Dynamos and Outflows in Simulations of Magnetized Collapsing Cores

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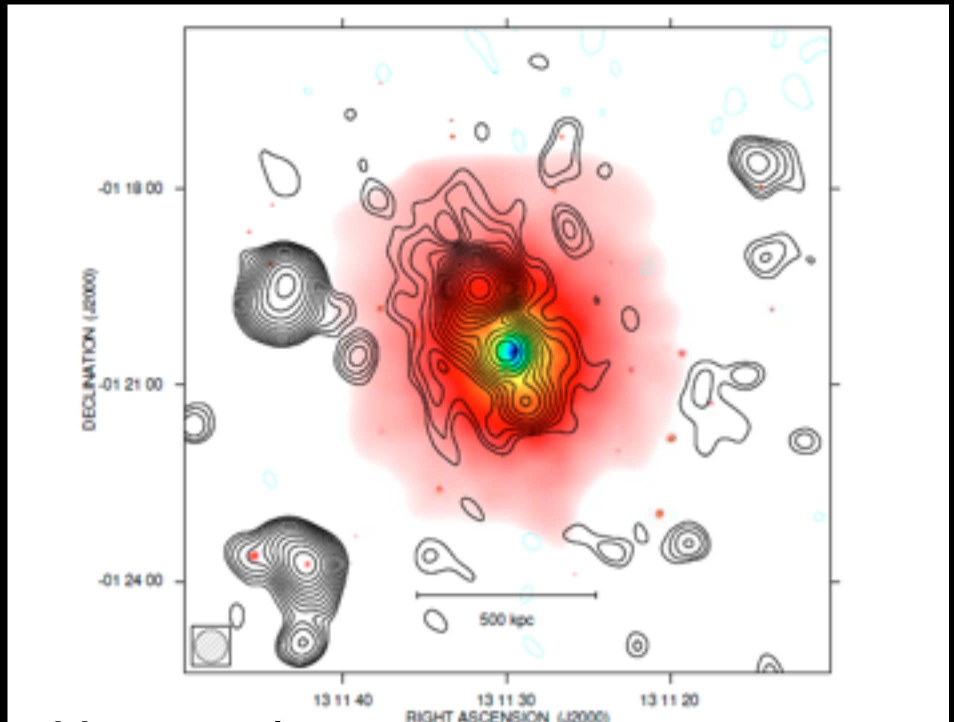
With substantial help and advice from
Christoph Federrath and Ralf Klessen

As well as many others here at ISIMA

Magnetic Fields are Ubiquitous in Interstellar Space

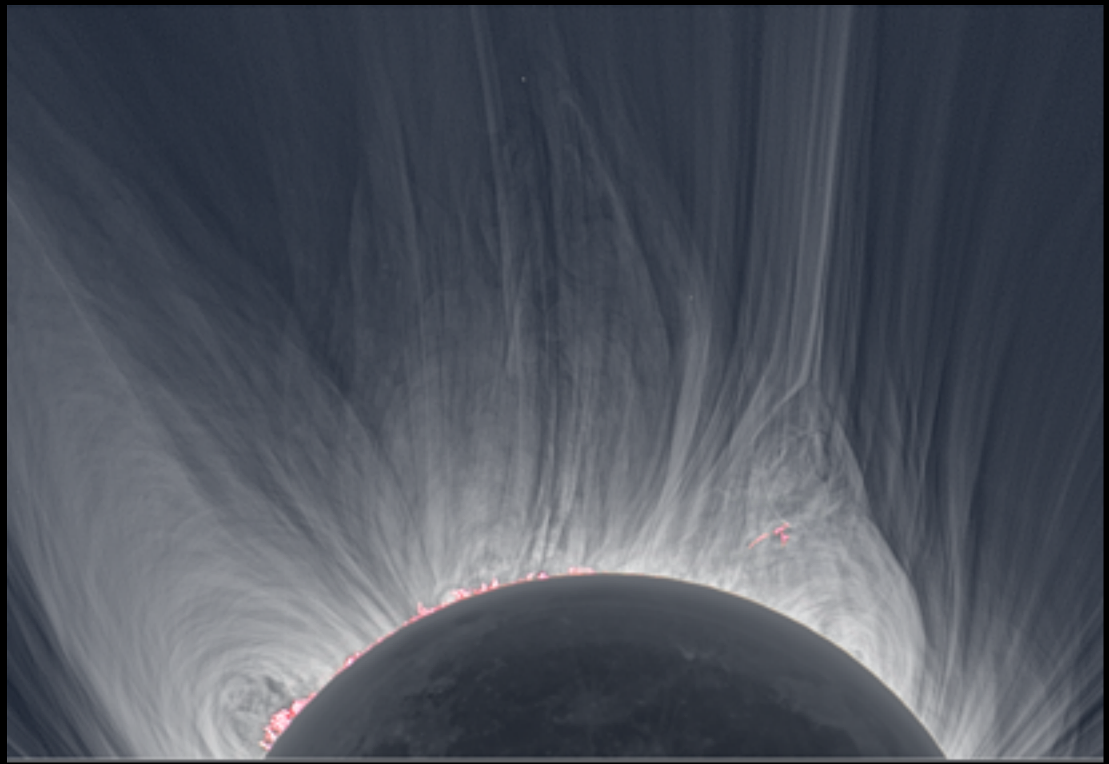
Galaxy Cluster Abell 1689



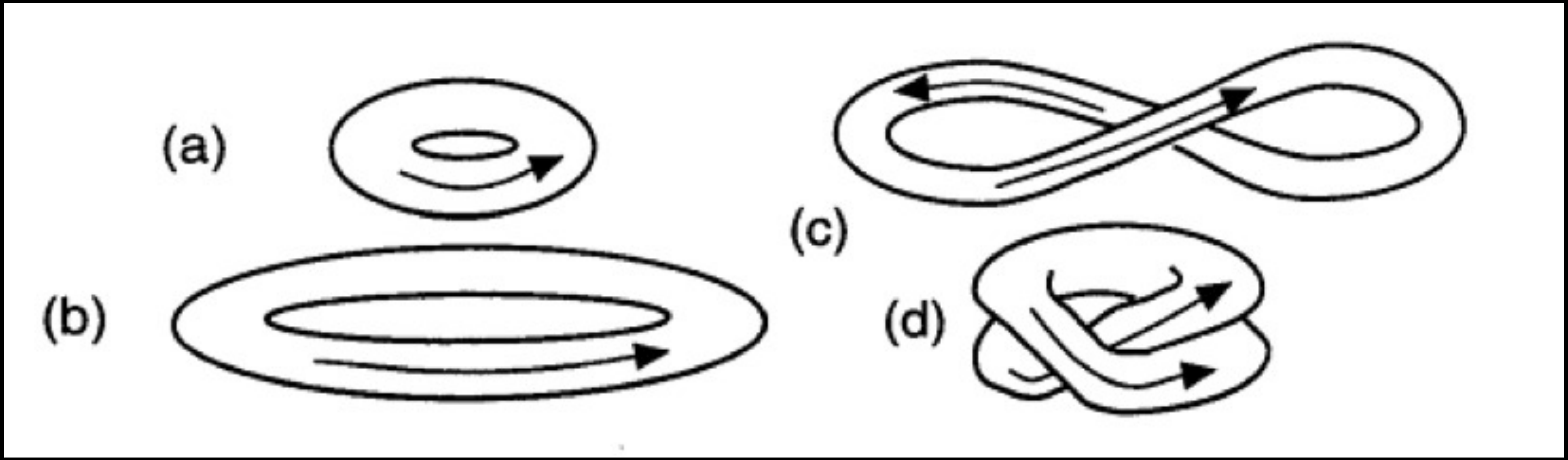
Vacca et al.

Spiral Galaxy M51

Fletcher et al. 2011



The bulk of the Magnetic Energy of the Universe was Generated in Dynamos



Zel’dovich ‘Stretch-Twist-Fold’ Dynamo

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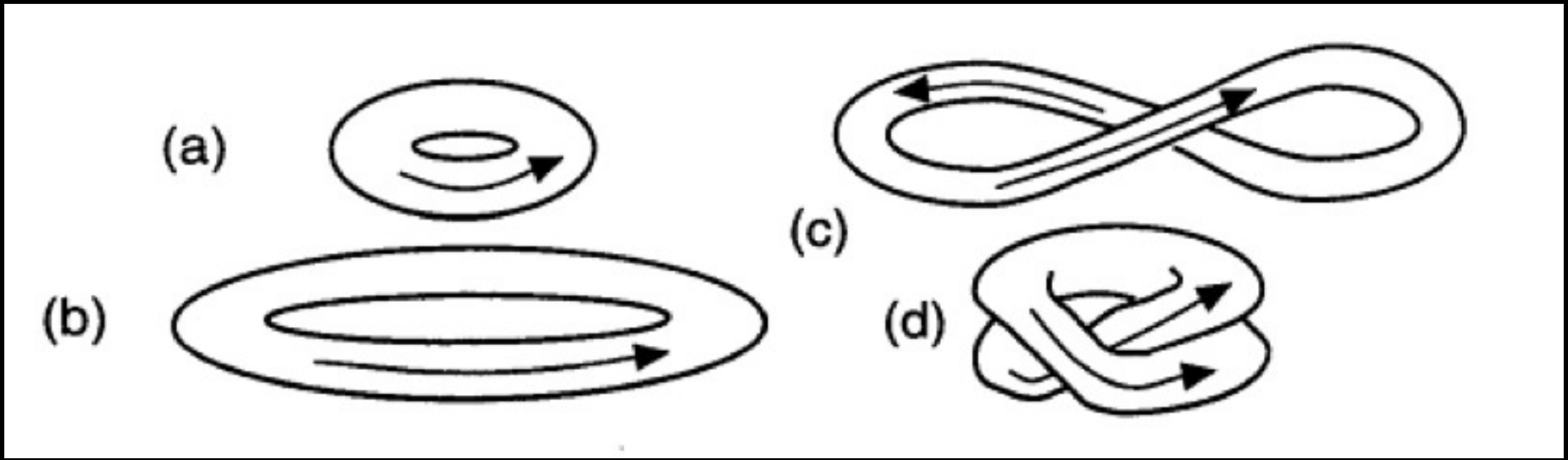


Zel'dovich 'Stretch-Twist-Fold' Dynamo

$$\frac{d}{dt}\int_V \frac{\mathbf{B}^2}{8\pi}dV = -\int_V \mathbf{v}\cdot(\mathbf{J}\times\mathbf{B})dV - \int_V \frac{J^2}{\sigma}dV - \int_S \frac{\mathbf{E}\times\mathbf{B}}{4\pi}d\mathbf{S}$$

$$\frac{d}{dt}\int_V \frac{1}{2}\rho\mathbf{v}^2 dV = +\int_V p\nabla\cdot\mathbf{v}dV + \int_V \mathbf{v}\cdot(\mathbf{J}\times\mathbf{B})dV + \int_V \rho\mathbf{v}\cdot\mathbf{g}dV$$

The Collapse of a primordial halo is a Unique Laboratory for Dynamo Theory

Thermodynamics

$$P \propto \rho^{1.1}$$

$$T_0 = 300 \text{ K}$$

Cloud Parameters

$$M_{\rm core} = 1.2 M_J$$

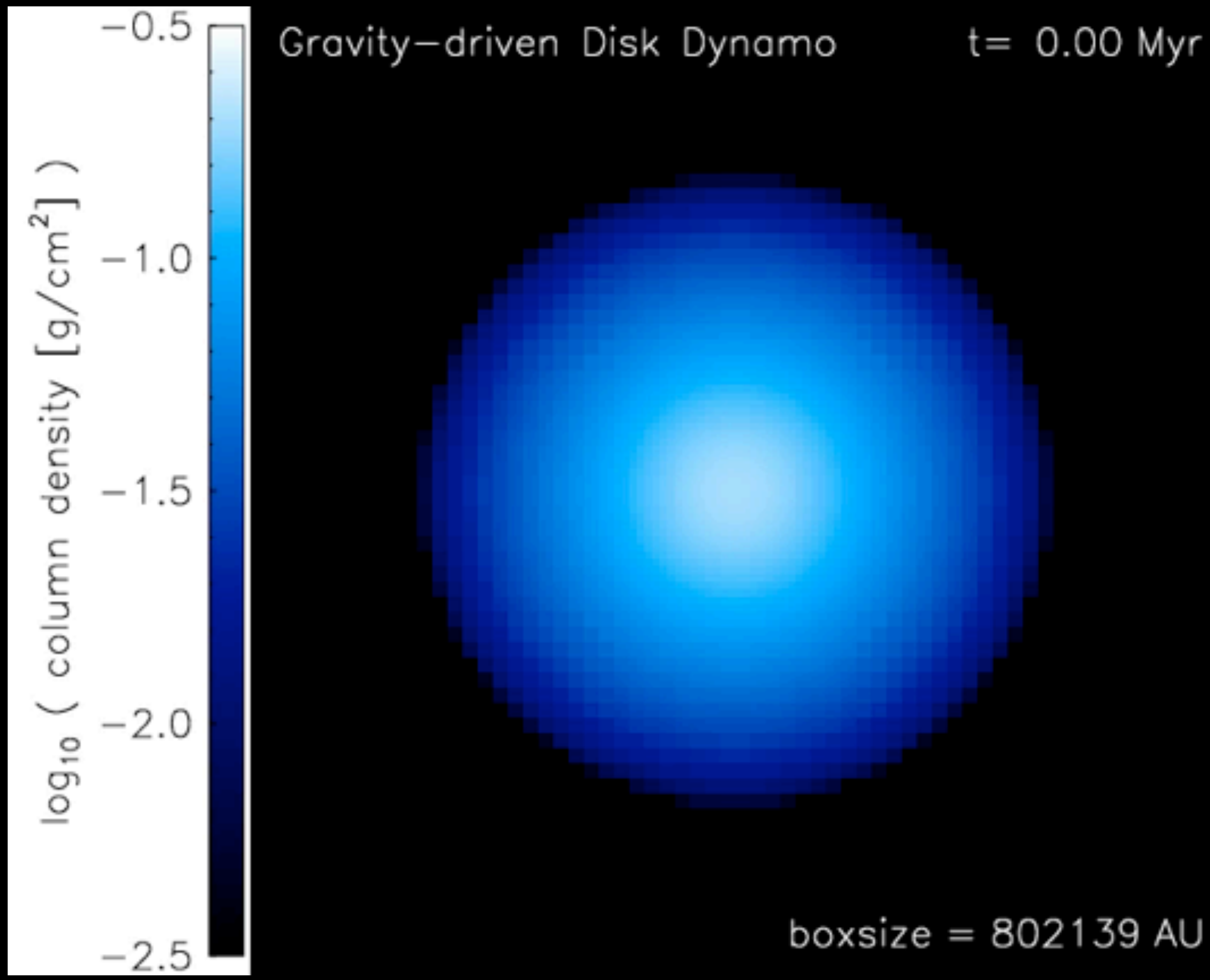
$$\frac{E_{\rm rot}}{E_{\rm grav}} = 0.07$$

Turbulence Parameters

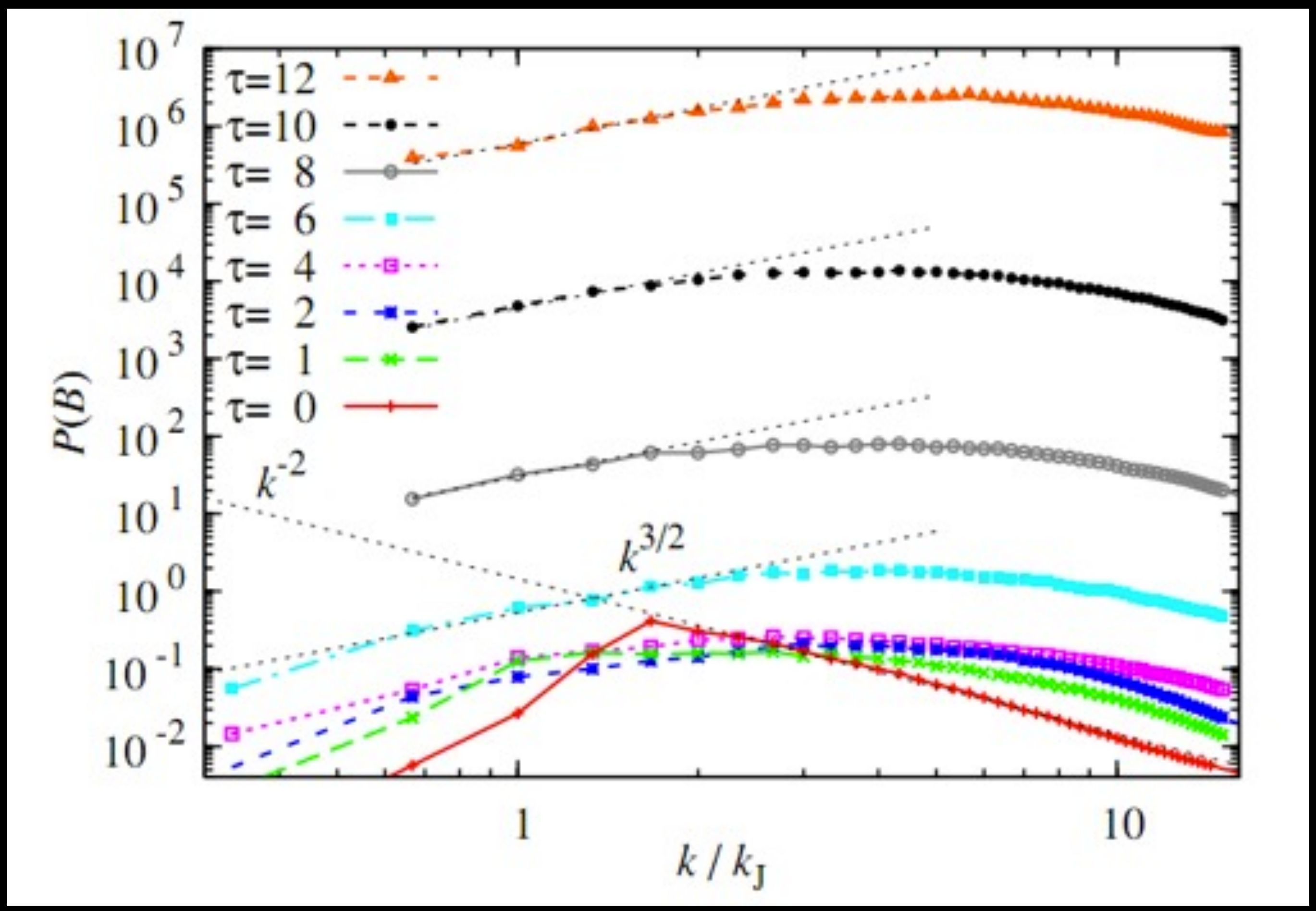
$$B_{\rm RMS} = 1 \ \mu{\rm G}$$

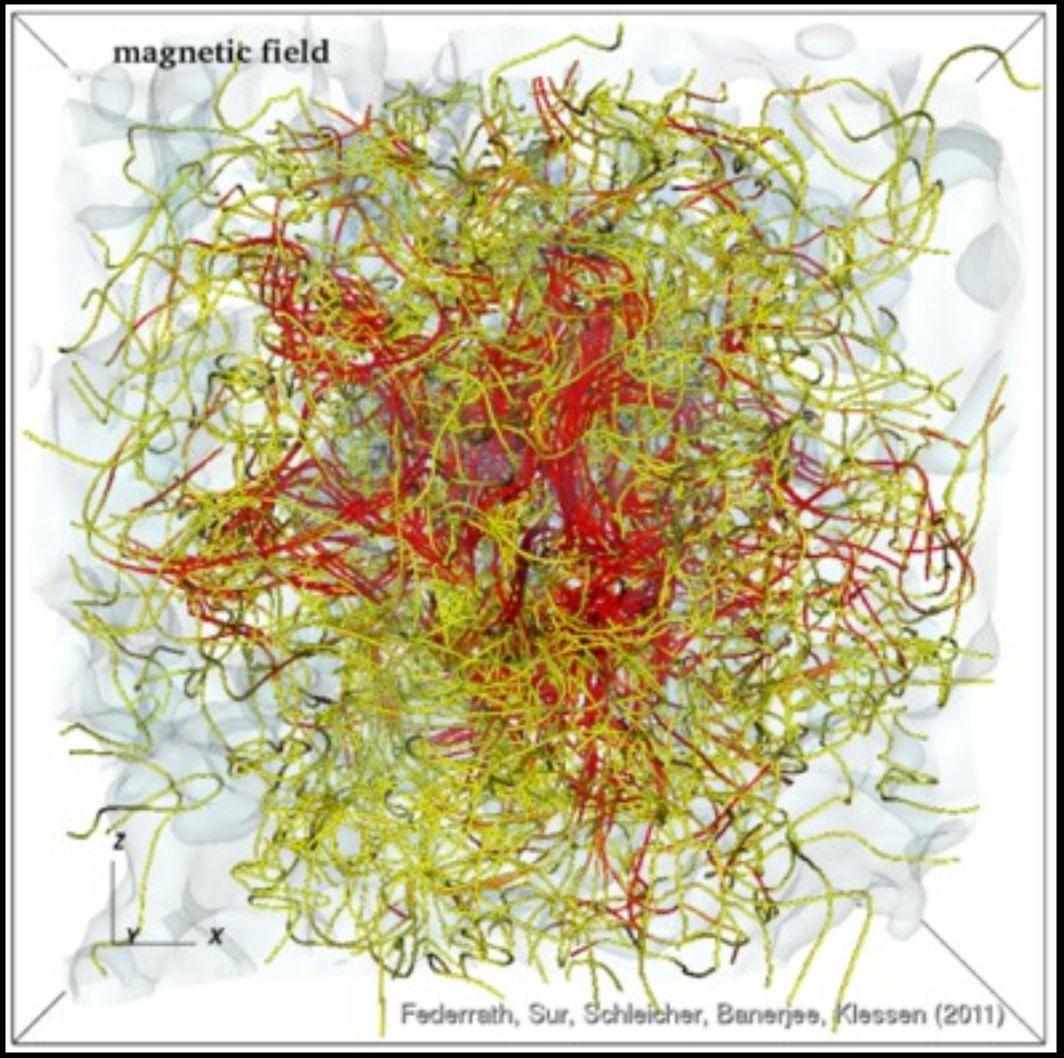
$$v_{\rm RMS} = c_s$$

$$P_{\mathbf{v},\mathbf{B}}(k) \propto k^{-2}$$



Magnetic Fields can be Generated on Small Scales...

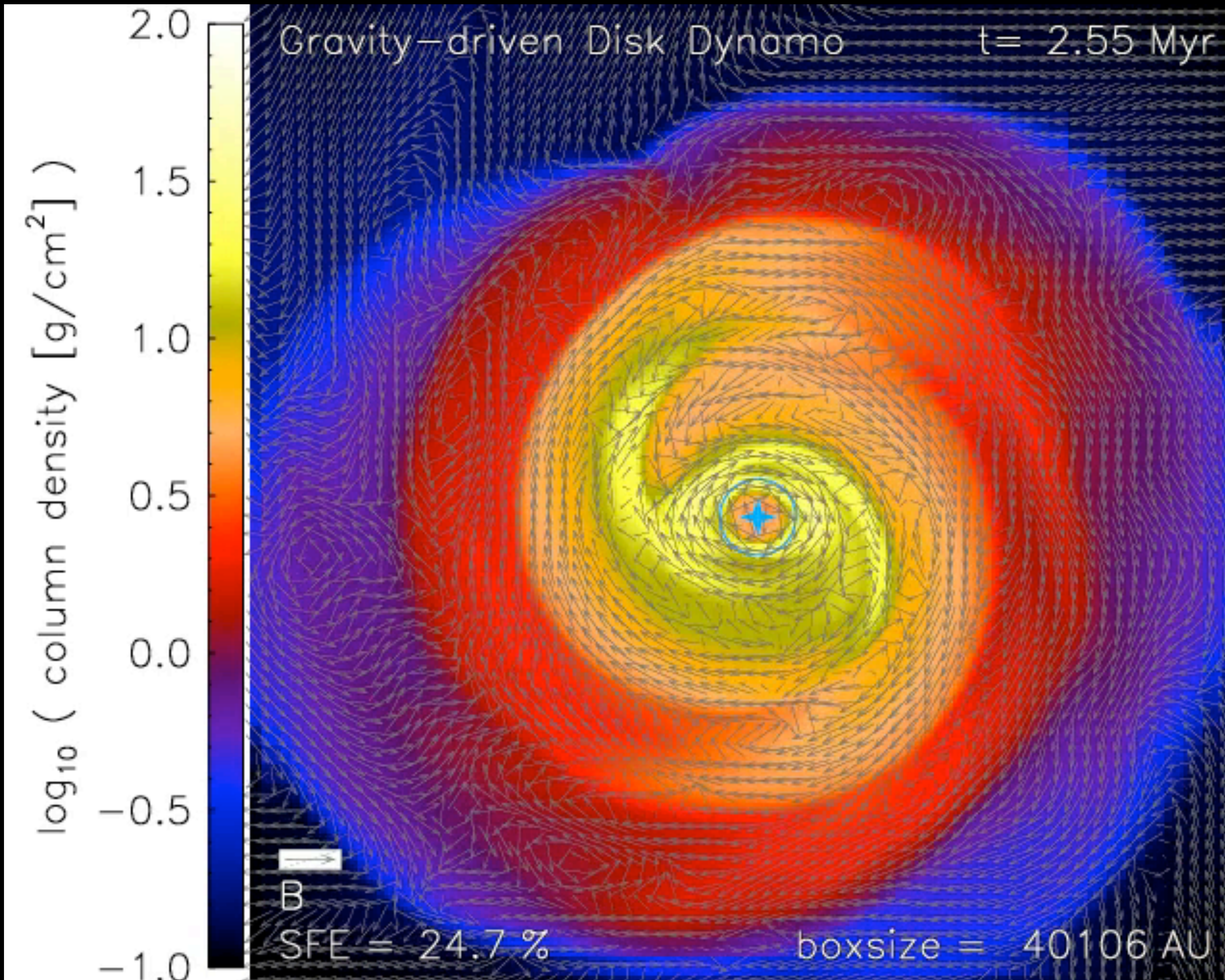




Federrath et al. 2011

And on large scales...

And on large scales...



Disk Dynamo Theory

Induction:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

Lesch 1993

Disk Dynamo Theory

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$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

$$\frac{\partial B_\varphi}{\partial t} = -\frac{\partial}{\partial r}(v_r \mathbf{B}_\varphi) + B_r r \frac{d\Omega}{dr}$$

Lesch 1993

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Take B_r ~ constant

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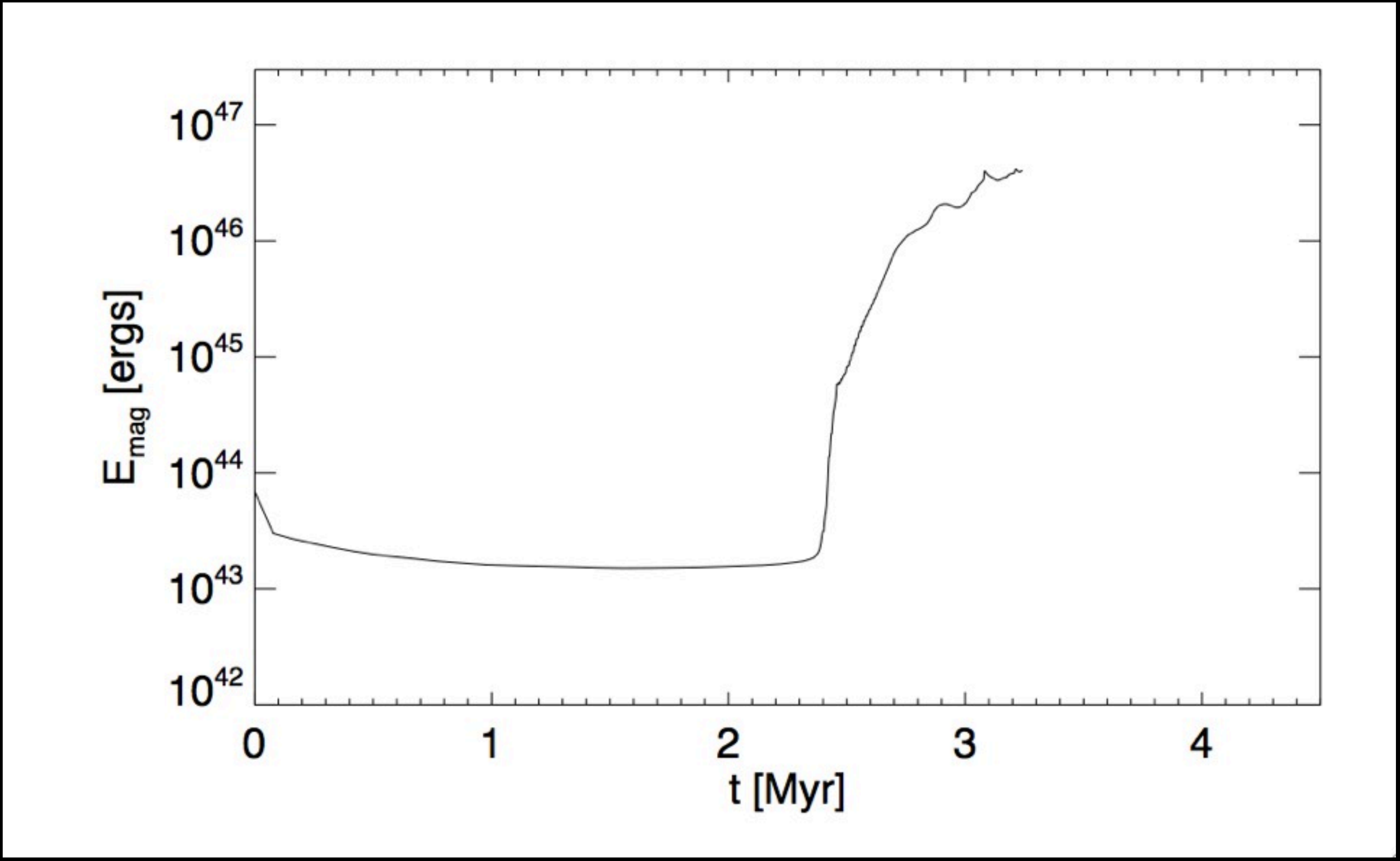
Take B_r ~ constant

$$B_\phi = \left(B_{\phi_0}(r_0) + \tau B_r r \frac{d\Omega}{dr} \right) \exp\left(\frac{t}{\tau}\right) - \tau B_r r \frac{d\Omega}{dr}$$

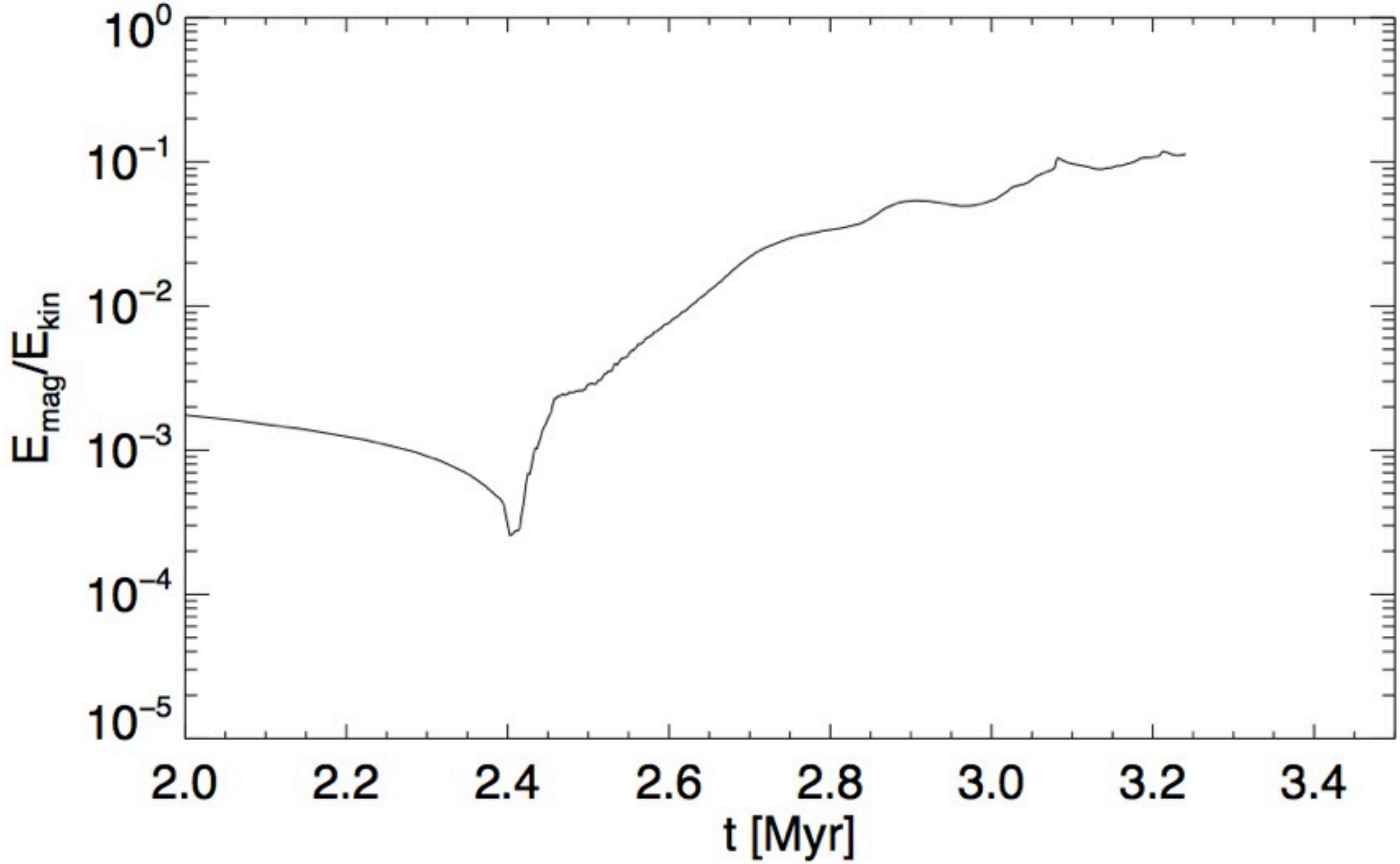
Where $\tau = -\frac{dv_r}{dr}$

Lesch 1993

A Disk Dynamo



A Disk Dynamo



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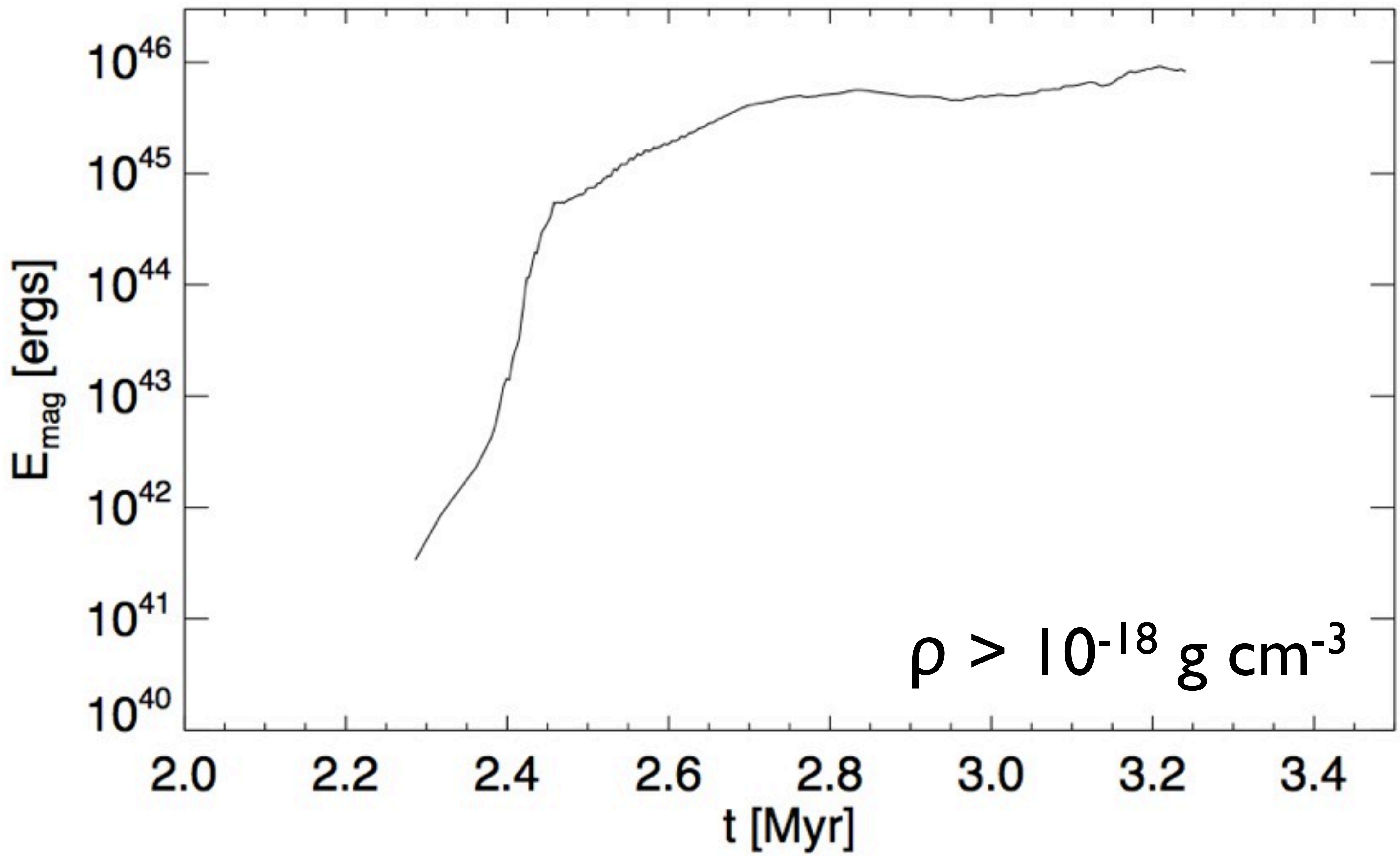


Is this an artifact?

We need a resolution study!

Two ways to define resolution

Jeans Resolution

We refine based on the local Jeans Length

$$\lambda_J = \left(\frac{15 k_B T}{4\pi G \rho \mu}\right)^{1/2}$$

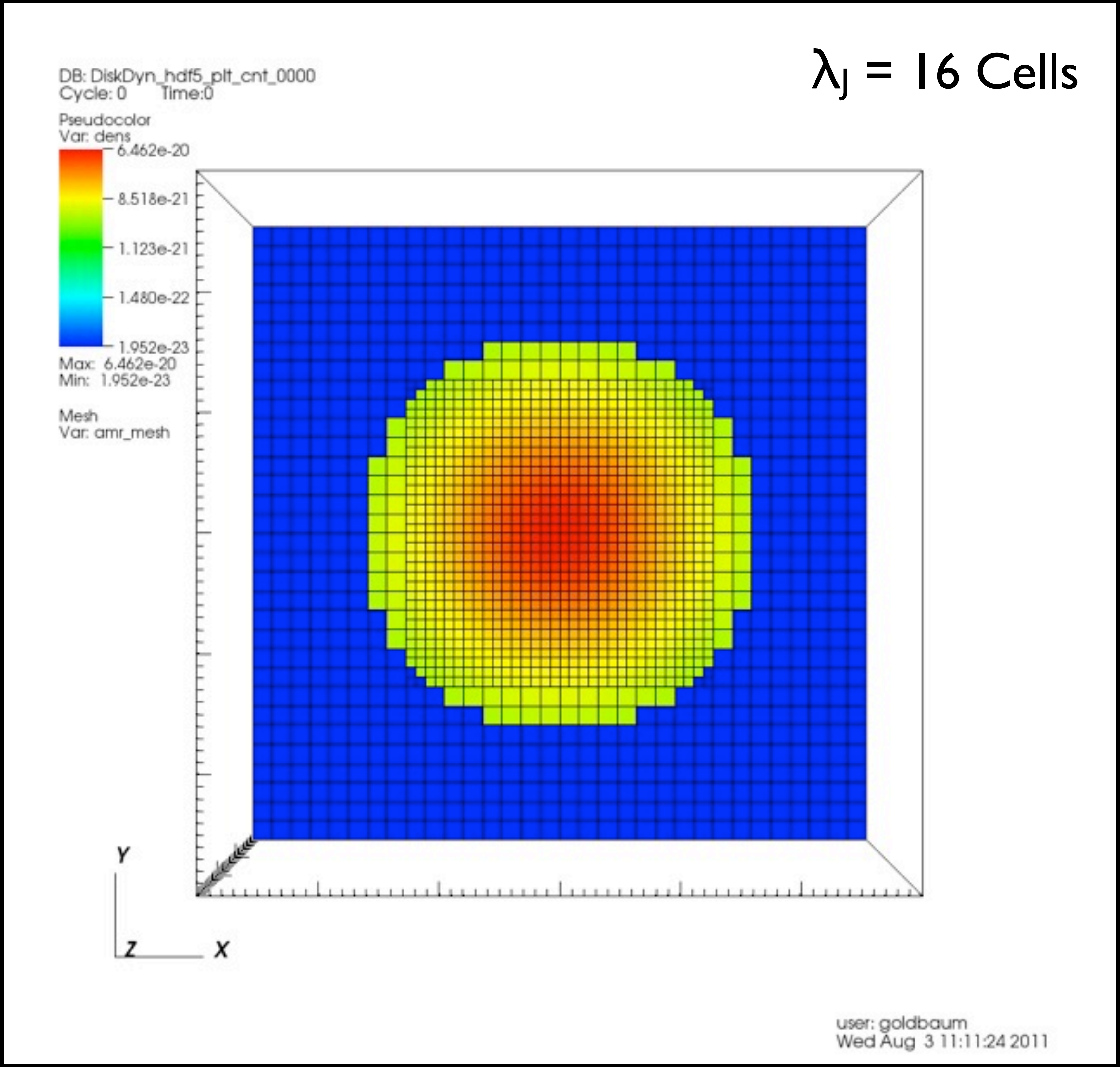
Regions of higher density are naturally more resolved

Can control the number of cells per Jeans length

$\lambda_J =$ 16, 32, and 64 cells

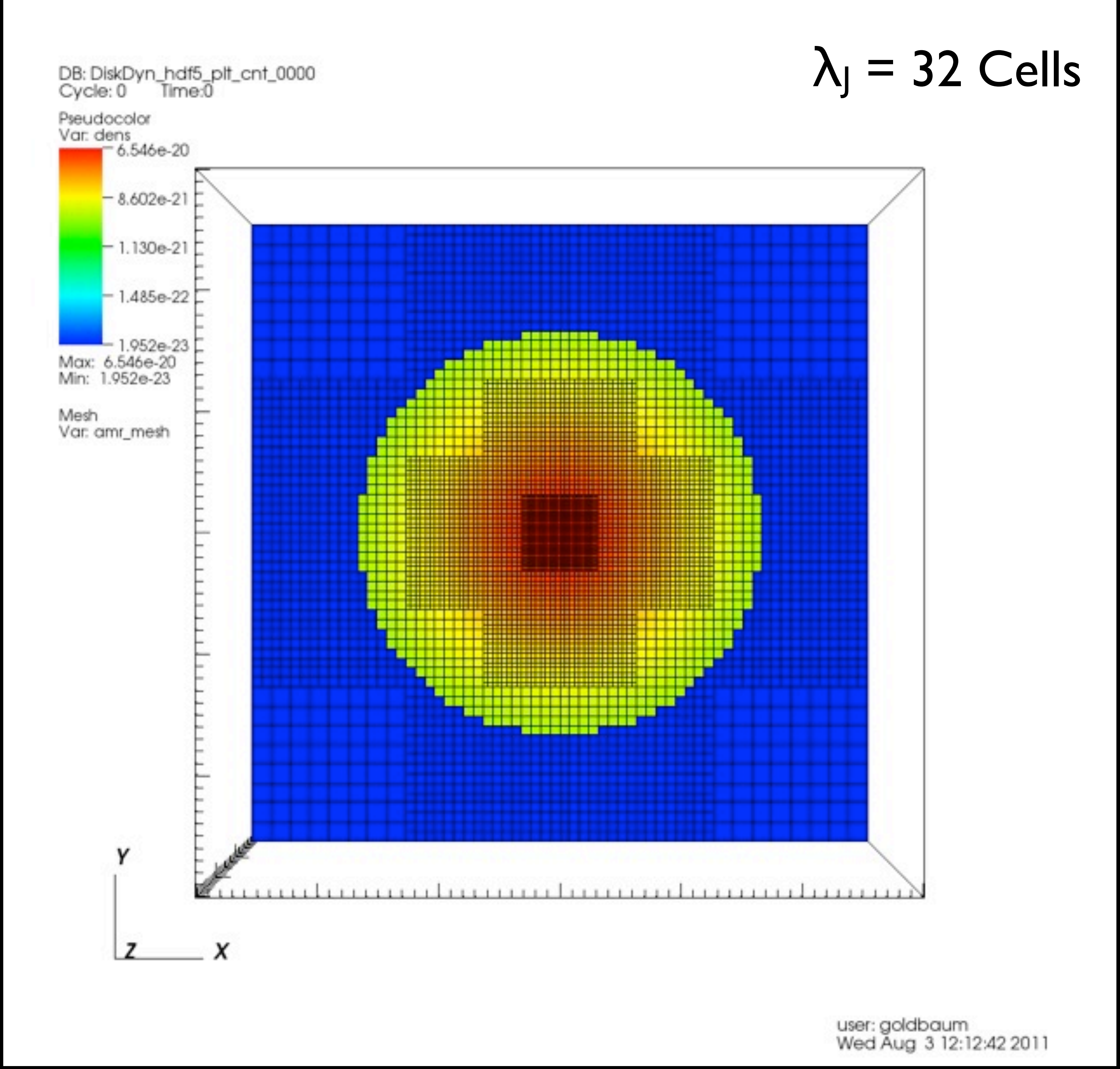
Two ways to define resolution

Jeans Resolution



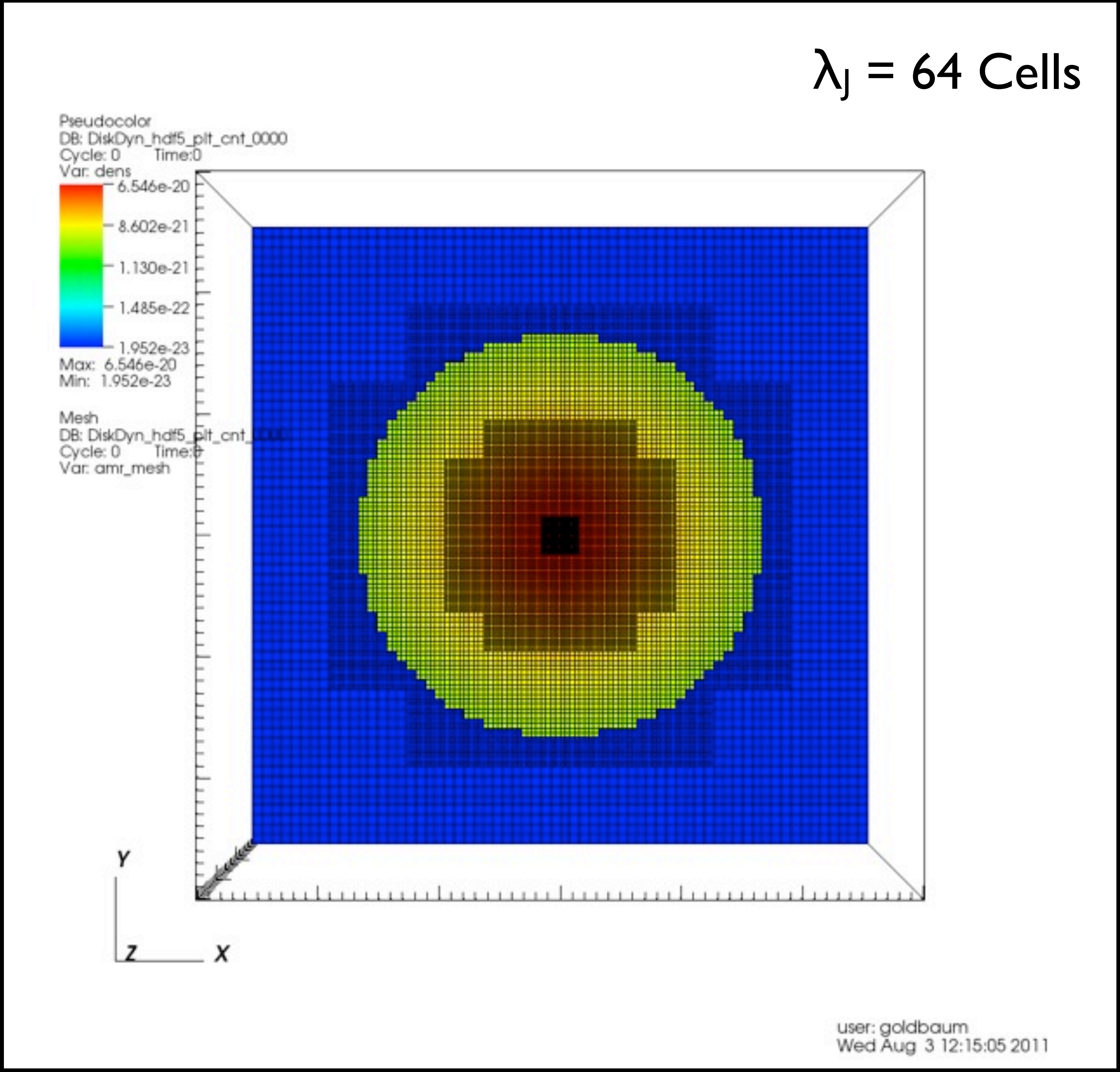
Two ways to define resolution

Jeans Resolution

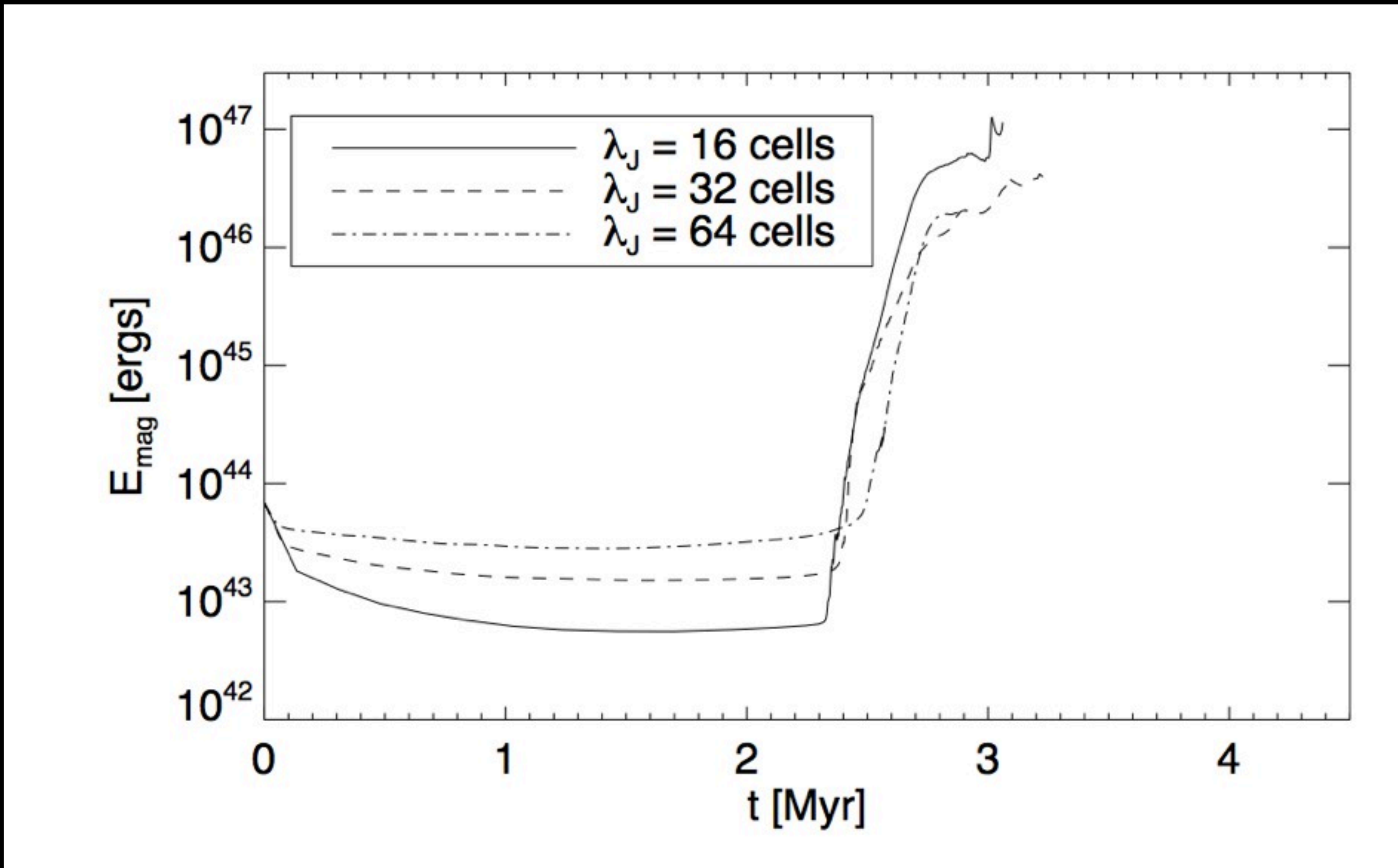


Two ways to define resolution

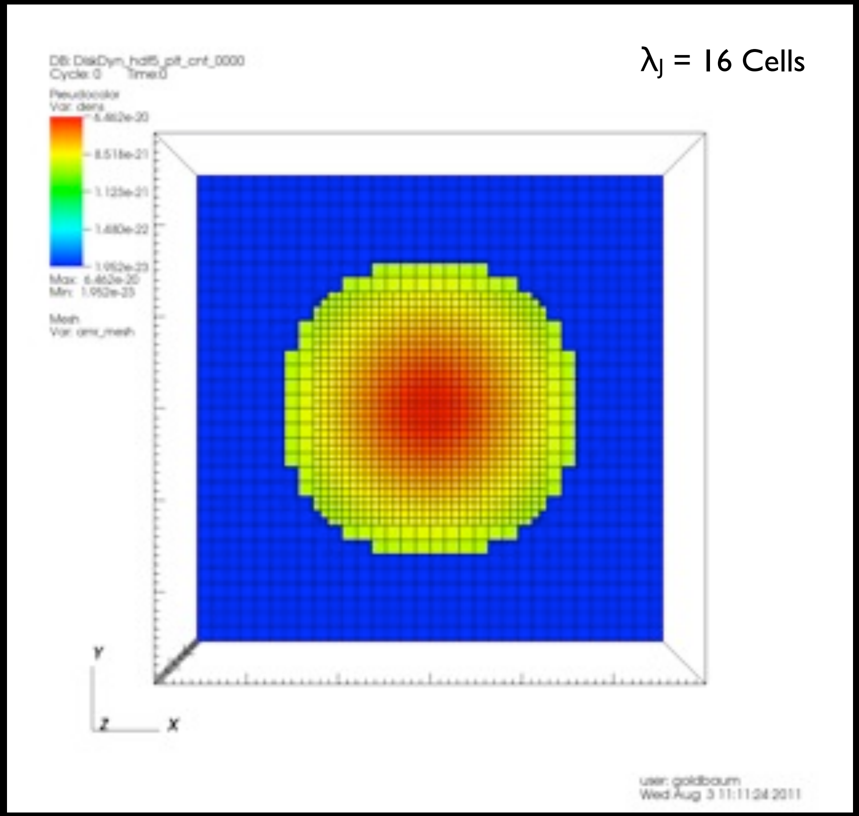
Jeans Resolution

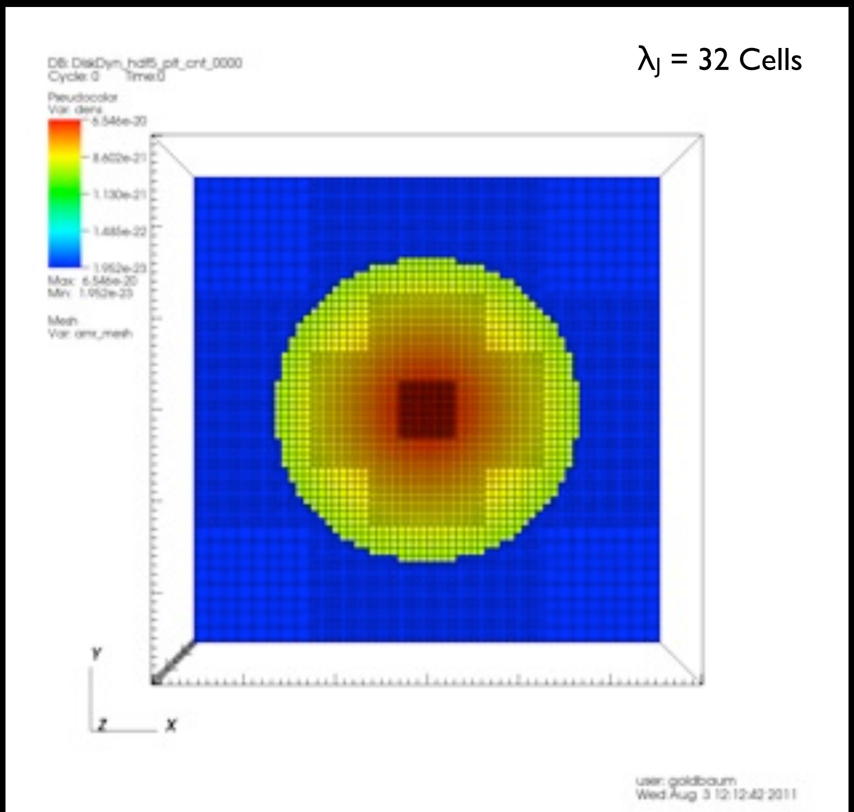


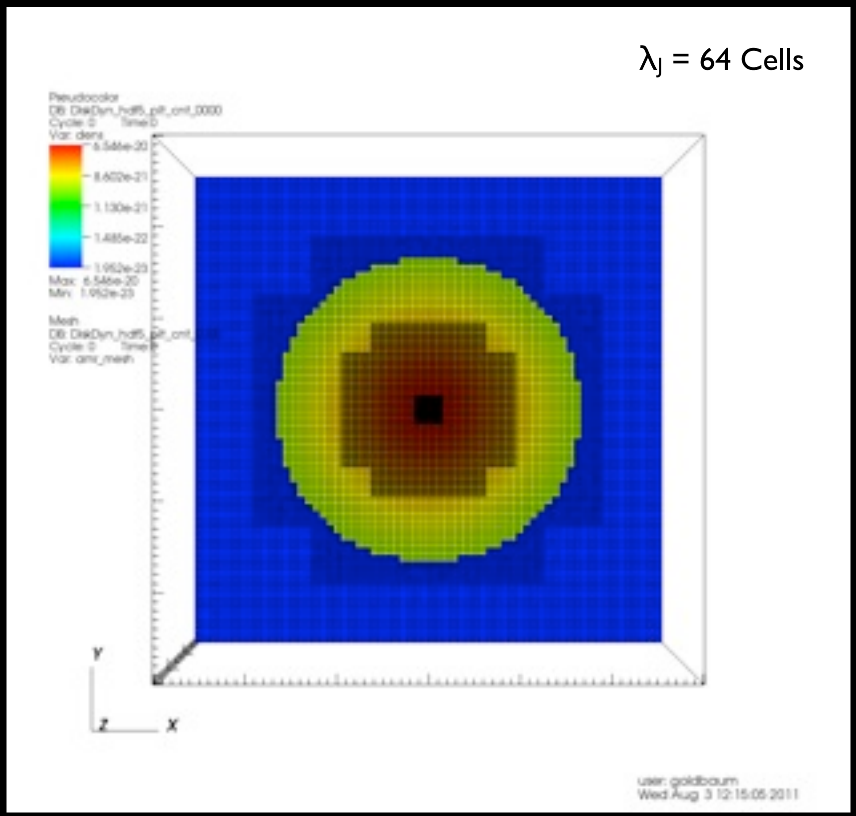
Growth Rate Does Not Depend on Jeans Resolution



Jeans resolution criterion allows us to resolve the initial conditions with more cells

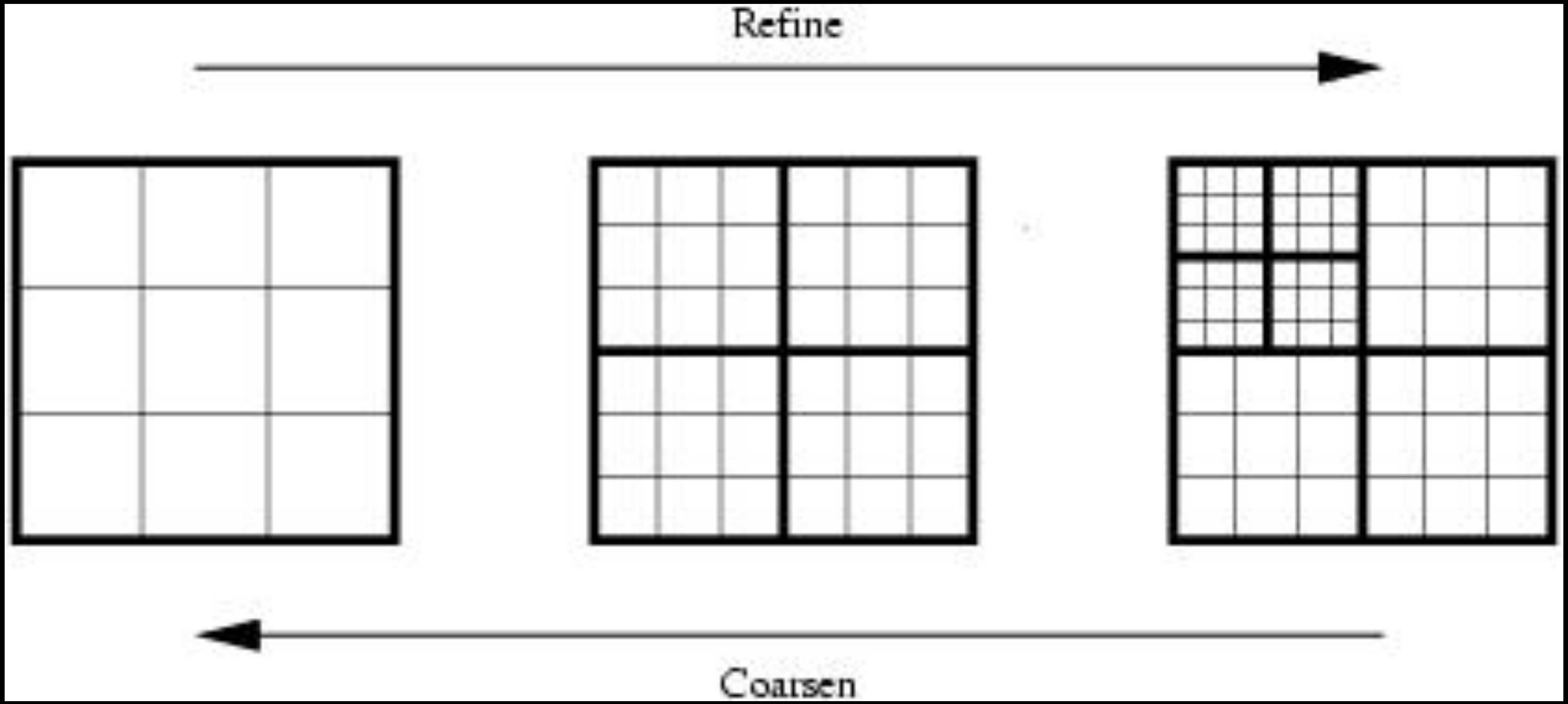






The disk is not necessarily more resolved at higher Jeans resolution

Disk resolution is determined by the maximum refinement level

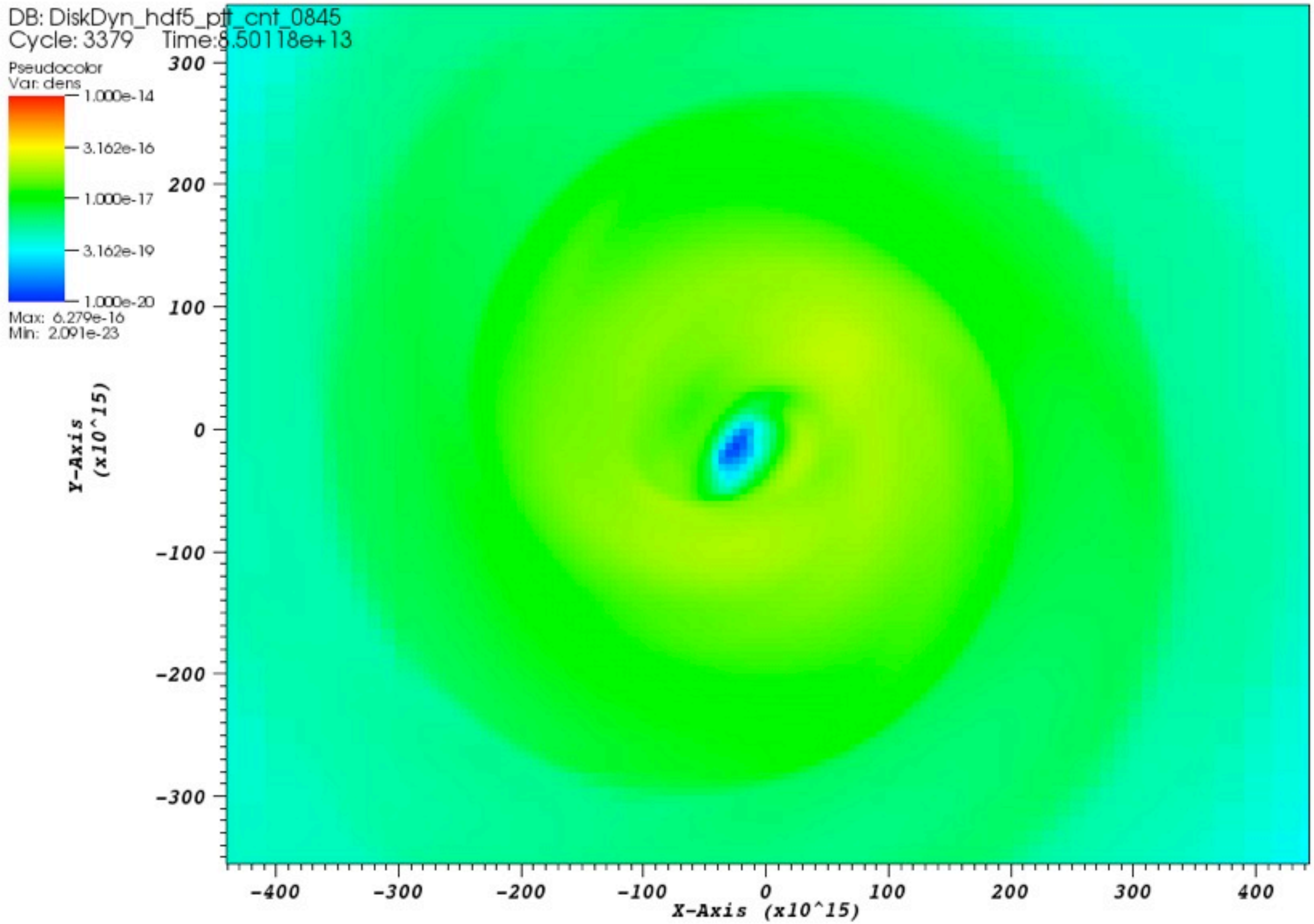


Choose three effective resolutions: 2048^3, 4096^3, 8192^3

Two ways to define resolution

Maximum Refinement Level

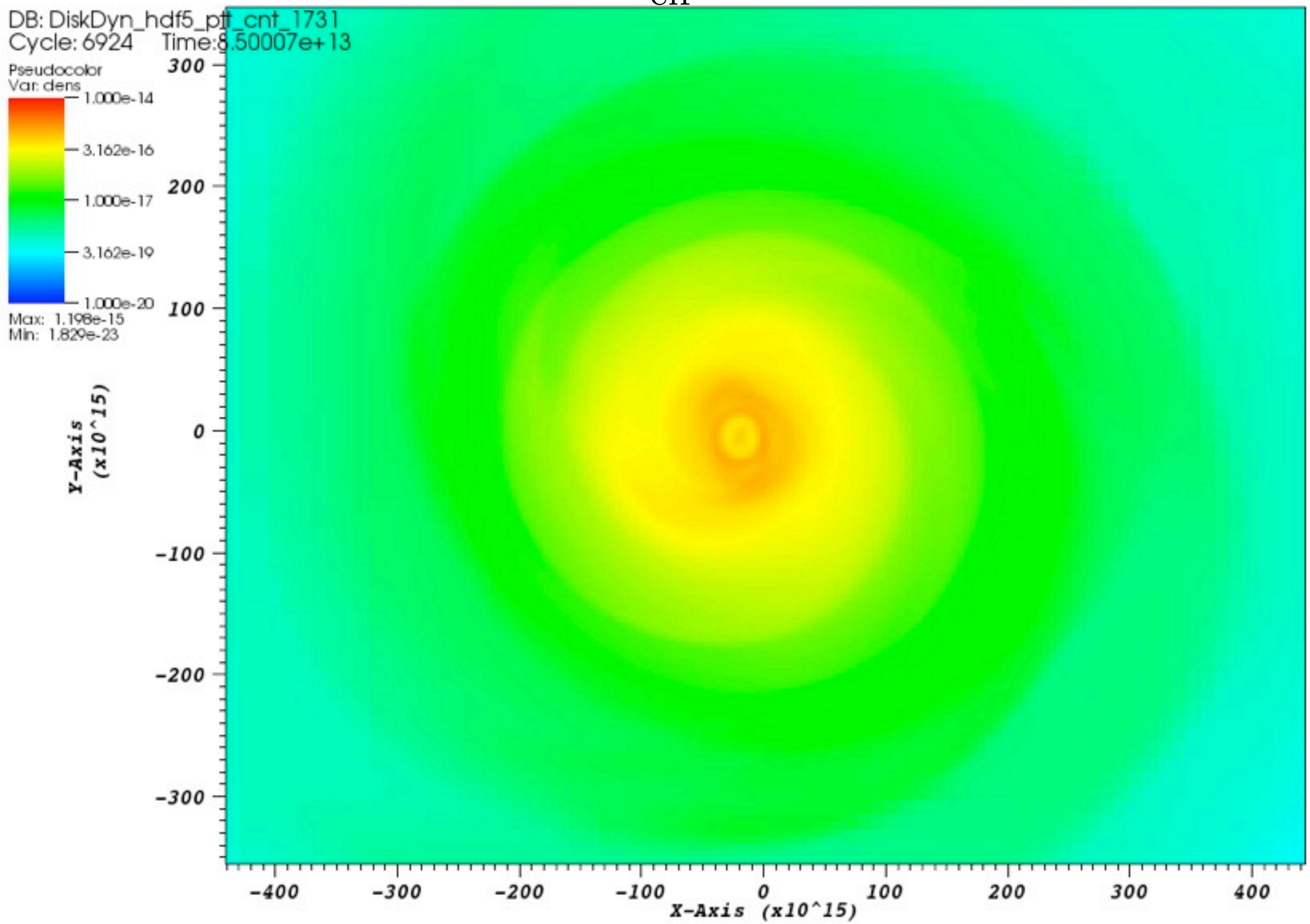
$R_{\rm eff} = 2048^3$



Two ways to define resolution

Maximum Refinement Level

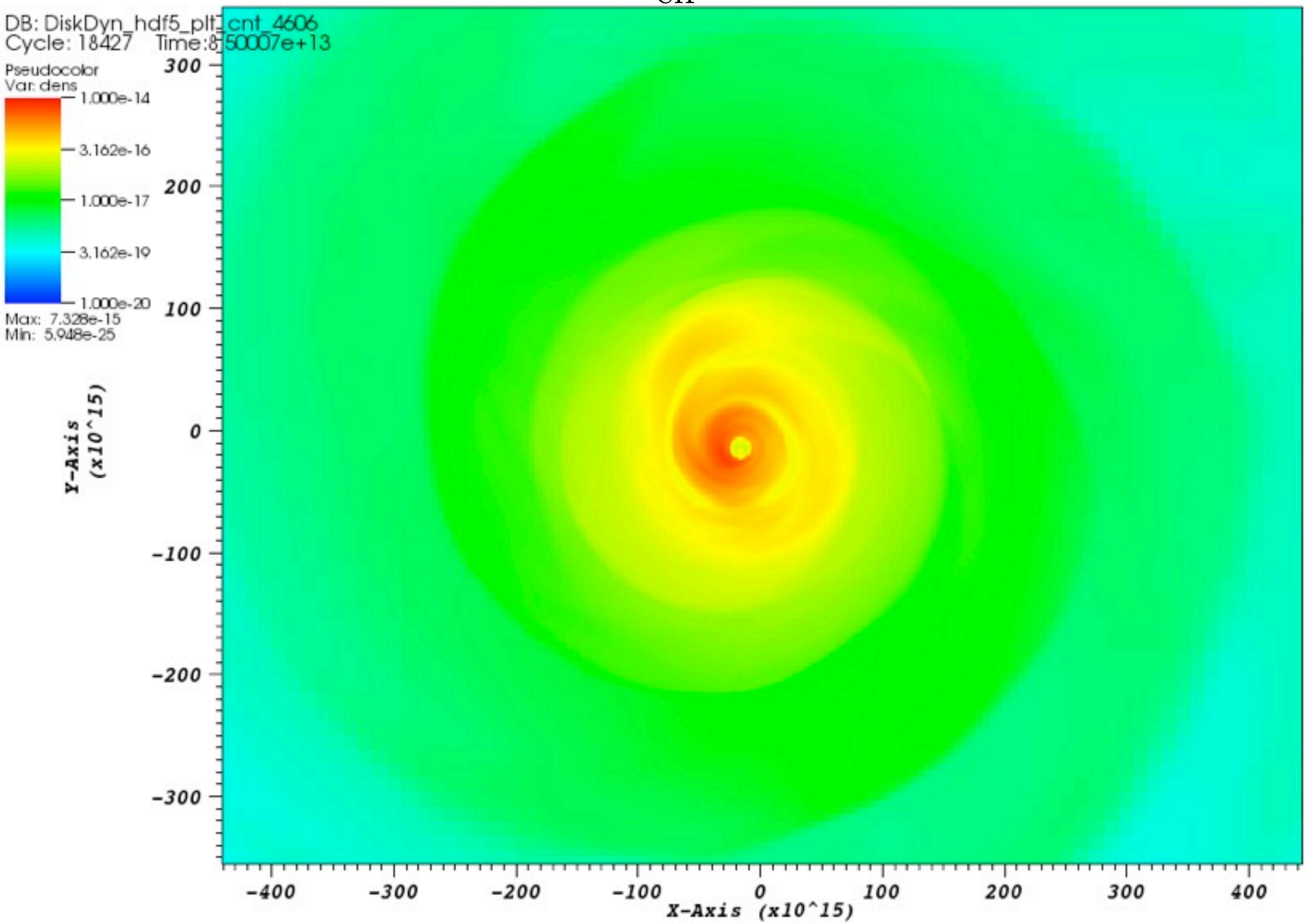
$R_{\text{eff}} = 4096^3$



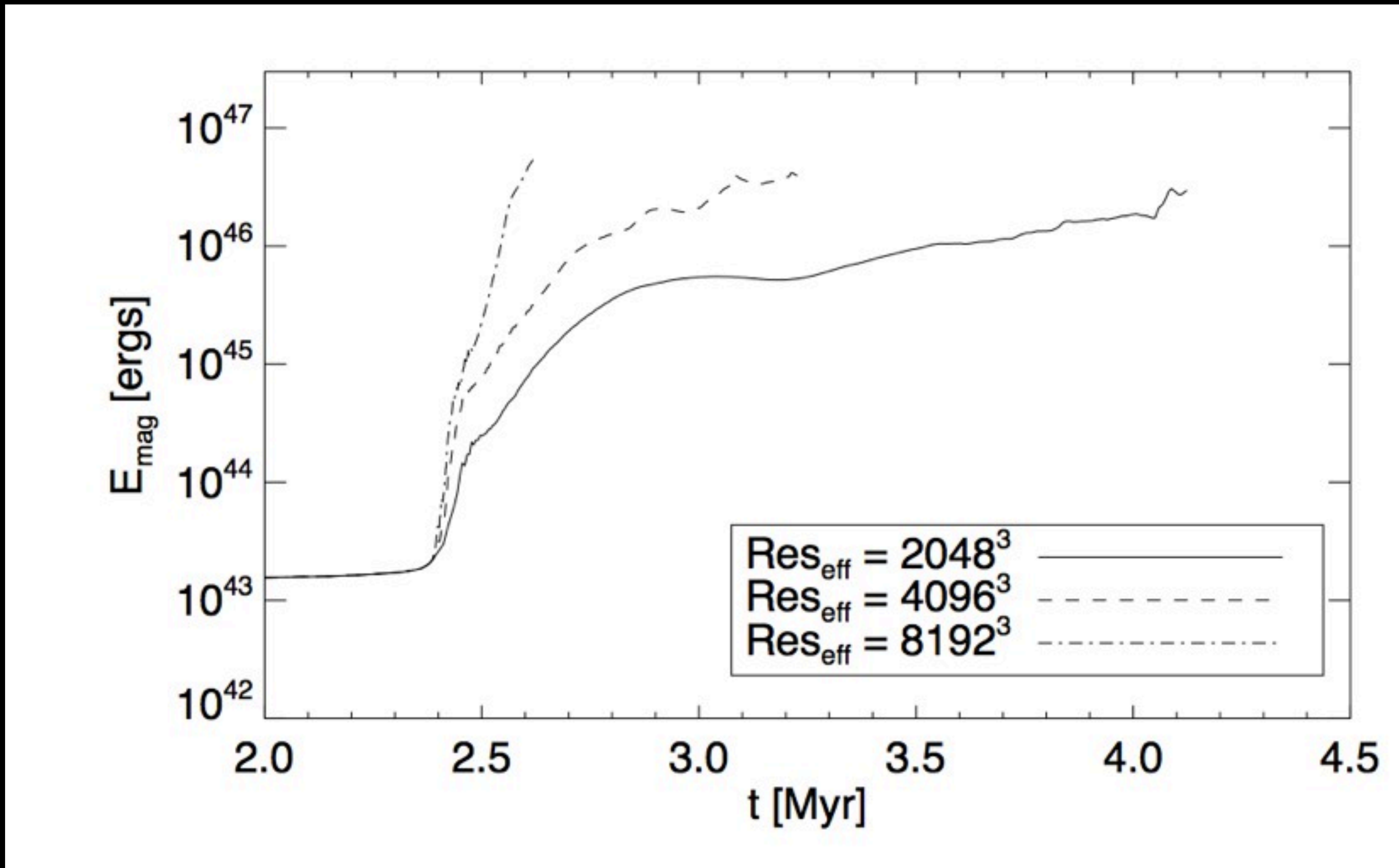
Two ways to define resolution

Maximum Refinement Level

$R_{\mathrm{eff}} = 8192^3$



Growth Rate Depends on Effective Resolution



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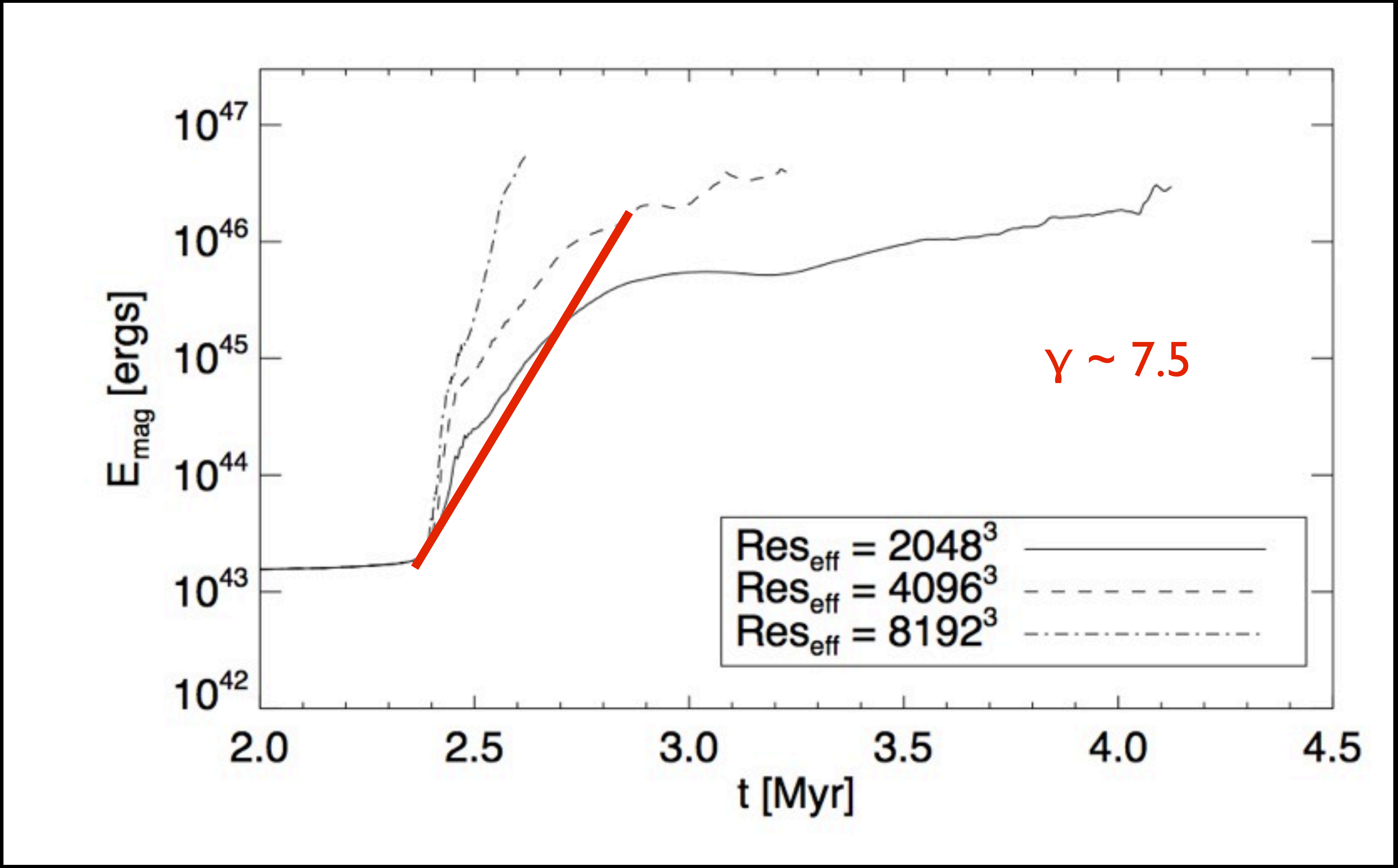

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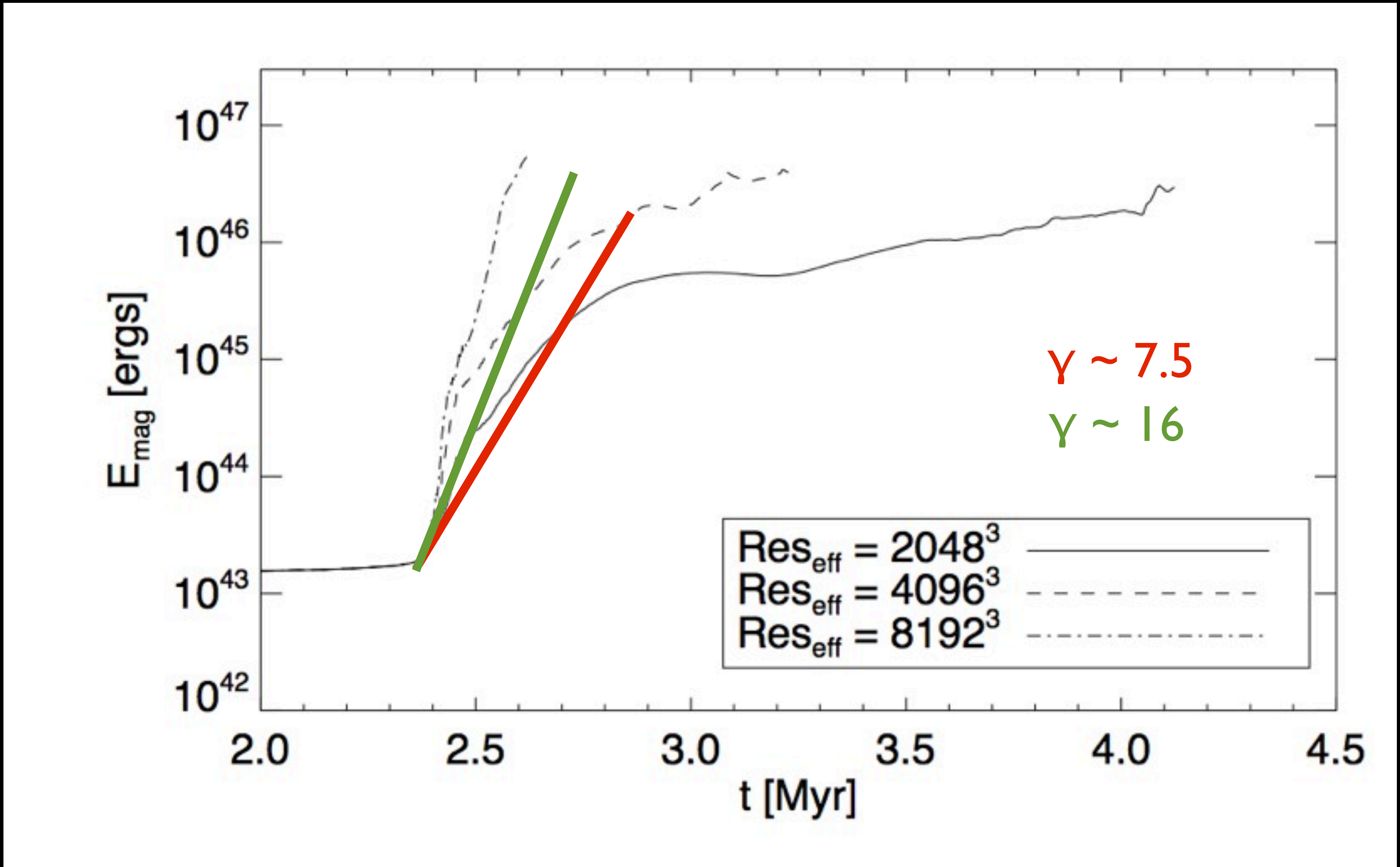

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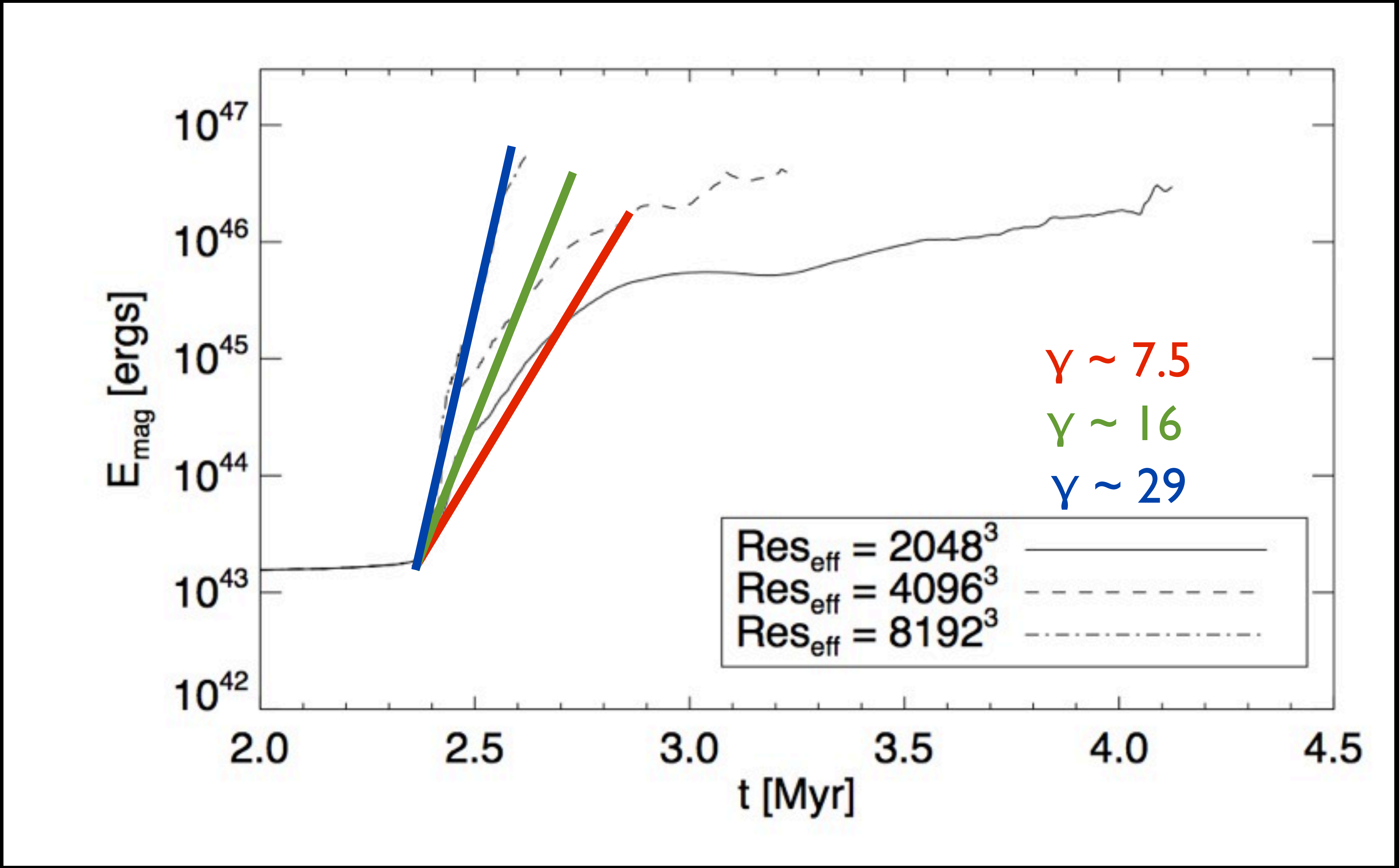

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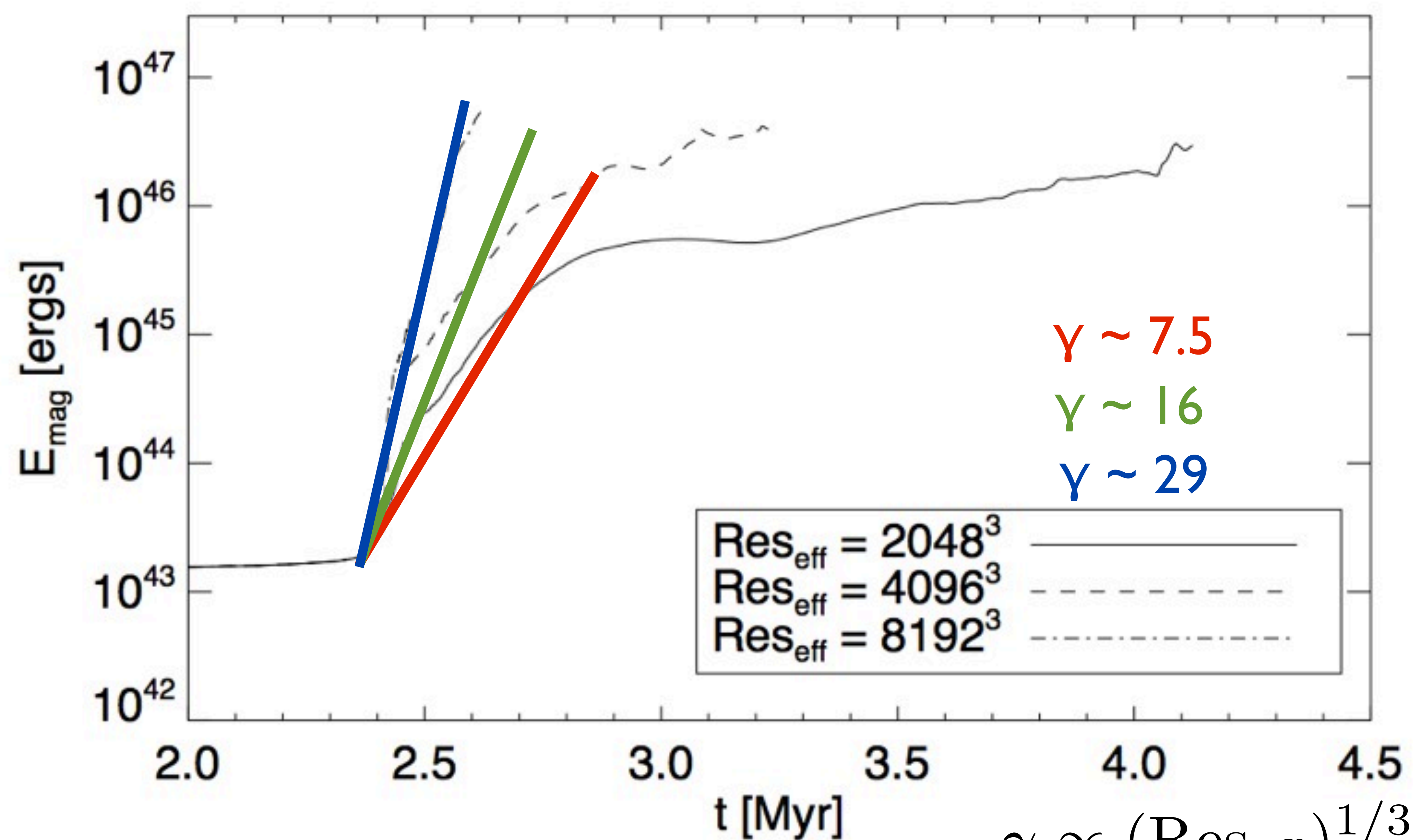

$$\gamma \propto (\mathrm{Res_{eff}})^{1/3}$$

Generation of Large-Scale Fields

$$\beta = \frac{P_{\rm gas}}{P_{\rm mag}}$$

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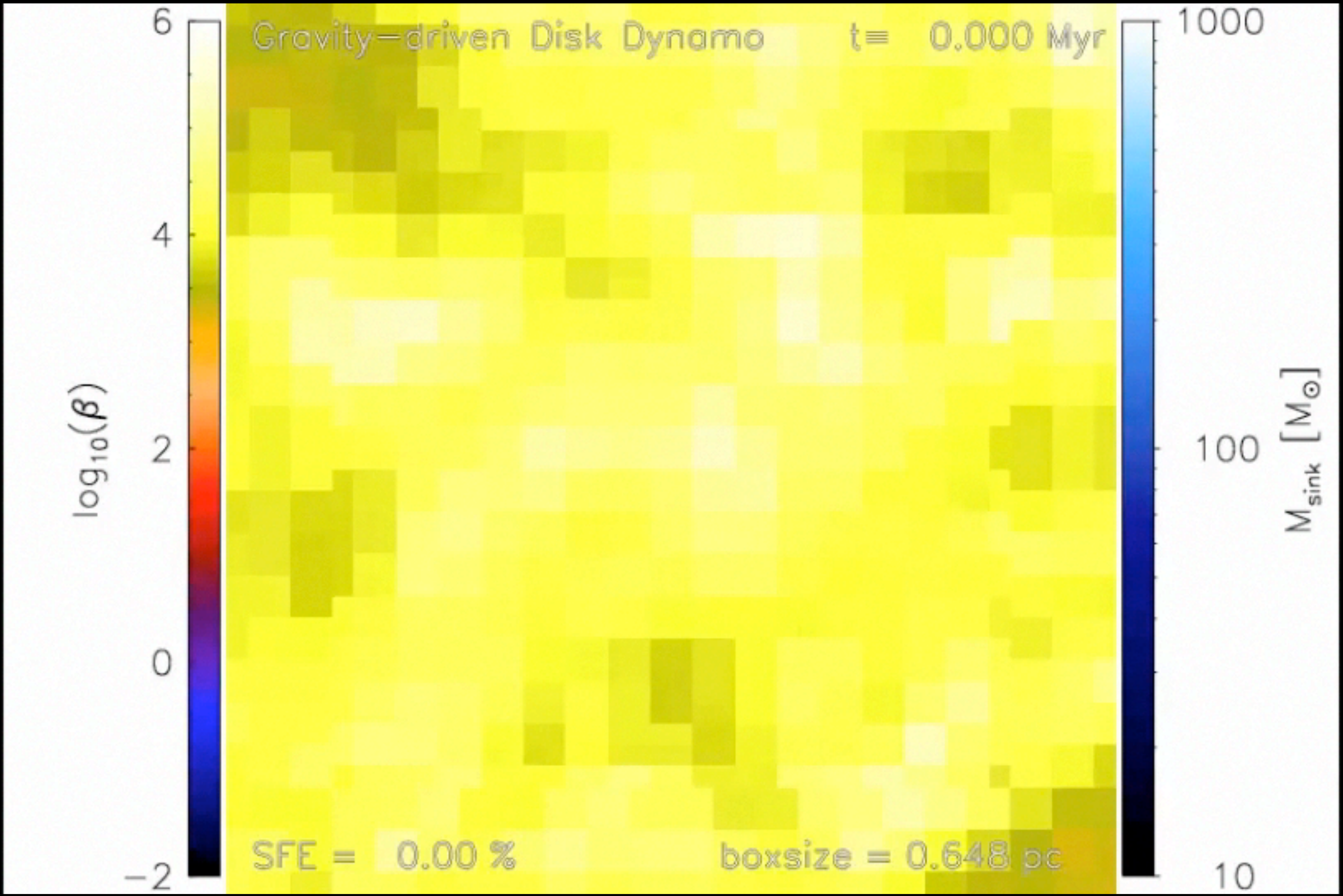

$$\beta = \frac{P_{\rm gas}}{P_{\rm mag}}$$

Summary

- Perfomed MHD simulations of collapsing cores
- Observed dynamo generation of magnetic fields
- Field growth depends on effective resolution and not on Jeans resolution
- Generated outflow from an initially randomly oriented magnetic field!