Numerical Simulations of physical processes driving galaxy evolution

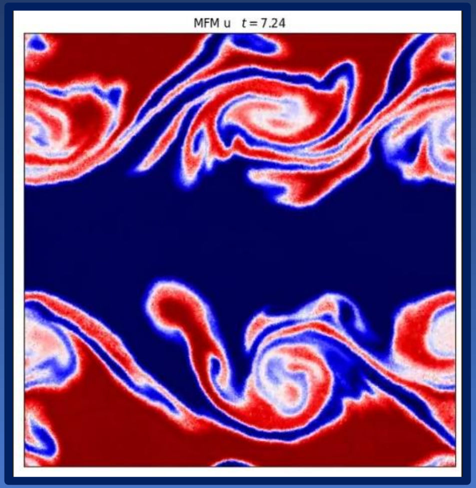
Lecture 2: Subgrid Physics

Rhea-Silvia Remus

Canary Islands Winter School, 24.11.2021

Summary: Computational Methods

Smooth Particle Hydrodyn.

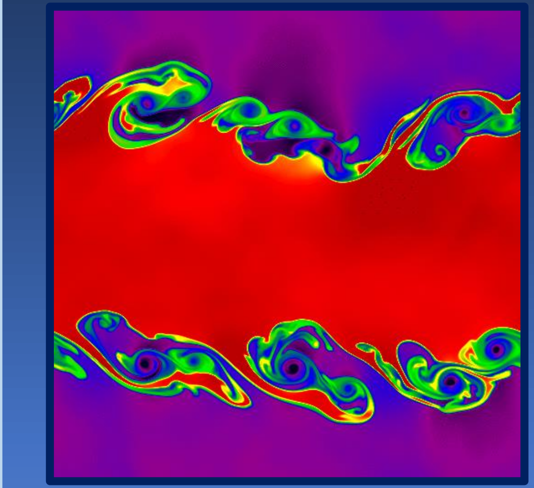


Courtesy
M. Niemeyer, K. Dolag

- ✓ Very good conservation properties (mass, momentum, total energy, angular momentum, entropy)
- ✓ shape invariant

- \- Instabilities do not grow sufficiently
- \- Mixing behind shocks not sufficient
- \- Shocks captured by artificial viscosity

Adaptive Mesh Refinement

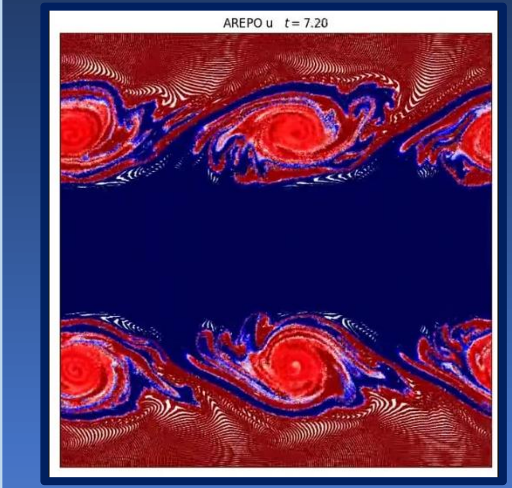


https://www.astro.princeton.edu/~jstone/Athena/tests/kh/kh.html

- ✓ Instabilities nicely grow
- ✓ Mixing between phases works well

- \- Energy conservation issues (especially for fast moving elements)
- \- Flow over cell boundaries becomes an issue for adaptive meshs
- \- Not shape invariant

Moving Mesh



Courtesy
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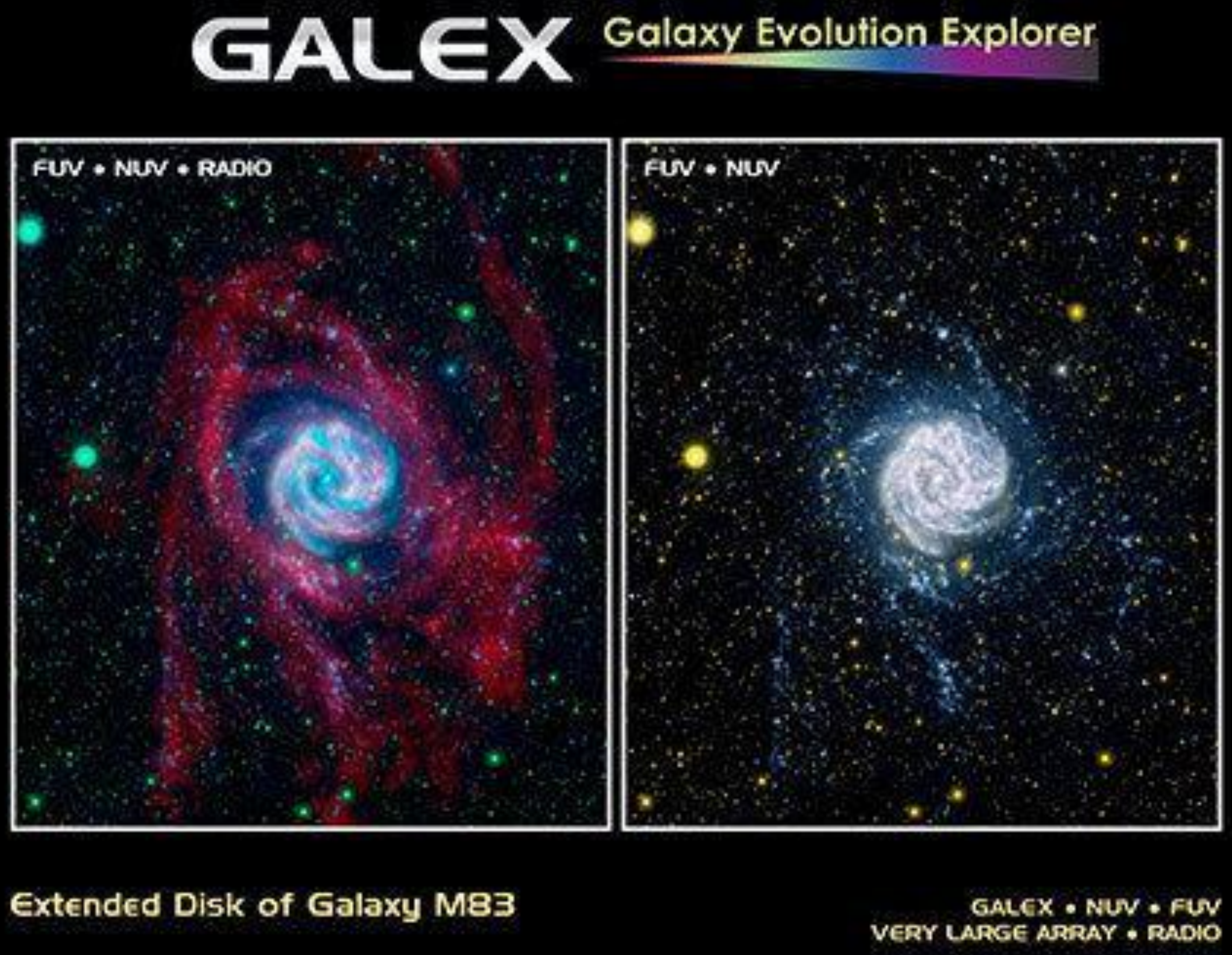
- ✓ All good things from the other two

- \- Flow over cell boundaries (only pseudo-Lagrangian)

Numerical Simulations: (Subgrid) Physics

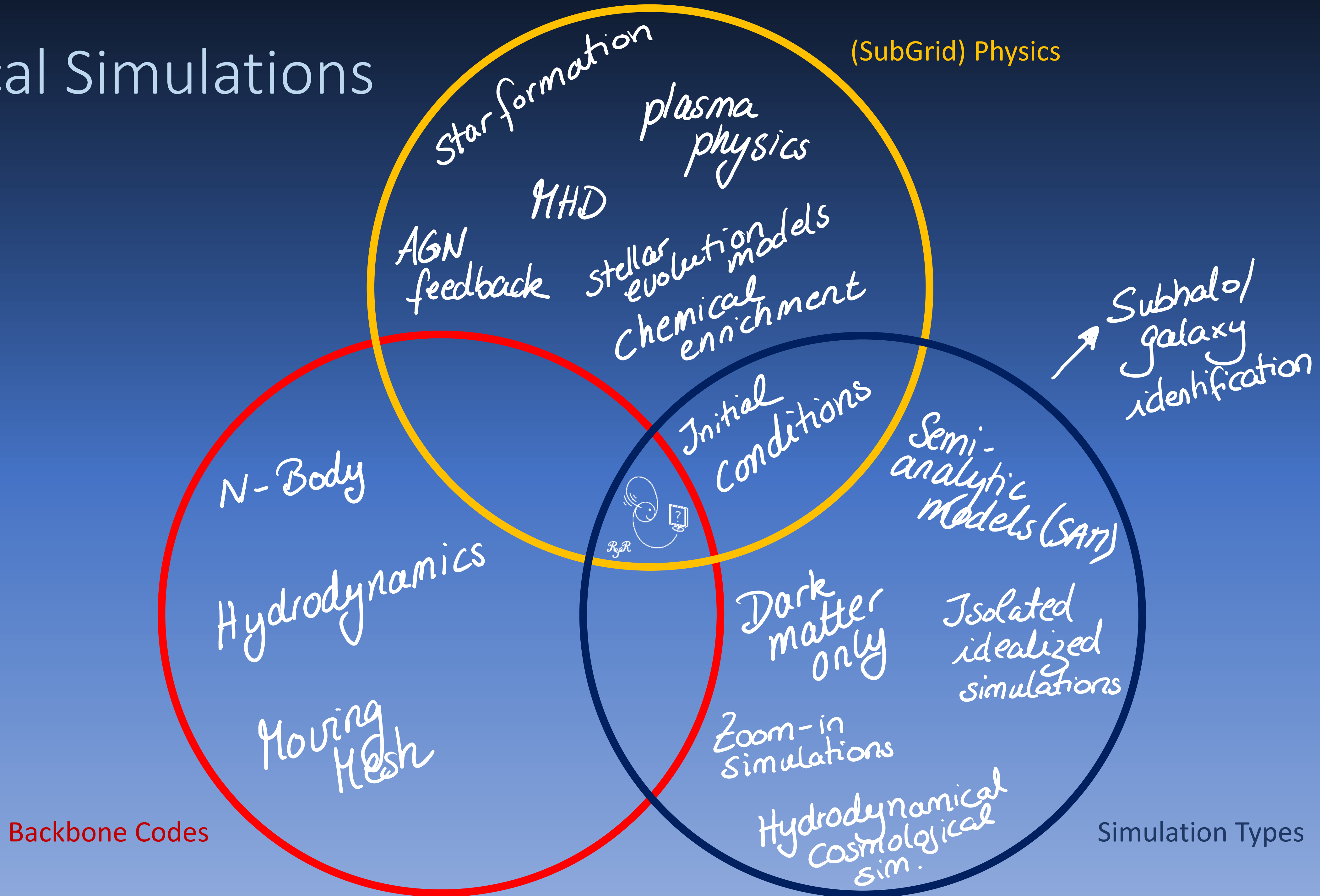
Getting the Universe alight

Introduction: It all starts with the gas



Apart from gravity and the general treatment of gas as either particles (SPH) or fluids (AMR), the physics that affect the baryons, like star formation processes, gas cooling, metal formation, AGN feedback, need to be modelled

Numerical Simulations



(SubGrid) Physics

star formation

plasma physics

MHD

AGN feedback

stellar evolution models

chemical enrichment

Initial conditions

Backbone Codes

N-Body

Hydrodynamics

Moving Mesh

Simulation Types

Semi-analytic models (SAM)

Dark matter only

Isolated idealized simulations

Zoom-in simulations

Hydrodynamical cosmological sim.

Subhalo/galaxy identification

Cooling

For stars to form, gas has to condense and cool down. This cooling is a function of density and temperature:

$$\Lambda(T, \rho)$$

Cooling

Basic Assumptions

- Optically thin
- Ionization equilibrium $(H, H^+, He, He^+, He^{++}, e^-)$
- 2-body processes $(\sim n^2)$

➡ $\Lambda(T)/n^2$

Cooling

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Cooling happens through:

- Recombination cooling
- Metal line cooling
- Bremsstrahlung cooling/free-free emission
- Compton cooling/heating

$$\Lambda(T)/n^2$$

Lets be more specific:

$$\Lambda(T)/n_e n_H$$

But since $n_e \approx n_H$

$$\Lambda(T)/{n_H}^2$$

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- Metal line cooling
- Bremsstrahlung cooling/free-free emission
- Compton cooling/heating

But in fact there are counter processes: heating also happens, mostly photoionization heating, but luckily the cooling usually wins

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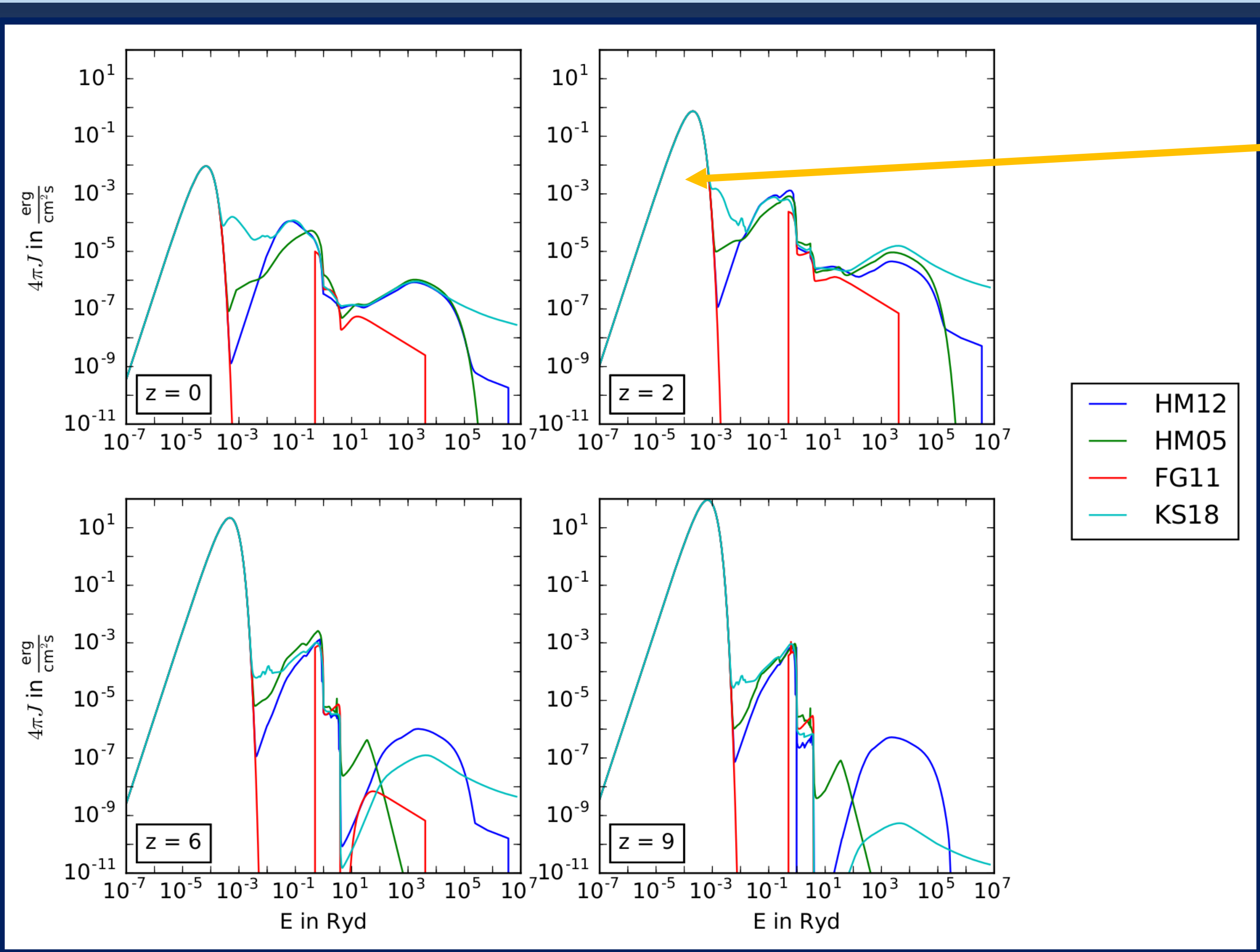
This cannot be calculated on the fly! Too many calculation needed!

Thus, cooling tables are used

UV Background



CMB Photons

Credit: S. Lueders

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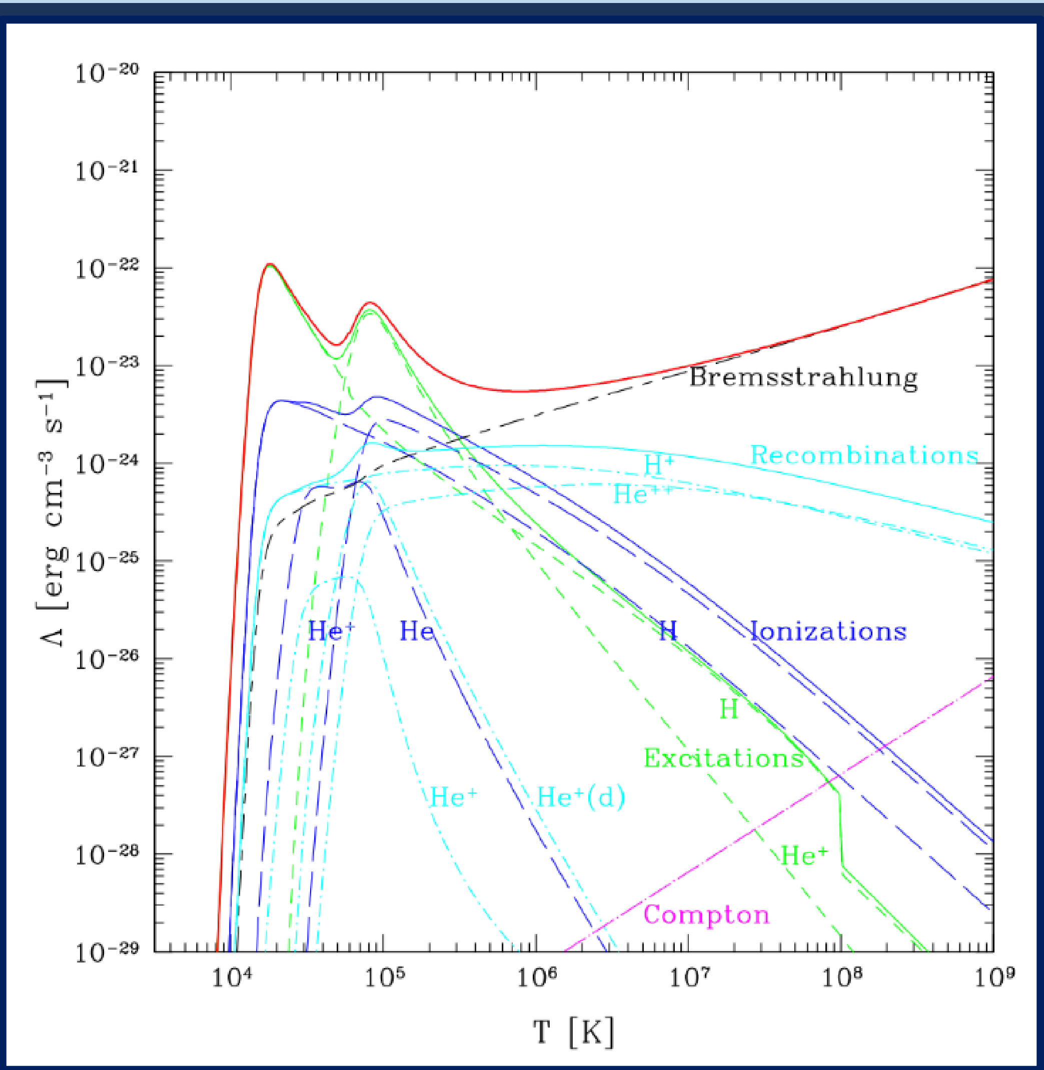

Maio et al., 2007

Cooling

Basic Assumptions

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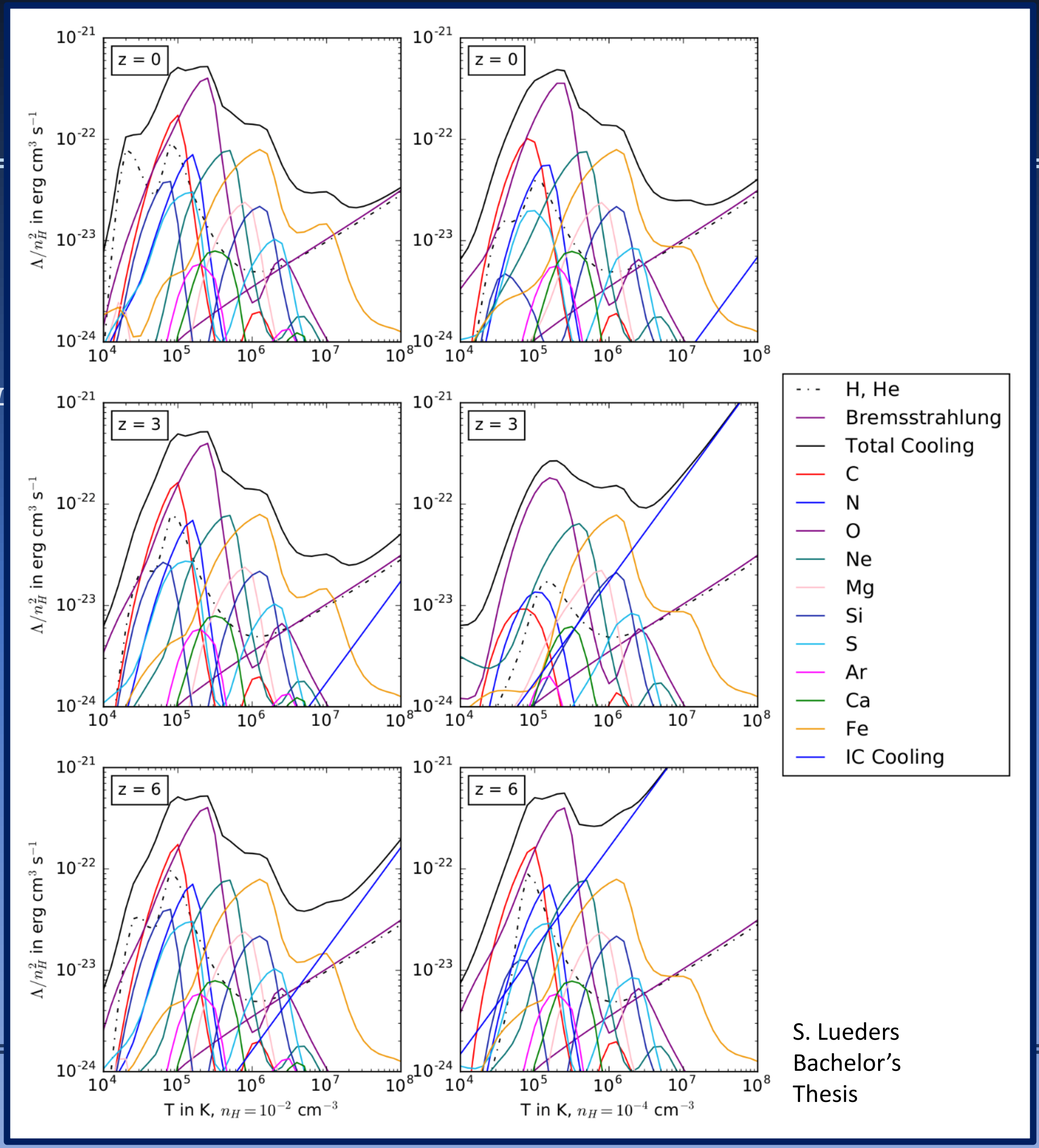
- Add Metals to the Cooling Process

$$\Lambda(T)/n^{2}$$



S. Lueders Bachelor's Thesis

Cooling

Basic Assumptions

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- Ionization equilibrium $(H, H^+, He, He^+, He^{++}, e^-)$
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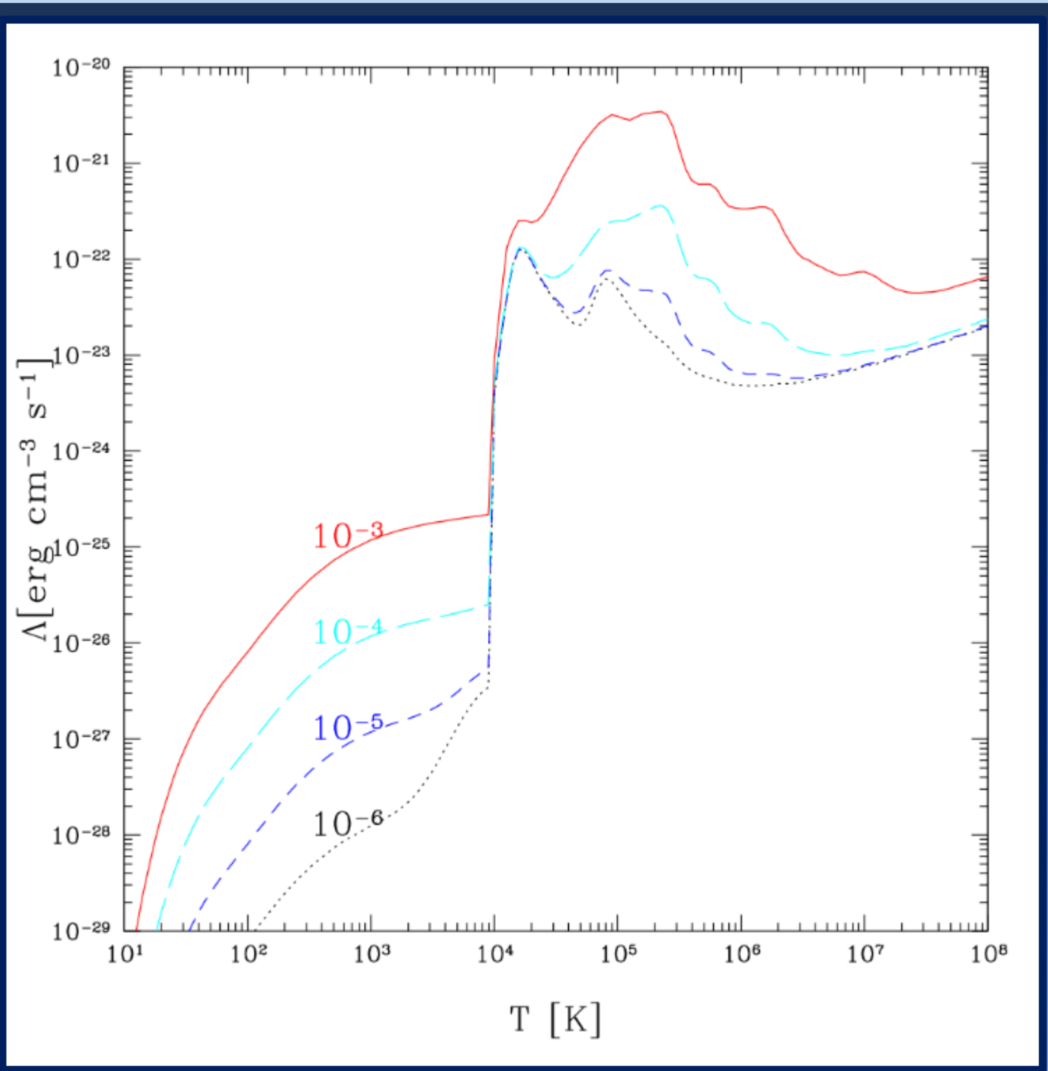
- Add Metals to the Cooling Process

- Below $T \sim 10^4 K$:
  - Solving balance equations
  - Cooling by molecules that need to be traced $(H_2, HD, \dots)$
  - Plus fine-structure transitions in metals (FeII, OI, SiII,CII…)



Maio et al., 2007

Cooling

Basic Assumptions

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- I
- 2
- A
- E
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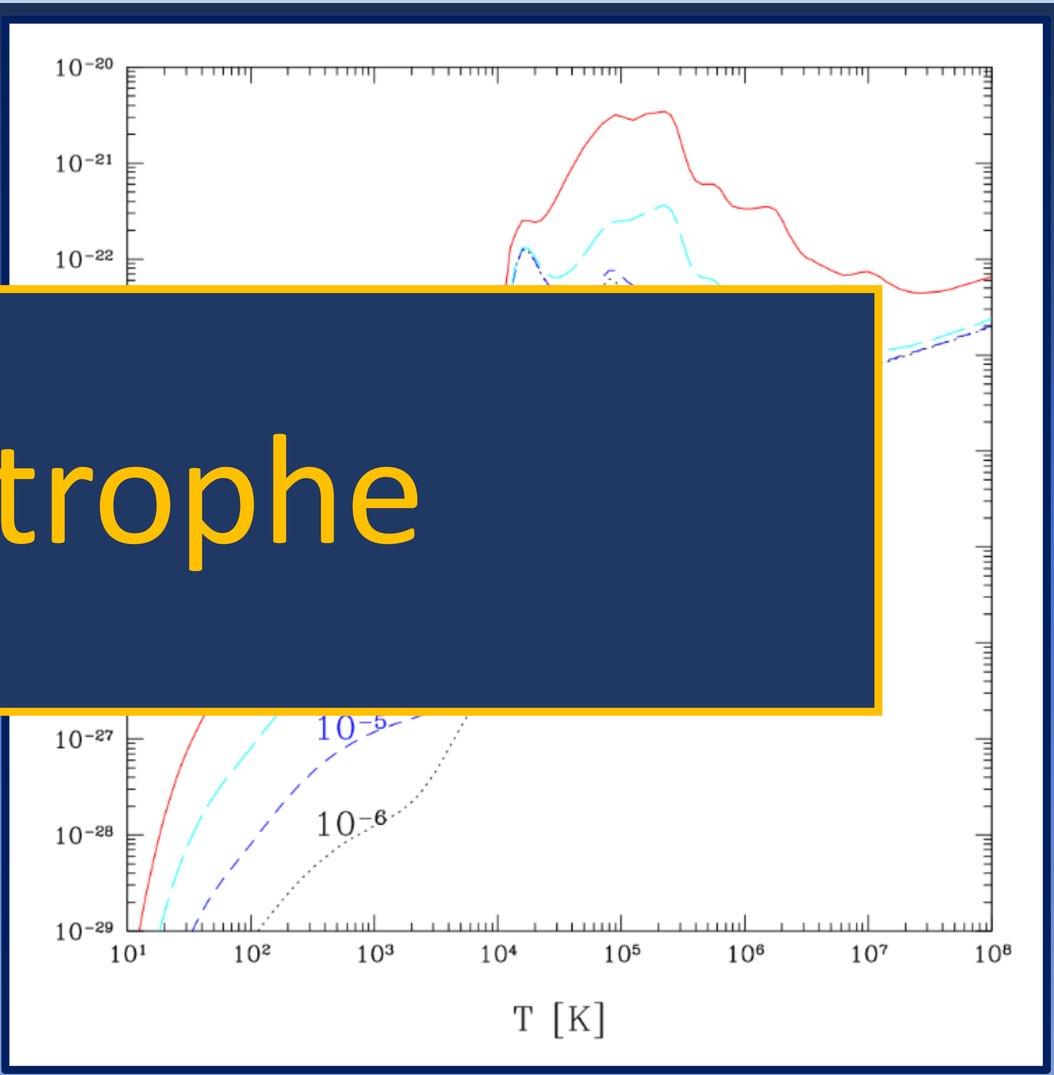
Cooling Catastrophe

$$\Lambda(T)/n^2$$



Maio et al., 2007

Star Formation

In nature, cooled gas will form stars → on scales way below our resolution!

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Basic Assumptions

- Convergent flow: $\nabla v \ < 0$
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- Jeans instability: ${}^{h}/_{c} > t_{dyn}$ with $t_{dyn} = (4\pi G\rho)^{-0.5}$

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➢ Conversion of cold gas into stars: $\frac{d\rho_*}{dt} = -\frac{d\rho}{dt} = \frac{c_*\rho}{t_*};$

c_*: star formation efficiency ($\approx 10\%$); t_*: star formation time (max. of t_{dyn} and t_{cool})

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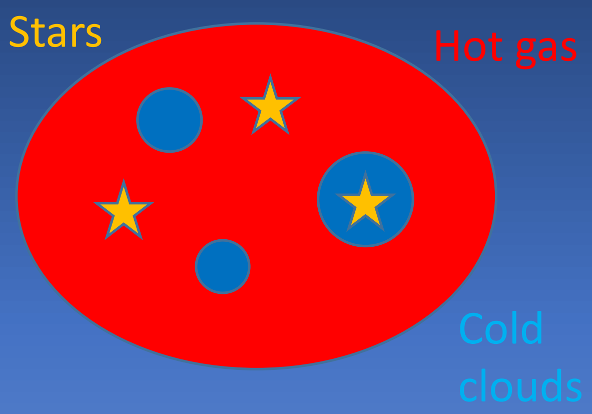
➢ When a significant fraction of gas is converted into stars, spawn new star particles

Star Formation

More elaborated: a multi-phase model

Springel & Hernquist 2002



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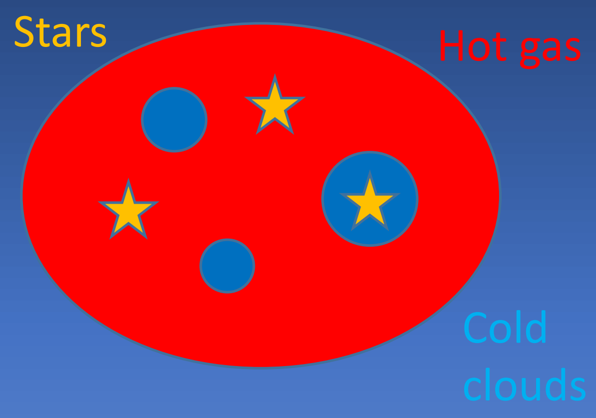

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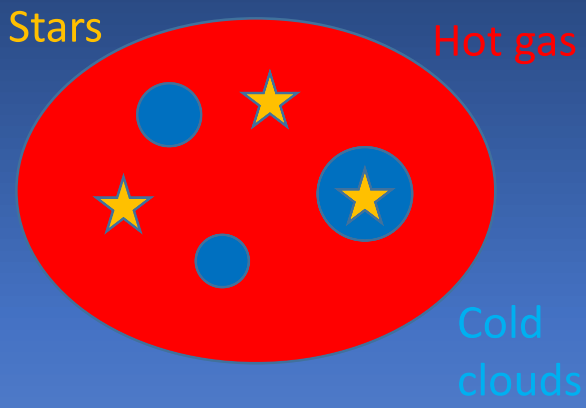
Cooling function



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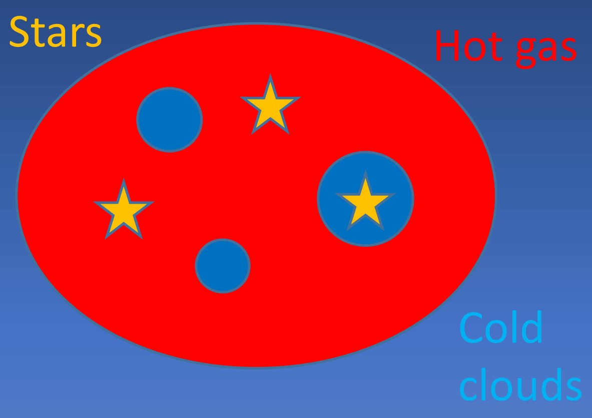
Star formation timescale

Supernova mass fraction



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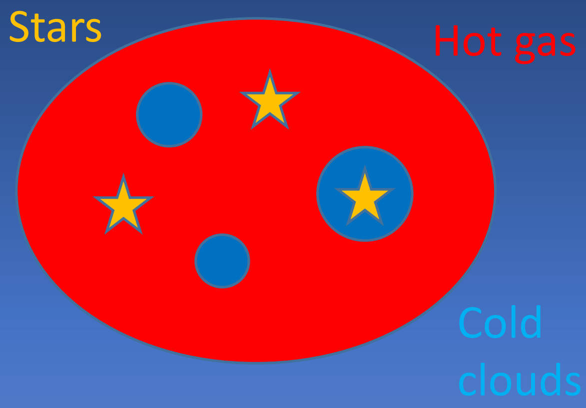
Cloud evaporation parameter



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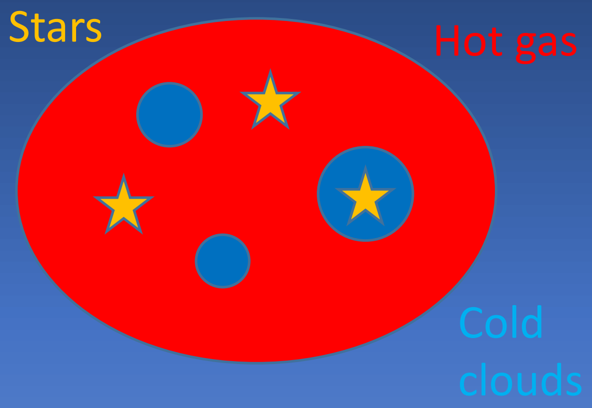

Self-regulated star-formation, but a complex set of differential equations needs to be solved

Star Formation

More elaborated: a multi-phase model

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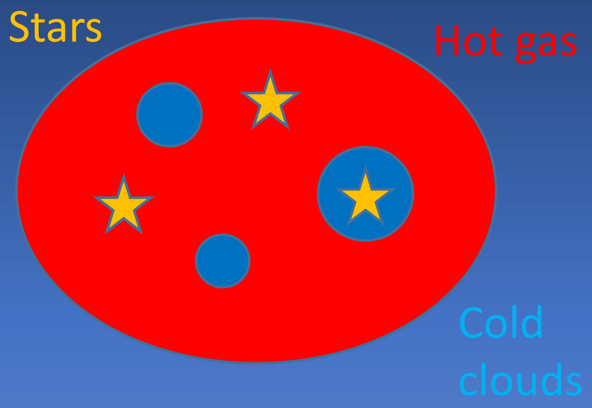
Self-regulated star-formation, but a complex set of differential equations needs to be solved



At the end, there are three free parameters left to adjust: the thermal instability density parameter, an evaporation efficiency parameter, and the star formation timescale. First two can be constrained by assumptions regarding the temperature range of the ISM.

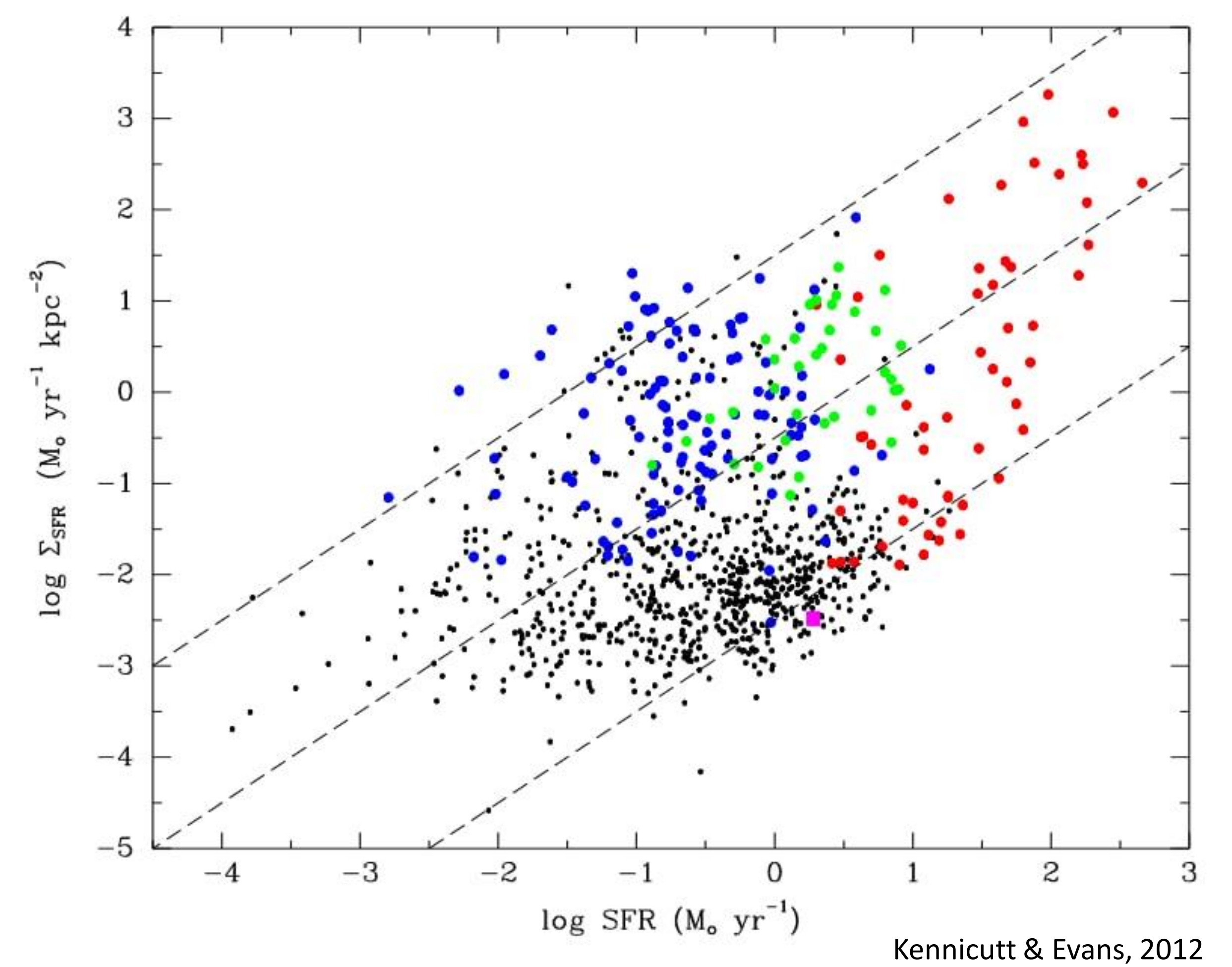
Star formation timescale can only be adjusted using Kennicutt-law (Kennicutt 1998)

Star Formation

Star formation timescale can only be adjusted using Kennicutt-law

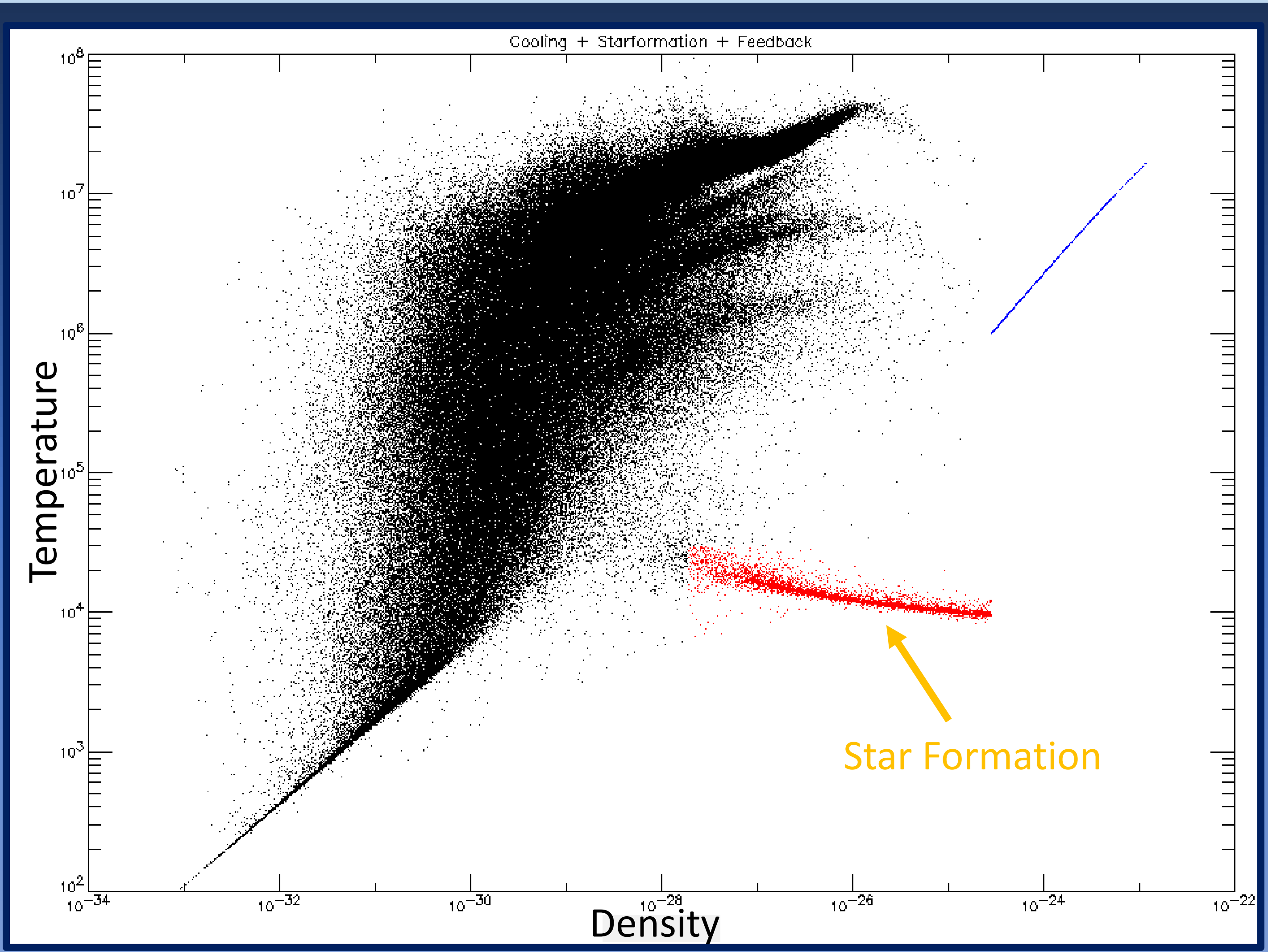
(Kennicutt 1998)

$$\Sigma_{\rm SFR} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{\rm gas}}{\rm M_\odot pc^{-2}} \right)^{1.4 \pm 0.15} \frac{\rm M_\odot}{\rm yr\, kpc^2}$$



Kennicutt & Evans, 2012

Star Formation

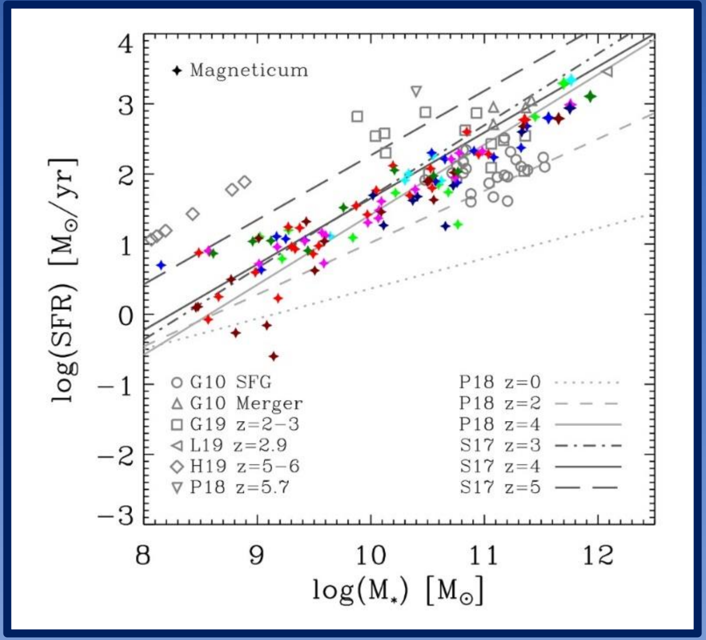


Credit: Klaus Dolag

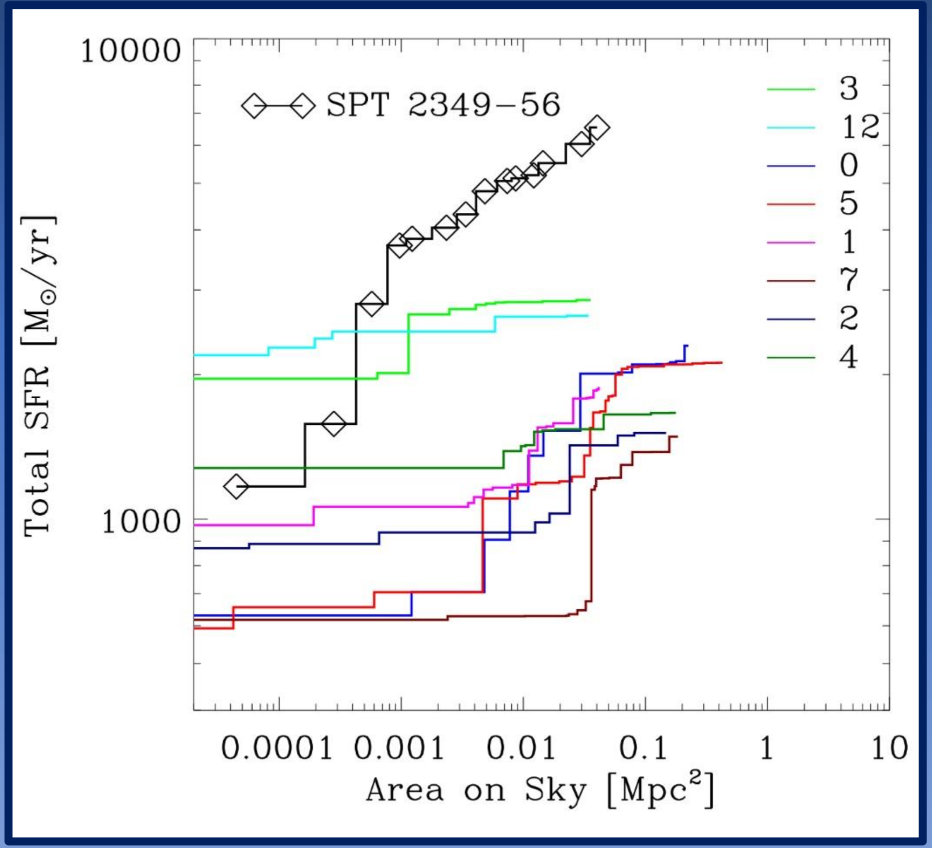
Star Formation

But:

Fail to reproduce high star formation rates seen at high redshifts, for example in proto clusters



Remus et al., 2022



SPT 2349-56:
Miller et al., 2018

Star Formation

How to improve?

- Schmitt-Kennicutt assumption is not correct for higher redshifts
- Star formation efficiency should be coupled to molecular gas, not cold gas in general

Star Formation

How to improve?

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→

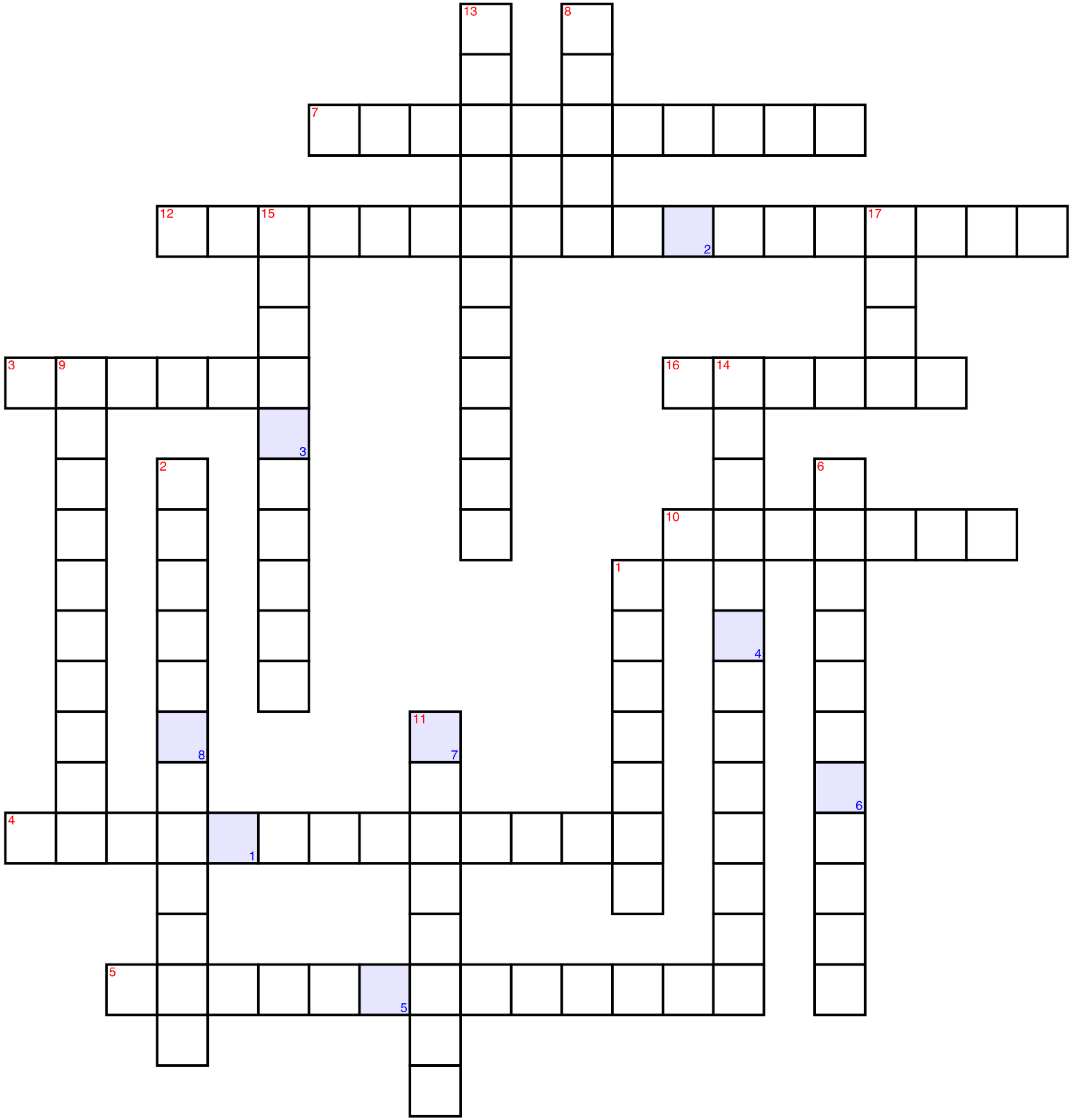
$$\frac{d\rho_*}{dt} = (1-\beta)\frac{\rho_c}{t_*}$$

Replace ρ_c by a mass loading that is coupled to the molecular hydrogen mass:

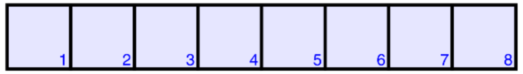
$$\dot{M}_{SF} = f_* \frac{M_{H_2}}{t_{dyn}}$$

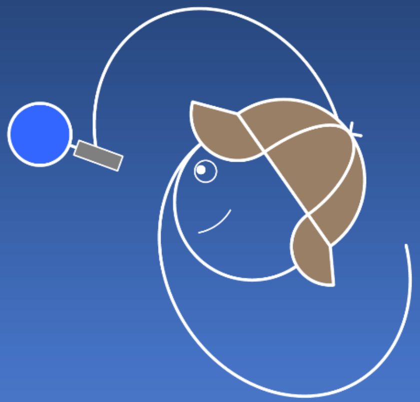
Blitz & Rosolowsky 2006,
Murante et al., 2010

Take a Break: Riddle



1. Necessary for gas to be able to form stars
2. Drives ionization in the early universe
3. Everything not hydrogen or helium
4. Basic process that transforms gas
5. Thermal, Kelvin–Helmholtz, Rayleigh–Taylor
6. Radiation from (hot) stars causes cloud _________
7. What star particles and countries have in common
8. A criterion for collapse but also a fashion item
9. Happens to gas through stellar death and at the stock market
10. The force that dropped an apple onto Newton
11. An IMF
12. Diffuse component in a galaxy cluster
13. Time-independent predictions are only possible for _________
14. Basic physics that describes baryons
15. To partition a plane into regions with certain properties
16. Caused by high-Mach-number flows
17. Most of the matter is like this





Feedback

Feedback

Feedback comes from two different sources:

1) Massive Stars and Supernovae
2) Supermassive Black Holes (AGN)

Feedback: Supernovae

Our stellar particles are not just single stellar particles but rather conglomerates of stars. Every time a star is born, it actually is a whole population of stars.

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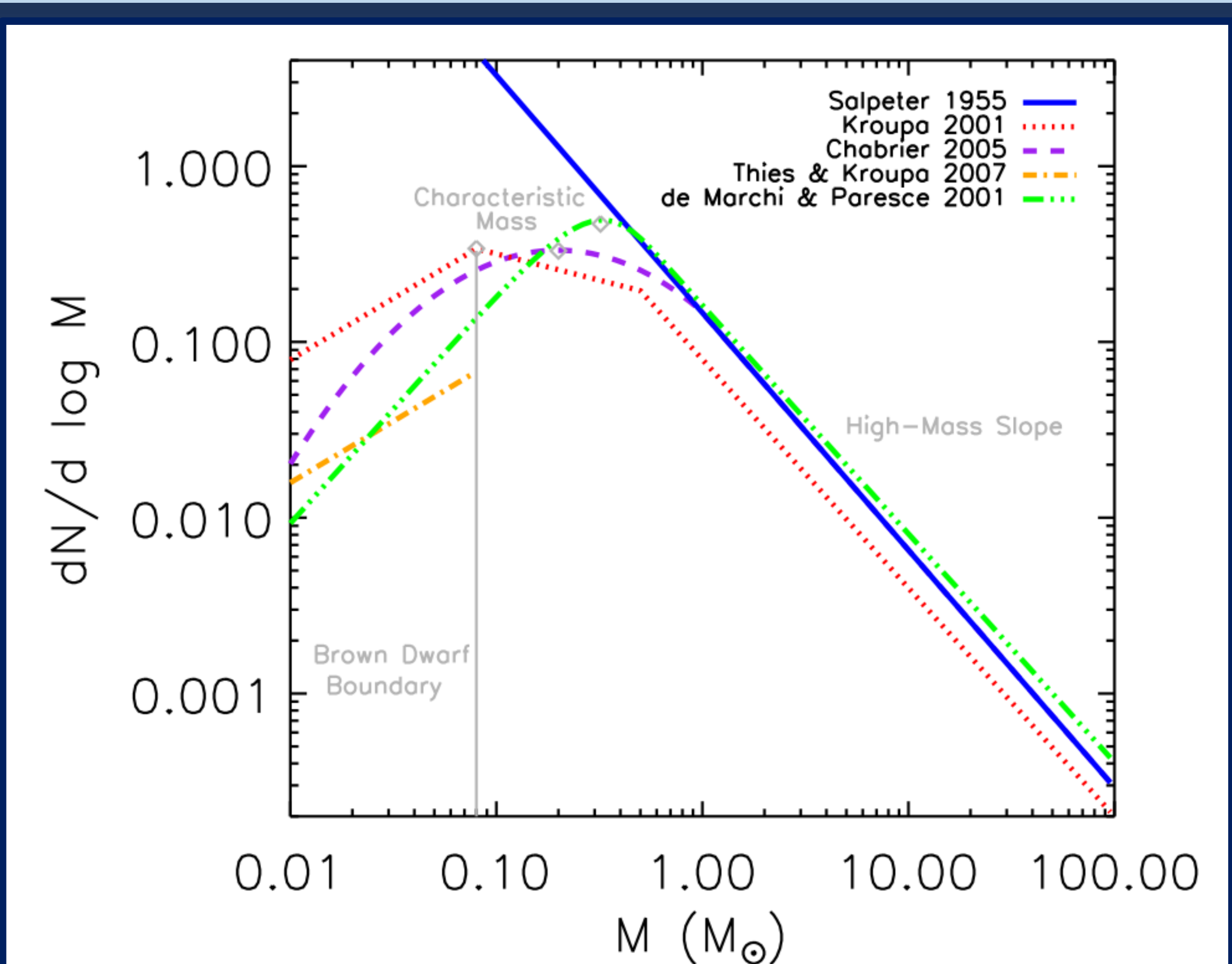
Here, we use an initial mass function (IMF) to emulate the population

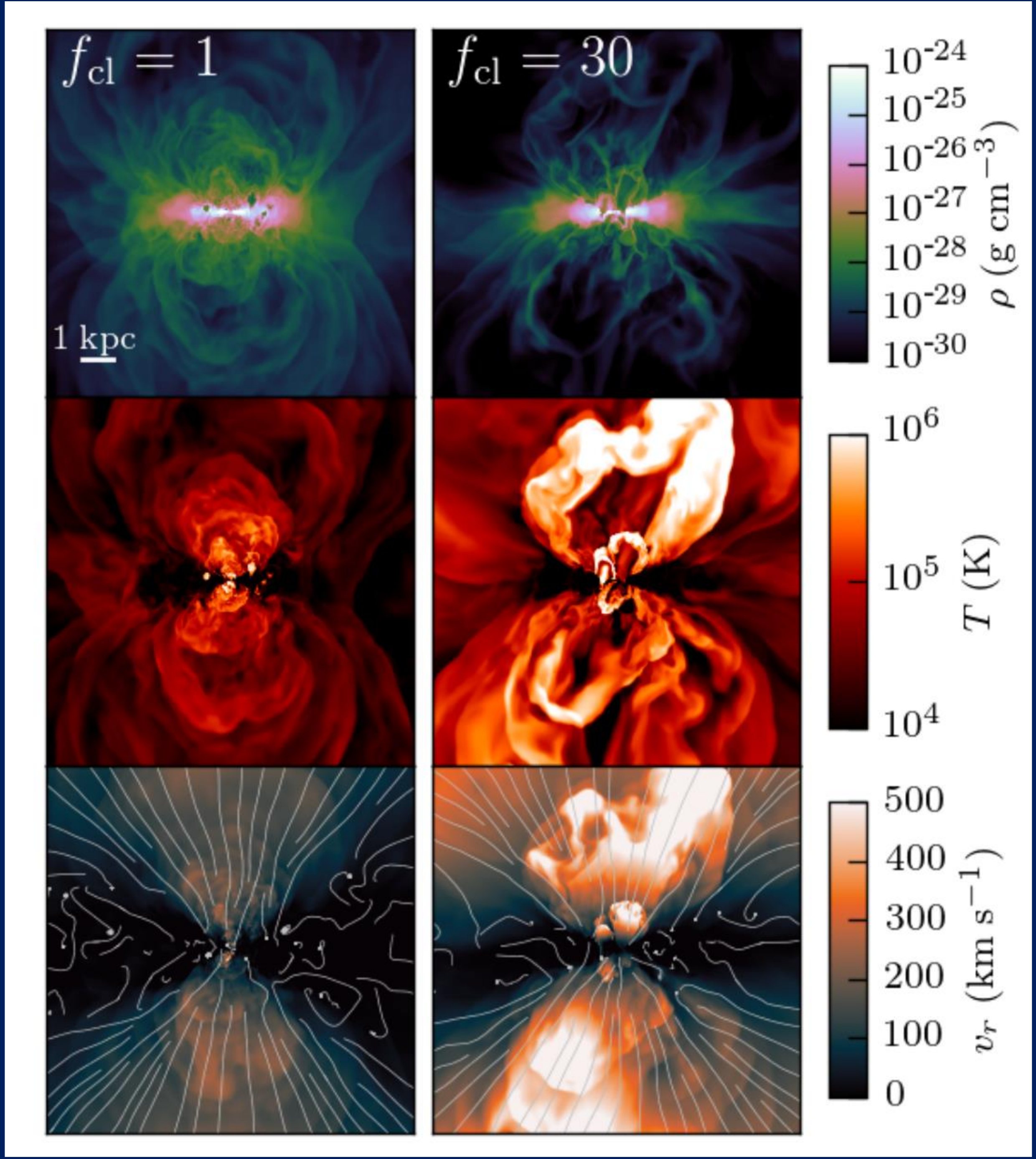
Feedback: Supernovae

Our stellar particles are not just single stellar particles but rather conglomerates of stars.
Every time a star is born, it actually is a whole population of stars.
Here, we use an IMF to emulate the population



Offner et al., 2014

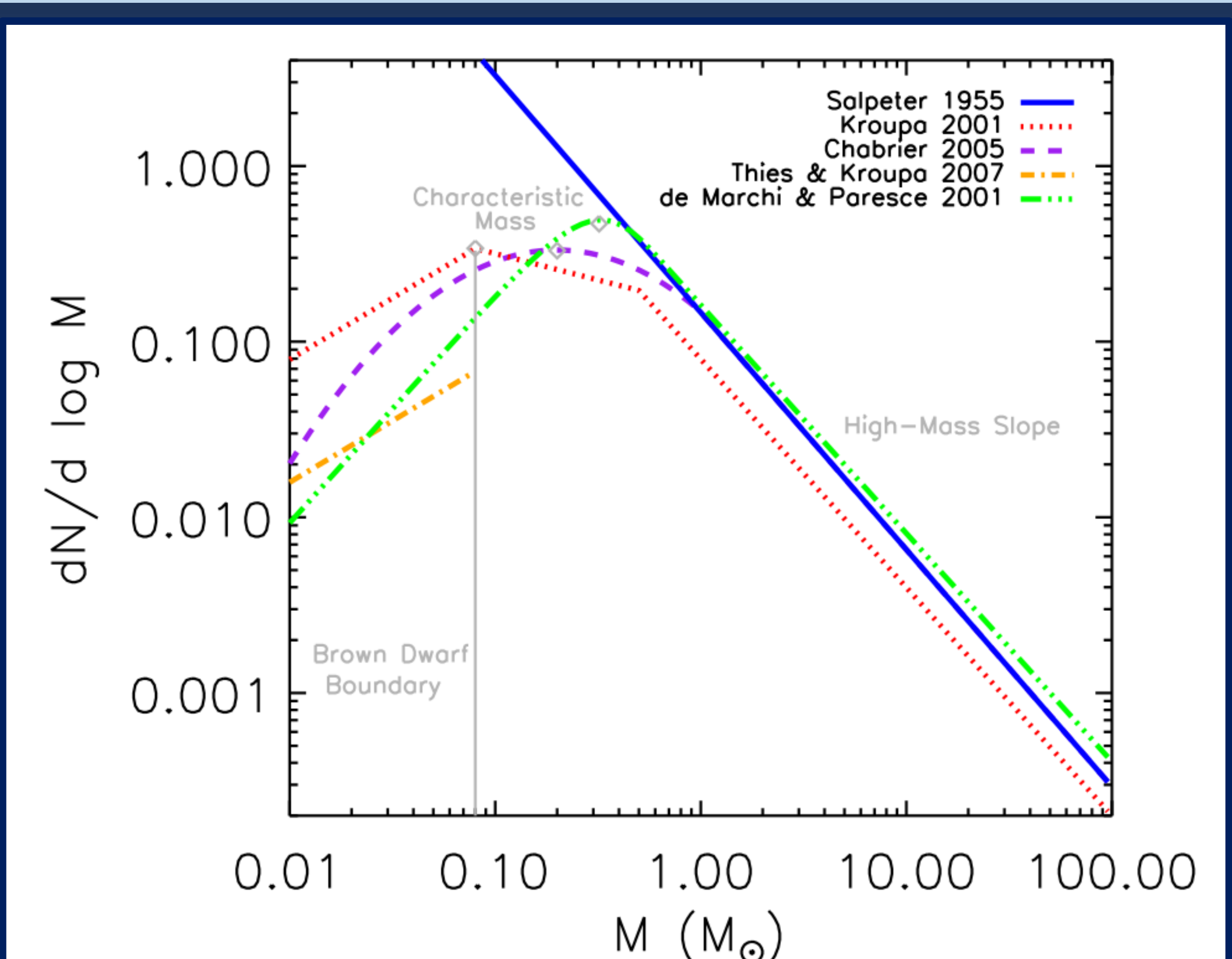
Feedback: Supernovae



Fielding et al., 2017

Feedback: Supernovae

But not just Supernovae, also massive stars have winds that drive (kinetic) feedback



Offner et al., 2014

Feedback: AGN

The existence of a Black Hole is often revealed by a jet that can be observed, as for example in M87, the second brightest galaxy of the Virgo cluster.

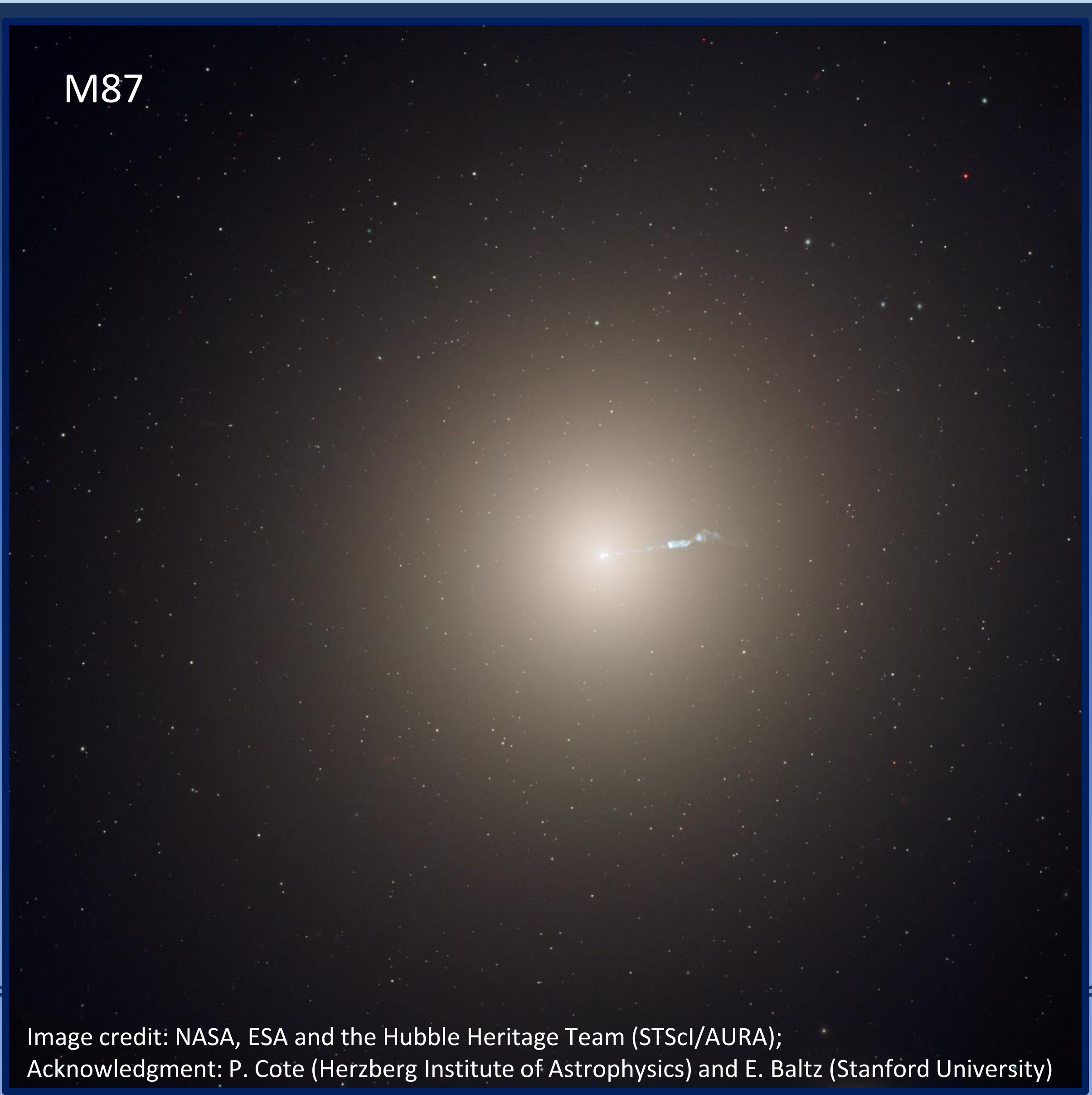


Image credit: NASA, ESA and the Hubble Heritage Team (STScI/AURA);
Acknowledgment: P. Cote (Herzberg Institute of Astrophysics) and E. Baltz (Stanford University)

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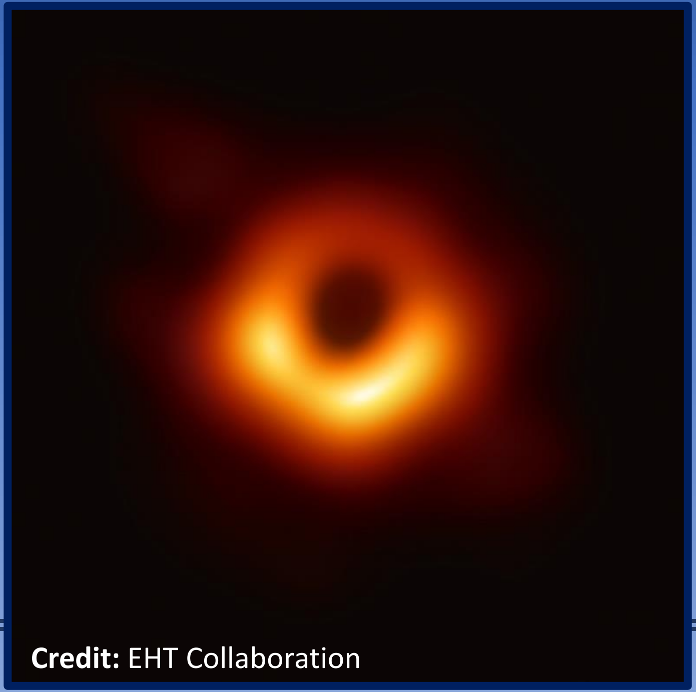
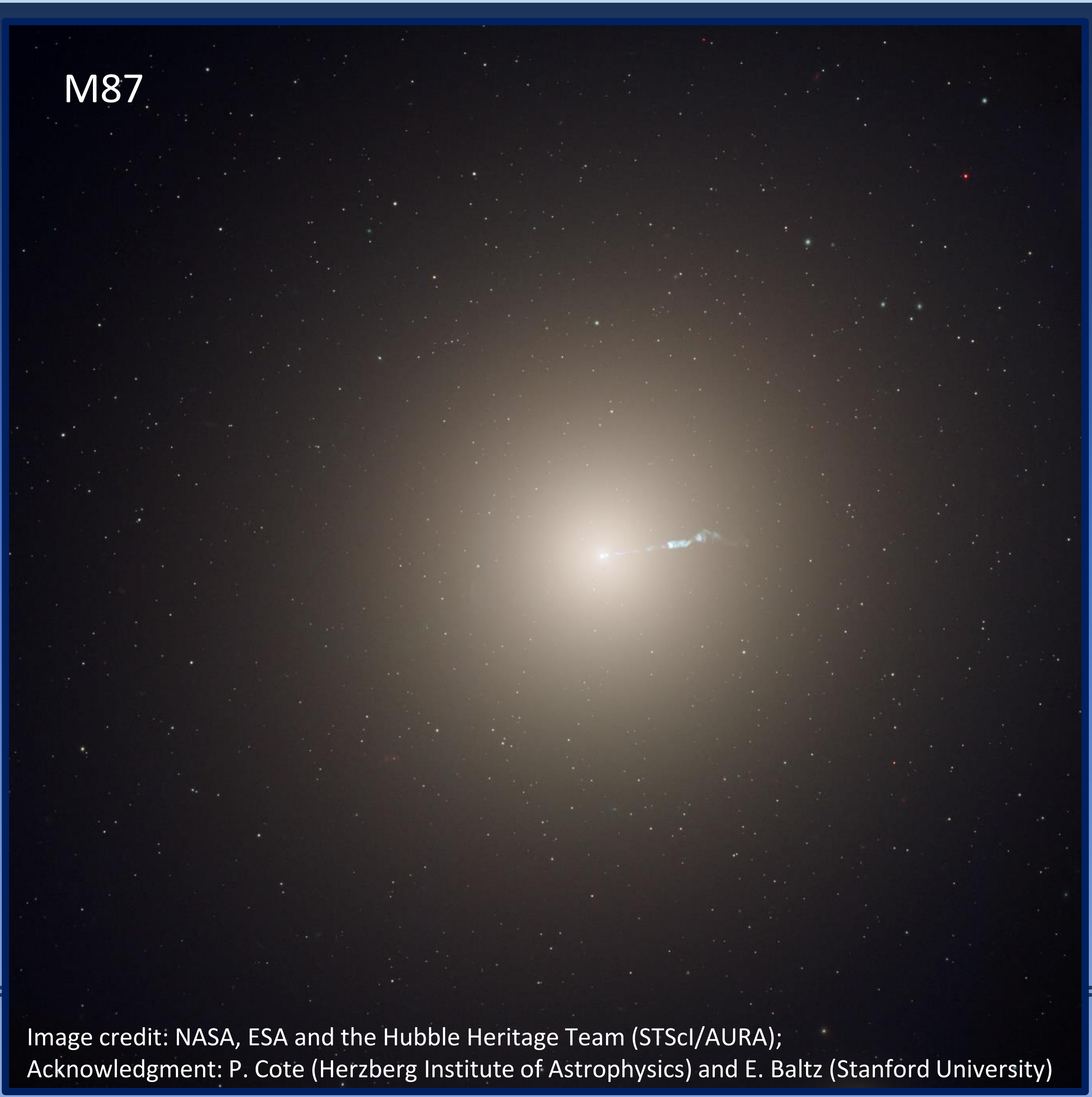

Credit: EHT Collaboration



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Feedback: AGN

Black Holes are included in the simulations as sink particles

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Seeding
↓
Accretion onto BH
↓
Feedback
↓
Merging

Feedback: AGN

Black Holes are included in the simulations as sink particles

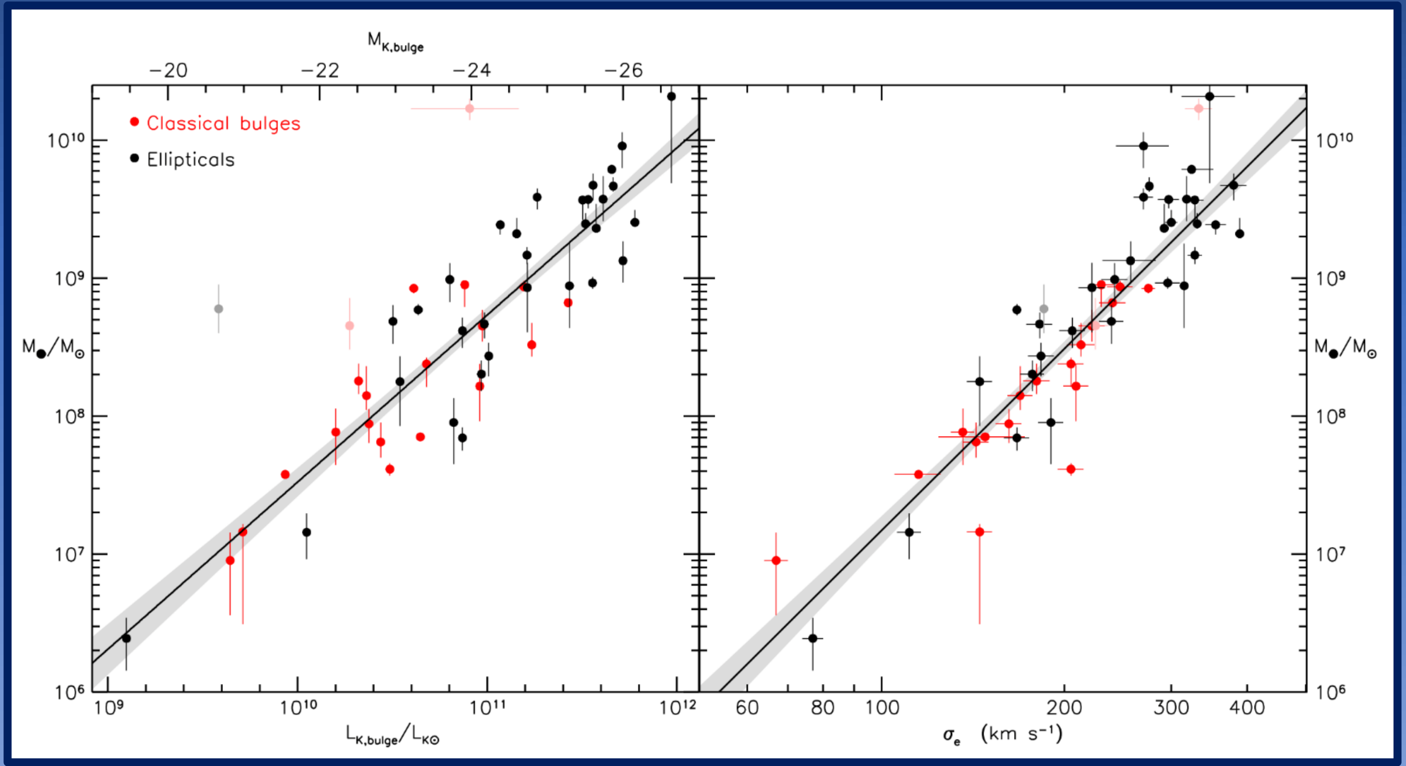
Seeding

Accretion onto BH

Feedback

Merging

Either seeding at a constant mass, or on the m_{BH}- σ relation



Kormendy & Ho 2013

Feedback: AGN

Black Holes are included in the simulations as sink particles

Seeding

↓

Accretion onto BH

↓

Feedback

↓

Merging

Bondi Accretion:

Gas density

$$\dot{M}_{\rm B} = \frac{4\pi \alpha G^2 M_{\rm BH}^2 \rho}{\left(c_{\rm s}^2 + v^2\right)^{3/2}},$$

Sound speed

Eddington Limit:

$$\dot{M}_{\rm Edd} \equiv \frac{4\pi G M_{\rm BH} m_{\rm p}}{\epsilon_{\rm r} \sigma_{\rm T} c},$$

Implemented:

$$\dot{M}_{\rm BH} = \min(\dot{M}_{\rm Edd}, \dot{M}_{\rm B}).$$

Springel et al., 2005

Feedback: AGN

Black Holes are included in the simulations as sink particles

Seeding

Accretion onto BH

Feedback

Merging

$$L_{bol} = 0.1\dot{M}_{BH}c^2$$

$$\dot{E}_{feedback} = f\ L_{bol}$$

efficiency

Feedback: AGN

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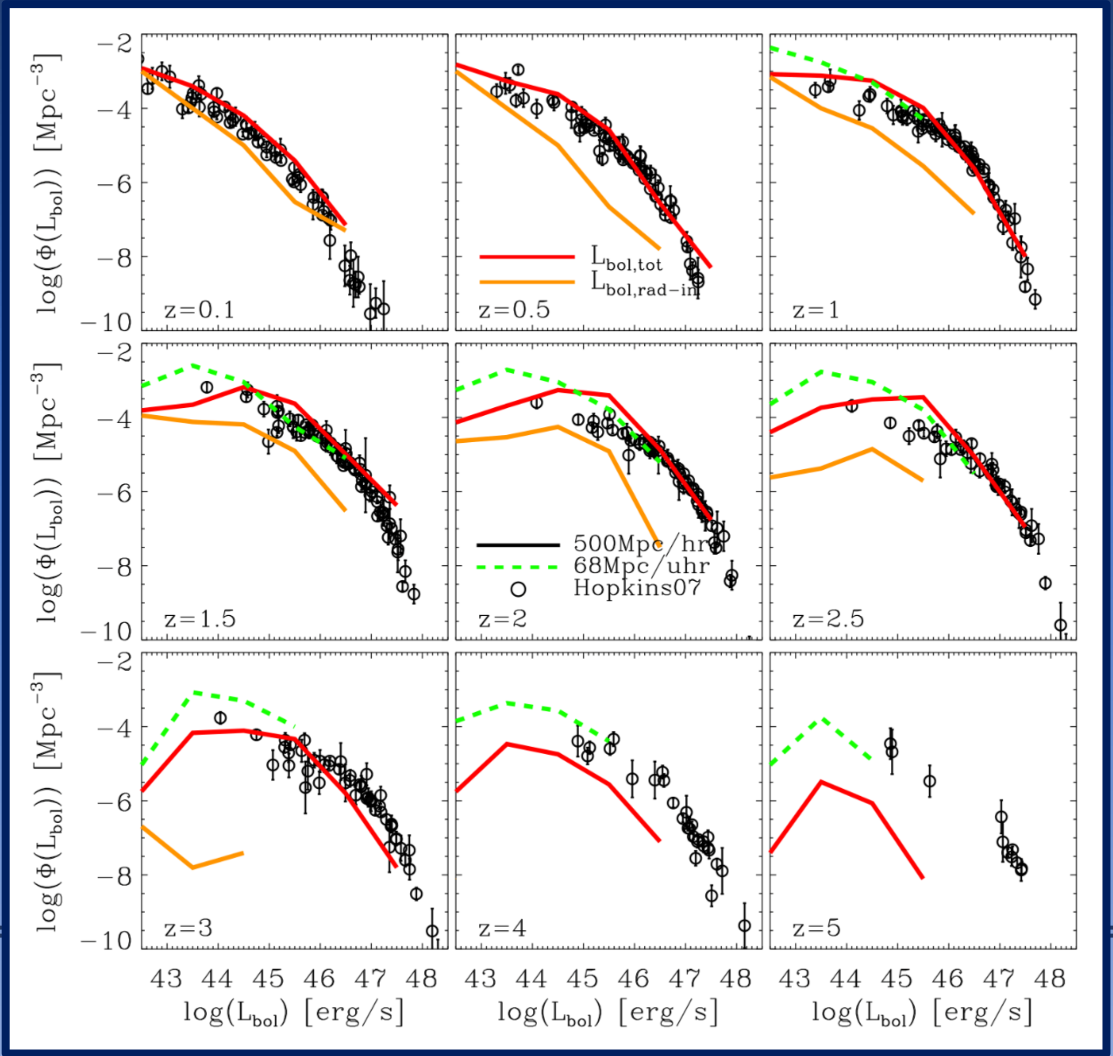
efficiency

Hirschmann et al., 2014



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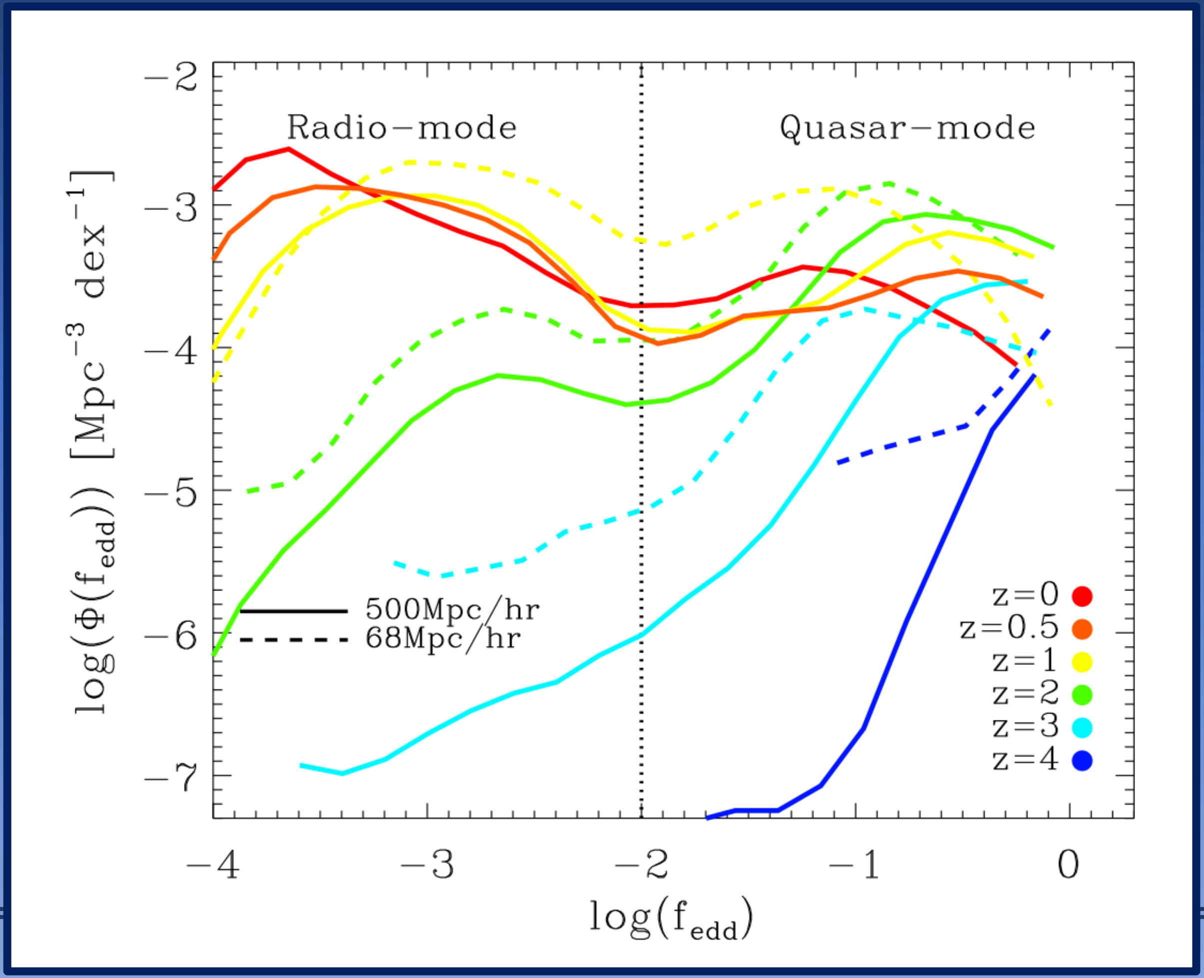
efficiency



Hirschmann et al., 2014

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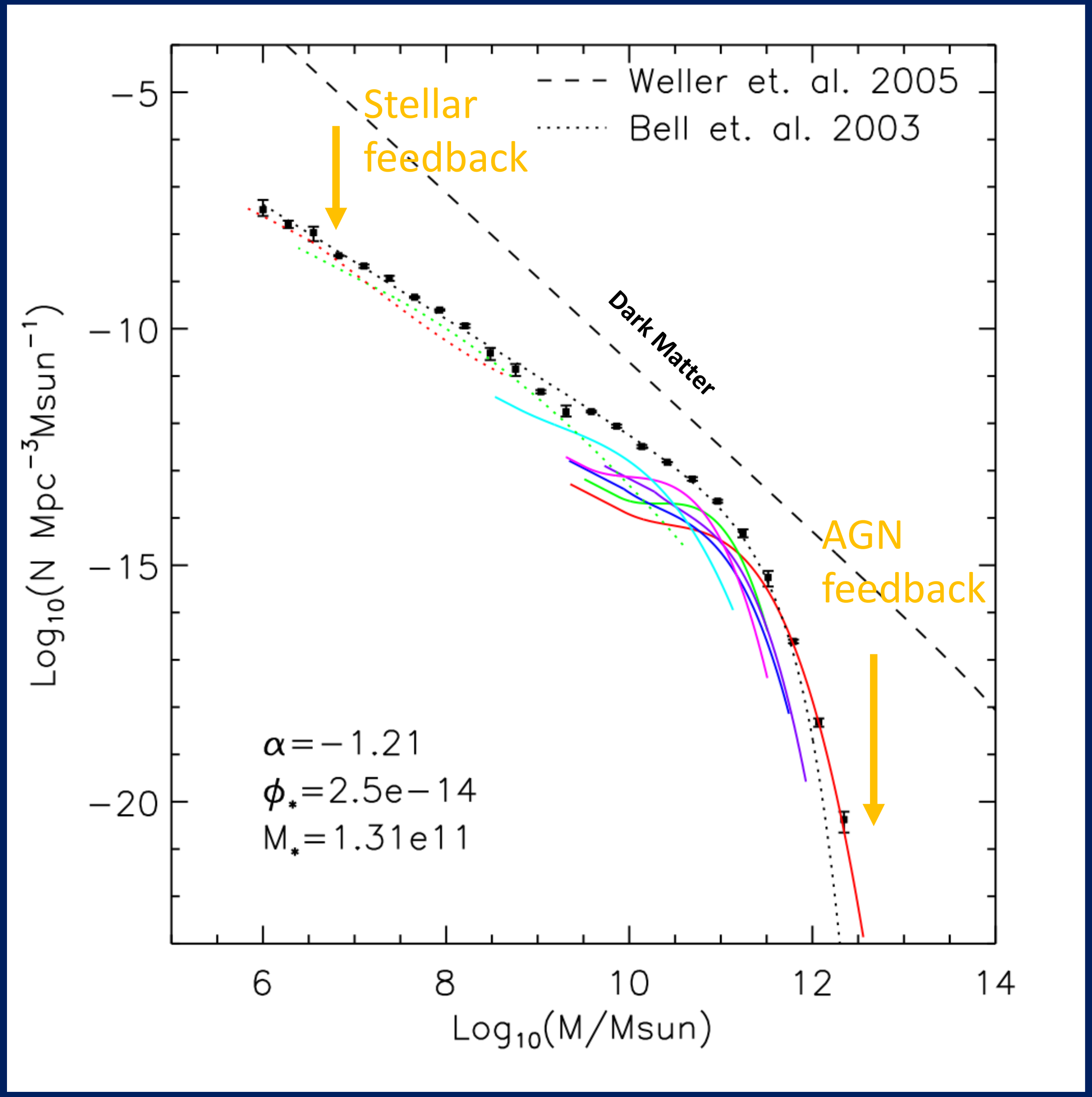
Pinning or no pinning?

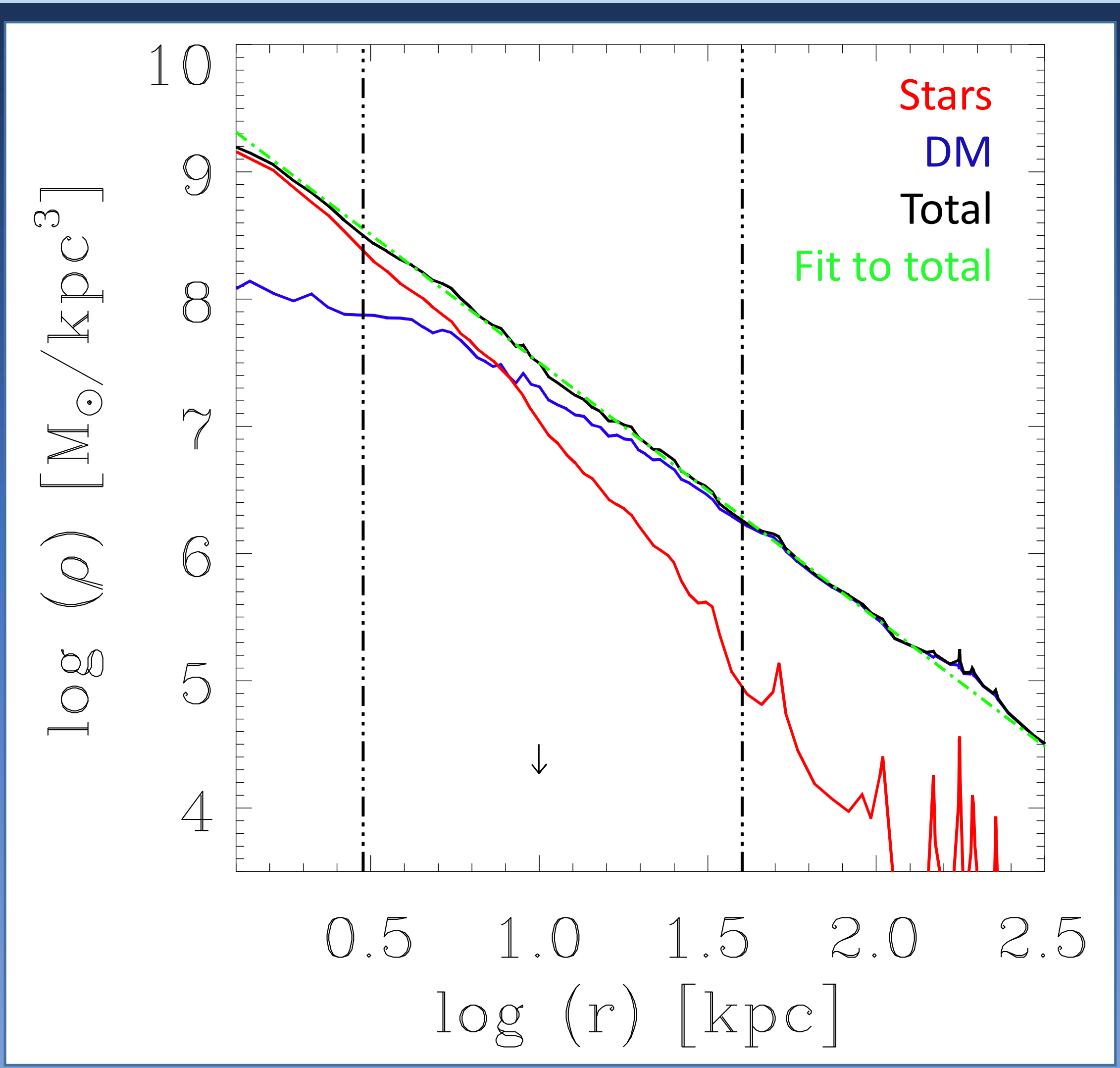
Feedback

How feedback influences galaxies



Read & Trentham 2005

Radial Density Profiles



Total radial density profiles can be fit by a single power law.

Inner part: Stars dominate the total profiles.

Outer part: Dark Matter dominates the total profiles.

$$\gamma = \frac{d\log(\rho)}{d\log(r)}$$

Most ETGs have slopes close to isothermal, i.e. $\gamma_{tot} \approx -2$, but they can be as steep as $\gamma_{tot} \approx -3$.

➡ This is independent of the included feedback models

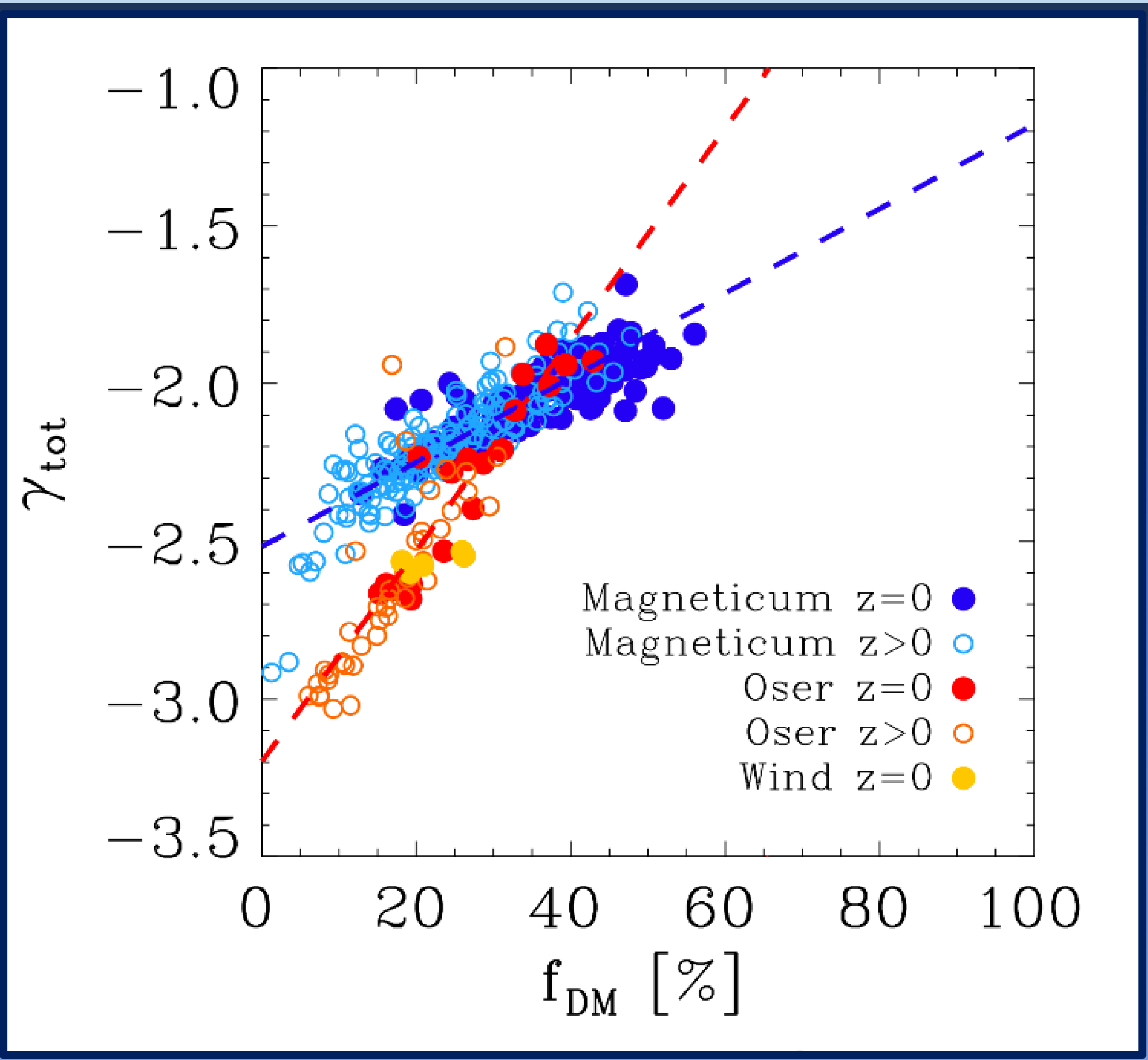
see Remus et al., 2013; 2017

The Role of Feedback

To understand the impact of the different feedback models on the implementation of these scaling relations, we use ETGs from simulations with different feedback models:

	SPH	AGN	Stellar Wind	Cooling	References
Magneticum	Improved	Yes	Weak	Incl. metals	Hirschmann et al., 2014; Teklu et al., 2015
Oser	Standard	No	No	Primordial	Oser at al., 2010;2012
Wind	Standard	No	Strong	Incl. metals	Hirschmann et al., 2013; 2015

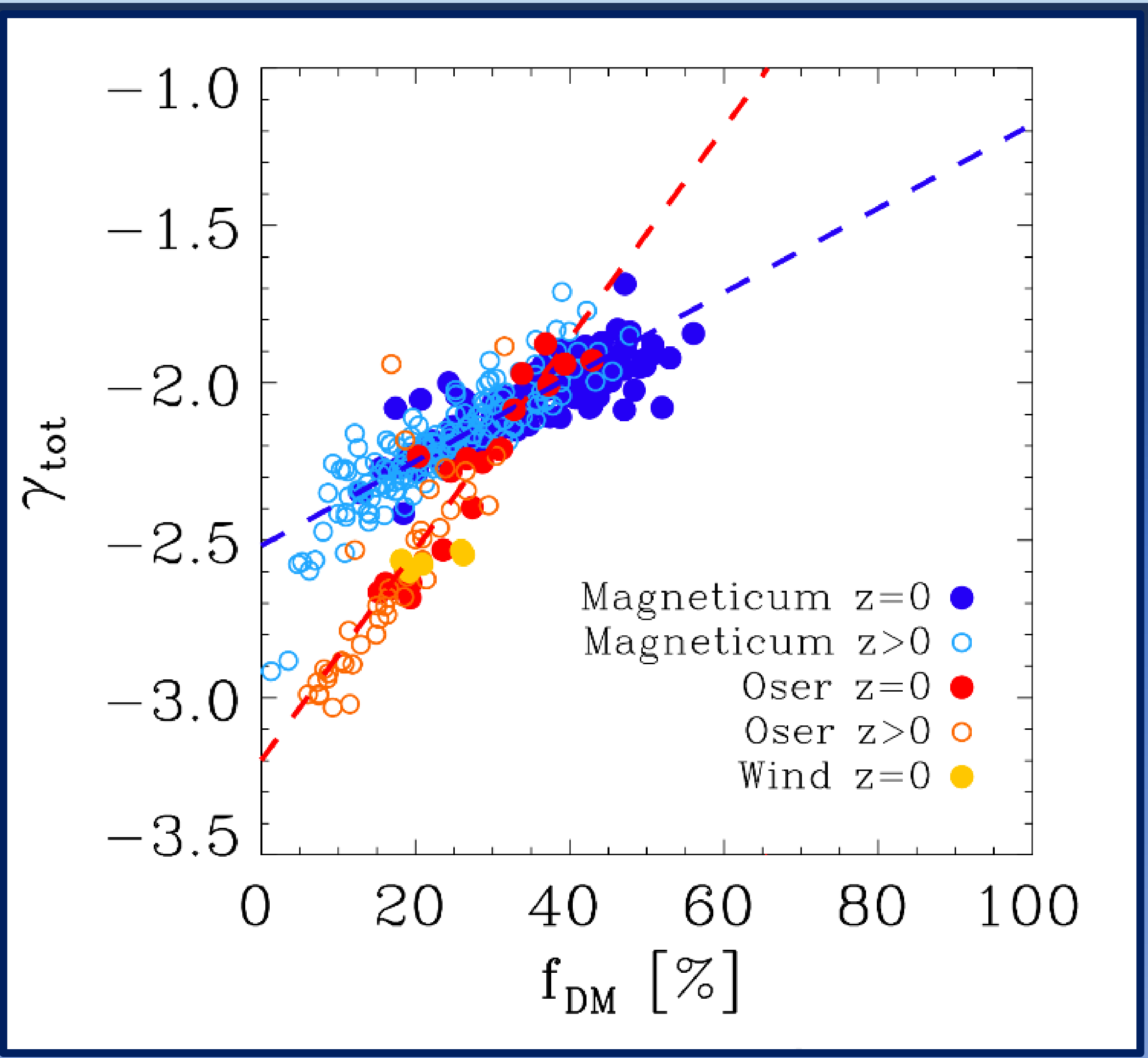
Central Dark Matter Fractions



The fraction of dark matter within the halfmass radius is lower at higher redshifts, and it is strongly correlated with the slope of the total density profiles.

Remus et al., 2017

Central Dark Matter Fractions

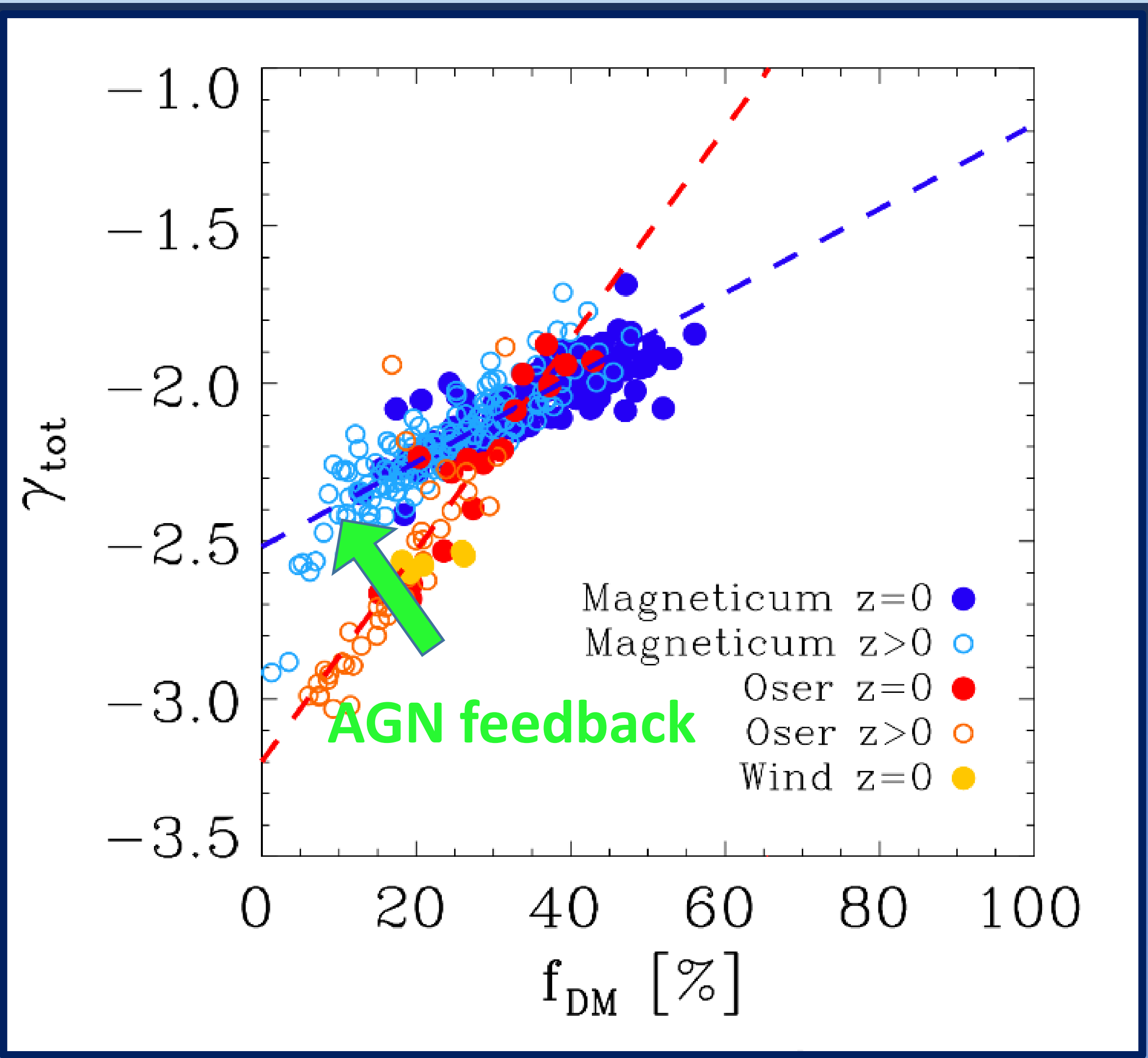


Remus et al., 2017

The fraction of dark matter within the halfmass radius is lower at higher redshifts, and it is strongly correlated with the slope of the total density profiles.

→ The correlation between the dark matter fraction and the total density slope already establishes at high redshifts

Central Dark Matter Fractions



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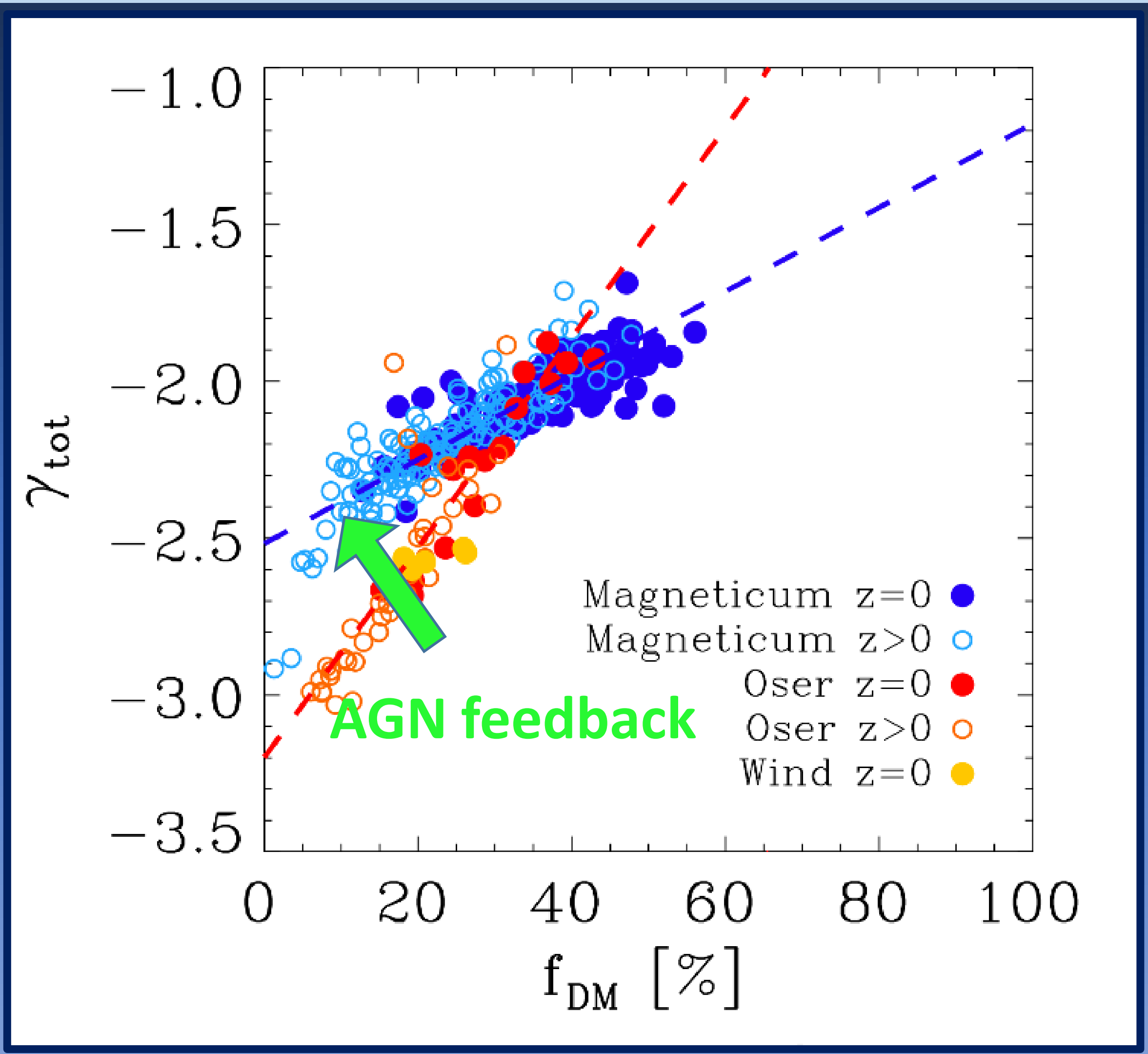
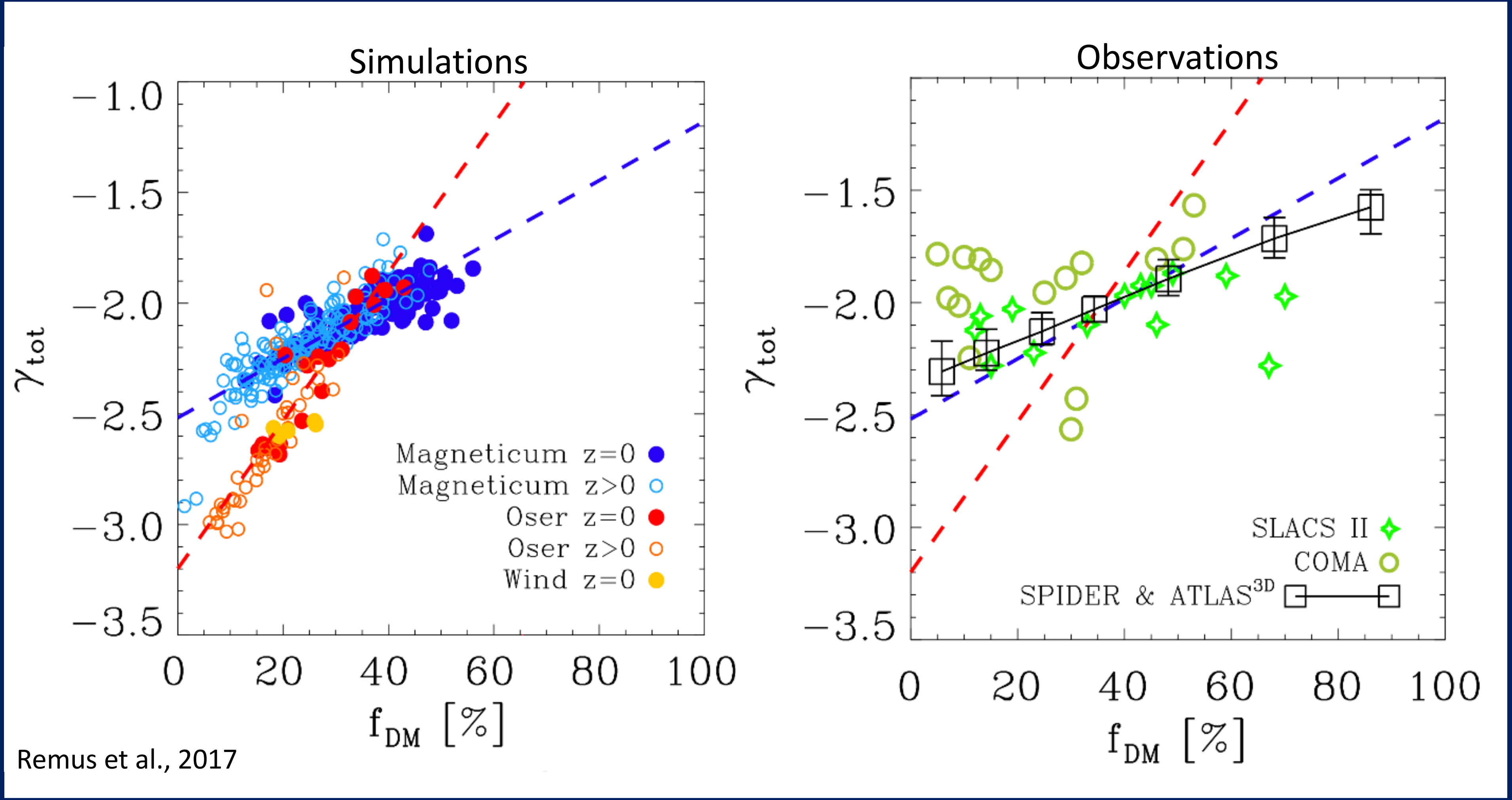


The fraction of dark matter within the halfmass radius is lower at higher redshifts, and it is strongly correlated with the slope of the total density profiles.

➡ The slope of this relation can be used to test the different feedback models

Remus et al., 2017

Co-Evolution of Dark Matter Fractions and Density Profiles



Remus et al., 2017

Observations:
SPIDER & ATLAS^{3D} : Tortora et al., 2014
Coma: Thomas et al., 2007
SLACS: Barnabé et al., 2011

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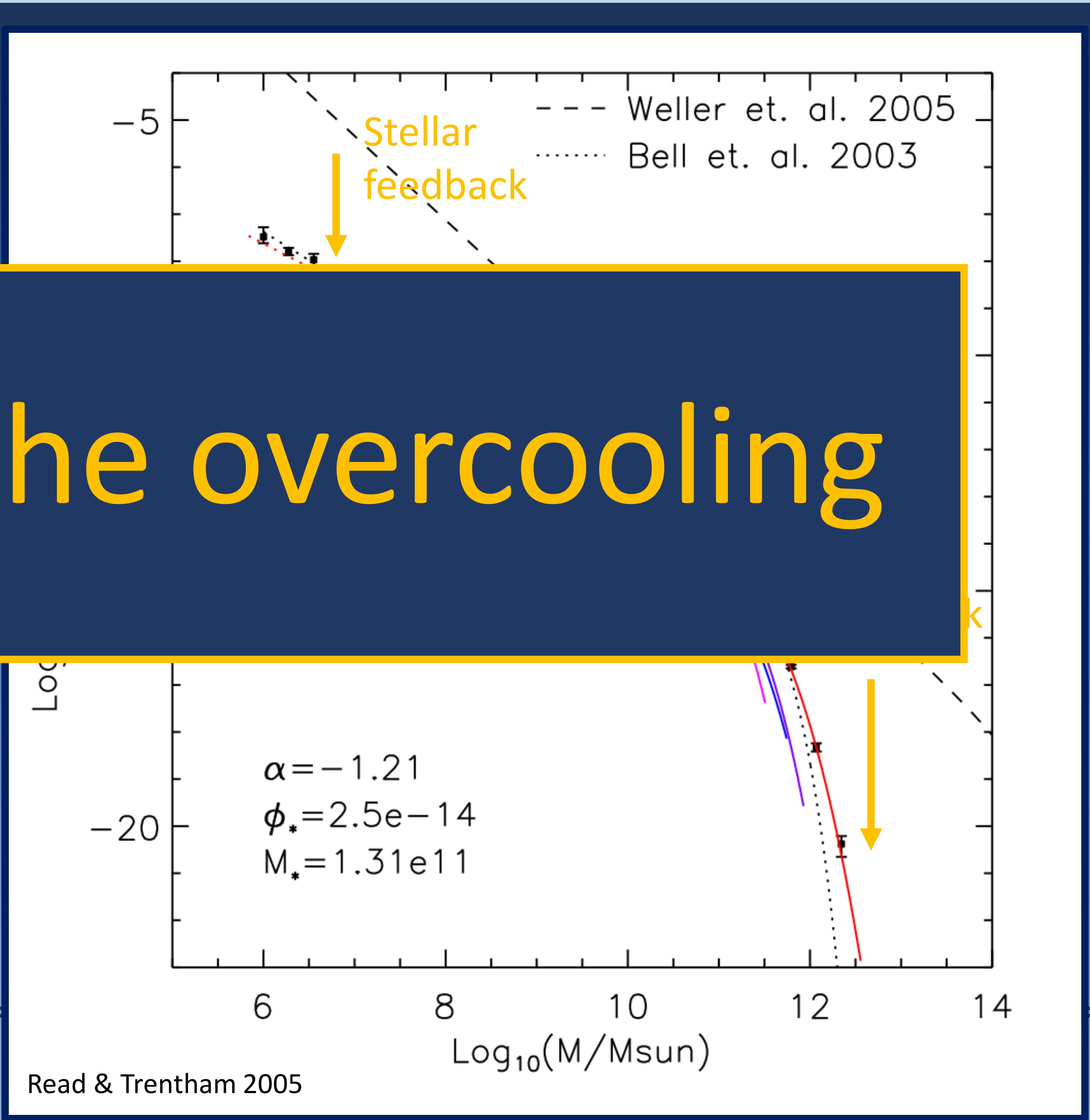
How feedback influences galaxies



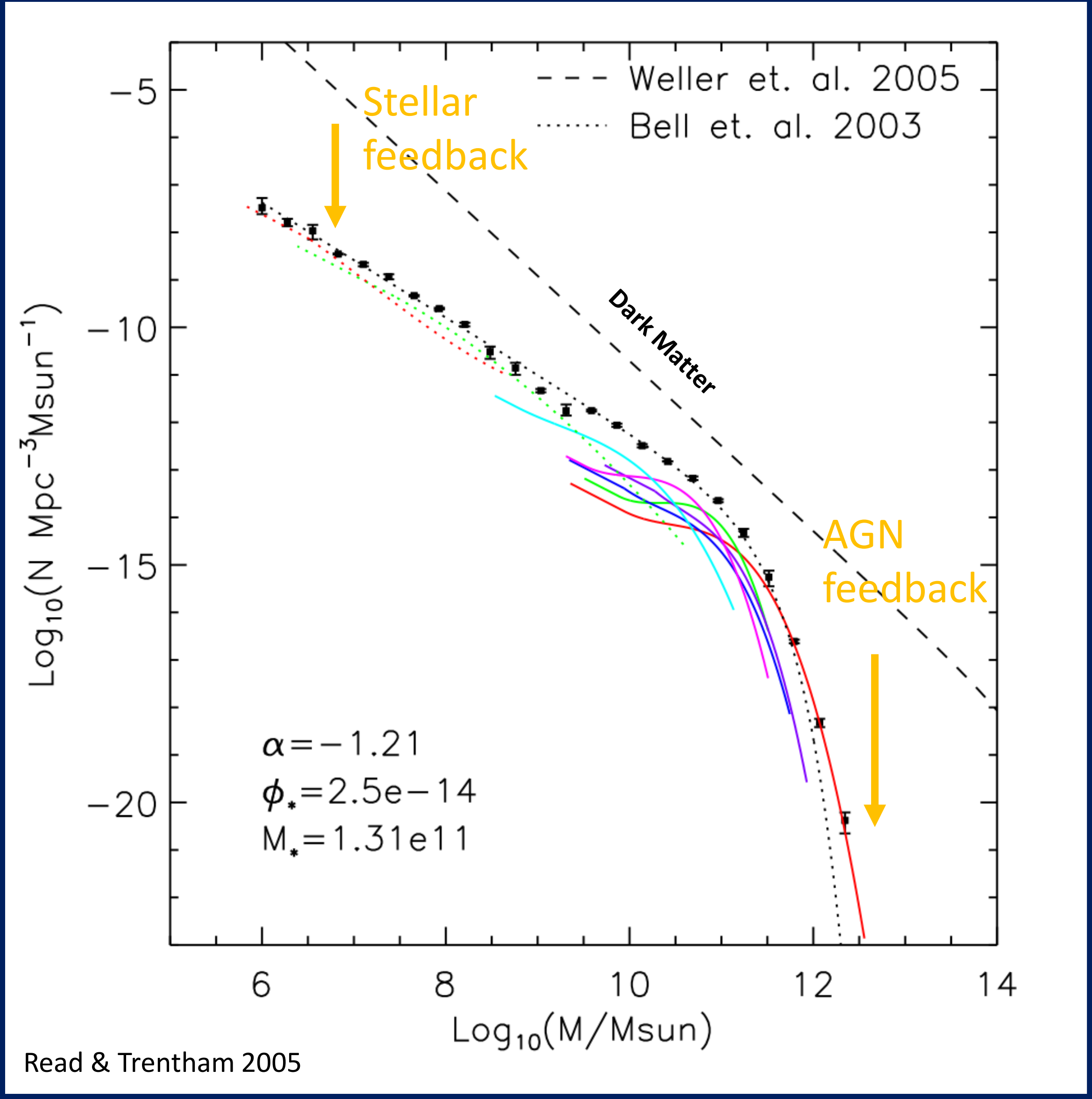
Read & Trentham 2005

Feedback stops the overcooling

Feedback

How feedback influences galaxies

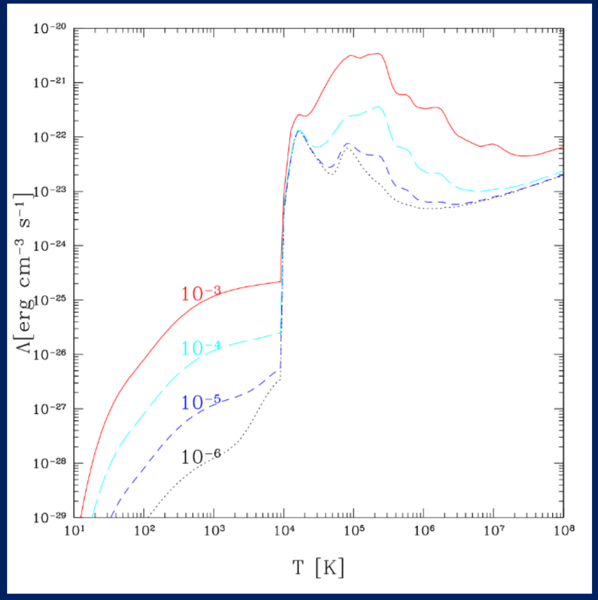
... but it burns holes into disks



Read & Trentham 2005

Summary: Including Physics

Cooling



Maio et al., 2007

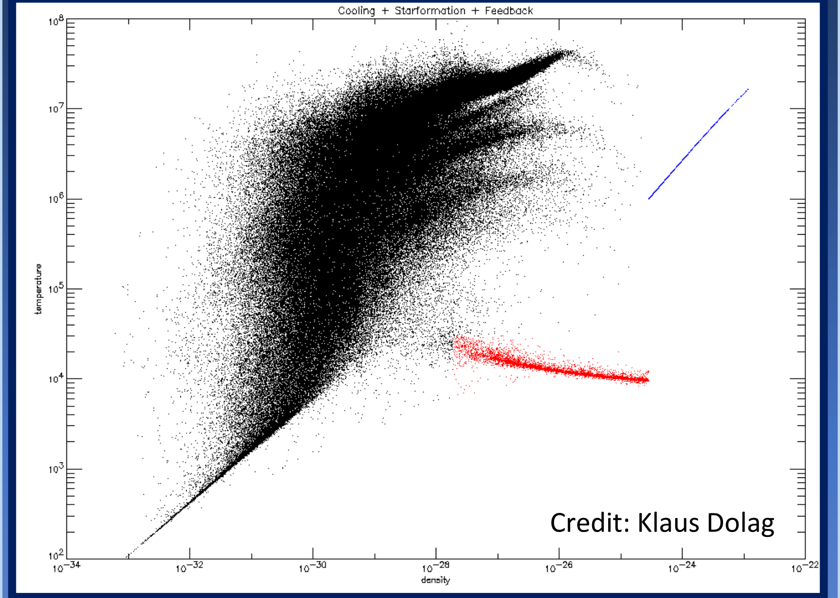
Basic Assumption:

- Optically thin
- Ionization equilibrium (H, H^+, He, He^+, He^{++},e^-)
- 2-body processes ($\sim n^2$)

$\Lambda(T)/n^2$

BUT: Cooling Catastrophe

Star Formation



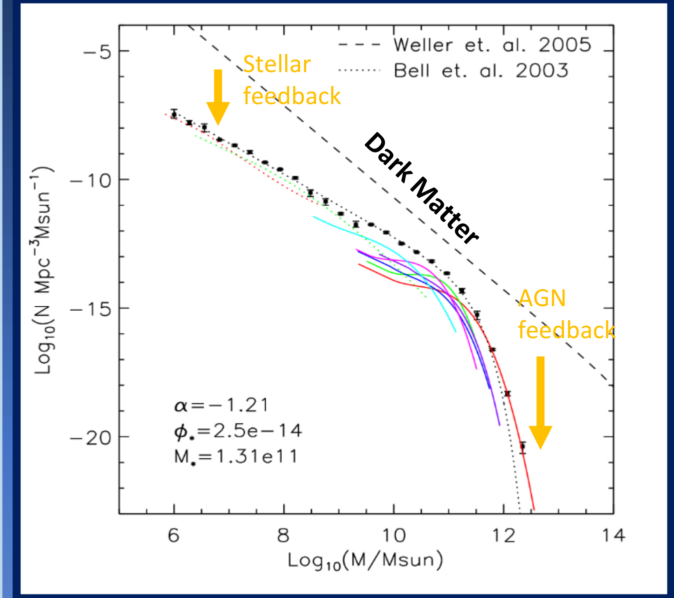
Credit: Klaus Dolag

Star formation subgrid model:

- Self-regulated star formation
- Set of differential equations needs to be solved.
- Produces reasonable galaxies at low z

BUT: star formation rates at high z not captured

Feedback



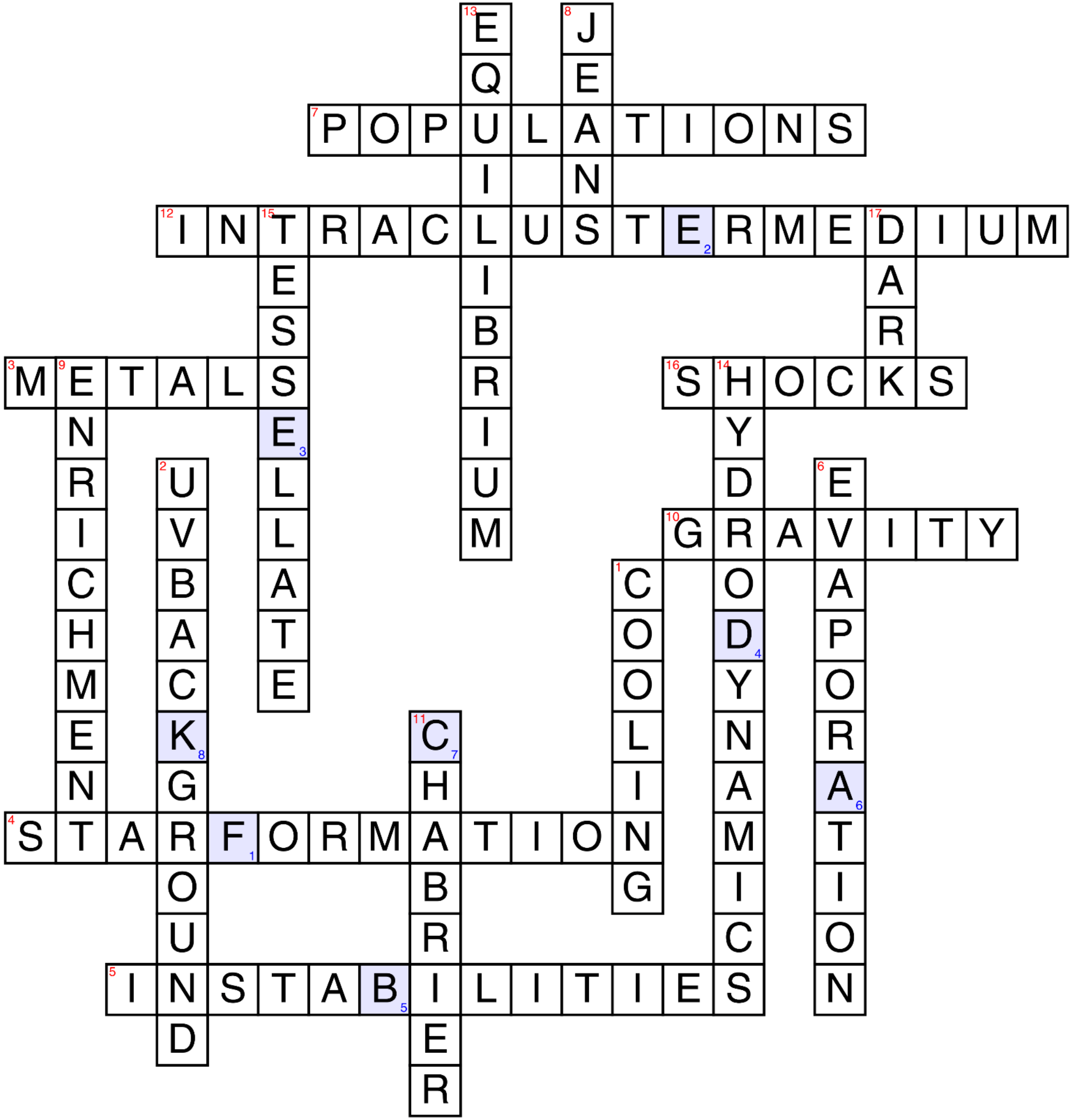
Read & Trentham 2005

Feedback comes from two different sources:

- Massive Stars and Supernovae
- Supermassive Black Holes (AGN)

Stops the Overcooling Catastrophe

BUT: Burns holes into disks



1. Necessary for gas to be able to form stars
2. Drives ionization in the early universe
3. Everything not hydrogen or helium
4. Basic process that transforms gas
5. Thermal, Kelvin–Helmholtz, Rayleigh–Taylor
6. Radiation from (hot) stars causes cloud ________
7. What star particles and countries have in common
8. A criterion for collapse but also a fashion item
9. Happens to gas through stellar death and at the stock market
10. The force that dropped an apple onto Newton
11. An IMF
12. Diffuse component in a galaxy cluster
13. Time-independent predictions are only possible for ________
14. Basic physics that describes baryons
15. To partition a plane into regions with certain properties
16. Caused by high-Mach-number flows
17. Most of the matter is like this

F	E	E	D	B	A	C	K
1	2	3	4	5	6	7	8