SKA Science Simulations

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Outline

– Mock surveys: N body simulations beyond the Trillion particle barrier
  “Galaxy Evolution, Cosmology and Dark Energy”

– Simulating cosmic reionization: radiation hydrodynamics
  “Probing the Cosmic Dawn”

– Cosmic magnetism: from small scale to large scale dynamos
  “Cosmic Magnetism”
EUCLID: a space mission to map the universe
Cosmological $N$ body simulations

- direct summation
- $P^3M$ or $AP^3M$
- parallel or vectorized $P^3M$
- distributed-memory parallel Tree
- distributed-memory parallel Tree PM
- distributed-memory parallel PM AMR

Swiss SKA day 2017
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)

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


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

Resources: 2 million node-hours (with GPU)
The Euclid Flagship Simulation

Doug Potter
Joachim Stadel
The diagram shows a scatter plot with the x-axis representing volume in Mpc³ and the y-axis representing mass in M⊙. The plot includes various simulations such as Millennium-Il (‘09), DarkSky-s (‘14), Bolshoi (‘11), QContinuum (‘14), MultiDarkP (‘13), Outer Rim (‘14), and others. The ultimate aim is indicated by an arrow pointing towards 3 Gpc – 2 trillion particles.
The pkdgrav3 N-Body Code

1. Fast Multipole Method, $O(N)$, 5th order in $\Phi$
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

6th Fastest Computer in the World. Upgrade to Haswell & P100 (now)
Benchmarks 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.

Thanks: Pablo Fosalba
The Light Cone
10 trillion particles
50 billion halos

\( z=2.3 \) (~10 Gyrs ago)

\( z=0 \) (the present)

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

Arrived at a big data problem with the light cone output.
Constraint on the reionization epoch

Robertson et al. (2015)
A new radiation hydrodynamics solver in RAMSEY

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:
\[
\int_{4\pi} (\ldots) \, d\Omega \quad \rightarrow \quad \frac{\partial E_\nu}{\partial t} + \nabla \cdot \mathbf{F}_\nu = -\kappa_\nu c E_\nu + S_\nu
\]
\[
\int_{4\pi} (\ldots) \, n\, d\Omega \quad \rightarrow \quad \frac{\partial \mathbf{F}_\nu}{\partial t} + c^2 \nabla \cdot \mathbf{P}_\nu = -\kappa_\nu c \mathbf{F}_\nu
\]

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

\[
\mathbf{P}_\nu = E_\nu \mathbf{D}_\nu \quad \mathbf{D}_\nu = \frac{1}{2} - \chi_\nu \mathbb{I} + \frac{3\chi_\nu - 1}{2} \mathbf{n}_\nu \otimes \mathbf{n}_\nu,
\]
\[
\chi_\nu = \frac{3 + 4 f_\nu^2}{5 + 2\sqrt{4 - 3 f_\nu^2}} \quad \text{and} \quad f_\nu = f_\nu \mathbf{n}_\nu = \frac{\mathbf{F}_\nu}{c E_\nu}
\]

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

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

\[
\int_{4\pi} (...) \, d\Omega \quad \rightarrow \quad \frac{\partial E_\nu}{\partial t} + \nabla \cdot F_\nu = -\kappa_\nu c E_\nu + S_\nu
\]

Angular moment’s equations:
\[
\int_{4\pi} (...) \, n d\Omega \quad \rightarrow \quad \frac{\partial F_\nu}{\partial t} + c^2 \nabla \cdot \mathbb{P}_\nu = -\kappa_\nu c F_\nu
\]

Coupling to hydrodynamics: 1- cooling and heating

\[
\frac{\partial E}{\partial t} + \nabla \cdot \left( u \left( E + P \right) \right) = \Gamma_{\text{rad}} - \Lambda_{\text{rad}}
\]

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

Coupling to hydrodynamics: 2- radiation force

\[
\frac{\partial \rho u}{\partial t} + \nabla \cdot \left( \rho u \otimes u + P \mathbb{I} \right) = F_{\text{rad}}
\]

\[
F_{\text{rad}} = \int_0^{+\infty} \frac{\kappa_\nu}{c} F_\nu \, d\nu
\]
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 for 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 $f_{\text{esc}}=10\%$ 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)

• Successful large-scale dynamos are slow with growth rate $\sim 0.1\Omega$ up to $\Omega$ 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.
Turbulent dynamo in a dwarf galaxy

Rieder & Teyssier (2016)

Cooling halo simulations

Swiss SKA day 2017
Magnetic field generation in dwarf galaxies

Rieder & Teyssier (2016)

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!