Introduction to Cosmology

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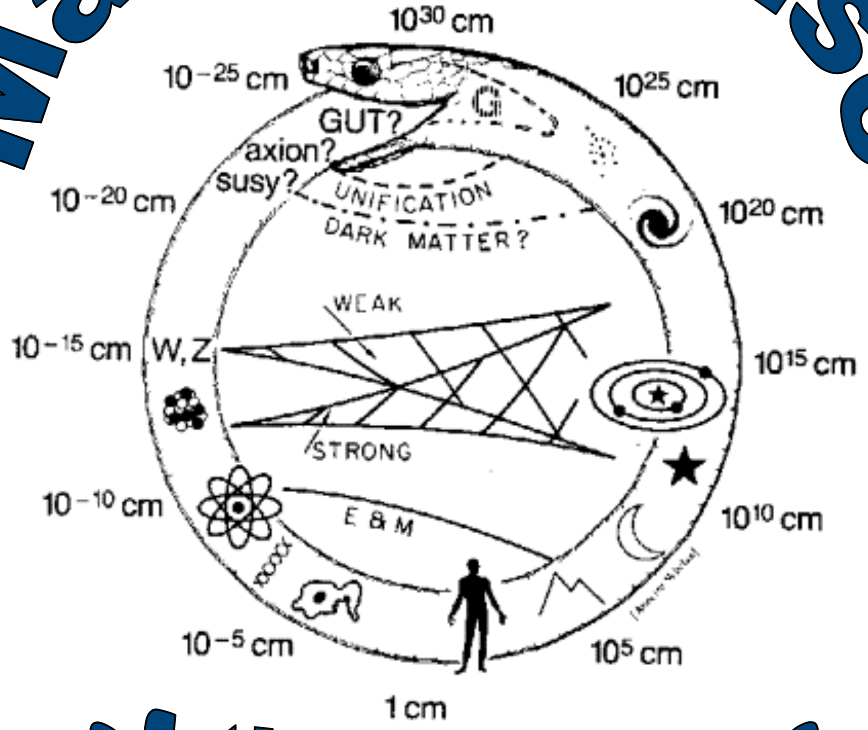
CERN Summer training Programme, 22-28 July 2008

- **Seeing the edge of the Universe:** From speculation to science
- **Constructing the Universe:** Relativistic world models
- **The history of the Universe:** Decoupling of the relic radiation and nucleosynthesis of the light elements
- **The content of the Universe:** Dark matter & dark energy
- **Making sense of the Universe:** Fundamental physics & cosmology

http://www-thphys.physics.ox.ac.uk/user/SubirSarkar/cernlectures.html

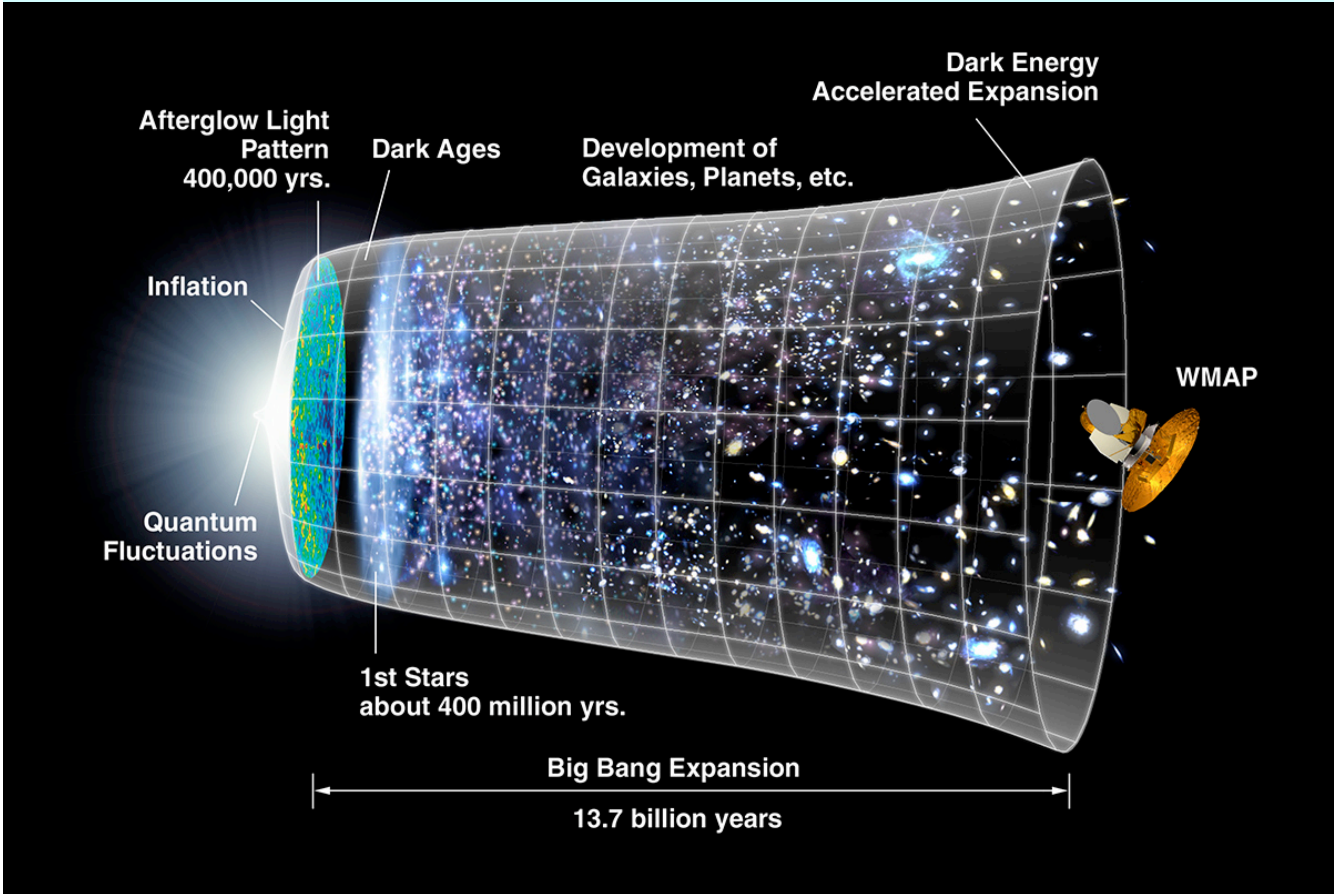
Lecture 5

Making sense of the universe

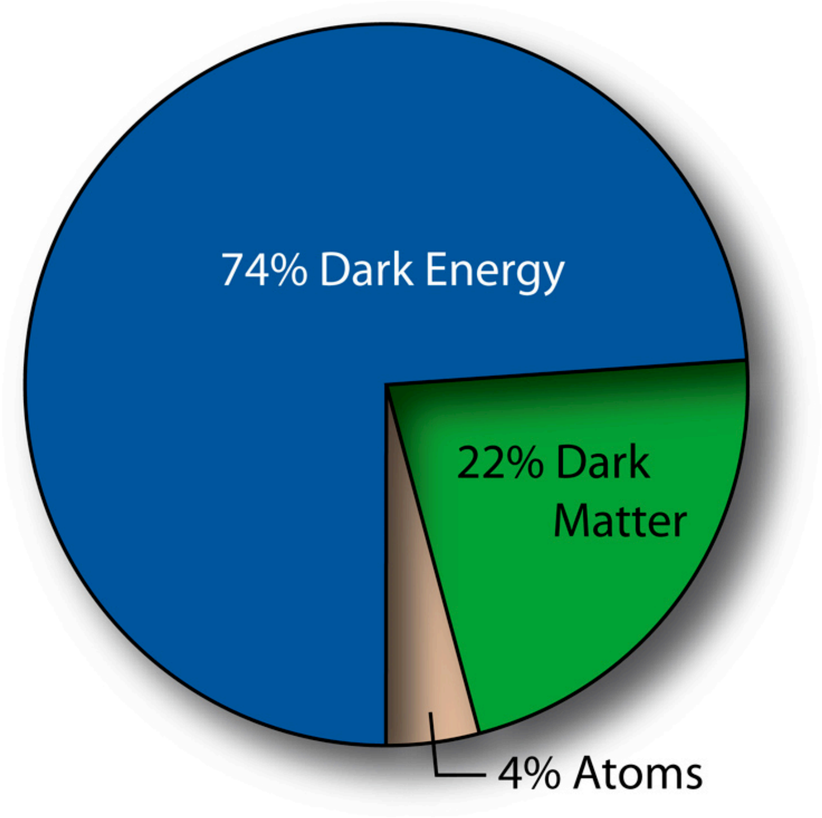


Fundamental physics and cosmology

A renaissance in observational cosmology has led to the emergence of a **'standard model' for the birth and evolution of our universe**



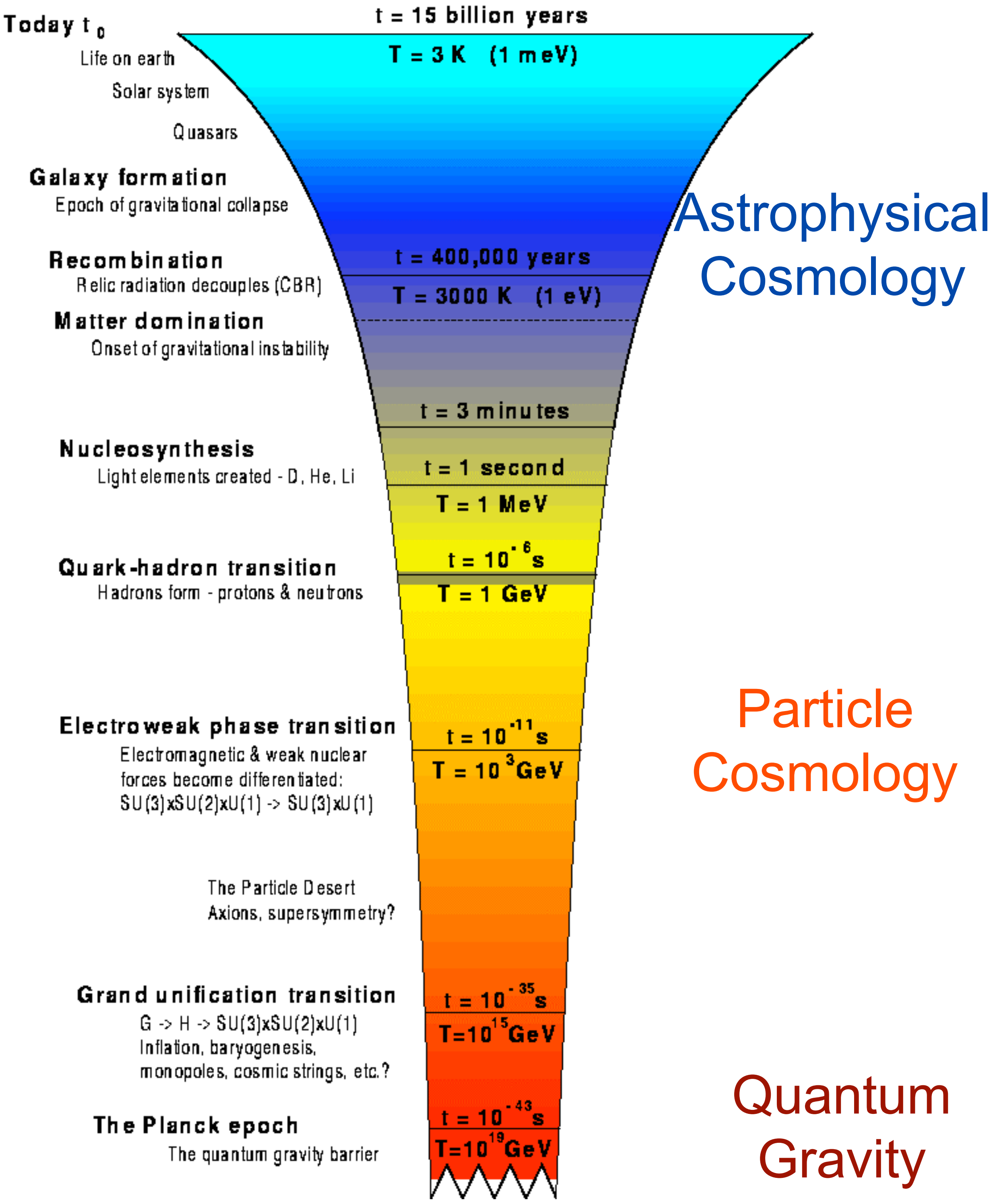
But these observations, as interpreted in the standard F-L-R-W cosmological model, lead us to a preposterous Universe dominated by unknown dark matter and bizarre dark energy



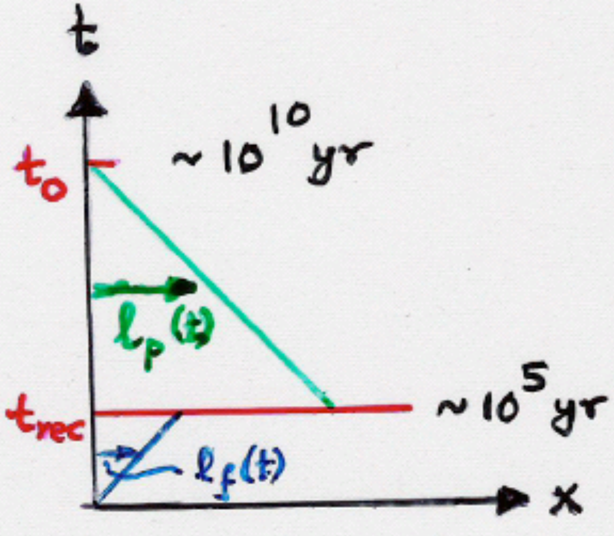
… cosmological data alone *require* new physics beyond the Standard Model

The early universe is an *unique* laboratory for probing such new physics … which must account for the observed asymmetry between matter and antimatter, generate dark matter (and dark energy), as well as the density fluctuations which seeded the formation of structure

… a fundamental theory must also account for the large entropy/information content of the universe (why is it so *big* and *old*?) and resolve the nature of the Big Bang singularity



The cosmological horizon problem (Misner '68)



$$\ell_p(t) = \int_t^{t_0} \frac{dt'}{a(t')} = 3t_0\left[1-\left(\frac{t}{t_0}\right)^{1/3}\right] \gg \ell_f(t) = \int_0^t \frac{dt'}{a(t')} \simeq 3t_0\left(\frac{t}{t_0}\right)^{1/3}$$

for $a \propto t^{2/3}$ with $a(t_0) \equiv 1$ for $t = t_{rec}$

So why is the relic radiation so uniform (to within 1 part in 10^5) over regions which were apparently *causally disconnected*?

The favoured solution is to invoke a period of *accelerated expansion* at early times – this is termed ‘**inflation**’

… Solved by (superluminal) inflation:

$\ddot{a} > 0$

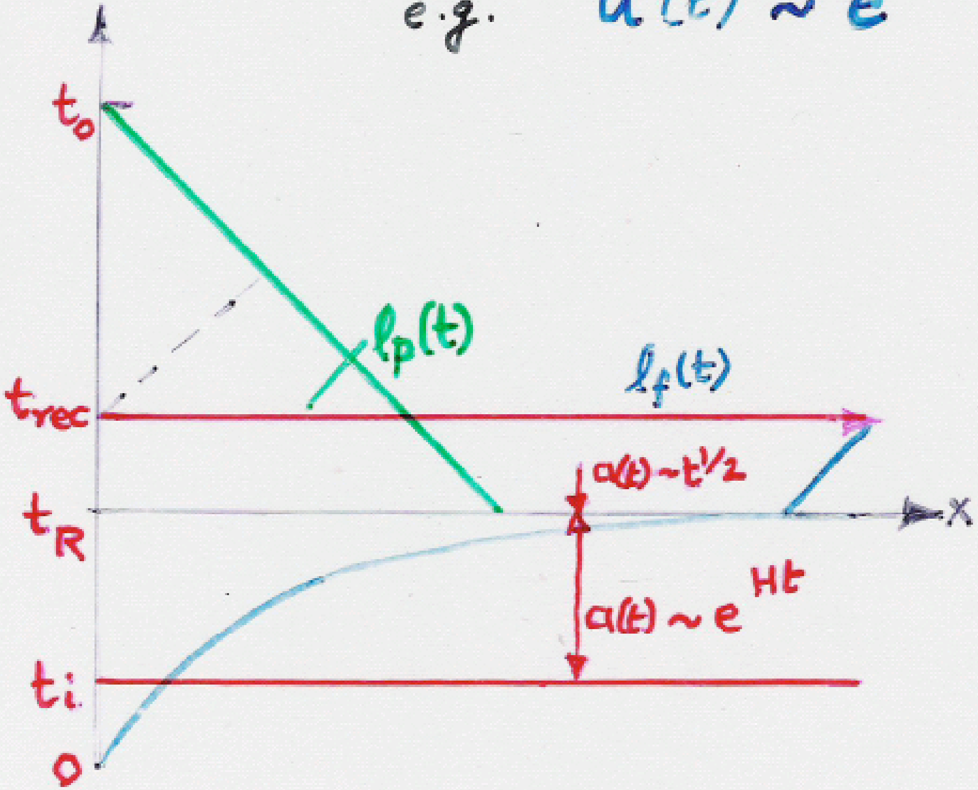
or, $\frac{d}{dt}\left(\frac{H^{-1}}{a}\right) < 0$

… more precisely

(requires $\rho + 3p < 0$)

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

e.g. $a(t) \sim e^{Ht}$



Require

$$e^{H\Delta t} \gtrsim \frac{l_p(t_R)}{l_f(t_R)} \simeq \left(\frac{t_0}{t_R}\right)^{1/2} = \left(\frac{T_R}{T_0}\right) \sim 10^{27}$$

$\Rightarrow$ inflationary period: $\Delta t \gtrsim 60\, H^{-1}$

The flatness problem

(Dicke & Peebles '79)

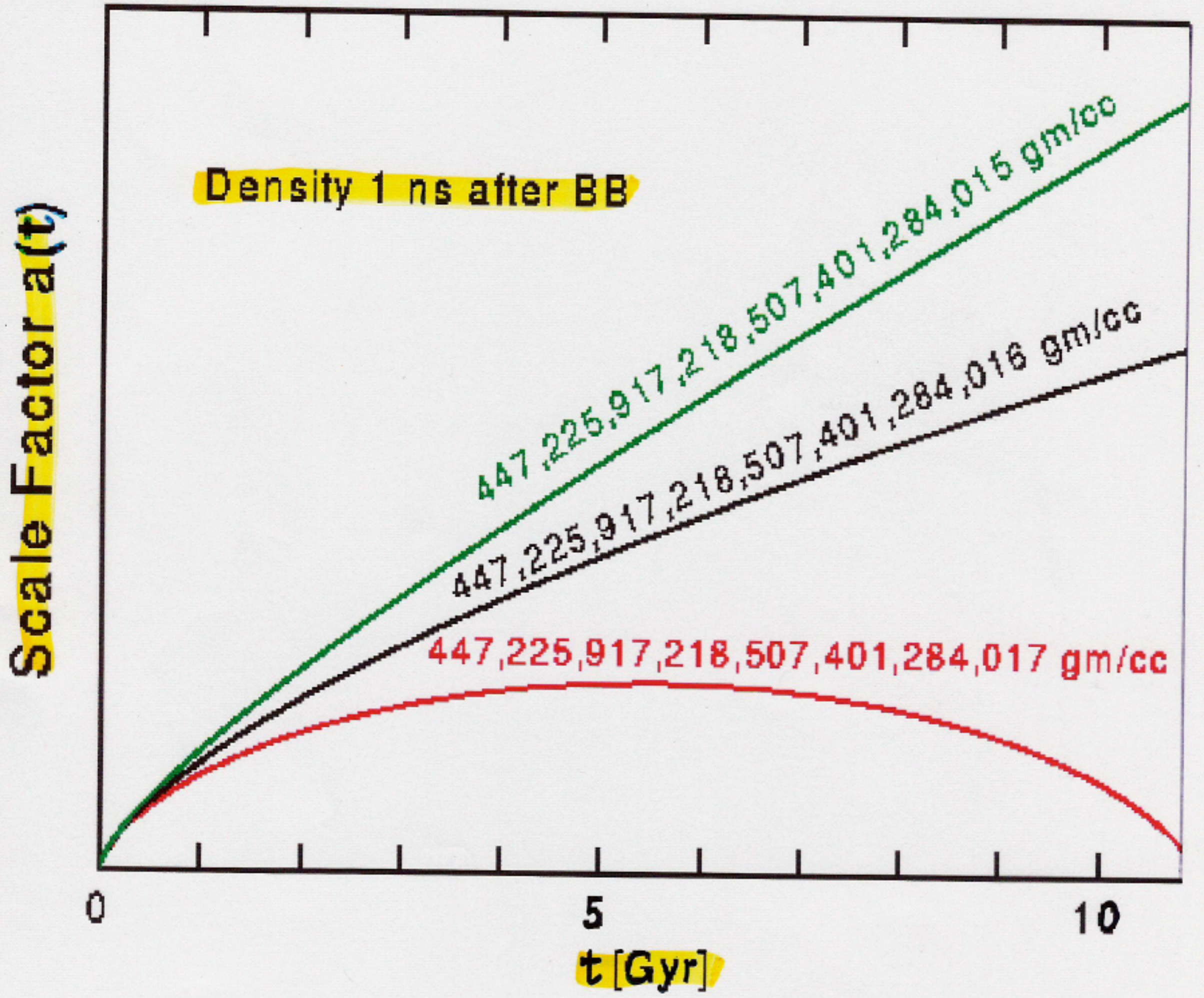
$$\Omega \equiv \frac{\rho}{\rho_{crit}} , \qquad \dot{\Omega} \propto 2\beta\,\Omega^{3/2\beta}(\Omega-1)^{\beta-1}$$

$$\rho_{crit} = \frac{3H^2}{8\pi G_N}$$

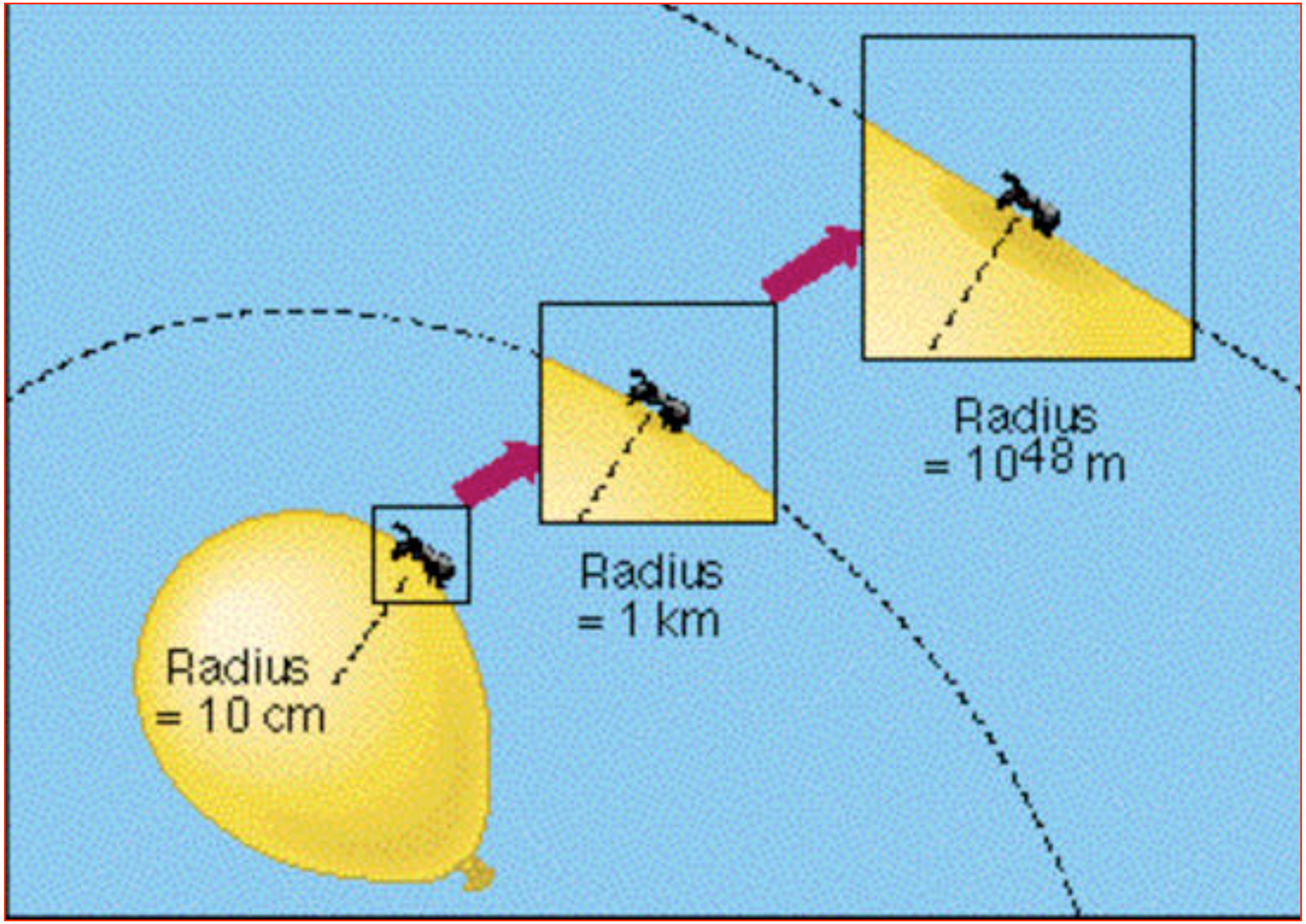
where $\beta \equiv \frac{\rho+3p}{2\rho} = \begin{cases} -1 & \text{... vacuum energy} \\ 1/2 & \text{... 'dust'} \\ 1 & \text{... 'radiation'} \end{cases}$

e.g. $\Omega = \frac{1}{1+\frac{t}{t_0}(\Omega_0^{-1/2}-1)^2}$, for $\beta = 1$

$$\boxed{\Omega - 1 = \frac{k}{a^2H^2}}$$

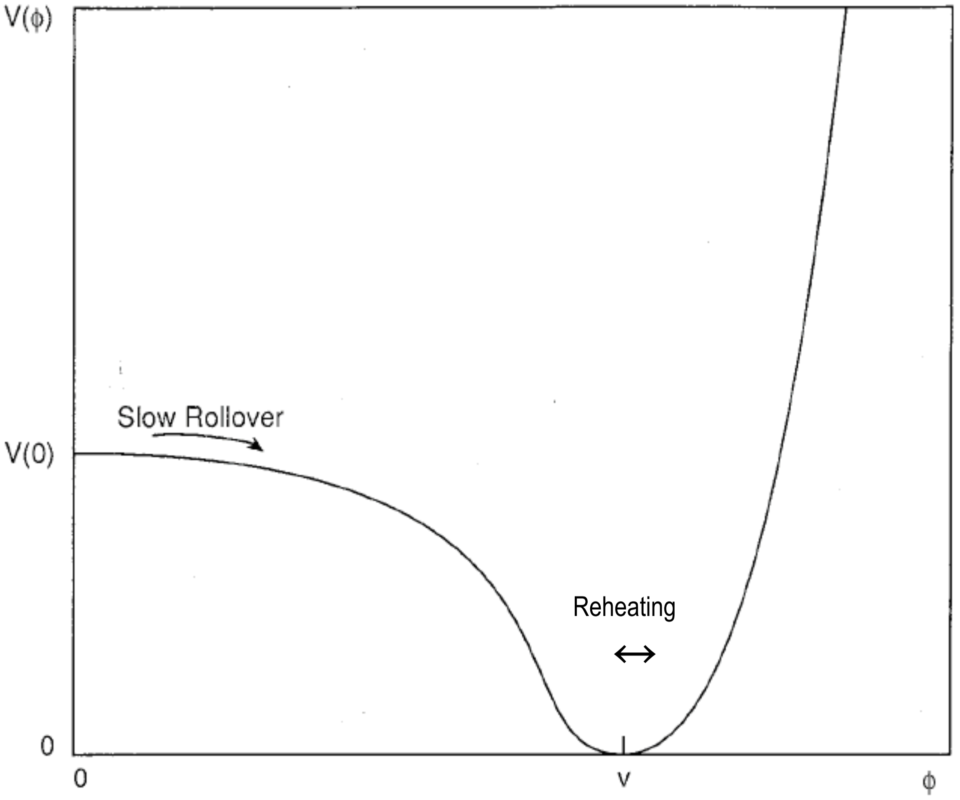


The solution is again inflation … to flatten the curvature of space



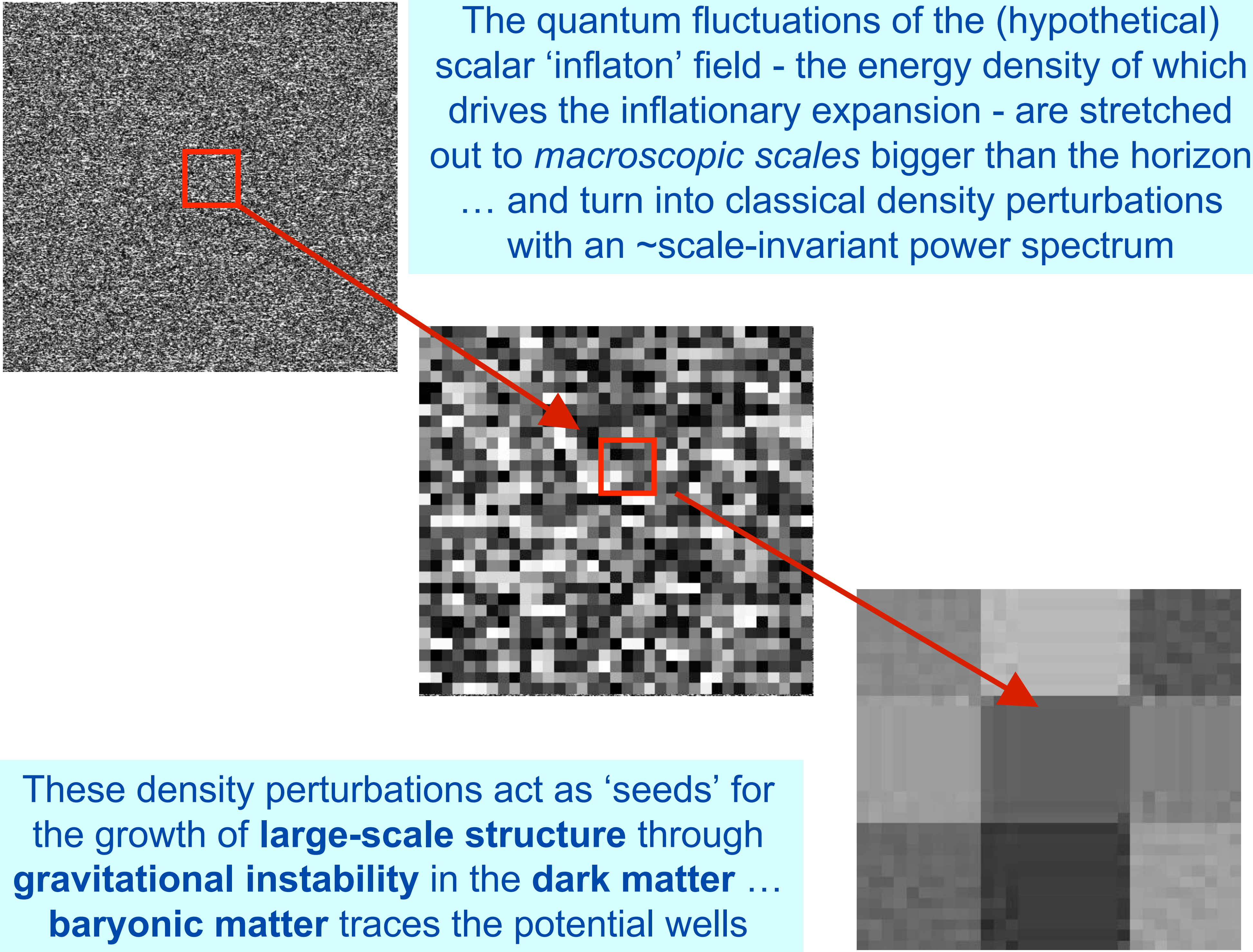
~30-60 e-folds of inflation suffices to solve the flatness problem
… note there may have been more than one episode of inflation

All this could have happened if the early universe had become dominated temporarily by the vacuum energy of a scalar ‘inflaton’ field which is displaced from the true minimum of its potential and evolves slowly towards it (while driving exponentially fast expansion) …



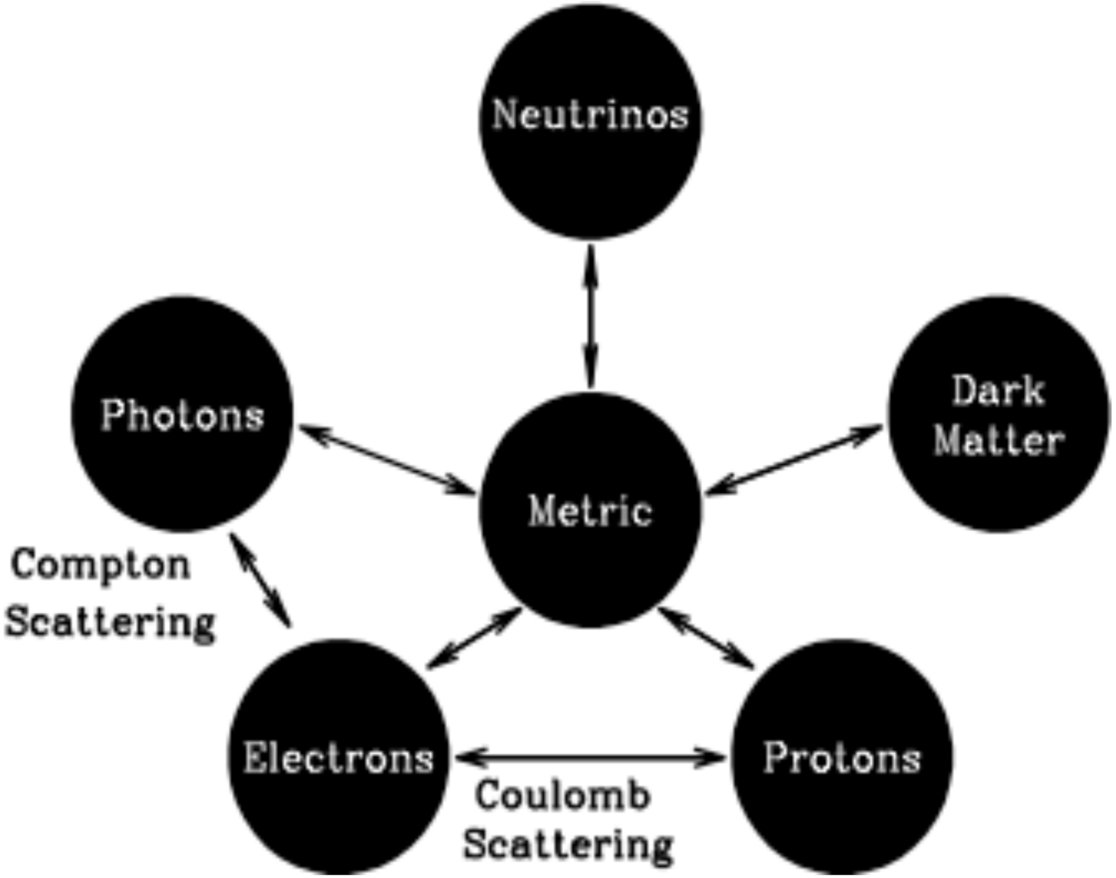
If the potential is sufficiently flat, the required number of e-folds of expansion can happen before the inflaton reaches its minimum … and converts its energy density into relativistic particles, starting off the hot radiation-dominated era

The quantum fluctuations of the (hypothetical) scalar ‘inflaton’ field - the energy density of which drives the inflationary expansion - are stretched out to *macroscopic scales* bigger than the horizon … and turn into classical density perturbations with an ~scale-invariant power spectrum



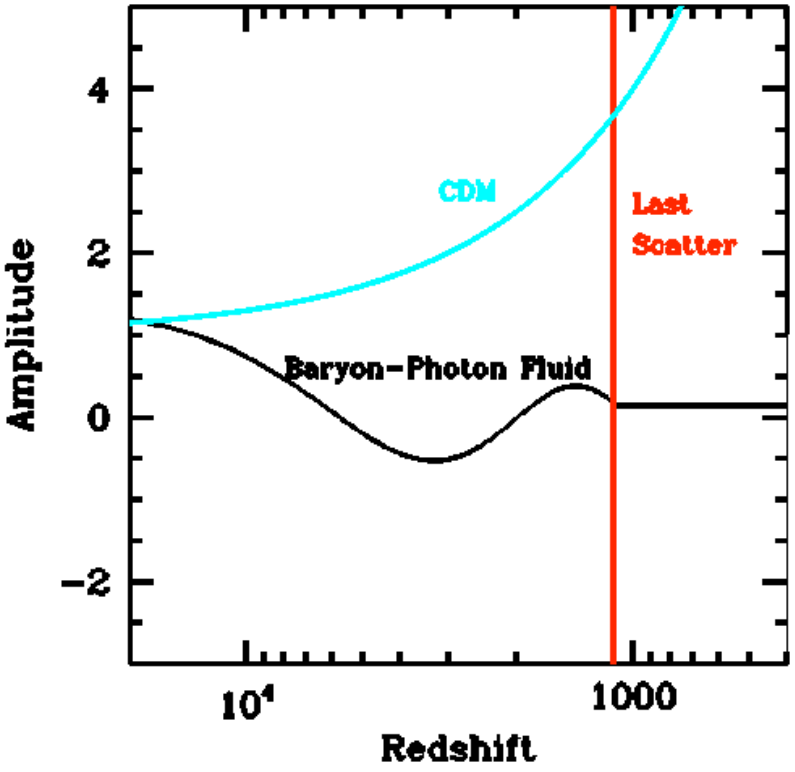
These density perturbations act as ‘seeds’ for the growth of **large-scale structure** through **gravitational instability** in the **dark matter** … **baryonic matter** traces the potential wells

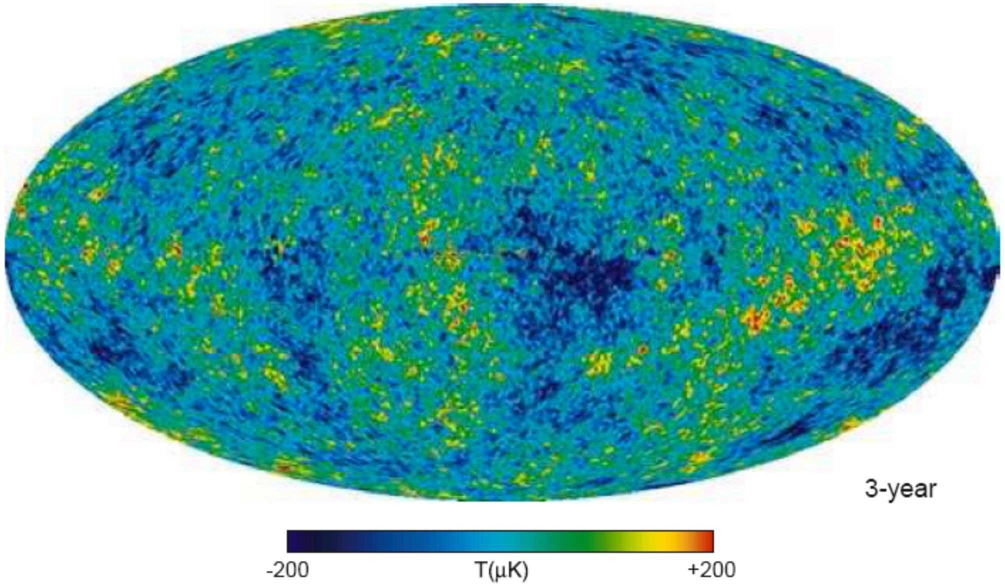
Perturbations in metric (generated during inflation) induce perturbations in photons and (dark) matter



These perturbations begin to grow through gravitational instability after matter domination

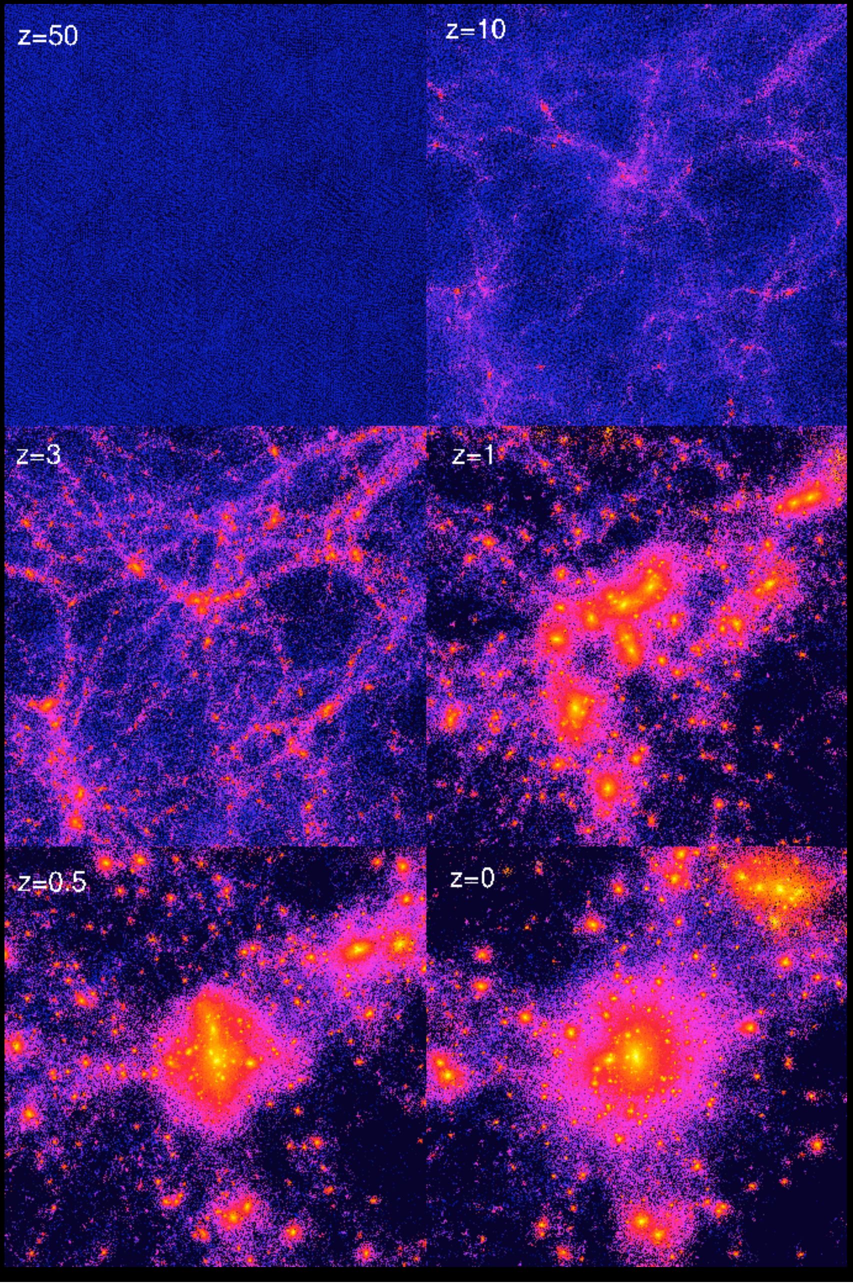
Before recombination, the primordial fluctuations just excite sound waves in the plasma, but can start growing already in the sea of *collisionless* dark matter …





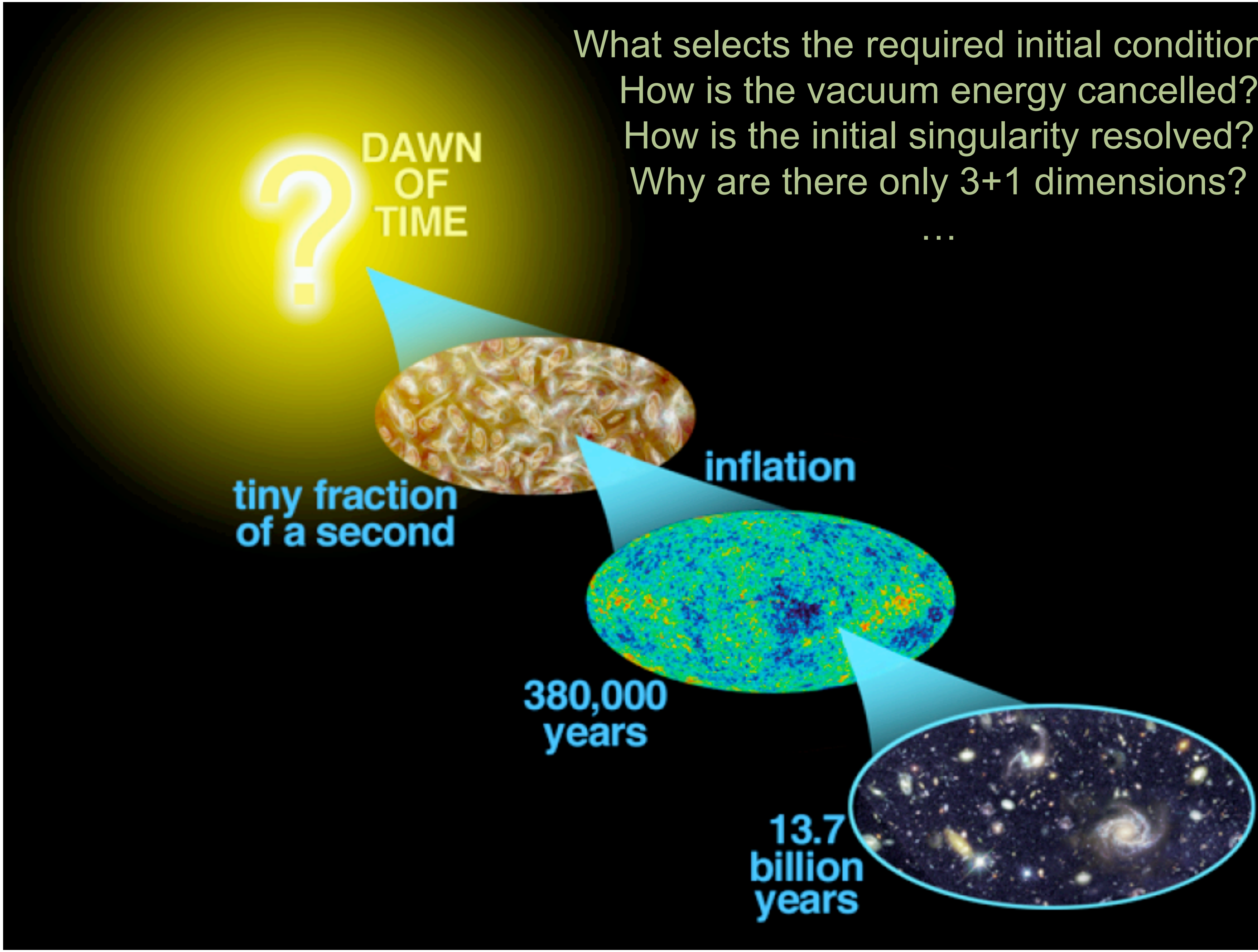
These sound waves leave an imprint on the last scattering surface of the CMB as the universe turns neutral and transparent - the ‘Cosmic Rosetta Stone’

Numerical simulations of the formation of structure through gravitational instability in *cold dark matter match* the observations



But we do not yet know the physics behind inflation or what came before it …

What selects the required initial conditions?
How is the vacuum energy cancelled?
How is the initial singularity resolved?
Why are there only 3+1 dimensions?
…



Being strongly interacting, nucleons and anti-nucleons should have annihilated each other nearly completely in the early universe …

Annihilation rate: $\Gamma = n\sigma v \sim m_N^{3/2} T^{3/2} \mathrm{e}^{-m_N/T} \frac{1}{m_\pi^2}$

cf. expansion rate: $H \sim \frac{\sqrt{g}T^2}{M_{\mathrm{P}}}$

i.e. ‘freeze-out’ at T ~ $m_N/45$, with: $\frac{n_N}{n_\gamma} = \frac{n_{\bar{N}}}{n_\gamma} \sim 10^{-19}$

However the observed ratio is 10^9 times *bigger* for baryons, and *no* antibaryons are present, so there must have been an **initial asymmetry** of:

$$\frac{n_B - n_{\bar{B}}}{n_B - n_{\bar{B}}} \sim 10^{-9}$$

i.e. for every 10^9 baryon-antibaryon pairs there was *1 extra baryon*

Sakharov conditions for baryogenesis:

1. Baryon number violation
2. *C* and *CP* violation
3. Departure for thermal equilibrium

In principle baryon number violation can happen even in the Standard Model through non-perturbative processes if the electroweak symmetry breaking phase transition is 1st order and therefore out-of-equilibrium … but CP-violation is *too weak*

Thus the generation of the observed matter-antimatter asymmetry *requires* new BSM physics - could be related to neutrino masses (which are likely due to lepton number violation) … interesting possibilities for **leptogenesis**

Thermal relics

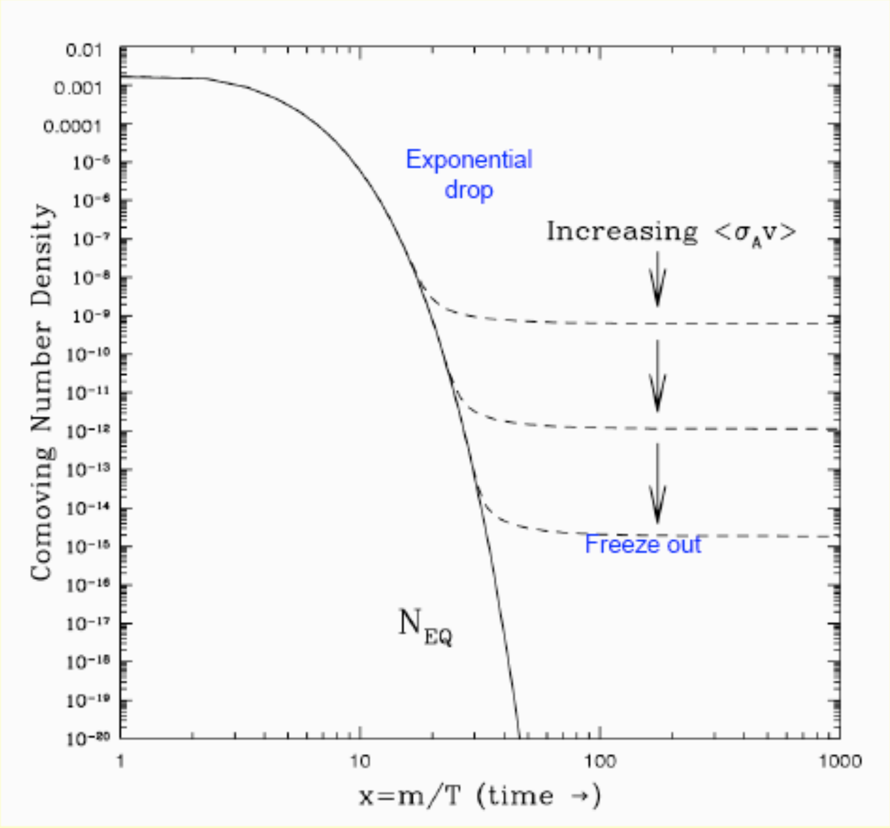
$$\dot{n} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\mathrm{T}}^2)$$

Boltzmann rate equation tries to maintain thermal equilibrium – but fails when reaction timescale exceeds 1/H: Freezeout

Two generic possibilities for when freezeout happens:

(1) relativistic: number density today ~ photon density)

(2) nonrelativistic: rarer than photons by exp(-mc^2/kT)



The relic abundance of a **Weakly Interacting Massive Particle** matches that of the dark matter if the annihilation cross-section is of order ~1 TeV^{-2} … hence there are *many* candidates for WIMPS in extensions of physics **beyond the Standard Model**

There must be a new **conserved quantum number** that ensures its stability (e.g. *R*-parity for the lightest supersymmetric particle) but the particle must **not** carry **electric or colour charge** so it would not bind to ordinary nuclei and form (unobserved) anomalous isotopes (so the LSP could be e.g. the neutralino)

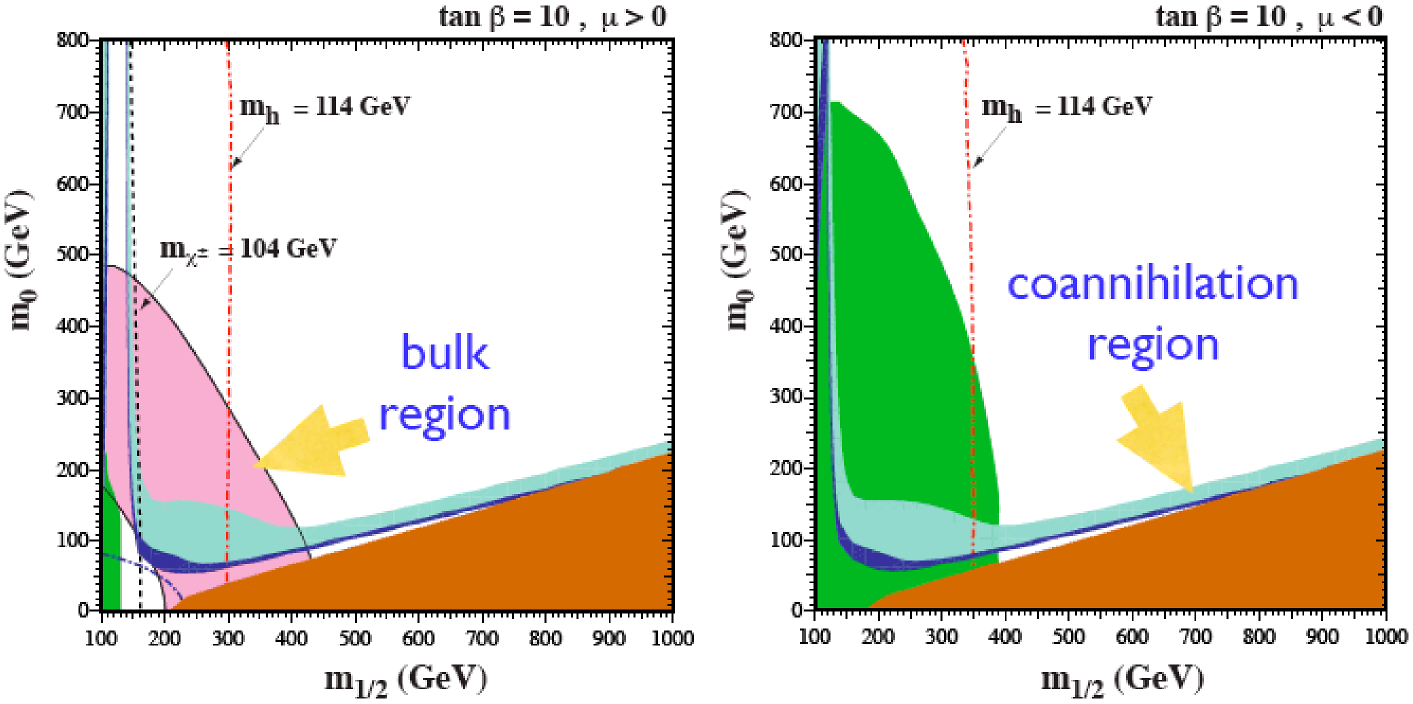
It is thus quite possible that the LHC will be able to directly produce the dark matter particles and thus complement the searches that are being carried out using both direct means (underground nuclear recoil detectors) and indirect methods (looking for annihilation γ-rays or ν from dark matter clumps)

🟩 excluded by b→sγ

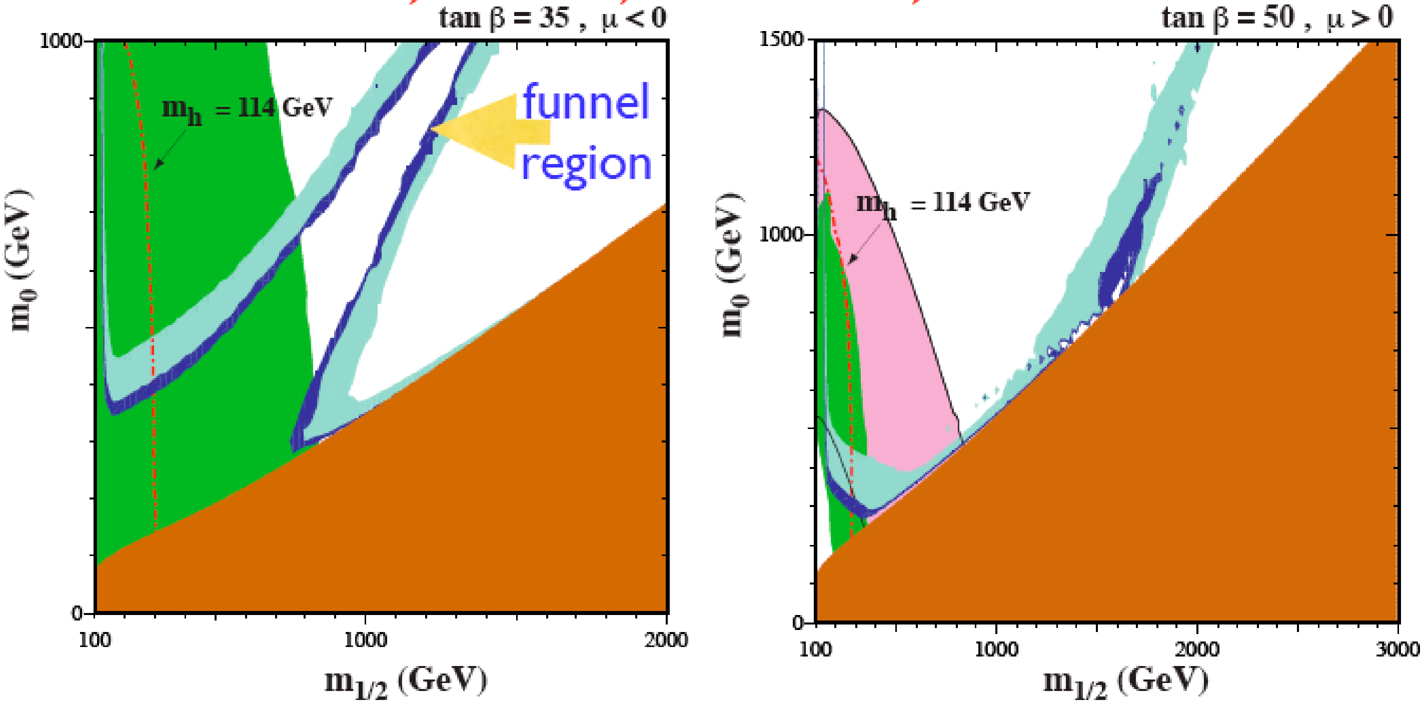
🟪 preferred by gμ-2

🟦 $0.1 \leq \Omega\chi h^2 \leq 0.3$

🟦 $0.094 \leq \Omega\chi h^2 \leq 0.129$



Ellis, Olive, Santoso, Vassilis




COSMOLOGY MARCHES ON
where did it all come from?
where did it all come from?
S. Harris

The End