# Two very different mhd codes for astrophysics: Athena and GIZMO.

*Scope and limitations*


AEGORA
COMPLUTENSE
RESEARCH GROUP ON
SPACE ASTRONOMY
AND DATA MINING

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UNIVERSITAS COMPLUTENSIS MATRITENSIS

## Basic equations to solve

Equation of mass continuity $$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

Equation of motion $$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + P) = 0$$

Equation of energy $$\frac{\partial E}{\partial t} + \nabla \cdot ((E + P)\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{B} \cdot v)) = 0$$

Induction equation $$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0$$

$$P = P_{hydro} + \frac{\boldsymbol{B} \cdot \boldsymbol{B}}{2} \qquad E = \frac{P_{hydro}}{\gamma - 1} + \frac{\rho(\boldsymbol{v} \cdot \boldsymbol{v})}{2} + \frac{\boldsymbol{B} \cdot \boldsymbol{B}}{2}$$

(No microscopic dissipation)

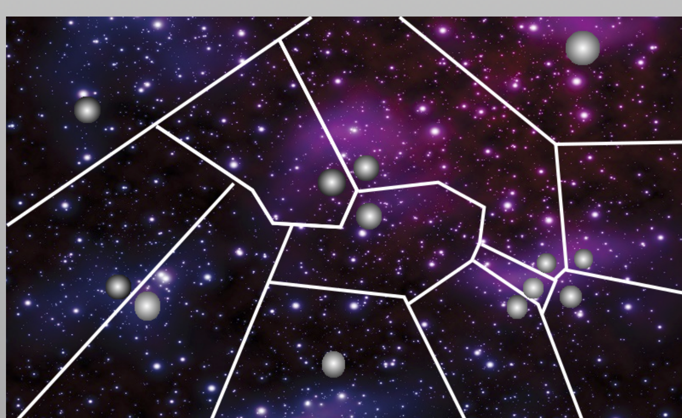
Smooth Particle
(magneto)Hydrodynamics

## SPH, SPMHD

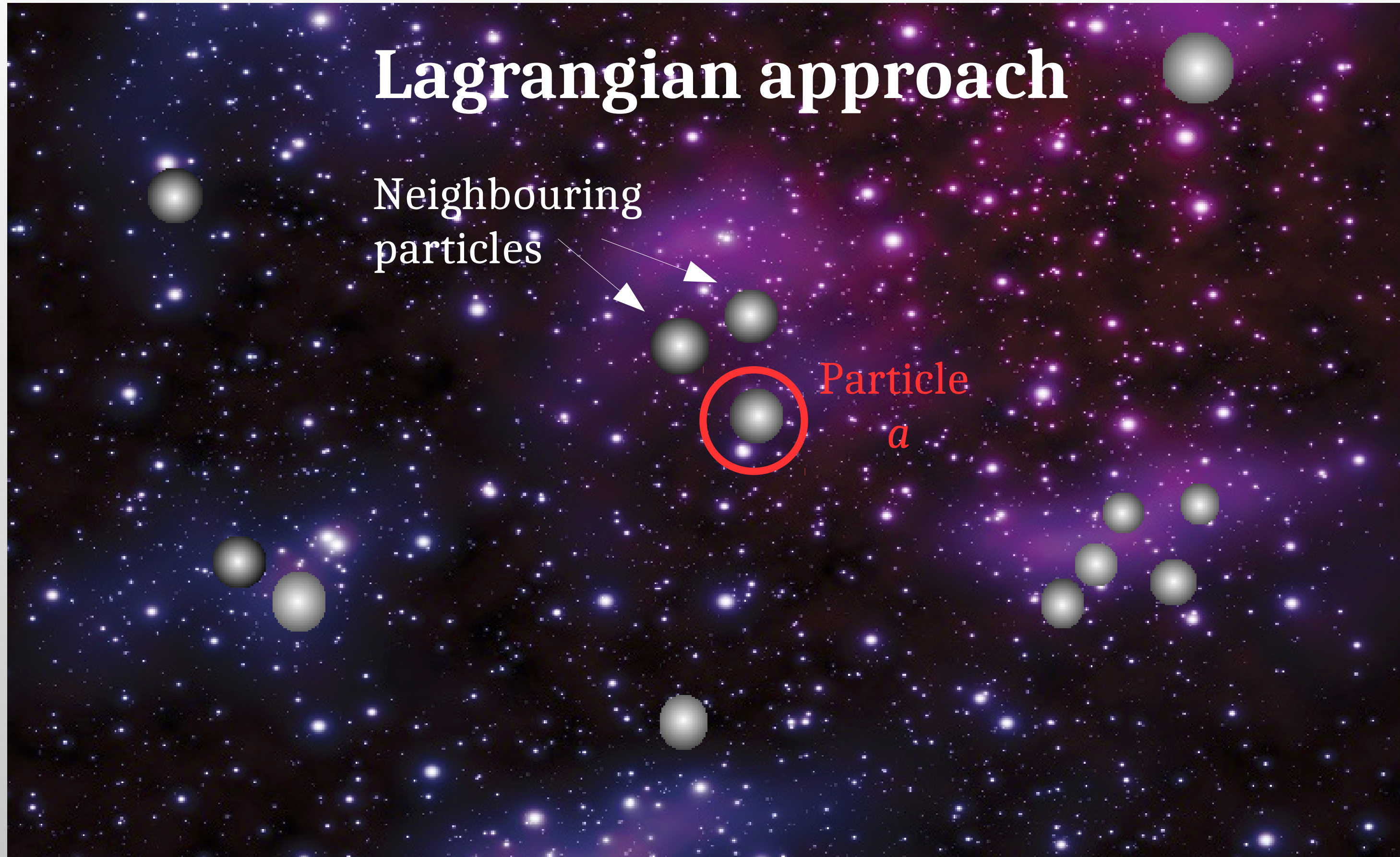
Grid-based codes
Finite differences

## Godunov methods

(finite volumes)



## Moving mesh/mesh-free + Godunov methods

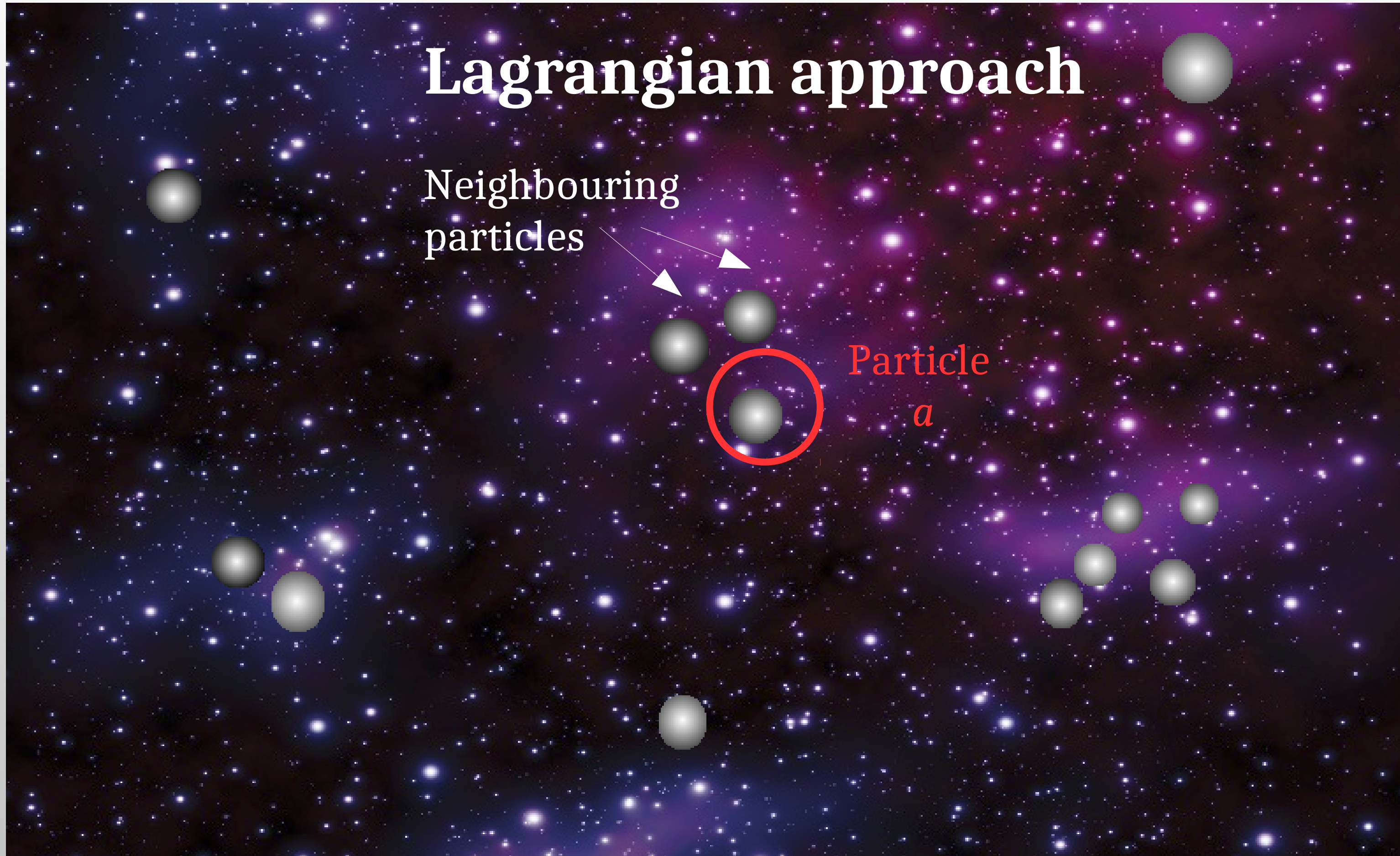



Since 1977 *(Lucy, 1977; Gringold & Monaghan, 1977)*

Fluid seen as a set of particles of mass $m$ that are moved with the local fluid velocity $v$

$$\rho_a = \sum_b m_b W\left(|r_a - r_b|, h_a\right)$$

Sum over neighbouring particles inside $R_{kern} h$




# PHANTOM *(Price et al. 2017)*

SPMHD code

https://phantomsph.bitbucket.io/

Last stable release: 13/03/2018

Developed over the last decade, Fortran 90


Volume discretised into cells
Fluid equations solved across the area/volume elements
Finite-volume Godunov schemes

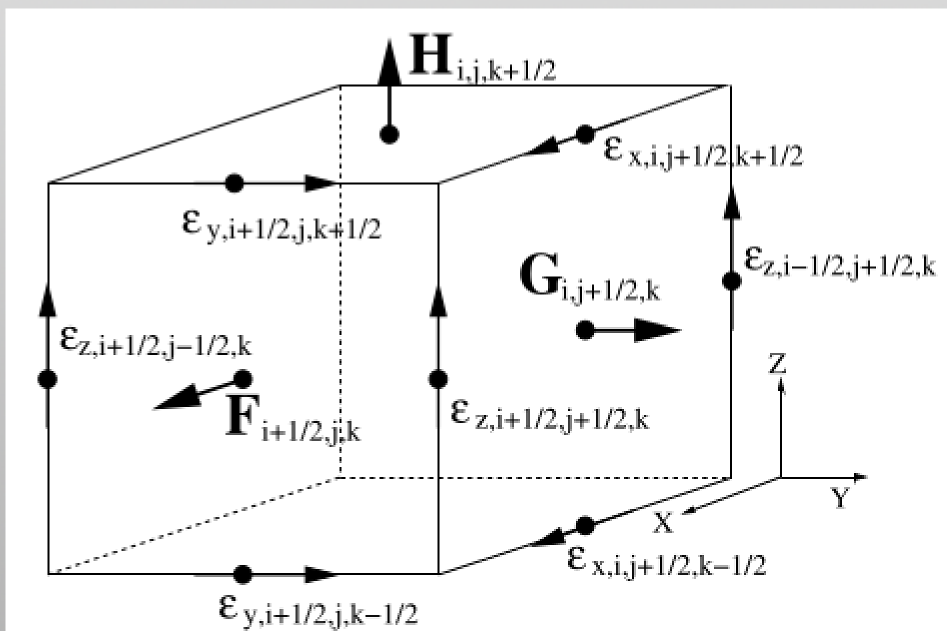
# ATHENA *(Stone et al., 2008)*

C language

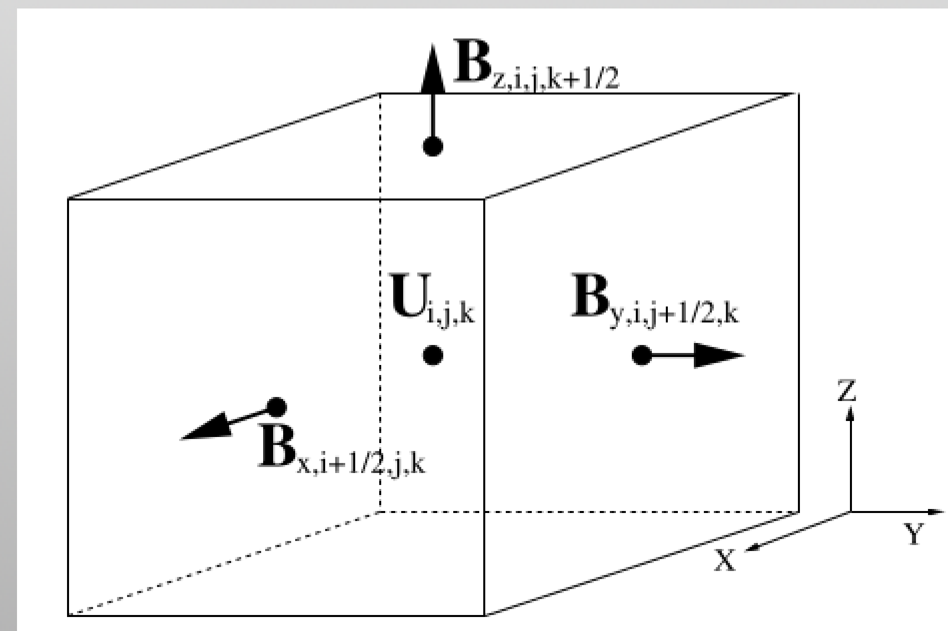
Publicly available. Latest version (v4.2) from 2013

https://princetonuniversity.github.io/Athena-Cversion/AthenaDocsDownLd

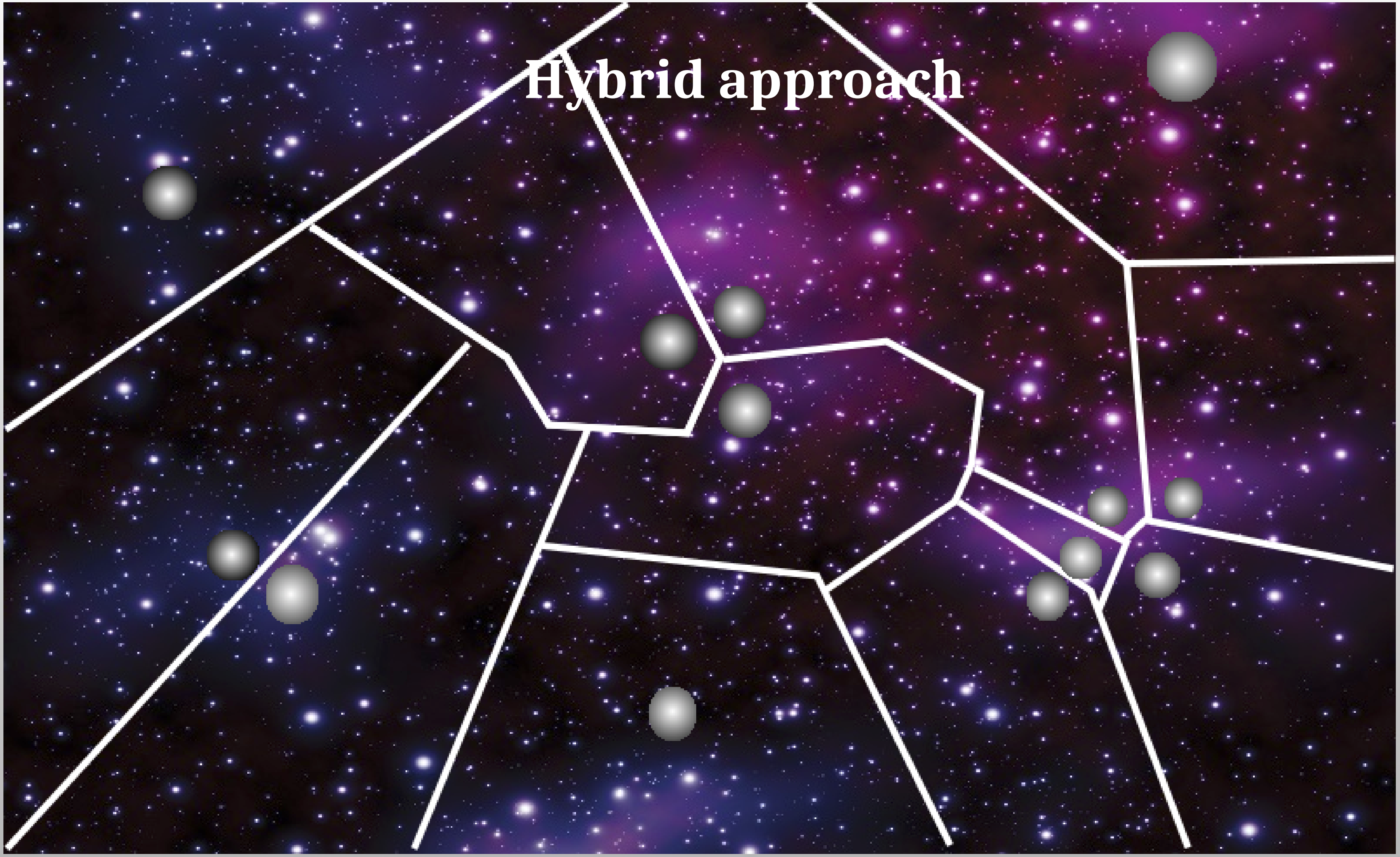
Documentation https://princetonuniversity.github.io/Athena-Cversion/




Mass, momentum and energy fluxes:
Finite volumes




Magnetic fields:
finite areas




Non-regular mesh
Cells move and deform continuously
Lagrangian + Finite-volume Godunov methods

# GIZMO *(Hopkins, 2015)*

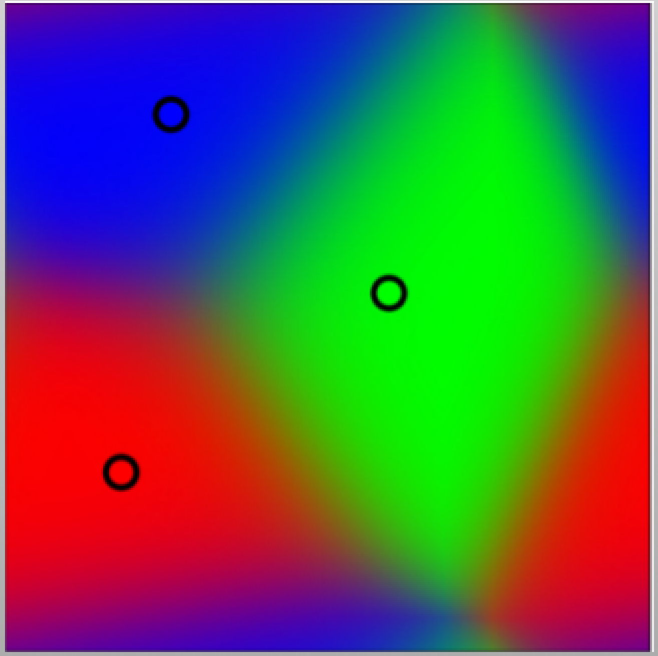
C language

Publicly available. Latest version 18/02/2018

https://bitbucket.org/phopkins/gizmo-public

Documentation:

http://www.tapir.caltech.edu/~phopkins/Site/GIZMO_files/gizmo_documentation.html



Lagrangian/Eulerian code
Meshless Finite Volume (MFV) and
Meshless Finite Mass (MFM) methods

# More about Athena

ATHENA

Implemented physics:

- Compressible HD/MHD in 1D/2D/3D
- Special Relativity HD and MHD
- Ideal gas equation of state (adiabatic and isothermal)
- Passive scalars advected with the flow
- Self gravity, static gravitational potential
- Ohmic resistivity, ambipolar diffusion and Hall effect
- Navier-Stokes and anisotropic (Braginskii) viscosity
- Isotropic/anisotropic thermal conduction
- Optically-thin radiative cooling
- Aerodynamic particles

Additional features:

- Cartesian/cylindric coordinates
- Static Mesh Refinement
- Shearing Box and orbital advection algorithm for MHD
- Parallelization

**2004 – 2008**: Private use

Magnetothermal Instability (MTI), Magnetorrotational Instability (MTI), Protoplanetary Discs (PPDs), Molecular Clouds (MC), MHD turbulence.

Algorithms development *(Gardiner & Stone, 2005, 2008)*

**2008**: Public version release *(Stone et al. 2008)*

Heat conduction *(Parrish, Stone and Lemaster, 2008)*

**2009**

Viscosity *(Dong & Stone, 2009)*

Resistivity *(Fromang & Stone, 2009)*

Charged particles *(Lehe, Parrish, Quataert, 2009)*

**2010**

Cylindrical coordinates *(Skinner & Ostriker, 2010)*

Shearing box and orbital advection scheme *(Stone & Gardiner, 2010)*

Aerodynamic particles *(Bai & Stone, 2010)*

**2011**

- Self-gravity *(Gong & Ostriker, 2011)*
- Relativistic MHD *(Beckwith & Stone, 2011)*
- Ambipolar diffusion *(Bai & Stone, 2011)*

**2012**

- Radiative MHD *(Gendelev & Krumholtz, 2012)*
- Radiative cooling, heating and heat conduction *(Choi & Stone, 2012)*
- Radiative transfer *(Davis, Stone & Jiang, 2012)*
- Orbital advection in cylindrical coordinates *(Sorathia et al., 2012)*
- Anisotropic conduction and Braginskii viscosity *(Kunz et al., 2012)*

**2013**

- Sink particles *(Gong & Ostriker, 2013)*
- *Hyperion*: Two-moment Radiation HD *(Skinner & Ostriker, 2013)*

**2014**

*Pegasus*: hybrid-kinetic particle-in-cell code *(Kunz, Stone & Bai, 2014)*
Dust particles in cylindrical coordinates *(Zhu et al., 2014)*
Another algorithm for radiation MHD *(Jiang, Stone & Davis, 2014)*

**2017**

*TIGRESS*,Three phase Interstellar Medium in Galaxies Resolving Evolution with Star formation and Supernova Feedback *(Kim & Ostriker, 2017)*

Instabilities

Protoplanetary & Accretion Discs

Turbulence

Interstellar Medium

Extragalactic

Radiative HD/MHD

Plasmas

Relativistic HD/MHD

- Magnetorrotational Instability
- Ambipolar diffusion
- Resistivity
- Hall effect
- Turbulence in magnetised discs
- Diffusion/dynamic of solids
- Concentration of particles in vortices/dusty vortices
- Planet-disc interactions
- Angular momentum transport
- Winds

- Super Novae feedback (radiation, chemistry)
- Molecular cloud formation
- Superbubbles
- Shocks
- Prestellar/magnetised cores
- Dusty HII regions
- Striations
- Particular regions: Virgo cluster, Vela C
- Dust polarization

- Galactic clusters: magnetic fields, turbulence
- Spiral shocks
- Barred galaxies
- Turbulence in discs
- Ram pressure stripping
- AGNs: jets, clouds, accretion disc, magnetic fields
- Galactic superbubbles
- Galactic winds
- Disc-corona interface
- Circumgalactic medium and feedback
- Formation of black holes
- Star formation

- Magnetorotational
- Thermal/magnetothermal
- Streaming Inst. *(Youdin & Goodman, 2005)*
- Current-driven
- Heat-flux Buoyancy inst. *(Quataert, 2008)*
- Wiggle Instability *(Wada & Koda, 2004)*
- Pulsating Instability of fast turbulent flames
- Kruskal-Schwarzschild
- Zombie Vortex (dusty vortex) *(Marcus et al., 2015)*

- MHD
- Turbulent flames
- Alfvénic turbulence
- Weak turbulence
- Galactic clusters
- Supersonic isothermal turbulence

- Radiation feedback in ULIRGS
- Hot accretion disc coronae
- Photoevaporative mass loss from hot jupiters
- Massive star envelopes
- Iron opacity bump
- Chemistry and radiative shielding in star forming galactic discs
- Dust-driven winds
- Dusty cloud  acceleration

- Magnetized Noh pinch problem
- HII regions
- Buoyancy instabilities
- Contact instabilities
- Weakly compressible MHD turbulence
- Coupling cosmic rays and thermal plasma
- Particle acceleration by a solar flare termination shock

- Magnetised jets
- Variability in AGNs
- Acceleration of relativistic electrons
- Kruskal-Schwarzschild instability

# More about GIZMO

GIZMO

Implemented physics:

- Compressible HD/MHD in 1D/2D/3D
- Cosmological integrations
- Radiative heating/cooling and chemistry
- Galaxy/Star/Black hole formation and feedback
- Non-standard cosmology
- Self-gravity with adaptive gravitational resolution
- Anisotropic conduction and viscosity
- Passive scalars, turbulent eddy diffusion, shearing box
- **Dusty fluids**
- Degenerate/stellar equations of state
- Elastic/plastic/solid-body dynamics
- Radiation hydrodynamics

Science: mainly cosmology, AGNs, galaxies

# MHD implementation *(Hopkins & Raives, 2016)*

Solution for the divergence problem: Constrained Transport (CT) method *(Evans & Hawley, 1988)*

CT difficult to implement in Lagrangian codes

How do they solve it: Powell 8-wave cleaning + Dedner cleaning

Powell 8-wave: subtracts unstable error terms resulting from non-zero divergence from the eq. of motion
Dedner cleaning: adds source terms that transport the divergence away and then dampss it.

$$\log\left(\frac{h_i|\nabla\cdot\boldsymbol{B}_i|}{|\boldsymbol{B}_i|}\right)\in[-7,-2],\sim-4$$

$h_i$=effective cell size

Charged grains *(Lee et al., 2017)*

$$\frac{d\boldsymbol{u}_d}{dt}=\frac{-\boldsymbol{u}_d-\boldsymbol{u}_{gas}}{t_s}+\frac{Z_d e}{m_d c}(\boldsymbol{u}_d-\boldsymbol{u}_{gas})\times\boldsymbol{B}$$

Dust-dust collisions not included

## Study the interaction of Alfvén waves with Molecular Clouds

Five fluids

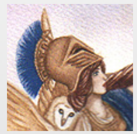
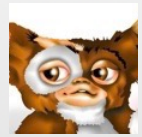
neutrals, ions, electrons, neutral grains, charged grains

Effects

ambipolar diffusion, interaction of charged species with charged grains

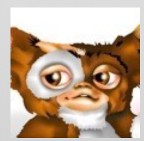
# Athena or GIZMO?

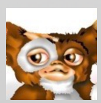

Key factors to be considered

## Popularity  

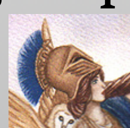
Athena (407 citations in 10 years), GIZMO (177 citations in 3 years)

## Efficiency/computational cost

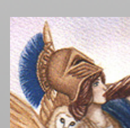
## Available modules 

## Support 

Google group

## Time 

Spent learning Athena + programming a module vs learning a new method

## $\nabla \cdot \boldsymbol{B} = 0$ 

## Particle collisions Ø

Bai & Stone (2010), ApJS, 190:297

Bai & Stone, (2011) ApJ, 736:144

Beckwith & Stone (2011) ApJS, 193:6

Choi & Stone (2012) ApJ,747:86

Davis, Stone & Jiang (2012) ApJS, 199:9

Dong & Stone (2009) ApJ 704:1309

Evans & Hawley (1988) ApJ 332:659

Fromang & Stone (2009) A&A, 507:19

Gardiner & Stone (2005) JCoPh, 205:509

Gardiner & Stone (2008) JcoPh, 227:4123

Gendelev & Krumholtz (2012) ApJ, 745:158

Gong & Ostriker (2011) ApJ, 190:297

Gong & Ostriker (2013) ApJS, 204:8

Gingold & Monaghan (1977) MNRAS, 181:375

Hopkins (2015) MNRAS, 450:53

Hopkins & Raives (2016) MNRAS, 455:51

Jiang, Stone & Davis (2014) ApJS, 213:7

Kim & Ostriker (2017) ApJ, 846:133

Kunz, Bogdanović, Reynolds et al. (2012) ApJ, 754:122

Kunz, Stone & Bai (2014) JcoPh, 259:154

Lee, Hopkins & Squire (2017) MNRAS, 469:3532

Lehe, Parrish, Quataert (2009) ApJ, 707:404

Lucy (1977) AJ, 82:1013

Marcus, Pei, Jiang et al. (2015) ApJ, 808:87

Parrish, Stone and Lemaster (2008) ApJ, 688:905

Price, Wurster, Nixon et al. (2017) arXiv: 1702.03930v1

Quataert (2008) ApJ, 673:758

Skinner & Ostriker (2010) ApJS, 188:290

Skinner & Ostriker (2013) ApJS, 206:21

Sorathia, Reynolds, Stone et al. (2012) ApJ, 749:189

Stone, Gardiner, Teuben et al. (2008) ApJS, 178:137

Stone & Gardiner (2010) ApJS, 189:142

Wada & Koda (2004) MNRAS, 349:270

Youdin & Goodman (2005), ApJ, 620:459

Zhu, Stone, Rafikov et al. (2014) ApJ, 785:122