Future improvements on simulations

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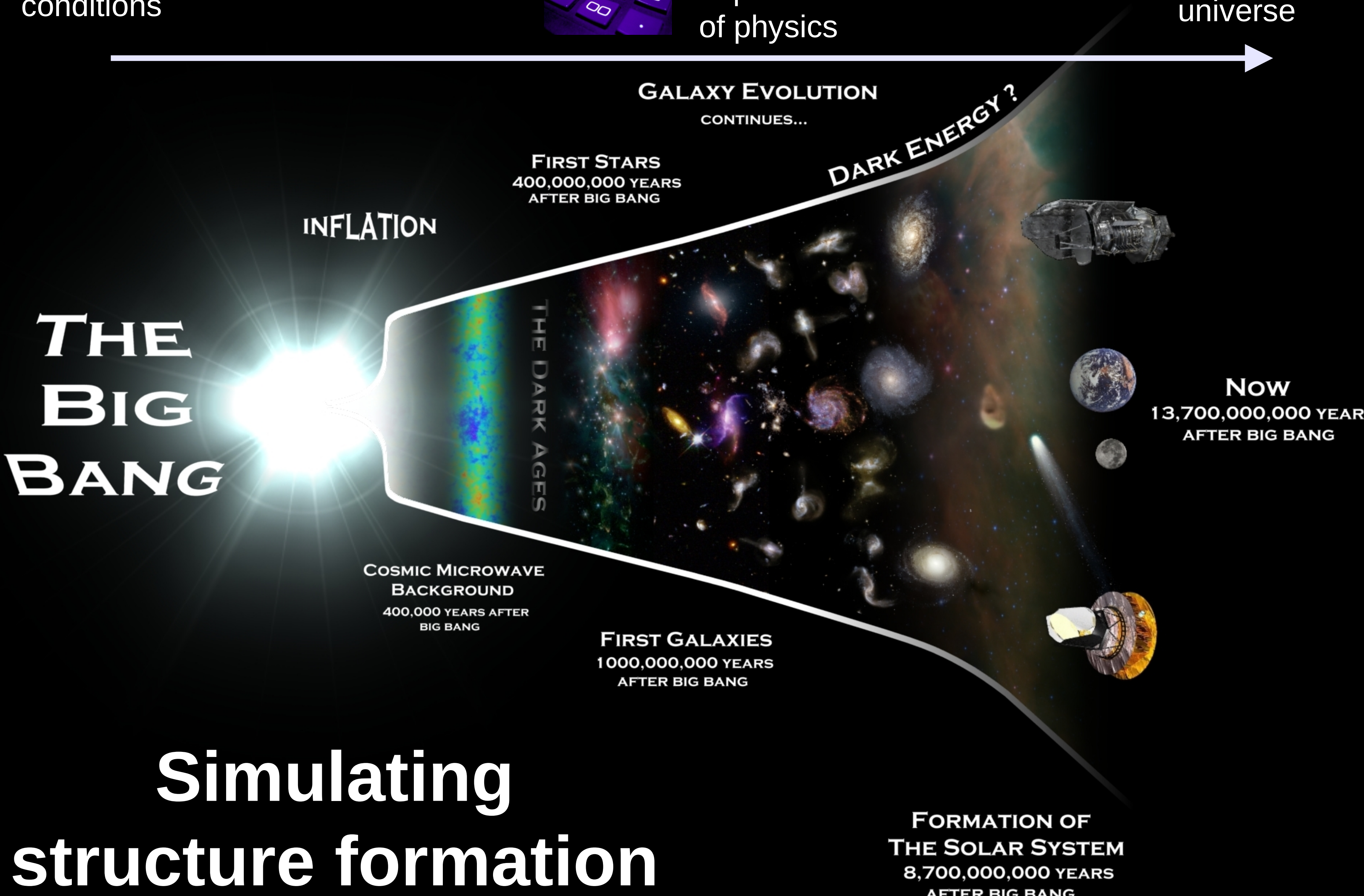
Dark Matter in the Milky Way
MITP Workshop
Mainz

initial conditions

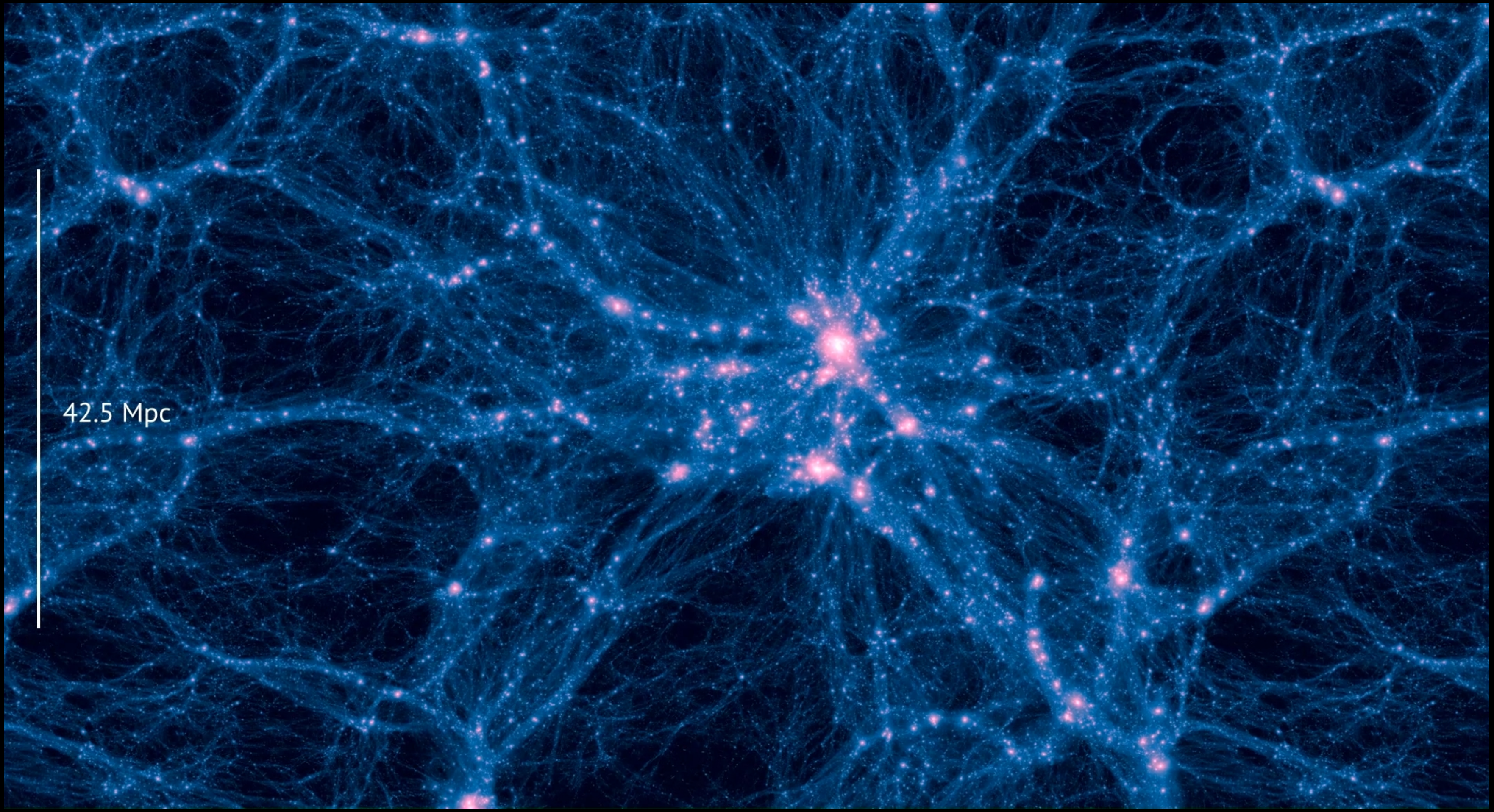
solve the equations of physics

virtual universe



Simulating structure formation

Connecting scales...



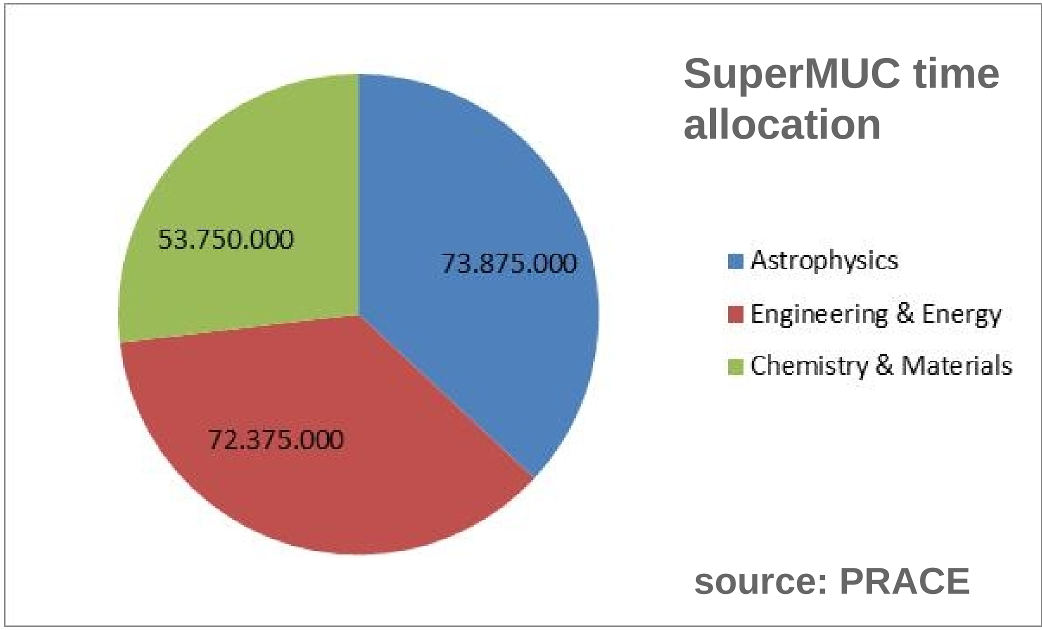

US/Texas
KRAKEN
US/Tennessee
US/Texas
Germany
France

Computing power is constantly increasing

- **Exaflop machines by ~2018**
- **Hybrid architectures are becoming the standard**

Credit: Nicole Hemsoth

Astrophysics has been one of the main driver behind computing power increase



RANK	SITE	SYSTEM	CORES	RMAX (TFLOP/S)	RPEAK (TFLOP/S)	POWER (KW)
1	National Super Computer Center in Guangzhou China	**Tianhe-2 (MilkyWay-2)** - TH-IVB-FEP Cluster, Intel Xeon E5-2692 12C 2.200GHz, TH Express-2, Intel Xeon Phi 31S1P NUDT	3,120,000	33,862.7	54,902.4	17,808
2	DOE/SC/Oak Ridge National Laboratory United States	**Titan** - Cray XK7 , Opteron 6274 16C 2.200GHz, Cray Gemini interconnect, NVIDIA K20x Cray Inc.	560,640	17,590.0	27,112.5	8,209
3	DOE/NNSA/LLNL United States	**Sequoia** - BlueGene/Q, Power BQC 16C 1.60 GHz, Custom IBM	1,572,864	17,173.2	20,132.7	7,890
4	RIKEN Advanced Institute for Computational Science (AICS) Japan	K computer, SPARC64 VIIIfx 2.0GHz, Tofu interconnect Fujitsu	705,024	10,510.0	11,280.4	12,660
5	DOE/SC/Argonne National Laboratory United States	**Mira** - BlueGene/Q, Power BQC 16C 1.60GHz, Custom IBM	786,432	8,586.6	10,066.3	3,945

source : Top500

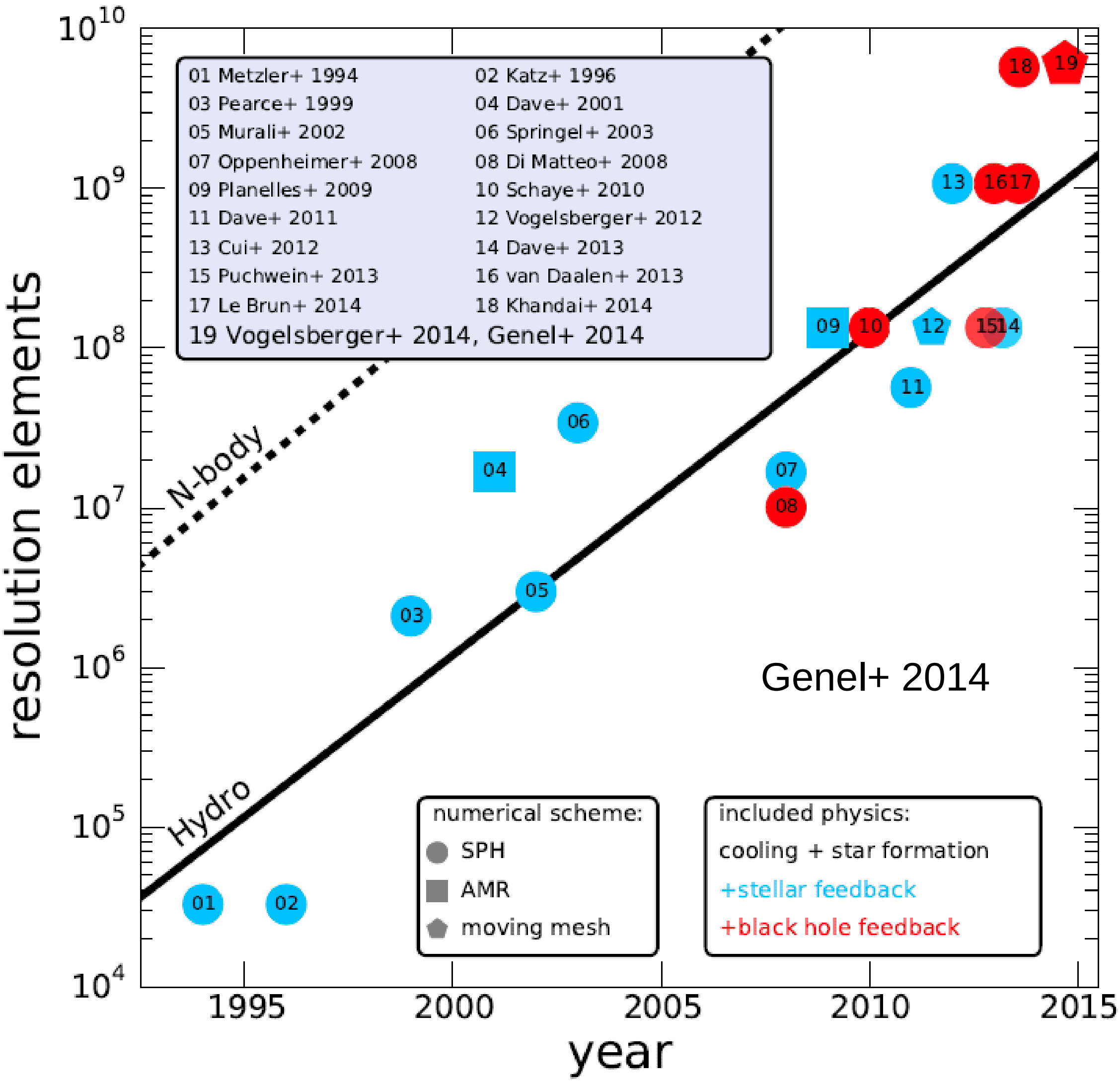
PFlops machines
N cores ~ 10^{5-6}

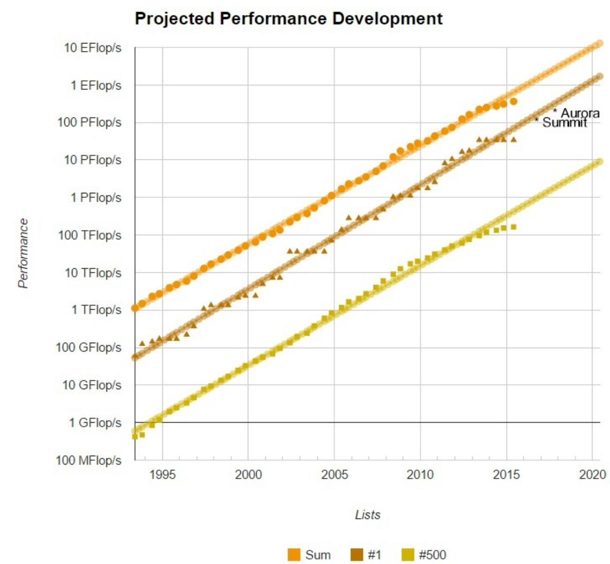
Simulations
N cores ~ $10^{3\text{-}4}$

Make better use of the hardware is crucial!

The state of the art

Moore's law for simulations





State of the art

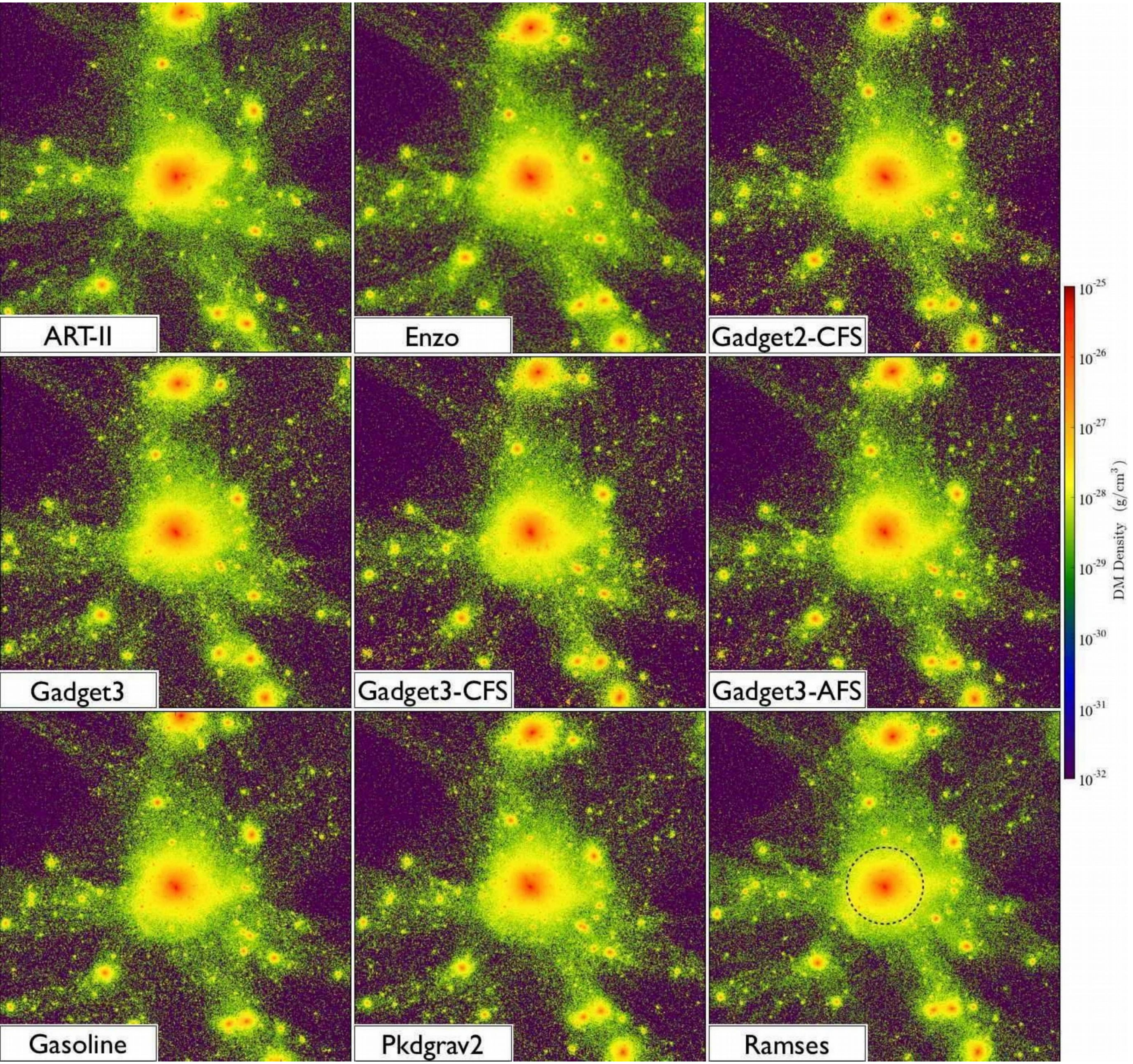
Boxes:

- ~10^{10} resolution elements
- ~1 kpc force resolution

Zoom-ins (for MW):

- ~$10^{7\text{-}8}$ resolution elements
- ~100 pc force resolution

$10^{6\text{-}7}$ CPUh to complete



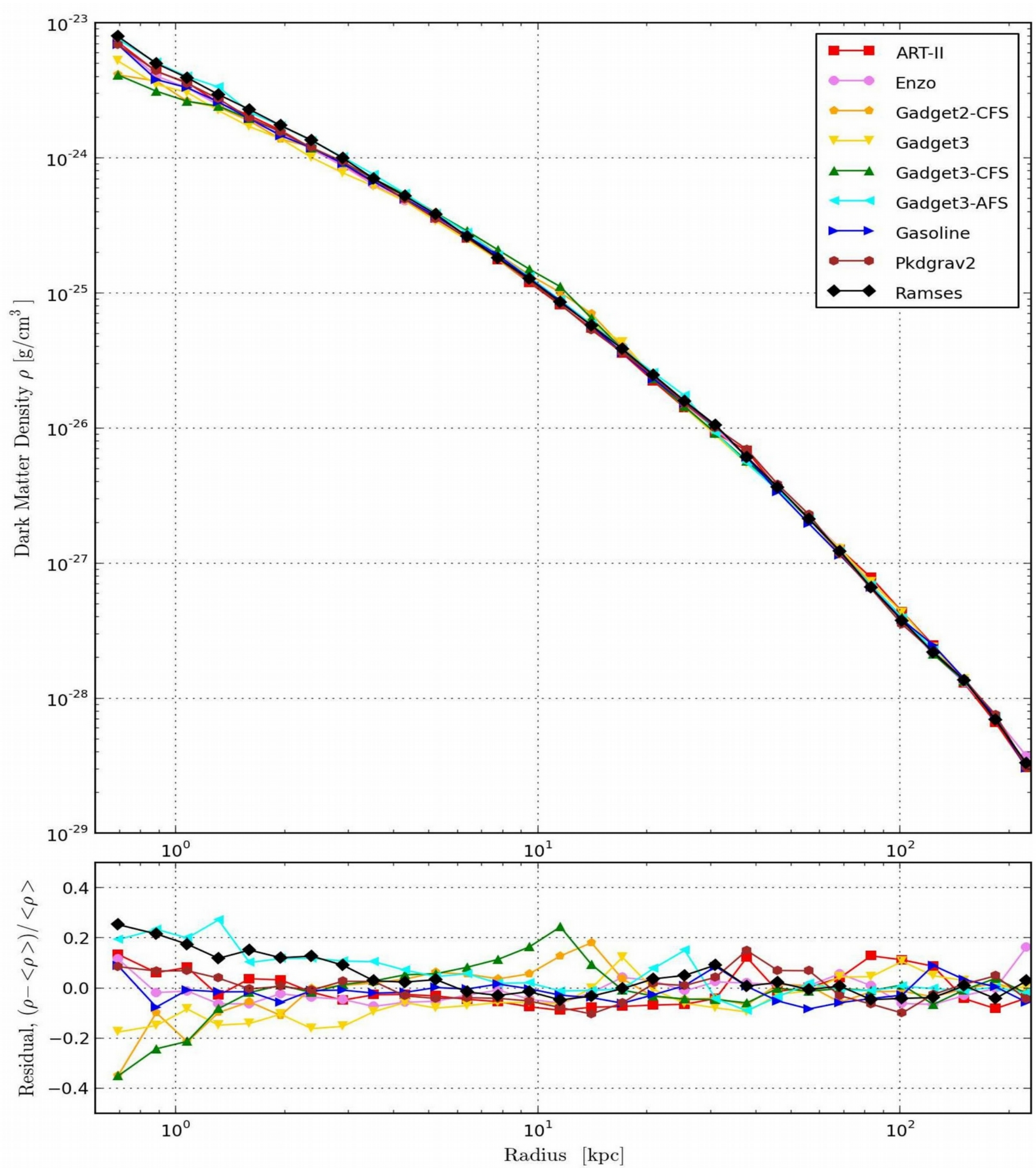
Gravity

We think we have it under control (if it is newtonian)

All solvers (multigrid, tree methods, Fourier methods, Tree-PM methods), are essentially in agreement

Agora project (Kim et al. 2014)

Gravity



Agora project (Kim et al. 2014)

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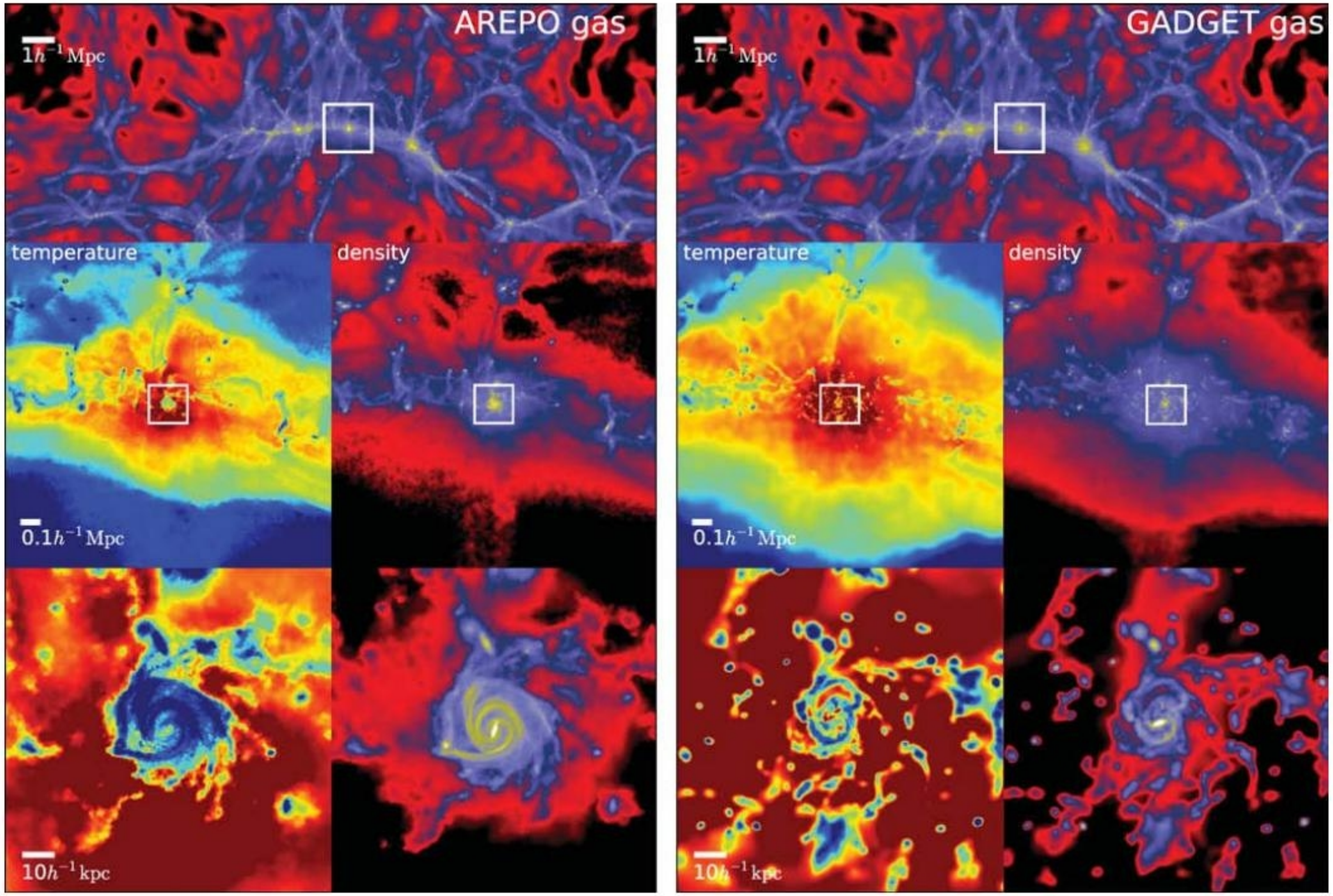
Hydrodynamics

Vogelsberger+ 2012



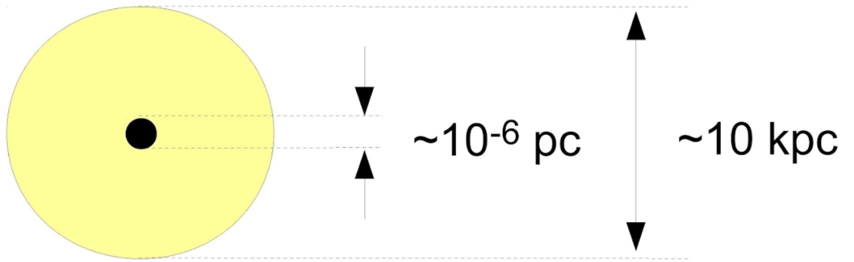
Physics is well understood but results can be dependent on the way equations are solved numerically

Discrepancy was larger ~5 years ago, now this issue is mitigated

Galaxy formation poses an enormous multi-scale physics problem

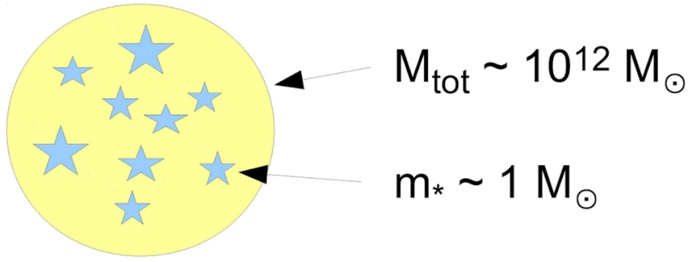
THE DYNAMIC RANGE CHALLENGE

A supermassive BH in a galaxy



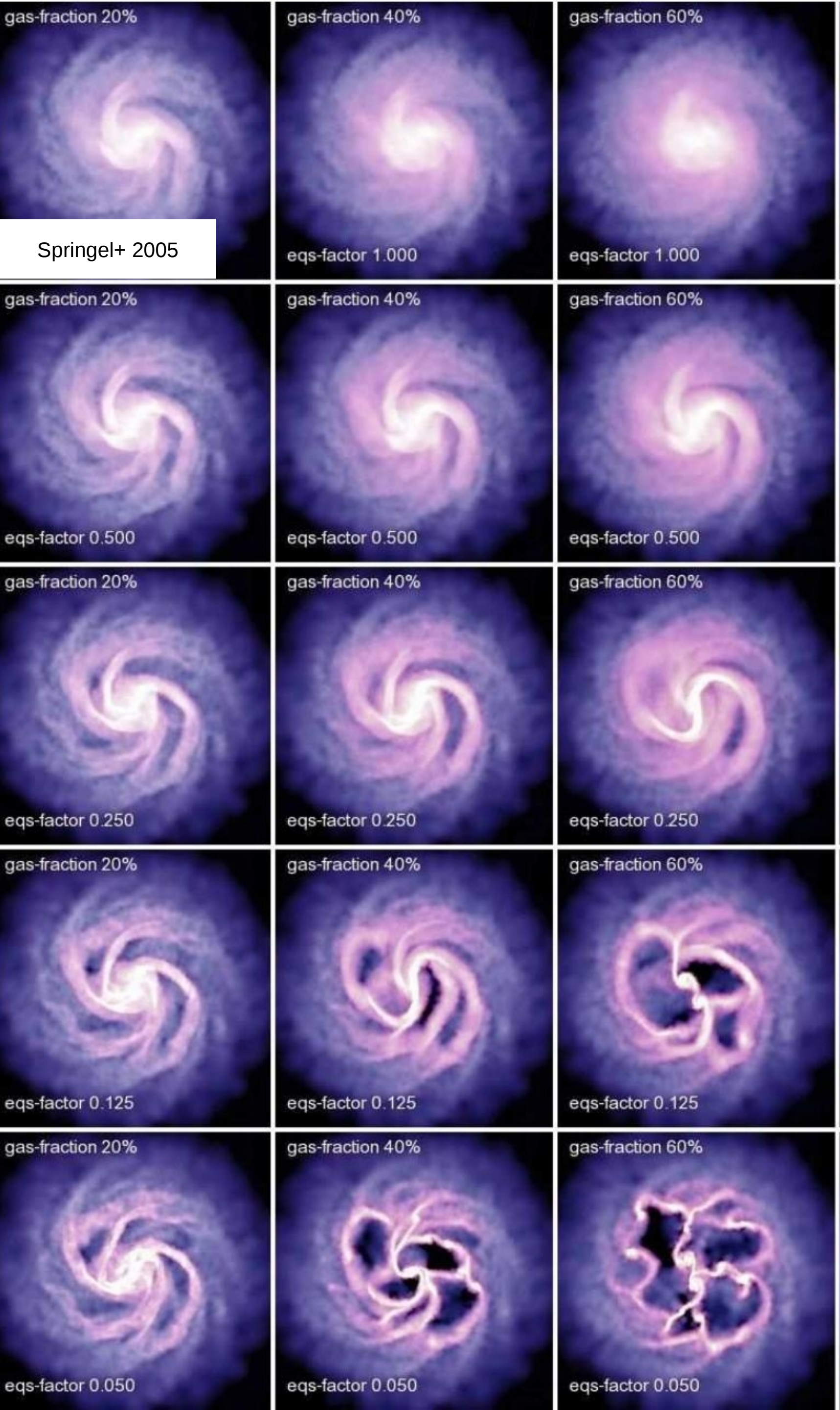
dynamic range of 10^{10}

Star formation in a normal galaxy



mass dynamic range of 10^{12}

Credit: Volker Springel



Subgrid physics

Any physical process that is relevant to the simulated scales but occurs *below the spatial resolution* of the simulation scales must be included using a subgrid model.

This is the major source of uncertainties in simulations!

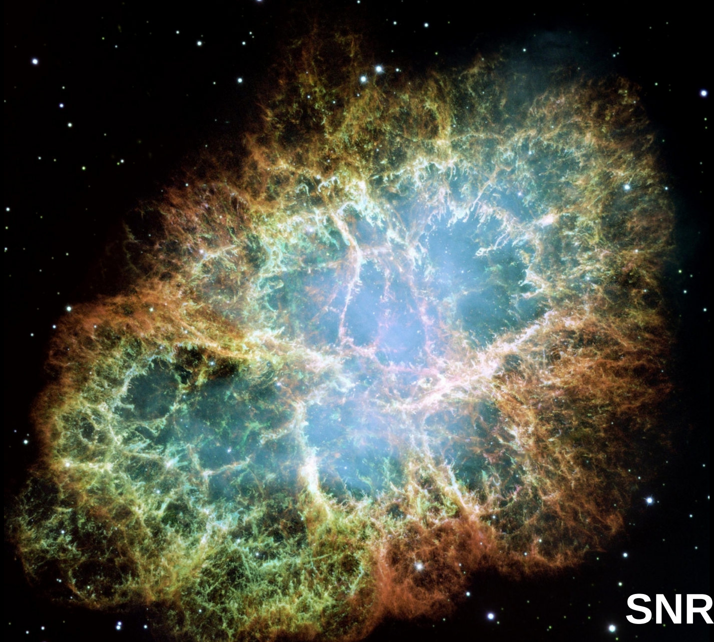
A (non-comprehensive) list:

- Star formation
- ISM physics
- Stellar physics: Evolution, winds, metal enrichment…
- **Supernova feedback**
- **AGN physics**
- Magnetic fields (generation)
- Cosmic rays (production and acceleration)
- Extra dark matter physics: self-interacting or decay
- ...

Supernova feedback

Insufficient resolution leads to ***overcooling***

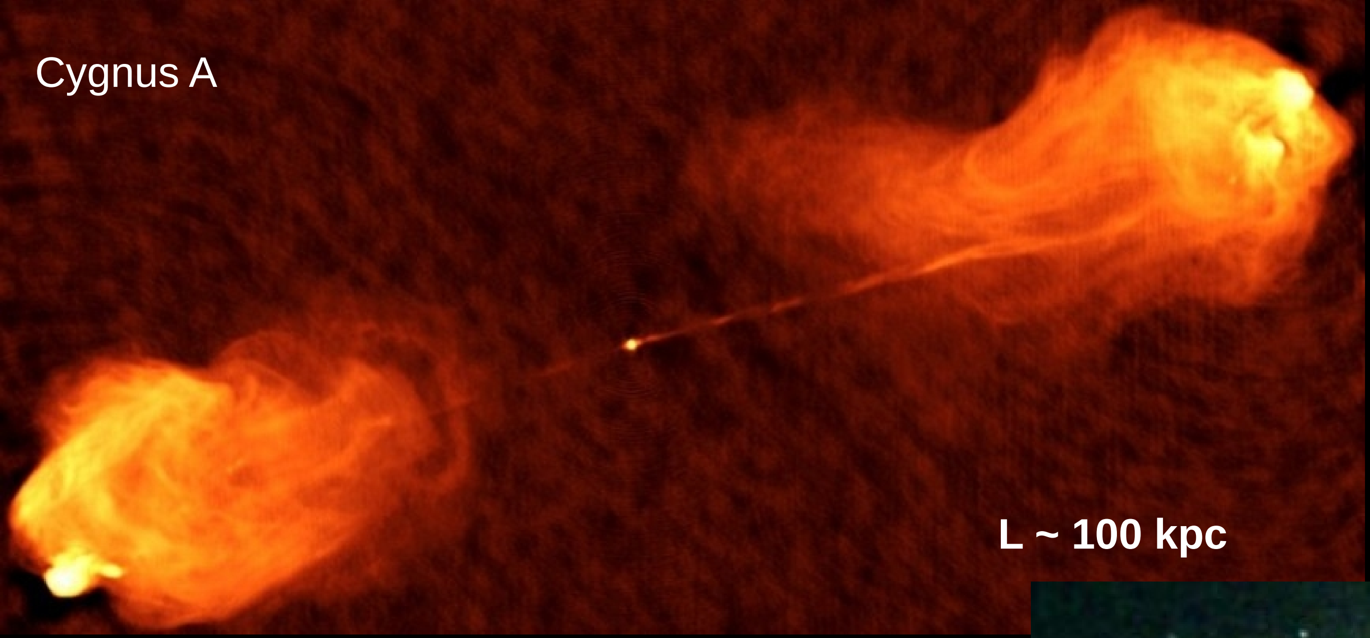
Many successful implementations, ***tailored*** to specific codes



SNR ~1 pc

superbubble ~100 pc

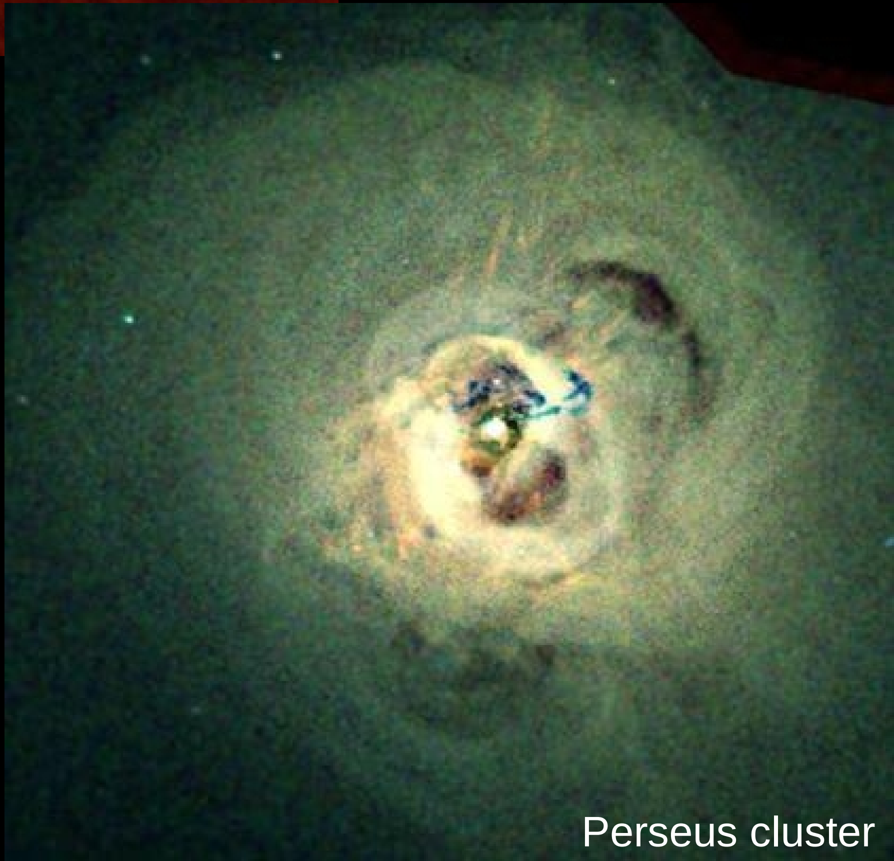
galactic wind ~10 kpc



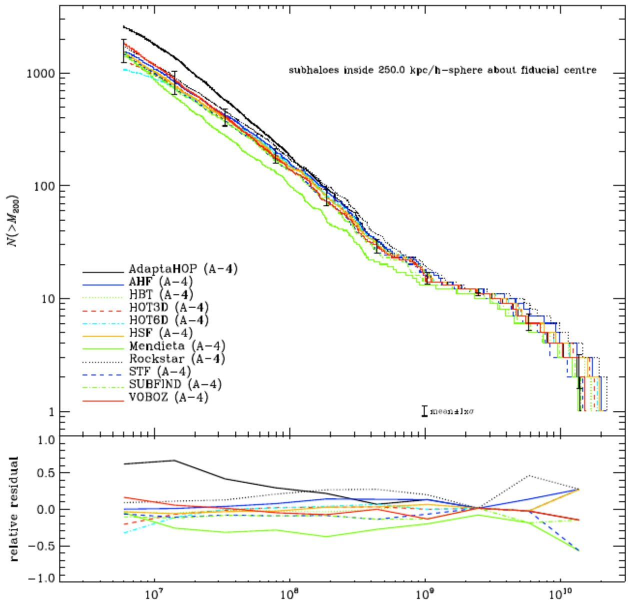
AGN feedback

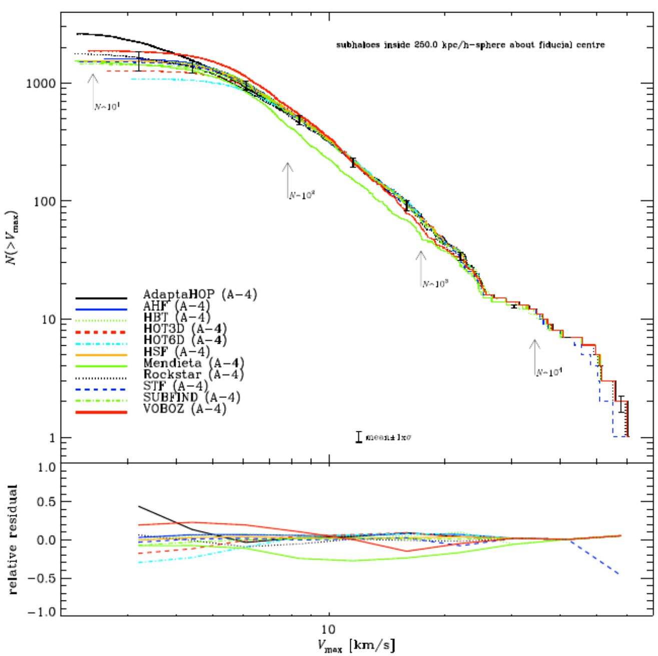
Very challenging to implement and benchmark

- Dynamic range in scales is larger than in SN feedback
- Relativistic physics
- Massive objects are rare, need to simulate large volumes
- Even zoom ins are expensive because of the large mass



Comparison Projects

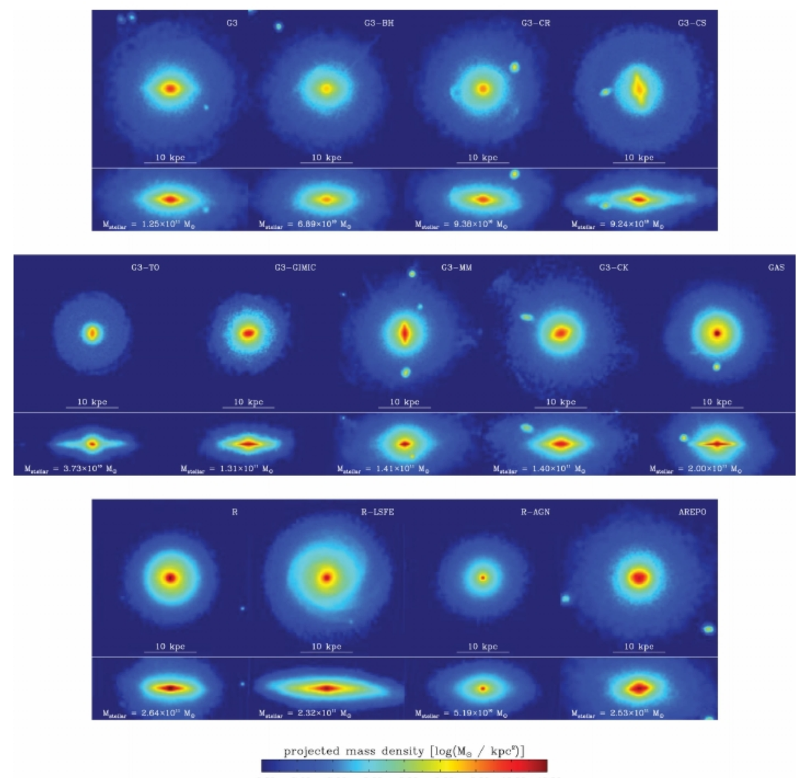




Subhaloes Going Notts (Onions+2012)

Key to improve methods and understand their limitations

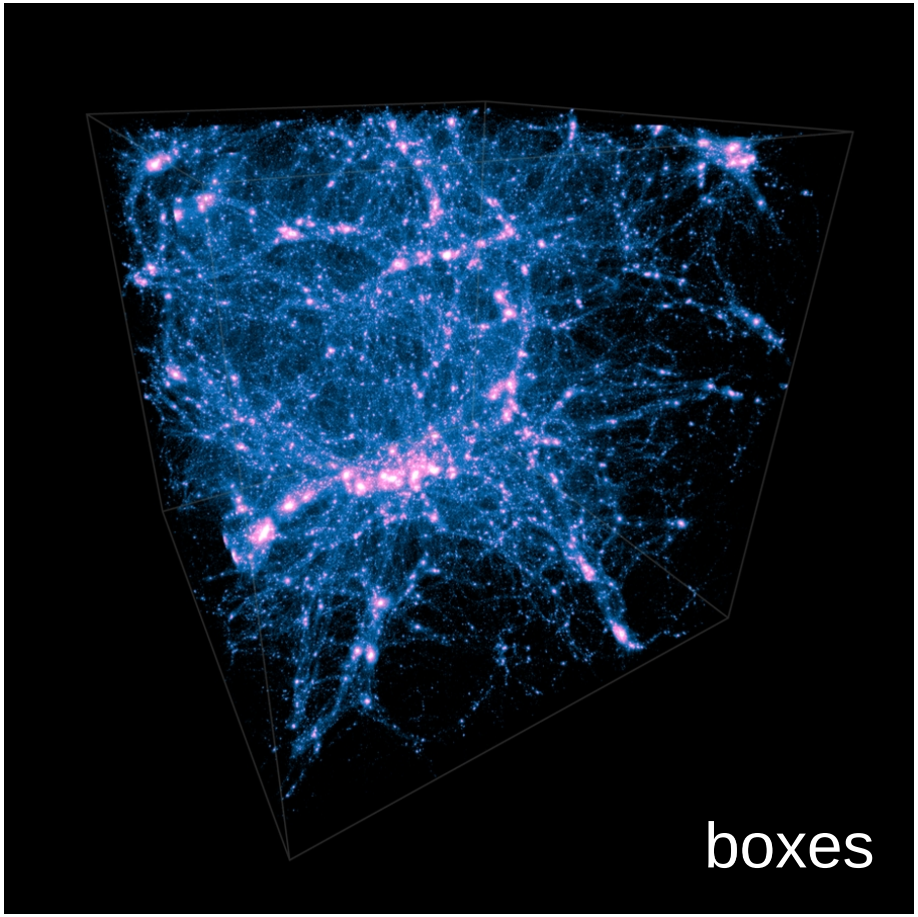
- It has proven to be difficult in practice (**politics**). Easier with analysis tools. Hopefully improving in the upcoming years (Agora, Scylla, ...)
- Done "within" the groups: different prescriptions encoded for the same physical process.

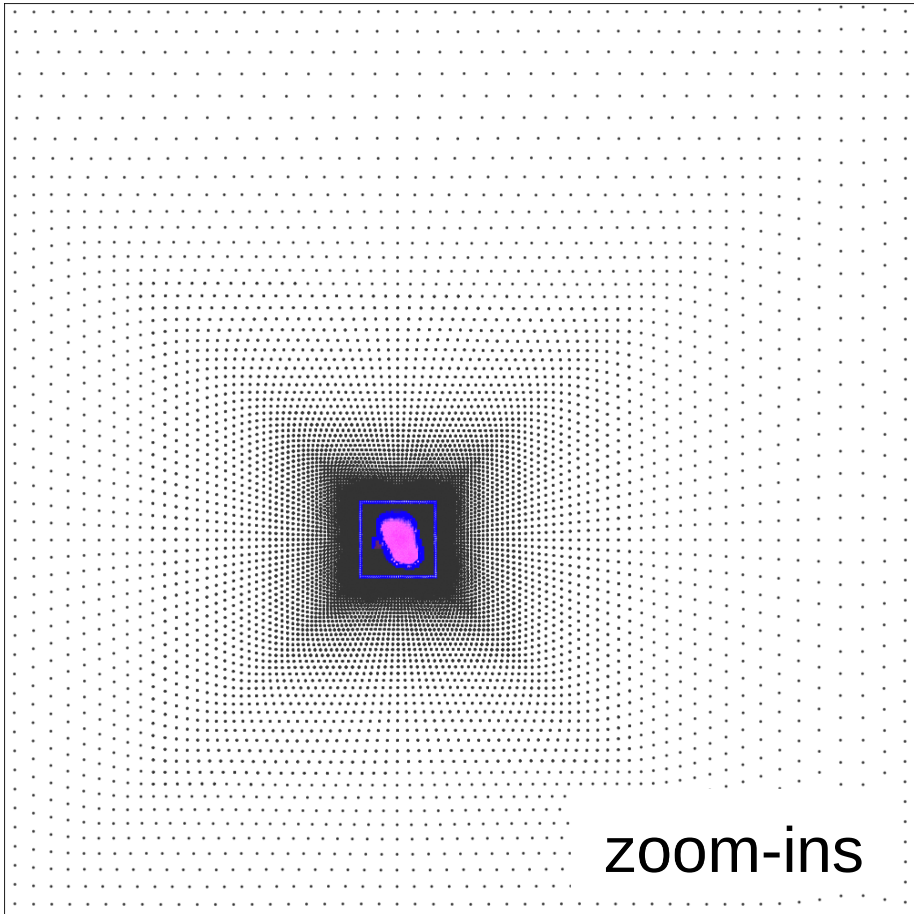


Aquila project (Scannapieco+2012)

Future directions

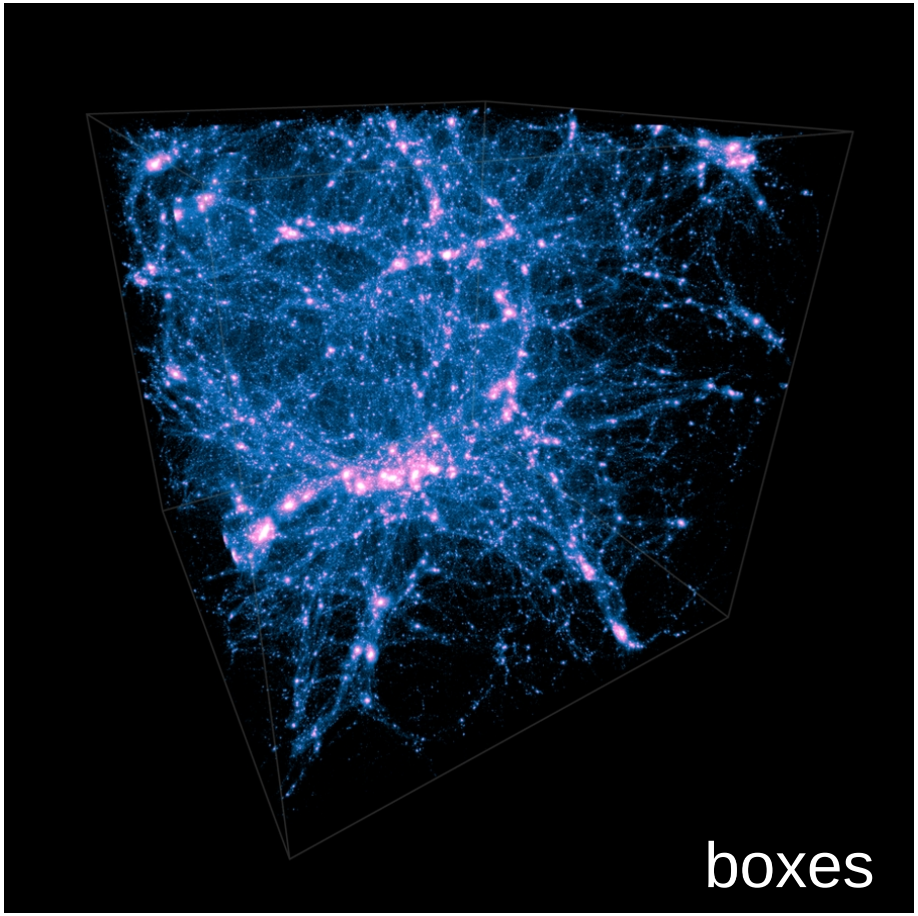
What to do with more computing power?





- More statistics
- More resolution

What to do with more computing power?



More statistics:

- Better sampling of the high-mass end and AGN feedback
- Larger volumes (~10 larger than state of the art or ~10^6 galaxies)

Challenges:

- Code scalability
- Memory consumption
- Data management (~PB)

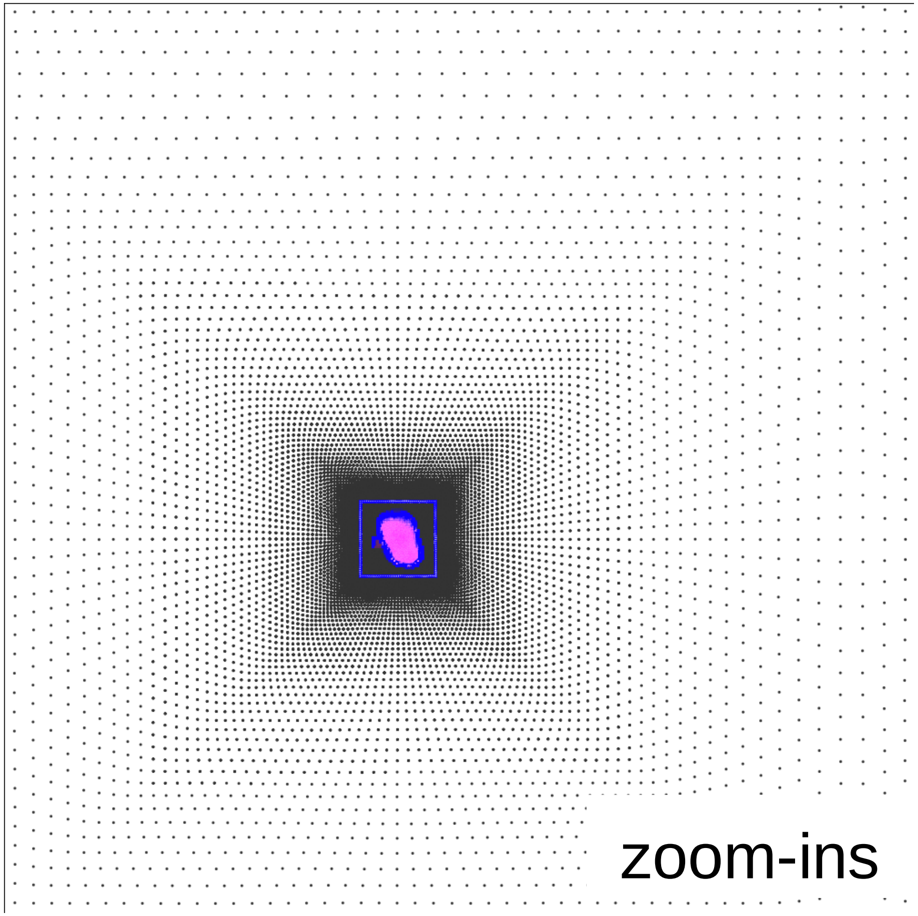
What to do with more computing power?

More resolution (goal ~ 1pc):

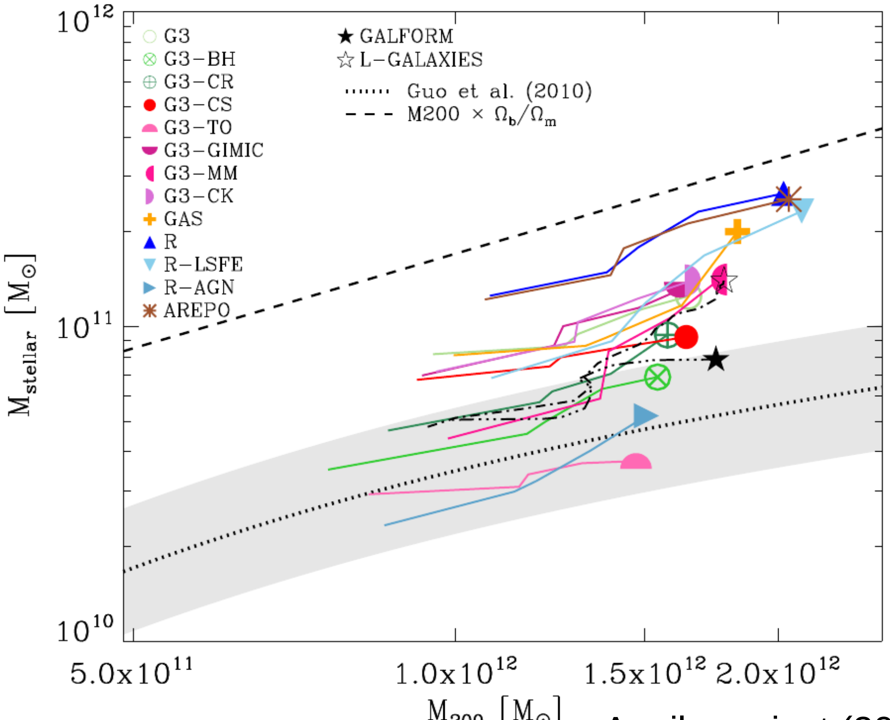
- More faithful implementation of physical processes (e.g. ISM physics)
- Stellar dynamics
- Exploration of the low-mass end (satellites)

Challenges:

- Load balancing (scalability)
- New physics implementation
- Convergence(?)

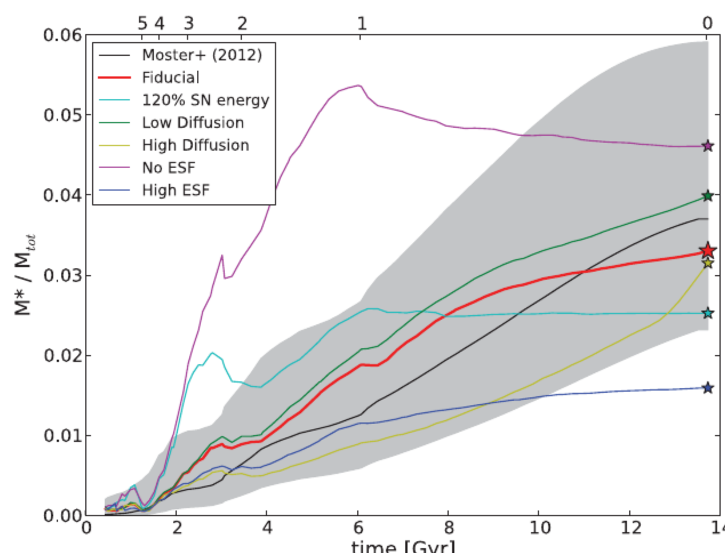


Stellar Masses



Aquila project (2012)

$M_*(z=0)$ was the **main benchmark** for hydrodynamical simulations **until the 2010's**



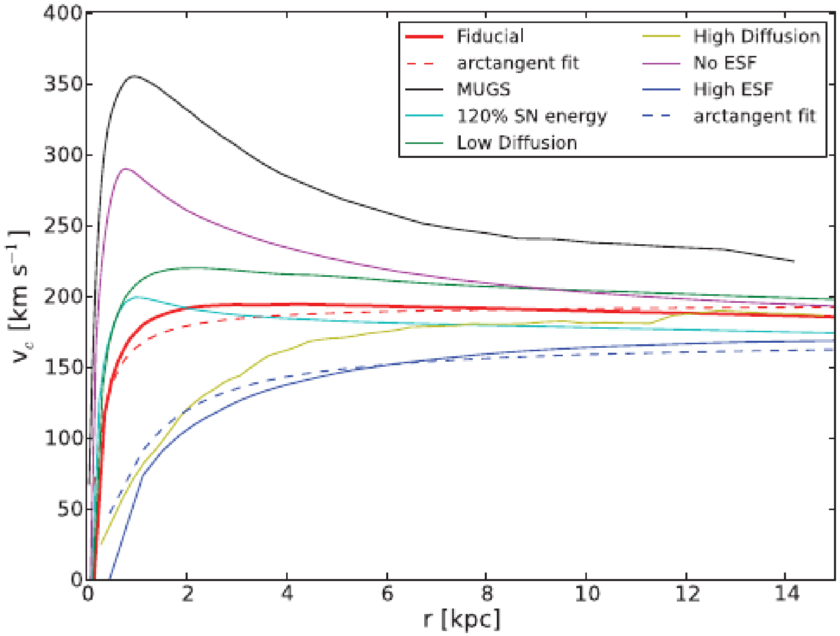
MAGICC project (2013)

Current status: full star formation rate history compatible with observations (from abundance matching)

Future: Stochasticity of the IMF...

Structure

Stinson+2013

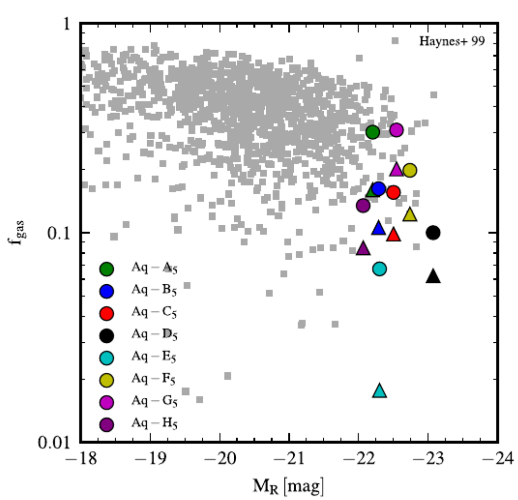


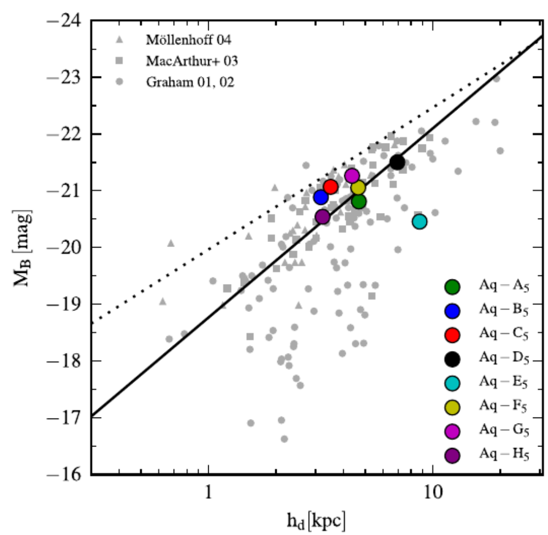
In the inner part of galaxies subgrid physics dominates what happens

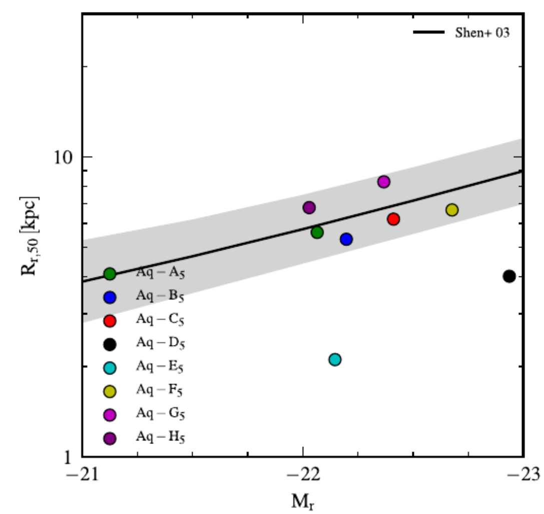
We have structural observations to constrain it from gas and stars

Question: how typical is the MW?

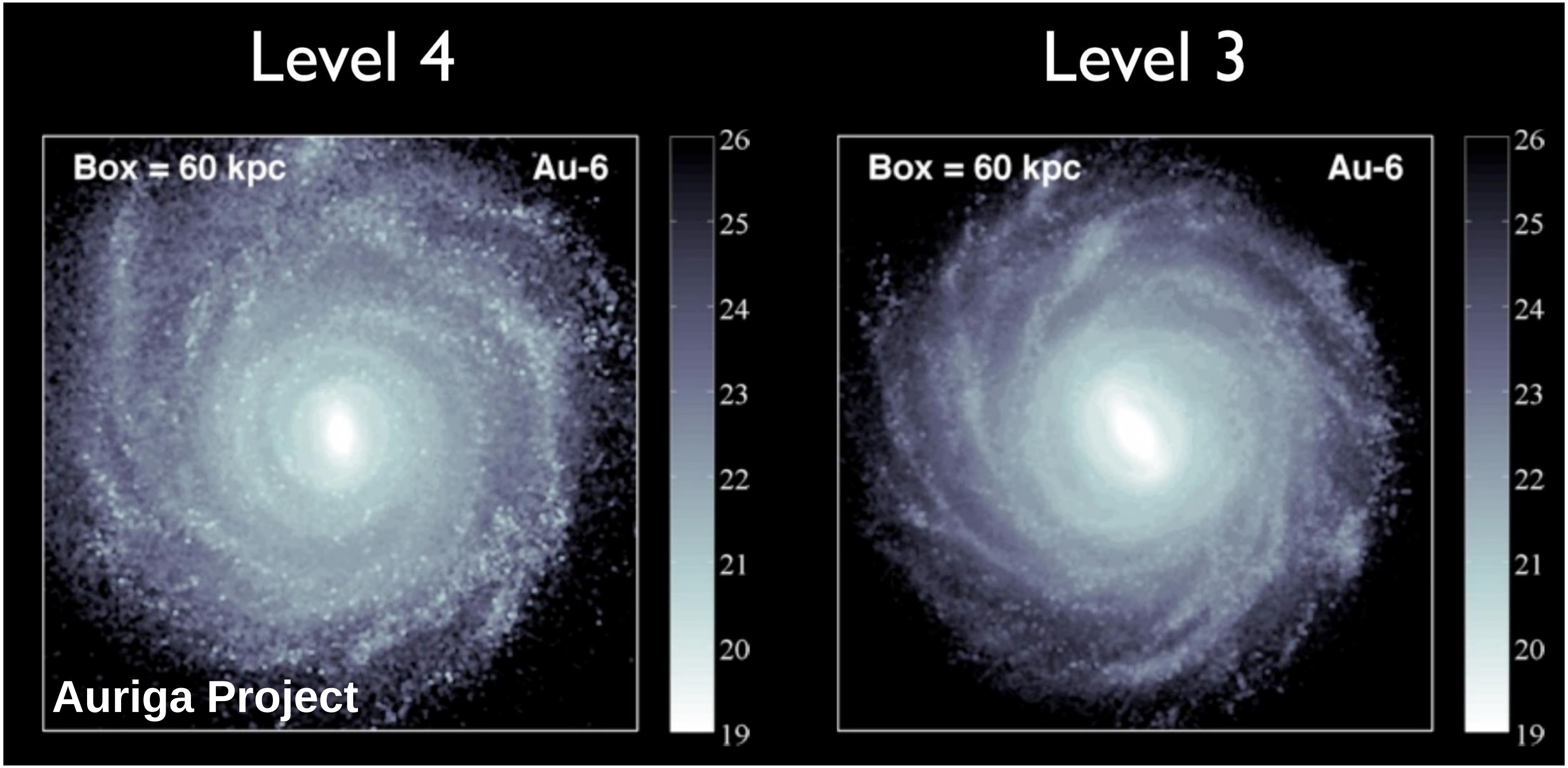
Marinacci+ 2015







Morphologies & disk



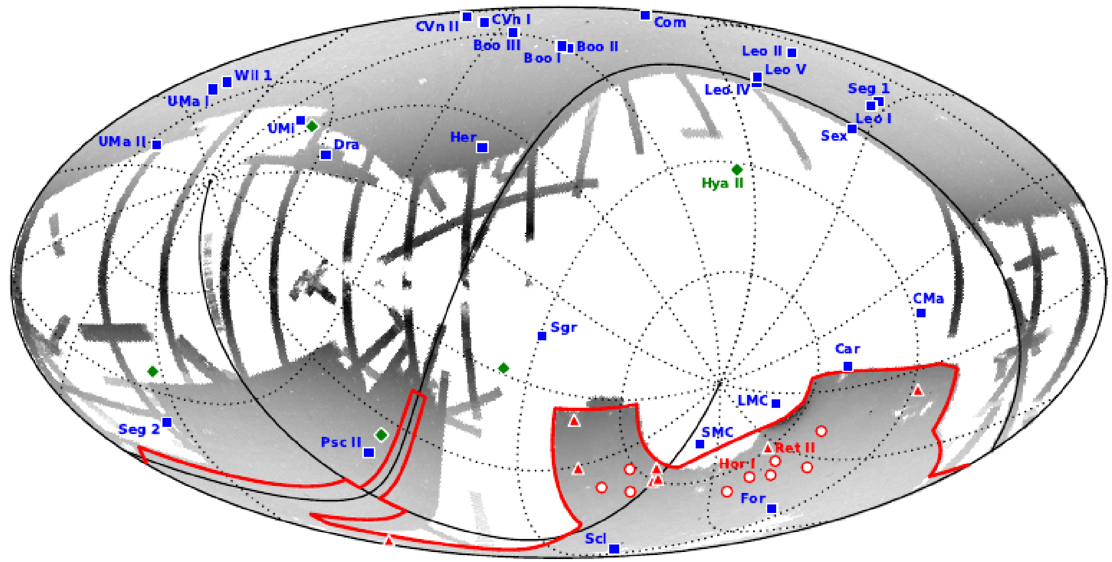
Forming a realistic disc both in terms of morphology and kinematics

Current challenges: thin disk (requires higher resolution? More realistic physics?)

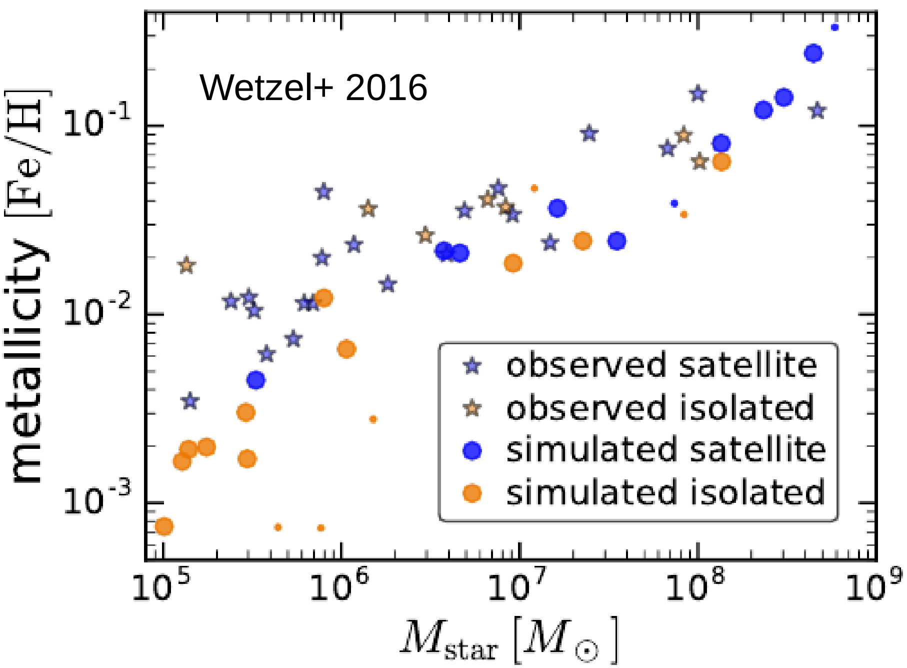
Satellites

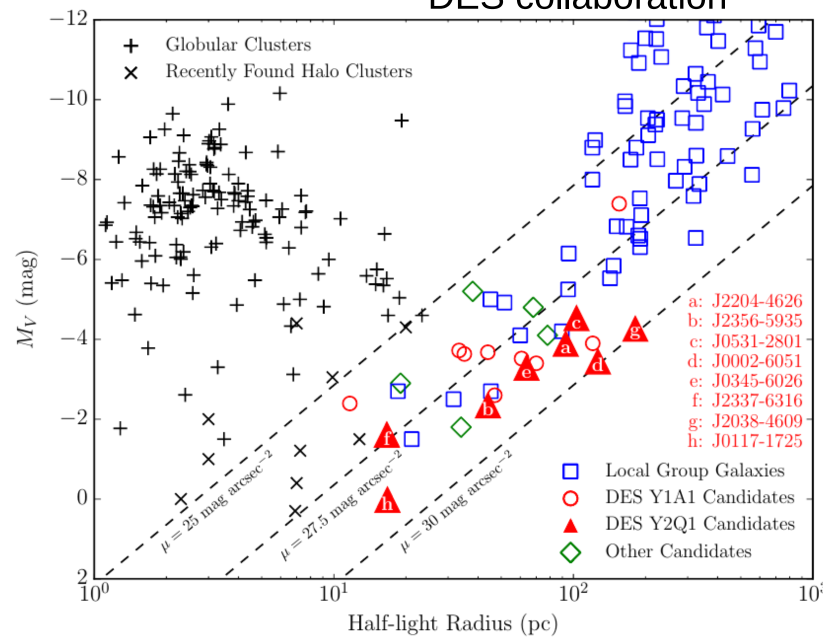
High resolution is also essential to simulate satellite galaxies:

- Properties of dwarfs and ultra-faint galaxies
- Accurate modeling of environmental effects (ram-pressure, tidal interactions...)

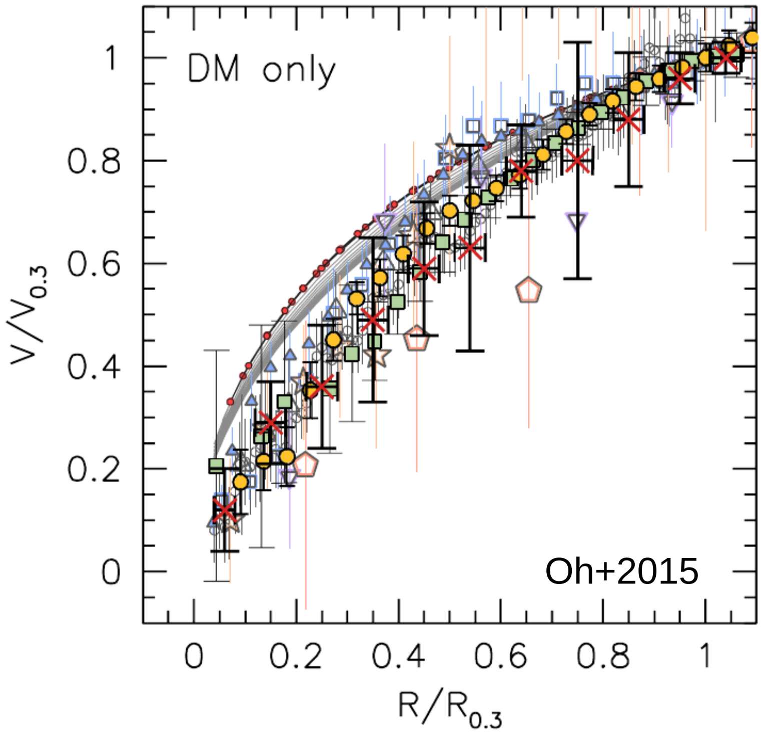


DES collaboration



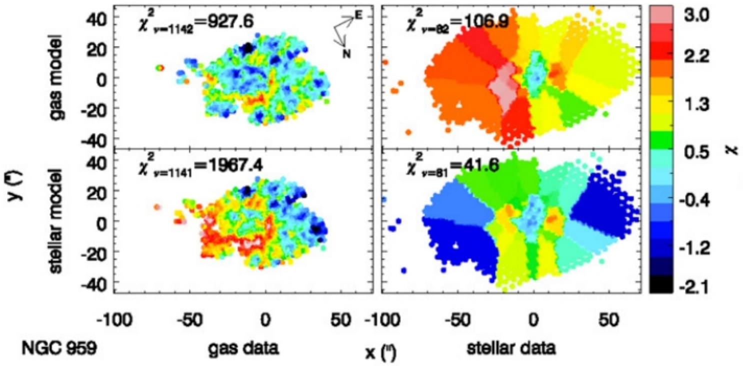


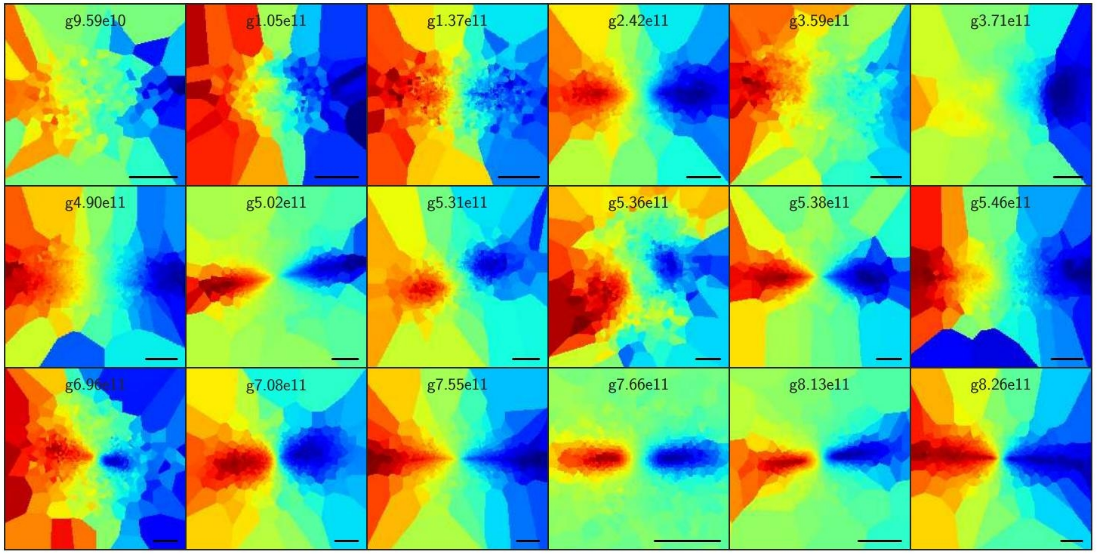
Detailed Kinematics



New simulations will also allows to do direct detailed comparison with kinematic data:

- Important observable to constrain mass content in galaxies: better understand systematics and limits
- **Current challenges:** incredible amount of 2D kinematic data (Integral Field) still to be reproduced from dwarfs to biggest galaxies



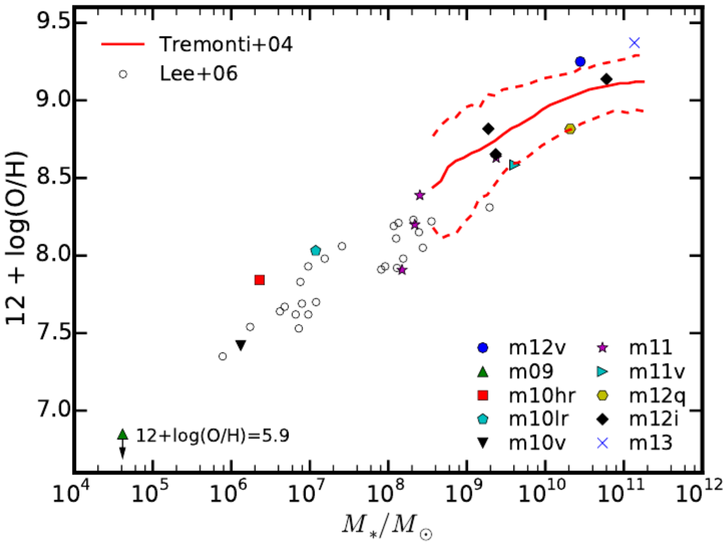


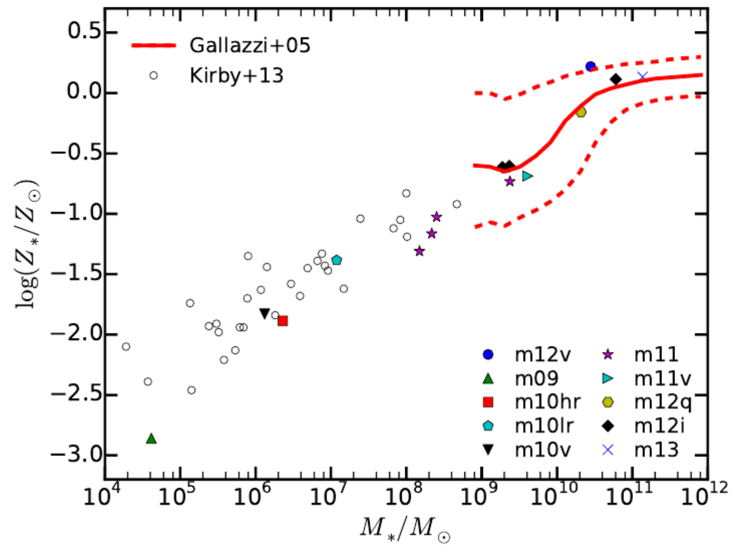
Adams+2014

Obreja+2016

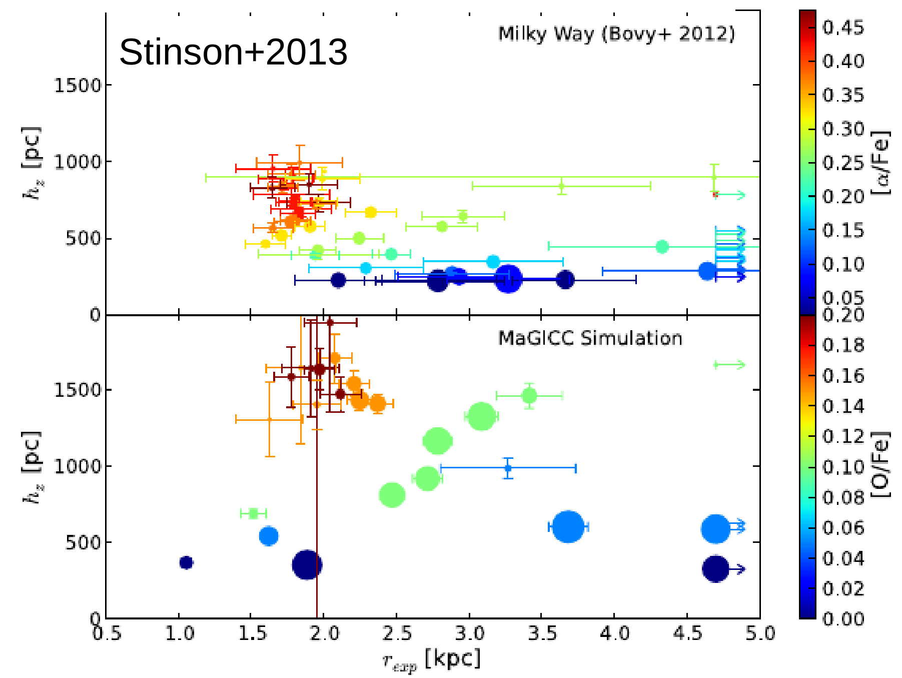
Metallicities

Ma+2016





Tight metallicity - stellar mass relation observed which is another constraint recently become standard.



Future:

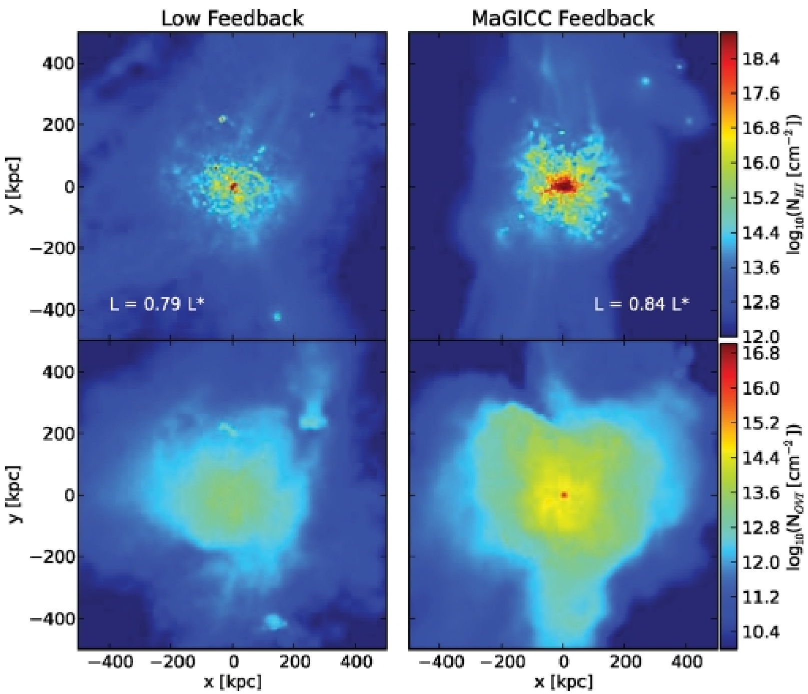
- Stellar structure and metallicity combined could help us constrain this (Brook's point). Lots of data on this from nearby galaxies.
- Possible avenue to explore with GAIA data

CGM

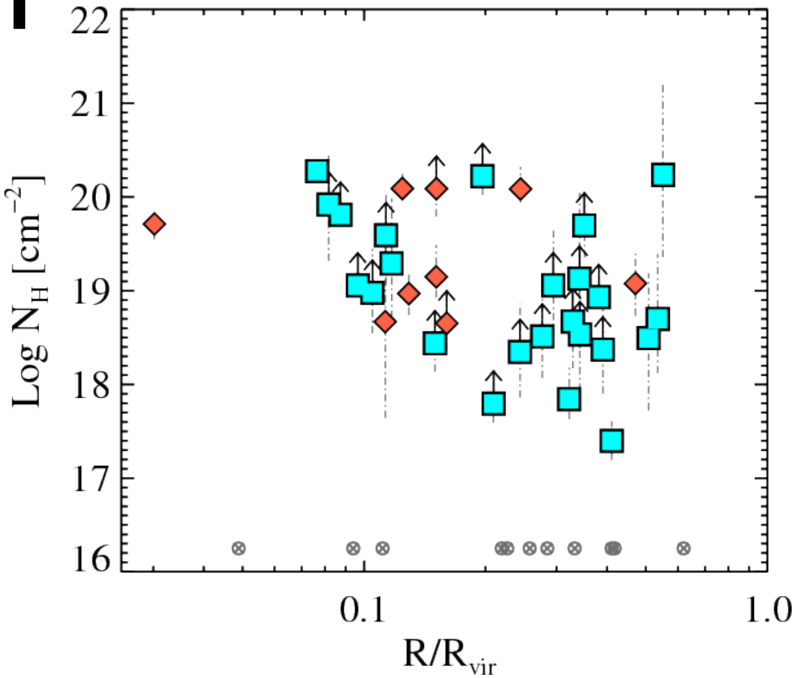
We also have observations of the gas properties around galaxies

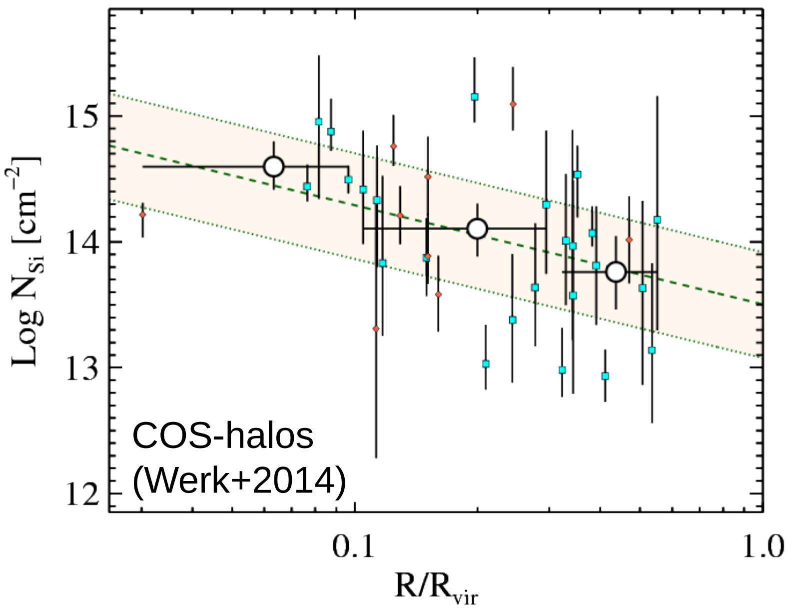
- CGM densities and metallicities as a current/future tighter constraint on feedback, and baryon content

- X-rays constraints: difficult but keep improving



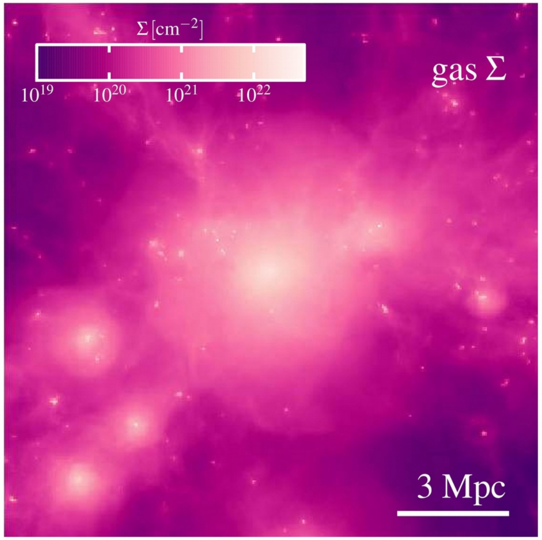
Stinson+2012

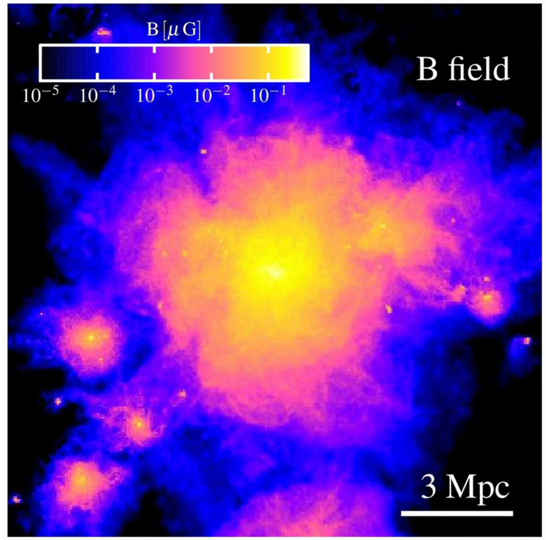


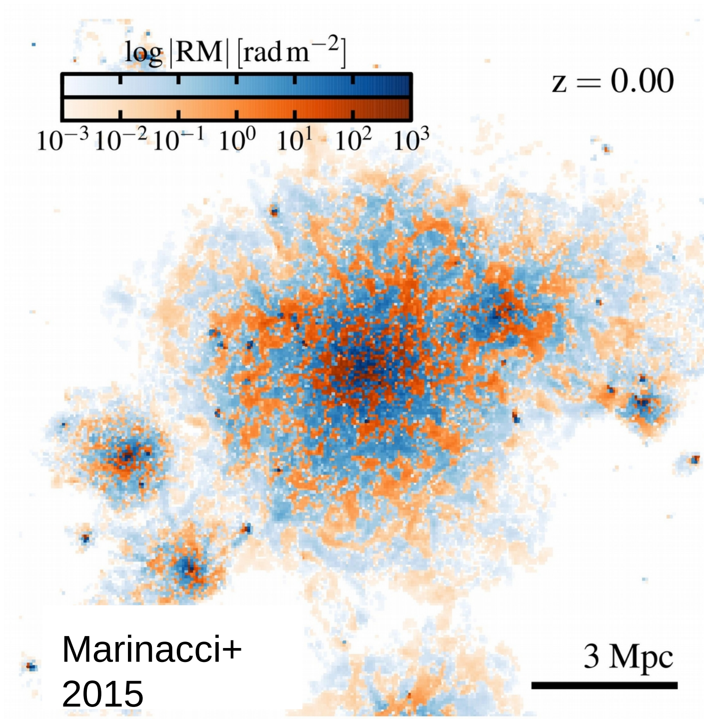


Upcoming physics

Magnetic Fields







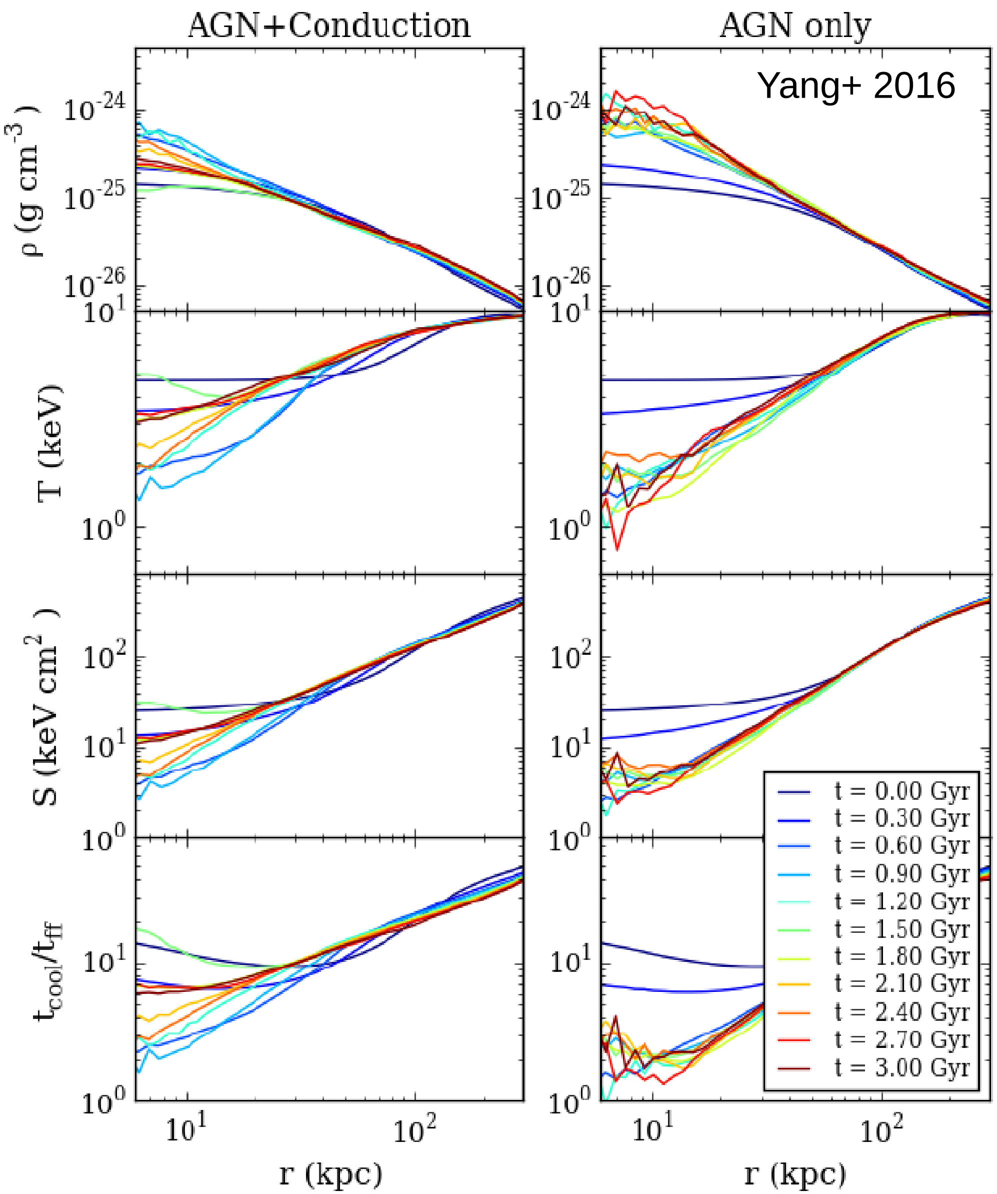
Marinacci+ 2015

Already included in cosmological simulations!

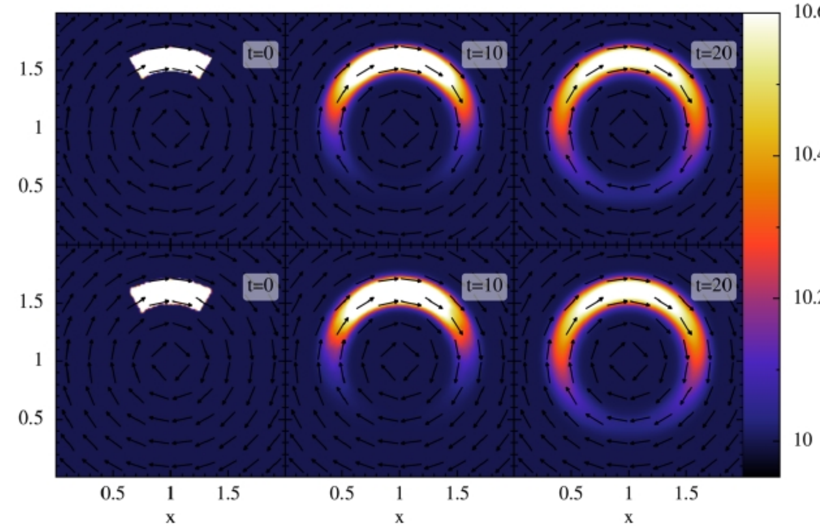
- Important for many astrophysical phenomena (for instance in the ISM)

- Higher resolution:
  - better study of B field amplification processes (dynamo)
  - inclusion of diffusive effects (resistivity, ambipolar diffusion...)

Thermal Conduction



Kannan+ 2016



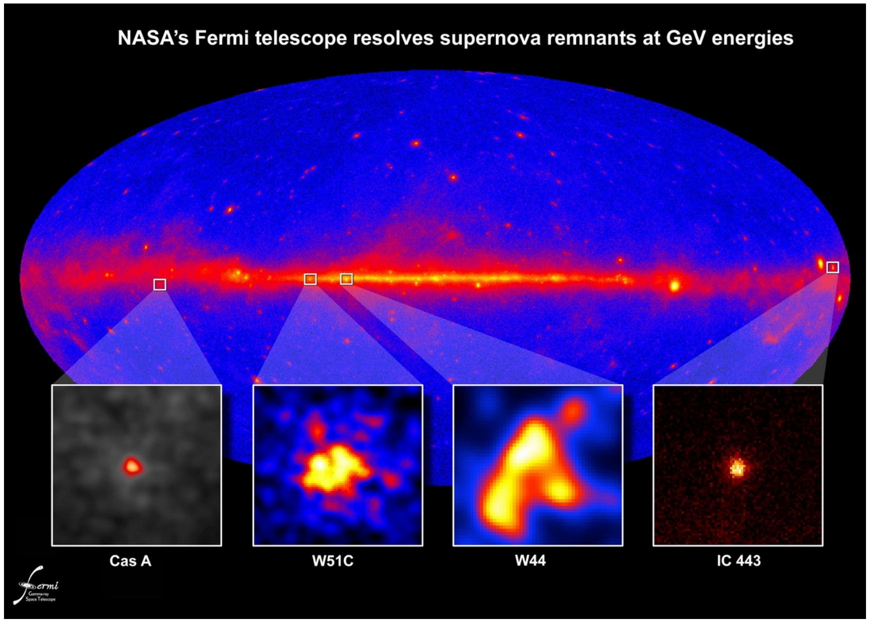
Important in high temperature plasma

Many studies focus on galaxy clusters (help alleviate cooling flows)

Tricky to implement numerically:

- Time step restrictions
- Anisotropic process with magnetic fields

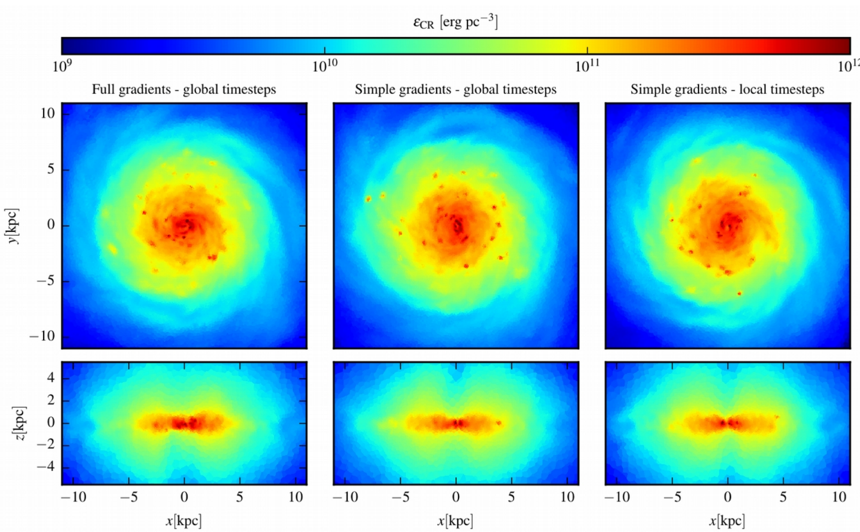
Cosmic Rays



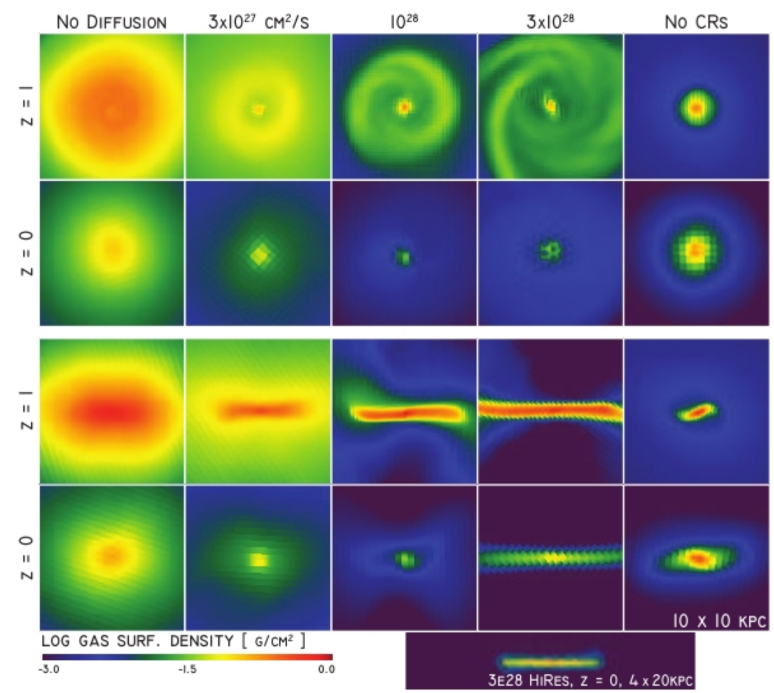
High energy particles produced by different phenomena.

Simulations model CR as a relativistic fluid. Currently only CR coming from Supernova but probably more in the near future. **Anisotropic transport** processes are important.

Hot topic! Expect results in the upcoming years.

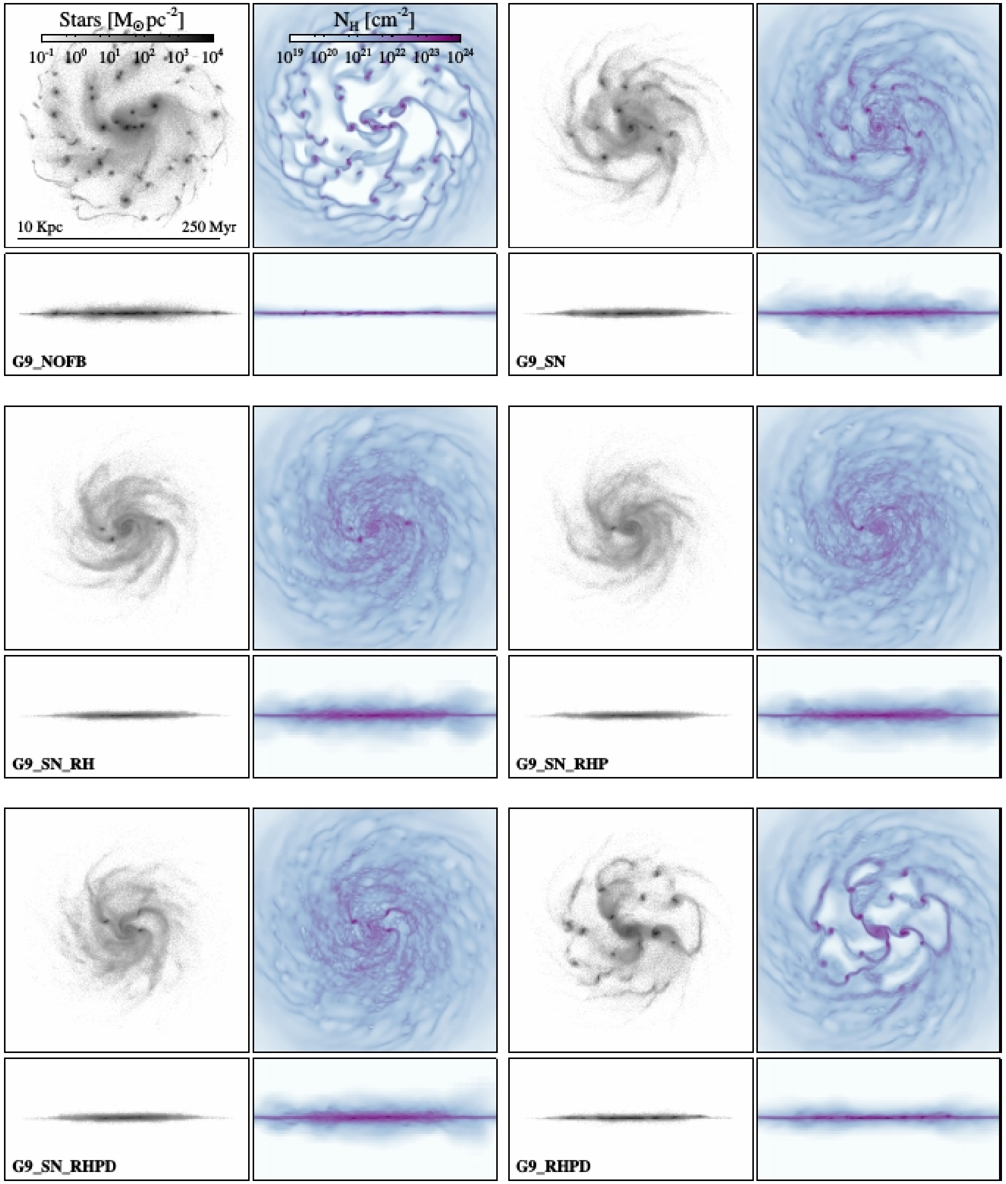


Pakmor+2016



Salem+2014

Radiative transfer



Ideally using radiative transfer codes will allow us to reduce several subgrid physics models.

Codes exist and keep improving but are **not able** to cover the **dynamical range** needed for galaxy formation.

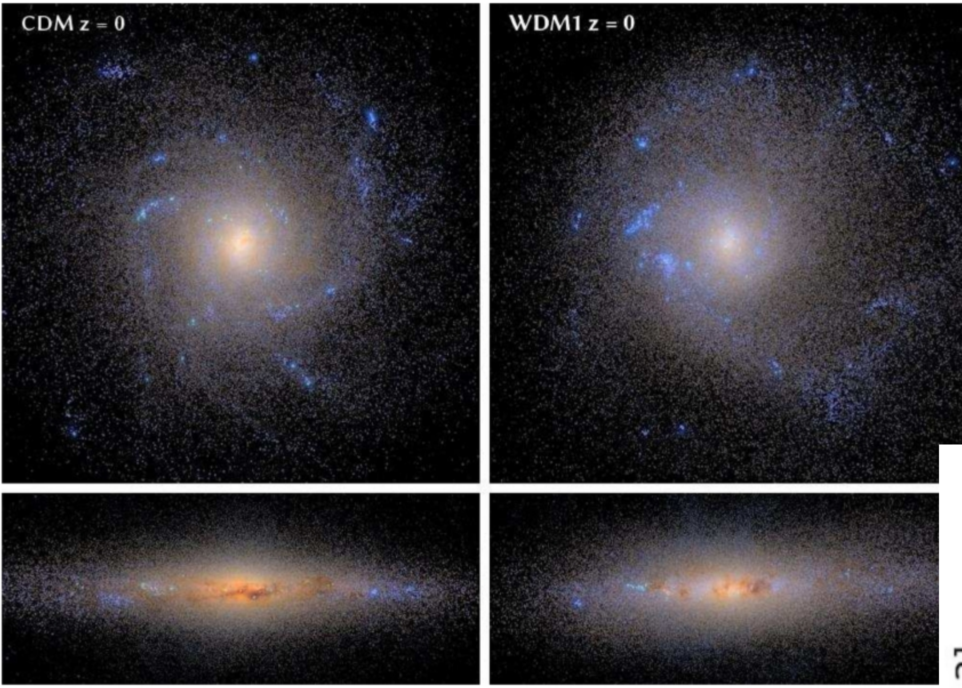
Currently:

- Non cosmological runs ~20 pc. Very helpful to understand baryonic processes and build effective models
- Cosmological runs can only be run down to z~4 (best case, several kpc resolution).

Semi radiative transfer codes: radiative transfer codes combined with subgrid physics.

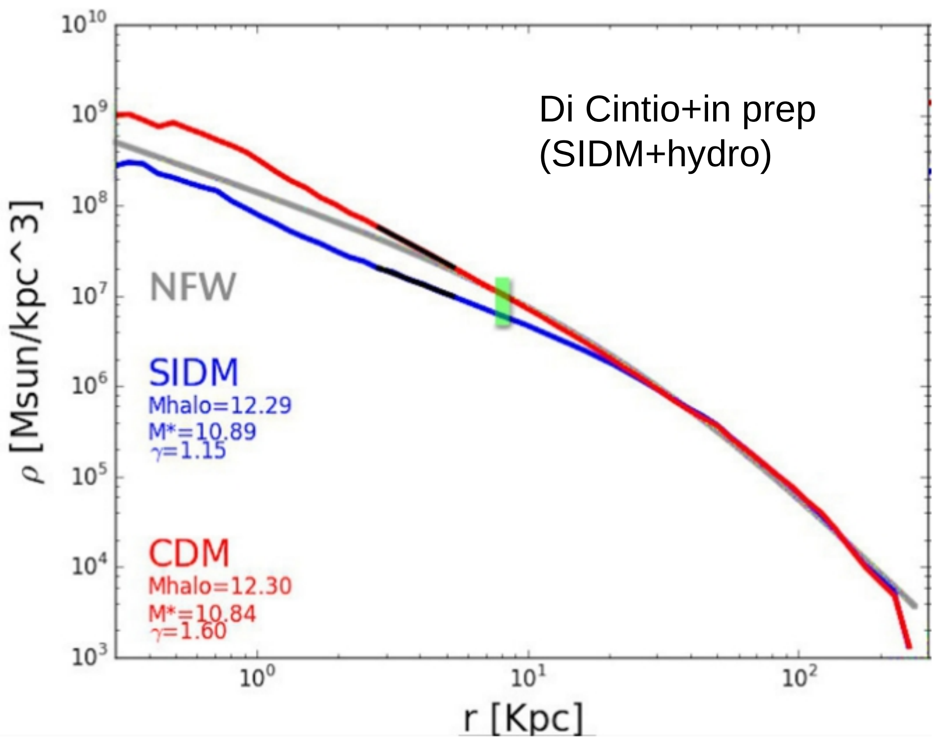
Rosdahl+2015

Self-interacting/warm DM



Herpich+2014
(WDM+hydro)

Several efforts to improve SIDM/WDM computational methods in the last years



Now with hydrodynamics!
Baryonic physics enhance or erase the effects?

Summary

- Cosmological hydrodynamical codes are (and will be in the next years) under constant development, both from computational and physics perspectives.
- The amount of data available to constrain simulations is already huge. This is good.
- As we move forward, different simulated observables become more solid, and groups (hopefully) converge on the role of different physical processes.
- The trick is decide (and agree) which observations we should focus our efforts on based on constraining power and lack of systematics.

FUTURE IS BRIGHT BUT PROBABLY SLOWER THAN WHAT WE WOULD WANT

Summary

proceedings). I found that the evolution is well fitted by

$$N = 400 \times 10^{0.215(\mathrm{Year}-1975)}, \qquad (1)$$

where the amplitude is normalized to the work of Miyoshi & Kihara (1975). Just for comparison, the total number of CDM particles of mass m_{CDM} in a box of the universe of one side L is

$$N = \frac{\Omega_{\mathrm{CDM}}\rho_{\mathrm{cr}}L^3}{m_{\mathrm{CDM}}} \approx 10^{83}\left(\frac{\Omega_{\mathrm{CDM}}}{0.23}\right)\left(\frac{L}{1h^{-1}\mathrm{Gpc}}\right)^3\left(\frac{1\mathrm{keV}}{m_{\mathrm{CDM}}}\right)\left(\frac{0.71}{h}\right). \qquad (2)$$

If I simply extrapolate equation (1) and adopt the WMAP parameters (Spergel et al. 2003), then the number of particles that one can simulate in a $(1h^{-1}\mathrm{Gpc})^3$ box will reach the real number of CDM particles in December 2348 and February 2386 for $m_{\mathrm{CDM}} = 1\mathrm{keV}$ and $10^{-5}\mathrm{eV}$, respectively. I have not yet checked the above arithmetic, but the exact number should not change the basic conclusion; simulations in the new millennium will be *unbelievably* realistic.

Suto (2005)