FYST17 Lecture 11
BSM and the cosmic connection

Thanks to G. Brooijmans, C. Grojean, T. Rizzo, L. Covi, M. Maggiore

Suggested reading: (sort of) Chap 13

Today

- Why go Beyond the SM?
  - What are the problems with the SM?
  - What direct measurements points to physics BSM
- Some attempts at solutions
  - Supersymmetry, Extended Higgs sector, Extra dimensions, the dark sector etc
- A little more on the connection to cosmology

Include very weakly coupled particles, nnbar oscillations at the ESS

Status of the Standard Model

19 parameters (+ ν masses)

Tested to precision level $10^{-3} - 10^{-12}$

Extremely successful!

But empirically incomplete

Structure quite complicated

Aesthetically unacceptable

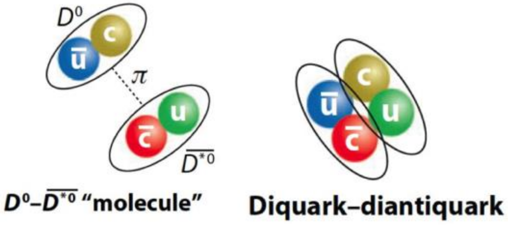
Many problems with naturalness

No quantum gravity

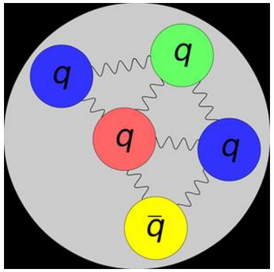
Missing answers to ”big” questions

Any direct evidence?

Certainly a few measurements that are not incorporated in the current Standard Model:

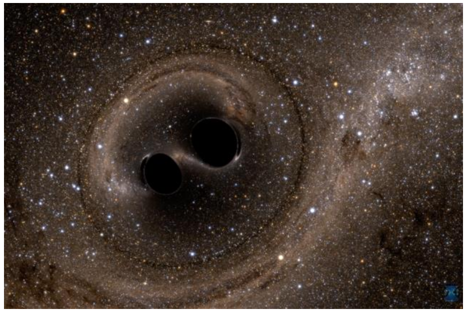


- Exotic baryons (X, pentaquarks etc)

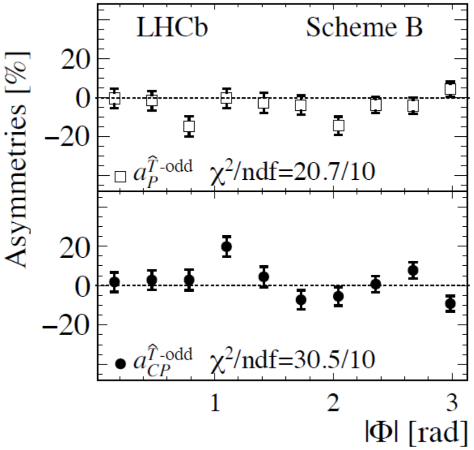


- Neutrino masses and oscillations!

- (Gravitational waves)



- The LHCb CP violation measurements (although <4σ)



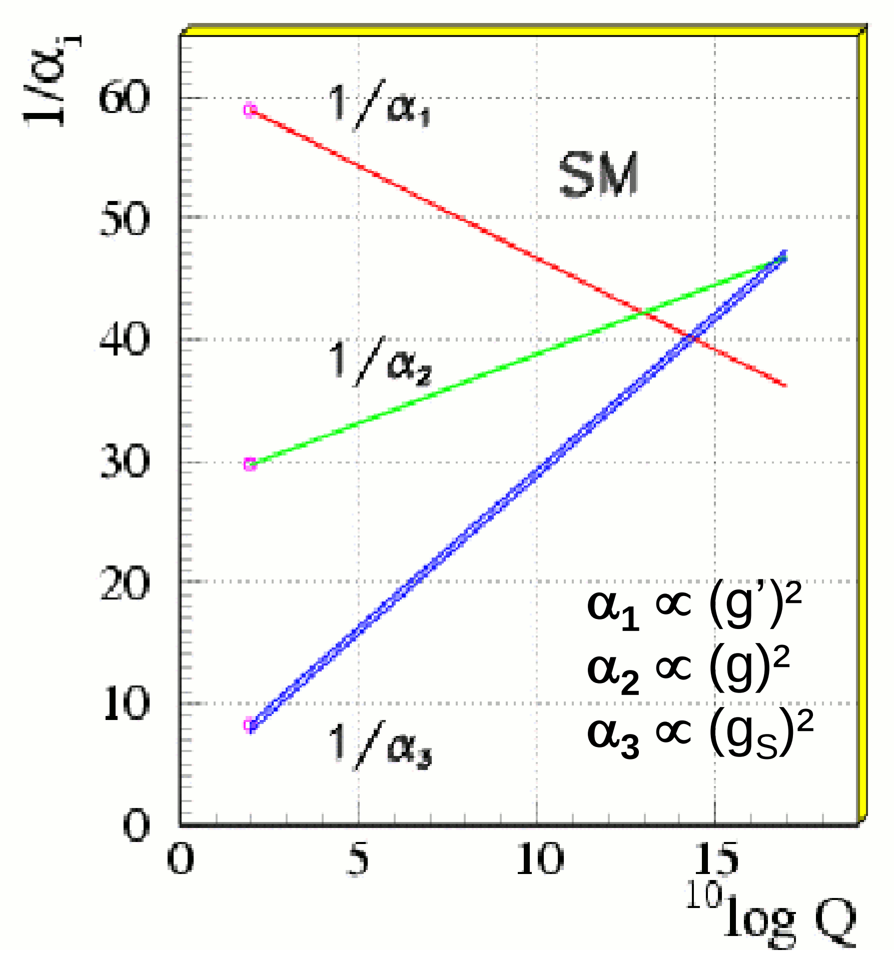
Is the Standard Model really fundamental?

- Does not appear so ($\gtrsim$ 25 parameters?!)
- Evidence of selective processes:
  - For instance, no neutral colored fermions
  - $q_d = q_e$ /N(colors) $\Rightarrow$ grand unification?
- ***Fragile:*** small changes in parameters $\Rightarrow$ very different physics!
  - If $m_d < m_u$: all protons decay $\Rightarrow$ no atoms
  - If $m_e > 4m_p - m_\alpha \Rightarrow$ Sun doesn't burn $\Rightarrow$ no us
  - If v >> TeV $\Rightarrow |m_n - m_p|$ large , rapid neutron decay $\Rightarrow$ no chemistry nor life

Examples of answers we need

- *What is the origin of CP violation?*
- *What is the origin of the matter/anti-matter asymmetry*
- *Why three gauge forces (so far)? And three generations?*
- *Why is the strong interaction strong? Why only left-handed particles participate in weak force?*
- *Gravity? Is there a unified description of all forces?*
- *Why is mass(W/Z/H) << mass(Planck)? (Hierarchy problem)*
- *Why is charge quantized?*
- *What is Dark Matter and Dark Energy? (and why Dark Energy now?)*
- *What was the Big Bang?*

Unification of coupling constants?

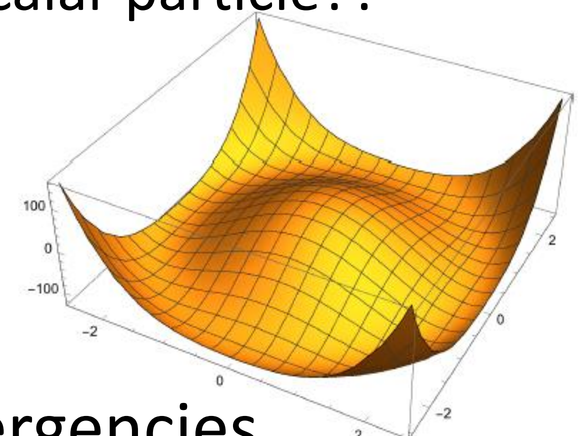


Extrapolating the Standard Model coupling constants to higher energies

http://pdg.lbl.gov

The Higgs discovery just adds to that list…

- What is it, really, a condensate in our Universe?
- Is it elementary?
  - If yes, why is there only 1 fundamental scalar particle??
- Why does it have mass^2 $\mu^2 < 0$?!

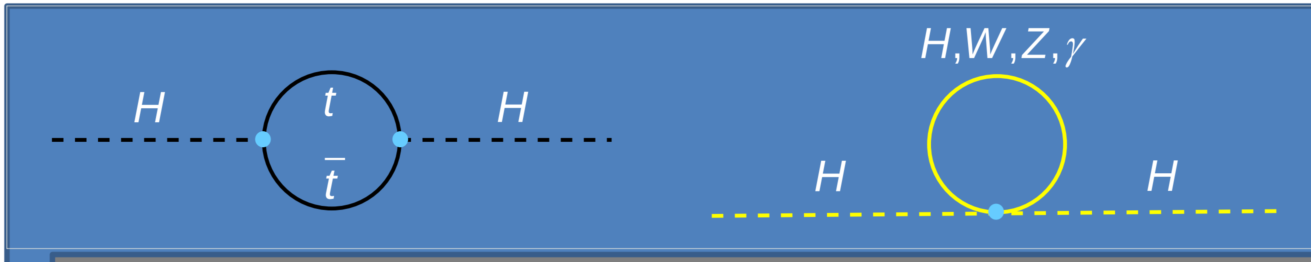


- Higgs mechanism gives quadratic divergencies

The “Gauge Hierarchy Problem”

Discover of Higgs boson with mass < 1 TeV means the Standard Model is complete !

However, when computing radiative corrections to the bare Higgs mass a problem occurs:



Higgs radiative corrections

$$m_H^2 = m_0^2 + \delta m_H^2 \quad \text{where:} \quad \delta m_H^2 \propto \underbrace{\int_0^\infty d^4k \, \frac{k^2 + m_f^2}{\left(k^2 + m_f^2\right)^2}}_{\text{Integral quadratically divergent}} + \ldots \xrightarrow{\text{cut-off}} \int_0^{\Lambda_{\text{cut-off}}} (\ldots) \propto \Lambda_{\text{cut-off}}^2$$

The cut-off sets the scale where new particles and physical laws must come in

Above the EW scale we only know of two scales: GUT (~10^{16} GeV) and Planck (~10^{19} GeV)

Such a cut-off would require an incredible amount of finetuning to keep m_H light

$$m_H^2 = (125\ GeV)^2 = m_0^2 + C \cdot \Lambda_{cut-off}^2$$

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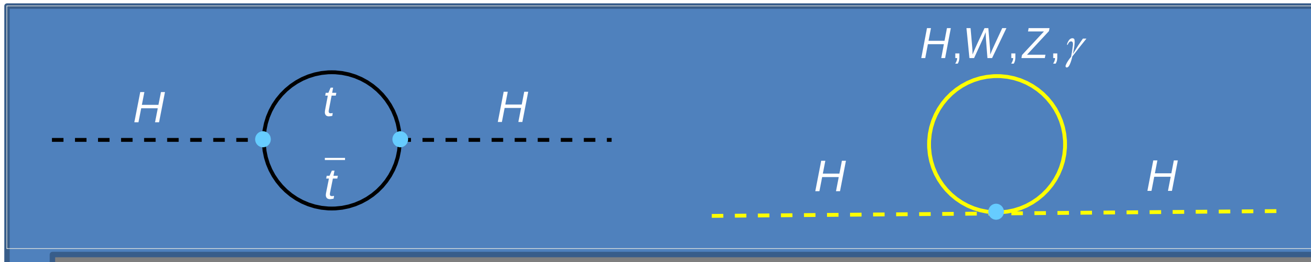

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Missing protection of scalar Higgs mass is related to **absence of a symmetry principle**. Setting $m_H = 0$ in SM Lagrangian, **does not restore any symmetry in the model**.

New physics models should address this. M_H should become a deviation from some exact symmetry, and is thus **intrinsically small** !

$$m_H^2 = (125\ GeV)^2 = m_0^2 + C \cdot \Lambda^2_{cut-off}$$

Hunting for answers

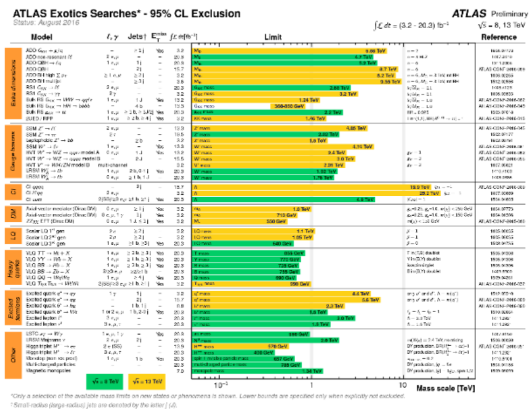
- Get more information
  - Measure particles and their interactions in details
    - Precision measurements
  - Observe new particles or interactions
    - Search in new areas in phase space
- Find the underlying pattern(s)
  - Hypothesize, build models
    - Internally consistent? Consistent with data?
    - Suggestions of where to look!

Experiment

Theory

Where to start?

- BSM *must* couple to SM fields (weakly?) but is it:
  - Resonant?
    - Does it have new massive particles decay to electrons, muons, quarks, bosons, ...?
  - ”SM-like”?
    - Same but includes some new long-lived particles in the decay chains (for instance dark matter)
  - New interactions, no new particles?
  - No new particles in reach?
    - Because they are hidden, or too heavy?
    - or don’t exist?



Supersymmetry (SUSY)

New symmetry ***fermions*** $\leftrightarrow$ ***bosons***

This symmetry is the most general extension of Lorentz invariance

SUSY has: N_{dof} (bosons) = N_{dof} (fermions)
[cf. SM: N_{dof} (bosons) << N_{dof} (fermions)]

Spin 0	Spin 1/2	Spin 1	Spin 3/2	Spin 2
sLeptons	Leptons		Gravitino	Graviton
sQuarks	Quarks			
Higgs	Higgsino			
	Photino	Photon		
	Zino	Z		
	Wino	W		
	Gluino	Gluon		

- To create *supermultiplets*, we need to add one *superpartner* to each SM particle
- Superpartners have opposite spin statistics but otherwise equal quantum numbers
- Need to introduce an additional Higgs doublet to the non-SUSY side $\rightarrow$ 5 Higgs bosons

But where are these partners?!
Supersymmetry must be broken (if realized)

Particle spectrum (minimal!)

In reality the new states would mix

Several ideas of how the supersymmetry is broken – intimately connected with EWK symmetry breaking

SM

SUSY

Eigenstates of mass	Spin 0	Spin 1/2	Spin 1
	$\tilde{\ell}_1, \tilde{\ell}_2$	ℓ	
	$\tilde{q}_1, \tilde{q}_2$	q	
	$h^0, H^0, A^0, H^\pm$	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	
		$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	$\gamma, Z^0, W^\pm$
		$\tilde{g}_a$	g_a

Squark/slepton mixing proportional to SM partner masses

→ largest for 3rd gen.

→ can become lightest squarks / sleptons

The gauge-mixed physical states that propagate in space and time and that can be observed.

Neutralinos: mass eigenstates of photinos, zinos, neutral higgsinos

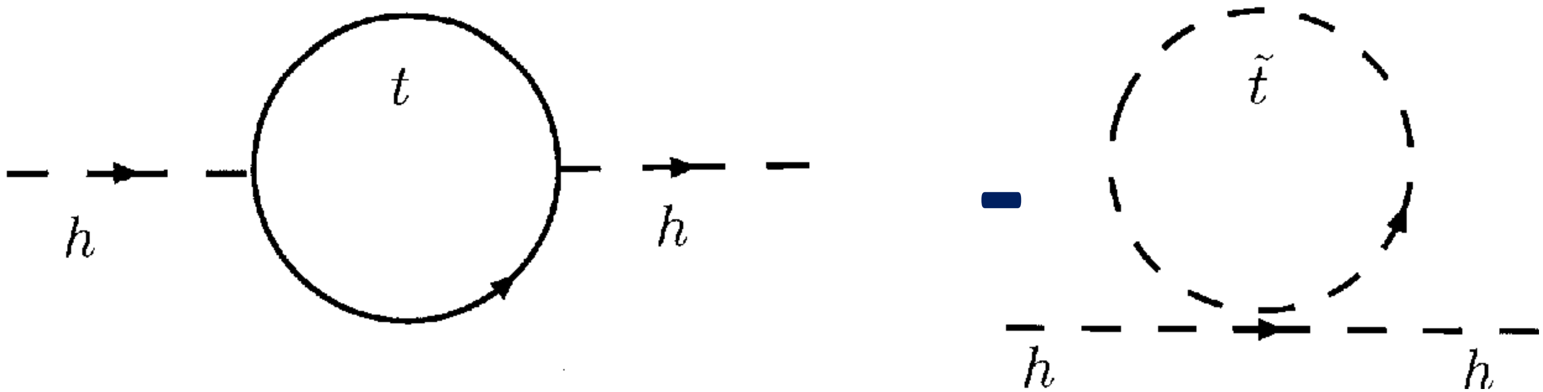
Charginos : mass eigenstates of winos and charged higgsinos

Since we don't know the mechanism, have to introduce $\mathcal{O}(100)$ new parameters

....

SUSY and the hierachy problem

If Supersymmetry not broken we would have perfect cancellation in the loops!



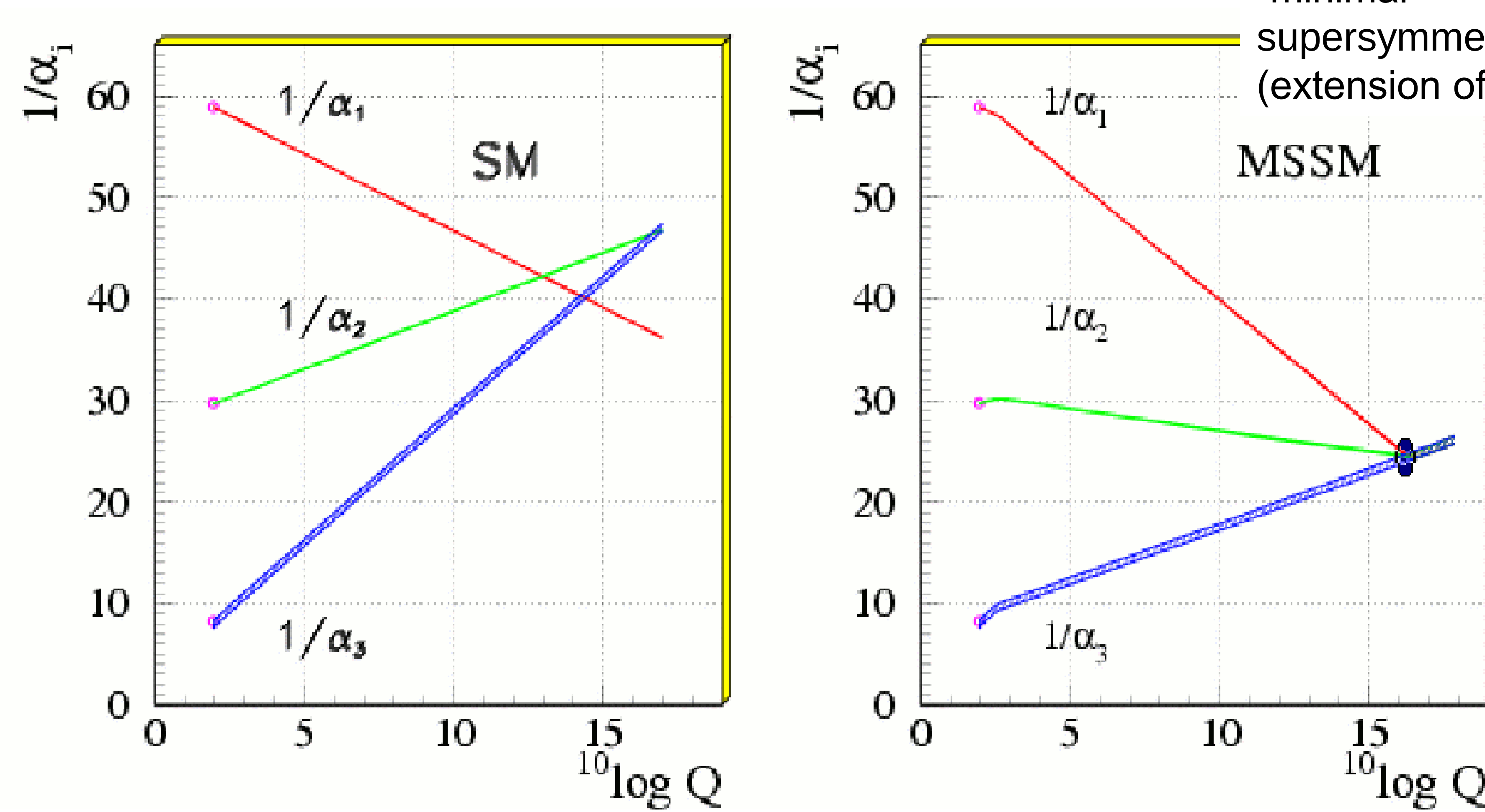
But as m($\tilde{t}$) $\neq$ m(t) they do not quite cancel, instead just a suppression

This still gives a decent result if |

m(fermion) – m(boson)| < $\mathcal{O}$(few TeV)

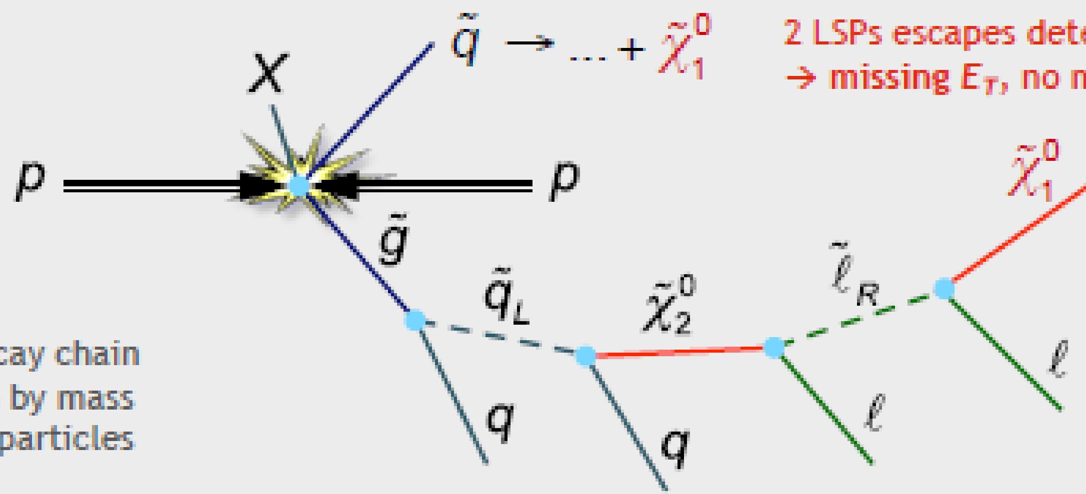
Unification of coupling constants with supersymmetry

“minimal supersymmetric (extension of) SM”



Characteristic SUSY Decay Cascades

- To avoid proton decay, a new conserved quantum number (R) is introduced, which forces a SUSY particle to decay in at least one other SUSY particle
- The lightest SUSY particle is thus stable (LSP), and must be neutral and colourless → WIMP (dark matter candidate)
- Typical **LSP is spin-½ neutralino.** It could also be a gravitino
- With R parity: SUSY production in pairs only → requires energy 2 × SUSY mass !



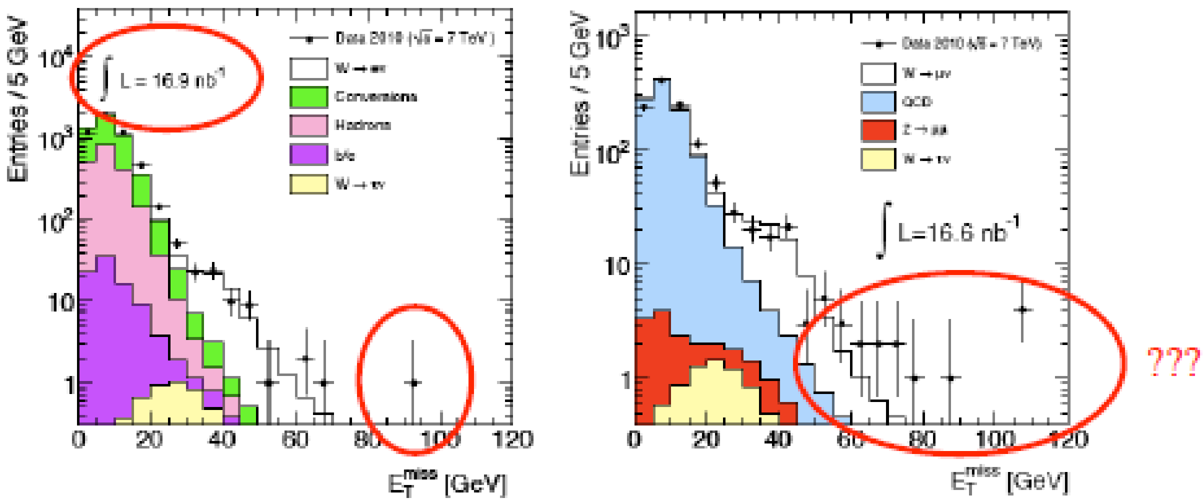
2 LSPs escapes detection
→ missing E_T, no mass peak !

"Typical" SUSY decay chain at the LHC, driven by mass hierarchy of SUSY particles

Missing ET

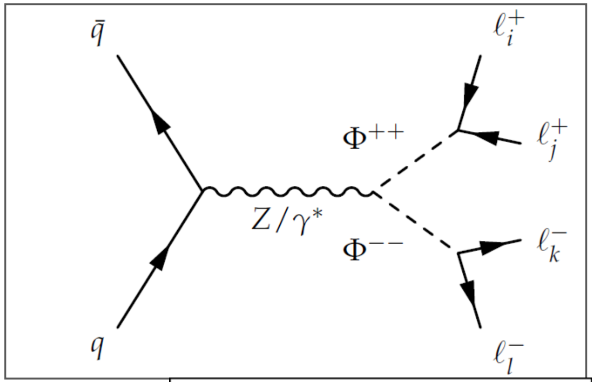
- "Evil" variable: - Σ (everything else)
  - Need to understand "everything else"
  - Good benchmark: leptonic W boson decays

Early 2010

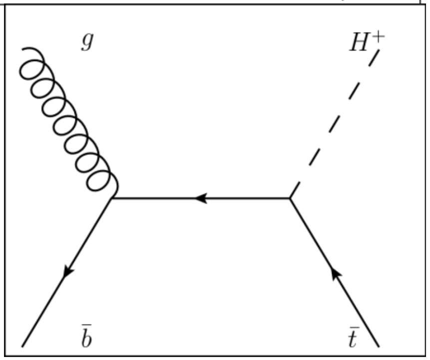


Analyses using missing E_T are very sensitive to calorimeter problems:
Often basic problems, such as a high voltage trip
But problems appearing with low frequency harder to spot and "clean up" – can still be biggest part of dataset after selection cuts!

Extended Higgs sector



In the Standard Model single Higgs doublet, often written as $\begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$ or $\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$



Extended: Many choices but a few constraints,

for instance suppression of FCNC and $\frac{M_W}{M_Z} = \cos\theta_W$

- Most successful: 2 Higgs doublet models (2HDMs)
  - Supersymmetry uses this
- See-saw models predict Higgs triplet with φ^0, $\varphi^{+/-}, \varphi^{++/--}$

General 2HDM Potential

$$
\begin{aligned}
V(\phi_1,\phi_2) &= \lambda_1\left(|\phi_1|^2 - v_1^2\right)^2 + \lambda_2\left(|\phi_2|^2 - v_2^2\right)^2 \\
&+ \lambda_3\left[\left(|\phi_1|^2 - v_1^2\right) + \left(|\phi_2|^2 - v_2^2\right)\right]^2 \\
&+ \lambda_4\left[|\phi_1|^2|\phi_2|^2 - \left(\phi_1^{*T}\phi_2\right)\left(\phi_2^{*T}\phi_1\right)\right] \\
&+ \lambda_5\left[\mathrm{Re}\left(\phi_1^{*T}\phi_2\right) - v_1 v_2\cos\xi\right]^2 \\
&+ \lambda_6\left[\mathrm{Im}\left(\phi_1^{*T}\phi_2\right) - v_1 v_2\sin\xi\right]^2
\end{aligned}
$$

All λ are real.

From “Higgs Hunter’s guide”.

$$
\begin{pmatrix}\phi^+ \\ \phi^0\end{pmatrix}_1 = \begin{pmatrix}0 \\ v_1\end{pmatrix}\frac{1}{\sqrt{2}} \quad ; \quad \begin{pmatrix}\phi^+ \\ \phi^0\end{pmatrix}_2 = \begin{pmatrix}0 \\ v_2 e^{i\xi}\end{pmatrix}\frac{1}{\sqrt{2}} \quad ; \quad \tan\beta = \frac{v_2}{v_1}
$$

Higgs Boson Spectroscopy

- One Charged Higgs with mass:

$$m_{H^\pm} = \sqrt{\lambda_4 (v_1^2 + v_2^2)}$$

- One CP-odd neutral Higgs with mass:

$$m_{A^0} = \sqrt{\lambda_6 (v_1^2 + v_2^2)}$$

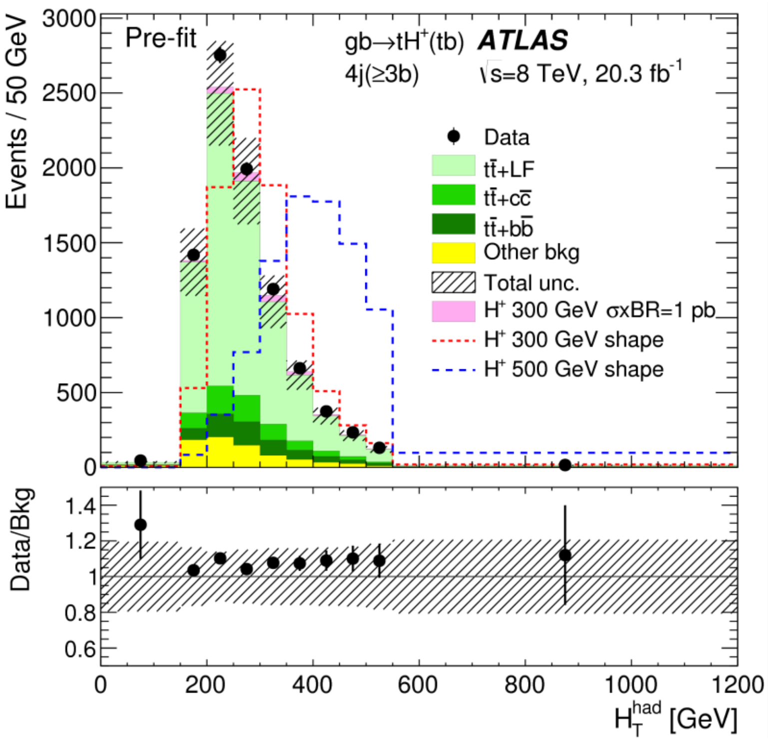
- And two CP-even higgs that mix.

$$M = \begin{pmatrix} 4v_1^2(\lambda_1 + \lambda_3) + v_2^2\lambda_5 & (4\lambda_3 + \lambda_5)v_1 v_2 \\ (4\lambda_3 + \lambda_5)v_1 v_2 & 4v_2^2(\lambda_2 + \lambda_3) + v_1^2\lambda_5 \end{pmatrix}$$

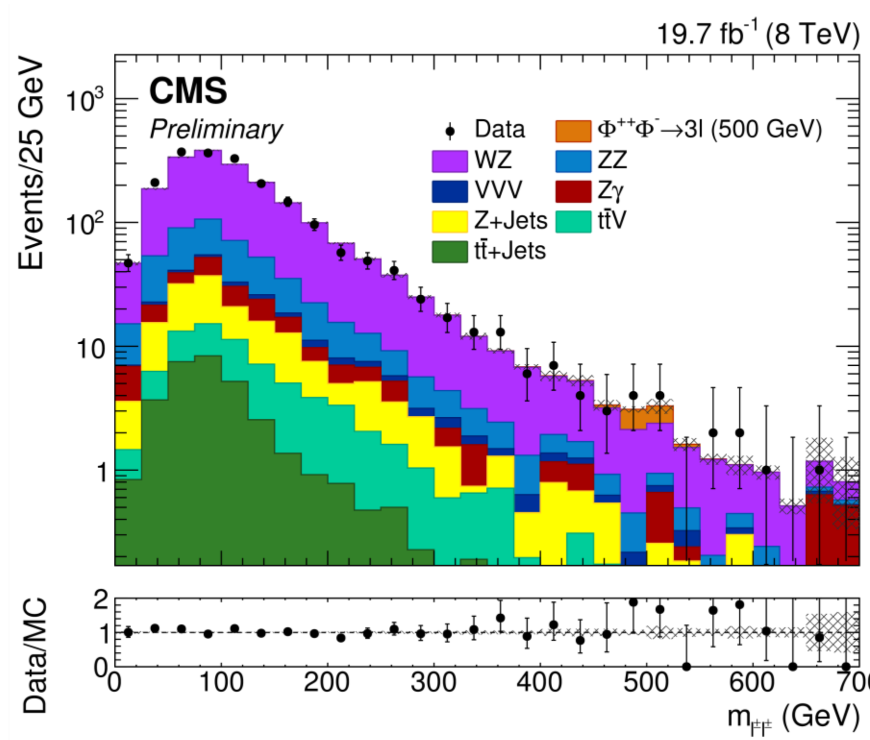
5 physical Higgs bosons! h, H, A, $H^\pm$

Examples of searches for extra Higgs bosons

Singly-charged



Doubly-charged

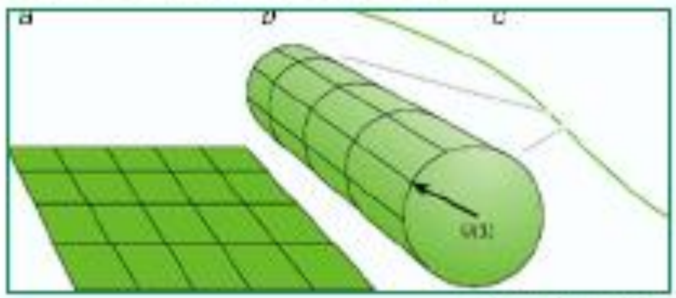


Limits around $\mathcal{O}$(200 GeV)

600 GeV

Extra Dimensions

- A promising approach to quantum gravity consists in adding extra space dimensions: string theory
  - Additional space dimensions are hidden, presumably because they are compactified



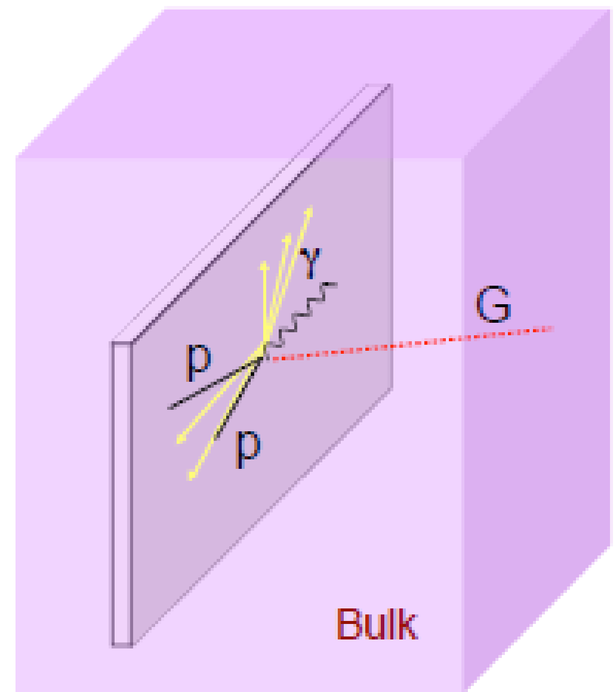
Source: PhysicsWorld

- Radius of compactification usually assumed to be at the scale of gravity, i.e. 10^{18} GeV
  - In '90 Antoniadis realized they may be much larger...

Phys Lett B246:377-384 1990

ADD extra dimensions

- "Large extra dimension" scenario (developed by Arkani-Hamed, Dimopoulos and Dvali): Phys.Lett. B429 (1998) 263-272
  - Standard model fields are confined to a 3+1 dimensional subspace ("brane")
  - Gravity propagates in all dimensions
  - Gravity appears weak on the brane because only felt when graviton "goes through"

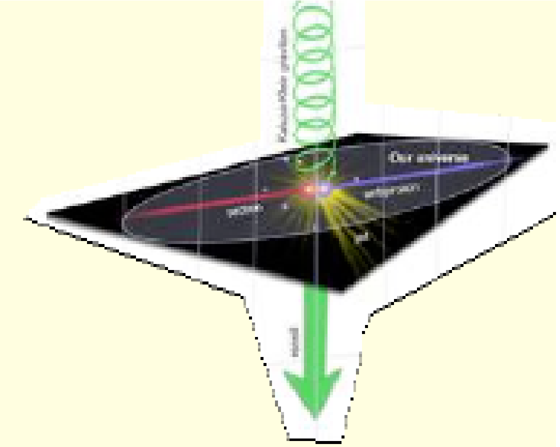


Drawing by K. Loureiro

ADD signatures

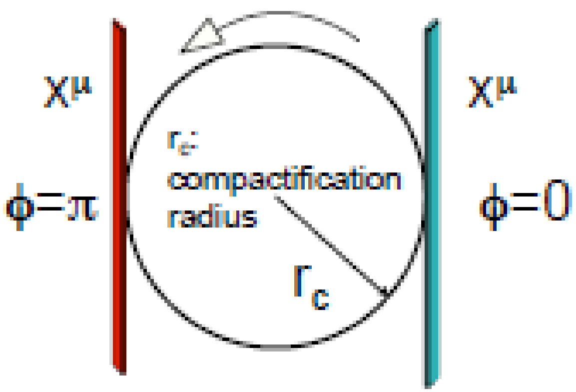
- Edges of extra dimensions identified
  - ➡ Boundary conditions
  - ➡ Momentum along extra dimension is quantized
  - Looks like mass to us
  - Very small separations → looks like continuum
  - Called Kaluza-Klein tower
- Coupling to single graviton very weak, but there are *lots* of them!
  - Large phase space → observable cross-section
    - Impacts all processes (graviton couples to energy-momentum)

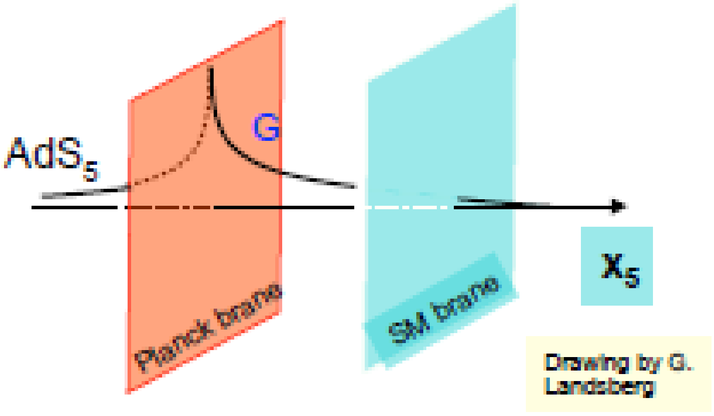
- Consider processes that involve the bulk (i.e. gravitons)
  - Translational invariance is broken
    - ➡ Momentum is not conserved ...
    - ... because graviton disappears in bulk right away
- Look for p p → jet/photon + nothing (i.e. $\not{E}_T$), or deviations in high mass/angular behavior in standard model processes
  - Graviton has spin 2, couples to energy-momentum!



Warped extra dimensions

- "Simple" Randall-Sundrum model:
  - SM confined to a brane, and gravity propagating in an extra dimension
  - As opposed to the original ADD scenario, the metric in the extra dimension is "warped" by a factor $\exp(-2kr_c\phi)$
  - (Requires 2 branes)



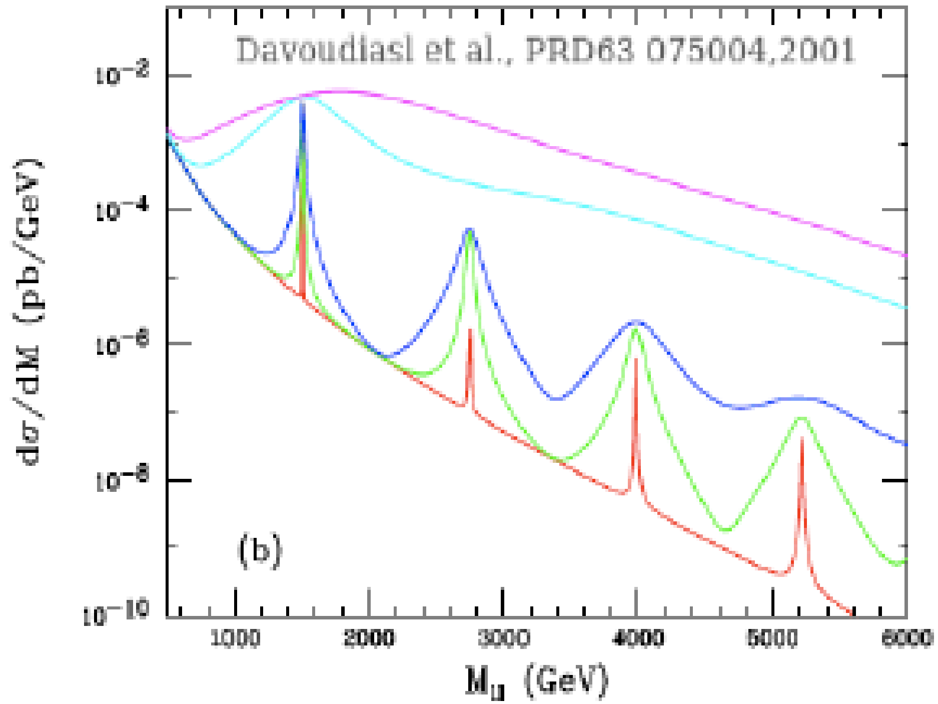


Graviton excitations

- In RS, get a few massive graviton excitations
  - Widths depend on warp factor k
  - Mass separation = zeros of Bessel function

➡ Smoking gun!

(BRs also different than Z':
e.g. γγ allowed)



A hidden ("dark") sector?

Rather than being heavy, could new particles be light but *very* weakly interacting?

e.g. new, light "hidden sector" of particles which are singlets wrt gauge group of the SM

- Several possibilities for renormalisable singlet operators which each involve some hidden sector particle **mixing** with some SM "portal particle" :
  - **Vector portal** – new U(1) B_{mn} – massive vector photon (paraphoton, secluded photon…) mixing with regular photon $\rightarrow eB_{mn}F^{mn}$
  - **Higgs portal** – new scalar field
  - **Axial portal** – new axial-vector field a – Axion Like Particles (to distinguish from Peccei–Quinn axion)
  - **Neutrino portal** – new heavy neutral leptons (HNL) $\rightarrow YH^{T}N'L$

- E.g. The **neutrino Minimal Standard Model** (**nMSM**) aims to explain :
  - Matter anti-matter asymmetry in the Universe, neutrino masses and oscillations, non-baryonic dark matter

by adding three right-handed, Majorana, Heavy Neutral Leptons (HNL), **N_1, N_2 and N_3**

The Neutrino Portal

- The **neutrino Minimal Standard Model** (**νMSM**) [T.Asaka, M.Shaposhnikov, Phys. Lett B620 (2005) 17] aims to explain
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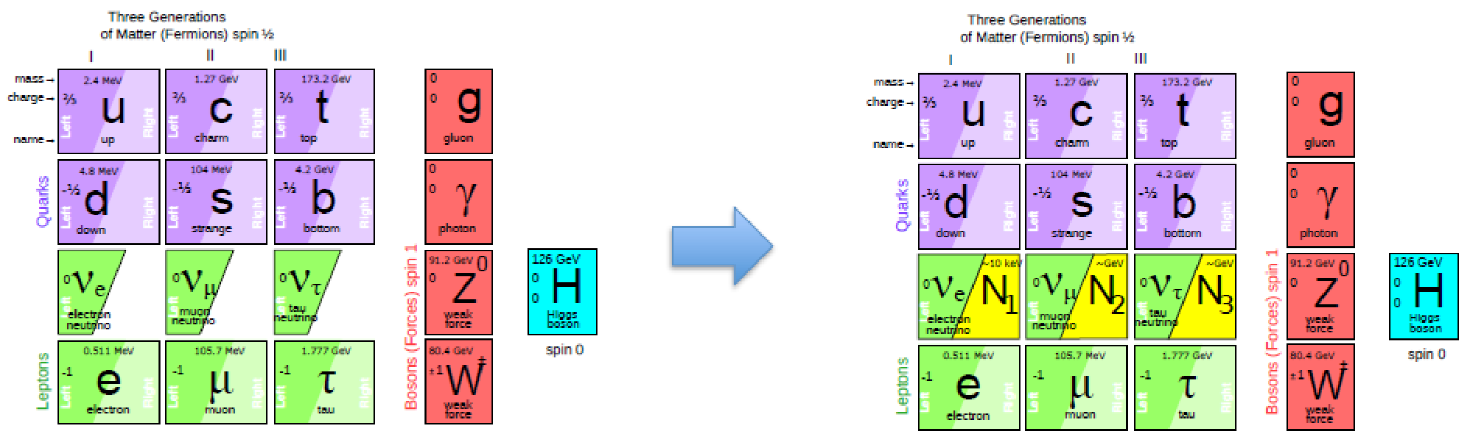
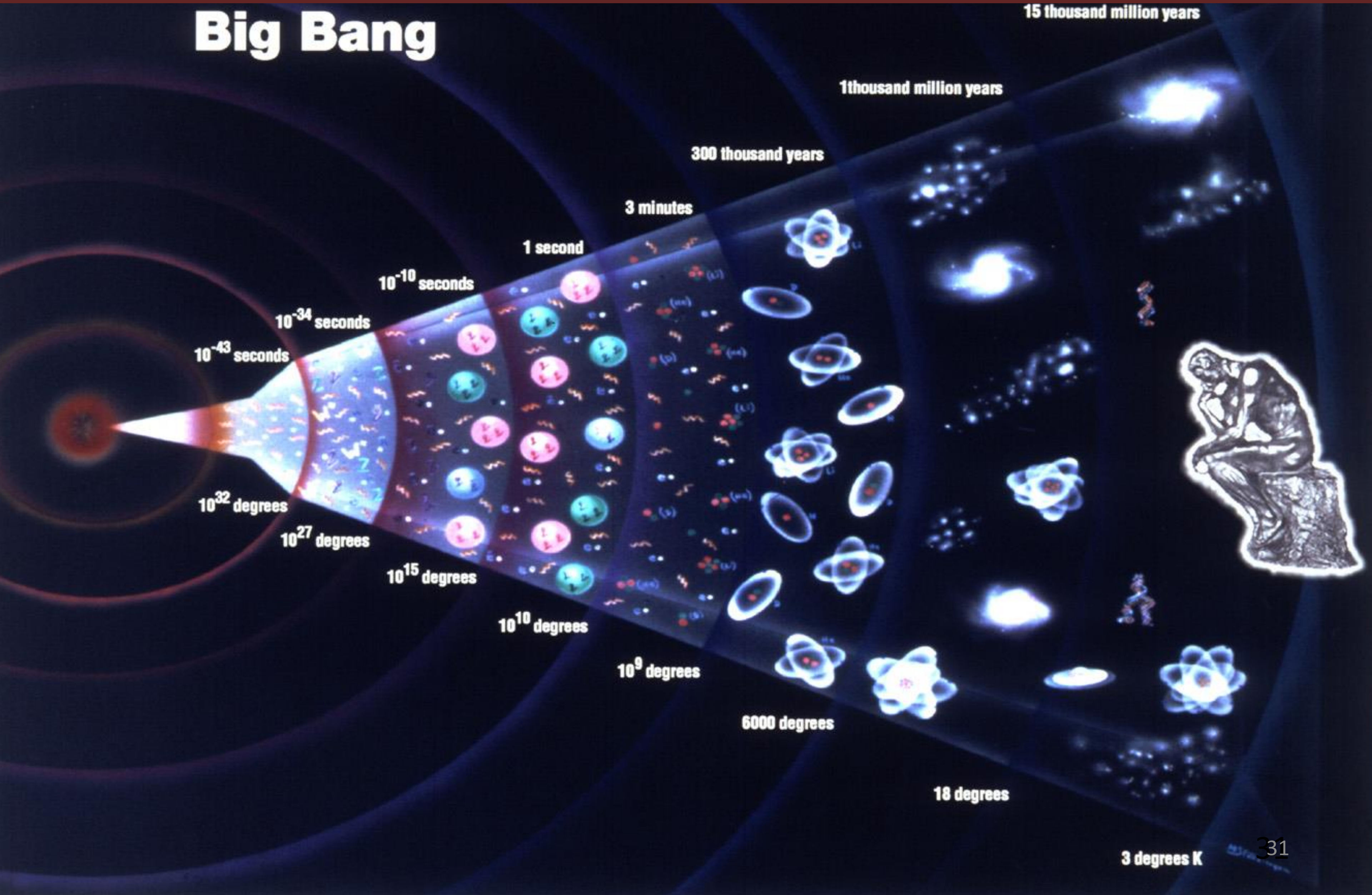


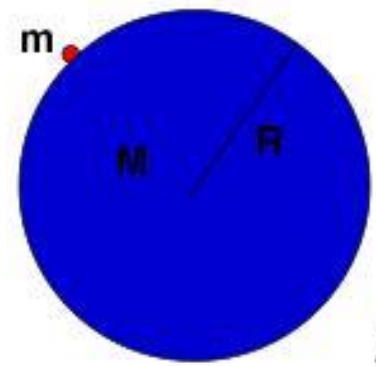
- **N_1** – mass in keV region, (warm) dark matter candidate
- **$N_{2,3}$** – mass in 100MeV – GeV region – generate neutrino masses via see-saw mech. and produce baryon asymmetry of the Universe

The expanding Universe



Understanding the expansion of the Universe within Newtonian gravity

We consider a test mass m at the border of a homogeneous sphere of density ρ, which is expanding with velocity $v = \dot{R}$.



$$M = (4\pi/3)R^3\rho$$

Its energy is

$$E = \frac{m}{2}v^2 + U = \frac{m}{2}v^2 - \frac{mMG}{R} = \frac{m}{2}v^2 - \frac{4\pi}{3}m\rho R^2 G$$

As energy is conserved, $2E/m =: -K = \text{constant} = \dot{R}^2 - 8\pi G\rho R^2/3$. With $H^2 = \left(\frac{\dot{R}}{R}\right)^2$ we obtain

$$H^2 + \frac{K}{R^2} = \frac{8\pi G}{3}\rho$$

This is the Friedmann equation (1922).

Understanding the expansion of the Universe within Newtonian gravity

Due to the expansion, the density decreases,

$$\rho = \frac{M}{\frac{4\pi}{3} R^3}\,, \qquad \dot{\rho} = -3\rho\frac{\dot{R}}{R}$$

If we insert this in the derivative of the Friedmann equation we find

$$\frac{d}{dt}\left[\left(\frac{\dot{R}}{R}\right)^2 + \frac{K}{R^2}\right] = 2\left[\frac{\ddot{R}}{R} \underbrace{- \left(\frac{\dot{R}}{R}\right)^2 - \frac{K}{R^2}}_{-8\pi G\rho/3}\right]\frac{\dot{R}}{R} = \frac{8\pi G}{3}\dot{\rho} = -8\pi G\rho\frac{\dot{R}}{R}$$

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}\rho < 0\,.$$

This is the 2nd Friedmann equation (1922). It requires that the expansion decelerates!

Expansion within General Relativity

Including general relativity these equations are modified:

$$\left(\frac{\dot{R}}{R}\right)^2 + \frac{K}{R^2} = \frac{8\pi G}{3c^2}\rho_E + \frac{\Lambda}{3}$$

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3c^2}(\rho_E + 3P) + \frac{\Lambda}{3}$$

P is the pressure and Λ is the cosmological constant,
ρ_E is the energy density. For ordinary matter $\rho_E = c^2\rho$, and c is the speed of light.
K now has a new interpretation. It is the curvature of space.

Introducing the 'density' parameters

$$\Omega_m = \frac{8\pi G\rho_E}{3c^2H^2}, \qquad \Omega_K = -\frac{K}{R^2H^2}, \qquad \Omega_\Lambda = \frac{\Lambda}{3H^2},$$

the first Friedmann eqn. becomes

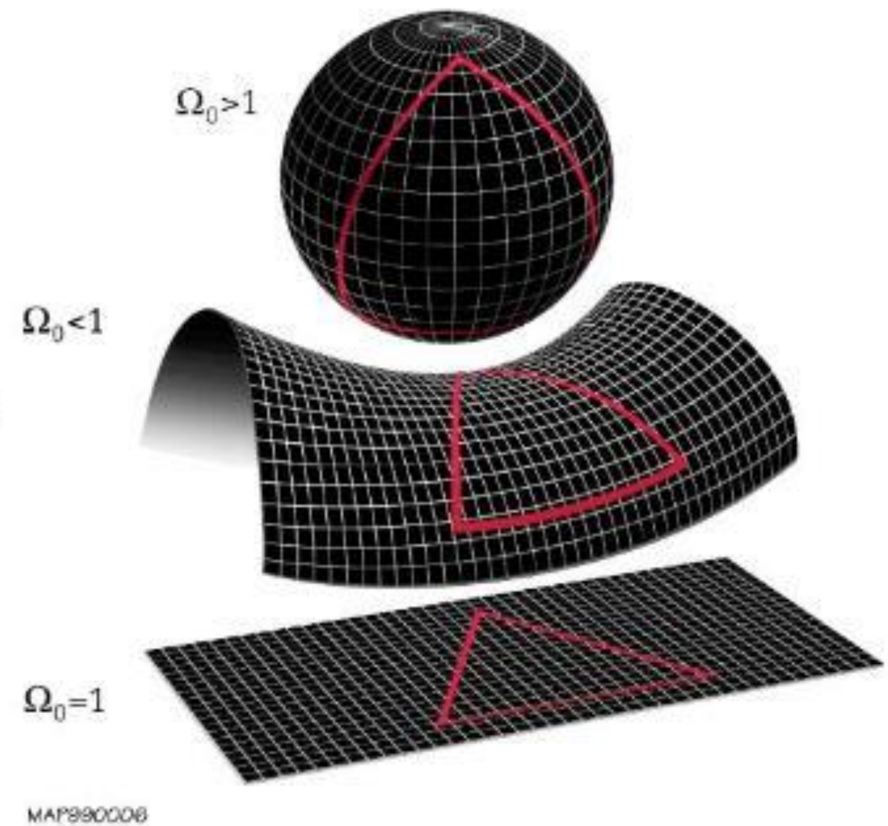
$$\Omega_m + \Omega_\Lambda + \Omega_K = 1 .$$

Curvature

$K > 0$ ($\Omega_K < 0$): spherical space,

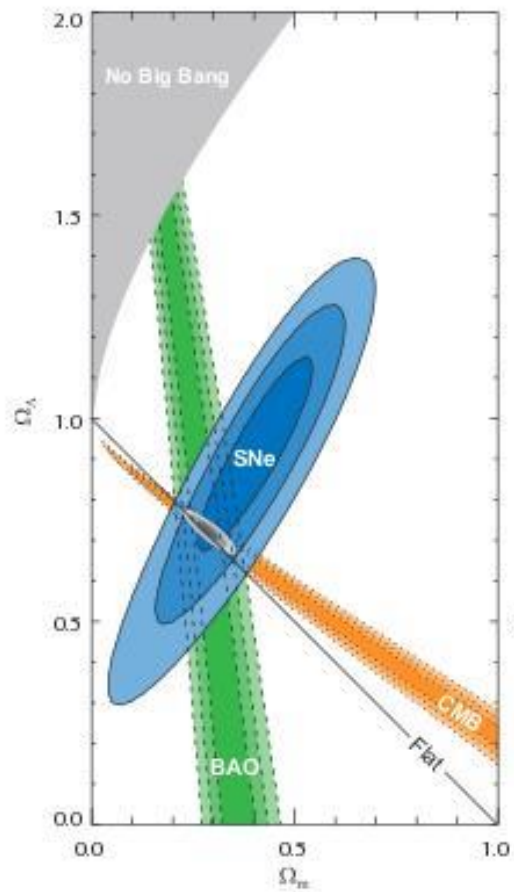
$K < 0$ ($\Omega_K > 0$): pseudo-spherical space (saddle),

$K = 0$ ($\Omega_K = 0$): flat space.

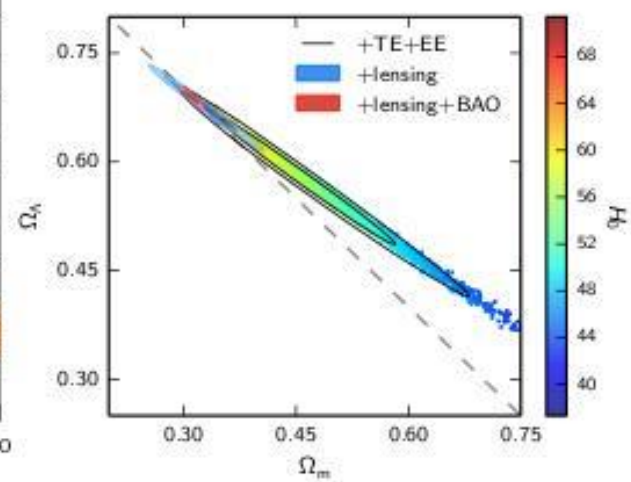


The Universe is accelerating

Matter, Ω_m, and cosmological constant, Ω_Λ (dark energy).



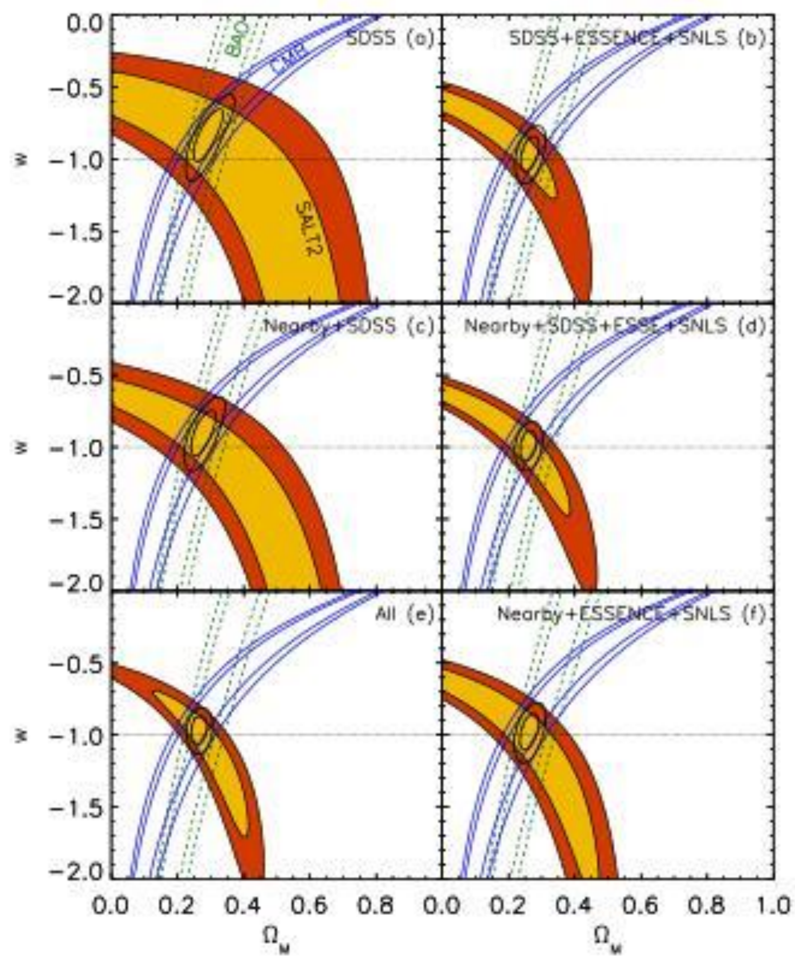
Supernova Cosmology Project, Suzuki et al. 2011



Planck 2015

The Universe is accelerating

If pressure is negative, $P = w\rho_E$ with $w < -1/3$ we can have accelerated expansion ($\ddot{R} > 0$) without a cosmological constant. Such a component is called dark energy. A cosmological constant corresponds to a dark energy component with $w = -1$.



The matter fraction and the parameter w of dark energy (Kessler et al. '09).

In addition to precision measurements with supernovaes we might also get information from the large scale structure of the Universe and from the CMB

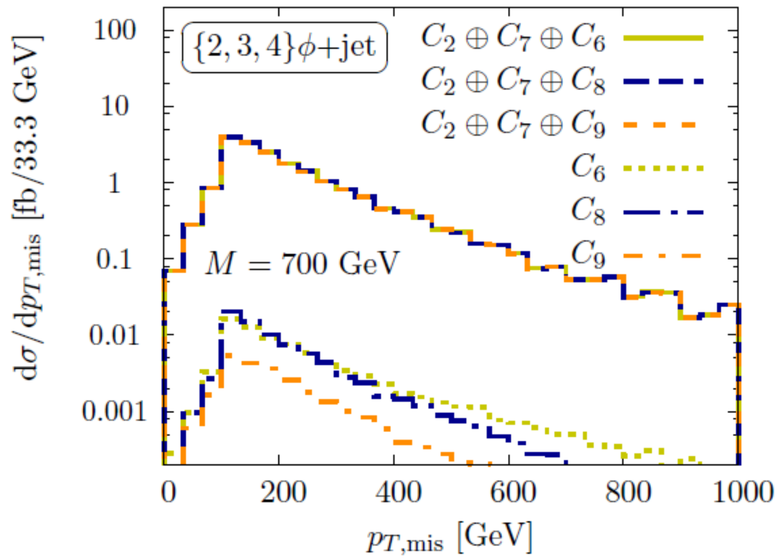
Dark energy particles?

Could it be particle, transmitting new force? Very abundant ... already strong limits on new forces

One idea: ”chameleons”. Complicated self-interactions and screening effects means strength of new field environmentally dependent $\Rightarrow$ explains/excuses why not seen yet

Dedicated Dark energy surveys – how about collider searches? Missing E_T, or resonance peaks could be reasonable signatures but may depend on $\sqrt{s}, p_T$ etc.

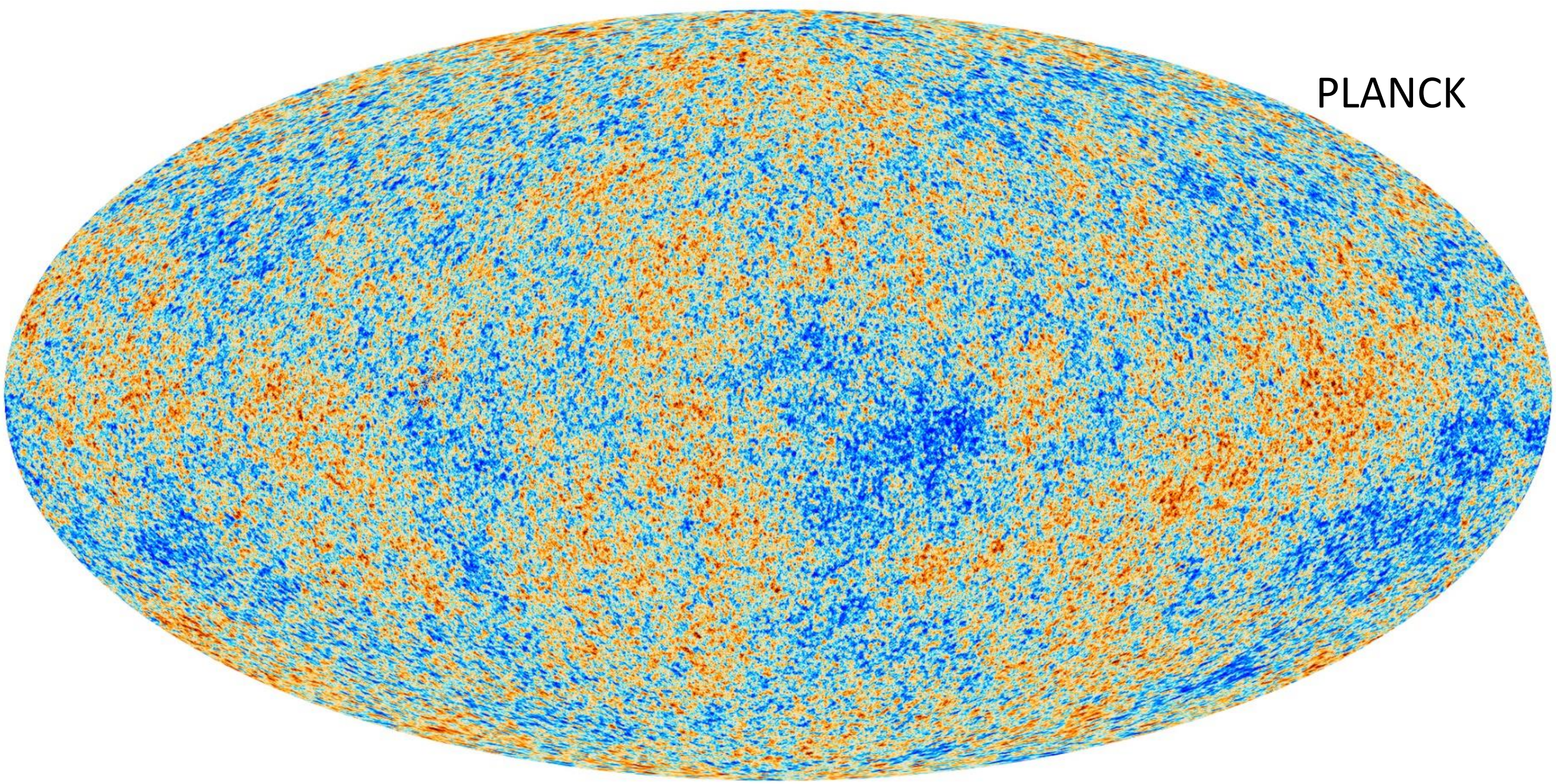
arXiv: 1604:04299



Cosmic Microwave Background

Remnant photons from when the Universe became transparent to radiation

Small fluctuations at particle levels boosted into galaxy-scale structures by inflation

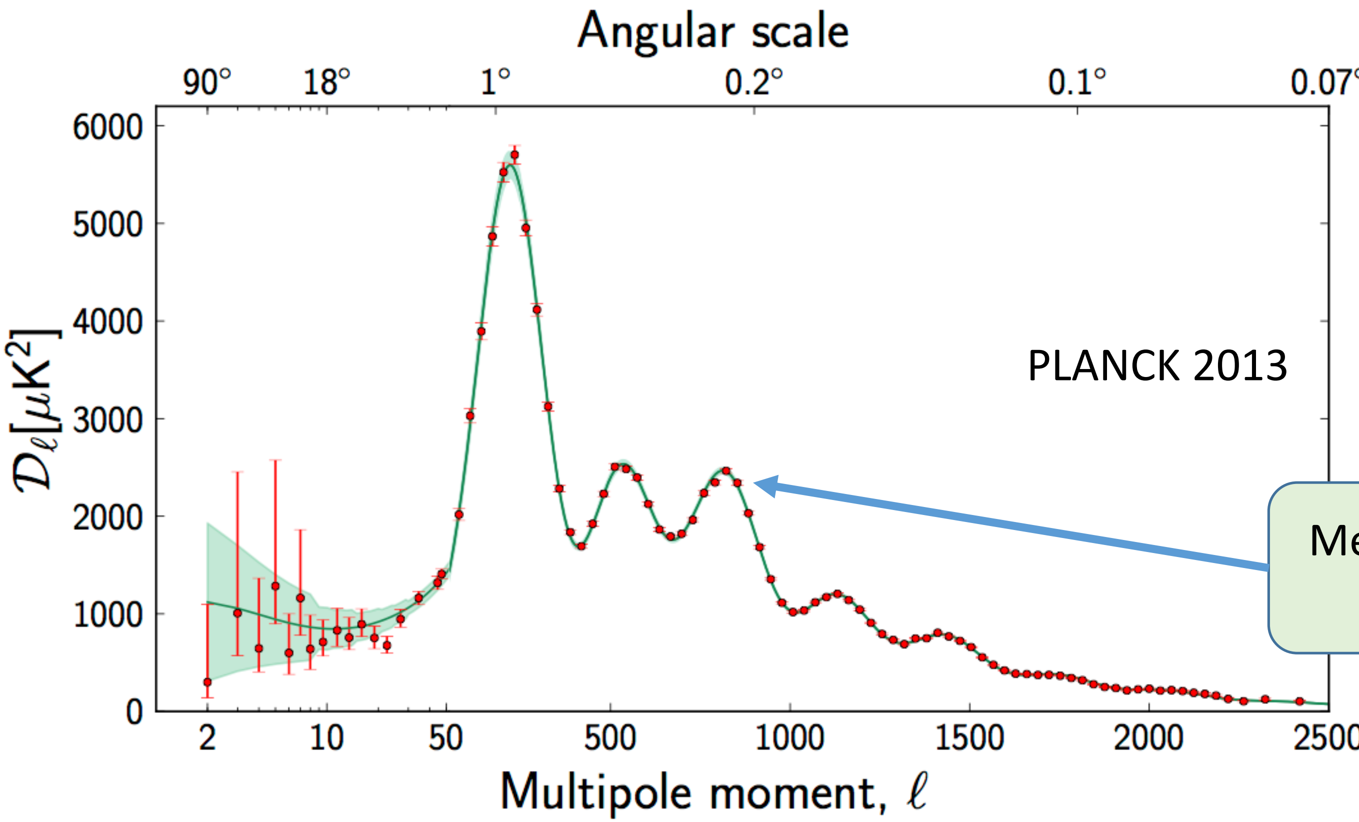


PLANCK

The sound of the CMB

CMB photons behaves like gas, carry sound waves caused by gravity (seen as hot and cold spots in the sky map)

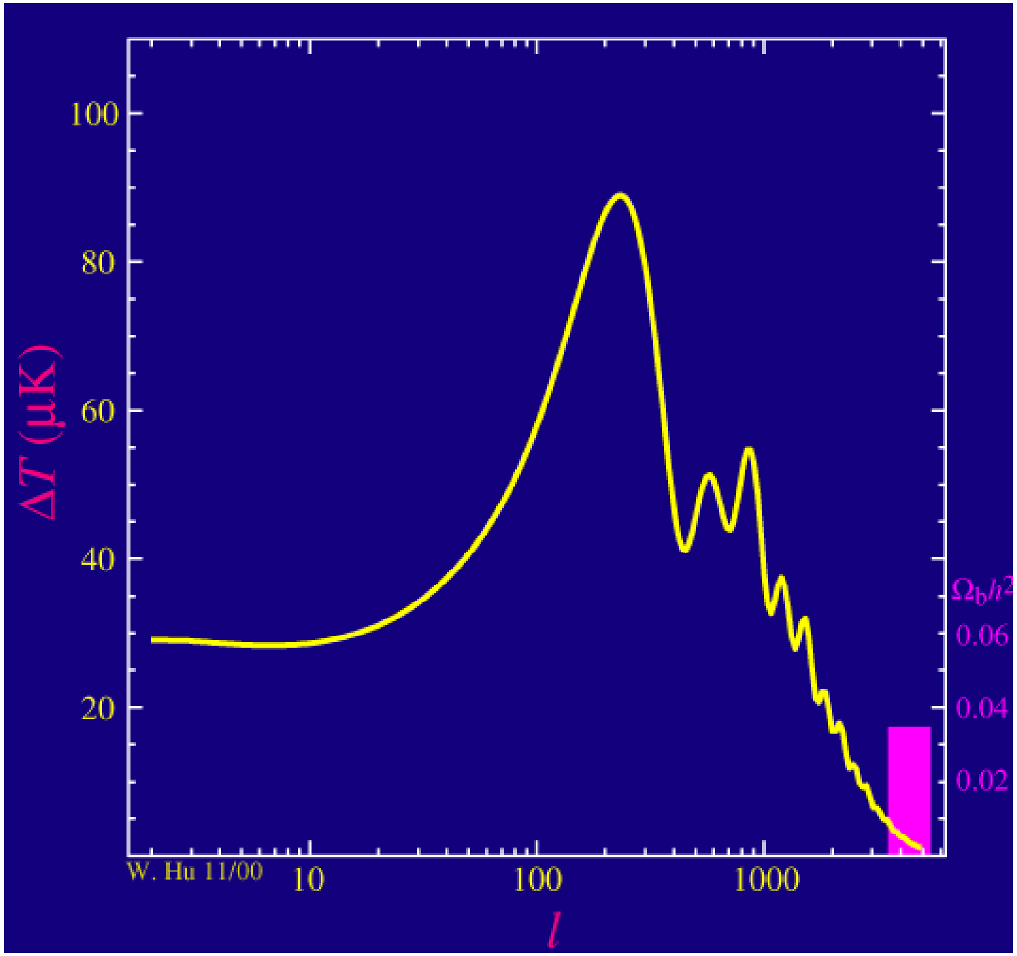
<u>Big gravitational events, like inflation, should be audible in the spectrum</u>. Inflation predicts a set of harmonics with frequency ratios of 1:2:3



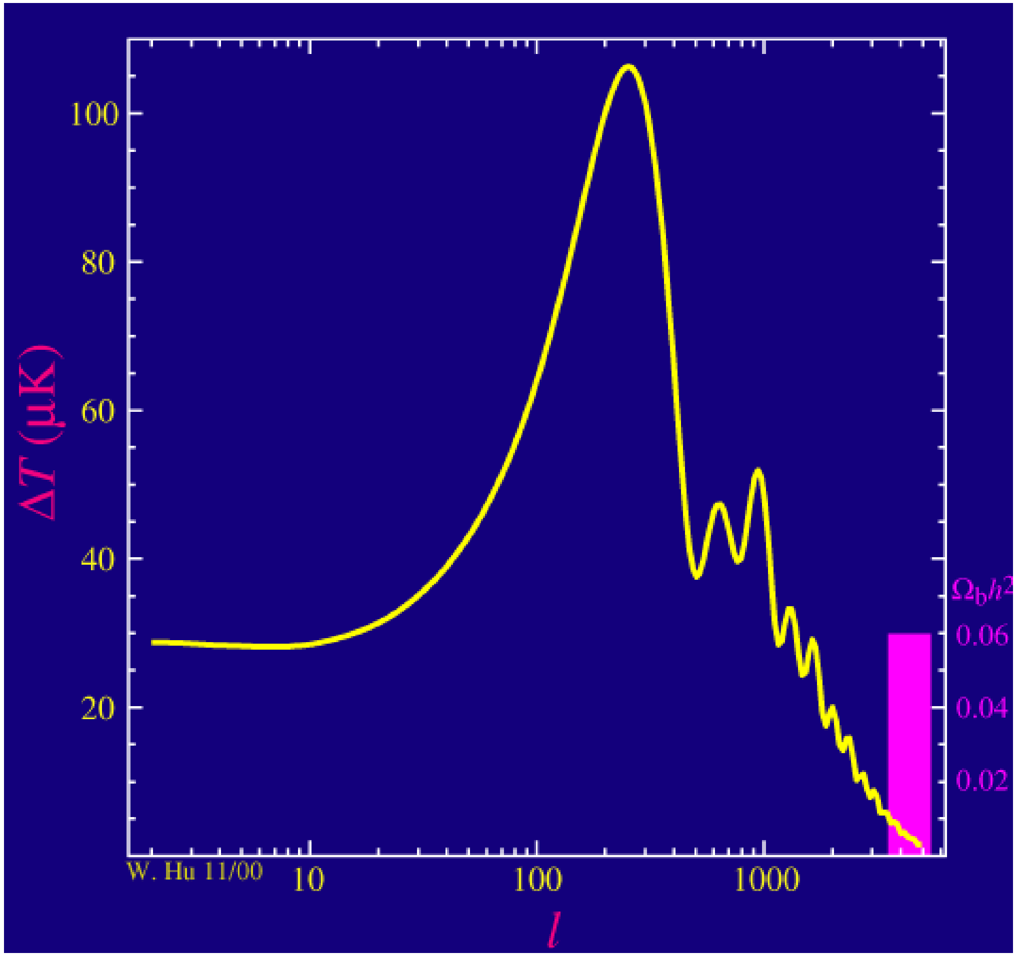
Dark Energy barely affects this picture
Dark Matter mainly indicated in 3rd peak

Measure physical density of the Dark Matter

Peak amplitudes sensitive to baryon density



Peak amplitudes sensitive to baryon density



Summary/outlook

- Many problems with current Standard model
- Many new models to take over (Some important models not mentioned, for instance: GUT models, Technicolor, Hidden valleys)
- The LHC energy scale is tuned to be sensitive to many of these, complementary to other current searches
- Several potential signatures requires new ”objects”, ie lepton-jets, long-lived heavy particles, ”quirks” etc
- Several good ideas but Nature decides which (if any) are true!
- **Inputs from cosmology has huge implications for particle physics!**
  - We don’t really know enough about gravity yet. So far Dark Energy and Dark Matter are still the best hypotheses.