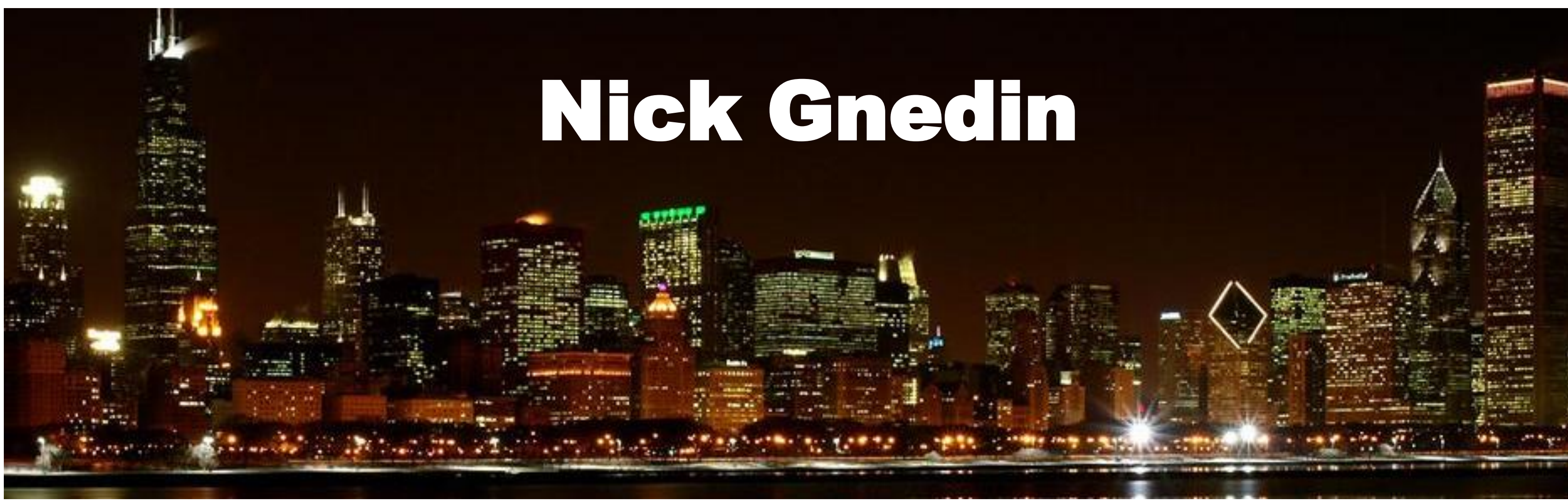
Modeling ISM Physics In Cosmological Simulations

(an attempt at reviewing)



Fermilab

THE UNIVERSITY OF CHICAGO

Should We Even Care?

- **Theorist**: stars form from gas a-la "Schmidt* law".

$$\dot{\rho}_* = \rho_g/\tau_*$$

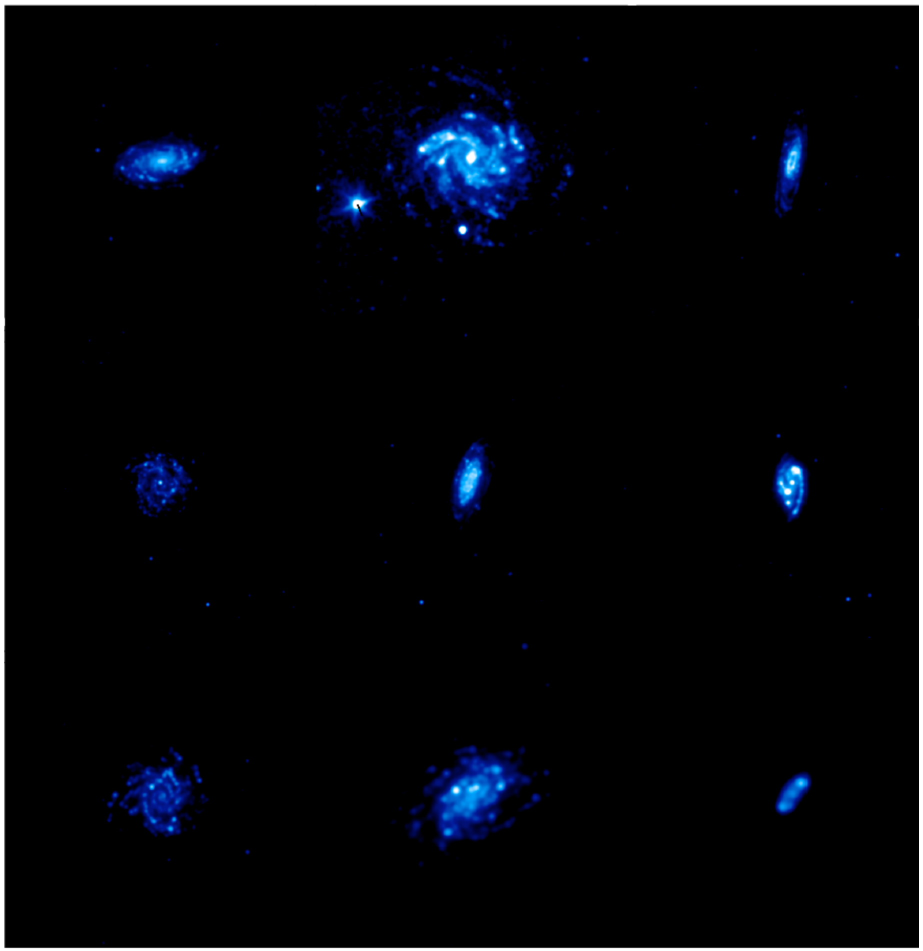
$$\frac{\mathrm{d}\rho_\star}{\mathrm{d}t} = \frac{\rho_c}{t_\star} - \beta\frac{\rho_c}{t_\star} = (1-\beta)\frac{\rho_c}{t_\star}$$

$$\dot{m}_* = m_\mathrm{g} A \left(1\ \mathrm{M}_\odot\ \mathrm{pc}^{-2}\right)^{-n} \left(\frac{\gamma}{G} f_\mathrm{g} P\right)^{(n-1)/2}$$

*This ansatz has nothing to do with Martin Schmidt

Should We Even Care?

- **Observer**: since when?



SFR distributions from 24 μm SINGS + GALEX

F. Walter &
The HI Nearby
Galaxy Survey

Should We Even Care?

- Star formation is complex, but one thing about it we know for sure:

Stars do not form from "gas".

They form in "star-forming gas".

- Proposition: *to understand overall galaxy formation, we do not need to model the ISM if we can identify which gas is star-forming* (with apologies to radio astronomers).

Which Gas Is Star-Forming?

- Identifying which gas is star-forming is easy: all gas with $A_V > 10$.

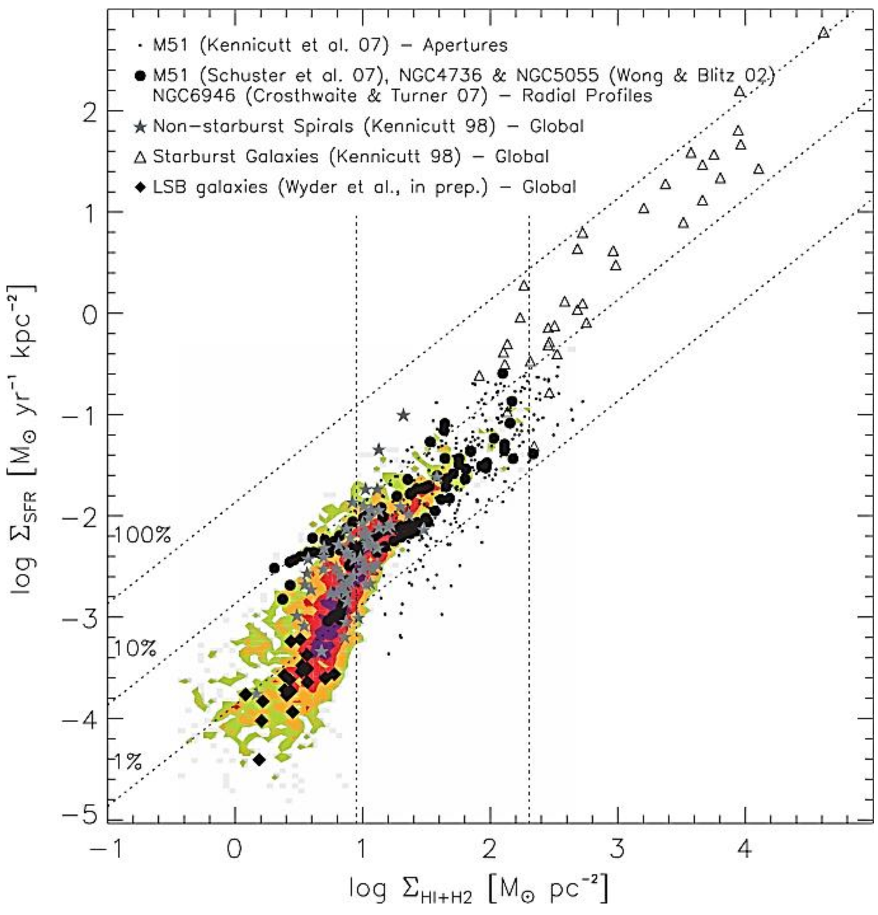
- Not a very practical recipe for cosmological simulations, though.
- “Star-formicity” of gas is a function of scale (as is almost everything else).

It's All About Scales

- Two distinct regimes of cosmological galaxy formation simulations:
  - Resolution >> 100 pc: disks are not resolved, galaxies are 2D. (NIHAO, EAGLE, Illustris, …)
  - Resolution << 100 pc: disks are resolved, galaxies are 3D. (FIRE, Agerts++, Ceverino++, …)

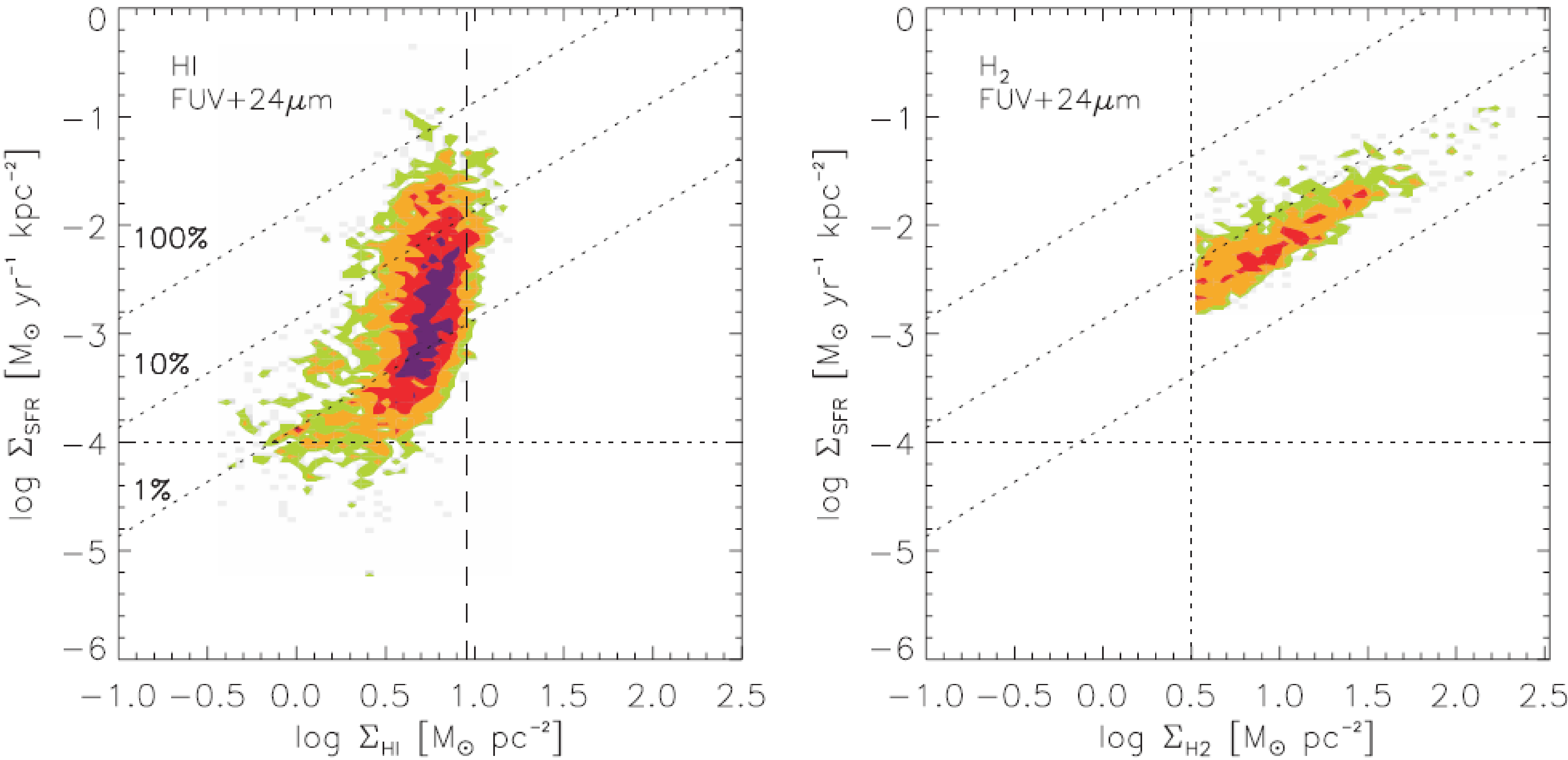
Kennicutt-Schmidt Relation

- The wrong way. (Where have you been for the last 8 years?)



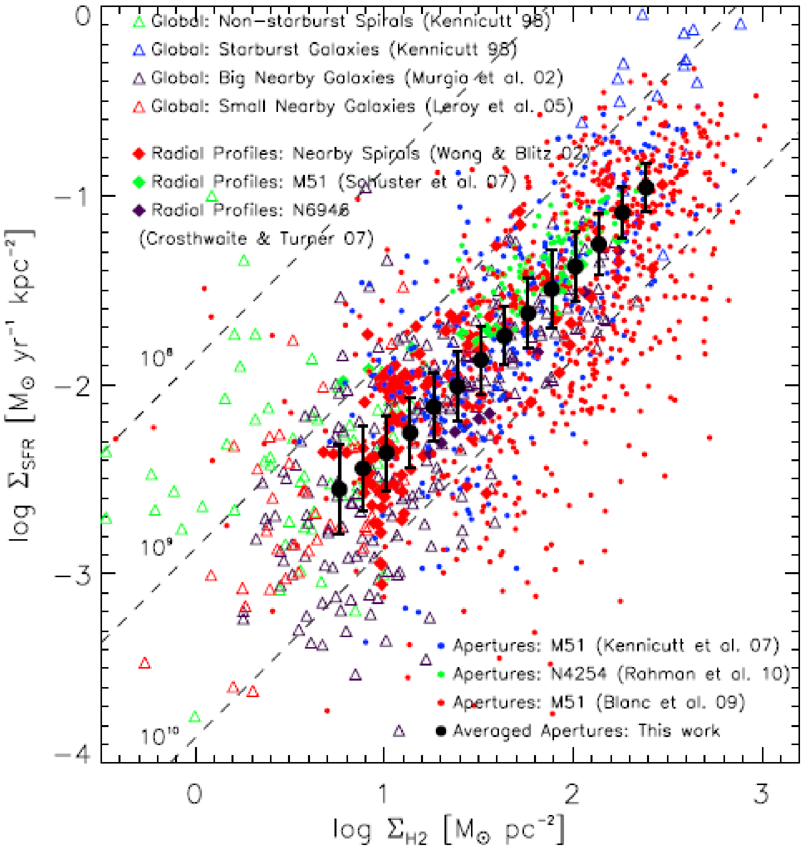
Kennicutt-Schmidt Relation

- The right way. Atomic hydrogen is ***not*** star-forming gas!

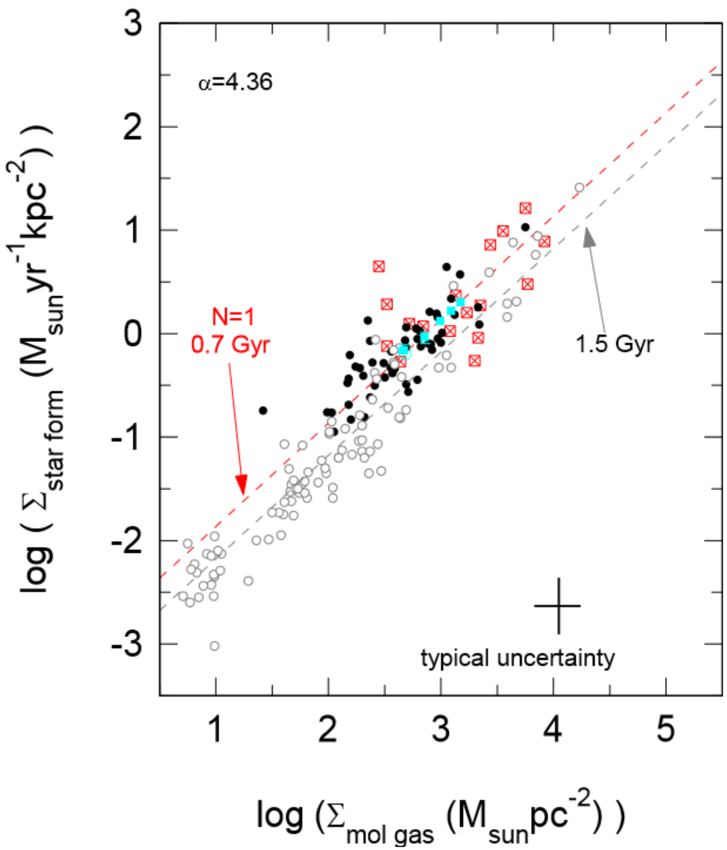


Kennicutt-Schmidt Relation

- The right way, more of it (and yes, there are exceptions, KSR is not a “law”).



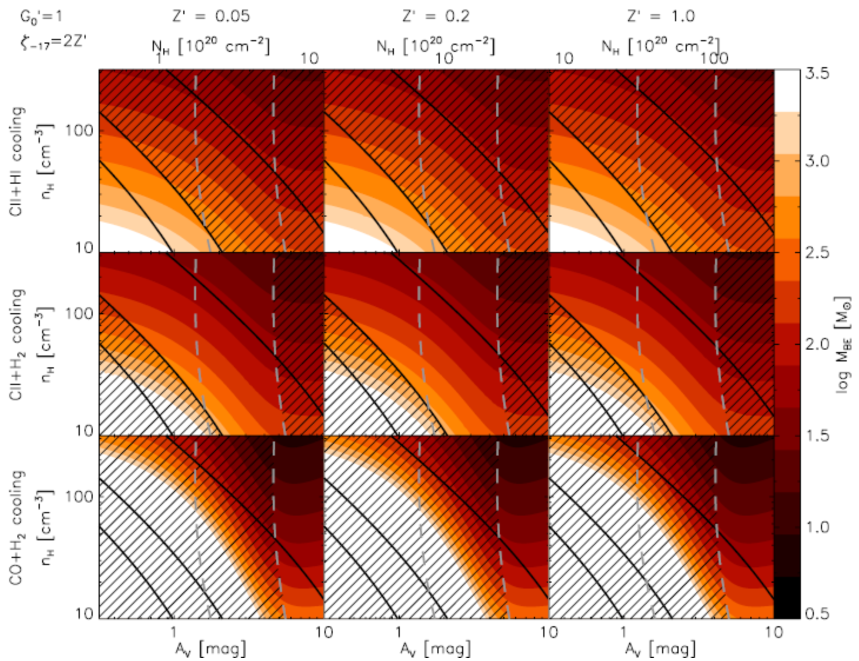
z=0 (Bigiel et al 2011)



High z (Tacconi et al 2013)

Kennicutt-Schmidt Relation

- On large (>> 100 pc) scales star-forming gas and molecular gas correlate well. It does not mean that molecules are necessary for star formation (rats correlate with humans).



(Krumholz, Leroy, McKee 2011)

- Dust shielding makes the gas both cold and molecular.

Kennicutt-Schmidt Relation

- All modern large-scale simulations account for the molecular gas in their star formation recipes,

$$\dot{\rho}_* = f_{\rm H_2} \frac{\rho_g}{\tau_{\rm SF}}$$

- They all do it differently, though.

The Devil Is In Details

- Simple threshold (Illustrus, NIHAO)

$$f_{\mathrm{H}_2} = \begin{cases} 1, & \rho > \rho_{\mathrm{SF}}, \cdots \\ 0, & \text{otherwise} \end{cases}$$

- Pressure formulation (EAGLE)

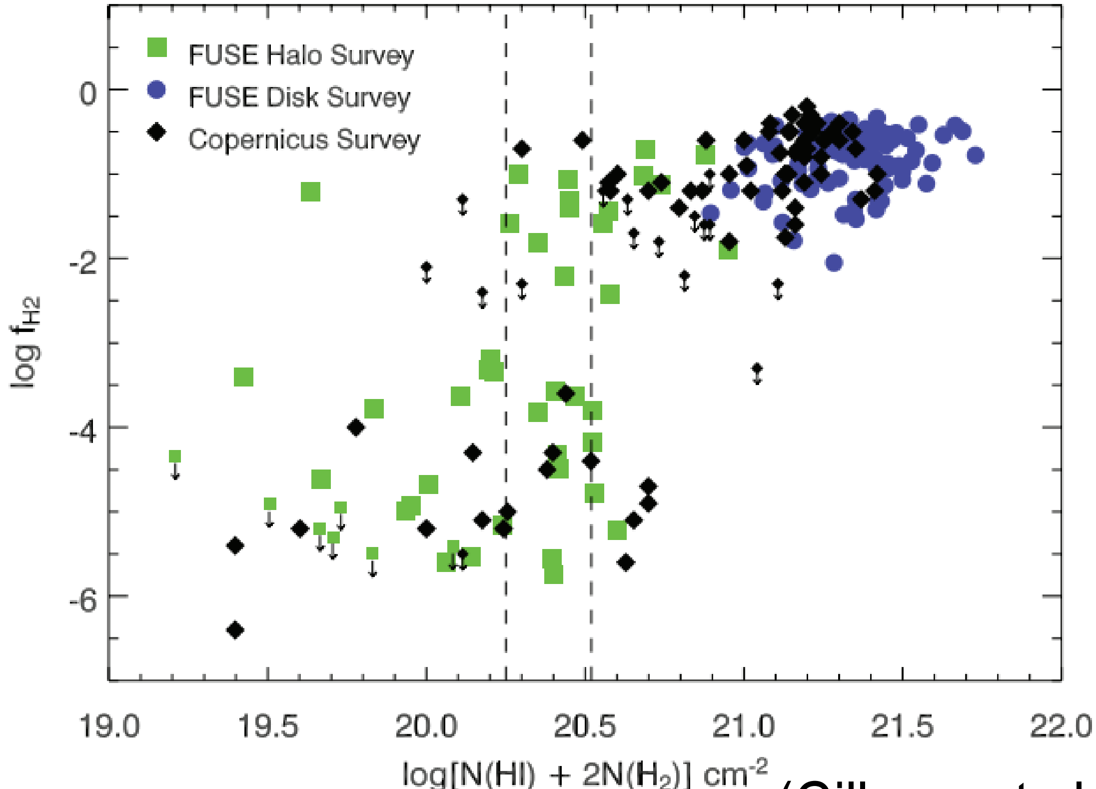
$$f_{\mathrm{H}_2} \propto P^{(n-1)/2} \quad (= \text{const for linear KSR})$$

- ISM model (Russian Mafia, Christensen++, Kuhlen, …)

$$f_{\mathrm{H}_2} = f_{\mathrm{H}_2}(n, T, [J_{\mathrm{LW}}], \ldots)$$

The Devil Is In Details

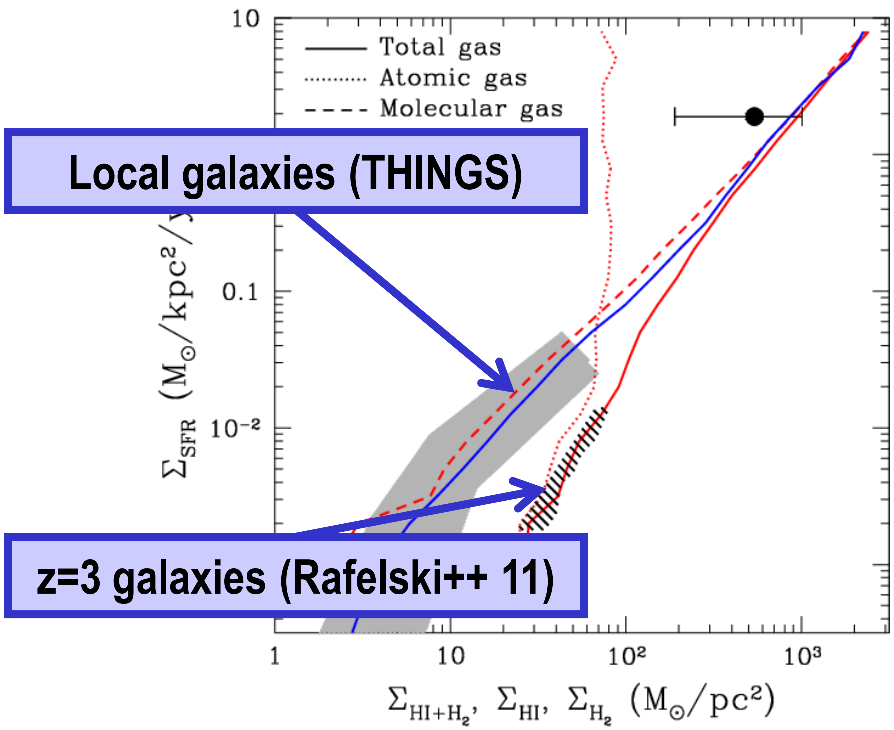
- The reason why simplistic recipes work is because the atomic-to-molecular transition is very sharp (sharper than $e^{-\tau}$).

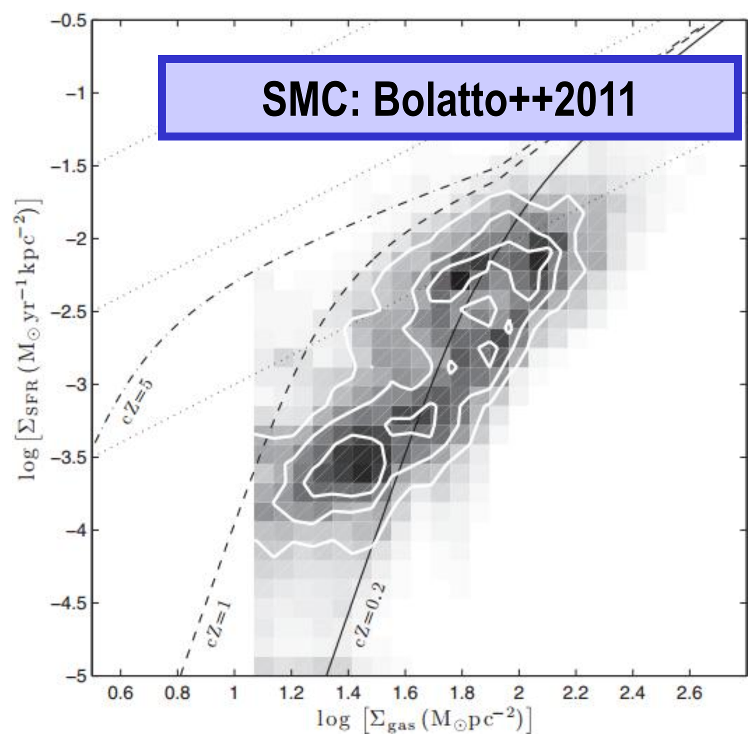


(Gillmon et al 2006)

The Devil Is In Details

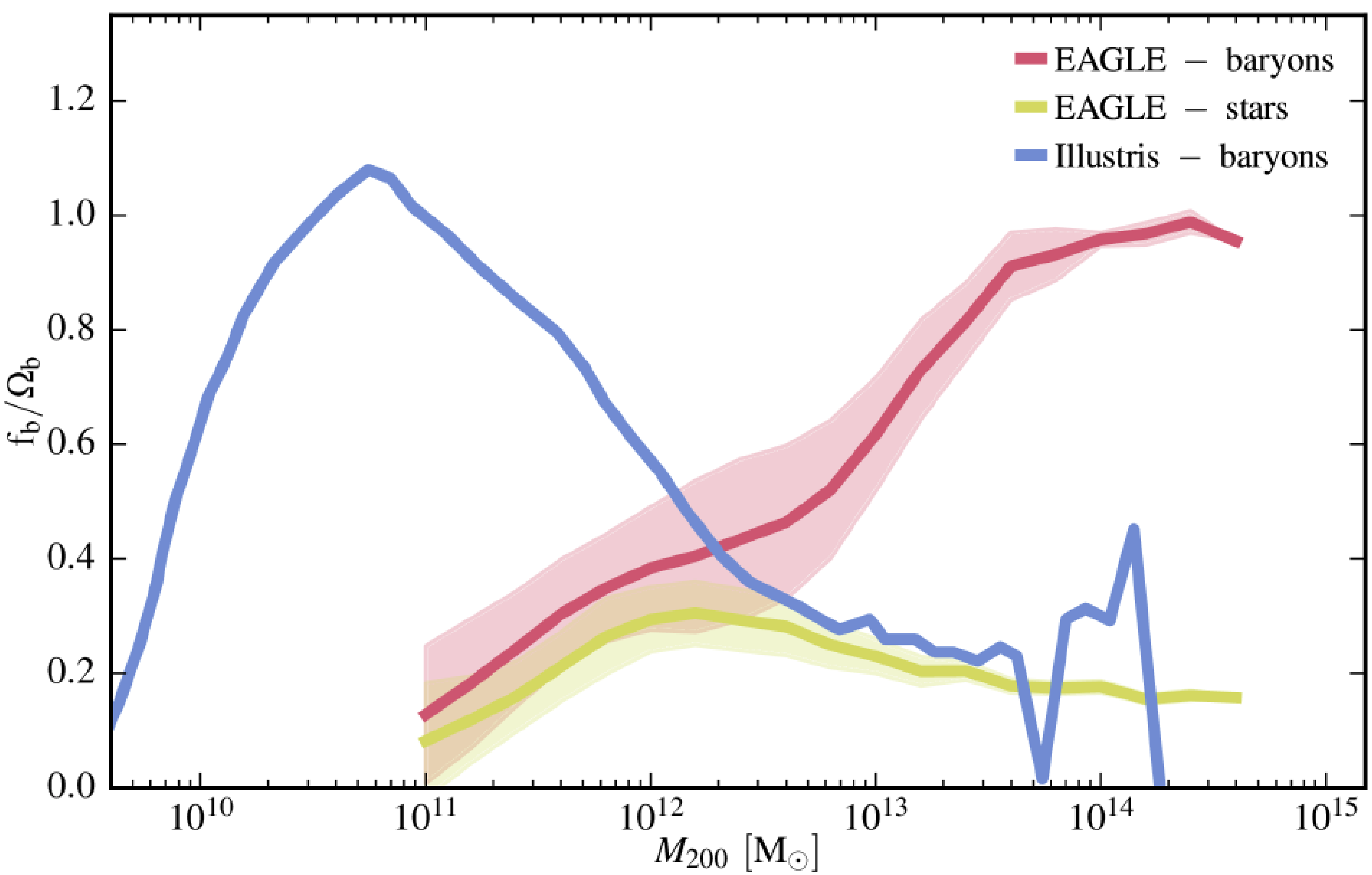
- A problem with simplistic recipes is that they are primarily calibrated at z=0, but atomic-to-molecular transition at high-z is different, because both Z and J_{LW} change.





The Devil Is In Details

- As the result, some of the simulations based on simplistic recipes “could be improved”.



The Devil Is In Details

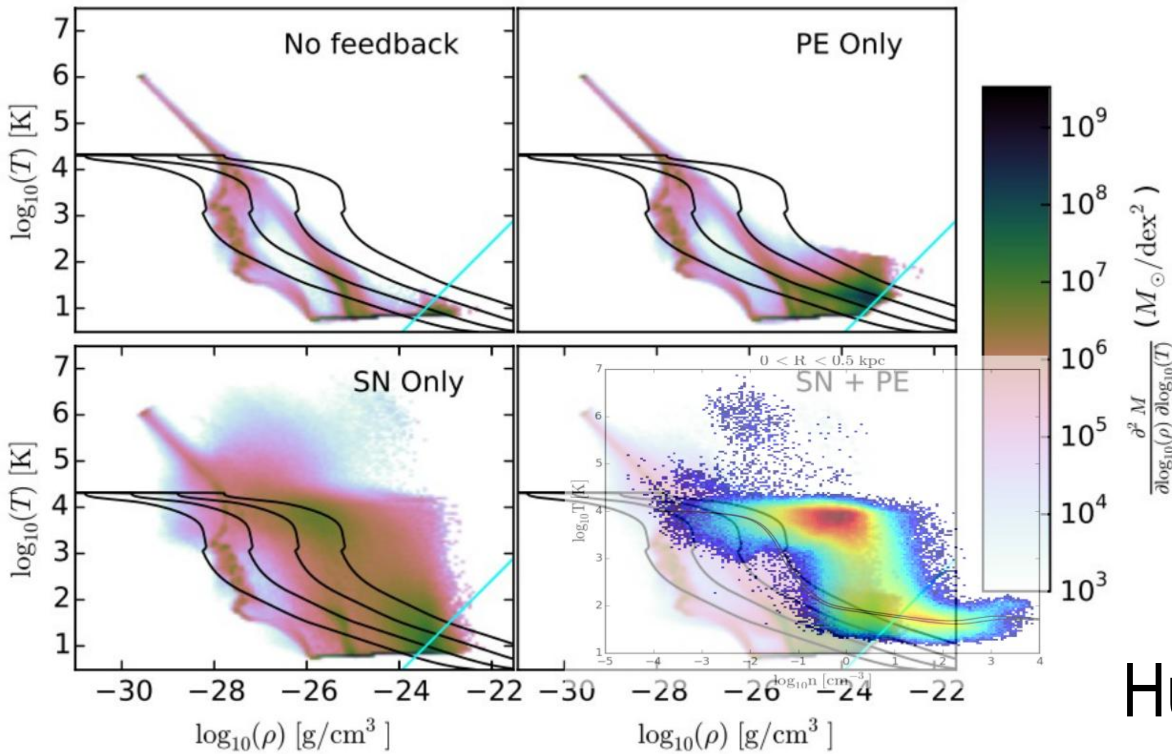
$$f_{\mathrm{H_2}} = f_{\mathrm{H_2}}(n, T, [J_{\mathrm{LW}}], \ldots)$$

- In modern simulations there is no real reason not to use an H_2 model. There are several of them, they are all largely consistent with each other (and where they are not, it is not clear who is right).
  - Pelupessy++ 06,
  - KMT09
  - GTK09, GK10, GD14
  - Christensen++ 12
  - …

Beyond gas phases

- Careful examination of all relevant (on large, >> 100 pc scales) pieces of ISM modeling is still lacking ➔ confusion is frequent.

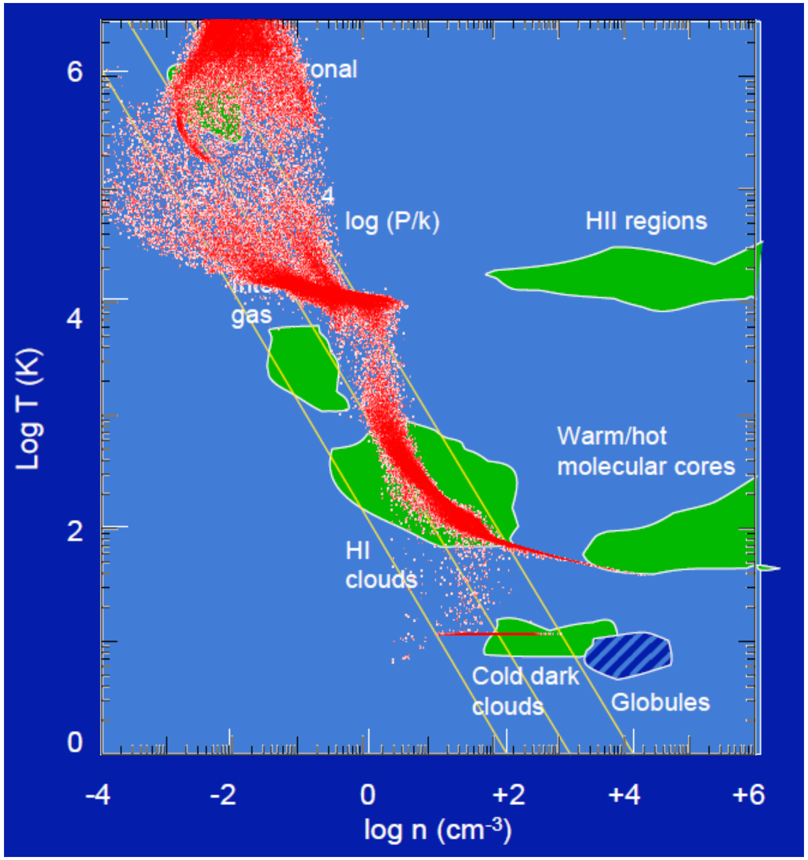
Forbes+ 2016 concluded that PE heating alone can suppress SFR in dwarfs.



Hu++, in prep

Crossing 2D/3D Boundary

- Models of ISM physics on small scales (<< 100 pc) likely should be very different than large-scale (>> 100 pc) models.
- With 10-30 pc resolution one starts to *identify* (<u>do not confuse with *resolve*</u>) individual GMCs.
- Hence, multiphase ISM comes out naturally.



Cooling

- Cooling (and heating) rates in the gas are strongly dependent on the radiation field*.
- A common approximation is to compute cooling and heating assuming cosmic background radiation (Kravtsov 2003, Wiersma+ 2008, GRACKLE, MUFASA, …).
- Alas, interstellar radiation field in the Milky Way is ~ 500 above the cosmic background. The same is true for z~2 galaxies.

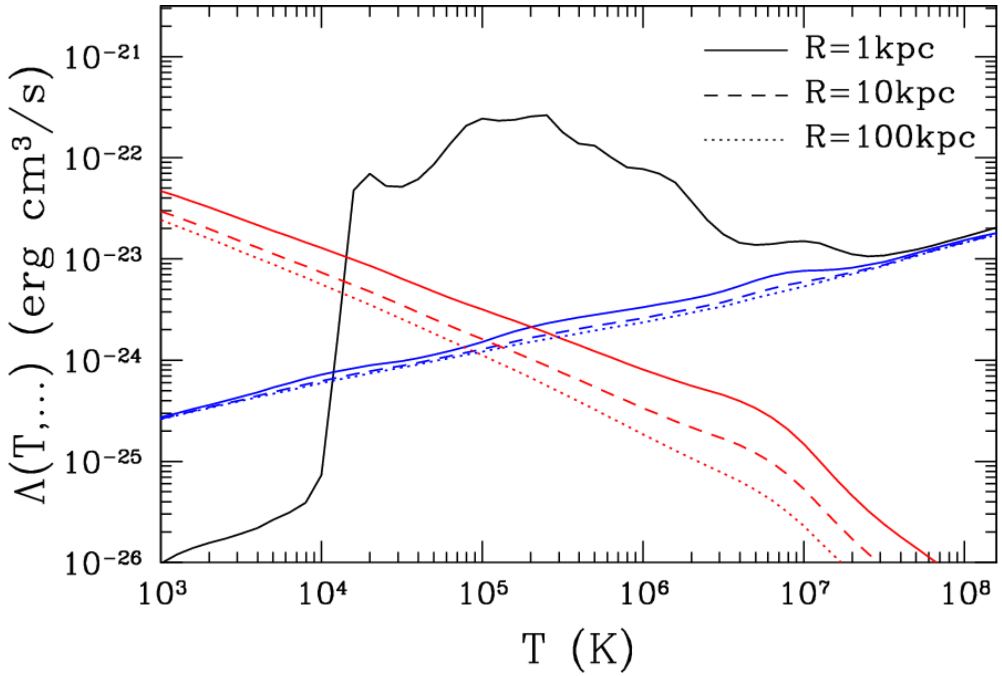
---

*Everyone knows it but not everyone does something about it.

Cooling

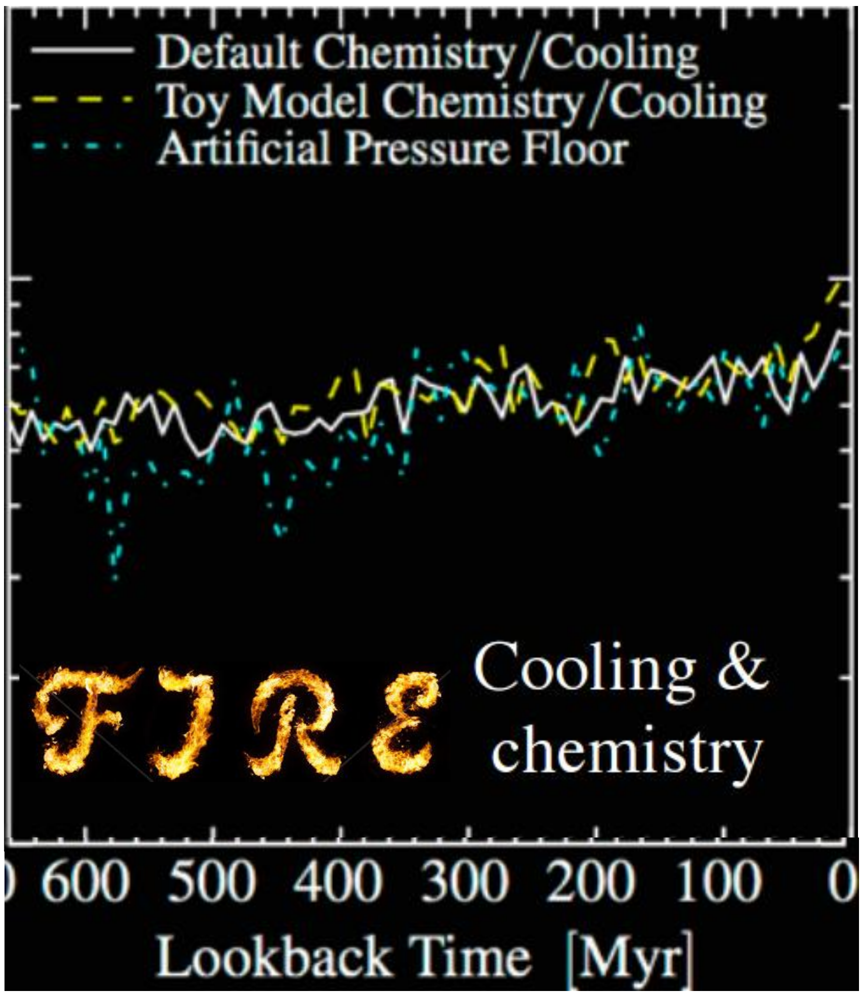
- Almost all large scale (>> 100 pc resolution) simulations use background-suppressed cooling/heating functions (i.e. *do it wrong*).
- Even many ~10 pc resolution models use such C/H functions.
- Only a few attempts to account for the full RF dependence (FIRE, ART).

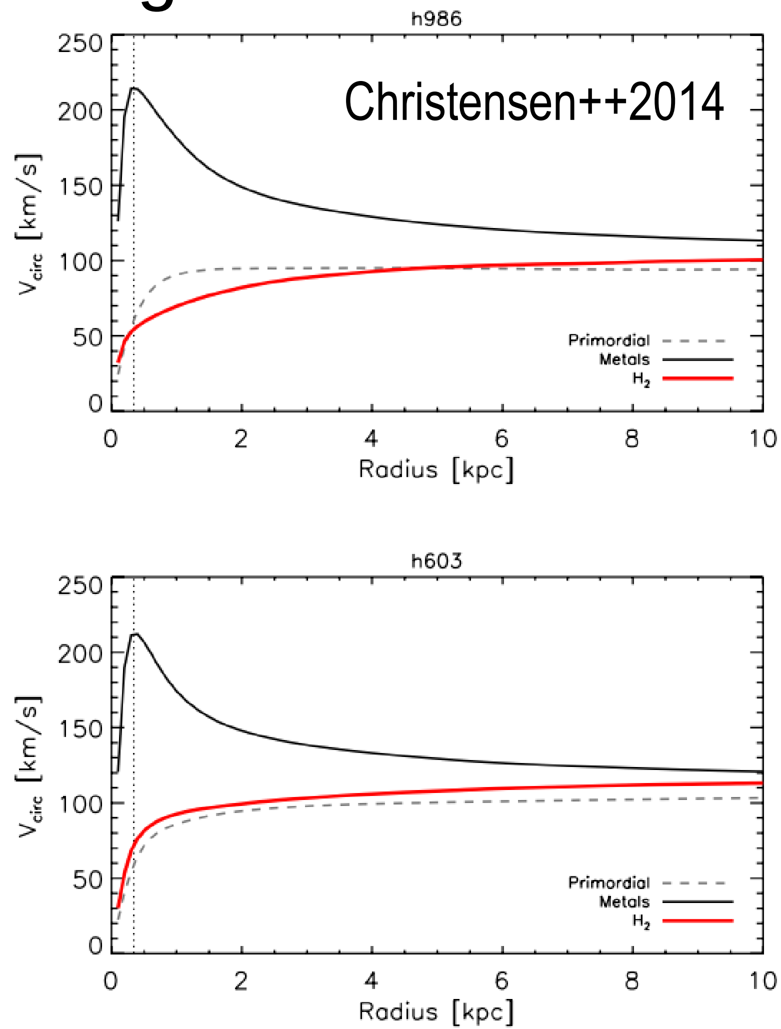
A QSO can disable cooling in its own halo.



Cooling

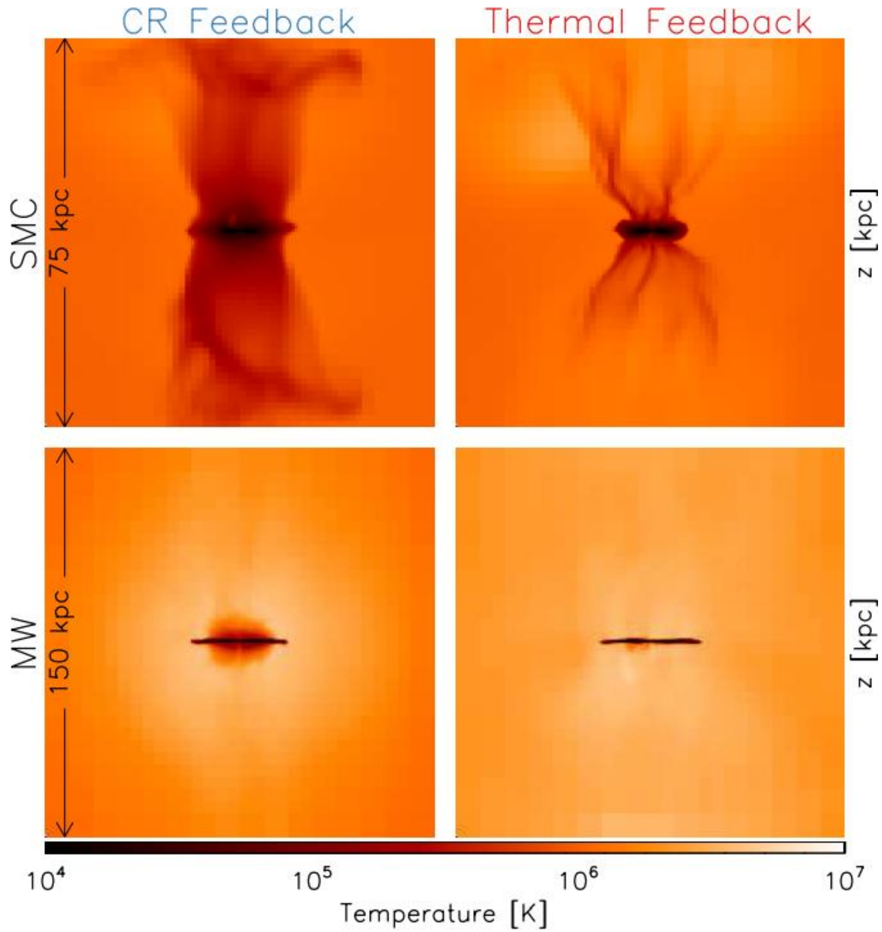
- But does it matter? The next big vote after Brexit.





Cosmic Rays

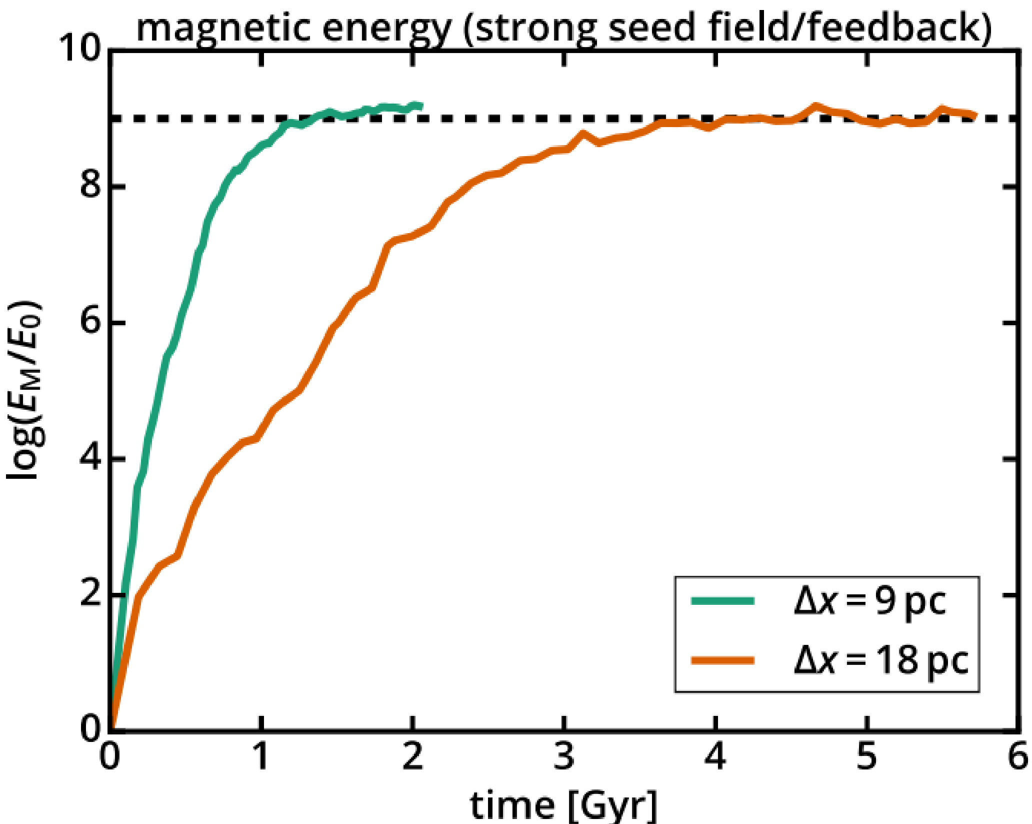
- Cosmic Rays are included in various forms, most commonly as a diffusion process.



- It is generally believed that CR feedback helps to drive galactic winds.
- It may be necessary to explain the ubiquity of cold gas in the outflows.

Magnetic Field

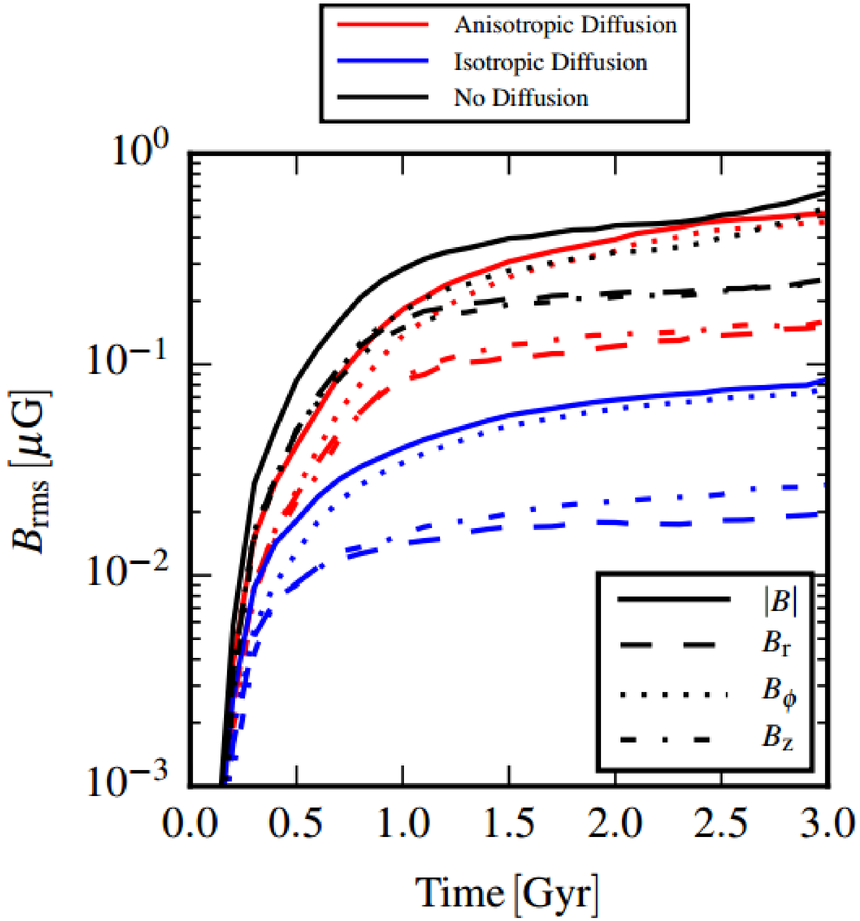
- MHD is included in most modern codes. Dynamo processes are entirely resolution dependent.
- Surprise! Saturation is at 1% of equipartition.



RAMSES:
Rieder & Teyssier 2016

Magnetic Field + CR

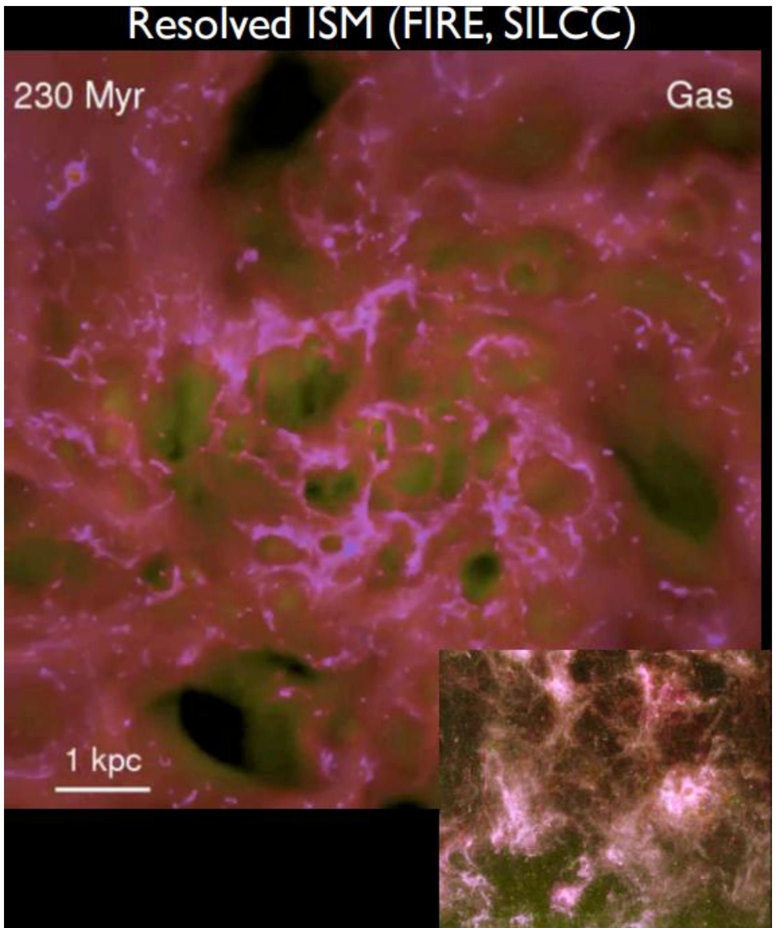
- Magnetic field and CR interact in a non-trivial way, they must be modeled together.

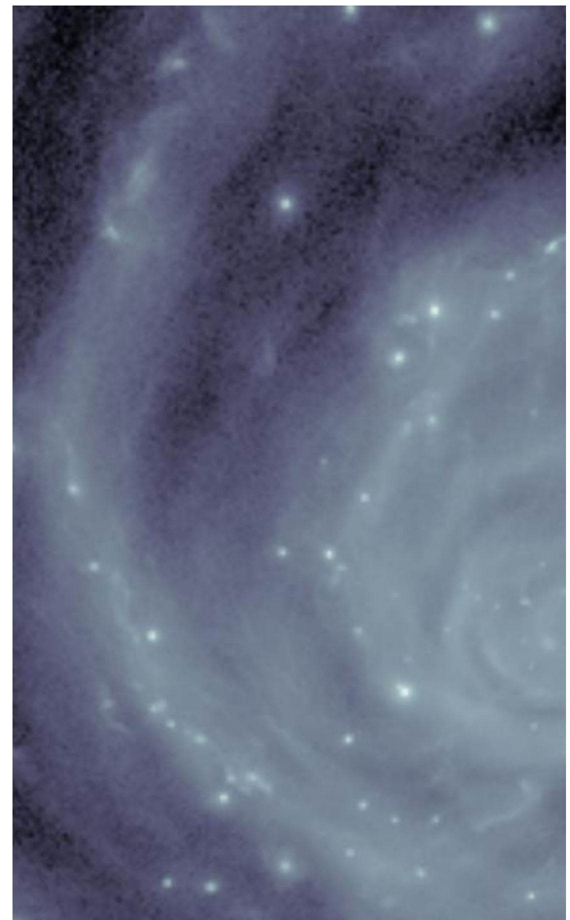


Pakmor++ 2016

Moving Forward

- High resolution simulations routinely get ISM (at least visually) right.



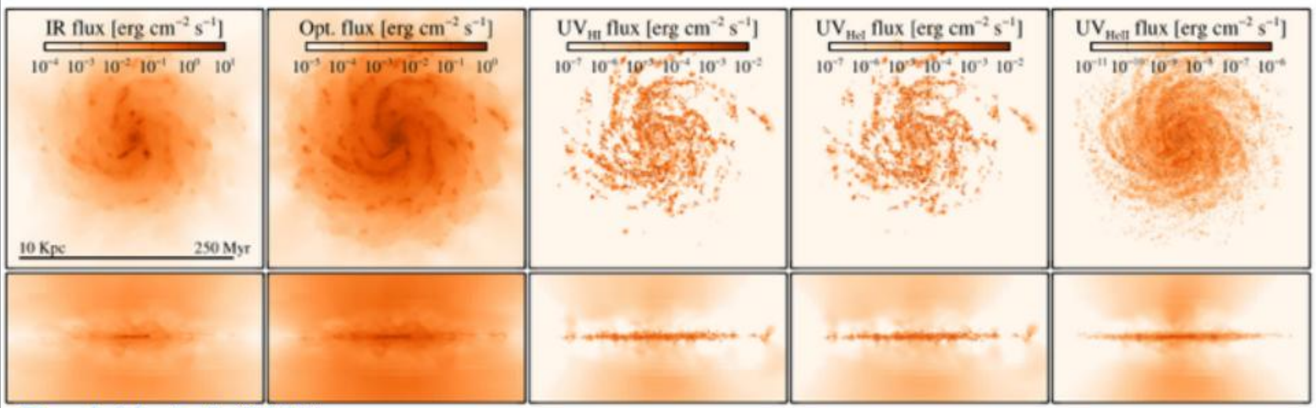


Moving Forward

- RT on galactic scales becomes highly sophisticated, including scattering on dust.

Galaxies that shine

Isolated galaxy with 5 different photons groups, photo-ionisation and dust absorption.



Rosdahl *et al.* (2015)

- 10^{11} solar masses halo
- 3×10^{9} solar masses baryonic disk
- 50% gas fraction.

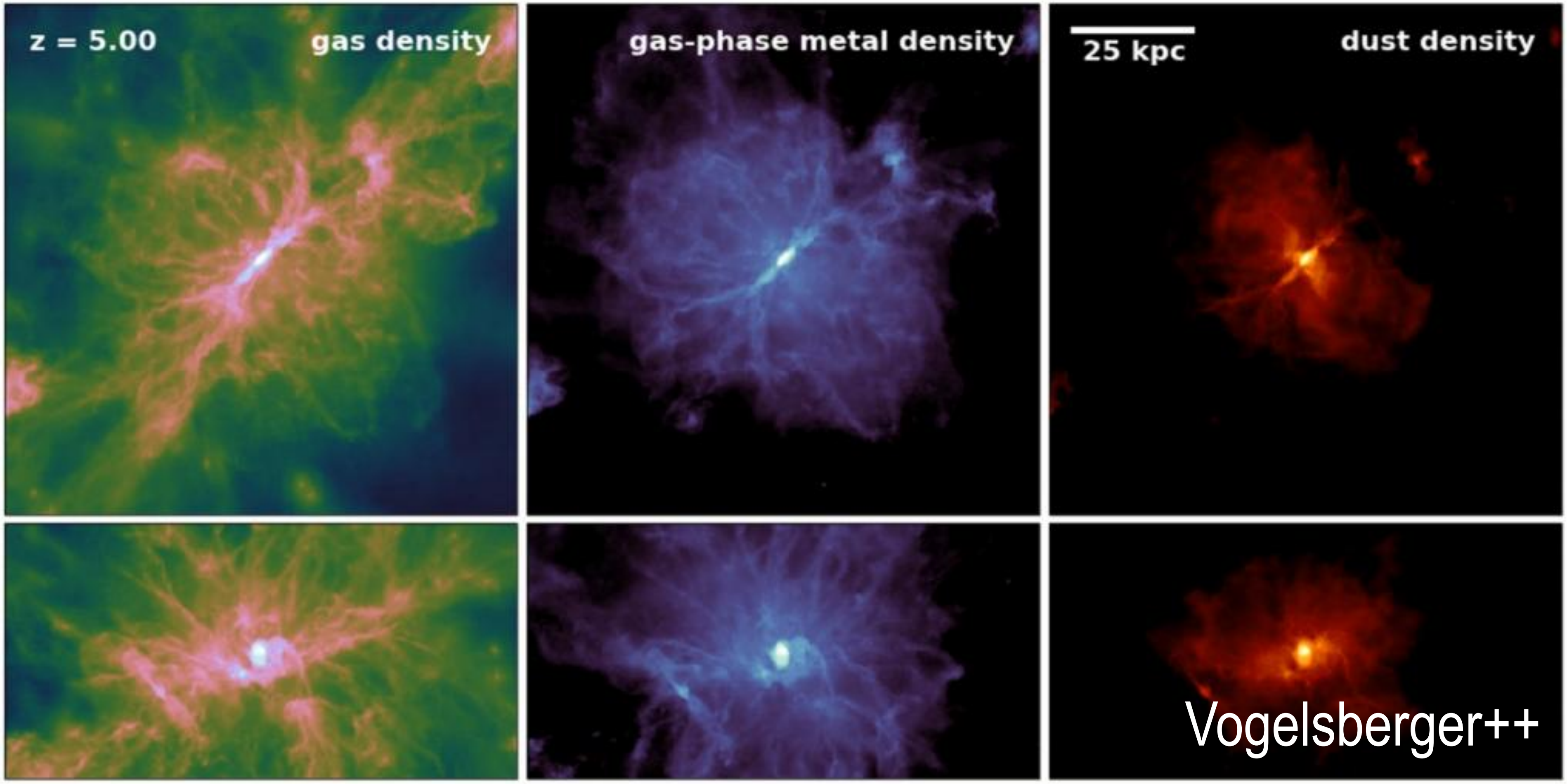
- 10^{6} stellar and DM particles
- 18 pc resolution
- 0.1 solar metallicity

Feedback processes:
- thermal SN energy injection (no trick)
- radiation from the B&C (2003) SEDs.
- HI and dust opacities

Radiative processes:
- photo-ionisation heating
- direct pressure from UV
- IR pressure from dust scattering

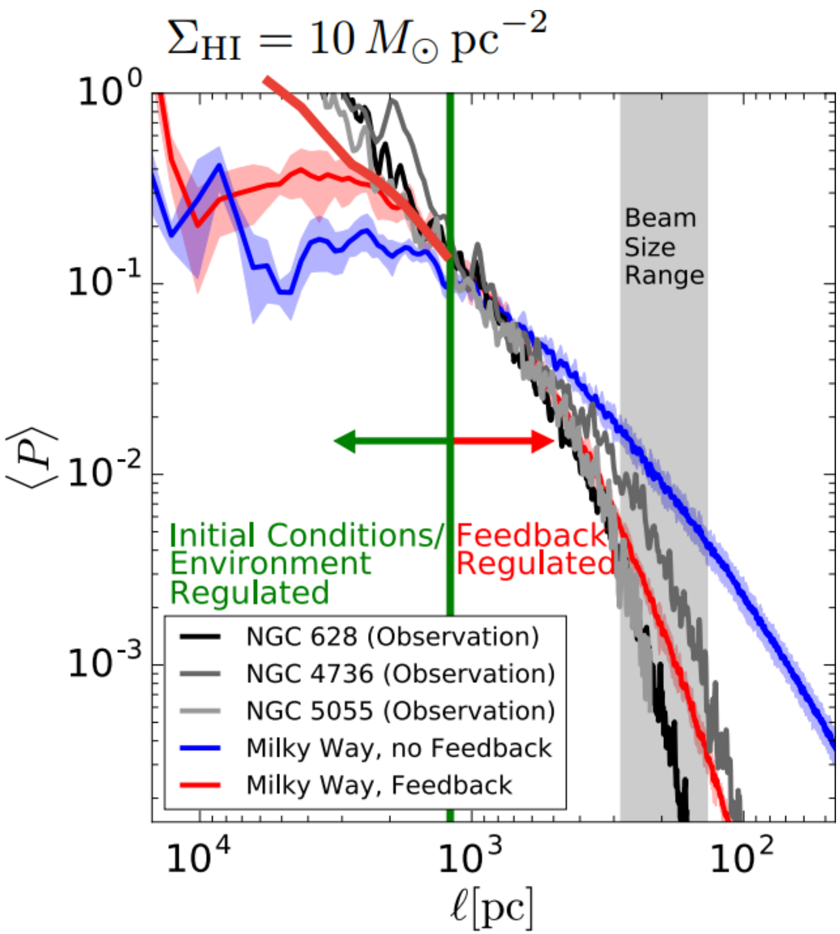
Moving Forward

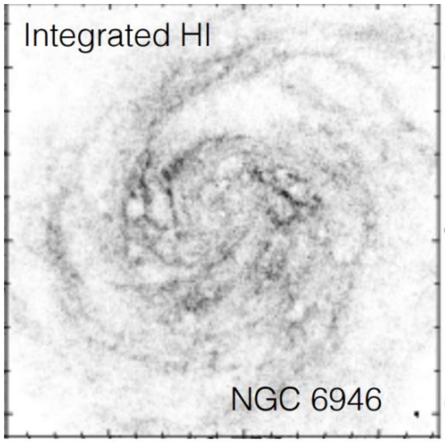
- Dust is a dynamically modeled component.



Moving Forward

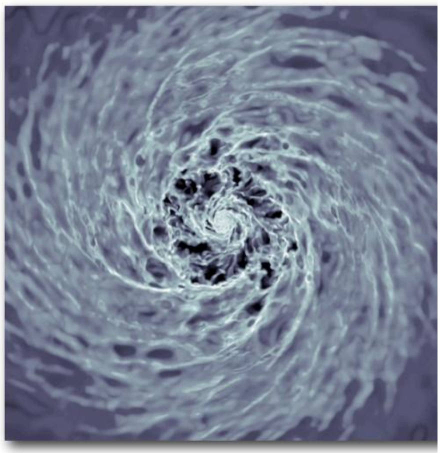
- Simulations start to reproduce details of HI distribution in galaxies.





THINGS (Walter et al. 2008)

vs.



Agerts++

Conclusions

- The record so far is mixed:
  - HI ➔ H_2 transition is modeled well and routinely, but only because H_2 is a good proxy for star-forming gas.
  - Cooling is often done incorrectly, but the jury is still out whether it matters that much.
  - Including physics one-effect-at-a-time often leads to confusing and inconsistent models.
- The field is changing rapidly, though, with highly sophisticated ISM modeling just around the corner (and some of us are there already).