Astronomer's Journey from Maxwell's to Higgs

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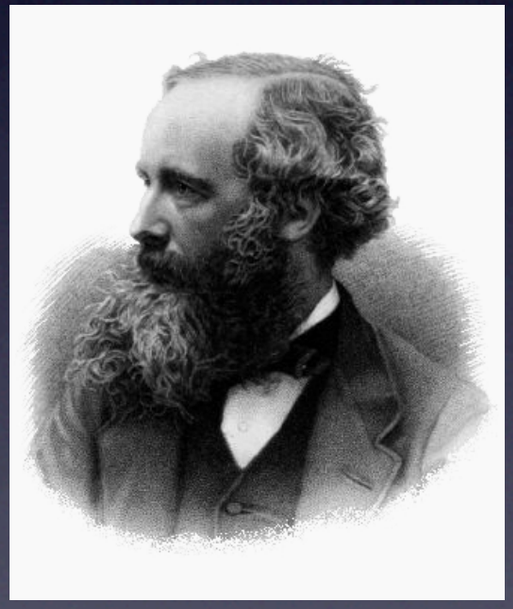
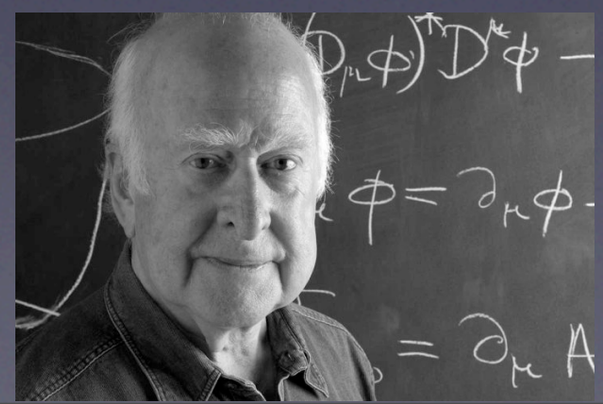
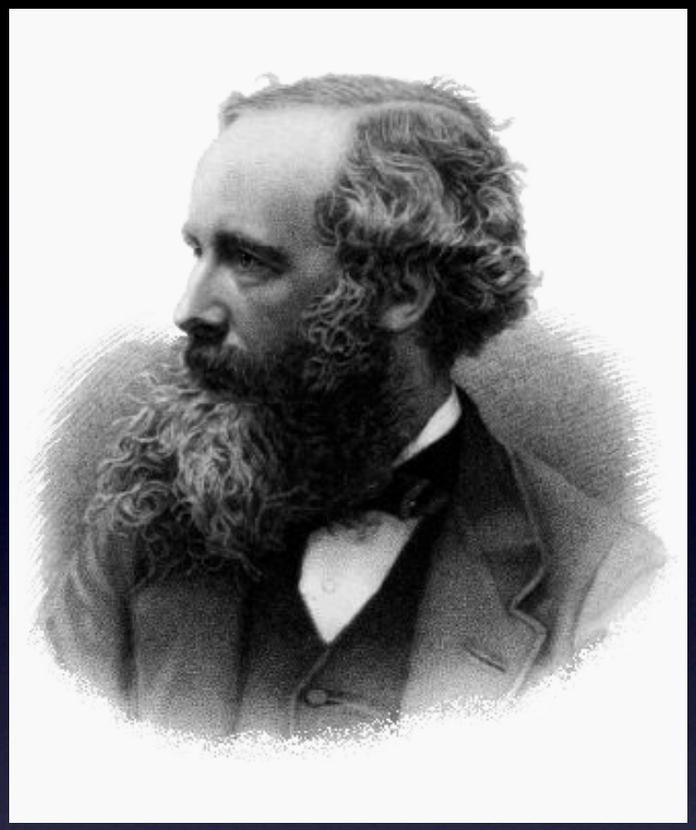
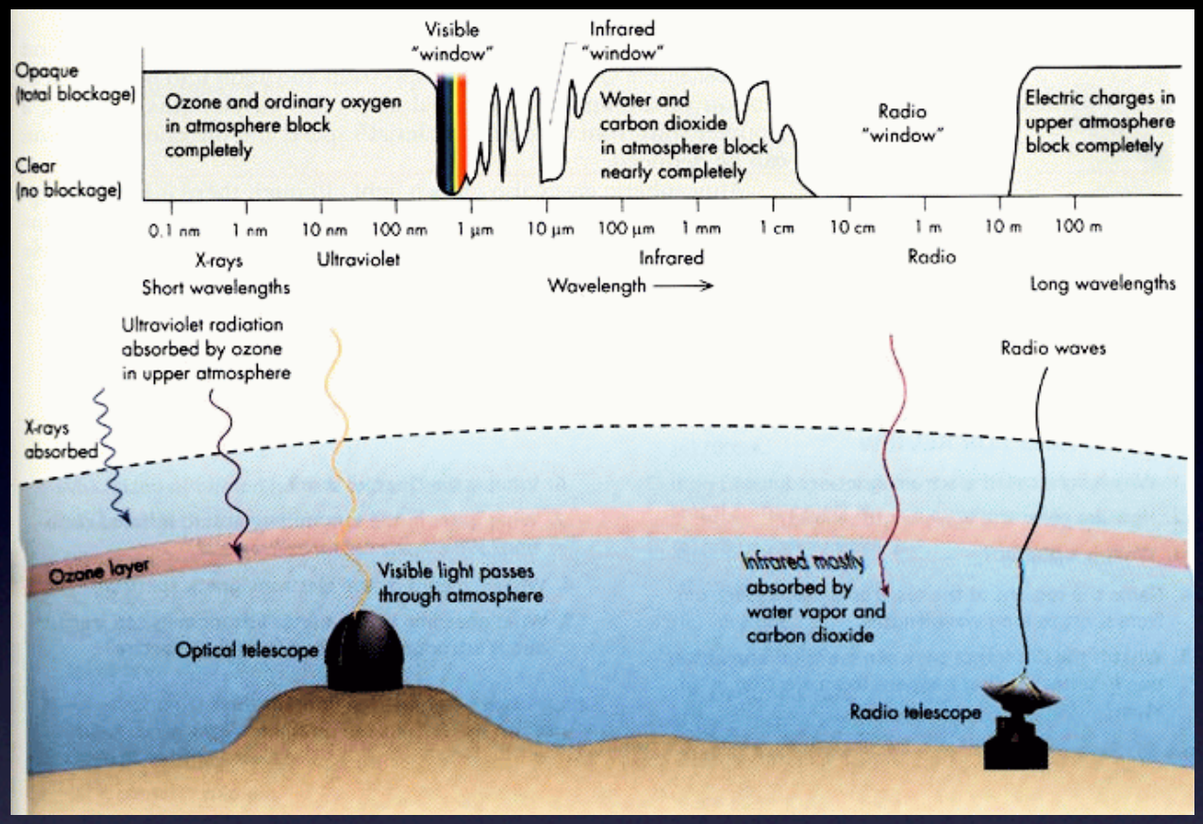


" Nature is imperfectly perfect " : in order to reveal her beauty we require a concept of an abstract mathematical world



Maxwell's legacy





Concept of Field which brought the scientific revolution of the 20th century physics

Maxwell-Boltzmann distribution revolutionized astronomy & astrophysics

Every cubic inch of Space is a

MIRACLE !

Walt Whitman

- Background radiation
- Virtual particles
- Dark matter
- Higgs potential
- Dark energy

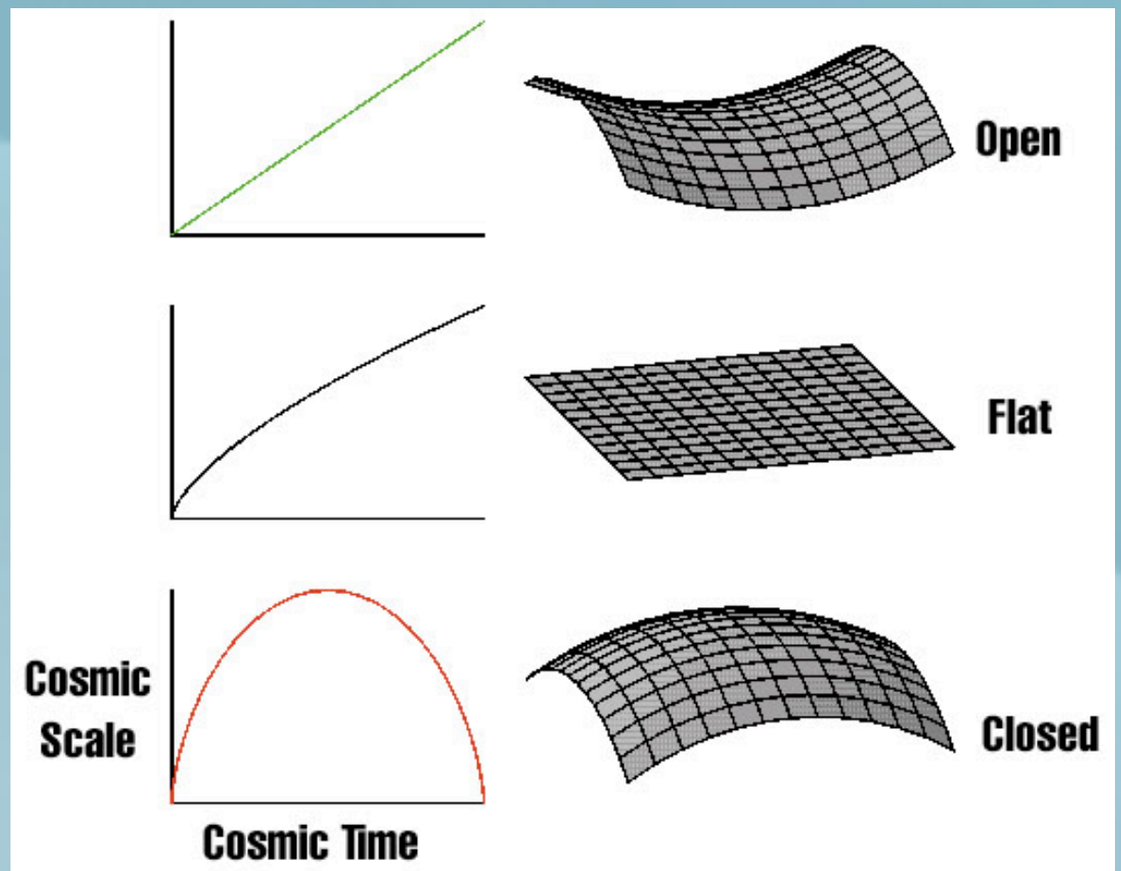
Questions & puzzles

- How to create the background radiation ?
- What is the origin of dark matter ?
- What is the origin of matter-anti-matter asymmetry ?
- What is the origin of dark energy ?
- What is the origin of neutrino masses?

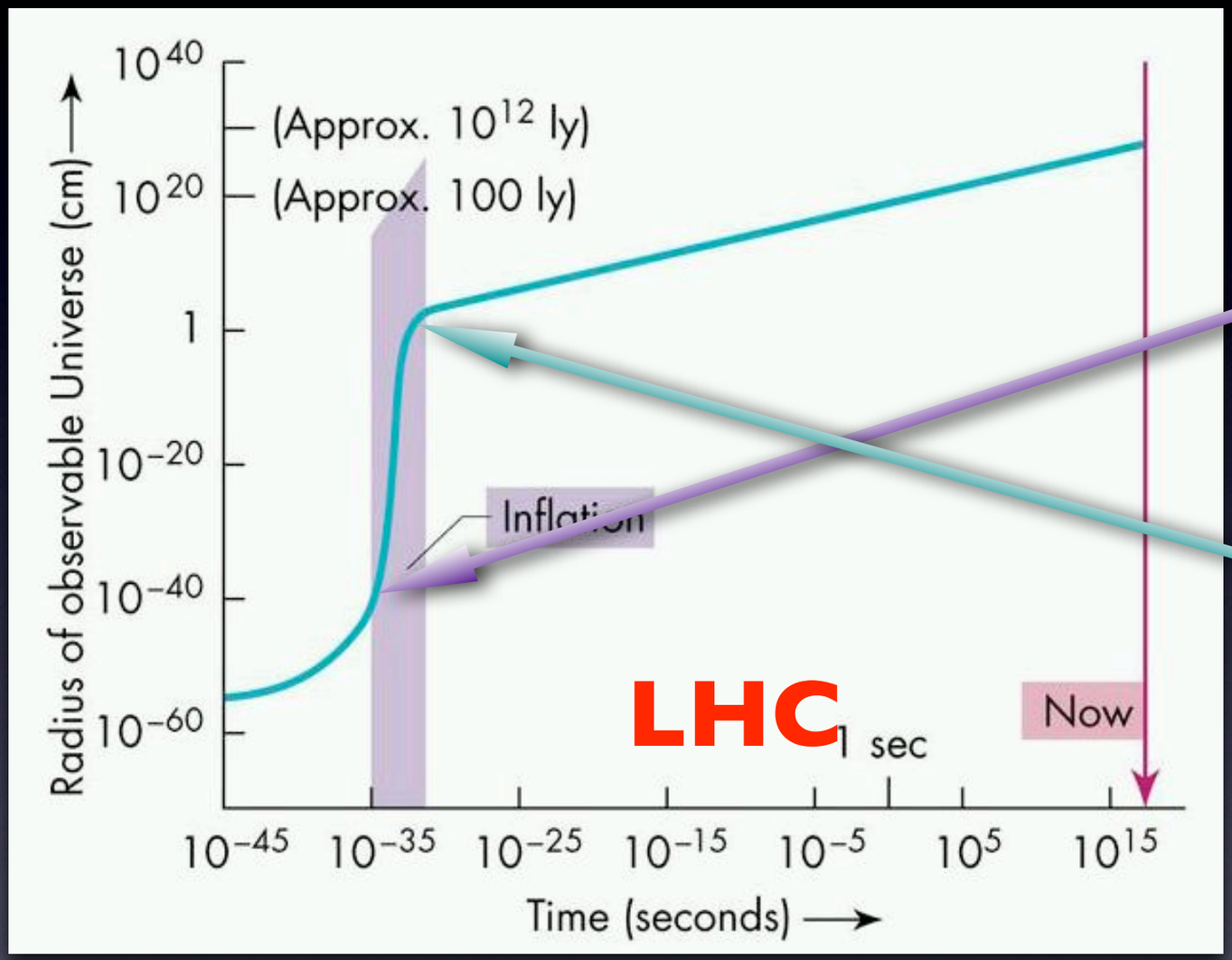
⋮

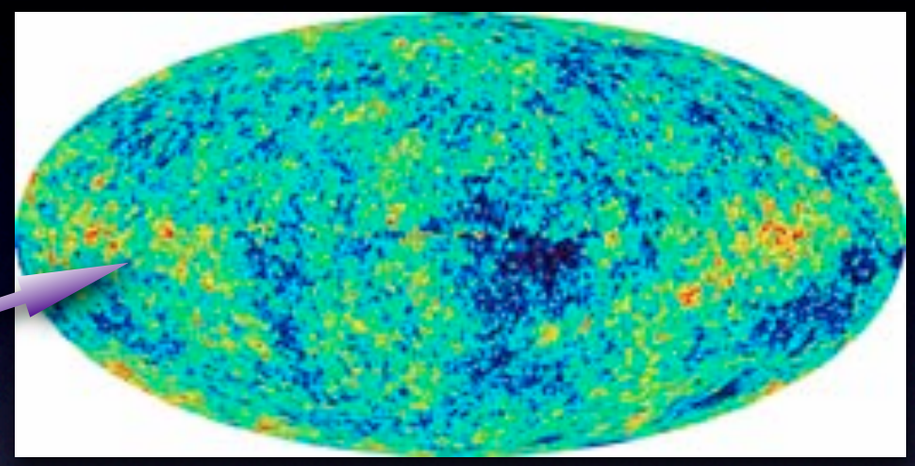
- How the Universe began ?

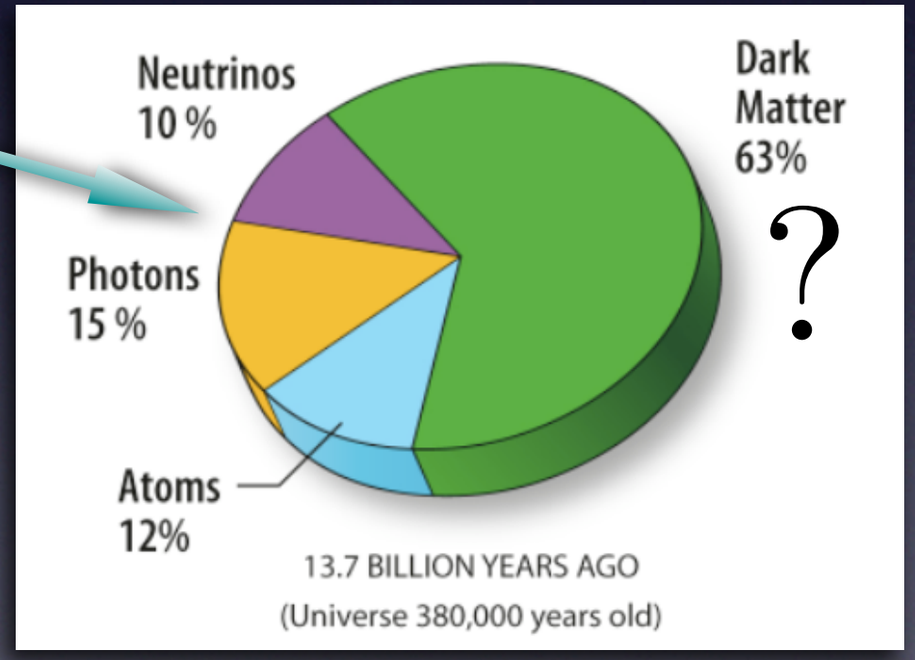
Inflation expands every cubic inch of space



Inflation creates matter & perturbations



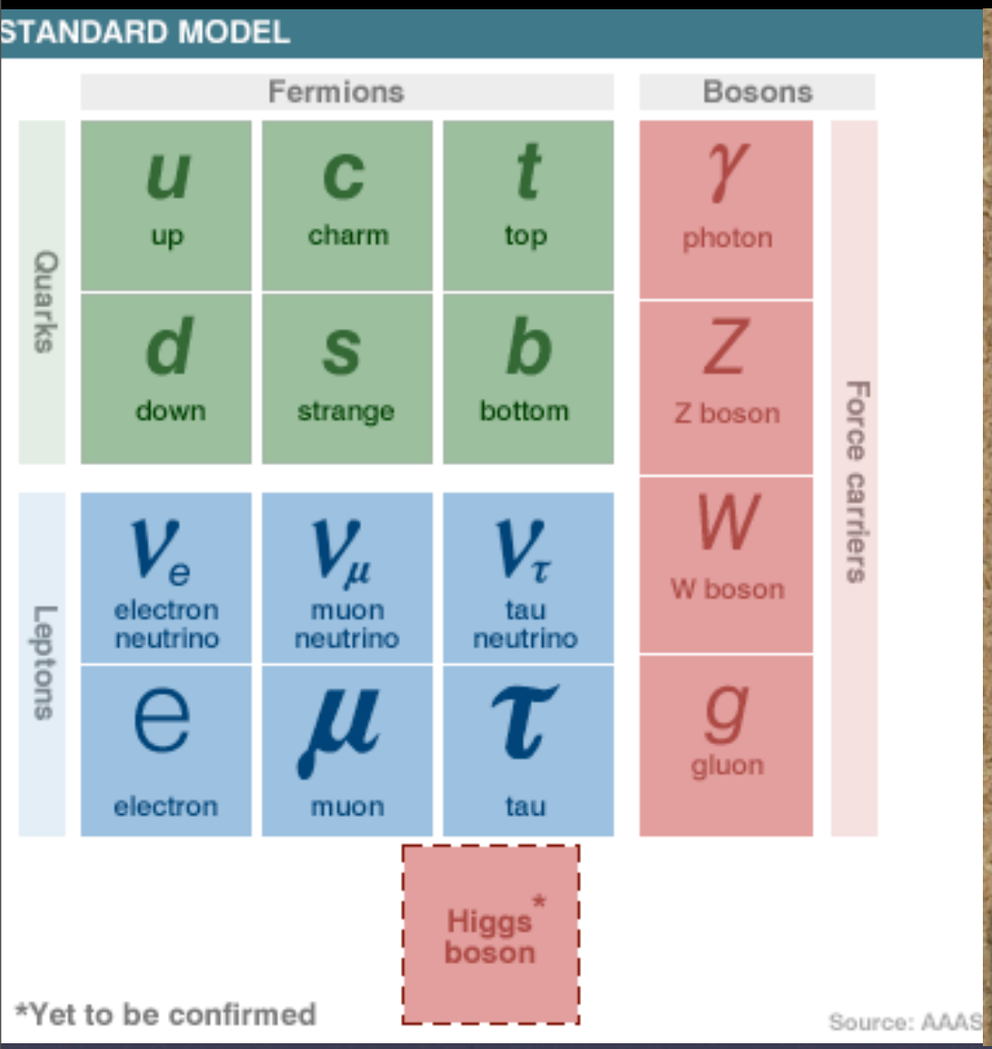




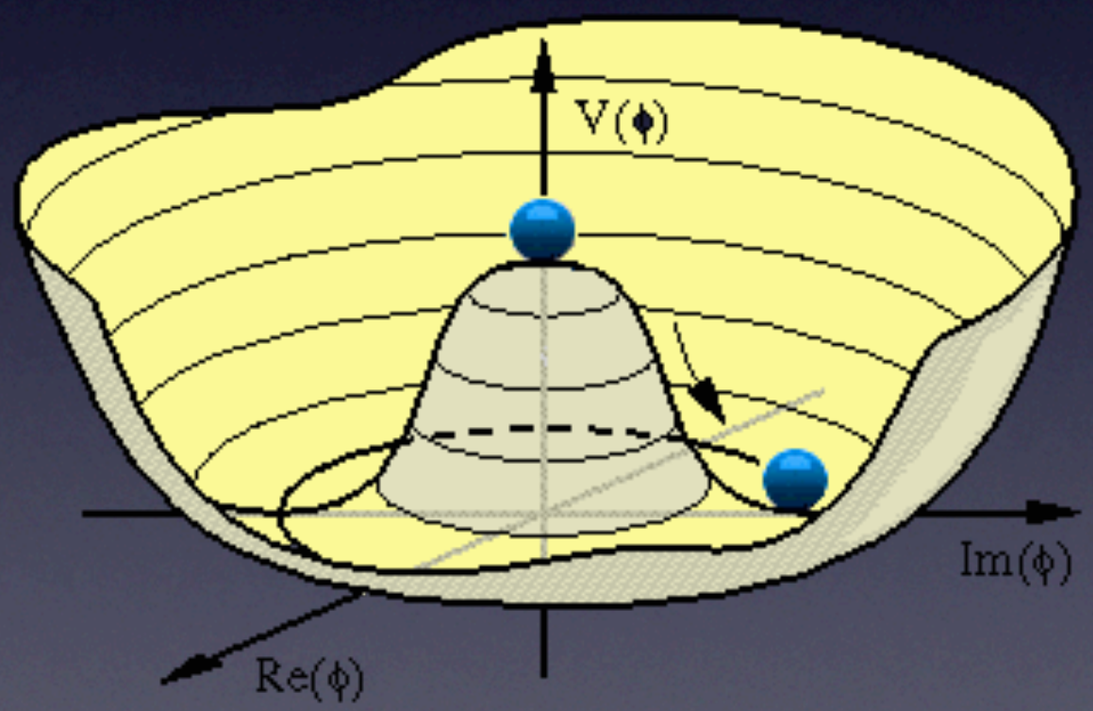
The Inflaton Vacuum cannot be arbitrary

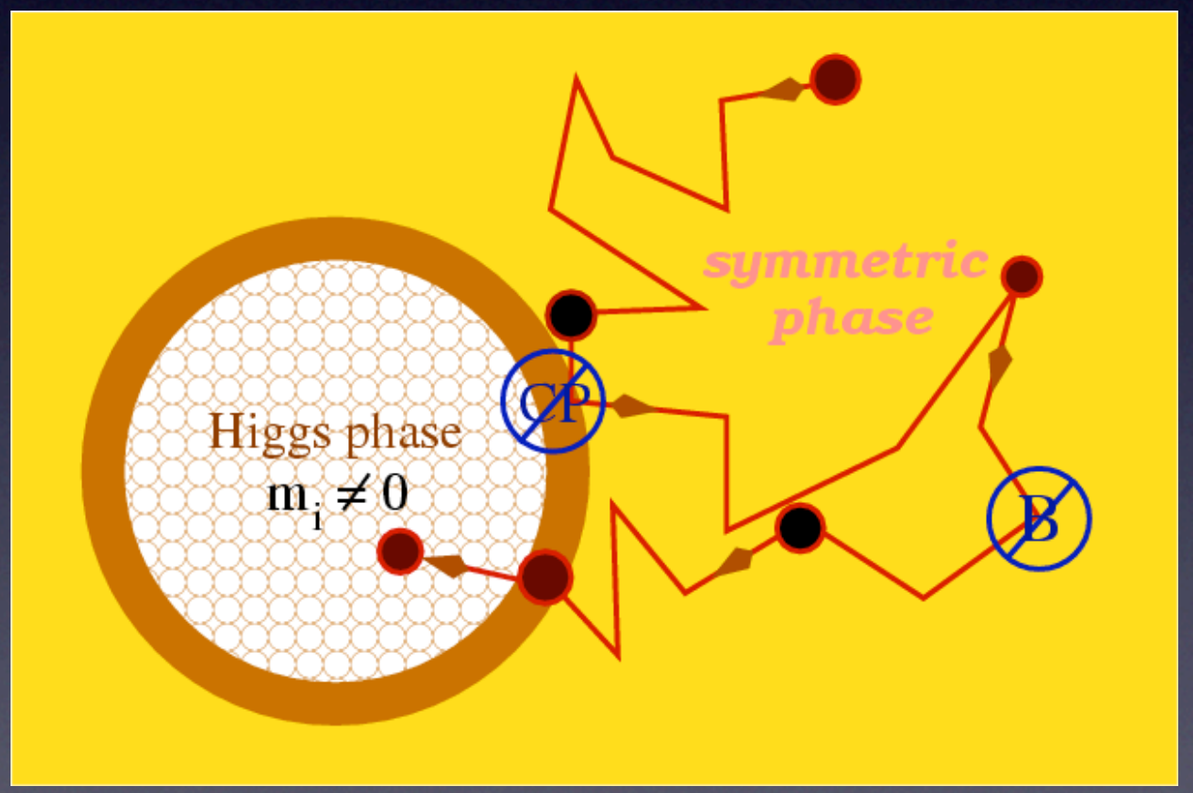
AM, Rocher, 1001.0993 Phys. Rept. (2010)

Tera-scale @ beyond



Higgs is different !

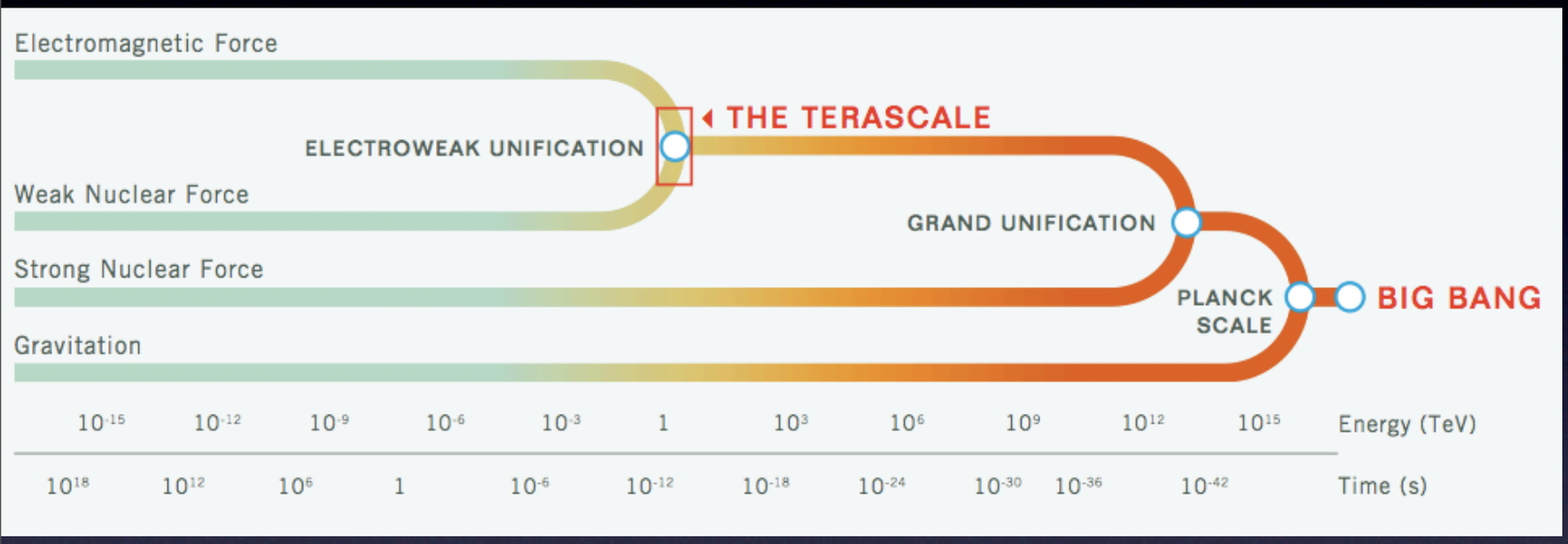


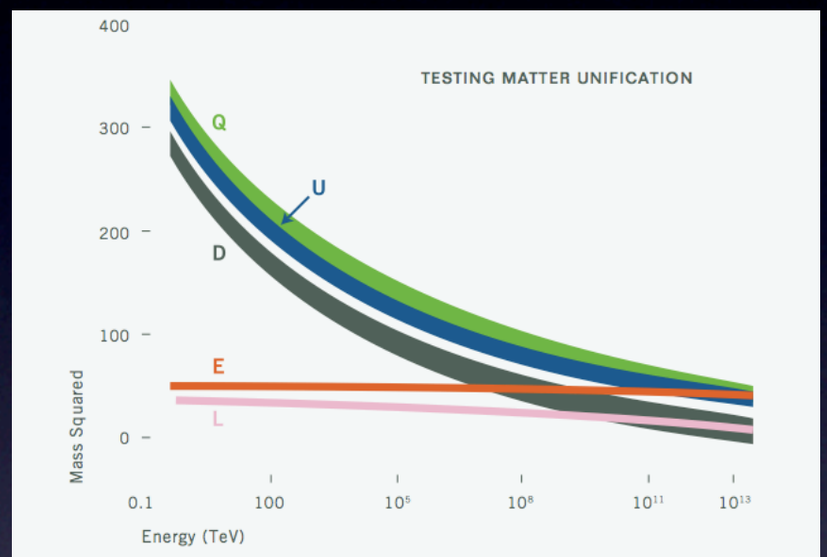


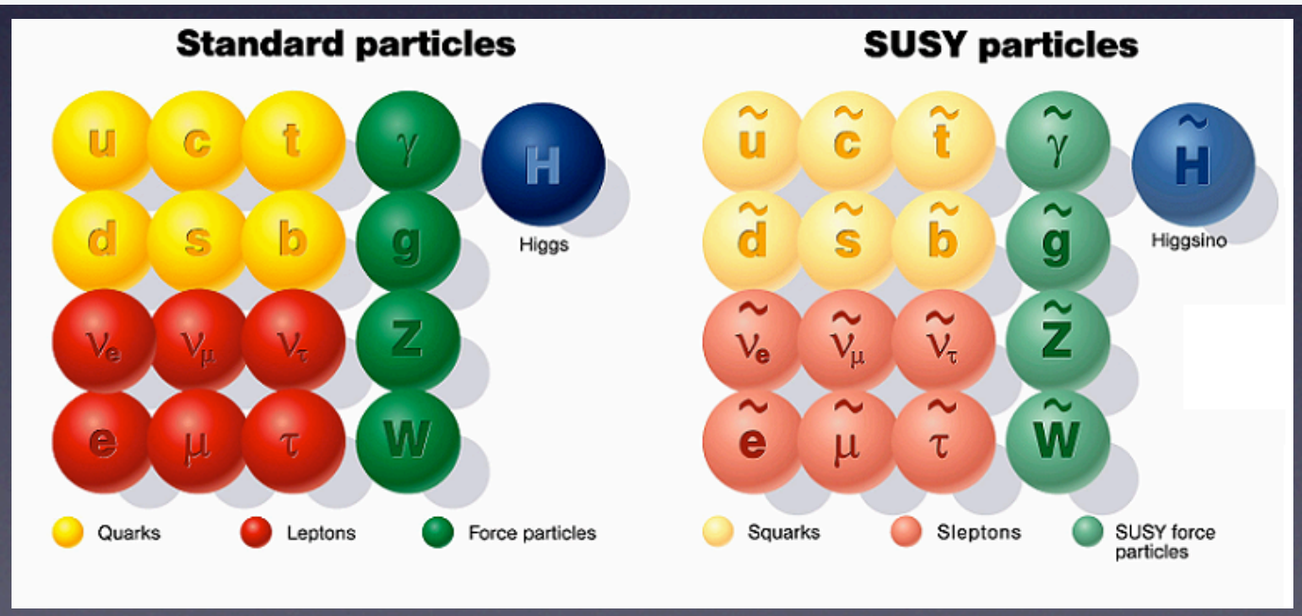
Higgs can really shape our Universe

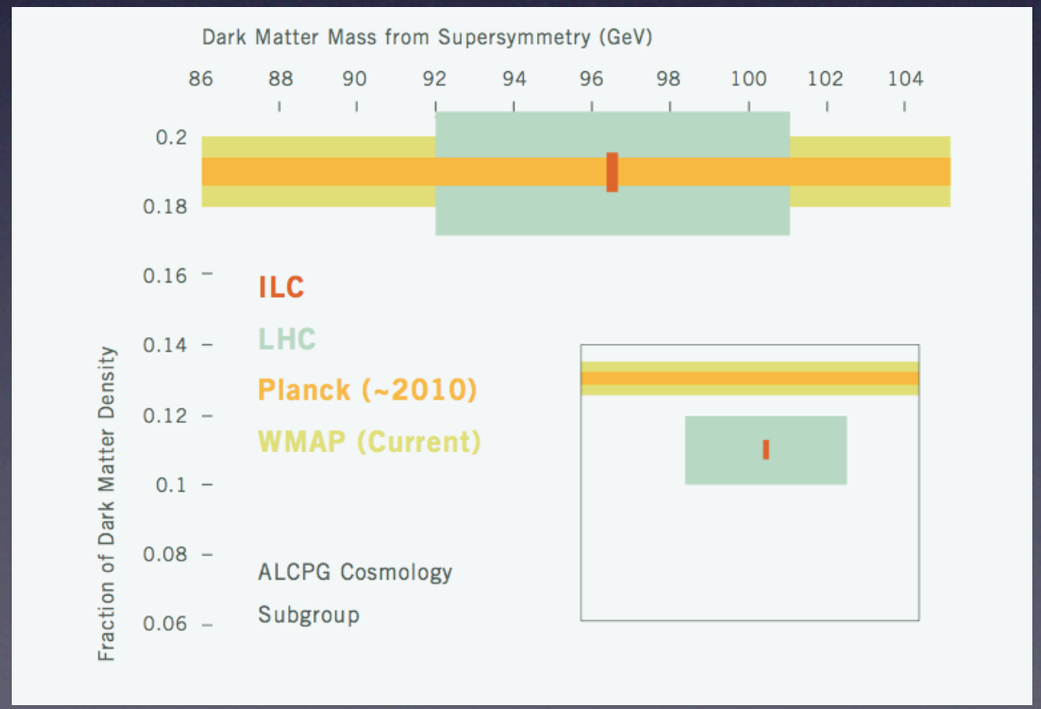
Higgs & Beyond : SUSY in the Desert

A simple setting which addresses many issues



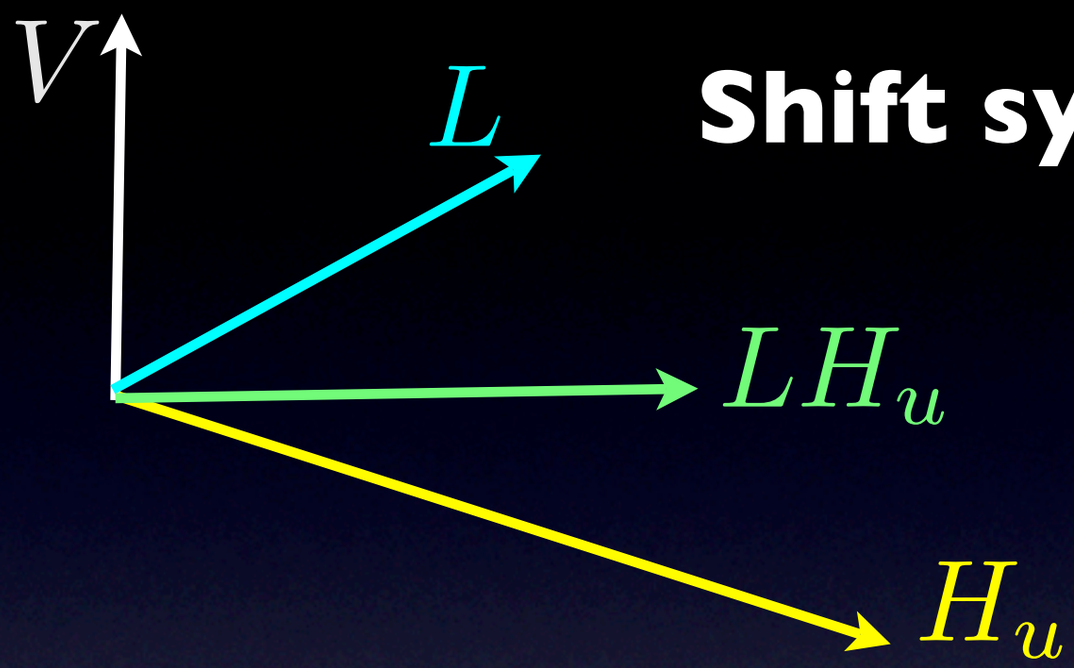






Many in this room have contributed towards our understanding of SUSY

SUSY Flat Directions



Shift symmetry

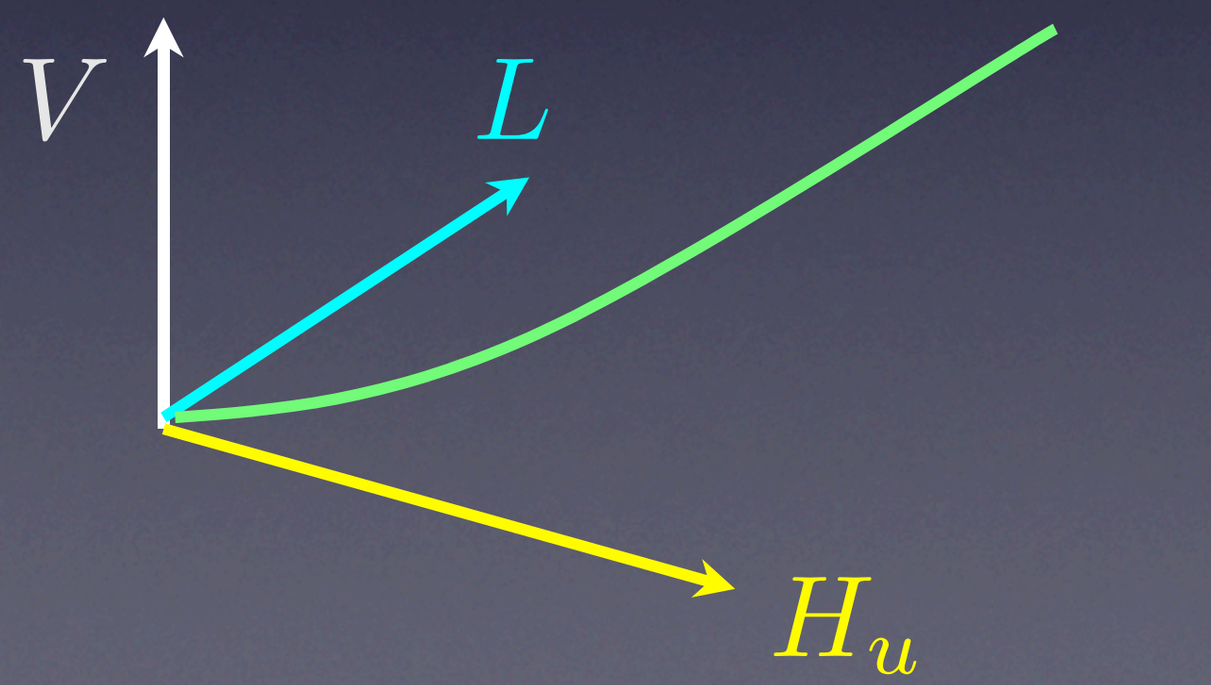
$$H_u = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ \phi\end{pmatrix},\ L = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi\\ 0\end{pmatrix}$$

$$\Phi = LH_u \equiv c\phi^2$$

$$In\ \ general\ \ \ \Phi = c\phi^m$$

SUSY is broken

Shift symmetry is broken



Enqvist, AM, Phys. Rept. (2004)

Did the Higgs boson puff up the Universe?

Allahverdi, Dutta, AM, Phys. Rev. Lett. (2007), New Scientist (2008)

Inflation, Baryons, Dark matter & Neutrino masses

$$W \sim h \mathbf{N H_u L}$$

$$(h \sim 10^{-12})$$

$$m_\nu \sim h \langle H_u \rangle \sim \mathcal{O}(0.1)\ \text{eV}$$

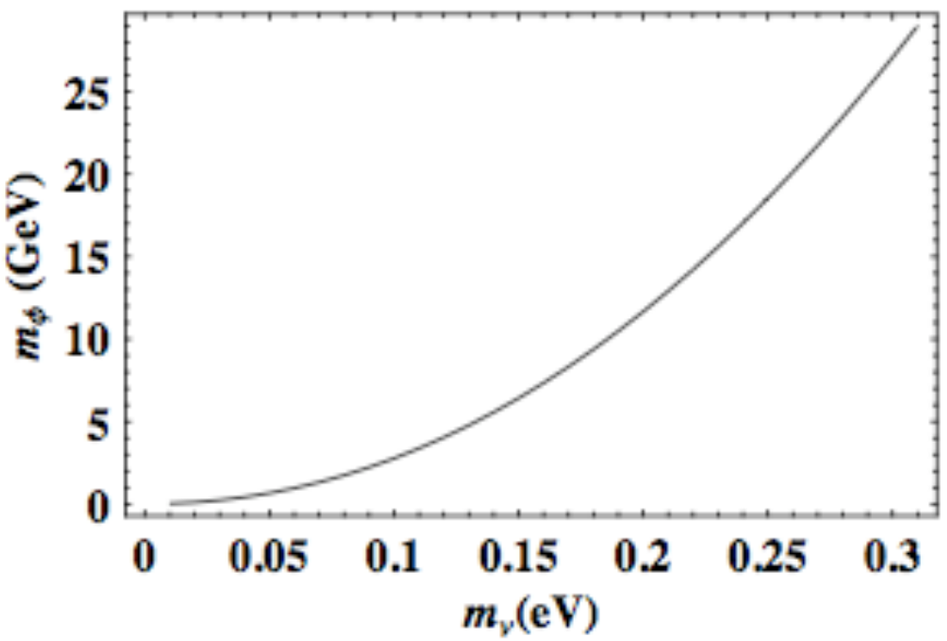
$$V = \frac{1}{2} m_\phi^2 \phi^2 - A \frac{h}{6\sqrt{3}} \phi^2 + \frac{h^2}{12} \phi^4$$

$$A \sim 4 m_\phi \sim \mathcal{O}(100)\ \text{GeV}$$

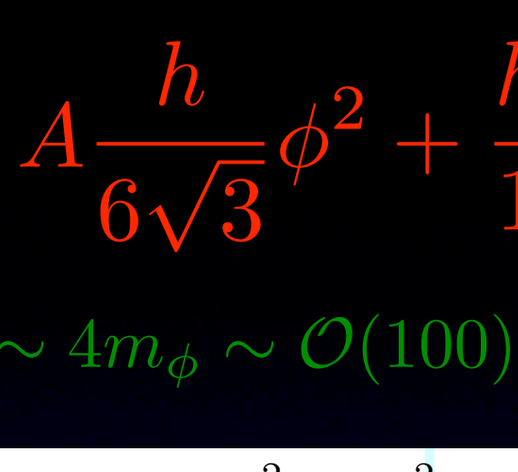
$$\phi = \frac{\widetilde{N} + H_u + \widetilde{L}}{\overline{3}}$$

$$V \sim 10^{32}\ (\text{GeV})^4$$

$$m_\phi^2 = \frac{m_{\tilde{N}}^2 + m_{H_u}^2 + m_{\tilde{L}}^2}{3}.$$



$$V'''(\phi_0) \neq 0,\ V'(\phi_0) \neq 0, V''(\phi_0) = 0$$



$\widetilde{N}$

Baryons

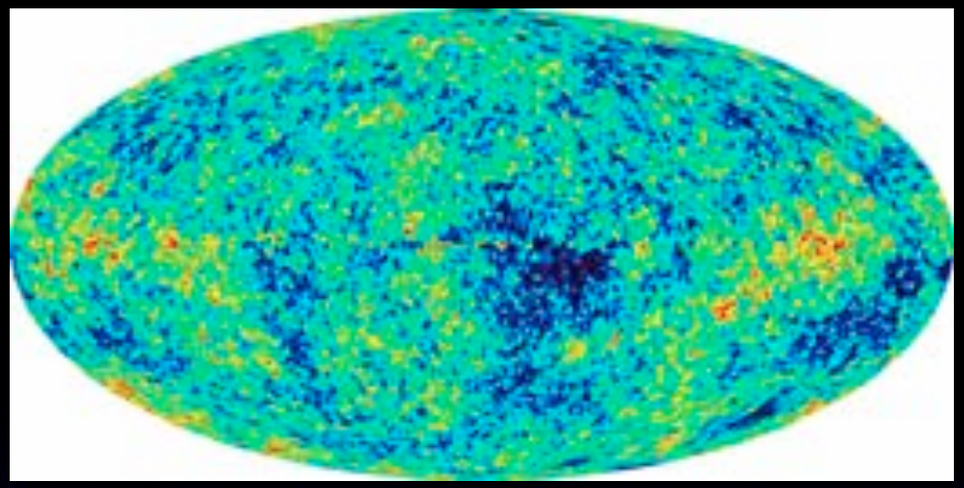
Electroweak symmetry is restored

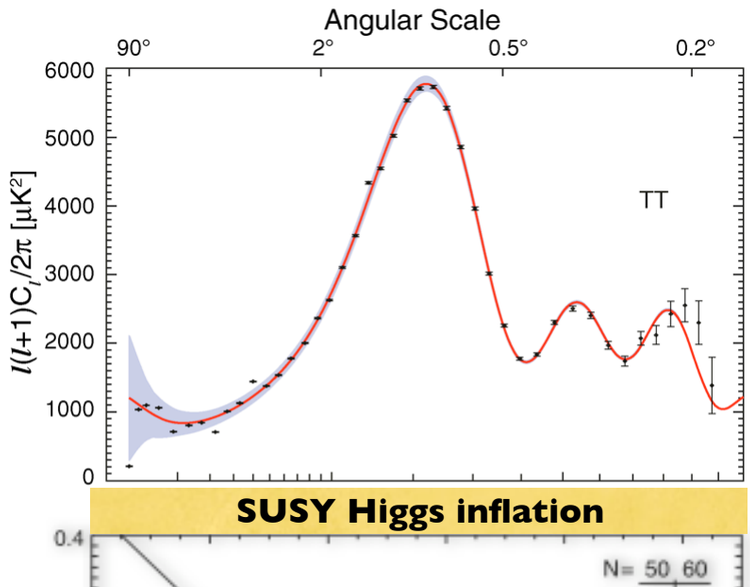
ϕ 10^{14} GeV

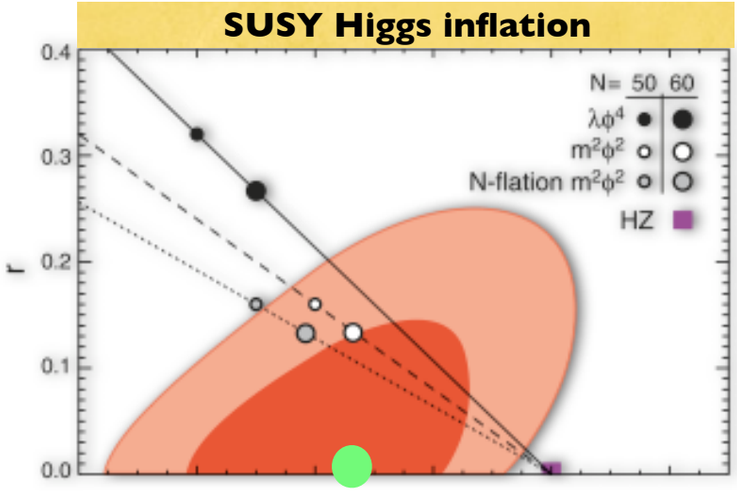
Allahverdi, Kusenko, AM , JCAP (2007)

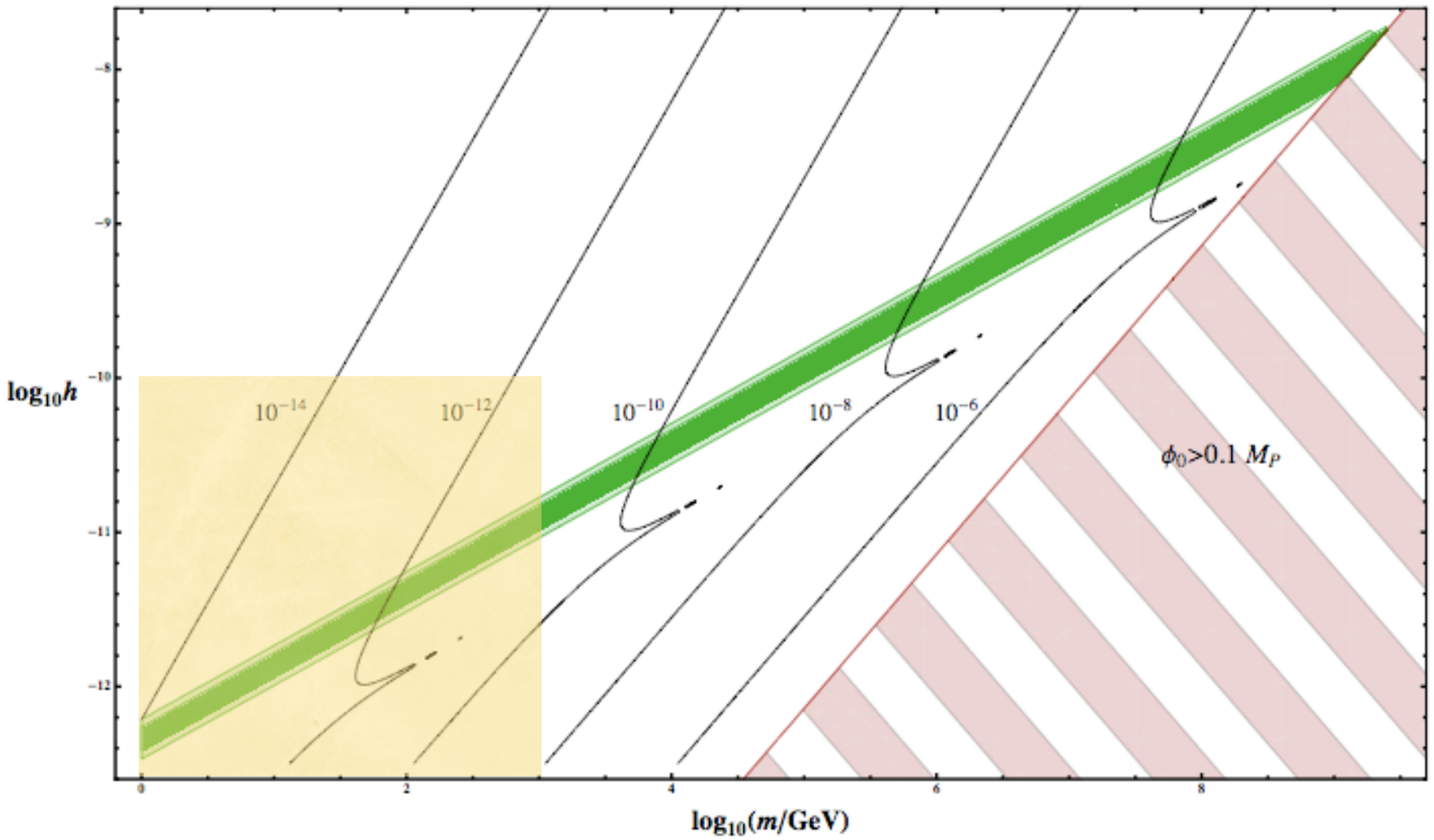
Kusenko, AM, Phys. Rev. Lett. (2009)

Higgs fluctuations in the sky!



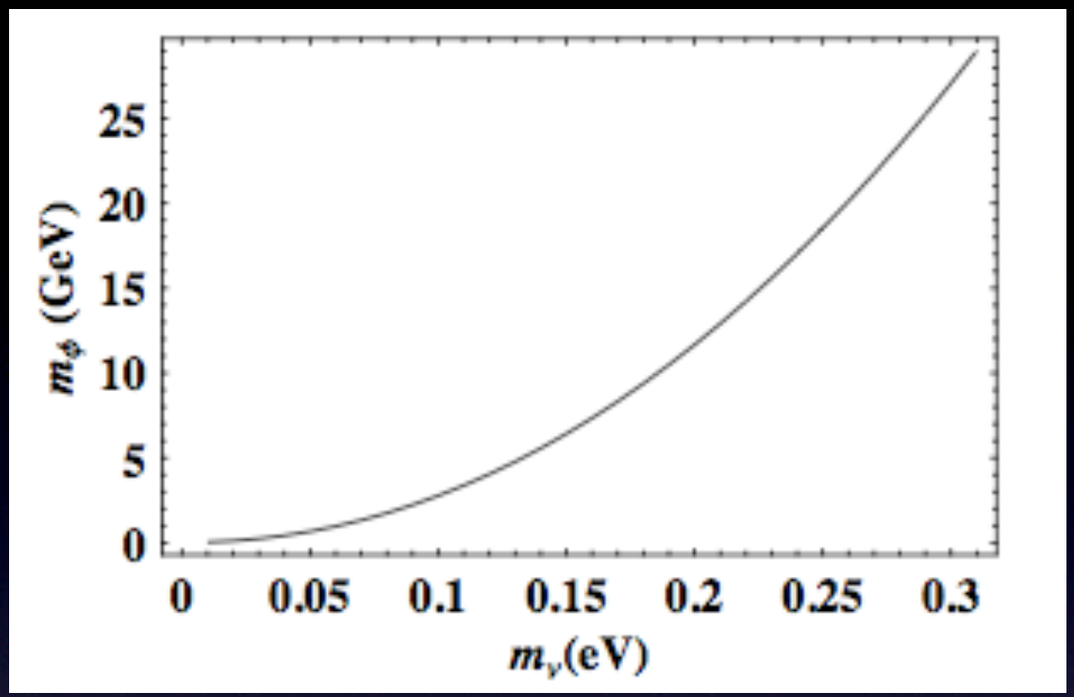






arXiv:1101.6046 [astro-ph.CO], Hotchkins, AM, Seshadri

Inflaton, Neutrino Mass & Sparticle Masses



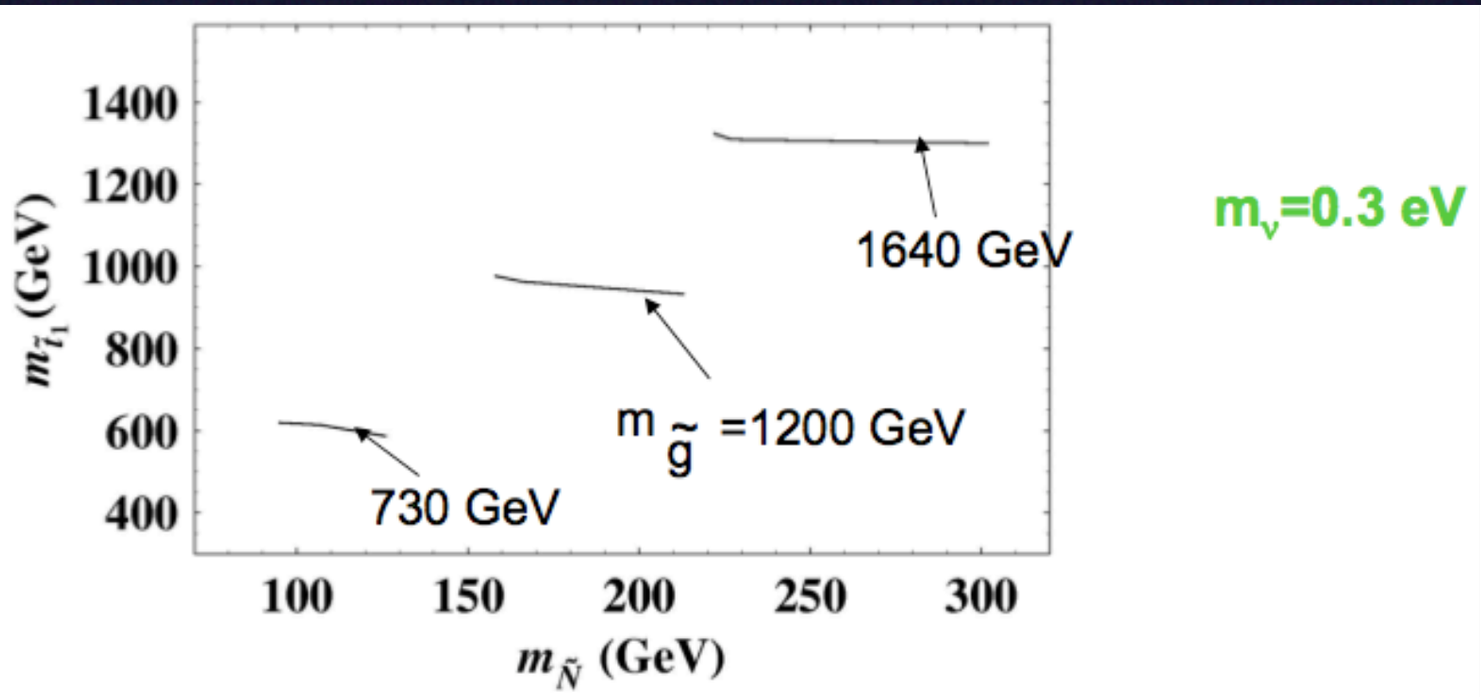
$$\phi_0 = \sqrt{3}\frac{m_\phi}{h} = 6 \times 10^{12}\ m_\phi \left(\frac{0.05\ \text{eV}}{m_\nu}\right),$$

$$V(\phi_0) = \frac{m_\phi^4}{4h^2} = 3 \times 10^{24}\ m_\phi^4 \left(\frac{0.05\ \text{eV}}{m_\nu}\right)^2.$$

✓ **Inflaton & Dirac Neutrino masses are correlated**

✓ **Inflaton & Sparticle masses are correlated**

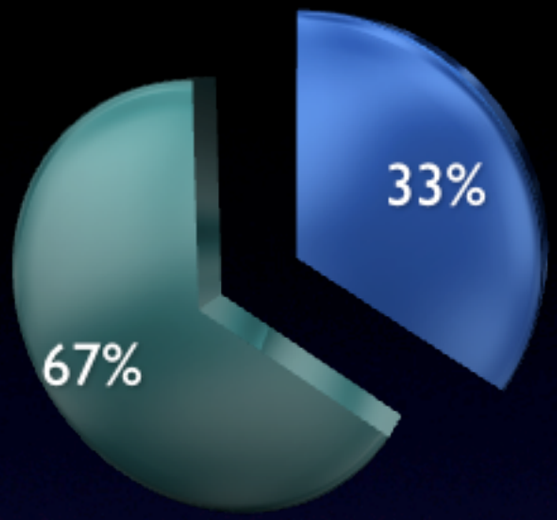
Potential discovery of Inflaton @ LHC

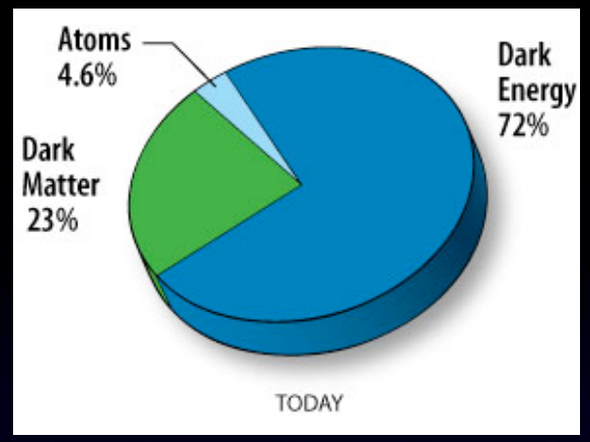


Each line: Left end m_0=0; Right end : M(sneutrino)=M(neutralino)

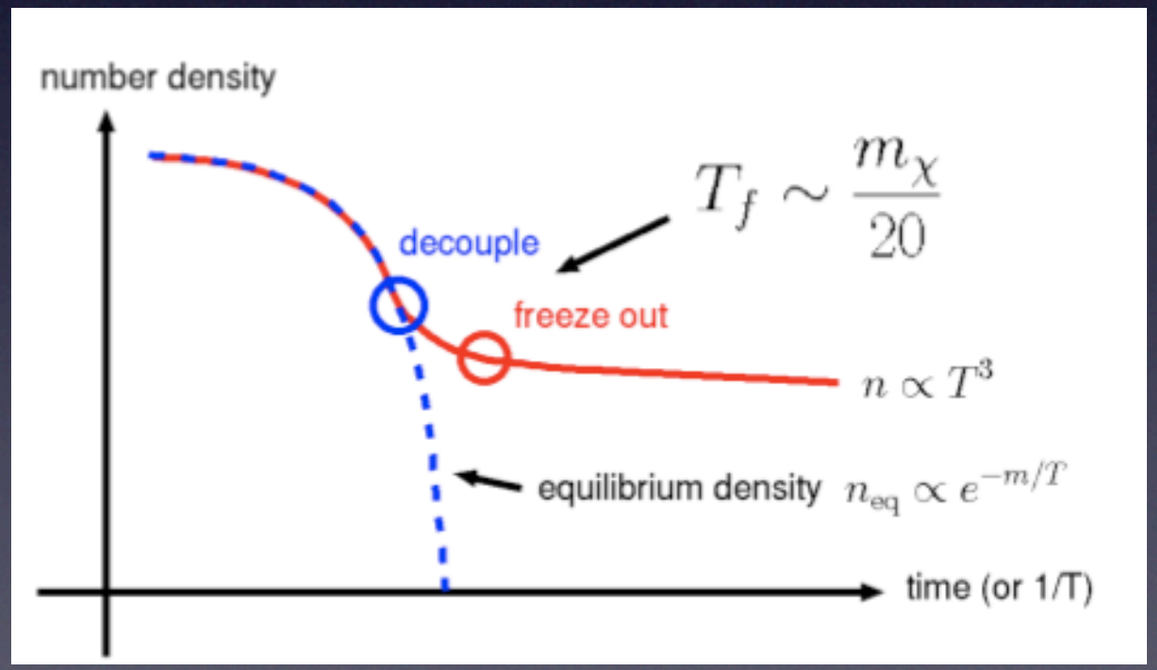
Allahverdi, Dutta, AM , Phys. Rev. Lett. (2007)

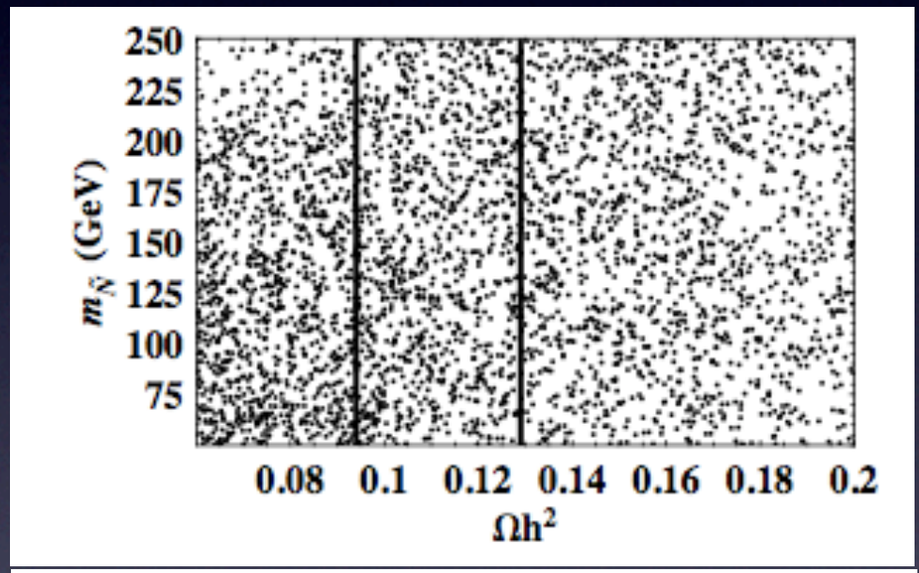
Dark matter as an Inflaton

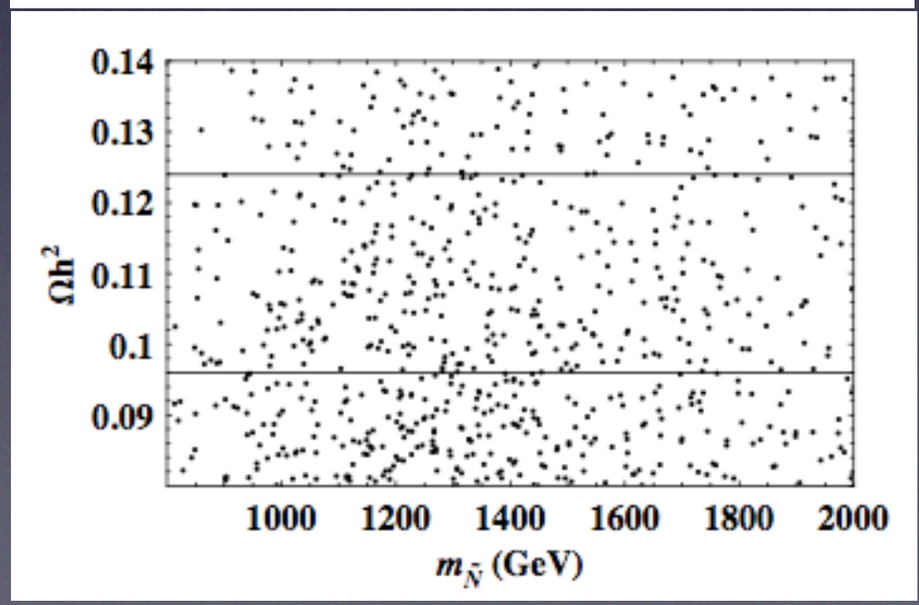




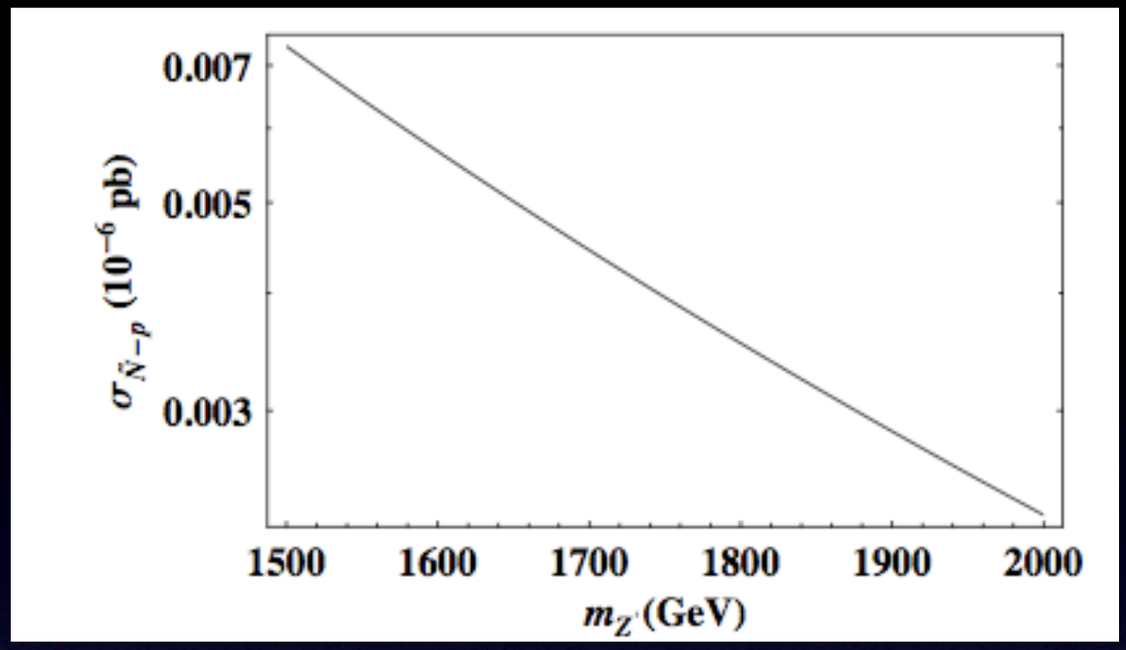
$$SU(3) \times SU(2) \times U(1)_Y \times U(1)_{B-L}$$







Signatures of Sneutrino Dark Matter



✓ **Direct Detection**

Sneutrino interacts with quarks via Z' exchange

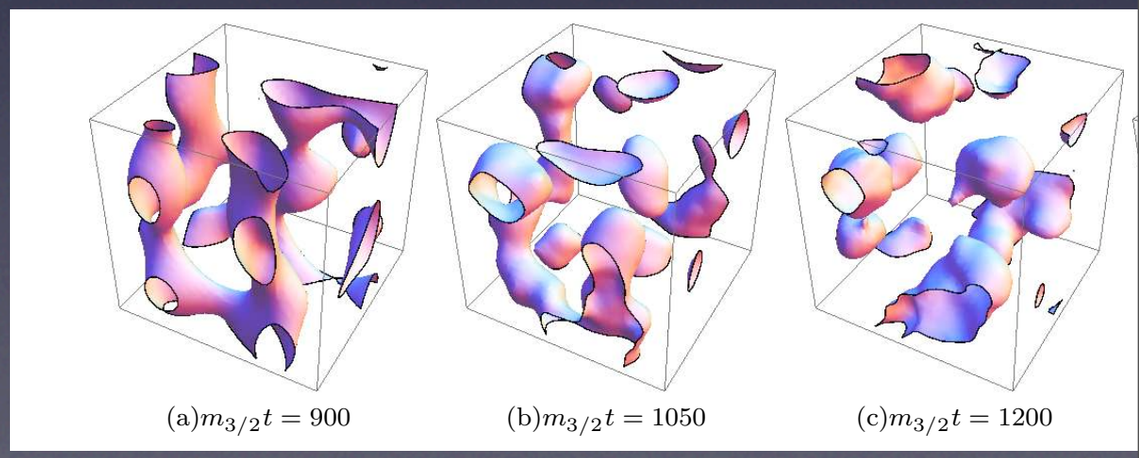
✓ **Collider signal**

LHC : Signal is similar to the Neutralino LSP

We need to pin down the spin of the Dark Matter

✓ **Indirect signal** Lumps of Sneutrino balls passing through earth creating neutrino shower

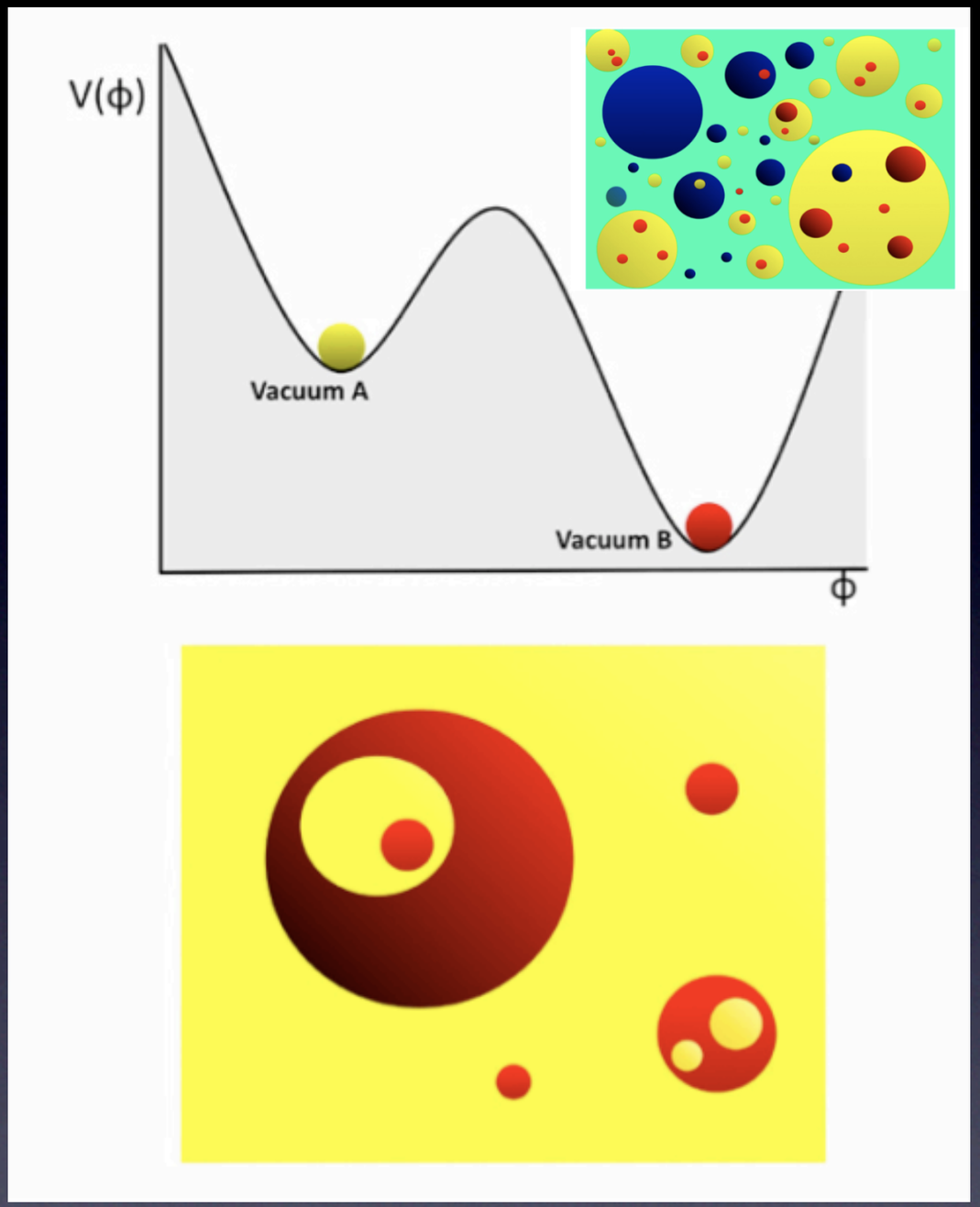
Gravity waves are excited during the formation of these lumps with a detectable signature by LIGO/LISA

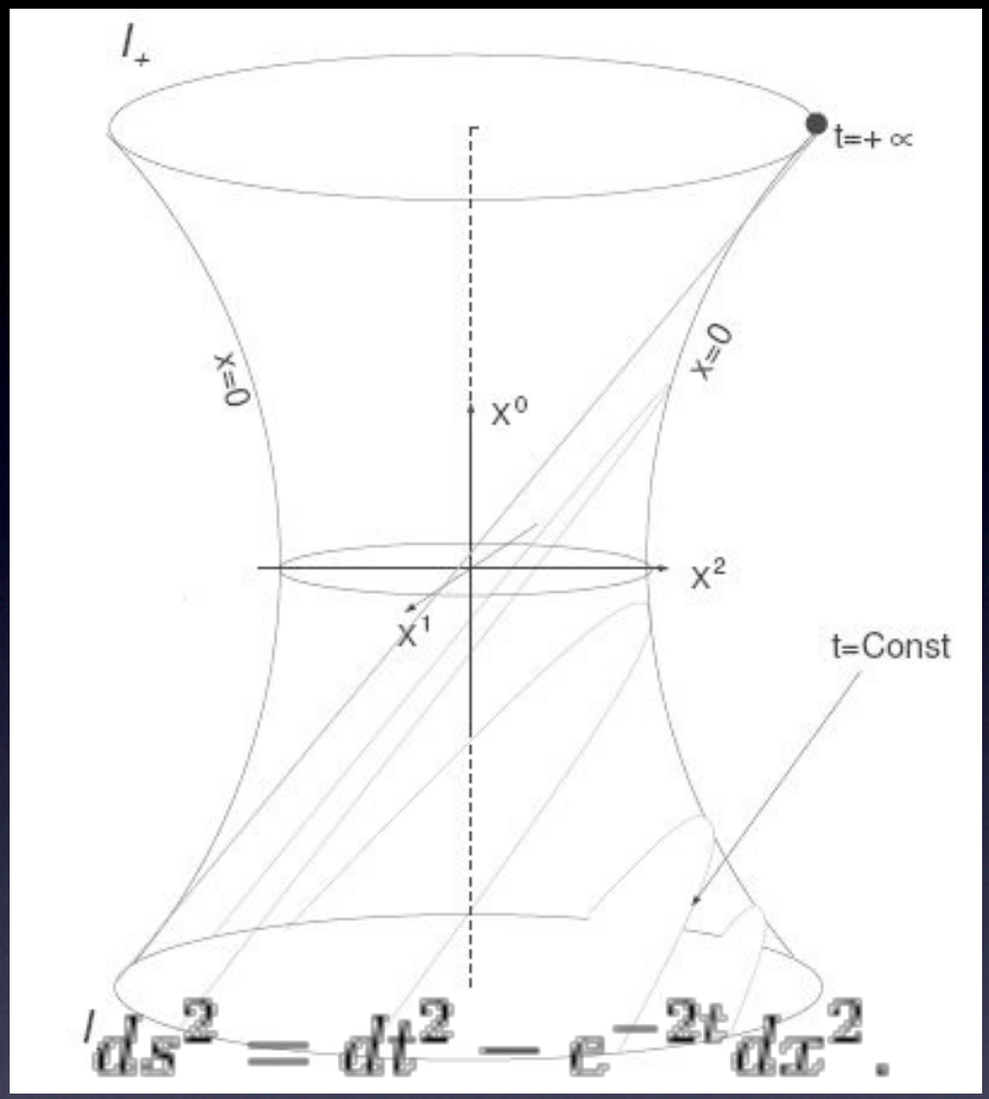


Allahverdi, Dutta, AM , Phys. Rev. Lett. (2007)

Kusenko, AM, Phys. Rev. Lett. (2008),

How the Universe began ?



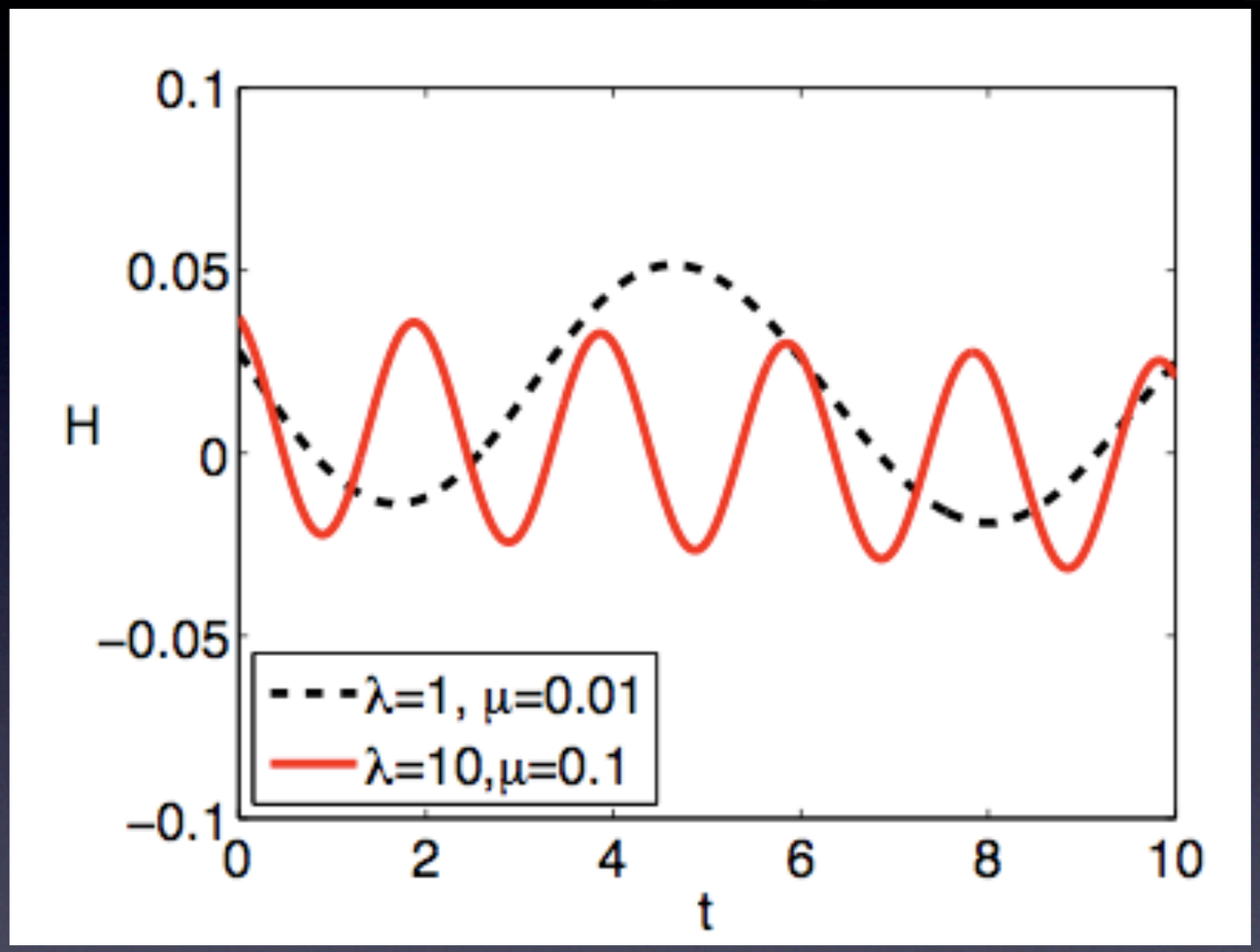


Inflation is not past eternal

Need to resolve the Cosmic Singularity problem

Magic without a magic : Resolution of a Big Bang Singularity

Asymptotically Free Gravity



$$S = \frac{M_p^2}{2}\int d^4x\,\sqrt{-g}F(R)$$

$$F(R) = R + \sum_{n=0}^{\infty}\frac{c_n}{M_*^{2(n+1)}}R\Box^n R$$

$$c_n = -\frac{1}{6}\frac{(-1)^{n+1}}{(n+1)!}$$

Biswas, AM, Siegel, JCAP (2006),
Biswas, Koivisto, AM, JCAP (2010)

Null and time like geodesics are complete

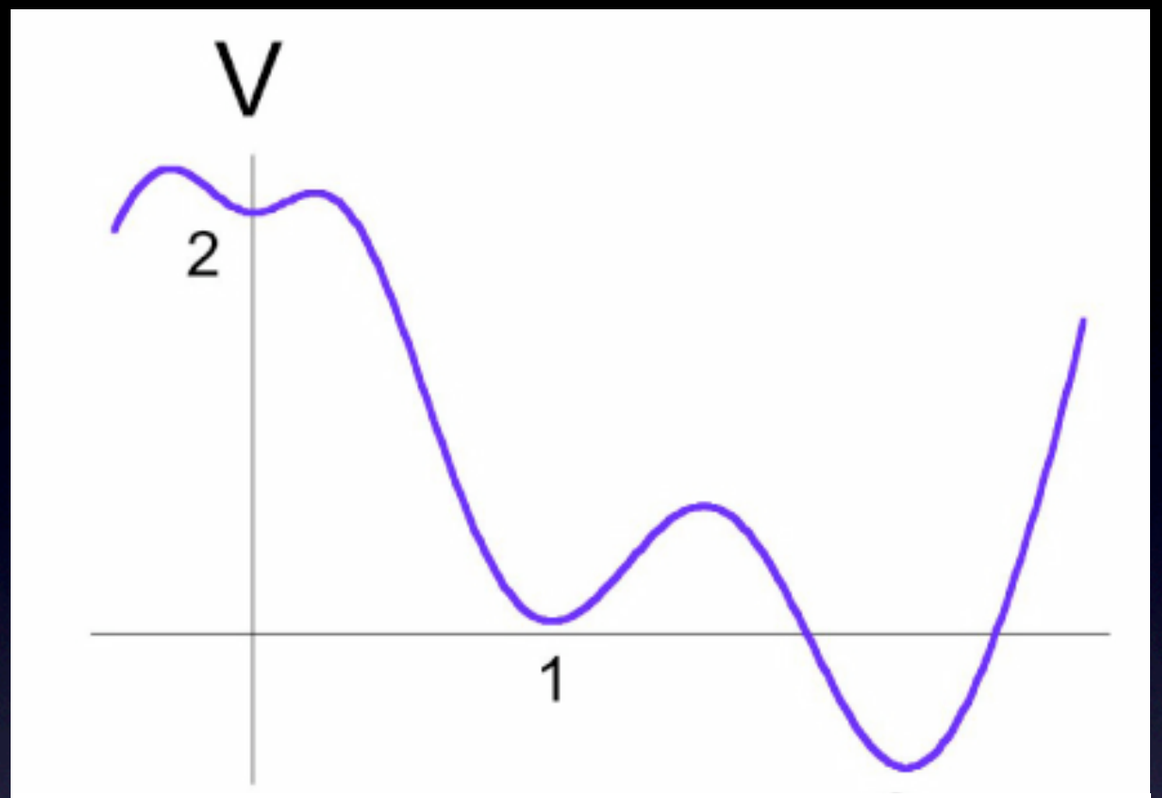
Inflation can be made Past & Future Eternal !

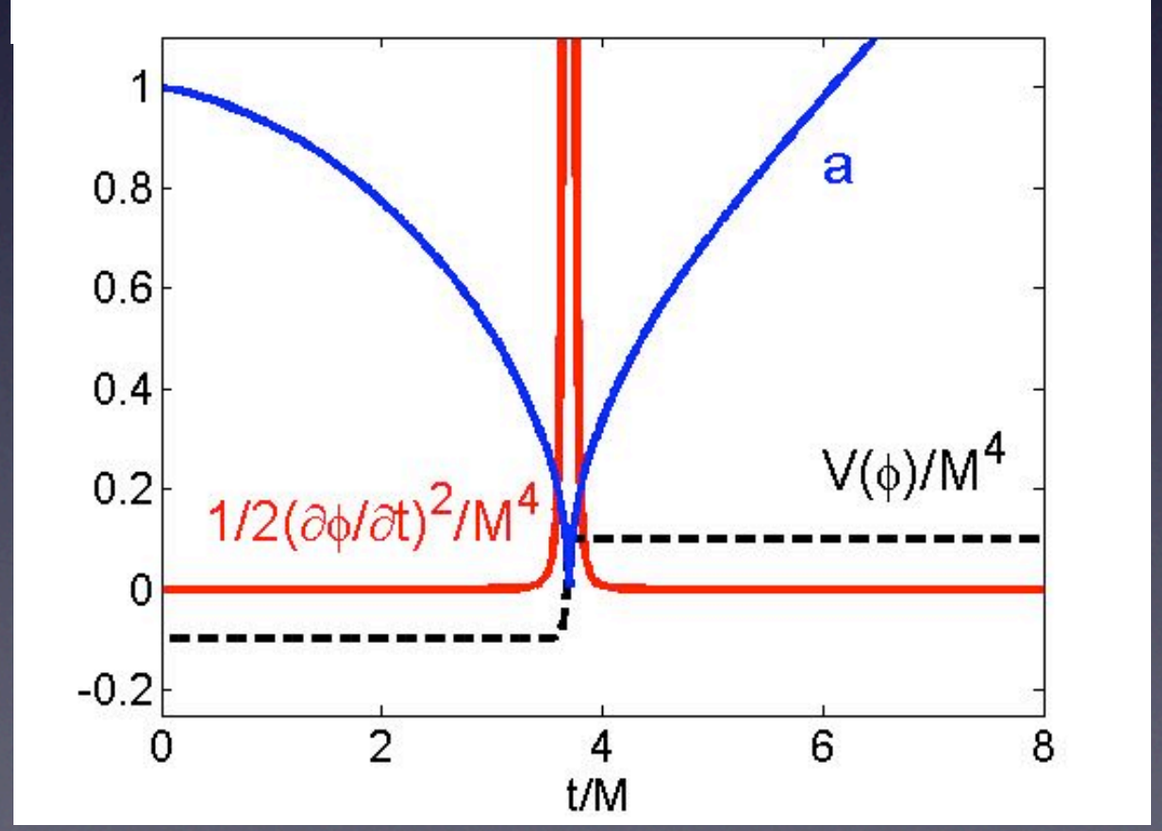
Cyclic Higgs

String theory landscape
Majority of vacua are anti De-Sitter

Large Kinetic term for Higgs is necessary

Biswas, Koivisto, AM (To appear soon)





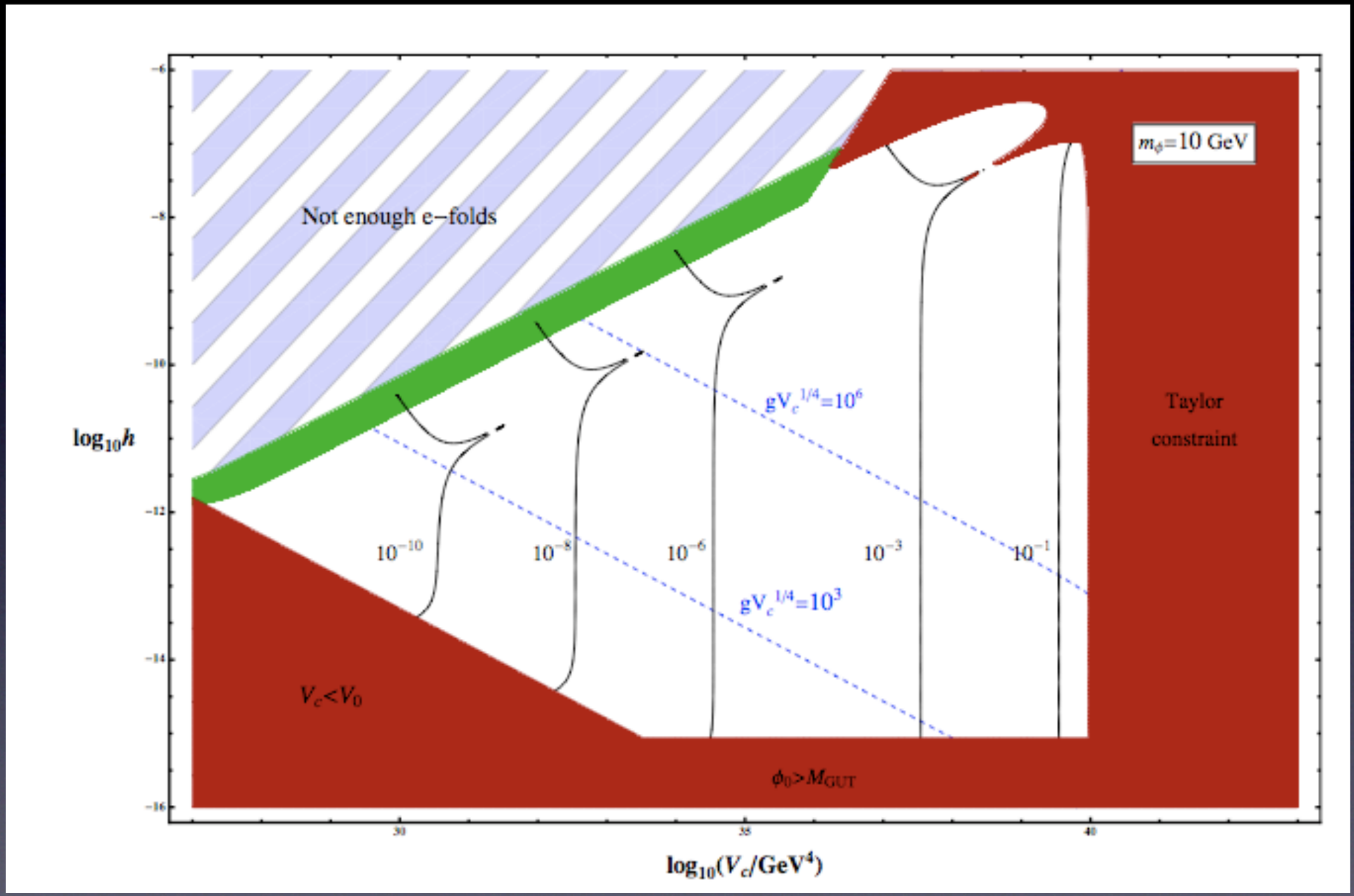
Conclusions

- **Higgs can puff up the Universe**
- **Higgs decay can create all matter, perturbations & dark matter**
- **Asymptotically free gravity is the most promising route to resolve the Big Bang Singularity**
- **Higgs kinetic energy can trigger a Cyclic Universe & possibly shed some light on how our Universe began**

We are still learning new tricks with gravity !

Hopefully by 2012 Higgs-Maxwell meeting we will learn something new

Embedding Higgs Inflation in NMSSM



arXiv:1101.6046 [astro-ph.CO], Hotchkins, AM, Seshadri

Gauged Inflaton

$$V = \frac{1}{2}m^2\phi^2 - A\lambda_6\frac{\phi^6}{M_{\rm P}^3} + \lambda_6^2\frac{\phi^{10}}{M_{\rm P}^6} \qquad m \sim 100\ {\rm GeV},\ \lambda_6 \sim \mathcal{O}(0.1),\ A \sim \mathcal{O}(10)m$$

Allahverdi, Enqvist, AM Phys. Rev. Lett. (2006)

Inflation is driven in the observable sector $W \sim \mathbf{udd}, \quad \mathbf{LLe}$

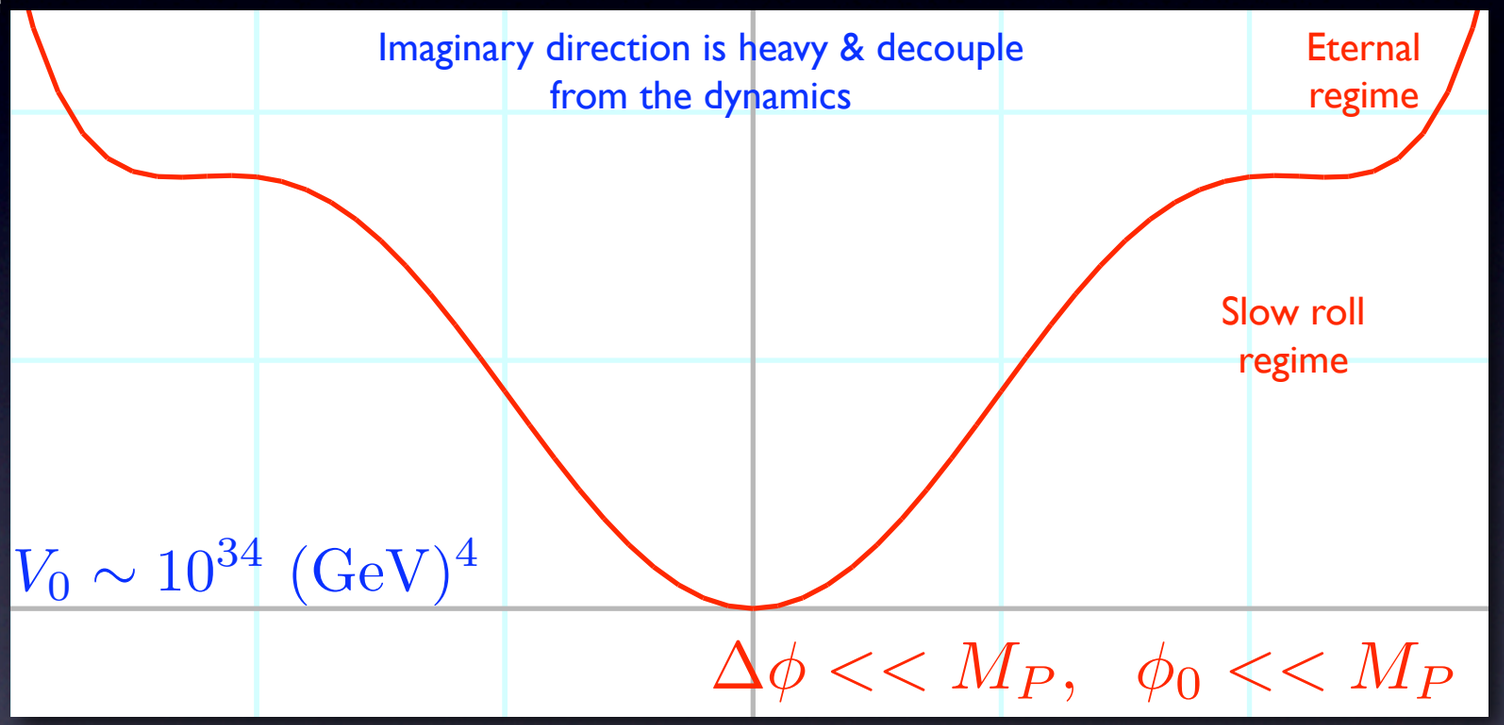
Inflation ends at the point of enhanced symmetry

Sub-Planckian VeV, Low scale inflation $H_{\rm inf} \sim 1\ {\rm GeV}$

Large e-foldings of inflation $\mathcal{N}_e \sim 10^3$

Reheat temperature $T_{\rm rh} \sim 10^2 - 10^3\ {\rm GeV}$

Trans-Planckian issues and moduli problems are solved



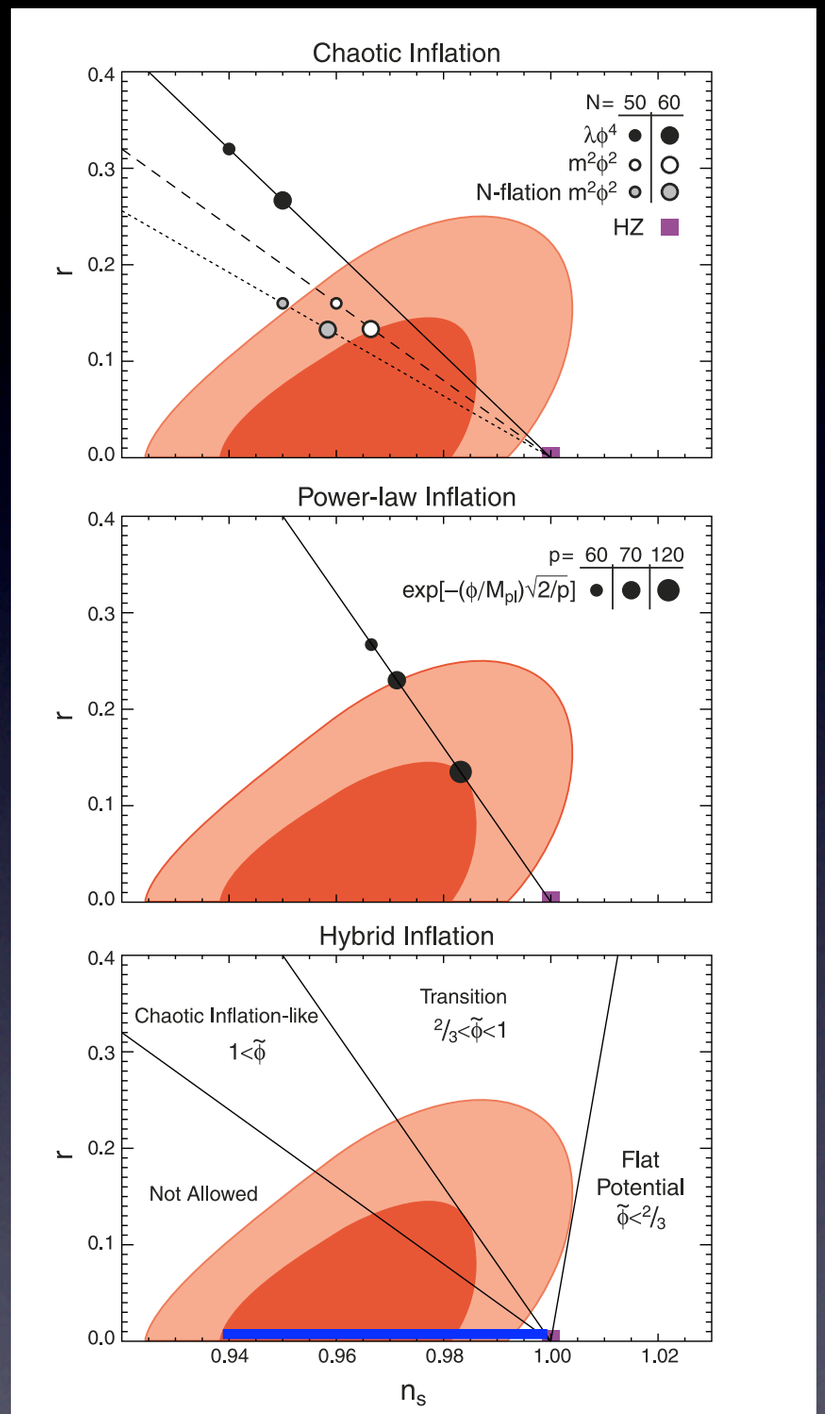
$\phi_0 = 3 \times 10^{14}\ GeV$

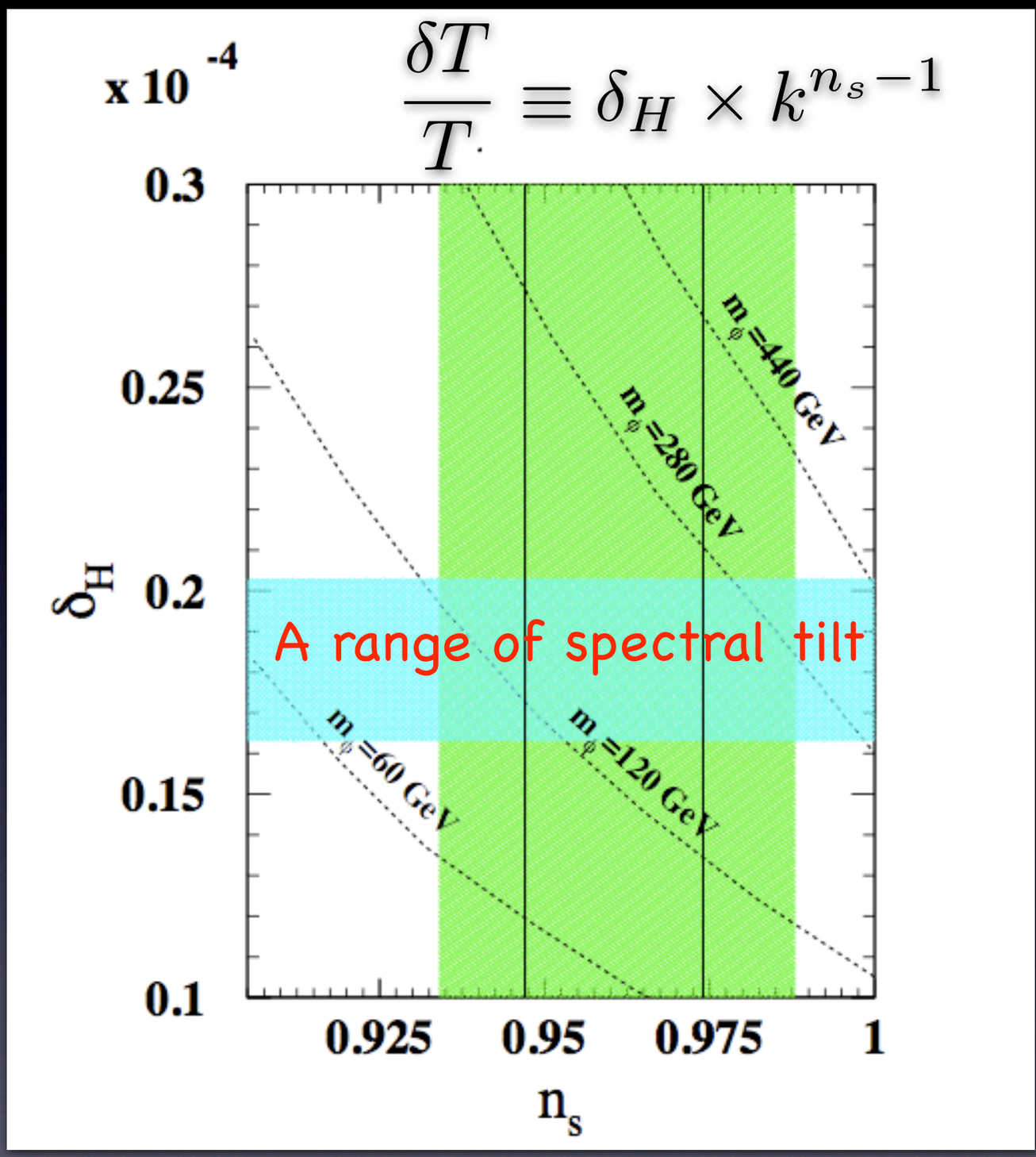
$$V'''(\phi_0) \neq 0 \quad V'(\phi_0) \neq 0, \quad V''(\phi_0) = 0$$

Inflation happens around the point of inflection

Allahverdi, Enqvist, Garcia-Bellido, AM, JCAP (2007), Allahverdi, Dutta, AM, PRD (2008)

CMB Observations



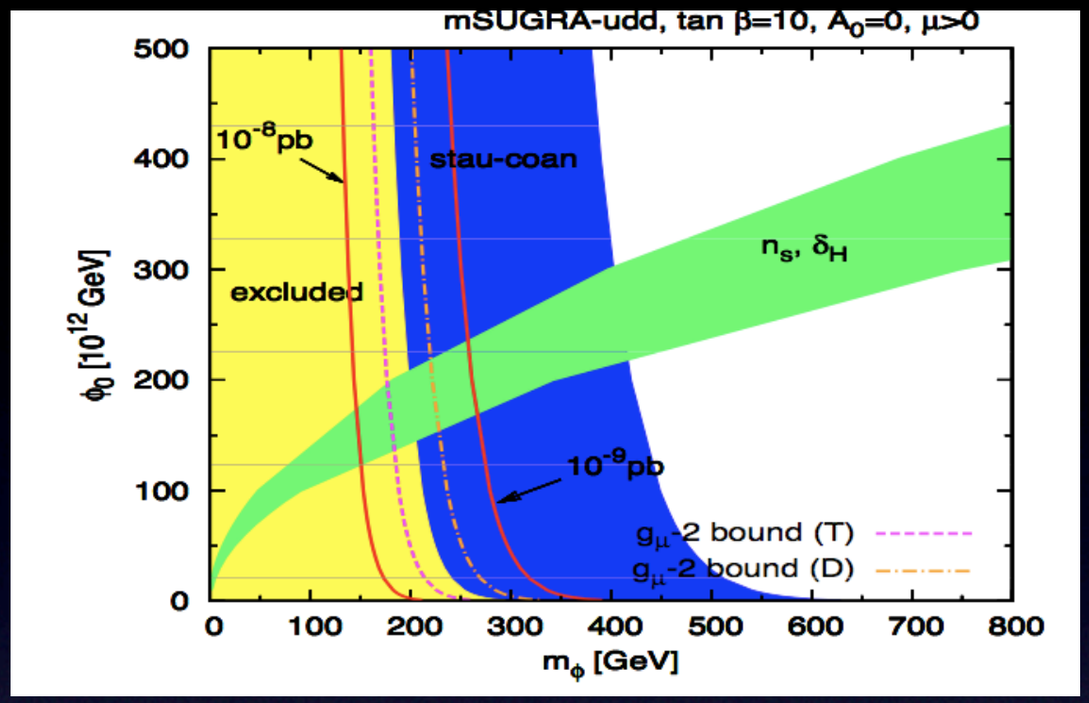


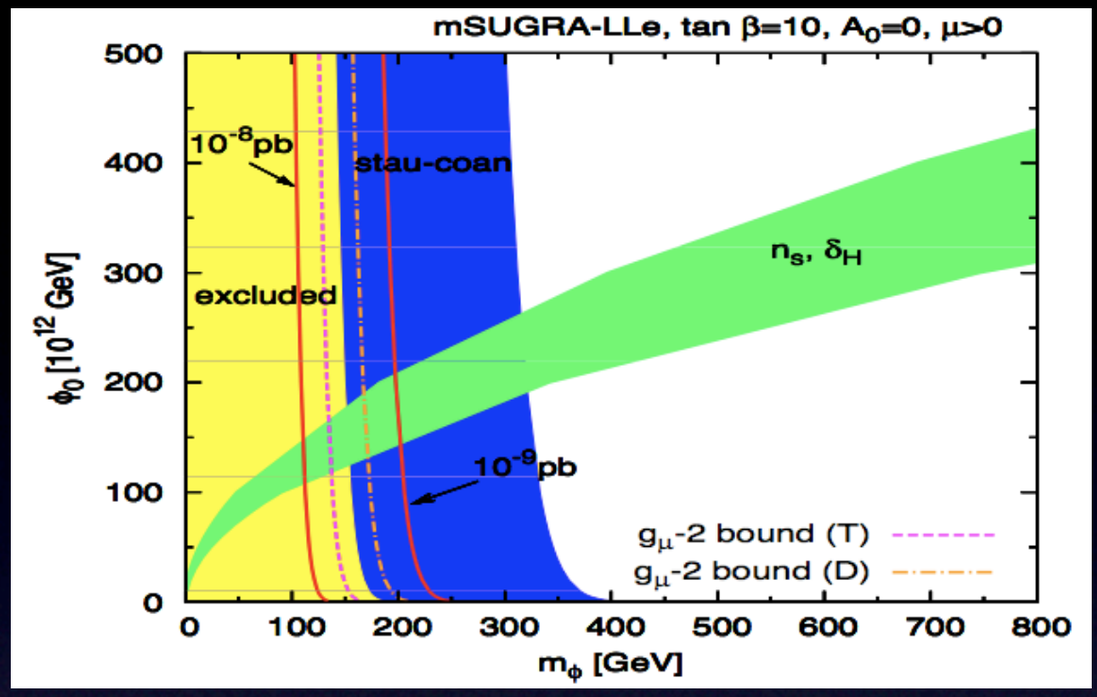
Allahverdi, Enqvist, AM, Phys. Rev. Lett. (2006) (saddle point)

Allahverdi, Enqvist, Garcia-Bellido, AM, JCAP (2007),

Allahverdi, Dutta, AM, PRD (2008) (Point of inflection, which gives a range of n_s)

Connection with LHC





Mass measurements at the LHC can also be used to constrain $m_\phi - \phi_0$ plane.

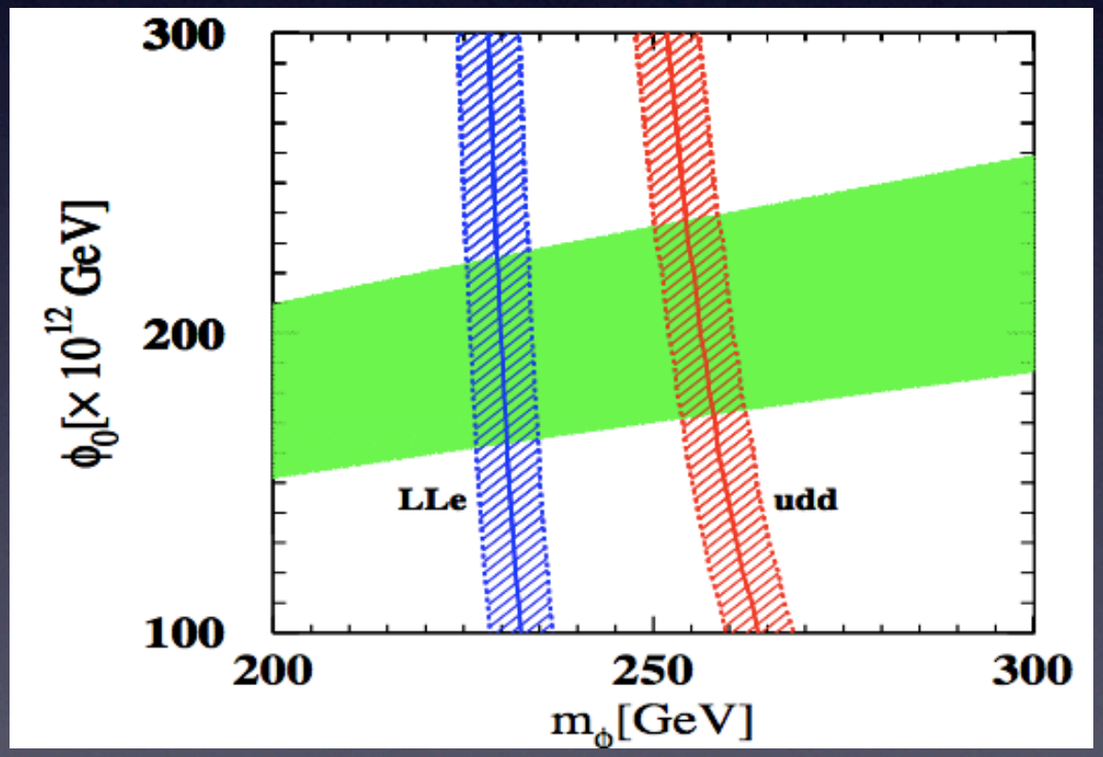
Consider a SUSY reference point in the co-annihilation region (all masses are in GeV):

$$m_0 = 210, m_{1/2} = 350, \tan\beta = 40, A_0 = 0$$

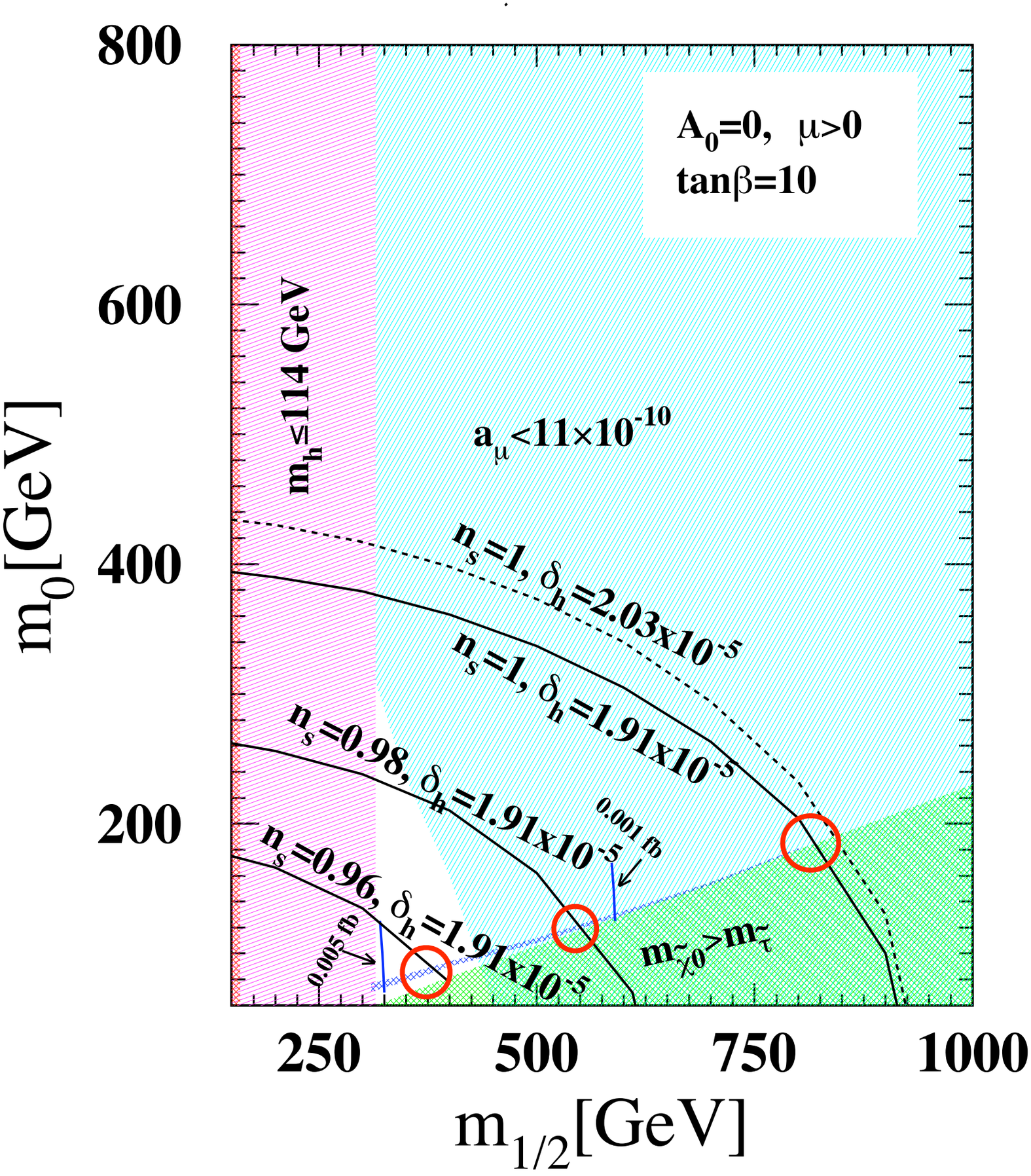
$$\Rightarrow m_{\chi_1^0} = 140.7, m_{\tilde{\tau}_1} = 151.3, m_{\tilde{\tau}_2} = 329$$

With $10\ fb^{-1}$ of data, LHC can determine high energy parameters:

$$m_0 = 210 \pm 4, m_{1/2} = 350 \pm 4, \tan\beta = 40 \pm 1, A_0 = 0 \pm 16$$



Allahverdi, Dutta, Santoso , Phys. Rev. D. (2010)



SUSY Dark Matter, Inflation, & LHC

Allahverdi, Dutta, AM
Phys. Rev. D (2007)