Physics and resolution challenges in galaxy formation simulations

Volker Springel

- Small scale – large scale connection
- The numerical challenge of bridging the gap
- Simulation code accuracy
- New physics implementations: Magnetic fields and cosmic rays in galaxy formation
The **EUCLID** satellite mission aims to measure **dark energy**

**CONSTRAINING THE EXPANSION HISTORY OF THE UNIVERSE**

- Uses galaxy clustering and weak lensing shear to constrain dark energy

- Already more than 1000 scientists in the Euclid consortium

- Project depends heavily on simulation calibration, requires $N \sim 5 \times 10^{12}$
The target accuracy of 1% for Euclid's power spectrum requires a precise understanding of baryonic physics impacts on large scales.

**POWER SPECTRUM IMPACT OF BARYONIC PHYSICS**

Semboloni et al. (2011)
The baryonic impact on large scales competes with modified gravity effects

POWER SPECTRUM IMPACT OF $f(R)$ GRAVITY AND AGN

Puchwein, Baldi & Springel (2013)
Numerous recent studies claim that baryonic physics can induce large dark matter cores and resolve CDM small-scale tensions.

**REPEATED OUTFLOWS MAY DO THE TRICK**

See also:
- Mashchenko, Couchman & Wadsley (2006)
- Governato et al. 2010
- Pontzen & Governato 2012
- Governato et al. 2012
- Maccio et al. 2012
- Martizzi et al. 2012
- Di Cintio et al. 2013
It is contested whether enough energy is actually available to create cores in this way

**LIMITS ON THE EFFICIENCY OF CORE FORMATION MECHANISMS**

**Garrison-Kimmel et al. (2013)**

Matching the observed central masses of $10^6$ Msun dSphs, the energy equivalent of more than 40,000 supernovae must be delivered with 100% efficiency directly to the dark matter... *more SN than ever exploded in such dwarfs.*

Single blow-out more efficient than several small ones.

See also:

Gnedin & Zhao (2002)
Ogiya & Mori (2011)
Bridging the gap: the numerical challenge
Galaxy formation poses an enormous multi-scale physics problem

THE DYNAMIC RANGE CHALLENGE

A supermassive BH in a galaxy

![Diagram of a galaxy with a supermassive black hole, showing a size scale of \( \sim 10^{-6} \text{ pc} \) to \( \sim 10 \text{ kpc} \) with a dynamic range of \( 10^{10} \).]

Star formation in a normal galaxy

![Diagram of a galaxy with star formation, showing a total mass \( M_{\text{tot}} \sim 10^{12} M_\odot \) and a stellar mass \( m_* \sim 1 M_\odot \) with a mass dynamic range of \( 10^{12} \).]
Achieving high local resolution usually implies high dynamic range in space, time, and mass

THE DYNAMIC RANGE CHALLENGE OF GALAXY SIMULATIONS

• Assume we want to realize a 10 pc resolution using a uniform grid, for example in a 10 Mpc volume.

• This would require $10^{18}$ cells – a billion times more than a $1000^3$ run, which is still a sizable simulation by today's standard.

• But actually, reducing the mesh size by a factor of 2 will also reduce the timestep by a factor of 2.

• So if you improve the linear dimension (of all cells) by a factor of 10, the computational cost goes up by a factor of $10^3 \times 10 = 10^4$.

• Going from a $1000^3$ to a million$^3$ cells in a uniform grid then means a cost increase of $10^{12}$.

• If computers keep getting faster at the current rate (a factor of 100 in 10 years), we merely have to wait 60 years for this.
Fortunately, high resolution is only required in a small fraction of the volume, making adaptive resolution techniques attractive.

REALIZING HIGH SPATIAL DYNAMIC RANGE THROUGH ADAPTIVE RESOLUTION

Example: Suppose you want to have 10 pc resolution in the ISM of the Galaxy, but the rest of the galaxy (radius 200 kpc) can be coarser resolved.

With a uniform mesh you need:

\[
\frac{4\pi}{3} \left( \frac{200 \text{ kpc}}{10 \text{ pc}} \right)^3 \approx 3.4 \times 10^{13}
\]

If you just fill the disk, say of radius 10 kpc and height 1 kpc, with high resolution you need:

\[
\frac{\pi (10 \text{ kpc})^2 \times 1 \text{ kpc}}{(10 \text{ pc})^3} \approx 3.1 \times 10^8
\]

So adaptive spatial resolution is the way to go.
The number of cores on the top supercomputers grows exponentially.

**EXTREME GROWTH OF PARALLELISM**

Exponential growth in parallelism for the foreseeable future

(figure by G. Sutmann)
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<th>Rank</th>
<th>Site</th>
<th>System</th>
<th>Cores</th>
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Future progress with cosmological simulations requires....

- More complete and realistic physics models
- Higher accuracy of numerical codes
- Better resolution (better use of existing and upcoming computing power)
Code accuracy
The Lagrangian character of SPH is automatically providing adaptive resolution that is very well suited for gravity-driven structure growth.

**DIFFERENT APPROACHES TO ADAPTIVE RESOLUTION**

**SPH**

- Provided one puts enough particles initially into the region of interest, an adaptive resolution with constant mass resolution is automatically obtained.

- The downside is, resolution is difficult or impossible to change on the fly.

- Multi-mass technique do not work very well as the accuracy in regions where particles of different mass interact is poor.
Eulerian codes can employ Adaptive Mesh Refinement (AMR) to realize high dynamic range.

DIFFERENT APPROACHES TO ADAPTIVE RESOLUTION

AMR

- Use a hierarchy of nested grids that allows in principle arbitrary dynamic range. Refinement criteria can be chosen almost arbitrarily.

- Quick motion of a small high-resolution region requires however frequent changes of the mesh hierarchy.

- Accuracy at grid boundaries suffers and normally goes down to 1\textsuperscript{st} order.
Similar to SPH, the method keeps the mass resolution approximately constant, independent of the clustering state.

If desired, dynamic mesh refinements and de-refinements are however possible, similar to AMR.

At any given time, only one mesh is tessellating the volume. The resolution changes gradually throughout space, in principal avoiding localized errors due to resolution changes.

Bulk motions do not introduce advection errors, nor reduce the timestep.
The Gresho vortex test in two dimensions

CONVERGENCE RATE AGAINST ANALYTIC SOLUTION FOR AREPO AND ATHENA

Initial conditions:

\( v_\phi(r) = \begin{cases} 
5r & \text{for } 0 \leq r < 0.2 \\
2 - 5r & \text{for } 0.2 \leq r < 0.4 \\
0 & \text{for } r \geq 0.4
\end{cases} \)

\( P(r) = \begin{cases} 
5 + 25/2r^2 & \text{for } 0 \leq r < 0.2 \\
9 + 25/2r^2 - 20r + 4\ln(r/0.2) & \text{for } 0.2 \leq r < 0.4 \\
3 + 4\ln 2 & \text{for } r \geq 0.4
\end{cases} \)
Much recent effort has aimed to improve SPH

PATCHING VANILLA SPH

Better parameterizations of artificial viscosity

Pressure-based formulations for improved contact discontinuities

Additional dissipation / diffusion to account for mixing

Higher-order interpolation kernels

Use of auxiliary grids

Price (2008)
Wadsley, Veeravalli & Couchman (2008)
Read, Hayfield & Agertz (2009)
Hess & Springel (2010)
Read & Hayfield (2012)
Hopkins (2012)
Dehnen & Hossam (2012)
...

New SPH variants show improved convergence rates

CONVERGENCE RATE AGAINST ANALYTIC SOLUTION FOR SPHS

Read & Hayfield (2012)
The computational cost to reach a desired Reynolds number in subsonic turbulence grows more quickly in SPH than in a mesh code.

**REYNOLDS NUMBER AND COMPUTATIONAL COST**

\[ \mathcal{R}_e \equiv \frac{V L}{\nu} \]

\[ \frac{\eta}{L_0} \sim \text{Re}^{-\frac{3}{4}} \]

Computational cost:  CPU \( \sim d^{-4} \), where  \( d = \text{mean cell/particle spacing} \)

Assume that we indeed can describe SPH by:

\[ \nu \approx \frac{1}{10} \alpha \nu_{\text{sig}} h \]

Price (2012)

CPU \( \sim \text{Re}^4 \)

In the (moving) mesh code we however find:

\[ \frac{\eta}{L_0} \sim d \]

CPU \( \sim \text{Re}^3 \)
physics in cosmological galaxy formation simulations
**Galaxy formation physics for cosmological simulations in AREPO**

**Cooling and metal enrichment**
- Nine elements followed independently
- Mass and metal loss of stars treated continuously over time based on stellar population synthesis models (similar to Wirsma et al. 2009)
- Ionization balance and cooling from H and He followed with direct chemical network (Katz et al. 1996)
- Metal line cooling added through CLOUDY lookup tables in density, temperature and redshift
- Simple self-shielding correction (Rahmati et al. 2013)

**Star formation and winds**
- Variant of Springel & Hernquist (2003)
- Cold dense gas stabilized by an ISM equation of state
- Winds are phenomenologically introduced, with an energy given as a fixed fraction of the supernova energy
- The wind velocity is variable, the mass flux follows for energy-driven winds
- Fiducial model scales wind with local dark matter velocity dispersion
- Winds are launched outside of star-forming gas, and metal-loading can be reduced if desired

**Black hole accretion and feedback**
- Black hole seeding and accretion model (Springel et al. 2005)
- Quasar-mode feedback for high accretion rates
- Radio-mode feedback for low accretion rates based on bubble-heating model (Sijacki et al. 2006)
- Radiative AGN feedback (change in heating/cooling due to variation of UVB) in proximity to an active black hole
- Reduction of accretion rate in low-pressure/low-density regimes to avoid large hot bubbles around black holes in quiescent state
- Black holes tied to potential minimum of halos

Vogelsberger et al. (2013)
Zooming in on dark matter halos reveals a huge abundance of dark matter substructure.

**DARK MATTER DISTRIBUTION IN A MILKY WAY Sized HALO AT DIFFERENT RESOLUTION IN THE AQUARIUS PROJECT**
Hydro simulations of the Aquarius systems produce Milky Way like galaxies.

STELLAR DISTRIBUTION AT THE CENTRE OF THE Aq-C-4 HALO
Our new hydrodynamical simulations finally make nice disk galaxies

STELLAR SURFACE BRIGHTNESS OF THE AQ-C-4 RUN

Marinacci, Pakmor & Springel (2013)

see Marinacci's talk...
Several important basic physical processes are still completely neglected in these simulations...

PARTIAL LIST OF MISSING PHYSICS

- Self-consistent radiative transfer
- Magnetic fields
- Cosmic ray physics
- (Anisotropic) thermal conduction
- Dust
Galaxies are magnetized

Typical field strengths in spirals of ~10μG

Assumed to be in equipartition with thermal gas pressure & cosmic rays

Dynamically important (?)

Magnetic fields may play an important role in galaxy formation

MAGNETIC FIELD STRENGTH IN M51

Fletcher et al. (2011)
We have a new ideal MHD implementation in AREPO that works well

**EQUATIONS AND SOME TESTS**

\[
U = \begin{pmatrix}
\rho \\
\rho v \\
\rho e \\
B \\
\psi
\end{pmatrix}
\]

\[
F(U) = \begin{pmatrix}
\rho v \\
\rho vv^T + p - BB^T \\
\rho ev + \rho v - B(v \cdot B) \\
Bv^T - vB^T + \psi I \\
c_h^2 B
\end{pmatrix}
\]

**Orszag-Tang vortex test**

- Pakmor, Bauer & Springel (2011)
- Pakmor & Springel (2013)

- 8-wave Powell scheme for divergence cleaning
- Approximate HLLD Riemann solver

**Magneto-rotational instability in 3D**

we get the correct linear growth rate
In isolated disk galaxy formation simulations, magnetic fields drive magnetically driven fountain like flows out of the disk.

SLICES THROUGH THE GAS DENSITY AND THE MAGNETIC FIELD

Pakmor & Springel (2012)
Simulations with magnetic fields produce similar disk galaxy morphologies

PROJECTED FACE-ON AND EDGE-ON MAPS OF THE EIGHT AQUARIUS GALAXIES  Pakmor et al. (2013)
An azimuthal magnetic field builds up as soon as there is a well defined gas disc.

Magnetic field in slices through the disc mid-plane of AQ-C at different times.
An azimuthal magnetic field builds up as soon as there is a well defined gas disc

MAGNTIC FIELD IN SLICES THROUGH THE DISC MID-PLANE OF AQ-D AT DIFFERENT TIMES
The field in the disk planes are highly ordered

MAGNTIC FIELD IN SLICES THROUGH THE DISC MID-PLANES
The magnetic field evolves to similar strength in all Aquarius systems
The results are insensitive to the magnetic seed field strength.
The predicted magnetic field strength agrees quite well with observations.

RADIAL PROFILE OF MAGNETIC FIELD STRENGTH IN SIMULATIONS AND OBSERVATIONS

Basu & Roy 2013
Perpendicular to the disks, the field is irregular and is heavily affected by the winds in the corona.

MAGNTIC FIELD IN SLICES ORTHOGONAL TO THE DISCS

(A set of images showing magnetic field variations in different slices orthogonal to the disks, with B [μG] scale on the right.)
The magnetic field declines approximately exponentially orthogonal to the discs

MAGNETIC FIELD STRENGTH AS A FUNCTION OF DISTANCE FROM THE DISC PLANE

![Graphs showing the magnetic field strength as a function of distance for different cases](image-url)
The pitch angle of the disc magnetic field is usually highly coherent – and sometimes flips

PITCH ANGLE AT Z=0 IN THE EIGHT AQUARIUS DISC SYSTEMS
The magnetic pitch angle in the discs sometimes shows flips.

TIME EVOLUTION OF THE PITCH ANGLE IN THE AQ-D SIMULATION
The largest change in the galaxy properties at z=0 lies in the gas fractions

**GAS FRACTION FOR DISC GALAXIES SIMULATED WITH AND WITHOUT MAGNETIC FIELDS**
Cosmic rays may play an important role in the ISM and ICM

**A SIMPLE FORMALISM FOR COSMIC RAYS**

Enßlin, Pfrommer, Jubelgas & Springel (2006)

**cosmic ray momentum spectrum**

\[
\frac{d^2 N}{dp \, dV} = C p^{-\alpha} \theta(p - q)
\]

**cosmic ray pressure**

\[
P_{CR} = \frac{C m_p c^2}{6} B^{\frac{1}{1+q^2}} \left( \frac{\alpha - 2}{2}, \frac{3 - \alpha}{2} \right)
\]

**adiabatic evolution**

\[
q(\rho) = \left( \frac{\rho}{\rho_0} \right)^{\frac{1}{3}} q_0, \quad \tilde{C}(\rho) = \left( \frac{\rho}{\rho_0} \right)^{\frac{\alpha - 1}{3}} \tilde{C}_0.
\]

**injection mechanisms**

- Supernovae injection
- Diffuse shock acceleration at structure formation shocks

**loss processes**

- Coulomb losses
- Cosmic ray diffusion
- Hadronic interactions, mostly pion production (catastrophic losses)
- Bremsstrahlung (negligible for protons)
Cosmic ray proton populations have several properties that may help galaxies to launch strong winds

EXPECTED PROPERTIES OF GALACTIC COSMIC RAY POPULATIONS

- 10-60% of the supernova energy is expected to come out initially as CRs through diffusive shock acceleration.

- CRs form a light fluid which tends to buoyantly escape from the disc. Due to magnetic coupling, this can drag ordinary gas along.

- The energy loss time-scales of relativistic protons due to Coulomb and hadronic interactions are long – much longer than the cooling time of the thermal gas.

- Dissipating CR energy into the thermal plasma increases the total pressure of the composite fluid due to the harder equation of state of the thermal plasma.

\[ \frac{\Delta E}{V} = \frac{P}{(\gamma - 1)} = \frac{P_{cr}}{(\gamma_{cr} - 1)} \]

- High mobility of CRs along already opened magnetic field lines (e.g. through Parker instability)
Cosmic rays injected by supernovae affect star-forming dwarf galaxies

**EDGE-ON GAS AND PRESSURE MAPS AND STELLAR PROFILES**

**$M = 10^{10} \, M_\odot/h$**

**$M = 10^{11} \, M_\odot/h$**

**$M = 10^{12} \, M_\odot/h$**

Jubelgas, Springel, Pfrommer, Enßlin (2006)
Cosmic ray streaming can drive outflows in small galaxies

**COSMIC RAYS AS A DRIVER OF WINDS**

Uhlig et al. (2012)

\[ \nu_{st} = -\lambda c_s \frac{\nabla P_{cr}}{|\nabla P_{cr}|} \]

\[ \lambda \geq 1 \]
We are able to take magnetic fields into account in cosmological simulations of disc galaxy formation.

Disc galaxies with magnetic fields show a slight suppression of star formation and higher gas fraction.

Magnetic field strength saturates at 10 $\mu$G in the center, declines to a few $\mu$G in outer regions of the disk.

Cosmic rays seem to be an important driver of galactic winds in small galaxies.

Bridging the gap more pressing than ever – there is a direct link from small-scale physics to cosmology!

We need to step up our efforts to make full use of existing computing technology – and those of the future.