Benasque Sep 12th, 2005

Observational Cosmology II

Enrique Gaztañaga
Institut d'Estudis Espacials de Catalunya, IEEC/CSIC
Instituto de Ciencias del Espacio, CSIC, Barcelona

1. Standard Cosmology: metric, F.Eq, dark matter & dark energy

-> Taller: Cosmological measures: distance, time

2. LSS: linear theory: Inflation
3. LSS: Non-linear theory: P(k), CMB

Spherical collapse, PS, N-body, Non-gaussianity

-> Taller: LSS: SC

2 Grants to do PhD at Barcelona:

www.ieec.fcr.es

Deadline: 15-Sep (Advisor+CV)

Start: 1-Oct-1005!

-*P.Fosalba:* CMB, polarization, LSS

-*F.Castander:* galaxies, clusters

-*J.Miralda-Escude:* Ly-alpha, early re-ionization, IGM, AGN-BH connection

-*M.Hernanz:* high energy astrophysics: X-rays, GR

-*J.Isern, I.Ribas:* Stellar & Galactic astronomy

- *J.M.Girart, C.Torrellas:* Interstellar Medium

-*A.Lobo:* Grativational Waves (LISA)

-*A.Rius, P.Elosegui*: Earth Sciences (GPS)

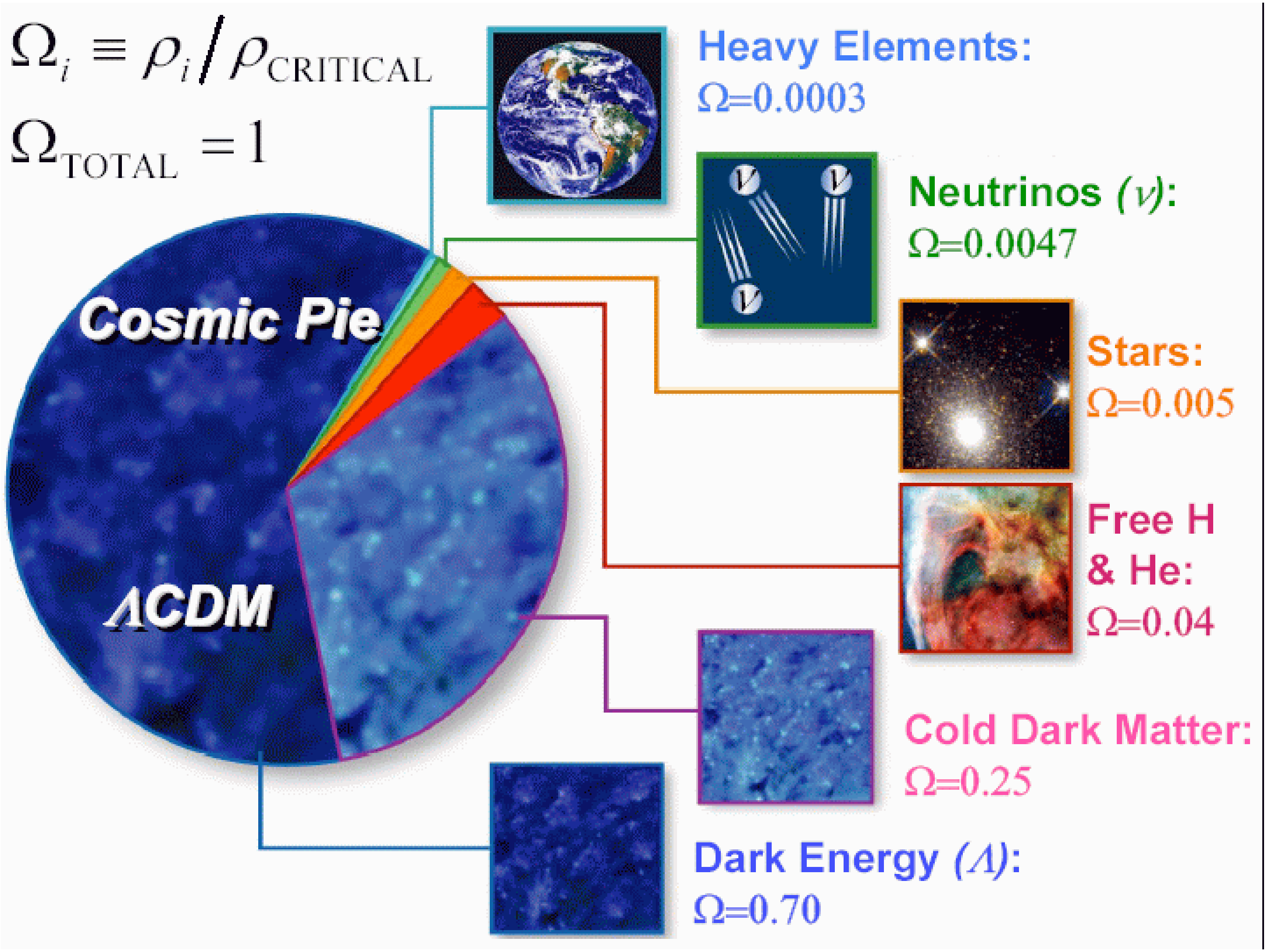
⇒LMT (INAOE)

=> Dark Energy Survey (Fermilab/USA)

Dark Matter problems:

Baryonic DM
Non-Baryonic DM

$$R_{\mu\nu} + \Lambda g_{\mu\nu} = -8\pi G \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right)$$

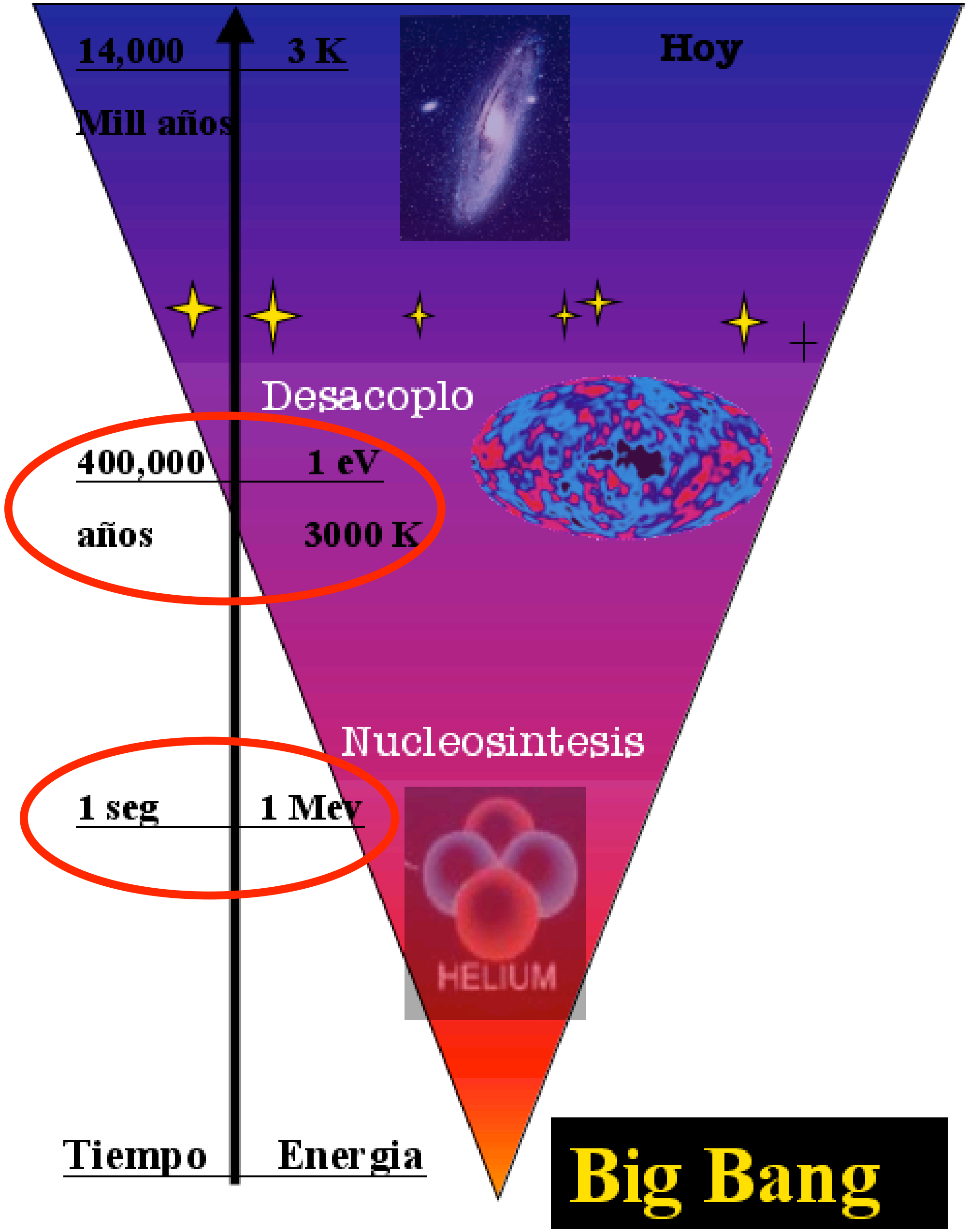


Predicciones del modelo

Big Bang:

ÁTOMOS

El universo está lleno de una radiación de fondo cuya temperatura es unos grados encima del cero absoluto. Cuando se formaron los átomos neutros (aproximadamente 400,000 anyos después del Big Bang), la radiación electromagnética esencialmente paró su interacción con la materia. La expansión de espacio enfrió la radiación de su valor inicial de aproximadamente 3000 K a su presente bajo valor de 3K



Estimation of age-T relation:

Wien law for BlackBody:
$E = ch/\lambda_{max} \sim 2.8\, K_B\, T$
$(K_B \sim 10^{-4}$ eV /K)

$E \sim 2.3 \; 10^{-4}$ eV ~ 2.7 K =>
$\lambda_{max} \sim 1.9$ mm

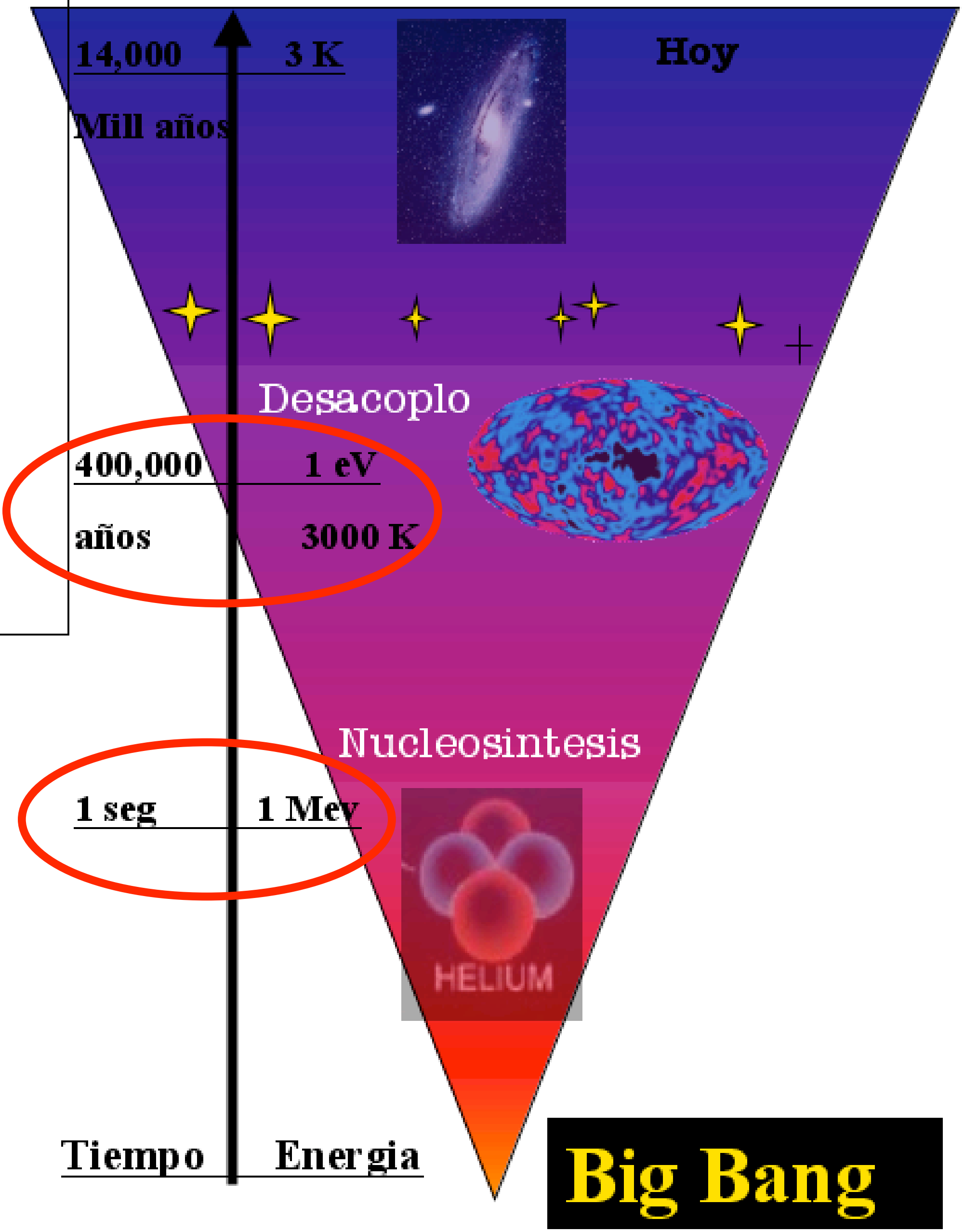
Stefan-Boltzman law:
$E \sim T^4 \sim a^{-4}$

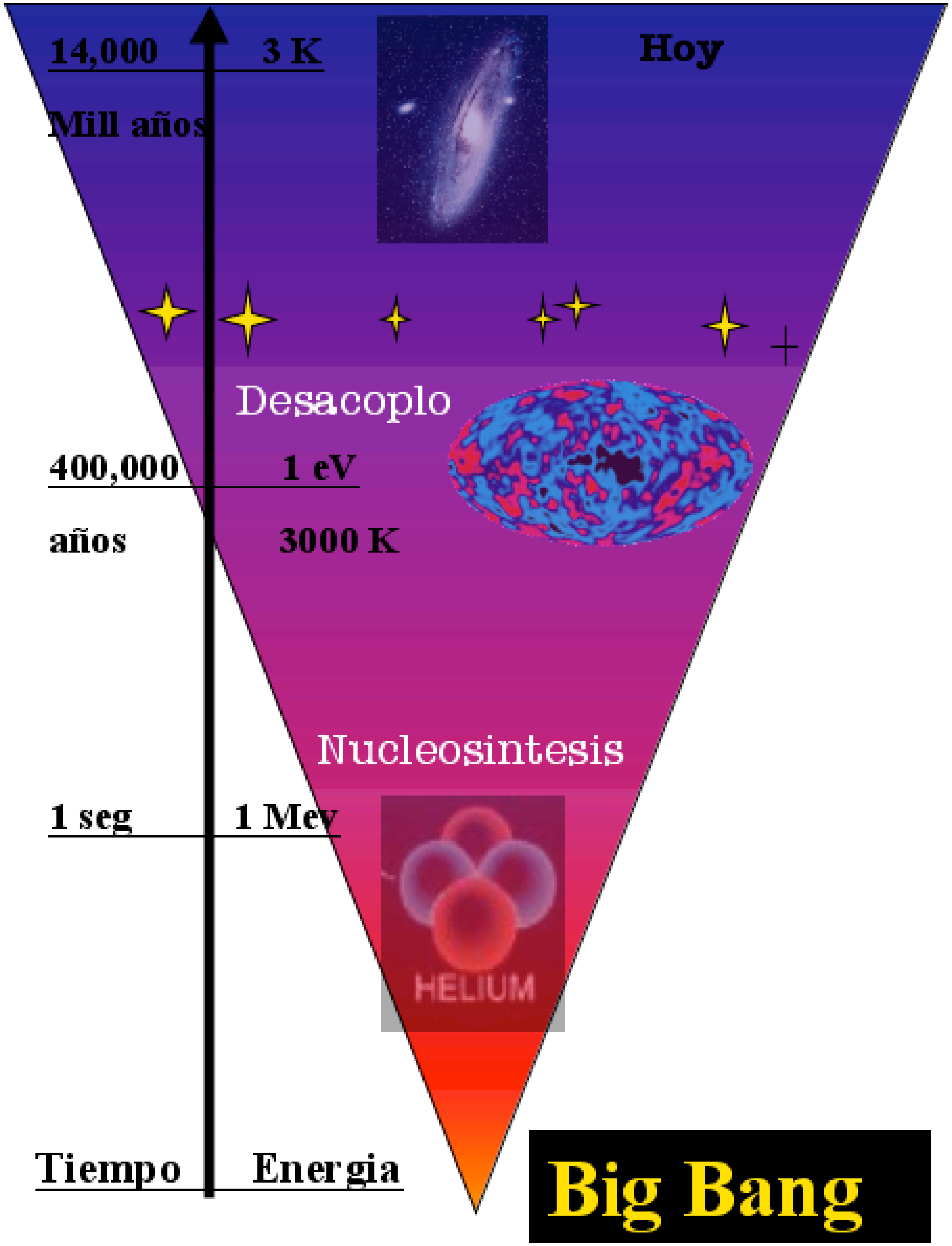
$$T = T_0/a = T_0\,(1+z)$$

given z we can calculate T

and also the age t_0 :

$$t_0(z) = H_0^{-1} \int_z^{\infty} \frac{dz}{(1+z)\; E(z)}$$





HOW DID WE GET HERE?

Two driving questions in Cosmology:

- Background: Evolution of scale factor a(t).

need Friedman Eq. (Gravity?)

need the matter-energy content

$$H^2(z) = H^2_0 \ [\ \Omega_M (1+z)^3 + \Omega_R (1+z)^4 + \Omega_K (1+z)^2 + \Omega_{DE} (1+z)^{3(1+w)} \ ]$$

$$r(z) = \int dz/H(z)$$

Dark Matter and Dark Energy!

- Structure Formation:

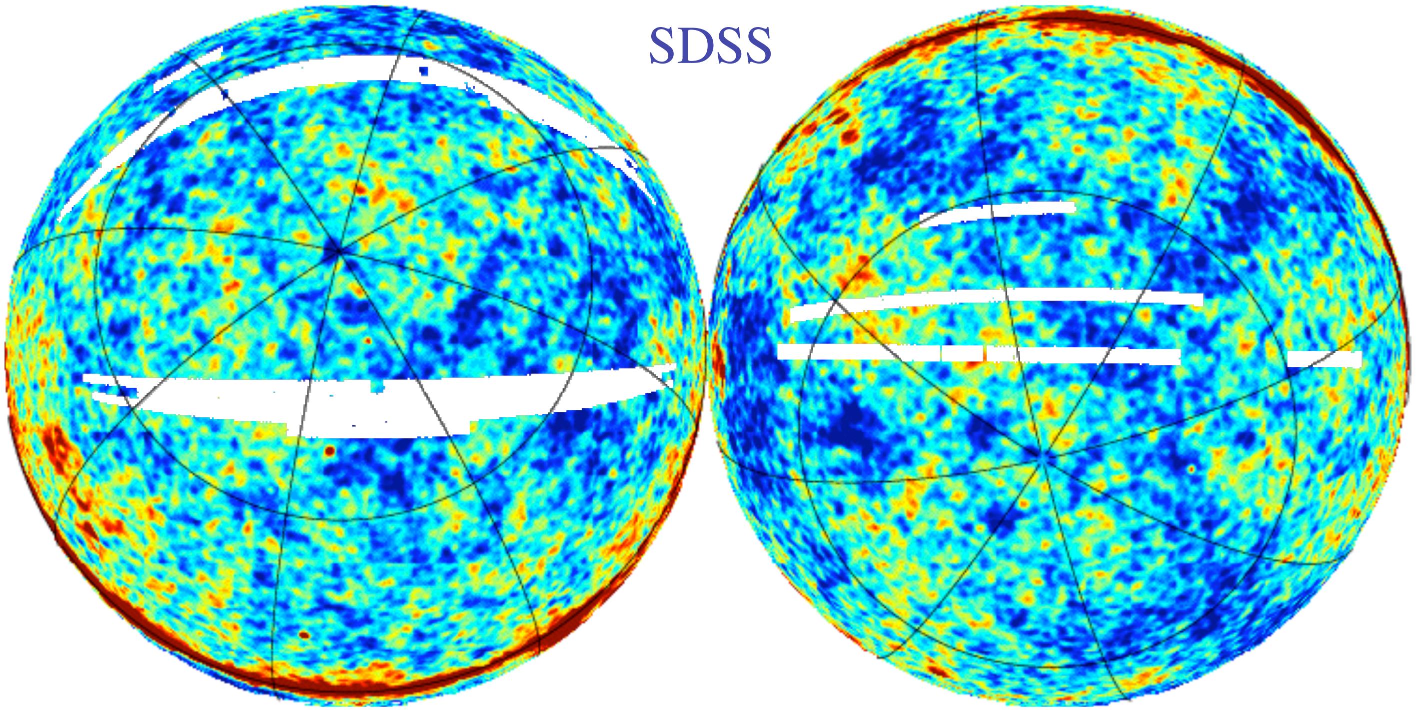
origin of structure (IC)

gravitational instability

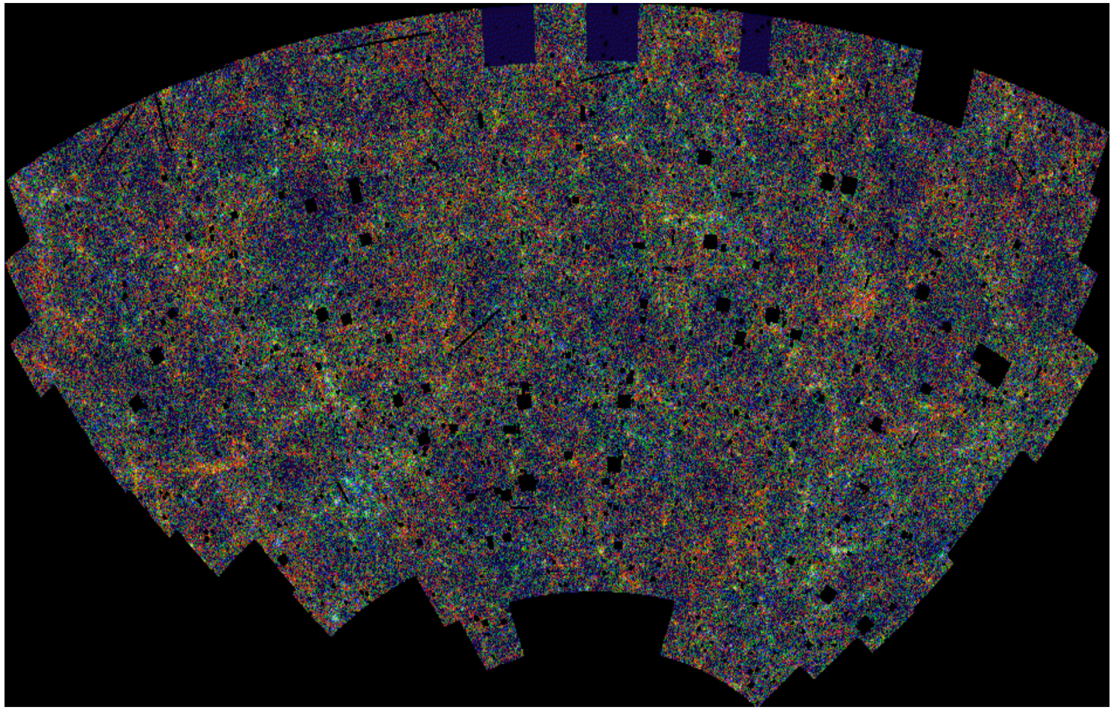
need the matter-energy content

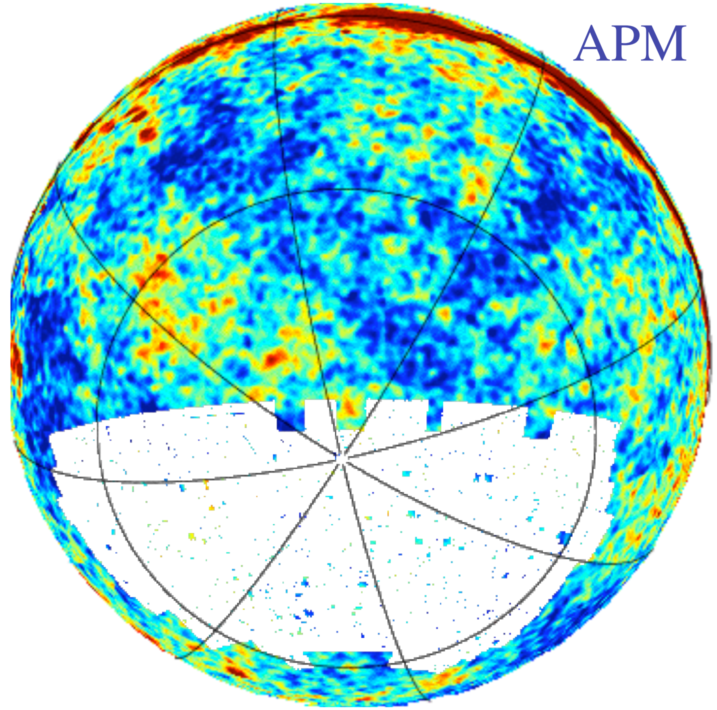
$$\delta'' + H\,\delta' - 3/2\ \Omega_m H^2 \delta = 0$$

galaxy formation (SFR)

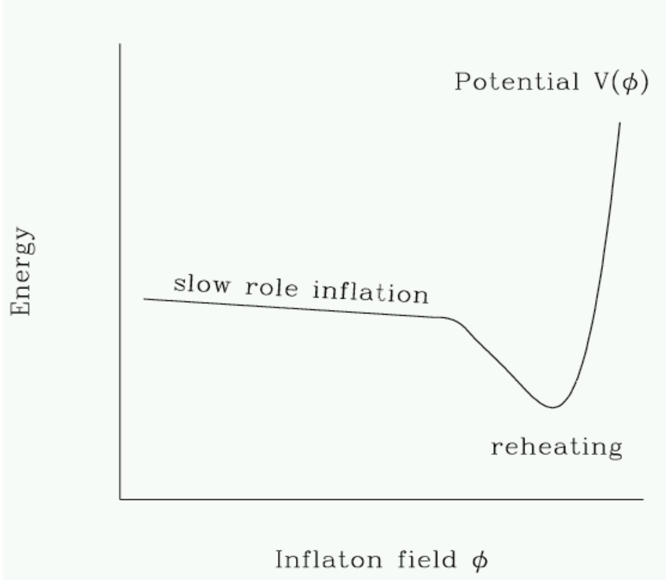


Annisotropies in CMB (SW) Correspond to the IC to LSS

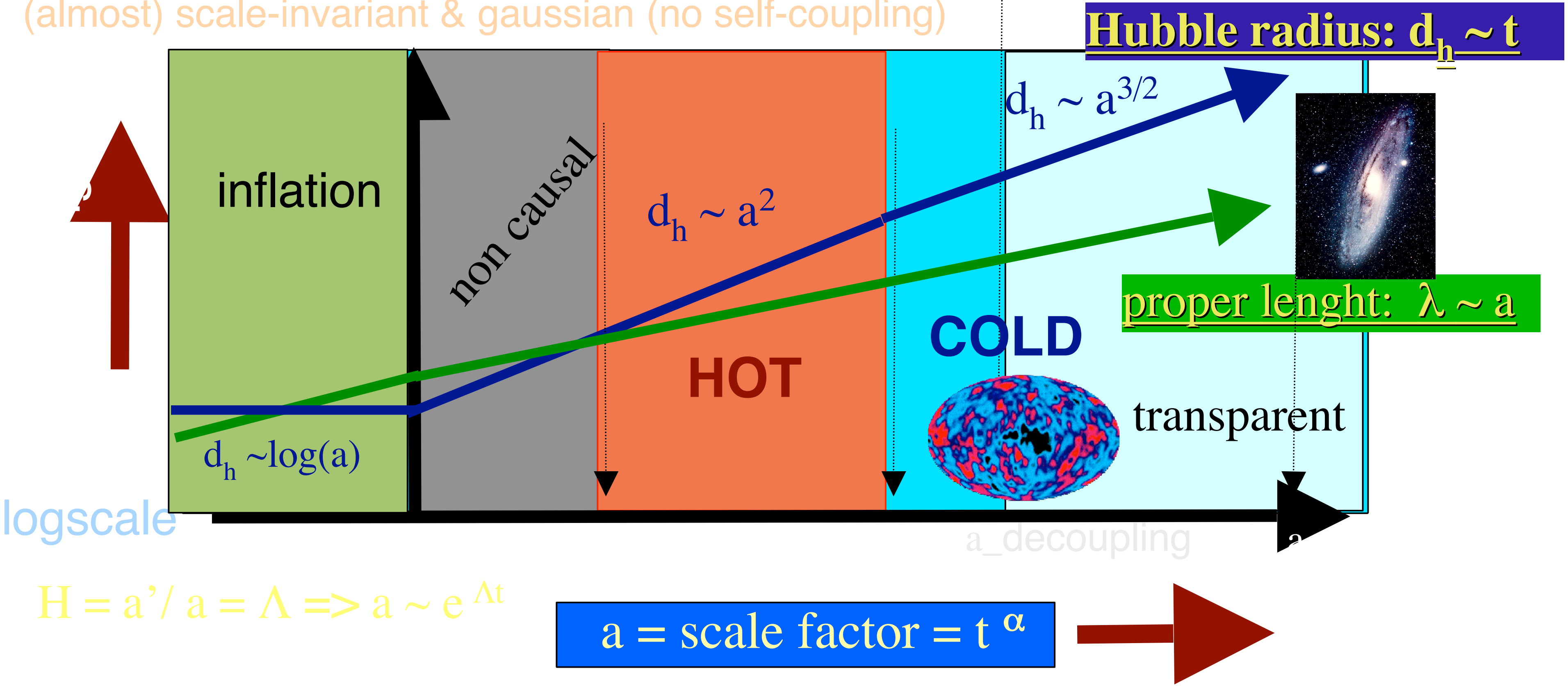




->Why is the universe so uniform on the largest scales?[!]
->Why causally disconnected regions are alike?
->Flatness problem: small deviations from W=1 are not stable
->Why is the physical scale of the universe so much larger than the fundamental scale of gravity, the Planck length?
->What produced the initial density fluctuations ?



- Predictions (?) of the Inflation Theory: Universe is flat, (almost) scale-invariant & gaussian (no self-coupling)



Describing Fluctuations at Sub-Horizon Scales

Density Field: $$\rho(\mathbf{x},t) = \bar{\rho}(t)\ [1 + \delta(\mathbf{x},t)]$$

Spatial average — Fluctuations

Stress-Energy Conservation

Velocity Field: $$\mathbf{V} = H(t)\,\mathbf{r} + \mathbf{v}(\mathbf{x},t)$$

Hubble Flow — Fluctuations

Stress-Energy Conservation II. Fluctuations

$$\delta T^{\mu\nu}_{;\nu} = 0$$

$$\frac{\partial \delta}{\partial \tau} + \nabla \cdot [(1+\delta)\mathbf{v}] = 0$$

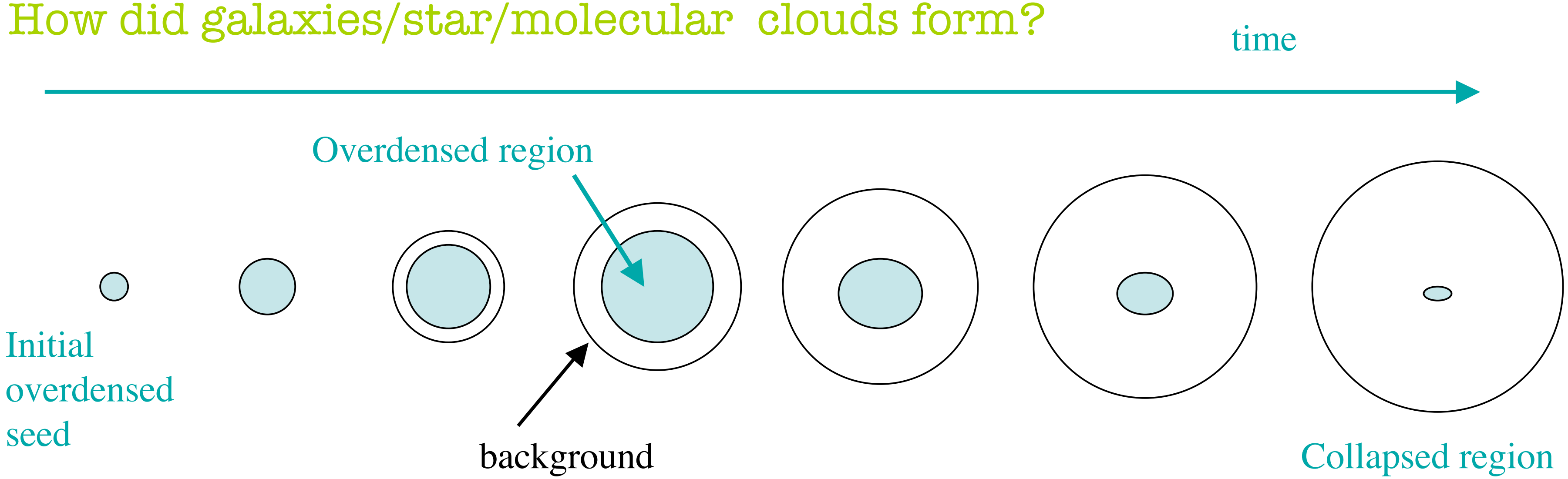
$$\frac{\partial \mathbf{v}}{\partial \tau} + \mathcal{H}\mathbf{v} + \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla \Phi$$

$$\text{Poisson } (\Omega_m = 1): \quad \nabla^2 \Phi = \frac{3}{2}\mathcal{H}^2 \delta$$

$$\nabla \cdot \mathbf{v} \equiv -\mathcal{H}\Theta, \qquad \mathcal{H} \equiv Ha$$

Where does Structure in the Universe come From?

How did galaxies/star/molecular clouds form?



Perturbation theory:

$$\rho = \rho_b (1 + \delta) \quad \Rightarrow \quad \Delta\rho = (\rho - \rho_b) = \rho_b \, \delta$$

$$\rho_b = M / V \quad \Rightarrow \quad \Delta M / M = \delta$$

With : $$\delta'' + H \delta' - 3/2 \, \Omega_m H^2 \delta = 0$$

in EdS linear theory: $\delta = a \, \delta_0$

Jeans Instability (linear regime)

$$\frac{d^2\delta_k}{d\tau^2} + \mathcal{H}\frac{d\delta_k}{d\tau} - \left(\frac{3}{2}\mathcal{H}^2\Omega_m - k^2 v_s^2\right)\delta_k = 0$$

If $\frac{3}{2}\mathcal{H}^2\Omega_m > k^2 v_s^2$ fluctuations will grow

$\delta_L(x,\tau) = D(\tau)\,\delta_0(x)$

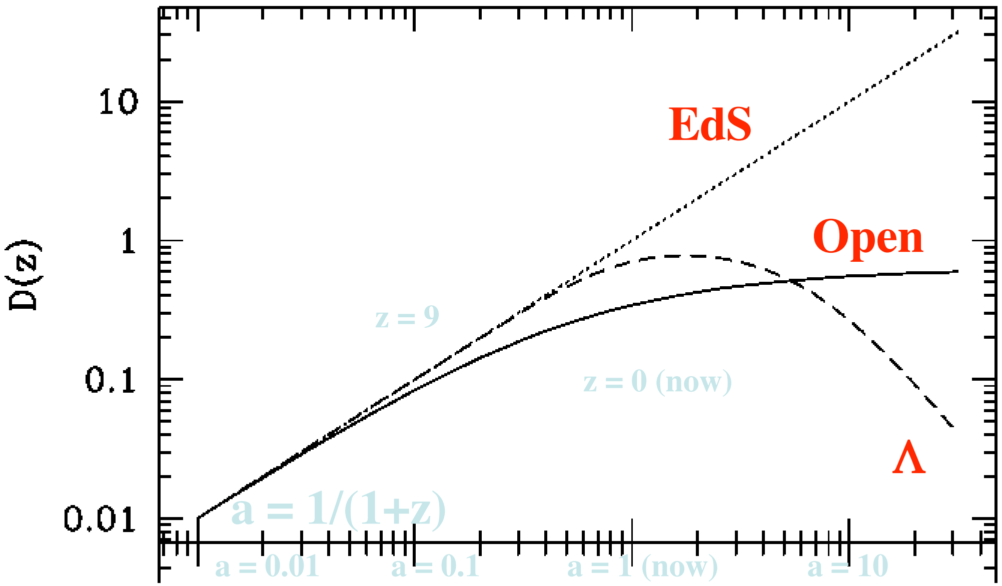
EdS

$\delta_L(x,\tau) = a(\tau)\,\delta_0(x)$

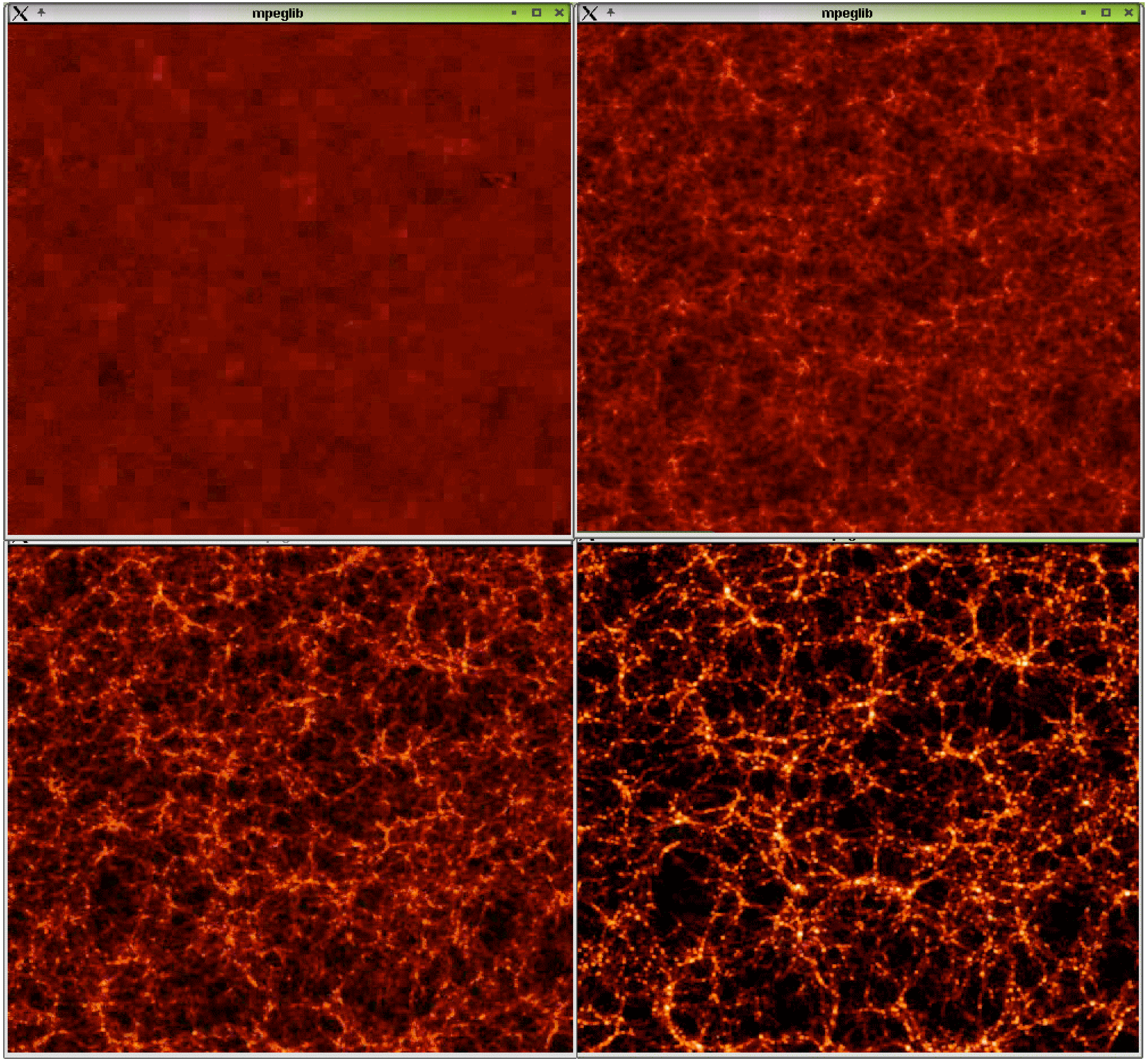
Another handle on DE:

-Friedman Eq. (Expansion history) can not separate gravity from DE
-Growth of sctructure could: models with equal expansion history yield difference D(z) (EG & Lobo 2001), **astro-ph/0303526 & 0307034)**

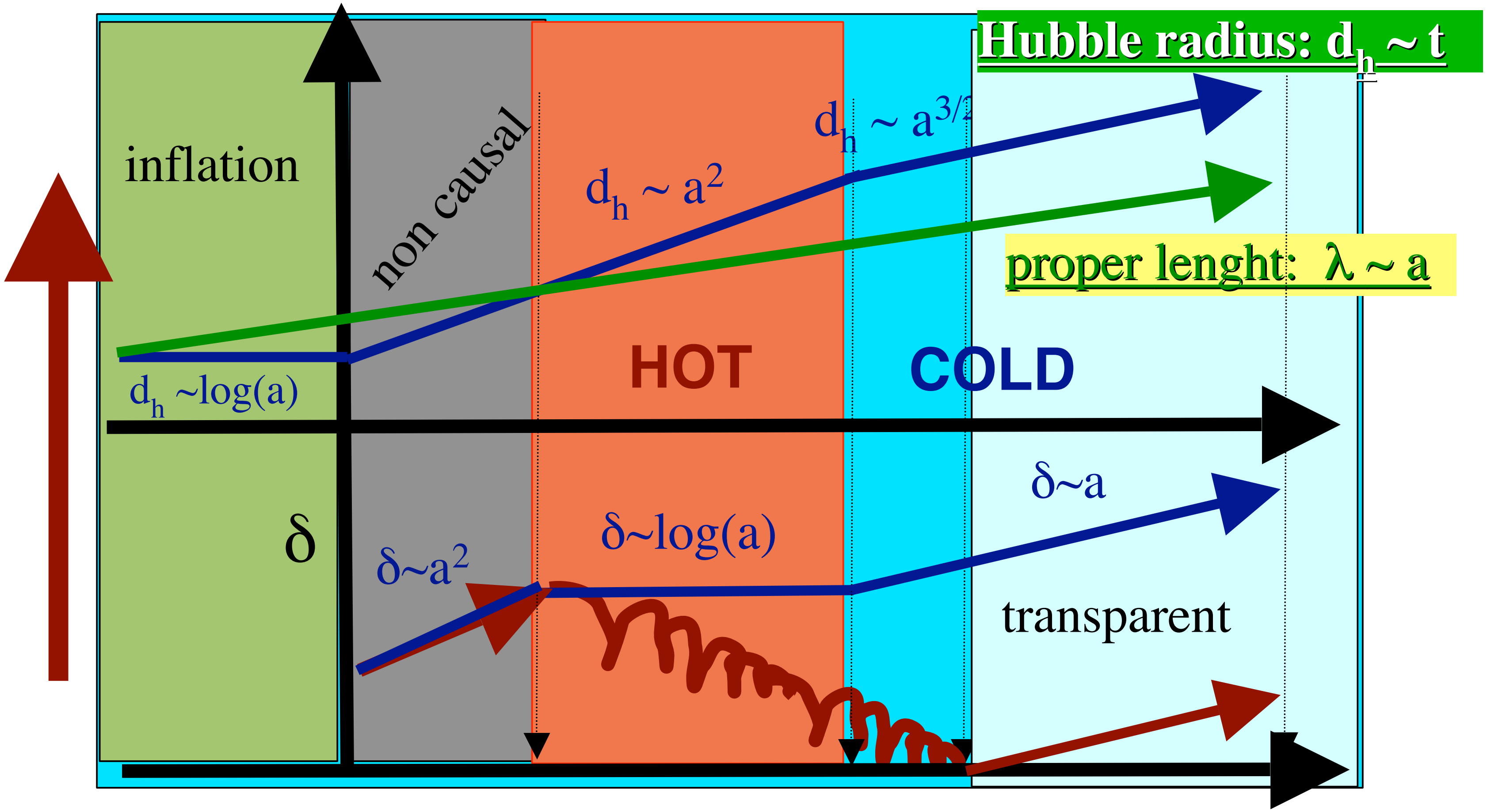
-Grat, but how do you get D(z) from observations?



VIRGO N-body simulations



growth of fluctuations



$a\_{decoupling}$

a = scale factor = t^{α} →

$$\delta'' + \alpha H \delta' - (\mu H^2 - k^2 v^2/a^2)\ \delta = 0$$

harmonic osc. for $\delta(k)$, $k=2\pi/\lambda$

HOT Damped oscilations: $a^2\mu H^2 < k^2 v^2$ **COLD** Growing fluctuations

$a^2\mu H^2 > k^2 v^2$