NATHAN GOLDBAUM
@njgoldbaum

SIMULATING THE UNIVERSE:
OPEN ASTROPHYSICS SIMULATION SOFTWARE

NCSA yt 円相 Enzo DXL

COUPLED GAS DYNAMICS AND SELF-GRAVITY

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{\mathbf{v}} = 0$$

Conservation of Mass

$$\frac{\partial \rho \vec{\mathbf{v}}}{\partial t} + \vec{\mathbf{v}} \cdot \nabla \rho \vec{\mathbf{v}} = -\nabla P - \rho \nabla \Phi$$

Conservation of Momentum

$$\frac{\partial e}{\partial t} + \vec{\mathbf{v}} \cdot \nabla e = -\frac{P}{\rho} \nabla \cdot \vec{\mathbf{v}}$$

Conservation of Energy

$$\nabla^2 \Phi = 4\pi G \rho$$

Newton's law of gravity

$$P = (\gamma - 1) e$$

Equation of state

COUPLED GAS DYNAMICS AND SELF-GRAVITY

$$\frac{D\rho}{Dt} = -\rho\nabla\cdot\vec{\mathbf{v}}$$ Conservation of Mass

$$\rho\frac{D\vec{\mathbf{v}}}{Dt} = -\nabla P - \rho\nabla\Phi$$ Conservation of Momentum

$$\frac{De}{Dt} = -\frac{P}{\rho}\nabla\cdot\vec{\mathbf{v}}$$ Conservation of Energy

$$\nabla^2\Phi = 4\pi G\rho$$ Newton's law of gravity

$$P = (\gamma - 1)\epsilon$$ Equation of state

LAGRANGIAN VS EULERIAN

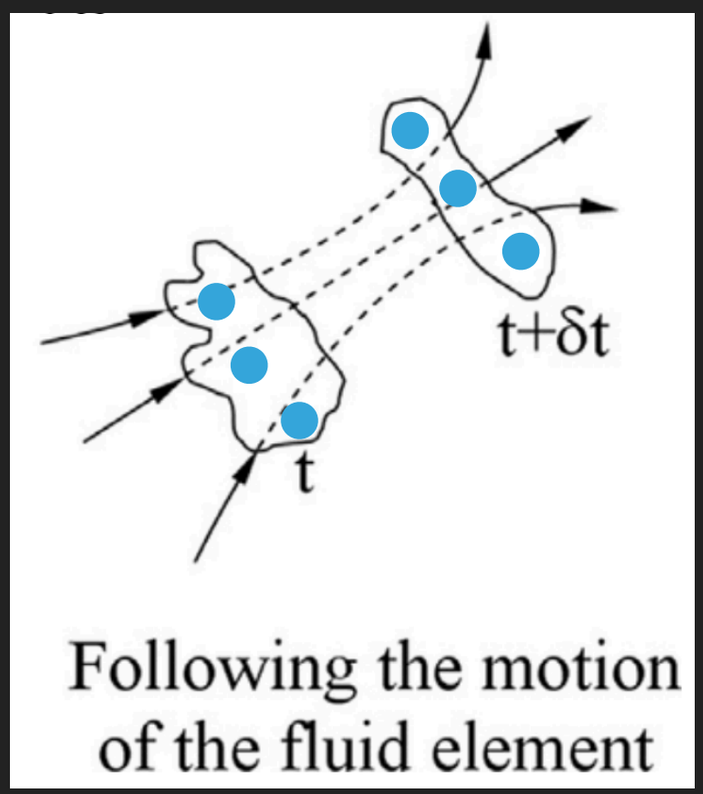
Lagrangian

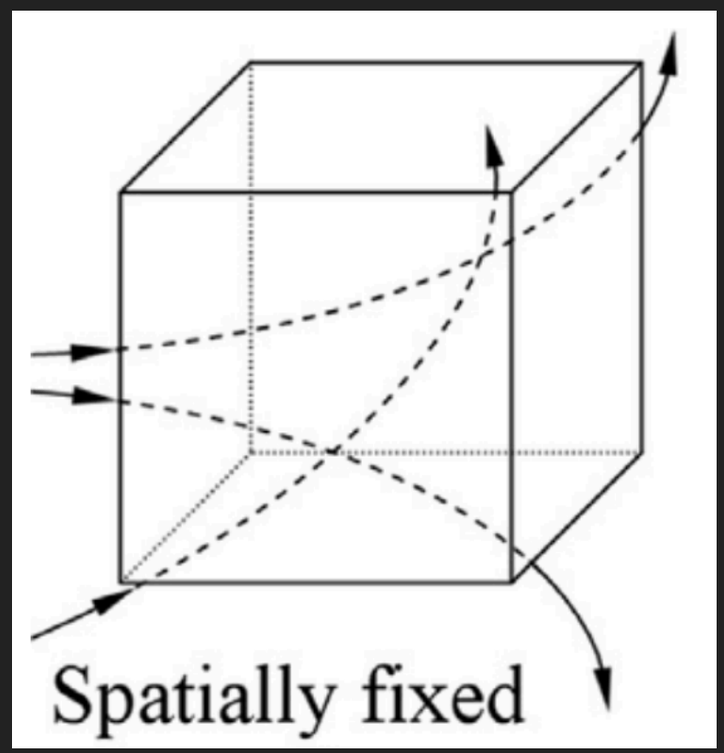
$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \tilde{\mathbf{v}} \cdot \nabla$$

Eulerian

Sample at positions that move with the flow

Sample at fixed locations on grid



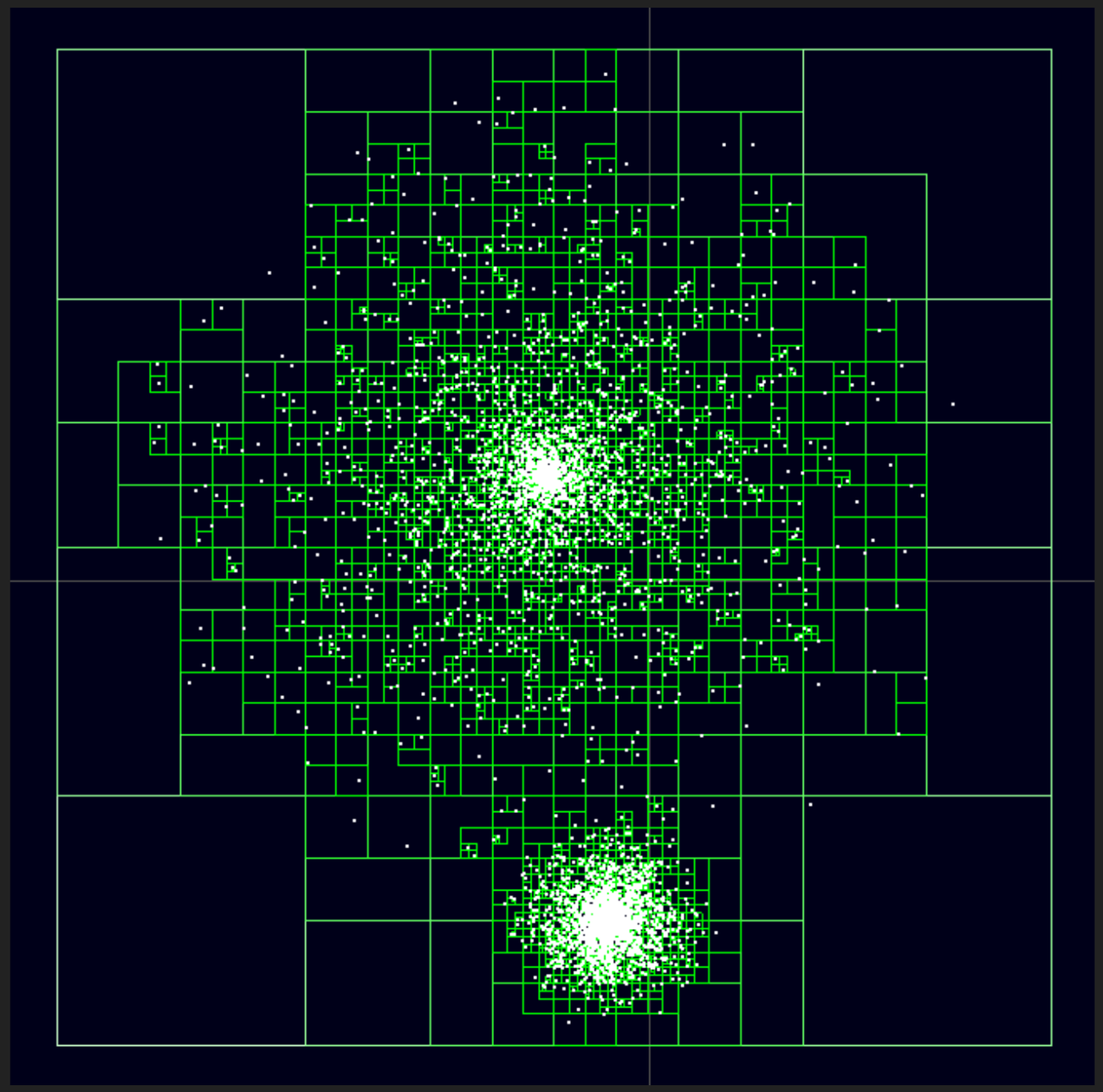


LAGRANGIAN METHODS

N-BODY METHODS FOR GRAVITY

- Deposit particle masses onto a 3D tree (KDtree or octree)
- Calculate forces from distant particles by treating all particles in a tree node as a single particle

BARNES-HUT TREE

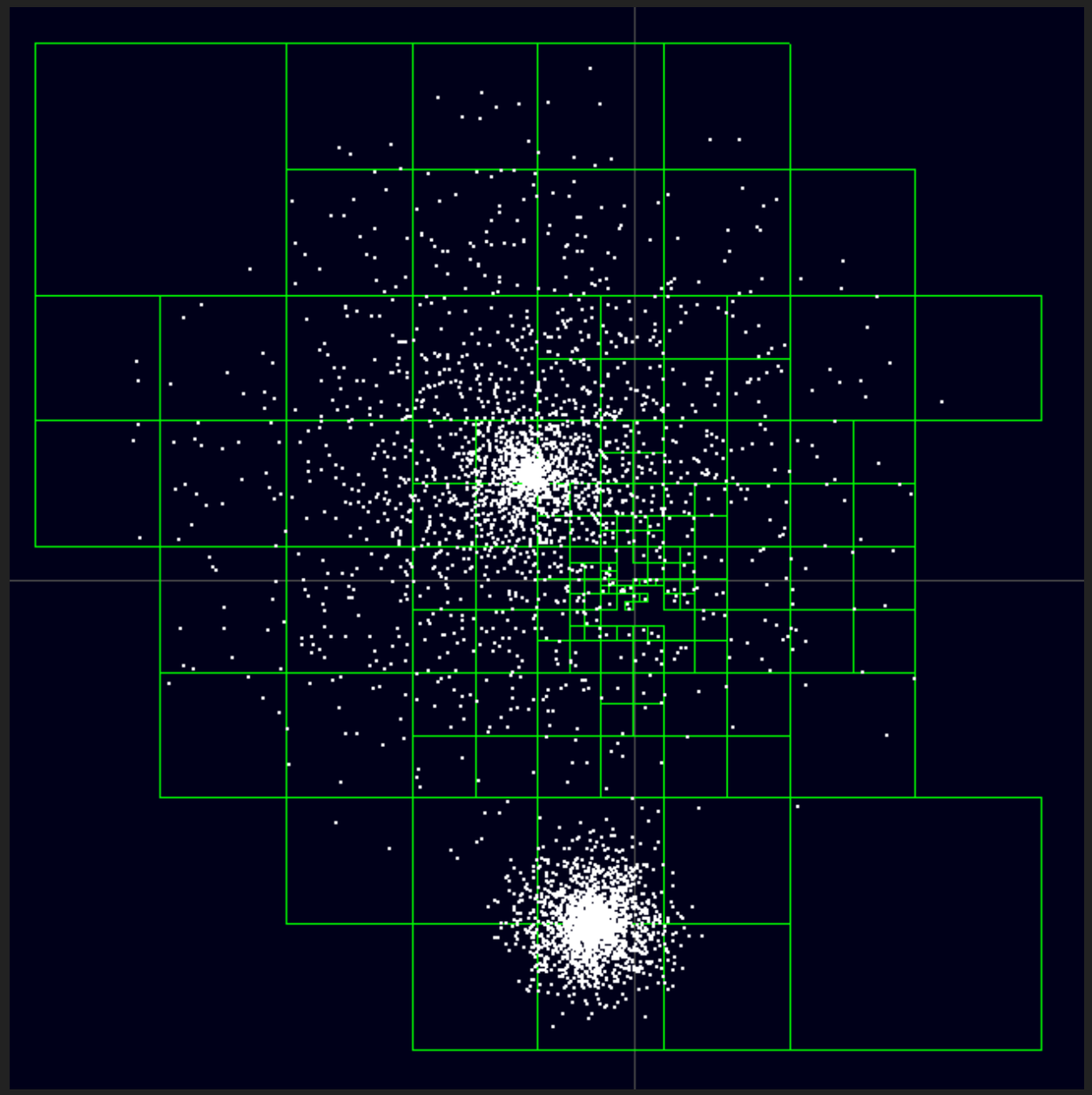


Credit: Wikipedia

N-BODY METHODS FOR GRAVITY

- Deposit particle masses onto a 3D tree (KDtree or octree)
- Calculate forces from distant particles by treating all particles in a tree node as a single particle

BARNES-HUT TREE

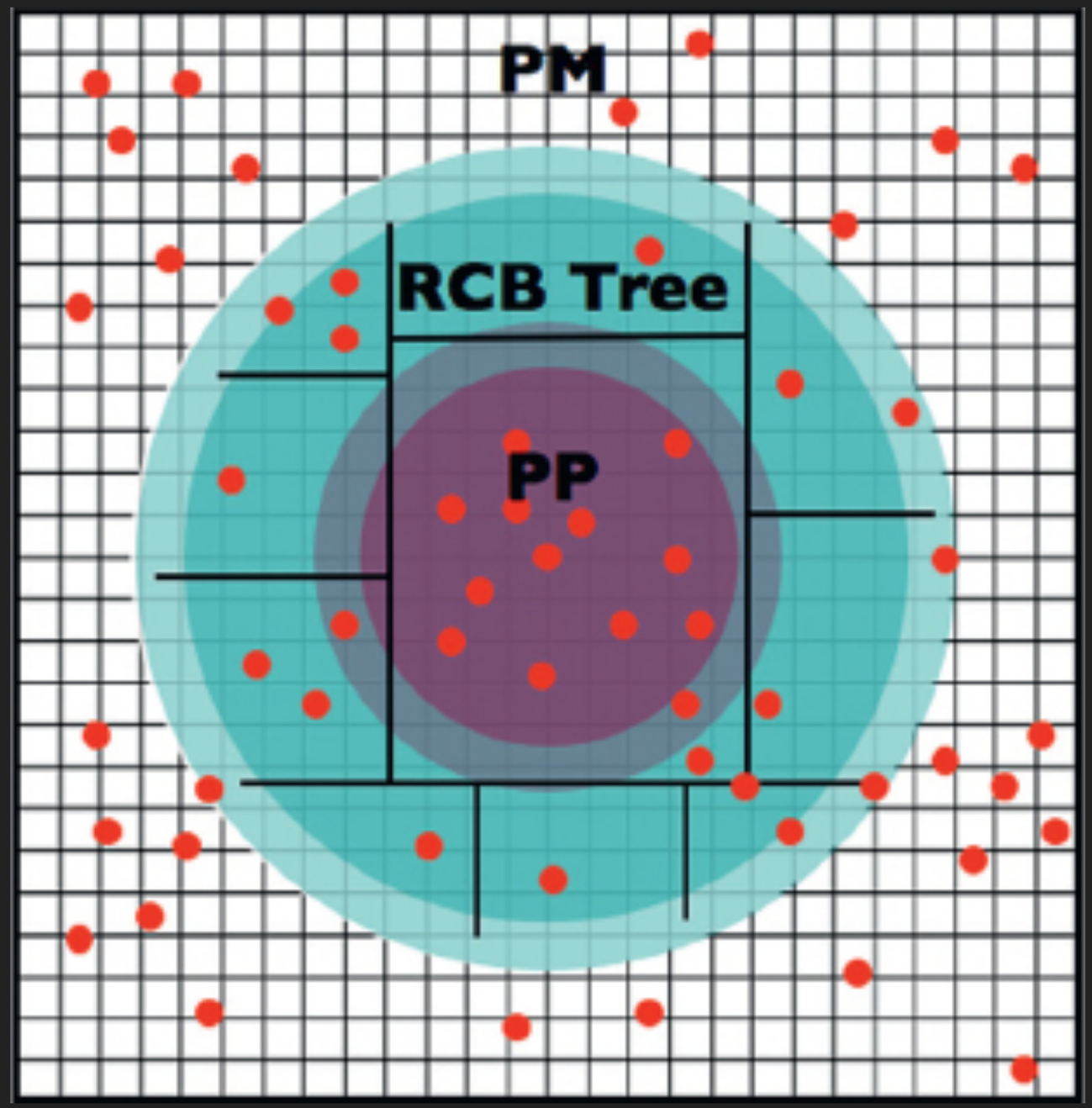


Credit: Wikipedia

N-BODY METHODS FOR GRAVITY

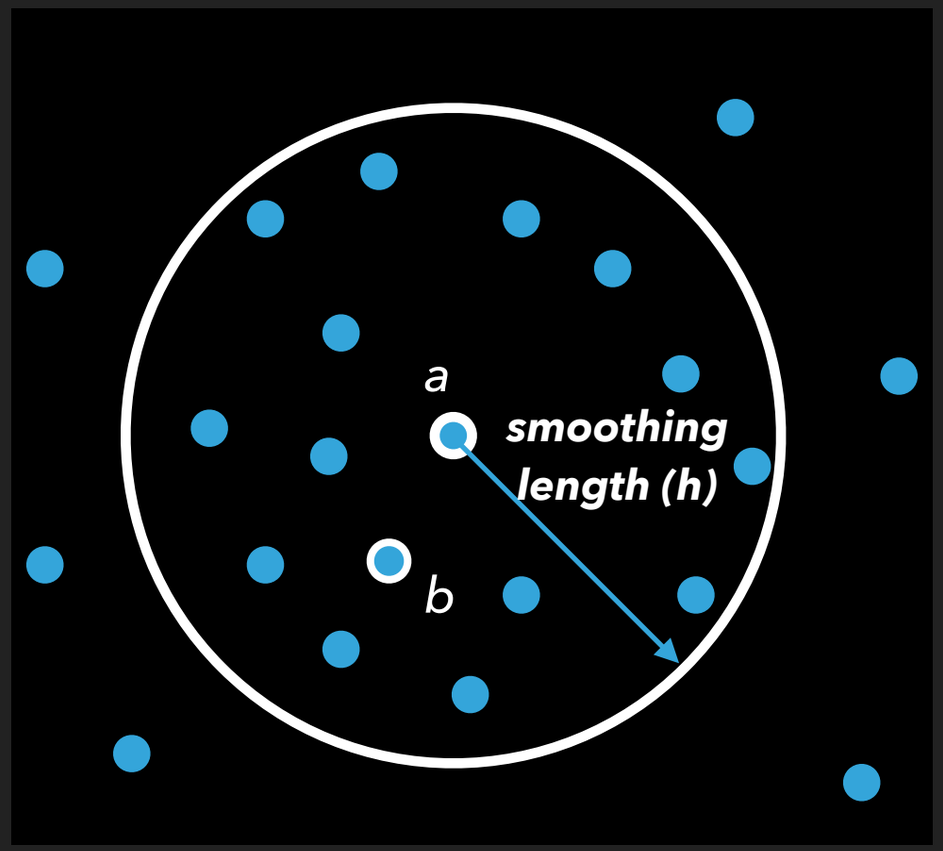
- Forces from nearby particles calculated from Newton's law of Gravitation
- Forces from particles at intermediate distance calculated using BH Tree
- Forces from most distant particles from FFT on grid

TREEPM



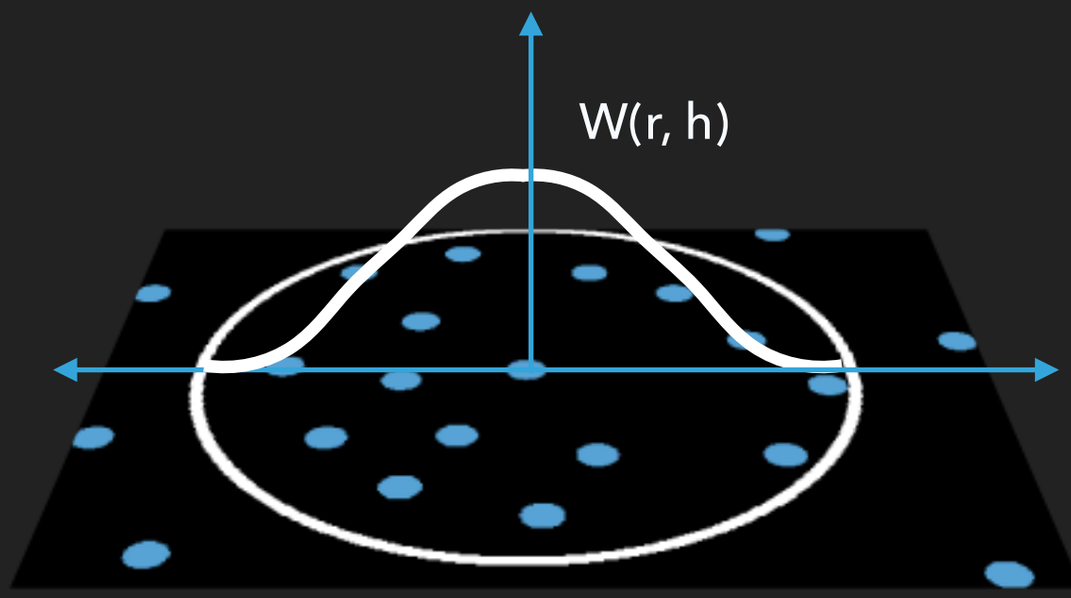
Habib et al. (2017)

SMOOTHED PARTICLE HYDRODYNAMICS



$$A(\mathbf{r}_a) \approx \sum_{b=1}^{N_{\text{neigh}}} \frac{m_b}{\rho_b} A_b W(|\mathbf{r} - \mathbf{r}_b|, h)$$

SMOOTHED PARTICLE HYDRODYNAMICS



$$A(\mathbf{r}_a) \approx \sum_{b=1}^{N_{\text{neigh}}} \frac{m_b}{\rho_b} A_b W(|\mathbf{r} - \mathbf{r}_b|, h)$$

Waterfall

up to 160 million fluid particles

Waterfall

up to 160 million fluid particles

LAGRANGIAN METHODS

Credit: NCSA AVL, Brant Robertson, Lars Hernquist

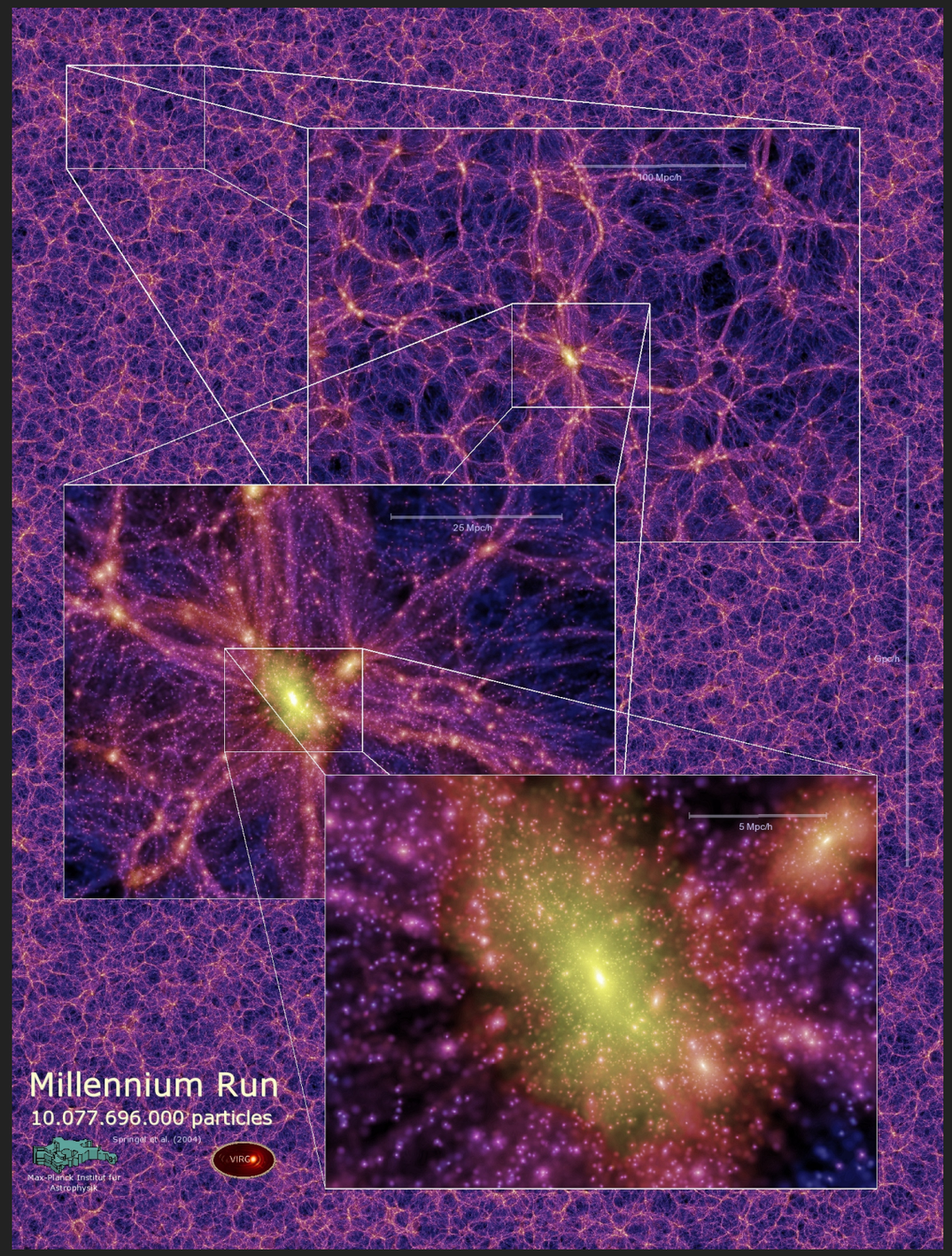
LAGRANGIAN METHODS

Credit: NCSA AVL, Brant Robertson, Lars Hernquist

PUBLIC LAGRANGIAN RESEARCH CODES

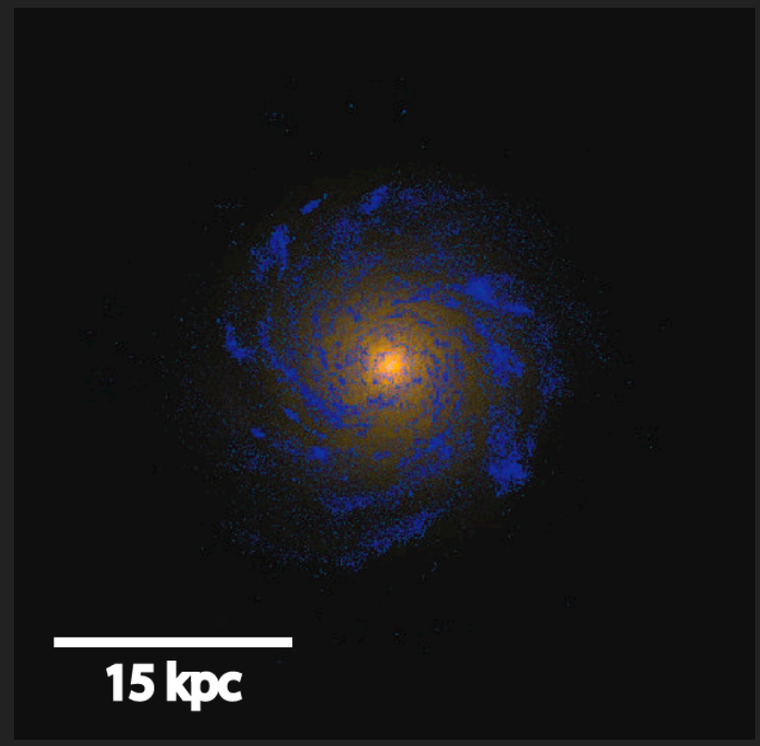
Gadget-2

Website	http://wwwmpa.mpa-garching.mpg.de/gadget/
Repository	N/A Tarball available from
Discretization	Smoothed Particle Hydrodynamics
Physics Modules	Adiabatic Hydrodynamics, TreePM Gravity (More modules available in private
Research Focus	Galaxy Formation, Cosmology
License	GPLv2
Publications (Citations)	Springel et al. (2005) (3179)
Language	C
Parallelism	MPI



Gasoline

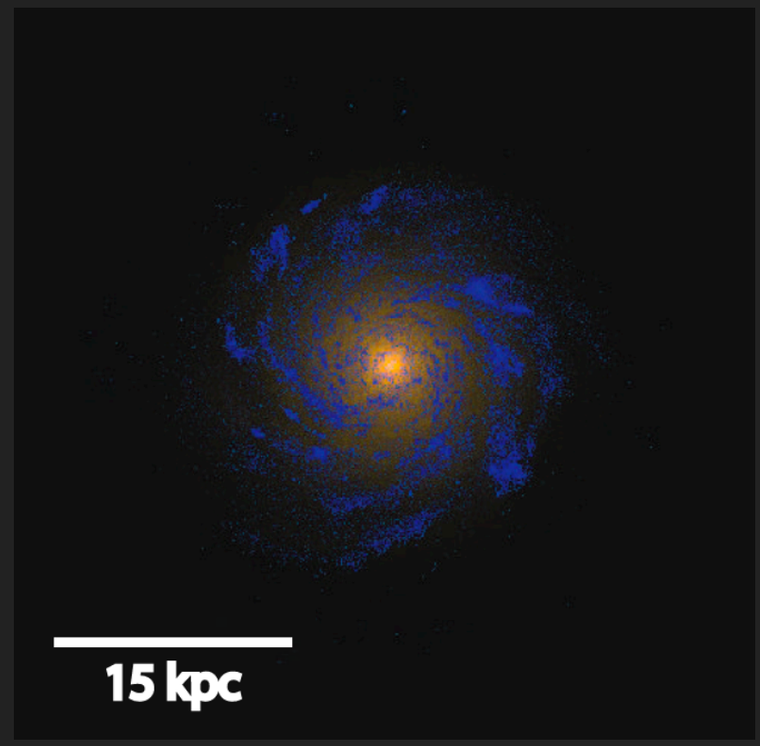
Website	http://gasoline-code.com
Repository	https://github.com/N-BodyShop/gasoline
Discretization	Smoothed Particle Hydrodynamics
Physics Modules	Tree Gravity, Hydrodynamics, Chemistry, Mixing, Star Formation and Feedback
Research Focus	Galaxy Formation
License	GPLv2
Publications (Citations)	Wadsley et al. (2004) (439)
Language	C
Parallelism	MPI, Charm++



Guedes et al. (2011)

Gasoline

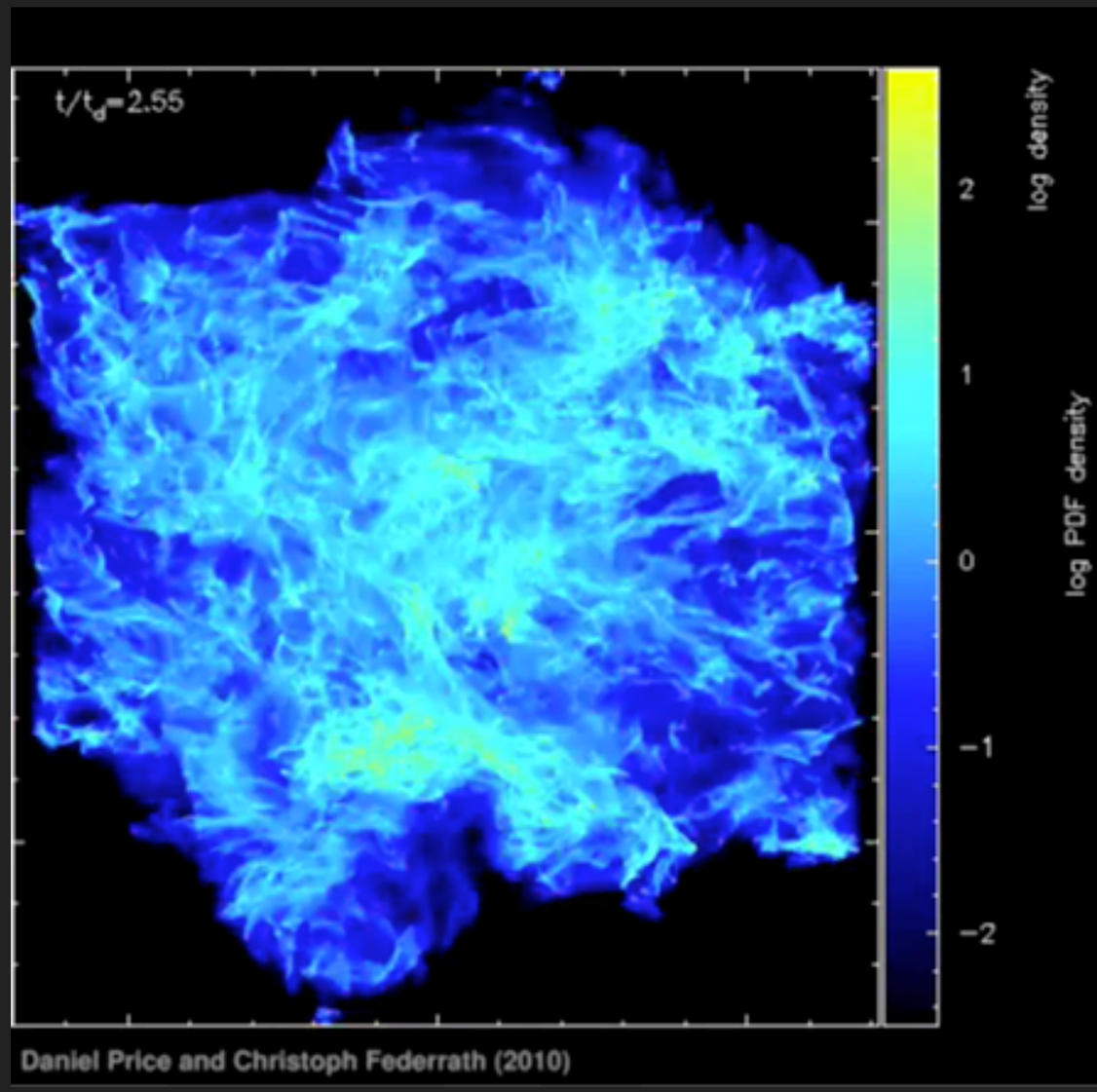
Website	http://gasoline-code.com
Repository	https://github.com/N-BodyShop/gasoline
Discretization	Smoothed Particle Hydrodynamics
Physics Modules	Tree Gravity, Hydrodynamics, Chemistry, Mixing, Star Formation and Feedback
Research Focus	Galaxy Formation
License	GPLv2
Publications (Citations)	Wadsley et al. (2004) (439)
Language	C
Parallelism	MPI, Charm++



Guedes et al. (2011)

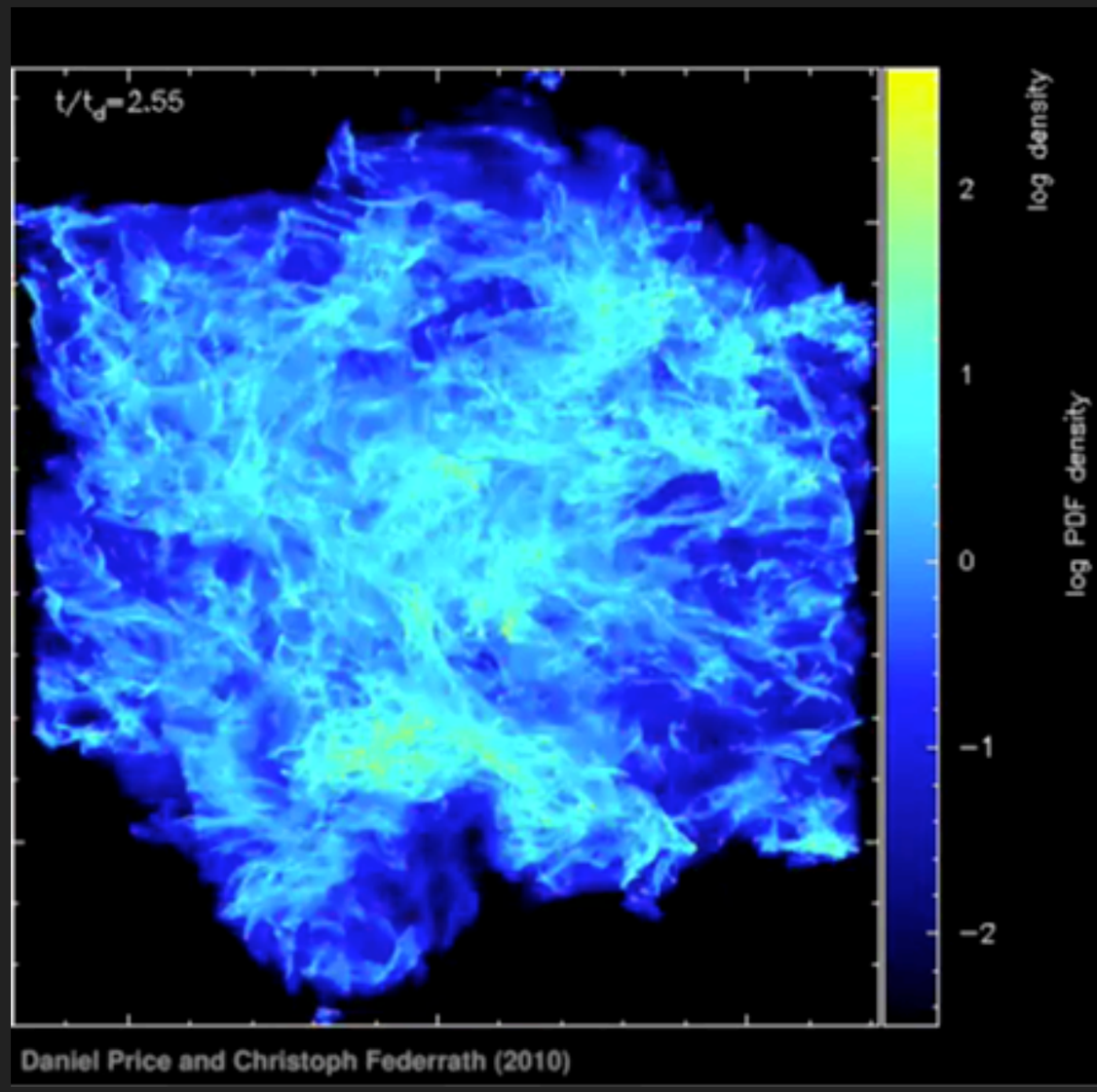
PHANTOM

Website	https://phantomsph.bitbucket.io/
Repository	https://bitbucket.org/danielprice/phantom
Discretization	Smoothed Particle Hydrodynamics
Physics Modules	Tree Gravity, MHD, Dust and Atomic Chemistry and Cooling, Cosmic Ray and Photoelectric Heating
Research Focus	Star and Planet Formation, ISM
License	GPLv3
Publications (Citations)	Price et al. (2017) (4)
Language	Fortran 90
Parallelism	MPI, OpenMP



PHANTOM

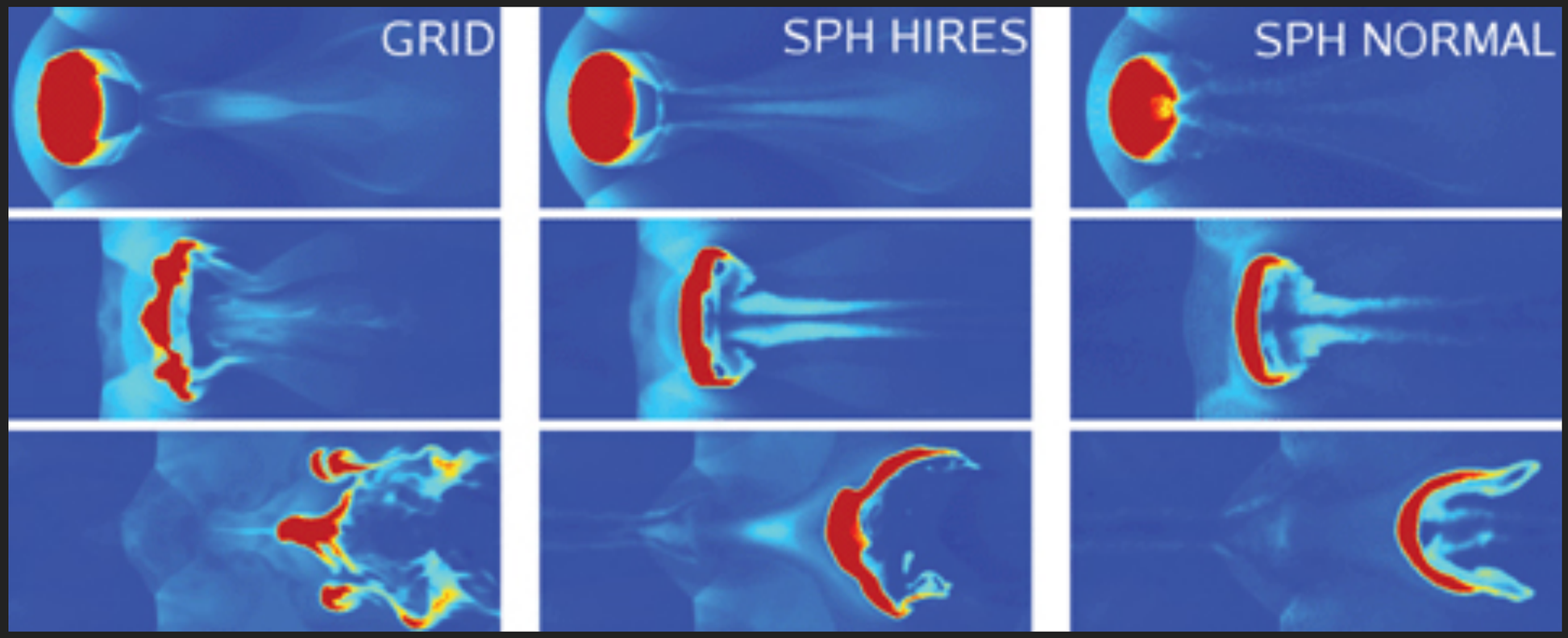
Website	https://phantomsph.bitbucket.io/
Repository	https://bitbucket.org/danielprice/phantom
Discretization	Smoothed Particle Hydrodynamics
Physics Modules	Tree Gravity, MHD, Dust and Atomic Chemistry and Cooling, Cosmic Ray and Photoelectric Heating
Research Focus	Star and Planet Formation, ISM
License	GPLv3
Publications (Citations)	Price et al. (2017) (4)
Language	Fortran 90
Parallelism	MPI, OpenMP



EULERIAN METHODS

PROBLEMS WITH SPH

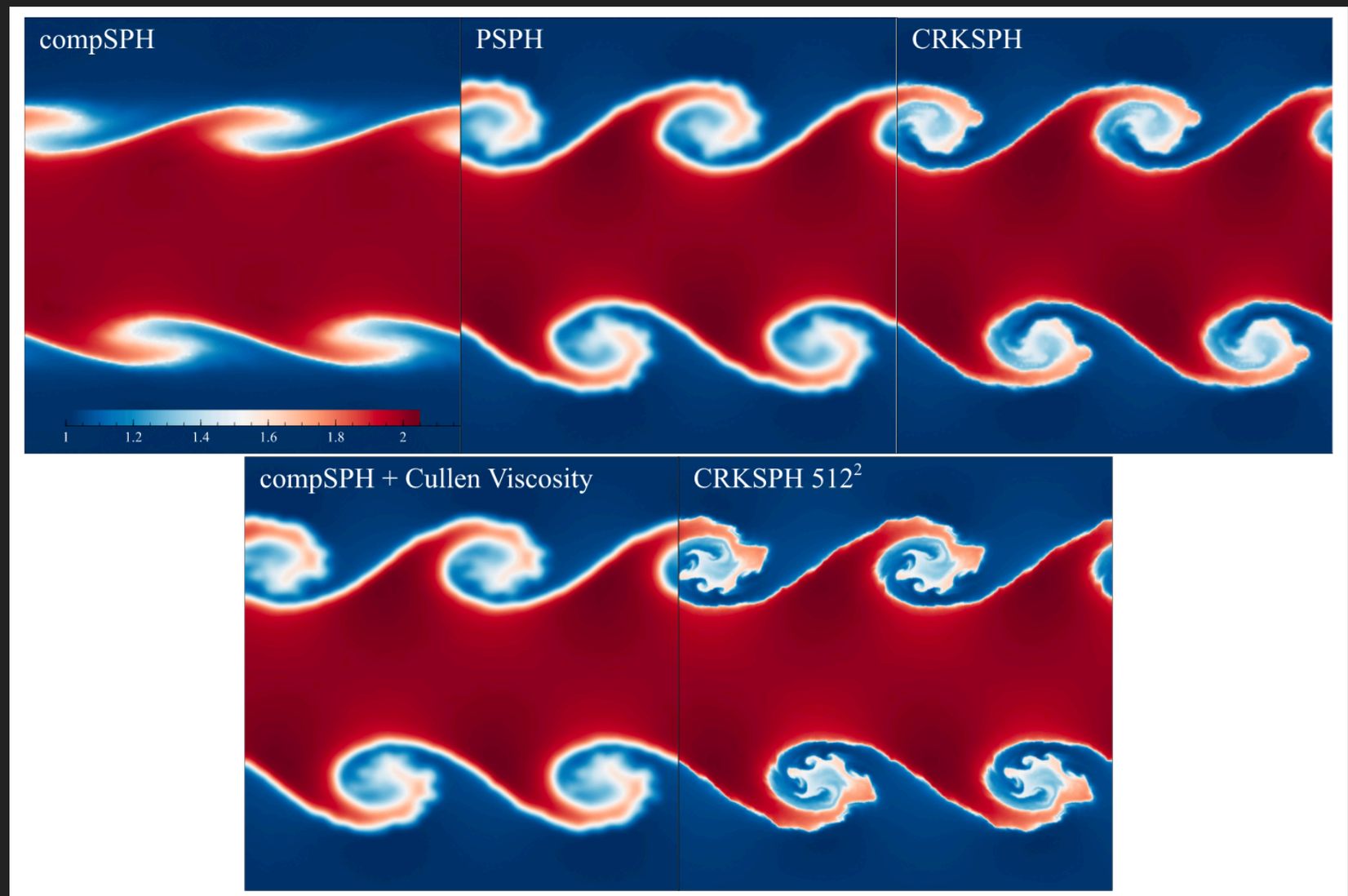
BLOB ADVECTION AND EVAPORATION



Agertz et al. (2007)

ALTERNATE SPH FORMALISMS DO BETTER

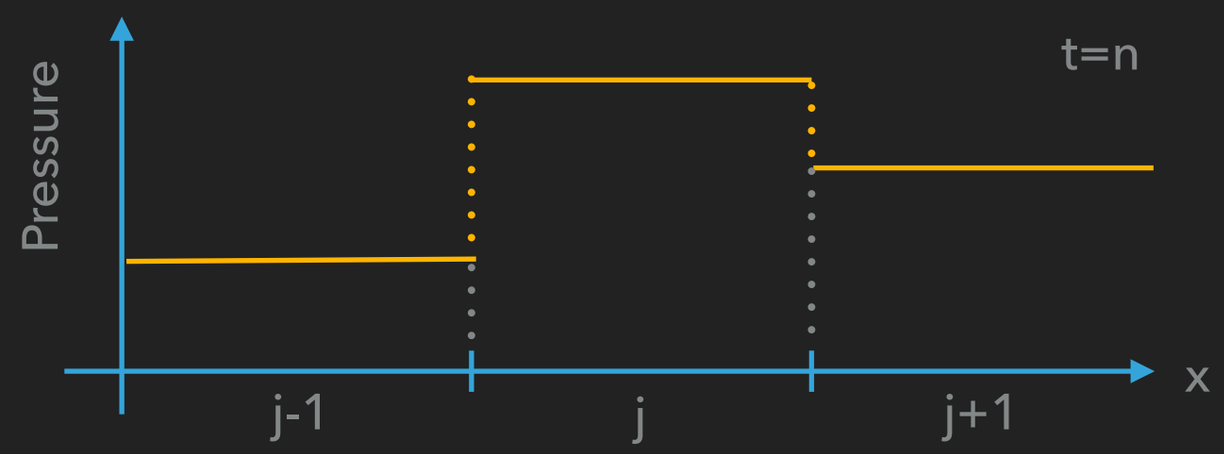
KELVIN-HELMHOLTZ TEST



Frontiere et al. 2016

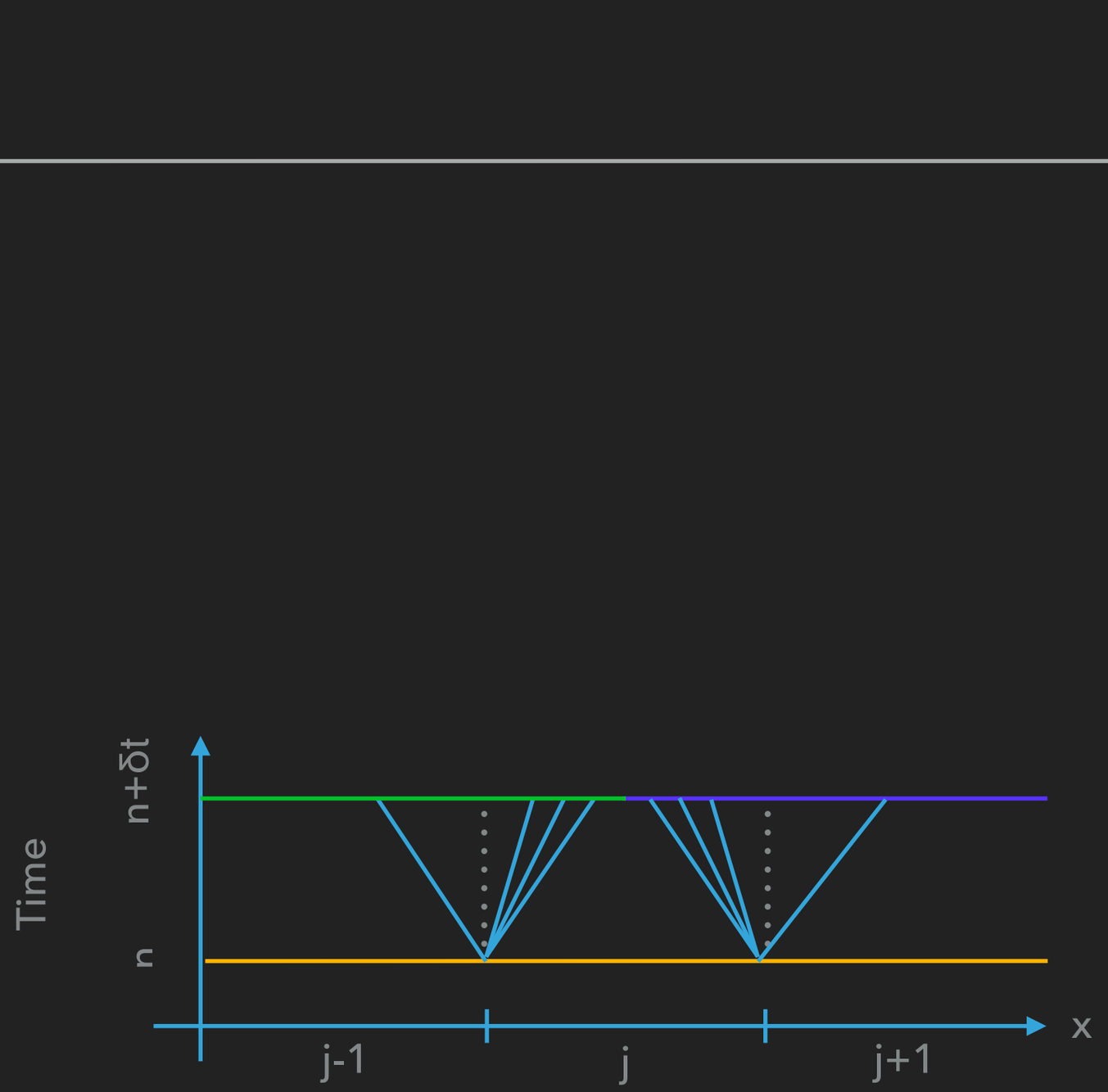
GODUNOV'S METHOD

Initial Data

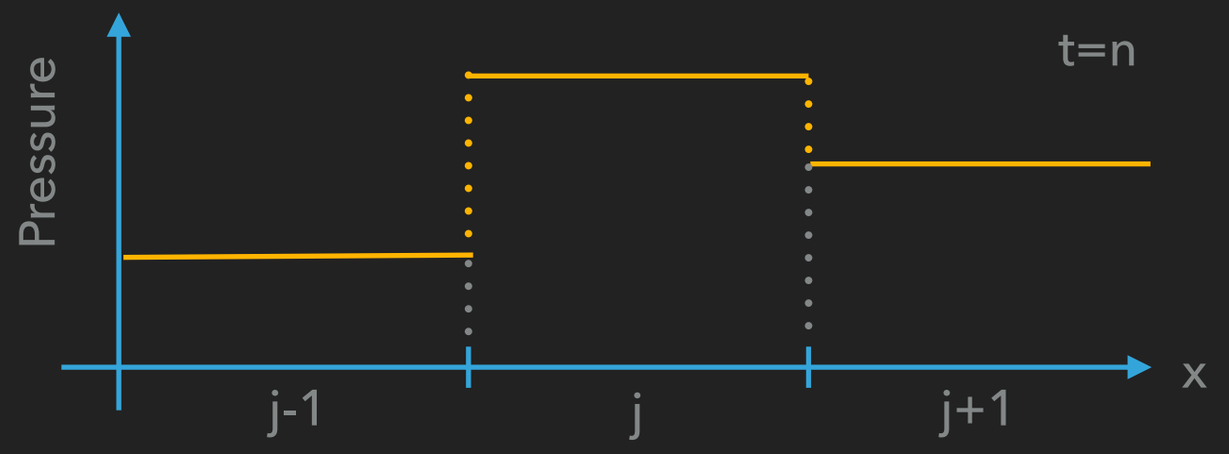


GODUNOV'S METHOD

Spacetime Evolution

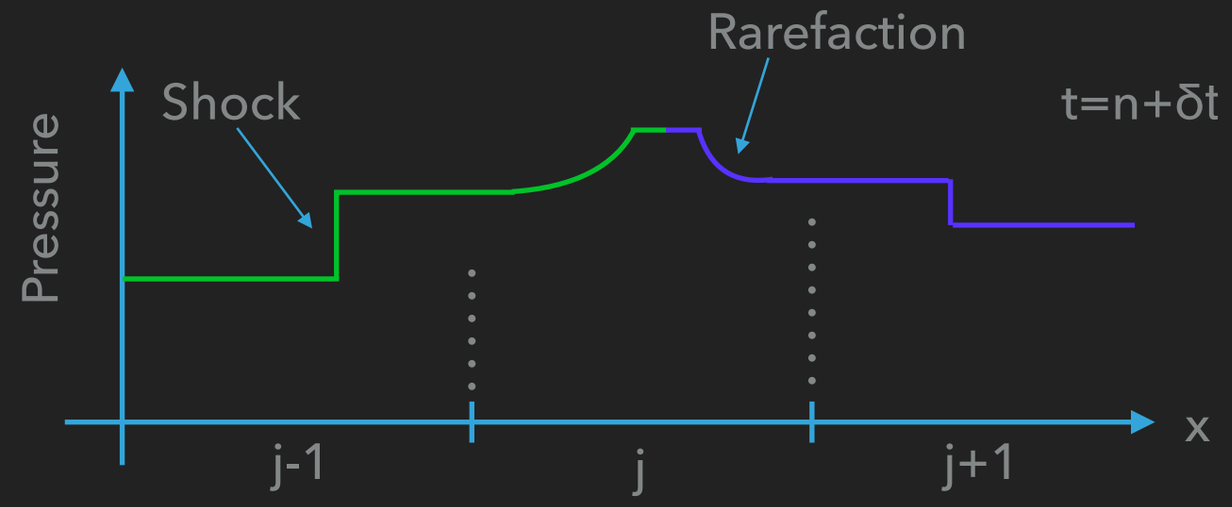


Initial Data

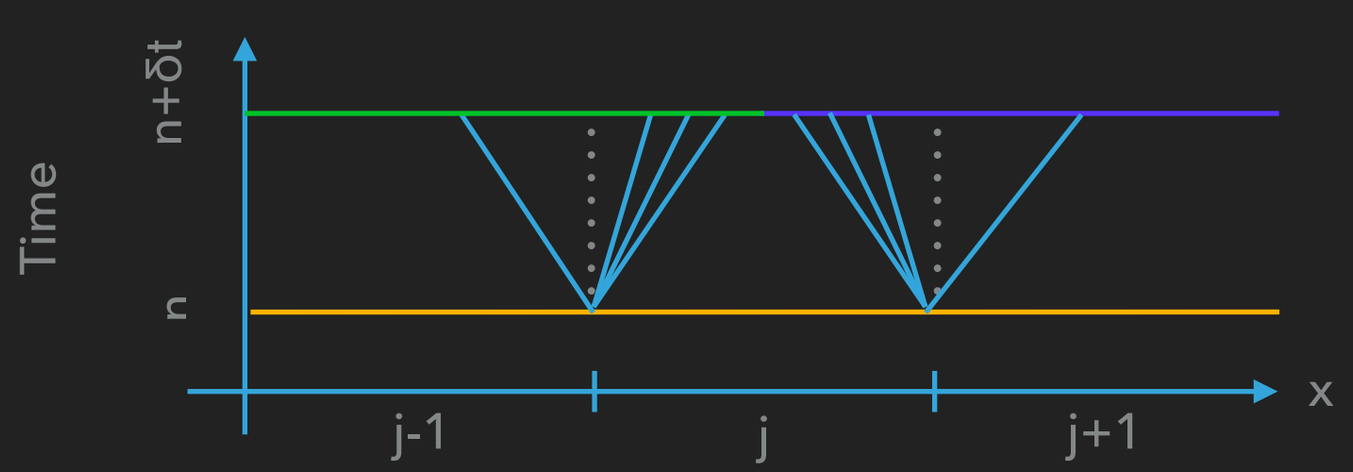


GODUNOV'S METHOD

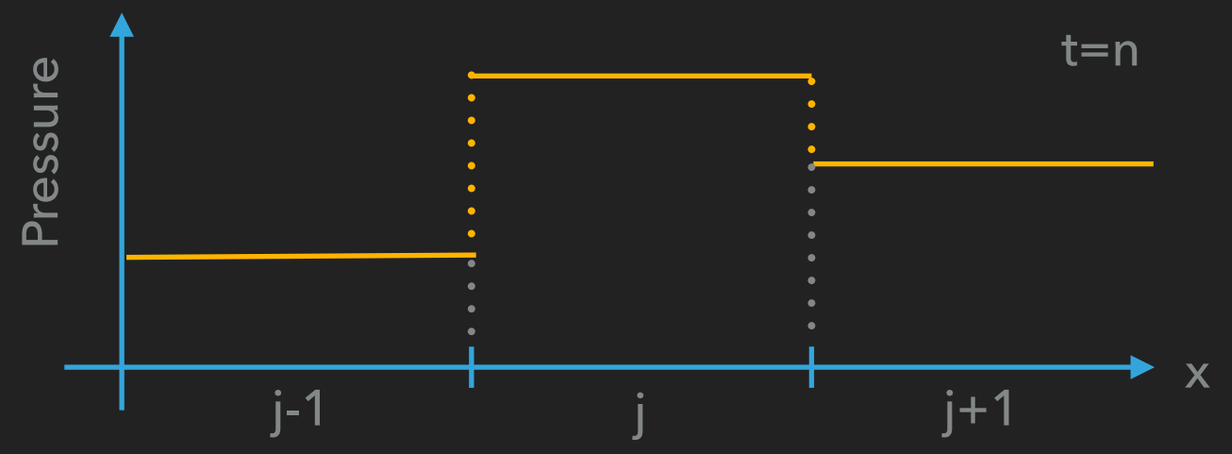
Evolved State



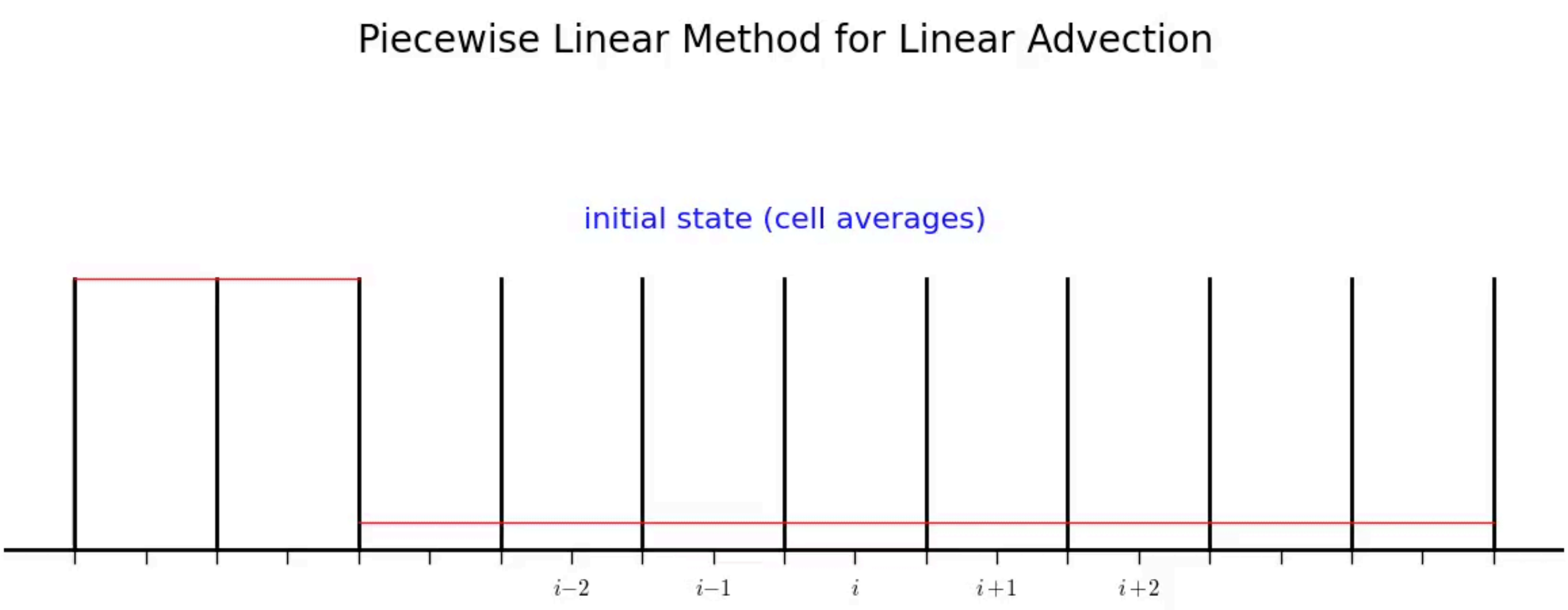
Spacetime Evolution



Initial Data

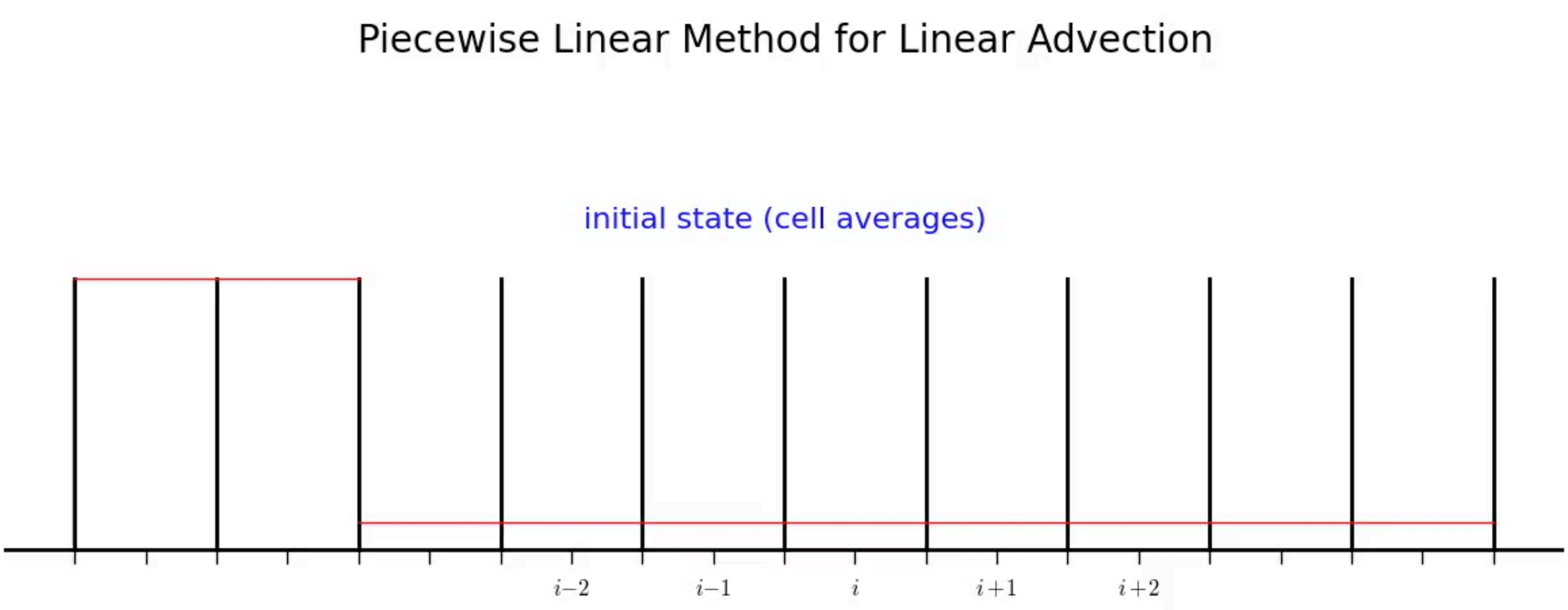


GUDUNOV'S METHOD



Credit: Mike Zingale

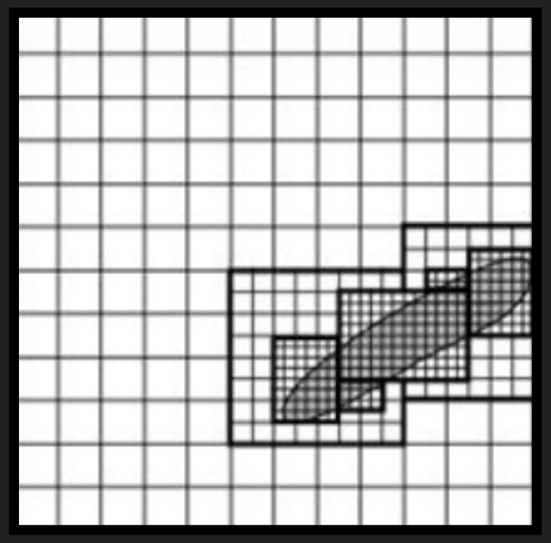
GUDUNOV'S METHOD



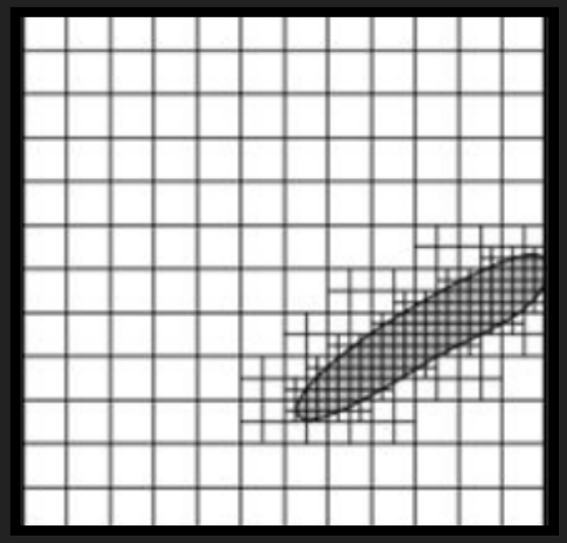
Credit: Mike Zingale

ADAPTIVE MESH REFINEMENT

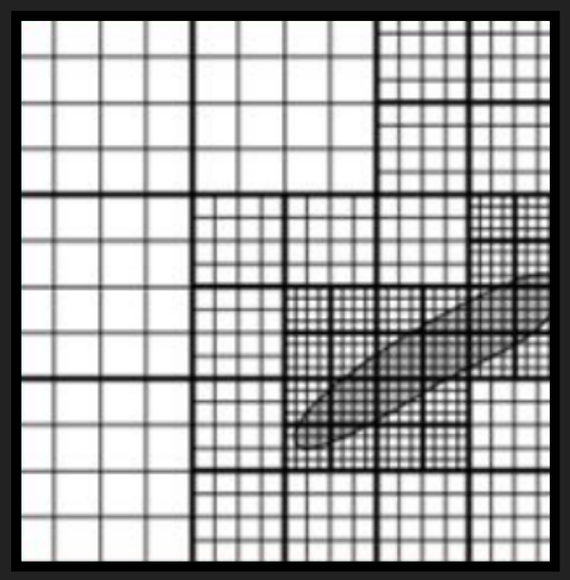
Block AMR



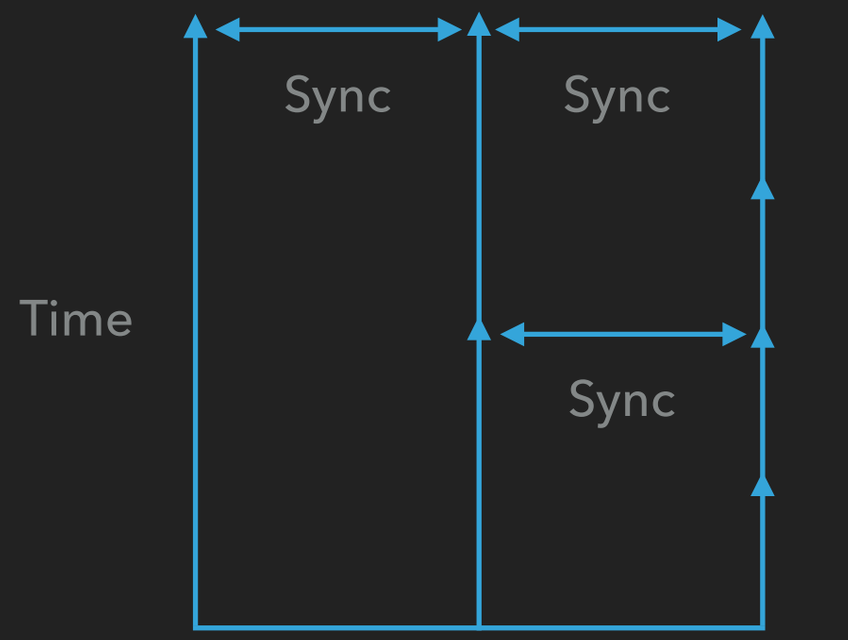
Oct AMR



Self-Similar Block AMR

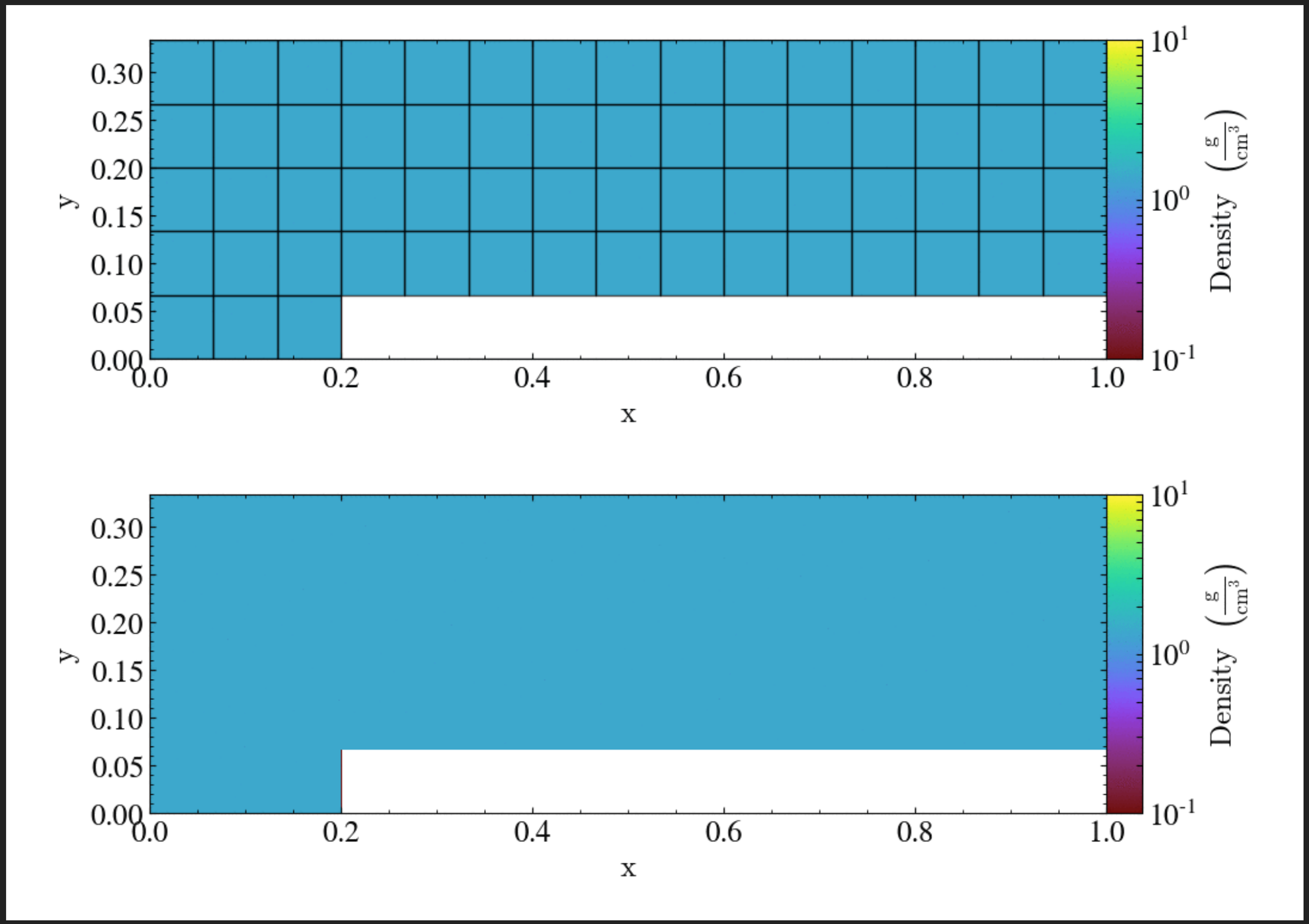


Adaptive Timestep

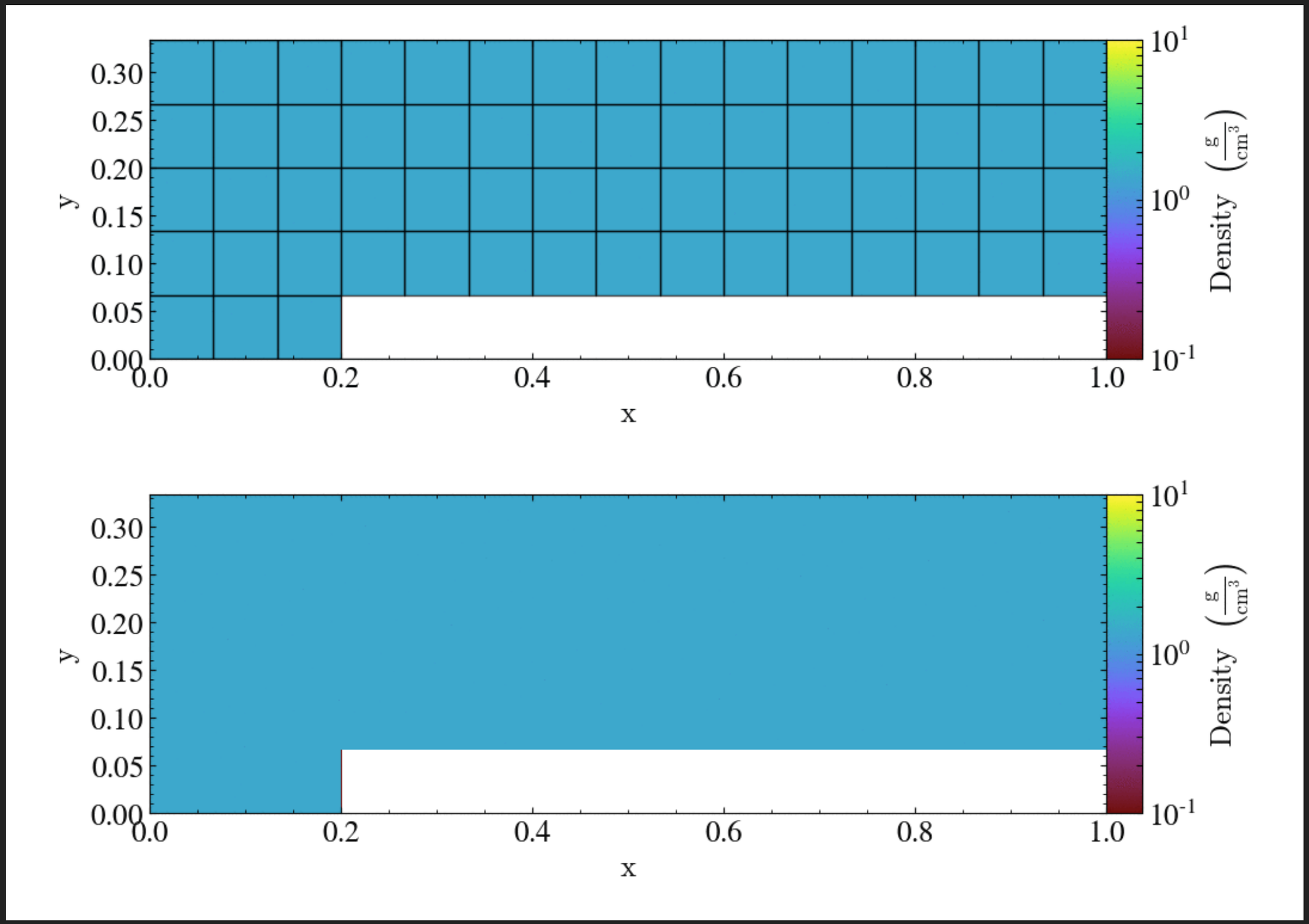


Berger & Oliger (1984)

ADAPTIVE MESH REFINEMENT



ADAPTIVE MESH REFINEMENT



PUBLIC EULERIAN RESEARCH CODES

RAMSES

Website	http://www.ics.uzh.ch/~teyssier/ramses/RAMSES.html
Repository	https://bitbucket.org/rteyssie/ramses
Discretization	Oct AMR
Physics Modules	Tree gravity, N-body particles, MHD, radiative transfer*, optically thin cooling, star formation and feedback
Research Focus	Cosmology, Galaxy Formation, Star Formation, General Astrophysics
License	CeCILL (GPLv3 Compatible)
Publications (Citations)	Teyssier et al. (2002) (832)
Language	Fortran 90
Parallelism	MPI

Simulated Antennae Galaxies
Renaud et al. (2015)

Mock observation of Horizon-AGN Simulation
Kaviraj et al. (2016)

RAMSES

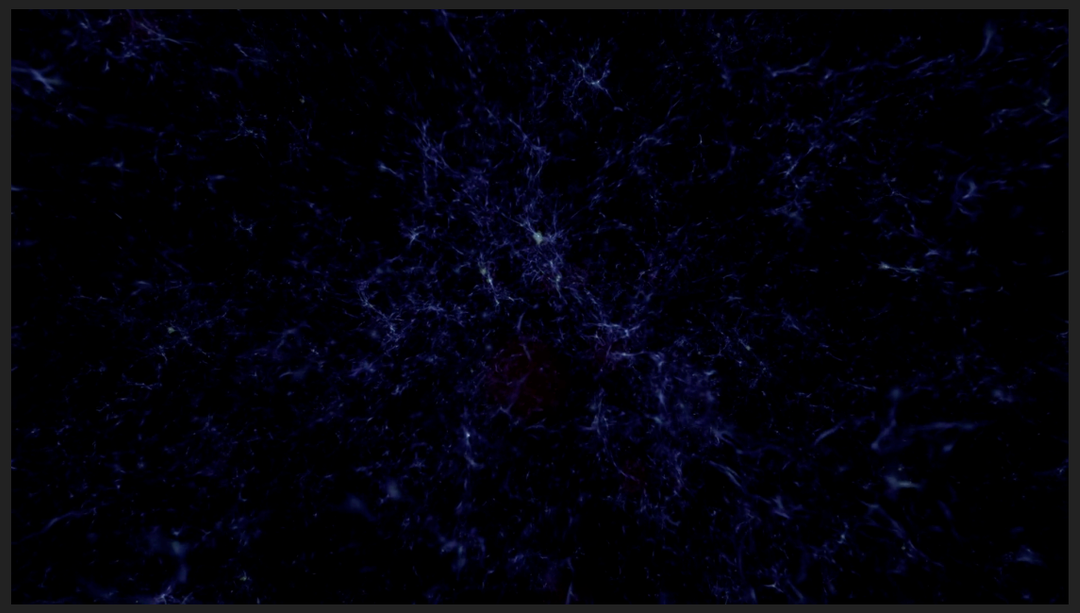
Website	http://www.ics.uzh.ch/~teyssier/ramses/RAMSES.html
Repository	https://bitbucket.org/rteyssie/ramses
Discretization	Oct AMR
Physics Modules	Tree gravity, N-body particles, MHD, radiative transfer*, optically thin cooling, star formation and feedback
Research Focus	Cosmology, Galaxy Formation, Star Formation, General Astrophysics
License	CeCILL (GPLv3 Compatible)
Publications (Citations)	Teyssier et al. (2002) (832)
Language	Fortran 90
Parallelism	MPI

Simulated Antennae Galaxies
Renaud et al. (2015)

Mock observation of Horizon-AGN Simulation
Kaviraj et al. (2016)

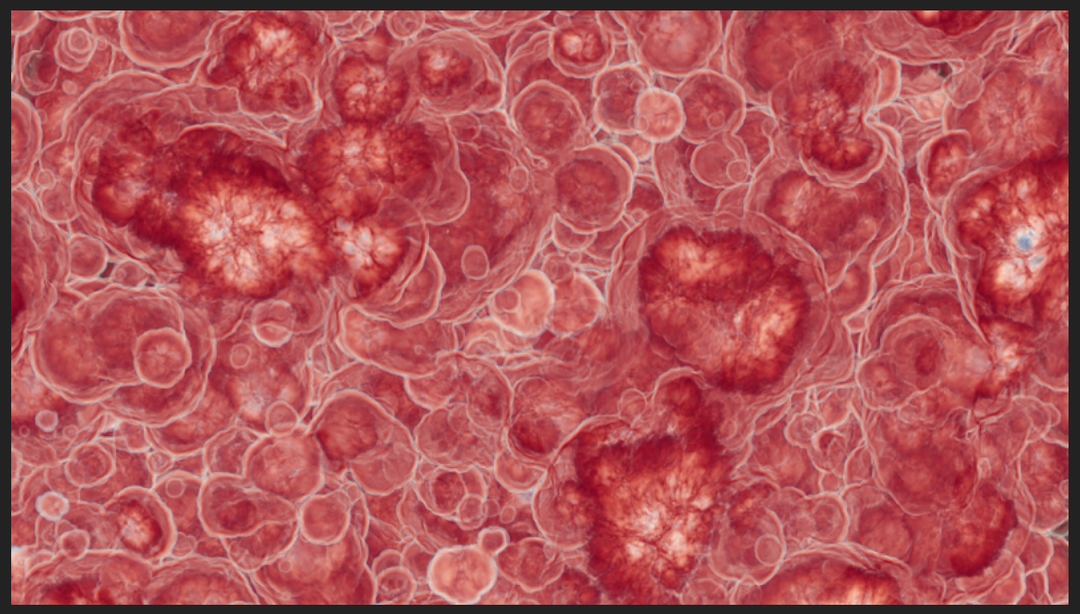
Enzo

Website	http://enzo-project.org/
Repository	https://bitbucket.org/enzo/enzo-dev
Discretization	Structured AMR
Physics Modules	Multigrid Gravity, MHD, Radiation, Chemistry, Star formation and feedback, Cosmology, Heat conduction
Research Focus	Cosmology, Star formation, Galaxy formation, General Astrophysics
License	NCSA License (BSD 3-Clause)
Publications (Citations)	Bryan et al. (2014) (258)
Language	C++, Fortran
Parallelism	MPI, CUDA



Smith et al. (2015)

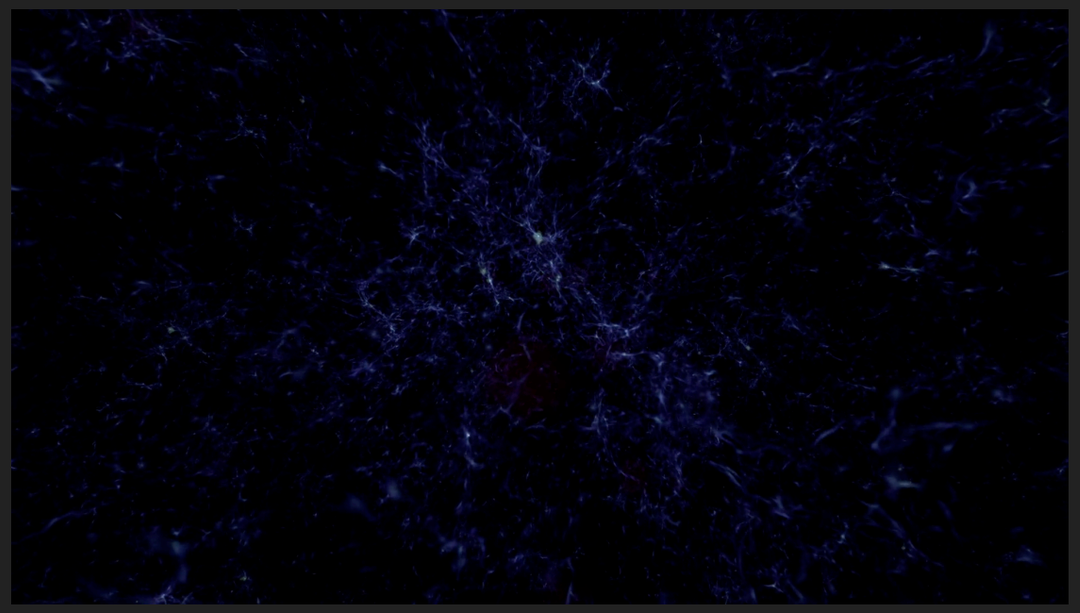
Viz Credit: NCSA AVL



Credit: Sam Skillman, Mike Norman

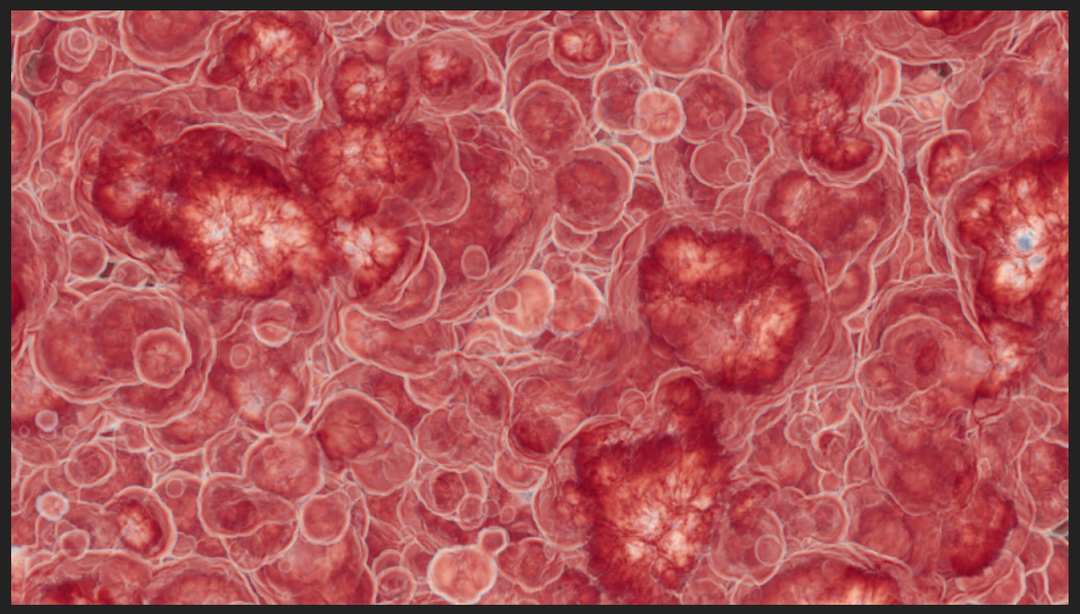
Enzo

Website	http://enzo-project.org/
Repository	https://bitbucket.org/enzo/enzo-dev
Discretization	Structured AMR
Physics Modules	Multigrid Gravity, MHD, Radiation, Chemistry, Star formation and feedback, Cosmology, Heat conduction
Research Focus	Cosmology, Star formation, Galaxy formation, General Astrophysics
License	NCSA License (BSD 3-Clause)
Publications (Citations)	Bryan et al. (2014) (258)
Language	C++, Fortran
Parallelism	MPI, CUDA



Smith et al. (2015)

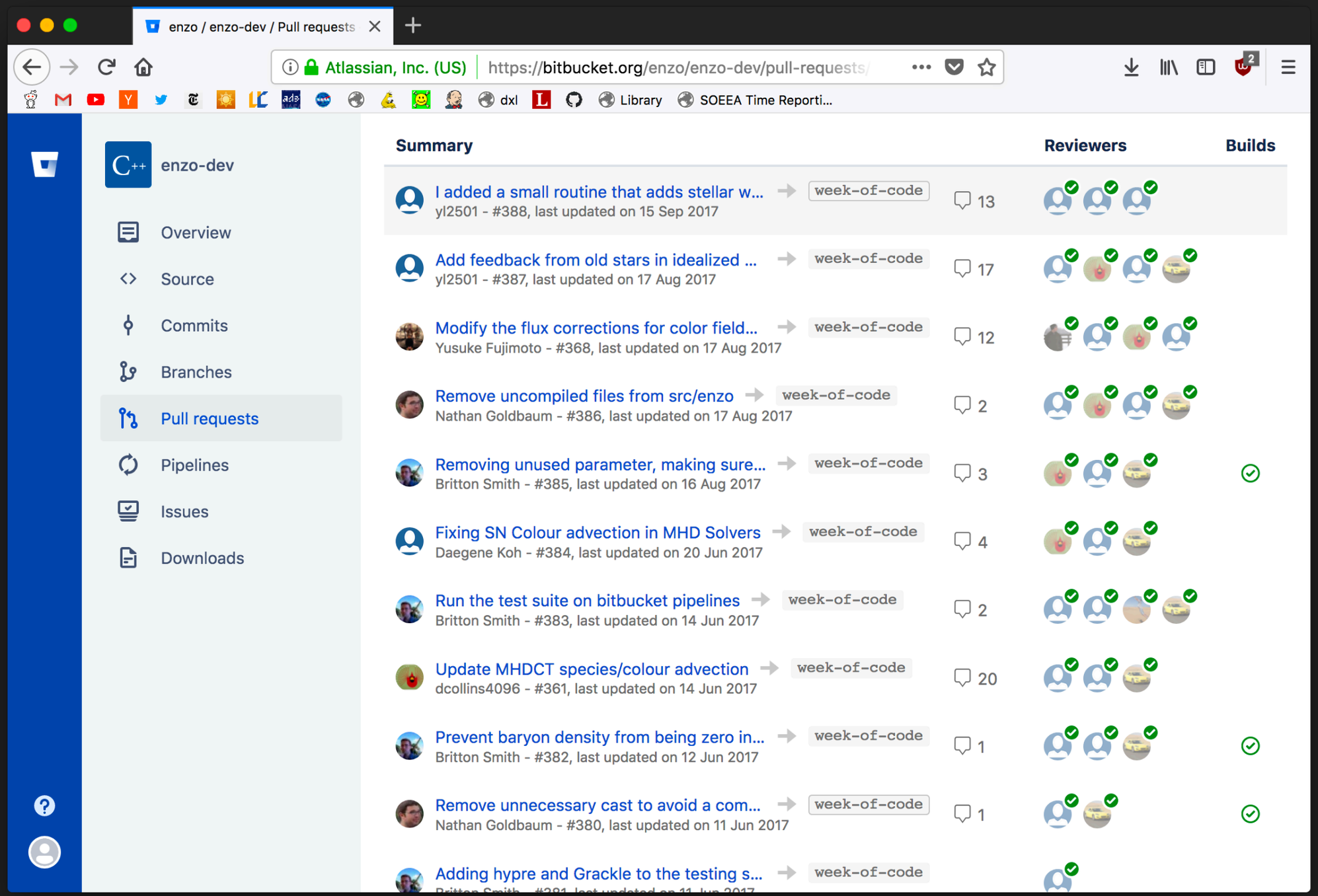
Viz Credit: NCSA AVL



Credit: Sam Skillman, Mike Norman

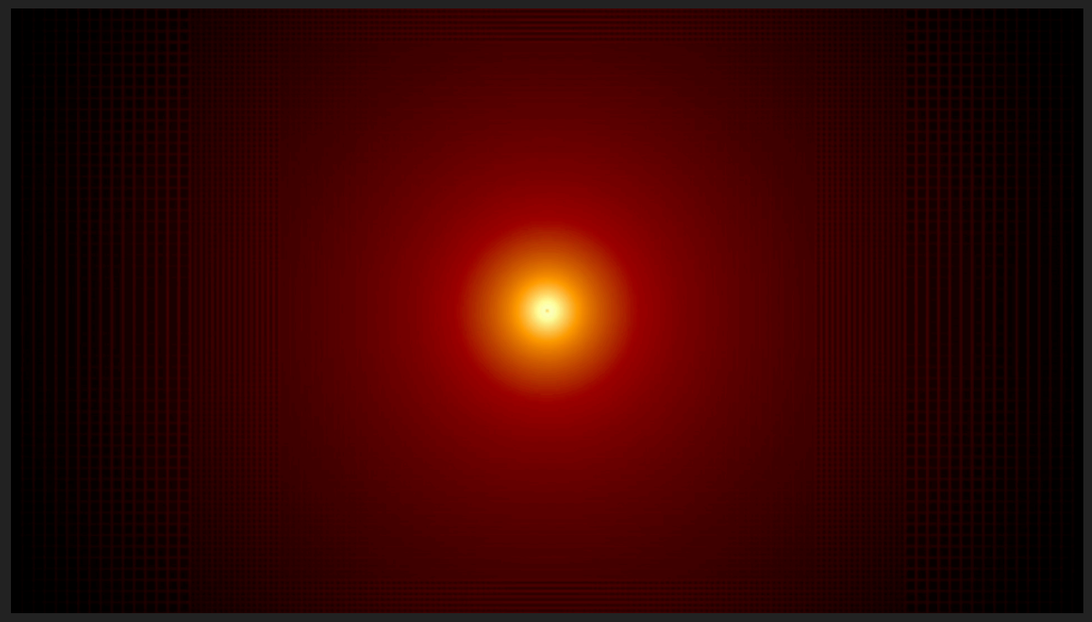
TEXT

COMMUNITY: ENZO'S BEST FEATURE



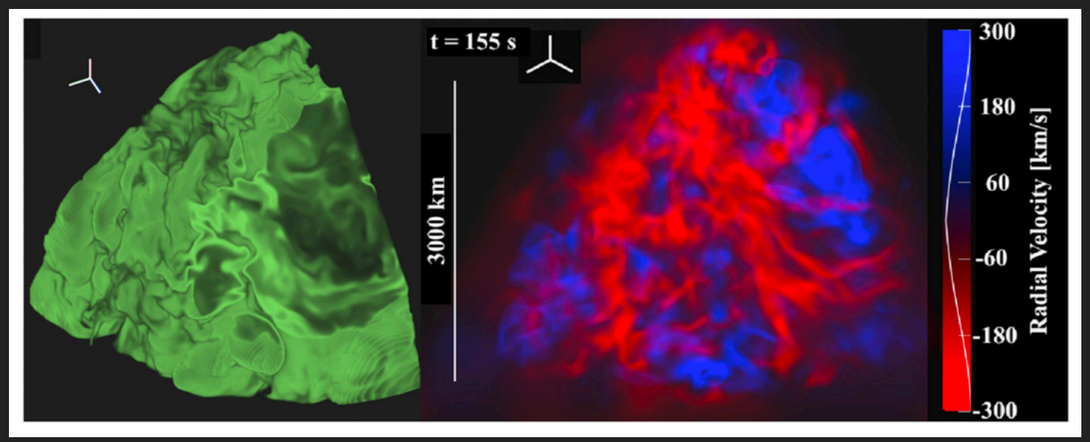
FLASH

Website	http://flash.uchicago.edu/site/
Repository	Private
Discretization	Strucured AMR
Physics Modules	Multipole and Multigrid Gravity, MHD, Multigroup Radiative Transfer, Diffustion and Conduction, Nuclear Burning
Research Focus	Supernovae, ISM, Turbulence, General Astrophysics
License	Source available upon request, cannot be redistributed
Publications (Citations)	Fryxell et al. (2000) (1024)
Language	Fortran 90
Parallelism	MPI



Galaxy cluster merger

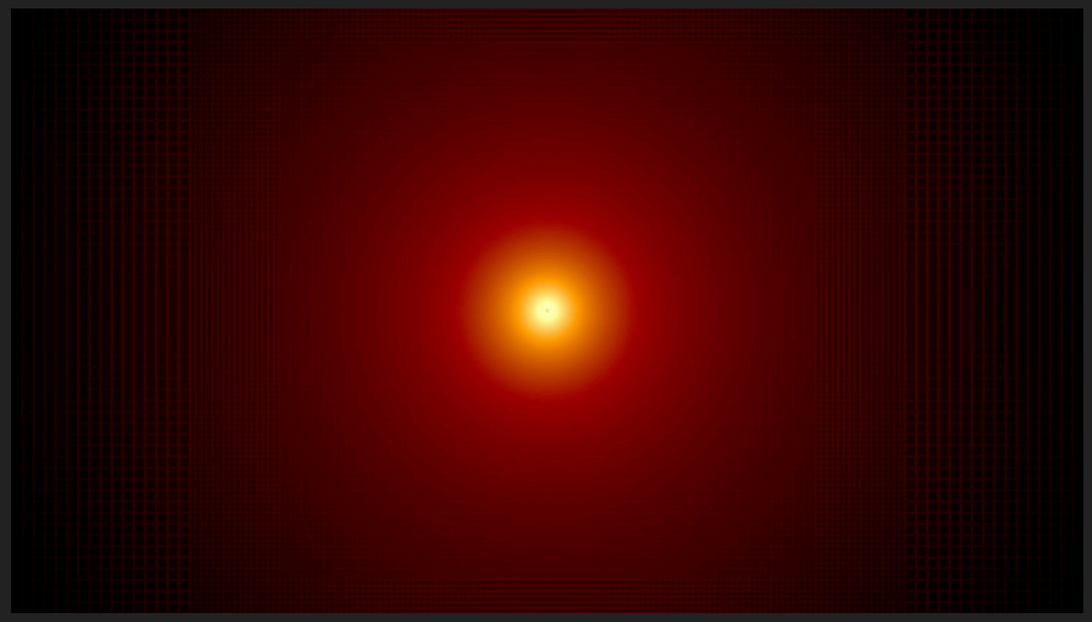
Credit: John ZuHone,
NASA Scientific Visualization Group



3D core collapse SN progenitor
Couch et al. (2015)

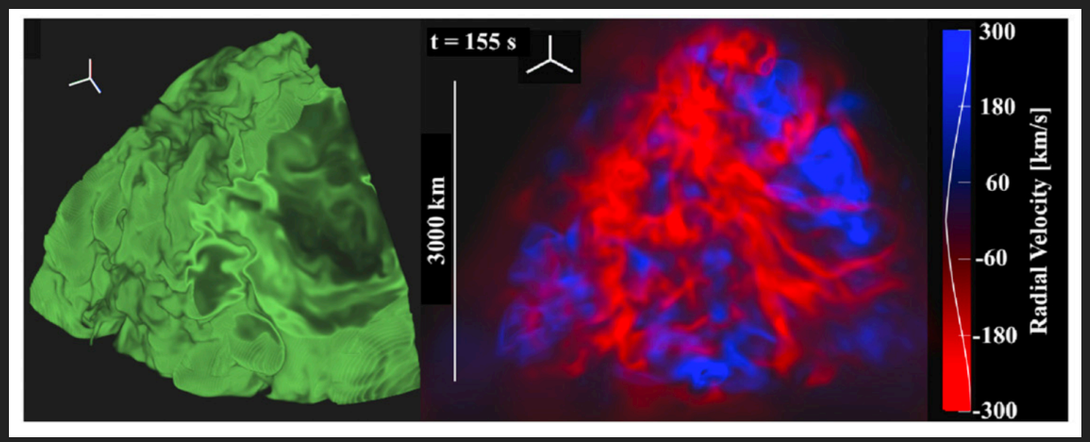
FLASH

Website	http://flash.uchicago.edu/site/
Repository	Private
Discretization	Strucured AMR
Physics Modules	Multipole and Multigrid Gravity, MHD, Multigroup Radiative Transfer, Diffustion and Conduction, Nuclear Burning
Research Focus	Supernovae, ISM, Turbulence, General Astrophysics
License	Source available upon request, cannot be redistributed
Publications (Citations)	Fryxell et al. (2000) (1024)
Language	Fortran 90
Parallelism	MPI



Galaxy cluster merger

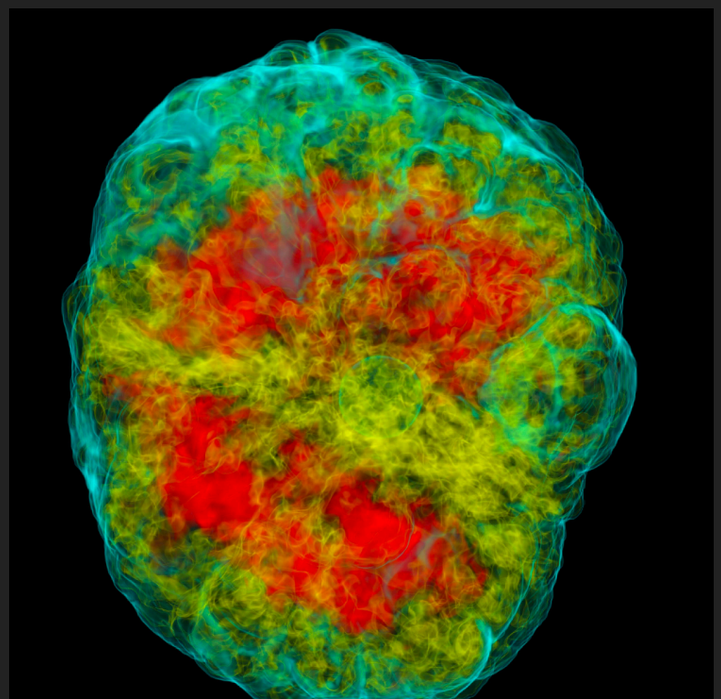
Credit: John ZuHone,
NASA Scientific Visualization Group



3D core collapse SN progenitor
Couch et al. (2015)

Einstein Toolkit

Website	https://einsteintoolkit.org/
Repository	https://bitbucket.org/einsteintoolkit/
Discretization	Structured AMR
Physics Modules	Coupled Spacetime Evolution and Hydrodynamics
Research Focus	Compact Objects
License	LGPL, GPL, MIT
Publications (Citations)	Loffler et al. (2011) (141)
Language	C, C++, Fortran 77, Fortran 90
Parallelism	MPI, CUDA, OpenCL

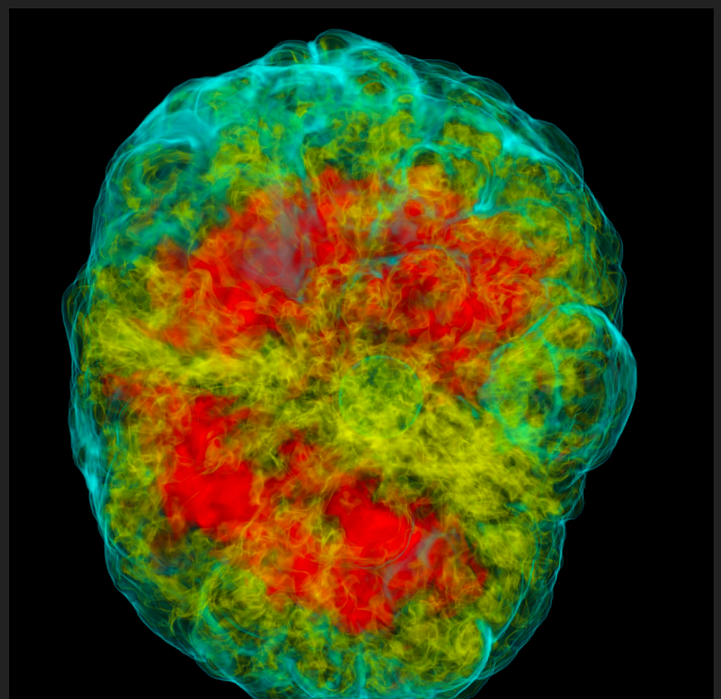


GRMHD Supernova Explosion
Roberts et al. (2016)

Gravitational Waves from BBH merger
Credit: Barry Wardell

Einstein Toolkit

Website	https://einsteintoolkit.org/
Repository	https://bitbucket.org/einsteintoolkit/
Discretization	Structured AMR
Physics Modules	Coupled Spacetime Evolution and Hydrodynamics
Research Focus	Compact Objects
License	LGPL, GPL, MIT
Publications (Citations)	Loffler et al. (2011) (141)
Language	C, C++, Fortran 77, Fortran 90
Parallelism	MPI, CUDA, OpenCL

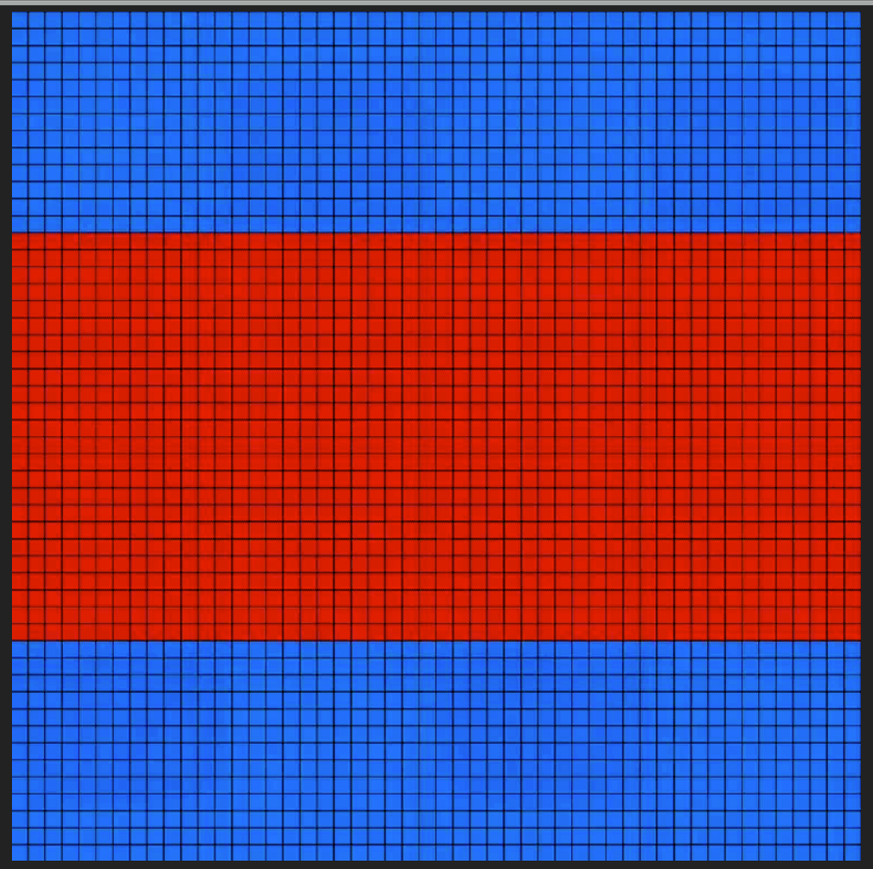


GRMHD Supernova Explosion
Roberts et al. (2016)

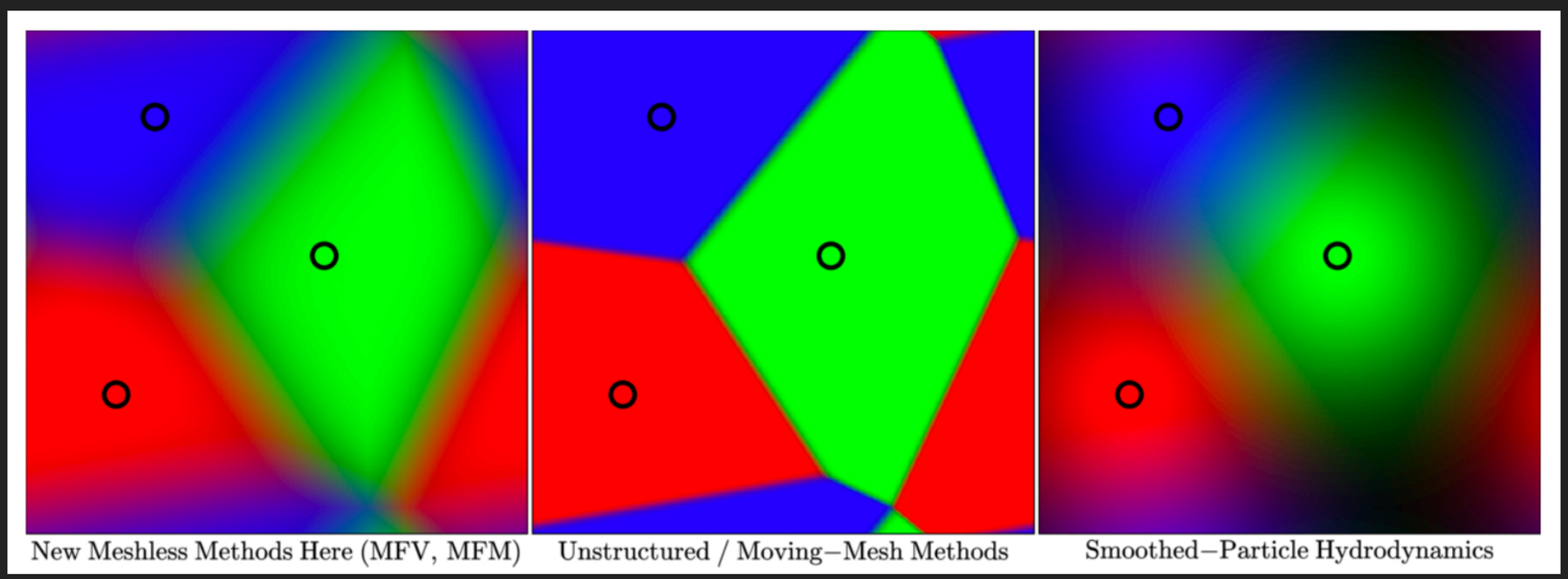
Gravitational Waves from BBH merger
Credit: Barry Wardell

FORWARD-LOOKING CODES

- AREPO and Gizmo



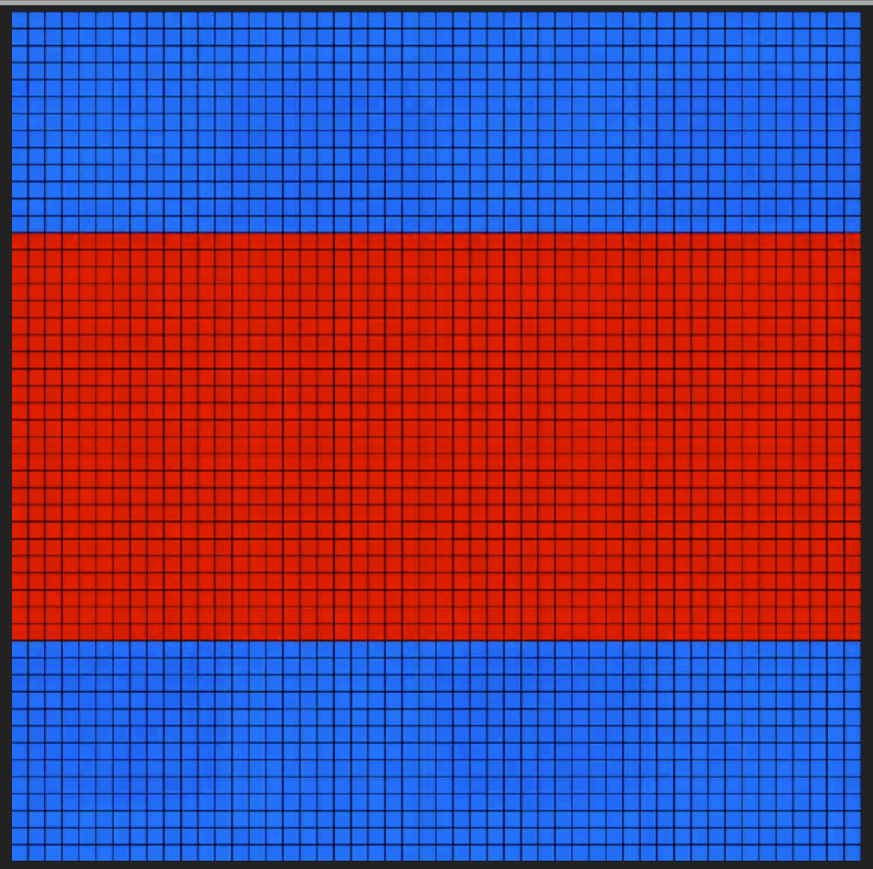
Springel et al. (2009)



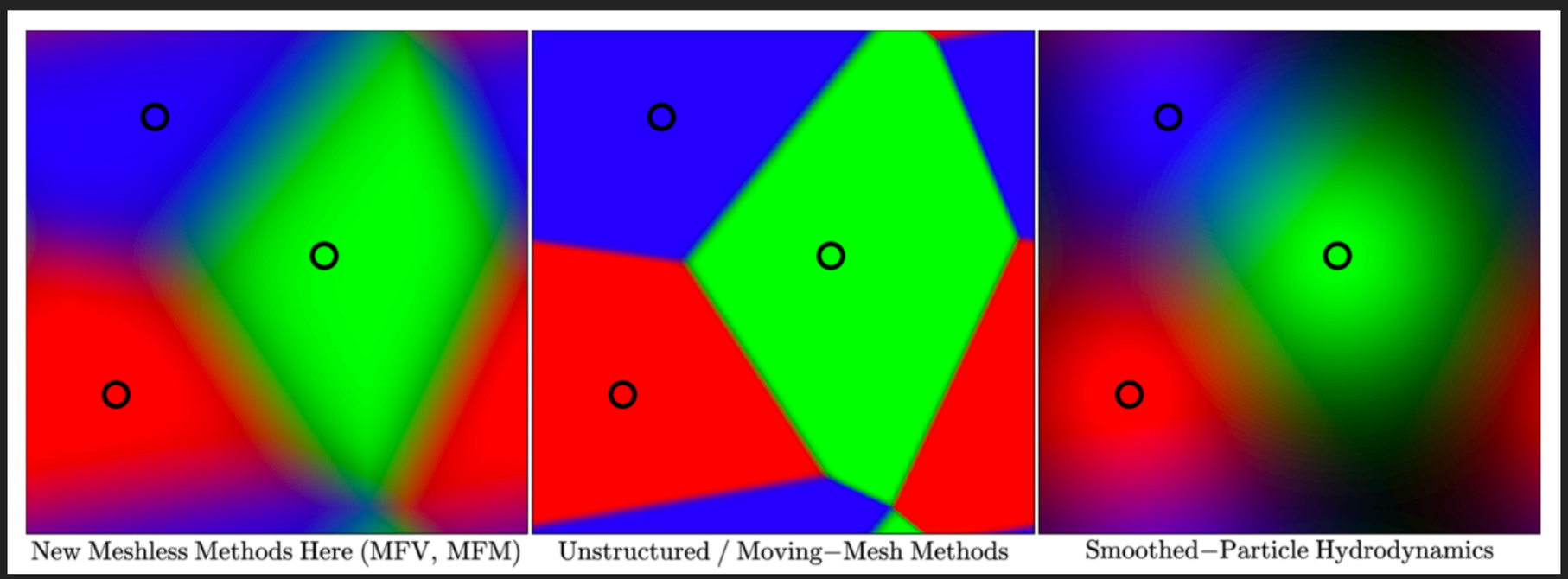
Hopkins et al. (2015)

FORWARD-LOOKING CODES

- AREPO and Gizmo



Springel et al. (2009)



Hopkins et al. (2015)

EXTRACTING INSIGHTS FROM ASTROPHYSICS SIMULATIONS WITH YT

What is yt?

A COMMUNITY OF PRACTICE

Tom Abel
Alex Bogert
Marianne Corvellec
Nicholas Earl
Austin Gilbert
David Hannasch
Max Katz
Kacper Kowalik
Doris Lee
Chris Malone
Andrew Myers
JC Passy
Anna Rosen
Noel Scudder
Britton Smith
Robert Thompson
Rick Wagner
John Zuhone

Gabriel Altay
Robert Bradshaw
Jared Coughlin
Hilary Egan
Adam Ginsburg
Cameron Hummels
Ben Keller
Matthew Krafczyk
Eve Lee
Jonah Miller
Jill Naiman
Hugo Pfister
Chuck Rozhon
Patrick Shriwise
Geoffrey So
Joseph Tomlinson
Mike Warren

Kenza Arraki
Corentin Cadiou
Brian Crosby
Daniel Fenn
Nathan Goldbaum
Suoqing Ji
Chang-Goo Kim
Mark Krumholz
Sam Leitner
Joshua Moloney
Desika Narayanan
John Regan
Douglas Rudd
Devin Silvia
Casey Stark
Stephanie Tonnesen
Charlie Watson

Kirk Barrow
Pengfei Chen
Weiguang Cui
John Forbes
William Gray
Allyson Julian
Ji-hoon Kim
Michael Kuhlen
Yuan Li
Chris Moody
Kaylea Nelson
Mark Richardson
Rafael Ruggiero
Sam Skillman
Antoine Strugarek
Matthew Turk
Andrew Wetzel

Ricarda Beckmann
Yi-Hao Chen
Andrew Cunningham
Enrico Garaldi
Markus Haider
Anni Järvenpää
Steffen Klemer
Meagan Lang
Alex Lindsay
Christopher Moody
Brian O'Shea
Sherwood Richers
Hsi-Yu Schive
Stephen Skory
Elizabeth Tasker
Miguel de Val-Borro
John Wise

Elliott Biondo
David Collins
Bili Dong
Sam Geen
Eric Hallman
Christian Karch
Fabian Koller
Erwin Lau
Yinghe Lu
Stuart Mumford
J.S. Oishi
Thomas Robitaille
Anthony Scopatz
Aaron Smith
Benjamin Thompson
Kausik Venkat
Michael Zingale

>100 CONTRIBUTORS AS OF JUNE 2017

"Scaling a code in the human dimension": https://arxiv.org/abs/1301.7064

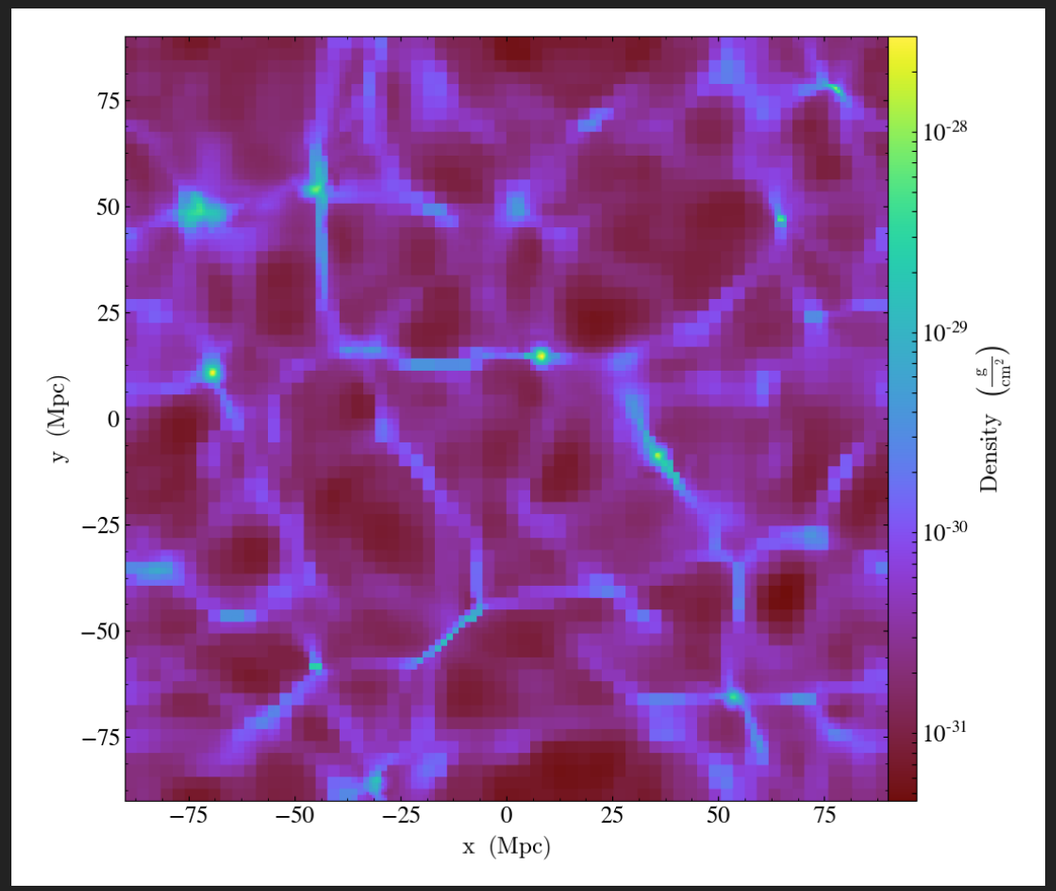
QUICK CALCULATIONS

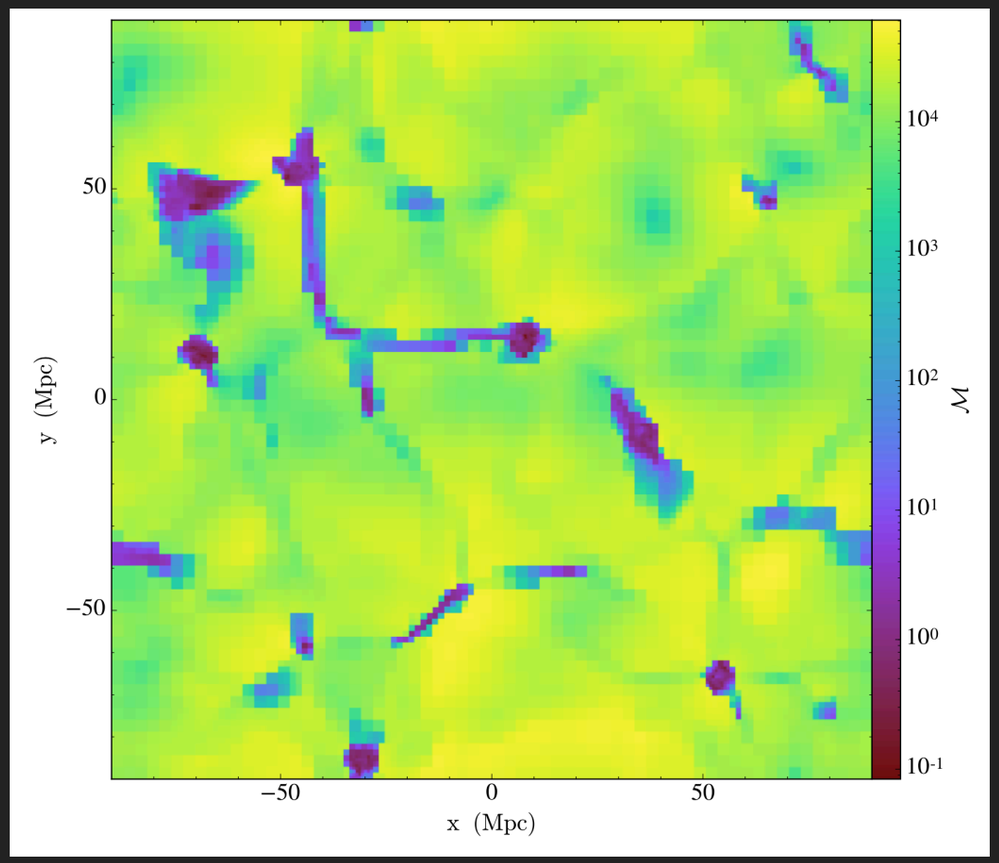
```
import yt
from yt.units import kiloparsec

ds = yt.load('IsolatedGalaxy/galaxy0030/galaxy0030')

sph = ds.sphere(center=ds.domain_center, radius=300*kiloparsec)
mean = sph.mean('temperature', weight='cell_mass')
mininum = sph.min('temperature')
maximum = sph.max('temperature')
std = sph.std('temperature', weight='cell_mass')

msg = "Minimum: {}\nMean: {}\nVariance: {}\nMaximum: {}\n"
print(msg.format(mininum, mean, std, maximum))
```

```
Minimum:  20.8445072174 K
Mean:     11212.3343006 K
Variance: 22968.9738919 K
Maximum:  24826104.0 K
```

VISUALIZING USER-DEFINED FIELDS

```
import yt

@yt.derived_field(units='', display_name=r'\mathcal{M}')
def mach_number(field, data):
    return data['velocity_magnitude']/data['sound_speed']

ds = yt.load('Enzo_64/DD0043/data0043')
p = yt.SlicePlot(ds, 'z', ['density', 'mach_number'])
p.save()
```

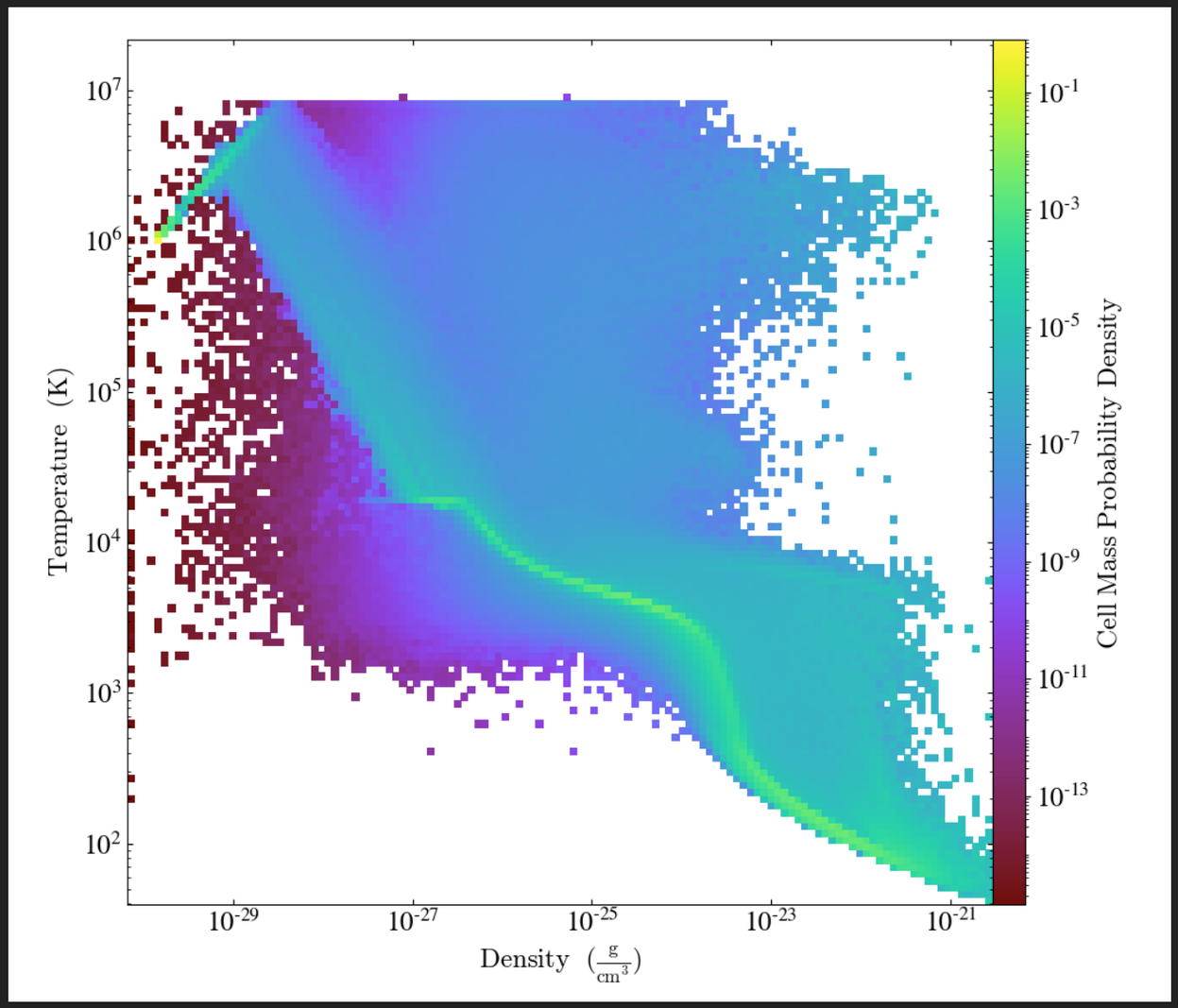




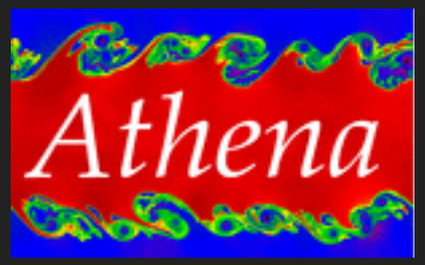
What is yt?

DATA SELECTION

```
import yt
from yt.units import megaparsec

ds = yt.load(â€šÀÃ²DD0600/DD0600â€šÀÙ)
max_val, max_loc = ds.find_max('density')

plot = yt.PhasePlot(
    ds.sphere(max_loc, 10*megaparsec),
    'density', 'temperature', 'cell_mass',
    weight_field=None, fractional=True)

plot.show()
```

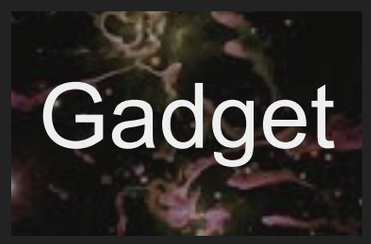


http://yt-project.org

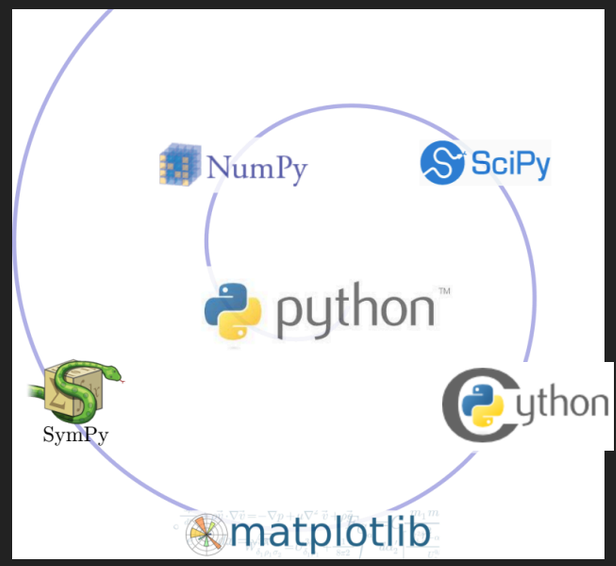


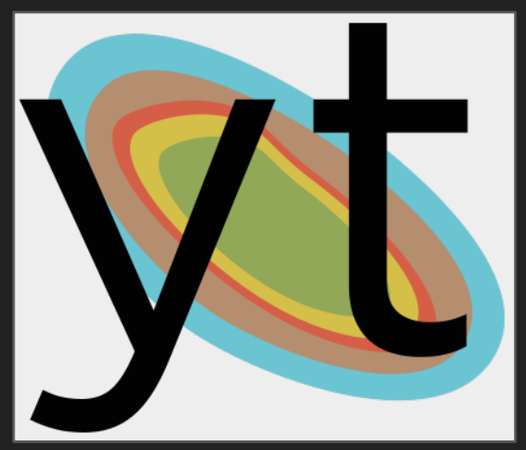
MOOSE

Gasoline

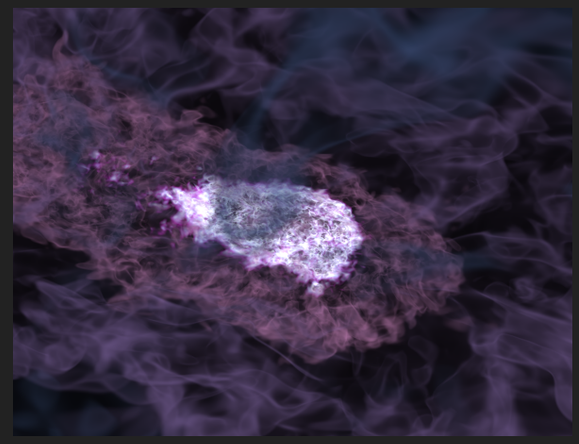


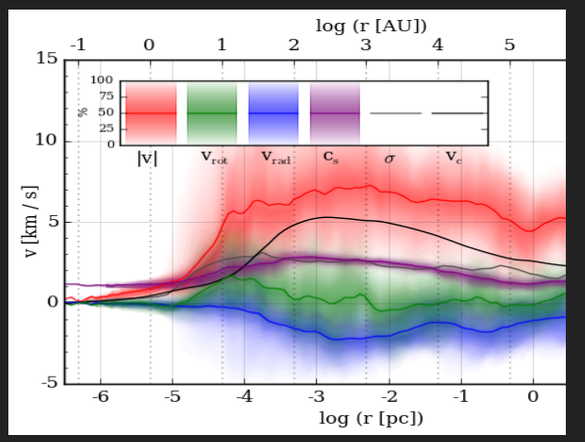
Ingest Data

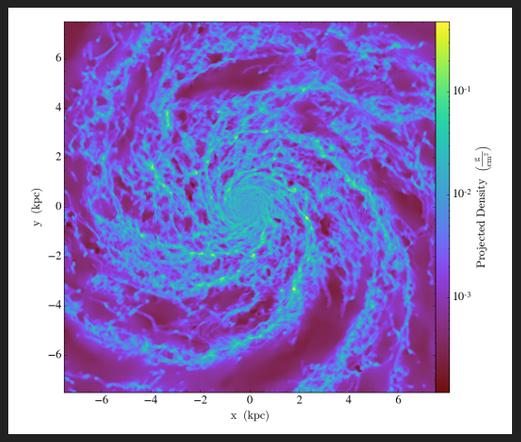


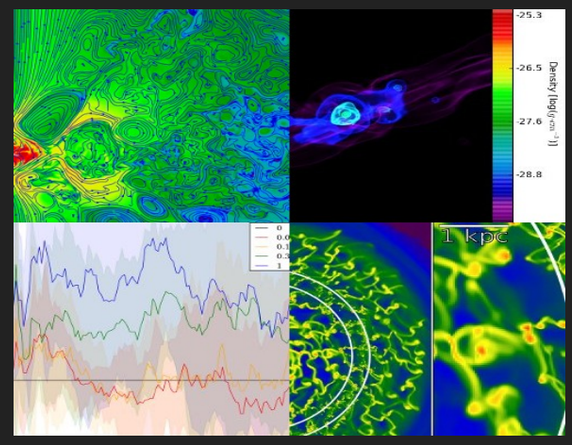


Analysis/ Visualization









NUMFOCUS

OPEN CODE = BETTER SCIENCE

https://github.com/yt-project/yt

Goldbaum et al. (2016)

Viz credit: NCSA AVL

Goldbaum et al. (2016)

Viz credit: NCSA AVL