Star formation in a turbulent cloud core with self-gravitational MHD adaptive mesh refinement

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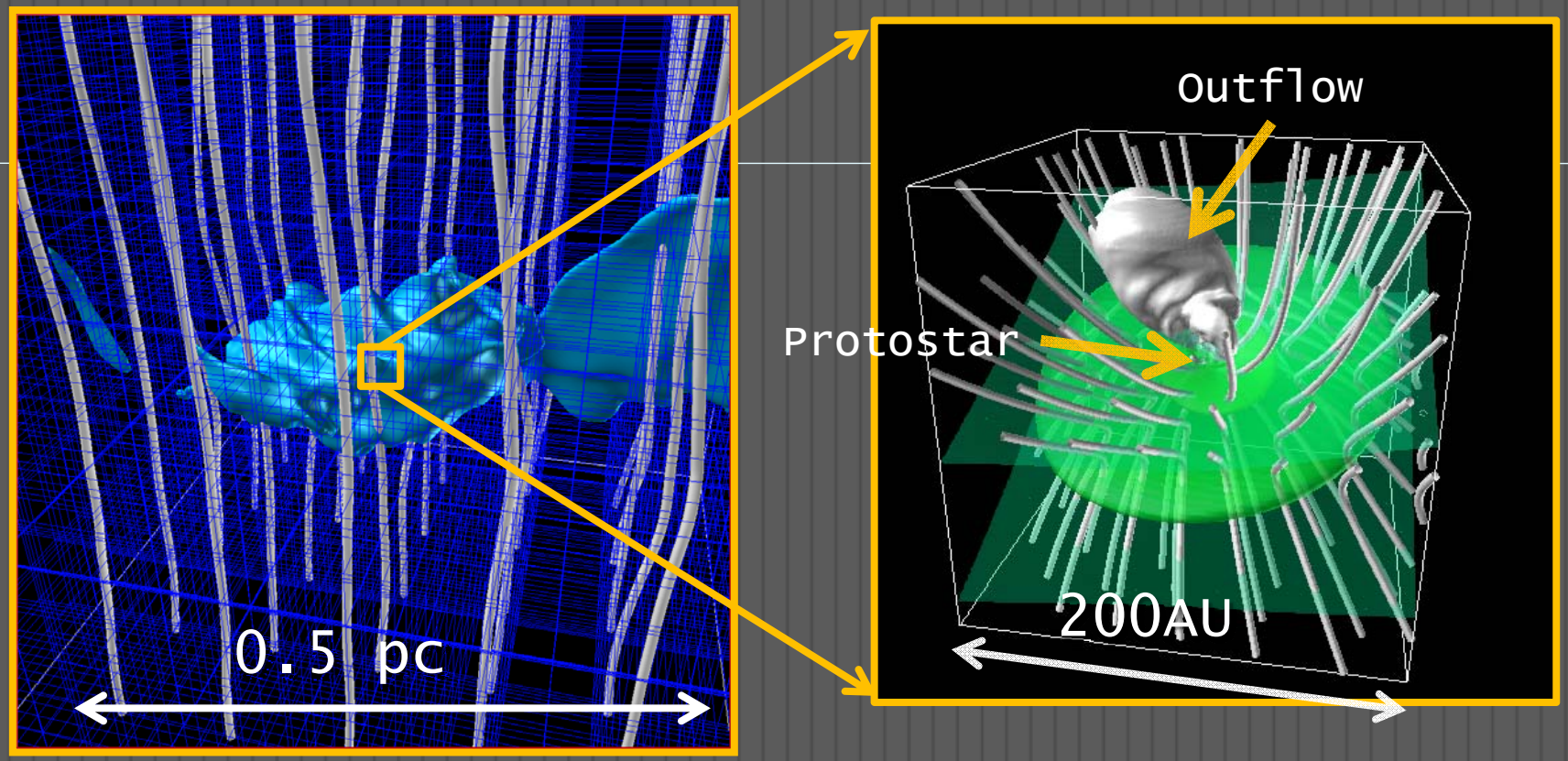
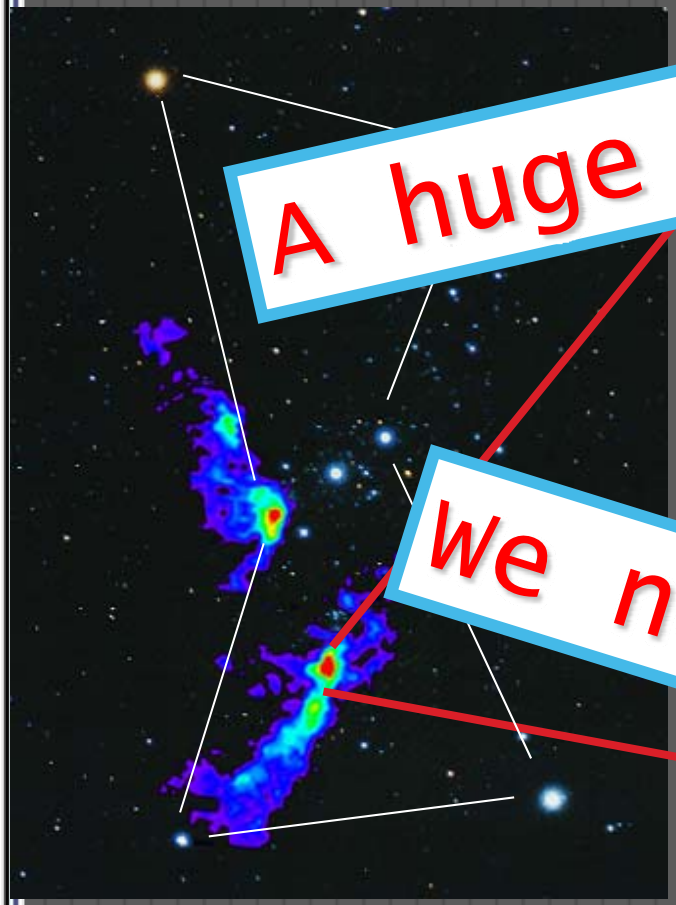


Outline

- Introduction
- Our AMR code: SFUMATO
- Star formation in magnetized turbulent cloud cores
- Summary

Introduction: Cloud to star



Orion molecular cloud
(optical+radio)
Tatematsu et al. (1993)

Onishi et al. (1999)

...ostar and outflow
(radio)

...0 AU
core)

Gueth & Guilloteau (1999)

A huge dynamic range

−5

We need adaptive mesh

1AU/0.1pc = 5×10

Development of our adaptive mesh codes

SFUMATO (AMR)
MHD, Seflgravity
(Matsumoto 2007)

Now developing
sink particle, etc.
(Matsumoto)

AMR

Nested Grid

Some NG codes were ported to AMR.

Resistivity (Ohmic dissipation)
(Machida, Inutsuka, & Matsumoto 2006)

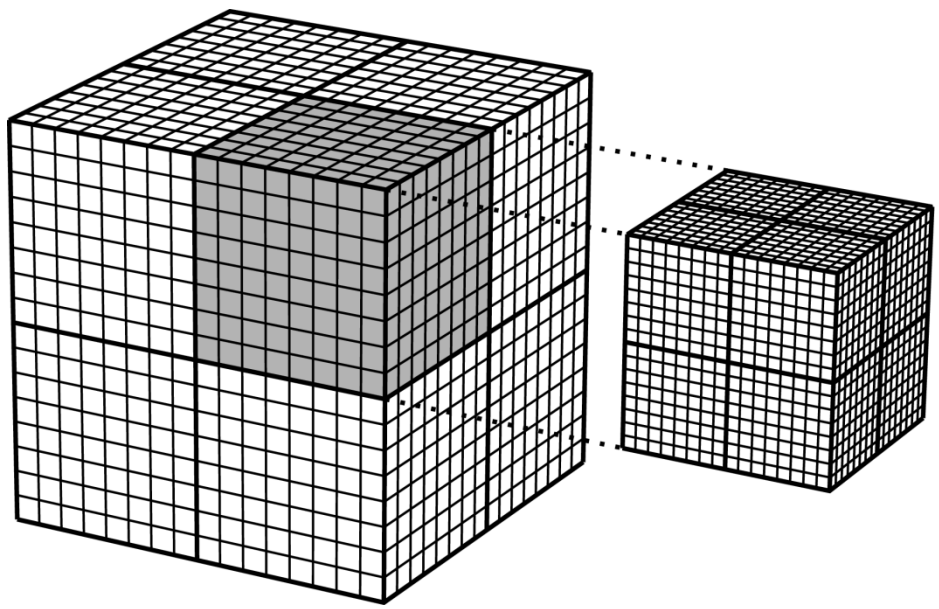
MHD
(Machida, Tomisaka, & Matsumoto 2004)

Hydrodynamics
Selfgravity
(Matsumoto & Hanawa 2003)

SFUMATO

- Block-structured AMR
  - Oct-tree structure
  - Parallel computation via MPI
- Hydrodynamics, MHD

div B

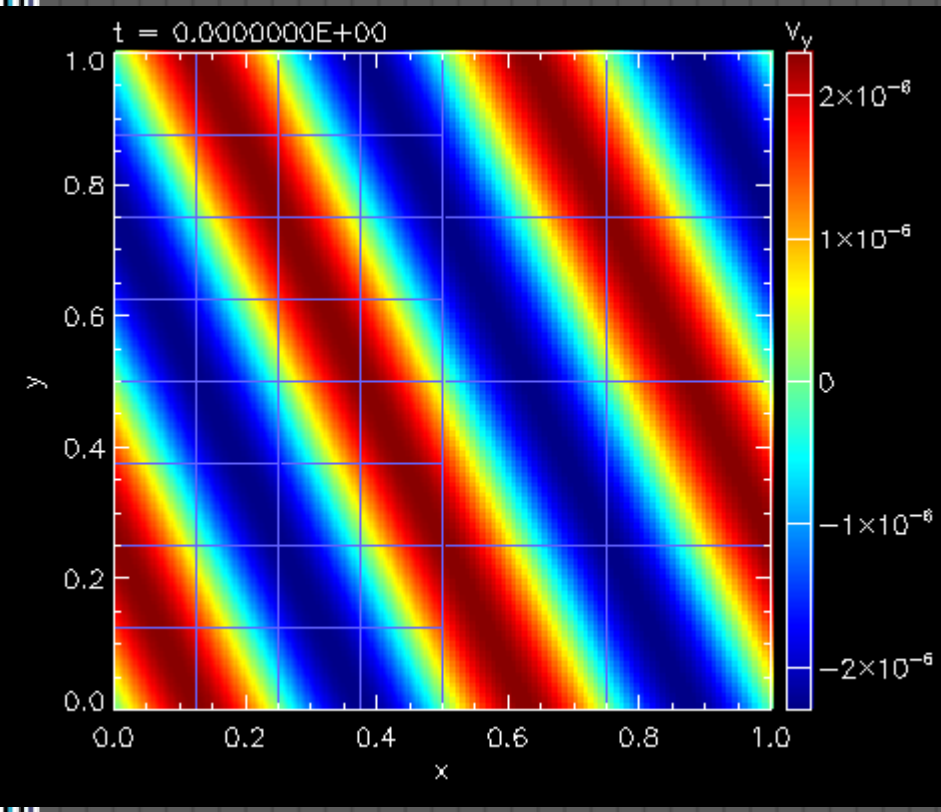


SFUMATO

- Block-structured AMR
  - Oct-tree structure
  - Parallel computation via MPI
- Hydrodynamics, MHD
  - Roe scheme + a hyperbolic cleaning of div B
  - Second order accuracy by TVD
- Selfgravity
  - Multigrid iteration
  - Second order accuracy

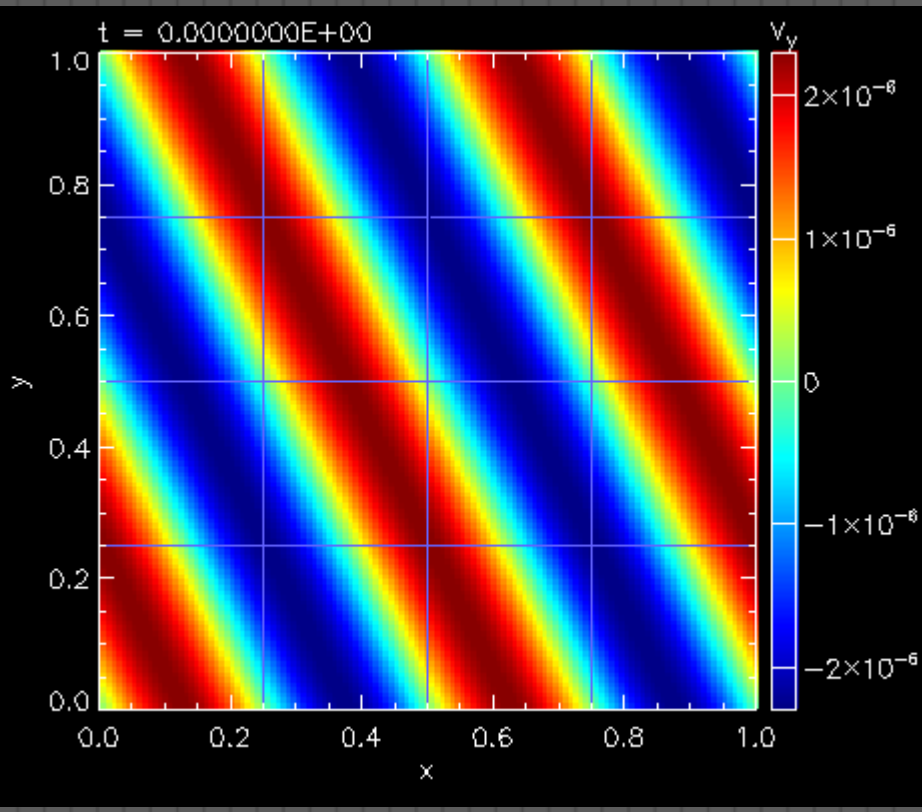
Convergence test for fast wave. Comparison among grid types

AMR grid



$\Delta x = 1/256, \quad \Delta x = 1/128$

Uniform grid

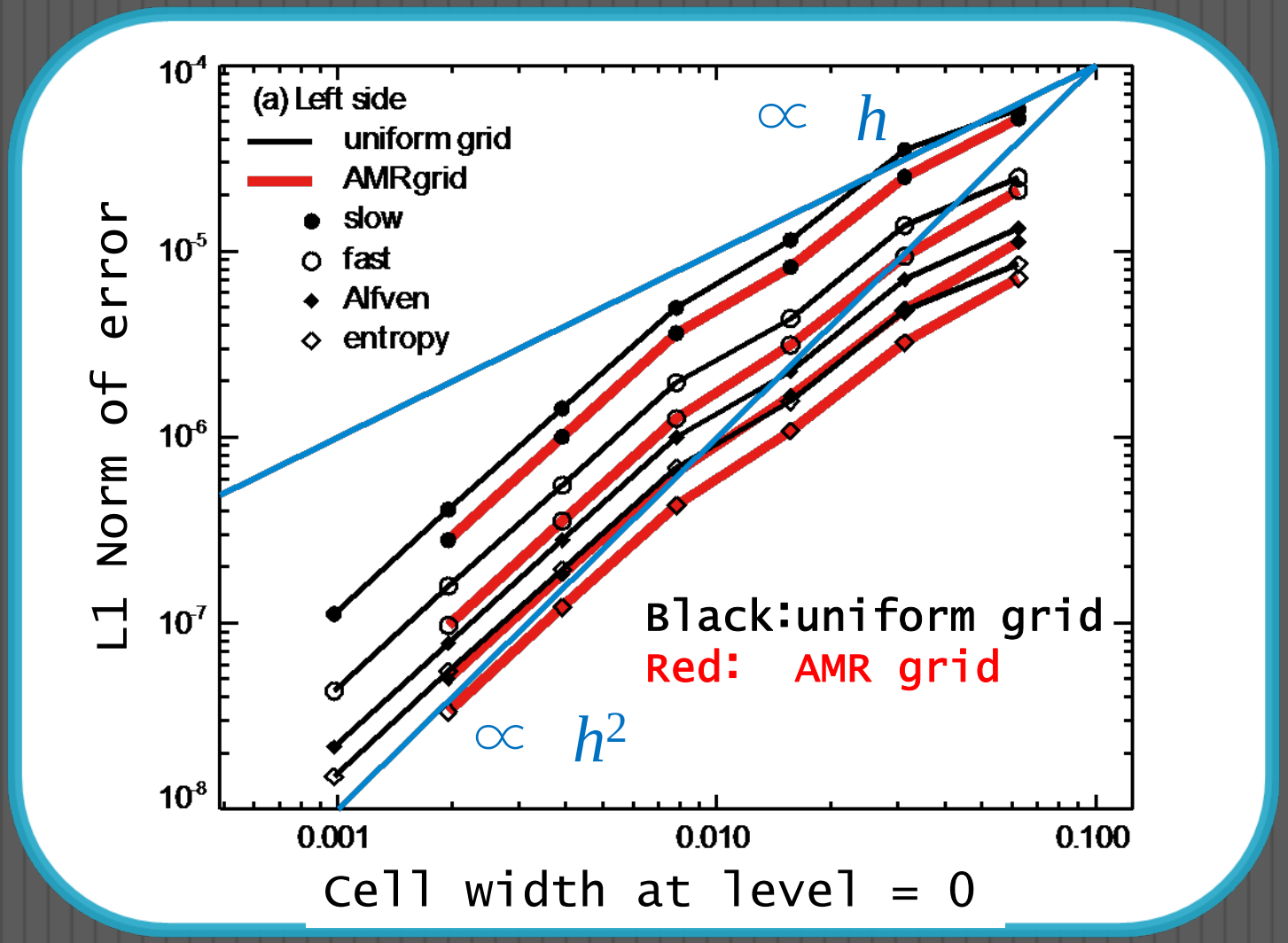


$\Delta x = 1/128$

Summary of the convergence test

2nd order @ $\Delta x << 1$

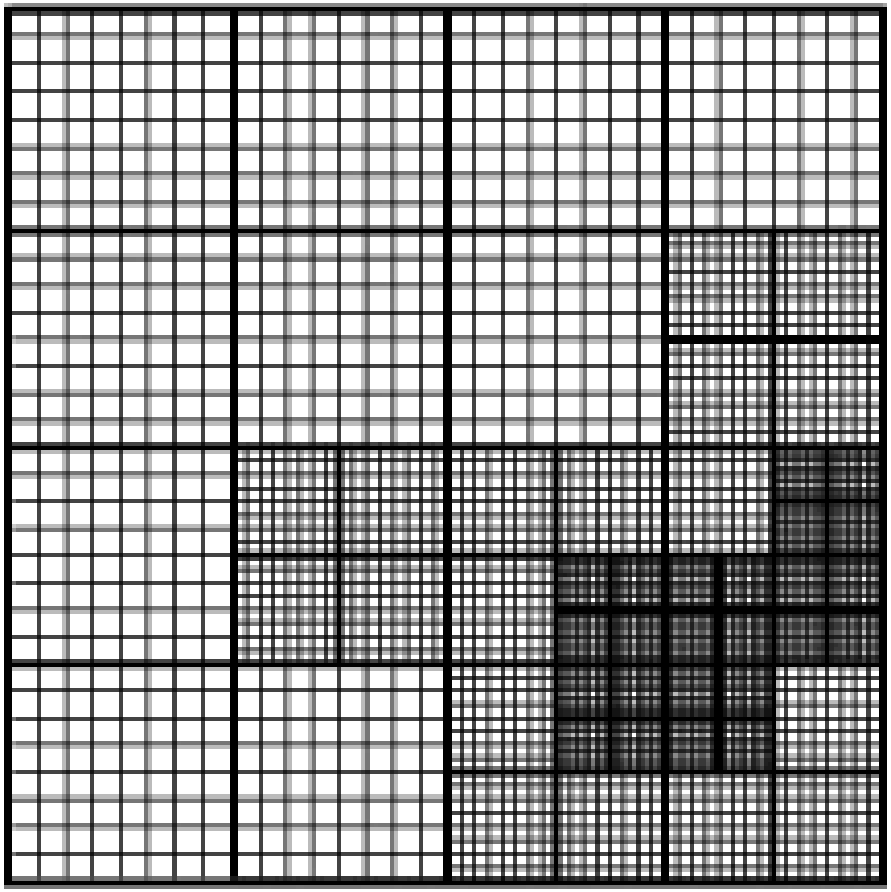
1st order @ $\Delta x \sim 1$



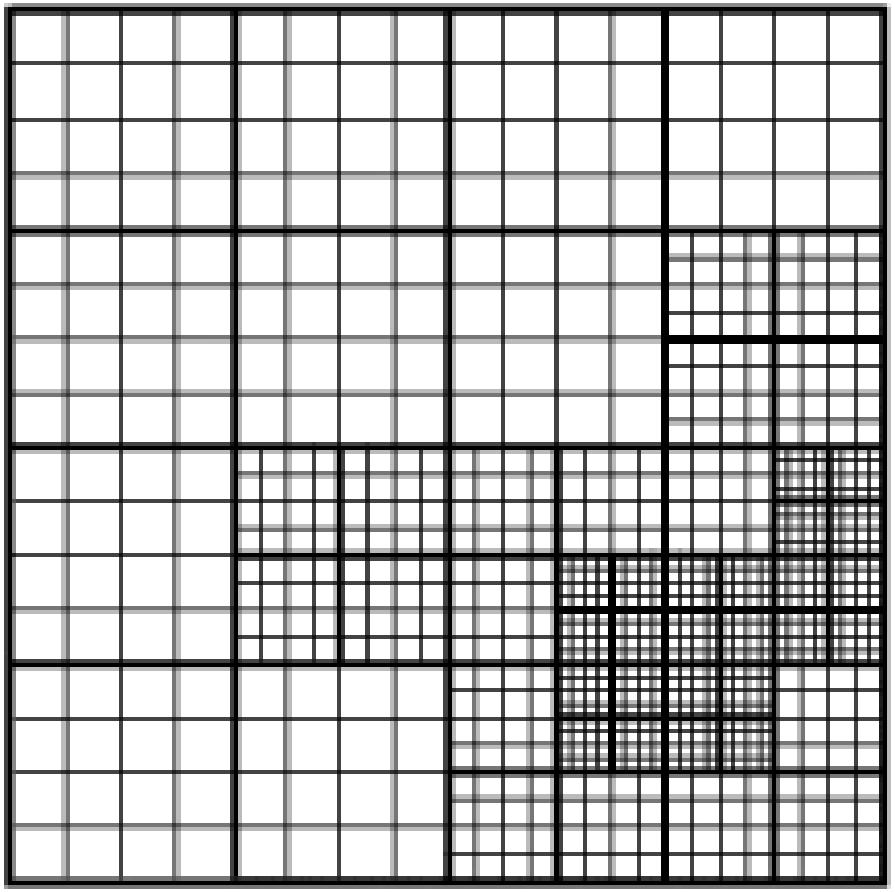
SFUMATO

- Block-structured AMR
  - Oct-tree structure
  - Parallel computation via MPI
- Hydrodynamics, MHD
  - Roe scheme + a hyperbolic cleaning of div B
  - second order accuracy by TVD
- Selfgravity
  - Three types of Multigrid iterations (Unique!)
  - Second order accuracy

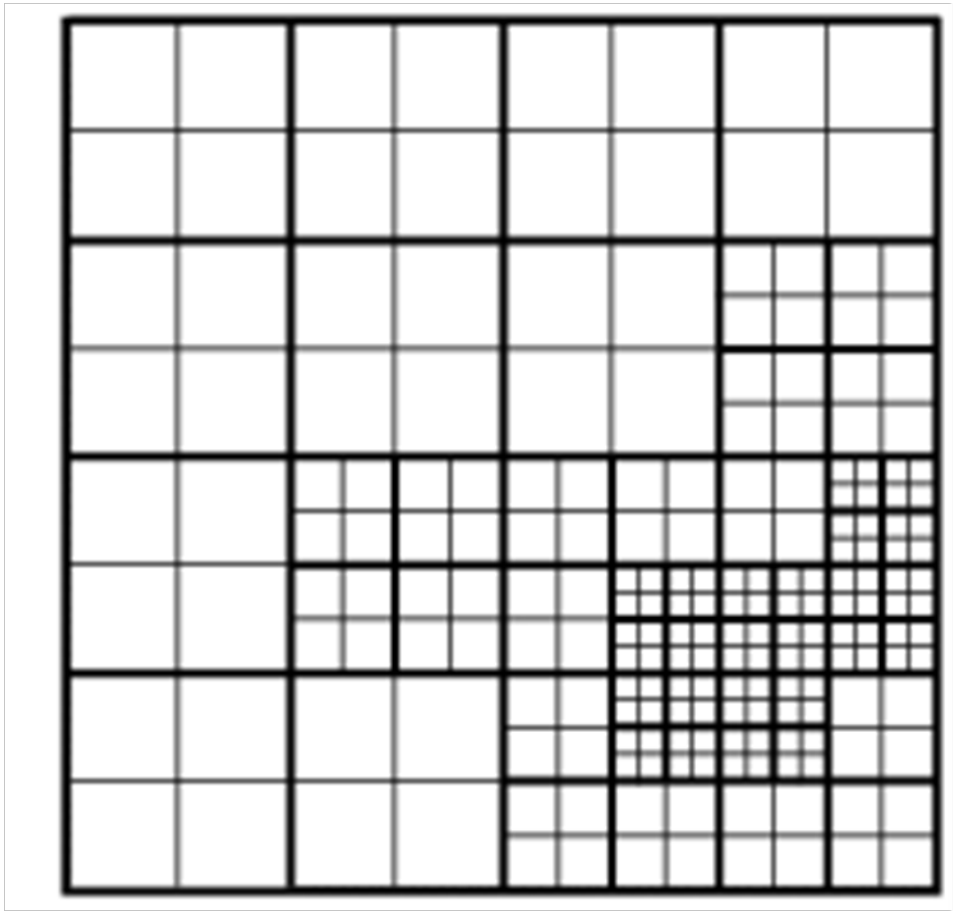
Multigrid iteration for seflgravity: How to coarsen AMR grid. An example.



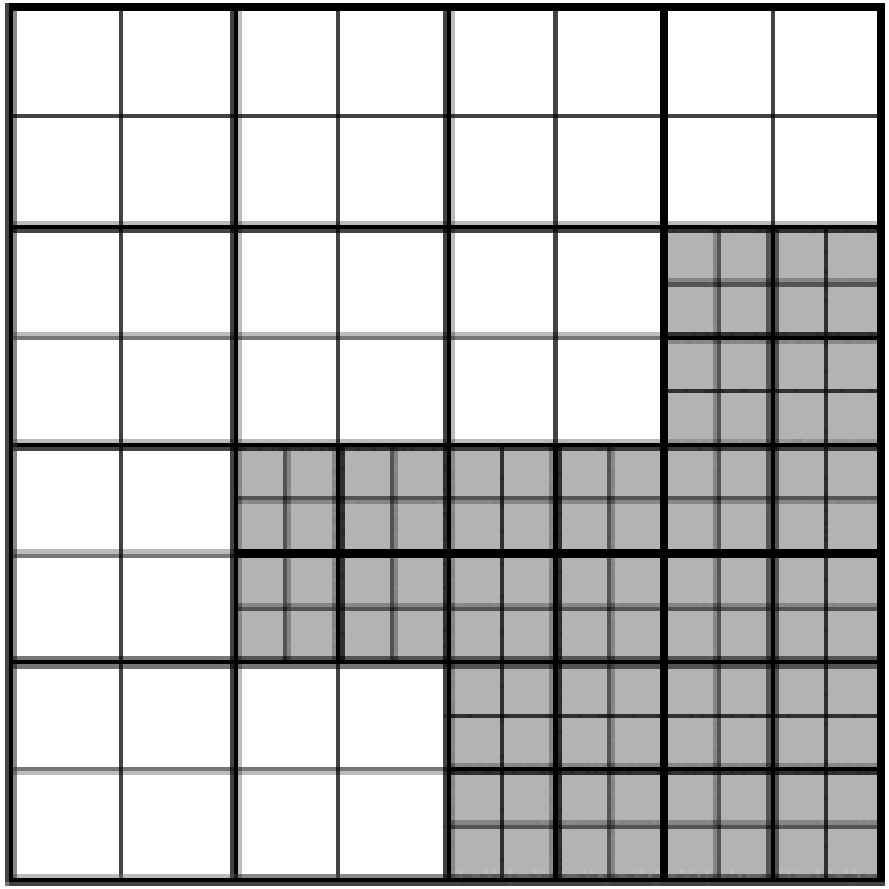
Multigrid iteration for seflgravity: Coarsen all cells over blocks and levels. Factor 2 coarsened.



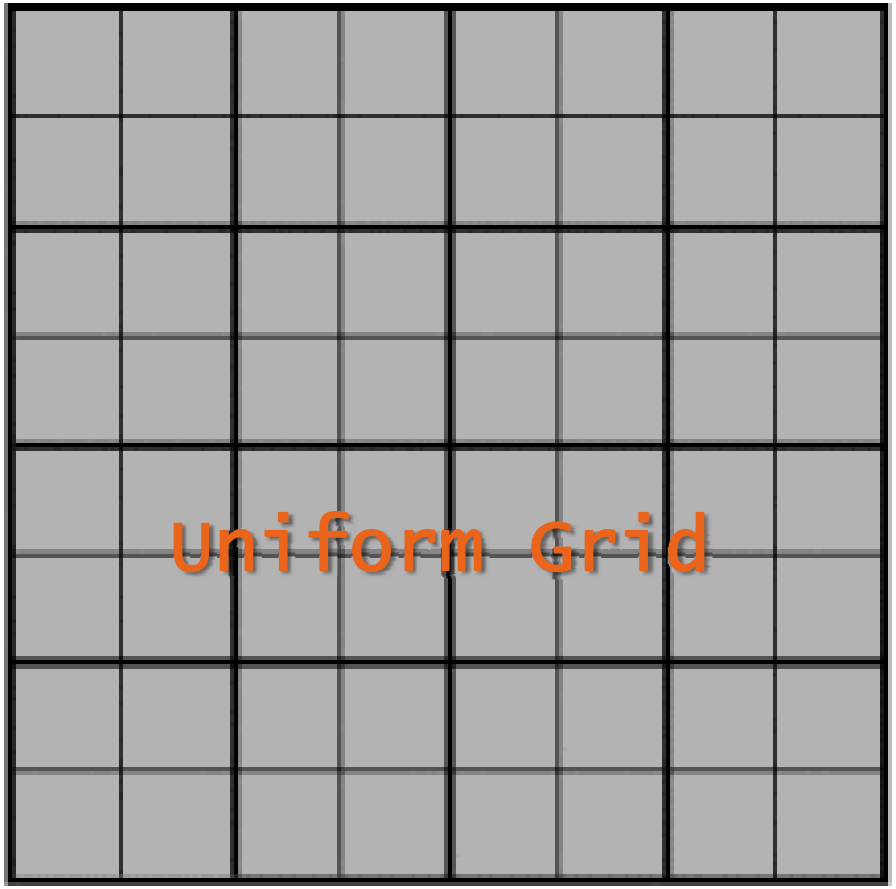
Multigrid iteration for seflgravity: Coarsen all cells over blocks and levels. Factor 4 coarsened.



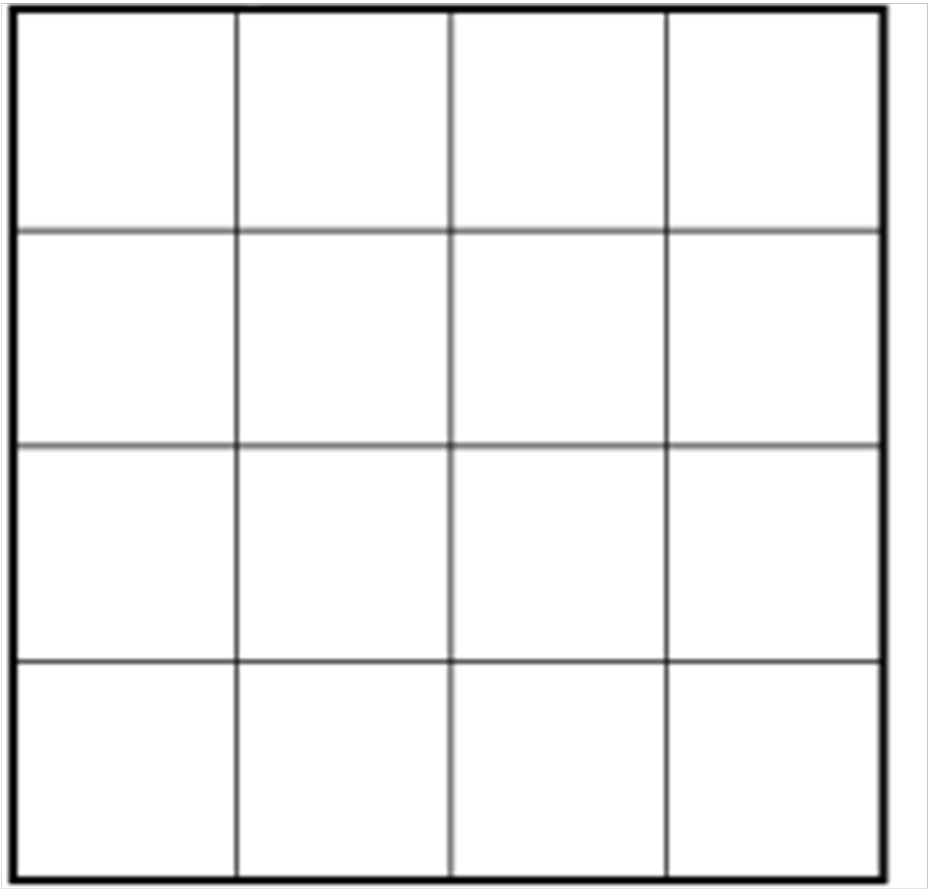
Multigrid iteration for seflgravity: Remove the finest grid. Factor 8 coarsened.



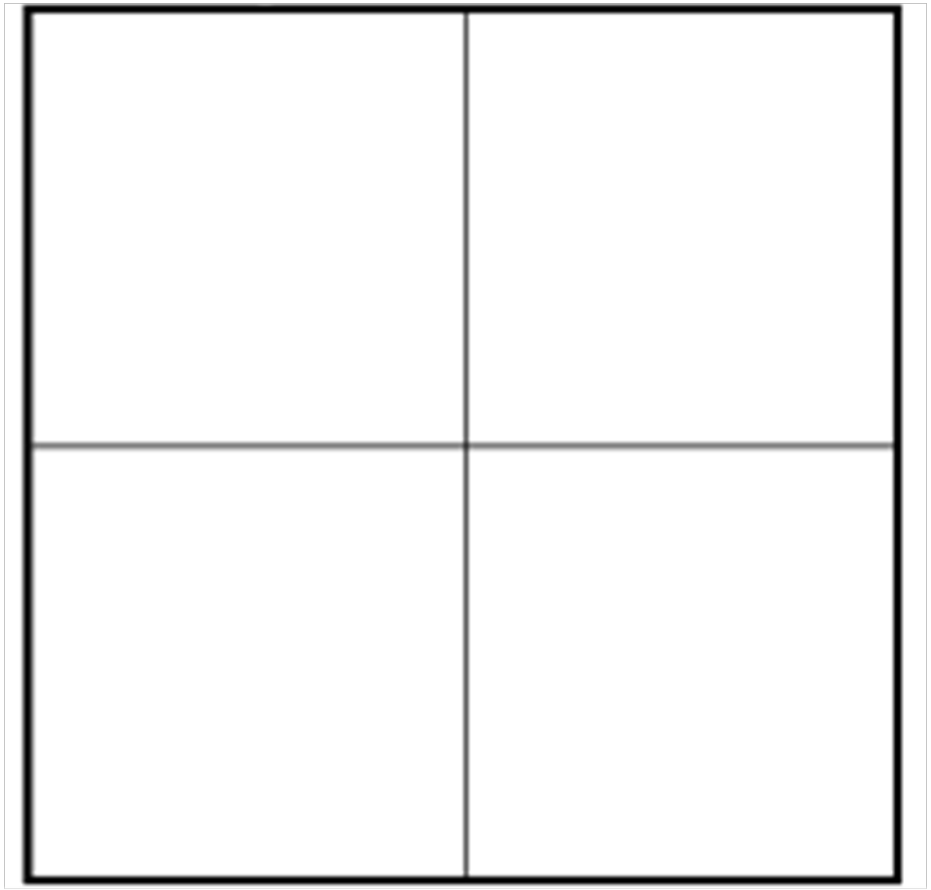
Multigrid iteration for seflgravity: Remove the finest grid more… Factor 16 coarsened.



Multigrid iteration for seflgravity: Remove the finest grid more… Factor 32 coarsened.

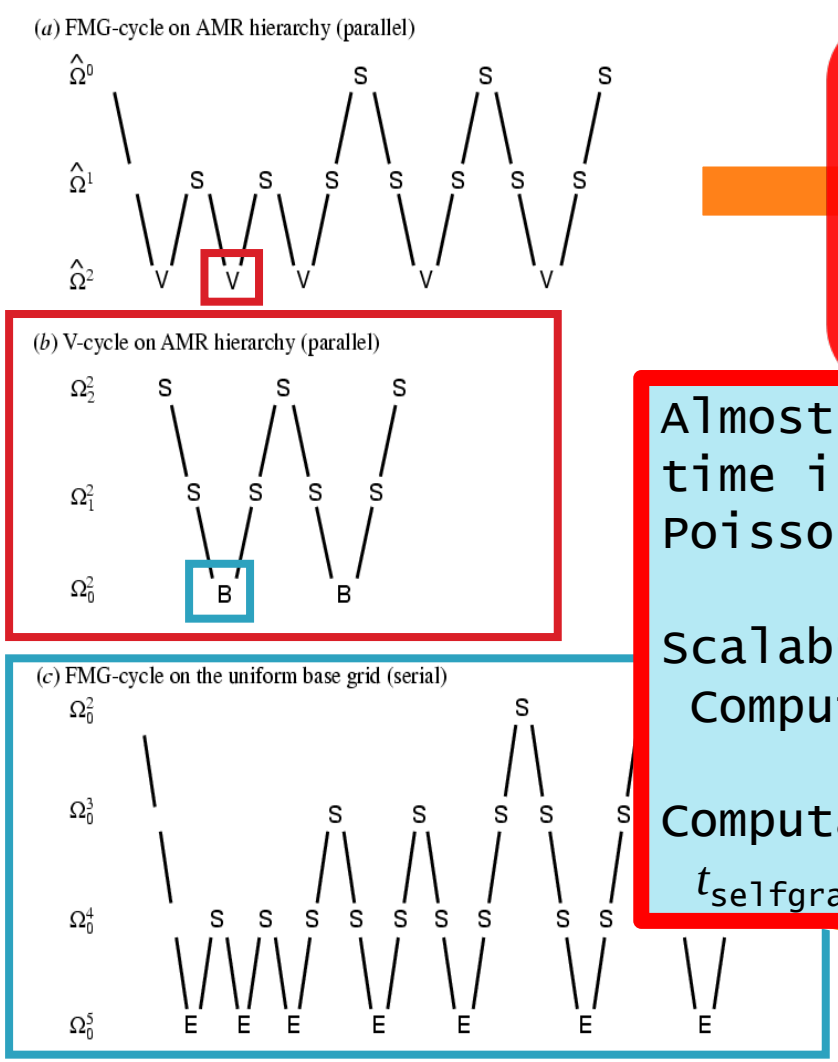


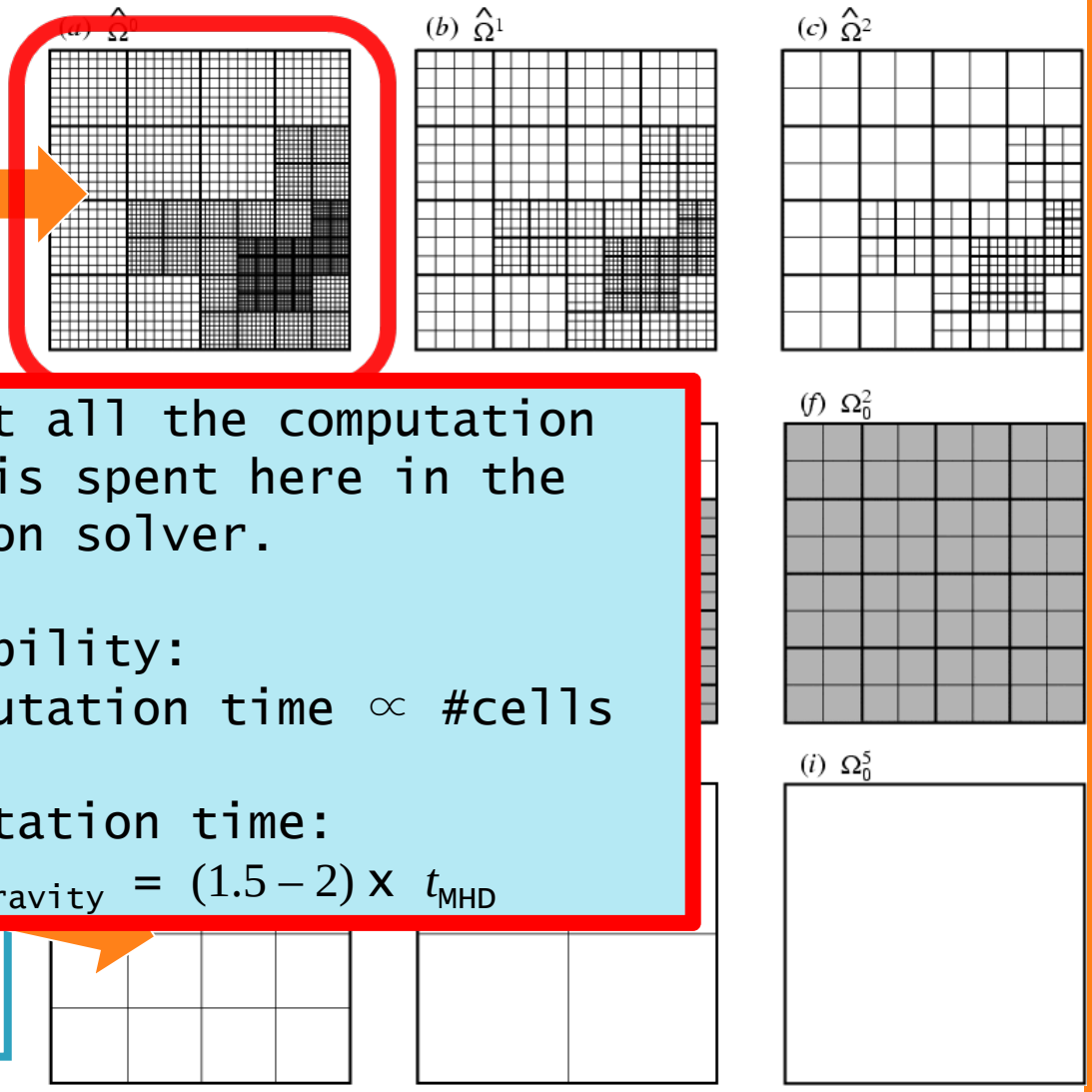
Multigrid iteration for seflgravity:
Coarsen an uniform grid.
Factor 64 coarsened.



Multigrid iteration for seflgravity: Coarsen an uniform grid. Factor 128 coarsened.

Summary of Poisson solver: Multigrid iteration @ AMR



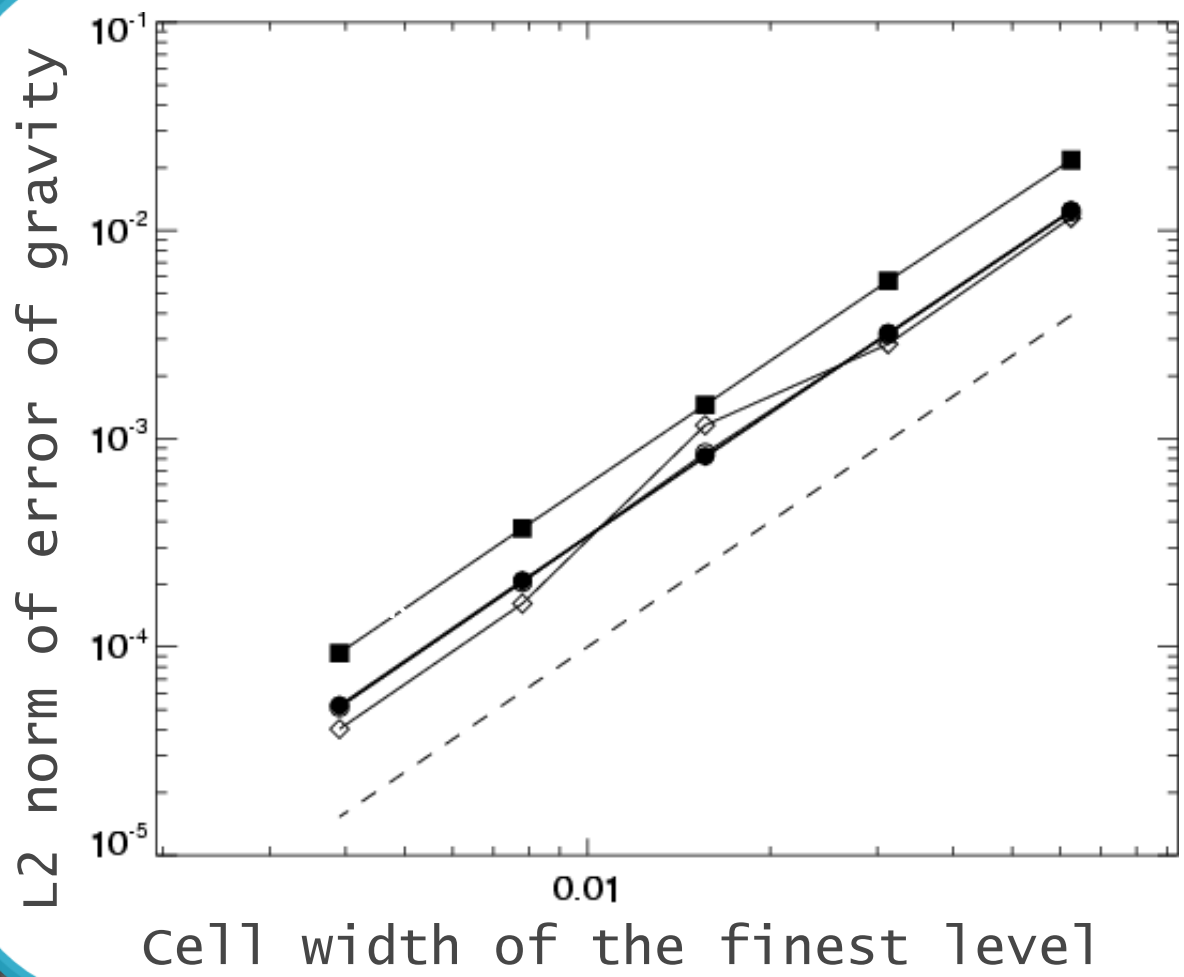


Almost all the computation time is spent here in the Poisson solver.

Scalability:
Computation time $\propto$ #cells

Computation time:
$t_{\mathrm{selfgravity}} = (1.5-2) \times t_{\mathrm{MHD}}$

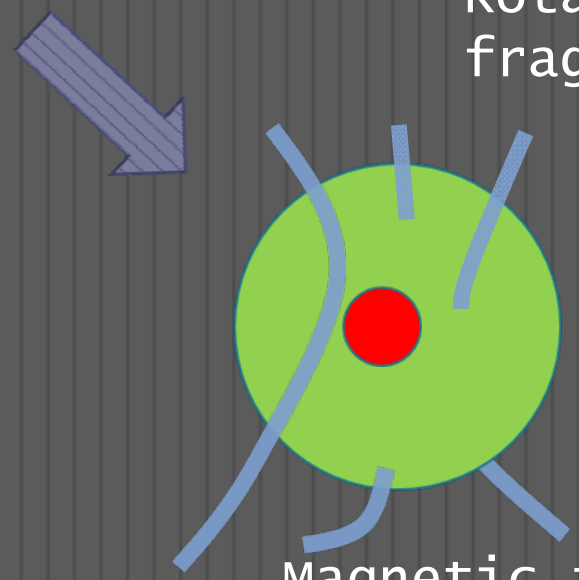
Convergence test of multi-grid method: 2nd order accuracy



- Source: binary stars
- Maximum level = 4
- Distribution of blocks is fixed.
- Number of cells inside a block is changed.

Introduction:
Traditional scenario of fragmentation

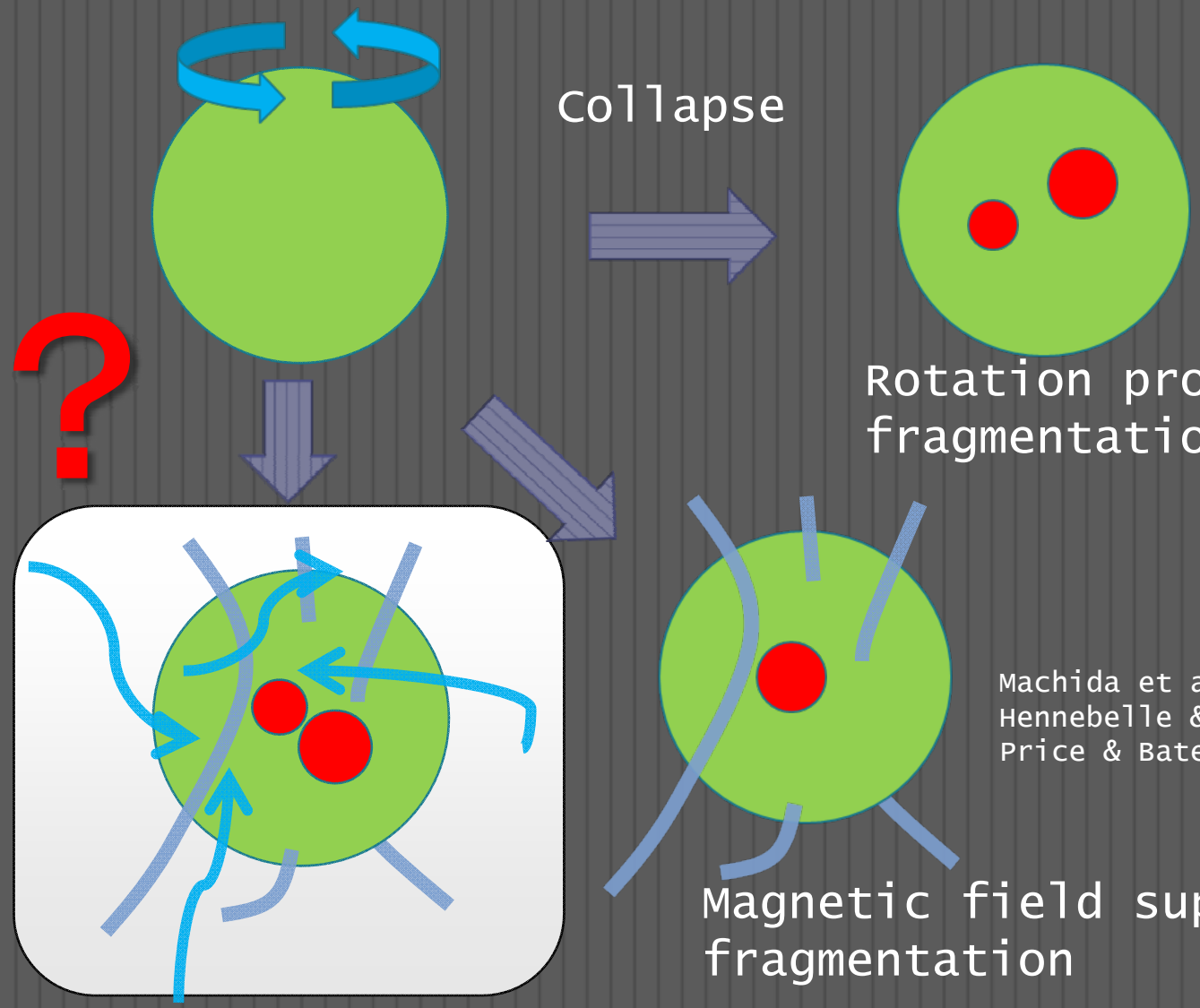
Rotation promotes fragmentation



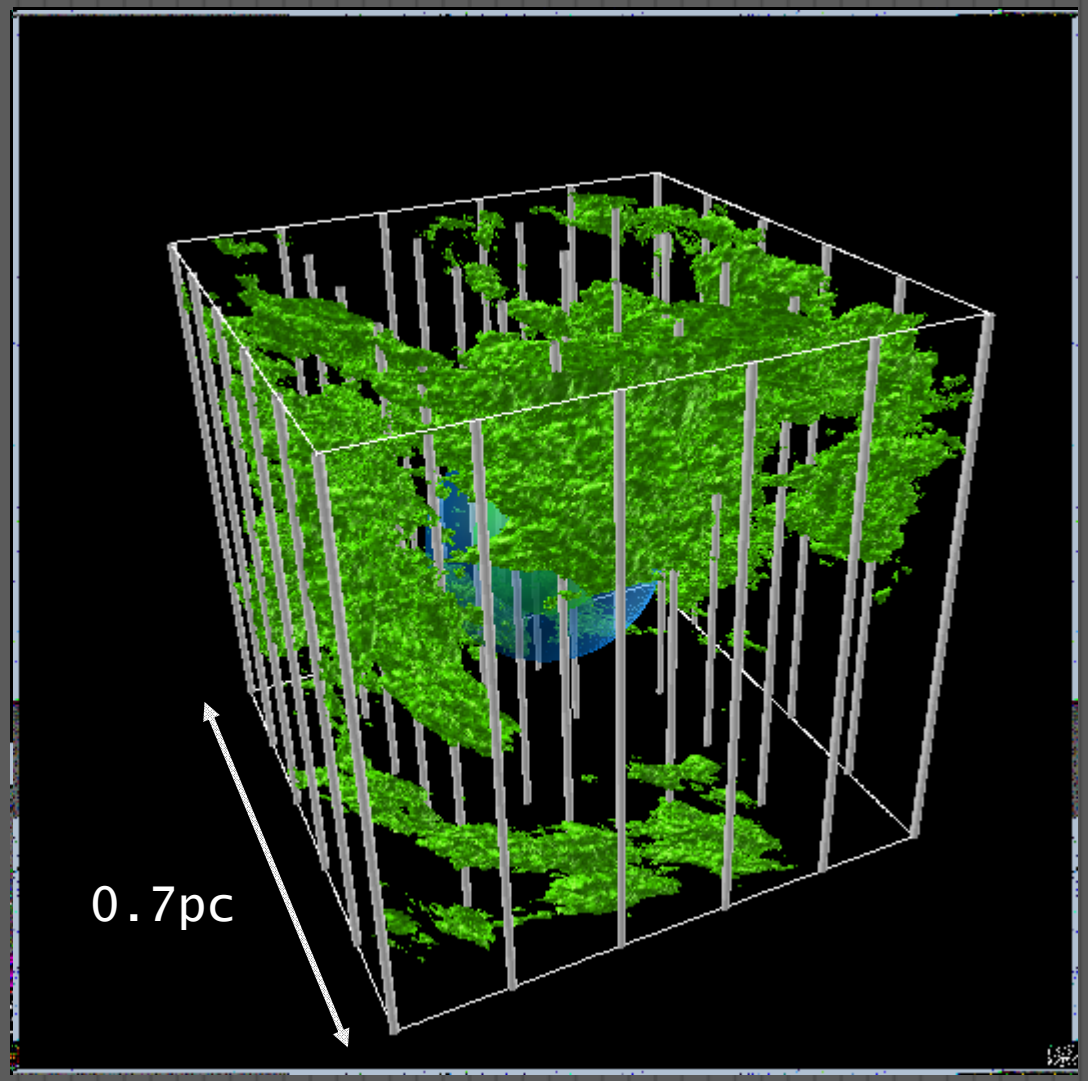
Machida et al. (2005)
Hennebelle & Fromang (2008)
Price & Bate (2008)

Magnetic field suppresses fragmentation

Introduction:
Does turbulence promote fragmentation?



Initial condition



Density:
BE sphere profile
Center: $10^4 cm^{-3}$
Radius: 0.17 pc
Mass: 6.1 M_{sun}

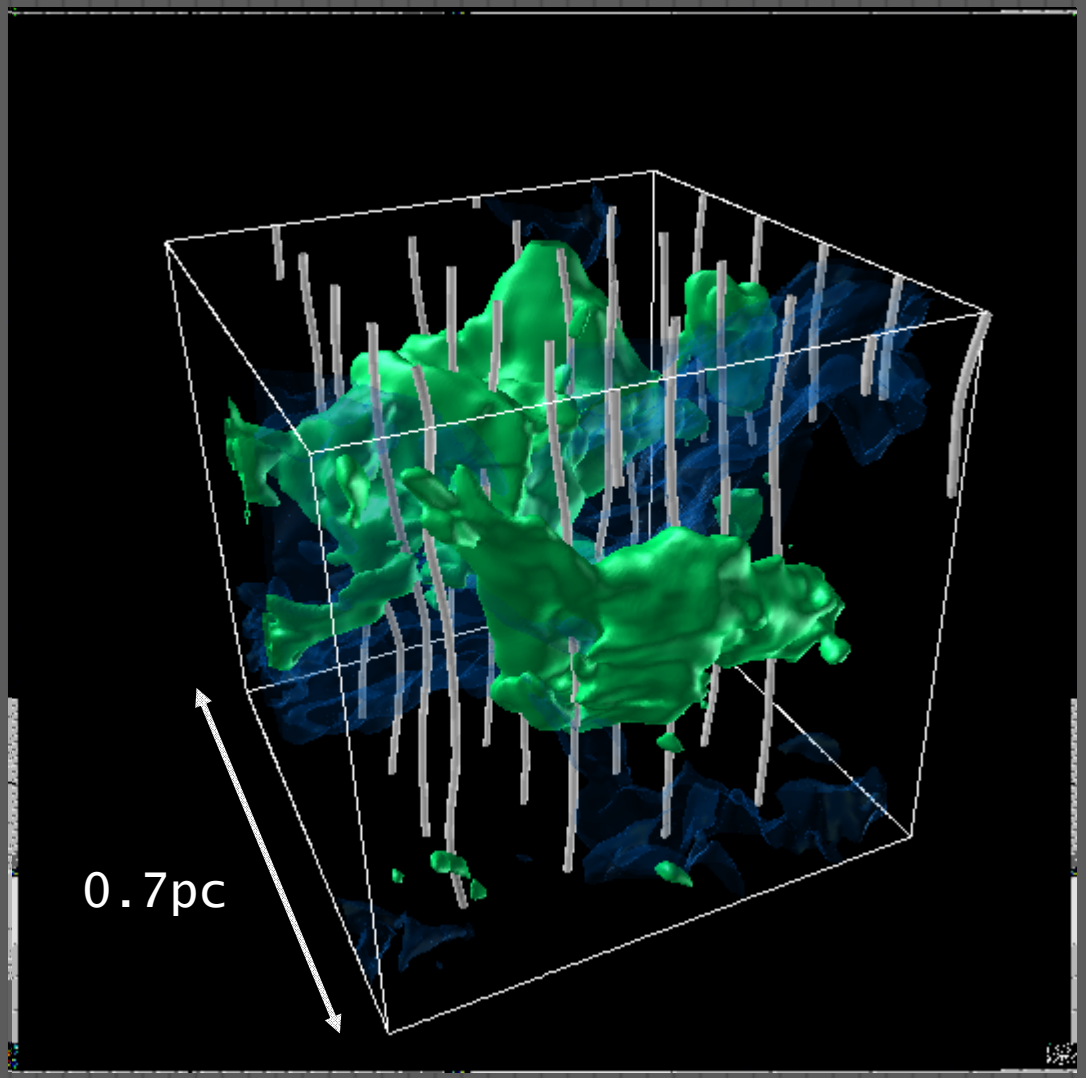
Moderate magnetic field:
18.6 μG

Turbulent flow:
$\langle v \rangle^2 \propto k^{-4}$
Mean Mach number
= 0.5 – 5

Barotropic EOS
Ideal MHD

Computation: XT4@CfCA NAOJ

The last stage (model with M=1)



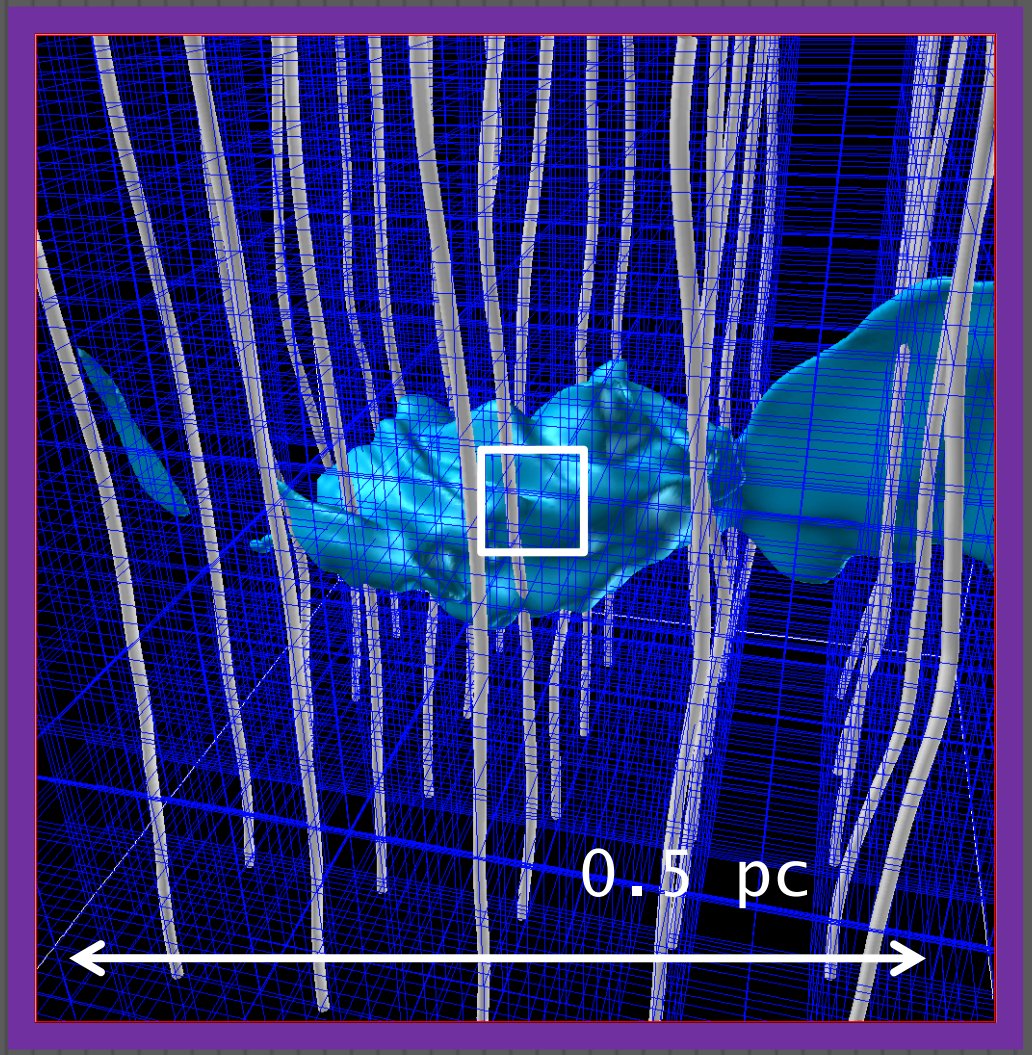
Density iso-surfaces:
0.1, 1, 10 ρ_0

Disturbed @low density
Flat @high density

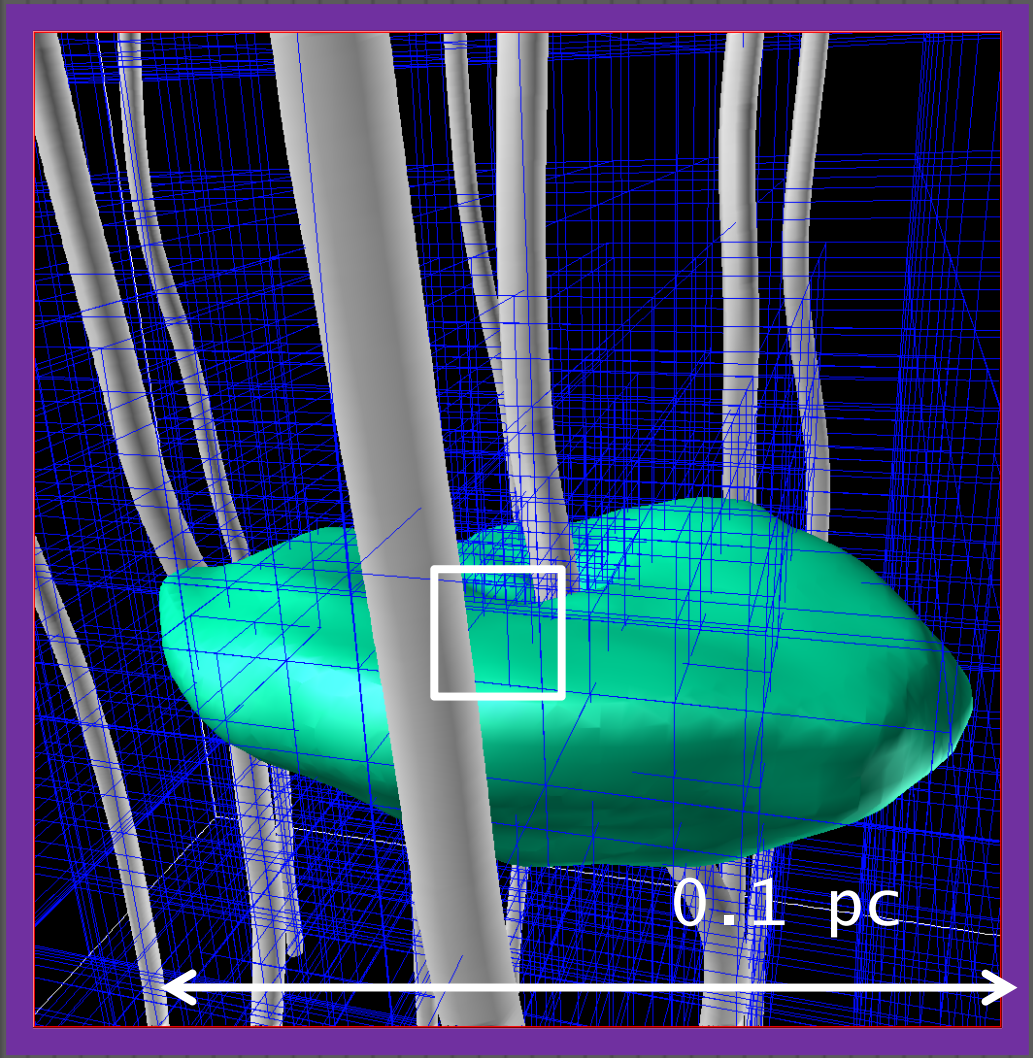
Magnetic field:
perpendicular to
a flat density
structure.

Turbulent flow of
the iso-surface:
M = 1.5

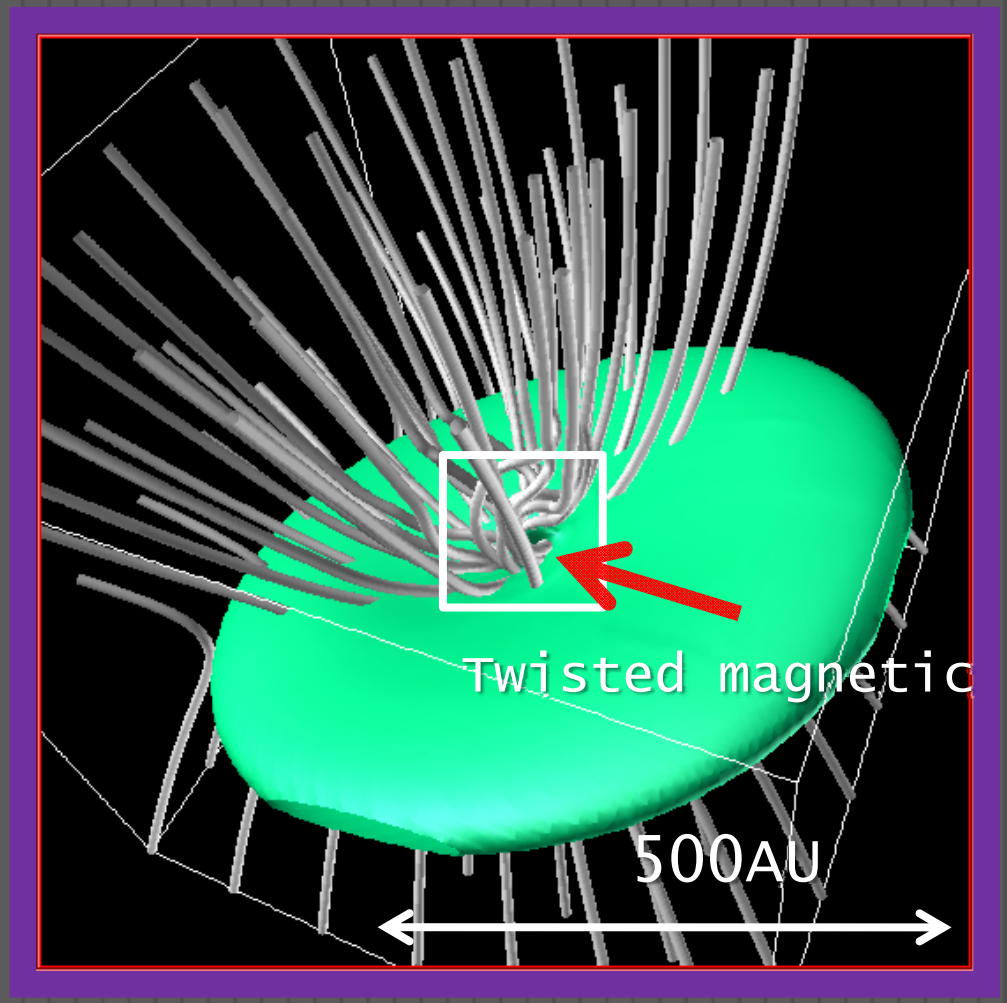
Zoom in on the cloud core: The cloud core is disturbed by turbulent flow.



Zoom in on the center: The cloud core is disturbed by turbulent flow.

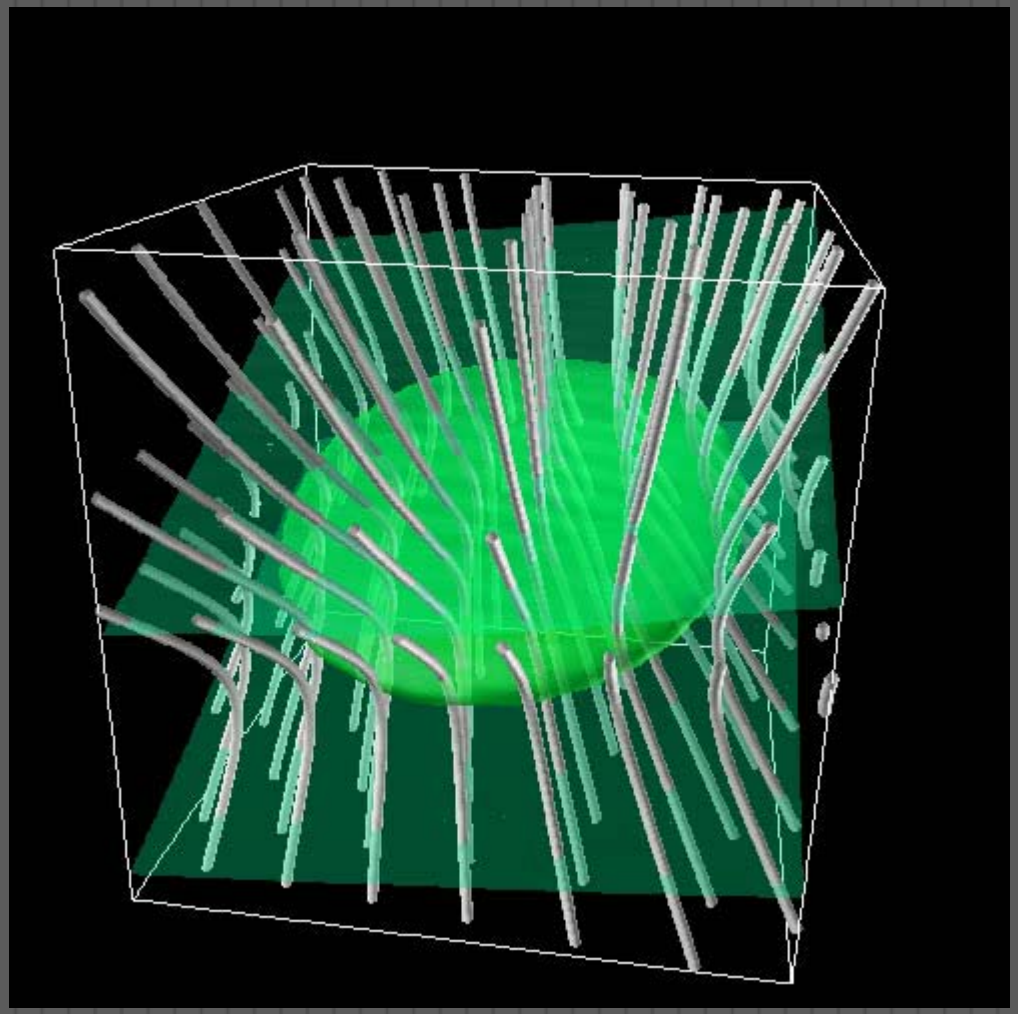


Zoom in on the center: Axisymmetry at collapsing region.



Zoom in on the center: Outflow from first core.

200AU

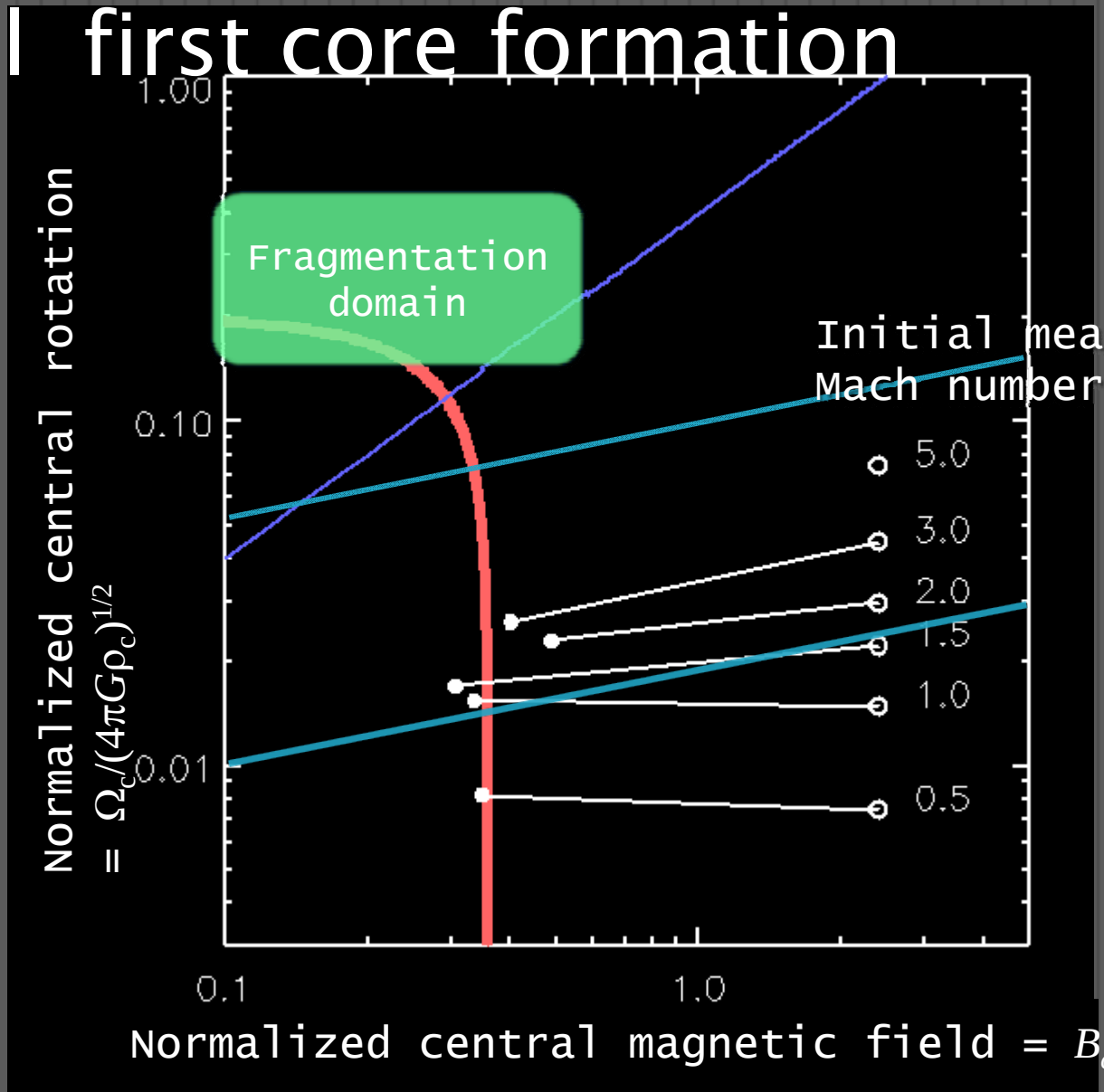


Isosurface of outflow: $v_r = 4$

Level=9

Magnetic flux – spin relation
So called the Machida-diagram.

Clouds do not fragment until first core formation



Summary

- SFUMATO, a selfgravitational MHD AMR code was developed.
  - Second order accuracy in time and space.
  - Fast Poisson solver using multigrid iterations.
- Gravitational collapse of magnetized cloud cores was performed.
- A cloud core is disturbed by turbulent flow, but a collapsed region is converged to an axisymmetric structure.
- Turbulent flow does NOT promote fragmentation until the first core formation when ideal MHD is assumed.
  - Ohmic dissipation may be necessary for a cloud to fragment (Machida et al. 2008; simulations by the nested-grid).
  - Cloud core may fragment during the second collapse.
  - For the later stage, a sink particle method may be necessary to solve.