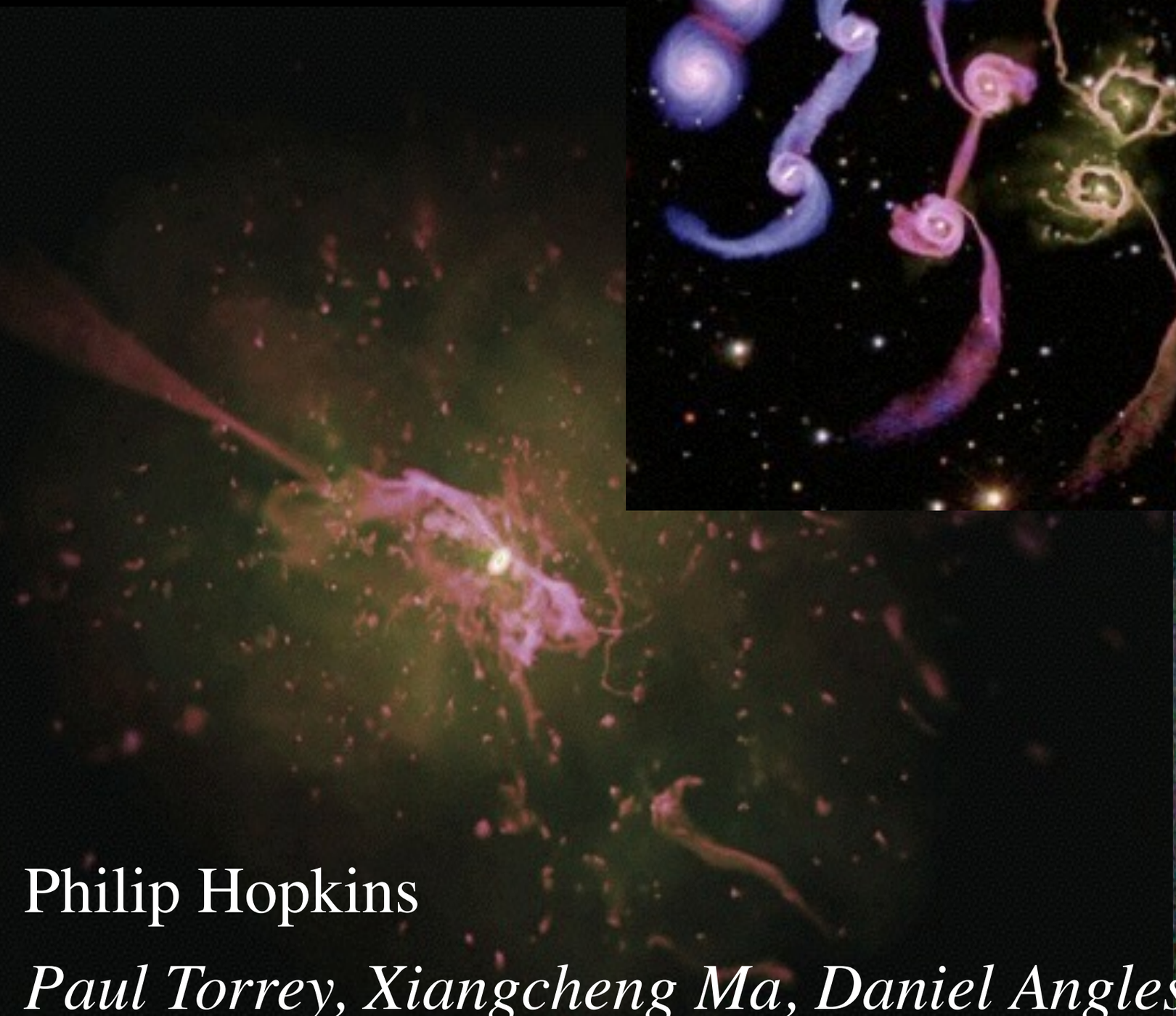
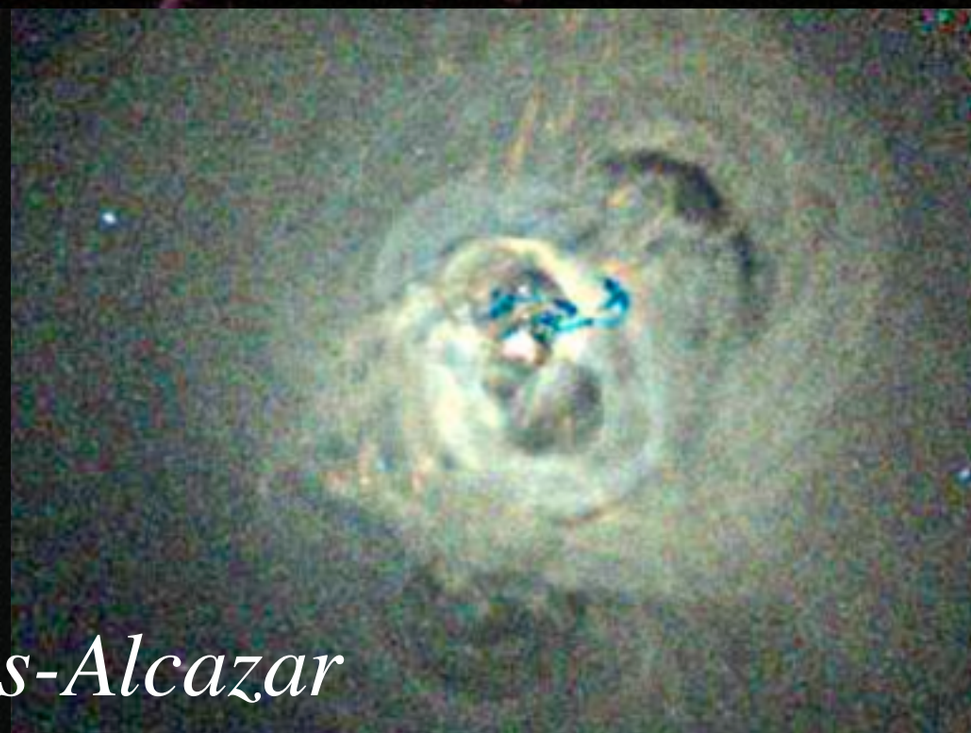
The Case for AGN Feedback



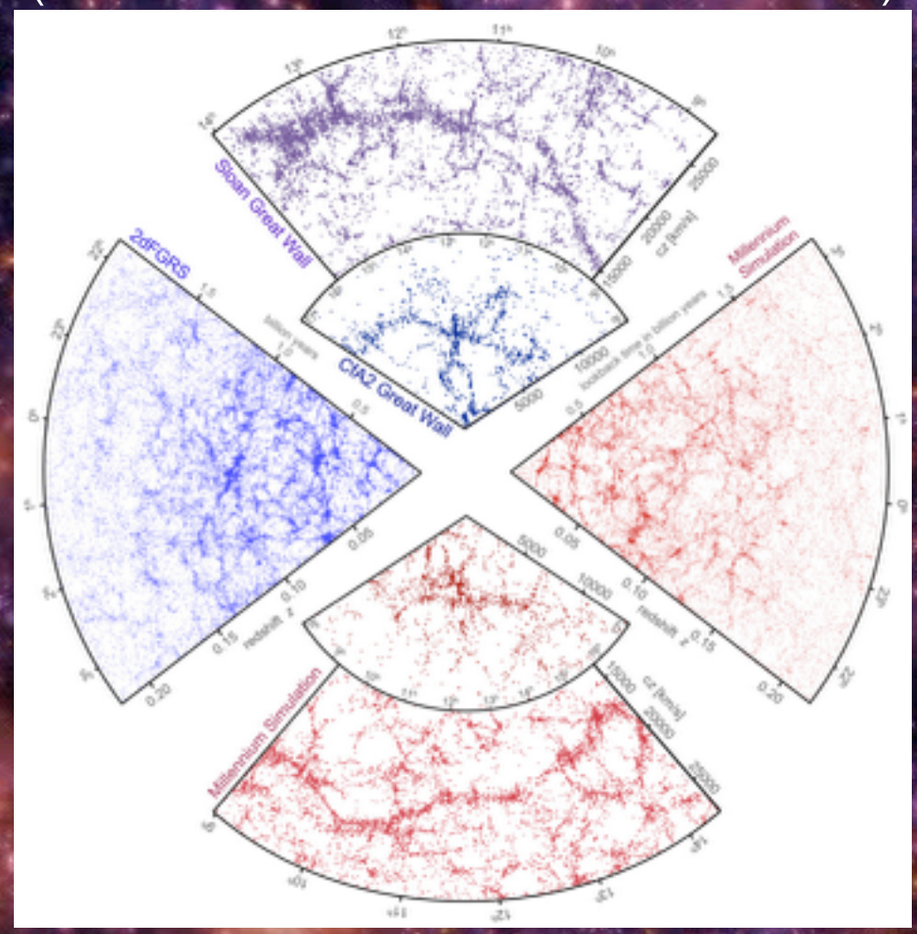


Philip Hopkins

Paul Torrey, Xiangcheng Ma, Daniel Angles-Alcazar

Large scales: Gravity +
CDM Works!

Observations vs Theory
(SDSS vs Millennium Simulation)



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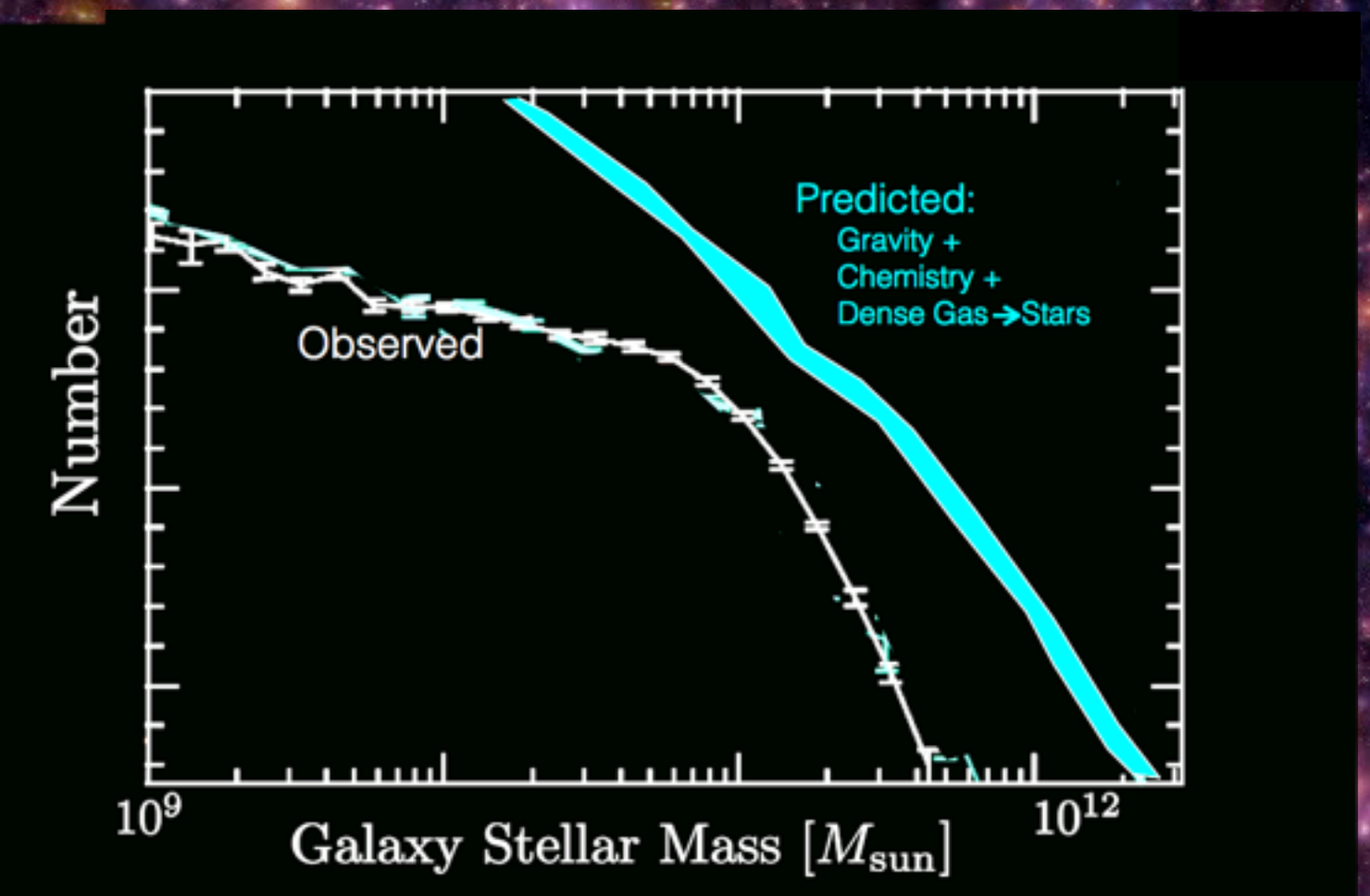

Observations vs Theory
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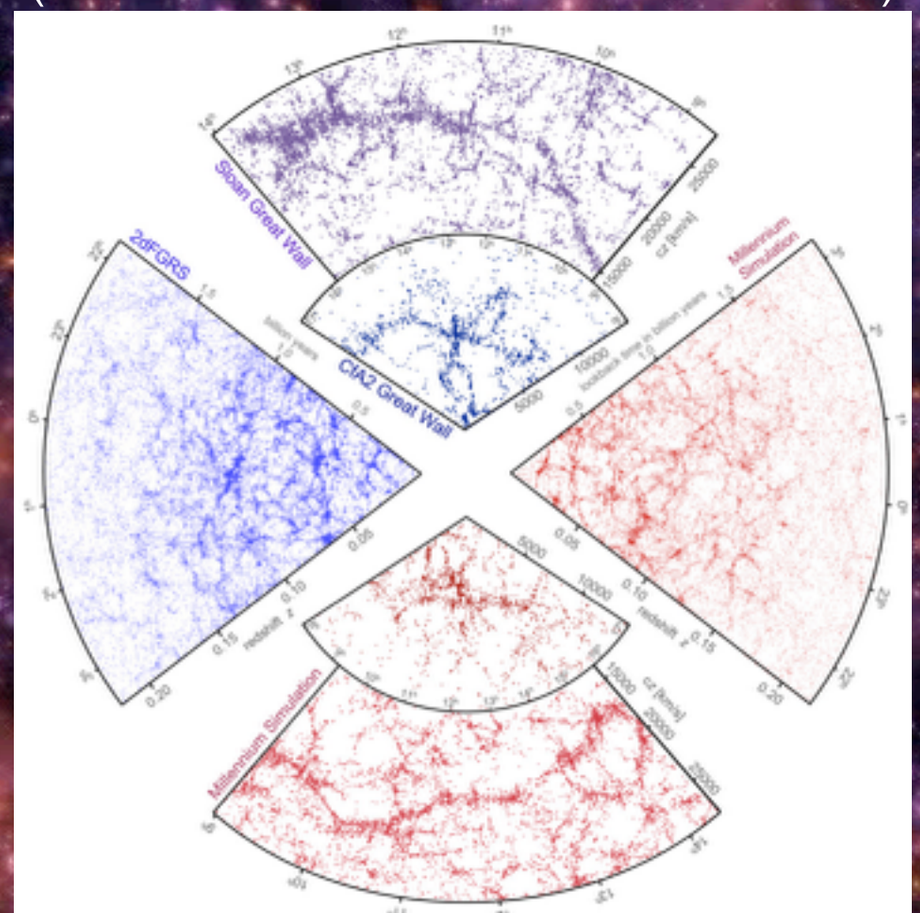
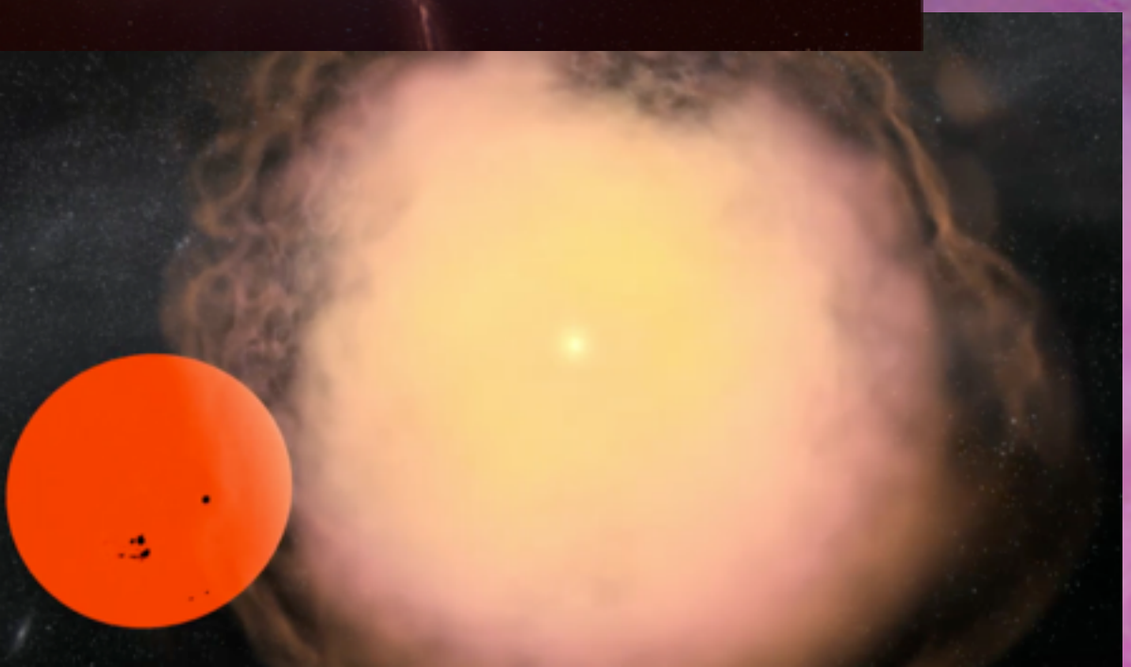


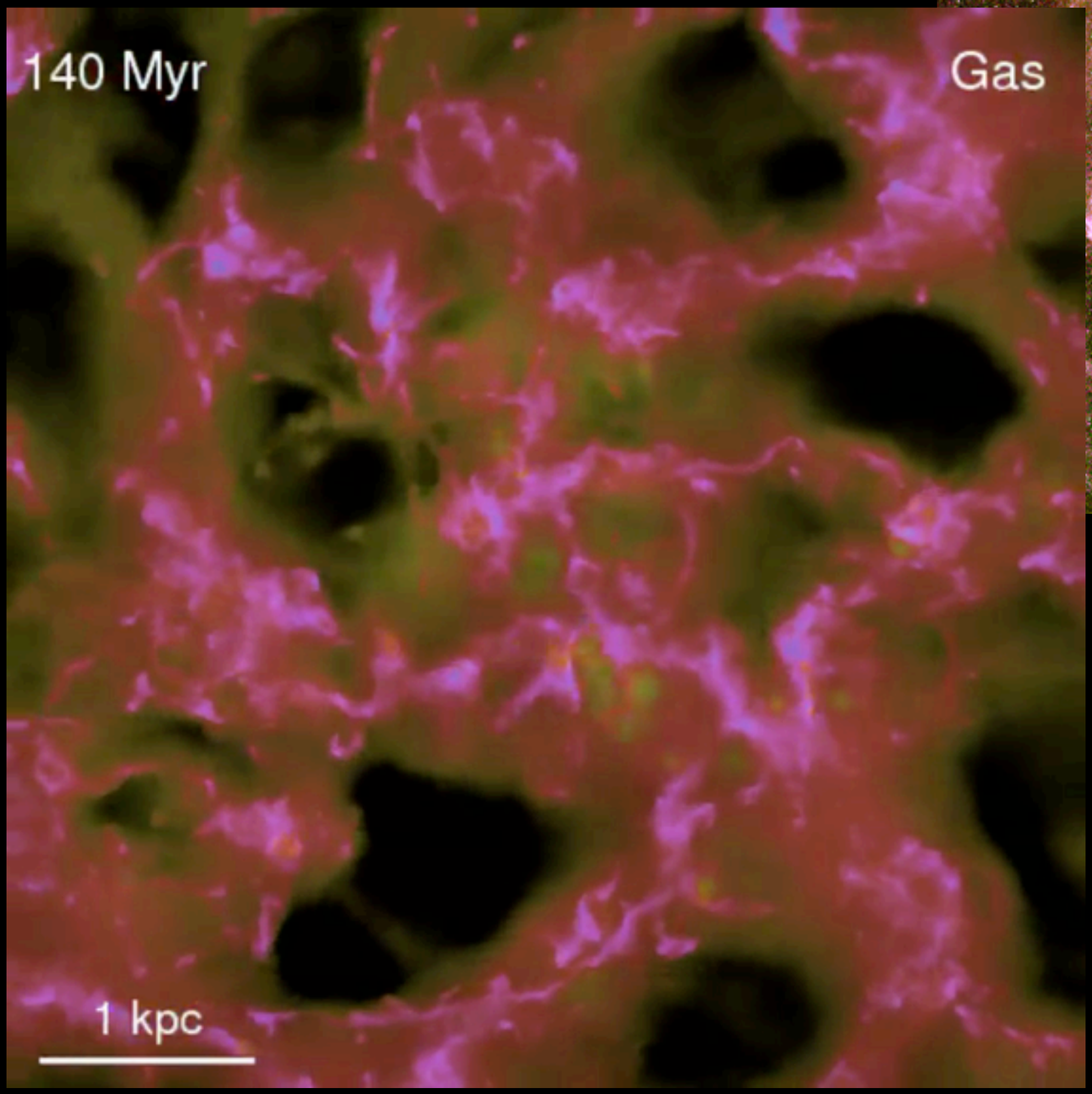
What's missing?



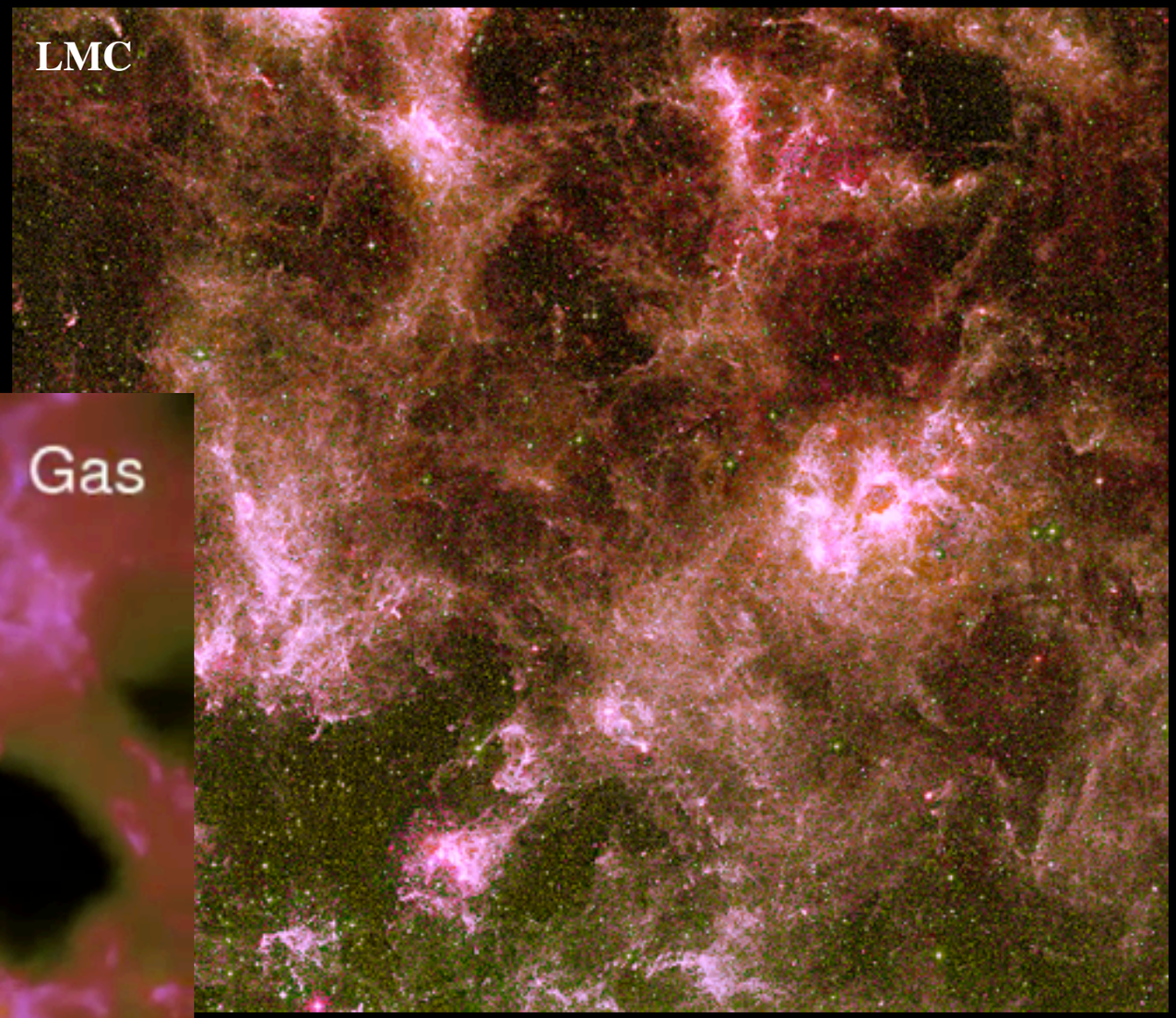
We have to simulate it!

- EVERYTHING on scales
  ~ 10^{-9} - 10^{27} cm is terribly messy,

… but we are doing it!



Yellow: hot (>10^6 K) Pink: warm (ionized, ~10^4K) Blue: cold (neutral <10^4 K)

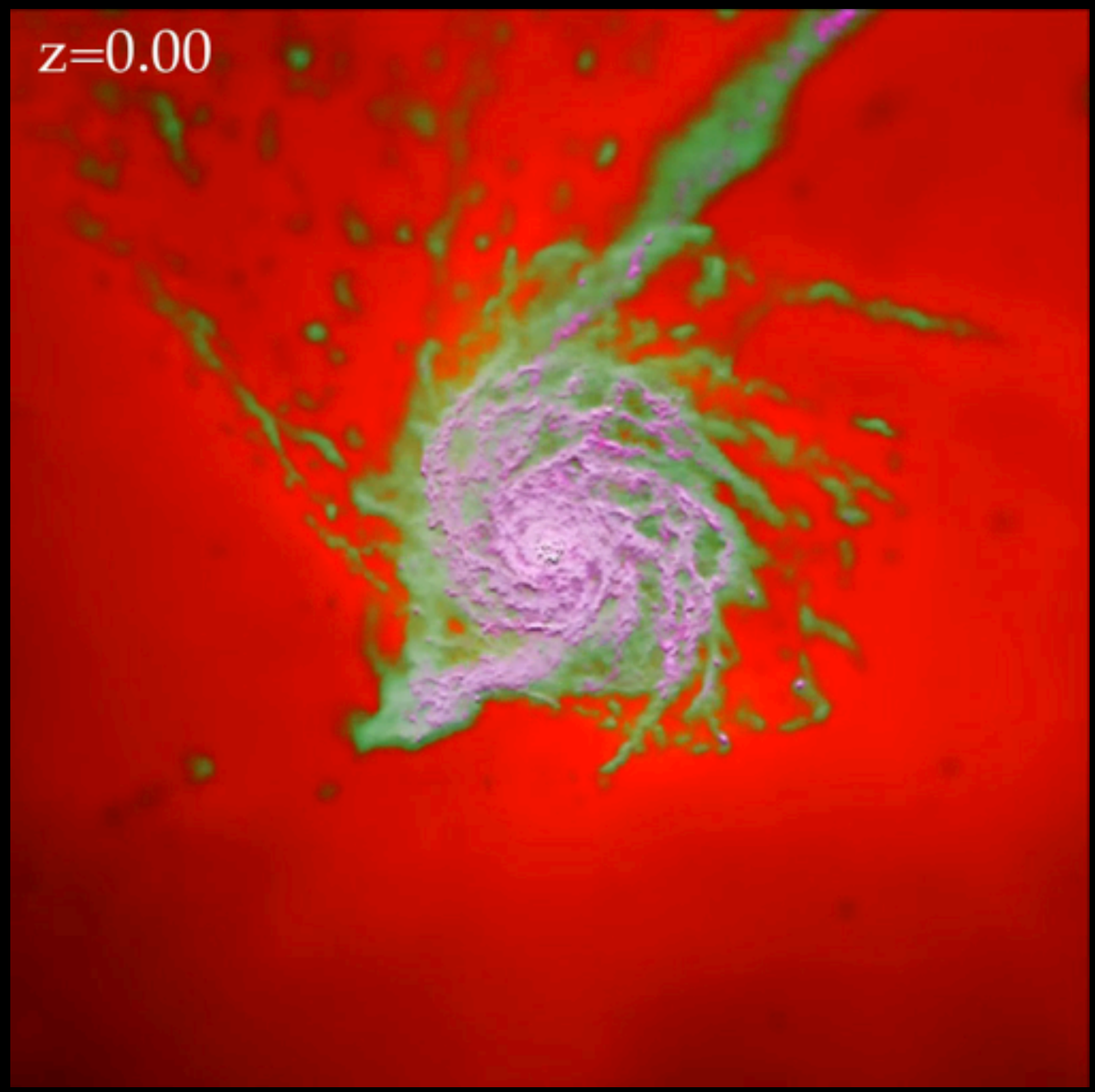


The FIRE Project:

- SNe (II & Ia)
- Stellar Winds (O & AGB)
- Photoionization (HII) & Photo-electric
- Radiation Pressure (IR & UV)
- Cosmic Rays

- all with…
  - Magnetic fields
  - Cooling, chemistry
  - Conduction, viscosity, etc.

The FIRE Project: (movies at fire.northwestern.edu)



Stars (Hubble image):

Blue: Young star clusters

Red: Dust extinction

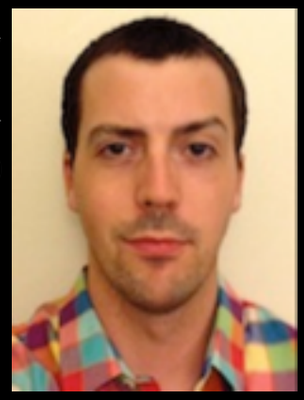
Gas: Magenta: cold $(< 10^4\,K)$

Green: warm (ionized)

Red: hot $(> 10^6\,K)$

The FIRE Project: Latte

Andrew Wetzel (arXiv:1602.05957)



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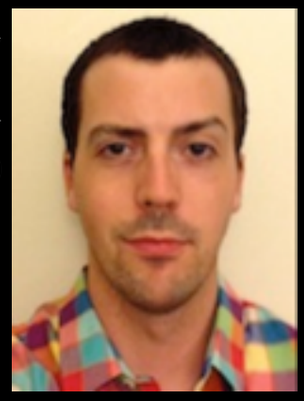

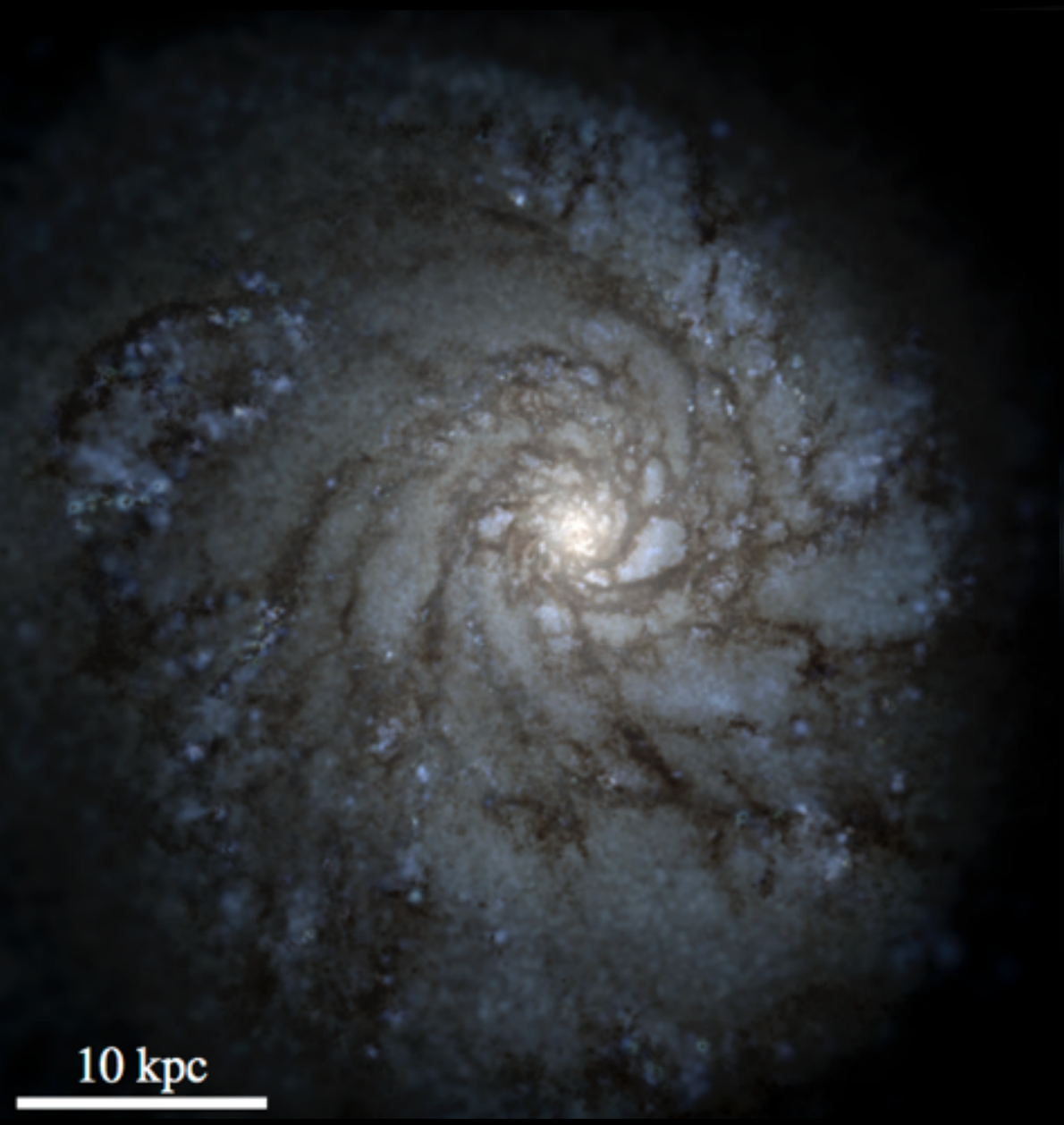

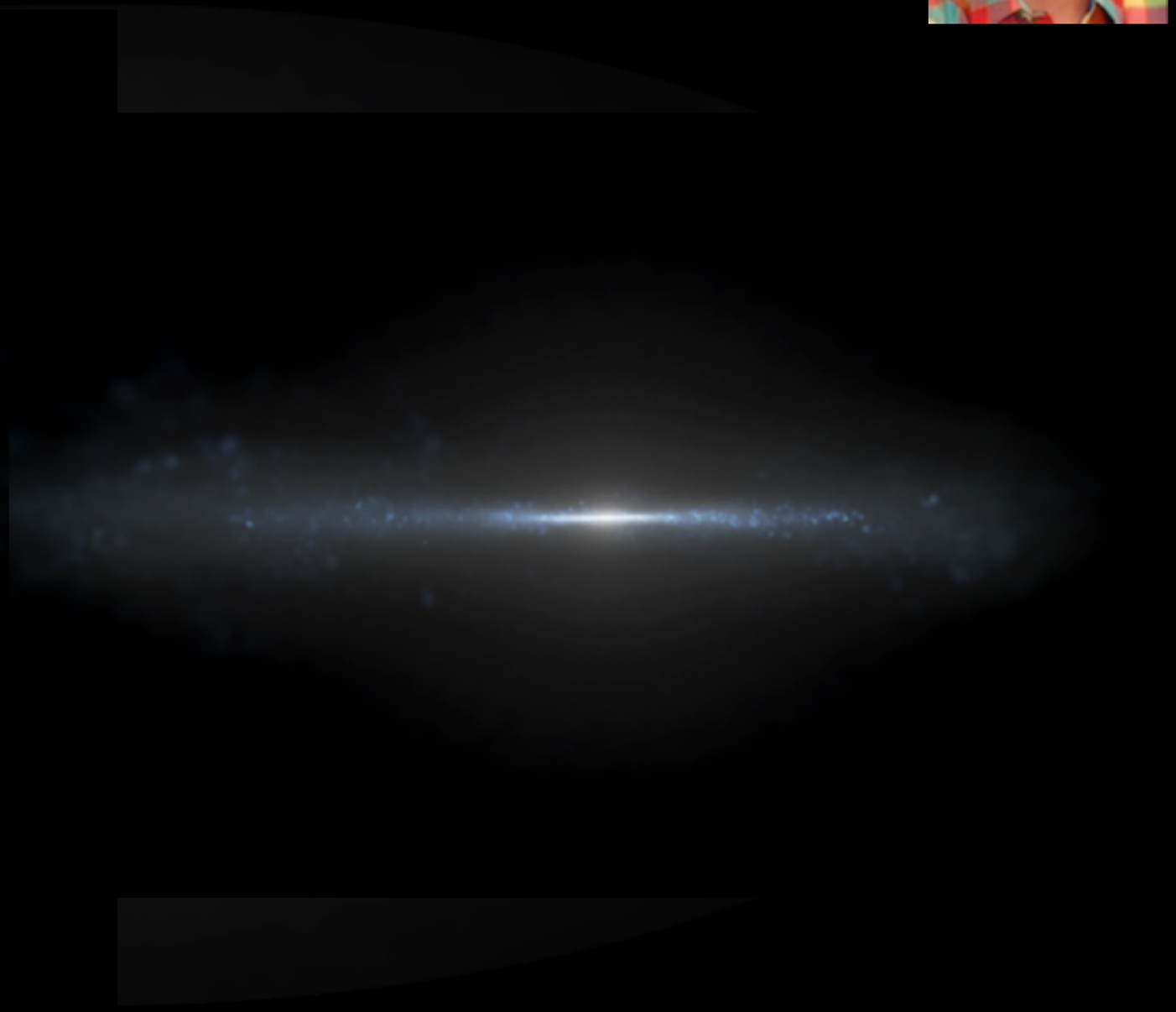

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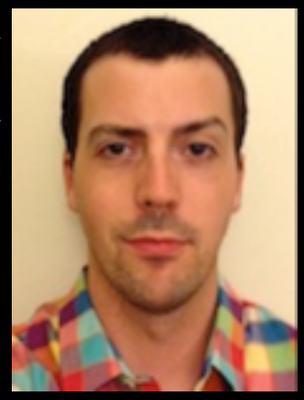

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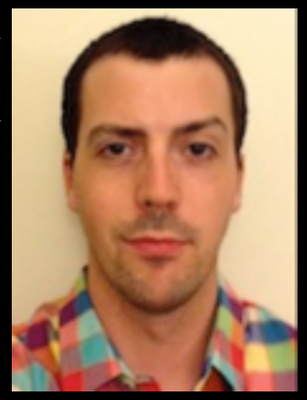
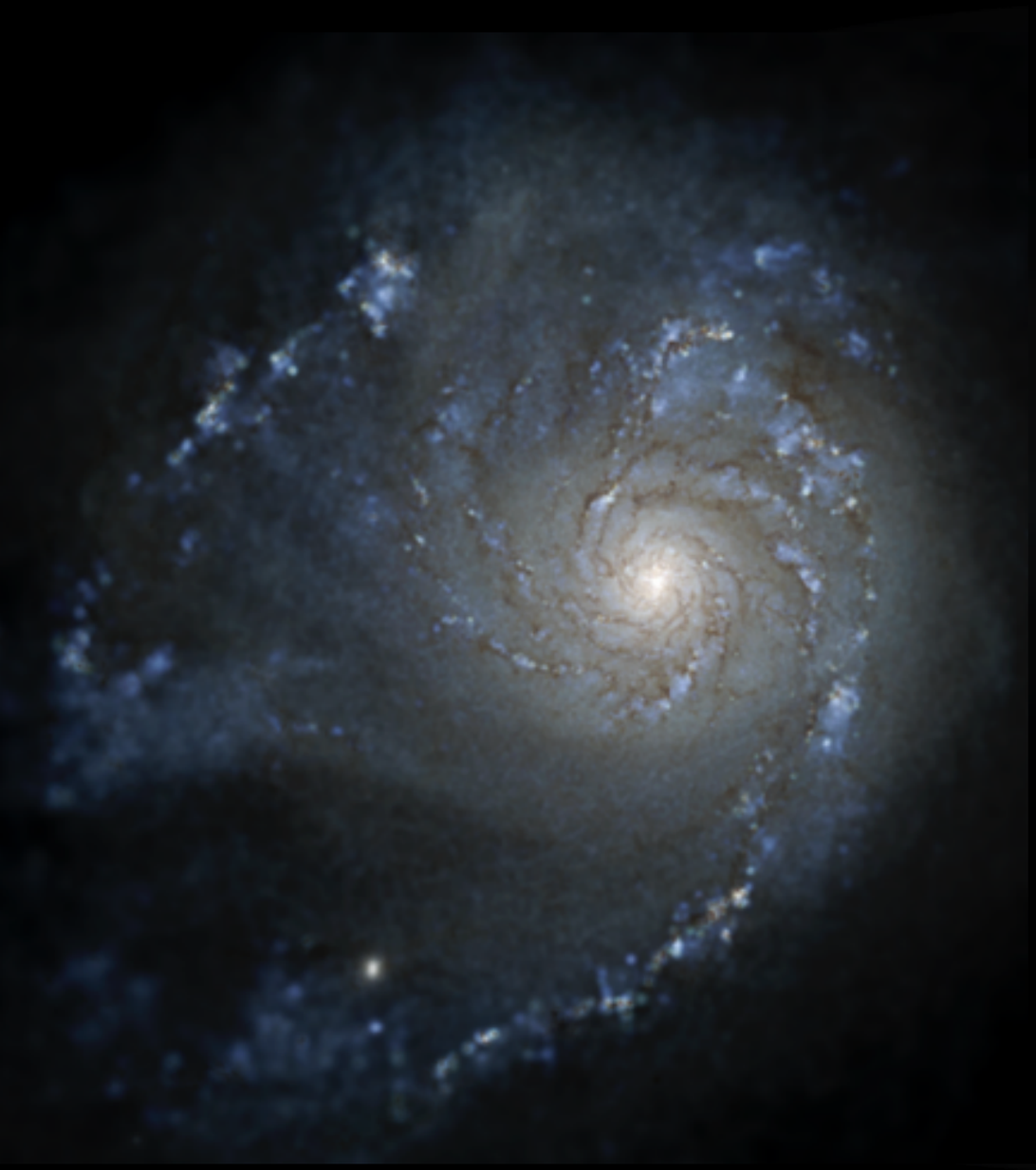
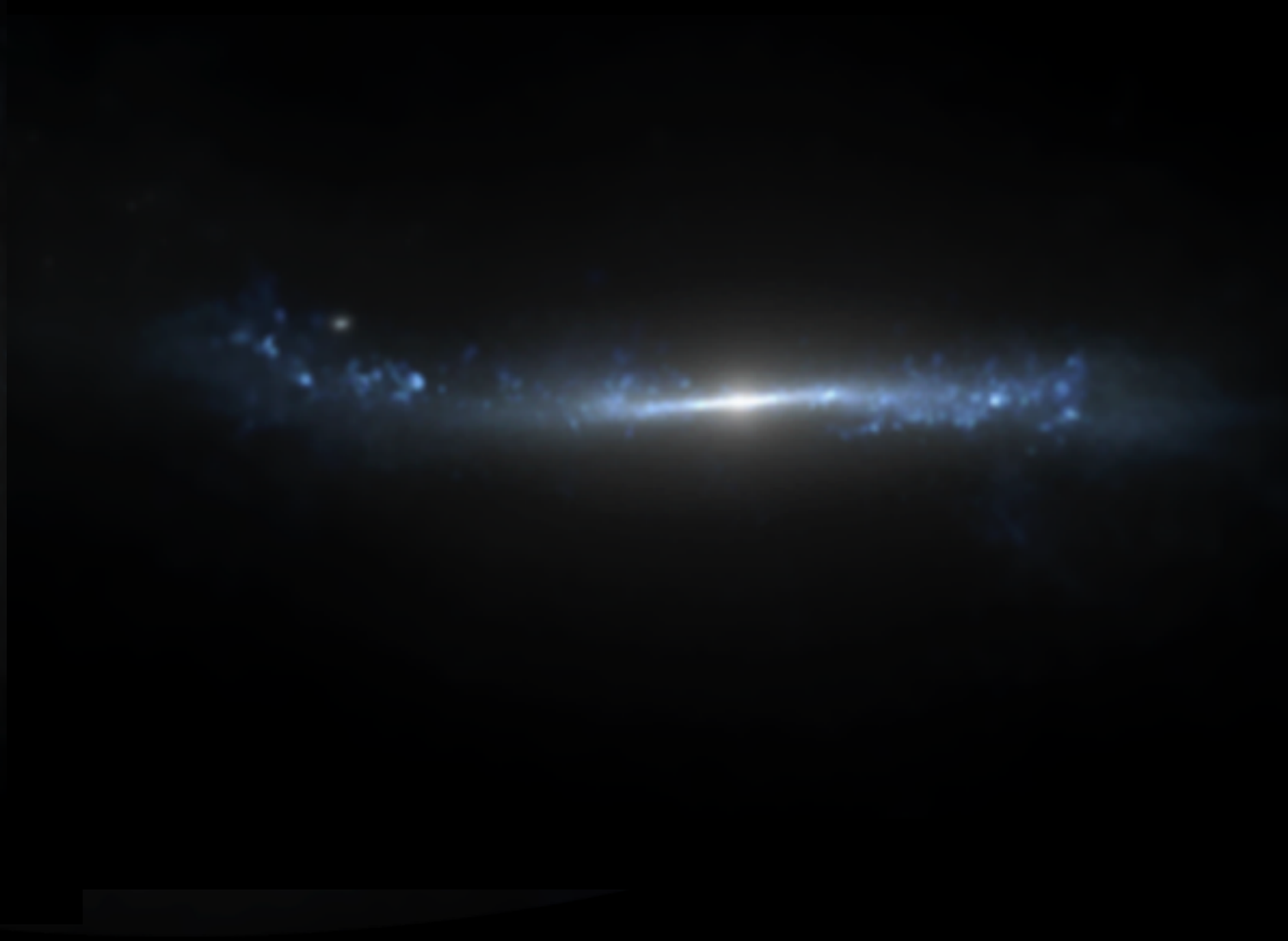


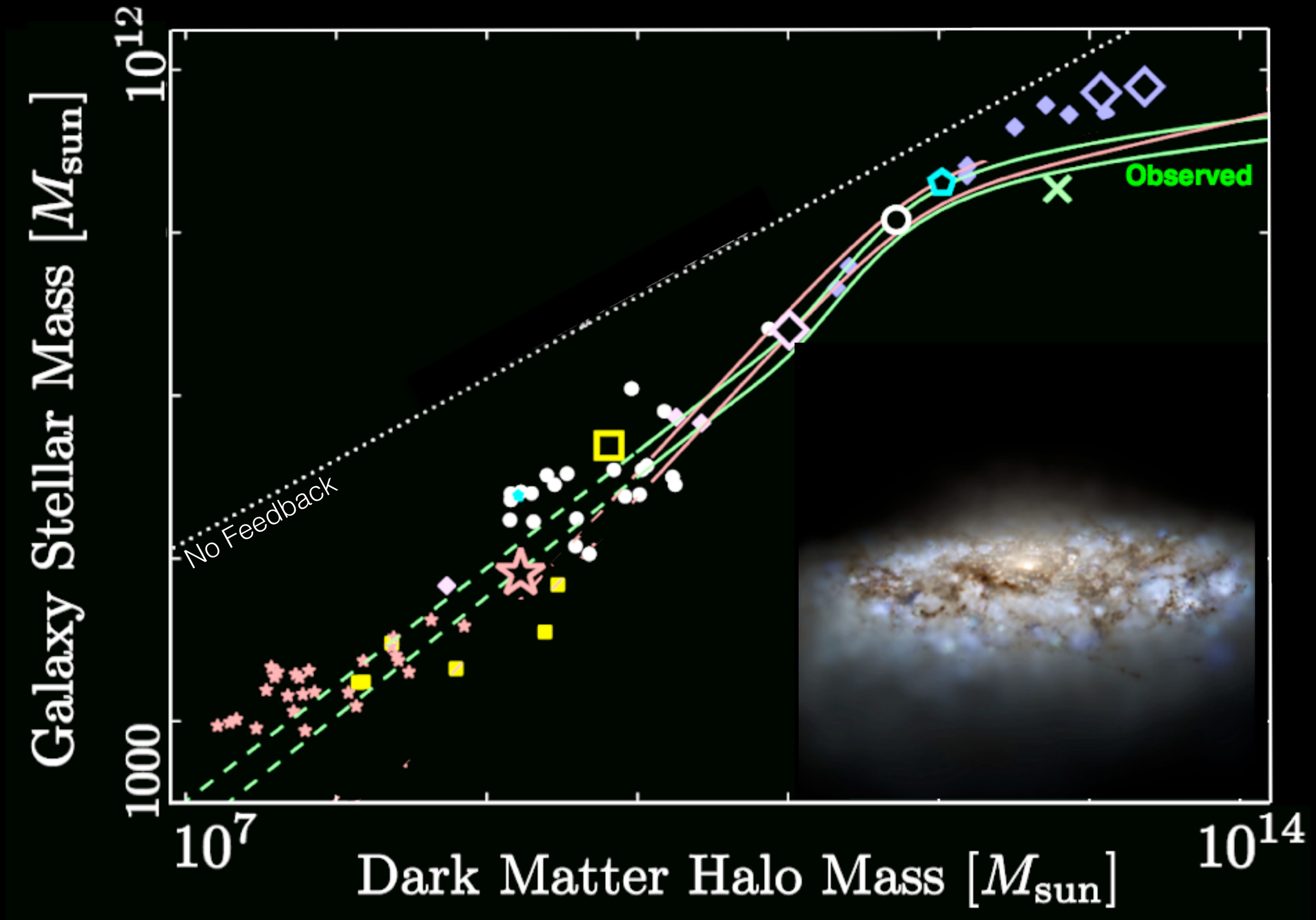




It Works!

THIS APPROACH IS PRODUCING REALISTIC GALAXIES

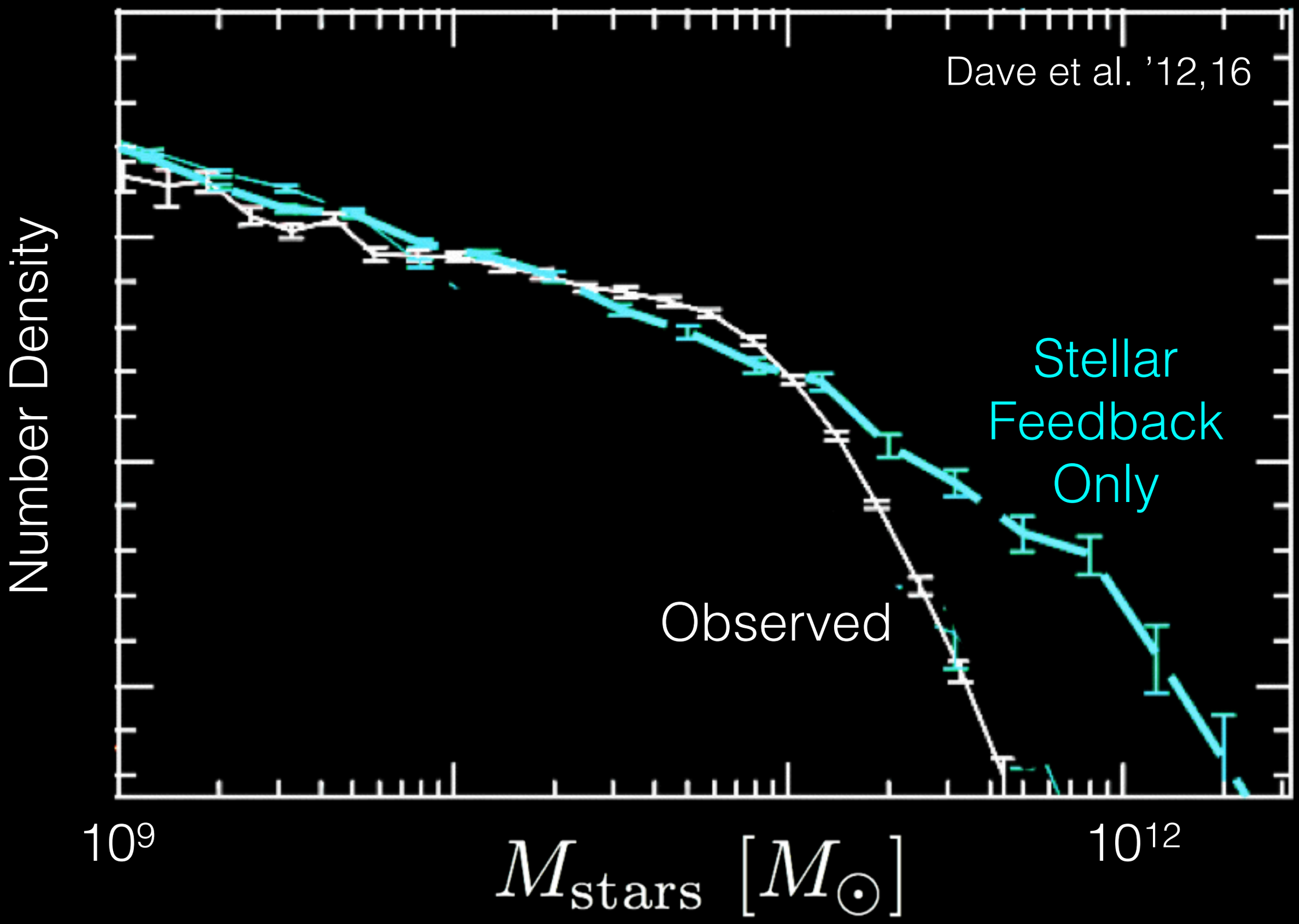
PFH et al.
(arXiv:1311.2073)



Where Does Feedback Fail?

Need Additional Physics To *Turn Off* Star Formation

STELLAR FEEDBACK + COOLING + HYDRO = COOLING FLOW PROBLEM

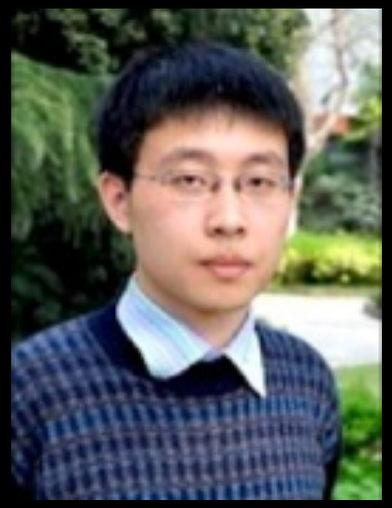


Quenching: Need Additional Physics

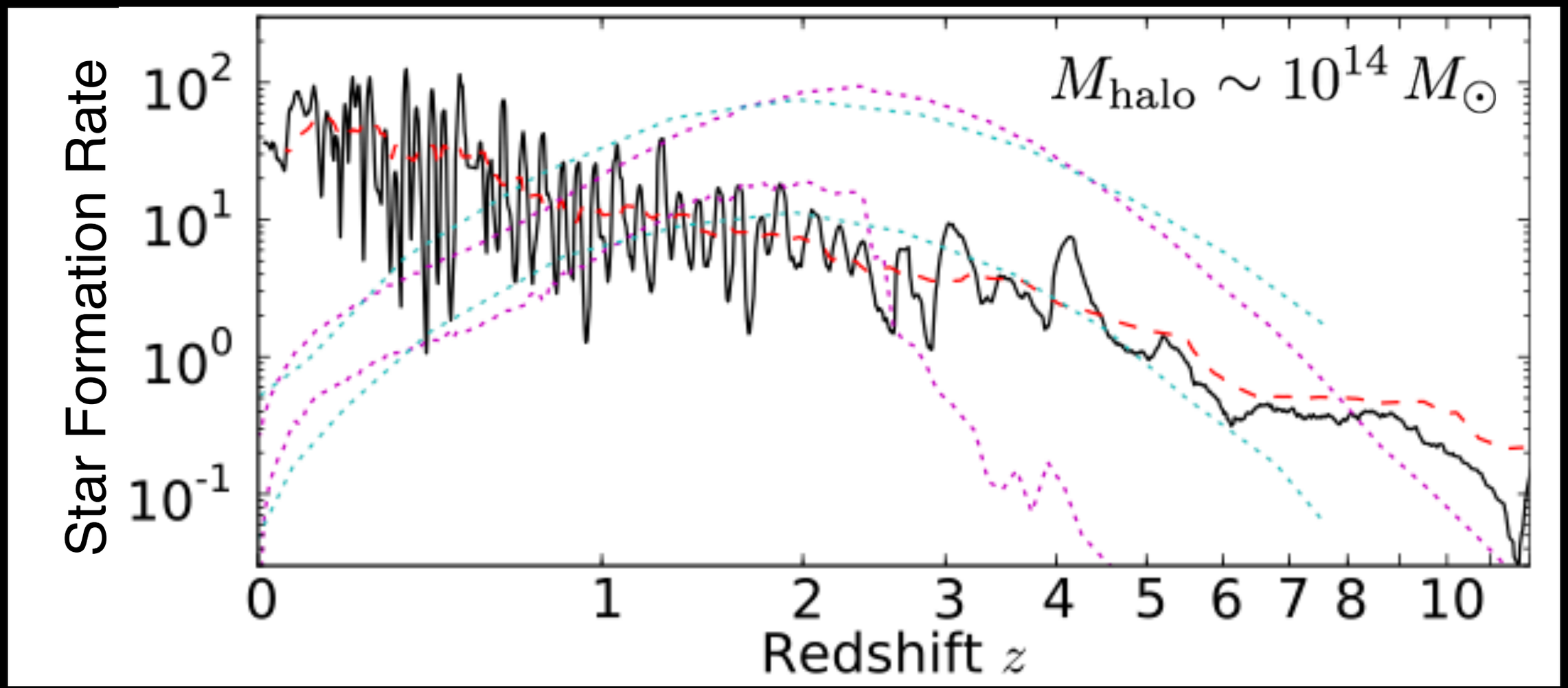
STELLAR FEEDBACK + COOLING + HYDRO = COOLING FLOW PROBLEM

- Virial shocks
- "Morphological Quenching"
- AGB Winds & SNe Ia
- Magnetic Fields, Conduction

→ Not Enough



Xiangcheng Ma
Robert Feldmann

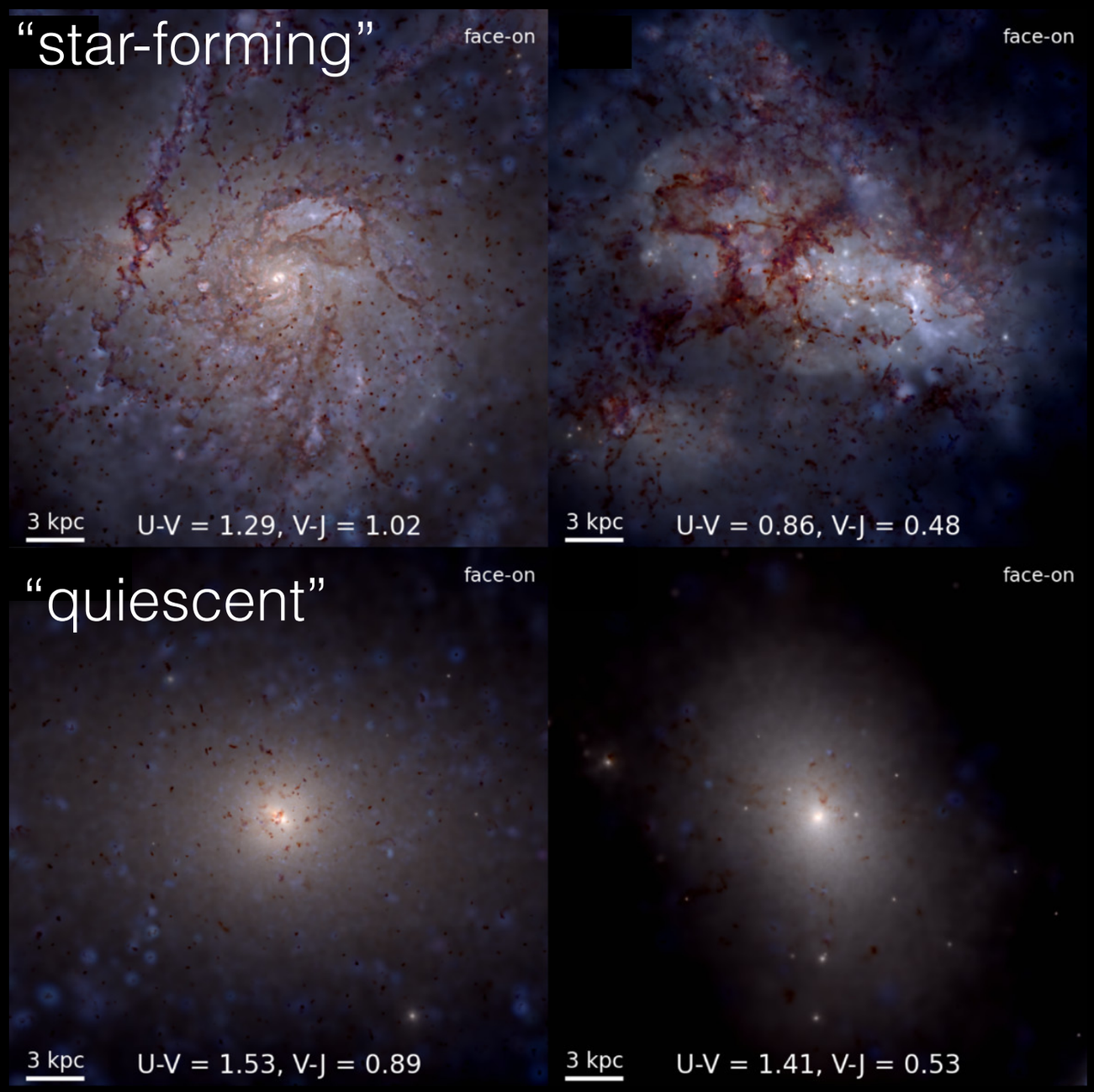


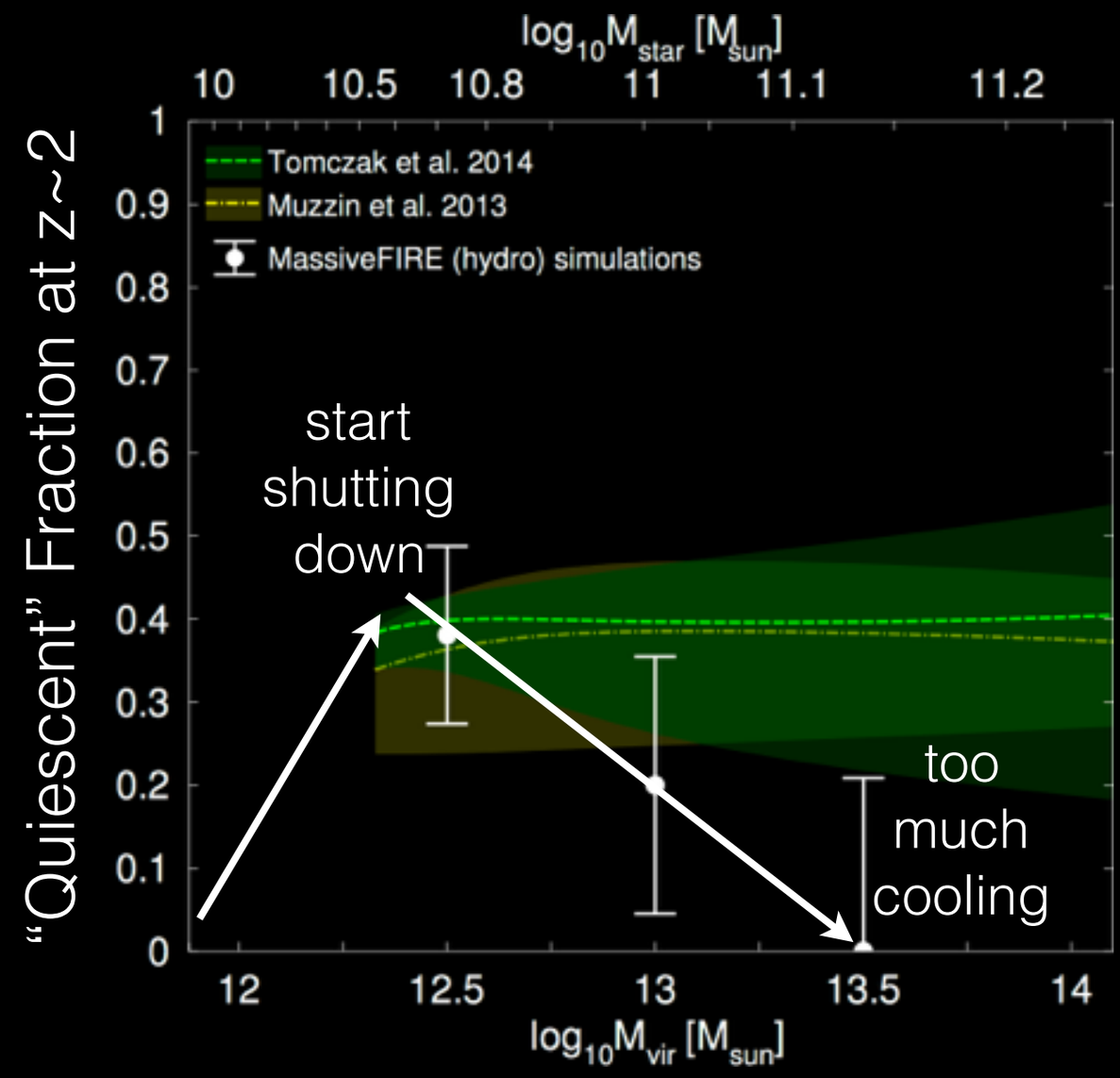
Long-Term Quenching: Need Additional Physics

STELLAR FEEDBACK + COOLING + HYDRO = COOLING FLOW PROBLEM

R. Feldmann
(arXiv:1601.04704)

Can *temporarily* "shut down"
(high-z quiescent populations)

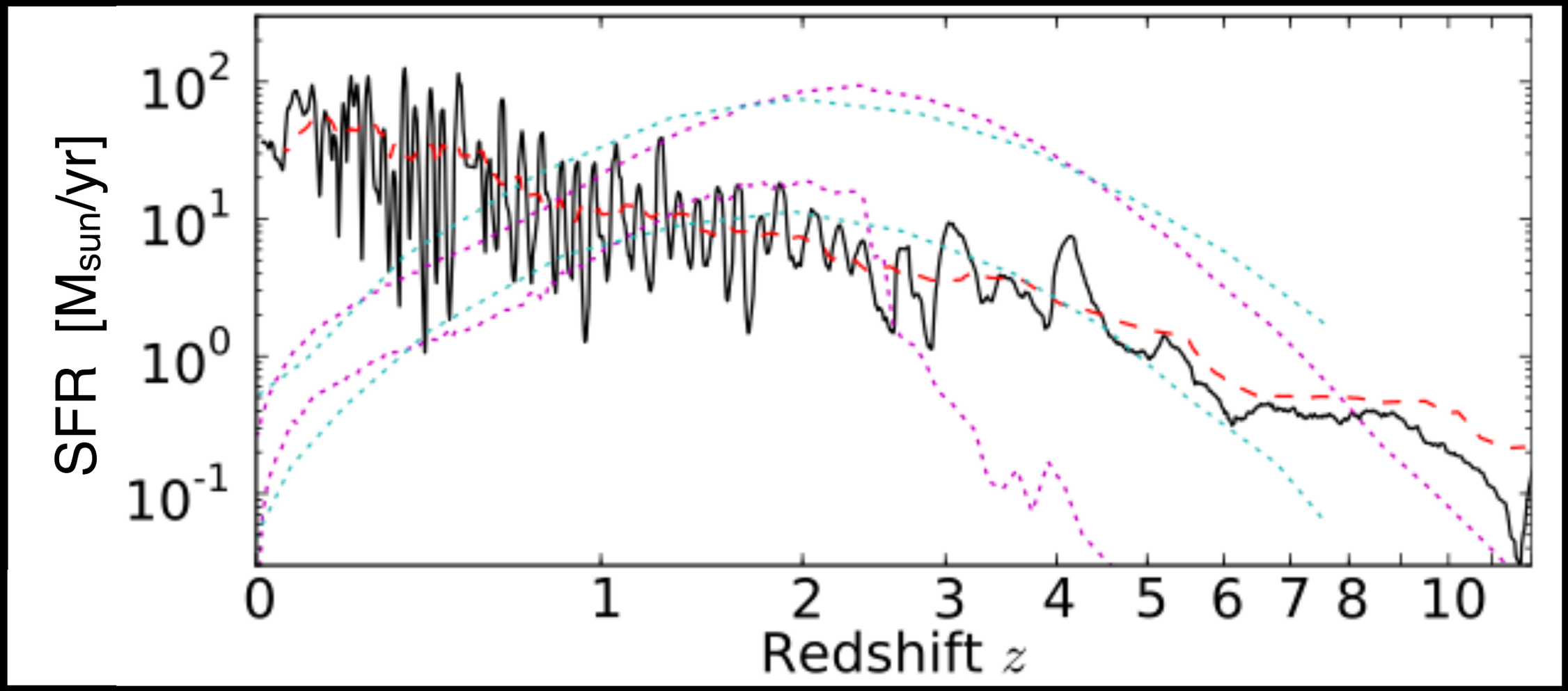




Can Gravitational Heating Do It?

IMPORTANT, BUT … **NO**

Reference?
(Literally all the theorists)



Virial shock-heating, stirring by clumps/substructure keeps 90% of gas hot

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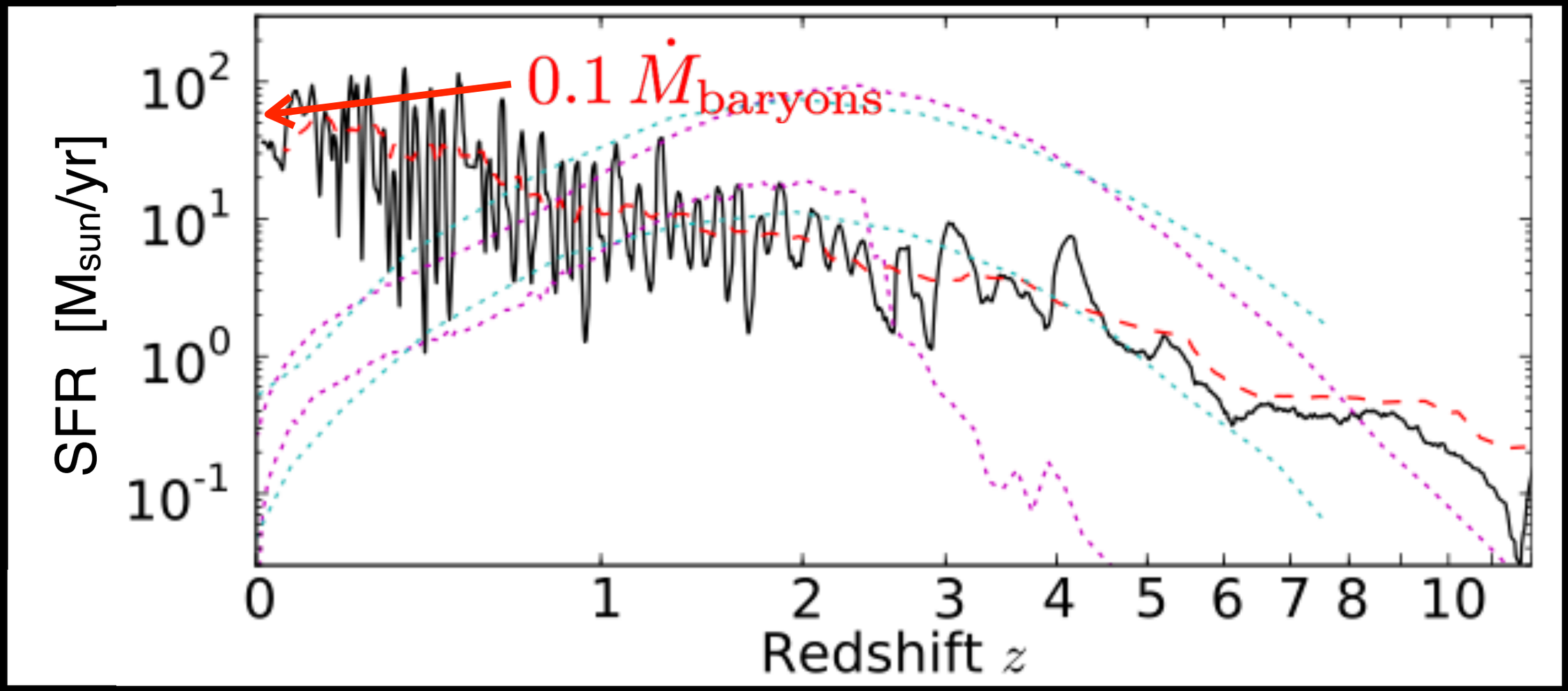

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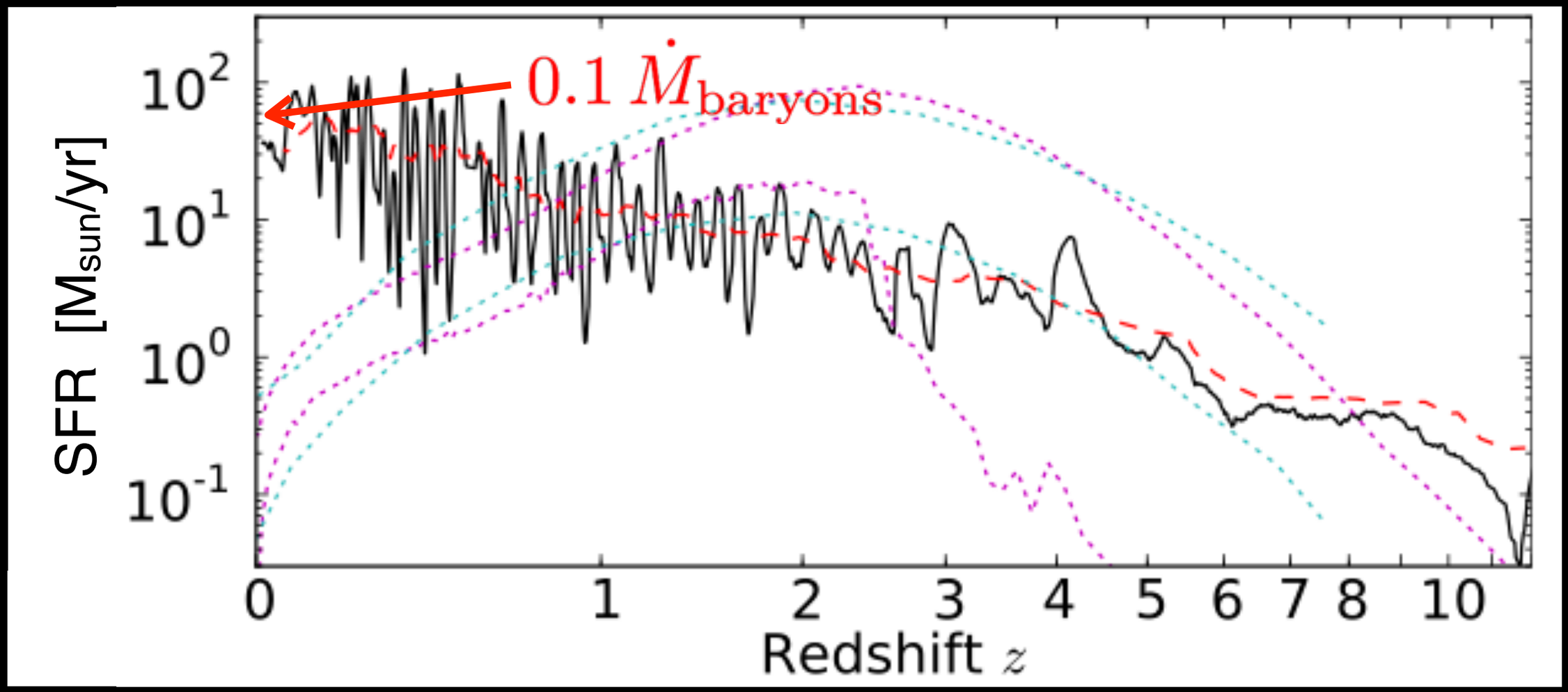

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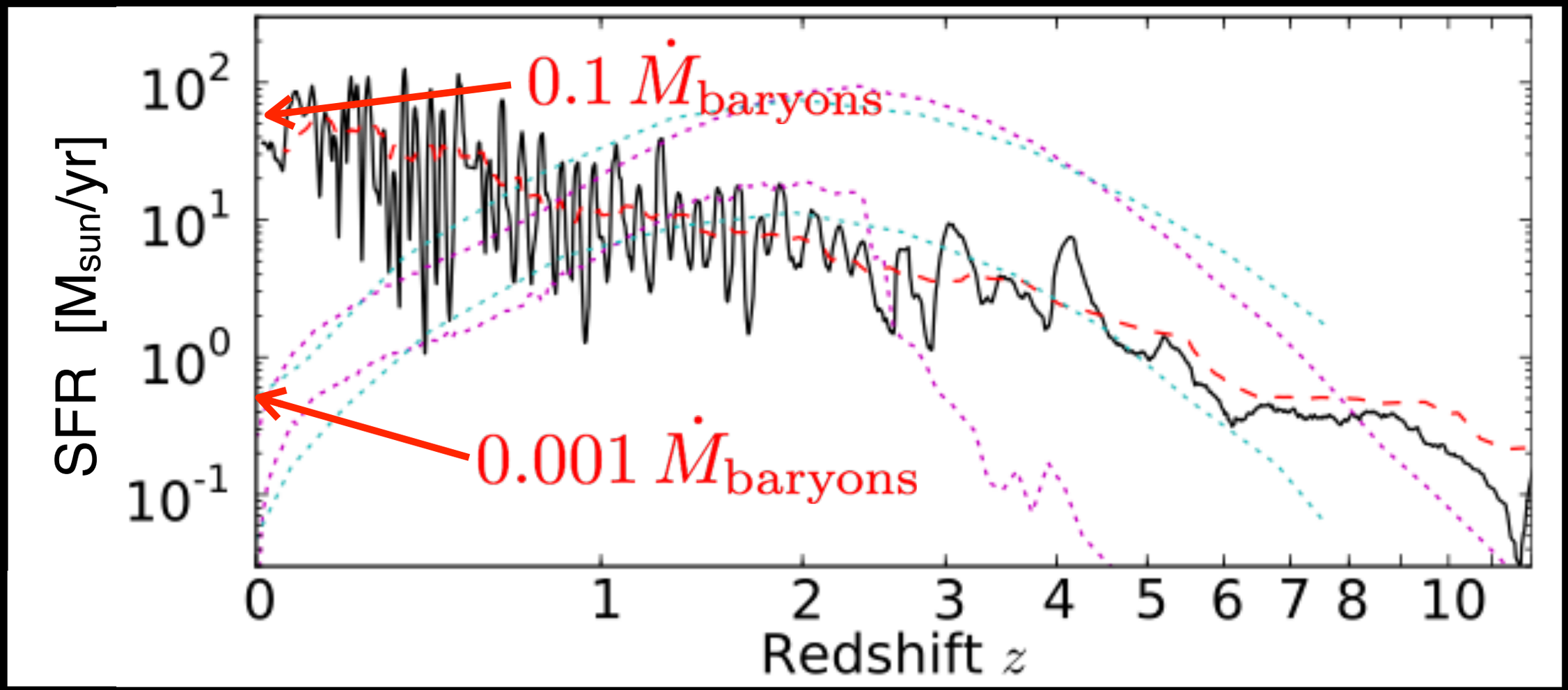

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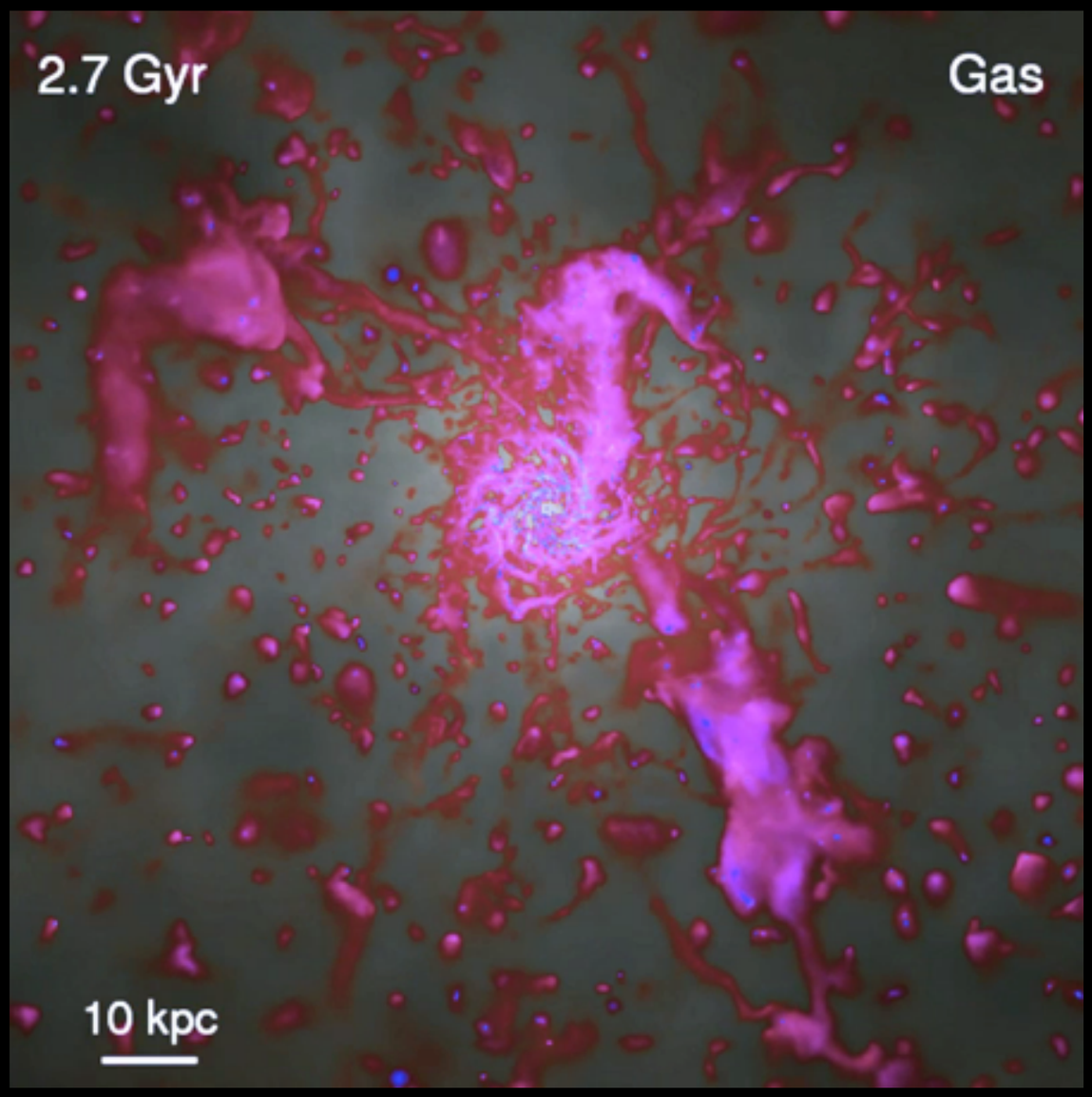
Lesson 1: Don’t Trust Models that Don’t Do Stars Right

SMALL GALAXIES BECOME BIG GALAXIES



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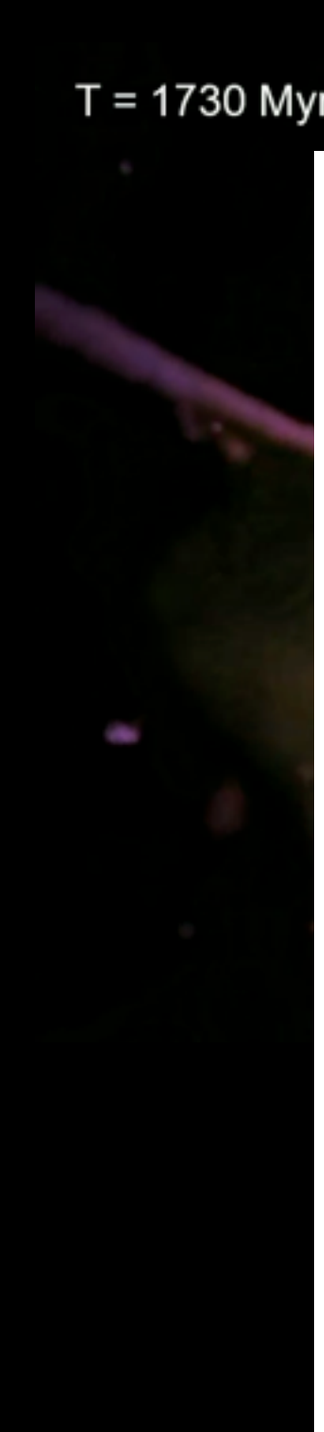

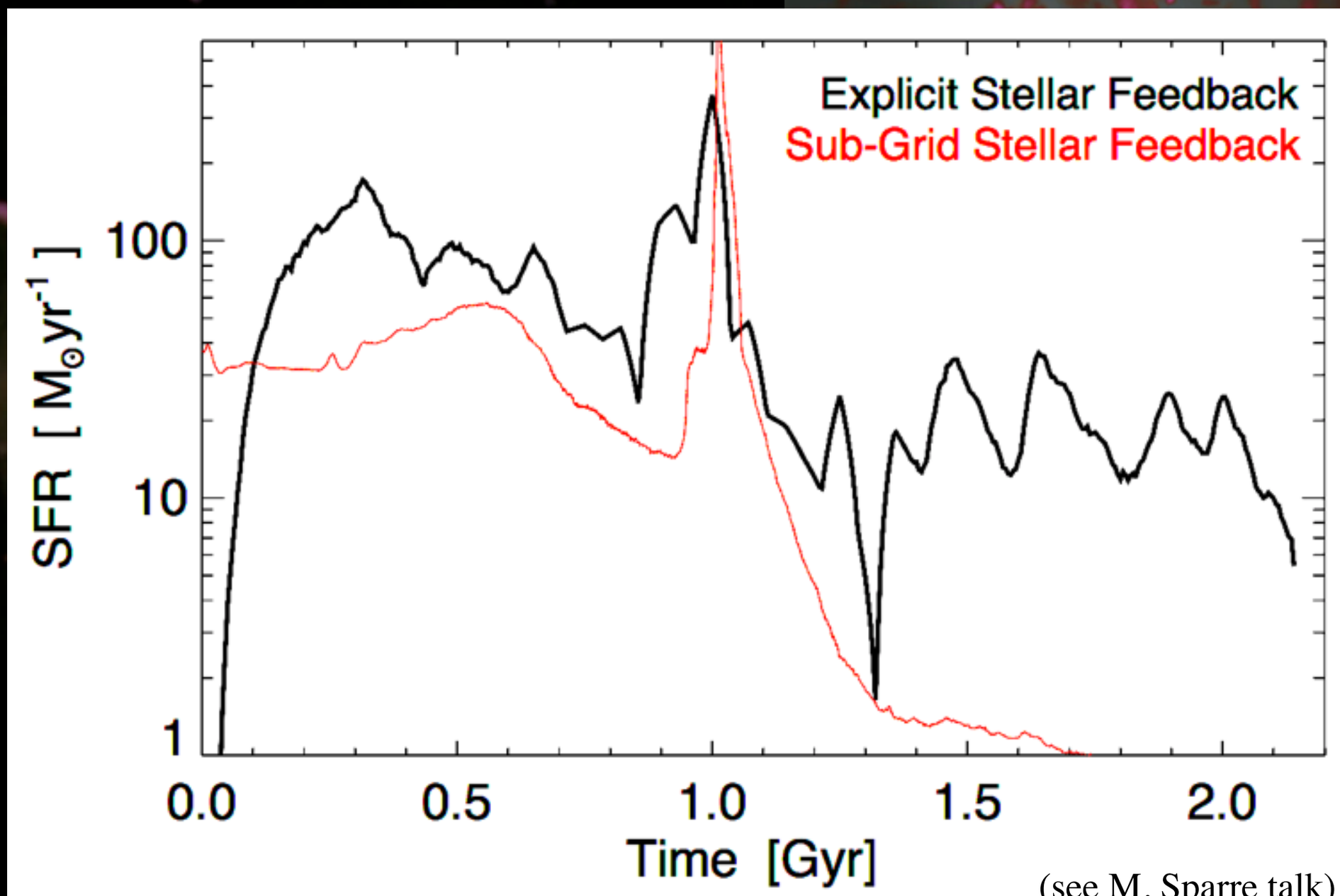

(see M. Sparre talk)

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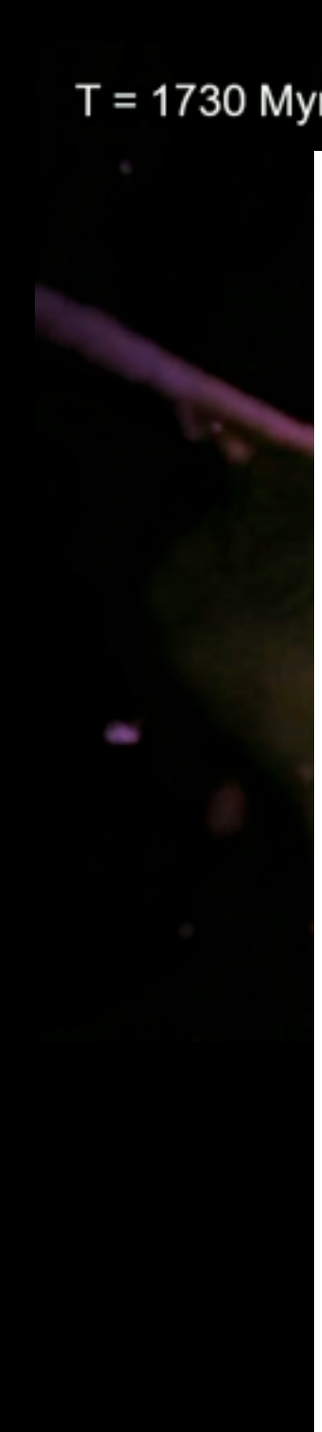
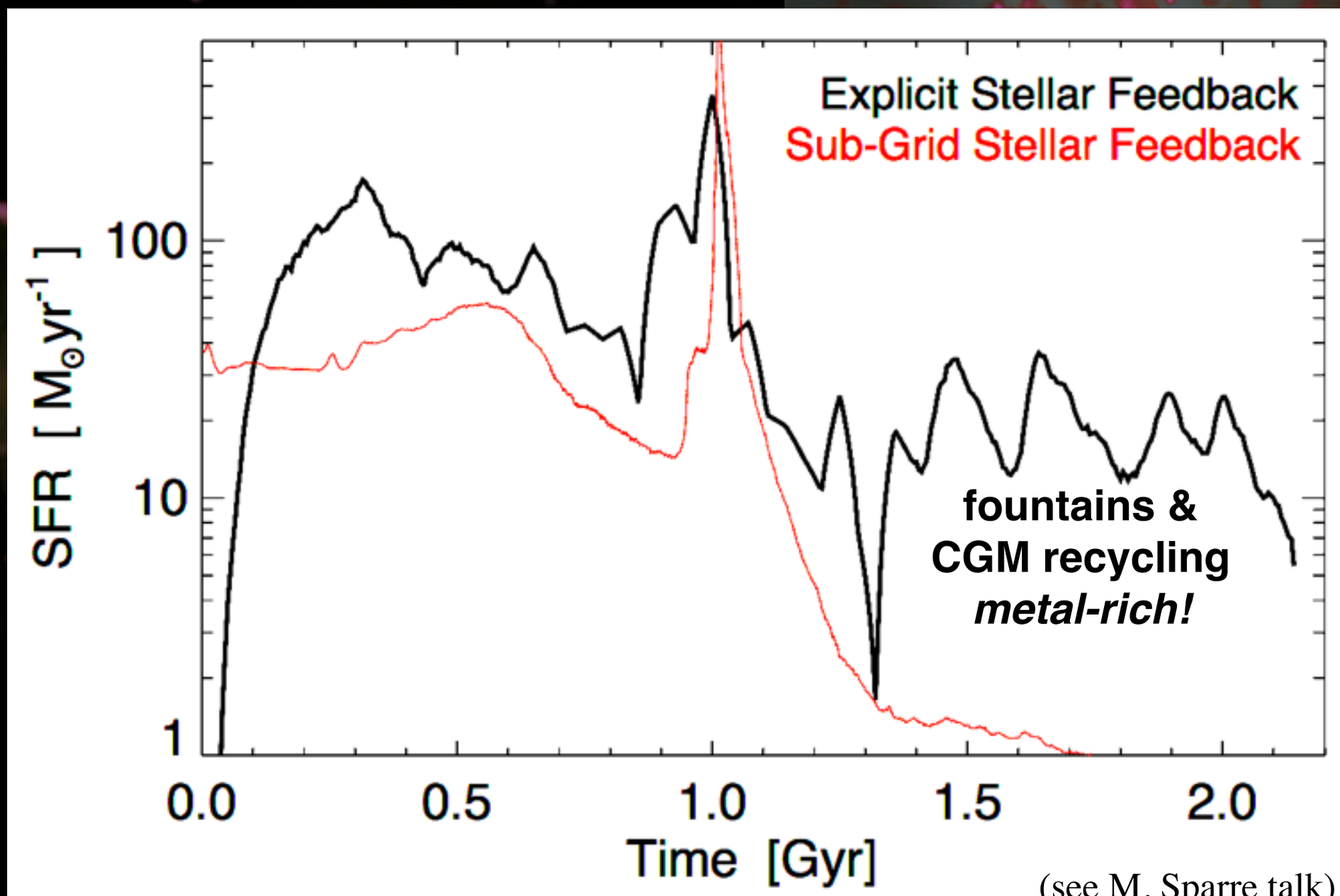




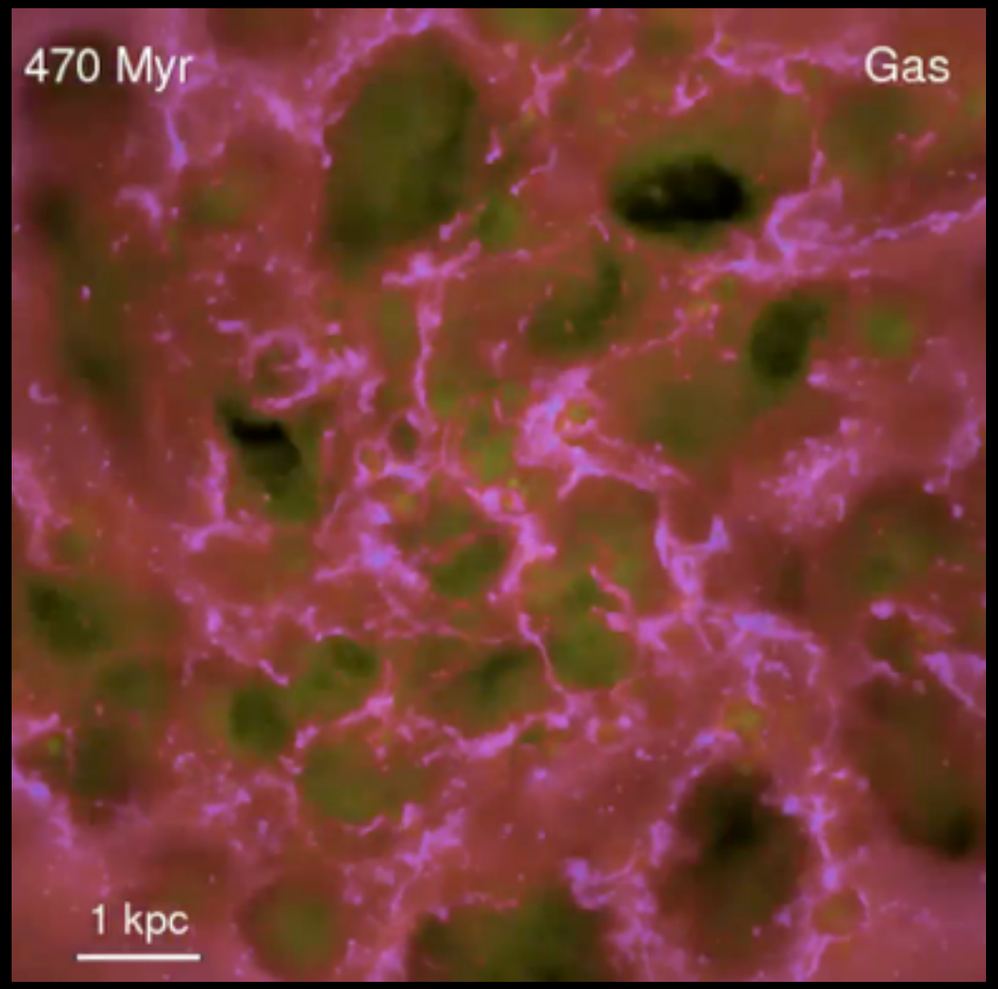
(see M. Sparre talk)

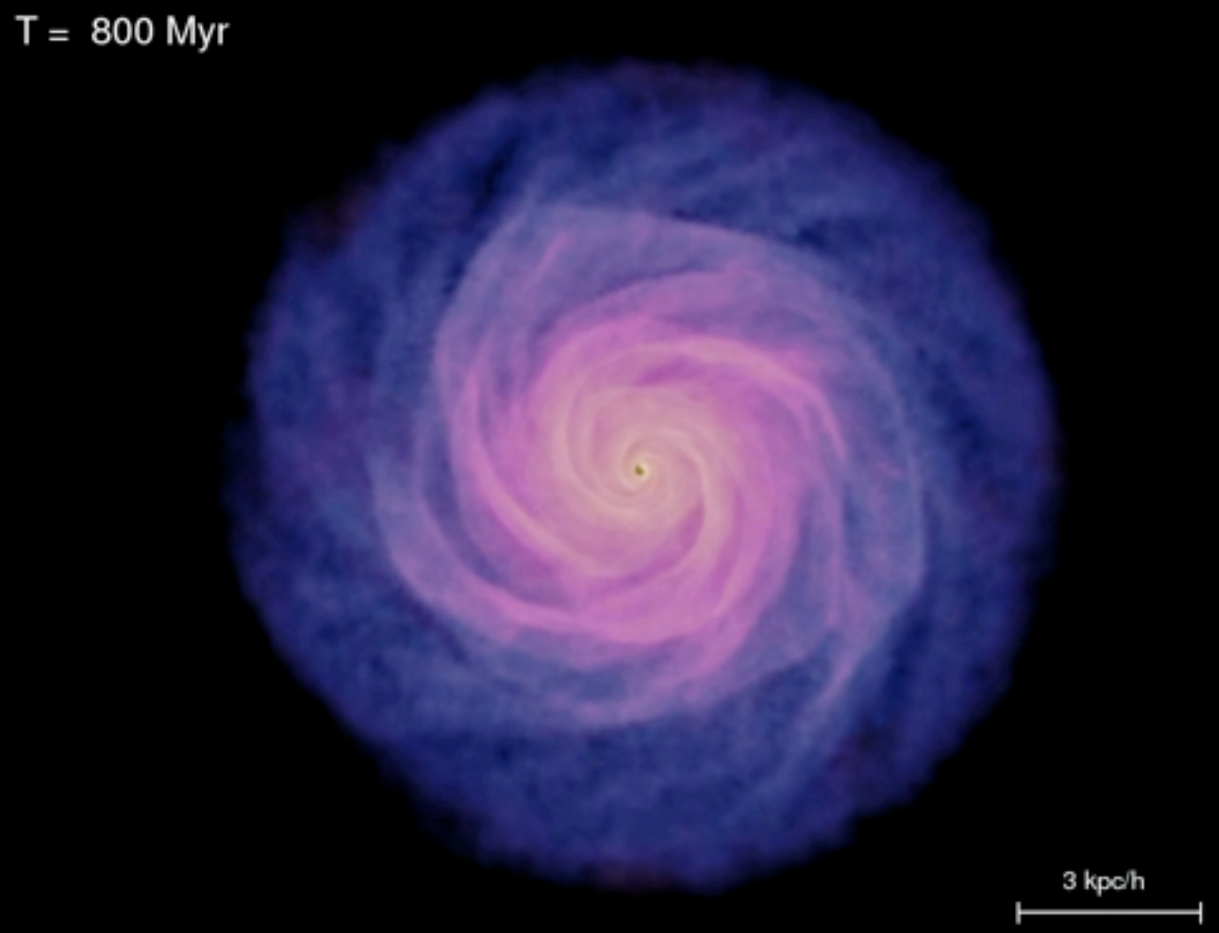
Lesson 2: "Shutting Down" Star Formation in the Disk

WHY IT'S HARD

$$Q_{\rm turb} = \frac{\sigma_{\rm turb}\,\kappa}{\pi\,G\,\Sigma} > 1$$

$$Q_{\rm therm} = \frac{c_s\,\kappa}{\pi\,G\,\Sigma} > 1$$





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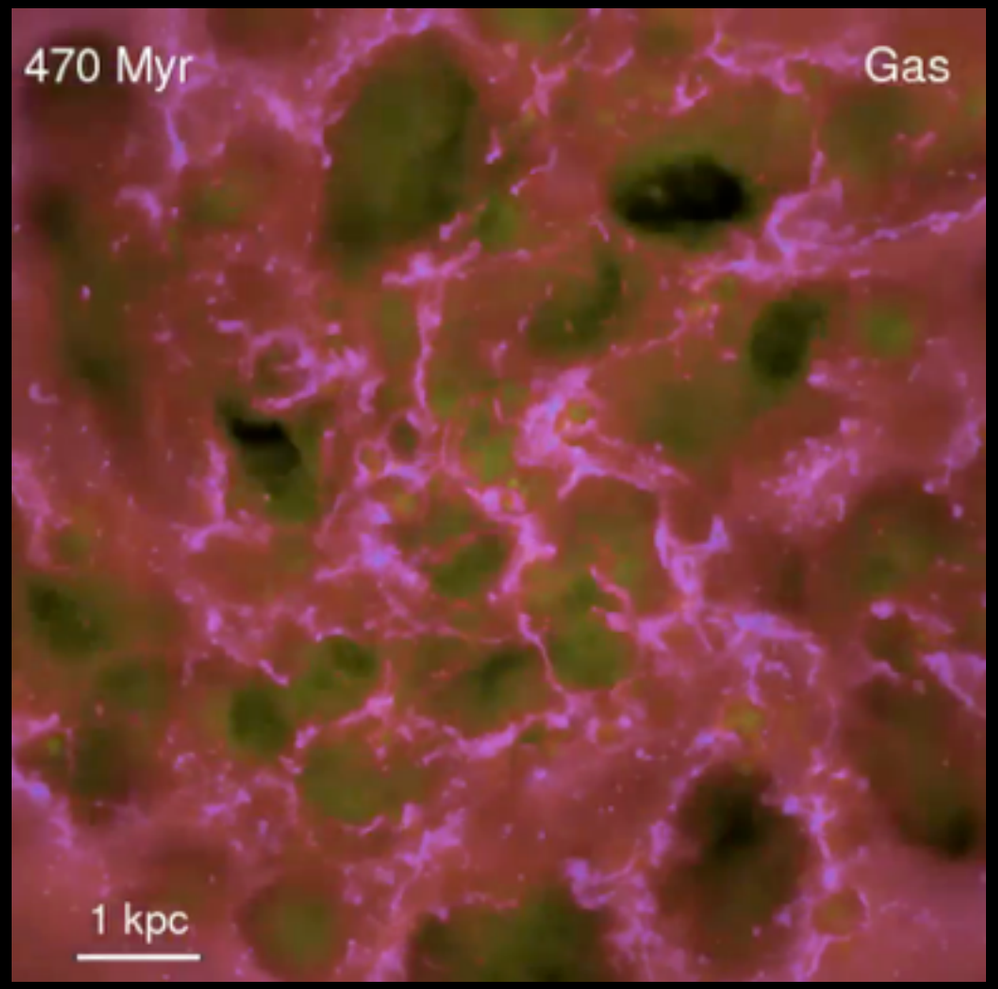
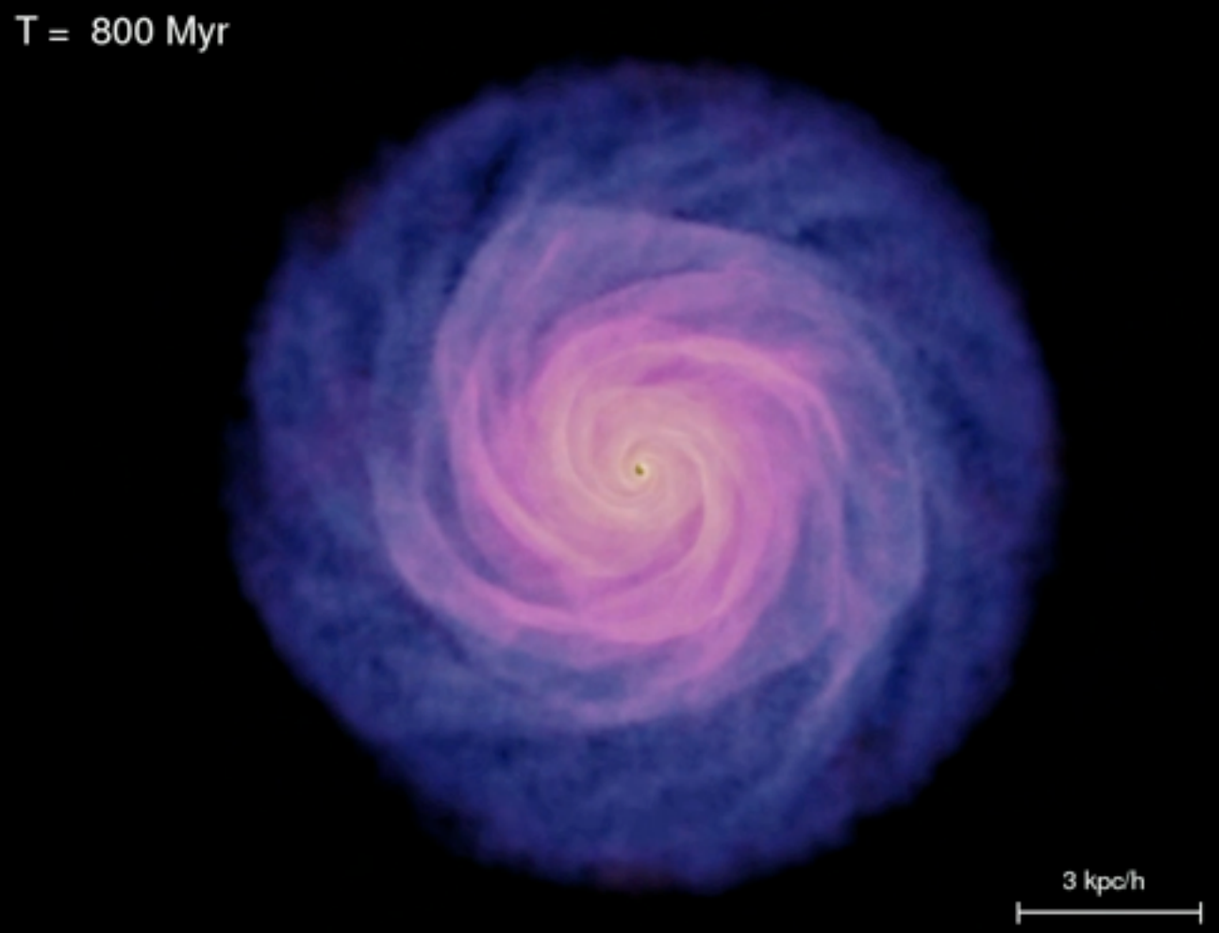




- *Self-Regulated* SF (K-S)
- *Suppressed* SF

Can "Morphology" Do It?

Morphological/'Toomre'/Dynamical Quenching (Martig, Dekel,+)

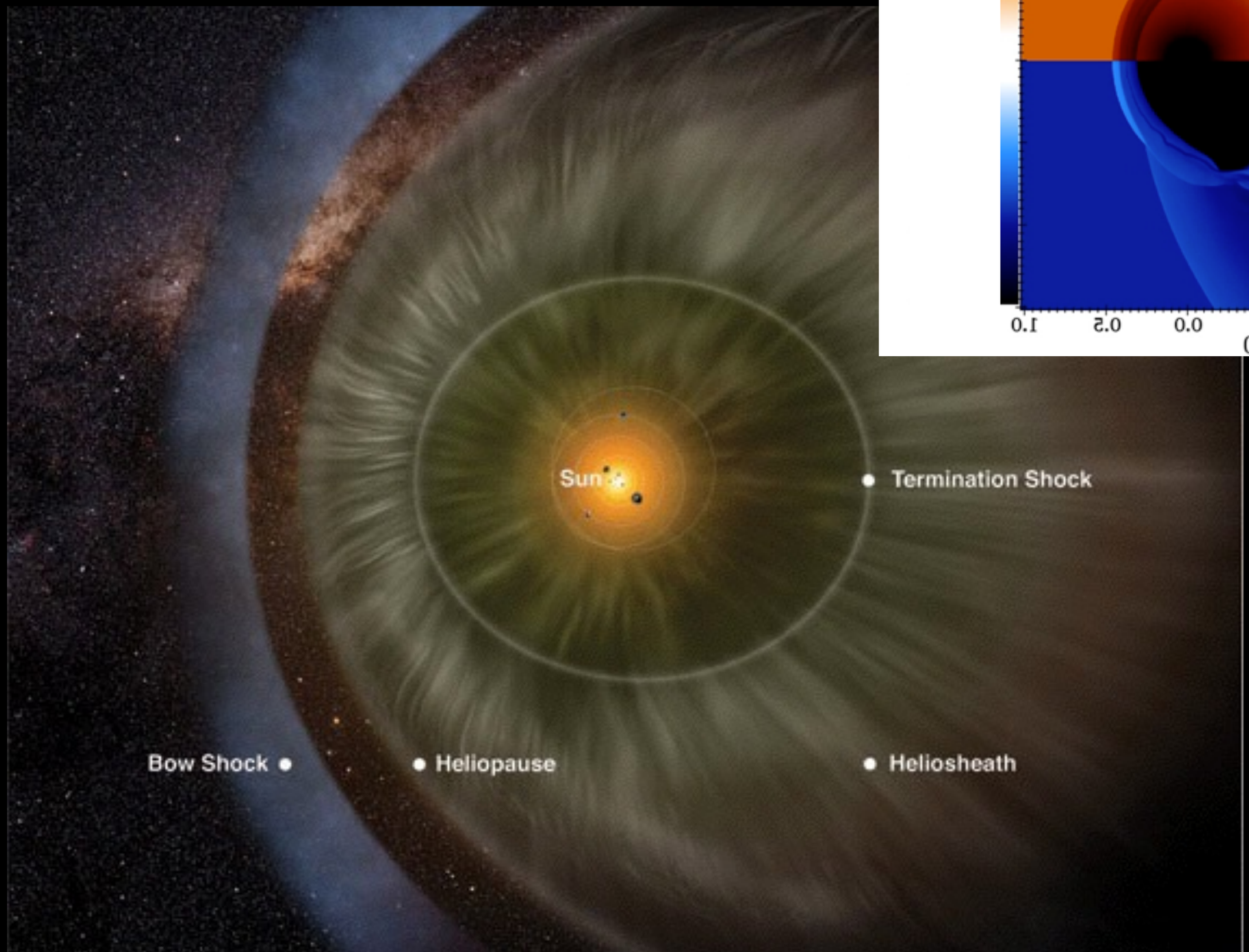
$$\text{Disk} \rightarrow \text{Bulge} \neq \text{Quenching}$$

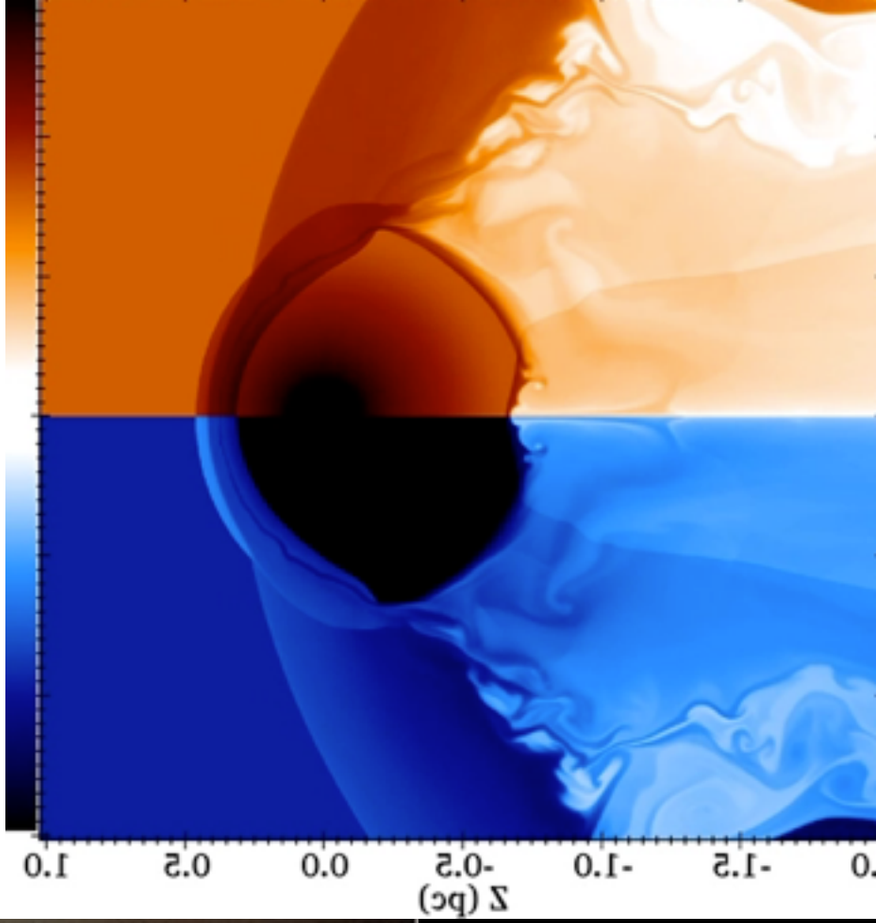
$$\text{Mass} \rightarrow \text{center} \neq \text{Quenching}$$

$$\begin{matrix} \text{Gas Depletion} \\ + \\ \text{Suppressed Cooling} \end{matrix} = \text{Quenching}$$

Can Stars Do It?

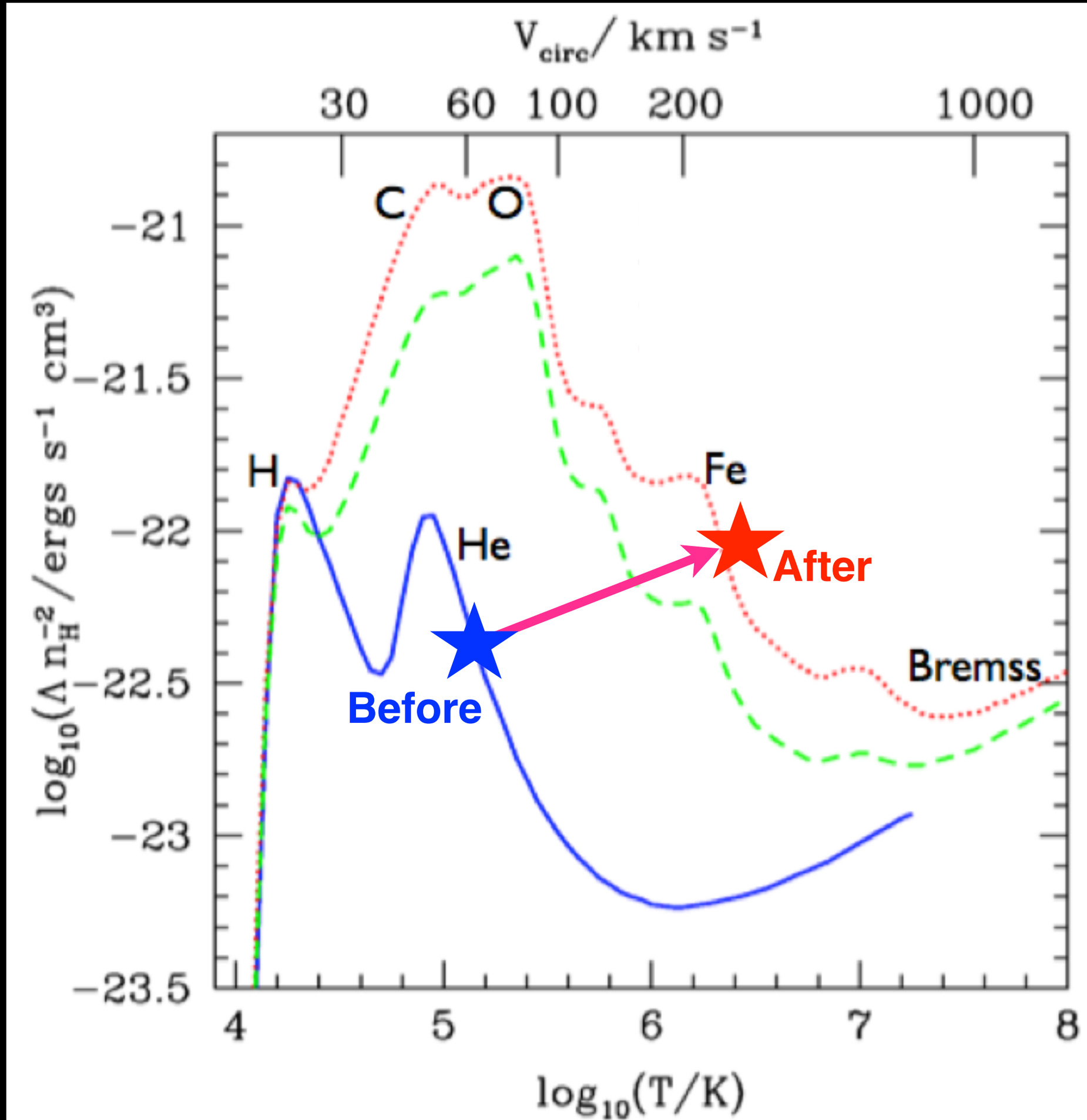
SNIa, AGB (Conroy+, Ostriker, Novak)





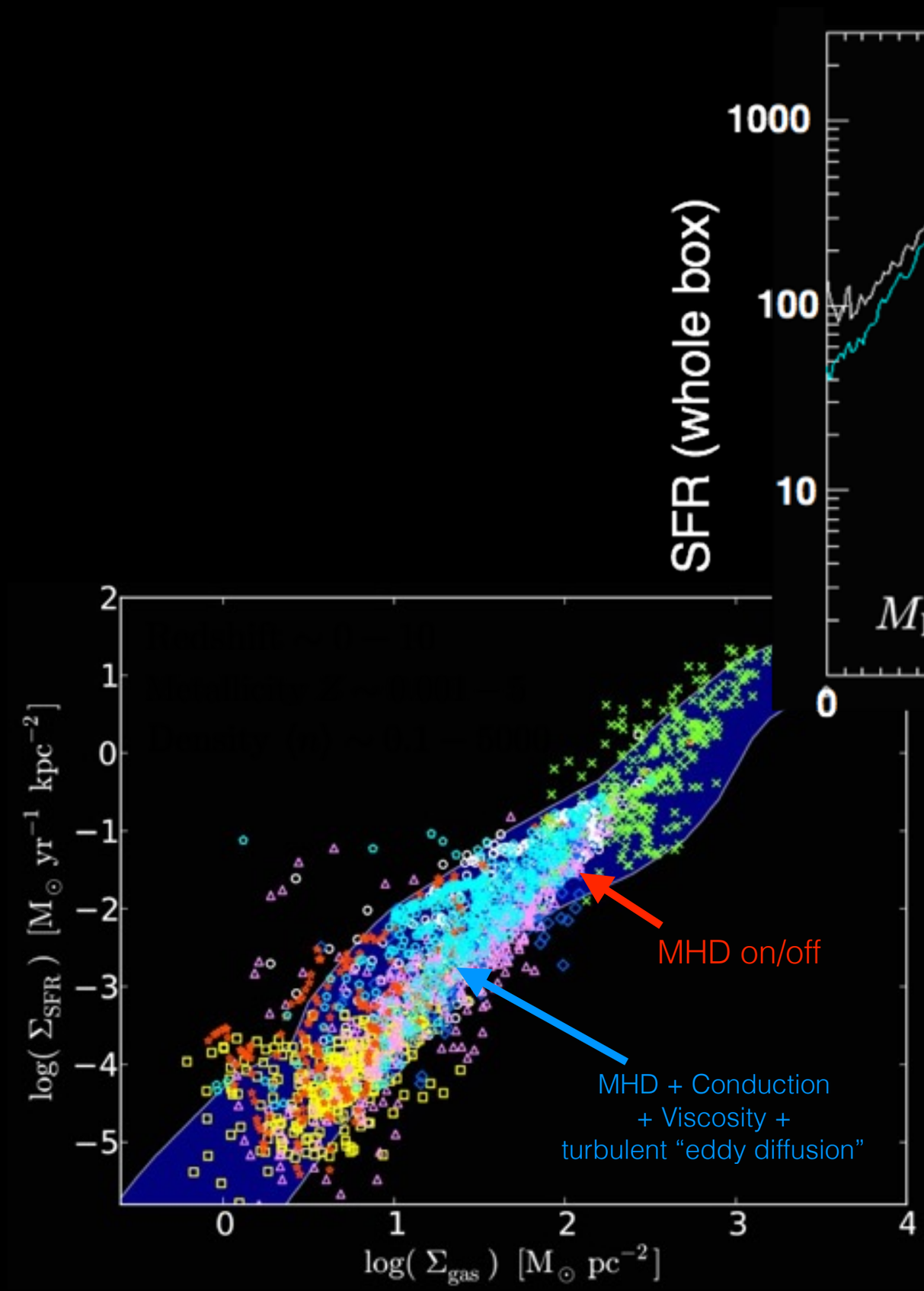
Metals Kill You!

Stellar mass loss is part of the ***PROBLEM***, not the solution

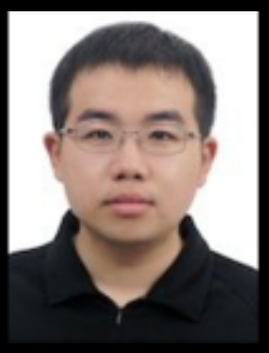


"What About Magnetic Fields?" : They Don't Save You!

MHD, Spitzer-Braginskii conduction & viscosity, micro-eddy diffusion …

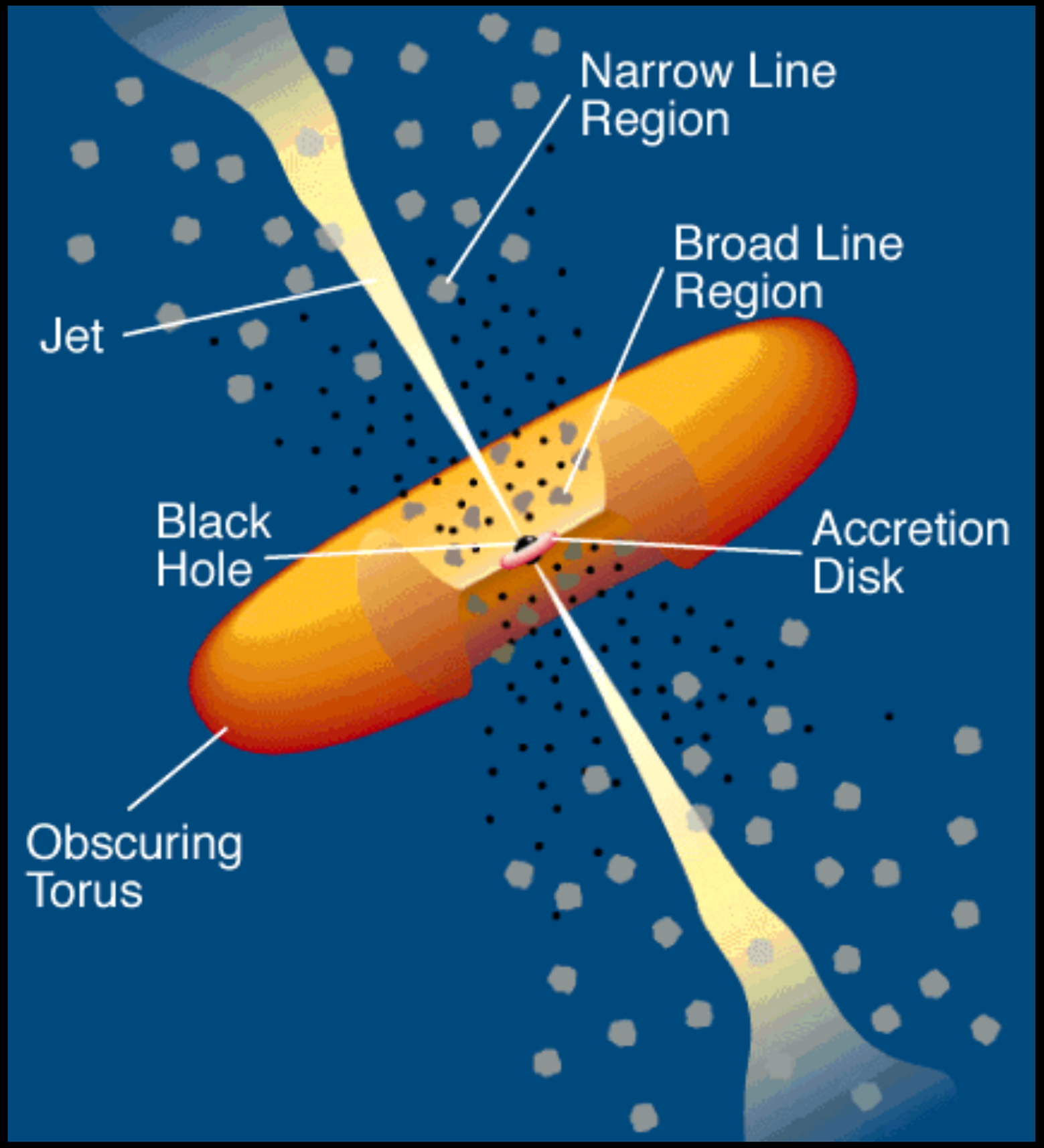


Kung-Yi Su
(arXiv:
1607.05274)



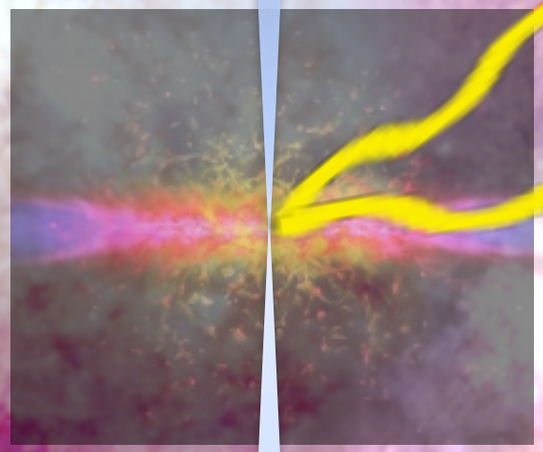
Ok, Let's Talk AGN

What Is An AGN?



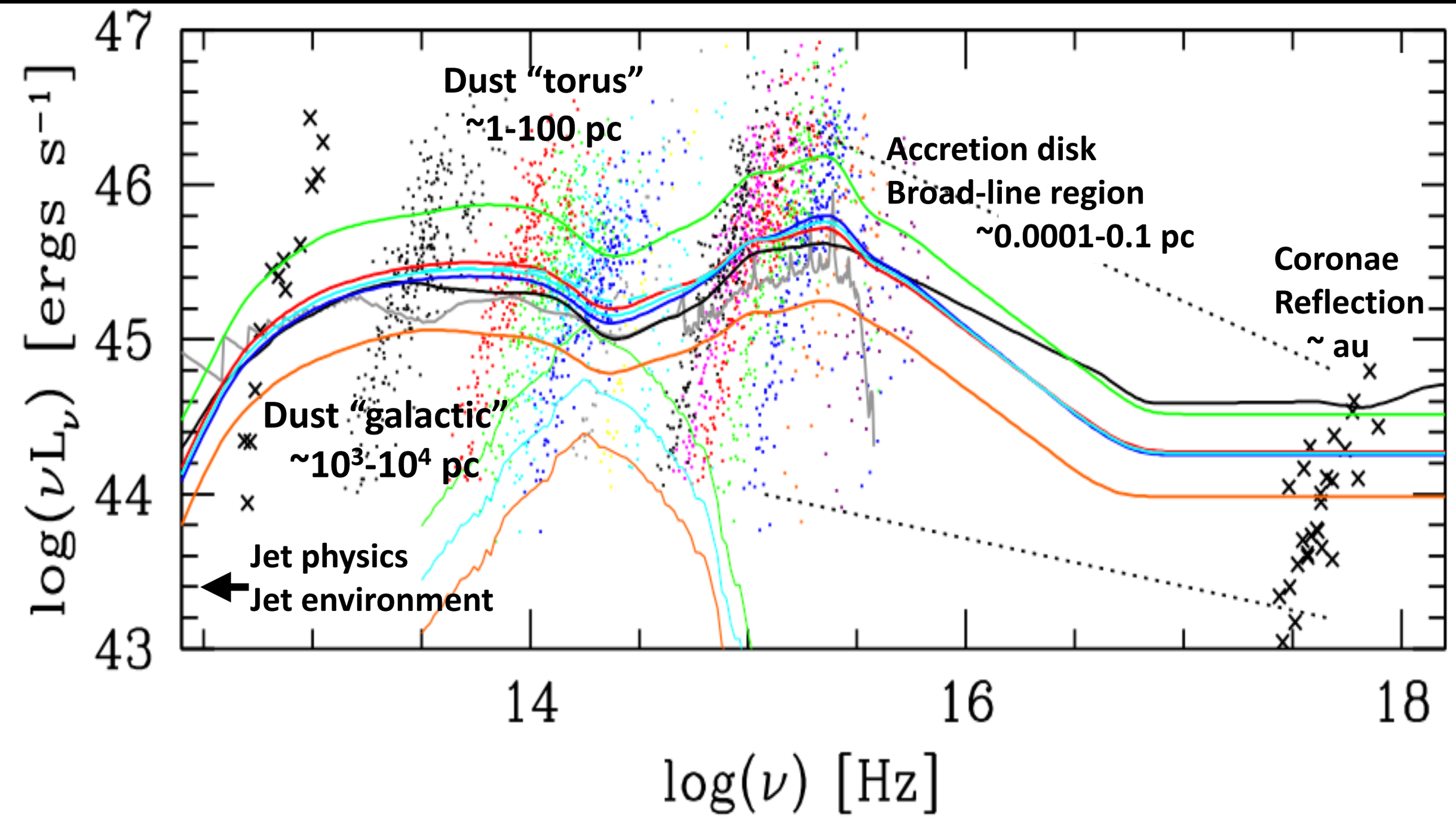
Urry & Padovani

No, not even that simple…



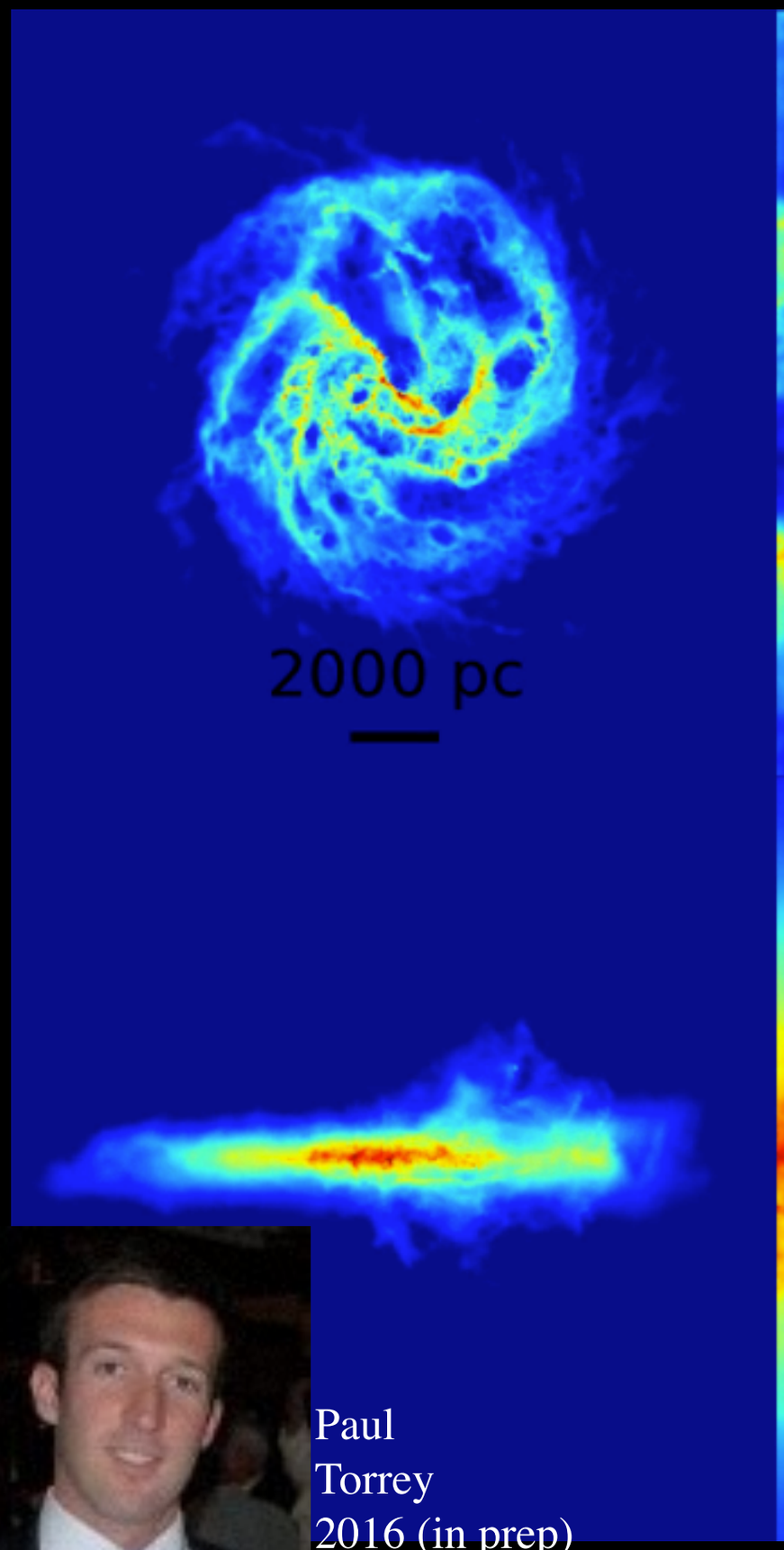
AGN are ***ecosystems***, not "*objects*"

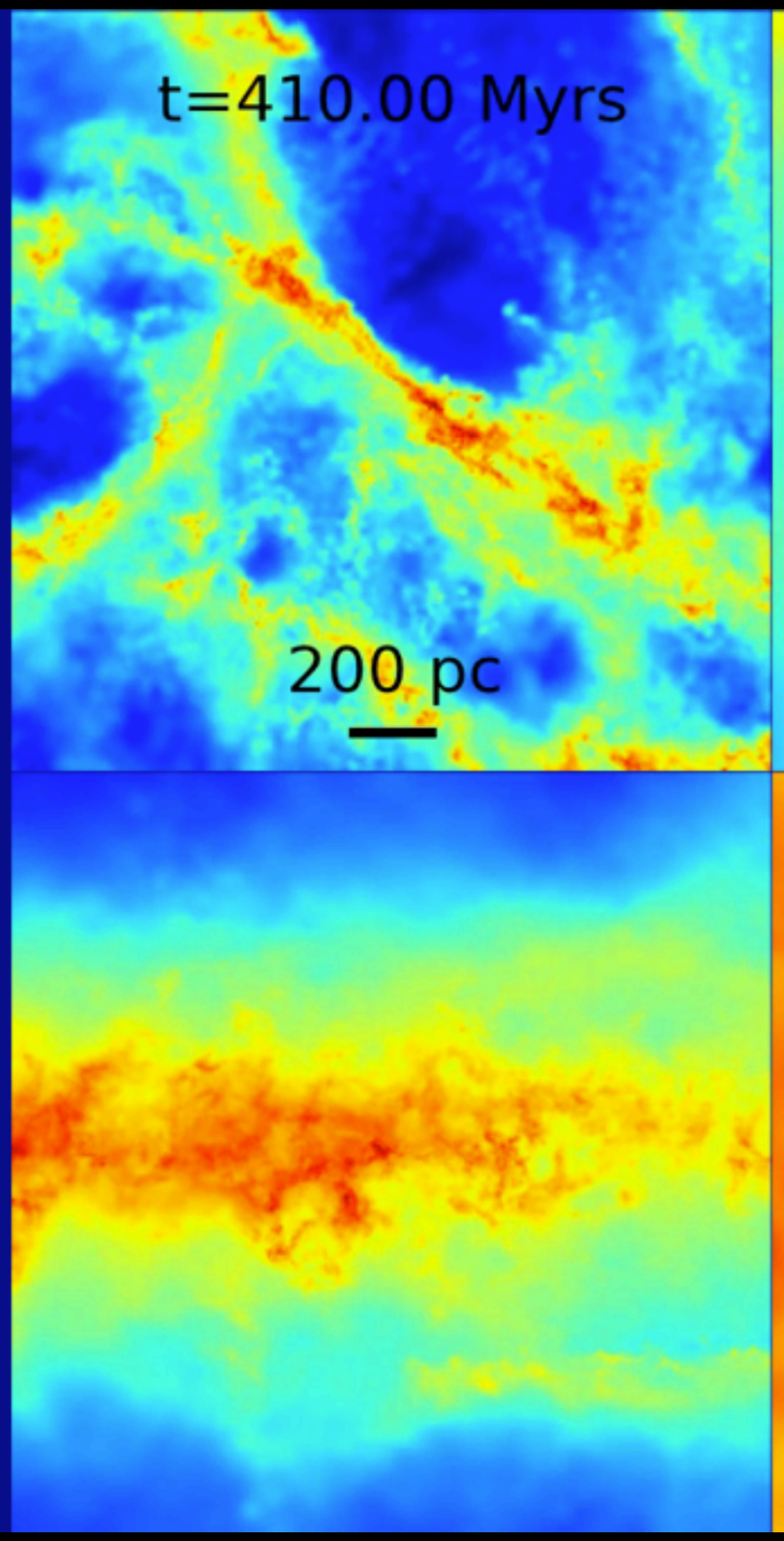
DIFFERENT SELECTION GIVES *DIFFERENT PHYSICS FROM DIFFERENT SCALES*

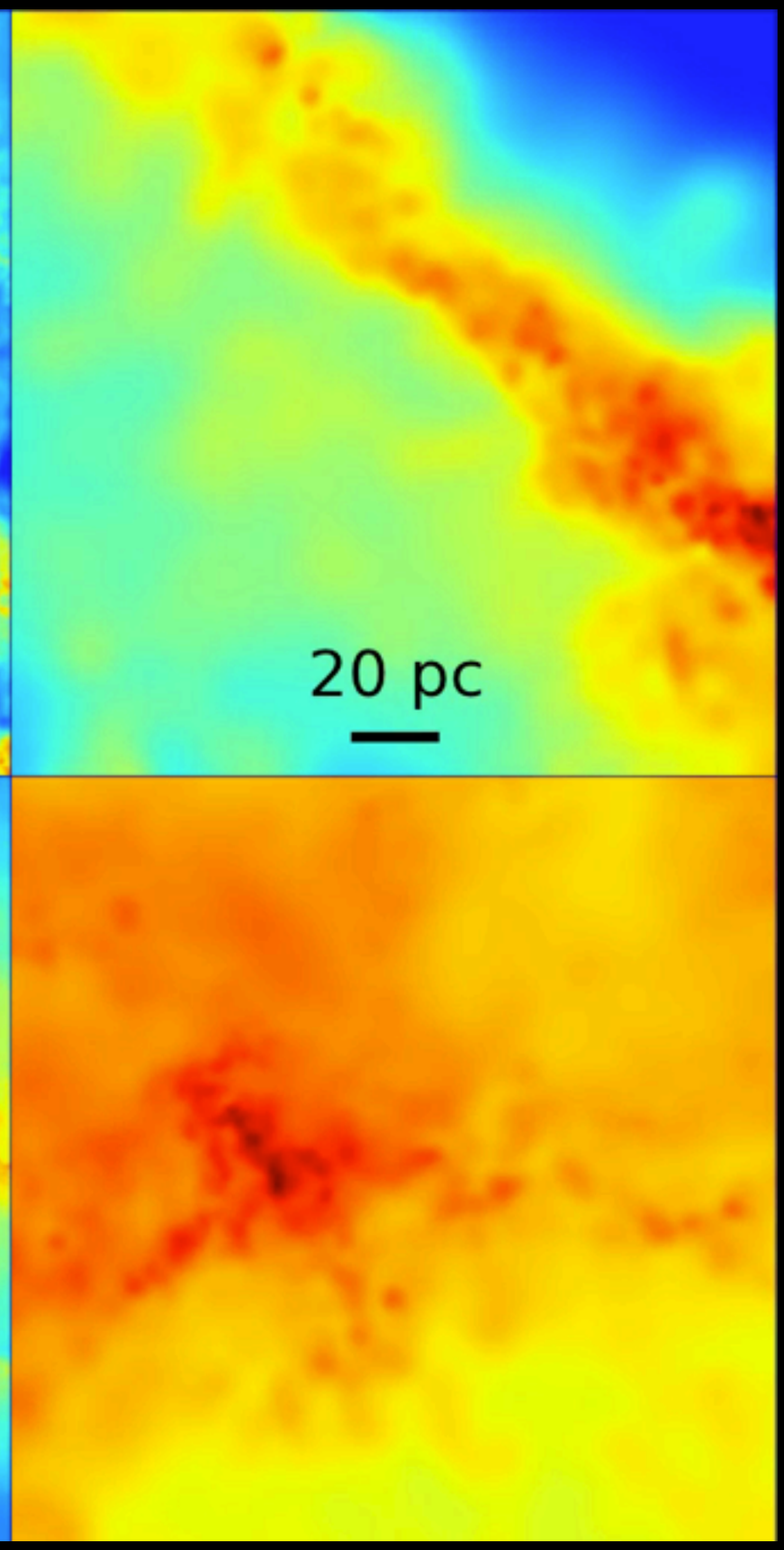


Richards et al. 06

Timescales Matter

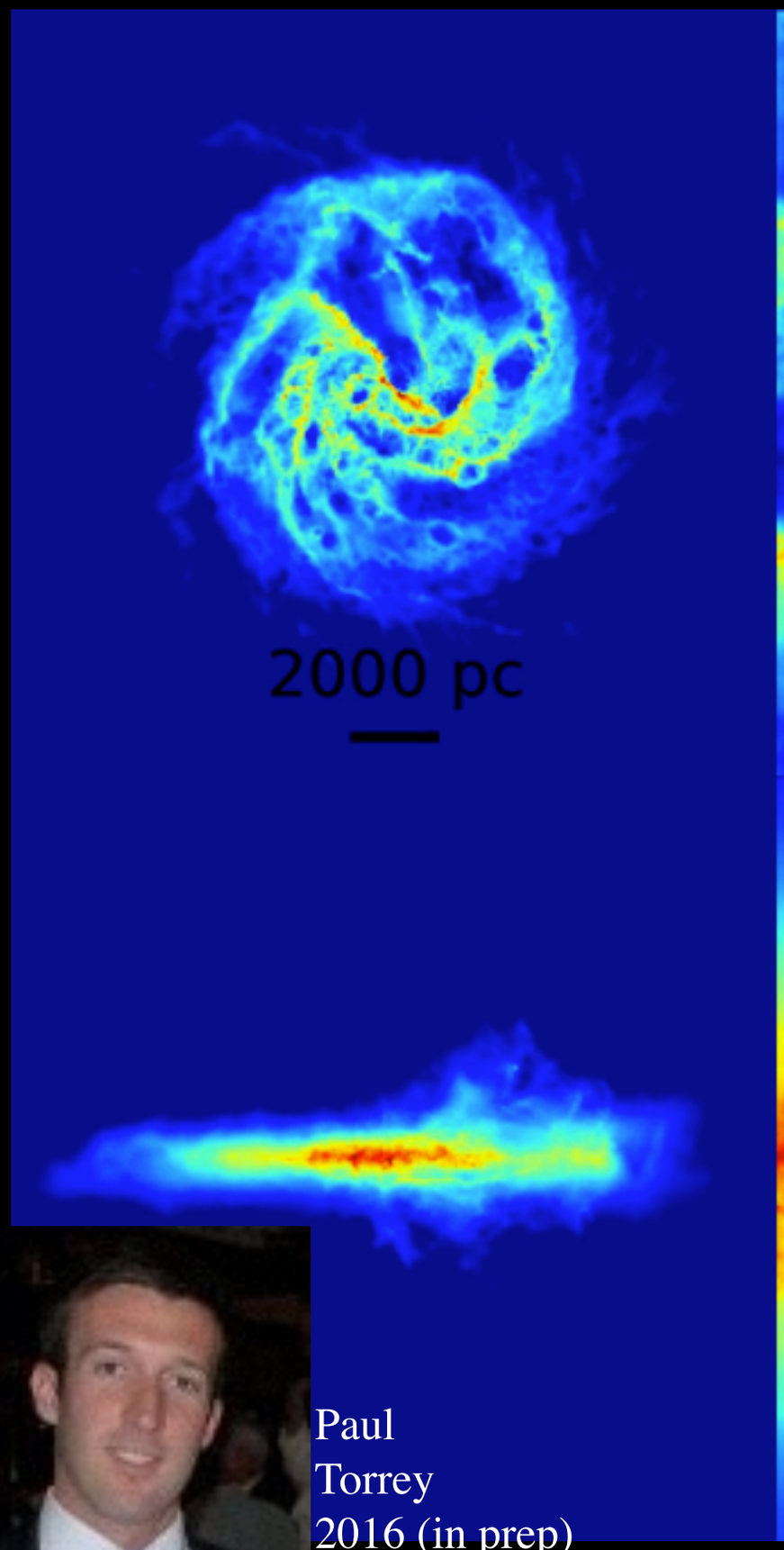


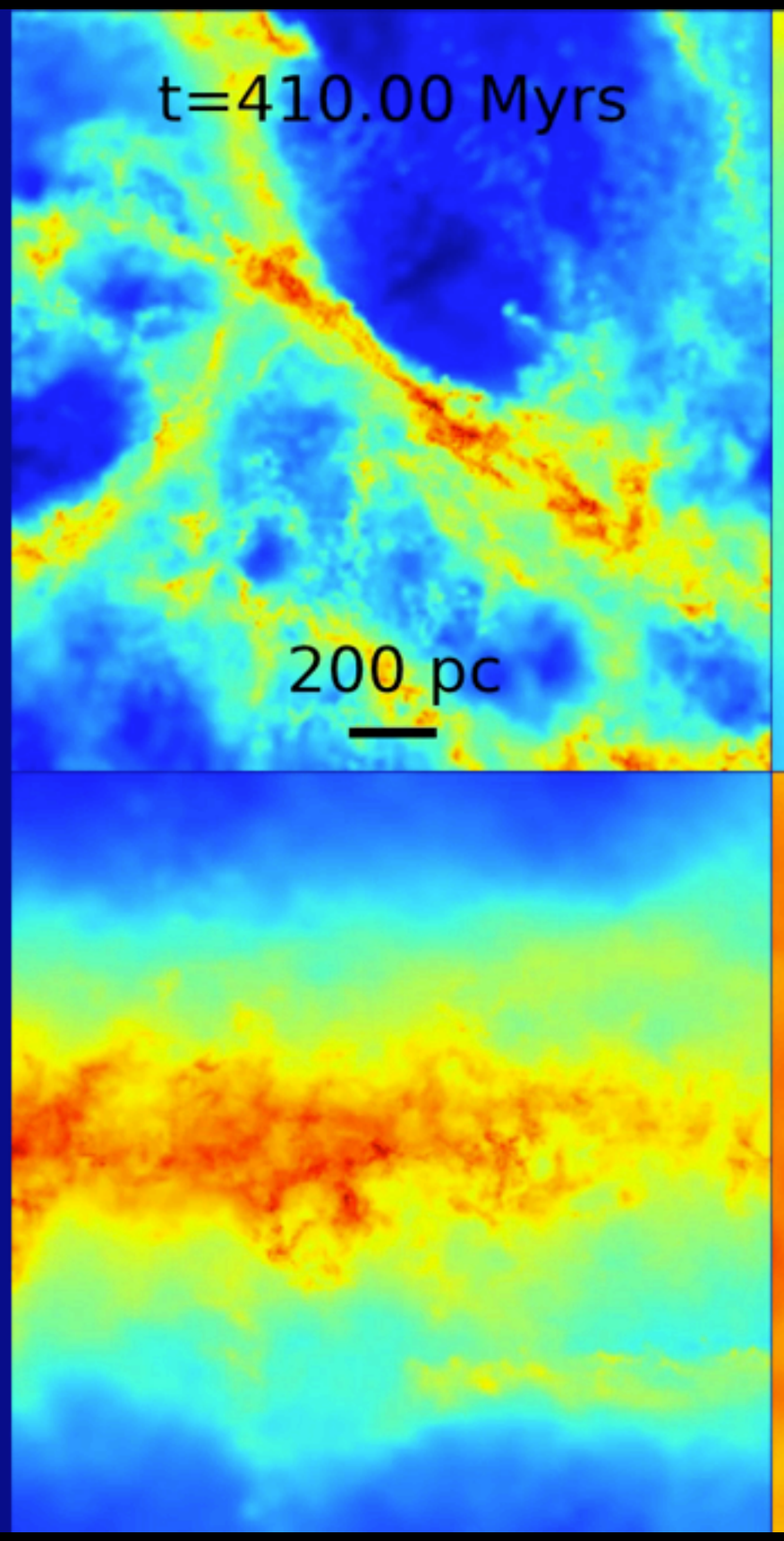


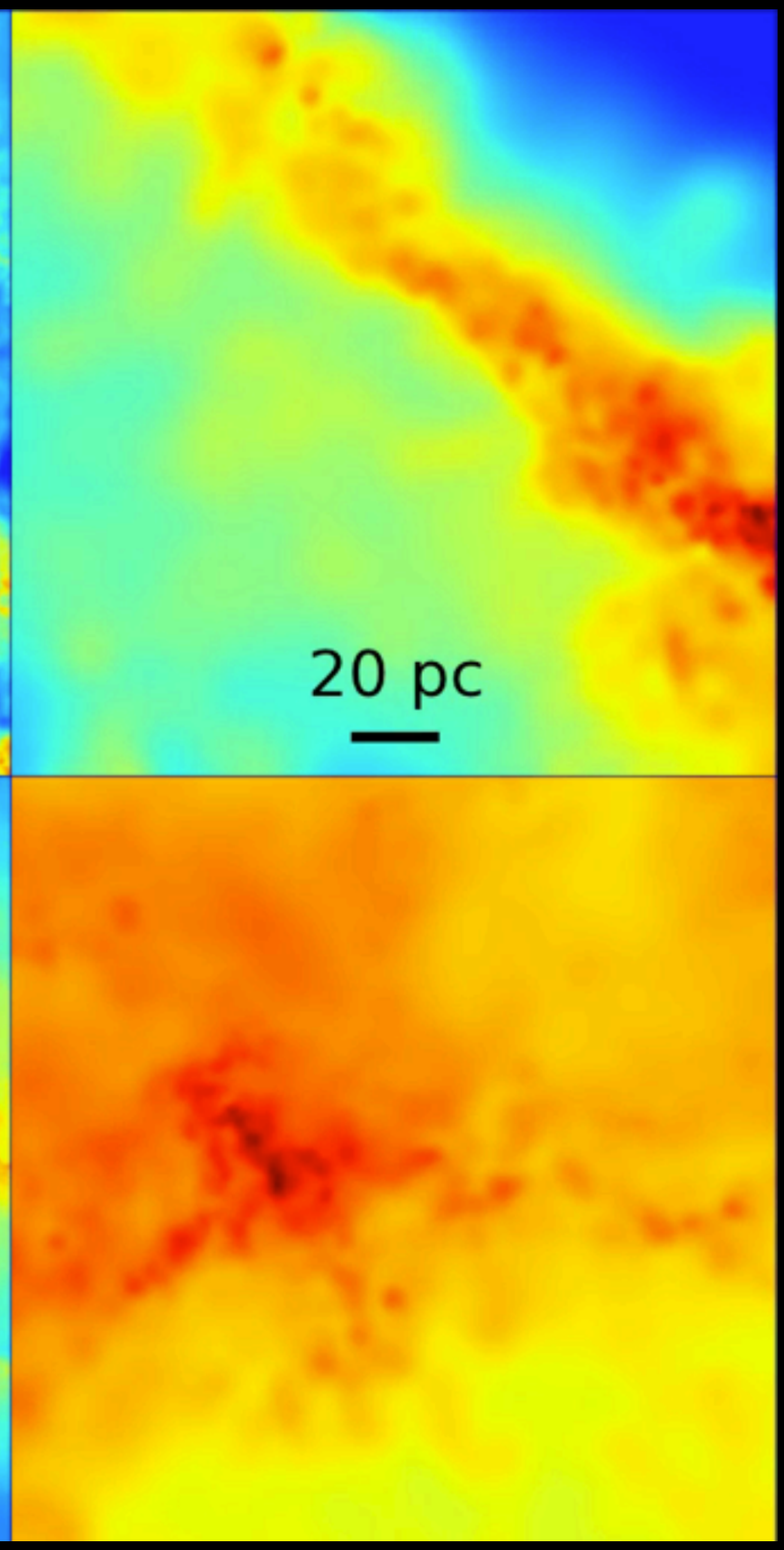


Paul
Torrey
2016 (in prep)

Timescales Matter







Paul
Torrey
2016 (in prep)

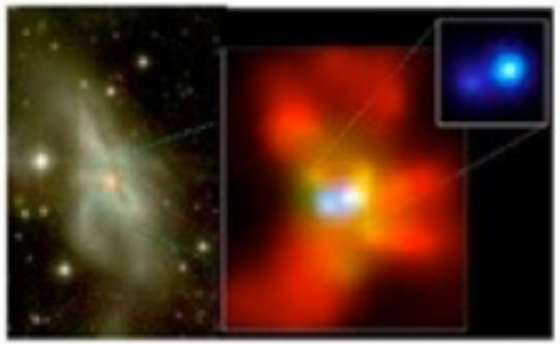
The Emerging View

	Stong(er) Jet	Weak(er) Jet
Radiatively Efficient (High[er] Accretion)	Radio Loud QSOs FR II's High-Excitation RG	Type-1 Radio-Quiet Type-2 Radio-Quiet
Radiatively Inefficient (Low[er] Accretion)	(some) LINERs non-HBLR RQ AGN (some) XBONGs	BL Lacs FR I's Low-Excitation RG

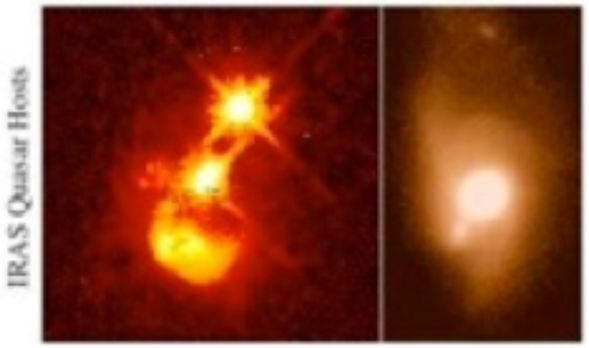
Mergers are Interesting

(c) Interaction/"Merger"

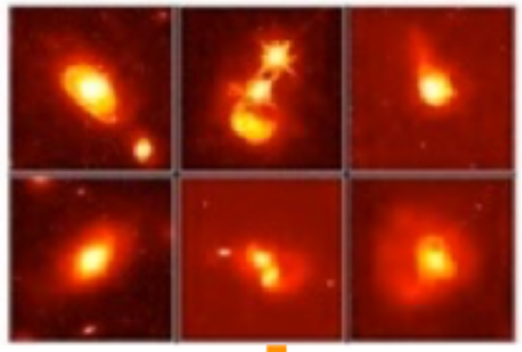
(d) Coalescence/(U)LIRG



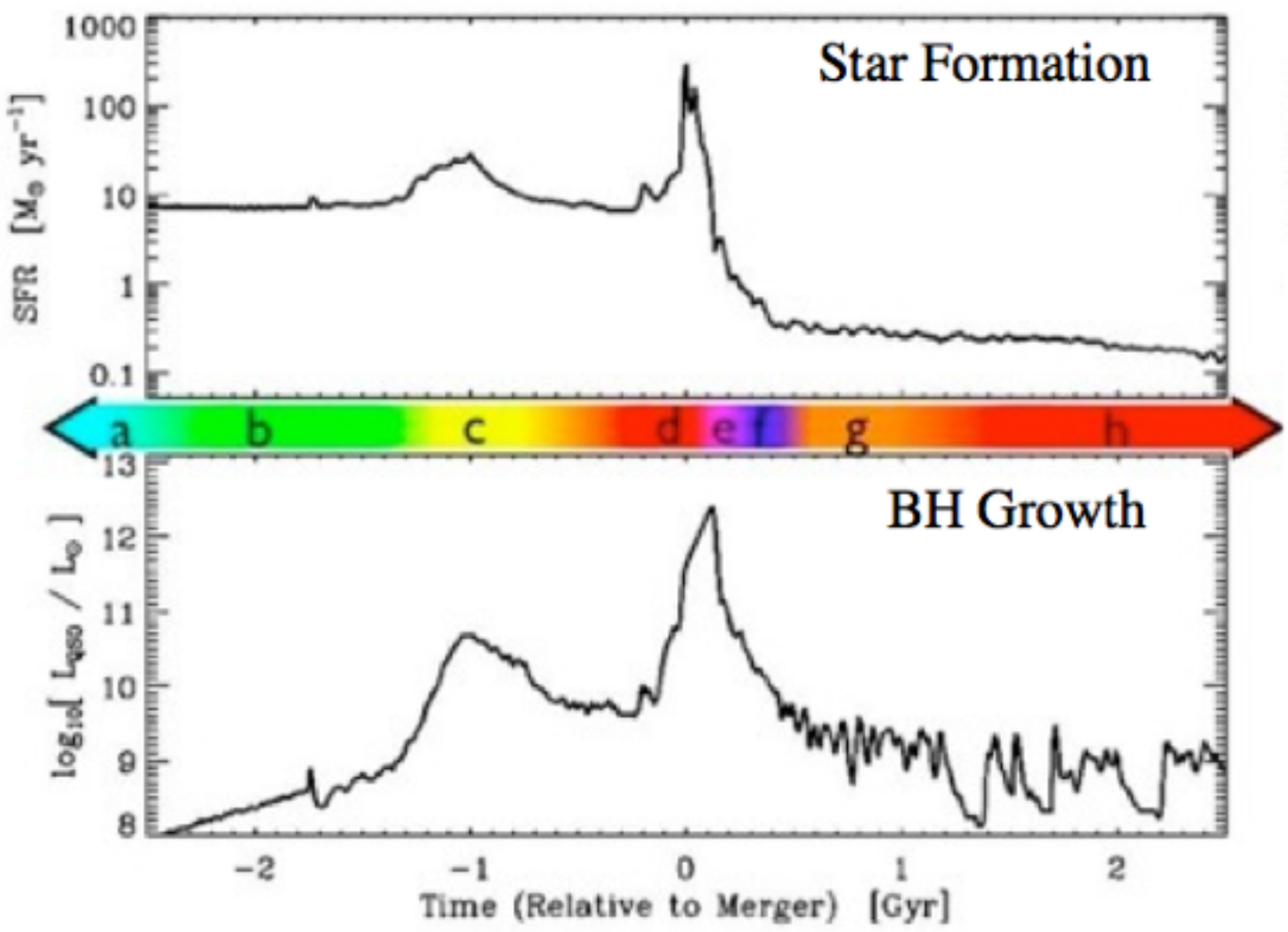
(e) "Blowout"



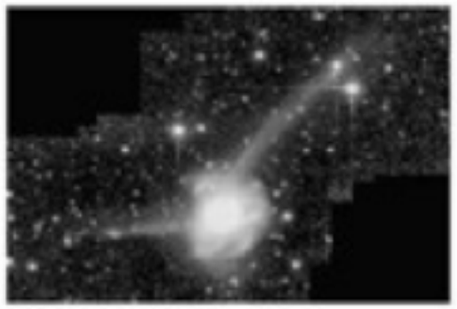
(f) Quasar



(b) "Small Group"



(g) Decay/K+A



(a) Isolated Disk

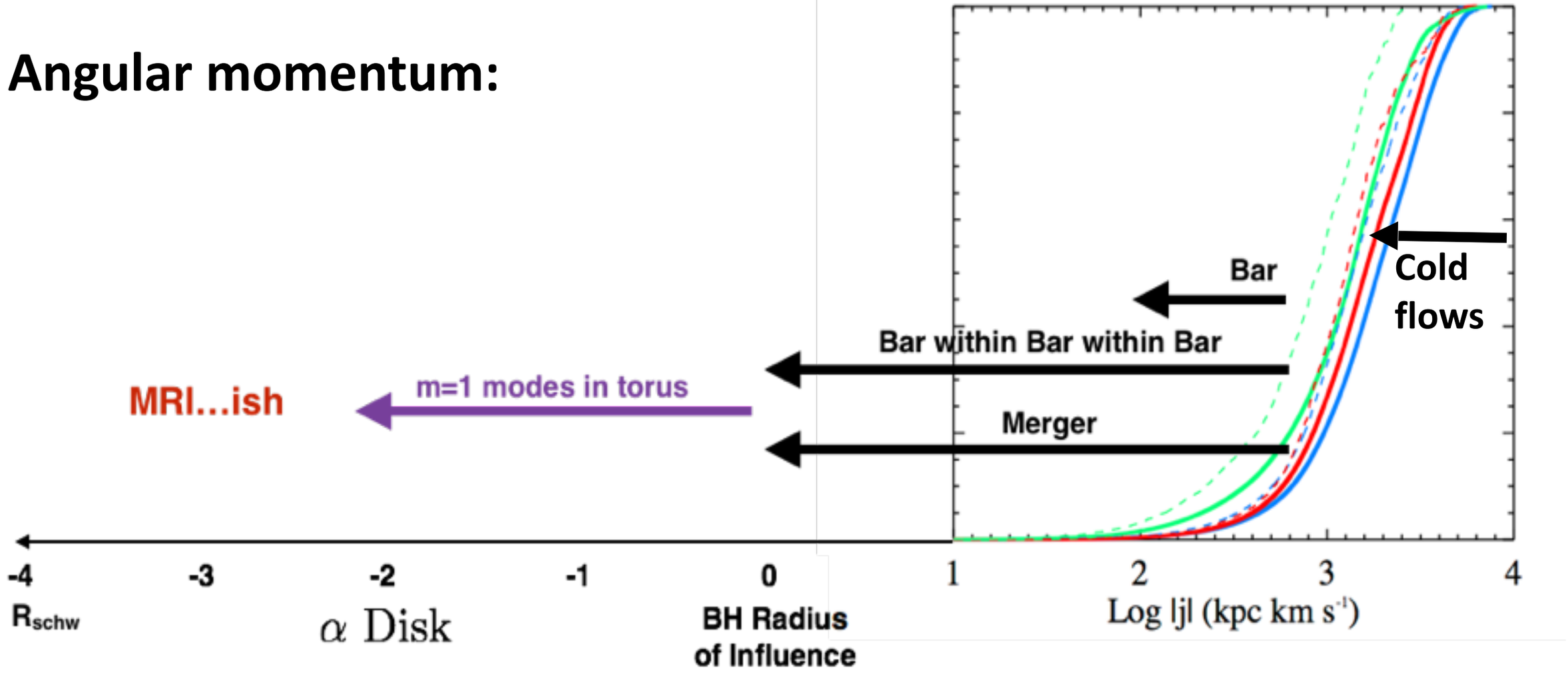
(h) "Dead" Elliptical

But Far From Unique!

AGN don't "*know*" about their host galaxies!

REMEMBER THE RANGE OF SCALES!

Angular momentum:



Daniel Angles-Alcazar 2013, 2016

PFH & Quataert 2012

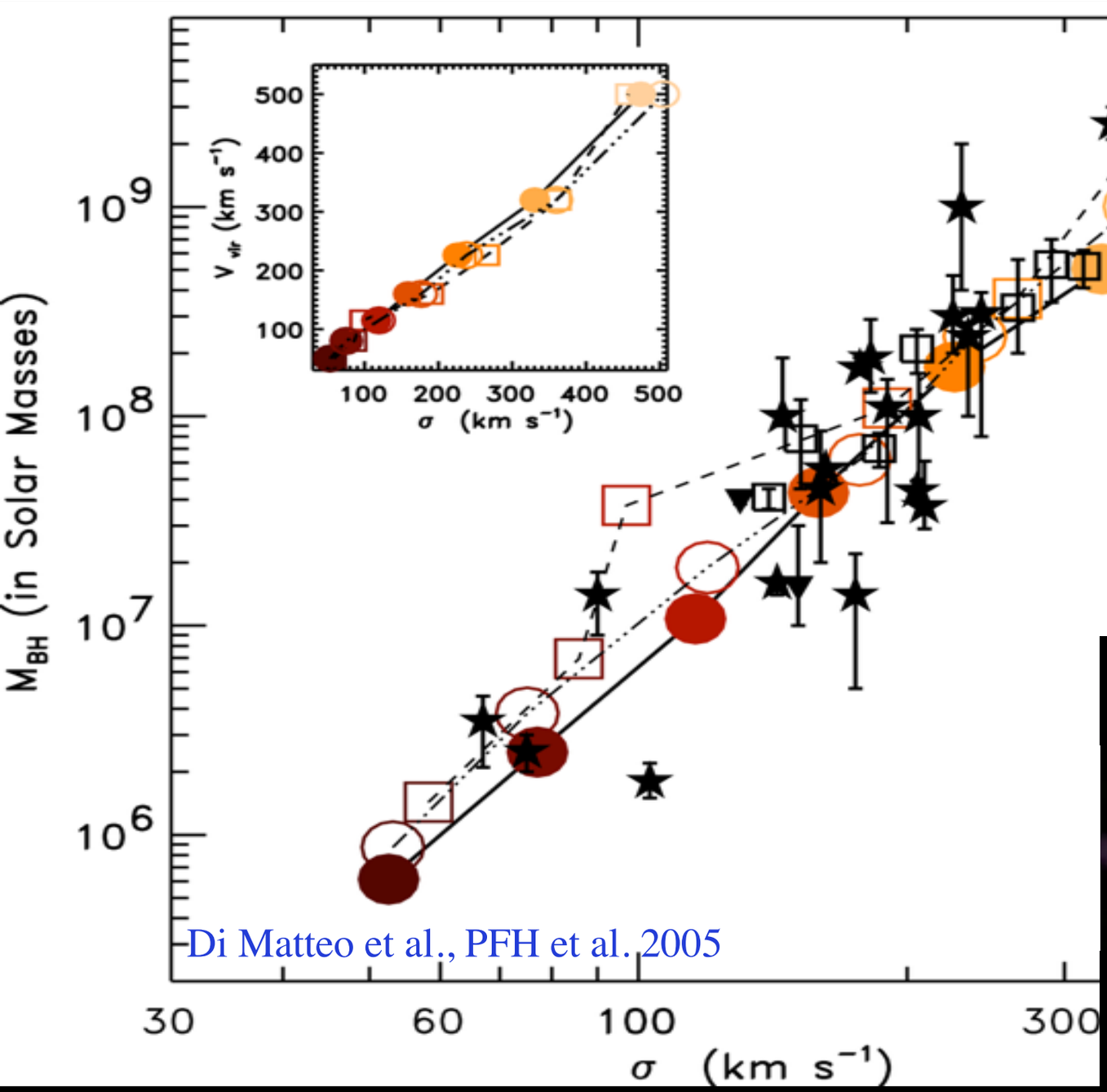
The Emerging View

	Low BHAR	High BHAR
More Gas in Galaxy Center (high nuclear SFR)	Star Formation consumes gas “Stochastic” downward fluctuation AGN Feedback clears disk region	Strong Gravitational Instabilities Binary-BH Torques?
Less Gas in Galaxy Center (low nuclear SFR)	Clump/GMC-BH collision “Stochastic” upward fluctuation “Just filled” disk	Bondi-Hoyle accretion Stellar mass loss “Draining” disk/torus reservoir from previous episode

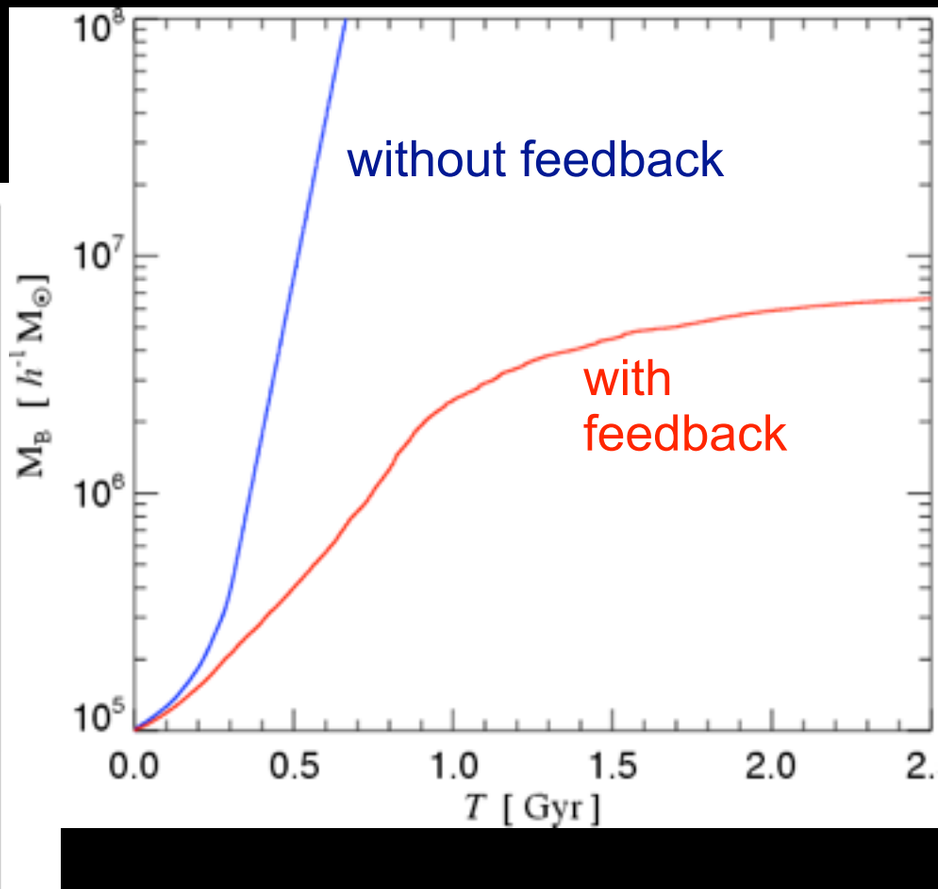
You Said “Feedback”?

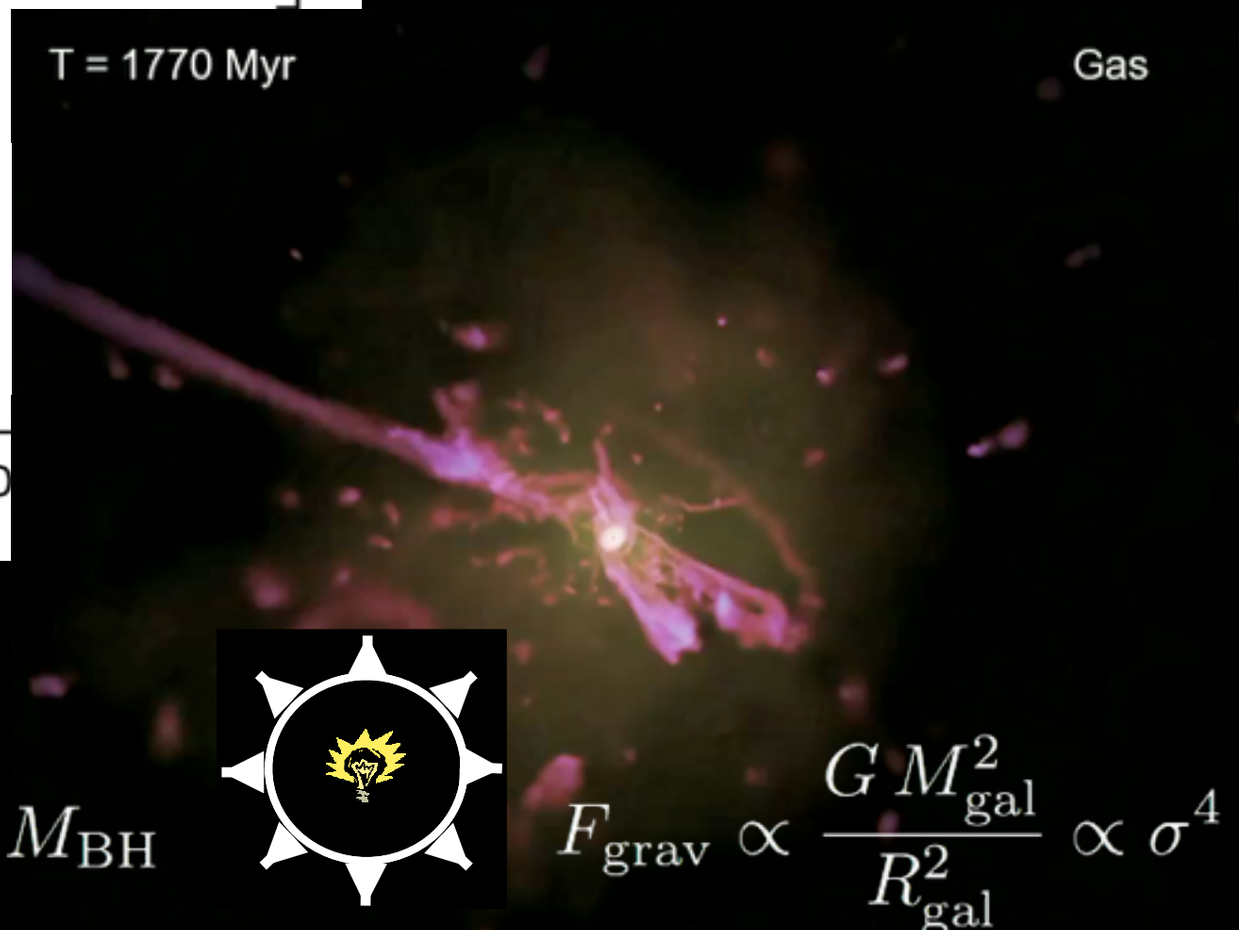
M-sigma Suggests *Self-Regulated* BH Growth

FEEDBACK PREVENTS RUNAWAY BLACK HOLE GROWTH



Di Matteo et al., PFH et al. 2005





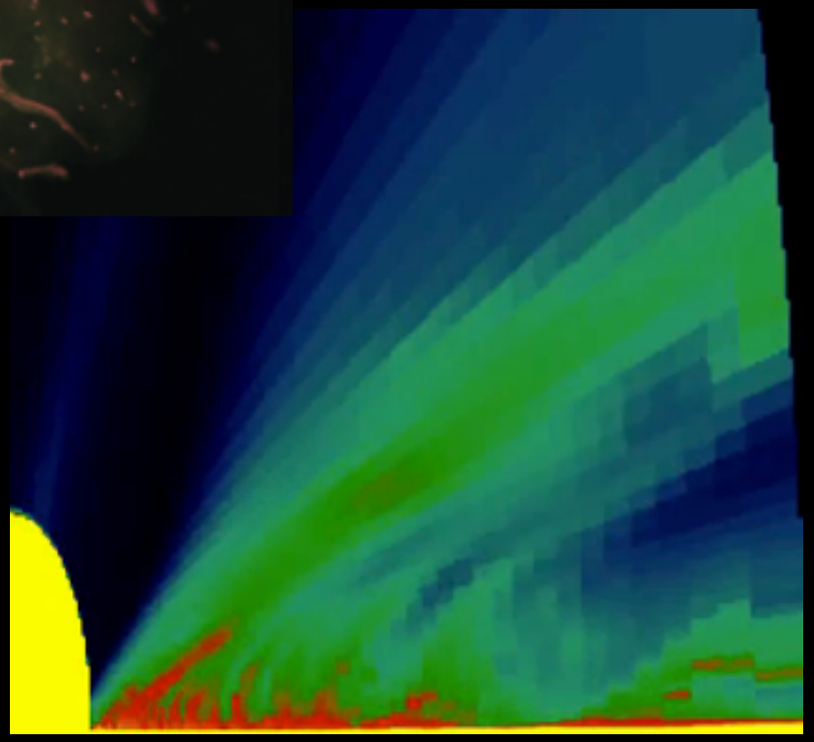
$$F_{\rm AGN} \propto M_{\rm BH}$$

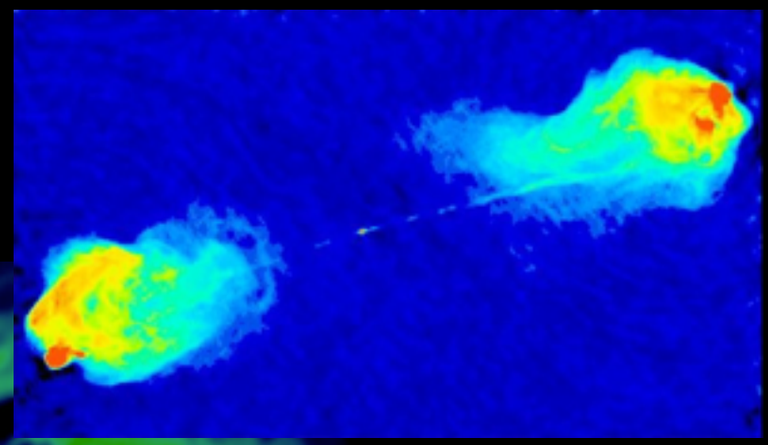
$$F_{\rm grav} \propto \frac{G\,M_{\rm gal}^2}{R_{\rm gal}^2} \propto \sigma^4$$

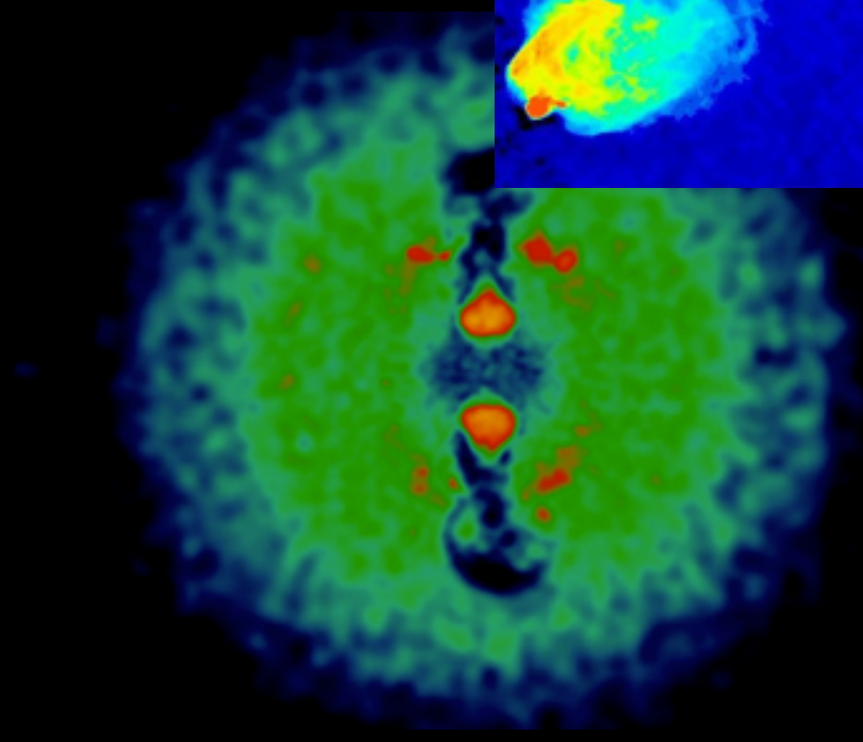
“Transition” vs. “Maintenance”

- “**Quasar**” mode (high mdot)
- Move mass (blue-red)?
- Rapid (~10^7 yr)
- Couples: small scales (<kpc)
- Regulates *Black Hole* Mass

- “**Radio**” mode (low mdot)
- Keep Red (prevent cooling)
- Persistent (intermittent?)
- Couples: large (~halo) scales
- Regulates *Galaxy* Mass

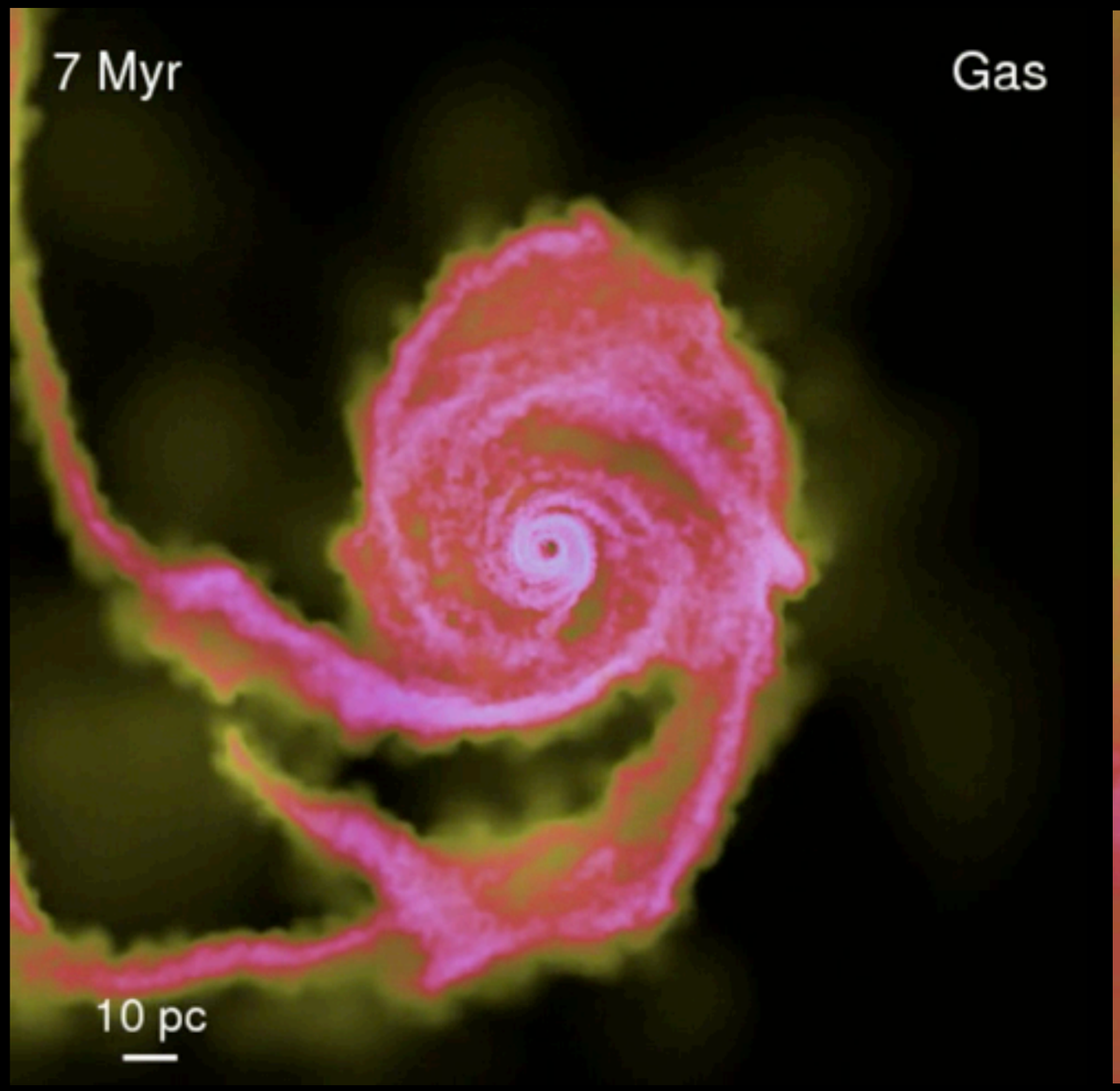




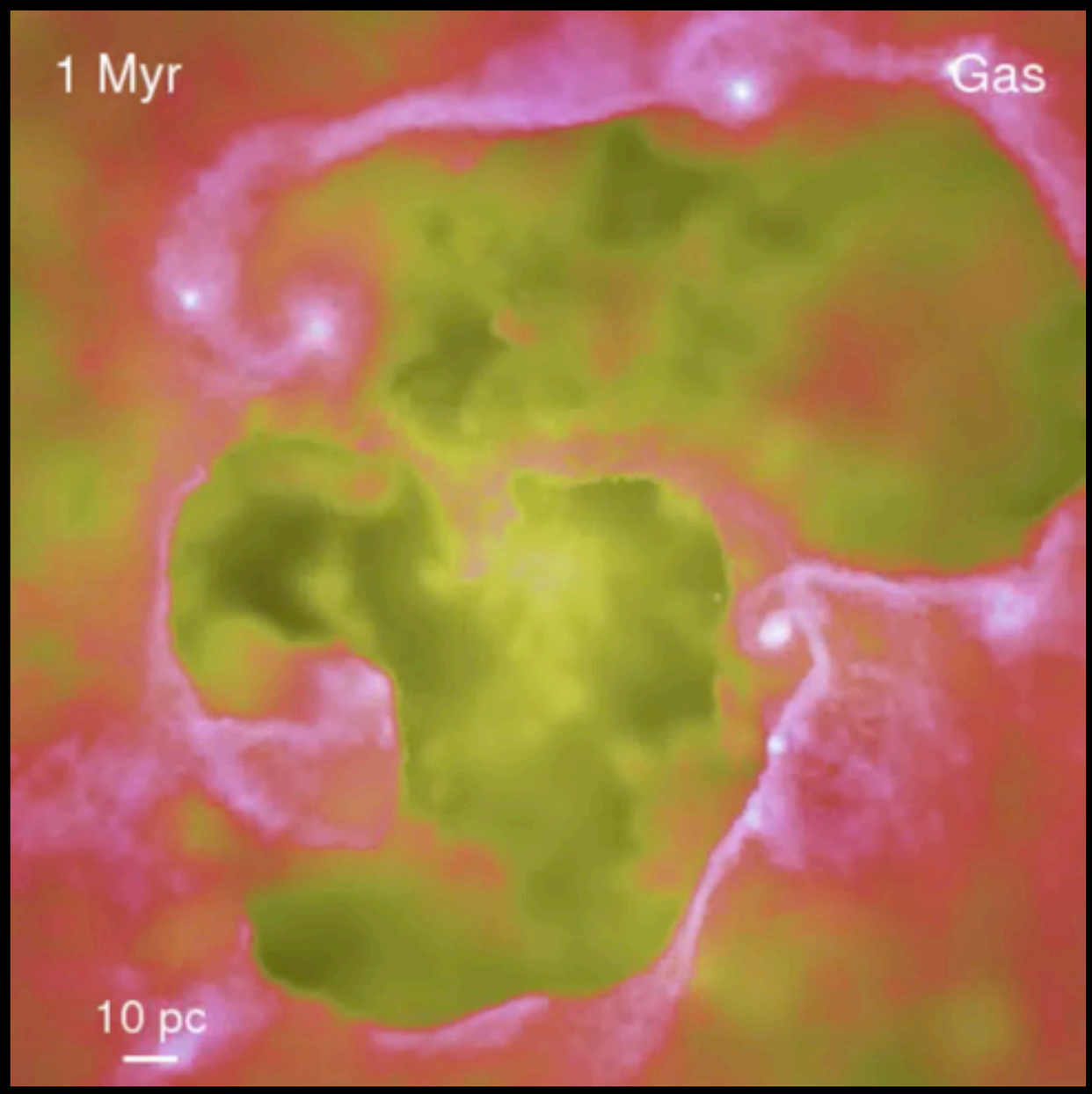


BAL Winds on ~1pc - 1kpc scales:

No BAL Winds



With BAL Winds



Torrey et al.
in prep

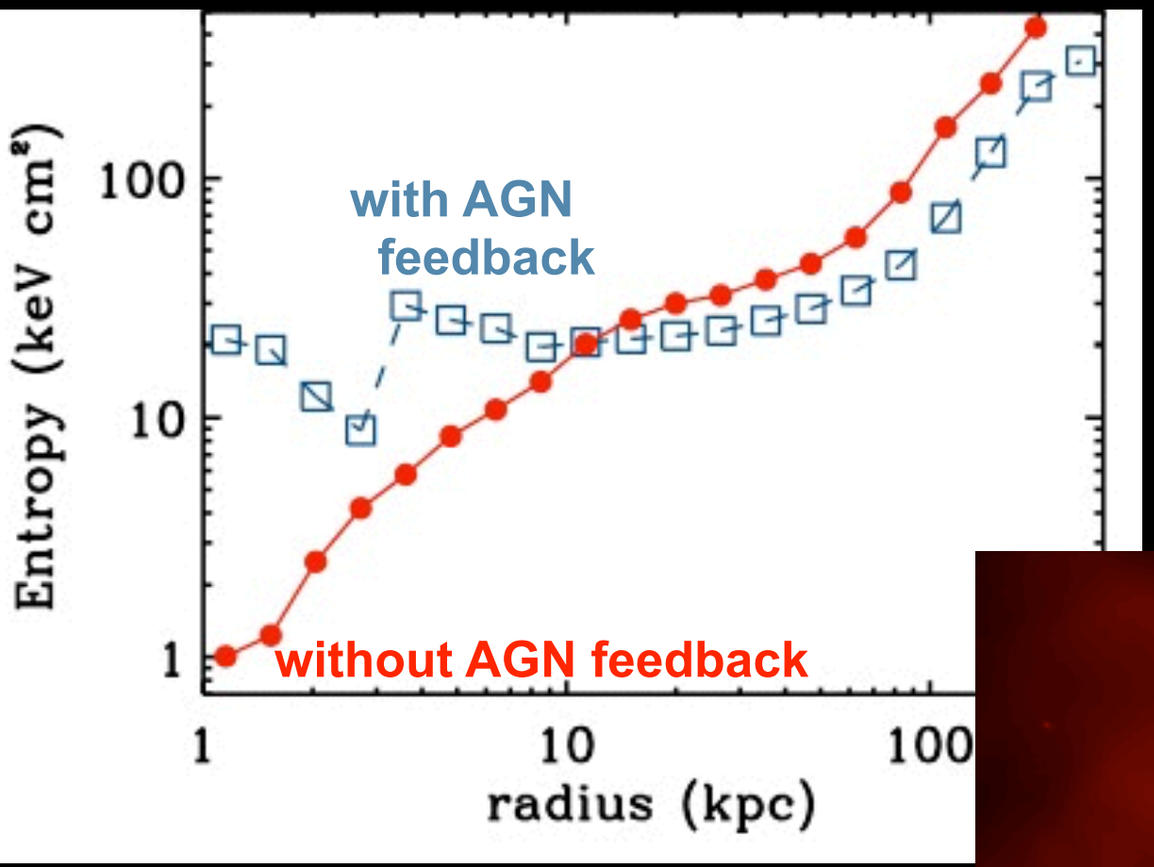
$$\dot{M}_{\rm launch}(0.1\,{\rm pc}) = 0.5\,\dot{M}_{\rm BH}$$

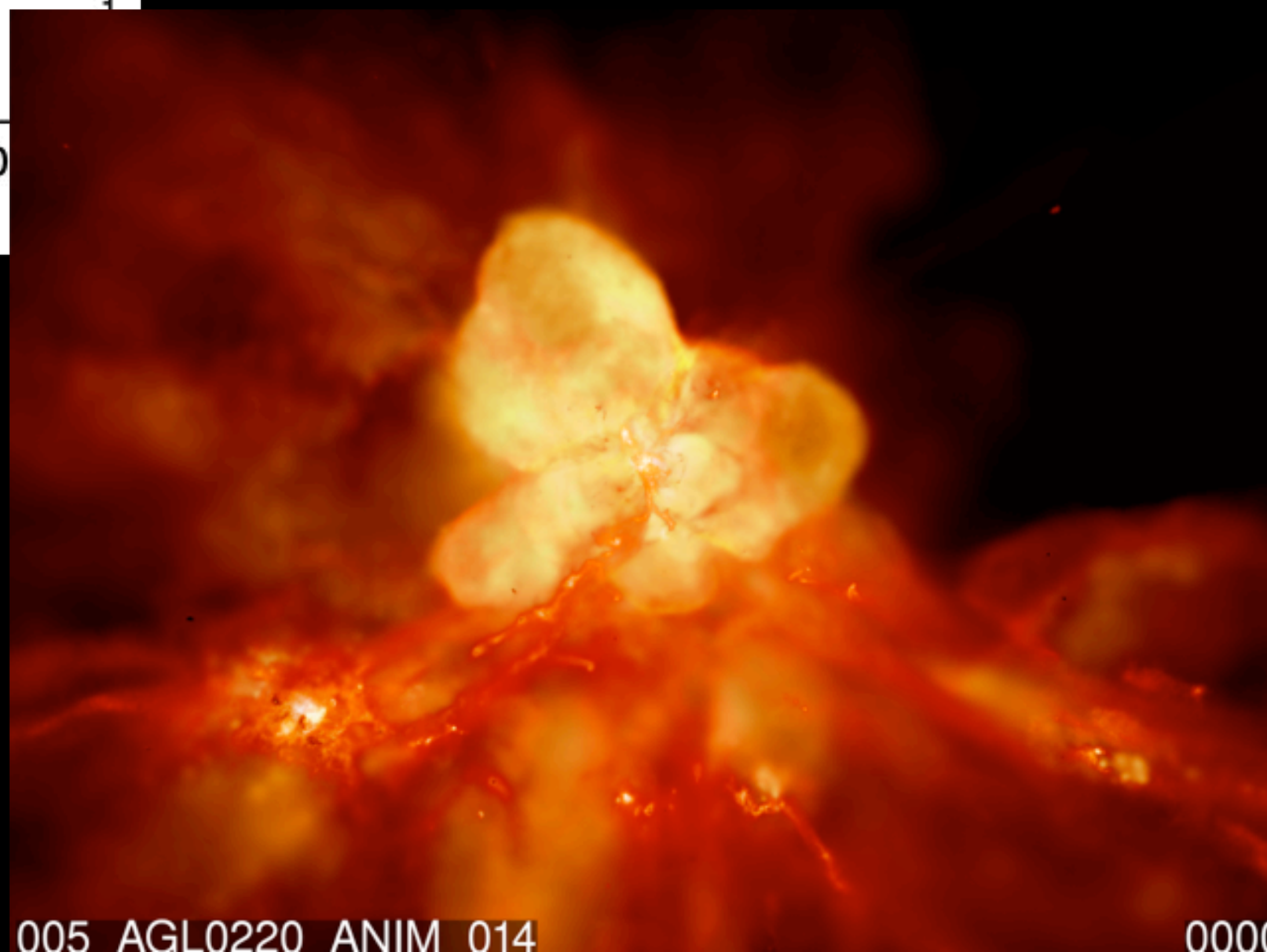
$$v_{\rm launch}(0.1\,{\rm pc}) = 10,000\,{\rm km/s}$$

Outflows May Be Significant for the ICM & IGM

SHUT DOWN COOLING FOR ~ COUPLE GYR IN BURSTS. PRE-HEATING?

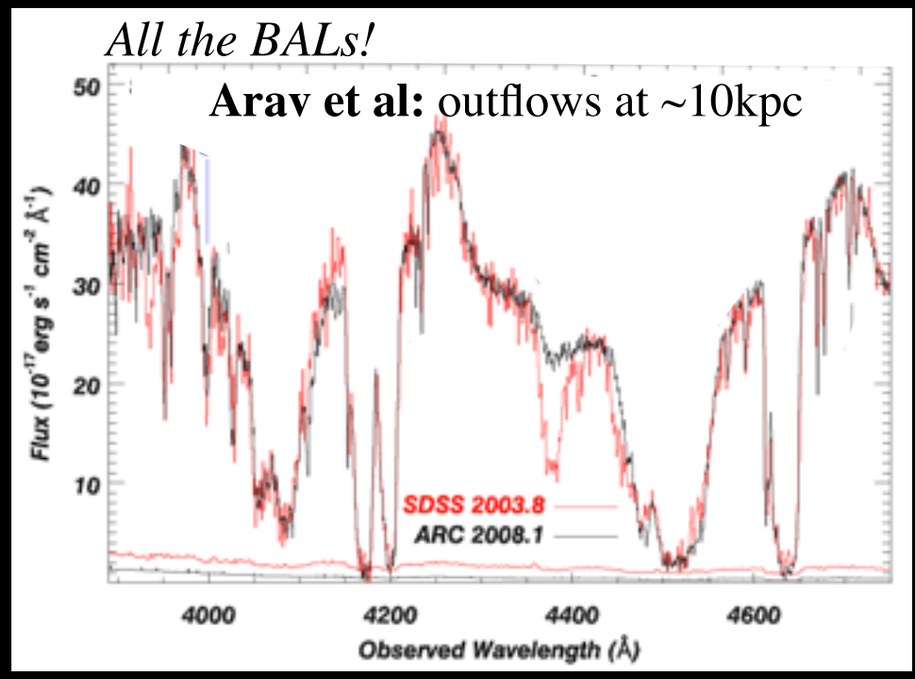
Illustris & Eagle simulation papers



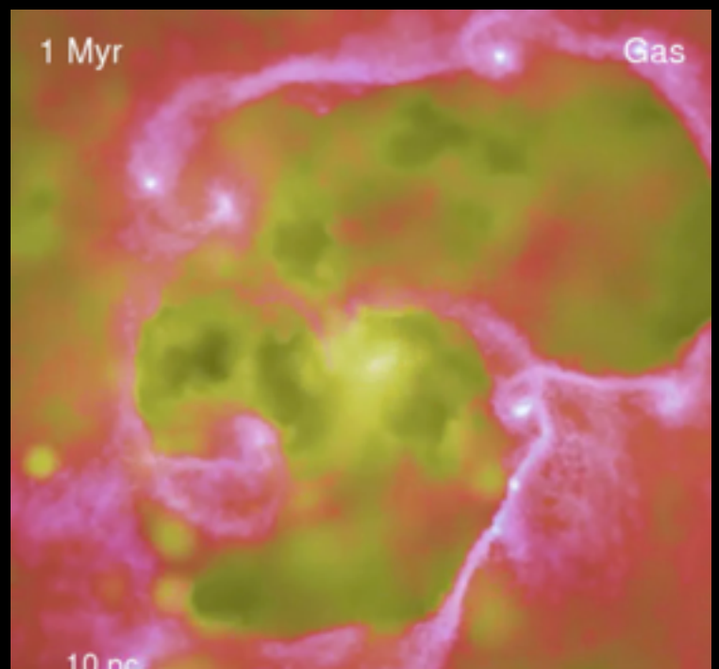


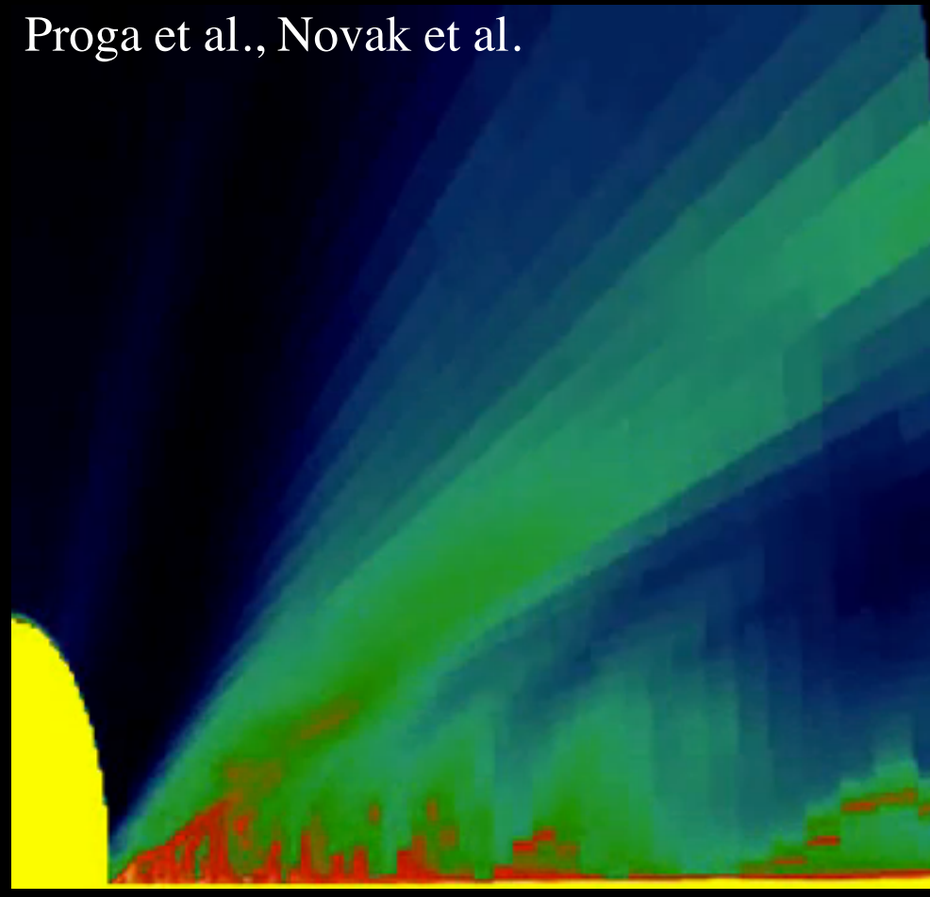
AGN Feedback: Now with Physics!

- Accretion-Disk Winds
  - "sweep up ISM" (molecular outflows) shock halo gas to $t_{cool} >> t_{dynamical}$



Proga et al., Novak et al.

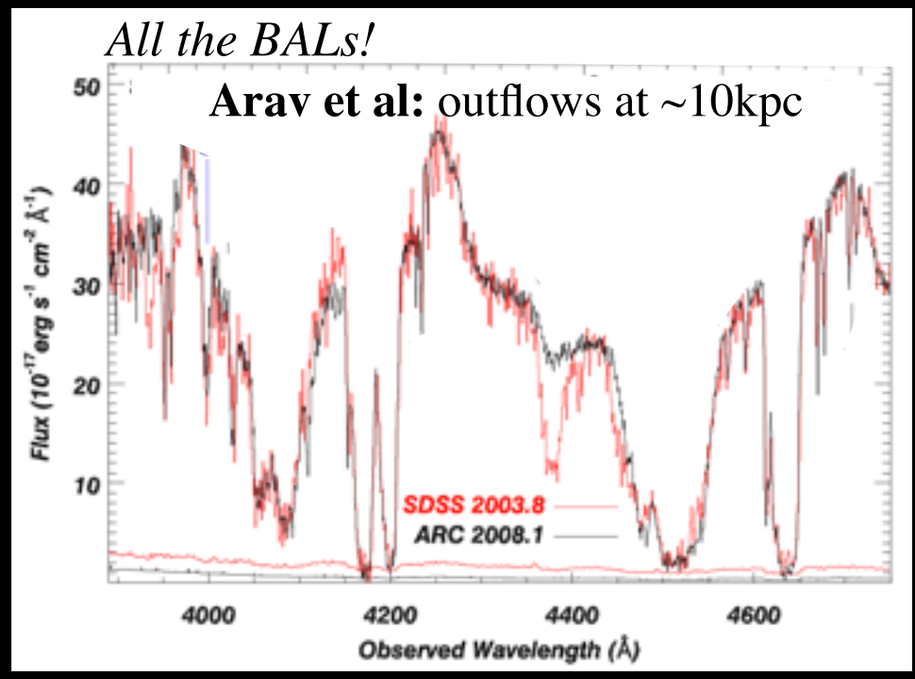




AGN Feedback: Now with Physics!

- Accretion-Disk Winds
  - "sweep up ISM" (molecular outflows)
    shock halo gas to $t_{cool} >> t_{dynamical}$

  - coupling: encounter multi-phase disk: need large covering
    duty cycle: >0.1 $L_{Eddington}$: ~1% (enough?)
    cooling? (Faucher-Giguere et al.): energy or momentum?



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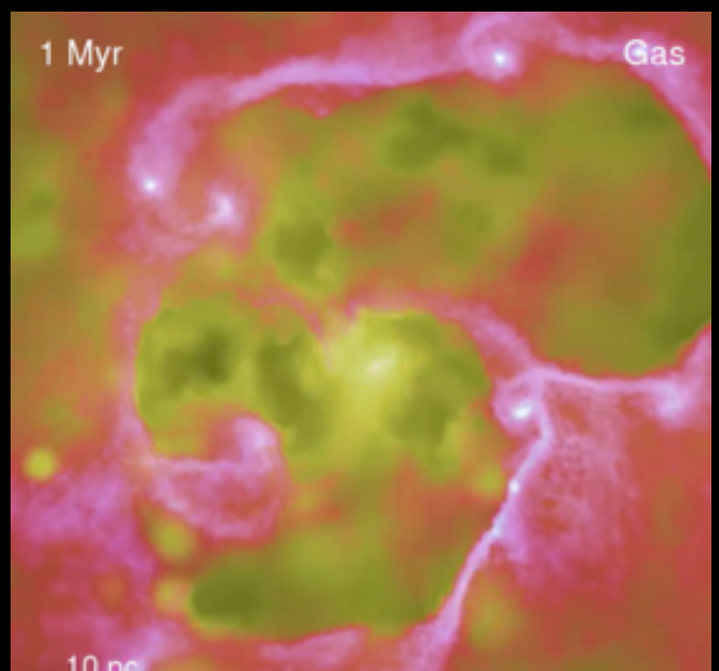

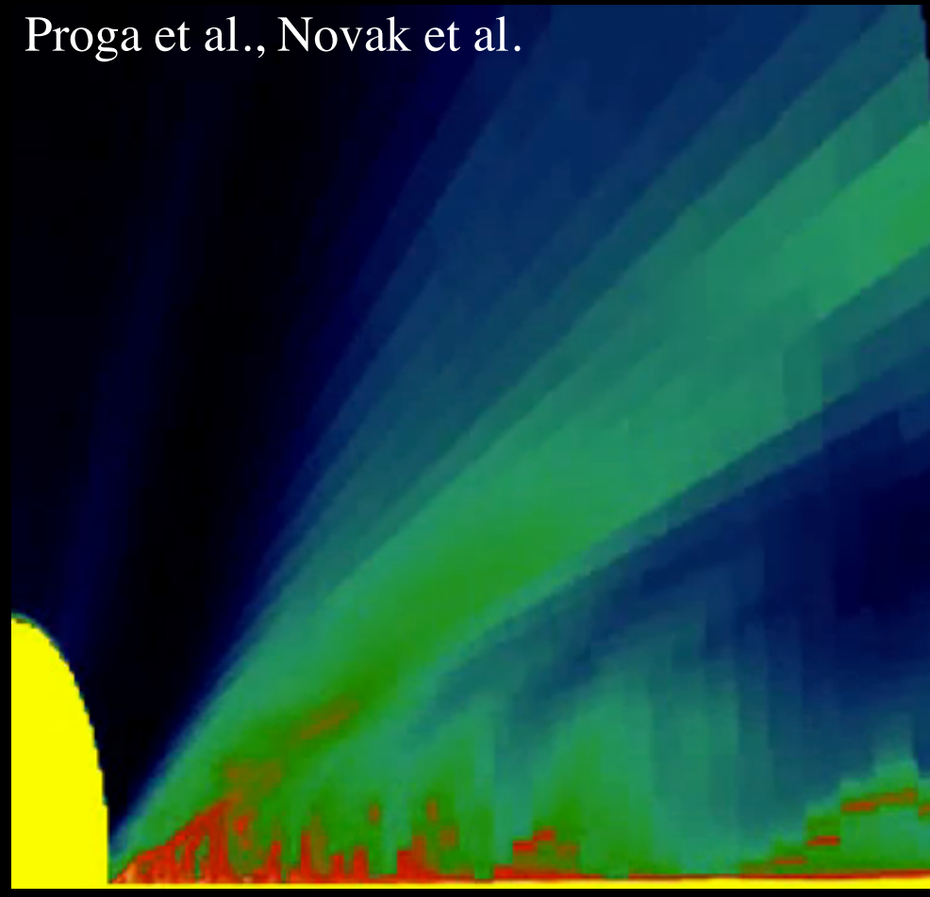

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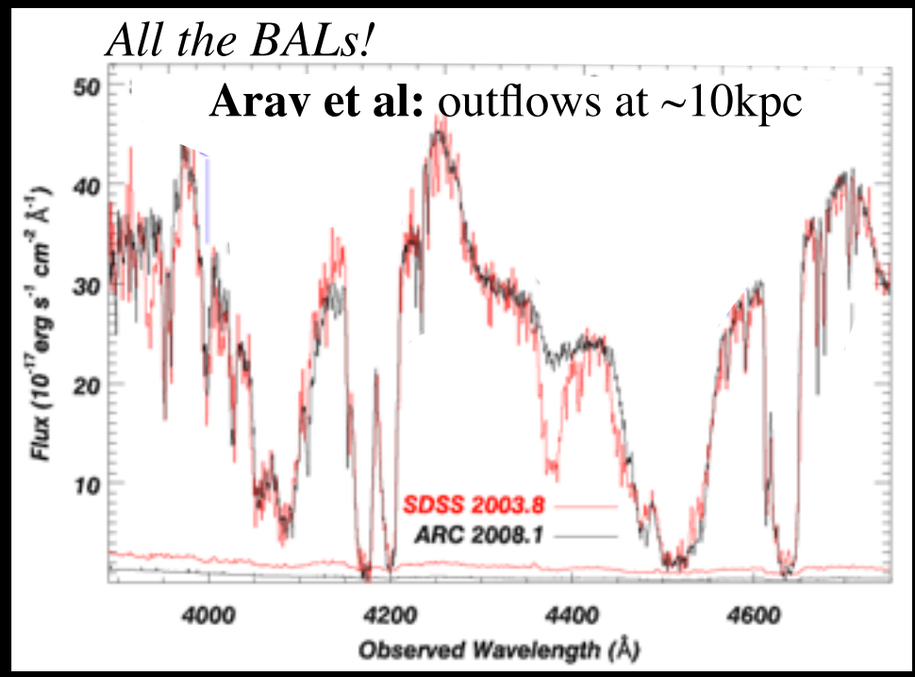
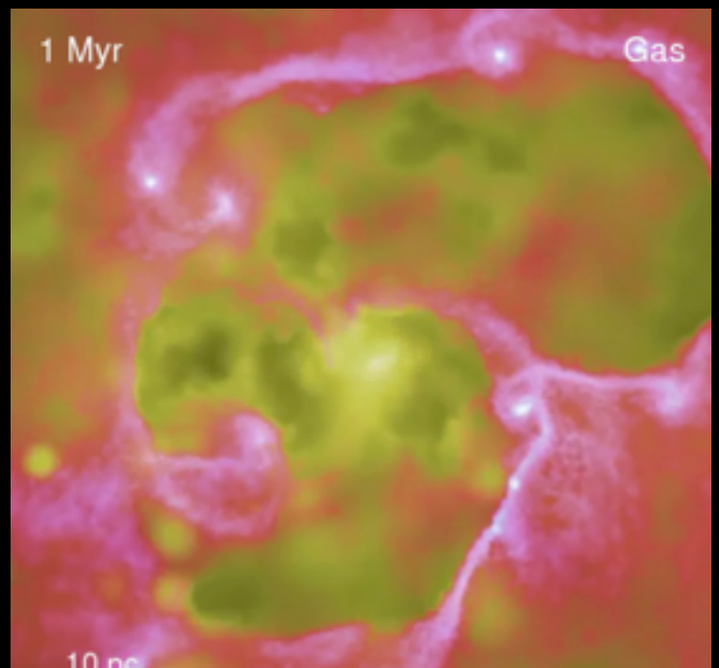
  - coupling: encounter multi-phase disk: need large covering
    duty cycle: >0.1 $L_{Eddington}$: ~1% (enough?)
    cooling? (Faucher-Giguere et al.): energy or momentum?

  - rare! (~1% duty cycle) & *only* luminous QSOs
    phases: molecular gas
    timescale: ~10 Myr to ~few kpc: *AGN is not the same,*
    & quenching has not yet happened





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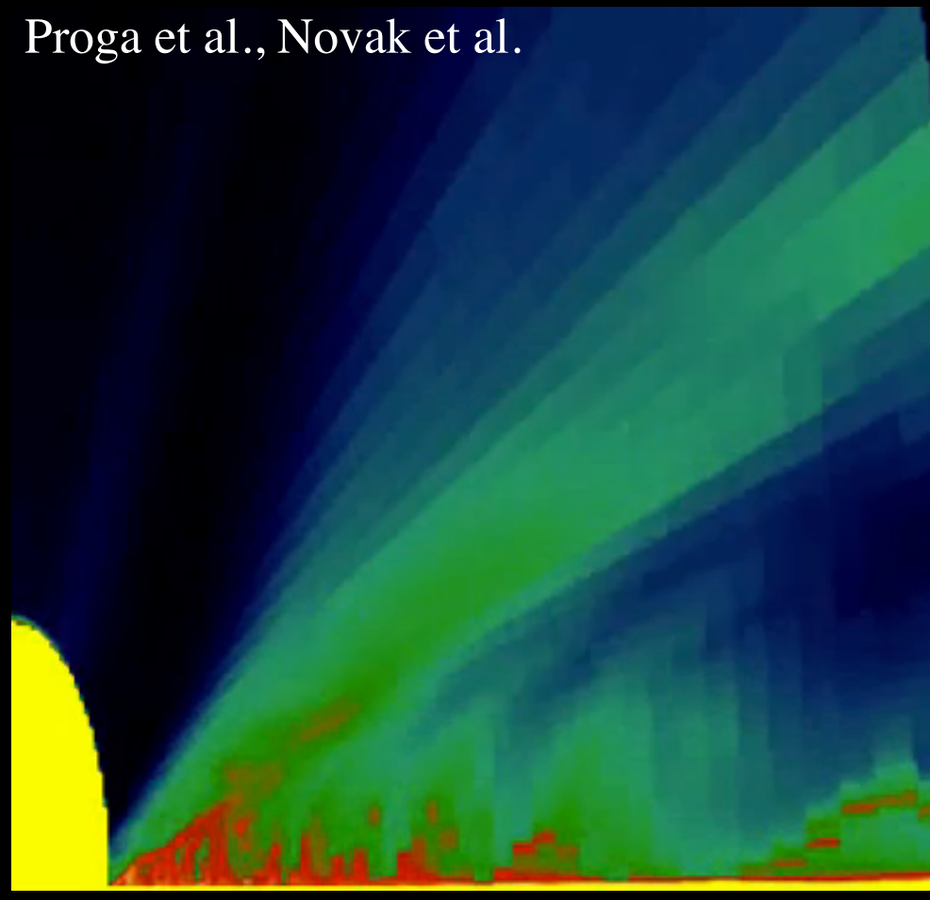
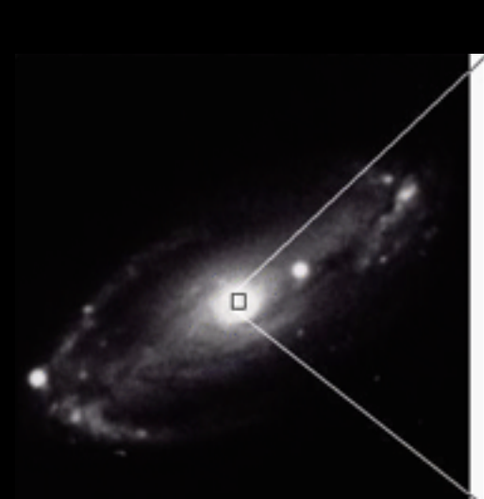
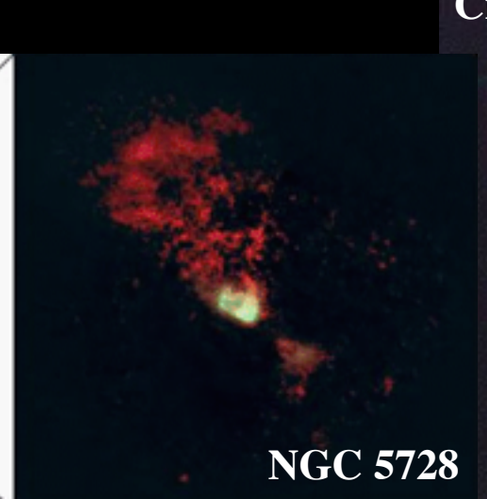


AGN Feedback: Now with Physics!

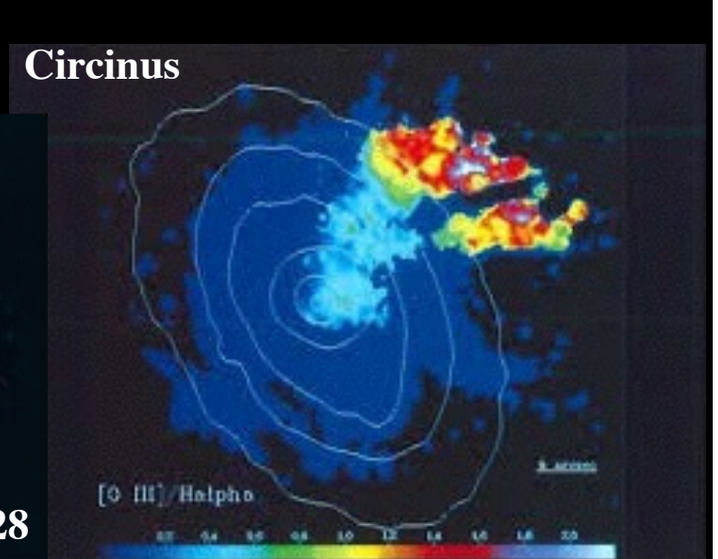
- Radiative Feedback
  - photo-ionization & compton heating (can't stop SF)
    radiation pressure: single-scattering (Eddington & dust),
    multiple-scattering (IR & Ly-alpha)

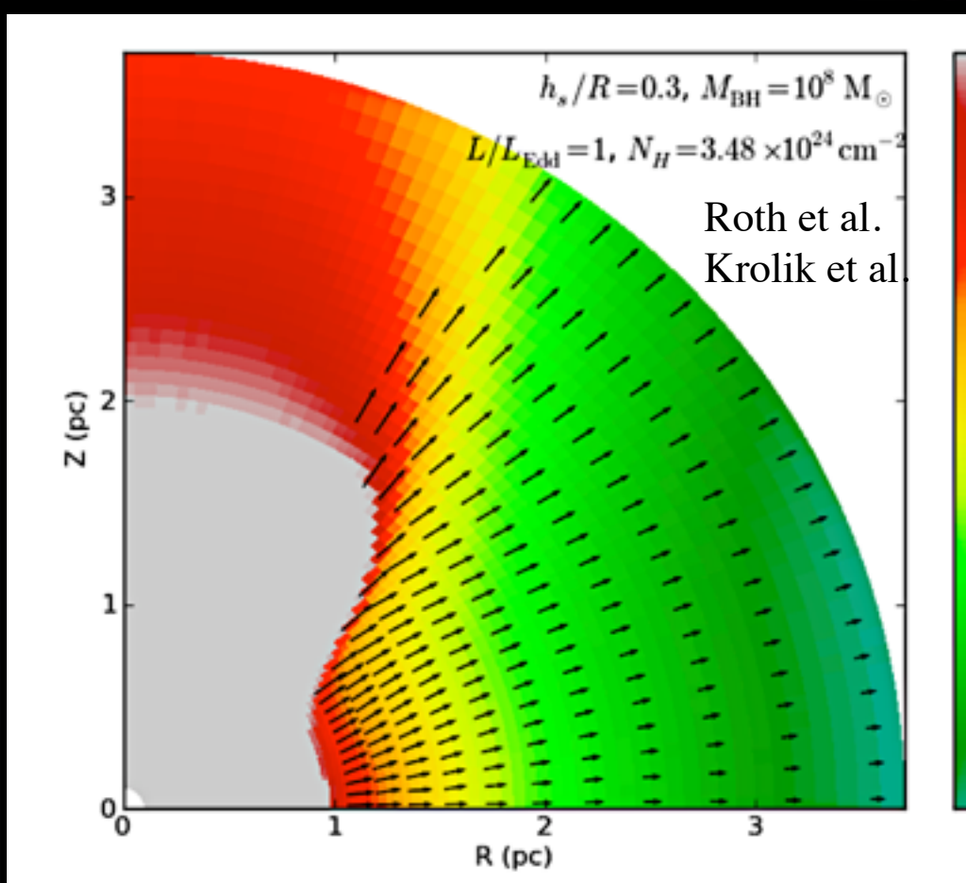
Mike Grudic
in prep





NGC 5728





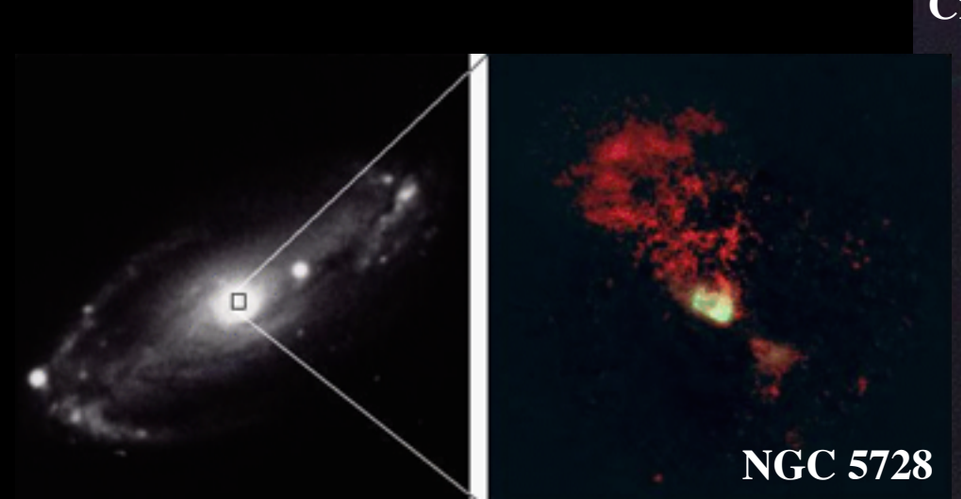
Roth et al.
Krolik et al.

AGN Feedback: Now with Physics!

- Radiative Feedback
  - photo-ionization & compton heating (can't stop SF)
    radiation pressure: single-scattering (Eddington & dust),
    multiple-scattering (IR & Ly-alpha)

  - coupling: non-linear radiation hydro
    duty cycle: L_{AGN} >> L_{Stars}: ~1% (enough?)
    launch zone: sublimation (0.1pc)? torus (10pc)? NLR (100pc)?

Mike Grudic
in prep



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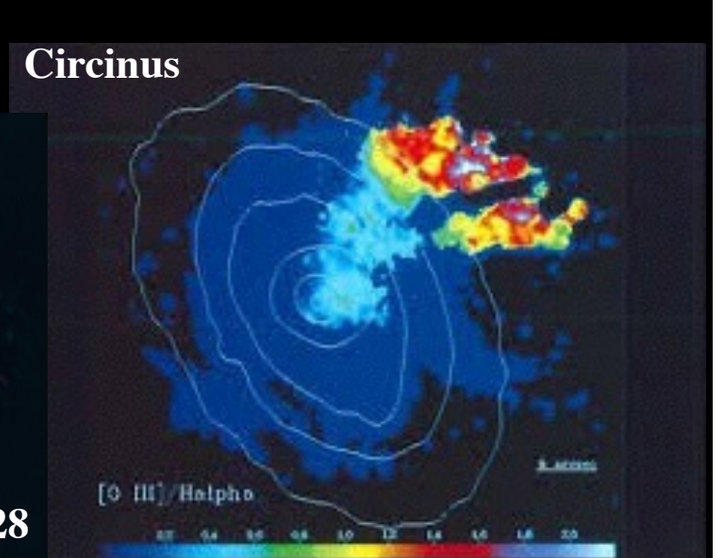

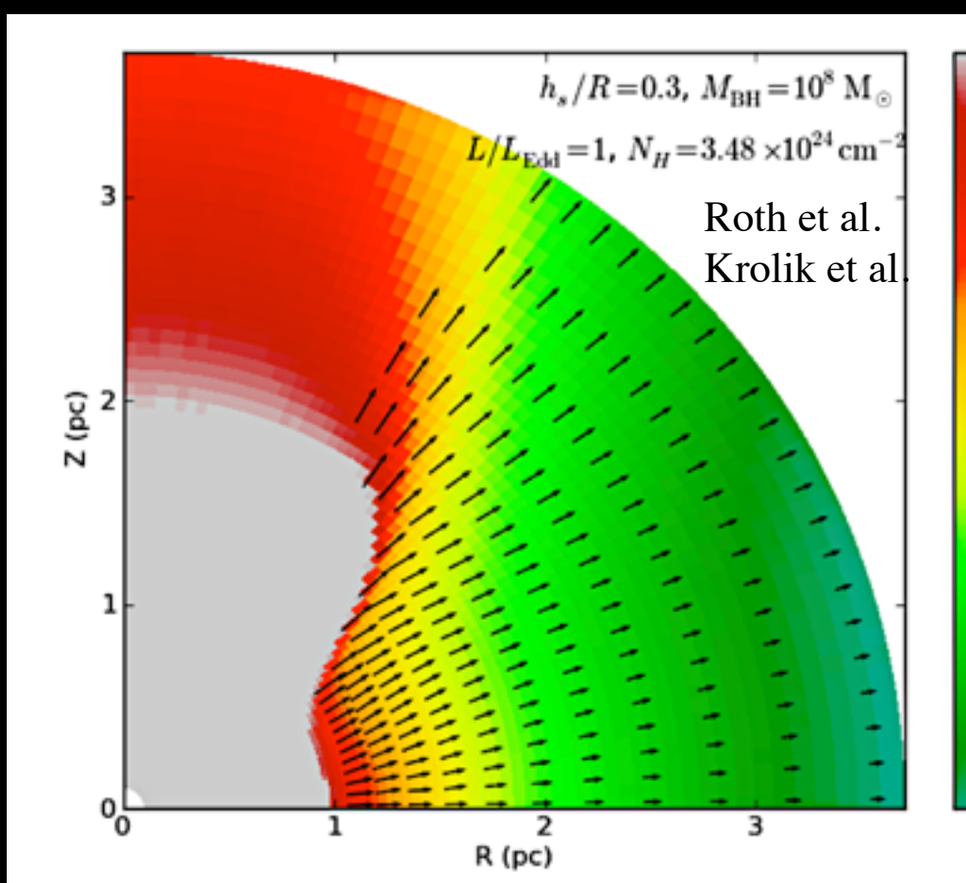

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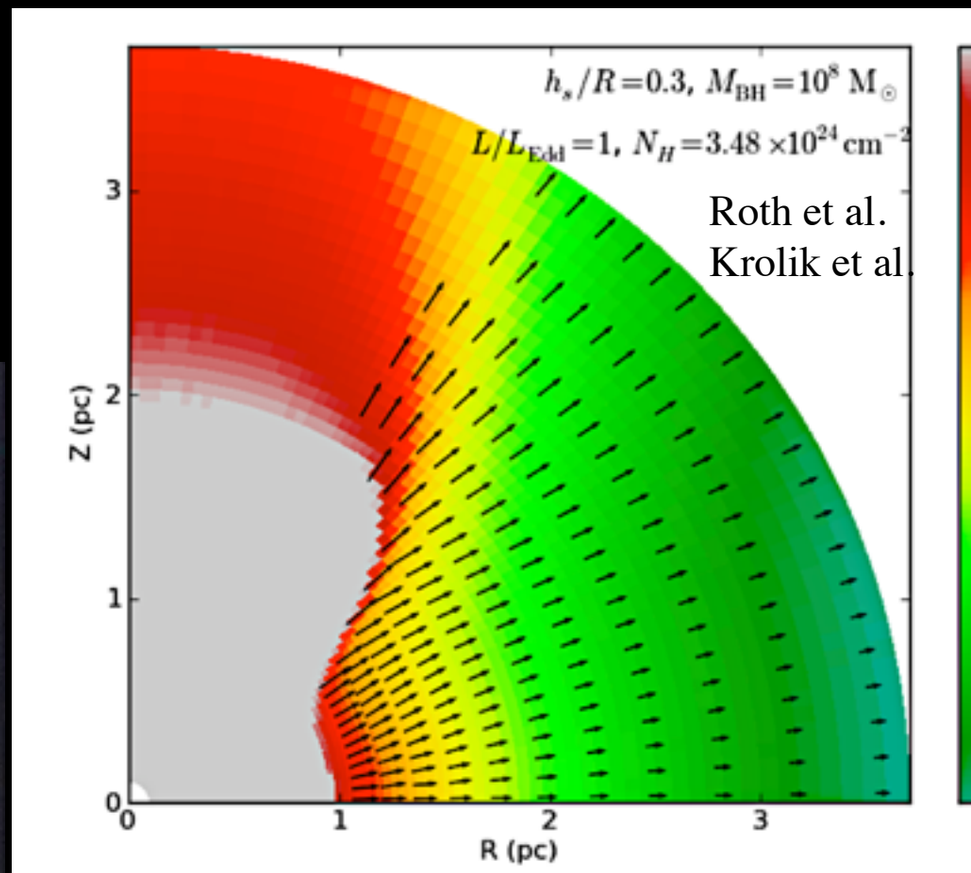
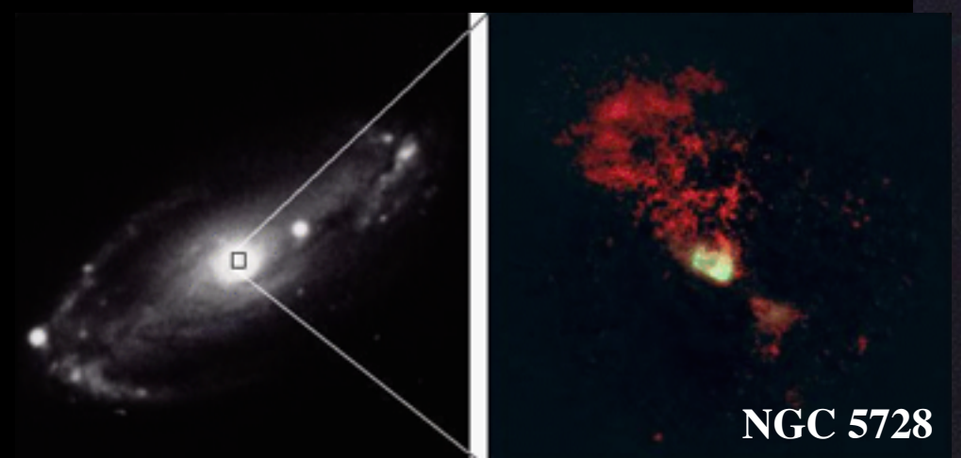
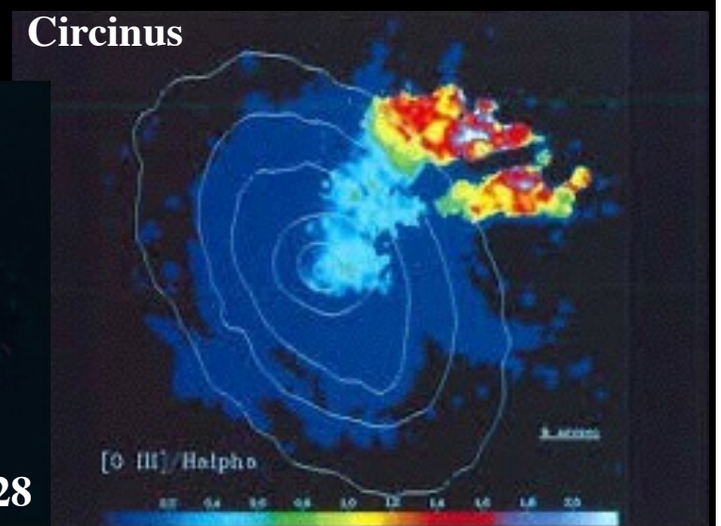
  - coupling: non-linear radiation hydro
    duty cycle: L_{AGN} >> L_{Stars}: ~1% (enough?)
    launch zone: sublimation (0.1pc)? torus (10pc)? NLR (100pc)?

  - rare! (~1% duty cycle) & *only* luminous QSOs
    slow acceleration to ~200-500 km/s: looks like stellar!
    time to leave launch region >> acceleration time
    "invisible acceleration" (no shocks, unique emission)

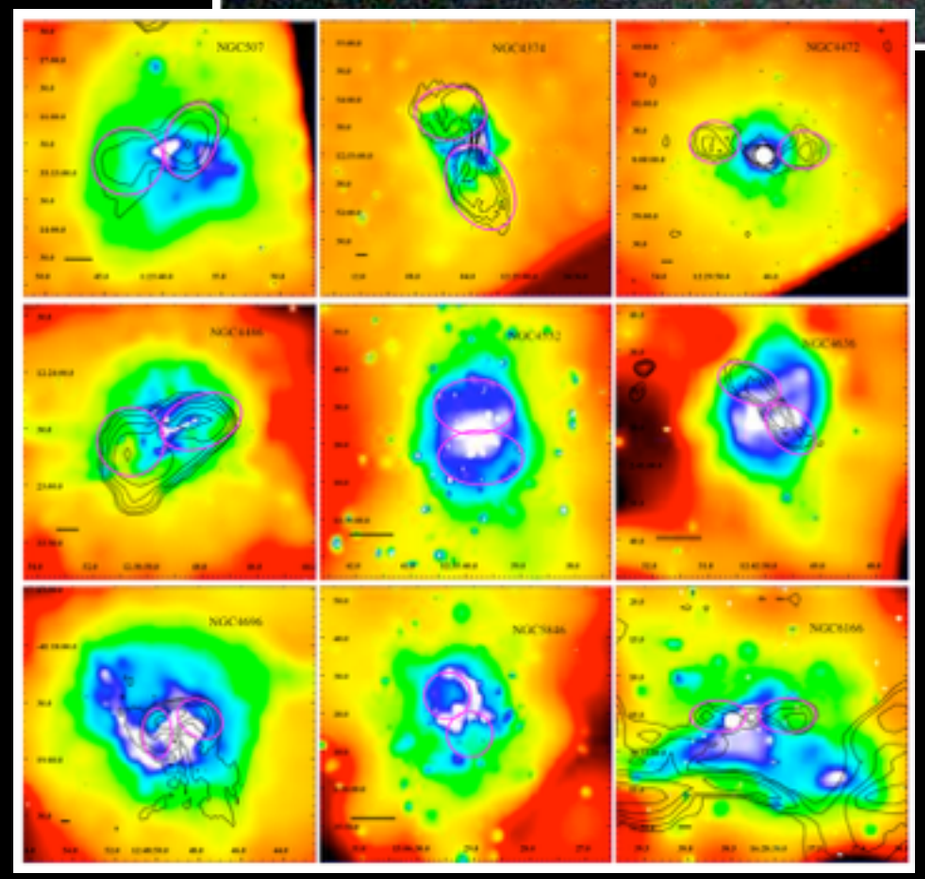




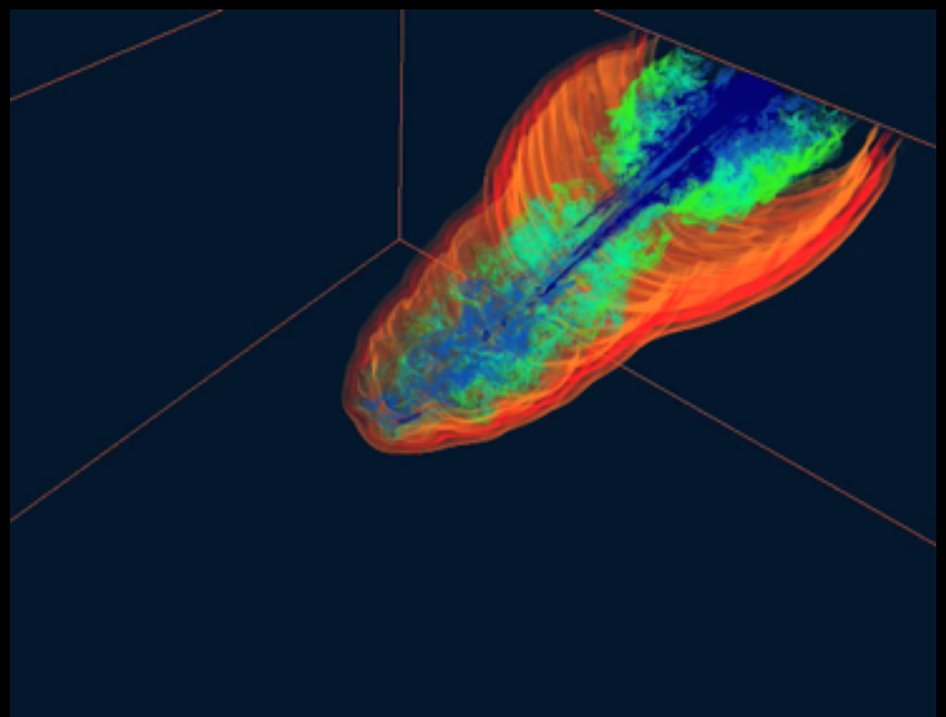


AGN Feedback: Now with Physics!

- Jets
  - heat IGM/ICM (low-density)
    "push" (but terminated by) high-density gas



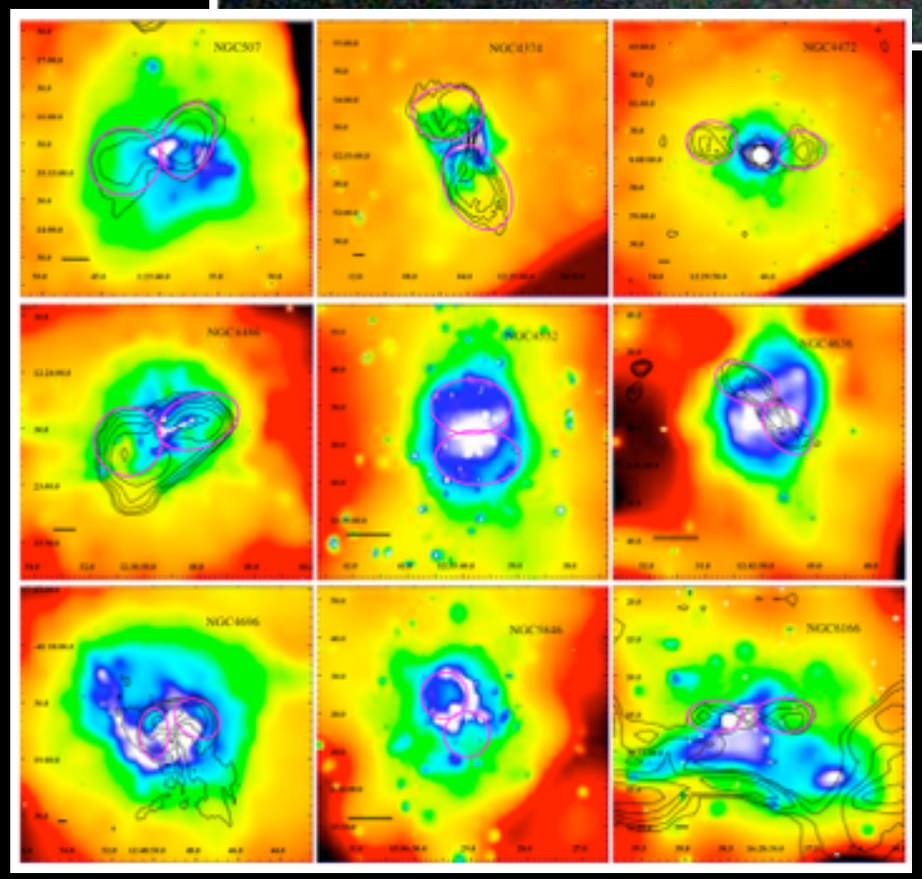
Allen, Best et al: Cooling-flow halos *all with jets/bubbles* — energy is there!



AGN Feedback: Now with Physics!

- Jets
  - heat IGM/ICM (low-density)
    "push" (but terminated by) high-density gas

  - generation: spin? accretion disk thickness/state?)
    coupling: bubbles-sound waves-cosmic rays-turbulence?



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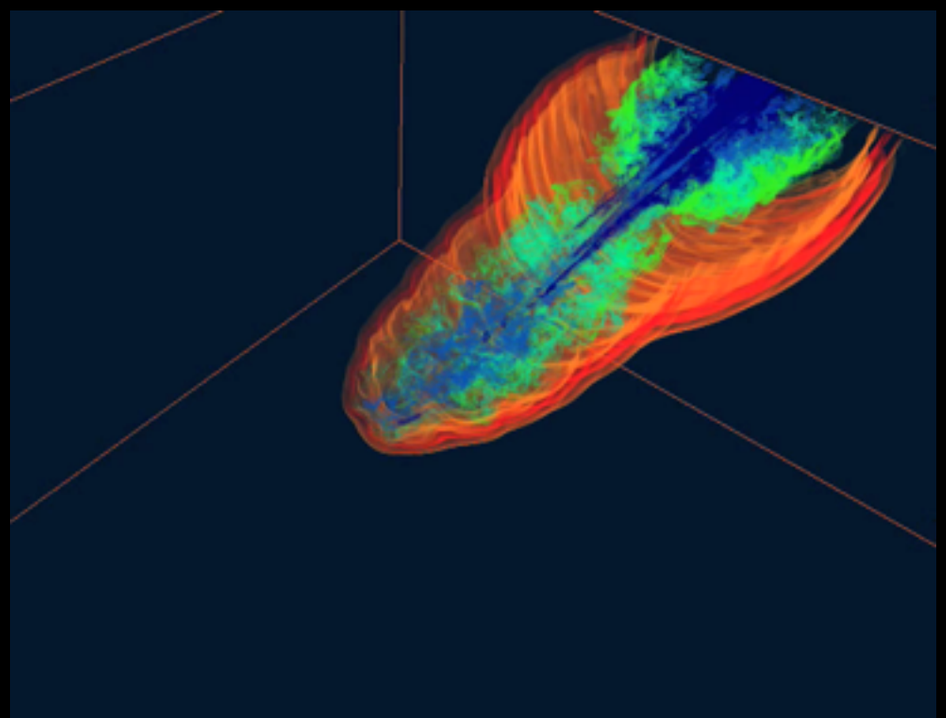
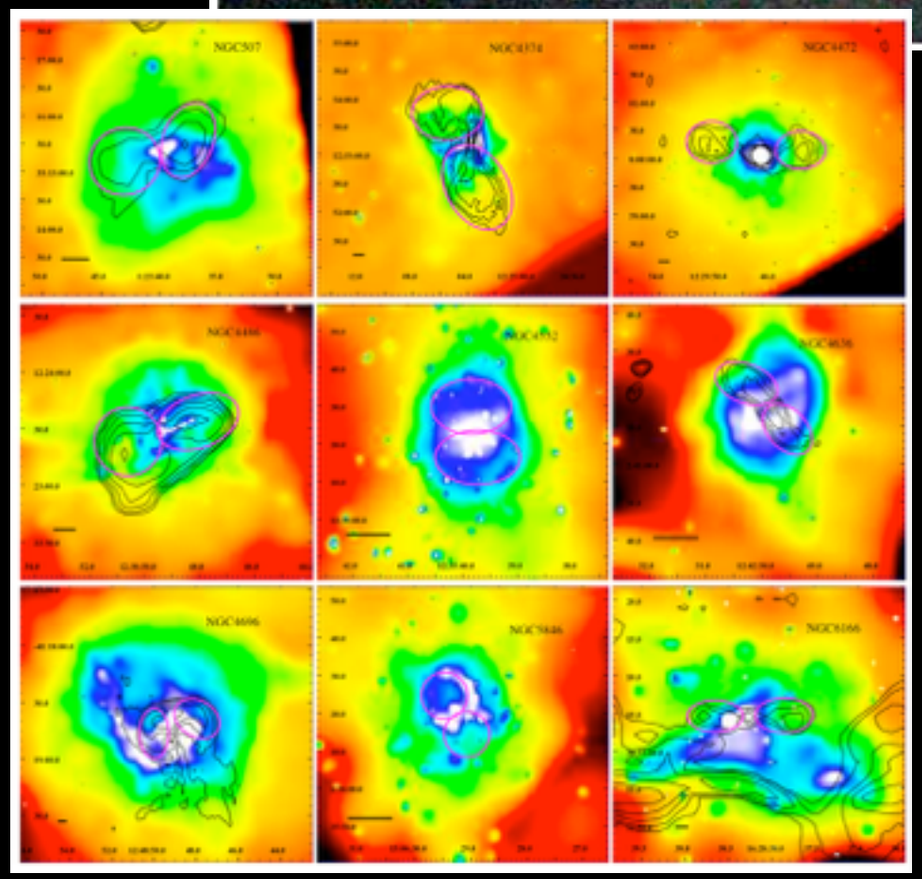


AGN Feedback: Now with Physics!

- Jets
  - heat IGM/ICM (low-density)
    "push" (but terminated by) high-density gas
  - generation: spin? accretion disk thickness/state?)
    coupling: bubbles-sound waves-cosmic rays-turbulence?
  - hard to see! (especially compact jets at high-z)
    necessary, but not *sufficient*! (lots of LLAGN)
    timescales: "work" done ~Gyr after AGN activity!
    — need to see CGM/ICM gas!



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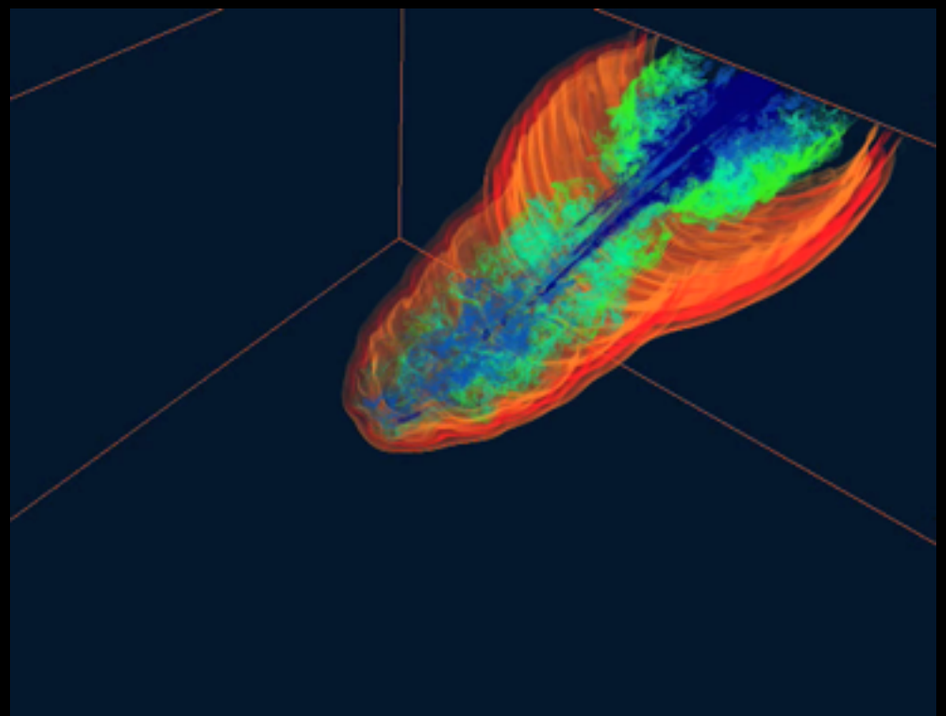
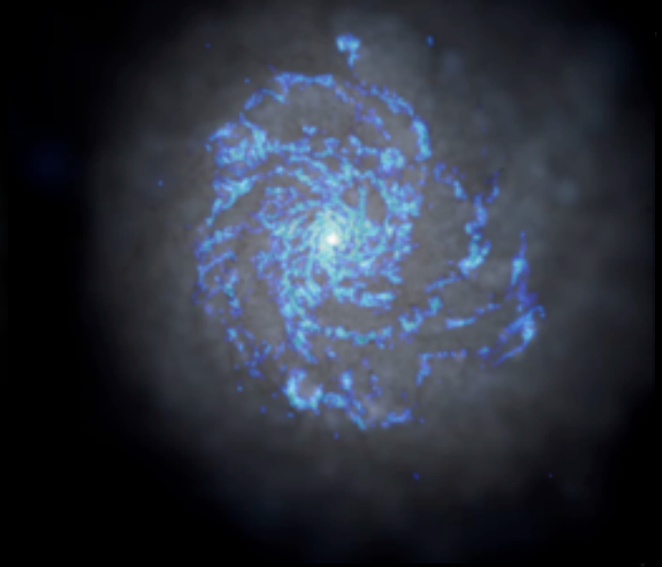


Pretty Pictures!

Observed Starlight

Molecular



Galaxy Merger

X-Rays

Star Formation