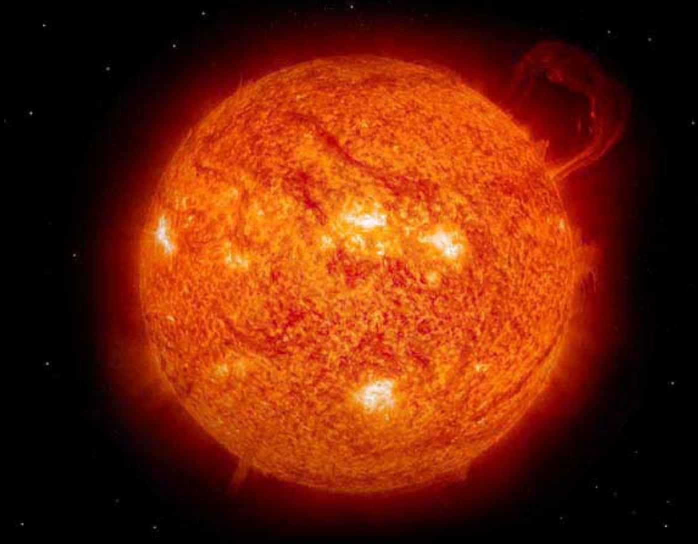
Greg Bryan - Columbia University / Flatiron Institute

THE FIRST STARS IN THE UNIVERSE

The sun as a star

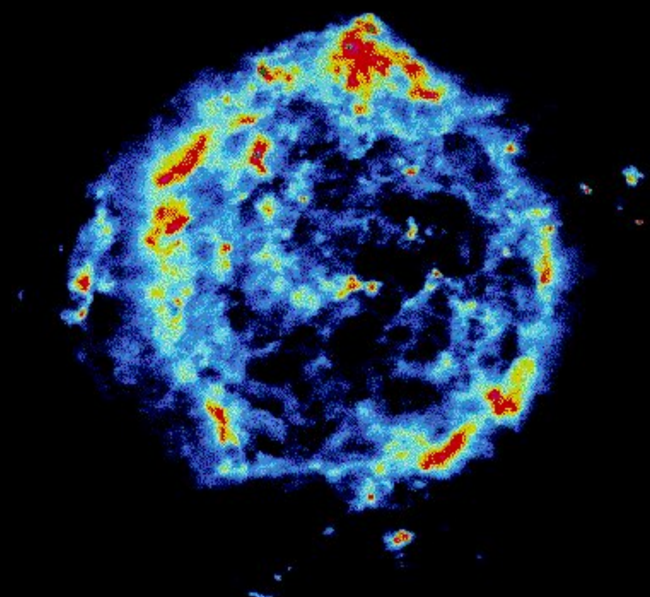


The sun produces energy by fusing

4 H ➡ 4 He

By the end of its life it will have
Converted 10% of its mass into He

Stars more massive then the sun will burn He into C, and even more massive stars will explode as supernovae, producing C, N, O, Fe… ("heavy elements")



The sun was born with about 2% of its mass in the form of "heavy elements" (the rest is He and H)

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The sun is a baby boomer

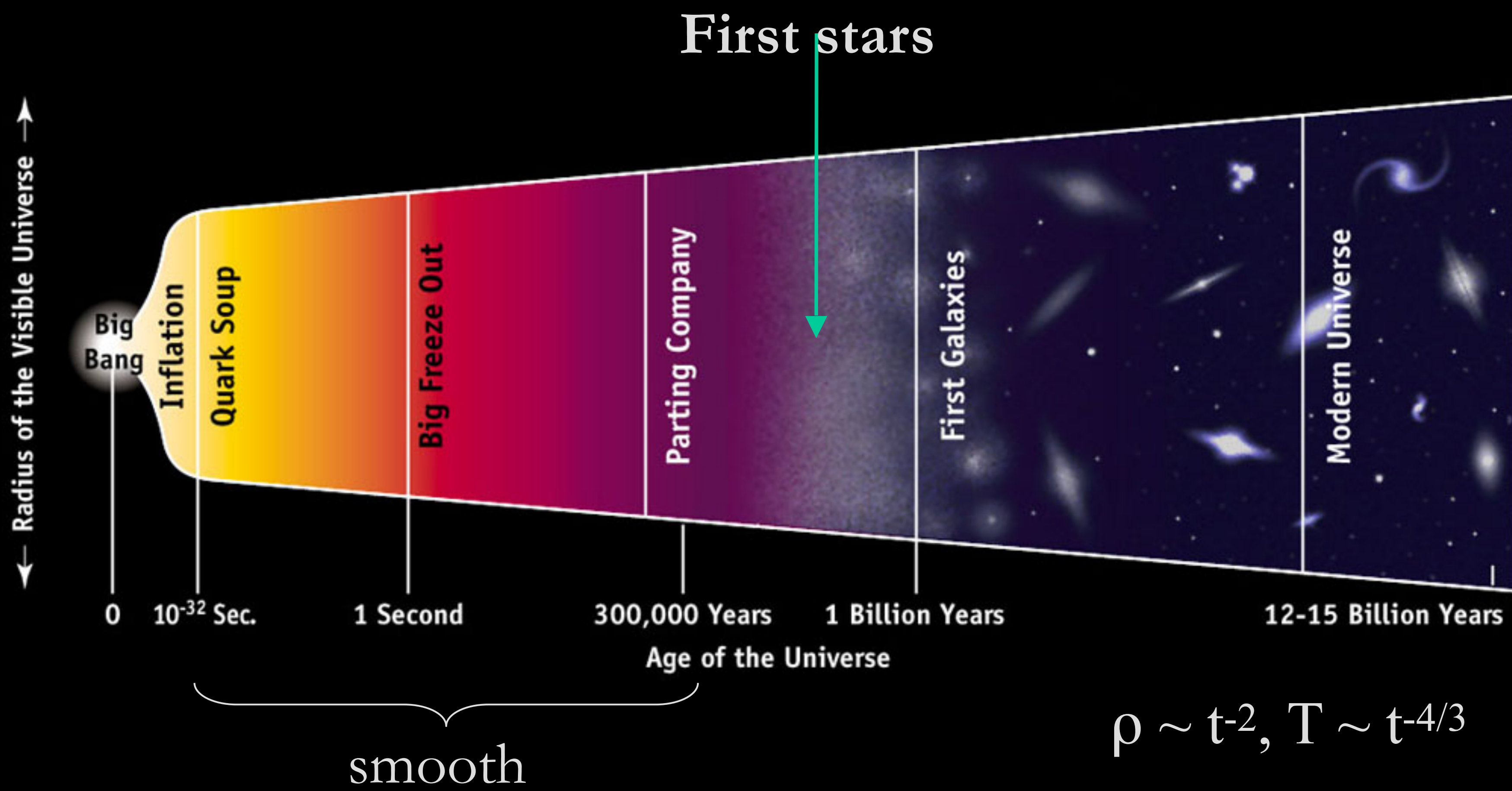
A galaxy slowly transforms its gas into stars. Winds from stars and supernovae pollute the galaxy's own gas supply.

Older stars have fewer "heavy elements". The oldest are composed of just Hydrogen (75%) and Helium (25%)
(+ traces of other elements).

Cosmic Evolution

- Older stars contain fewer "heavy elements"
- Oldest stars are nearly "pure"
  - Primordial gas: 76% H and 24% He (and nothing else)
- What about the very first stars?
  - No completely primordial star ever observed
  - Where is the first generation of stars?
    - What were they like?

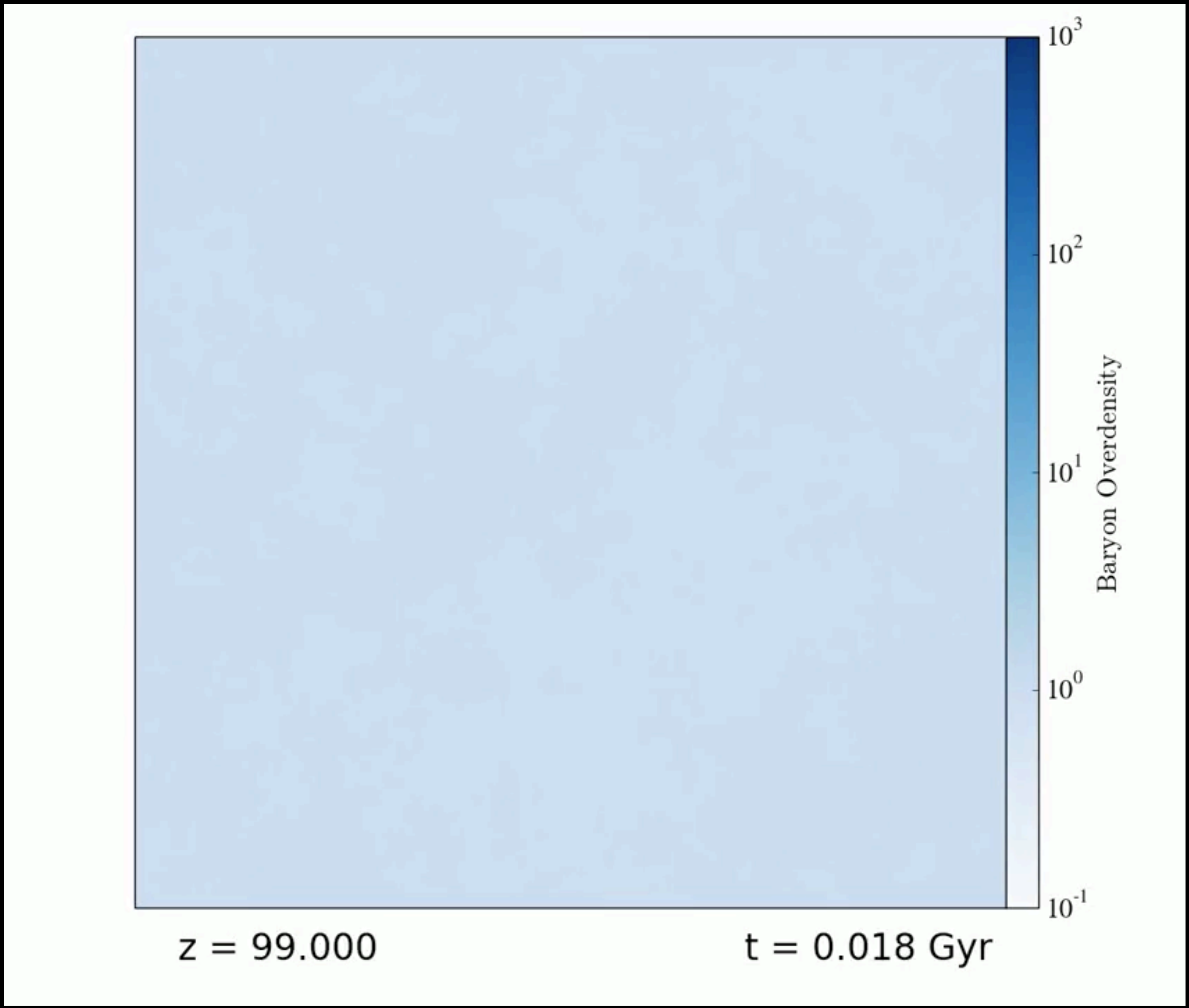
The Cosmological Context



$\rho \sim t^{-2}$, $T \sim t^{-4/3}$

- First stars form before the first galaxies
- How massive? Observable? Where are they today?

Gravity brings everything together



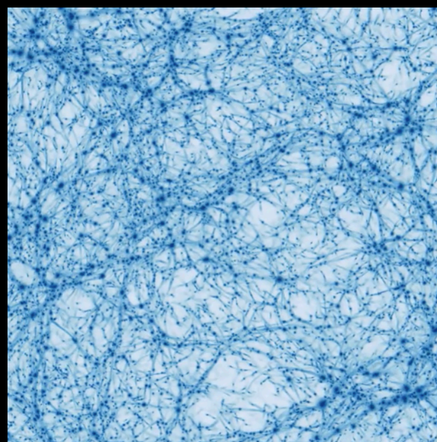
Simulating the first stars

- Partial Differential Equations
  - Fluid equations
  - Gravity
  - Very simple chemistry (H, He only!)
  - Radiative cooling
- Extreme Resolution required:
  - From cosmological scales down to a single star

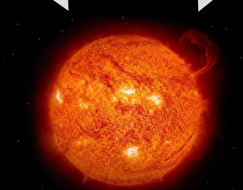
    $L/r_{sun} \sim 10^{21}$ m $/10^{9}$ m $\sim$ **10^{12} dynamic range!**

First stars: extreme resolution

The scale of a "fair sample" of Universe



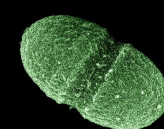
to



stellar radius

is equivalent in scale of the earth

to



bacterium

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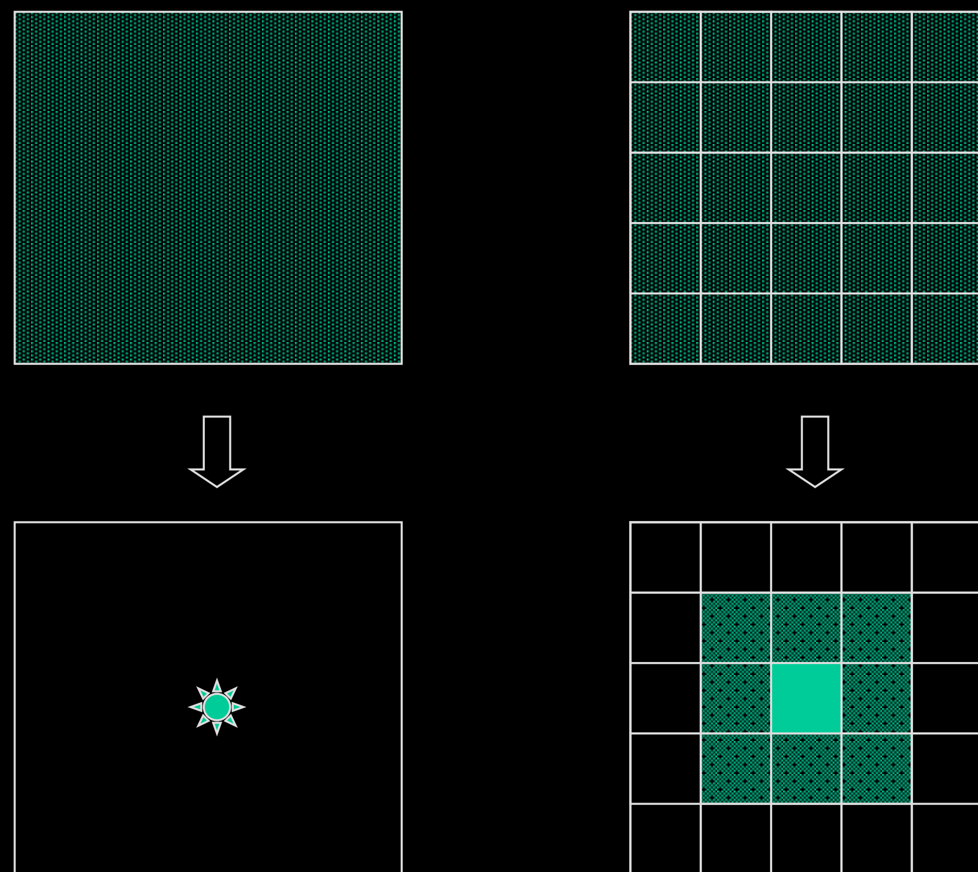
The problem with simulating gravitational collapse on a computer

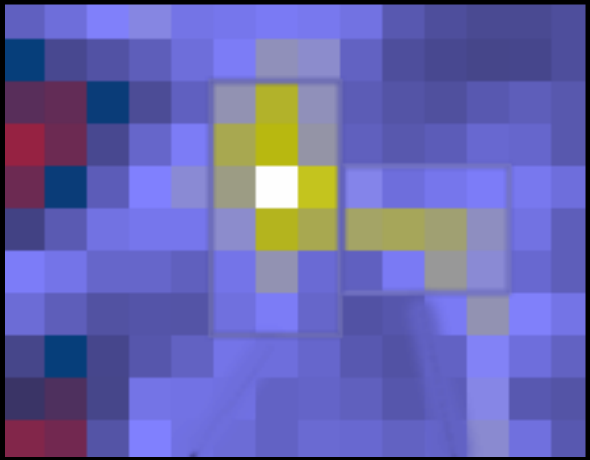
continuous discrete

Initial state nearly homogeneous

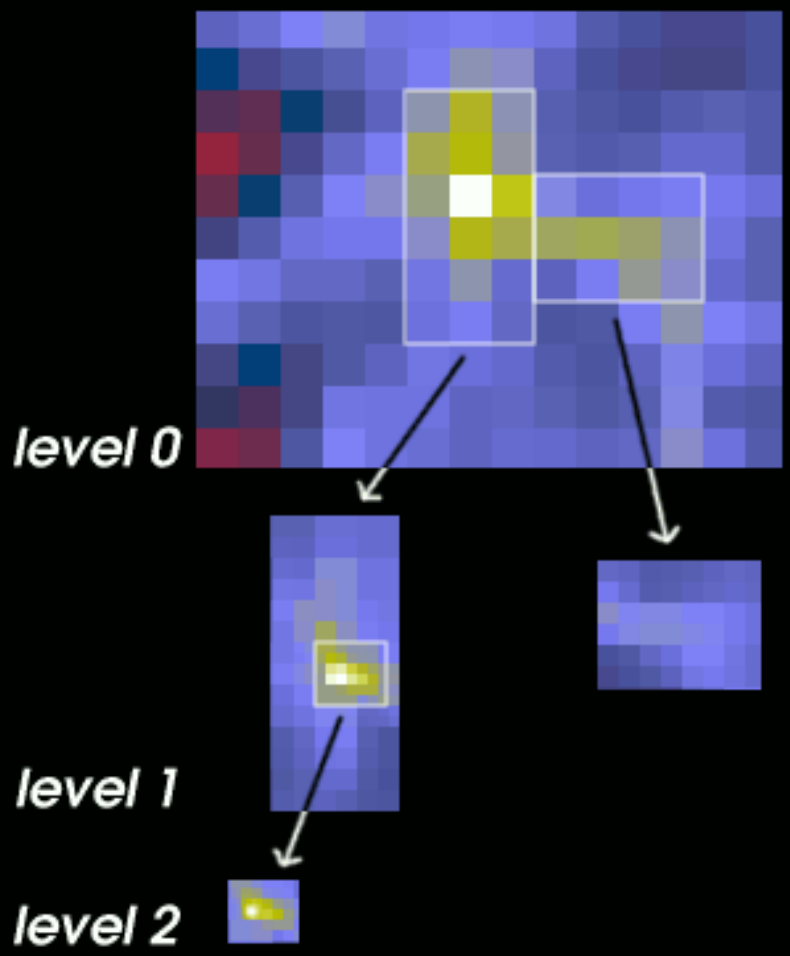
Highly concentrated final state



Adaptive mesh refinement



Adaptive mesh refinement



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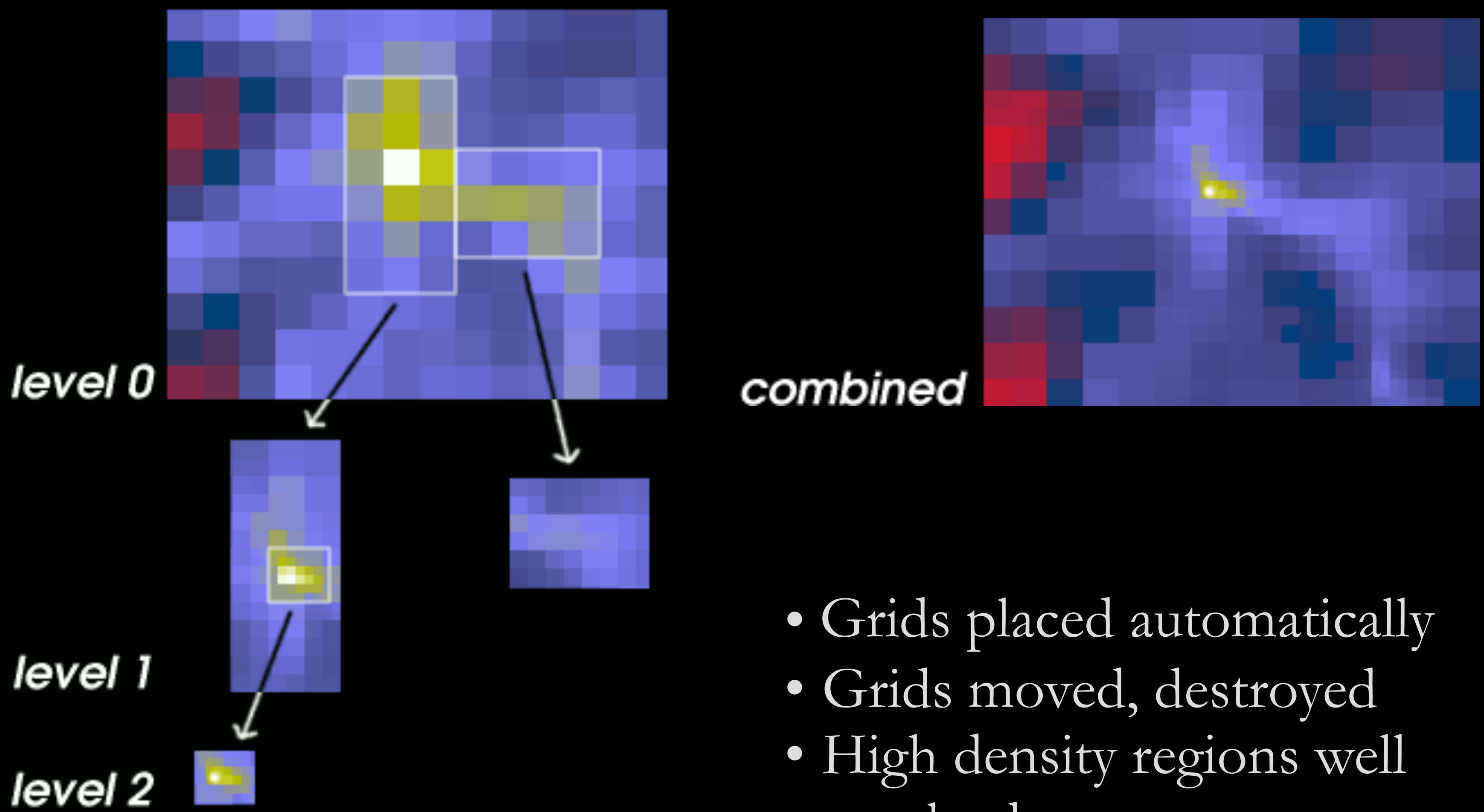
Adaptive mesh refinement



- Grids placed automatically
- Grids moved, destroyed
- High density regions well resolved
- Low density regions poorly resolved

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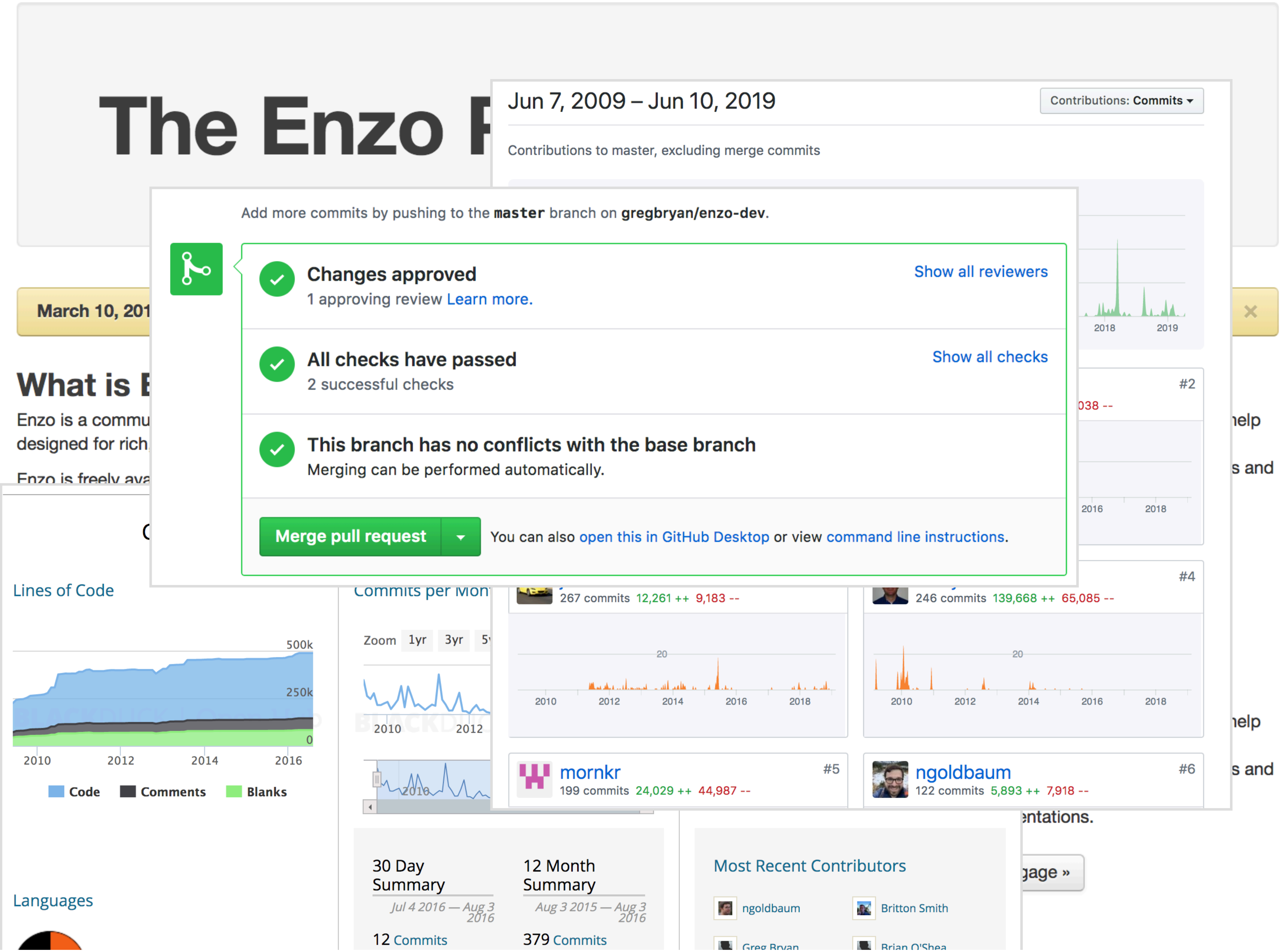
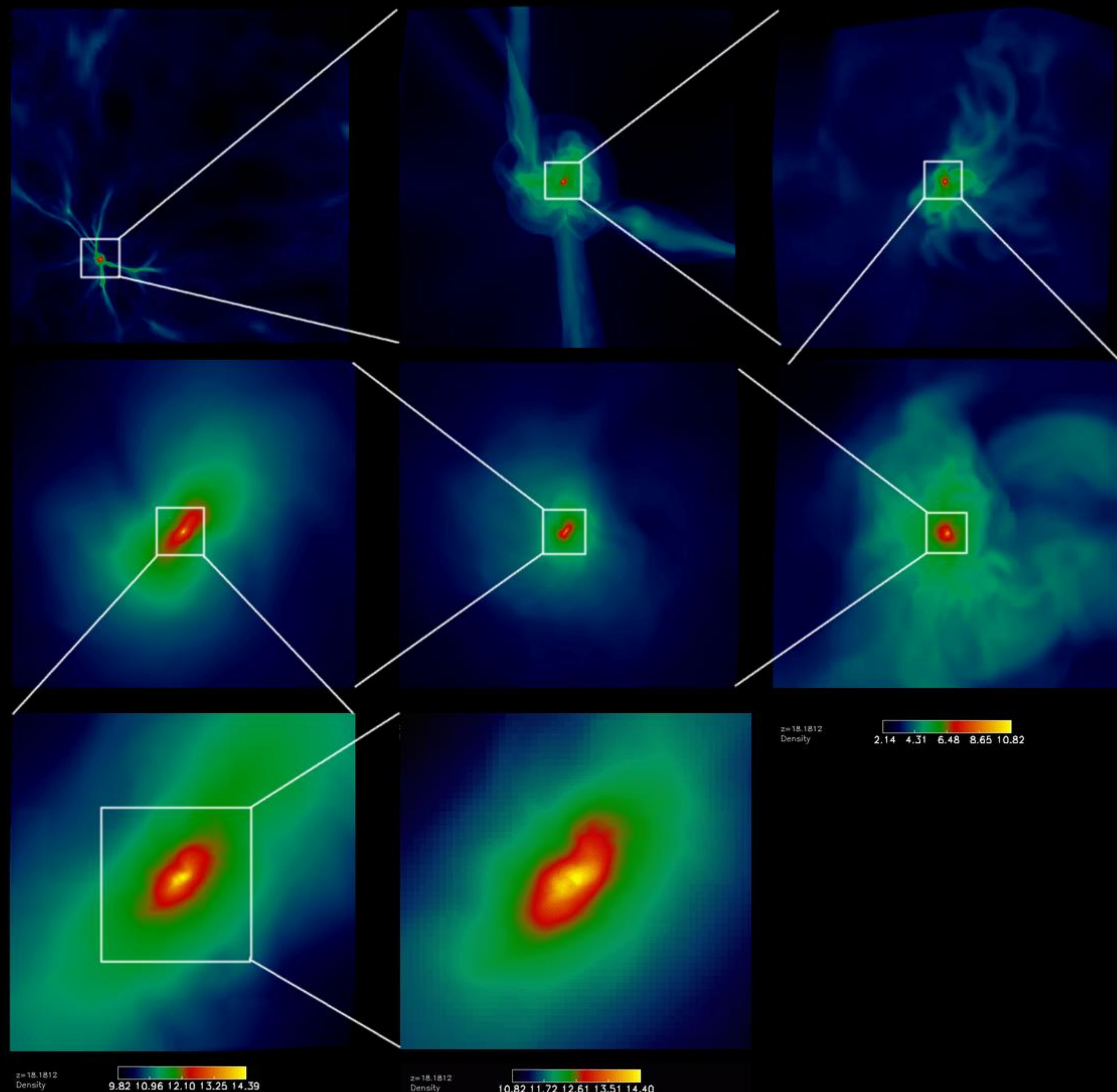

The Enzo
March 10, 201
What is E
Enzo is a commu
designed for rich
Enzo is freely ava
Jun 7, 2009 – Jun 10, 2019
Contributions: Commits
Contributions to master, excluding merge commits
Add more commits by pushing to the master branch on gregbryan/enzo-dev.
Changes approved
1 approving review Learn more.
Show all reviewers
All checks have passed
2 successful checks
Show all checks
This branch has no conflicts with the base branch
Merging can be performed automatically.
Merge pull request
You can also open this in GitHub Desktop or view command line instructions.
Lines of Code
Code
Comments
Blanks
Commits per Mon
Zoom 1yr 3yr
267 commits 12,261 ++ 9,183 --
246 commits 139,668 ++ 65,085 --
mornkr #5
199 commits 24,029 ++ 44,987 --
ngoldbaum #6
122 commits 5,893 ++ 7,918 --
30 Day Summary
Jul 4 2016 — Aug 3 2016
12 Commits
12 Month Summary
Aug 3 2015 — Aug 3 2016
379 Commits
Most Recent Contributors
ngoldbaum
Britton Smith
Greg Bryan
Brian O'Shea
Languages

Visualization: Kaehler (Discovery Channel)

Simulation: Abel/Bryan/Norman

Simulation results: 10^6 $M_\odot$ halo, one stellar core



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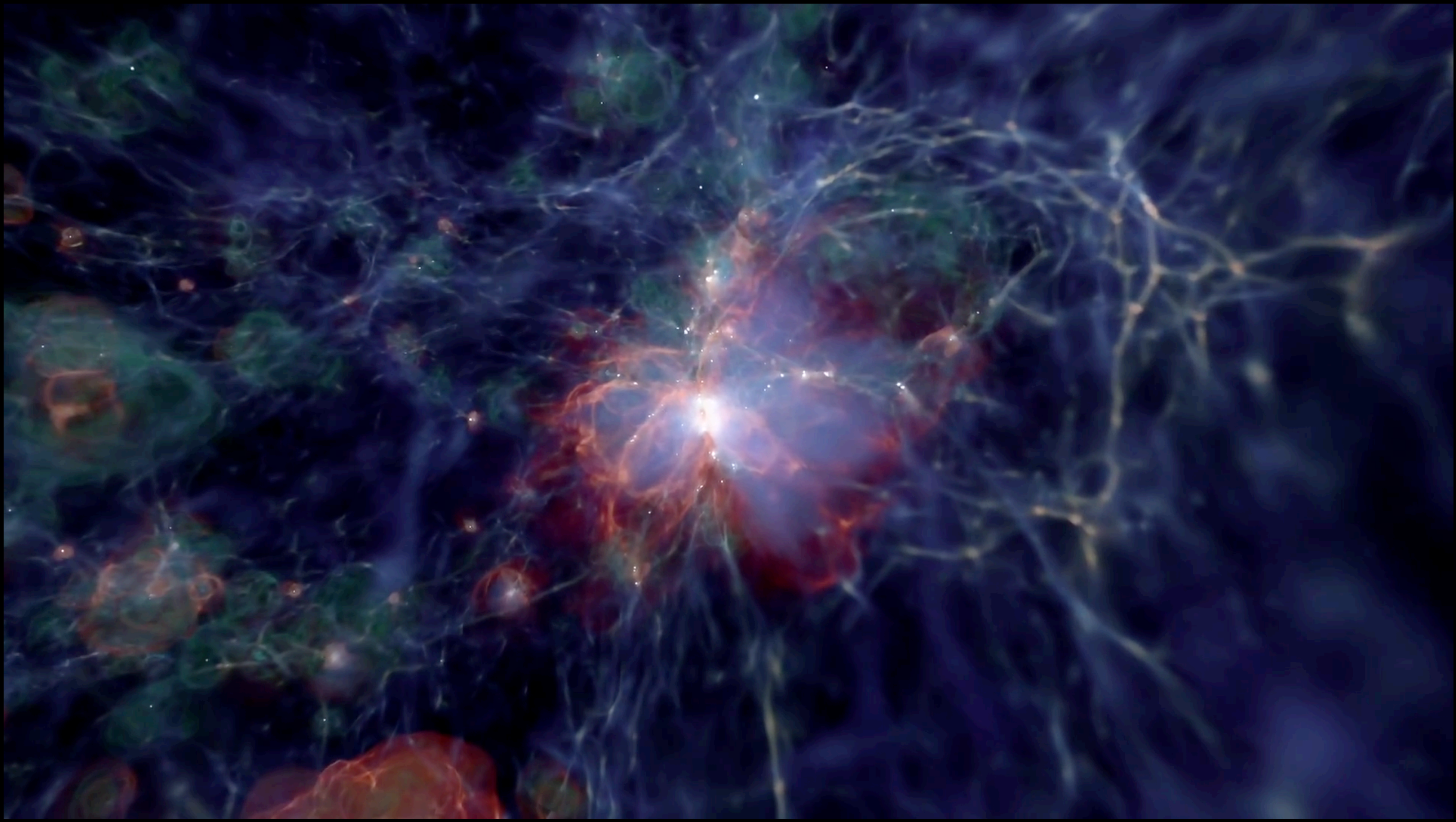
What do the first stars look like?

- Massive (~30-300 times mass of sun)
  - Large (~10 times radius of sun)
  - Hot (~20 times hotter than the sun)
  - Bright (~10^6 times brighter than the sun)
  - Short-lived (3 Myr vs. 10 Gyr for sun)
  - Likely fate: supernovae!
- Observed to date?
  - None seen so far
    - lowest stellar "pollution" ~ 10^{-4} of sun
  - Origin of first heavy elements

Next steps

- Challenges:
- Dive deeper into the first star
  - More physics in dense core
  - Evolve first star for longer
- Model the second star (and beyond)
  - Predict observational signatures
  - Model the reionization of the Universe

What about the second star?



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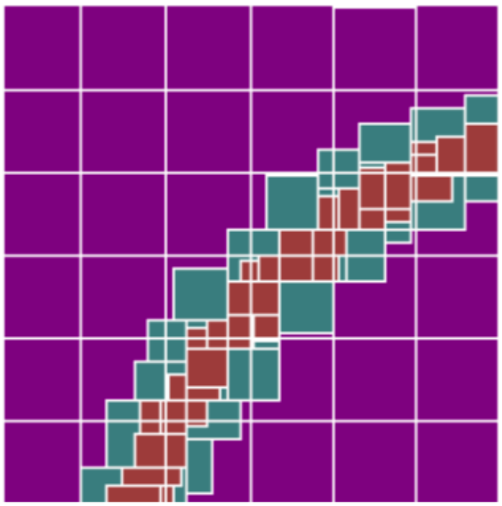
Limits of current code/technique

- Issues:
  - Performance scales poorly beyond 10^4 cores
  - Memory usage not optimal
  - Code infrastructure aging
    - harder to add/maintain features

- Solution: Cello/Enzo-E
  - completely new implementation

New design/implementation: Cello/Enzo-E

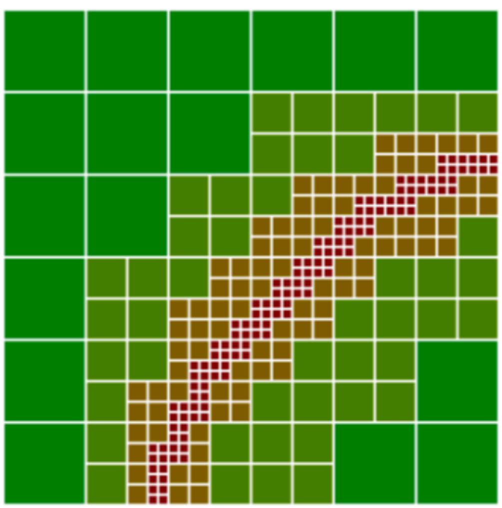


Enzo

Structured AMR

Variable shaped patches

Neighbors & parent communication



Enzo-E/Cello

Array of octrees

Fixed shaped blocks

neighbors only communication

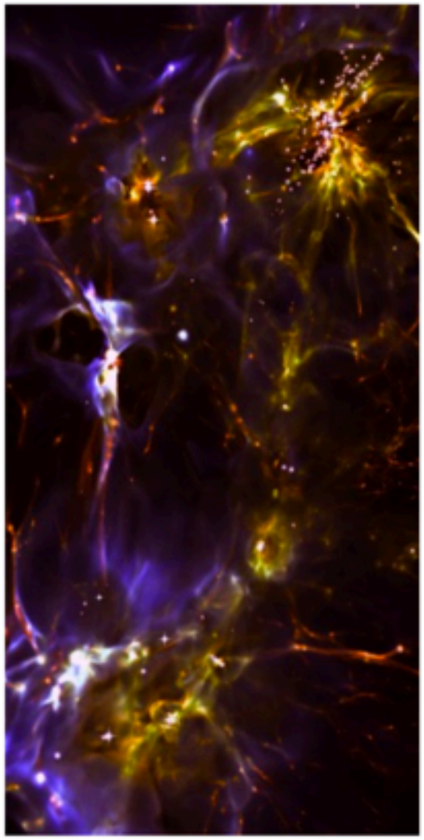
Cello/Enzo-E

How does Enzo-E address Enzo's limitations?

Enzo-E/Cello approach

- Memory usage
  - AMR structure is fully distributed
  - uniform blocks reduce fragmentation
  - ghost zones allocated when needed*
- Mesh quality
  - 2-to-1 refinement constraint maintained
- Parallel task definition
  - uniform field array sizes in blocks
  - sizes determined by user
- Parallel task scheduling
  - asynchronous data-driven task scheduling
  - block-local time stepping*
- Data locality
  - only nearest-neighbor communication

Enzo



[John Wise]

Summary

- First stars from gravitational collapse
  - primordial gas (H, He only)
  - massive (~30 - 300 times mass of sun)
  - explode as Supernovae, produce C, N, O…
- Open source high-performance code
  - Enzo - well-tested, many users
  - Enzo-E - next generation

Thanks to: National Science Foundation, NASA
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