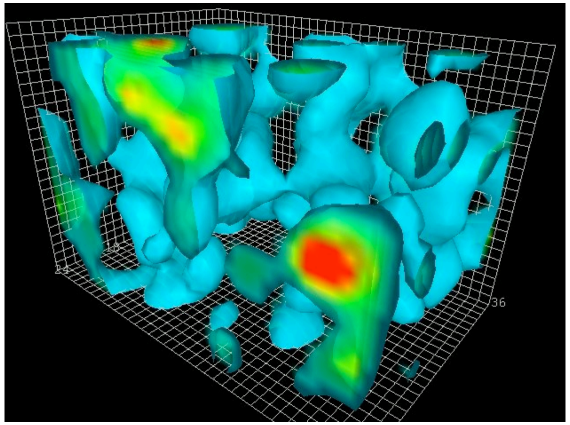
Colliders & Cosmology

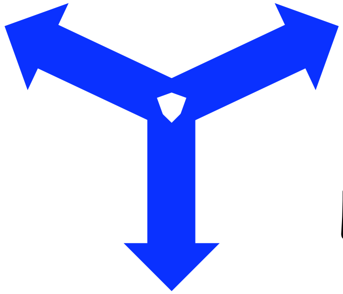
G.F. Giudice

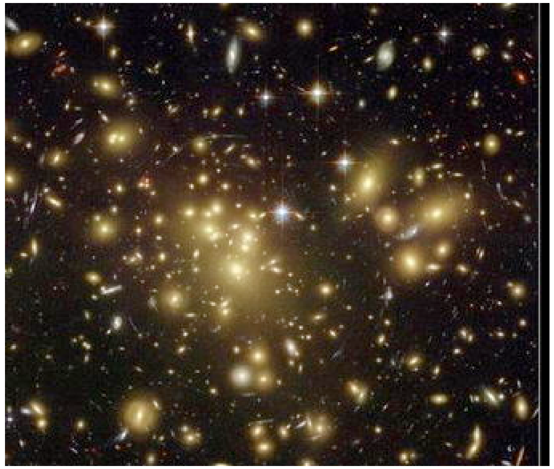
"Neutrino Oscillations in Venice"
16 April 2008

Link between particle physics and cosmology has been one of the most striking success of our field



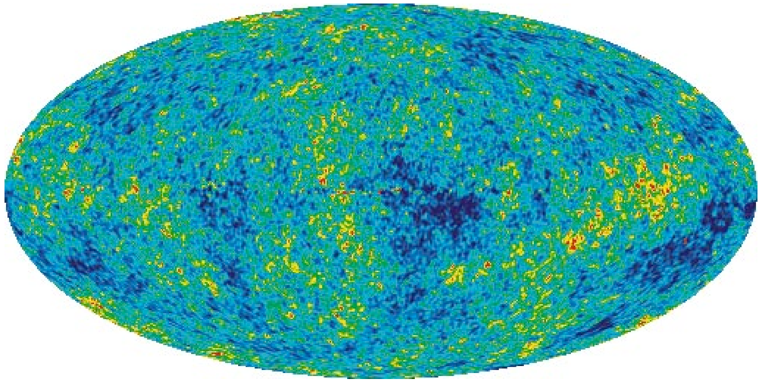
Quantum mechanical field fluctuations





Large scale structure of the Universe

Cosmic Microwave Background

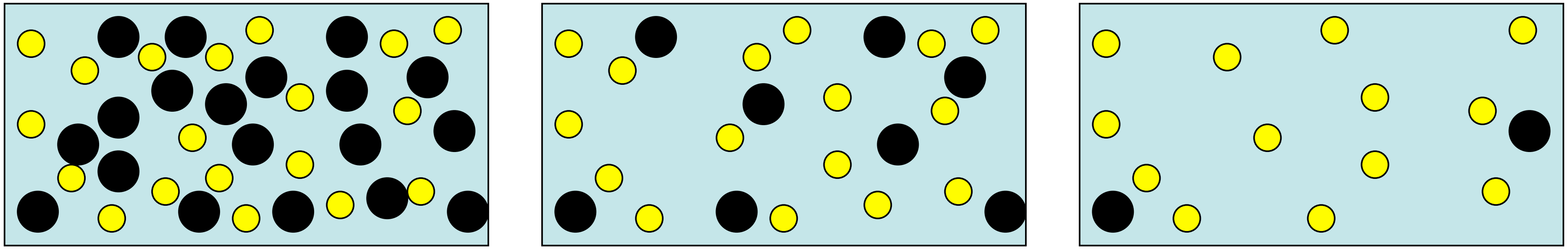


Both collider experiments and cosmological observations were necessary to reach our present understanding

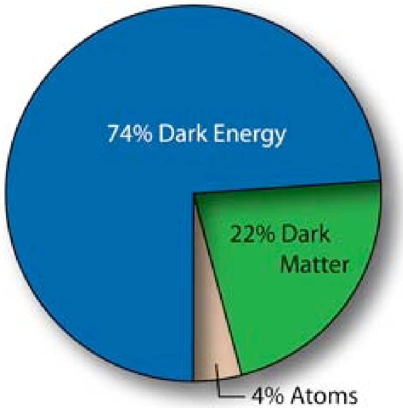
How will the LHC contribute to cosmology?

The most promising LHC result for cosmology is

Dark Matter



$T \gg M$ $\qquad$ $T \approx M$ $\qquad$ $T \ll M$



Thermal relic density of massive particles

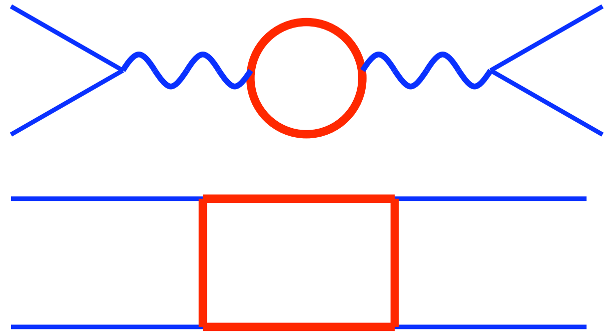
$$\Omega_{DM} = \frac{(4\pi)^2}{3}\sqrt{\frac{\pi}{45}}\,\frac{x_f g_S(\gamma)}{g_*^{1/2}}\,\frac{T_\gamma^3}{H_0^2 M_P^3 \sigma} = 0.22\,\frac{\text{pb}}{\sigma}$$

Coincidence or evidence for new physics at the Fermi scale?

Impossible to overestimate the importance of discovering DM at the LHC

Most viable new theories of EW have a DM candidate

Excluded by LEP



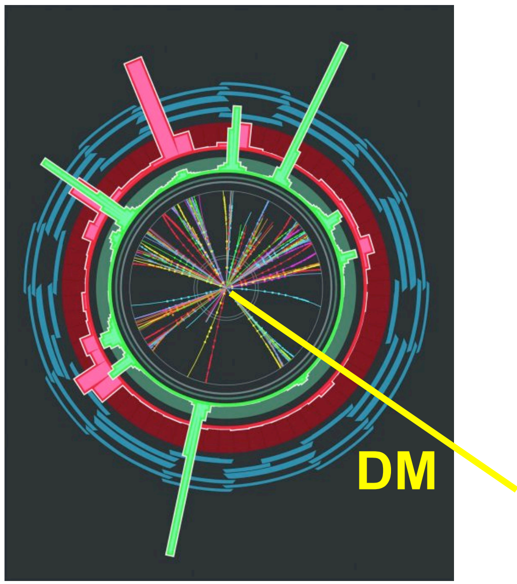
can be OK

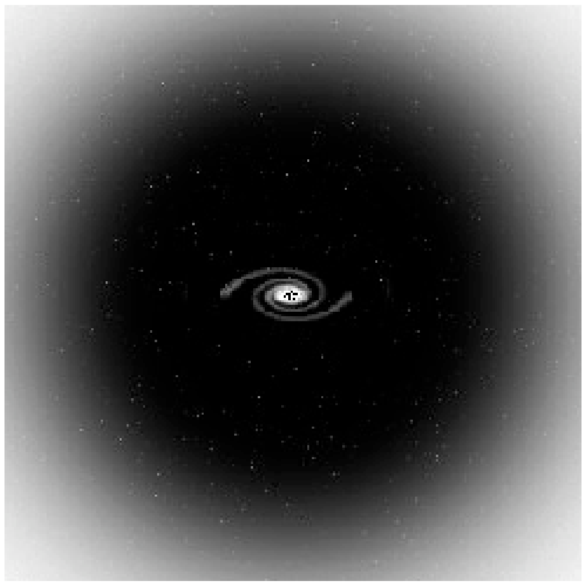
Discrete symmetry (*R*, *T*, *KK*) make
lightest new particle stable

Supersymmetry, Little Higgs, Extra Dimensions
have a DM candidate

How can LHC establish that a new discovery is the DM of the Universe?

1) If excess of $\not{E}_T$ is observed, DM is the prime suspect

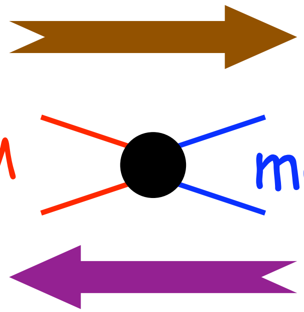




2) Reconstructing relic abundance

Early Universe

DM interactions ⇒ DM



matter ⇒ Ω_{DM}

LHC

- As in BBN, where many nuclear cross sections are necessary to reconstruct primordial abundances
- Requires high precision and knowledge of the mass spectrum (LHC +ILC?)
- Learn about the history of the universe up to $T_f = m_{DM} / 20$ (1 ns after the Big Bang)
- Sensitive to changes of H around freeze-out (dark energy?)
- Possible only for thermal relics

Collider experiments do not distinguish between stable ($\tau > 10^{17}$ s) and long-lived ($\tau > 10^{-7}$ s) particle

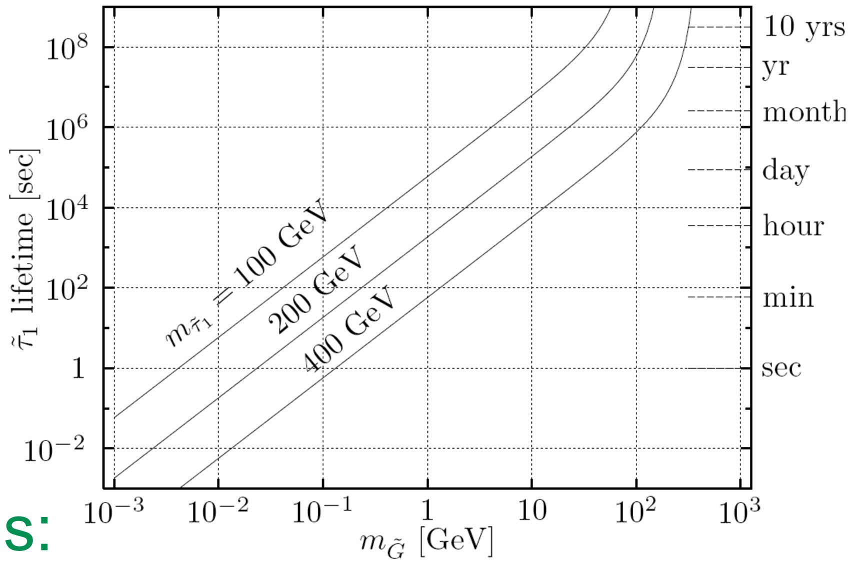
$$P' \to P \;\Rightarrow\; \Omega_{P'} = \frac{m_{P'}}{m_P}\Omega_P$$

Gravitino

Long-lived charged particle at the LHC ($\tilde{\tau} \to \tau \tilde{G}$)

Hamaguchi-Kuno-Nakaya-Nojiri; Feng-Smith; Ellis-Raklev-Øye; Hamaguchi-Nojiri-de Roeck

Distinctive ToF and energy loss signatures



"Stoppers" in ATLAS/CMS caverns:

- Measure position and time of stopped $\tilde{\tau}$; time and energy of τ
- Reconstruct susy scale and gravitational coupling

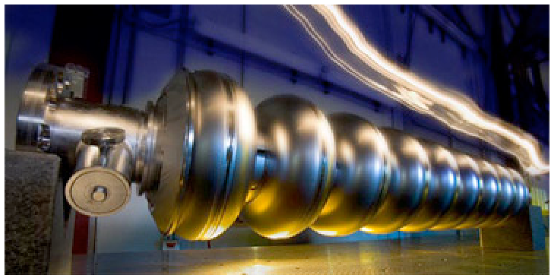
3) Combining collider with DM searches

Complementarity of information

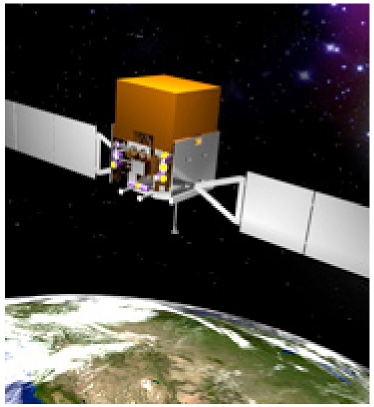
LHC

Direct detection

DM



ILC



Indirect detection

Direct detection

relies on $\begin{cases} \text{local DM density } (\rho = 4 \text{ to } 13 \times 10^{-25}\ \text{g/cm}^3) \\ \text{velocity distribution } (v = 230 \pm 20\ \text{km/s}) \end{cases}$

ρ is estimated by averaging over kpc,
but solar system moves at 10^{-3} pc/yr:
fluctuations at small scales?

SI σ dominated by Higgs exchange depends on $\langle N | m_s \bar{s} s | N \rangle$
uncertainty up to a factor of 4

Mass measurement from distribution of recoil energy
(at least 20% uncertainty from velocity distribution)

By 2010 it will reach $\sigma_{SI} \sim 10^{-9}$ pb (most of susy models)

Indirect detection

Gamma rays from galactic center: satellite based GLAST and Cerenkov Telescopes HESS, MAGIC, VERITAS

Prospect of discovery depends critically on DM density at inner pcs of MW and on properties of astrophysical bckgd (Bright source has been observed)

Positrons: e^+ lose most of the energy within few kpc

Sample of local DM (good probe of σ if DM distribution is uniform)

Neutrinos: annihilation of DM captured by the Sun

$\sigma_{SD} \sim 10^{-3}$ pb generates 10^3 events/yr at IceCube, but is invisible in direct detection

Collider experiments

Precise tests of DM mass and particle-physics parameters

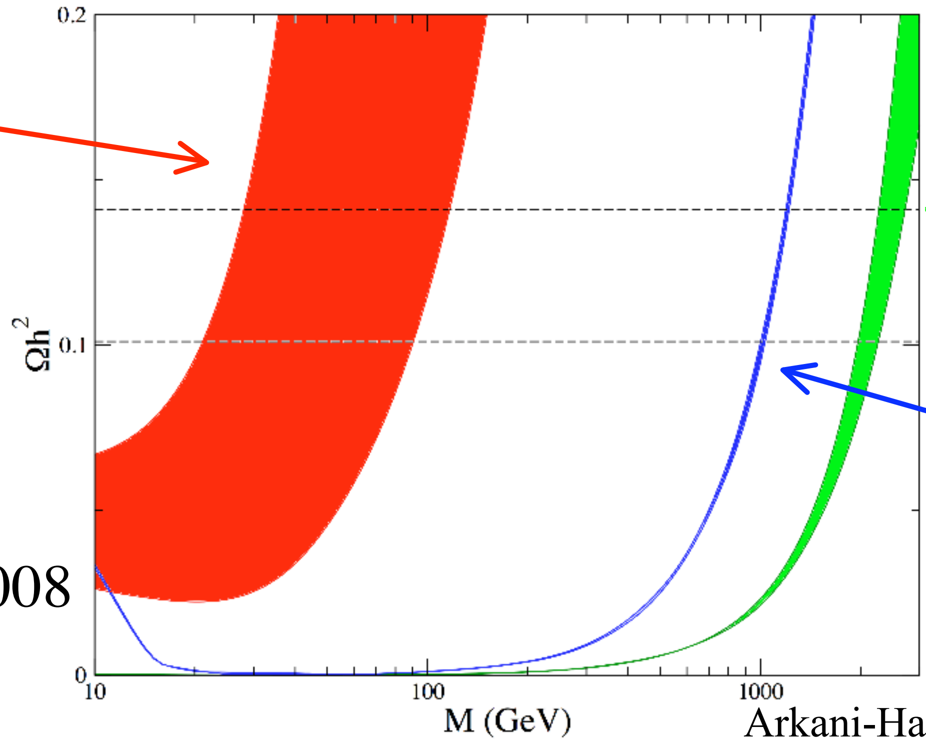
No (or indirect) information on: cosmological stability, cosmological abundance, halo density

Complementarity of different searches

Only detection by different methods can conclusively identify the nature of DM

4) Identify model-dependent features

DM neutralino in supersymmetry



Arkani-Hamed-Delgado-Giudice

Bino: $1.1 < \frac{\tilde{m}_{e_R}}{M_1} < 3$

Wino: $1.5 < \frac{\tilde{m}_{\ell_L}}{M_2} < \infty$

Higgsino: $1.5 < \frac{\tilde{m}_t}{\mu} < \infty$

$$\Omega_{DM} h^2 = 0.105 \pm 0.008$$

Neutralino: natural DM candidate for light supersymmetry

Quantitative difference after LEP & WMAP

Both M_Z and Ω_{DM} can be reproduced by low-energy supersymmetry, but at the price of some tuning.

Correct relic abundance under special conditions:

- Heavy susy spectrum: Higgsino (1 TeV) or Wino (2.5 TeV)
- Coannihilation Bino-stau (or light stop?)
- Nearly degenerate Bino-Higgsino or Bino-Wino
- S-channel resonance (heavy Higgs with mass $2m_\chi$)
- Slepton masses close to the LEP bound
- T_{RH} close to T_f
- Decay into a lighter particle (*e.g.* gravitino)

All these possibilities have a very critical behavior with underlying parameters

Identifying one of these features at the LHC will be in indication in favor of DM

Cosmology & the Higgs boson

Main goal of LHC is to unveil the mechanism of EW
$\Rightarrow$ discovery of the Higgs boson

Scalar particle responsible for phase transition

$\Downarrow$

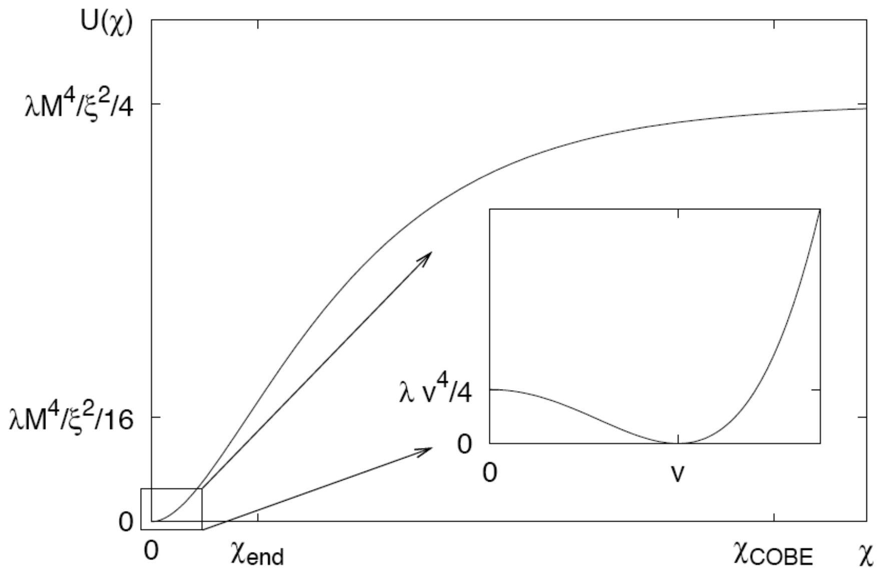
analogous to the mechanism usually assumed for inflation

With some stretch of imagination, we can use the Higgs as inflaton

$$S = \int d^4x \sqrt{-g} \left(\xi H^+ H R + \text{"SM"} \right)$$

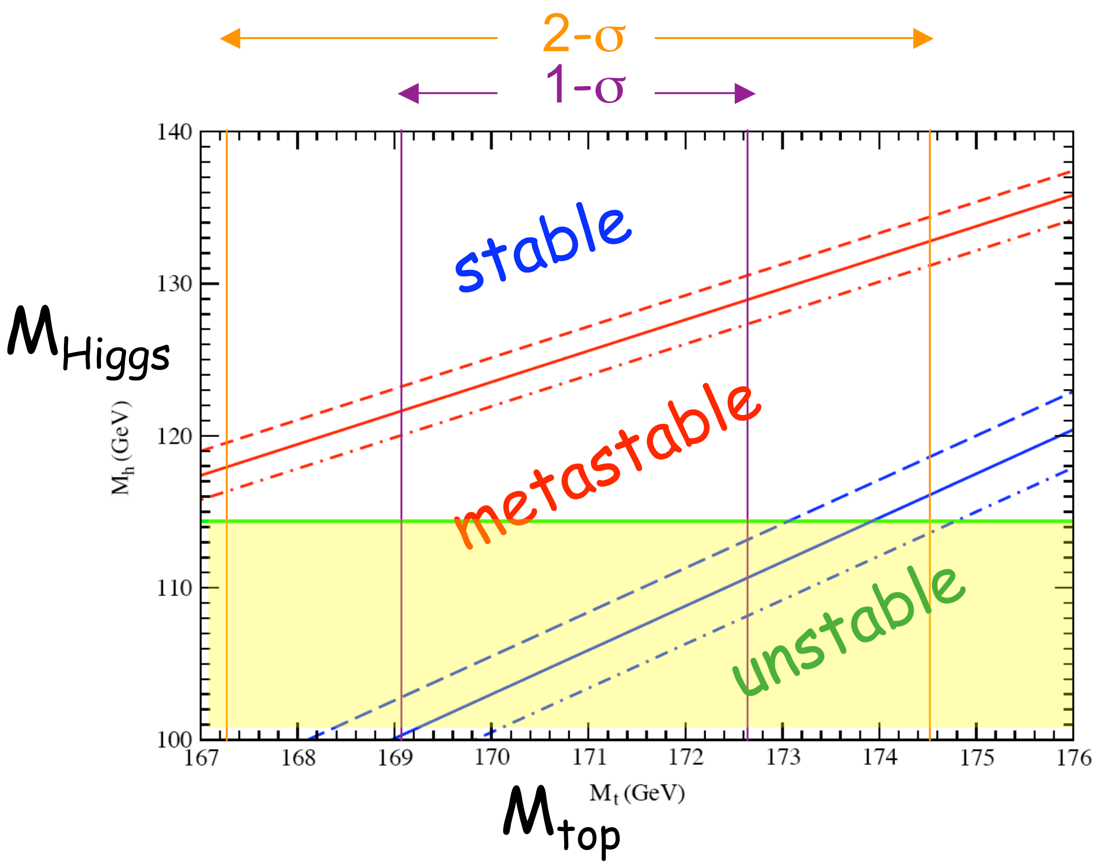
with $\xi = 5 \times 10^4 \sqrt{\lambda}$

Bezrukov-Shaposhnikov



The measurement of the Higgs mass can give us info about the early history of the Universe

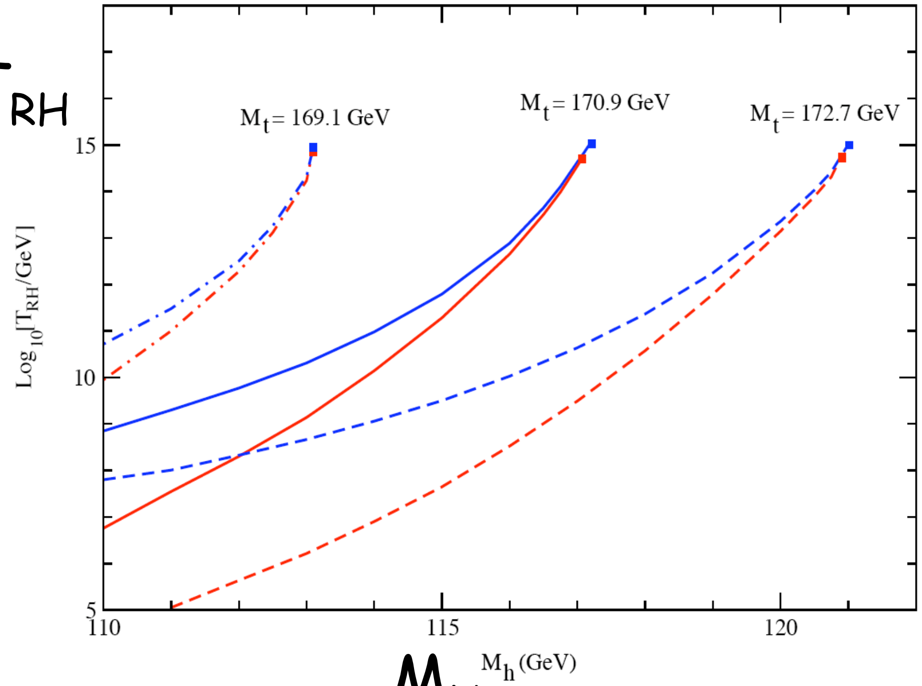
Suppose SM valid up to very high scales



If experiments show we live in the “metastable region”: limits on any Higgs fluctuation in the early Universe

Thermal fluctuations

log$_{10}$ T_{RH}



M_{Higgs}

Instant reheating

H_I = 10^{13} GeV

Espinosa-Giudice-Riotto

Higgs fluctuations during inflation

Any scalar lighter than *H* gives rise to scale-invariant perturbations on superhorizon scales

Assume Higgs is minimally-coupled $\langle h^2 \rangle \approx \frac{H^3 t}{4\pi^2}$ (small t)

If *H* >> Λ (the instability scale): an exponentially small fraction of initial comoving volume survives the quantum fluctuations

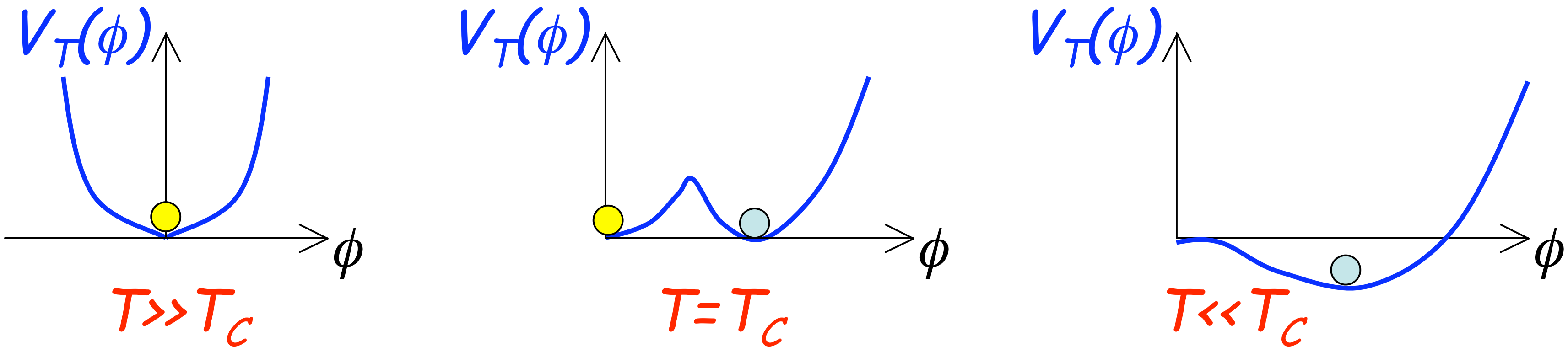
AdS regions collapse and disappear

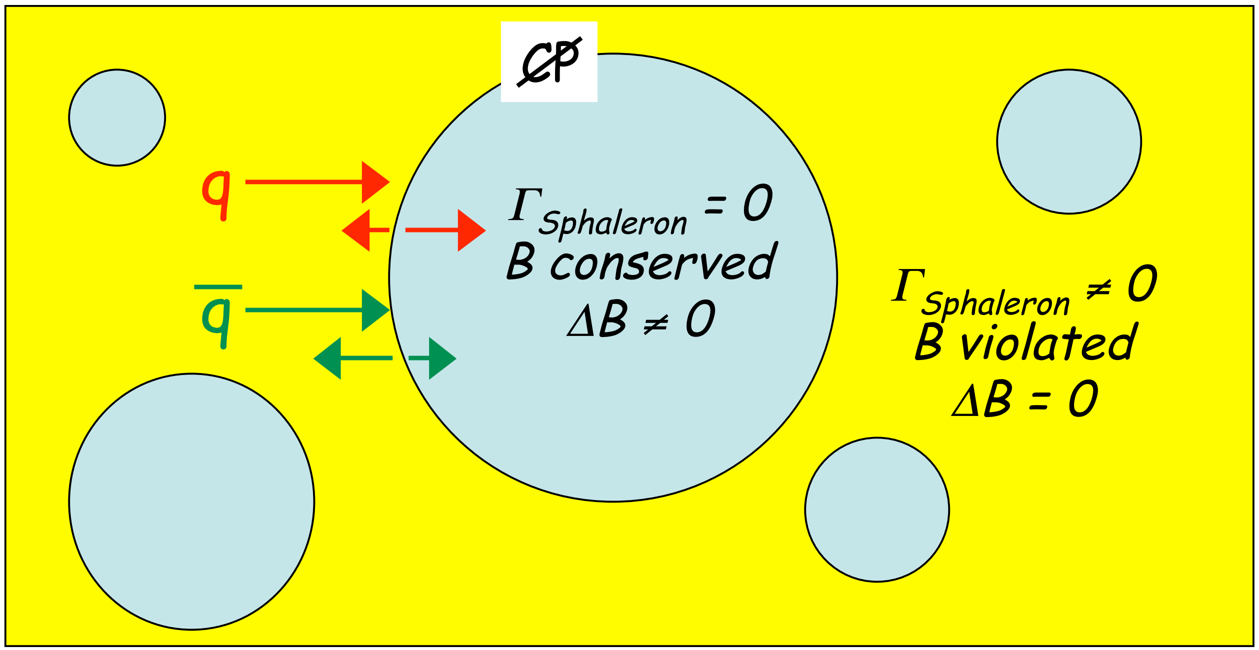
Surviving patches of the Universe have exponentially small probability of reproducing observed curvature perturbations

$$\zeta = \frac{H^2}{2\pi\,\dot{\phi}} \qquad \zeta_{obs} = 5 \times 10^{-5}$$

If primordial gravity waves are detected in *B*-mode of CMB polarization & if the Higgs is in the metastable region ⇒ the Universe is exponentially improbable

Does the EW phase transition generate the observed baryon asymmetry?

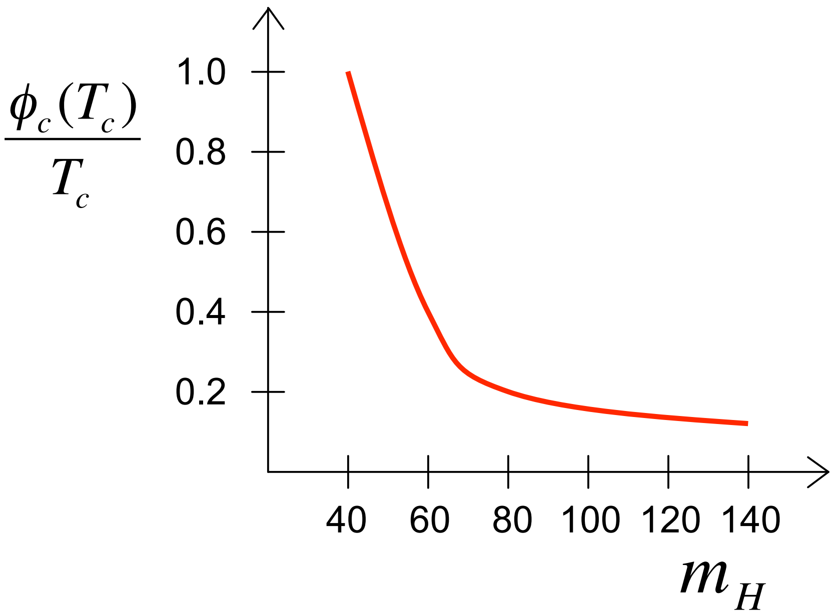




Out of equilibrium condition

Sphalerons do not erase ΔB if

$$\frac{\phi_c(T_c)}{T_c} \geq 1$$



$$\frac{\phi_c(T_c)}{T_c} \geq 1 \quad \Rightarrow \quad m_H < 40 \text{ GeV}$$

Is it possible with new physics?

Loop effects from new particles
strongly coupled to the Higgs boson

In Supersymmetry: light stop window

- 120 GeV < $\tilde{m}_{tR} < m_t$ ($\tilde{t}_L$ very heavy)
- 114 GeV < m_H < 120 GeV
- large phase in μM_2 (to generate $\not{CP}$ effect)

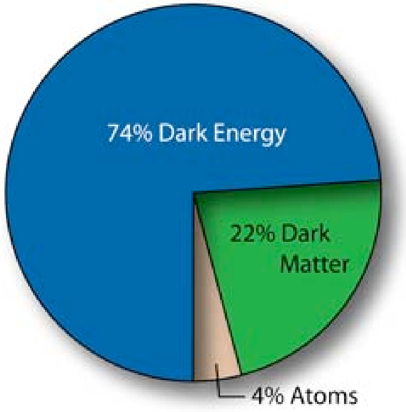
- It can be identified at the LHC
- EDM very close to the experimental limit
$d_e > 0.3 \times 10^{-27}$ ecm (Exp: $d_e < 1.6 \times 10^{-27}$ ecm)

Limits are relaxed in extended scenarios

- New singlet scalars (tree-level or loop effects)
- Effective interactions $\frac{1}{\Lambda^2}\left(H^+H\right)^3, \quad \Lambda \approx$ 500 GeV - 1 TeV
- Fermions strongly coupled to Higgs

Correlation between cubic Higgs coupling and $\frac{\phi_c(T_c)}{T_c}$

Difficult to measure at the LHC, but possible at 20% level at the SLHC (or ILC)



DARK ENERGY

Cosmological constant?

$\rho_\Lambda^{1/4} = 10^{-3}$ eV Similar (and more acute) problem as hierarchy m_W / M_P

Is there any explanation using symmetries or dynamics?

The LHC will probably not tell us what Dark Energy is, but it will tell us something about principles of naturalness

TWO OPTIONS

- SM valid up to $E_{max} \approx$ TeV and replaced by new theory

Argument works

Cancellation of	Existence of
electron self-energy	positron
π^+-π^0 mass difference	ρ
K_L-K_S mass difference	charm
gauge anomaly	top

Not free from problems: why no echoes from TeV region?

- $E_{max} >>$ TeV $\Rightarrow$ why m_H and $\rho_\Lambda^{1/4} << E_{max}$?

reject effective-theory approach?

LHC will tell us which is Nature's choice

Complexity

←

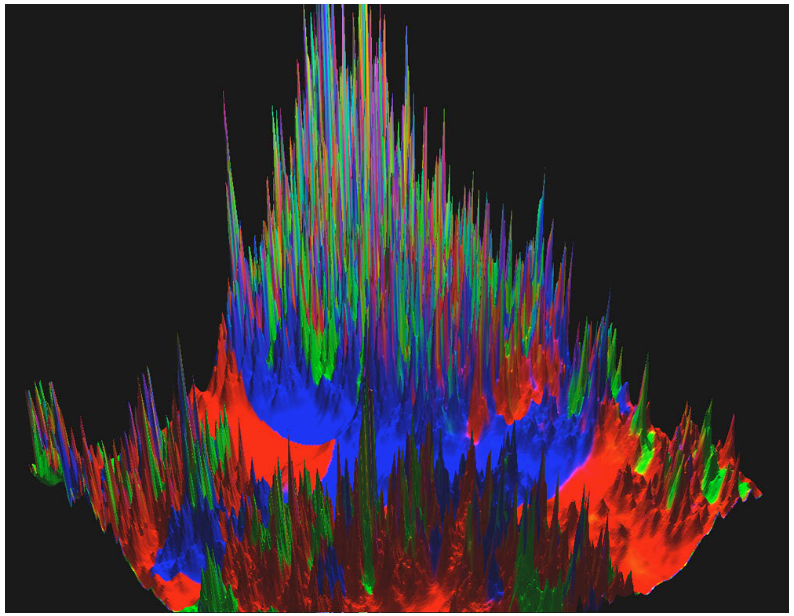
life ← biochemistry ← atomic physics ← SM ← “final theory”

→

Microscopic probes

Breaking of naturalness would require new principles

- the “final theory” is a complex phenomenon with IR/UV interplay
- some of the particle-physics parameters are “environmental”



The multiverse

CONCLUSIONS

The discovery of the connection between elementary particles and cosmology has been a great intellectual achievement, allowing us to explore the very beginning of the history of the Universe

The LHC will give us important information also relevant to cosmology

- The nature of the dark matter
- Higgs mass and a metastable Universe
- EW phase transition and cosmic baryon asymmetry
- Naturalness principle and the cosmological constant