The Public Release of OpenGadget3

Luca Tornatore, OATS

USB-C General Assembly

9 - 13 March, 2026 Trieste

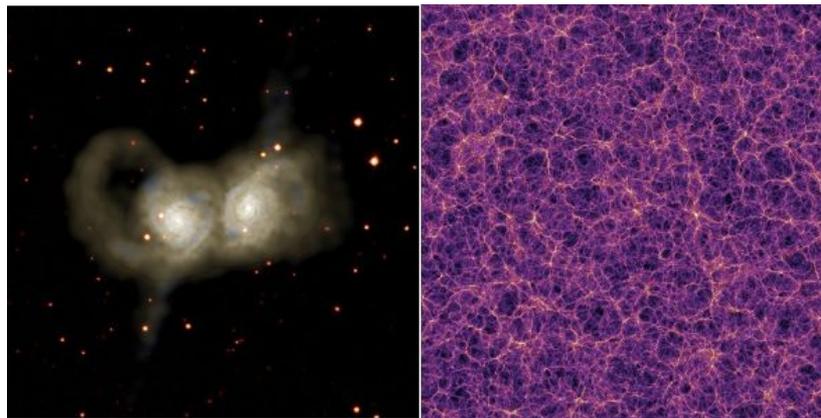**INAF** - V. Biffi D. Goz, G. Lacopo, G. Granato, U. Maio, G. Murante, A. Ragagnin, L. Tornatore
LMU - K. Dolag, L. Boss, L. Di Federico, F. Groth, G. Karademir, L. Sala
UniTS - S. Borgani, M. Valentini, A. Damiano

The OPENGADGET3 Code

- **Formation and evolution of LSS and galaxies in cosmological frame**

- **Zoomed-in simulations of galaxy clusters**

- **Single-galaxy evolution**

- Written in **C / C++**
- Parallelised with **MPI** and **OpenMP**
- **scalable I/O** on proprietary format and HDF5
- **GPU accelerated** with both OpenACC and OpenMP
- **Highly portable**: already runs on *all* EuroHPC platforms

The OPENGADGET3 Code

Key HPC Features	Portability Scalability GPU offloading
Key Physics Modules Publicly released	Brief overview of the main physics modules that will be released and maintained

The OPENGADGET3 Code

Key HPC Features

Portability
Scalability
GPU offloading

**Key Physics Modules
Publicly released**

Brief overview of the main physics modules that will be released and maintained

OG3 Code : Portability

Cluster	Deucalion	Discoverer	Karolina	Leonardo	Lumi	MareNostrum	MeluXina	Vega
Partitions	CPU,GPU	CPU	CPU,GPU	CPU,GPU	CPU,GPU	CPU,GPU	CPU,GPU	CPU,GPU
Access	✓ , ✓	✓	✓ , ✓	✓ , ✓	✓ , ✓	✓ , ✓	✓ , ✓	✓ , ✓
Deploy	✓ , ✓	✓	✓ , ✓	✓ , ✓	✓ , ✓	✓ , ✓	✓ , ✓	✓ , ✓
Benchmark	x, x	x	✓ , x	✓ , ✓	✓ , x	x, x	x, x	x, x

A noteworthy detail: in the frame of the SPACE CoE OpenGadget3 has been **deployed** and **run** on *all* **EuroHPC computational framework**, both on CPU and GPU partitions (where available).

The code supports *all* the GPUs vendors: NVIDIA AMD (intel)

It also runs seamlessly on arm architectures (and hence on the new Grace-Hoppers)

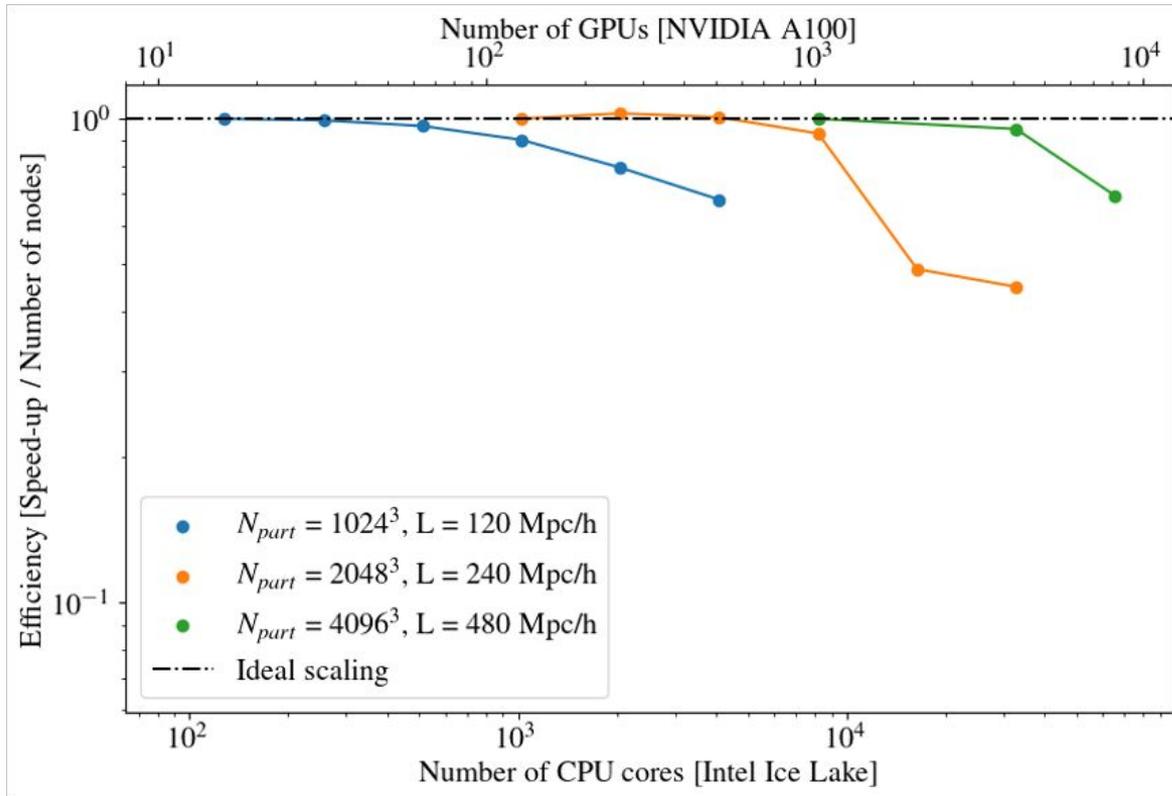# OG3 Code : Parallel Performance - Strong Scaling
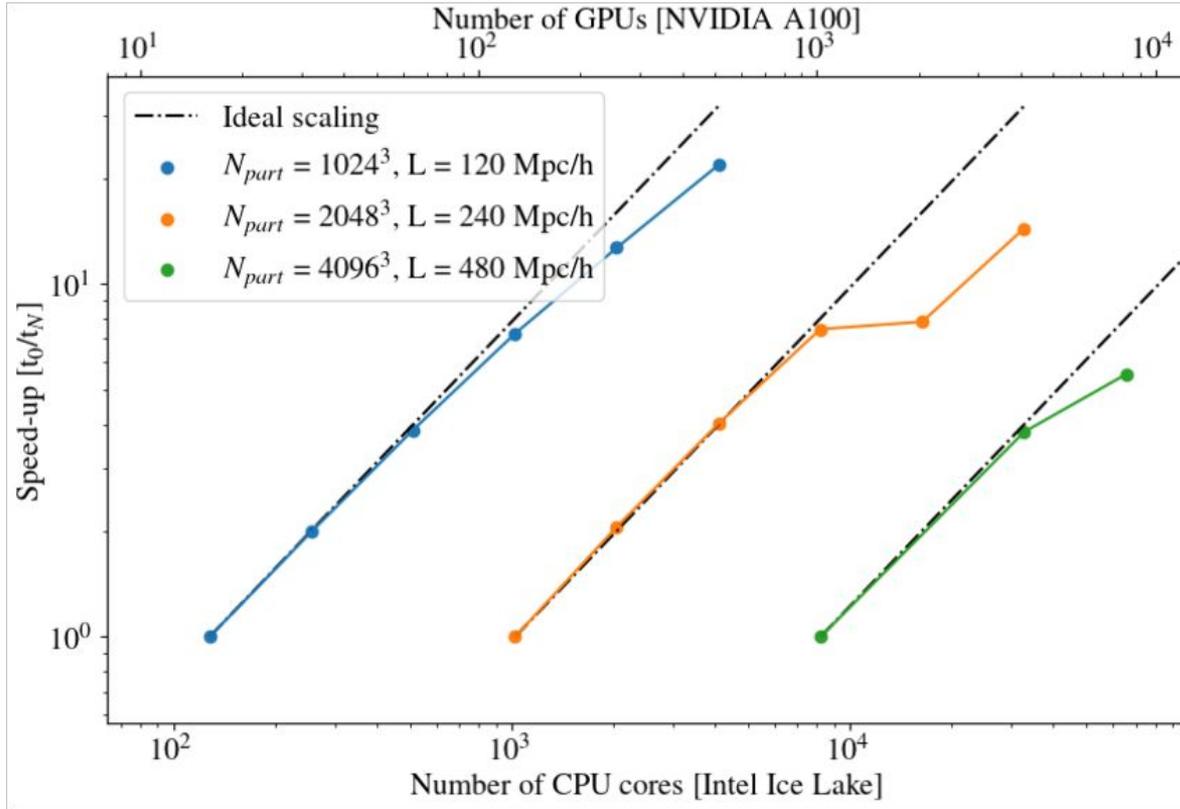
Strong scaling results obtained 1.5yr ago on Leonardo with **9000** GPUs
Joint effort with CINECA in the fram of SPACE CoE.

note the 64x fold in resources

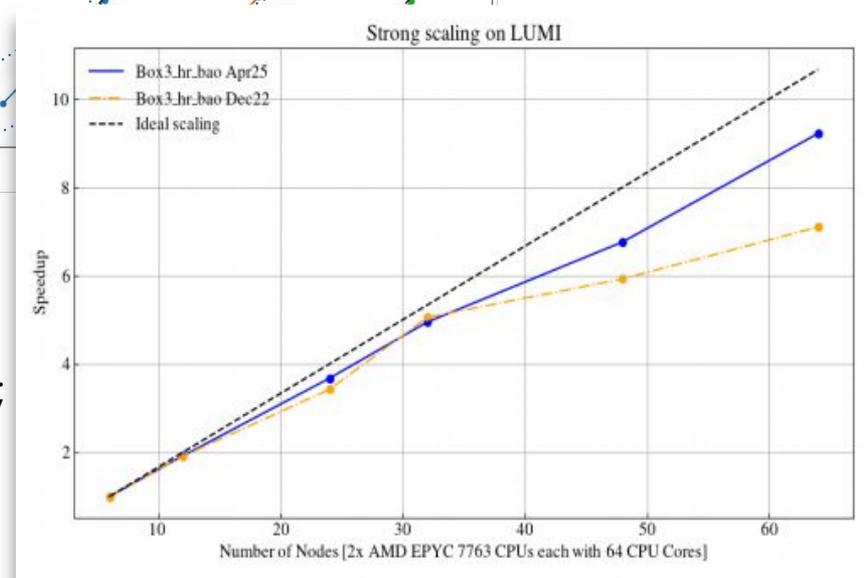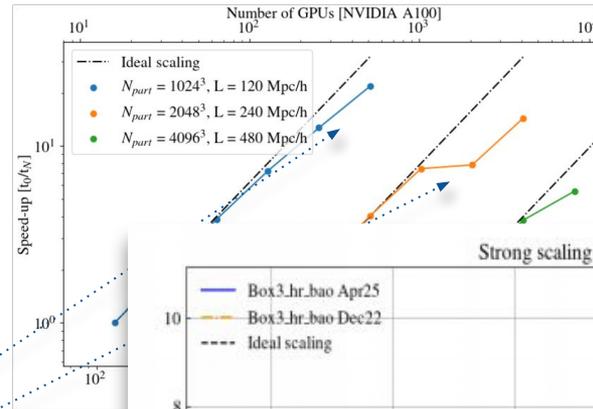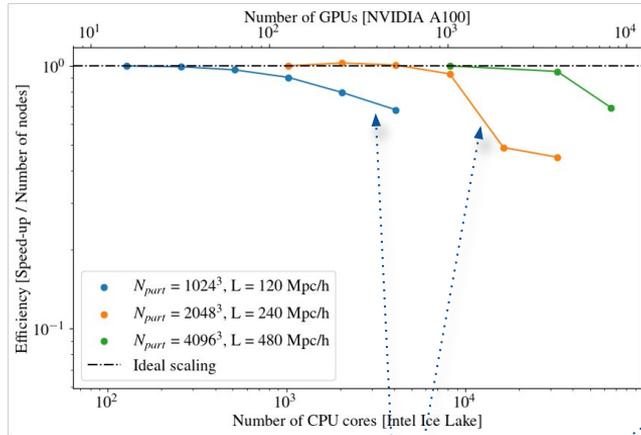# OG3 Code : Parallel Performance - Weak Scaling

WEAK scaling results obtained 1.5yr ago on Leonardo with **9000** GPUs
Joint effort with CINECA in the fram of SPACE CoE.

note the 64x fold in resources

OG3 Code : Parallel Performance - Weak Scaling

These inefficiencies have known causes; some have been fixed, some are being reworked.
→ development and evolution are continuous processes

OG3 Code : GPU offloading

Module name	Description	GPU offloading
GRAVITY Tree Walk	Tree walk specific for gravity using Barnes&Hut	OpenACC OpenMP
GRAVITY Neighbour search	Neighbour search for the *kNN* problem	OpenACC OpenMP
HYDRO Find Hsml	Tree walk to find SPH neighbours	OpenACC OpenMP
HYDRO Compute Gradients	Estimate of SPH density-dependent quantities	OpenACC OpenMP (WIP)
HYDRO Thermal conduction	Thermal conduction estimate using conjugate gradients	OpenACC OpenMP (WIP)
EXTRAPHYSICS	Physical processes using *kNN* neighbours	OpenACC (WIP) OpenMP (WIP)

The GPU offloading is vendor agnostic

OpenACC
A. Ragagnin
& K. Dolag, G. Karademir (LMU),
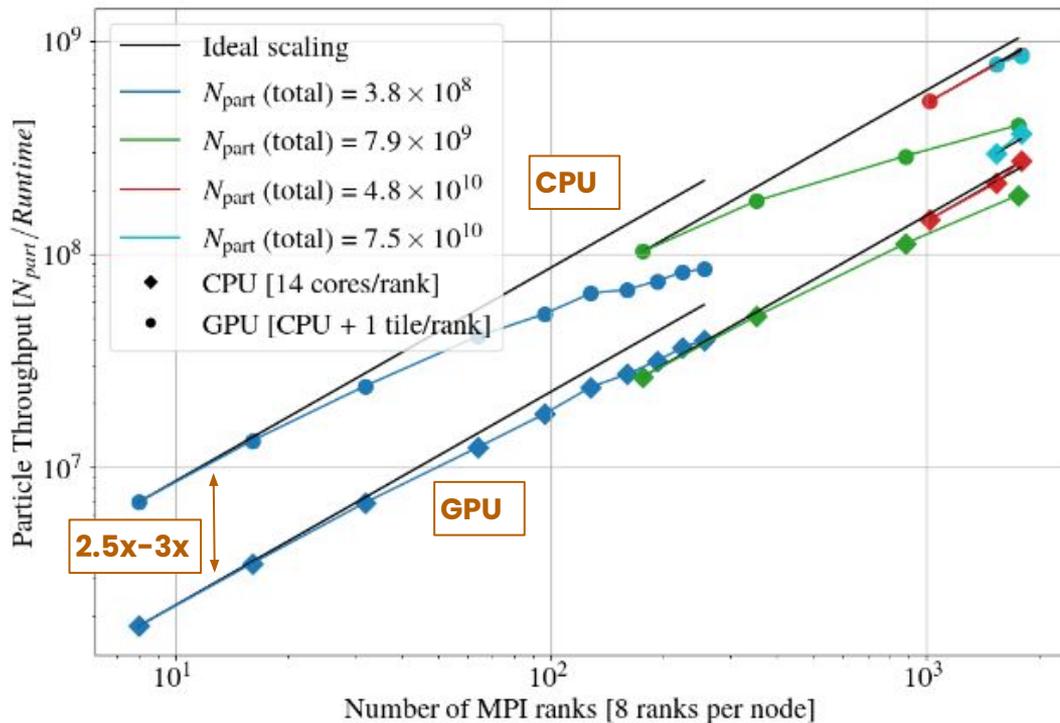D. Goz, G. Lacopo, T. Tarchi, L.T. (INAF)

NVIDIA

AMD **intel**

OpenMP with Intel's support
K. Dolag, D. Goz, G. Karademir,
G. Lacopo, A. Ragagnin, T.
Tarchi, L.T.

OG3 Code : GPU offloading - performance (A. Ragagnin+, in prep)

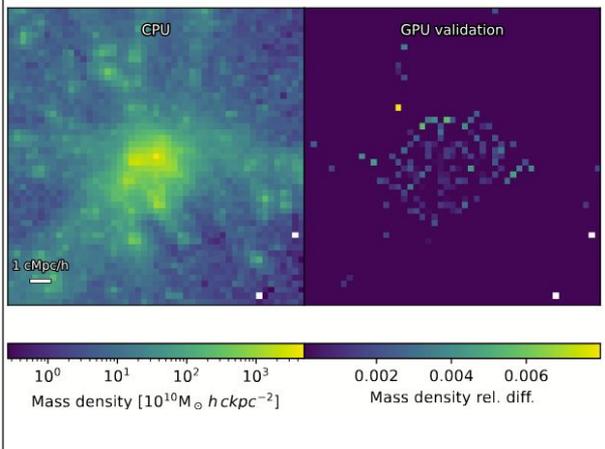Strong scaling results obtained recently

SuperMUC @ LRZ
Intel-Based (CPU + GPU)

Note that the GPU runs scale better due to a better work efficiency

OG3 Code : GPU offloading - Accuracy

DMO run

Legacy vs. ported code have slightly differences: GPU KDK-needed drifts are performed alltogether (small price to pay)

High Accuracy Achieved

MHD Ryu&Jones+95 shock tube
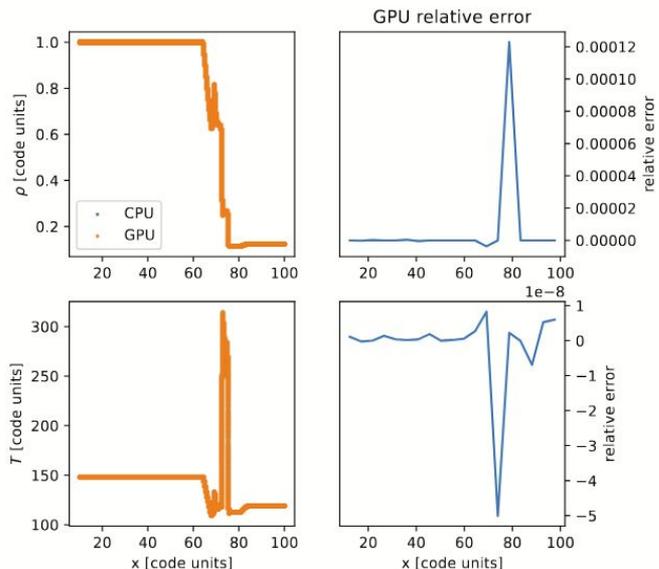
full-physics Dianoga galaxy
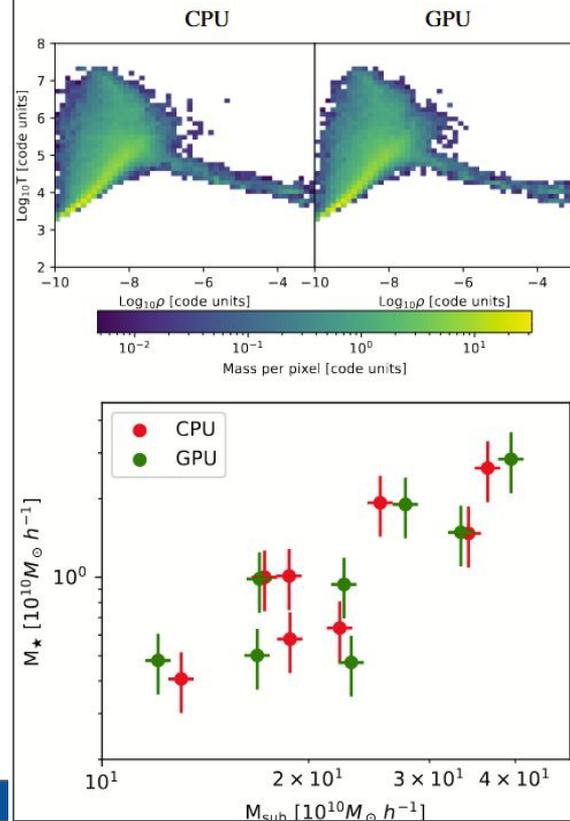
The OPENGADGET3 Code

Key HPC Features

Portability
Scalability
GPU offloading

**Code features &
Key Physics Modules
Publicly released**

Brief overview of the main physics modules that will be released and maintained

Why Numerical Simulations ? → coupling with ML solvers ?

HOT
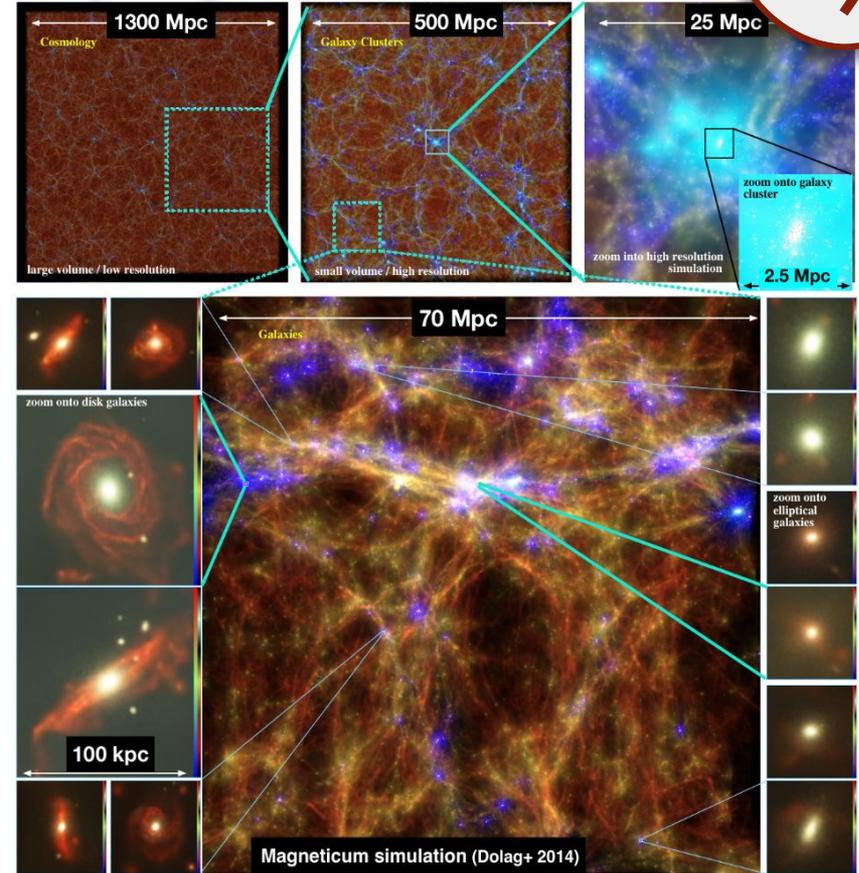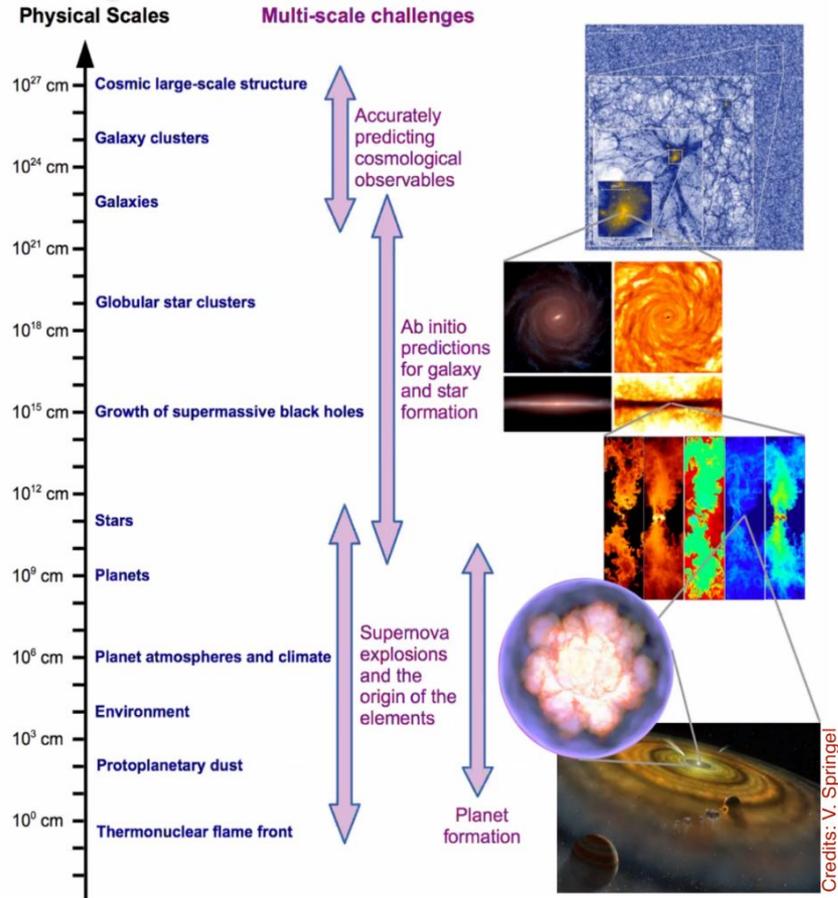
Thanks to M. Valentini (UniTS) for assembling this effective slide

The OPENGADGET3 Code

It is part of the "**Gadget family**"

- Lagrangian, **particle**-based code
- The **Gravity** solver is PM-Tree based
- The **Two** **Hydro** solver are based either on **SPH** or **MFM**
- It will be released with **full physics**
- It will be released with **GPU** support

Gadget (2000)

⬇

Gadget-2 (2005)

⬇

Gadget-3
Never disclosed publicly

Lot of derivations
SWIFT, GIZMO, MP-Gadget,Leiden
flavours, **OpenGadget3**

The OPENGADGET3 Code

It is part of the "**Gadget family**"

- Lagrangian, **particle**-based code
- The **Gravity** solver is PM-Tree based
- The **Two** **Hydro** solver are based either on **SPH** or **MFM**
- It will be released with **full physics**
- It will be released with **GPU** support

Gadget (2000)

⬇

Gadget-2 (2005)

⬇

Gadget-3
Never disclosed publicly

Lot of derivations
SWIFT, GIZMO, MP-Gadget, Leiden flavours, **OpenGadget3**

The OPENGADGET3 Code
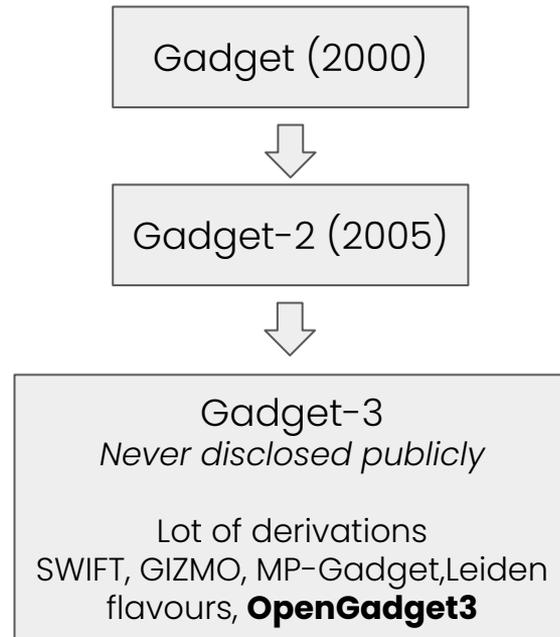
It is part of the "**Gadget family**"

- Lagrangian, **particle**-based code
- The **Gravity** solver is PM-Tree based
- The *Two* **Hydro** solver are based either on **SPH** or **MFM**
- It will be released with **full physics**
- It will be released with **GPU** support

- **Star Formation & Galactic Winds**
  - "classic" Springel & Hernquist, +coupled with stellar evolution
  - MUPPI, sophisticated multi-phase treatment
- **Radiative cooling** in a cosmic UV background
  - Legacy H+He
  - Metal-dependent with a table creation framework from cloudy
- **Non-equilibrium** H, He, H_2 Chemistry and Cooling
- **Stellar Evolution** and Feedback Detailed energy and chemical feedback from SnII, SnIa, low-interm. mass stars
- **Black Holes /1** Formation, stochastic accretion and feedback radio | quasar mode by sub-grid models

The OPENGADGET3 Code

It is part of the "**Gadget family**"

- Lagrangian, **particle**-based code
- The **Gravity** solver is PM-Tree based
- The *Two* **Hydro** solver are based either on **SPH** or **MFM**
- It will be released with **full physics**
- It will be released with **GPU** support

- **Black Holes dynamic & merger**
  "natural" positioning in potential wells by dynamical friction
- **Black Holes spin modelling**
- **Dust modelling**
  Tracking abundances of small and large. carbon and silicate grains
- **Self-Interacting dark matter**
  Tracking abundances of small and
- **Cosmic Rays**

OG3 Code : MFM - Meshless Finite Mass

New Meshless Methods Here (MFV, MFM)   Unstructured / Moving−Mesh Methods   Smoothed−Particle Hydrodynamics
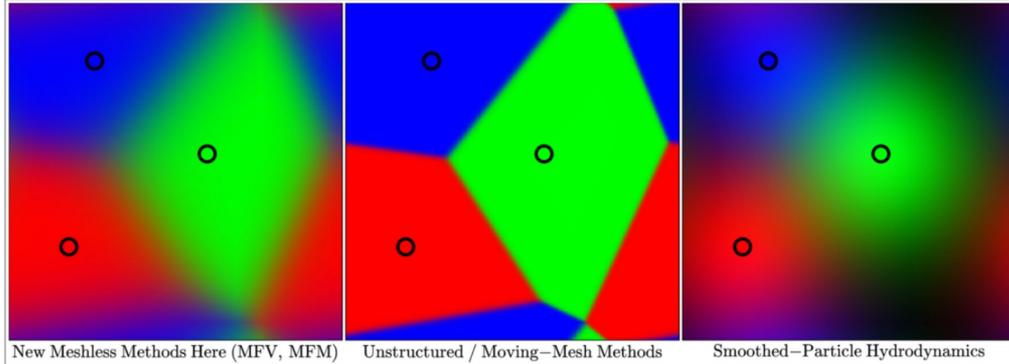
Hopkins (2015)
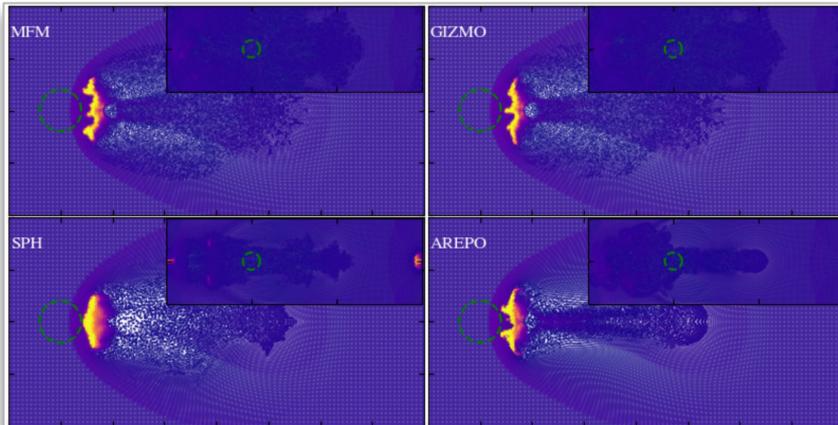
A *Lagrangian* method for fluid dynamics that calculates the continuous fluxes of momentum and energy between neighboring particles by solving the Riemann problem over their overlapping effective volumes.

→ no artificial viscosity and less numerical viscosity

- Effectively bridges the gap between SPH and grid methods.
- Natural spatial adaptivity
- Exact mass conservation
- high-order matrix gradient estimators → sharp shock-capturing and reduced numerical diffusion
- Much Improved turbulence & mixing
- More fine structure

OG3 Code : Metal-dependent Cooling with CIE

L. Di Federico (LMU)
L. Sala (LMU)
L. T.

Main direct (**emission**) mechanisms at **T ≥ 104 K**:

→ Bremsstrahlung (free-free): a free electron is deflected while interacting with an ion
→ Recombination (free-bound): an electron recombines with an ion.
→ Radiative de-excitation (bound-bound): a bound electron decays to a lower energy level.

Accounted in CIE:

→ Collisional ionisation (bound-free): an electron bound to a neutral atom or to an ion is freed by a collision (typically with a free electron)

→ Collisional excitation (bound-bound): a bound electron is excited to a higher energy level by a collision (typically with a free electron)

→ Photoionization: UV background
→ Compton cooling/heating: CMB

OG3 Code : Metal-dependent Cooling with CIE

L. Di Federico (LMU)
L. Sala (LMU)
L. T.

Coll. Ioniz. Equilibrium
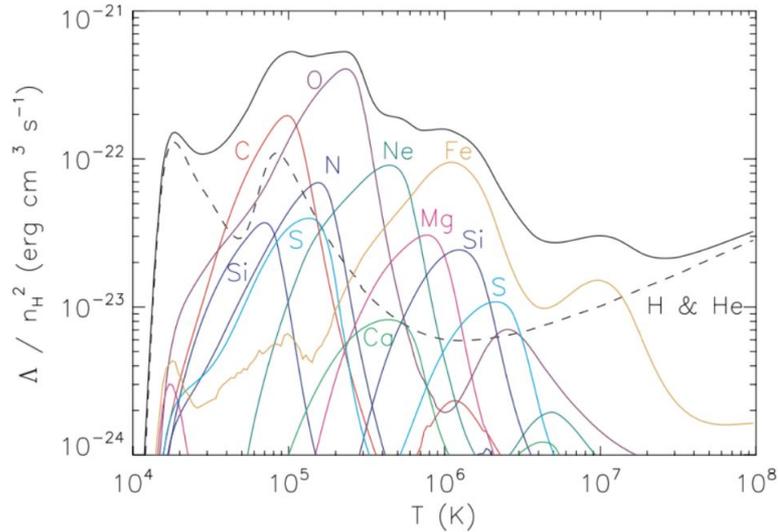
Photoionization Equilibrium

Wiersma et al. adopted since 2007

L. DI Federico @ LMU has built a framework to quickly build updated tables from **cloudy** for the element of interest.

Different UV background models can be adopted when building the cooling tables.

OG3 Code : Non-eq. H,H2,He chemistry & Cooling (U. Maio, INAF)

$H + e^- \rightarrow H^+ + 2e^-$
$H^+ + e^- \rightarrow H + \gamma$
$H + \gamma \rightarrow H^+ + e^-$
$He + e^- \rightarrow He^+ + 2e^-$
$He^+ + e^- \rightarrow He + \gamma$
$He + \gamma \rightarrow He^+ + e^-$
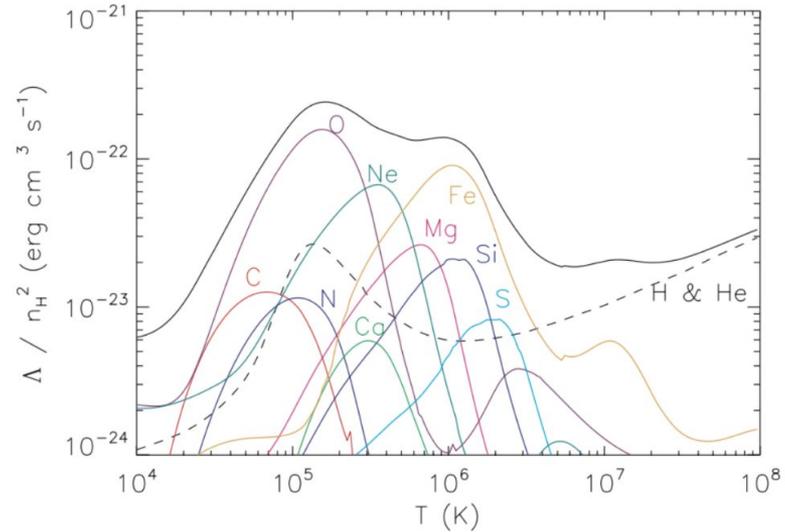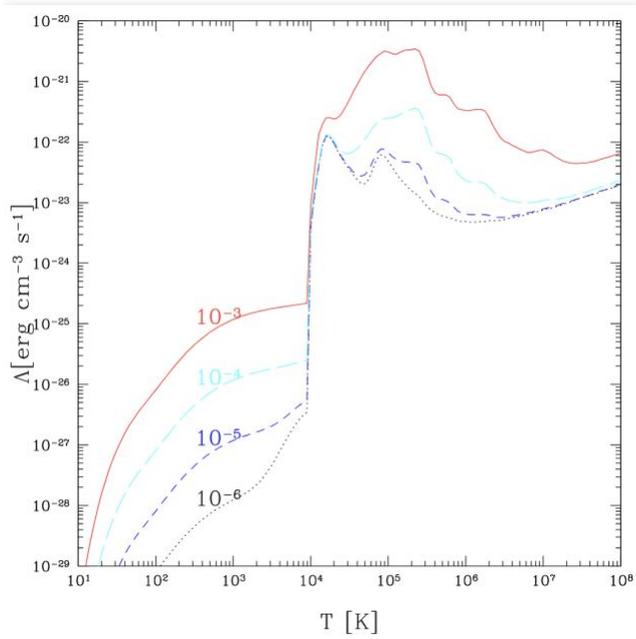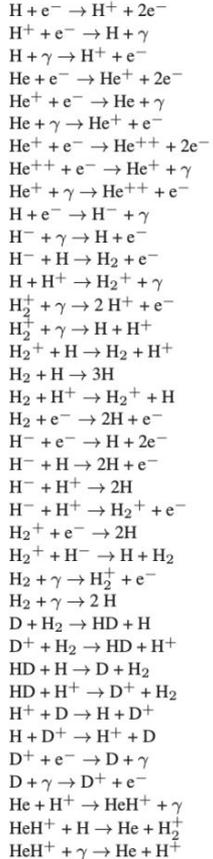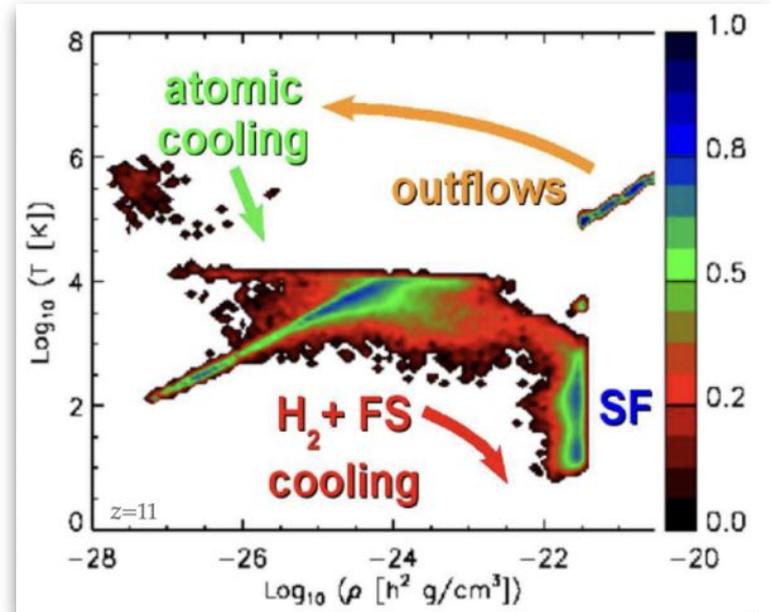$He^+ + e^- \rightarrow He^{++} + 2e^-$
$He^{++} + e^- \rightarrow He^+ + \gamma$
$He^+ + \gamma \rightarrow He^{++} + e^-$
$H + e^- \rightarrow H^- + \gamma$
$H^- + \gamma \rightarrow H + e^-$
$H^- + H \rightarrow H_2 + e^-$
$H + H^+ \rightarrow H_2^+ + \gamma$
$H_2^+ + \gamma \rightarrow 2H^+ + e^-$
$H_2^+ + \gamma \rightarrow H + H^+$
$H_2^+ + H \rightarrow H_2 + H^+$
$H_2 + H \rightarrow 3H$
$H_2 + H^+ \rightarrow H_2^+ + H$
$H_2 + e^- \rightarrow 2H + e^-$
$H^- + e^- \rightarrow H + 2e^-$
$H^- + H \rightarrow 2H + e^-$
$H^- + H^+ \rightarrow 2H$
$H^- + H^+ \rightarrow H_2^+ + e^-$
$H_2^+ + e^- \rightarrow 2H$
$H_2^+ + H^- \rightarrow H + H_2$
$H_2 + \gamma \rightarrow H_2^+ + e^-$
$H_2 + \gamma \rightarrow 2H$
$D + H_2 \rightarrow HD + H$
$D^+ + H_2 \rightarrow HD + H^+$
$HD + H \rightarrow D + H_2$
$HD + H^+ \rightarrow D^+ + H_2$
$H^+ + D \rightarrow H + D^+$
$H + D^+ \rightarrow H^+ + D$
$D^+ + e^- \rightarrow D + \gamma$
$D + \gamma \rightarrow D^+ + e^-$
$He + H^+ \rightarrow HeH^+ + \gamma$
$HeH^+ + H \rightarrow He + H_2^+$
$HeH^+ + \gamma \rightarrow He + H^+$

Tvir>104K: H-cooling halo
Tvir<104K: H2-cooling halo

Ref: Maio+ Works

Gas cooling determines a loss of gas pressure support and subsequent collapse in the DM potential wells.
At high densities this ignites star formation (SF) and related feedback (heating, outflows, metal spreading)

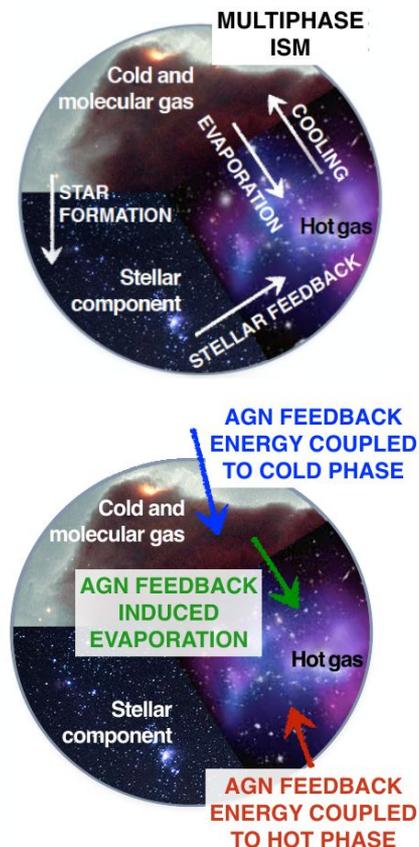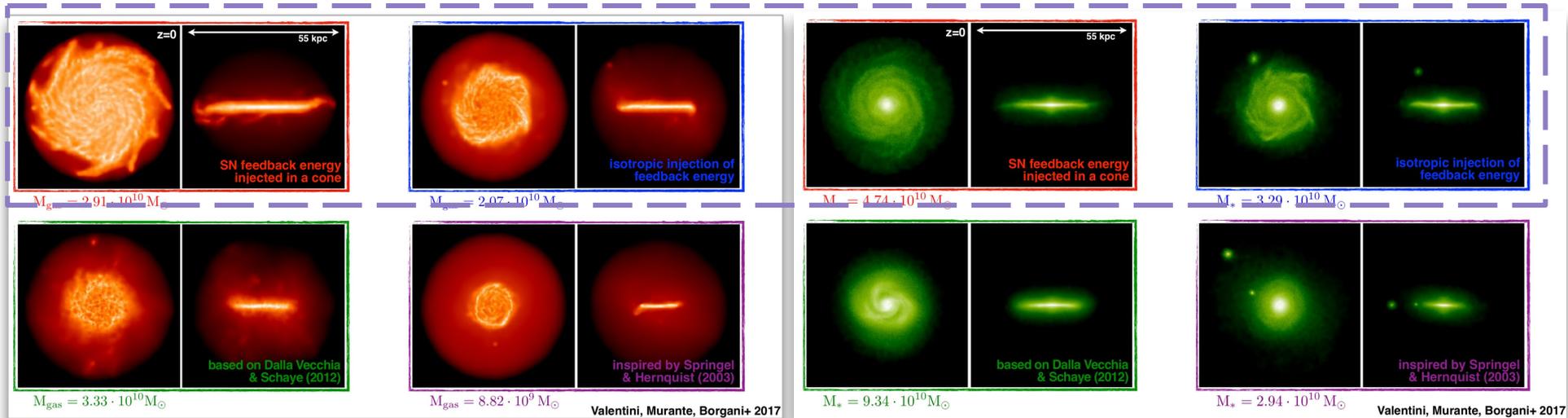# OG3 Code : Star-Formation, besides standard Springel & Hernquist

1 Effective model, based on density threshold, coupled with Stellar Evolution & Feedback model   L.T. +

2 MUPPI   Murante+ 2010, 2015; Valentini+ 2017–2023

OG3 Code : Star-Formation - MUPPI

Murante, Valentini et al.

- **Multiphase** gas particles:
  hot, **cold** and **stellar** components

- Mass and energy flows between components

- **Dust** formation and evolution
  (Granato+ 2021, Parente+ 2022)

- **H2 –based star formation**
  (Valentini+ 2023, Ragone-Figueroa+ 2024)

- **Coupled with**
  - **AGN feedback** on hot & cold gas depending on physical properties
  - Metal-dep. **Cooling** and **Stellar evolution** (L.T.)

MULTIPHASE ISM

Cold and molecular gas

COOLING

EVAPORATION

STAR FORMATION

Hot gas

Stellar component

STELLAR FEEDBACK

AGN FEEDBACK ENERGY COUPLED TO COLD PHASE

Cold and molecular gas

AGN FEEDBACK INDUCED EVAPORATION

Hot gas

Stellar component

AGN FEEDBACK ENERGY COUPLED TO HOT PHASE

OG3 Code : Star-Formation - MUPPI

Murante, Valentini et al.

Impact on galactic morphology

Top line: MUPPI (two different energy injection geometries)
Bottom line: less sophisticated models

OG3 Code : Stellar Evolution

L.T. et al.

Once a star is born, it is evolved as a Single Stellar Population of coeval stars.
Ingredients:

- IMF
- Lifetime function
- Stellar model : mass /time ranges for
  - low-intermediate mass stars
  - Sn II
- Delay-Time-Distribution for Sn Ia
- Yields

"Star formation modes" *will* be available:
multiple stellar evolution models active in a simulation
→ different stellar evolutions, depending on the physical properties of the gas
(PopIII, variable IMFs, …)

Seeding

Halo constraints

$$M_h > M_{h,seed} \qquad M_{h,seed} = 5 \cdot 10^{10} M_\odot/h$$

$$M_{*,h}/M_h = 2\%$$

$$M_{*,h}/M_{DM,h} = 5\%$$

$$M_{gas,h}/M_{*,h} = 10\%$$

Black hole seed

$$M_{BH,seed} = M_0 \frac{M_{*,h}}{f_* M_{DM,seed}} \qquad M_0 = 10^5 M_\odot/h$$

Thanks to A. Damiano (UniTS) for assembling this slide

Feeding

by accretion

$$\min(\dot{M}_{Bondi}, \dot{M}_{Edd})$$

Bondi accretion rate:

$$\dot{M}_{Bondi} = \frac{4\pi^2 M_{BH}^2 \rho \alpha}{(c_s + v)^{3/2}}$$

Eddington limit:

$$\dot{M}_{Edd} = \frac{4\pi M_{BH} G m_p}{\eta_r \sigma_T c}$$

by mergers

$$\Delta r < d_{merg}$$

$$v_{rel} < c_s$$

$$\frac{|\Phi_{BH_1} - \Phi_{BH_2}|}{a} < 0.5 c_s^2 - v_{rel}^2$$

Feedback

thermal

$$\dot{E} = \eta_r \eta_f \dot{M}_{BH} c^2$$

Eff. 0.05

Quasar Mode

Eff. 0.2

Radio Mode

Adopted from seminal work by Springel et al. 2005.

Heavily modified and evolved since by: S. Borgani, A. Damiano, K. Dolag, D. Fabjan, G. Murante, L. Sala, M. Valentini, L.T.
Valentini+ 2020: angular mom. *Dep., hot&cold gas accretion*

Dynamical mass	$M_{BH,dyn} = M_{DM}$ for $M_{BH,dyn} < M_{BH,true}$
Dynamical friction	$\vec{a}_{BH} = \vec{a}_{grav} + \vec{a}_{DF}$
Repositioning	$\vec{x}_{BH} = \vec{x}_{min,neigh}$

EAGLE
Shaye et al. 2014

ILLUSTRIS
Sijacki et al. 2015

BLUE TIDES
Feng et al. 2016

IllustrisTNG
Pillepich et al. 2016

SIMBA
Davè et al.2019

OG3 Code : Black Holes - positioning (A. Damiano, UniTS)

Dynamical mass	$M_{BH,dyn} = M_{DM}$ for $M_{BH,dyn} < M_{BH,true}$
Dynamical friction	$\vec{a}_{BH} = \vec{a}_{grav} + \vec{a}_{DF}$
Repositioning	$\vec{x}_{BH} = \vec{x}_{min,neigh}$

$$f_a(\vec{v}_a) = \sum_{i}^{N(<b_{max,corr})} \frac{\delta(\vec{v}_a - \vec{v}_i)}{\tilde{n}_{BH}}$$
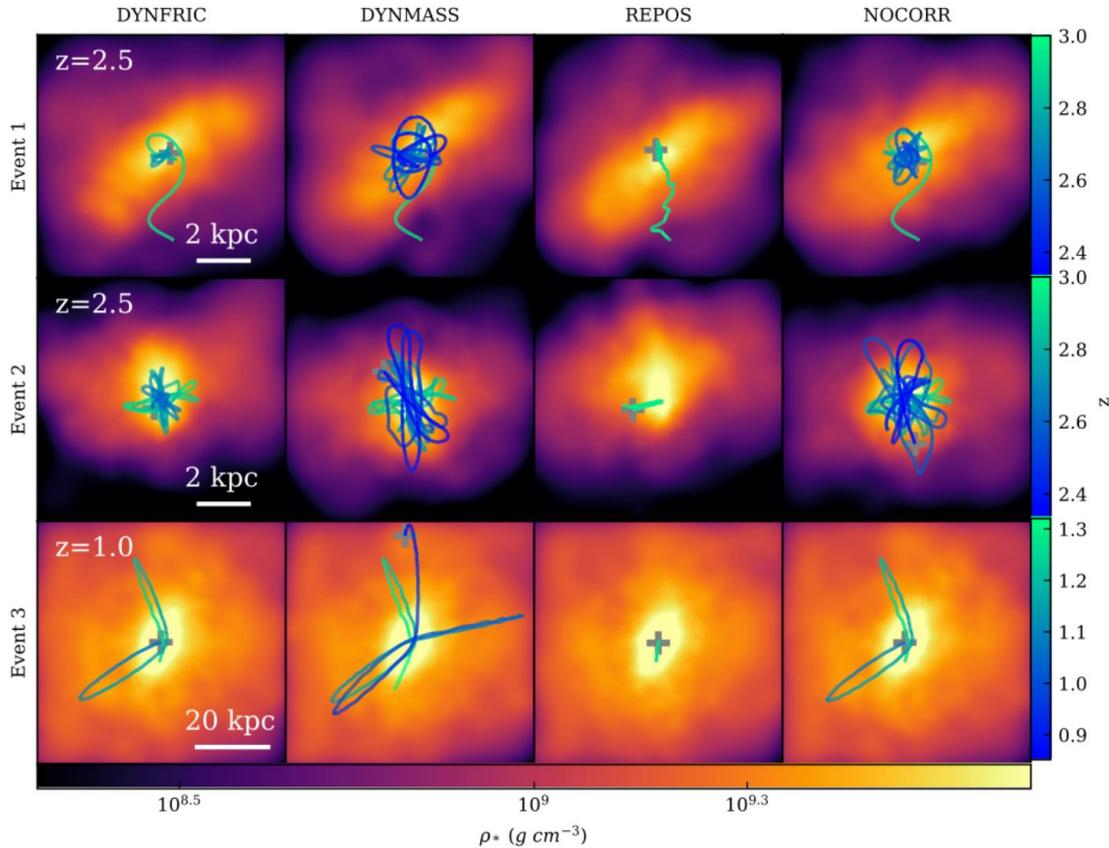
$$a_{DF} = \sum_{i=1}^{N(<b_{max,corr})} -\frac{2\pi G^2}{\tilde{n}_{BH}} m_i (m + m_i) \ln\left(1 + \frac{b^2}{b_{90}^2}\right) \frac{\hat{v}_{0,i}}{v_{0,i}^3}$$

Very elegant and effective implementation of
Dyn. Fric. by
A. Damiano, M. Valentini, S. Borgani, G. Murante, L.T.

More *efficiently* and "naturally" binds BH in the centre of potential wells.
More *accurate* spiraling and timing in mergers

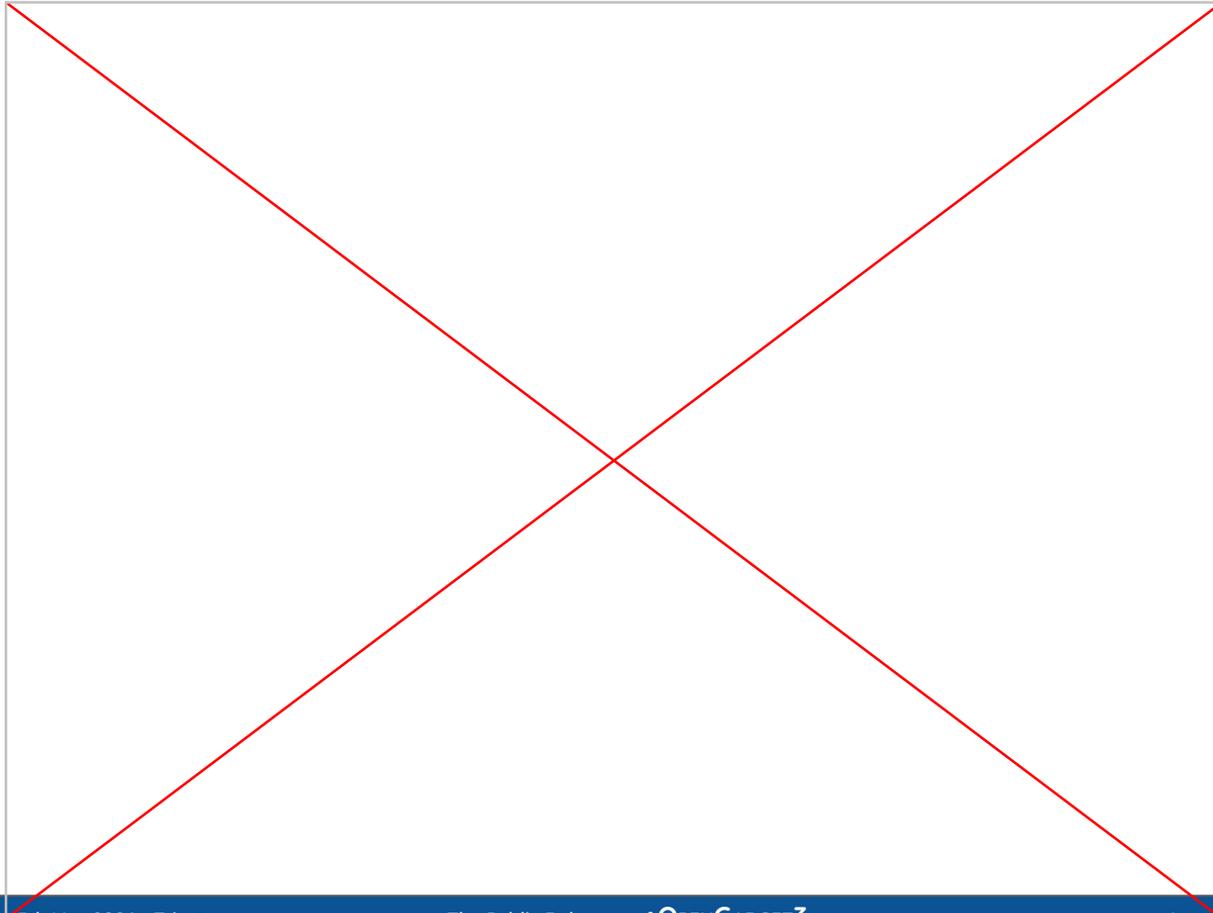# OG3 Code : Black Holes - positioning

(A. Damiano, UniTS)

Correcting for unresolved Dyn. Friction provides good BH centering, reduces *wandering* BHs, captures fairly BH–BH mergers

Different numerical prescriptions for BH **positioning** impact on BH dynamics,
and hence on **AGN feedback** and BH–BH **mergers**
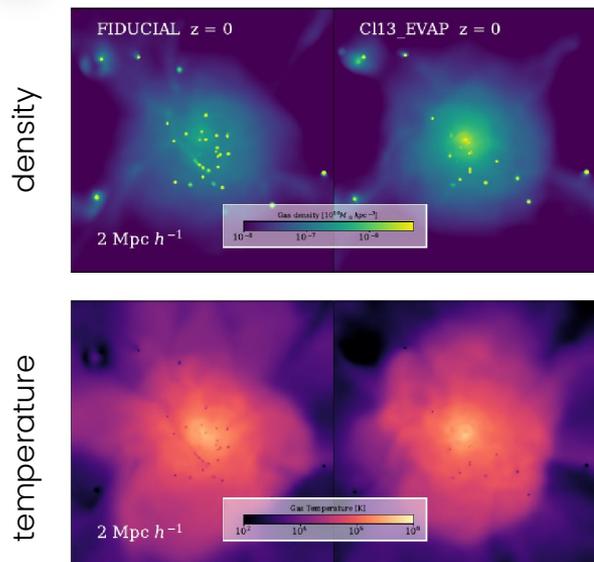
From A. Damiano +, 2024

OG3 Code : Black Holes - Spin modelling
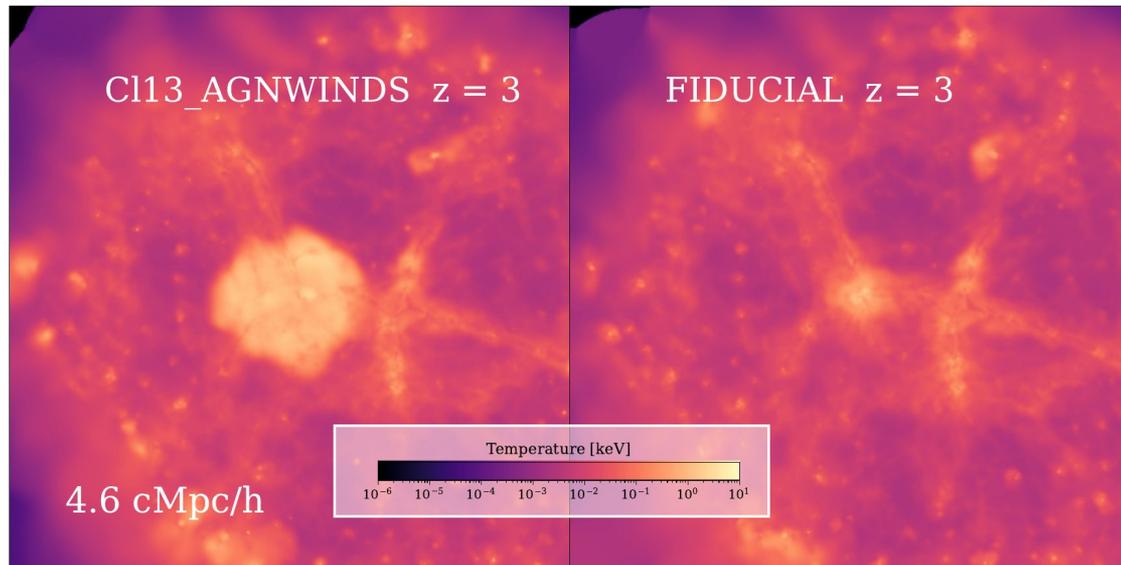
(L. Sala, LMU)

Courtesy by
L. Sala

OG3 Code : Black Holes - Keep params under control

density

temperature

FIDUCIAL z = 0   Cl13_EVAP z = 0

Gas density [10⁹ M_⊙ kpc⁻¹]

2 Mpc h^{-1}

Gas Temperature [K]

2 Mpc h^{-1}

From A. Damiano +, 2026, in review

Without (*left*) and with (*right*)
cloud evaporation

**Two examples
one key message**

Cl13_AGNWINDS z = 3   FIDUCIAL z = 3

Temperature [keV]

4.6 cMpc/h

From A. Damiano +, 2026, in review

Wind particle *included* in BH feedback (*left*) and *excluded* from the feedback (*right*)
WINDS included / excluded from BH feedback

BH modeling in simulations involves many parameters,
implementation details and sub-grid assumptions / models;
having their impact under control is of paramount importance

OPENGADGET3 – Conclusions

A **code**

> Feature-rich
>
> Performant
>
> Massively-parallel
>
> Accelerated

for **cosmological LSS- and galaxy- evolution** simulations

will be **open-source available** soon (June 2026).

Given to the community to build community.

Collaborations most welcome (ML community, are you listening?)