Modeling Massive Cluster Formation with Stellar Feedback using FLASH and AMUSE

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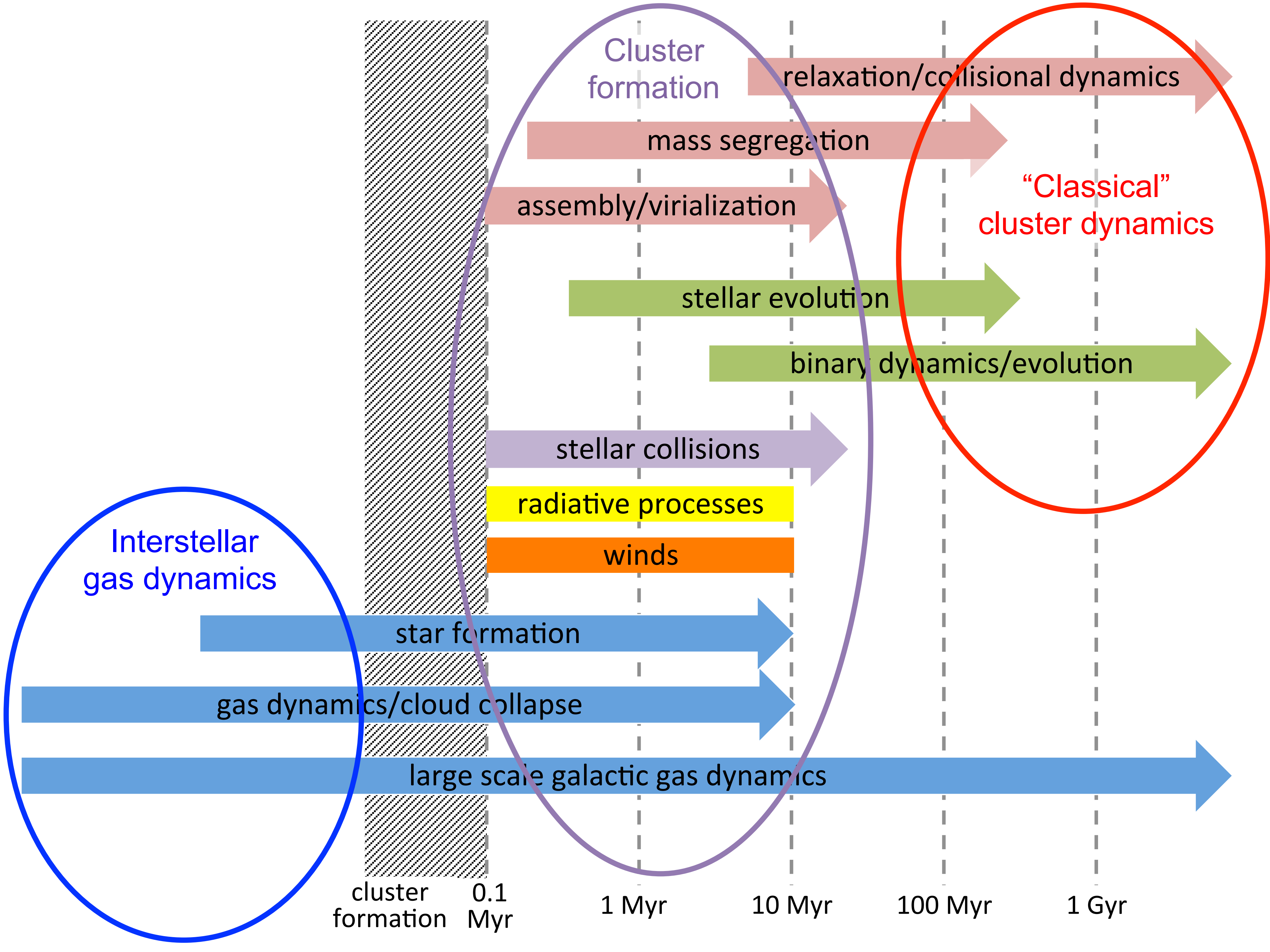
Ralf Klessen (Heidelberg)
Simon Portegies Zwart (Leiden)

Astrophysical Context

- Eva Grebel's list…
  - test model predictions for high-mass, high-density star formation
  - disruption and longevity ✓
  - effect of the environment ✓
  - universality of the IMF ✗?
  - mass segregation ✓
  - age spreads ✓
  - impact of massive stars ✓
  - feedback ✓
  - dust ✗
  - multiple populations ?

Numerical Context

- multiphysics problem – gas, stellar dynamics, radiation, stellar evolution
- multiscale problem – large dynamical range in length and time scales



Cluster formation
relaxation/collisional dynamics
mass segregation
assembly/virialization
"Classical" cluster dynamics
stellar evolution
binary dynamics/evolution
stellar collisions
radiative processes
winds
Interstellar gas dynamics
star formation
gas dynamics/cloud collapse
large scale galactic gas dynamics
cluster formation
0.1 Myr
1 Myr
10 Myr
100 Myr
1 Gyr

Numerical Context

- multiphysics problem – gas, stellar dynamics, radiation, stellar evolution
- multiscale problem – large dynamical range in length and time scales

- can't (shouldn't?) do everything in a single code
- can (should) couple codes modeling different regimes
  - gas dynamics
  - star formation
  - radiative and mechanical feedback
  - stellar dynamics
  - stellar and binary evolution
  - stellar collisions

AMUSE

Astrophysical Multipurpose
Software Environment
(Pelupessy et al. 2013)

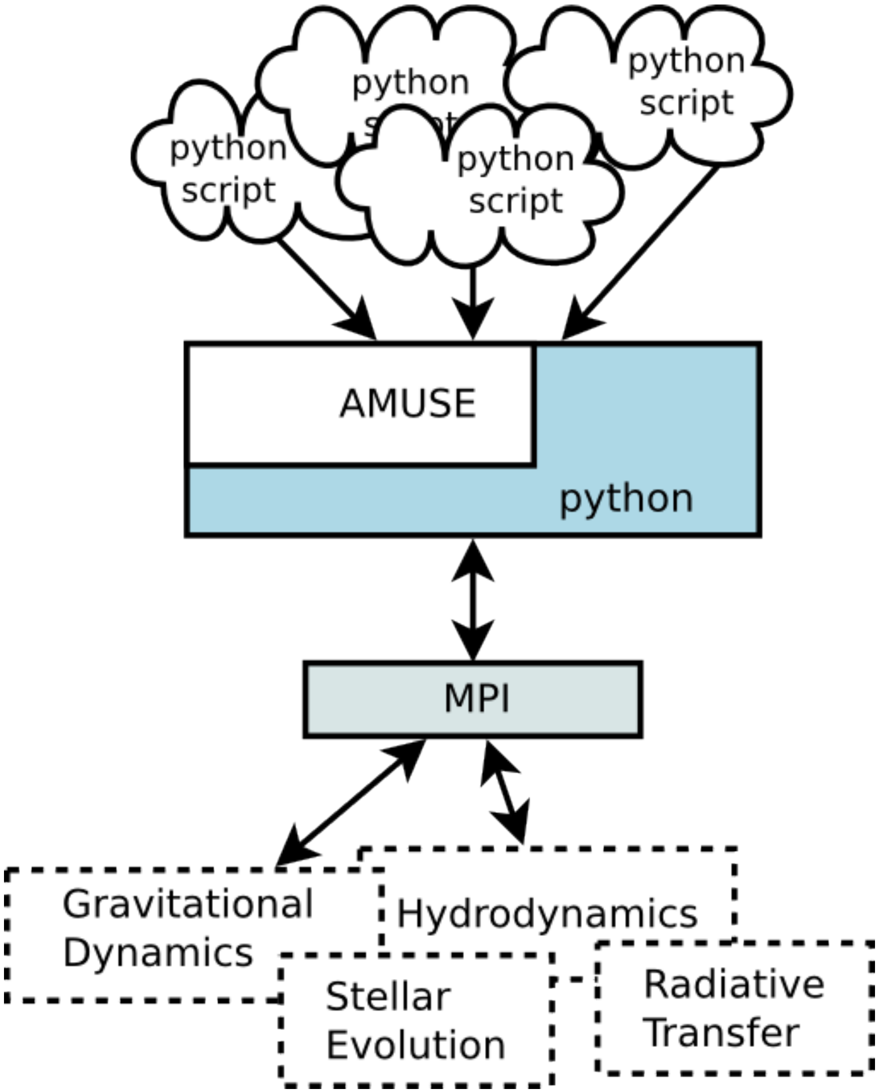
http://amusecode.org

- software implementation of MODEST goals
- built on “community modules” implementing basic physics
- multiple modular implementations of key physical processes
- standardized interfaces

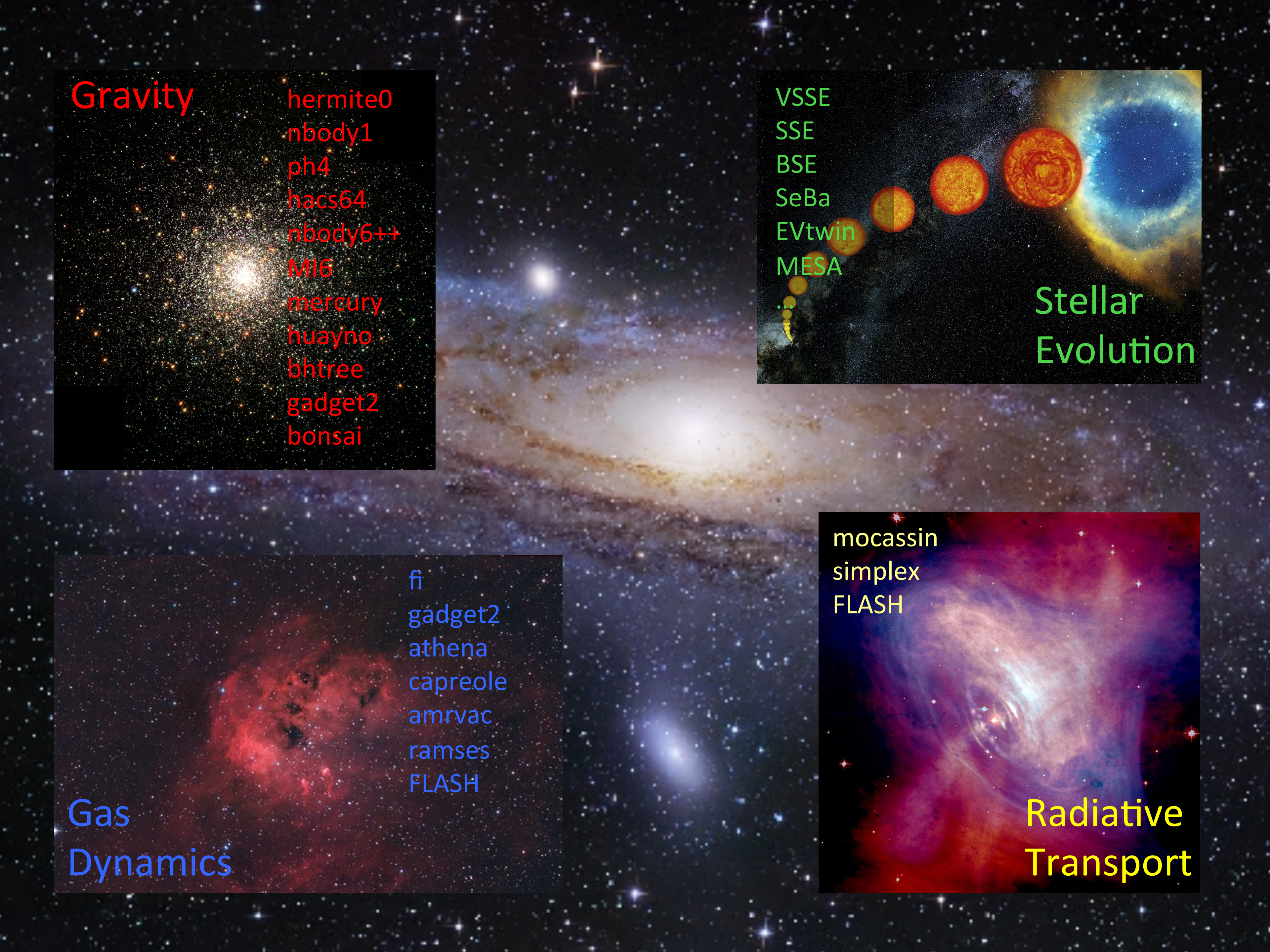
```
code.particles.add_particles(bodies)

code.evolve_model(1|units.Myr)
```

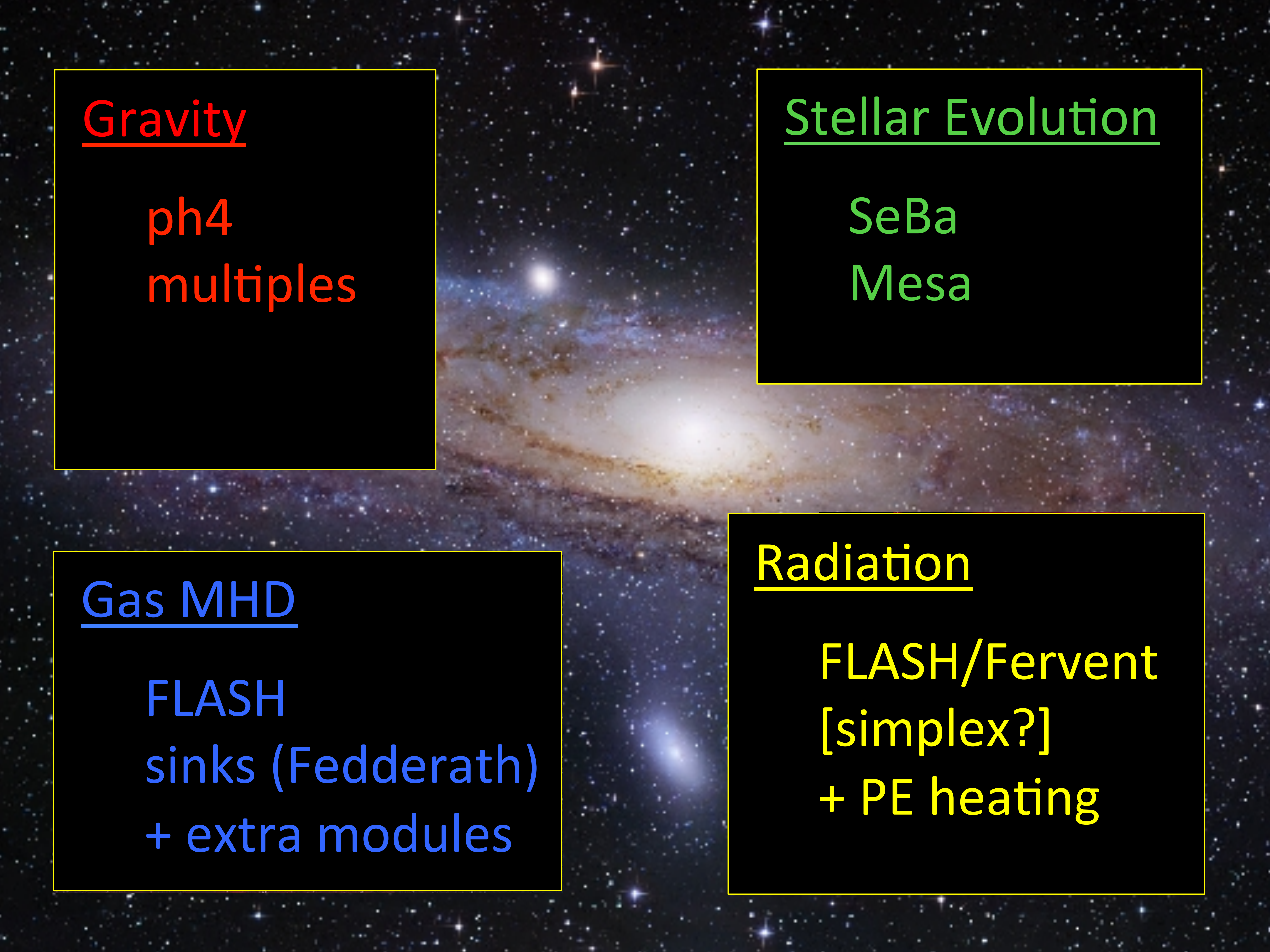
units!

AMUSE



- user scripts written in Python
- AMUSE management layers for data coherence, units, MPI communication
- community modules: C, C++, Fortran, CUDA, Python, Java, …

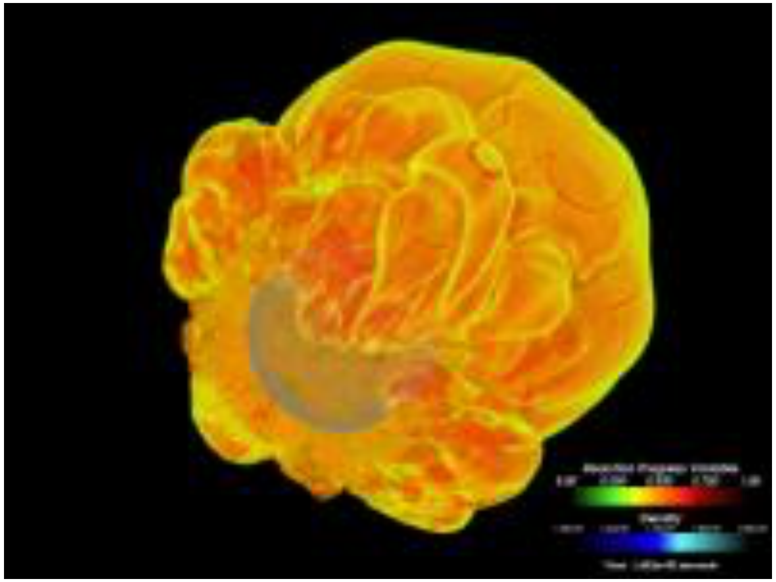

Gravity
hermite0
nbody1
ph4
hacs64
nbody6++
MI6
mercury
huayno
bhtree
gadget2
bonsai
VSSE
SSE
BSE
SeBa
EVtwin
MESA
...
Stellar Evolution
fi
gadget2
athena
capreole
amrvac
ramses
FLASH
Gas Dynamics
mocassin
simplex
FLASH
Radiative Transport


Gravity
ph4
multiples
Stellar Evolution
SeBa
Mesa
Gas MHD
FLASH
sinks (Fedderath)
+ extra modules
Radiation
FLASH/Fervent
[simplex?]
+ PE heating

FLASH

Fryxell et al. 2000

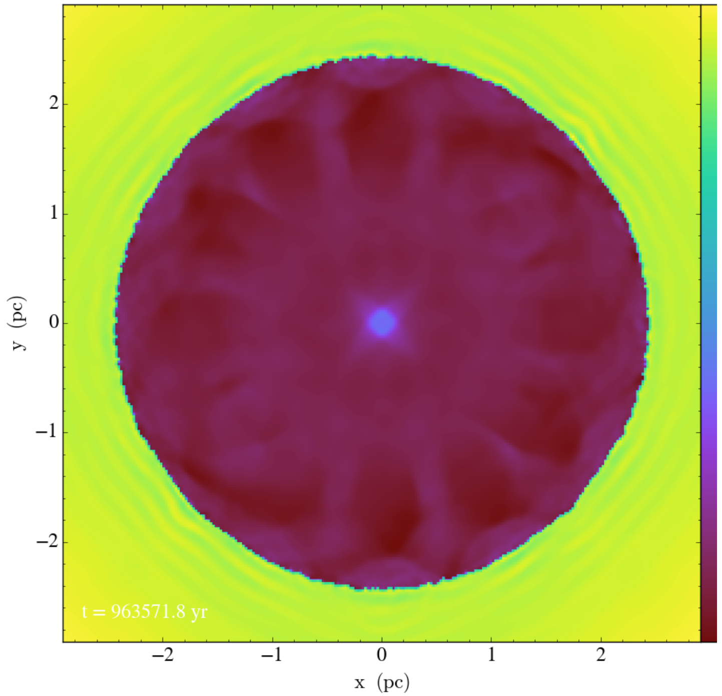
http://flash.uchicago.edu

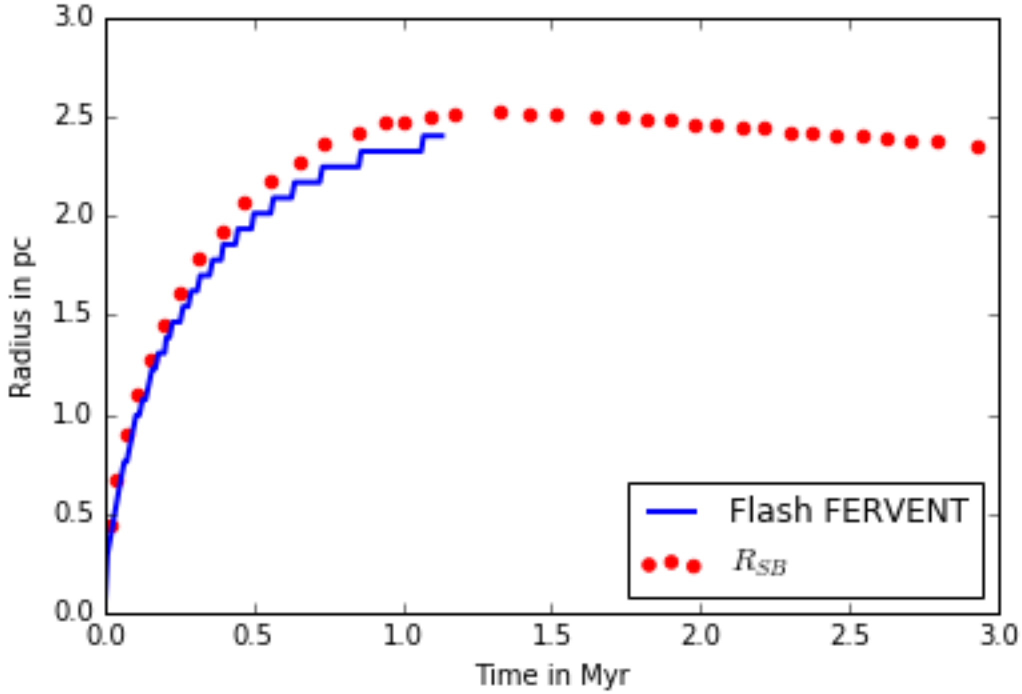


- PPM magnetohydrodynamics
- grid AMR (Paramesh/Chombo)
- various EoS, heating/cooling
- multiple (M)hydro solvers
- multiple gravity module
- particle treatment
- custom modules for sink particles, radiation, winds, explosions, etc.

Radiative Feedback

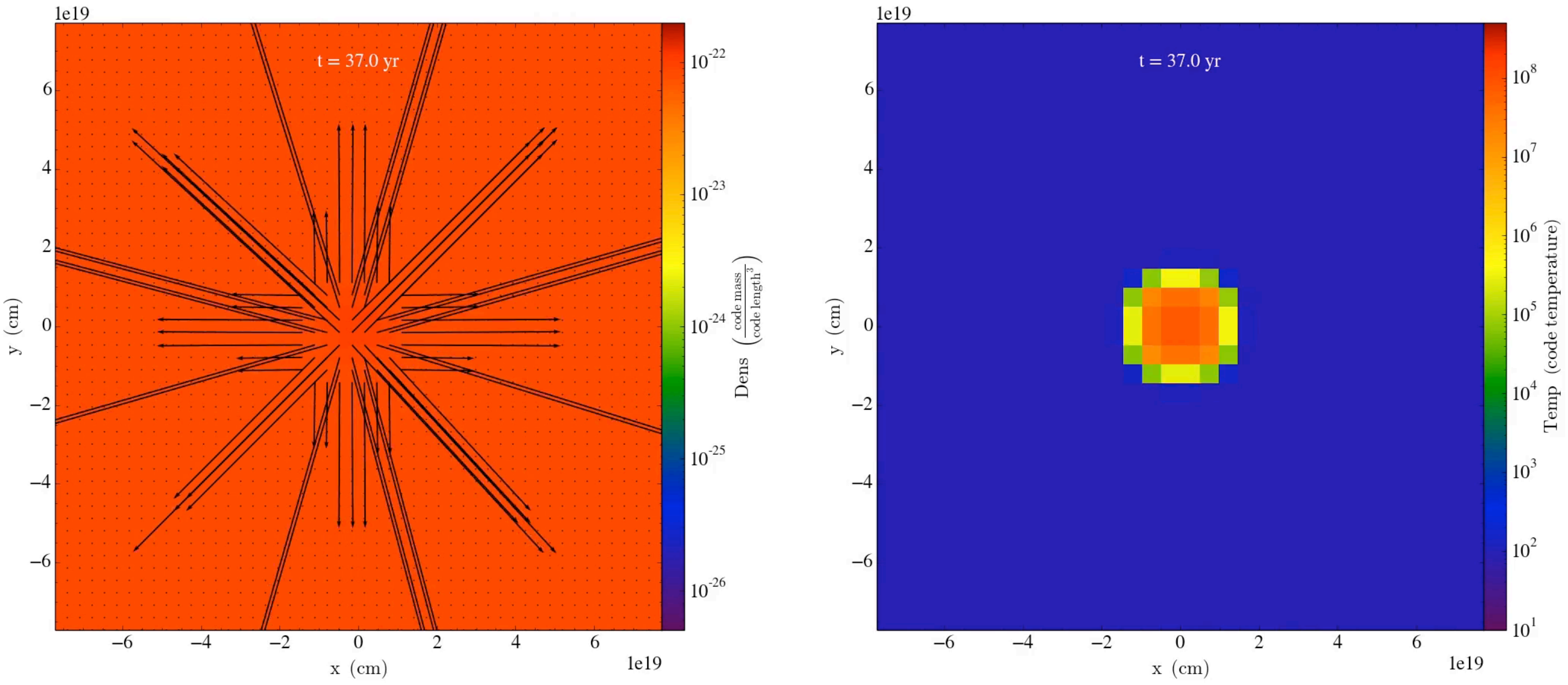
- Fervent module in FLASH (Baczynski et al. 2005)
  - RT code
  - some chemistry
  - ionizing feedback and non-equilibrium dynamics
- StarBench simulation (Bisbas et al. 2015):

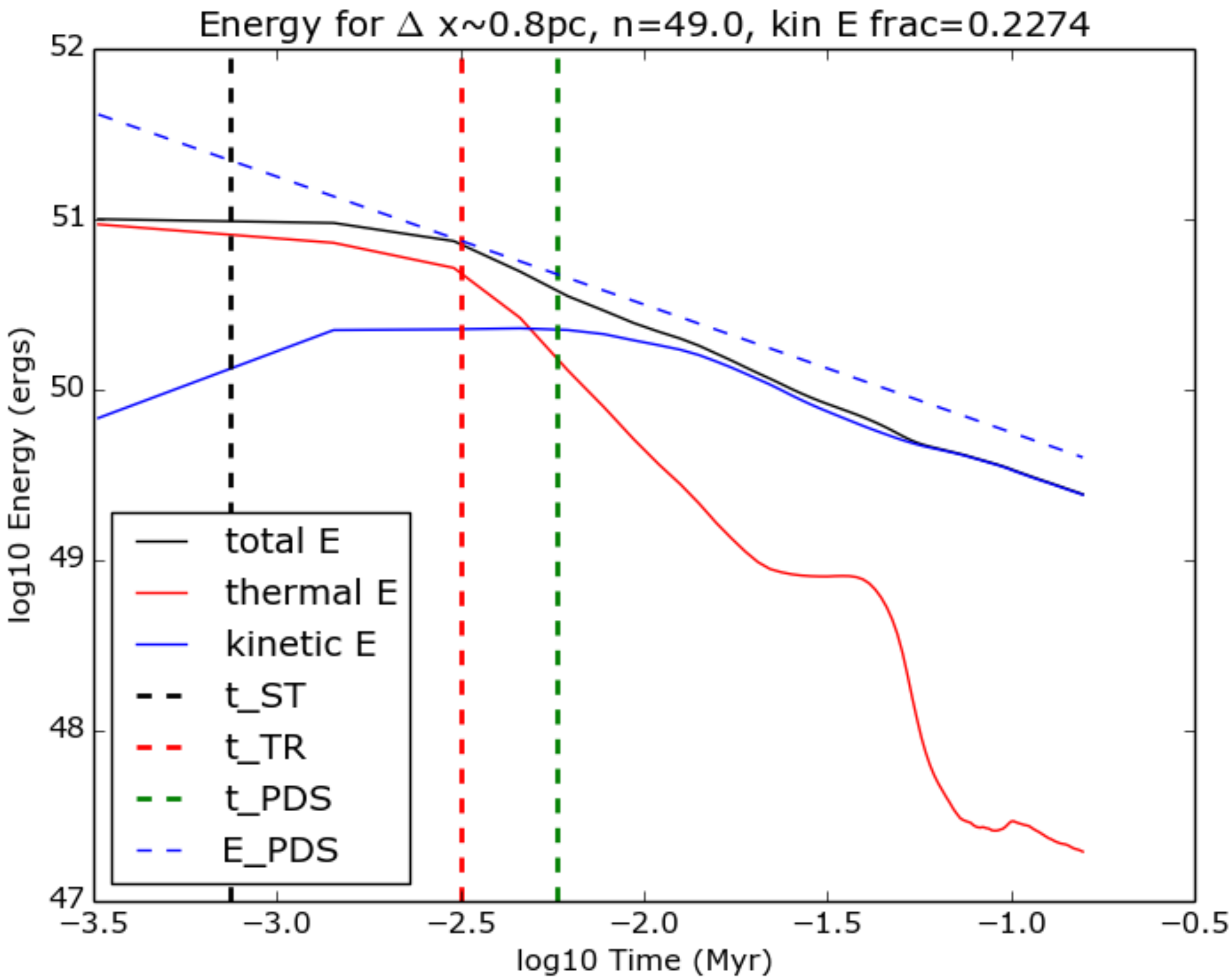




Supernovae

- module written by J. Wall
- implementation follows Simpson et al (2015)
- mix of kinetic/thermal energy properly tuned to grid scale

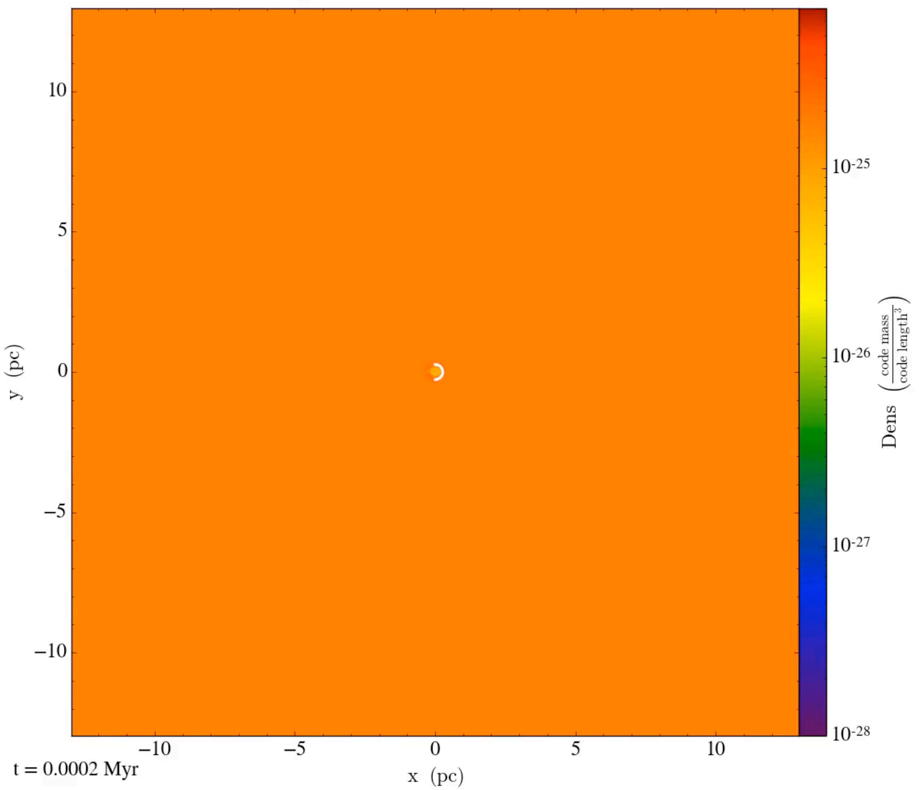


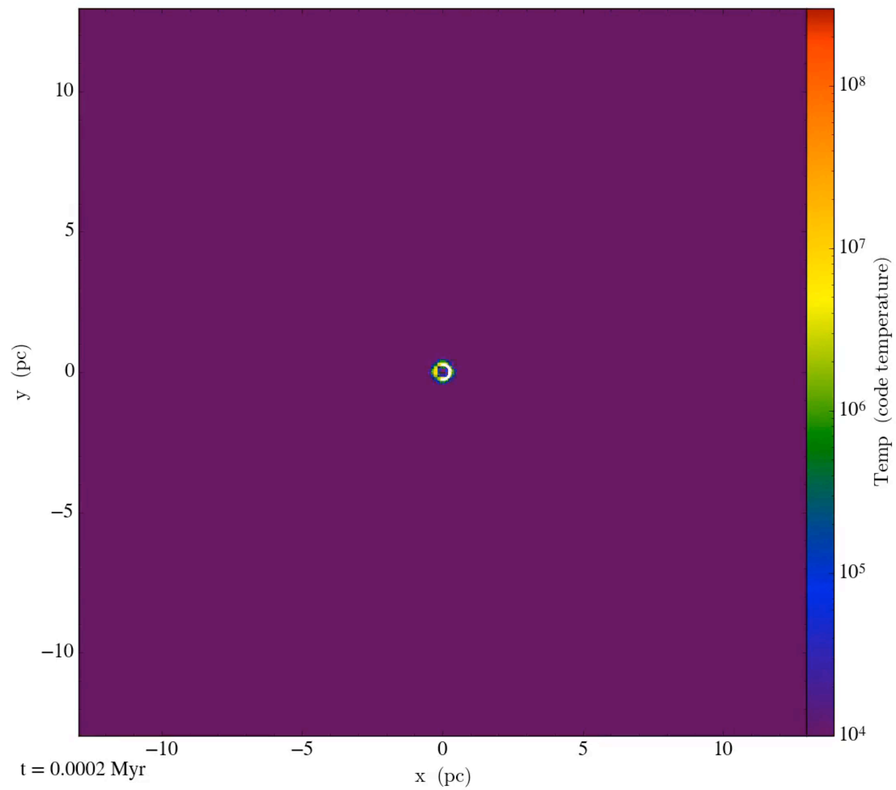


Energy for Δ x~0.8pc, n=49.0, kin E frac=0.2274
52
51
50
49
48
47
log10 Energy (ergs)
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
log10 Time (Myr)
total E
thermal E
kinetic E
t_ST
t_TR
t_PDS
E_PDS

Mechanical Feedback

- winds module written by J. Wall, A. Pelligrino
- wind description similar to SN formulation, conserves momentum, energy

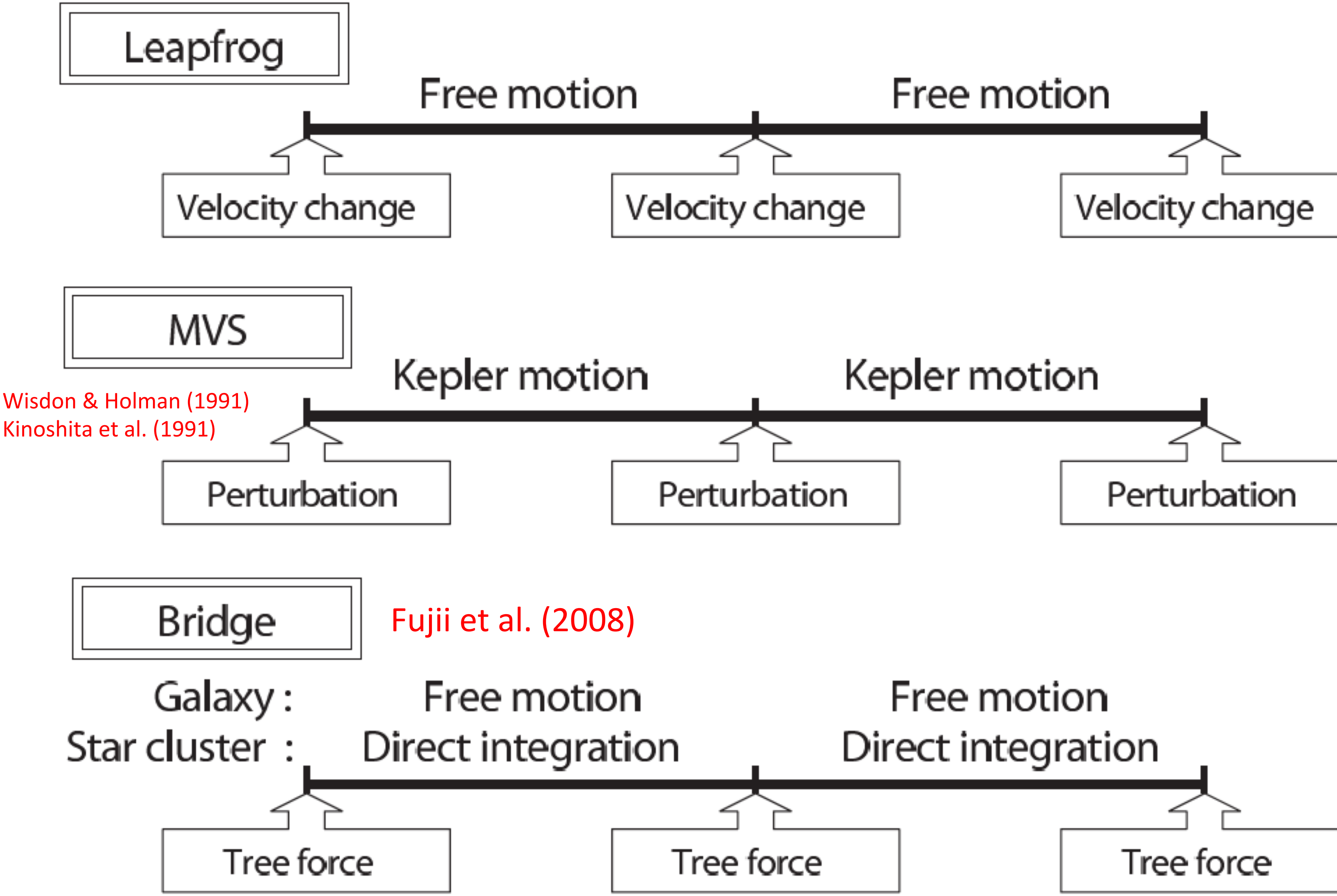


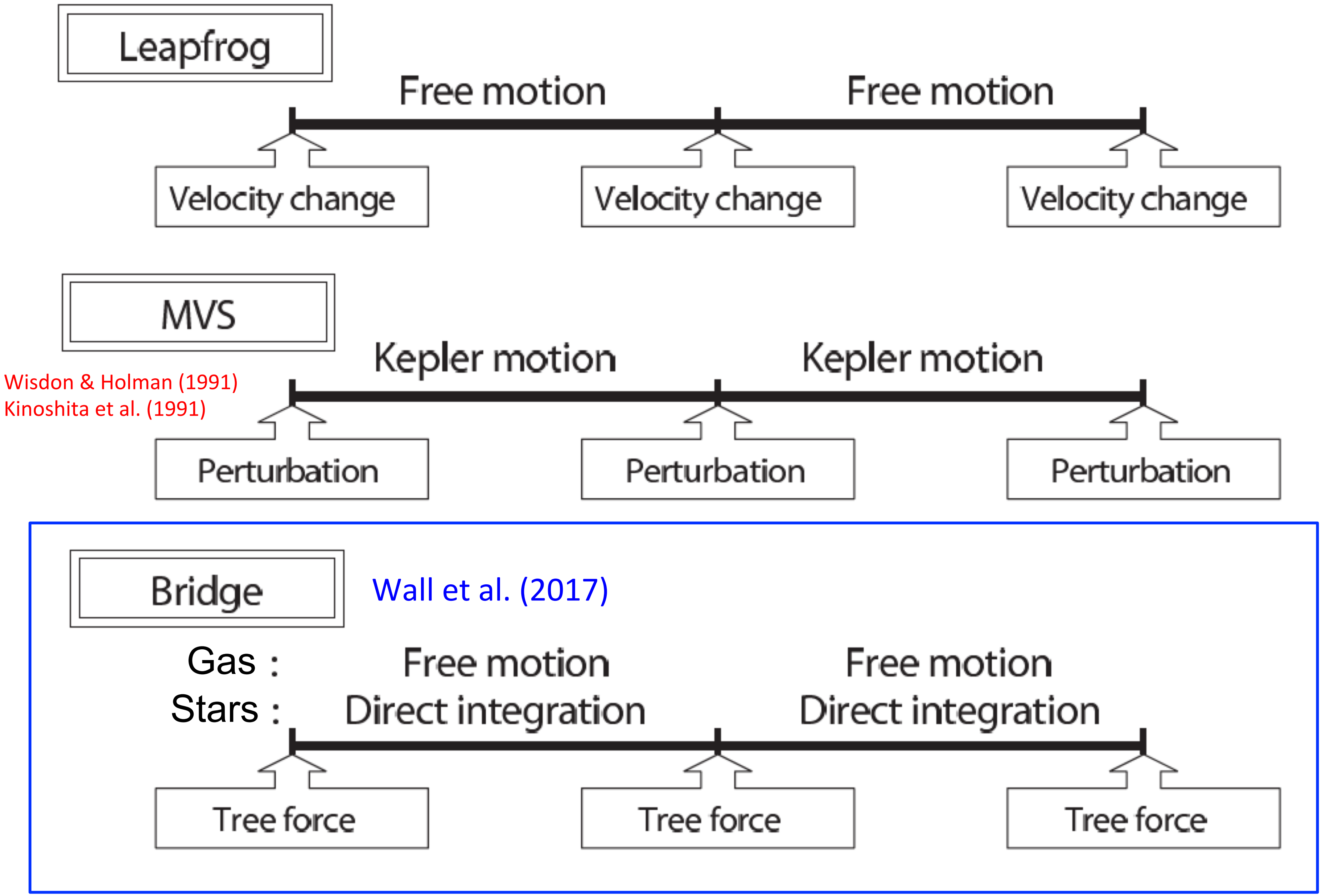


Code Coupling — Bridge

Fujii et al. (2008)

- small-scale with large-scale
- short time scale with long time scale
- gravity with gravity
- gravity with gas dynamics
- gas dynamics with radiative transfer
- anything with external (tidal) fields


Leapfrog
Free motion
Free motion
Velocity change
Velocity change
Velocity change
MVS
Wisdon & Holman (1991)
Kinoshita et al. (1991)
Kepler motion
Kepler motion
Perturbation
Perturbation
Perturbation
Bridge
Fujii et al. (2008)
Galaxy :
Star cluster :
Free motion
Direct integration
Free motion
Direct integration
Tree force
Tree force
Tree force


Leapfrog
Free motion
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Wisdon & Holman (1991)
Kinoshita et al. (1991)
Kepler motion
Kepler motion
Perturbation
Perturbation
Perturbation
Bridge
Wall et al. (2017)
Gas :
Stars :
Free motion
Direct integration
Free motion
Direct integration
Tree force
Tree force
Tree force

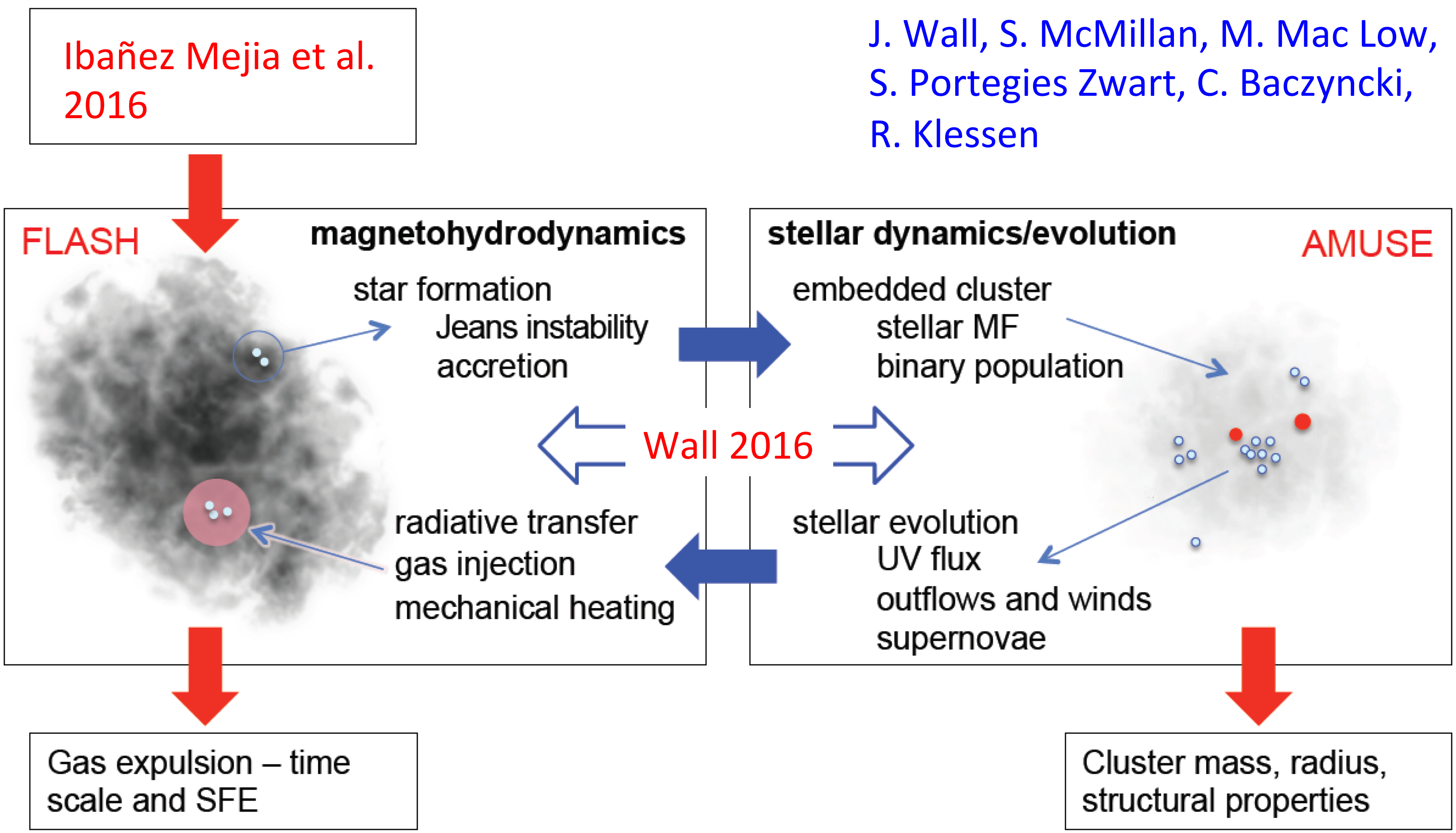
What We'd Like

- don't have dynamic range to span <10 AU to >100 pc scales
  - focus on ~100 AU to ~10 pc (factor of $>10^4$)
- may have to cut some corners on small scales
  - e.g. star formation
- realistic BCs from Ibanez-Mejia et al. (2017)
  - "real" galaxy-scale simulations
- target cluster mass range $10^3 - 10^7\ M_\odot$
- deliverables
  - gas expulsion time scale and survival probability of LMCs
  - SFE, etc.
  - net UV emission
  - dependence on mass
  - multiple populations?

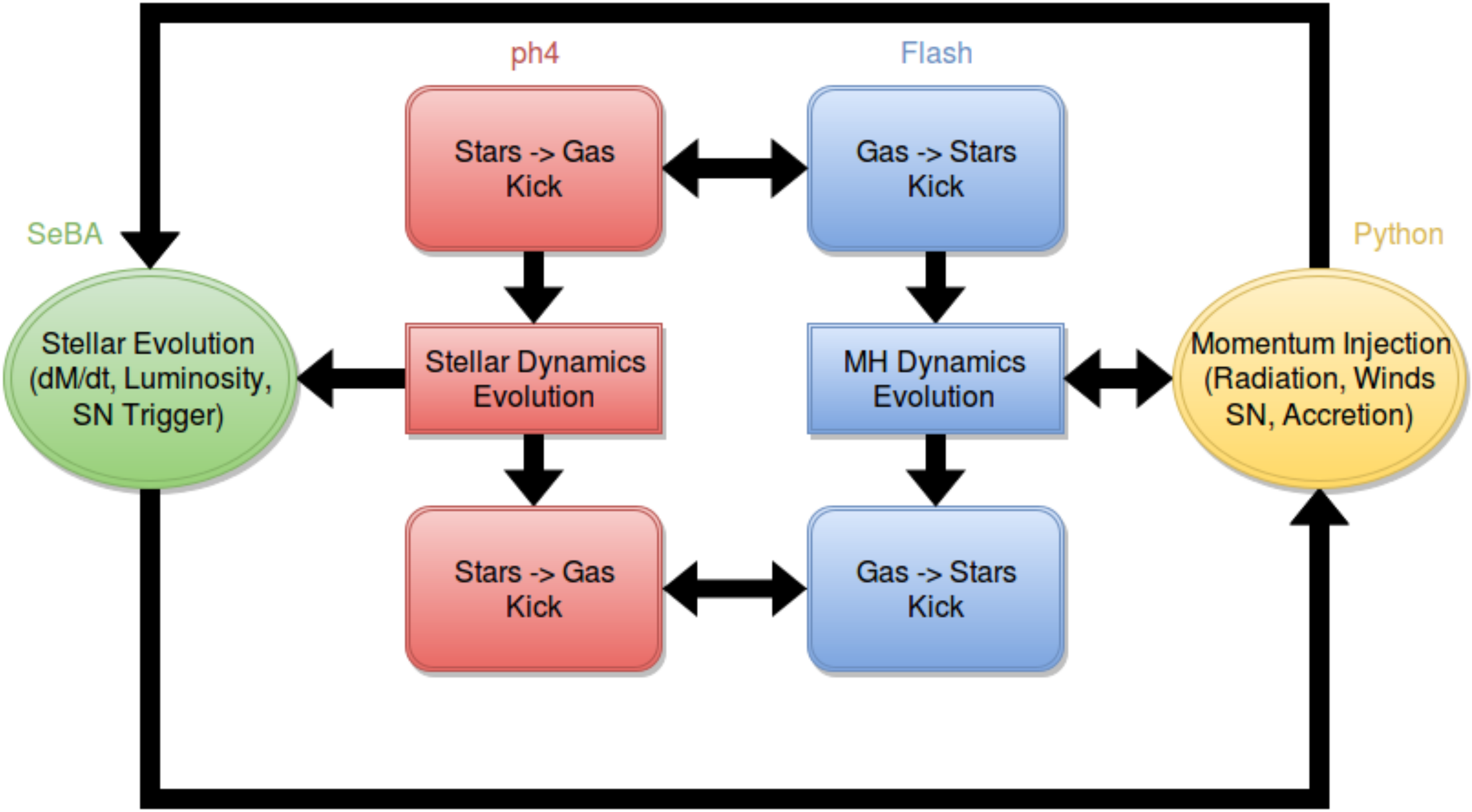
AMUSE-FLASH Coupling

- the new kitchen sink – Wall et al. in prep

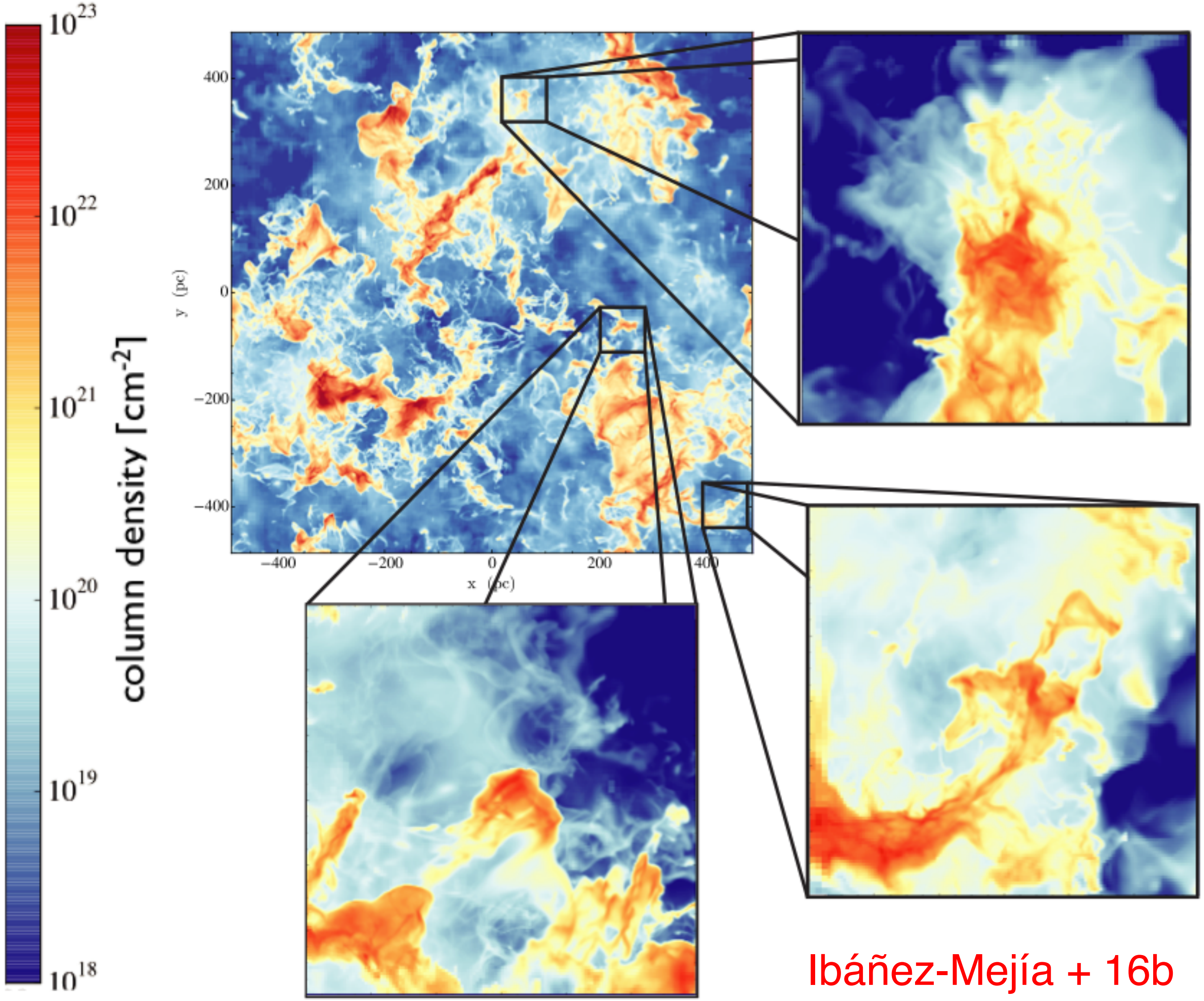
J. Wall, S. McMillan, M. Mac Low, S. Portegies Zwart, C. Baczyncki, R. Klessen



AMUSE-FLASH Coupling

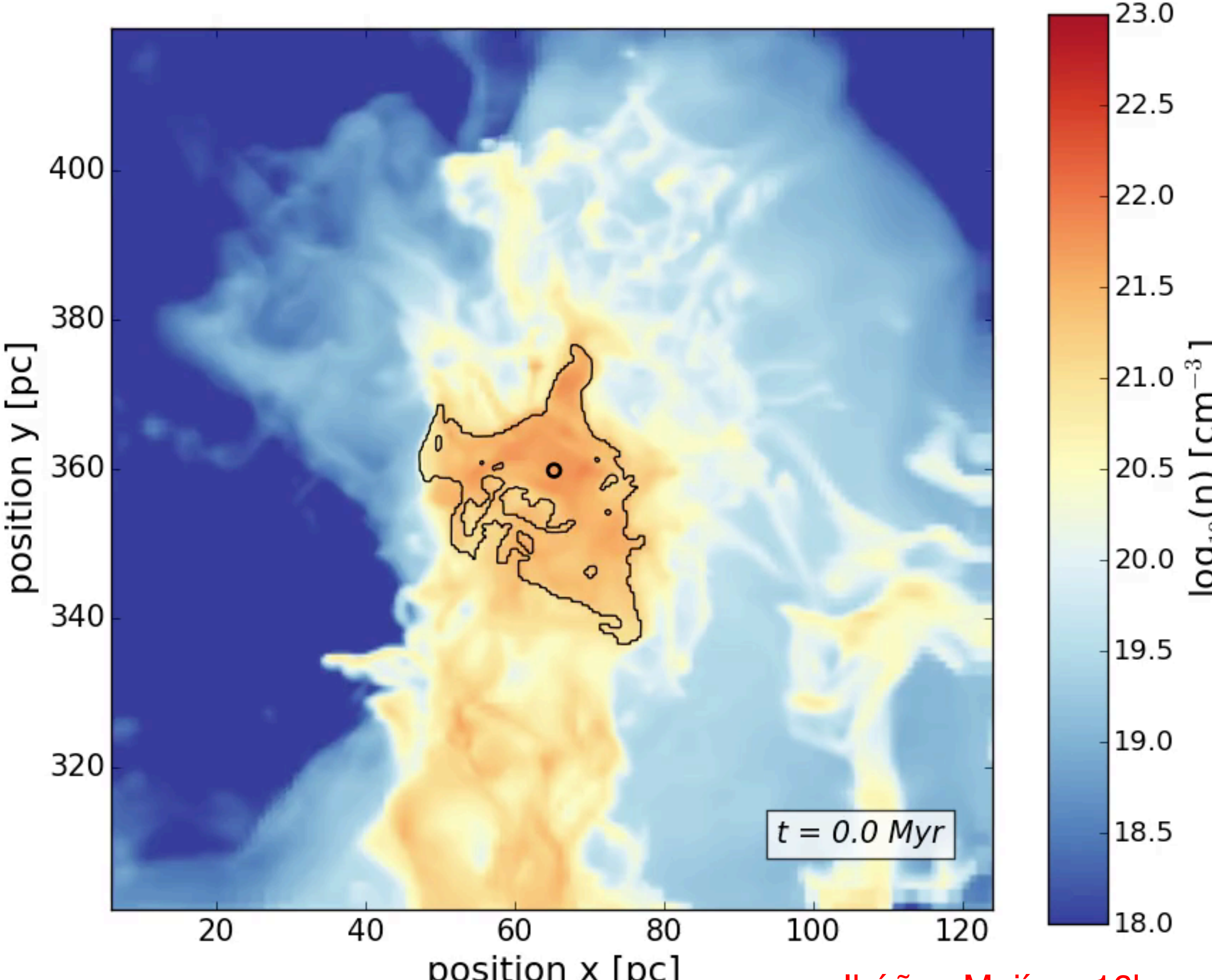


Simulating Individual Clouds



Ibáñez-Mejía + 16b

Δx = 0.12 pc

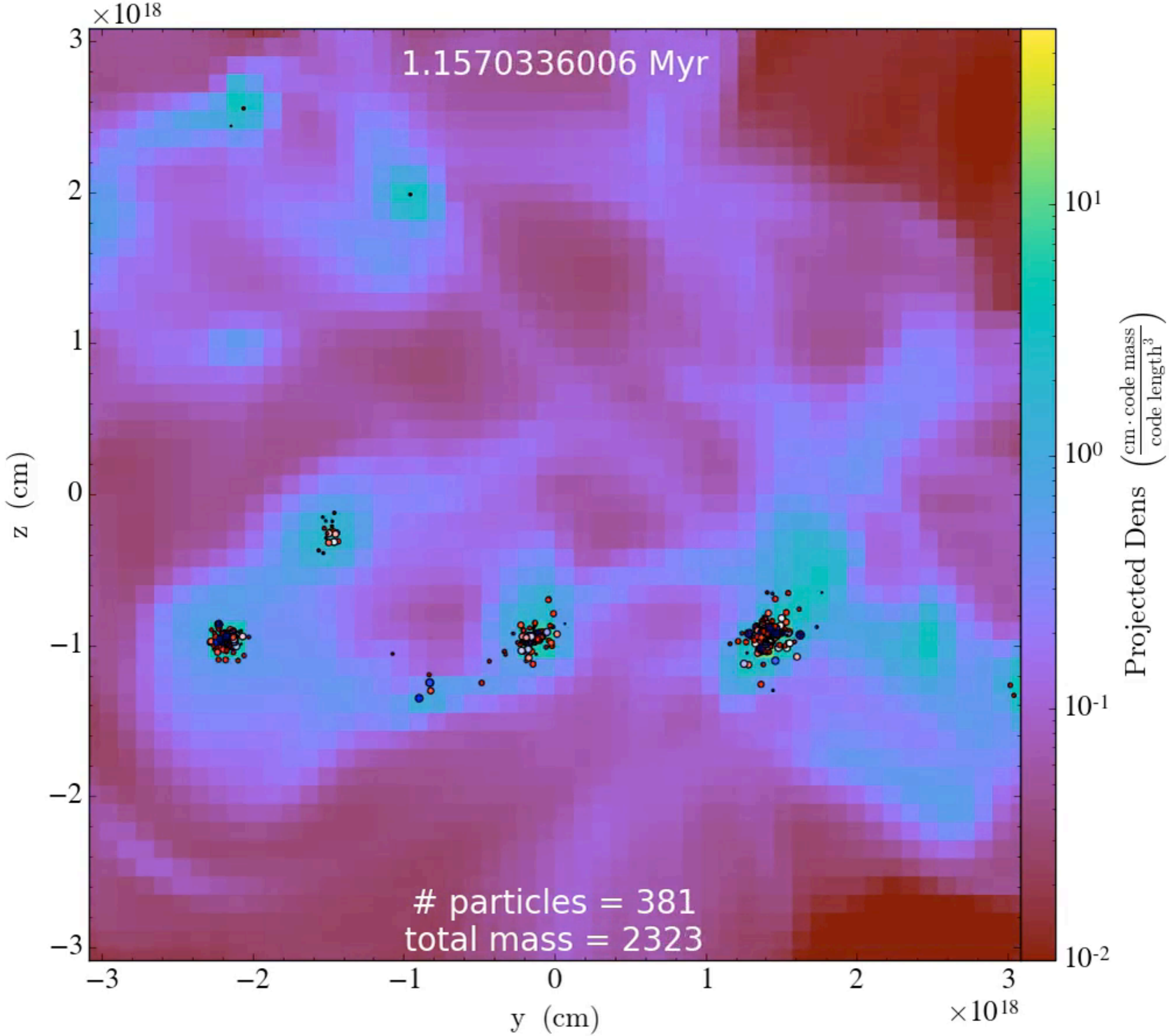


Ibáñez-Mejía + 16b

Making Stars

- “traditional” approach – sinks and accretion
- can do this for $10^3\ M_\odot$...
- ...but it may not (won't?) scale to $10^{6\text{-}7}\ M_\odot$
- interested in massive stars only
- low-mass stars obviously important for other reasons
- but just need the right total stellar mass for the dynamics for large-scale energetics and gas expulsion

- alternative
  - add stars to a cell with probability $\rho/t_{ff} \sim \rho^{3/2}$ (Elmegreen 1997; Goldbaum et al 2015)
  - create star of mass M only if mass $>2M$ in cell



1.1570336006 Myr
particles = 381
total mass = 2323
z (cm)
y (cm)
×10^18
×10^18
Projected Dens (cm·code mass / code length^3)
10^1
10^0
10^-1
10^-2

Summary

- cluster formation is a multiphysics, multiscale problem
- we already know how to address it (at least in principle)
- AMUSE is designed to facilitate code combination to attack complex problems
- combines modules for dynamics, stellar evolution, MHD, and radiative transfer (FLASH)
- tested new modules for (photoelectric heating), supernovae, and winds
- still experimenting with star formation algorithms
- first simulations for $10^3 – 10^4$ $M_\odot$ systems
- methods paper and much larger simulations soon