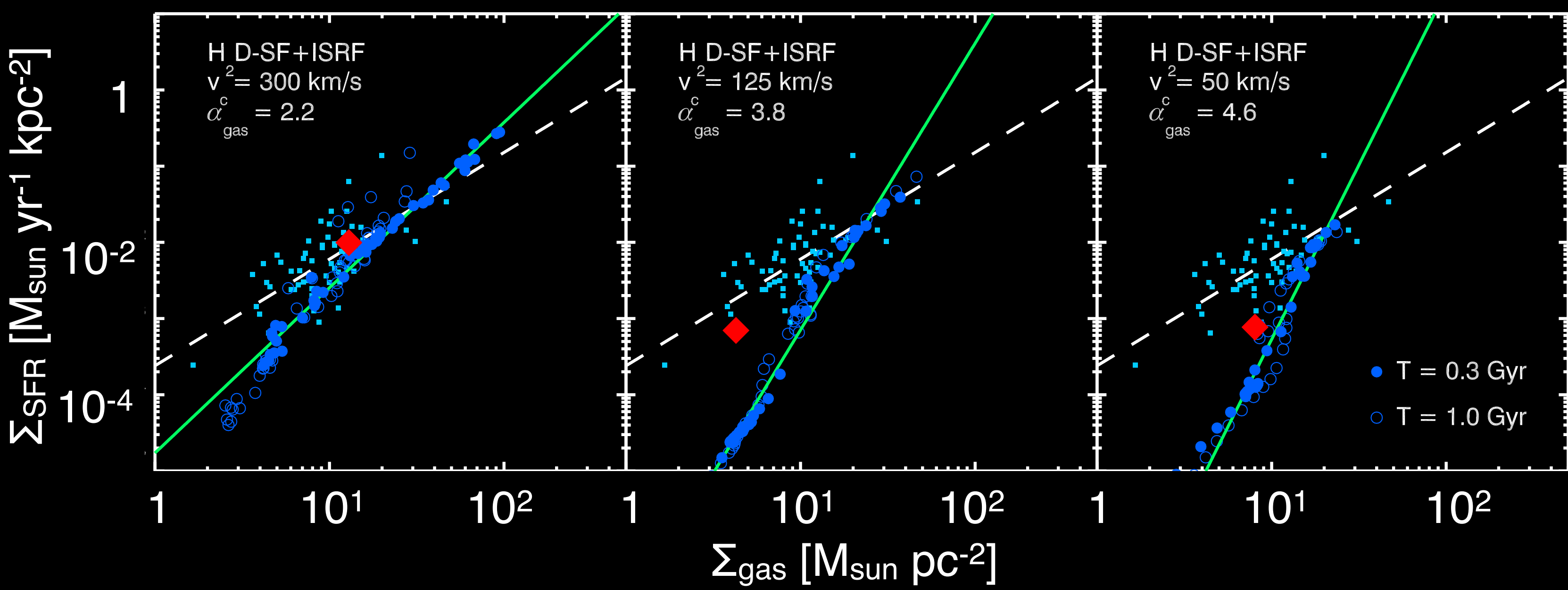
Blitz & Rosolowsky (2006)

Simulation Results:

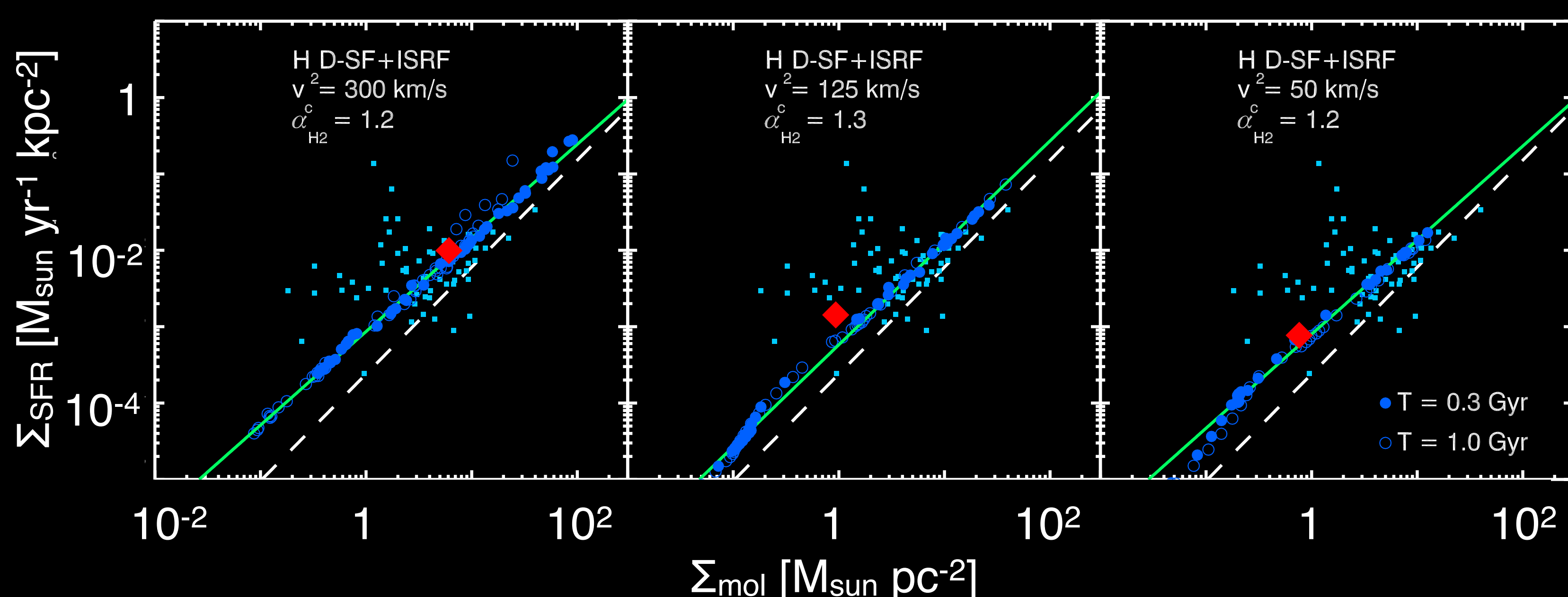


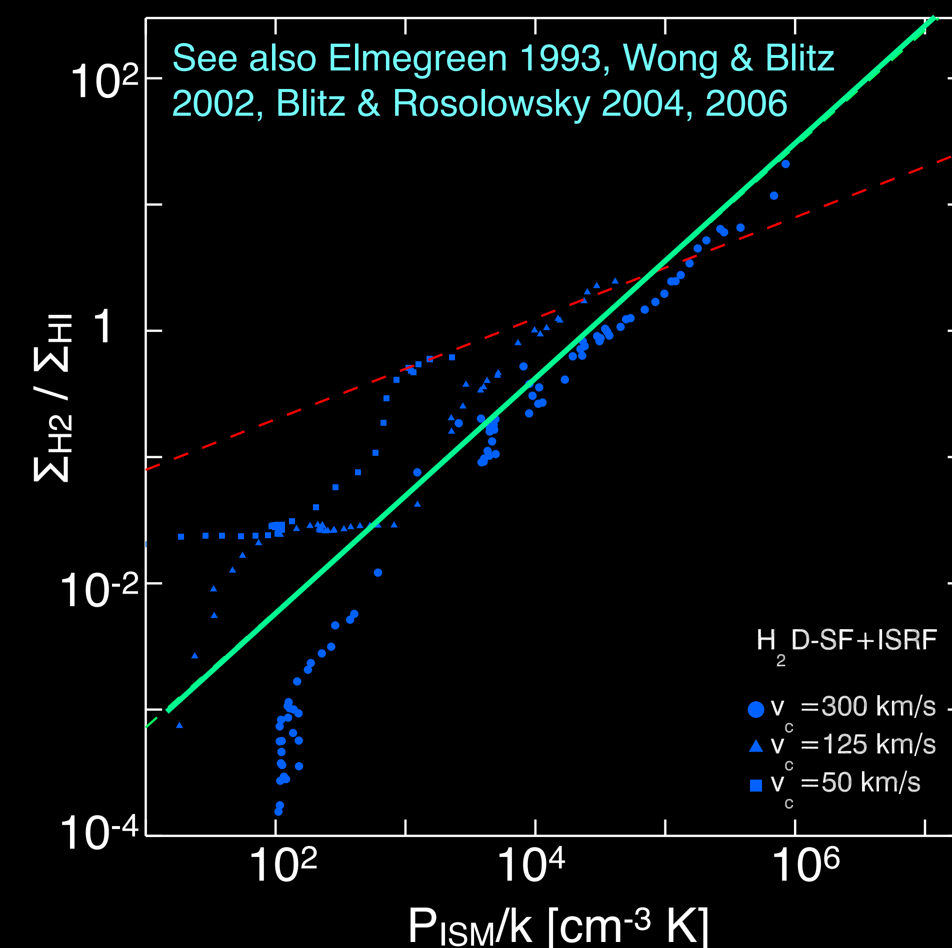
Results: Global Star Formation Relations in Disks

Total Gas Kennicutt-Schmidt Relation



H2 Gas Kennicutt-Schmidt Relation





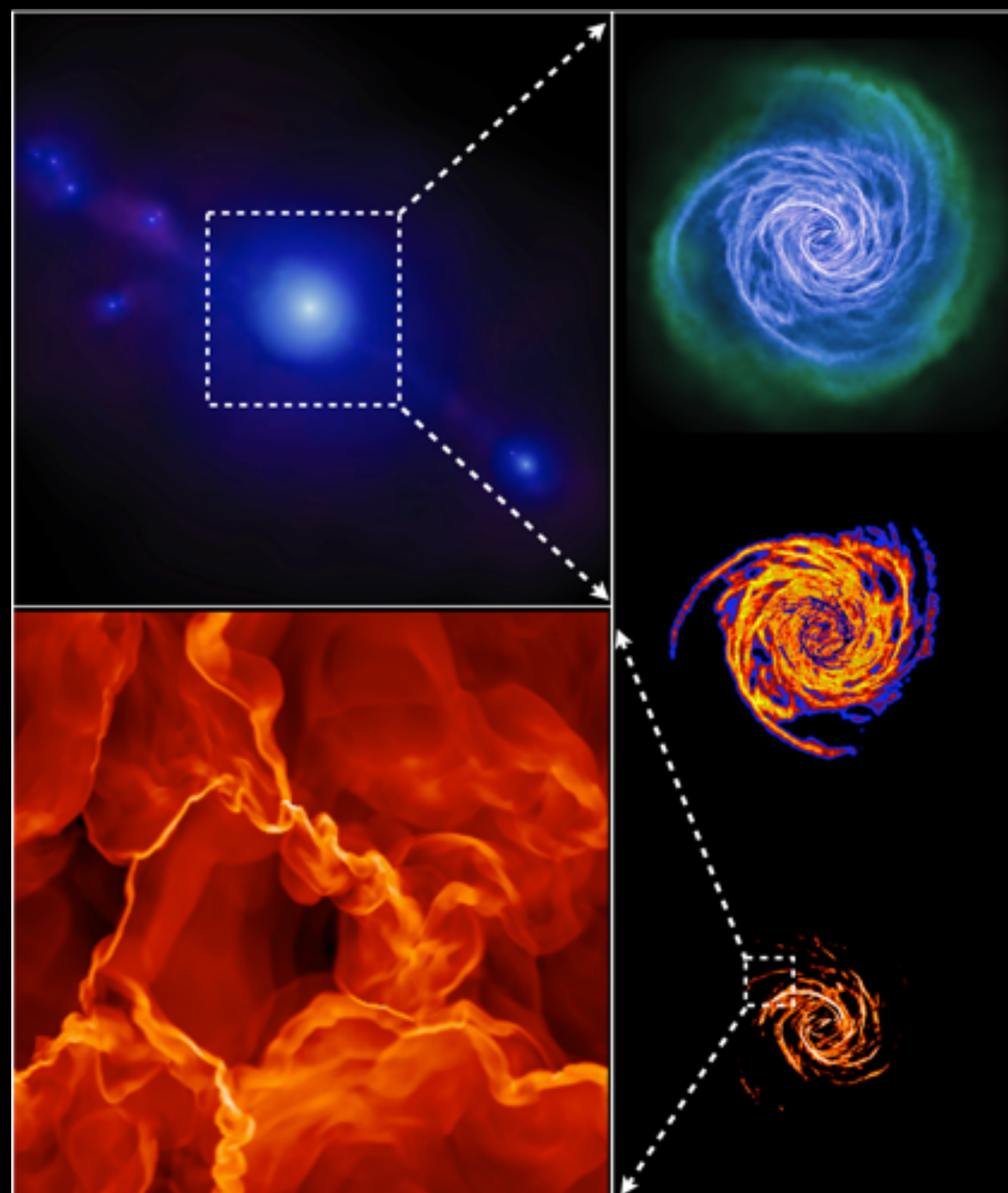
f_{H2}- Pressure Relation

RK08 simulations match total and molecular gas Kennicutt relations, and f_{H2}-pressure relation.

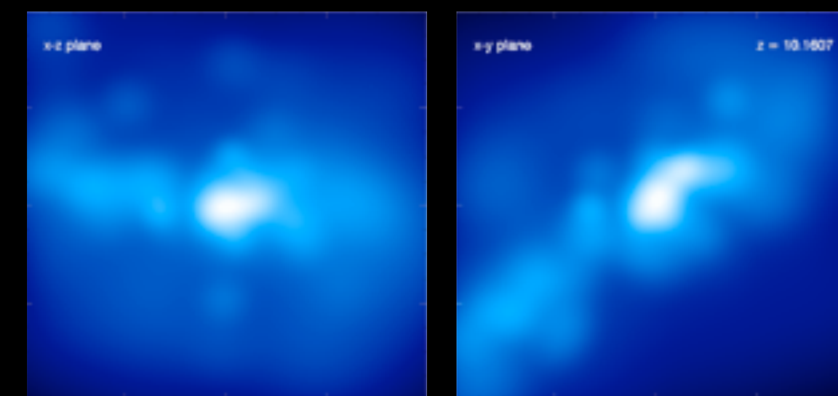
Unsolved Problems in Galactic Star Formation

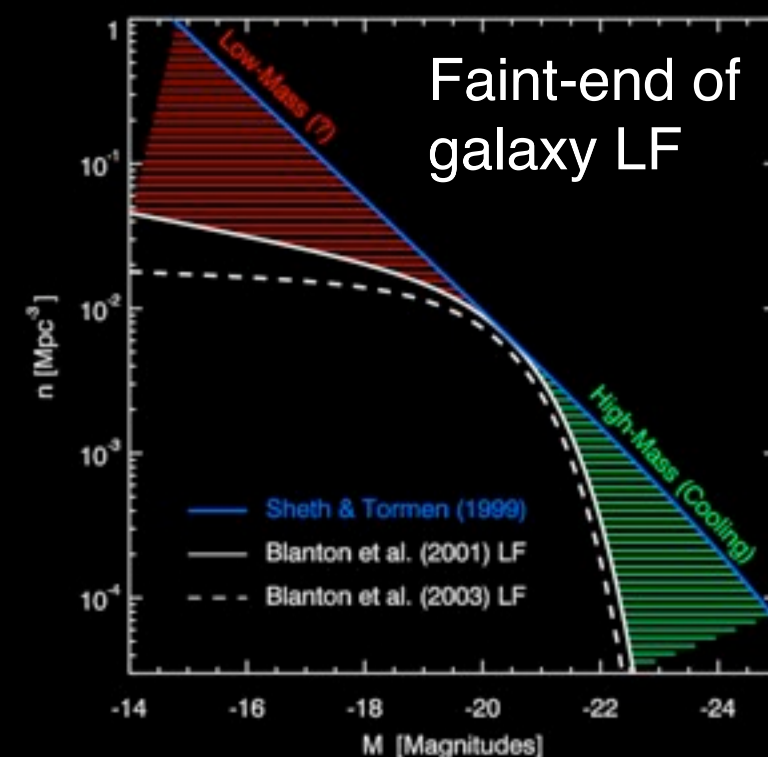
What is the interplay between cosmological gas inflow, disk dynamics, and the creation and destruction of molecular gas?

How is star formation efficiency related to supersonic turbulence?



Does the regulation of star formation change galaxy morphology and LFs?

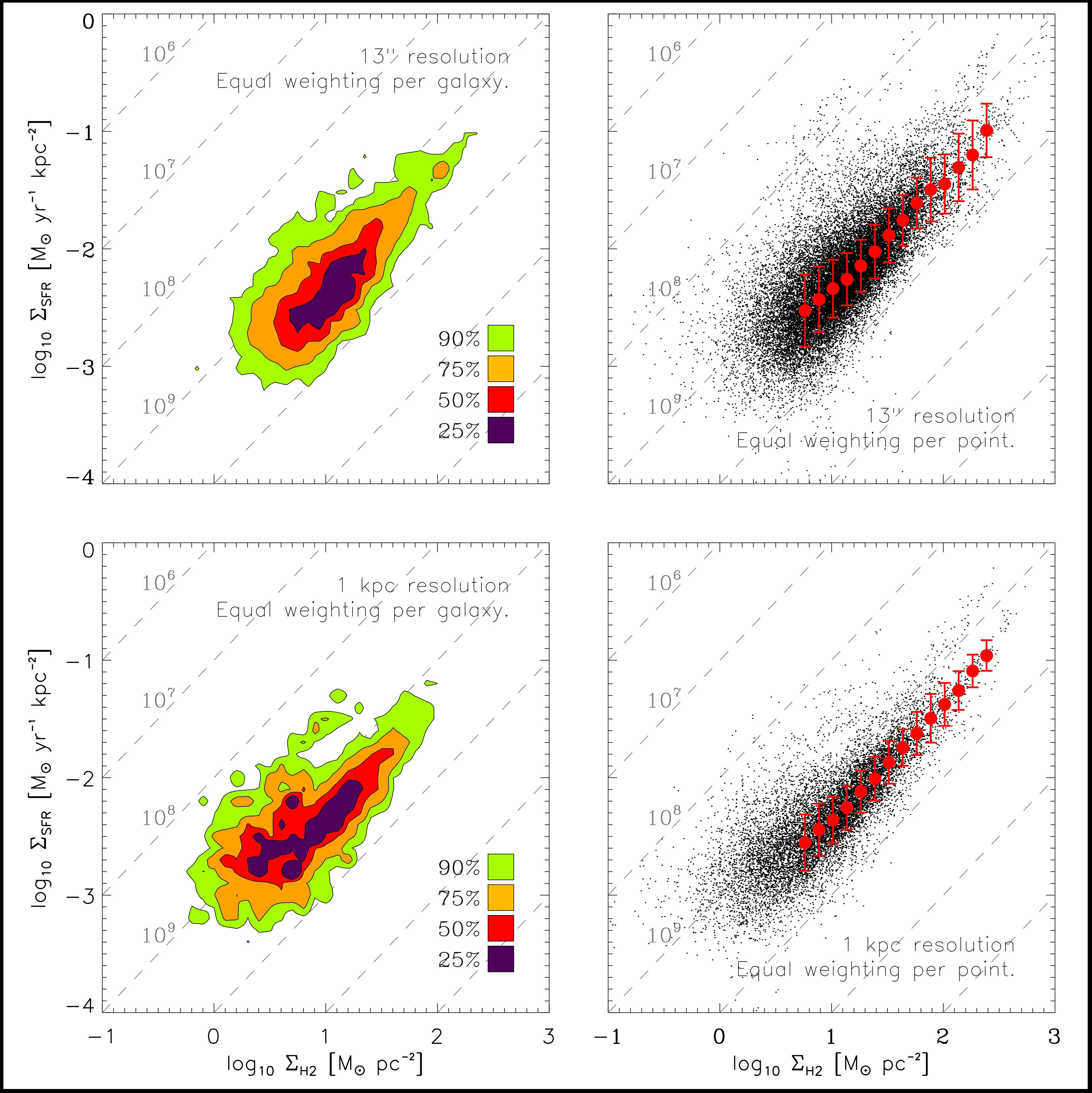


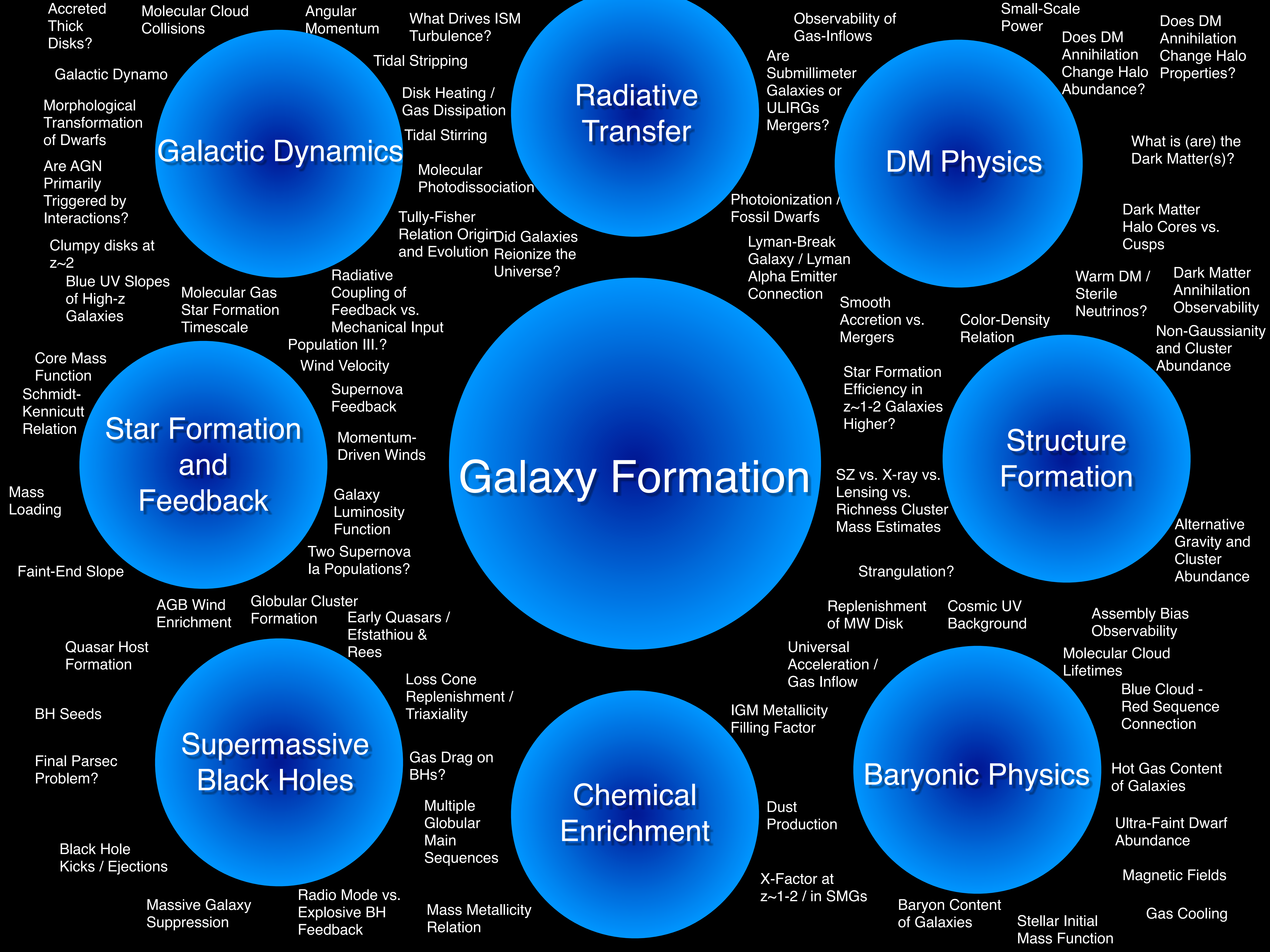


Global Timescale for Star Formation?

Bigiel et al. 2011 report that the star formation timescale is constant and the molecular S-K relation is linear.

In galaxy formation, solved problems often become unsolved after more data are available!




Galaxy Formation
Galactic Dynamics
Radiative Transfer
DM Physics
Star Formation and Feedback
Structure Formation
Supermassive Black Holes
Chemical Enrichment
Baryonic Physics
Accreted Thick Disks?
Molecular Cloud Collisions
Angular Momentum
What Drives ISM Turbulence?
Tidal Stripping
Galactic Dynamo
Morphological Transformation of Dwarfs
Disk Heating / Gas Dissipation
Tidal Stirring
Are AGN Primarily Triggered by Interactions?
Molecular Photodissociation
Clumpy disks at z~2
Tully-Fisher Relation Origin and Evolution
Did Galaxies Reionize the Universe?
Blue UV Slopes of High-z Galaxies
Molecular Gas Star Formation Timescale
Radiative Coupling of Feedback vs. Mechanical Input
Population III.?
Observability of Gas-Inflows
Are Submillimeter Galaxies or ULIRGs Mergers?
Small-Scale Power
Does DM Annihilation Change Halo Abundance?
Does DM Annihilation Change Halo Properties?
What is (are) the Dark Matter(s)?
Photoionization / Fossil Dwarfs
Lyman-Break Galaxy / Lyman Alpha Emitter Connection
Dark Matter Halo Cores vs. Cusps
Warm DM / Sterile Neutrinos?
Dark Matter Annihilation Observability
Smooth Accretion vs. Mergers
Color-Density Relation
Non-Gaussianity and Cluster Abundance
Core Mass Function
Wind Velocity
Schmidt-Kennicutt Relation
Supernova Feedback
Star Formation Efficiency in z~1-2 Galaxies Higher?
Momentum-Driven Winds
Mass Loading
Galaxy Luminosity Function
SZ vs. X-ray vs. Lensing vs. Richness Cluster Mass Estimates
Alternative Gravity and Cluster Abundance
Two Supernova Ia Populations?
Faint-End Slope
Strangulation?
AGB Wind Enrichment
Globular Cluster Formation
Early Quasars / Efstathiou & Rees
Replenishment of MW Disk
Cosmic UV Background
Assembly Bias Observability
Quasar Host Formation
Universal Acceleration / Gas Inflow
Molecular Cloud Lifetimes
Loss Cone Replenishment / Triaxiality
Blue Cloud - Red Sequence Connection
BH Seeds
IGM Metallicity Filling Factor
Final Parsec Problem?
Gas Drag on BHs?
Hot Gas Content of Galaxies
Multiple Globular Main Sequences
Dust Production
Ultra-Faint Dwarf Abundance
Black Hole Kicks / Ejections
X-Factor at z~1-2 / in SMGs
Magnetic Fields
Radio Mode vs. Explosive BH Feedback
Massive Galaxy Suppression
Mass Metallicity Relation
Baryon Content of Galaxies
Stellar Initial Mass Function
Gas Cooling

Black Hole Spins

Volonteri et al 2005 Semi-analytical model of BH spin distribution.

Based on Extended Press-Schechter merger histories, analytical models for dynamical friction, gas accretion, and BH-BH mergers.

In this model, even radio-quiet AGN are rapidly spinning.

Radio luminosity is likely connected to spin and accretion rate.