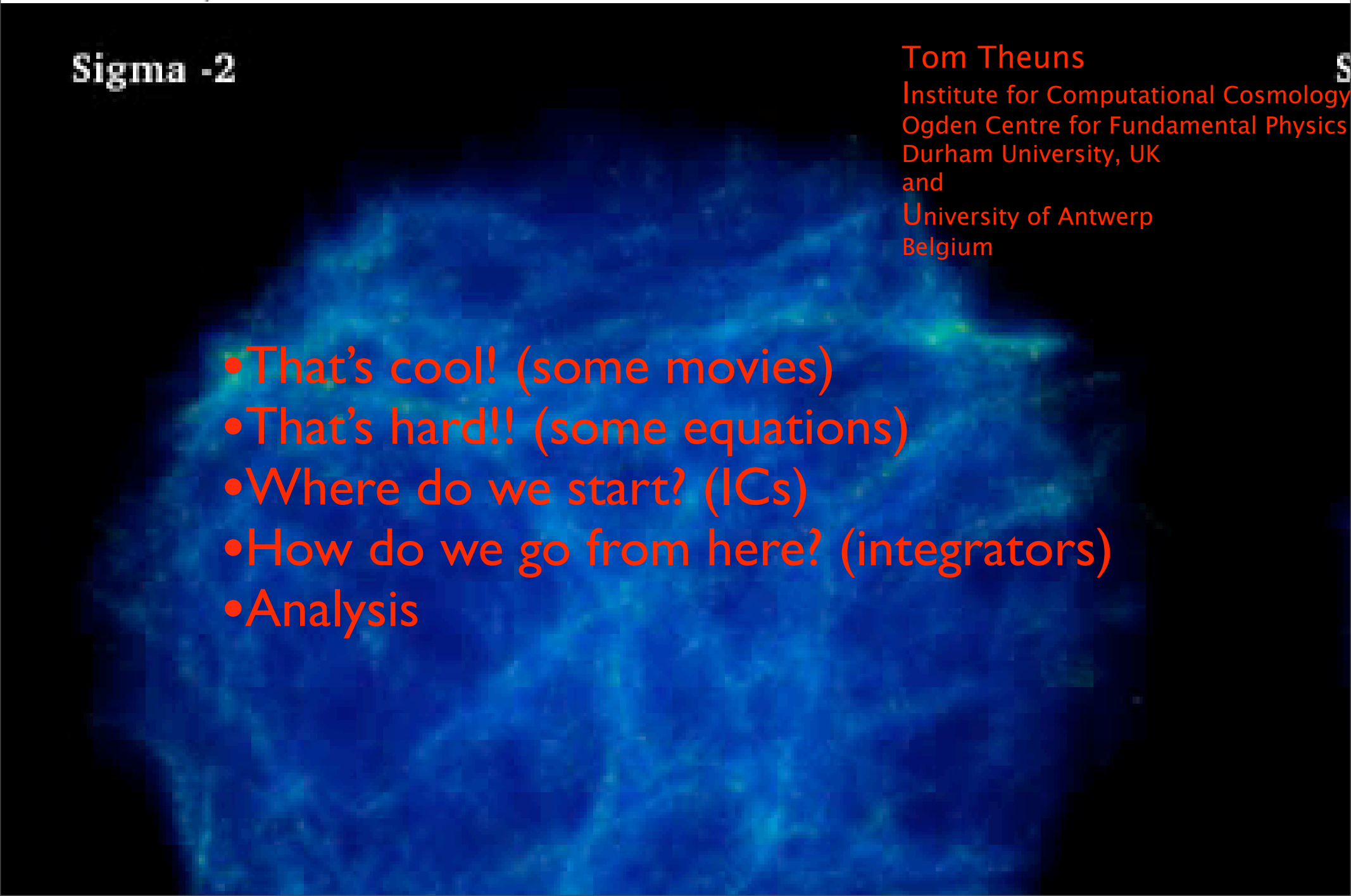
Cosmology, Theory & Simulation



Tom Theuns
Institute for Computational Cosmology
Ogden Centre for Fundamental Physics
Durham University, UK
and
University of Antwerp
Belgium

- That's cool! (some movies)
- That's hard!! (some equations)
- Where do we start? (ICs)
- How do we go from here? (integrators)
- Analysis


Multi-wavelength view of M81

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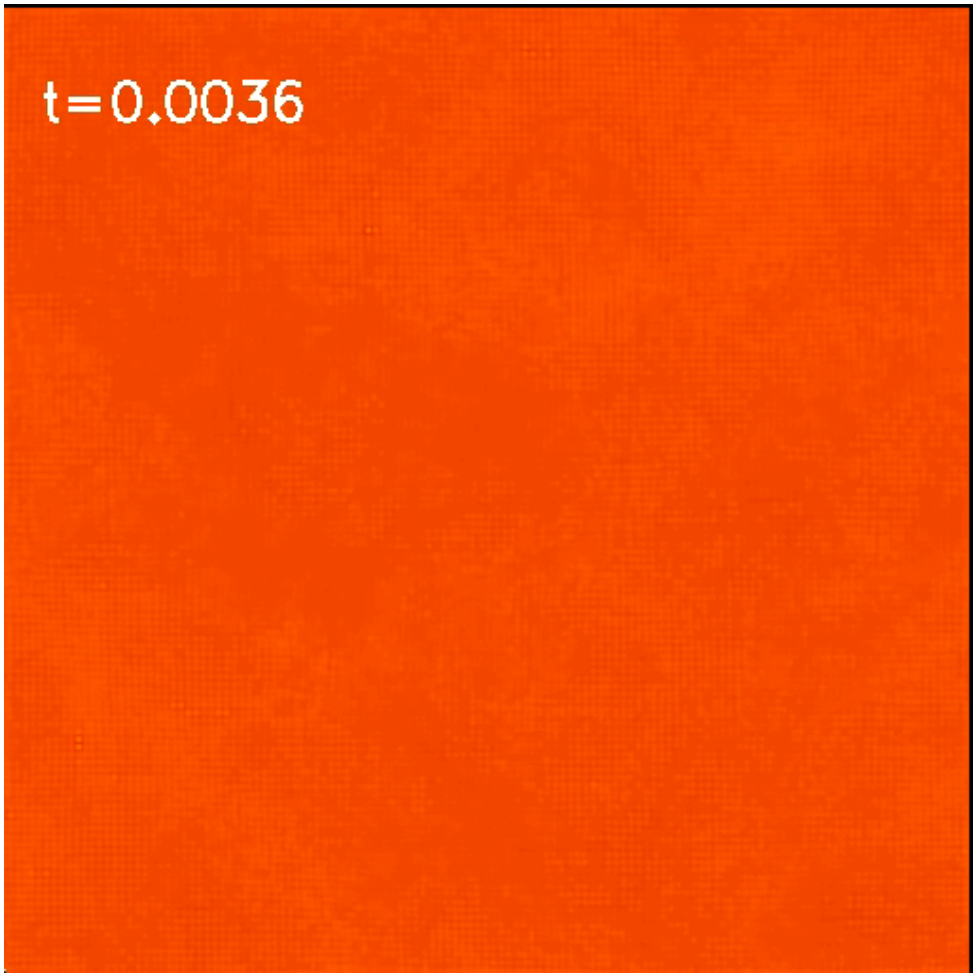
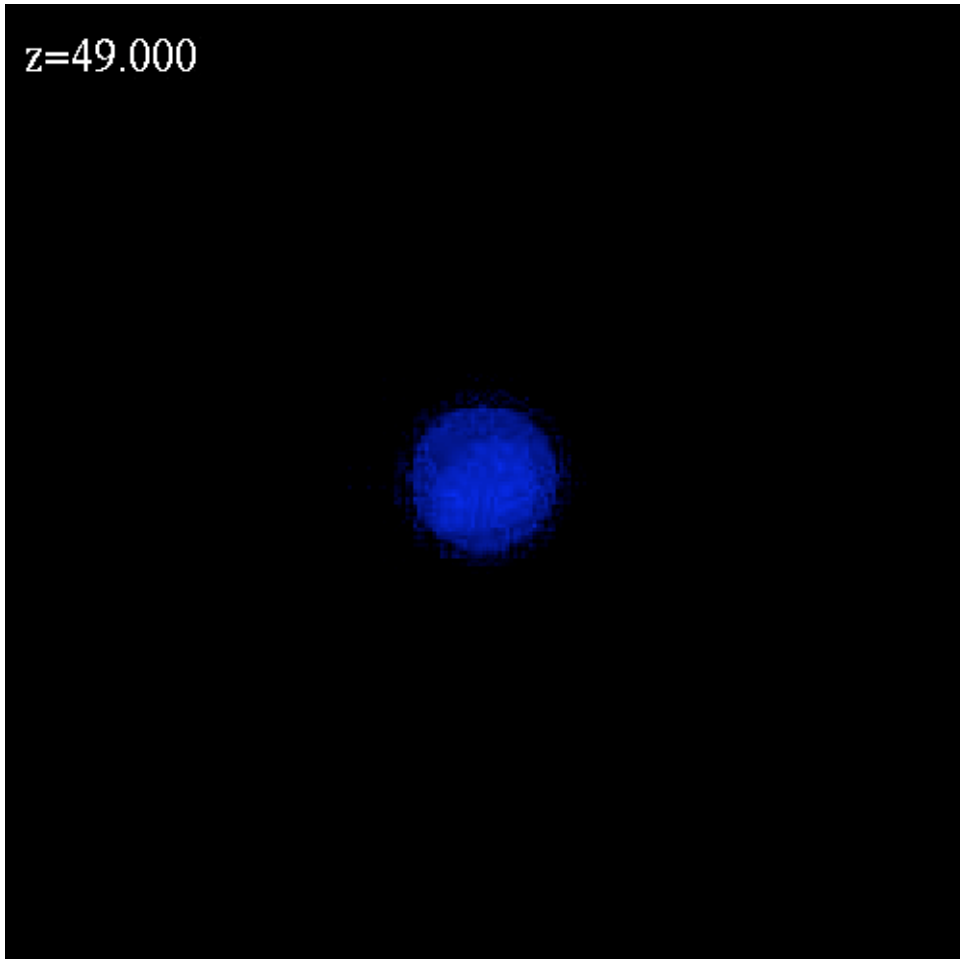
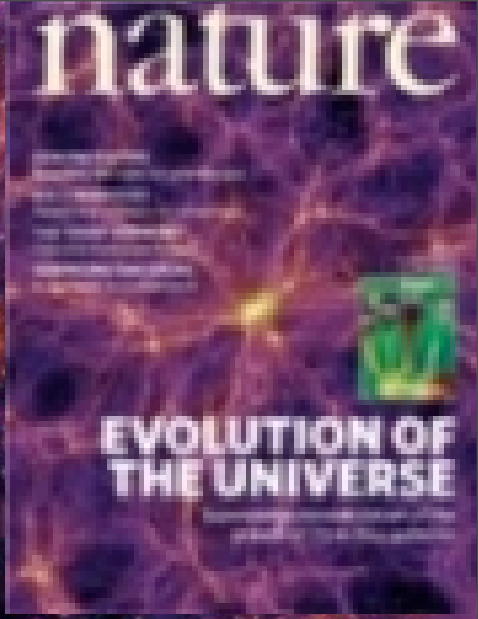
Jenkins



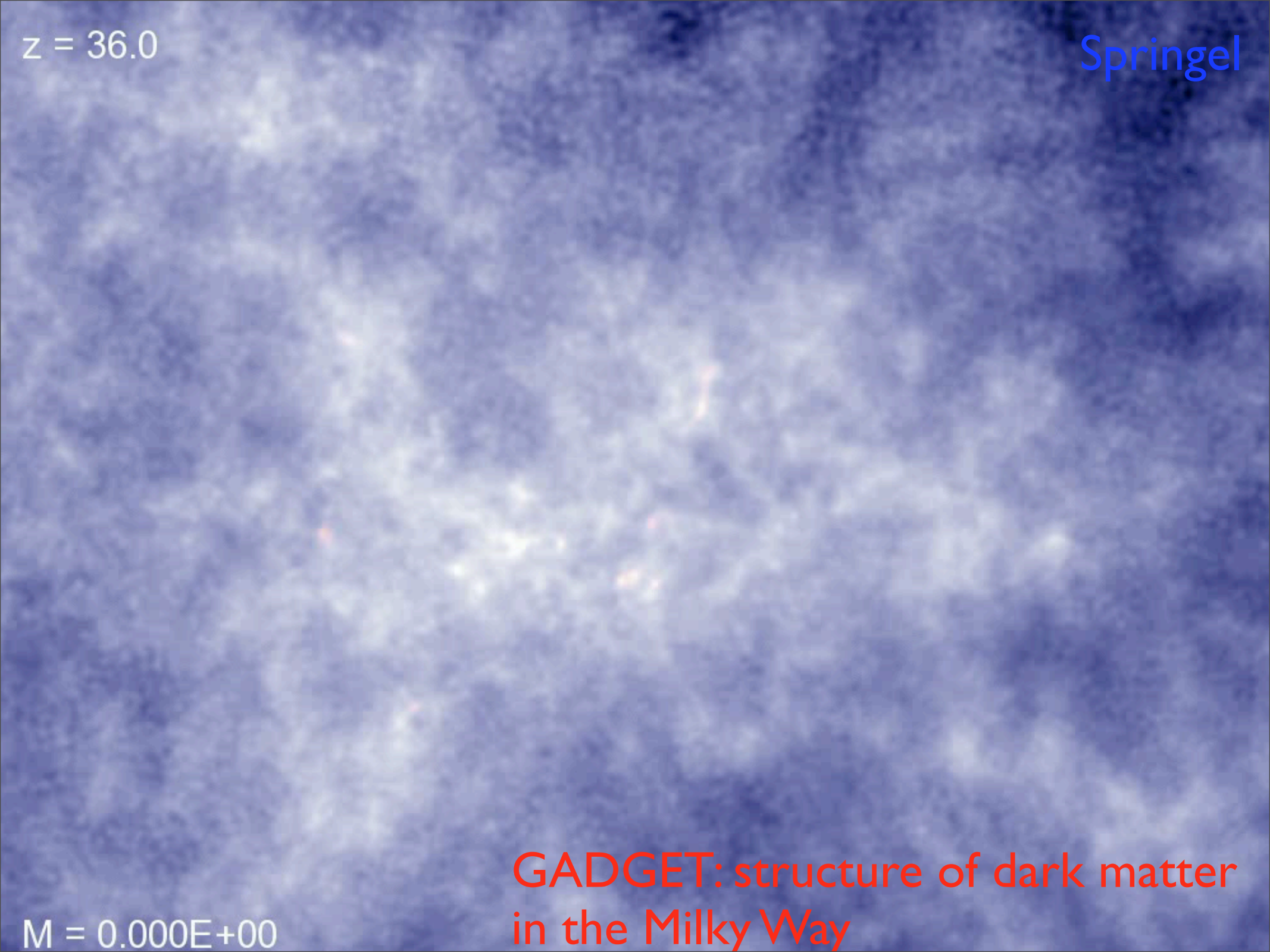


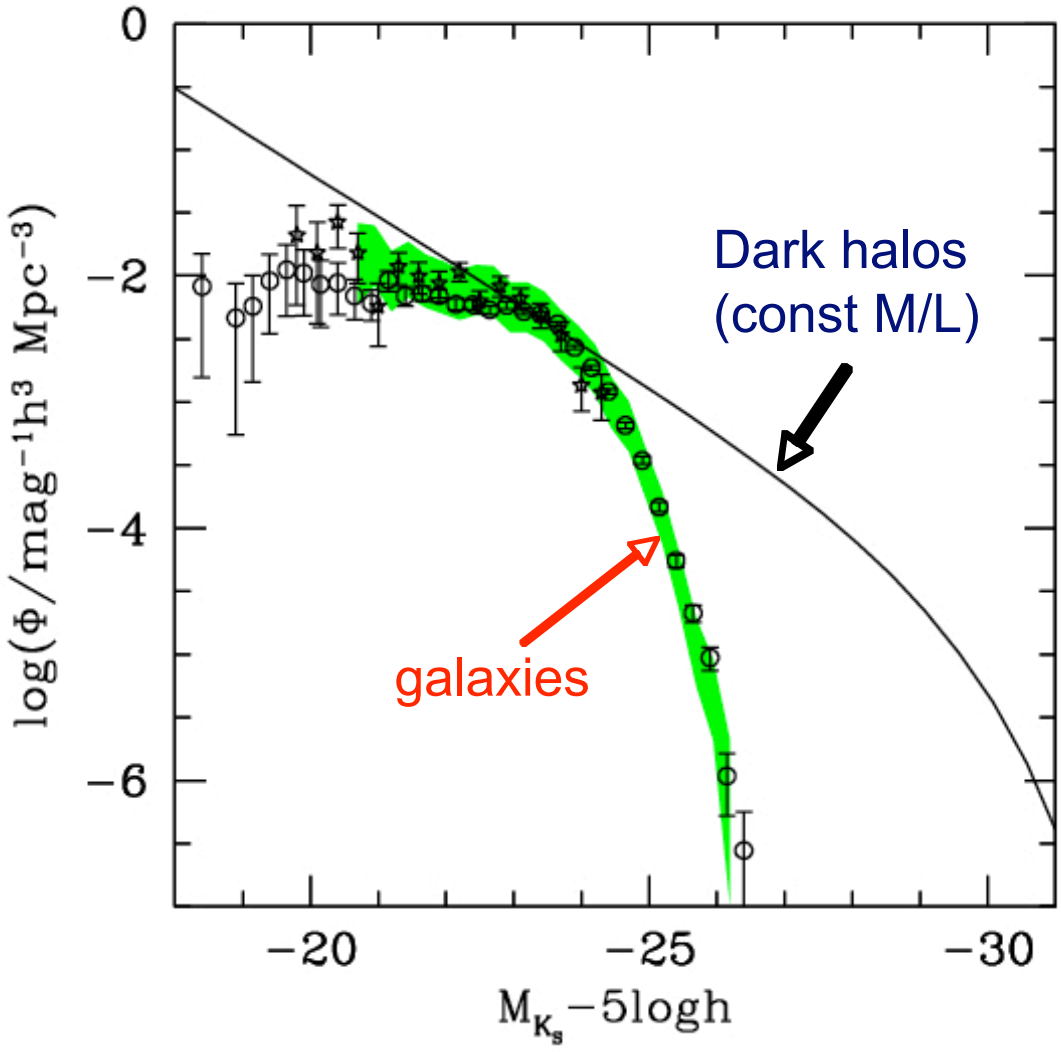
HYDRA: formation of structure

Springel



GADGET: structure of dark matter

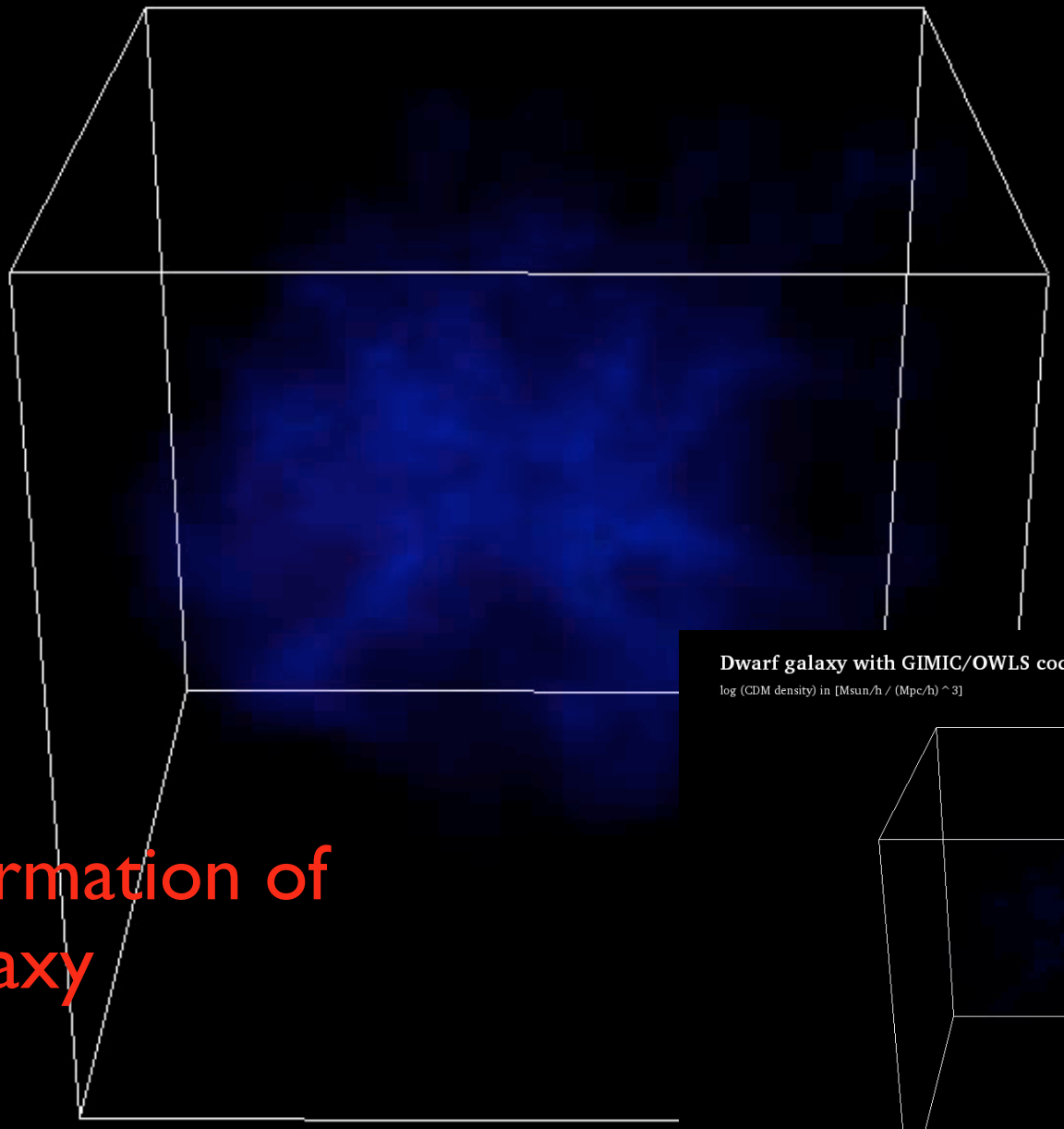

z = 36.0
Springel
GADGET: structure of dark matter
in the Milky Way
M = 0.000E+00


0
−2
−4
−6
log(Φ/mag⁻¹h³ Mpc⁻³)
−20
−25
−30
M_Ks −5logh
Dark halos
(const M/L)
galaxies

Dwarf galaxy with GIMIC/OWLS code

log (Gas density) in [Msun/h / (Mpc/h) ^ 3]

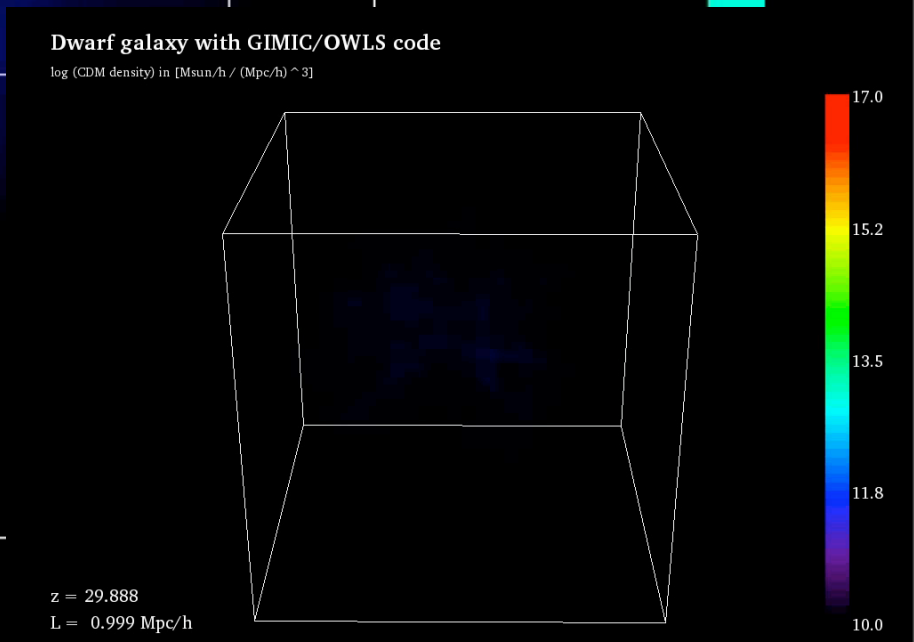
Crain & TT



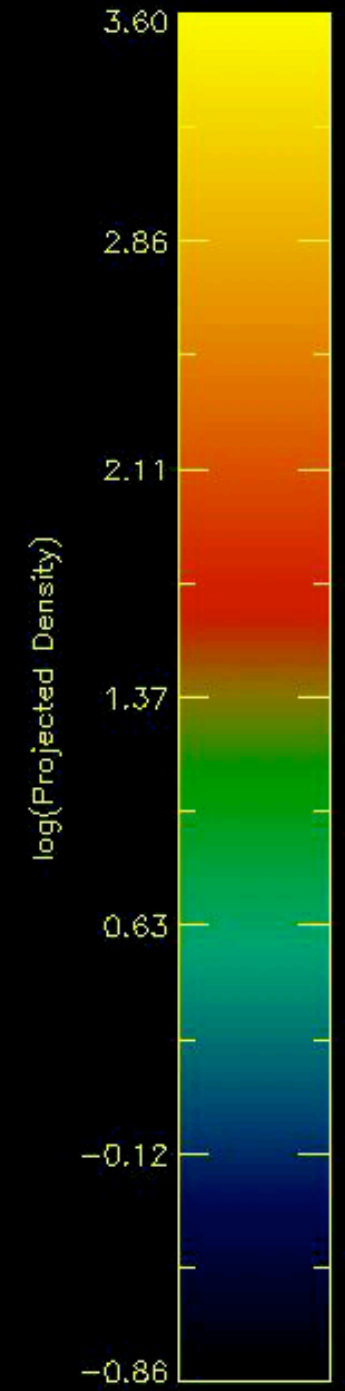
GADGET: formation of individual galaxy

z = 29.888

L = 0.999 Mpc/h



Wise & Abel



ENZO: first galaxies

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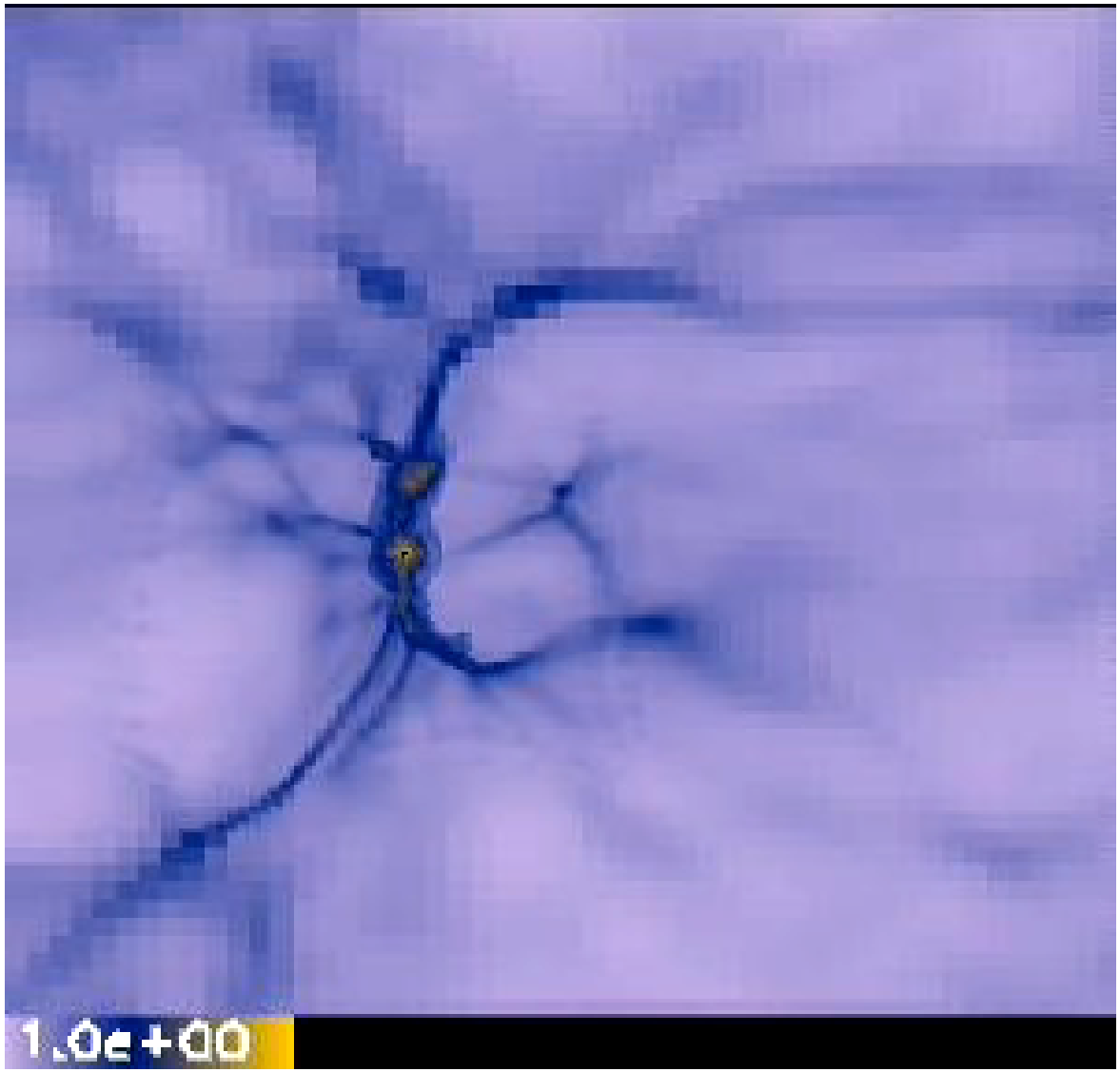
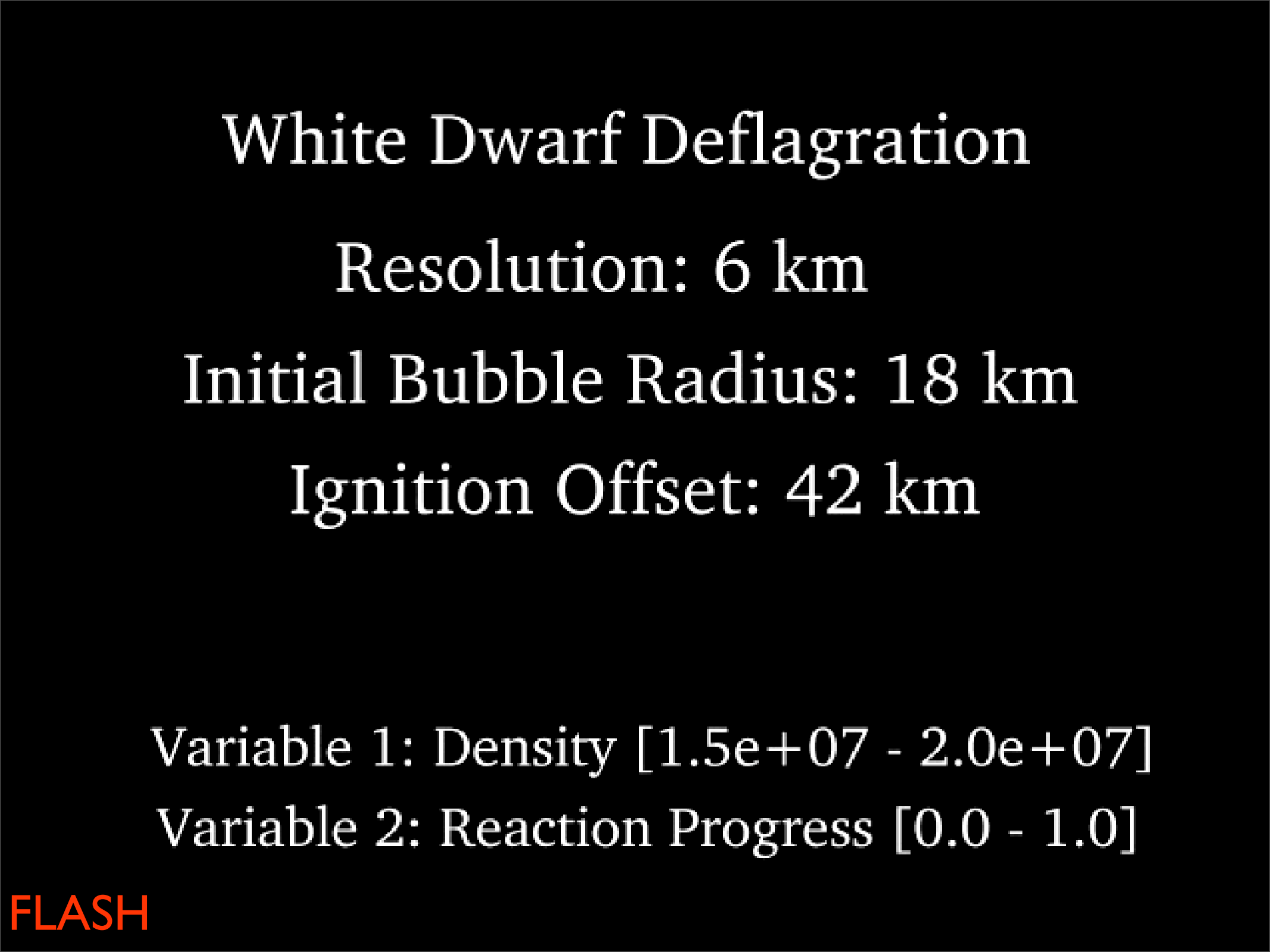
Abel



ENZO: first stars

Tom Theuns

ICC Institute for Computational Cosmology


White Dwarf Deflagration
Resolution: 6 km
Initial Bubble Radius: 18 km
Ignition Offset: 42 km
Variable 1: Density [1.5e+07 - 2.0e+07]
Variable 2: Reaction Progress [0.0 - 1.0]
FLASH

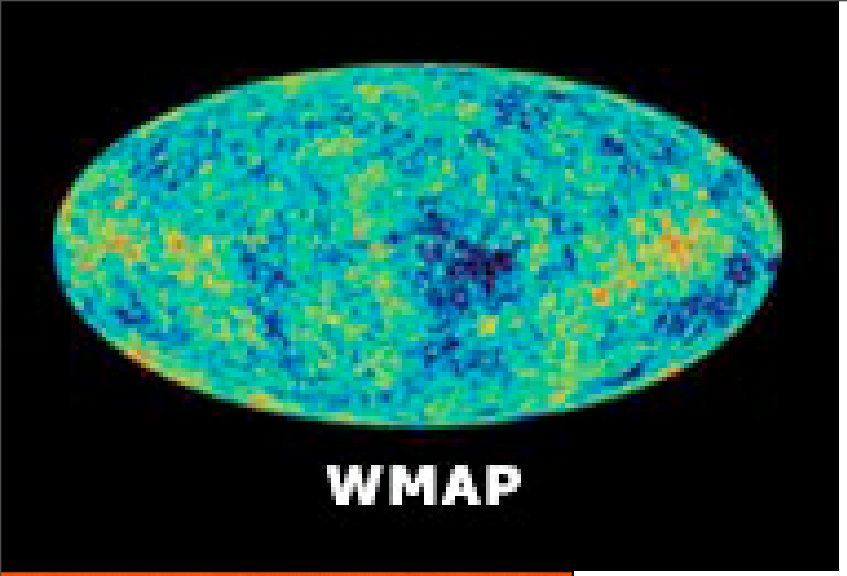
Durham University

What we want:

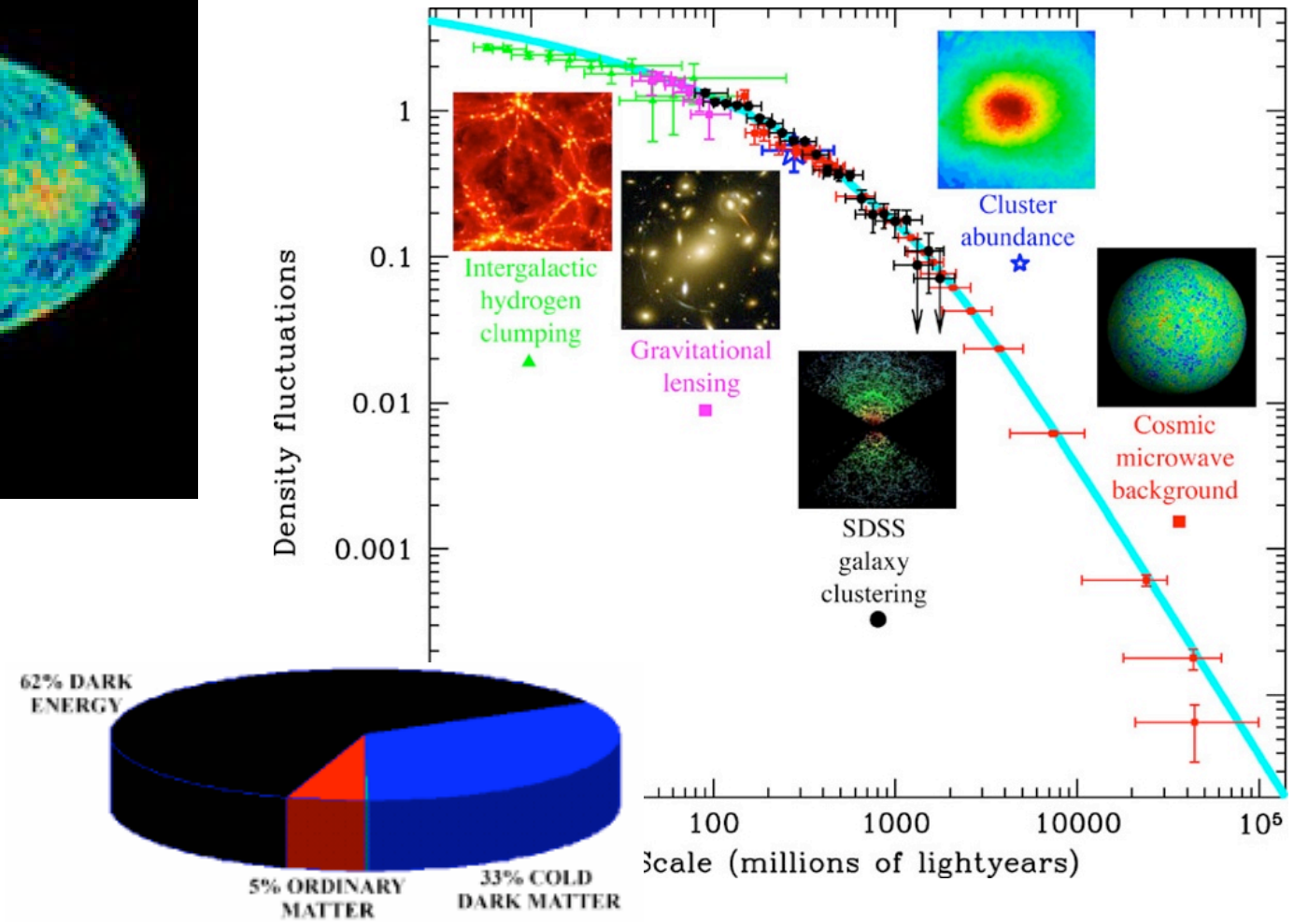
compute how the Universe came into existence
follow how quantum fluctuations generated perturbations

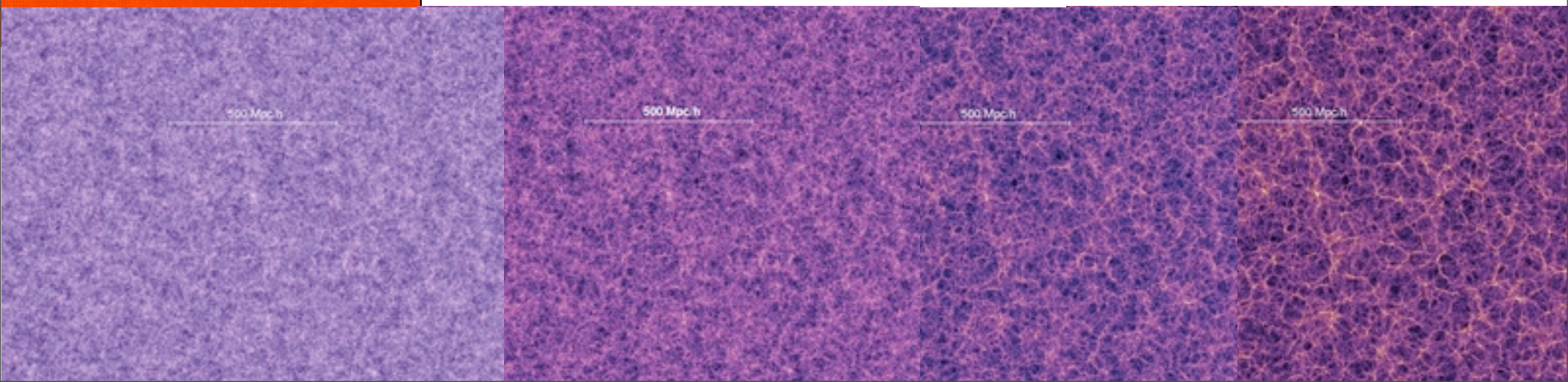
1.follow how structures form in the dark matter
2.how gas accretes in these structures
3.and forms stars
4.and forms metals
5.and forms planets
6.and forms people
7.and .....

100001.and write some papers
100002.and get a PhD


WMAP


t=0.0036


Density fluctuations
1
0.1
0.01
0.001
Intergalactic hydrogen clumping
Gravitational lensing
Cluster abundance
SDSS galaxy clustering
Cosmic microwave background
100
1000
10000
10⁵
Scale (millions of lightyears)
62% DARK ENERGY
5% ORDINARY MATTER
33% COLD DARK MATTER


500 Mpc/h
500 Mpc/h
500 Mpc/h
500 Mpc/h

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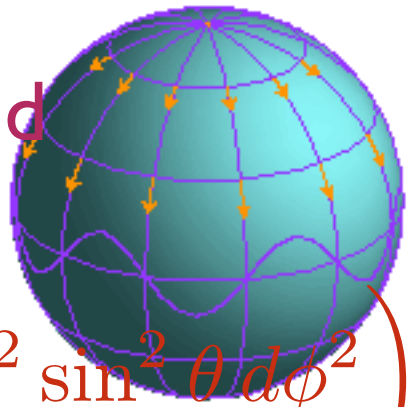
Basic description of space-time



1)Measuring distances in a homogeneous and isotropic Universe: FRW

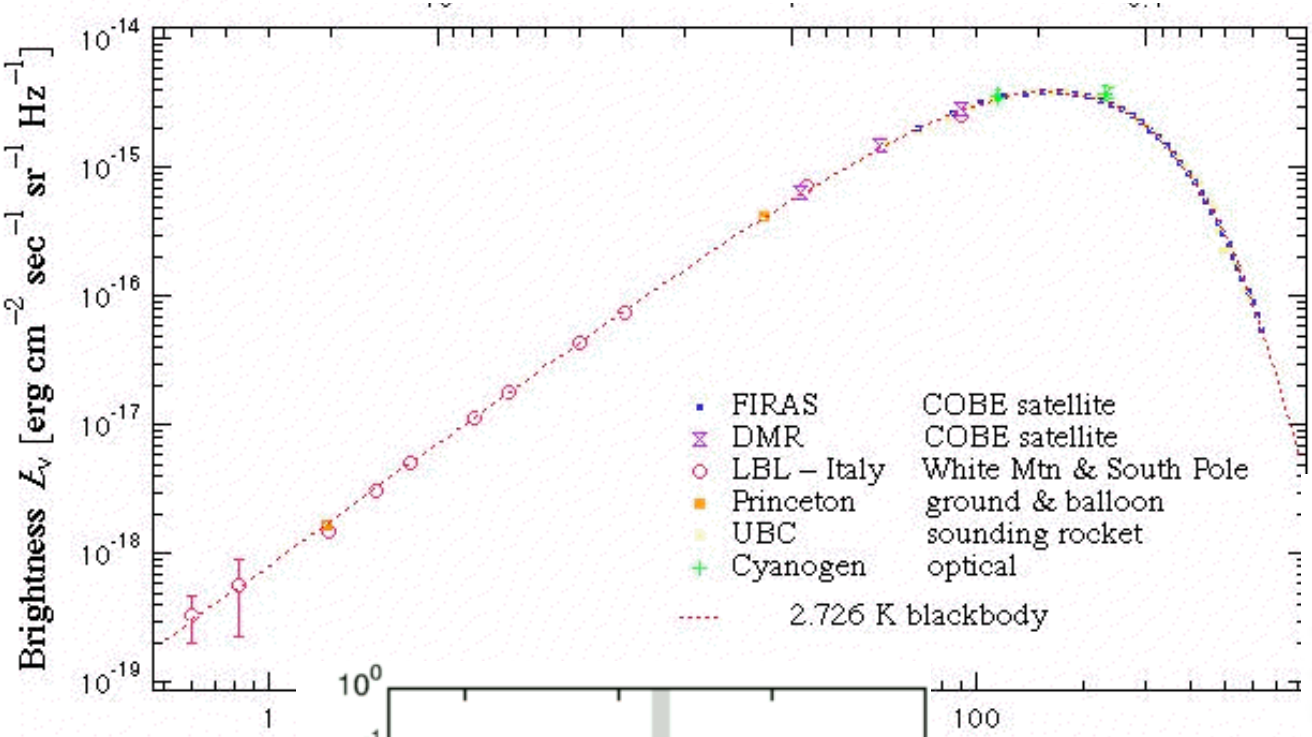
$$ds^2 = -dt^2 + a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta\, d\phi^2\right)$$

2)Dynamics of the expansion: GR

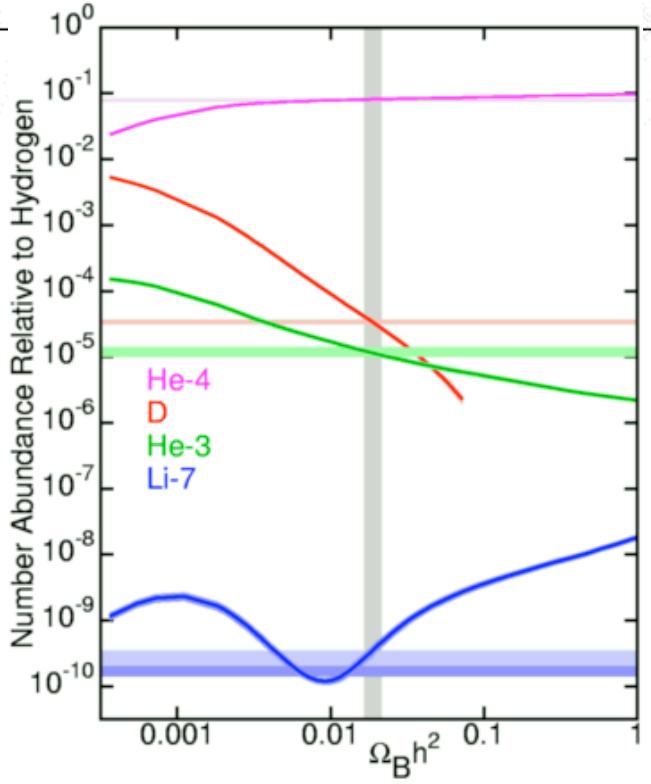
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

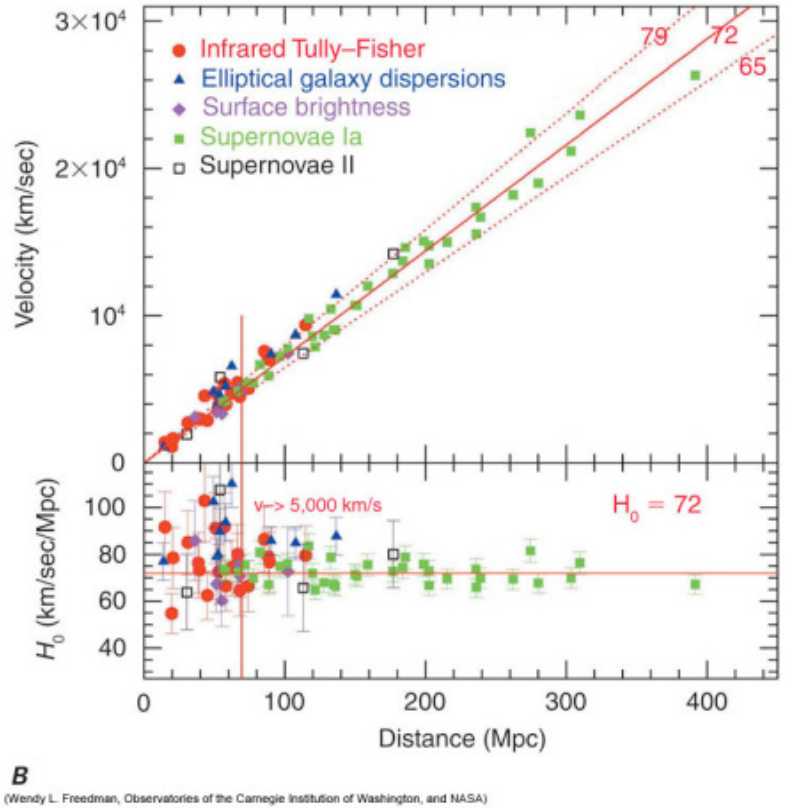
The three pilars of this "Big-Bang" model



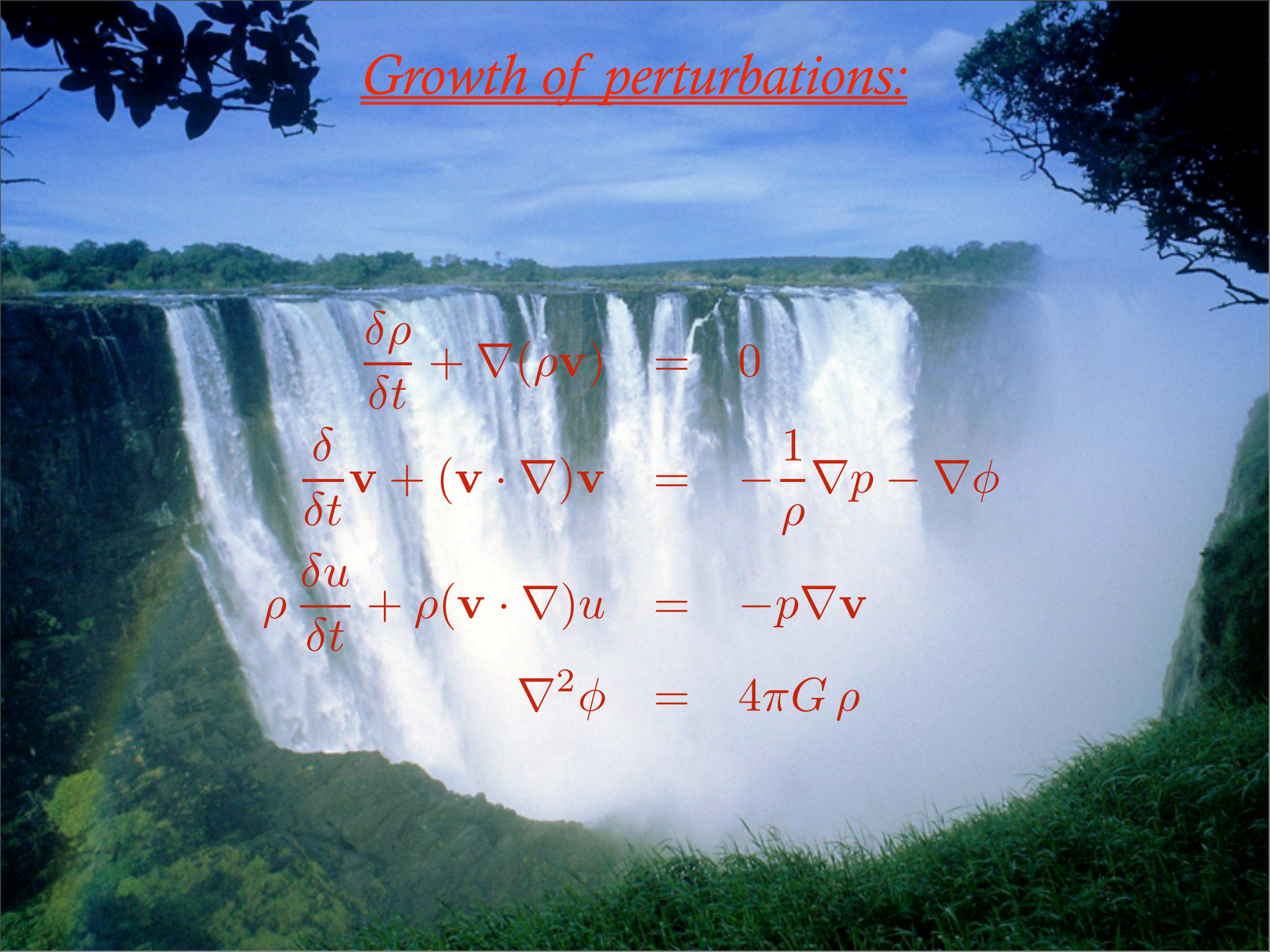
CMB



BBN



Expansion



Growth of perturbations:

$$\frac{\delta \rho}{\delta t} + \nabla(\rho \mathbf{v}) = 0$$

$$\frac{\delta}{\delta t}\mathbf{v} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{\rho}\nabla p - \nabla\phi$$

$$\rho\frac{\delta u}{\delta t} + \rho(\mathbf{v}\cdot\nabla)u = -p\nabla\mathbf{v}$$

$$\nabla^2\phi = 4\pi G\,\rho$$

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Co-moving variables:

$$\mathbf{r} = a\,\mathbf{x}$$

$$\mathbf{v} = \dot{a}\,\mathbf{x} + a\,\dot{\mathbf{x}}$$

Physical values

Co-moving values

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Lagrangian versus Eulerian dynamics:

$$(\frac{\delta}{\delta t} + \mathbf{v}\cdot\nabla)\rho \equiv \frac{d\rho}{dt} = -\rho\nabla\mathbf{v}$$

Eulerian time derivative

Lagrangian time derivative

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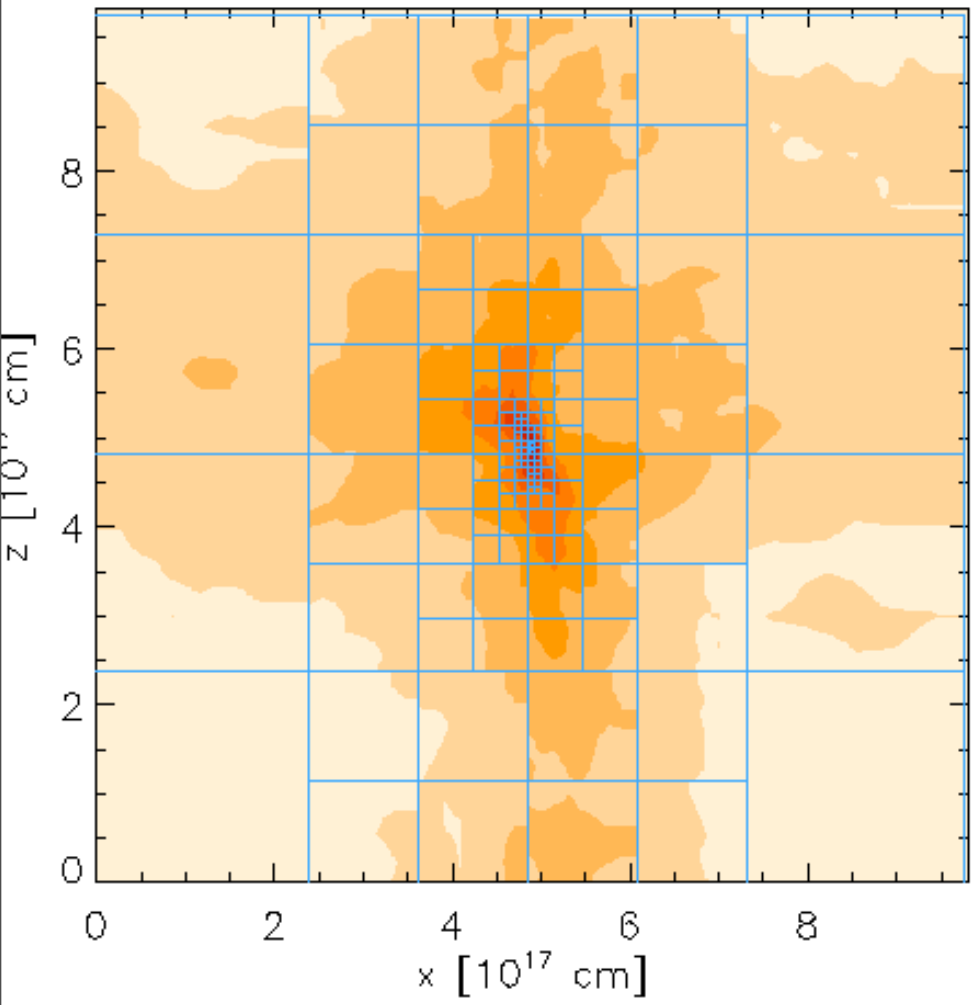
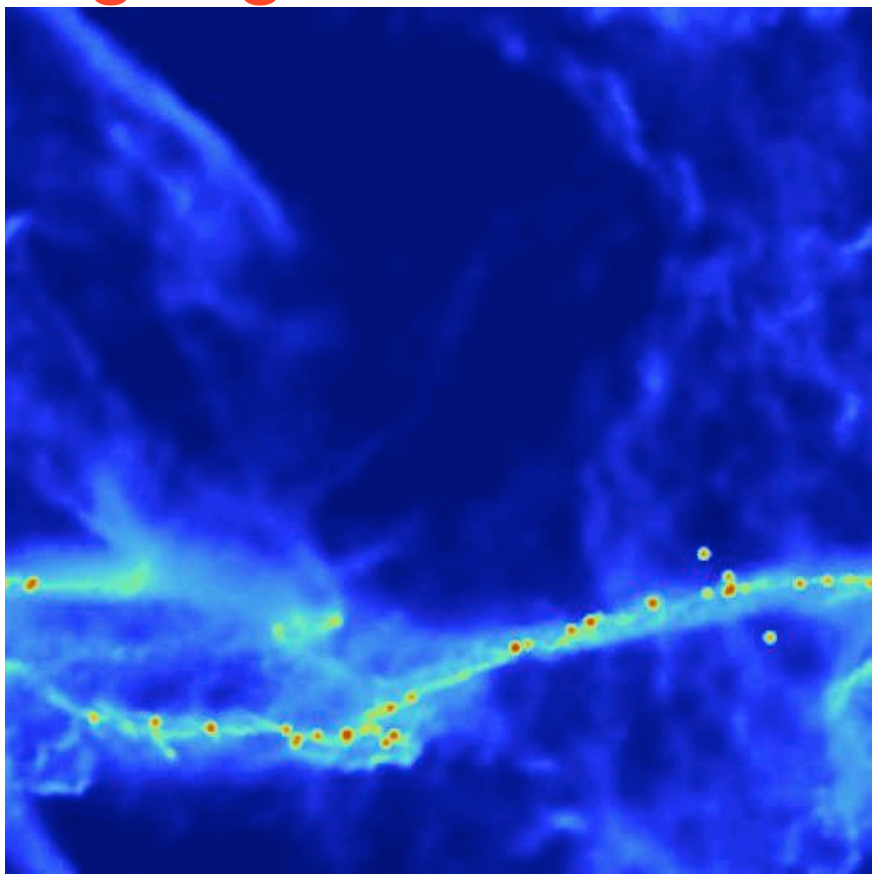
Eulerian codes



Zeus, Ramses, Flash, Enzo

Lagrangian codes



Gadget, Hydra, Gasoline, TreeSPH

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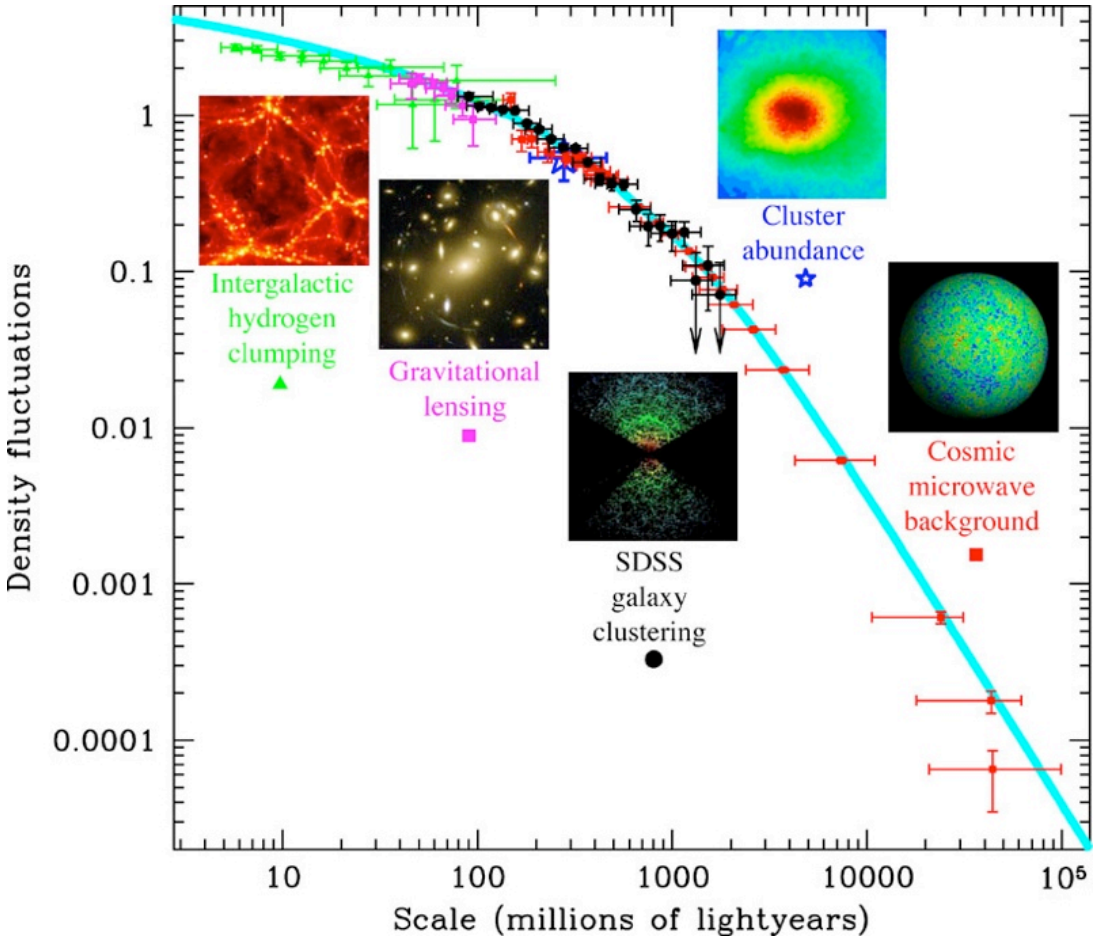
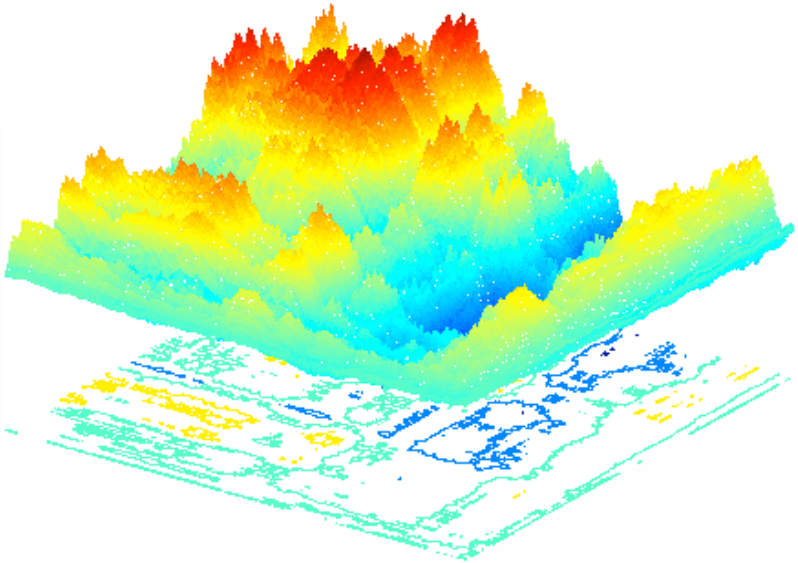
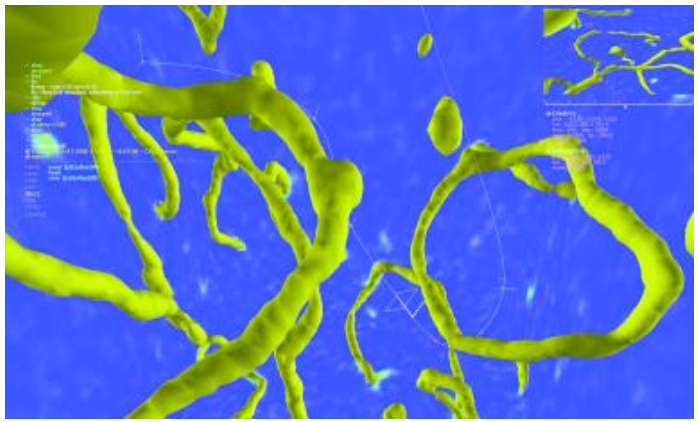
Initial conditions





Linear transfer function



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Numerical issues: time integration

$$\frac{d\mathbf{r}}{dt} = \mathbf{v}$$

$$\frac{d\mathbf{v}}{dt} = \mathbf{a}$$

$$\mathbf{r}^{n+1} = \mathbf{r}^n + \mathbf{v}^n \Delta t + \frac{1}{2}\mathbf{a}^n \Delta t^2 + \cdots$$

$$\frac{\mathbf{r}^{n+1} - \mathbf{r}^n}{\Delta t} = \mathbf{v}^n$$

$$\frac{\mathbf{v}^{n+1} - \mathbf{v}^n}{\Delta t} = \mathbf{a}^n$$

$$t = n\Delta t$$

$$\mathbf{r}^{n+1} = \mathbf{r}^n + \mathbf{v}^n \Delta t$$

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$$\mathbf{r}^{n+1} = \mathbf{r}^n + \mathbf{v}^n \Delta t + \frac{1}{2}\mathbf{a}^n \Delta t^2 + \cdots$$

$$\frac{\mathbf{r}^{n+1} - \mathbf{r}^n}{\Delta t} = \mathbf{v}^n$$

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$$t = n\Delta t$$

$$\mathbf{r}^{n+1} = \mathbf{r}^n + \mathbf{v}^n \Delta t$$

Euler scheme

$$\frac{\mathbf{r}^{n+1} - \mathbf{r}^n}{\Delta t} = \mathbf{v}^{n+1/2}$$

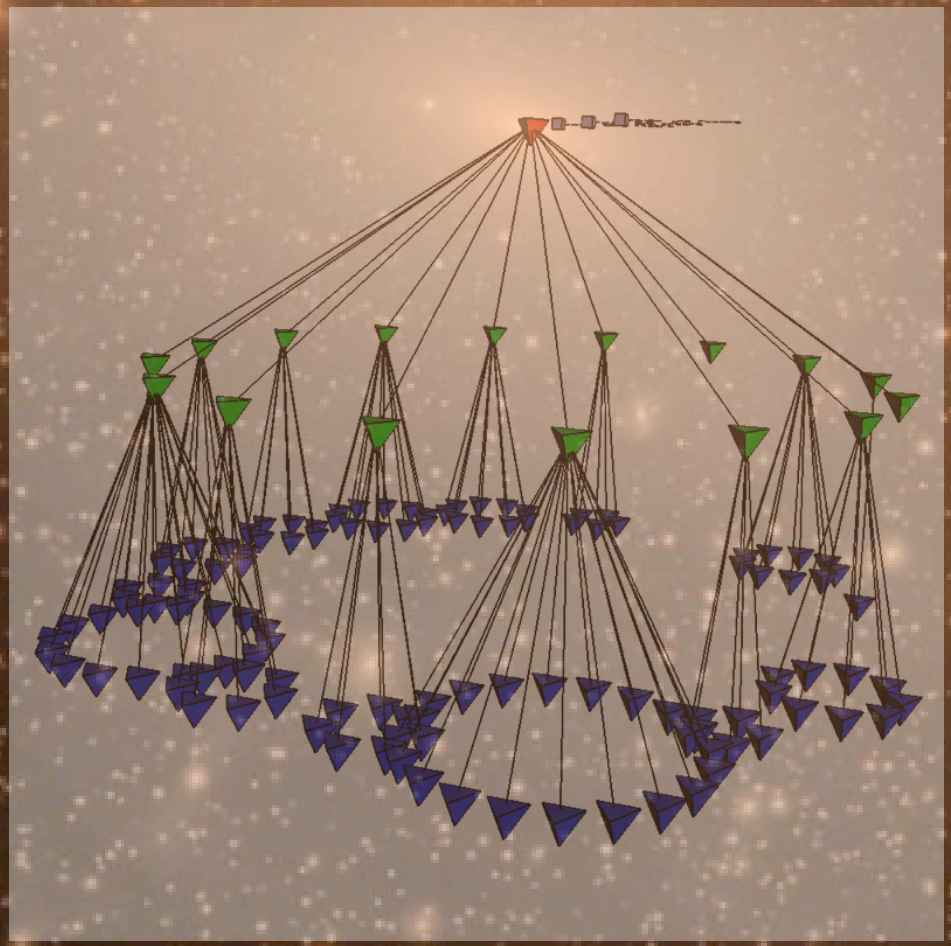
$$\frac{\mathbf{v}^{n+1/2} - \mathbf{v}^{n-1/2}}{\Delta t} = \mathbf{a}^n$$

Leap-frog scheme

$$\mathbf{r}^{n+1} = \mathbf{r}^n + \mathbf{v}^{n+1/2} \Delta t = \mathbf{r}^n + \mathbf{v}^n \Delta t + \frac{1}{2}\mathbf{a}^n \Delta t^2$$

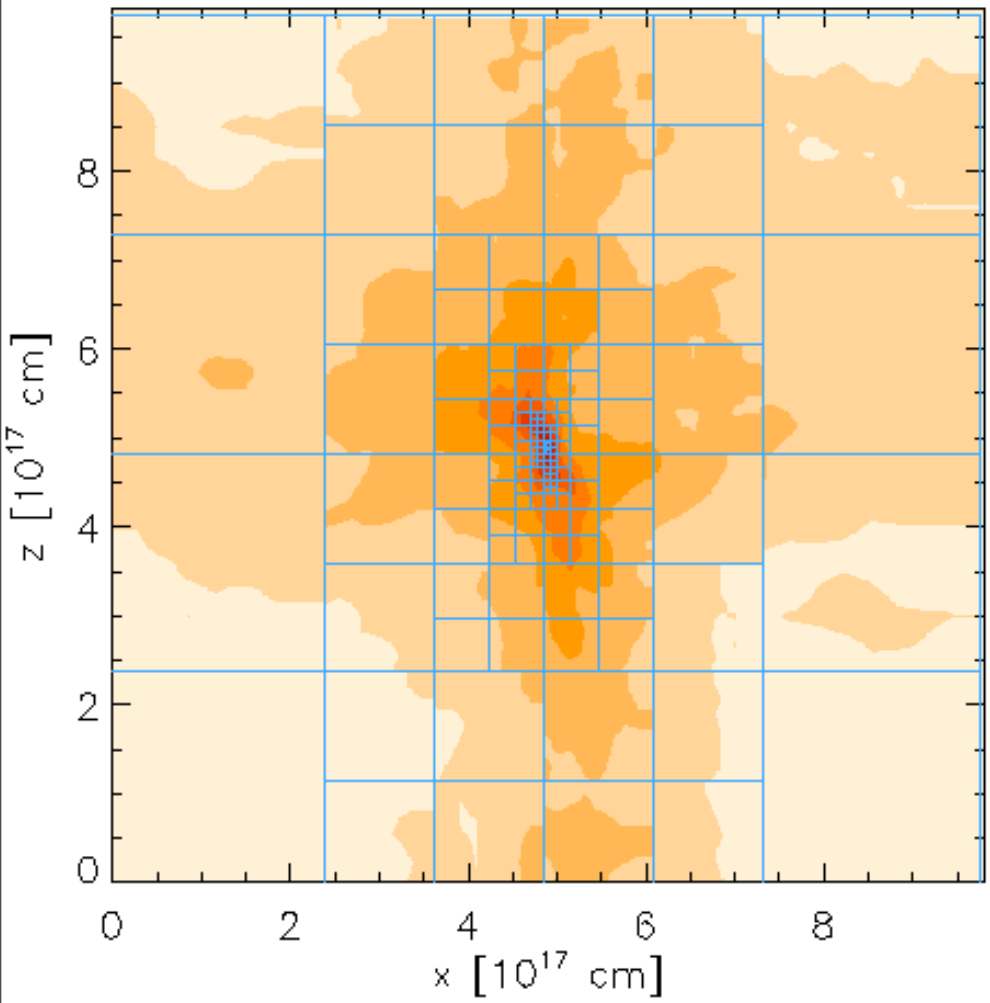
Numerical issues: computing gravity

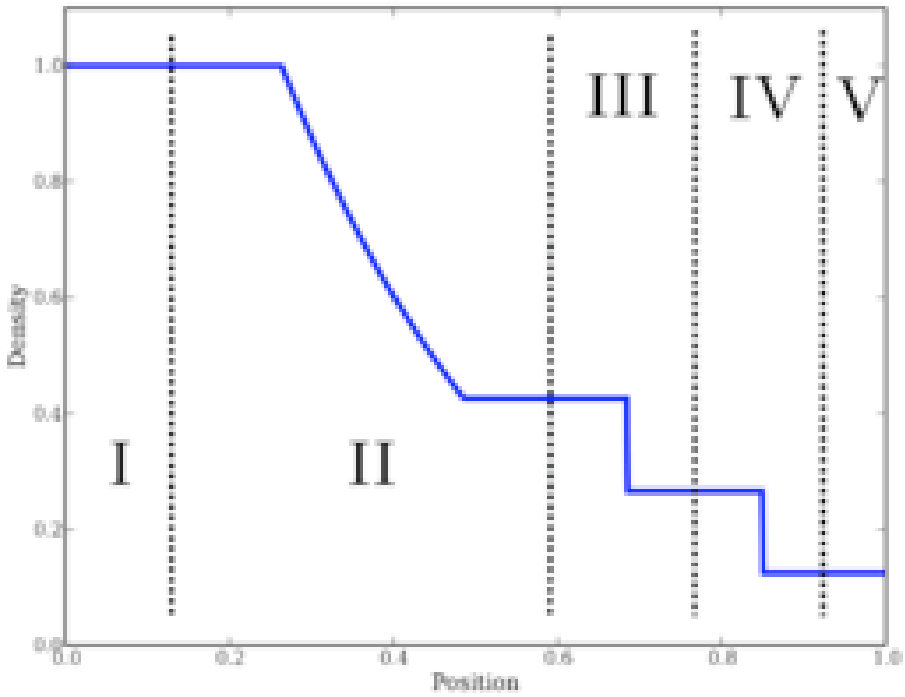
$$\mathbf{a}_i = \sum_{j \neq i} \frac{\mathbf{r}_i - \mathbf{r}_j}{r_{ij}^3} G m_j \left(\mathbf{r}_i - \mathbf{r}_j\right)$$



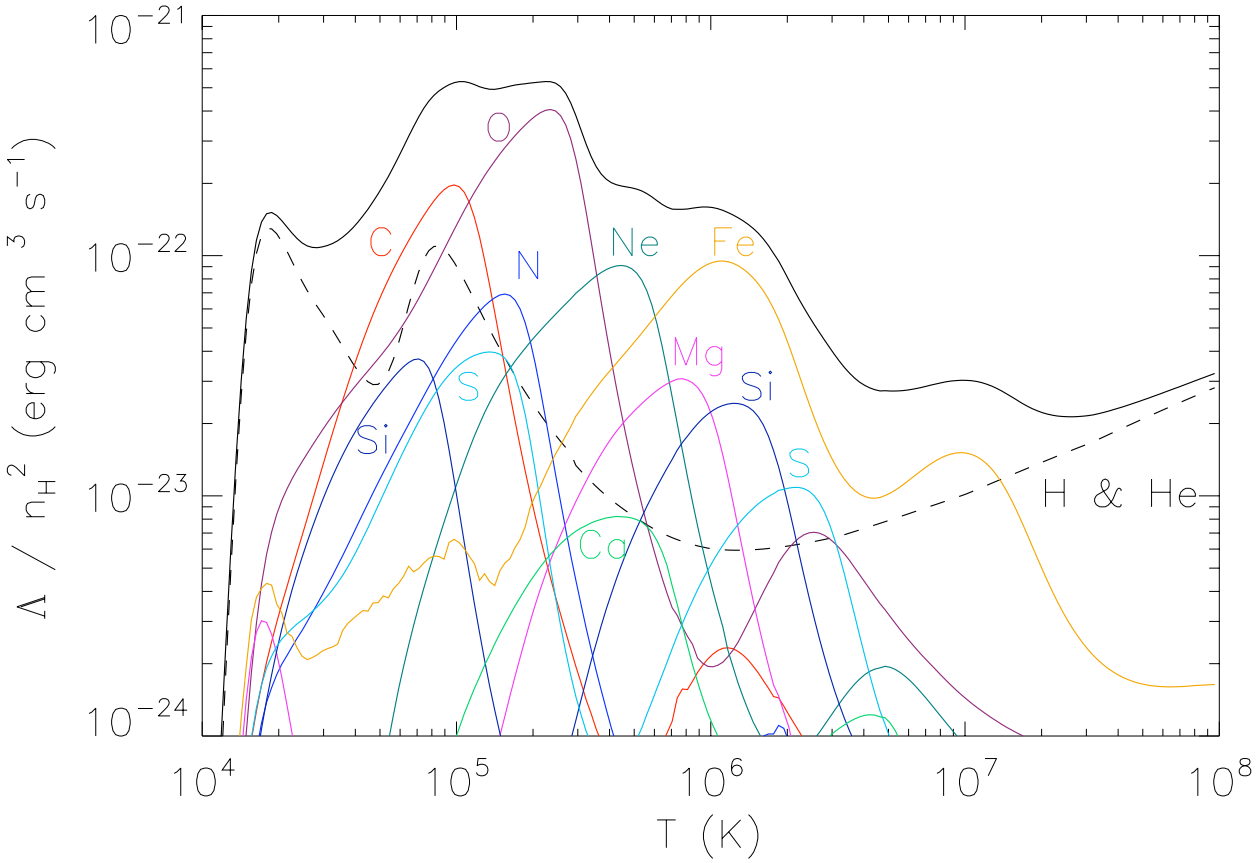
80 kpc

Numerical issues: hydrodynamics





Numerical issues: extra physics



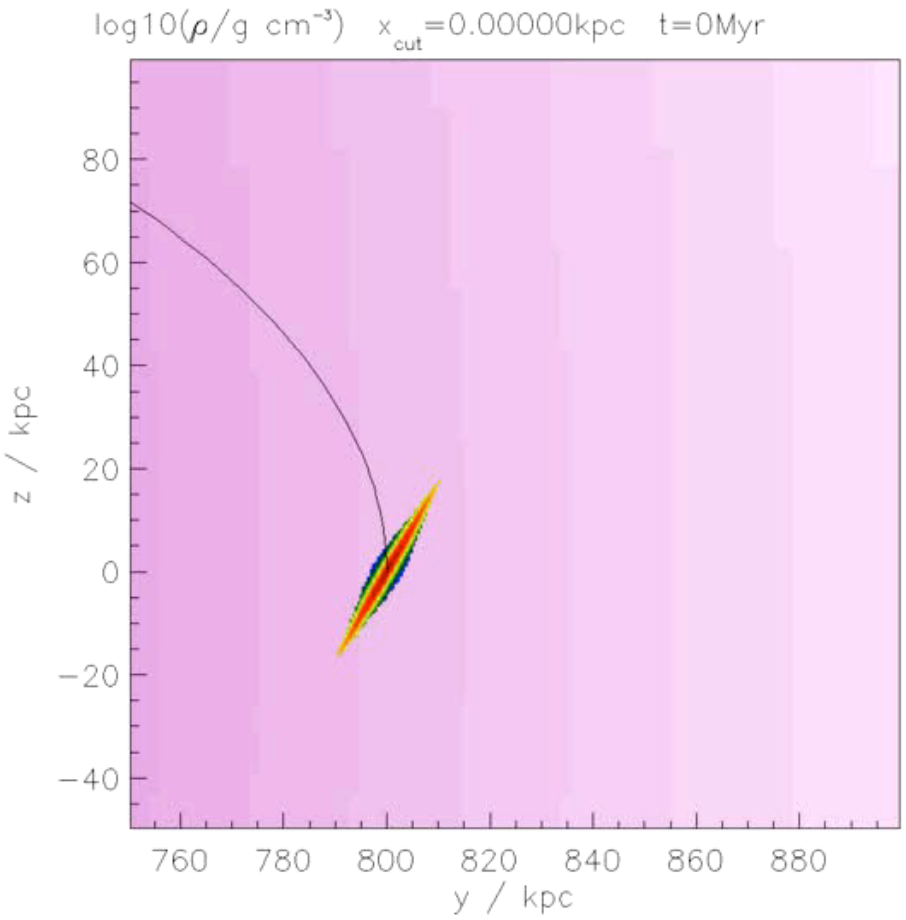
Radiative cooling rate of gas as function of temperature for different elements

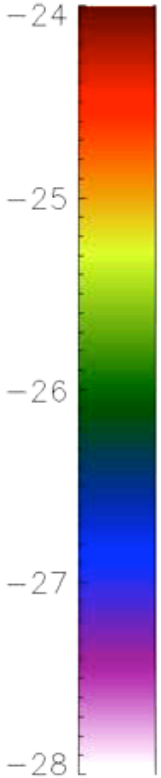
Role of AGN:
Cold accretion
during mergers
gives rise to QSOs

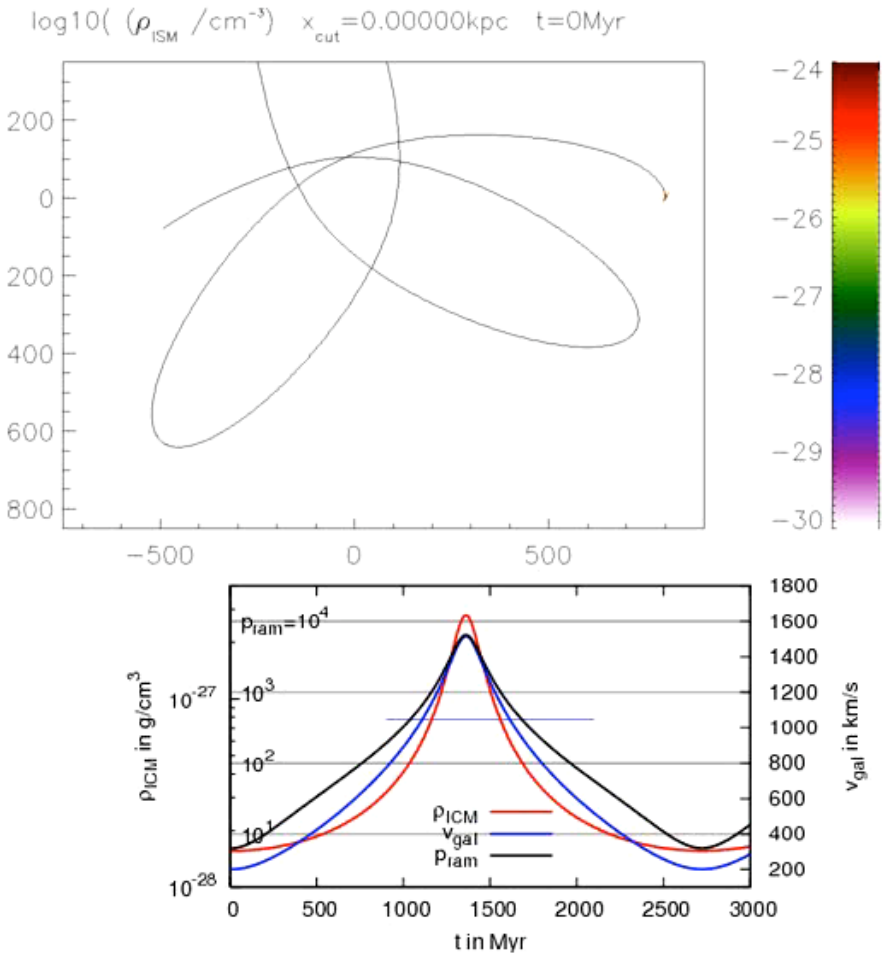
Numerical issues: extra physics

- Magnetic fields
- Cosmic rays
- Energy input from stars
- Energy input from AGN
- Heating by ambient radiation field
- Cooling by gas, molecules, dust
- ....

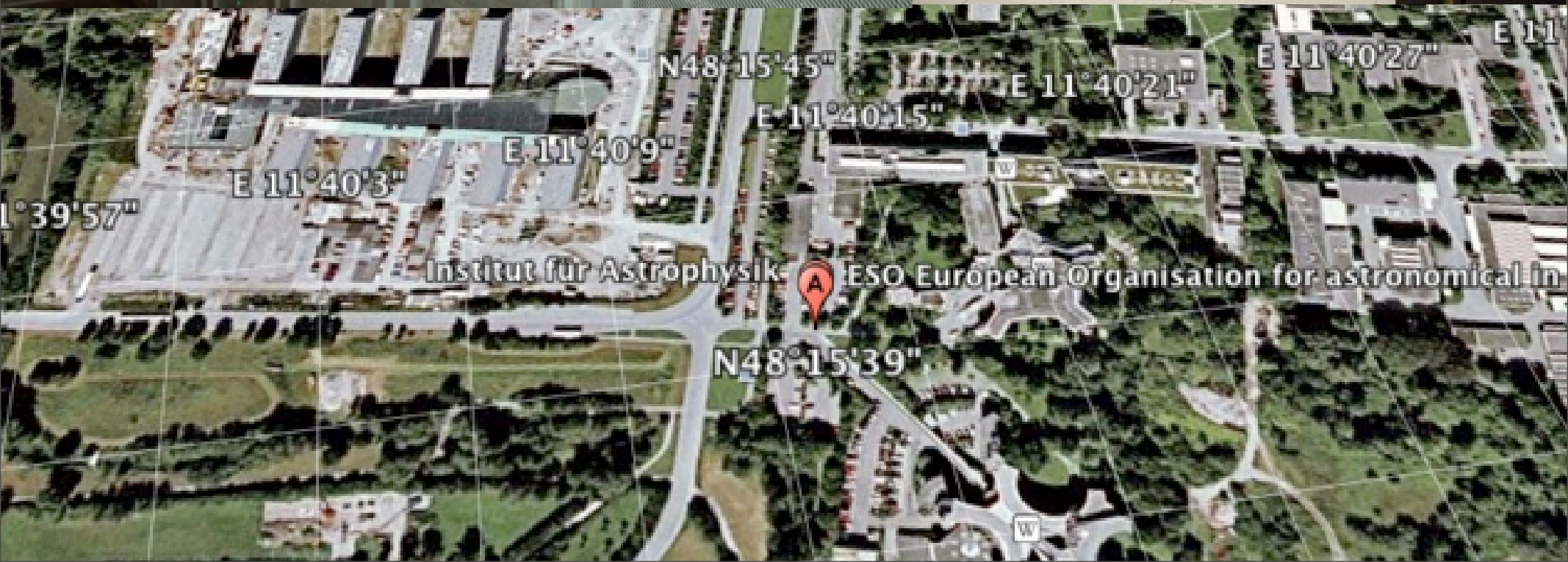
Numerical issues: extra physics



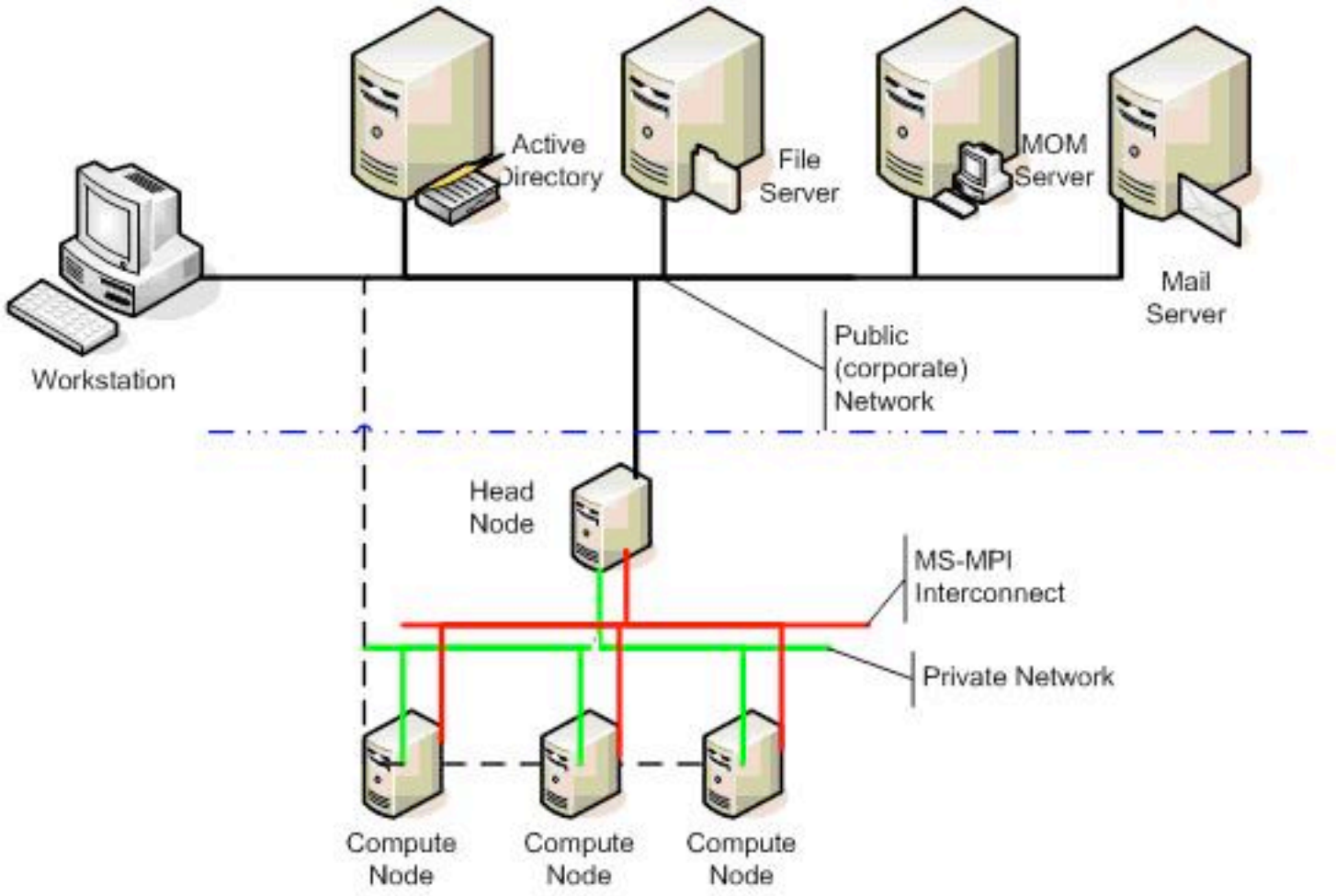





IBM


N48°15'45"
E 11°40'27"
E 11°40'21"
E 11°40'15"
E 11°40'9"
E 11°40'3"
Institut für Astrophysik
ESO European Organisation for astronomical in
N48°15'39"

Numerical issues: parallel computing



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M Norman

V Springel

ENZO

Gadget

Flash

C/C++/Fortan, 80 k lines)

C, 80k lines

Fortan/C, 120k lines

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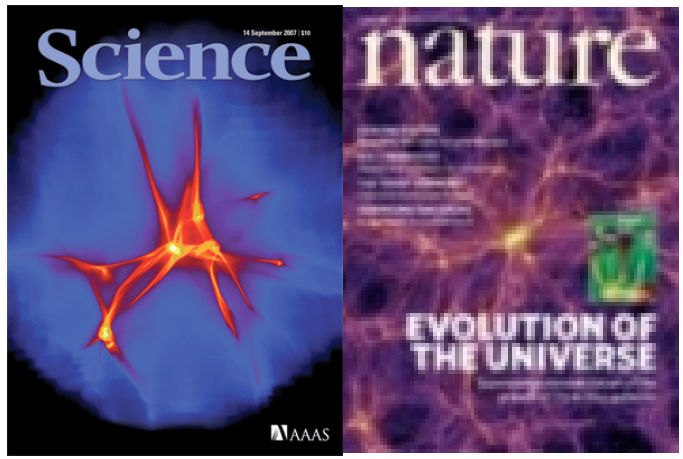
Writing simulation code requires man-years of effort

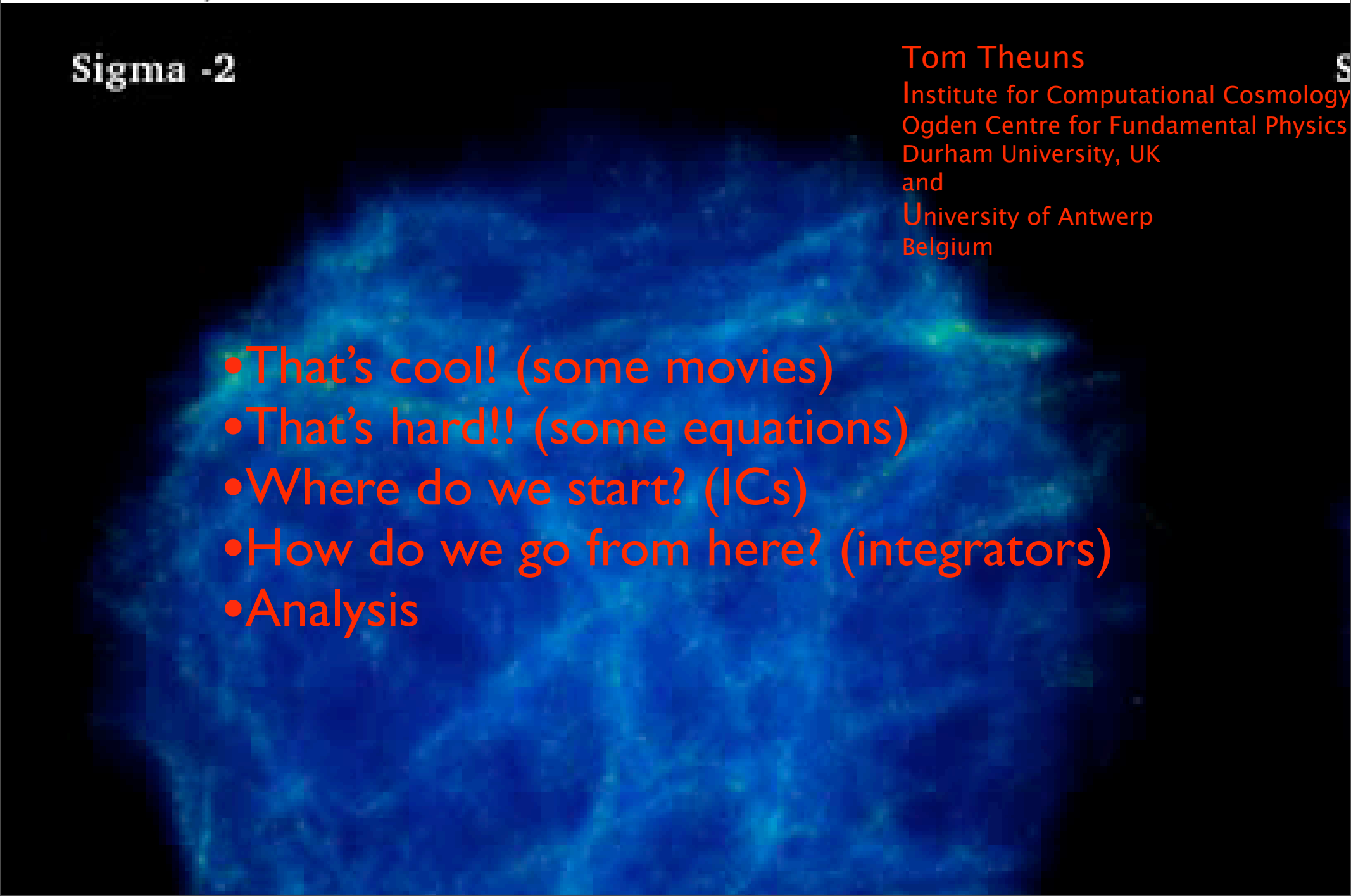
- Large simulations produce TBytes of data: analysis is major part of project
- Hard/impossible to analyse on small computer
- Big team to get most out of investment

Movies essential, not just for showing off, but as way of data-mining: discover unexpected features of simulation)

Data format, units and dimensions major sources of errors/hassle



Cosmology, Theory & Simulation



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- That's cool! (some movies)
- That's hard!! (some equations)
- Where do we start? (ICs)
- How do we go from here? (integrators)
- Analysis

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