SKA Science Simulations

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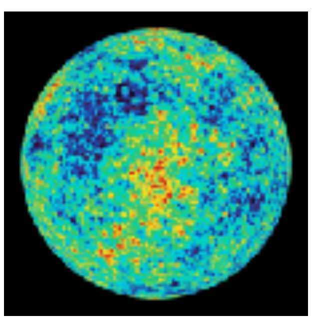
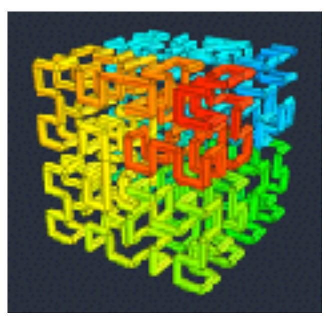
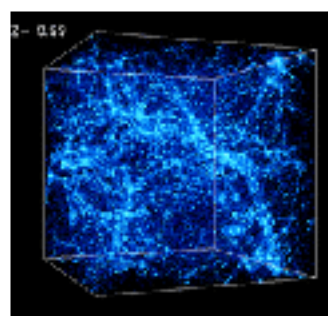
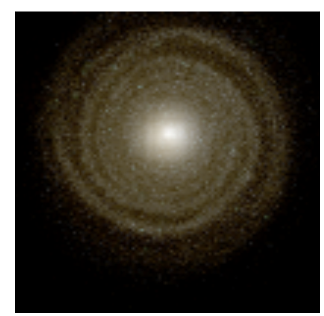
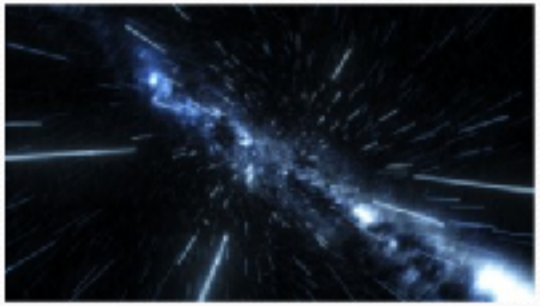





Outline

– Mock surveys: N body simulations beyond the Trillion particle barrier

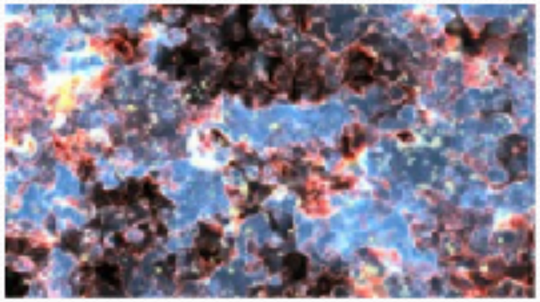
“Galaxy Evolution, Cosmology and Dark Energy”



Galaxy evolution, cosmology and dark energy

– Simulating cosmic reionization: radiation hydrodynamics

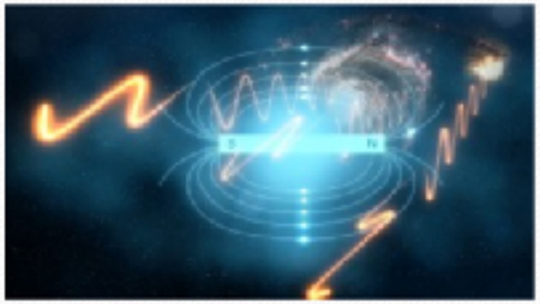
“Probing the Cosmic Dawn”



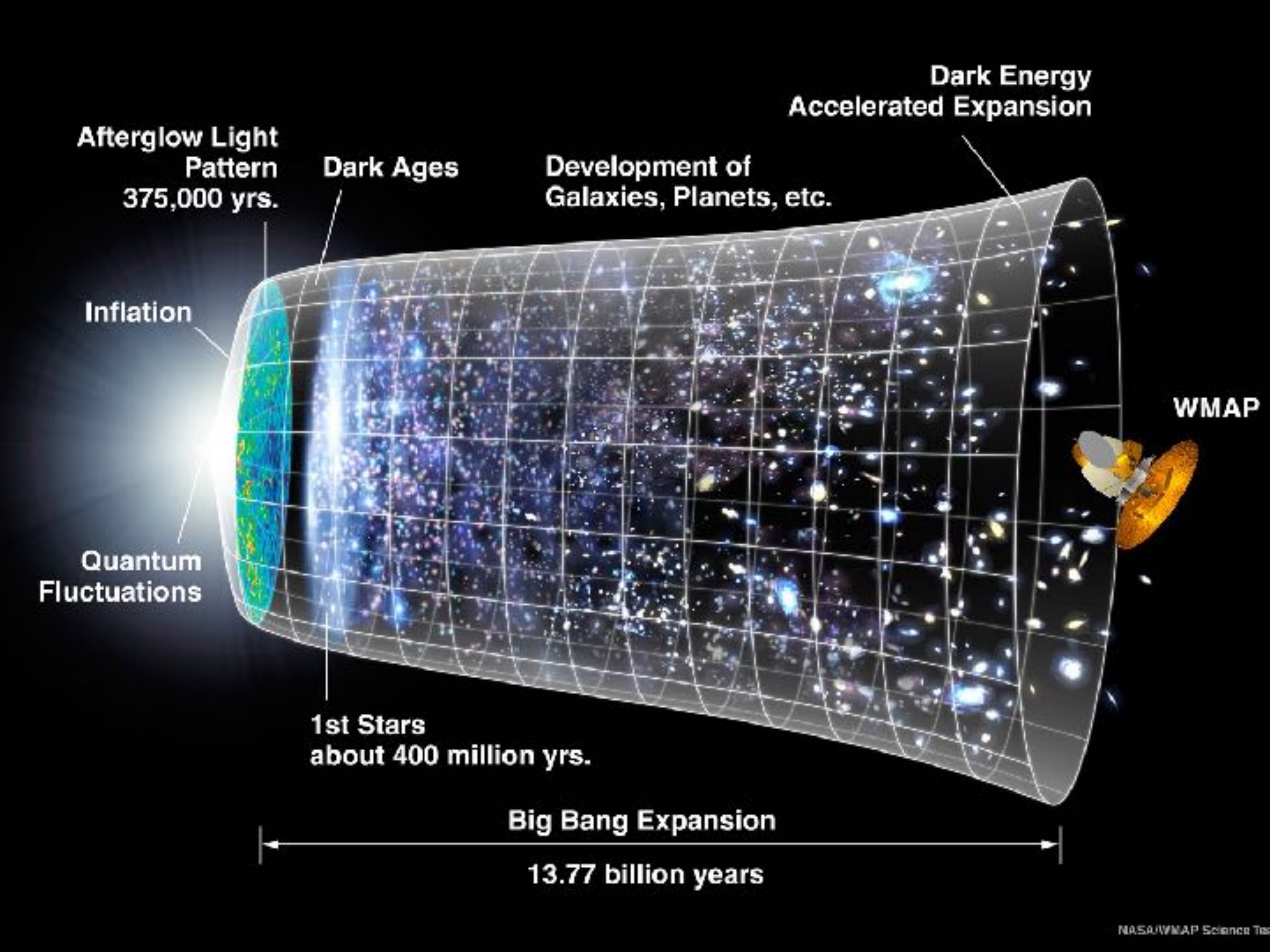
Probing the dark ages – the first black holes and stars

– Cosmic magnetism: from small scale to large scale dynamos

“Cosmic Magnetism”



Investigating the origin and evolution of cosmic magnetism

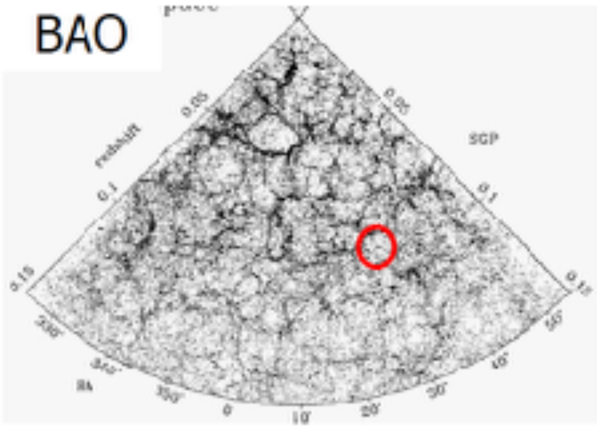


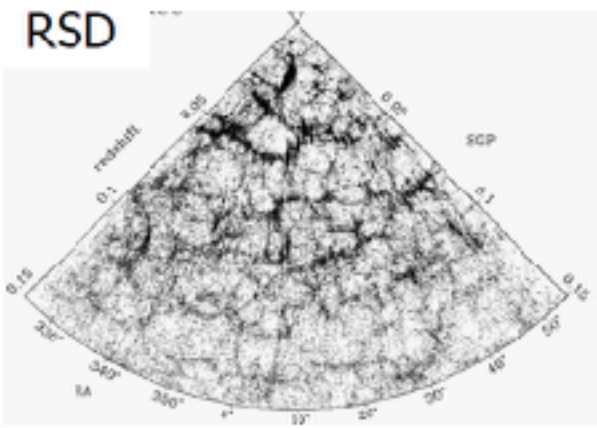
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years
NASA/WMAP Science Team

EUCLID: a space mission to map the universe

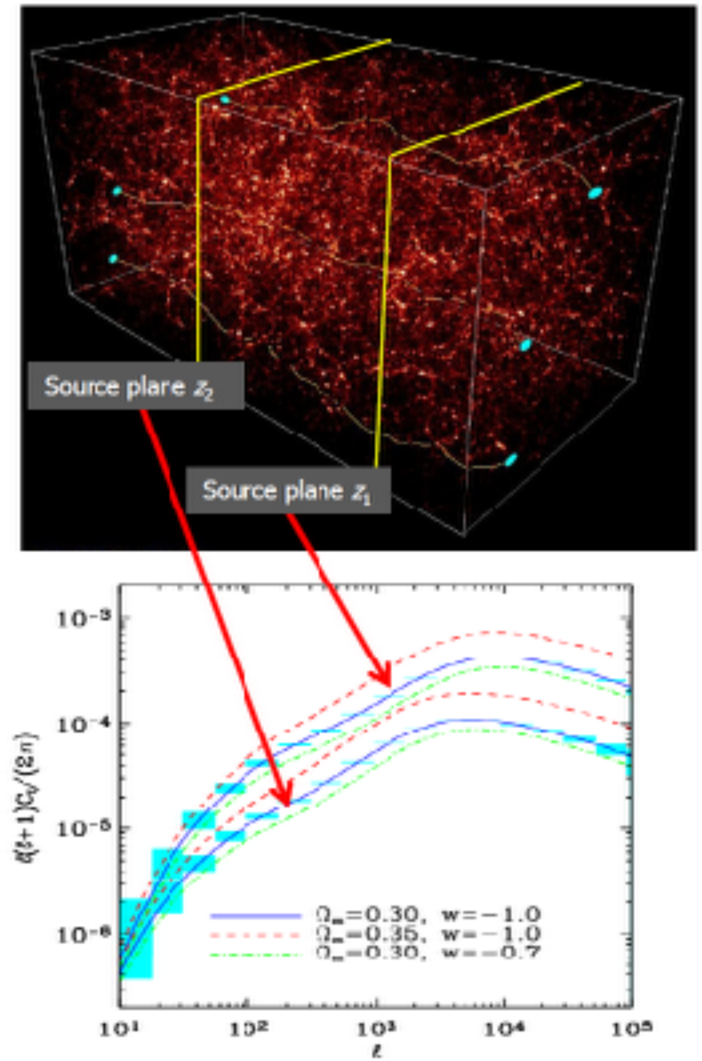
BAO, RSD and WL over 15,000 deg^2

50 million galaxies with redshifts

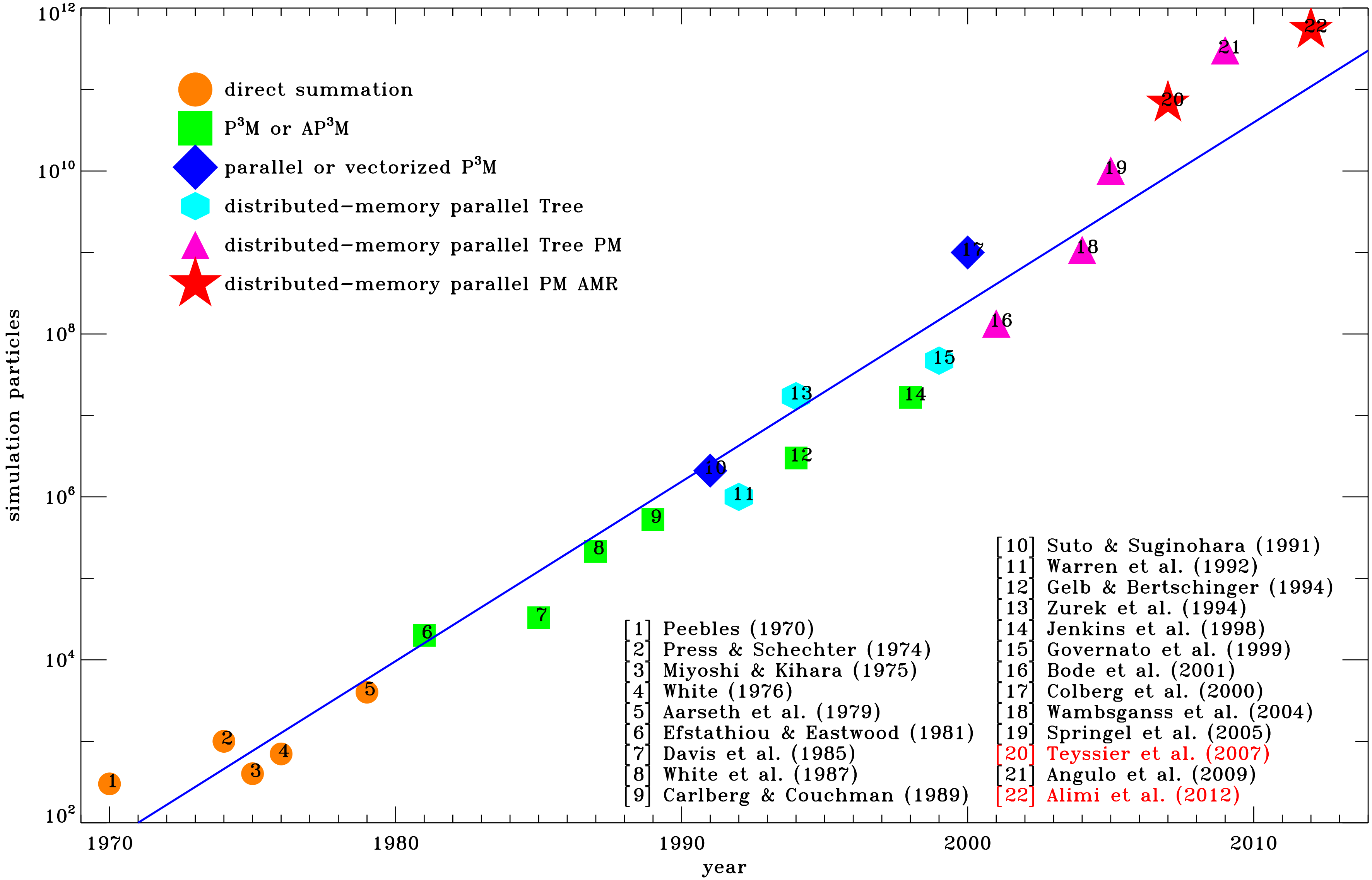




1.5 billion sources with shapes, 10 slices



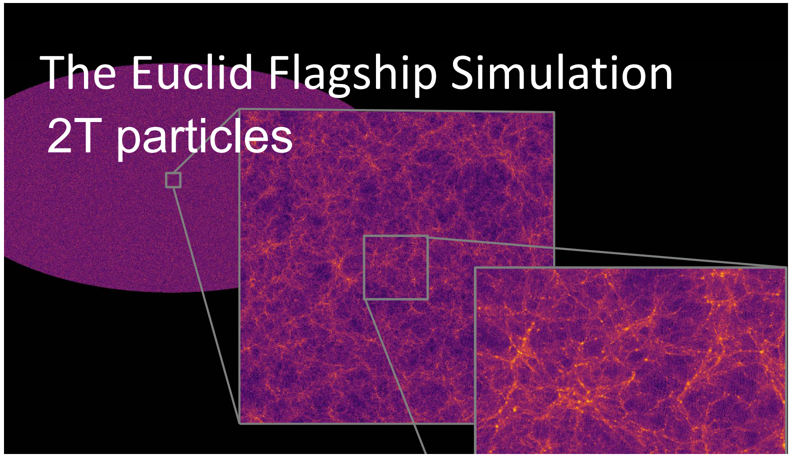
Cosmological N body simulations



Cosmological simulations: computing requirements

Mock galaxy catalogues: one simulation every year with 10T particles. Galaxy population on the light cone with HOD/AM/SAM techniques with lensing maps.

Resources: 2 million node-hours (with GPU)



Potter, Stadel, Teyssier 2017

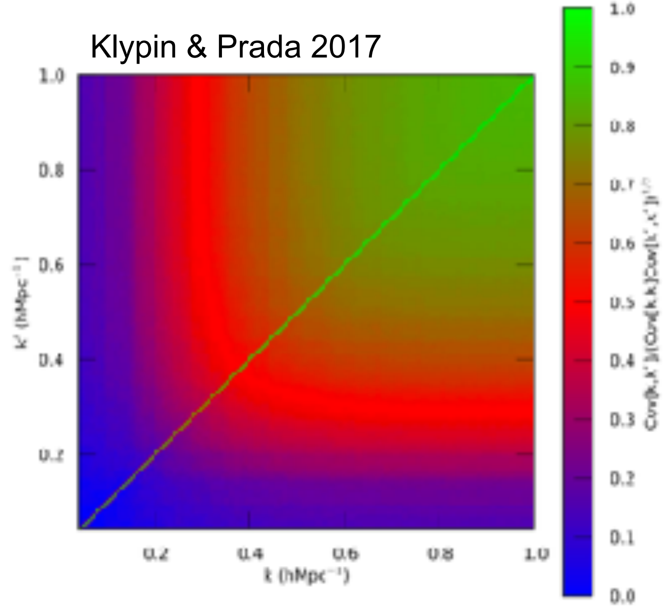
Emulators: 50 such simulations (one per set of cosmological parameters)

Coyote: Heitmann et al. 2014, Mira-Titan; Heitmann et al. 2016

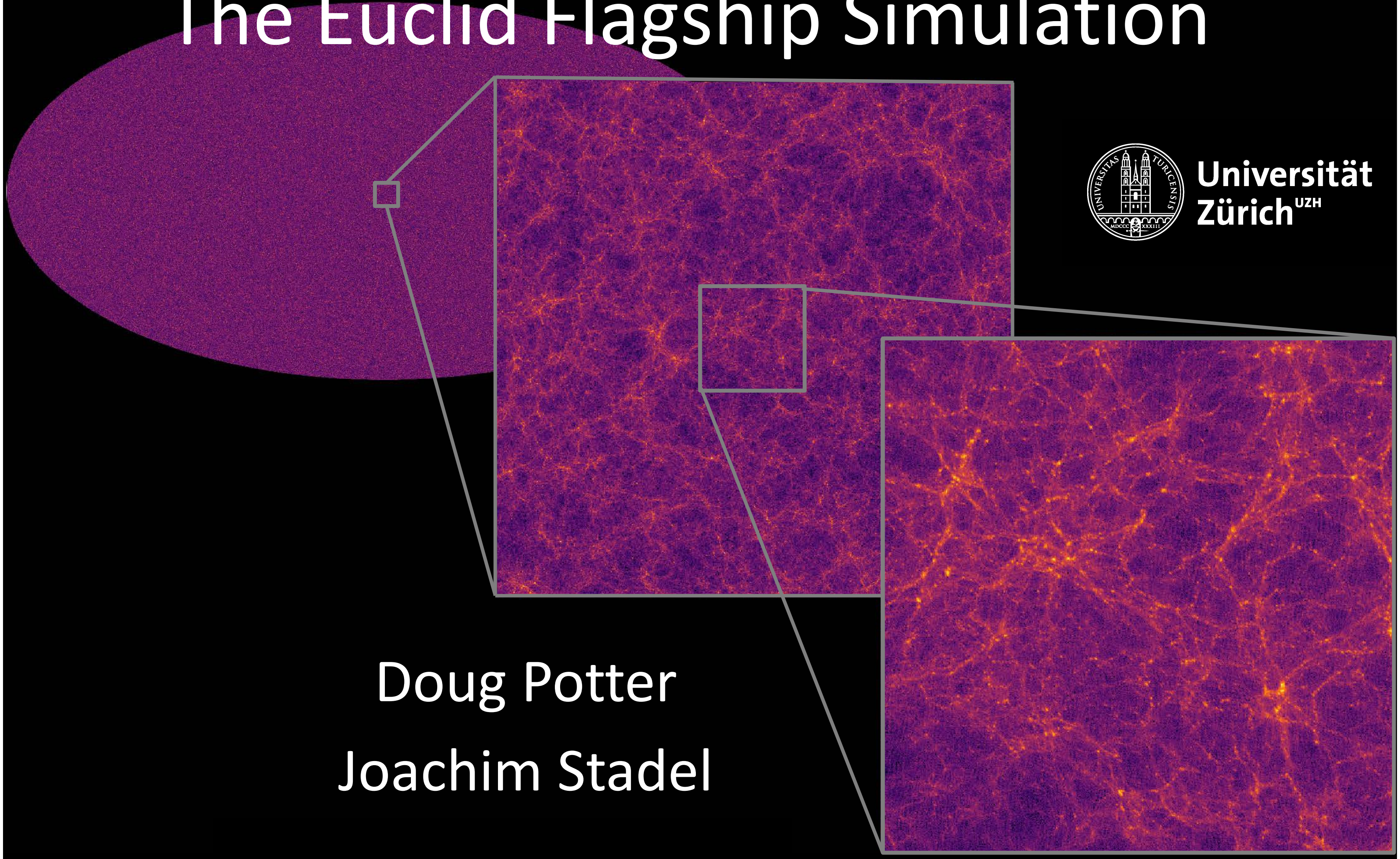
Covariance matrices: 3000 simulations with 8B particles every year.

Resources: 2 million node-hours (with GPU)

Klypin & Prada 2017



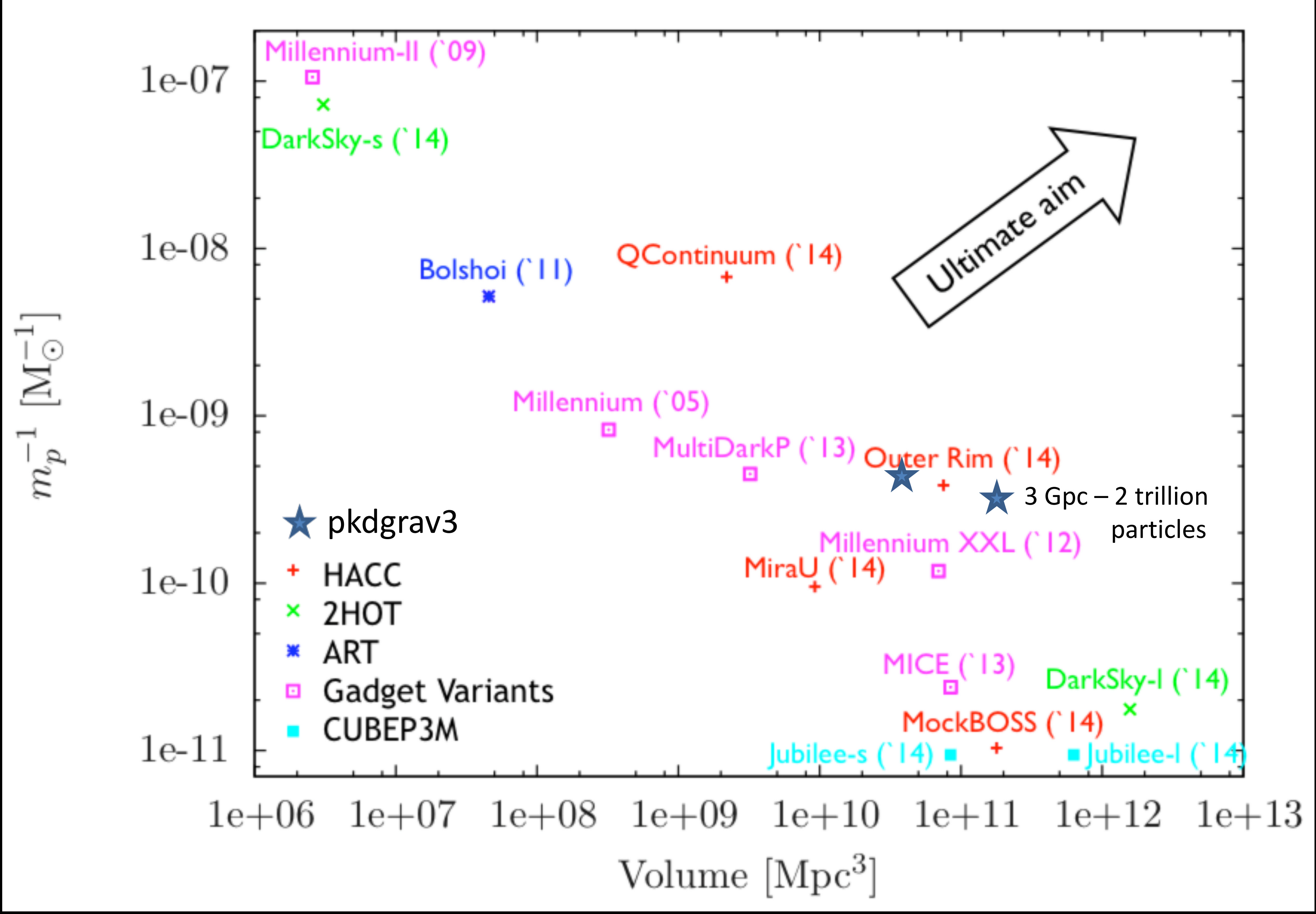
The Euclid Flagship Simulation



Universität Zürich[UZH]

Doug Potter

Joachim Stadel



Millennium-II (`09)
DarkSky-s (`14)
Ultimate aim
Bolshoi (`11)
QContinuum (`14)
Millennium (`05)
MultiDarkP (`13)
Outer Rim (`14)
3 Gpc – 2 trillion particles
pkdgrav3
HACC
2HOT
ART
Gadget Variants
CUBEP3M
Millennium XXL (`12)
MiraU (`14)
MICE (`13)
DarkSky-l (`14)
MockBOSS (`14)
Jubilee-s (`14)
Jubilee-l (`14)
1e-07
1e-08
1e-09
1e-10
1e-11
m_p^{-1} [$M_\odot^{-1}$]
1e+06
1e+07
1e+08
1e+09
1e+10
1e+11
1e+12
1e+13
Volume [Mpc^3]

The pkdgrav3 N-Body Code

1. Fast Multipole Method, O(N), 5^{th} order in Φ
2. GPU Acceleration (Hybrid Computing)
3. Hierarchical Block Time-Stepping
4. Dual tree gravity calculation for very active particles
5. Very efficient memory usage per particle
6. On-the-fly analysis
7. Asynchronous direct I/O for checkpoints, the light cone data and halo catalogs.
8. Available on www.pkdgrav.org (bitbucket.org)

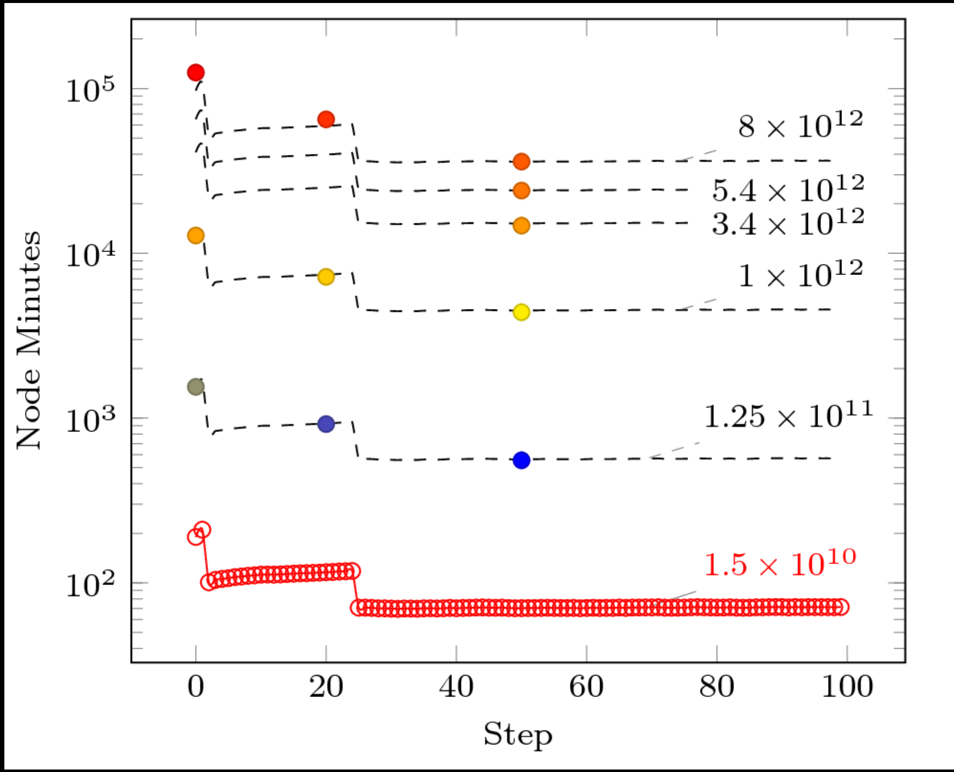
Piz Daint – over 5000 GPU Nodes

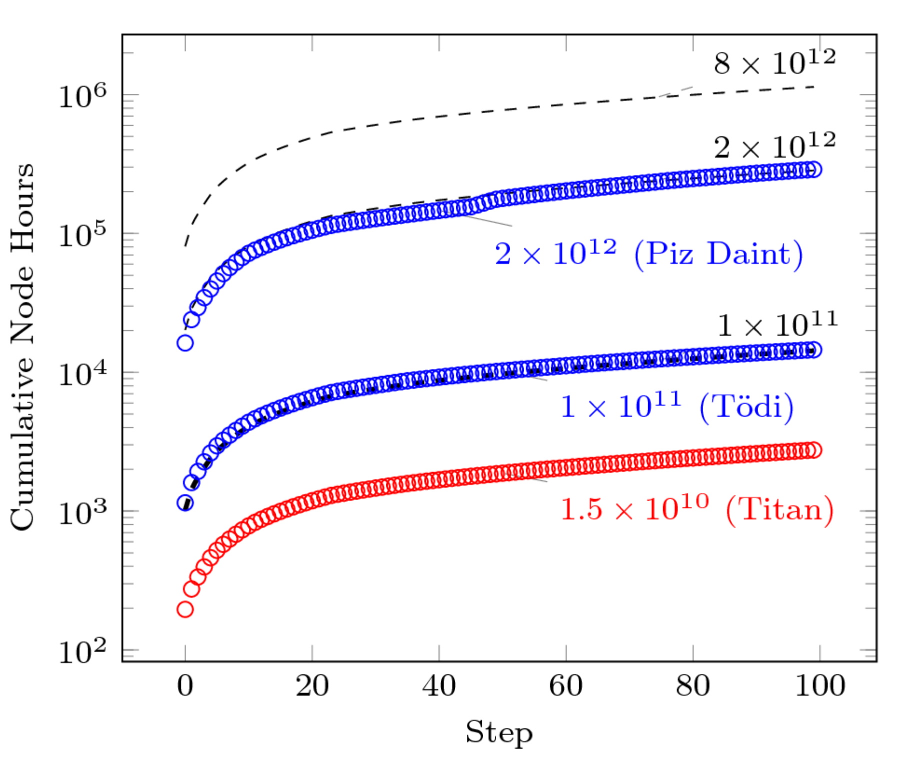
6^{th} Fastest Computer in the World. Upgrade to Haswell & P100 (now)…

Benchmarking on Titan and Piz Daint

Nearly Perfect Weak Scaling makes performance prediction very accurate for these simulations.
120 seconds for an all N gravity solve!

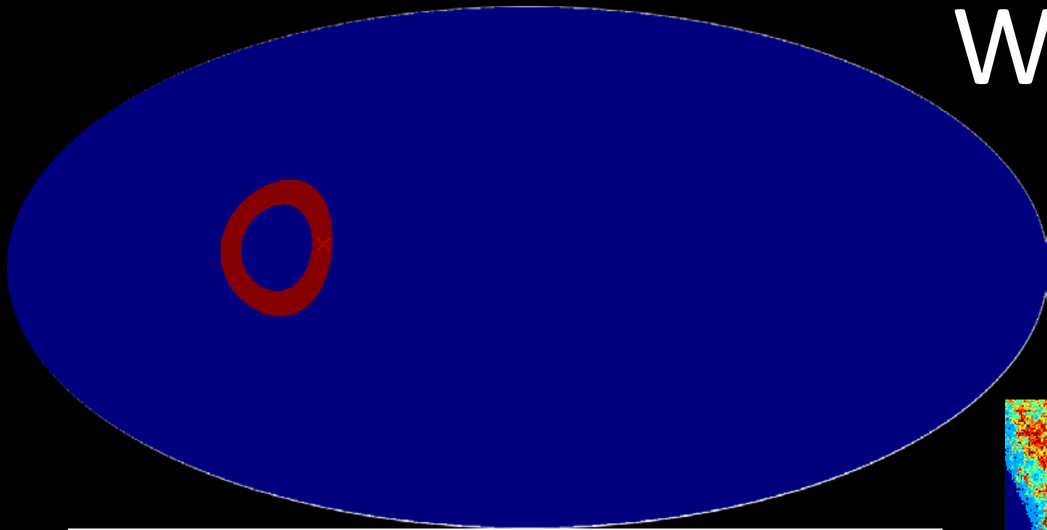
We show that it is quite feasible to run 8 trillion particles on Titan with a little over 1 million node hours. **10 PFlops**

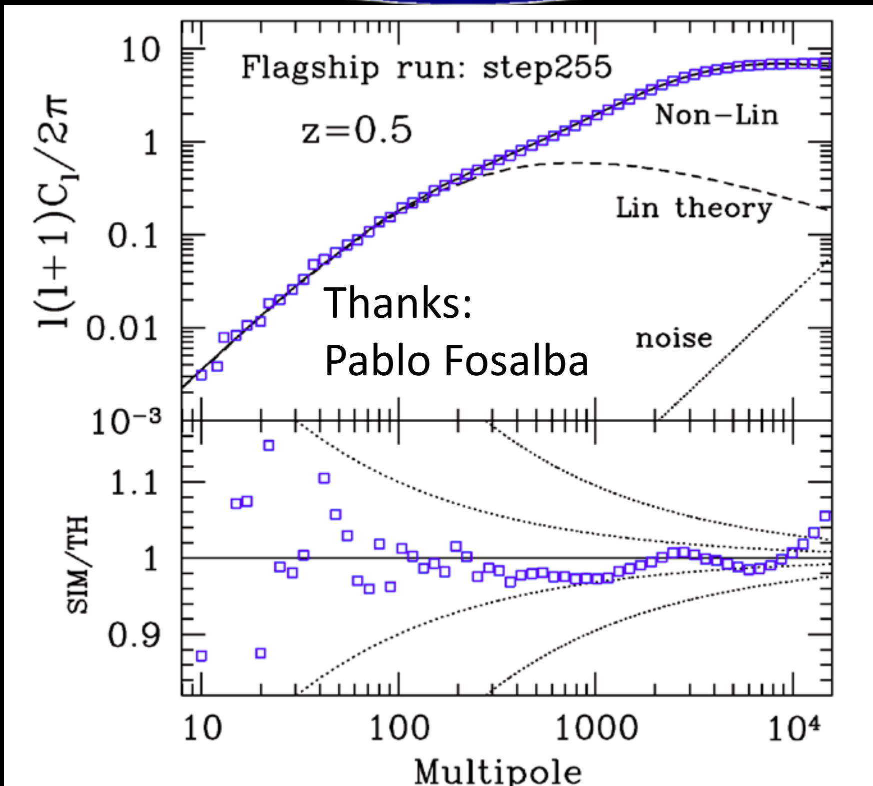


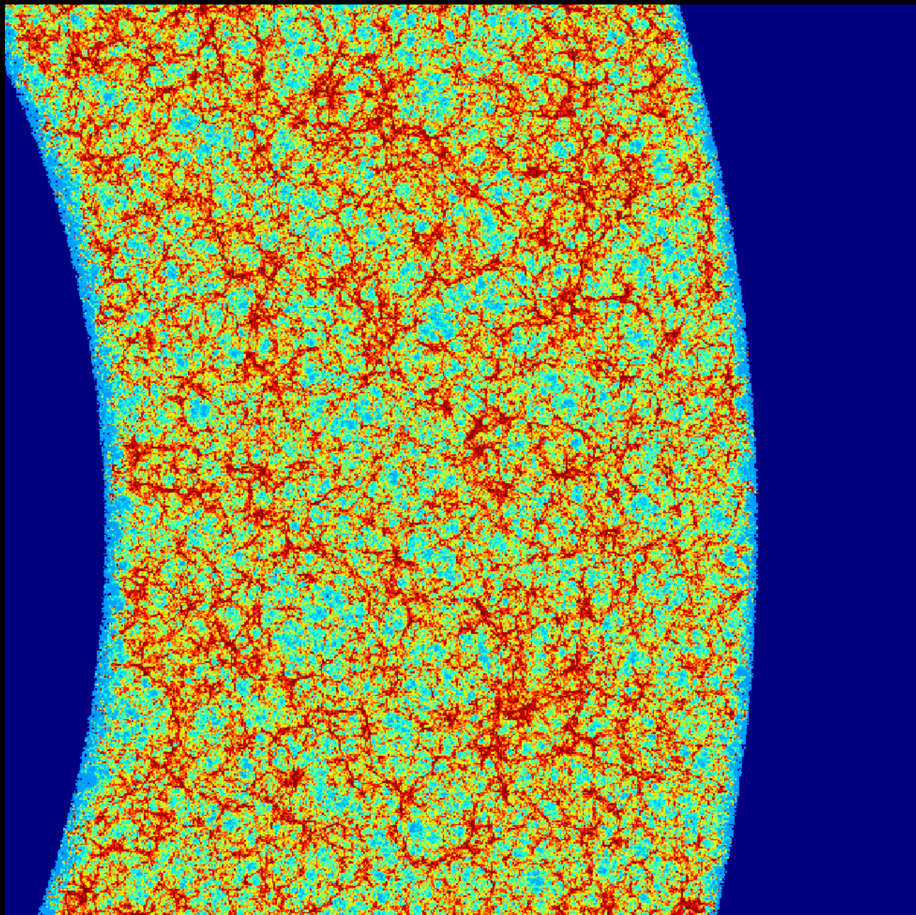


Weak lensing maps

There are O(400) such maps which form a set of spherical, concentric, lensing planes to distort the shapes of the background galaxies.





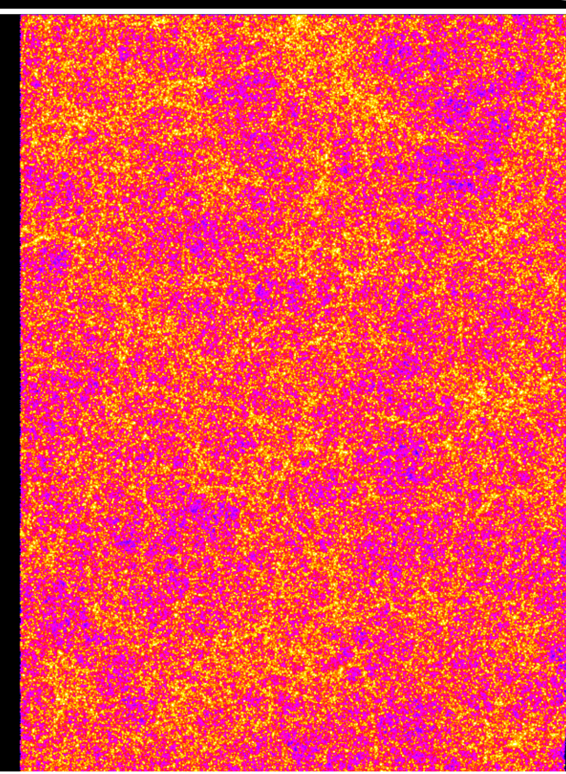


Arrived at a big data problem
with the light cone output.

The Light Cone
10 trillion particles
50 billion halos

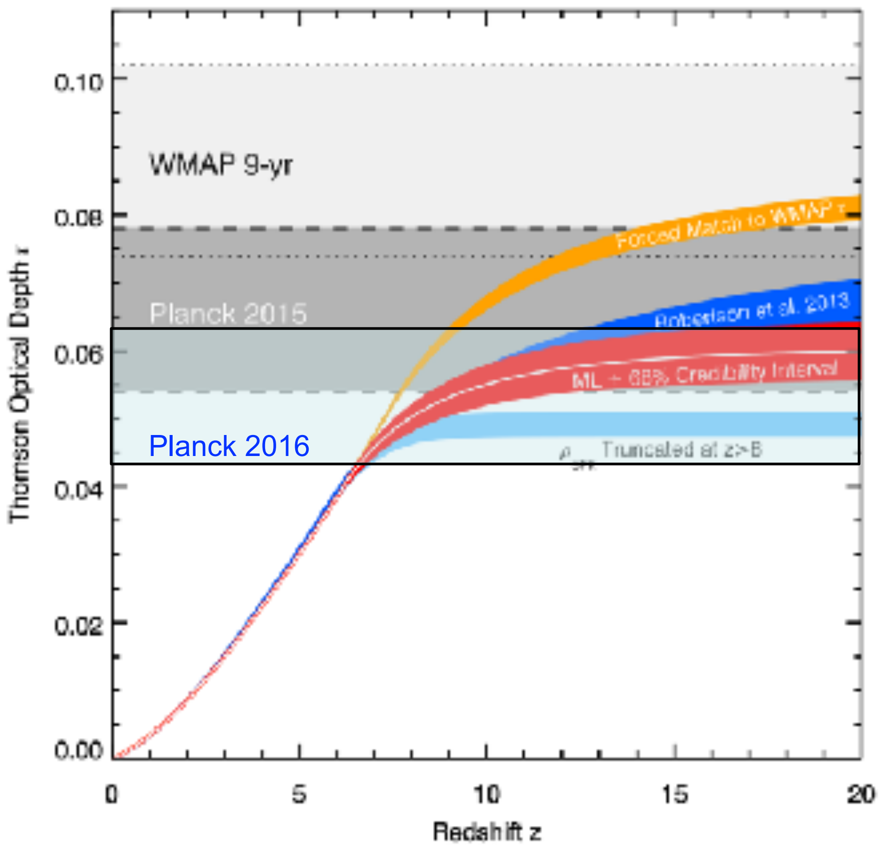
z=0
(the present)

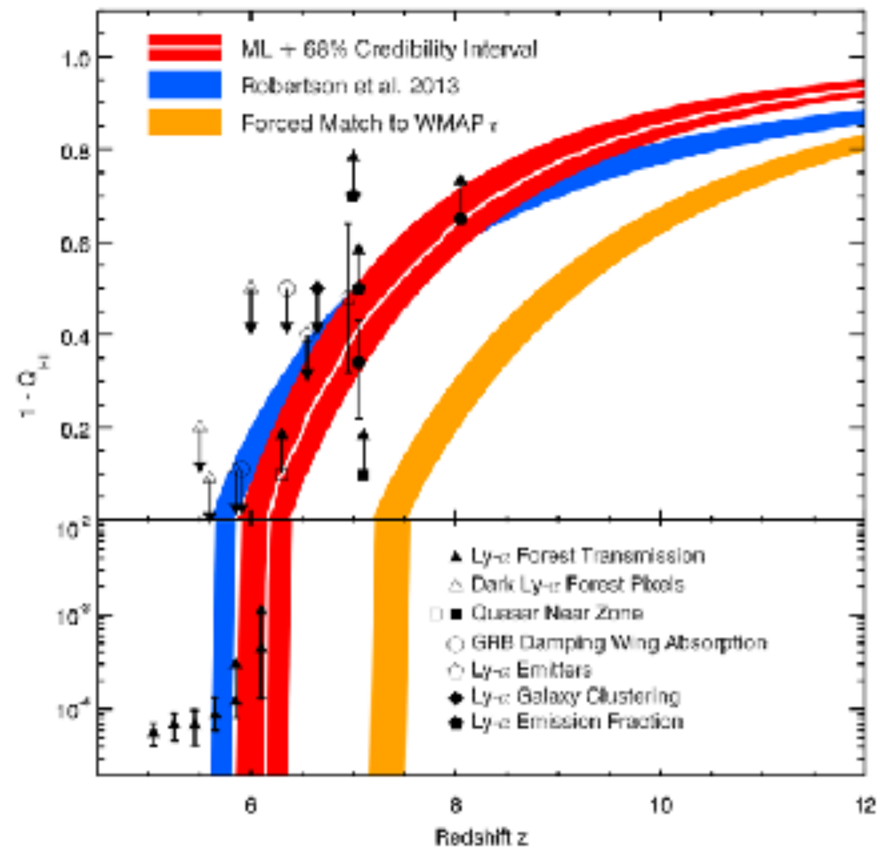
z=2.3 (~10 Gyrs ago)



>150’000 blocks (files) make
up this light cone data, 220 TB

Constraint on the reionization epoch





Robertson et al. (2015)

A new radiation hydrodynamics solver in RAMSES

Radiative transfer equation: $$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \mathbf{n}\frac{\partial I_\nu}{\partial \mathbf{x}} = -\kappa_\nu I_\nu + \eta_\nu$$

Angular moment's equations:

$$\int_{4\pi} (\ldots)\,\mathrm{d}\Omega \longrightarrow \frac{\partial E_\nu}{\partial t} + \nabla\cdot\mathbf{F}_\nu = -\kappa_\nu c E_\nu + S_\nu$$

$$\int_{4\pi} (\ldots)\,\mathbf{n}\mathrm{d}\Omega \longrightarrow \frac{\partial \mathbf{F}_\nu}{\partial t} + c^2\nabla\cdot\mathbb{P}_\nu = -\kappa_\nu c\mathbf{F}_\nu$$

The geometry of the radiation field is encoded in the Eddington tensor. We approximate its angular distribution by a Lorentz-boosted dipole (Levermore 1984)

$$\mathbb{P}_\nu = E_\nu\mathbb{D}_\nu \quad \mathbb{D}_\nu = \frac{1-\chi_\nu}{2}\mathbb{I} + \frac{3\chi_\nu - 1}{2}\mathbf{n}_\nu\otimes\mathbf{n}_\nu,$$

$$\chi_\nu = \frac{3+4f_\nu^2}{5+2\sqrt{4-3f_\nu^2}} \quad \text{and} \quad \mathbf{f}_\nu = f_\nu\mathbf{n}_\nu = \frac{\mathbf{F}_\nu}{cE_\nu}$$

We obtain an hyperbolic system of conservation laws with source terms.
Numerical implementation similar to grid-based hydro solvers, using the Godunov method with a Lax-Friedrich Riemann solver.
Aubert & Teyssier (2008, 2010)
Rosdahl et al. (2013), Rosdahl & Teyssier (2014).

A new radiation hydrodynamics solver in RAMSES

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$$\int_{4\pi} (\ldots)\, \mathbf{n}\mathrm{d}\Omega \longrightarrow \frac{\partial \mathbf{F}_\nu}{\partial t} + c^2 \nabla \cdot \mathbb{P}_\nu = -\kappa_\nu c \mathbf{F}_\nu$$

Coupling to hydrodynamics: 1- cooling and heating

$$\frac{\partial E}{\partial t} + \nabla \cdot (\mathbf{u}\,(E+P)) = \Gamma_{\mathrm{rad}} - \Lambda_{\mathrm{rad}}$$

$$\Gamma_{\mathrm{rad}} = \int_0^{+\infty} \kappa_\nu c E_\nu \mathrm{d}\nu \quad \text{and} \quad \Lambda_{\mathrm{rad}} = \int_0^{+\infty} S_\nu \mathrm{d}\nu$$

Coupling to hydrodynamics: 2- radiation force

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u} + P\mathbb{I}) = \mathbf{F}_{\mathrm{rad}} \qquad \mathbf{F}_{\mathrm{rad}} = \int_0^{+\infty} \frac{\kappa_\nu}{c}\mathbf{F}_\nu \mathrm{d}\nu$$

Implicit or explicit time integration

The Godunov method is based on the explicit time integration scheme.
The M1 approximation results in an effective “radiation fluid” with “sound waves” velocity close to the speed of light.
This gives a very restrictive Courant condition fro stability of the integration.
For one large hydro step, we usually need 100 to 1000 radiation sub-cycles.

Solution 1: use the implicit time integration scheme. It is stable for large time steps but requires large sparse matrix solvers (CPU intensive, convergence and parallel computing issues) and can be inaccurate and slow in non-stationary cases.

Solution 2: reduce the speed of light *when valid (“slow light approximation”)*.

Solution 3: use GPU acceleration to speed-up the explicit radiation solver, while using the correct value for speed of light, and compute the fluid evolution on the host.

The third solution was implemented using the CUDA programming language on Nvidia graphics cards in the CUDATON library. Works only on Cartesian grids. (Aubert & Teyssier 2010).

Modelling cosmic reionization

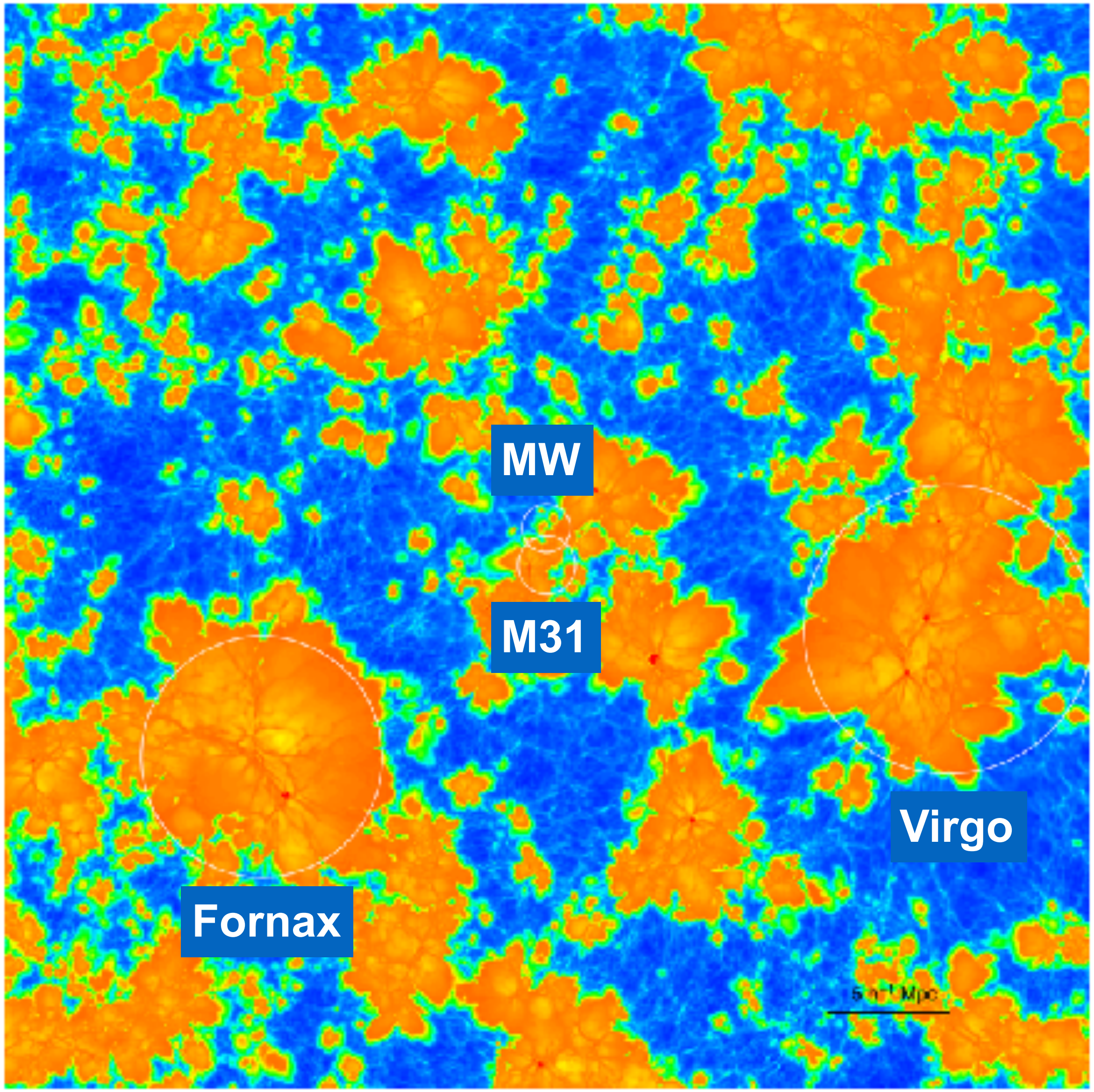
RAMSES-RT using M1 and GPU acceleration (CUDATON library).

Self-consistent model of the cosmic re-ionisation using dwarf galaxies as source of ionising radiation.

Initial conditions (WMAP5) were designed to reproduce our local universe (CLUES).

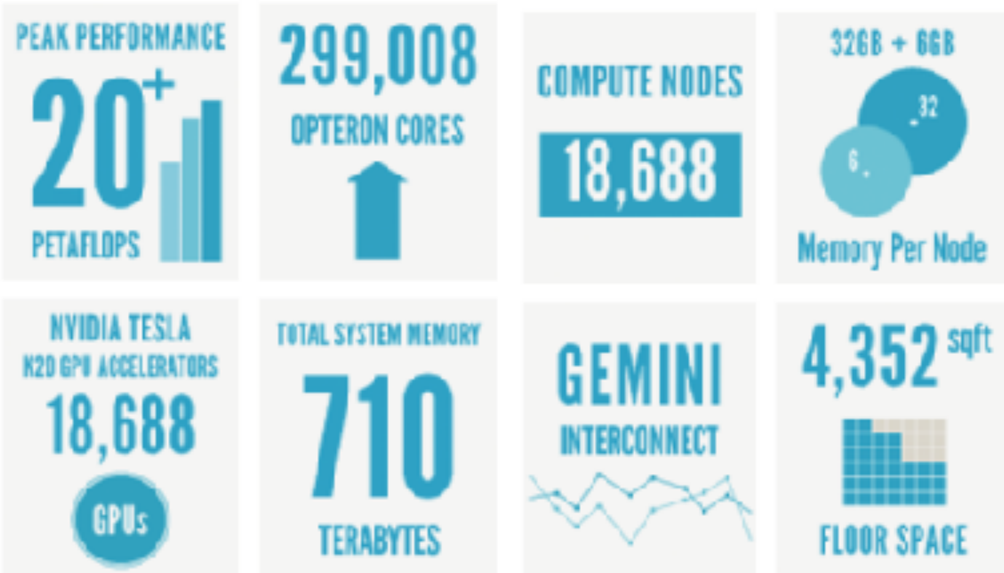
Used to derive interesting constraints on the SF history, the escape fraction…

Ocvirk et al. (2015)



INCITE proposal 2013 (PI Shapiro/Teyssier)

TITAN at Oak Ridge National Laboratory



The CoDa simulation:

64 Mpc/h periodic box (no AMR)

4096^3 cells 15 kpc/h comoving

4096^3 dark matter particle

8192 Titan nodes

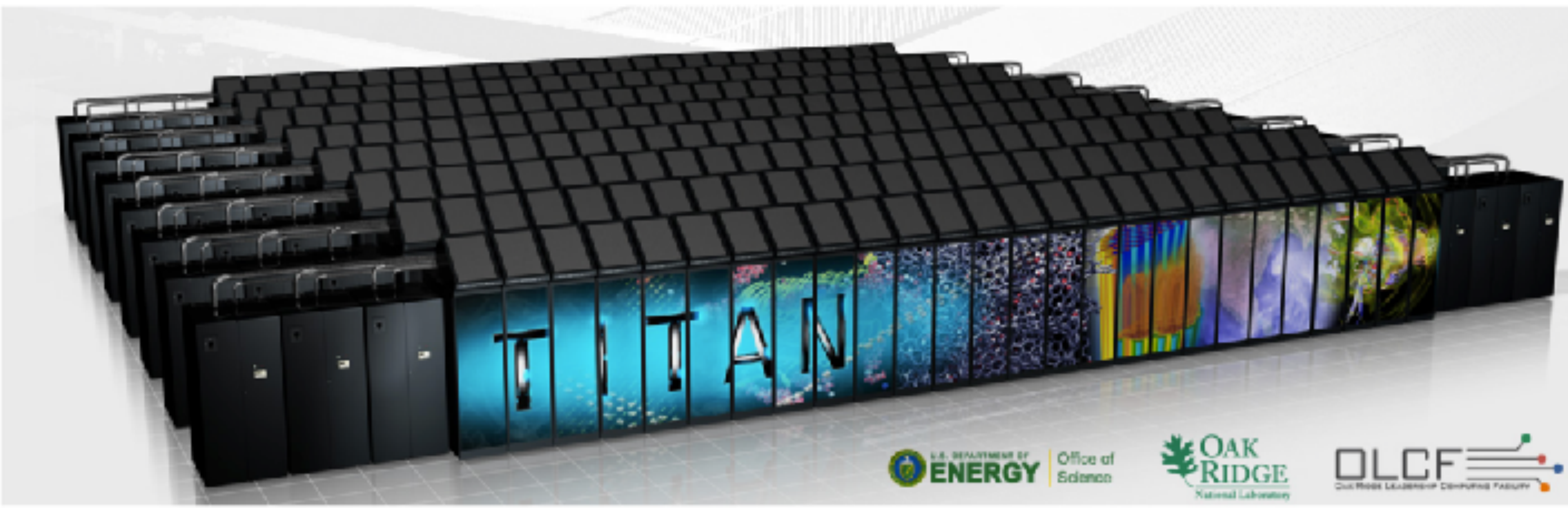
16 CPU and 1 GPU per node

11 days = 2 million node hours

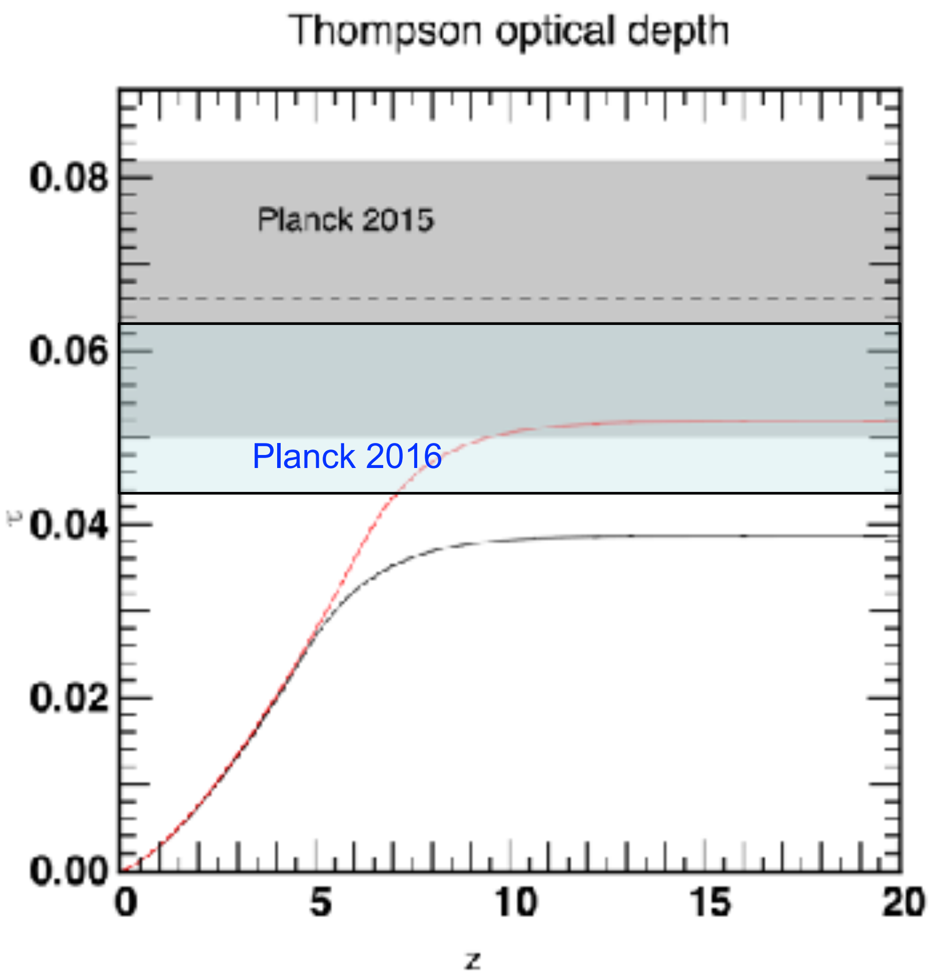
2000 hydro time steps

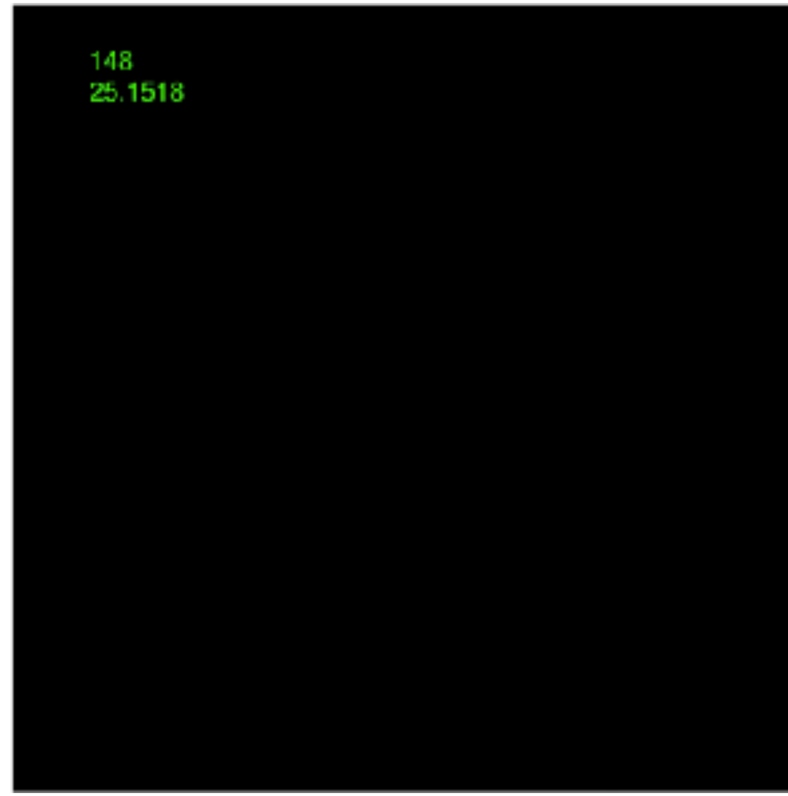
1 million radiation time steps

140 snapshots, 2 PB of data



Cosmic reionization in a supercomputer

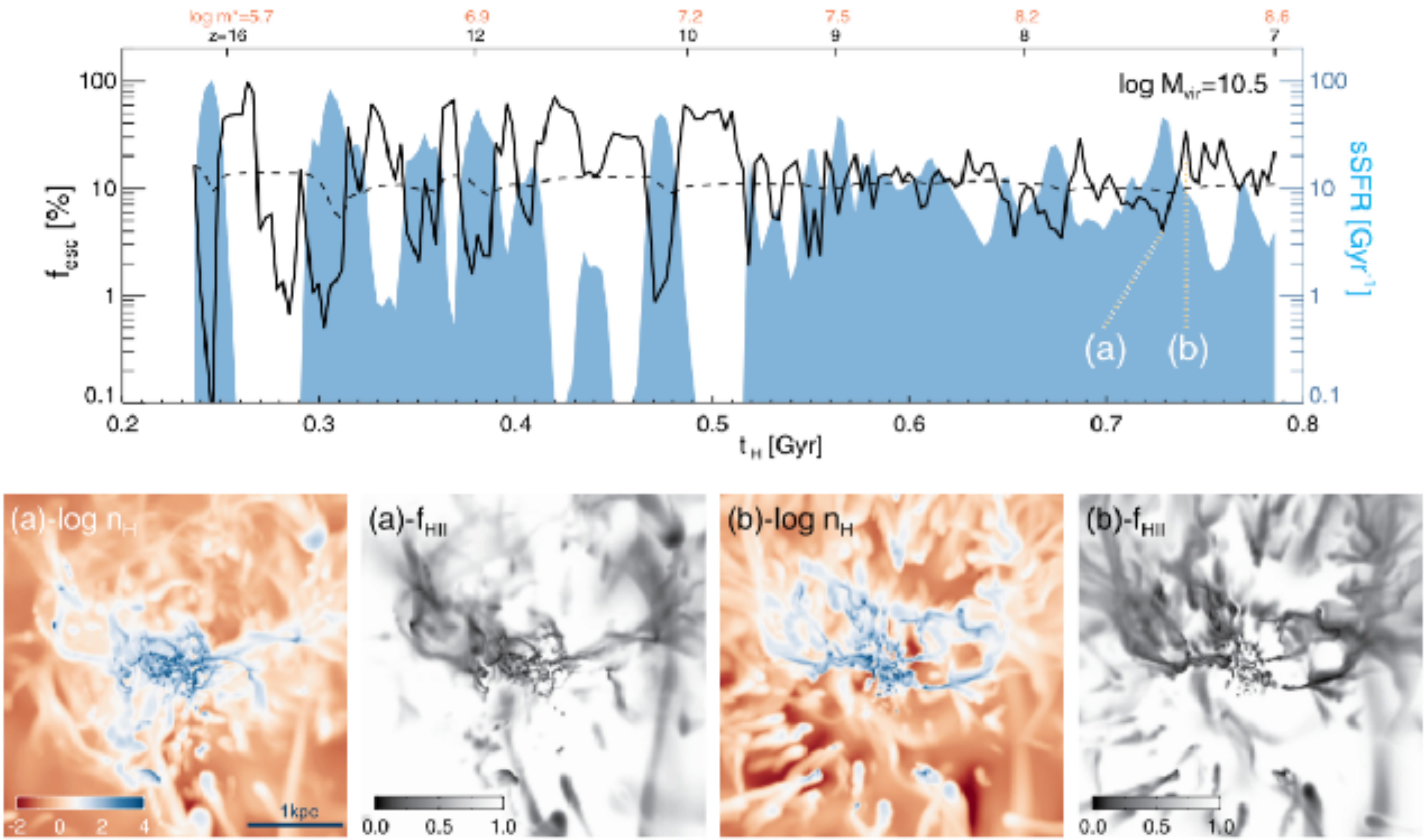




The adopted UV escape fraction from galaxies is the key parameter.

Adopting f_esc=10% matches observational constraints (Ocvirk et al. 2015).

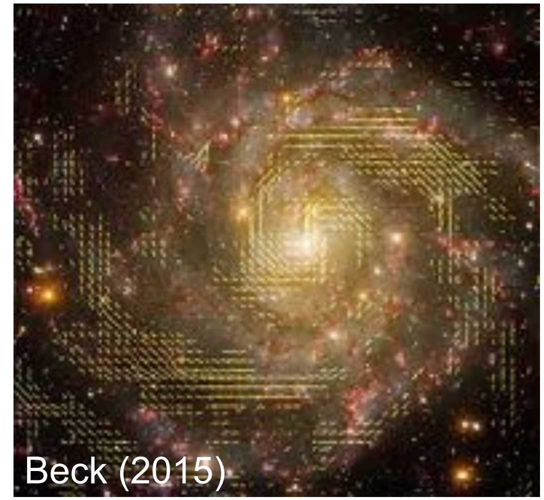
Computing the escape fraction



Kimm & Cen (2014)

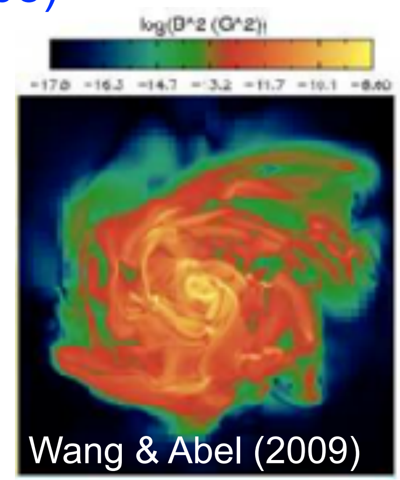
The origin of cosmic magnetic fields

- Biermann battery at the EoR sets the initial field around 10^{-20} G (Gnedin *et al.* 2000).
- Current magnetic fields in local galaxies reaches several 10^{-6} G (Beck 2015).
- High-redshift galaxies seems to have 10x larger fields, probably even increasing with increasing redshift (Bernet, Miniati & Lilly 2013)



Beck (2015)

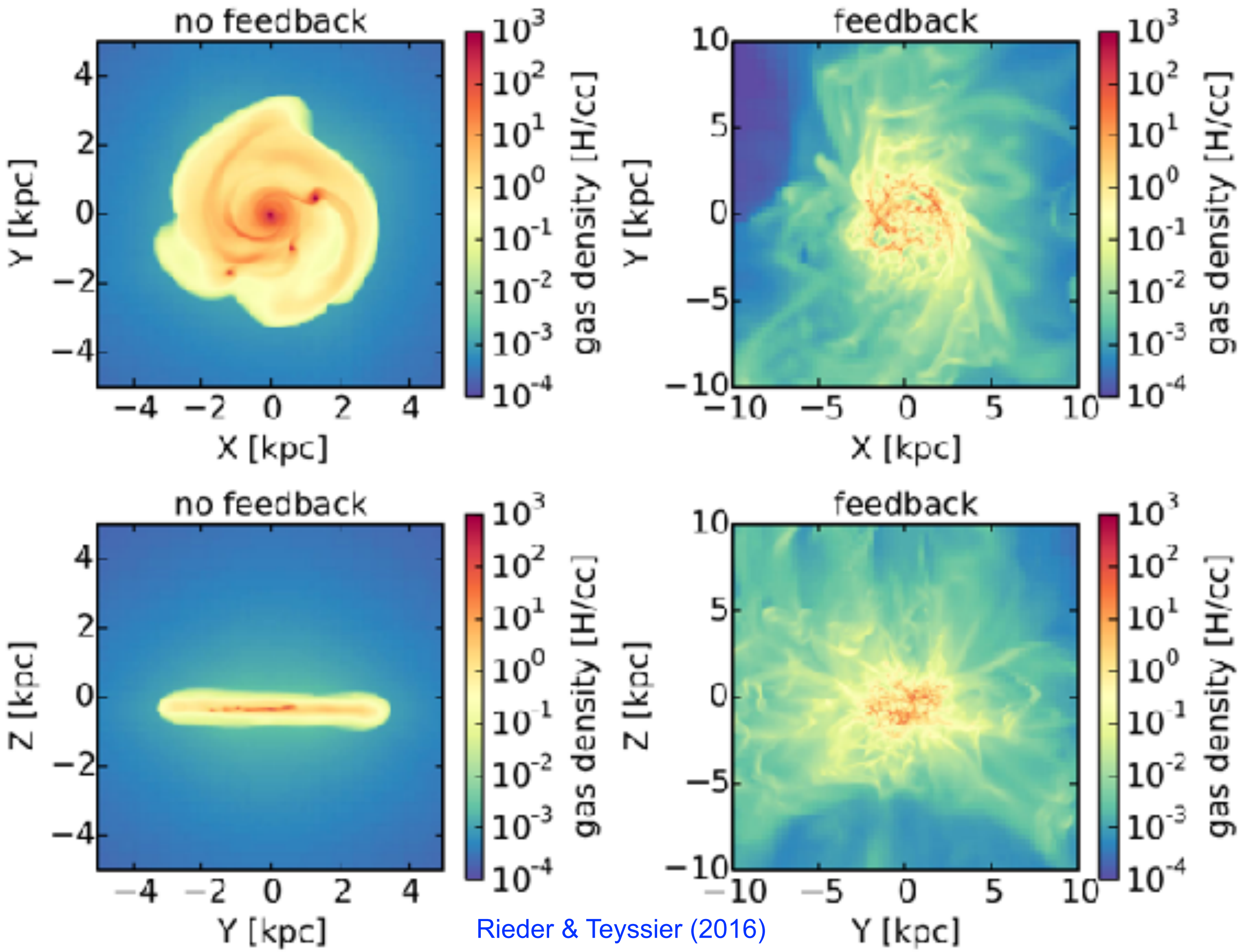
- Successful large-scale dynamos are slow with growth rate $\simeq 0.1\Omega$ up to Ω Hanasz *et al.* (2004), Pariev *et al.* (2007), Gressel *et al.* (2008)
- Early galaxy formation MHD simulations with no or weak feedback show moderate field amplification: Wang & Abel (2009), Dubois & Teyssier (2010)
- Recent simulations Beck *et al.* (2012), Pakmor & Springel (2013) or semi-analytical models Rodrigues *et al.* (2015) favour the scenario of a small scale dynamo at high redshift.



Wang & Abel (2009)

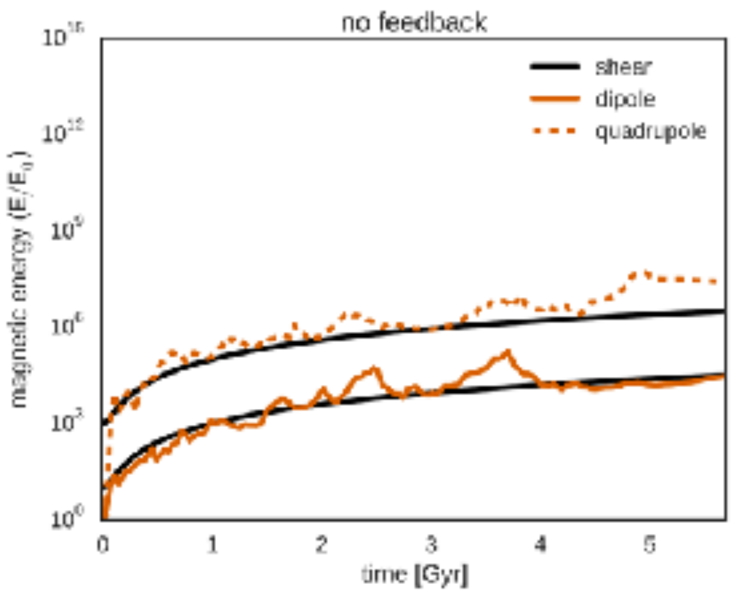
Turbulent dynamo in a dwarf galaxy

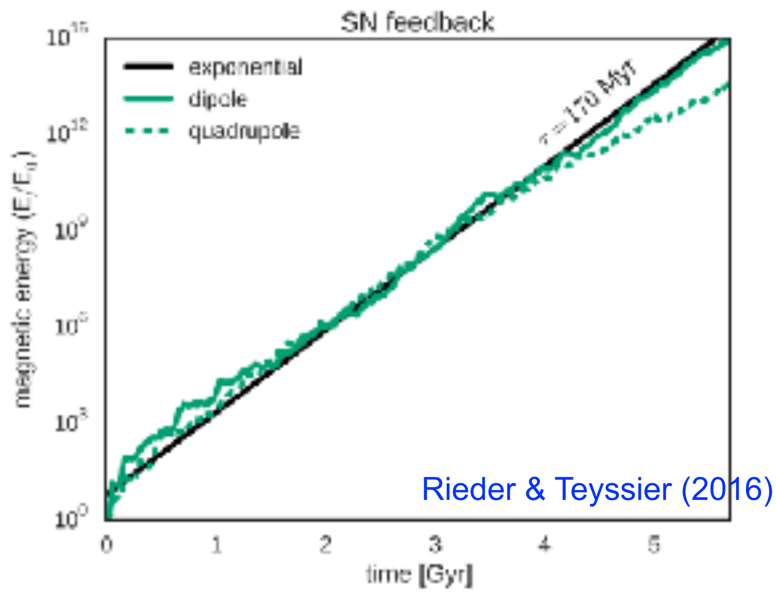
Cooling halo simulations

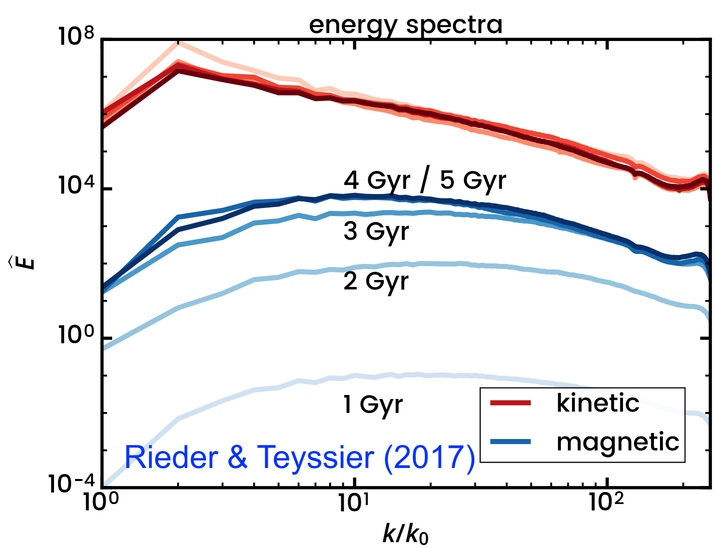


Rieder & Teyssier (2016)

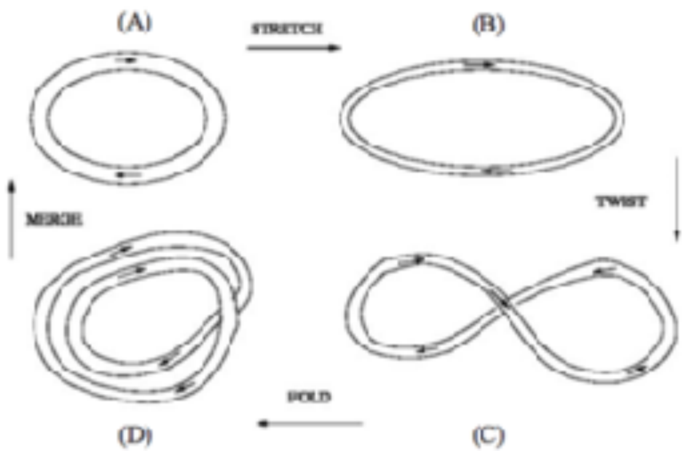
Magnetic field generation in dwarf galaxies





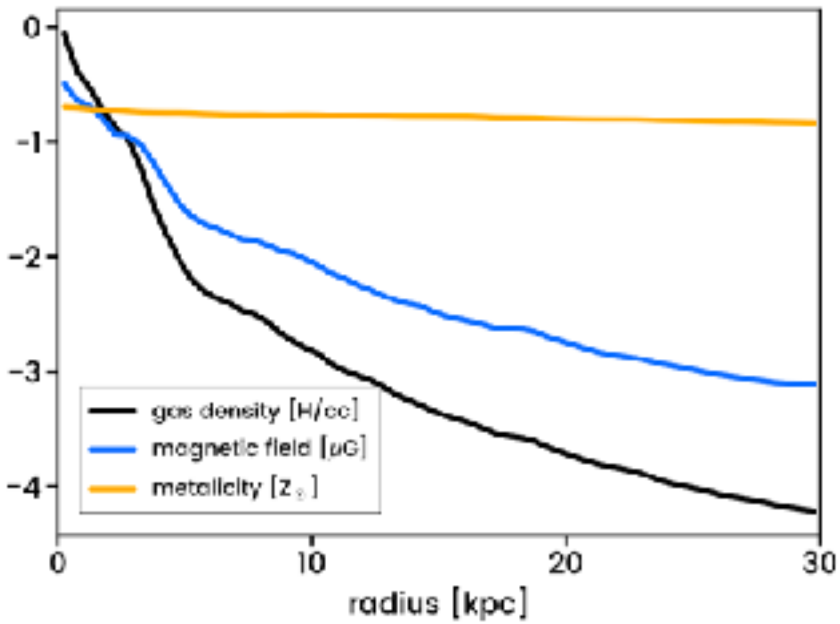


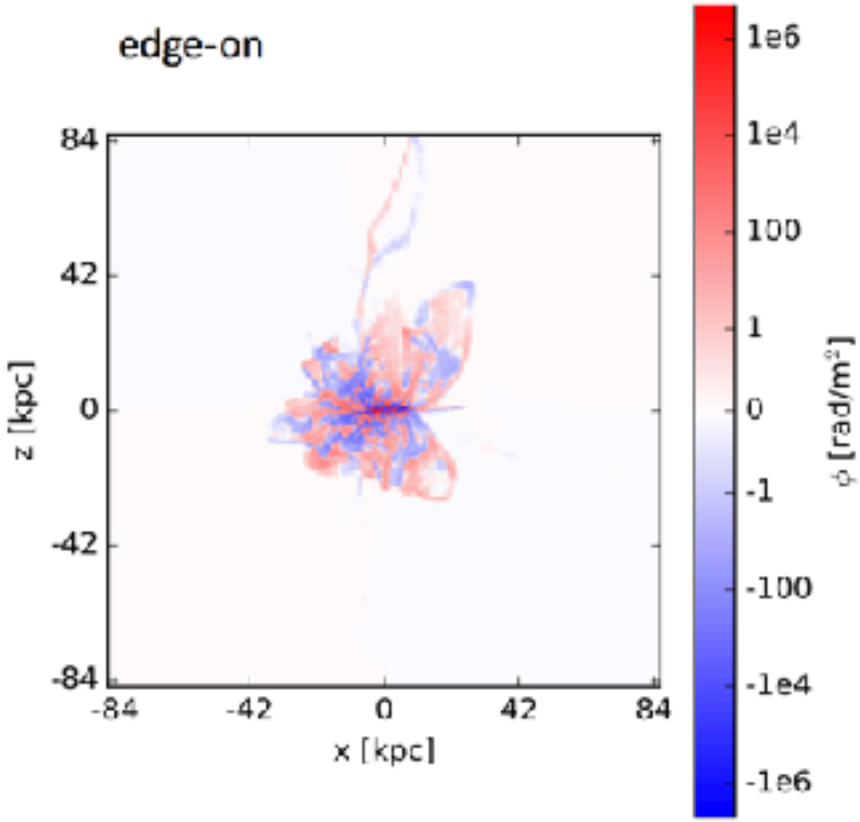
Stretch-twist-fold-merge mechanism



Observational signatures of the small-scale dynamo

Rieder & Teyssier 2017

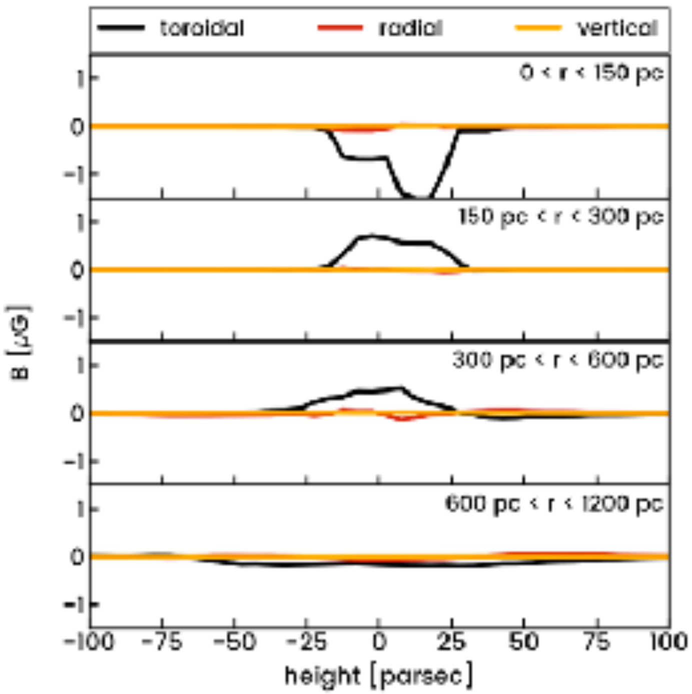


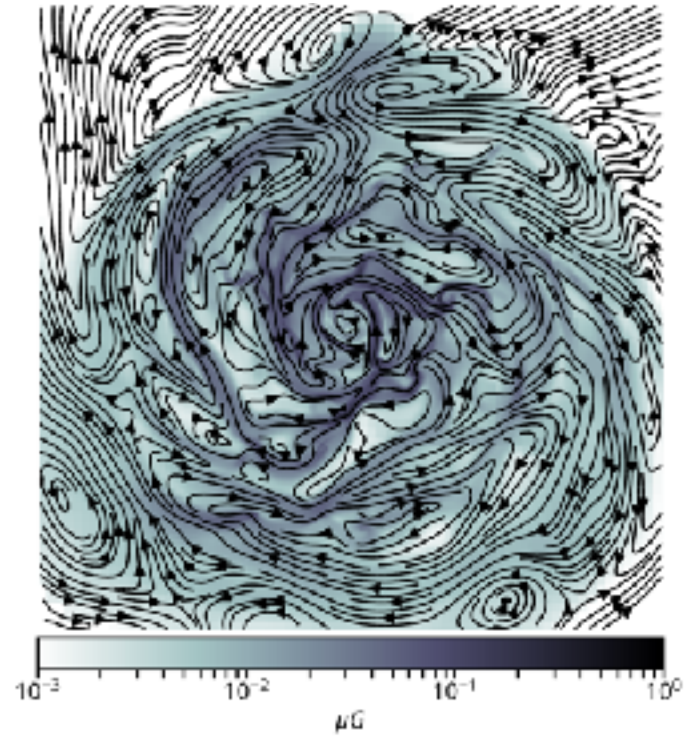


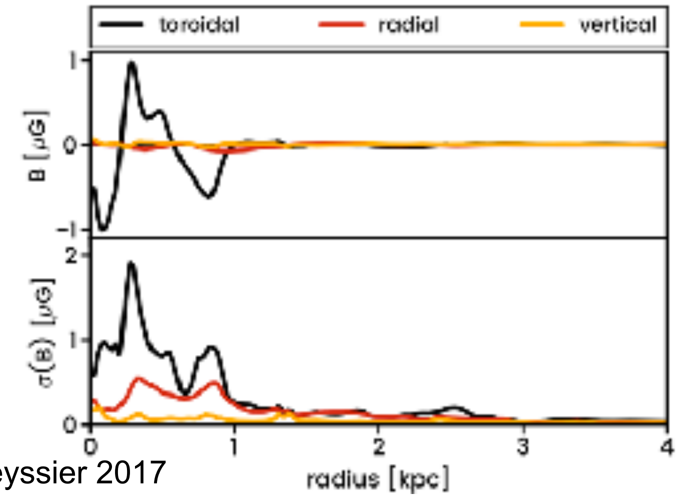
Simulation of a 10^{12} Msol halo with strong feedback and comparing to new VLA spectral data on 50 quasars with/without MgII absorption (Kwang Seong Kim and Simon Lilly, arxiv/1604.00028).

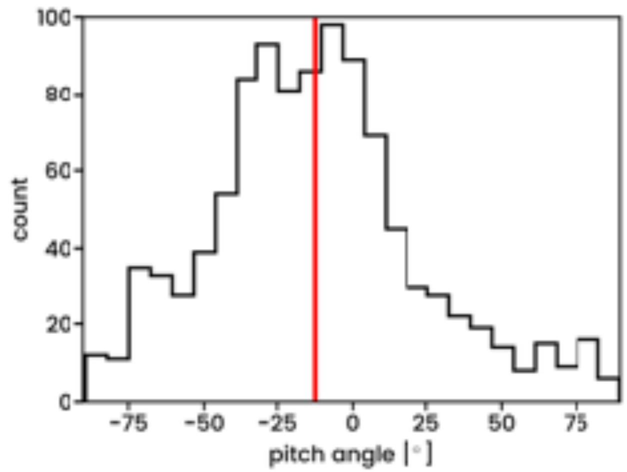
Saturated small scale dynamo within strong galactic winds compares favourably with observations at intermediate redshifts.

Transition to quiescence: final magnetic configuration





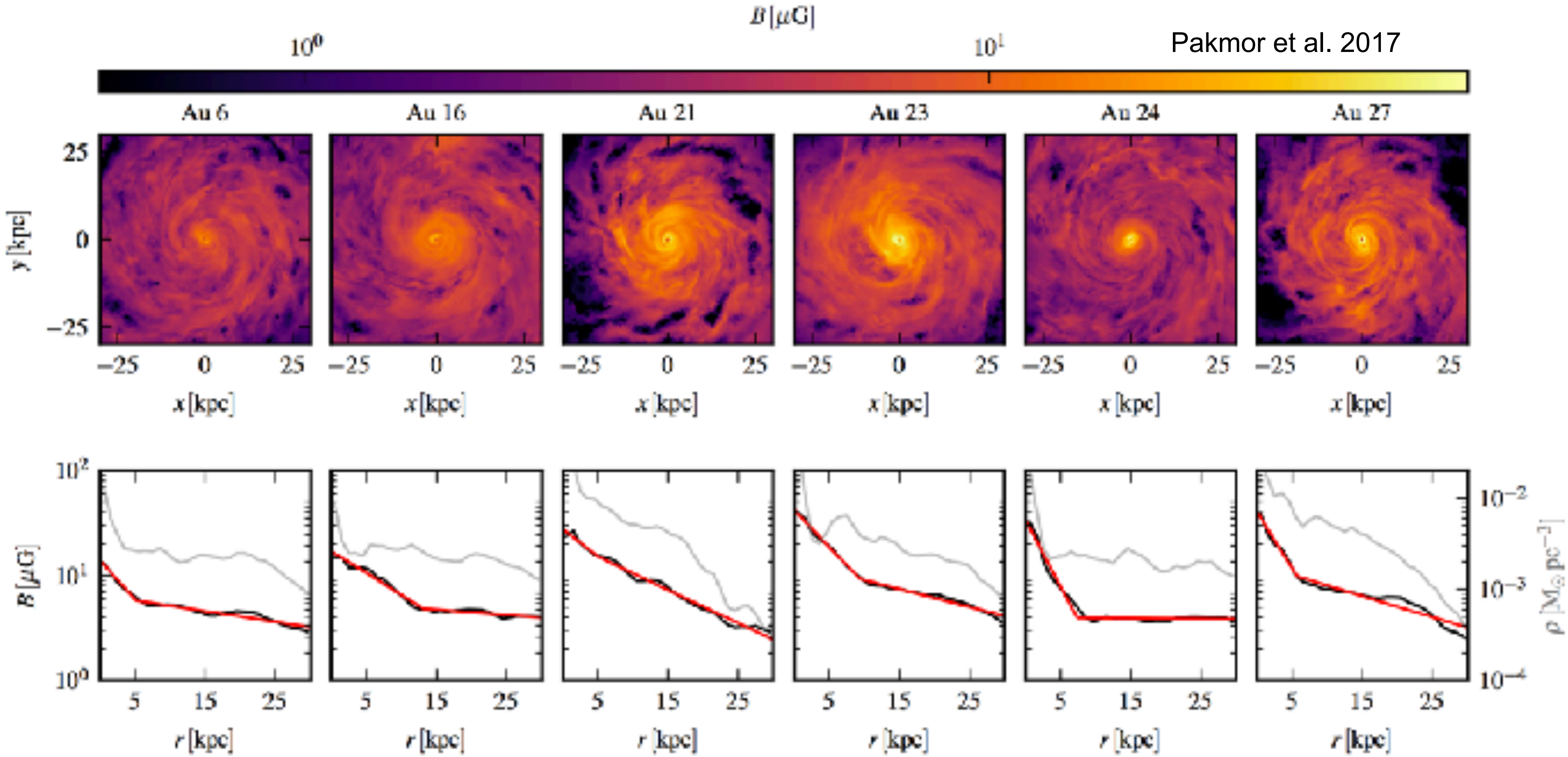




Rieder & Teyssier 2017

Cosmological MHD simulations

Pakmor et al. 2017



Conclusions

- Large N body simulation with Halo Model for galaxy mocks, emulators and covariance matrices. Large international coordination.
- Beyond 100 Trillions particles for SKA cosmology?
- Cosmic reionization simulations with radiative transfer (and radiation hydrodynamics) on similar volumes.
- Galaxy formation simulations with detailed feedback models and radiative HII/HI/H2 physics.
- Cosmic magnetism within the cosmological context (small scale/large scale dynamos) and simulations of detailed observables

Thank you !