Particle Physics and Cosmology at Crossroads

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PARTICLE PHYSICS

- Understood up to energy scale $E \sim 100$ GeV, down to distances $r \sim 10^{-16}$ cm
  - Particles, their interactions described by the Standard Model
  - Yet to be discovered: the Higgs boson
- High expectations for next domain of energies, $E \sim$ a few TeV
  - To be probed by LHC: $p-p$ collider at energy 7×7 TeV at CERN.

    Due to start in 2008
- MAJOR HINTS COME FROM COSMOLOGY

COSMOLOGY

- Matured to exact science in the last 15 – 20 years
- Various ways to measure the Universe at large
  - Standard candles (Type 1 Supernovae):
    measure expansion rate today and in relatively recent past
  - Deep surveys of galaxies and quasars:
    almost 10^6 objects $\Longrightarrow$ map of the Universe
    up to distances 4000 Mpc $= 12 \cdot 10^9$ light yrs
  - Angular dependence of the temperature and polarization of Cosmic Microwave Background
  - Abundances of light elements
  - Ly-α forest, gravitational lensing, ...

- Consistent picture of present and early Universe
- But to large extent orthogonal to existing knowledge in particle physics
- Total energy density today

$$\rho_0 = (5.3 \pm 0.5)\ \frac{\text{GeV}}{\text{m}^3}$$

- Energy density in baryons (protons, neutrons)

CMB, nucleosynthesis

$$\rho_B = 0.24\ \frac{\text{GeV}}{\text{m}^3}$$

ABOUT 4.5% ONLY

- Neutrinos, photons, electrons contribute even less
- Most energy is due to something unknown

Even more...

- Both dark matter $= 20 \div 25\%$
and dark energy $= 75 \div 70\%$

Dark matter

- Needed for galaxy formation
- Required to fit CMB data
- Exists in galactic halos
  - rotation of stars / gas clouds around galaxies
- “Seen” in galactic clusters

- New neutral stable (on cosmological scale) heavy particle
  - Does not exist in the Standard Model
  - Stability: new conserved quantum number $\Longleftrightarrow$ new symmetry

Best guess: WIMP (cf. Yukawa's pion)

- Pair produced in early Universe at $T \simeq M$, pair-annihilate at $T < M$, freeze out at $T \sim M/20$
  - Calculable in terms of mass (log dependence) and annihilation cross section ($1/\sigma$ dependence)
- To have right present abundance:
  - Mass range: $(10 - 1000)$ GeV
  - Strength of interactions $\simeq$ weak force: annihilation cross section $= 10^{-35} - 10^{-36}$ cm^2

IF SO:

- Excellent chance for LHC
- Possibly detectable underground (interactions with our matter), underwater/under-ice and/or in space (annihilation products):

  about 1000 particles / m^3 here and now

- Window into the Universe at $T \sim 1 - 10$ GeV, $t \sim 10^{-6} - 10^{-8}$ s

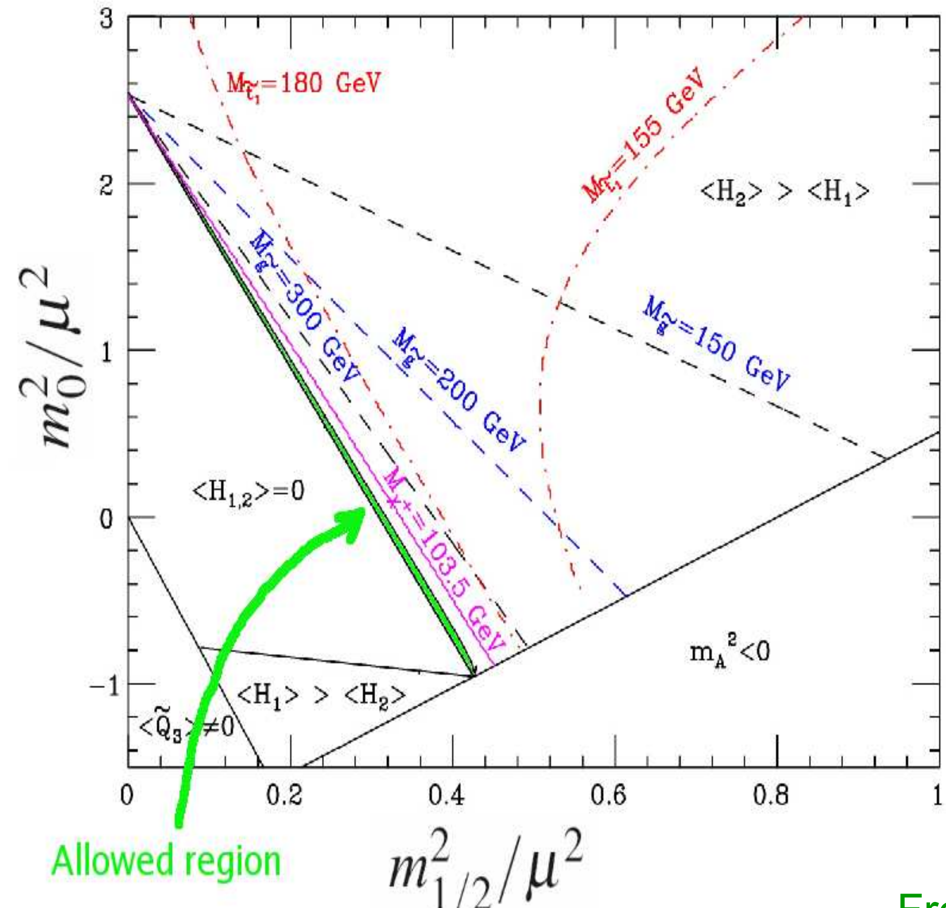
Well motivated theoretical framework:

LOW ENERGY SUPERSYMMETRY

- Plenty of new particles with $M = 100 - 1000$ GeV.
  The lightest is stable and neutral in many concrete models

Warning: supersymmetric models are already constrained experimentally

mSUGRA



From Giudice, Rattazzi' 06

- Besides WIMPs, many more candidates to dark matter particle:
  from well motivated — axion, gravitino
  to much less motivated — 10 keV sterile neutrino, Q-balls, ...
  - Often much harder to detect
  - Need to dial parameters to get the energy density right

WHY

$$\rho_{Baryons} = \rho_{Dark\ matter}$$

within a factor of 5?

- Both were very small in the early Universe.
- Origins are very likely different

hint from cosmology that worked

BARYON ASYMMETRY $\Longleftrightarrow$ NEUTRINO OSCILLATIONS

- Another problem in cosmology:
  the Universe is baryon-asymmetric
  There is matter, no antimater

  - What's the problem?

Early Universe ($T > 10^{12}$ K $= 100$ MeV):
creation and annihilation of quark-antiquark pairs $\Longrightarrow$

$$\frac{n_q - n_{\bar{q}}}{n_q + n_{\bar{q}}} \sim 10^{-9}$$

How was this asymmetry generated in the course of the cosmological evolution?

Sakharov' 67
Kuzmin' 70

Conservation laws in the Standard Model

- Energy, momentum
- Baryon number $(N_q - N_{\bar{q}})$

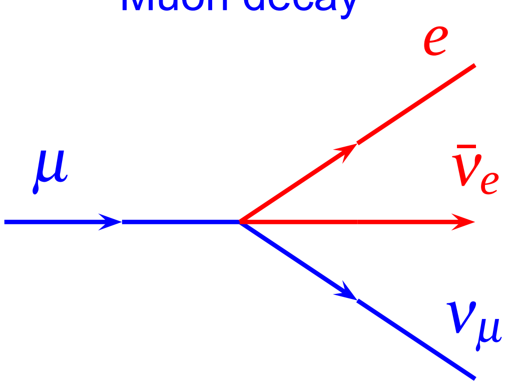
proton is stable, $\tau_p > 10^{33}$ yrs!

- Lepton numbers

$$L_e = (N_{e^-} + N_{\nu_e}) - (N_{e^+} + N_{\bar{\nu}_e})$$

$$L_\mu \;, \quad L_\tau$$

Muon decay

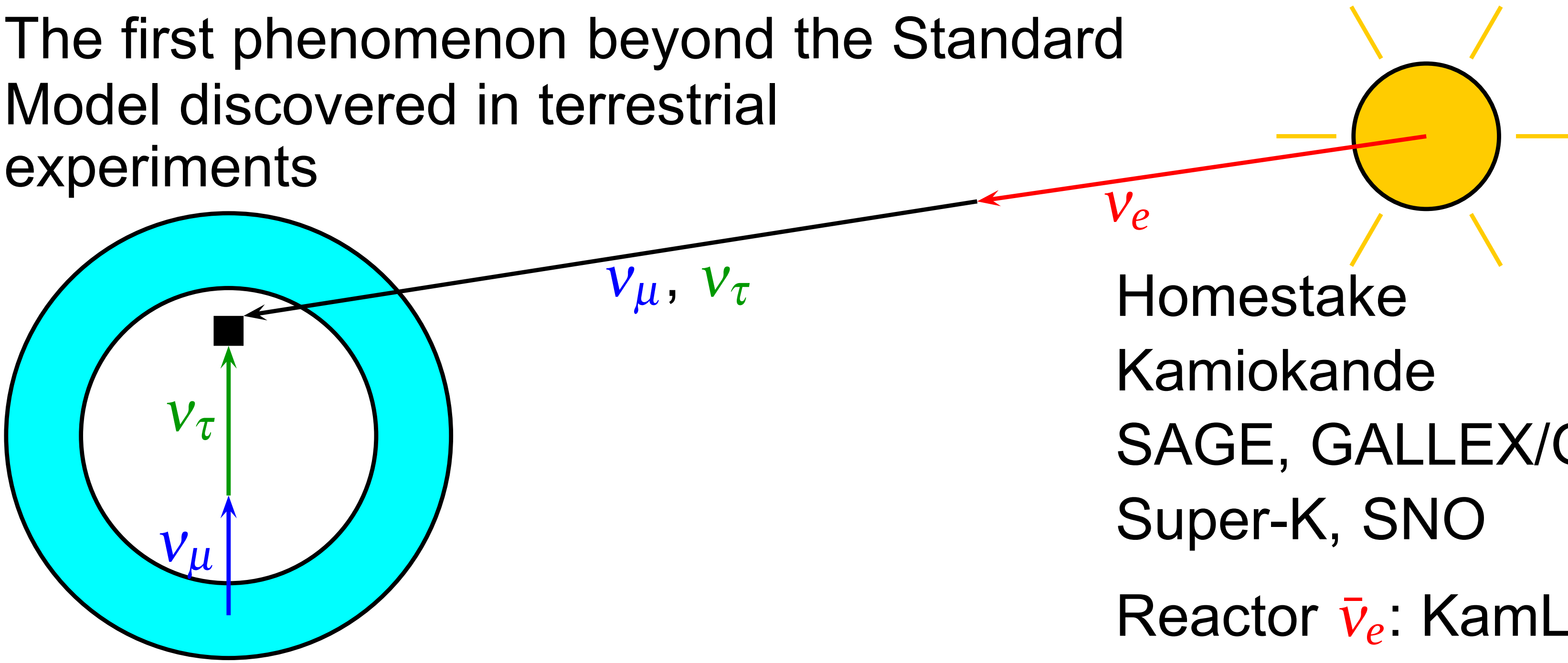


$\mu \not\rightarrow e\gamma \,,\quad$ Br $< 10^{-11}$

Baryon asymmetry cannot be explained within the Standard Model

Key: neutrino oscillations

The first phenomenon beyond the Standard Model discovered in terrestrial experiments



Super–K

Accelerator ν_μ: K2K, Minos

Homestake

Kamiokande

SAGE, GALLEX/GNO

Super-K, SNO

Reactor $\bar{\nu}_e$: KamLAND

Lepton numbers are NOT conserved

NB

- LSND anomaly: claim for $\nu_\mu \to \nu_e$ oscillations with $\Delta m^2 = 0.1 \div 1$ eV^2 $\Longrightarrow$ would need new, “sterile” neutrino

April 11, 2007:

MiniBooNe at Fermilab

LSND anomaly is not there

Such a relief ...

SCENARIO FOR GENERATION OF BARYON ASYMMETRY

suggested long before the discovery of ν oscillations

Fukugita, Yanagida' 86

- Baryon number is not quite conserved in the Standard Model

  $(B-L)$, $(L_i - L_j)$ are conserved, but $B \leftrightarrow L$ possible

  Way too weak *in vacuo* to be observable

't Hooft' 76

- Standard Model: $B \leftrightarrow L$ strong at high temperatures,

  $T \gtrsim 100$ GeV

Kuzmin, VR, Shaposhnikov' 85

- Lepton asymmetries generated at high T

  by interactions that are responsible for ν oscillations

  - Lepton asymmetries reprocessed into baryons

    by SM $B \leftrightarrow L$

STILL A SCENARIO, BUT

measured

$$
\begin{aligned}
|m^2_{\nu_2} - m^2_{\nu_1}| &= 0.8 \cdot 10^{-4}\ \text{eV}^2 \\
|m^2_{\nu_3} - m^2_{\nu_2}| &= 2.5 \cdot 10^{-3}\ \text{eV} \\
m_\nu &< 1\ \text{eV}
\end{aligned}
$$

JUST IN RIGHT BALLPARK FOR PRODUCING REQUIRED B ASYMMETRY

- More weight when CP-violation in ν oscillations discovered
- Hardly can be proven unequivocally

NO REASON FOR

$$\rho_{Baryon} = \rho_{Dark\ matter}$$

Dark energy

- Does not clump
- Has negative pressure $\Longrightarrow$ gives rise to accelerated expansion of the Universe

$$\frac{d\log R}{dt} \equiv H = \left(\frac{8\pi}{3}G\rho\right)^{1/2}$$

Energy density $\rho \approx$ const $\Longrightarrow$ $R(t) \approx e^{\text{const}\cdot t}$

But for $\rho \approx$ const

$$dE \approx \rho dV = -p dV \quad \Leftrightarrow \quad p \approx -\rho$$

Observationally $\quad p = w\rho, \quad w = -1 \pm 0.1$

- Present value

$$\rho_{DE} \approx 4\ \frac{\text{GeV}}{\text{m}^3} = (2 \cdot 10^{-3}\ \text{eV})^4 \qquad \hbar = c = 1$$

- “Good” candidate: vacuum (not the only one!)

Lorentz-invariance:

$$T_{\mu\nu}^{(vac)} = \rho^{(vac)} \eta_{\mu\nu}, \quad \rho^{(vac)} = \text{const}$$

$$p^{(vac)} = -\rho^{(vac)}$$

- TWO HARD PROBLEMS
  - Particle physics scales are much larger than 10^{-3} eV

    Strong interactions: $\Lambda_{QCD} \sim 1$ GeV
    Electroweak : $M_W \sim 100$ GeV
    Gravitational : $M_{Pl} \sim 10^{19}$ GeV

  - No reason for $\rho^{(vac)} \ll \Lambda_{QCD}^4,\ M_W^4,\ M_{Pl}^4$

DISCREPANCY OF AT LEAST 10^{44}

Lagrangian of the Standard Model + gravity:

$$L = L_{QCD} + L_{EW} + M_{Pl}^2 \, R + \Lambda$$

$$\rho = \Lambda_{QCD}^4 + M_W^4 + M_{Pl}^4 (?) + \Lambda$$

Need cancellations to 10^{-44}, 10^{-56}, 10^{-124}, resp.

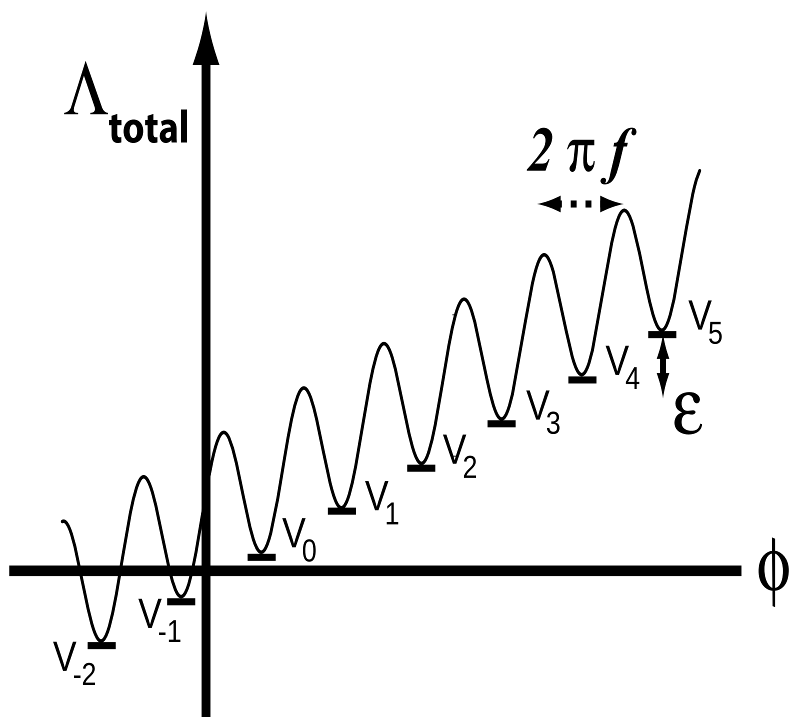
- Cosmlogical constant problem: hint towards
  - Long pre-history of the Universe
    + relaxation
  - Something unpleasant (for a theorist): anthropic selection

Relaxation mechanisms

- Introduce new light field(s)
- Arrange things in such a way that no matter what "true" cosmological constant is, it gets compensated (relaxed) to a tiny value

Dolgov' 82 – 06; Abbott' 85; Peccei, Sola, Wetterich' 87;
Brown, Teitelboim' 88; V.R.' 00; Bousso, Polchinski' 00, etc.

Example: long sequence of phase transitions



- Can work at a pre-historic cosmological epoch only $\Longrightarrow$ déjà vu Universe

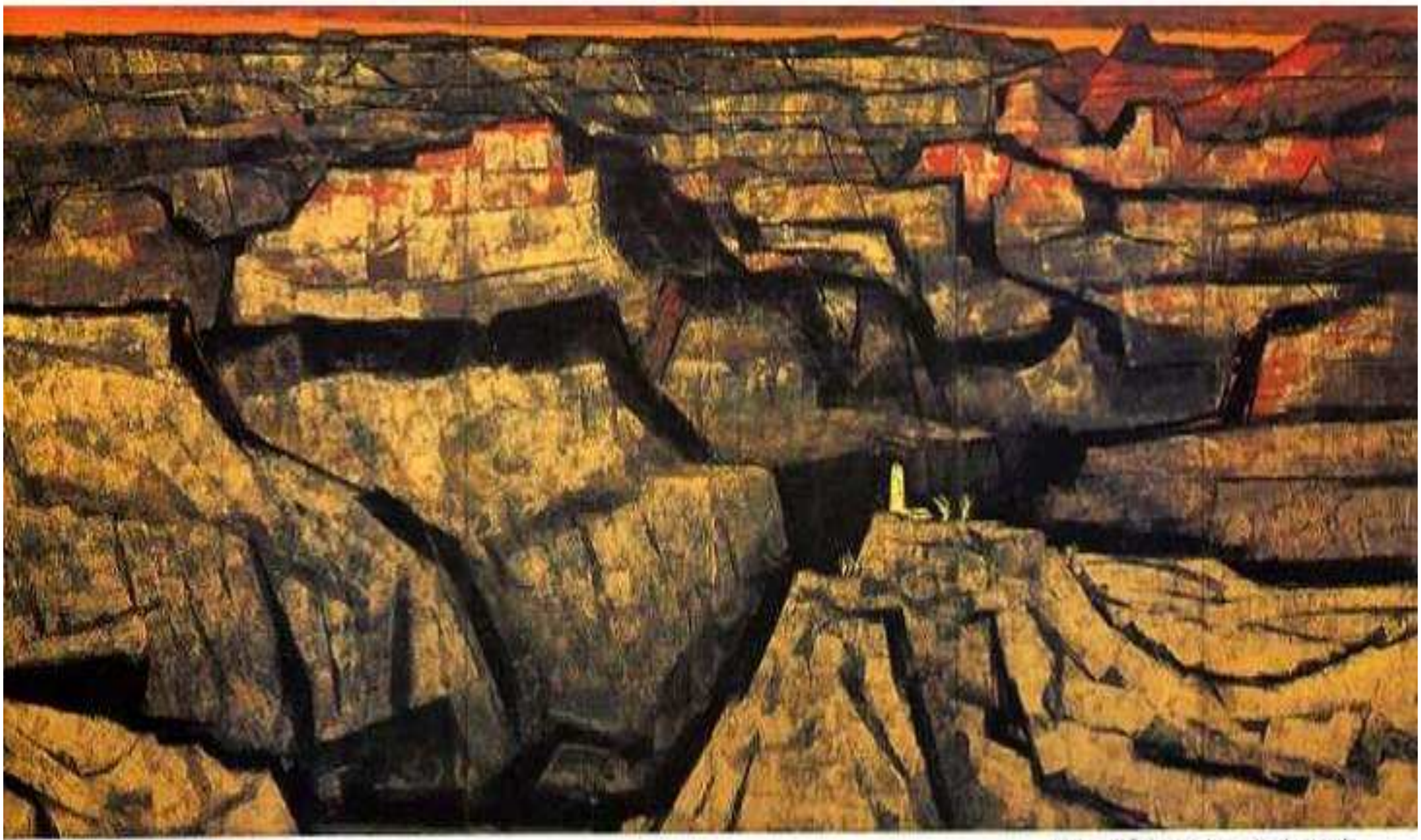
V.R.' 00; Steinhardt, Turok' 06

  - Reason: at known cosmological stages vacuum makes just a fraction of energy density. Both vacuum energy and particles' energy would get compensated. Would contradict cosmological data.
  - Furthermore, relaxation to the present tiny value takes much longer than 10^{10} yrs.
    - Experimental checks appear hopeless
    - Present value of ρ_{DE} is an accident

Anthropic principle/environmentalism

"Our location in the Universe
is neccessarily priviledged to
the extent of being compatible
with our existence as observers"

B. Carter' 1974



Anthropic principle/environmentalism:

- disappointing for a theorist

allows for arbitrary fine-tunings between fundamental parameters

- hard to disprove; after all we do exist

unless all particle physics parameters
are calculated in a unique way
in “theory of everything”

- but it may (hopefully not) get more support
in near future if no or insufficient “new physics” is found at LHC

A candidate to environmentally determined quantity:

ELECTROWEAK SCALE

Electroweak scale $M_W \sim 100$ GeV:

- *In Standard Model* has no reason to be much lower than $M_{Pl} \sim 10^{19}$ GeV
- *In Standard Model* is unprotected from large contributions due to physics at $E \gg M_W$, very much like the cosmological constant
- May well be small anthropically otherwise, e.g., quarks would be too heavy $\Longrightarrow m_p > m_n$, no stable hydrogen
- However, unlike the cosmological constant, can be small in *extensions* of Standard Model

Best developed example: supersymmetry. But there are others.

All these extensions require a lot of "new physics" in TeV energy range

IT IS AGAIN UP TO EXPERIMENT TO SETTLE THE ISSUE

More hints to come

INFLATION

makes the Universe large and spatially flat;

the Universe gets hot after post-inflationary reheating

- According to the simplest picture, occurs due to a scalar field (inflaton) that slowly rolls down its potential
  - Inflaton field takes large values, $\Phi > M_{Pl}$
- Expansion rate $\Longleftrightarrow$ energy scale of inflation

$$H \sim 10^{14} \text{ GeV}$$

- Vacuum fluctuations, initially of short wavelengths, become large as momenta redshift below H
  $\Longrightarrow$ eventually transform into perturbations in energy density
  $\Longrightarrow$ CMB anisotropy, galaxies, clusters
  - gravitational waves are created too

Predictions

Scalar and tensor perturbations $\equiv$
density perturbations and gravity waves:

- Gaussian fields

- Almost, *but not exactly*, flat power spectra: per log interval of wavelengths

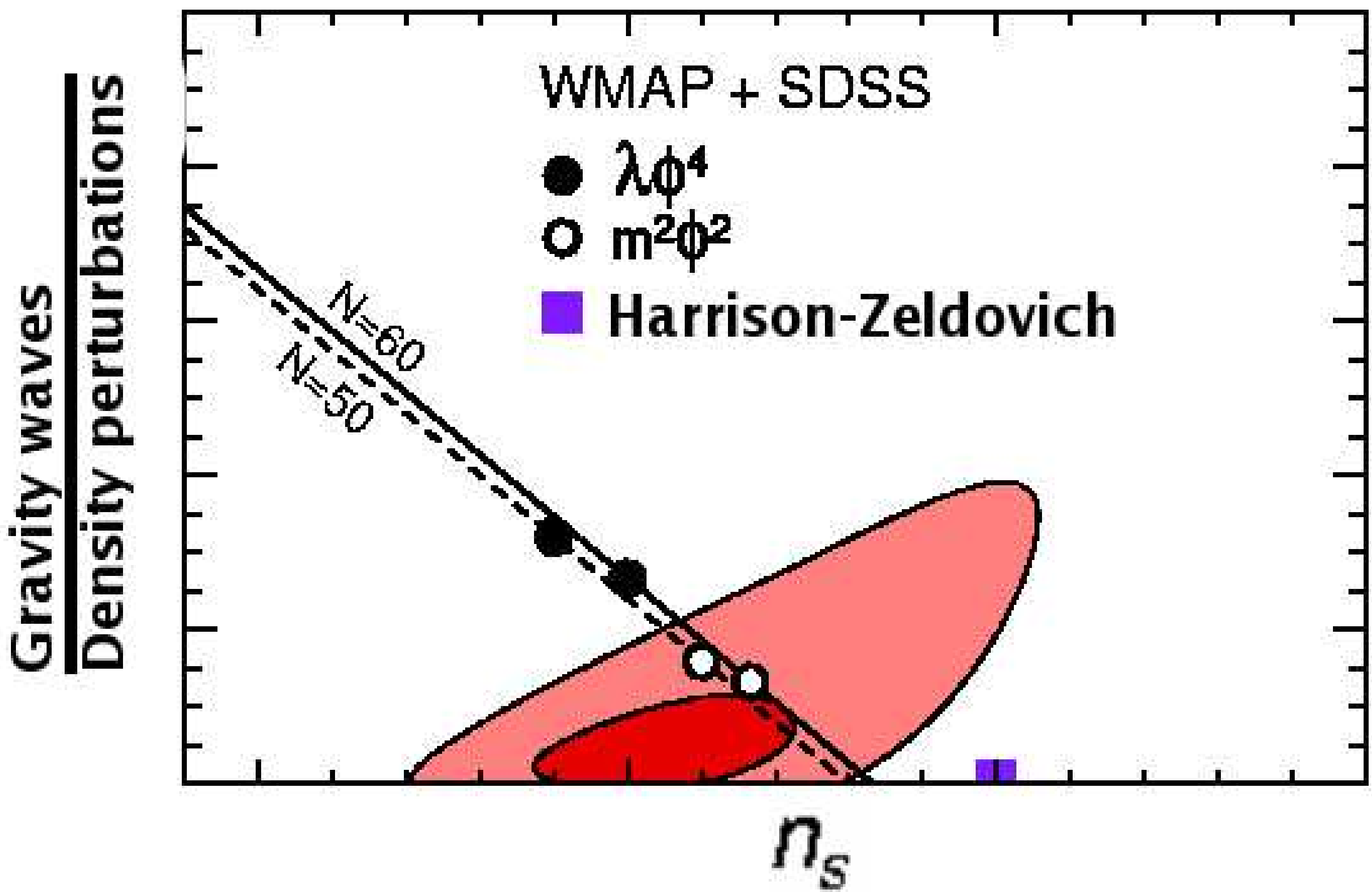
$$\left\langle \left(\frac{\delta\rho}{\rho}\right)^2 \right\rangle = A_S \left(\frac{k}{k_*}\right)^{n_S - 1} , \quad n_S \approx 1$$

$$\langle (h_{ij}^{TT})^2 \rangle = A_T \left(\frac{k}{k_*}\right)^{n_T} , \quad n_T \approx 0$$

$$n_T = -\frac{1}{8} \cdot \frac{A_T}{A_S} , \quad \text{small}$$

- Density perturbations in *adiabatic* mode $\Longleftrightarrow$
same chemical composition of cosmic plasma everywhere

First (still weak) evidence
for tilt ($n_s \neq 1$) and/or gravity waves



- If predictions are confirmed:
  - Quantum field theory works up to energies 10^{14} GeV

    – at least at linearized level

    – both for inflaton and graviton

    – 10^{14} GeV is energies and spatial momenta, not momentum transfer

  - Inflaton potential is pretty flat even at $\Phi > M_{Pl}$,

$$
\begin{aligned}
V(\Phi) = m^2\Phi^2 \quad &+ \quad \lambda\Phi^4 + \dots \\
m \quad &\lesssim \quad 10^{13}\ \text{GeV} \\
\lambda \quad &\lesssim \quad 10^{-13}
\end{aligned}
$$

- If not confirmed: depends
  - Nothing dramatic if gravity waves not observed
  - Very dramatic if $n_T > 0$:

    $p < -\rho$, ghost-like behavior
    strong indication of Lorentz-violation

  - Admixture of non-adiabatic modes:

    dark matter / baryon asymmetry
    created *before hot stage*

ALL THIS WILL BE SETTLED DOWN
IN RELATIVELY NEAR FUTURE

TO CONCLUDE:

We are living through interesting times.

Current theory of particle physics has its problems
Most important is the origin of electroweak scale

Cosmology provides controversial hints:

- Dark matter points towards “new physics” in TeV energy range
- Dark energy points towards anthropic selection

Upcoming LHC will make crucial impact

- More hints to come from detailed observational studies of primordial cosmological perturbations