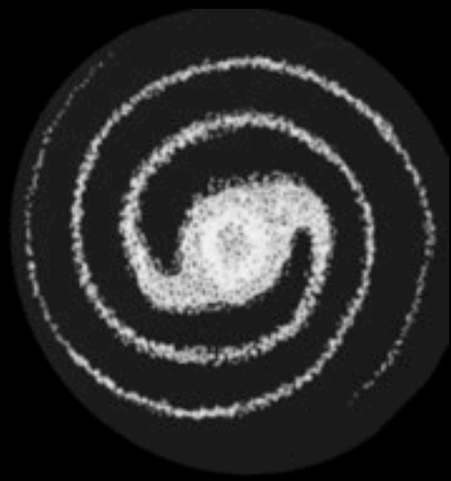
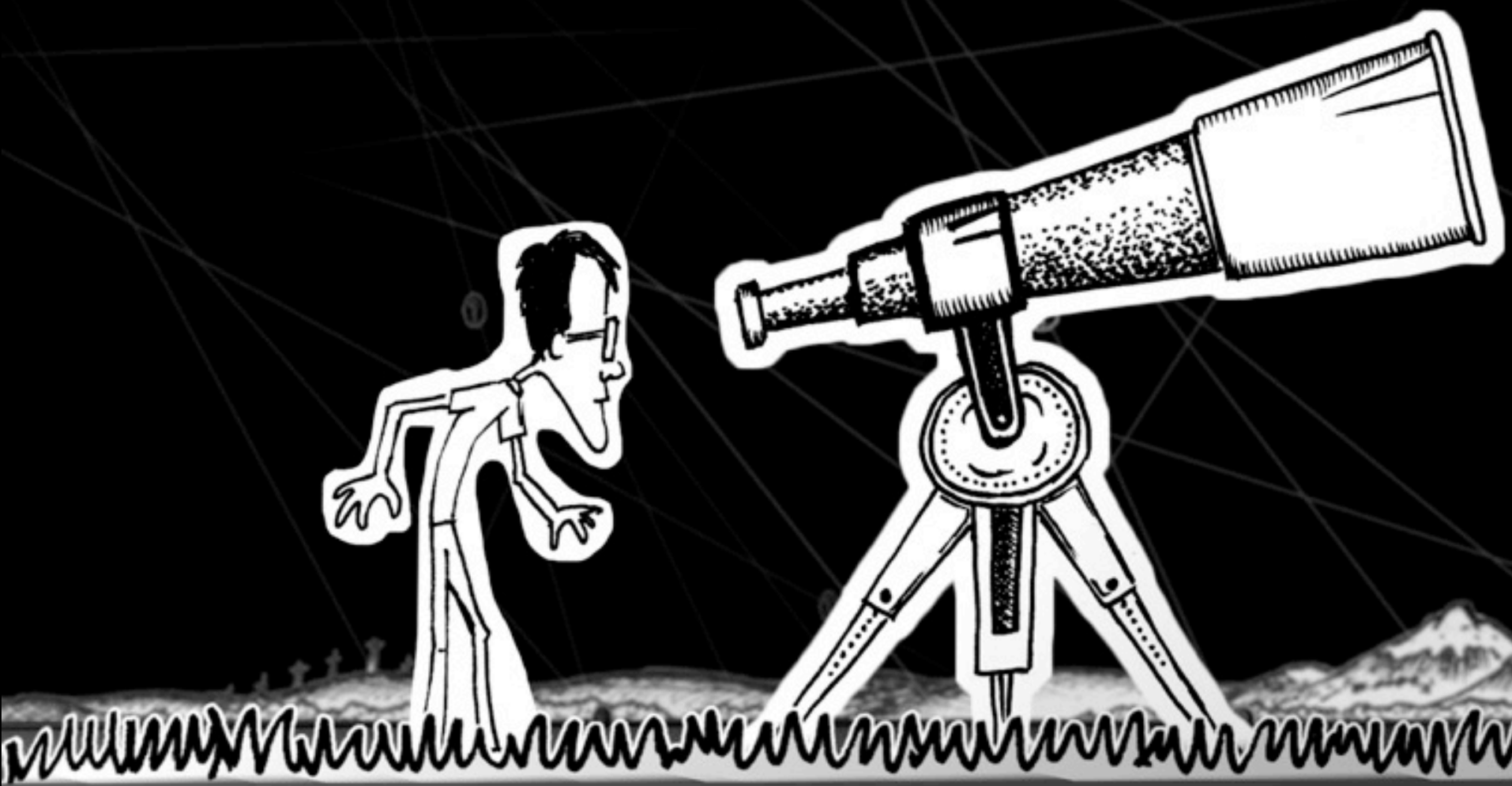
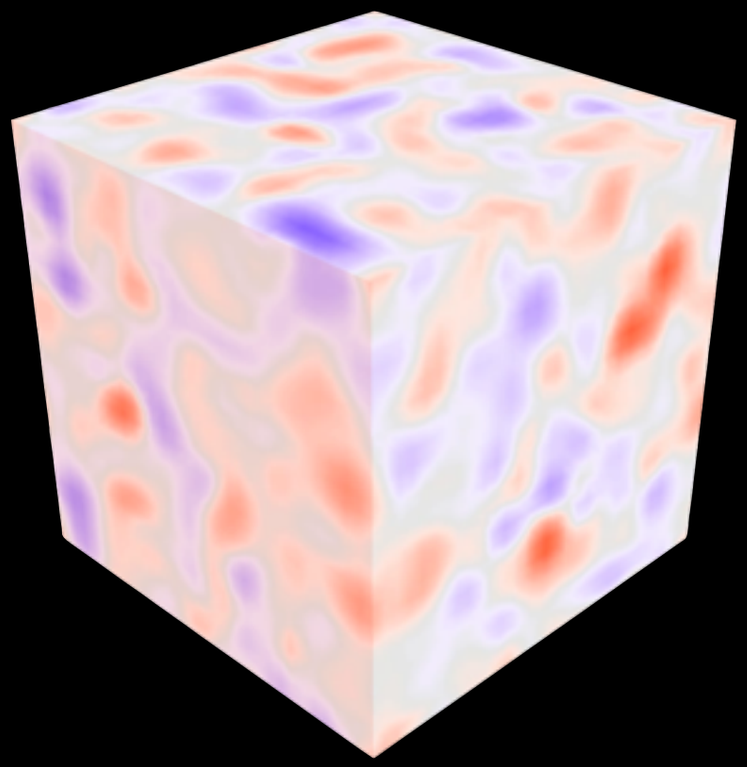
Simulating the Universe



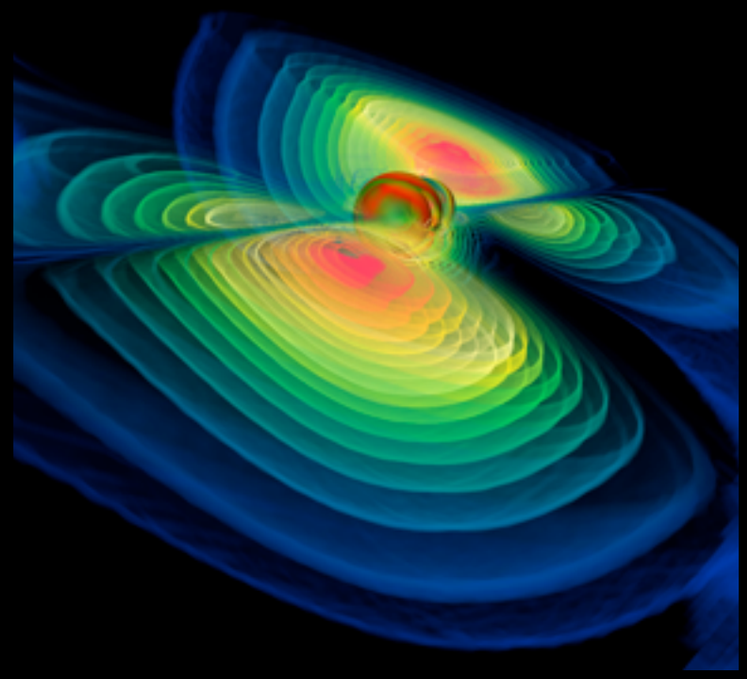


Andrew Pontzen
Oxford Astrophysics

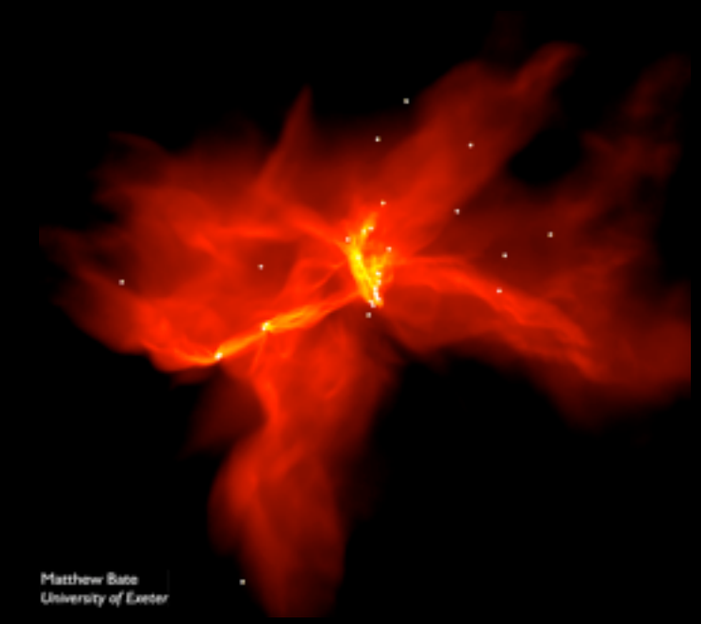
Species of simulation

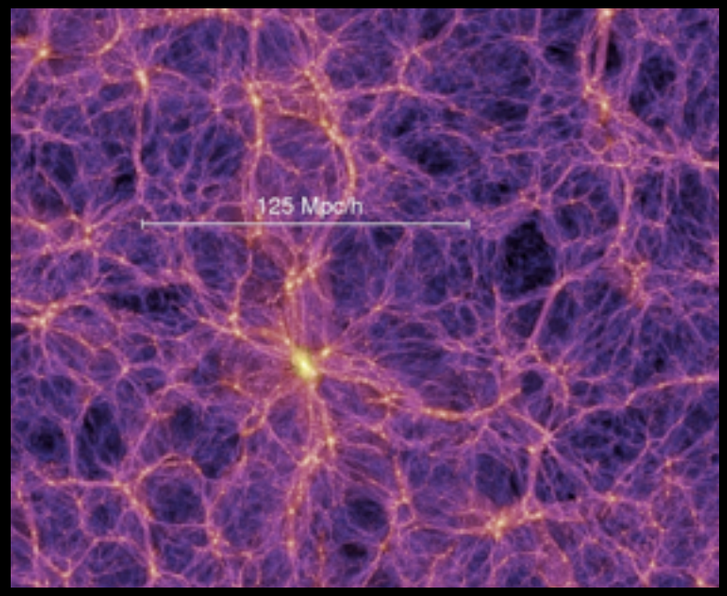


field theory



relativistic





non-relativistic

gravity

basic physics

fluid mechanics

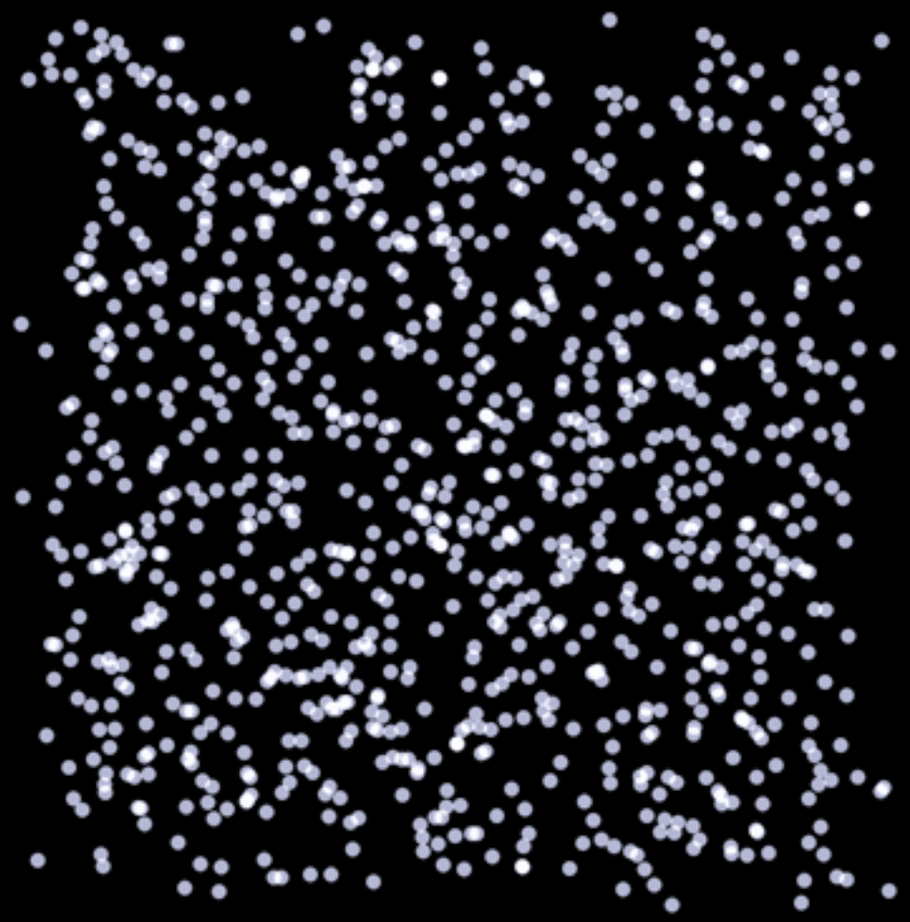
magnetohydrodynamics

initial conditions

simulation

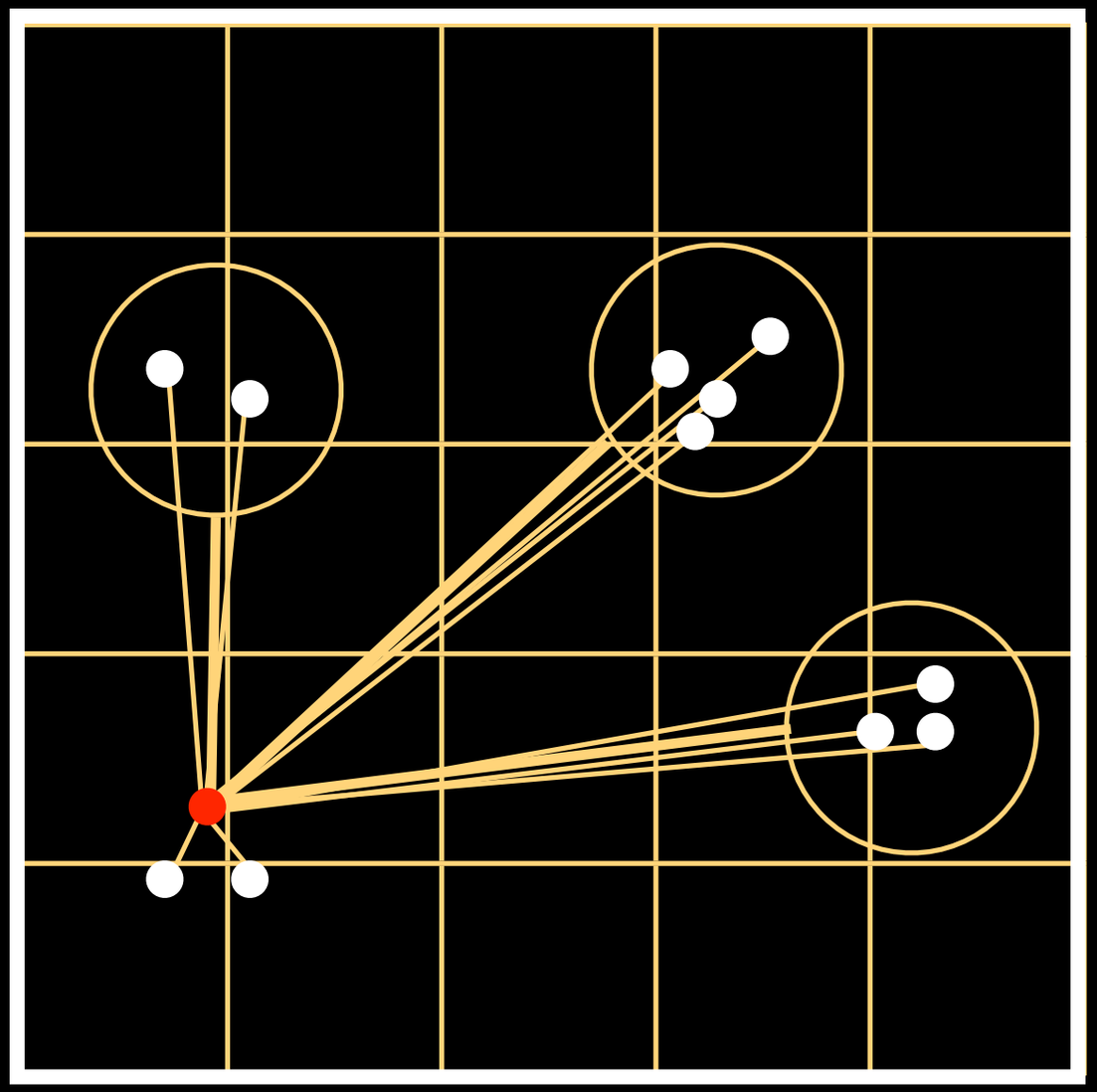
virtual observations

Dark matter: gravity alone



$$F_i = \sum_j GM_j |x_i - x_j|^2$$

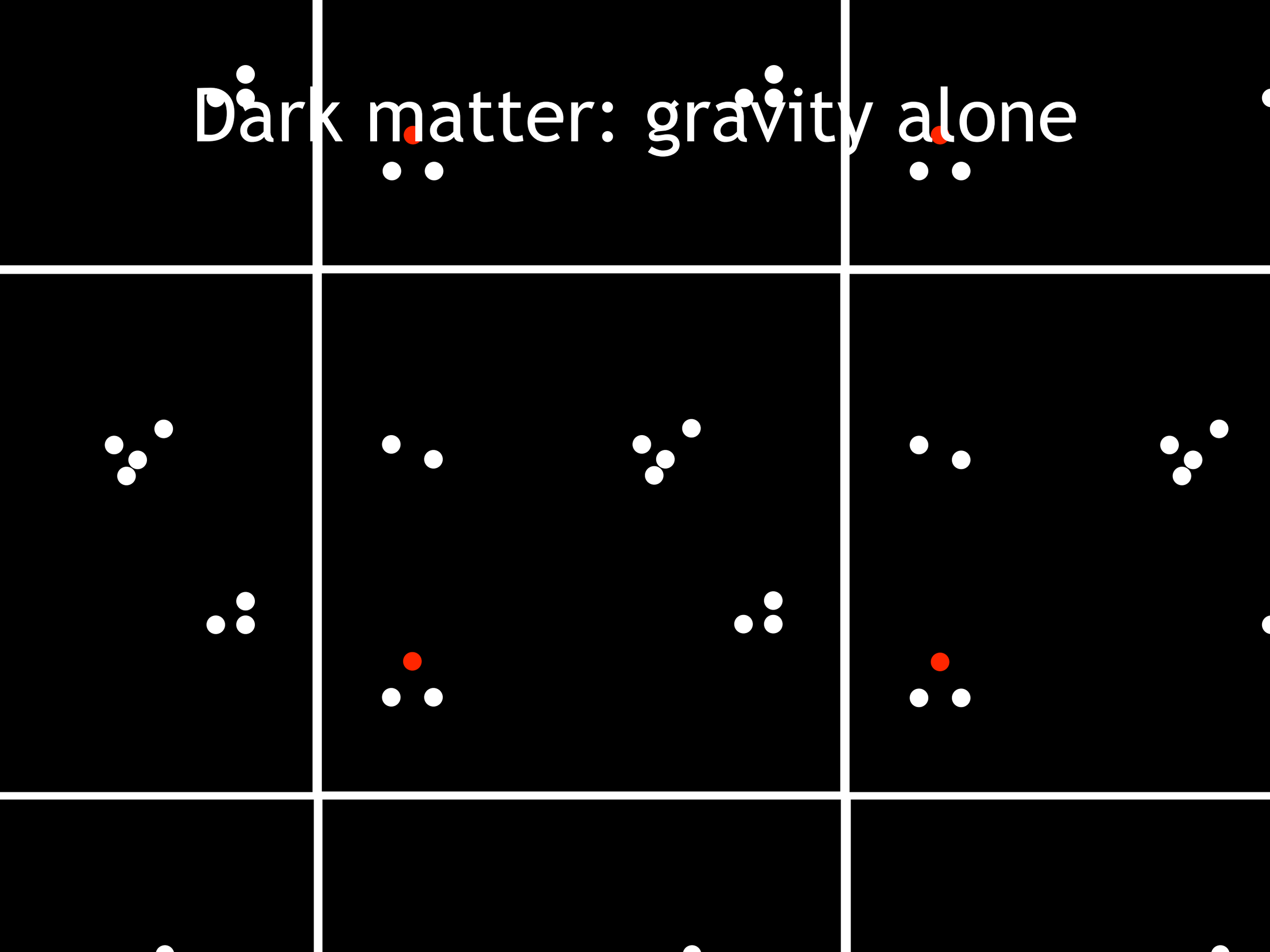
Dark matter: gravity alone



N log N
operations
per timestep

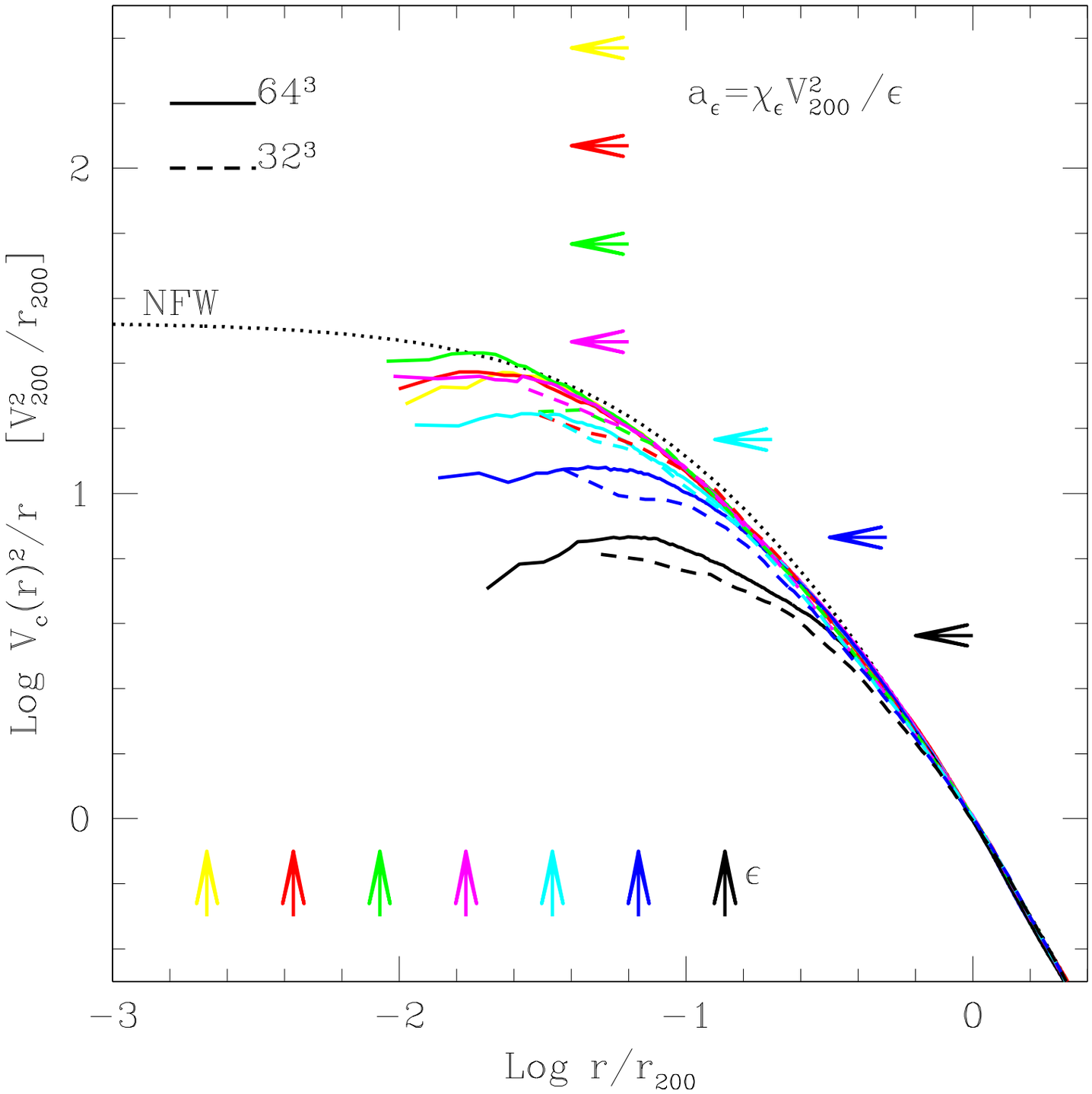
N^2 operations
per timestep

Dark matter: gravity alone

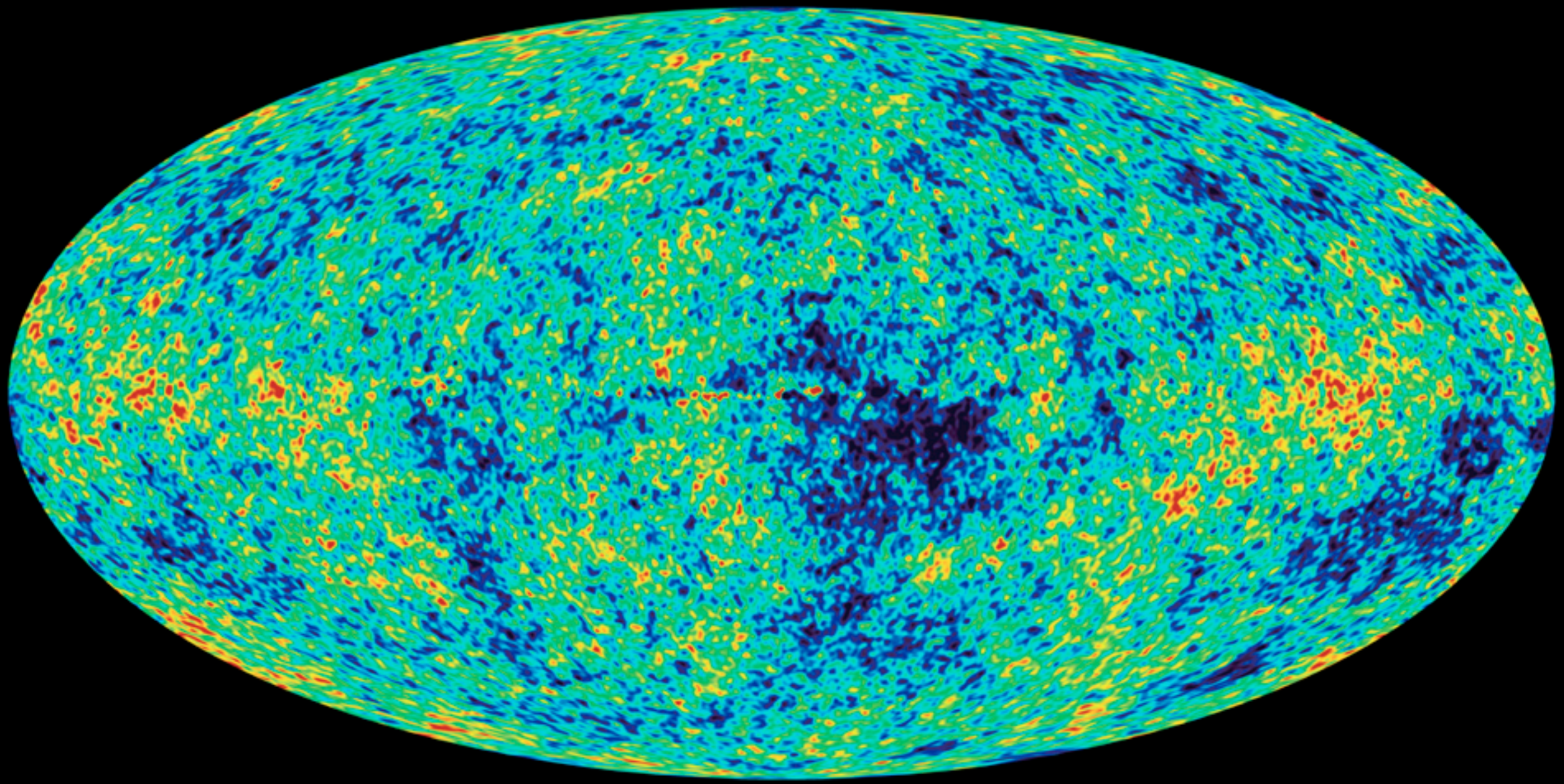


$$\frac{\text{mass in horizon}}{100\ \text{GeV}} \sim 10^{77}$$

“Millennium-XXL” ~ 10^{11}


64³
32³
$a_\epsilon = \chi_\epsilon V_{200}^2 / \epsilon$
NFW
ϵ
Log $V_c(r)^2/r$ $[V_{200}^2 / r_{200}]$
Log r/r_{200}
2
1
0
−3
−2
−1
0

Power+ 2003



Galaxy formation sequence by **Andrew Pontzen**
for **BBC Stargazing Live** Series 2 ep 2.

Clip 1: the Big Bang to 1.7 billion years.

Dark matter only (green/yellow/white).

OXFORD MARTIN SCHOOL

UNIVERSITY OF OXFORD

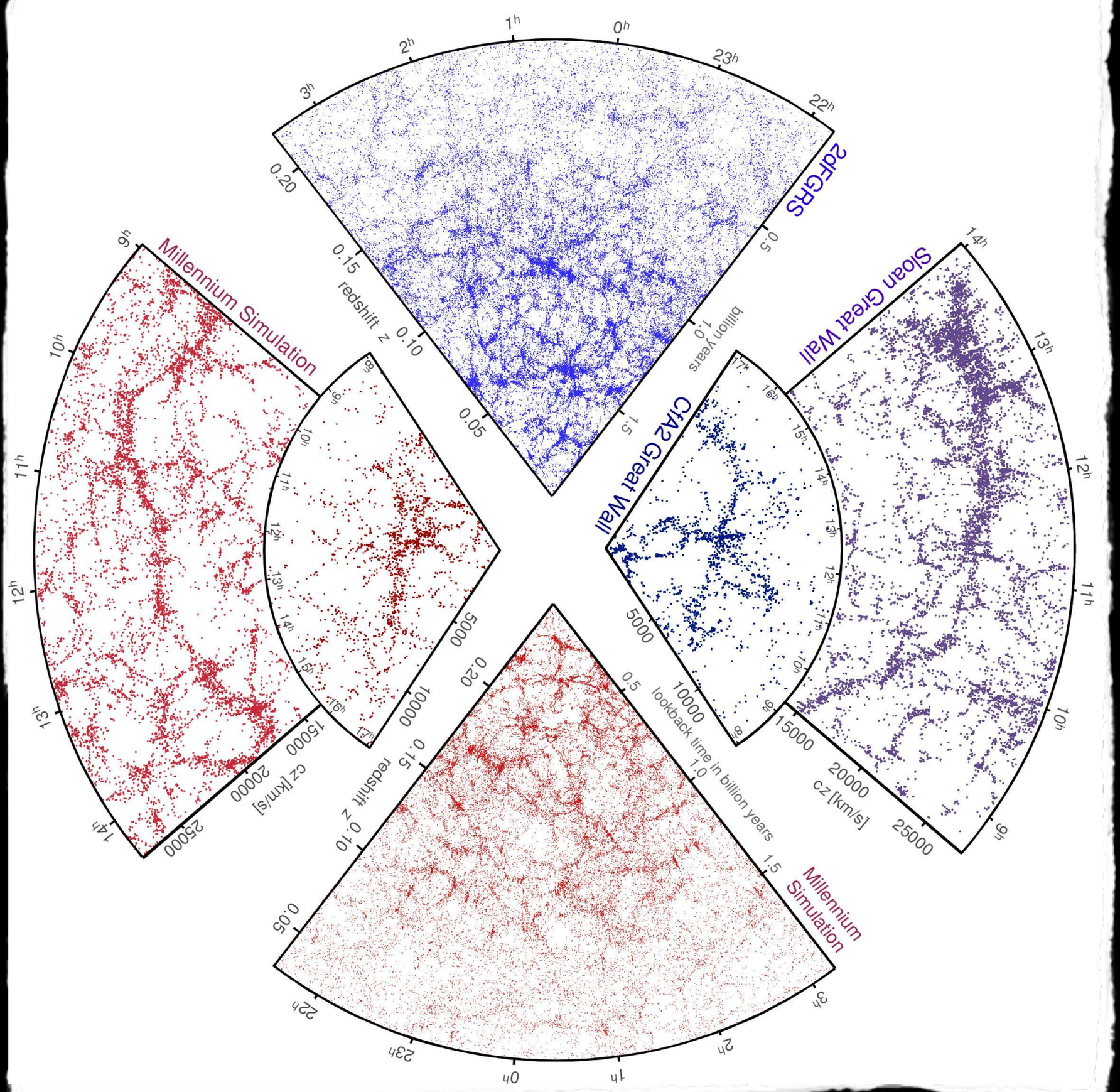
JAMES MARTIN 21ST CENTURY SCHOOL

www.cosmocrunch.co.uk / tweet @apontzen

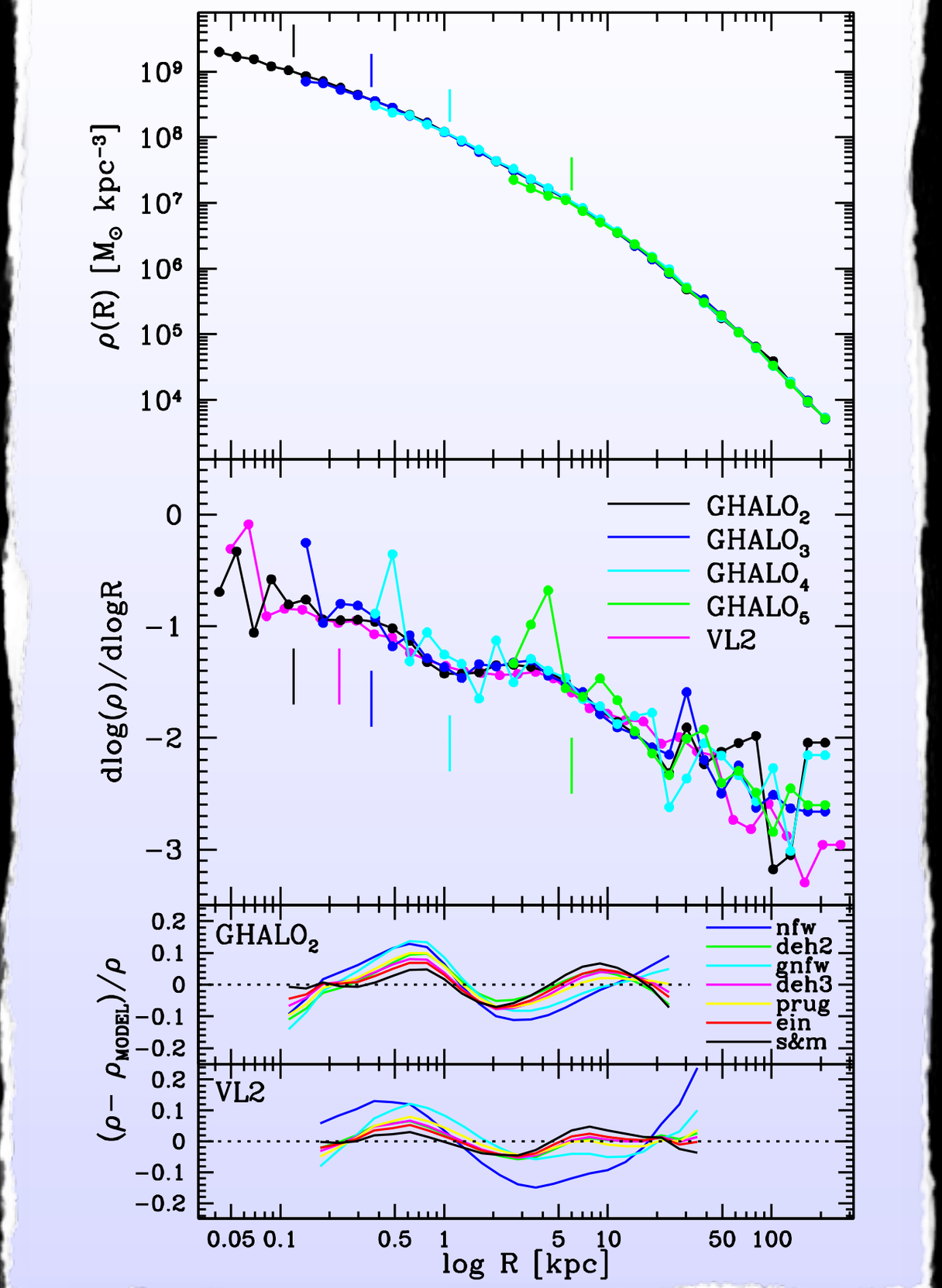
Simulations by Andrew Pontzen, Fabio Governato, Alyson Brooks, Jillian Bellovary on Berg (the University of Oxford's DiRAC facility, jointly funded by STFC and the large facility capital fund of BIS) and NASA's advanced supercomputing facility.

Rendered by Andrew Pontzen using **pynbody** (http://pynbody.googlecode.com) on Berg.

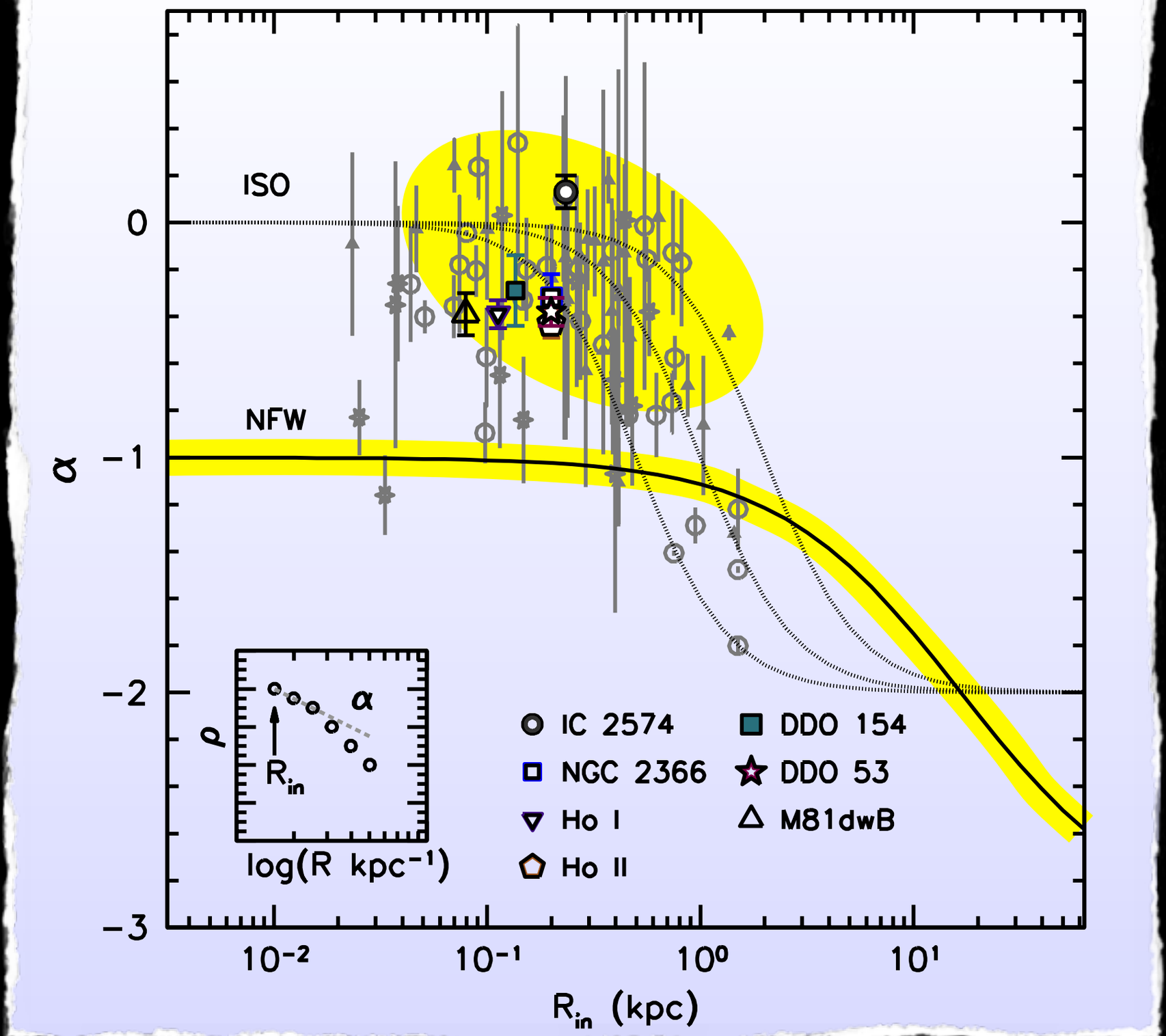
Simulation code **Gasoline** by James Wadsley and Tom Quinn.
Metal cooling by Sijing Shen. Molecular hydrogen physics by Charlotte Christensen.



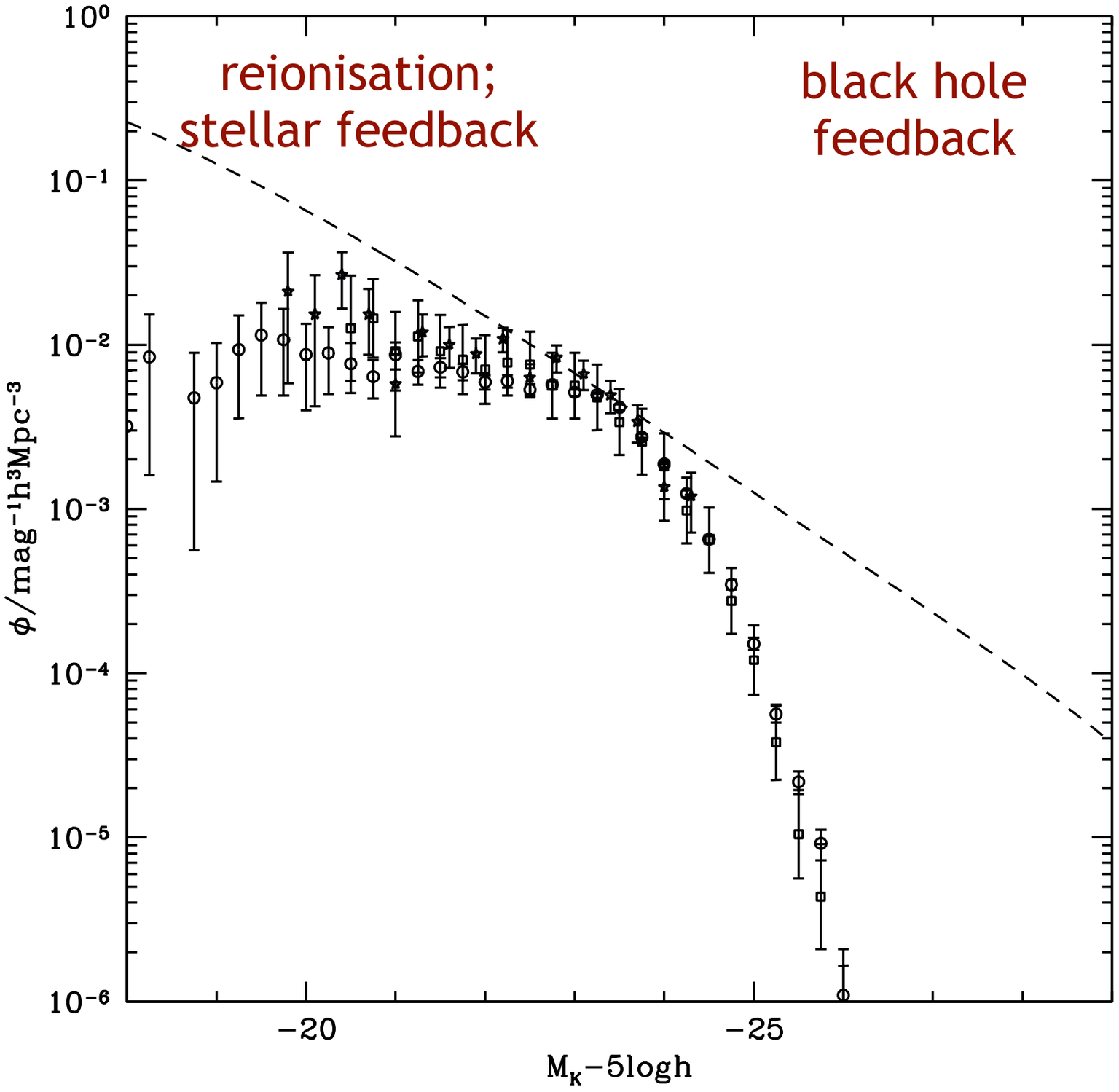
Springel, Frenk & White 2006



Stadel et al
2008 “GHALO”



Oh et al
2011, AJ



Benson et al 2003

gravity

basic physics

fluid mechanics

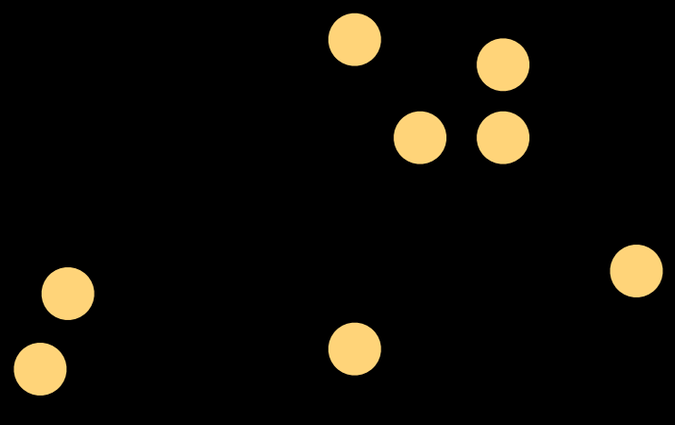
magnetohydrodynamics

initial conditions

simulation

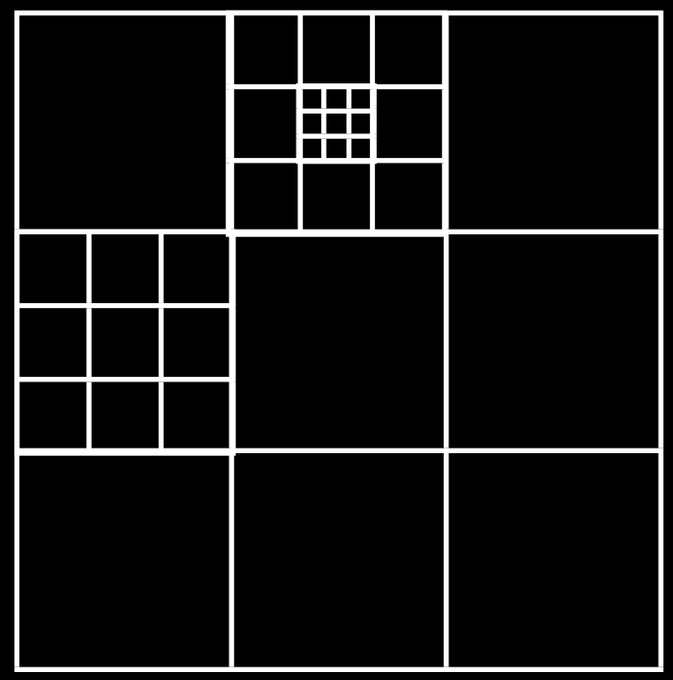
virtual observations

Smoothed Particle Hydrodynamics



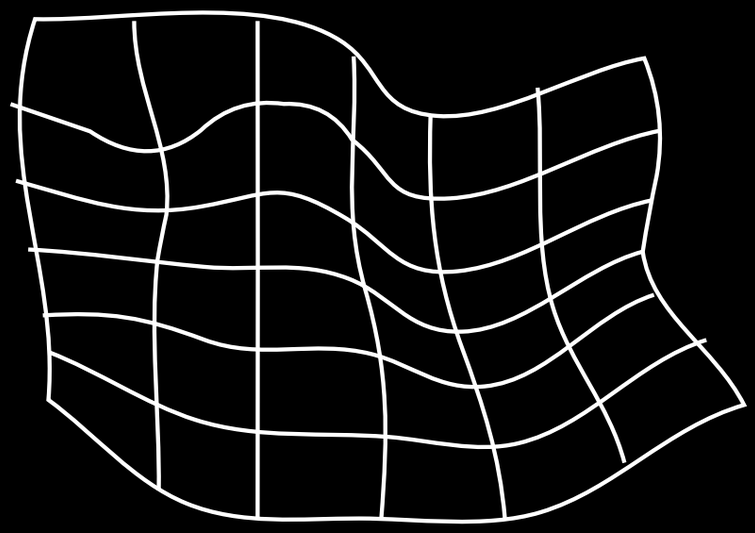
e.g. gadget, gasoline

Adaptive Mesh Refinement

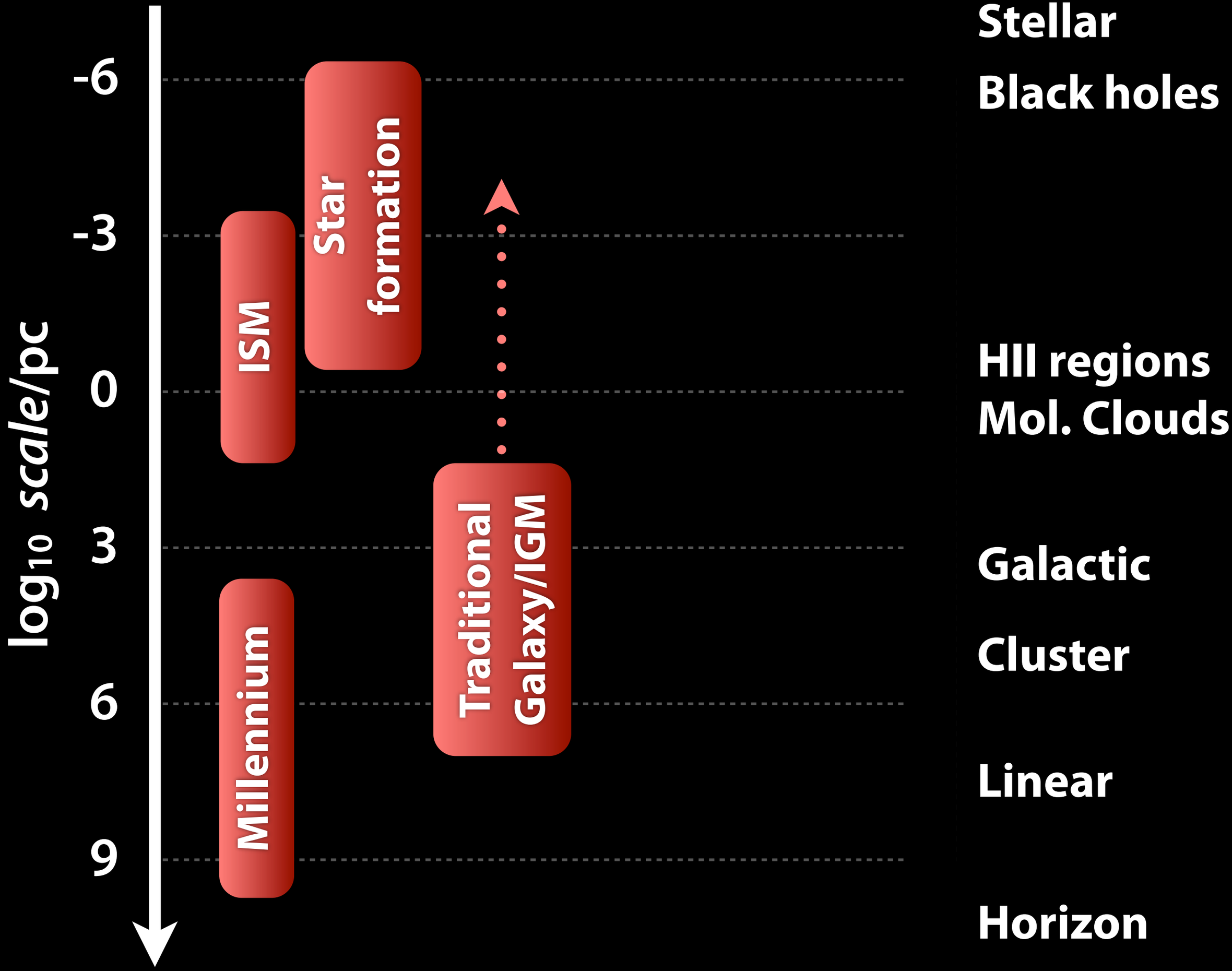


e.g. ramses, ENZO

Moving mesh
("AREPO")



+Semi-analytics
e.g. GALFORM


log10 scale/pc
-6
-3
0
3
6
9
ISM
Star formation
Millennium
Traditional Galaxy/IGM
Stellar
Black holes
HII regions
Mol. Clouds
Galactic
Cluster
Linear
Horizon

gravity

basic physics

fluid mechanics

magnetohydrodynamics

initial conditions

simulation

‘sub-grid’ physics

stellar feedback

black hole feedback

virtual observations

Gasoline: Prescriptions

Wadsley/Quinn/Stadel

Star Formation

threshold T, ρ
Schmidt relation, param c*
Stinson+ 06 cooling shutoff
Kroupa IMF, SN param ε_{SN}

Metals

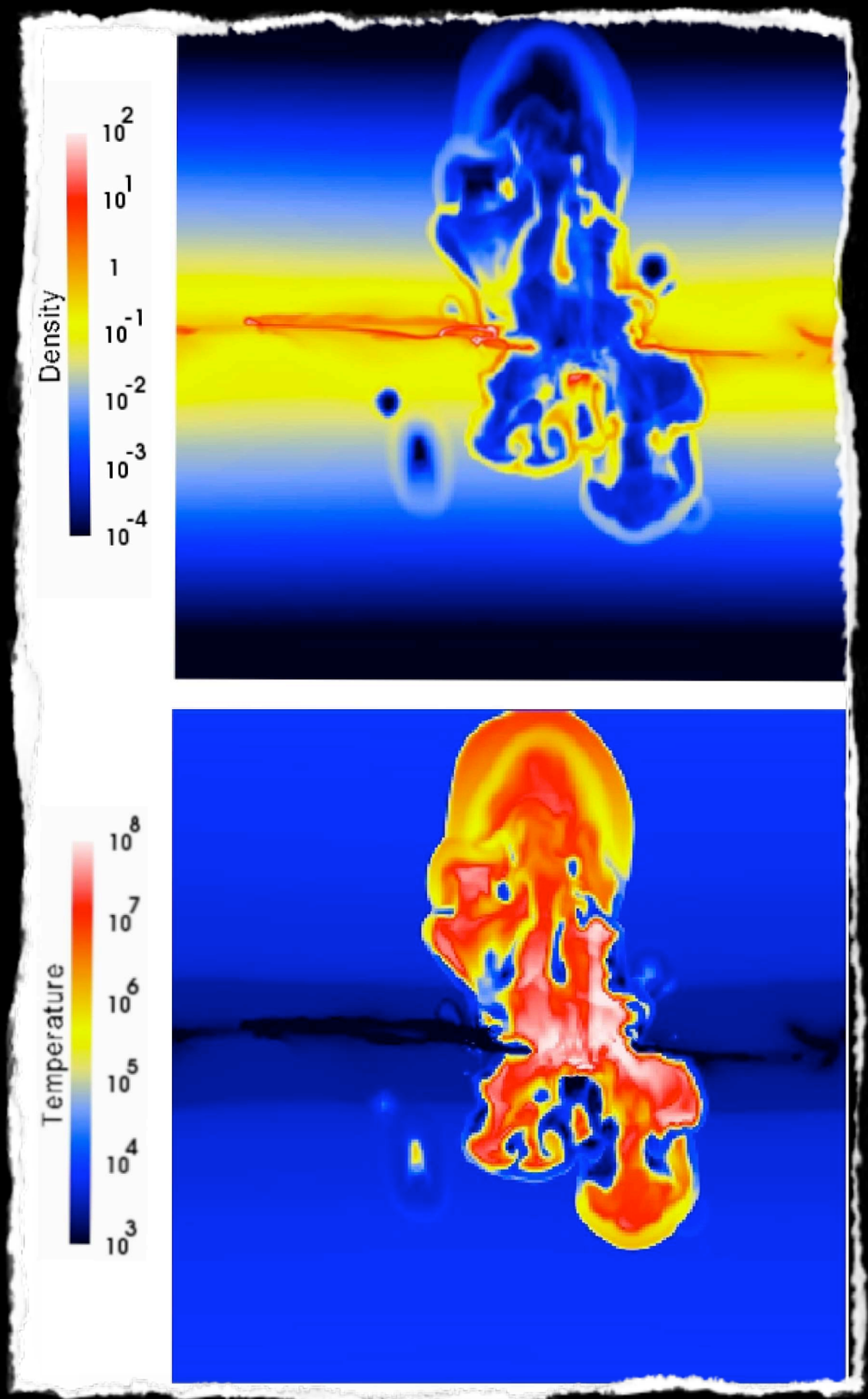
from SN1a, SNII, AGB
Woosley & Weaver yields
O and Fe
turbulent diffusion

UV Background

Haardt & Madau (06)
self-shielding (Pontzen 08)

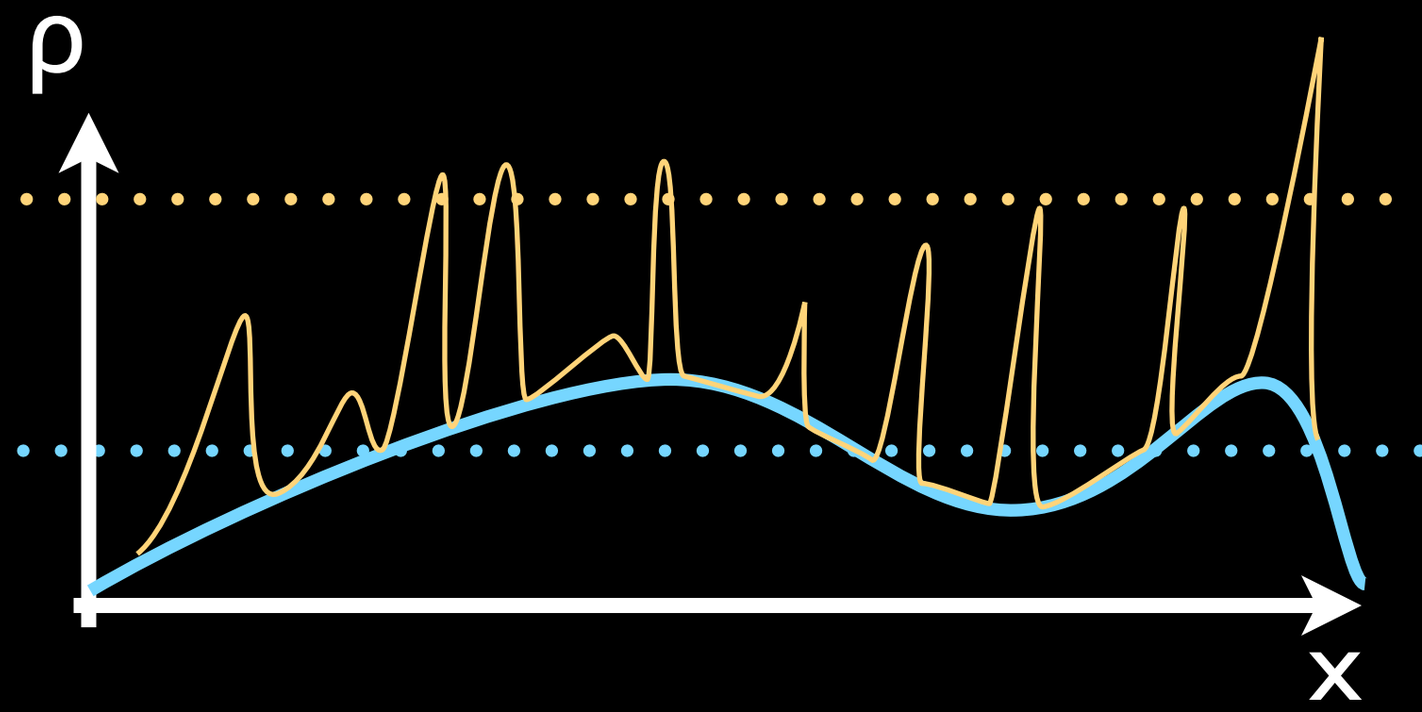
Cooling

Metal lines (Shen)
+ H_2 (Christensen)



Ceverino & Klypin 08

Outflows arise naturally in high resolution ISM models



Redshift

4.2 3.6 3.3 3.0 2.7 2.4 2.1

10^8

$M_{gas}(<r)/M_\odot$

10^6

1.5 2.0 2.5 3.0 3.5

t/Gyr

1 kpc

500pc

200pc

ρ/m_p cm^{-3}

1.5

0.0

-1.5

-3.0

10 kpc

Pontzen & Governato 2012

Redshift

4.2 3.6 3.3 3.0 2.7 2.4 2.1

1.0

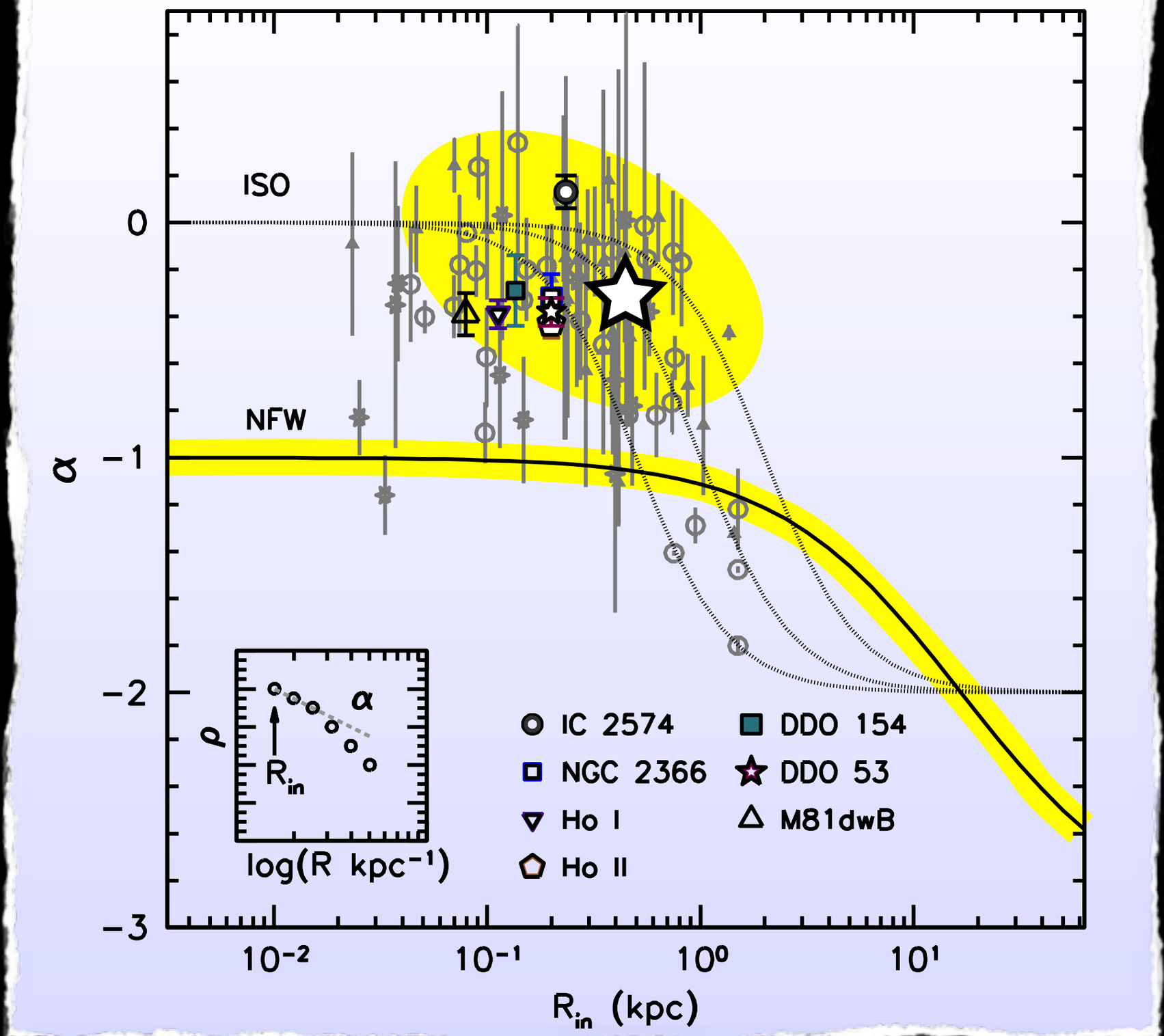
0.1

<r> / kpc

1.5 2.0 2.5 3.0 3.5

t/Gyr

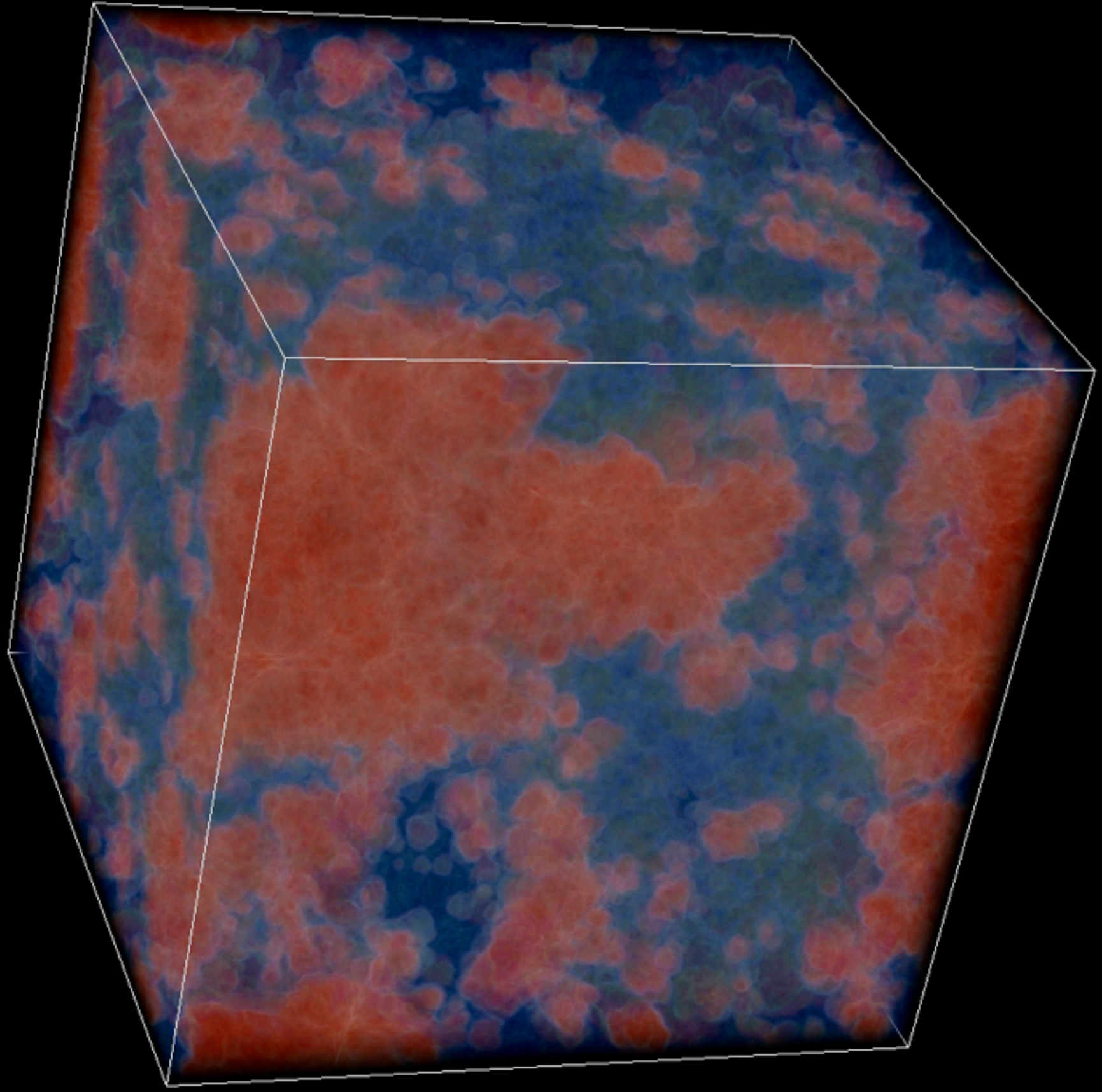
Pontzen & Governato 2012



Oh et al
2011, AJ

C II C IV O VI

Oppenheimer, Davé, Finlator 2009



Aubert & Teyssier 2010

Impress your friends by mentioning

- Dwarf galaxies (abundance/masses?)
- Massive ellipticals (downsizing?)
- Low surface brightness galaxies
- Bulgeless galaxies
- Better motivated black hole/supernova feedback; systematic understanding of how to scale these processes with resolution
- Better radiative transfer; magnetic fields; cosmic rays; ISM structure

Impress your friends by mentioning

- The correspondence between simulations and GR at/beyond second order
- Implementation of relativistic sources (e.g. neutrinos, dynamic dark energy etc)
- Implementation of modified gravity
- Explanation of the ‘NFW’ profile
- Explanation/proof for softening convergence? (Actually I’m the only person in the world who seems to worry about that one, so perhaps don’t bother with it and just point to convergence studies instead.)

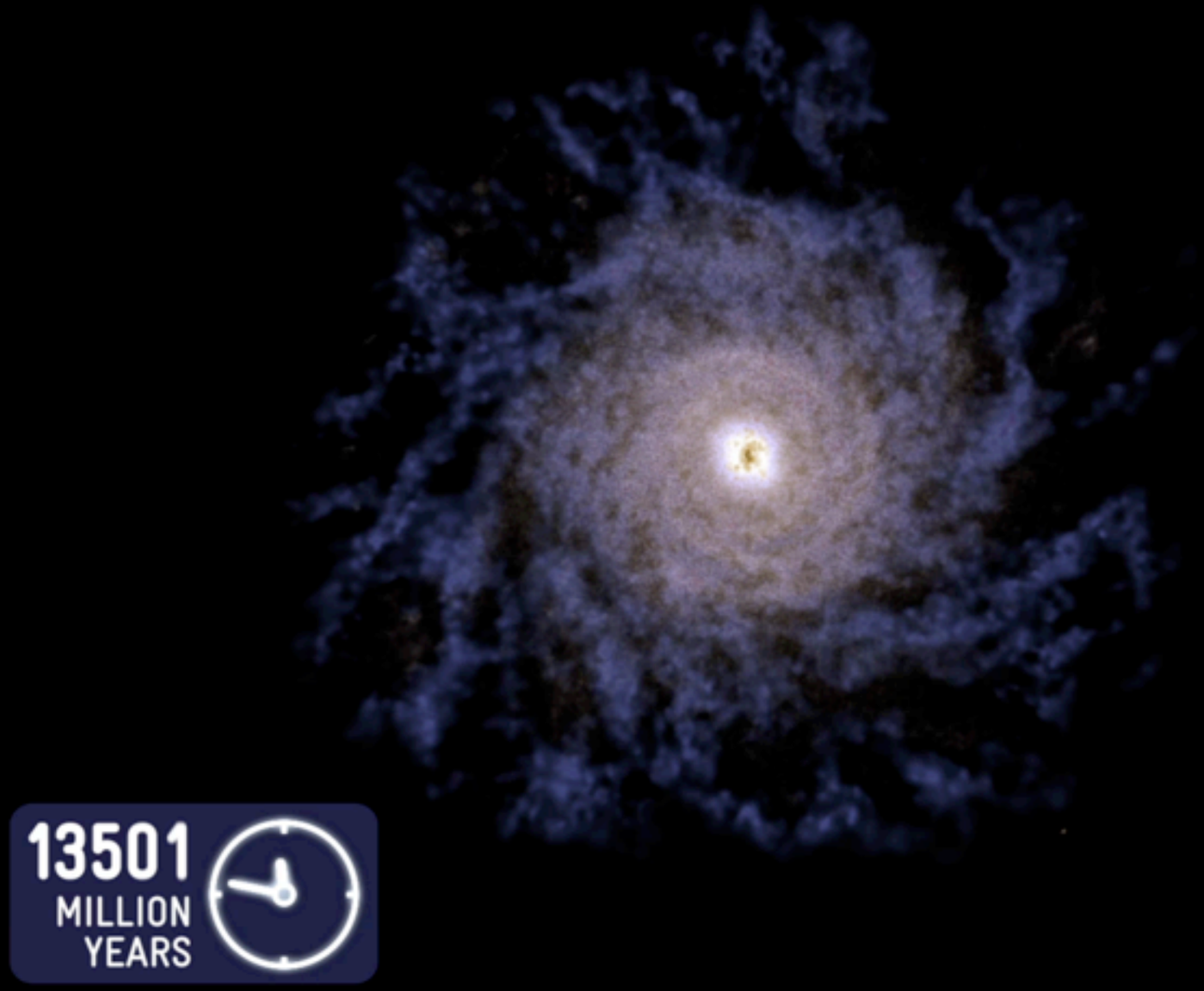
Impress your friends by mentioning

- Use of new architectures e.g. GPUs
- Efficient storage/indexing of large output datasets
- Making codes ‘scale’ to next generation supercomputers

Why simulations (or SAMs)?

- You want to see what an observed population corresponds to and how sensitive it is to different physics;
- You want to see the effect of a specific piece of physics on galaxies;
- You want to test toy models against something slightly more realistic;
- You want to produce mock datasets (extrapolate from known populations to something modestly new?)

Don’t be too literal.



Feel free to email/tweet me: @apontzen
andrew.pontzen@astro.ox.ac.uk

Andrew Pontzen
Oxford Astrophysics