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
  - What can (new) experiments say about these?
- A little more on the connection to cosmology

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

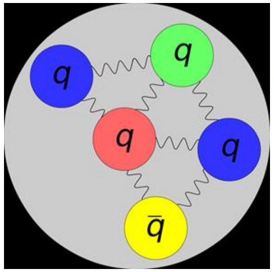
No quantum gravity

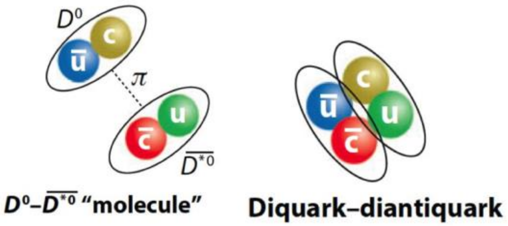
Missing answers to ”big” questions

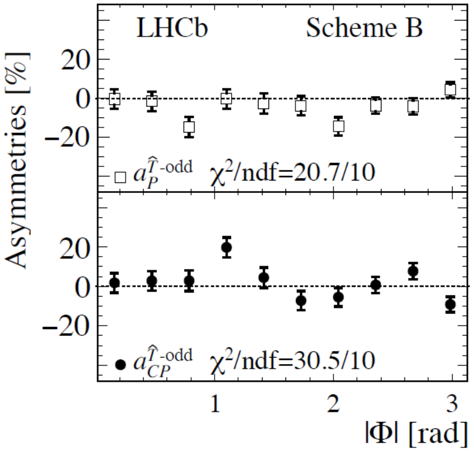
Any direct evidence against it?

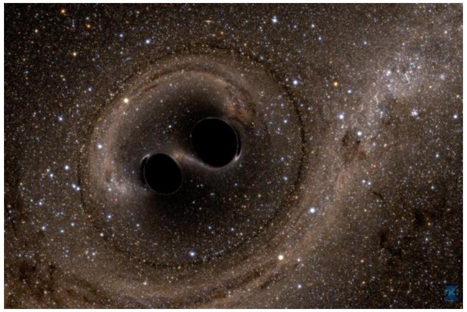
Certainly a few measurements that are not incorporated in the current Standard Model:

- Exotic baryons (X, pentaquarks etc)
- Neutrino masses and oscillations!
- (Gravitational waves)
- The LHCb CP violation measurements (although <4σ)









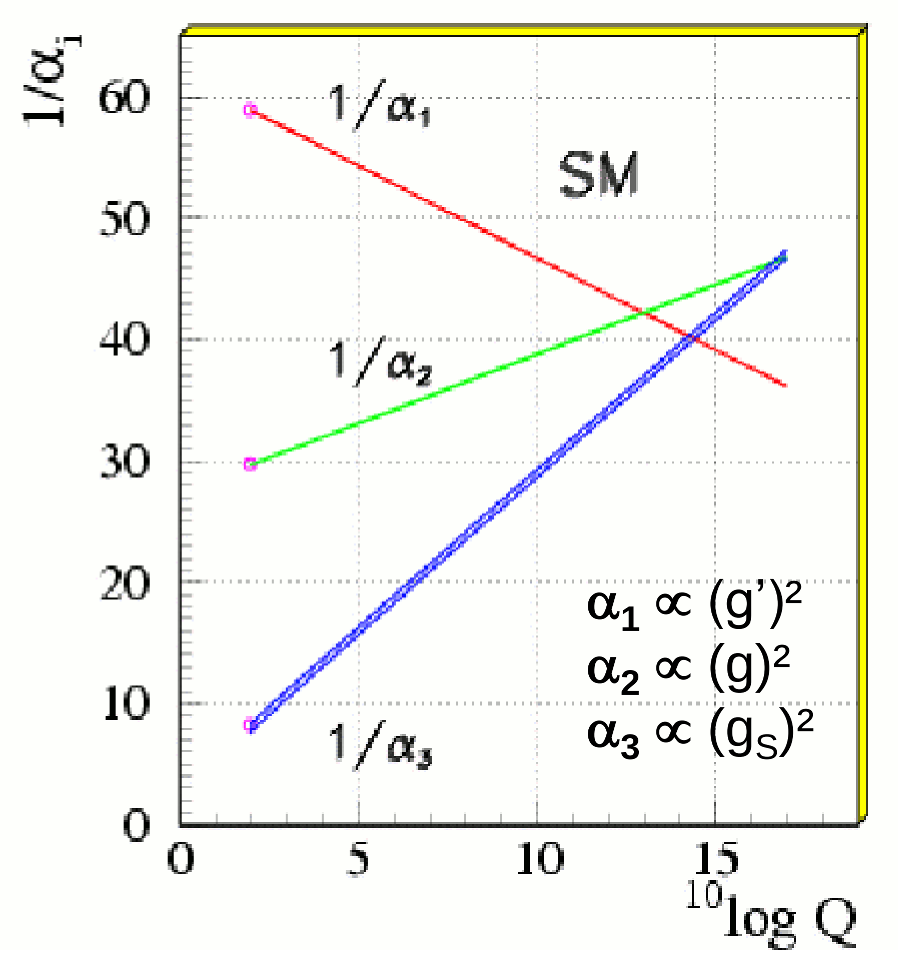
Is the Standard Model really fundamental?

- Does not appear so ($\gtrsim$ 25 parameters?!)
- Evidence of selective processes:
  - For instance, no neutral colored fermions
  - $q_d = q_e /N(\text{colors}) \Rightarrow$ 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 $v >> \text{TeV} \Rightarrow |m_n - m_p|$ 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?

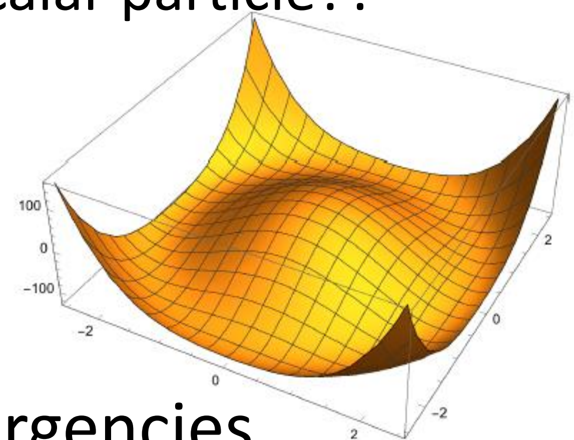


Extrapolating the Standard Model coupling constants to higher energies

http://pdg.lbl.gov

The Higgs discovery just adds to that list…

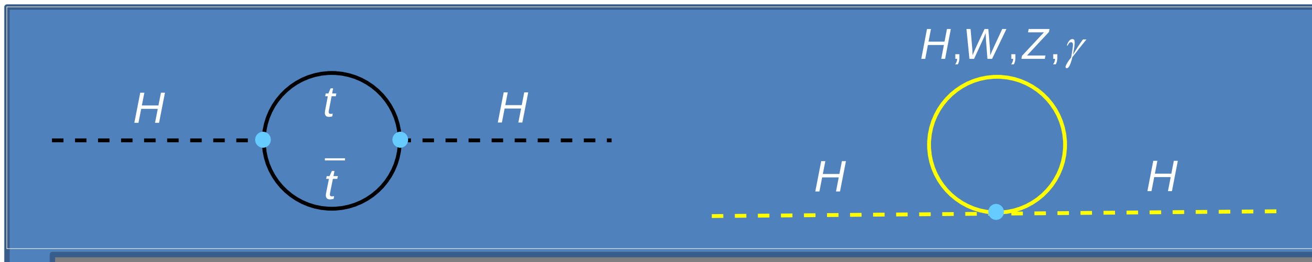
- What is it, really, a condensate in our Universe?
- Is it elementary?
  - If yes, why is there only 1 fundamental scalar particle??
- Why does it have mass² $\mu^2 < 0$?!
- Higgs mechanism gives quadratic divergencies



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

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

Integral quadratically divergent

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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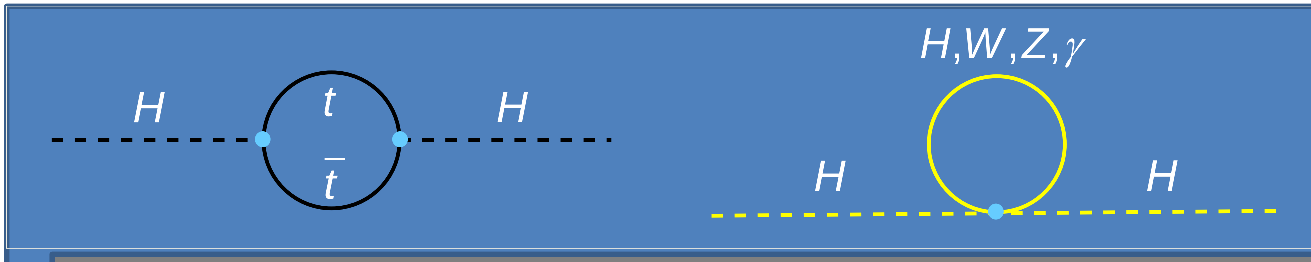

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Integral quadratically divergent

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** !

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

Hunting for answers

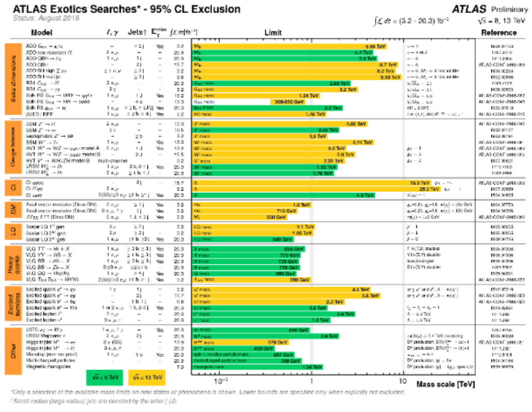
- Get more information
  - Measure particles and their interactions in details
    - Precision measurements
  - Observe new particles or interactions
    - Search in new areas in phase space
- Find the underlying pattern(s)
  - Hypothesize, build models
    - Internally consistent? Consistent with data?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

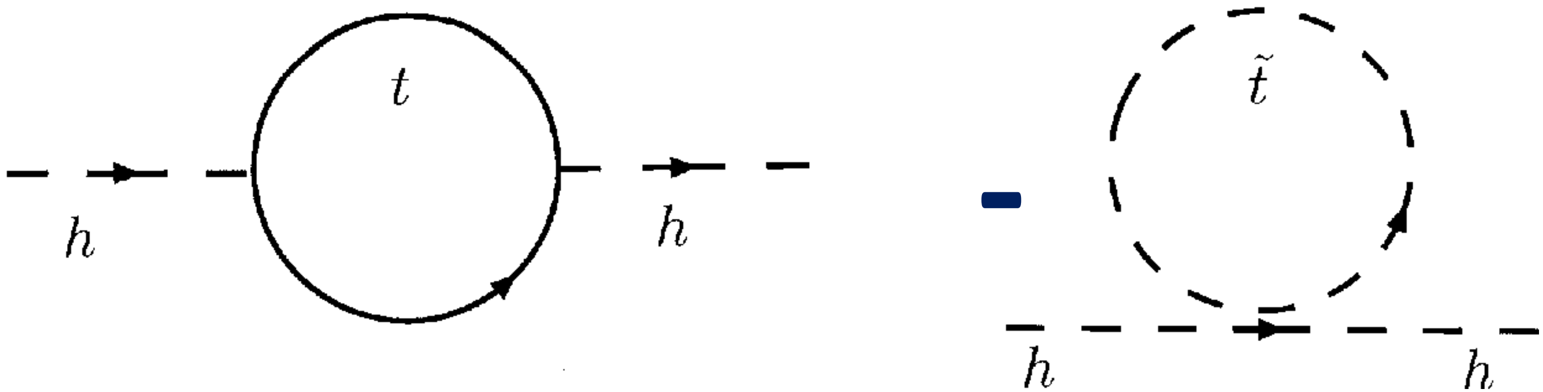
Charginos : mass eigenstates of winos and charged higgsinos

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

....

SUSY and the hierachy problem

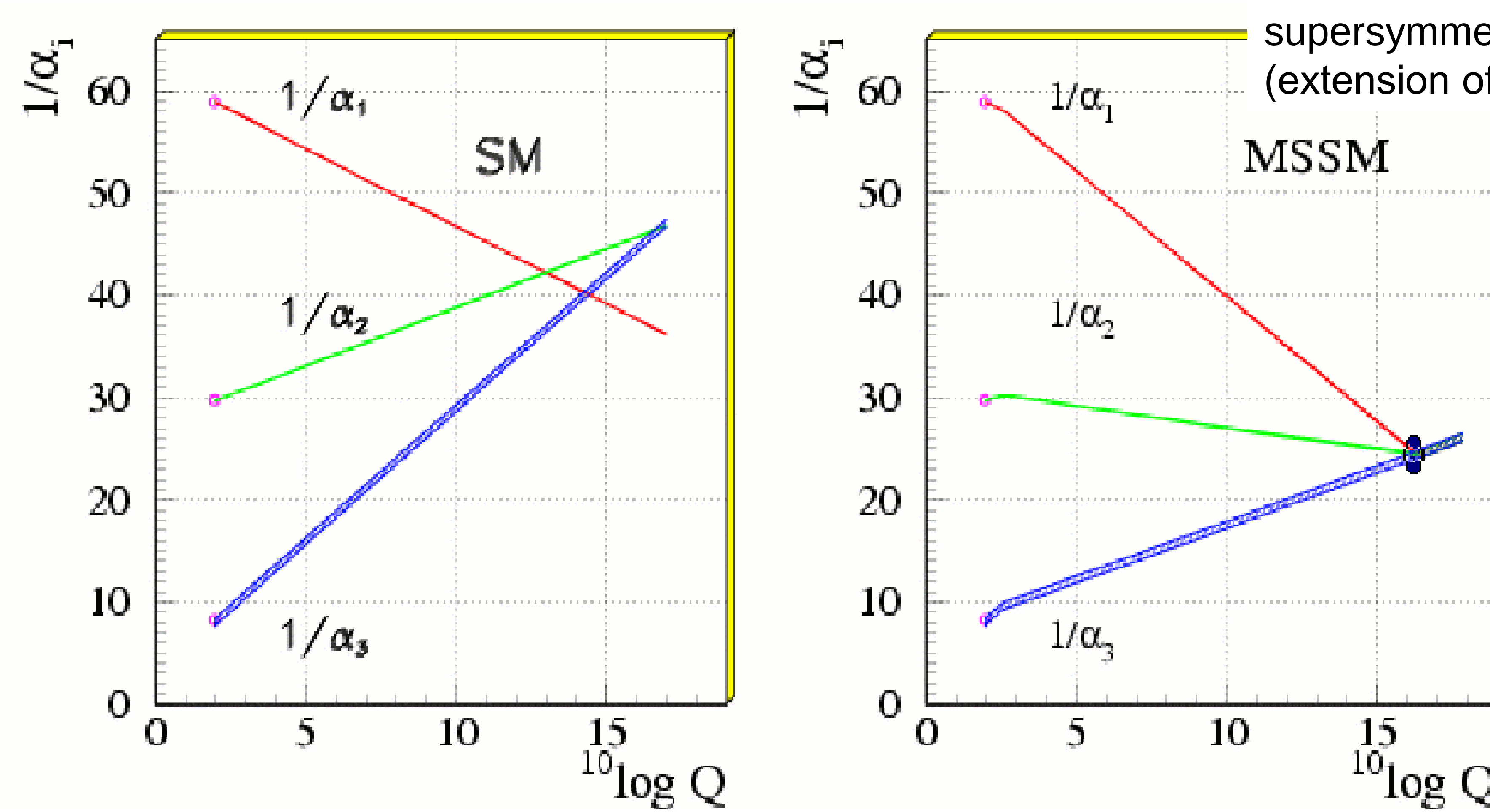
If Supersymmetry not broken we would have perfect cancellation in the loops!



But as m($\tilde{t}$) ≠ 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)

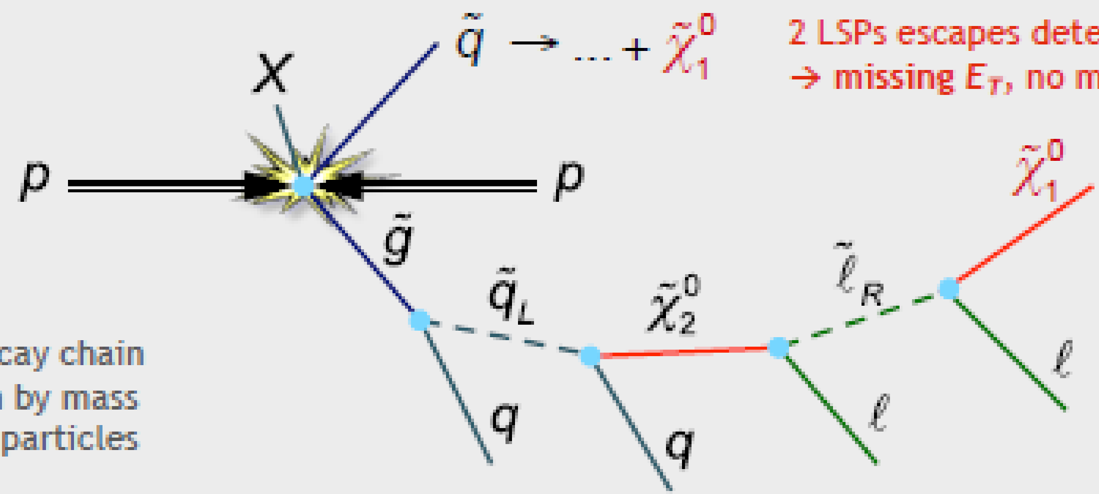
Unification of coupling constants with supersymmetry

“minimal supersymmetric (extension of) SM”



Characteristic SUSY Decay Cascades

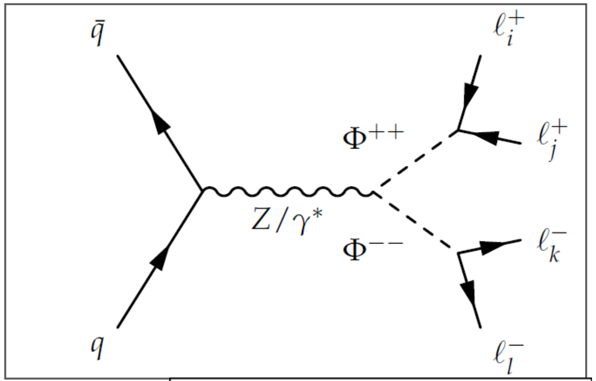
- To avoid proton decay, a new conserved quantum number (R) is introduced, which forces a SUSY particle to decay in at least one other SUSY particle
- The lightest SUSY particle is thus stable (LSP), and must be neutral and colourless → WIMP (dark matter candidate)
- Typical **LSP is spin-½ neutralino.**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

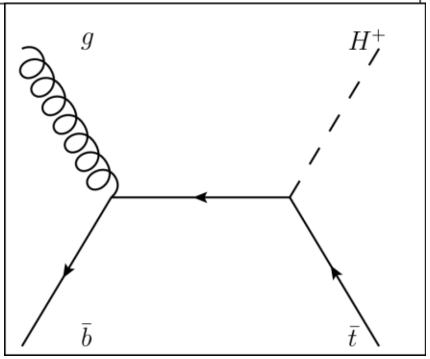


2 LSPs escapes detection
→ missing E_T, no mass peak !

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

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

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

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:

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

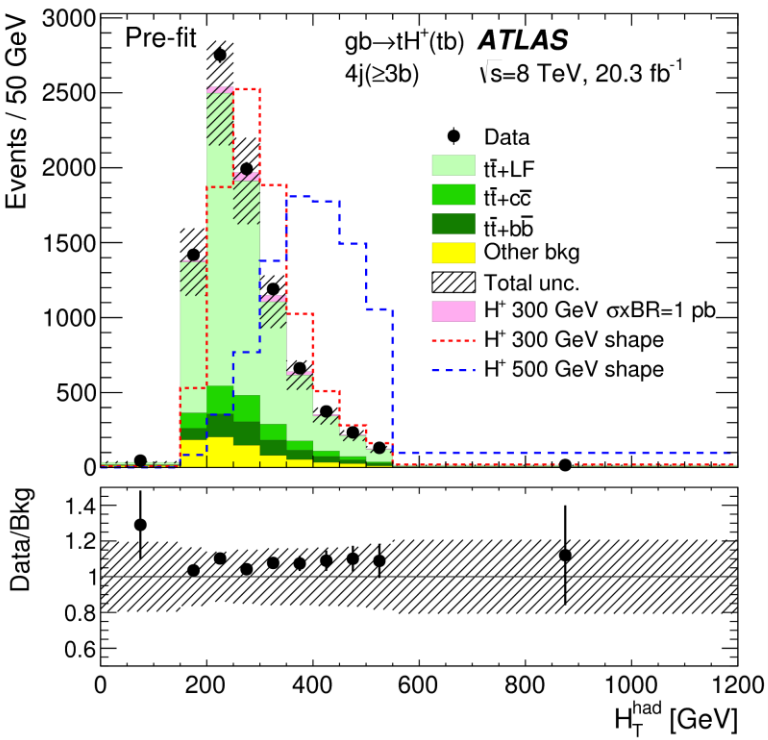
- And two CP-even higgs that mix.

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

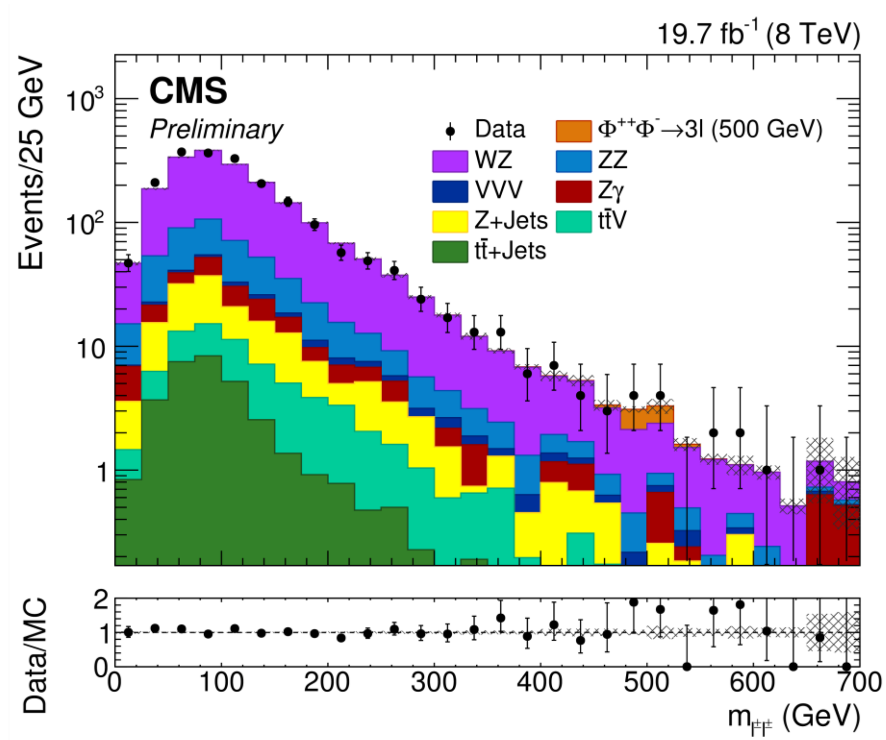
5 physical Higgs bosons! h, H, A, $H^\pm$

Examples of searches for extra Higgs bosons

Singly-charged



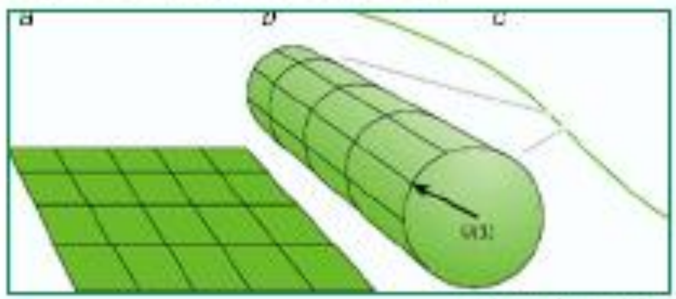
Doubly-charged



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

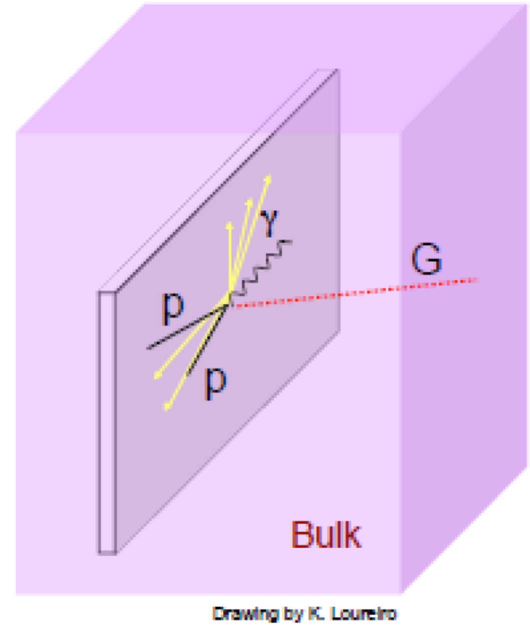
- Radius of compactification usually assumed to be at the scale of gravity, i.e. 10^{18} GeV
  - In '90 Antoniadis realized they may be much larger...

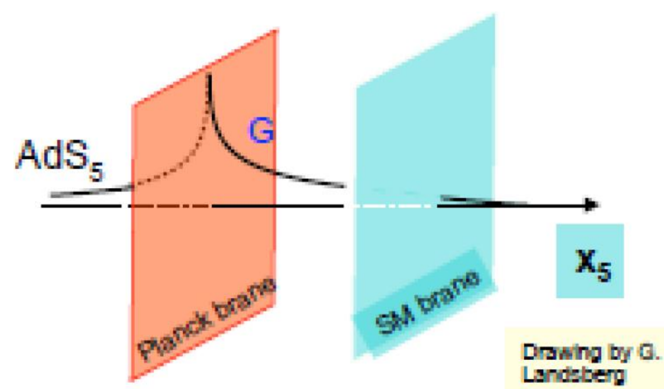
Phys Lett B246:377-384 1990

Several types of Extra Dimensions!

Some examples are:

- ADD - Large extra dimensions
  - Arkani-Hamed, Dimopoulos, Dvali 1998.
  - SM fields confined to 3+1 D subspace ”brane”
  - Gravity propagates in all dimension and thus appear weak to us on the brane
- Warped – Randall-Sundrum extra dimensions
  - Two branes are required
  - The metric in the extra dimension is now warped by an exponential factor





Signatures - examples

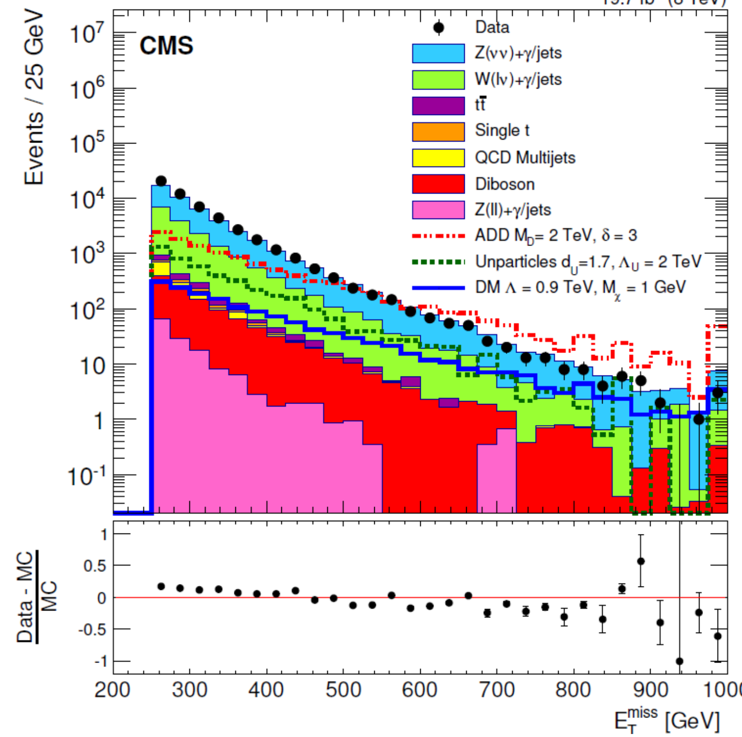
ADD

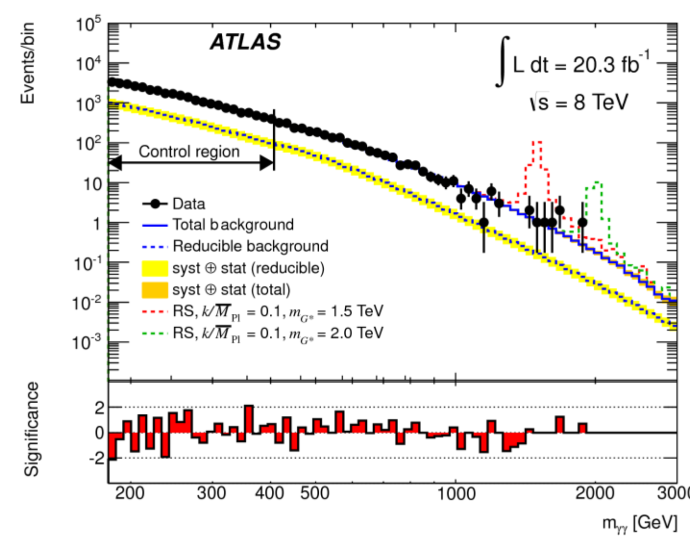
- Gravity couples to (E,p). Lots of gravitons $\Rightarrow$ observable σ!
- Momentum along extra-D quantized – looks like mass to us $\Rightarrow$ Kaluza-Klein towers (with Z’, W’ etc)
- (seemingly) non-conservation of energy due to gravitons escaping the brane $\Rightarrow$ mono-jets

RS

- Massive graviton excitations
- Intrinsic widths depends on warp factor
- BR to SM particles differ from for instance Z’ or heavy Higgs decays

arXiv 1408.3583





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 → $eB_{mn}F^{mn}$
  - **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) → $YH^{T}N'L$

- 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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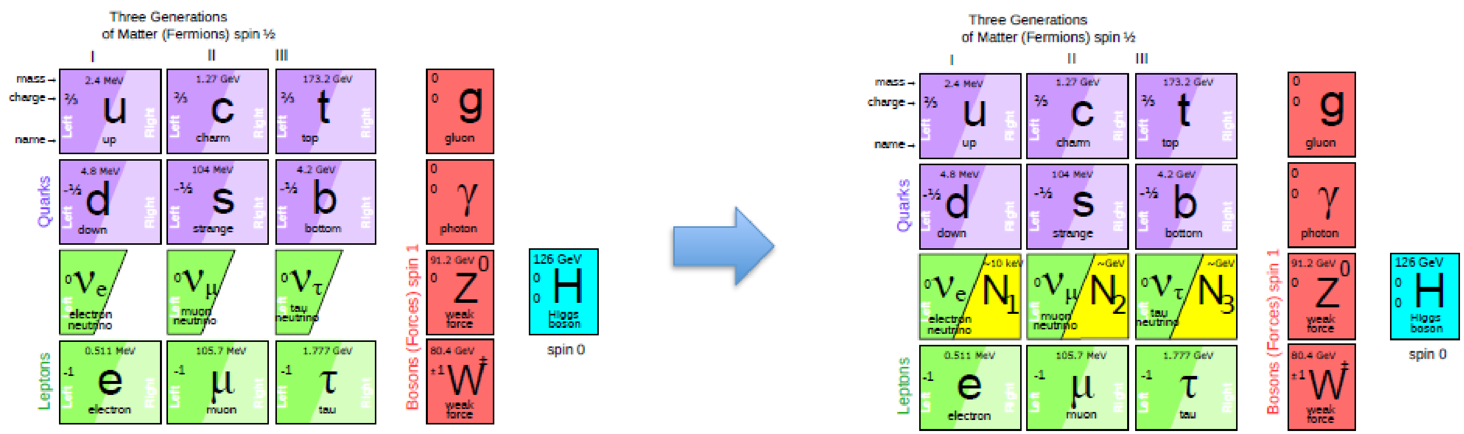
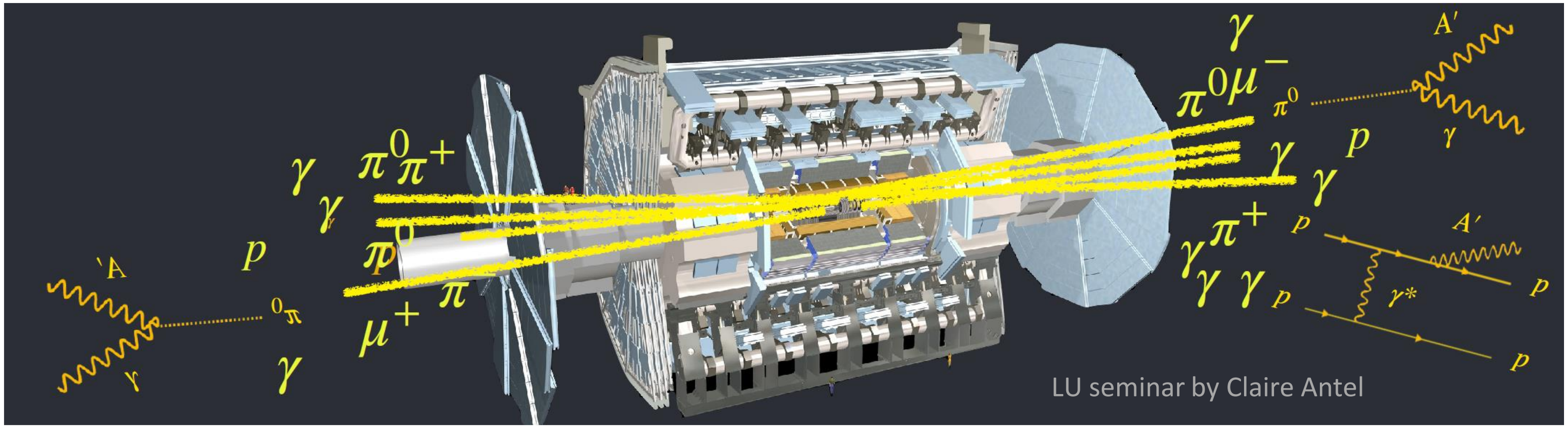


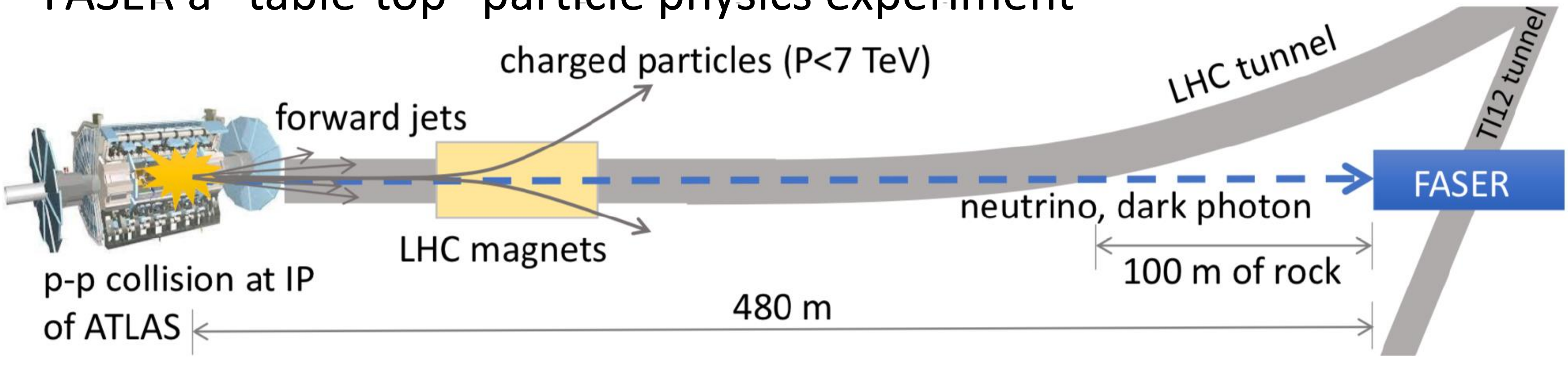
- N_1 – mass in keV region, (warm) dark matter candidate
- $N_{2,3}$ – mass in 100MeV – GeV region – generate neutrino masses via see-saw mech. and produce baryon asymmetry of the Universe

Detecting *very* weakly interacting particles?

What if new physics is relatively light but too weakly coupled to be noticed at the ”regular” LHC experiments? Weak couplings typically means long-lived Energetic light physics with high cross section in the forward region:

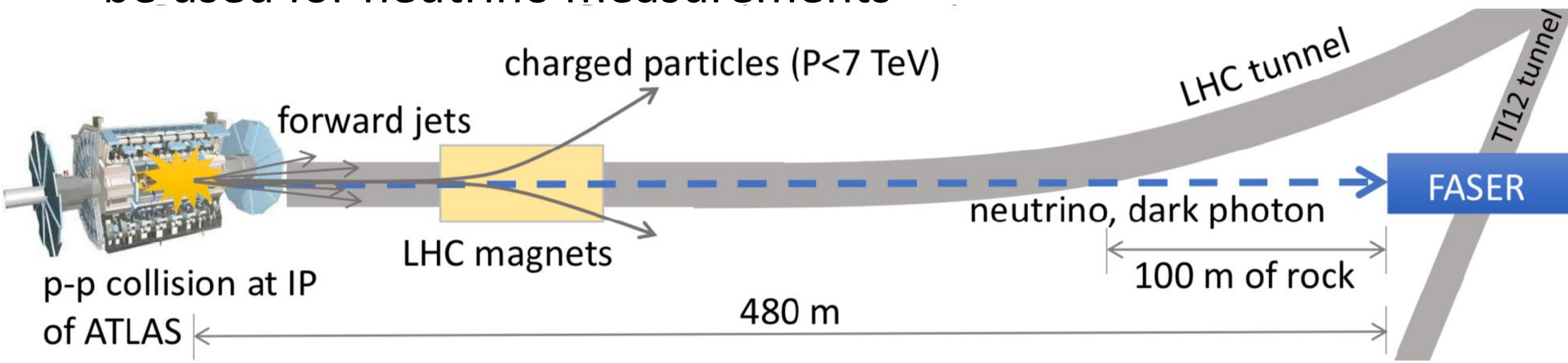


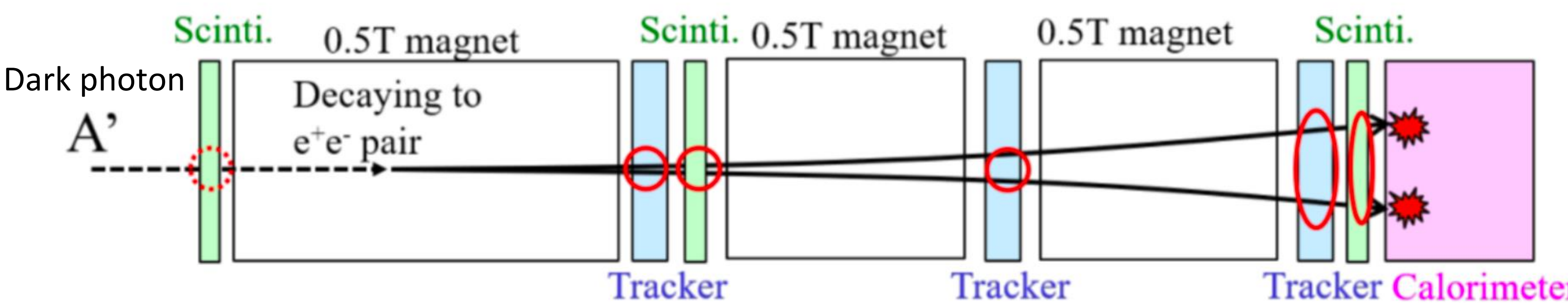
FASER a “table-top” particle physics experiment



Detecting *very* weakly interacting particles?

FASER can set limits on new weakly interacting particles and also be used for neutrino measurements





BSM with neutrons (ESS)

Do neutrons oscillate? Would violate B, L conservation – but we (think we) know that this is mainly an accidental symmetry at perturbative level

SUSY, unification models, extra dimensions, L-R symmetric models etc:

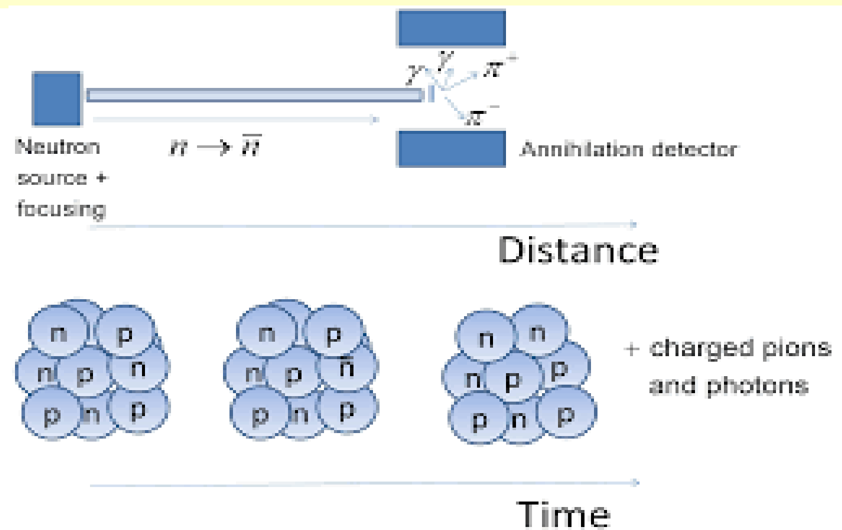
$$P_{n\to\bar{n}} = \left(\frac{\varepsilon_{n\bar{n}}}{\Delta E}\right)^2 \sin^2(\Delta E \times t) \;\; ; \; \Delta E = E_n - E_{\bar{n}} \;\; ; \;\; \varepsilon_{n\bar{n}} < 10^{-29} \text{ MeV}$$

Dark sector:

So, need to search as a function of B

$$P_{n\to n'} = \left(\frac{\varepsilon_{nn'}}{\Delta E}\right)^2 \sin^2(\Delta E \times t) \quad ; \quad \Delta E = \mu_n \bullet B - \mu_{n'} \bullet B' \;\; ; \; \varepsilon_{nn'} = \delta m_{nn'} + \kappa' \mu_{n'} \bullet B' + \kappa \mu_n \bullet B$$

Striking signature (1.8 GeV) when anti-neutrons annihilate



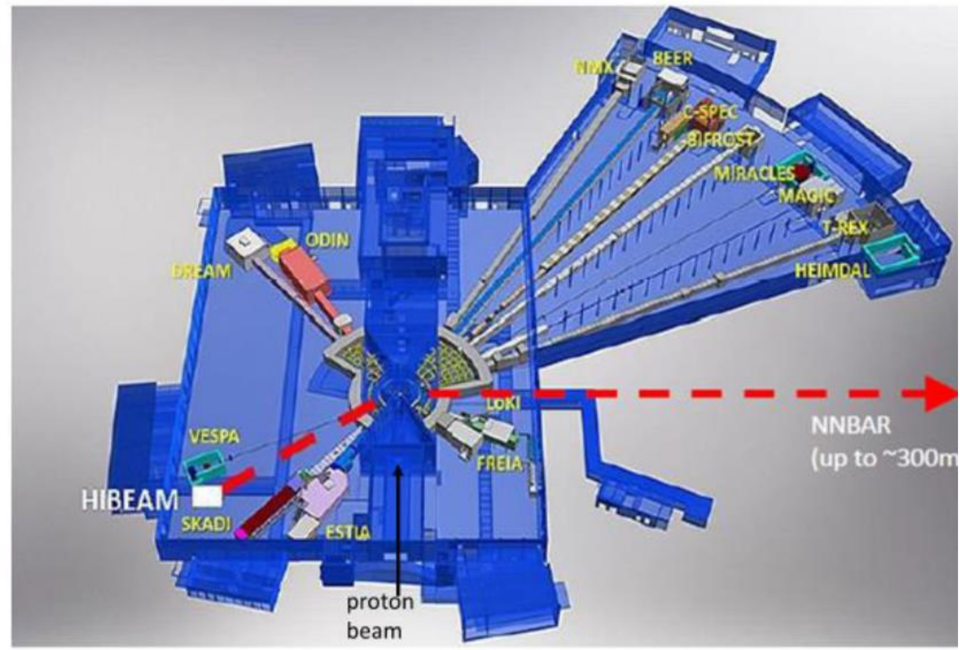
HIBEAM and NNbar

Staged experiment:

1. HIBEAM

(high intensity baryon extraction and measurement)

- mid to late 2020's
- world leading searches for $n \rightarrow n'$ (mid-to-late 2020's)
- search for $n \rightarrow \overline{n}$ (with lower sensitivity)
- R&D for full experiment.



2. NNBAR

- Extremely high precision searches $n \rightarrow \overline{n}$, $n \rightarrow n'$
- Improve sensitivity to oscillation probability by a factor ~10^3
- Late 2020's

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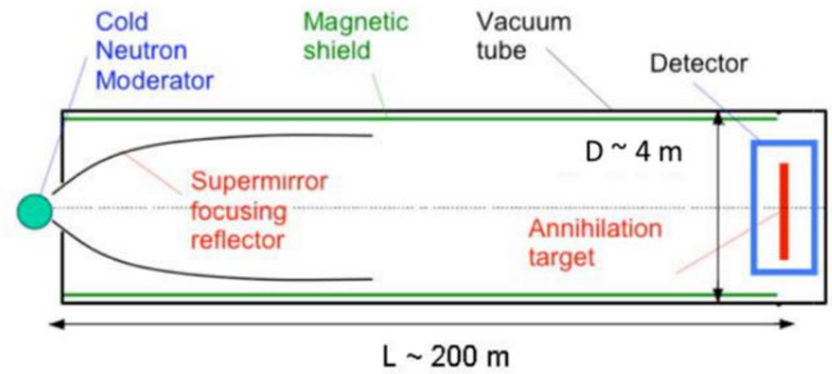

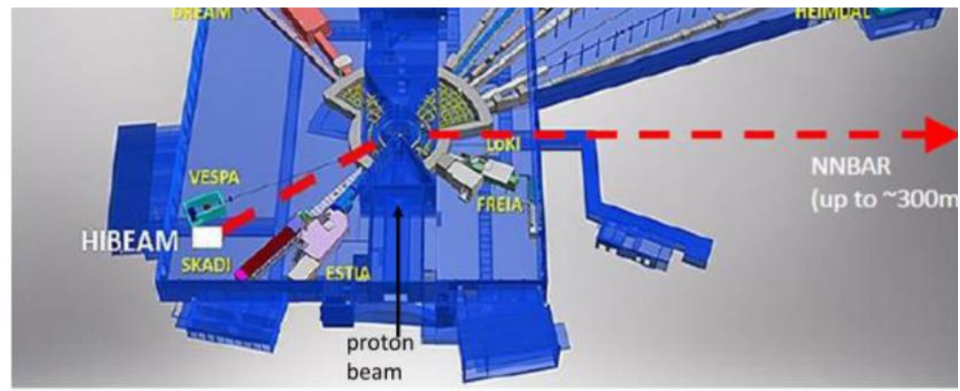

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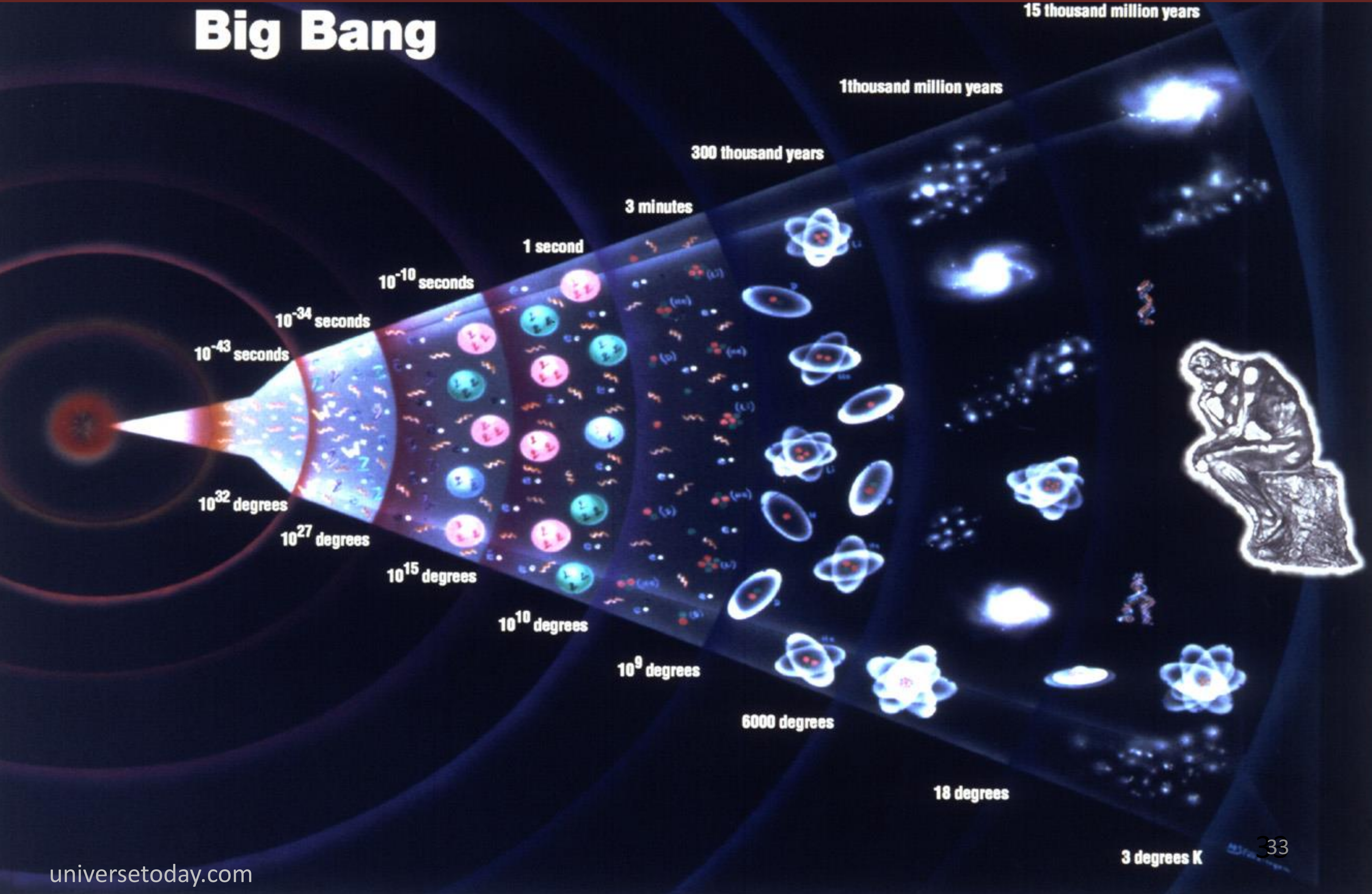
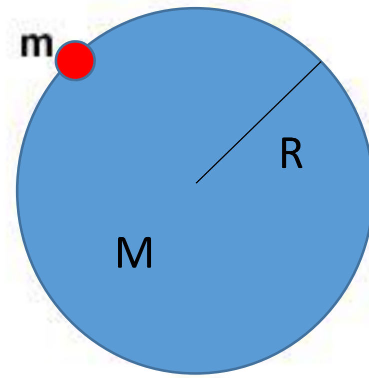
The expanding Universe



universetoday.com

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

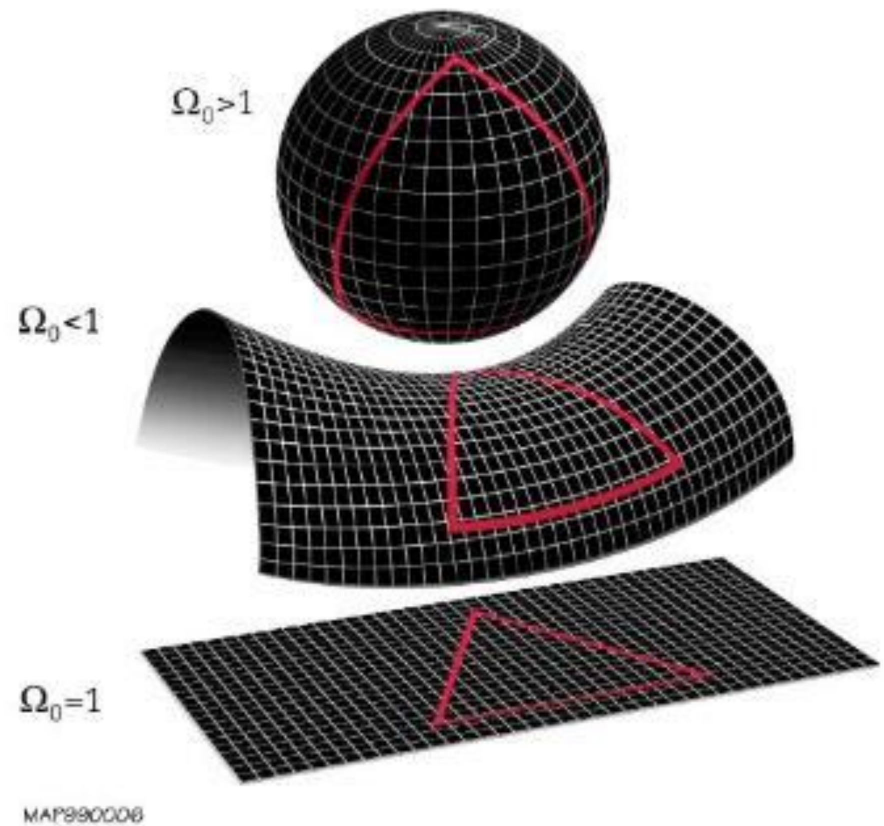
$$\Omega_m + \Omega_\Lambda + \Omega_K = 1\,.$$

Curvature

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

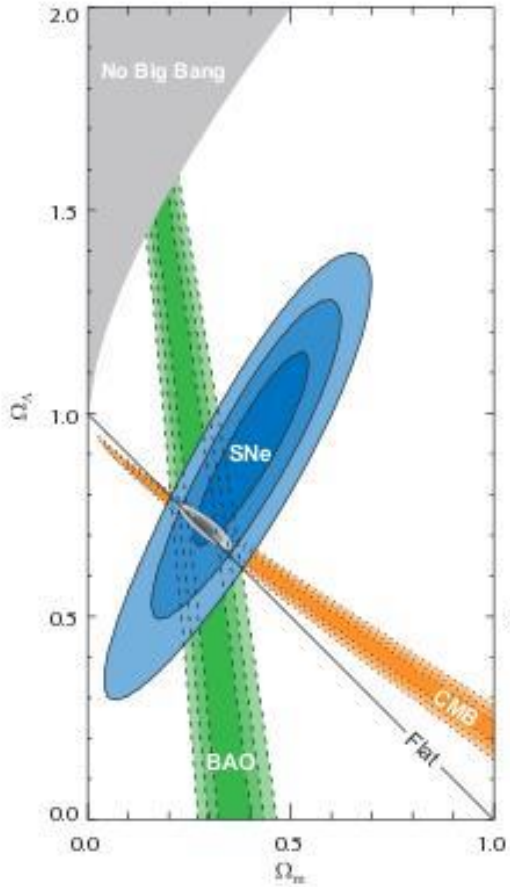
$K < 0$ ($\Omega_K > 0$): pseudo-spherical space (saddle),

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

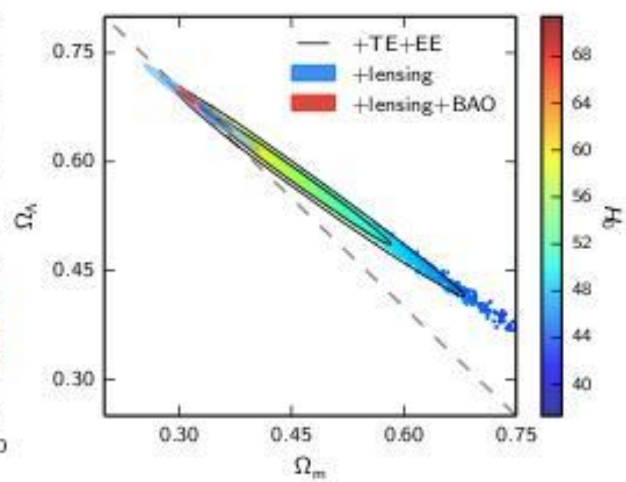


The Universe is accelerating

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



Supernova Cosmology Project, Suzuki et al. 2011



Planck 2015

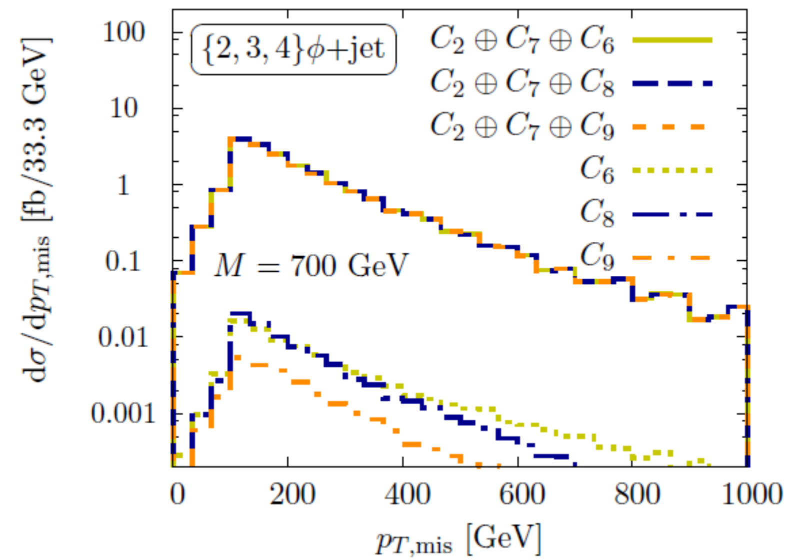
Dark energy particles?

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

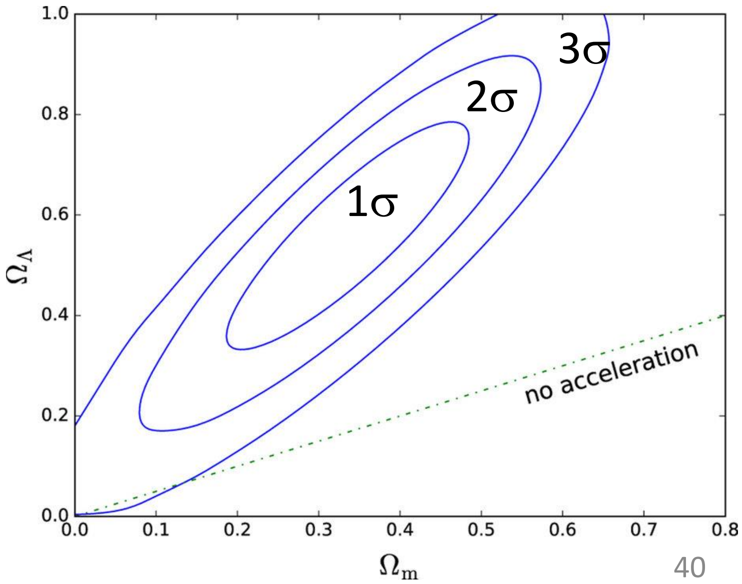


How well do we know what we know about Dark Energy?

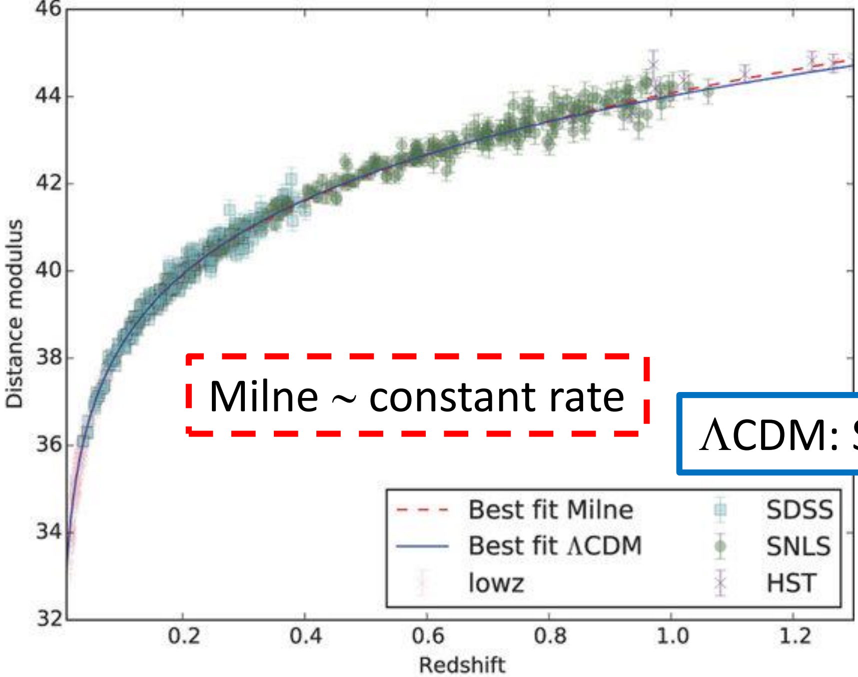
- 2016 paper by S. Sakar et al [Nature Scientific reports 6:35596] claims that the evidence for Dark Energy is in fact less than 3 σ
  - e.g. constant acceleration rate not excluded!
- Original analysis used Type Ia supernovae as "standard candles". Main argument against is that nowadays there are many more of these known $\Rightarrow$ one can use more rigorous statistical methods instead of assuming all have the same light profile.
- New analysis use maximum likelihood estimator to get best fit to the (now large) dataset

$$p_{\mathrm{cov}} = \int_0^{-2\ \log\ \mathcal{L}/\mathcal{L}_{\max}} f_{\chi^2}(x;\nu)\,\mathrm{d}x,$$

(where f is pdf of χ^2 random variable with ν degrees of freedom)



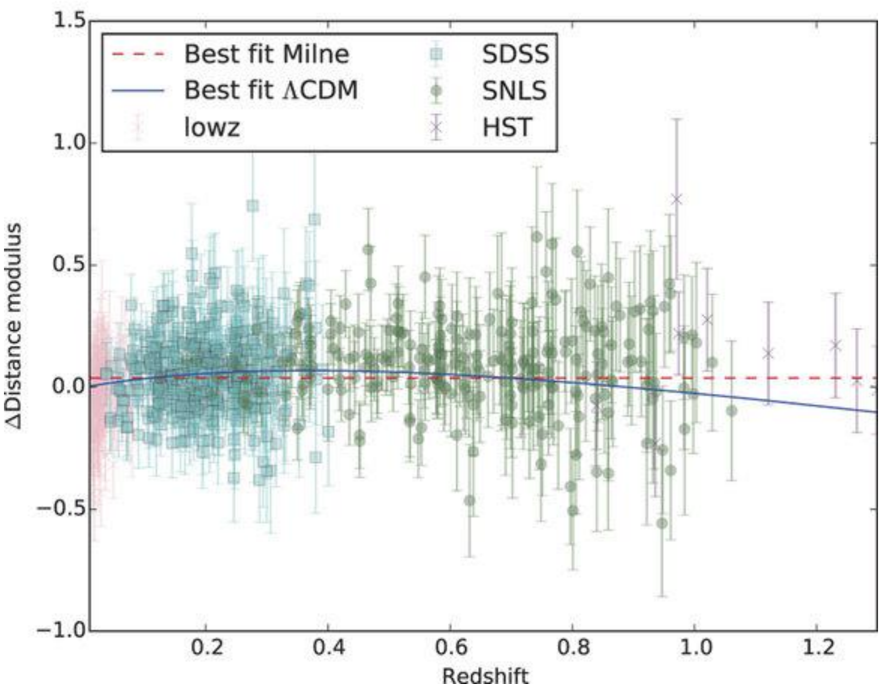
Looking closer at the data



Milne ~ constant rate

ΛCDM: SM cosmology with accelerating rate

Officially no resolution yet
Another paper published this Fall:
https://arxiv.org/abs/1808.04597



Other scientific support for Dark Energy hypothesis, such as for instance large scale structures in the Universe.
Dark Energy proponents claim that the data used by Sakar et al is old and that it is really 6σ (but I didn't find that published)

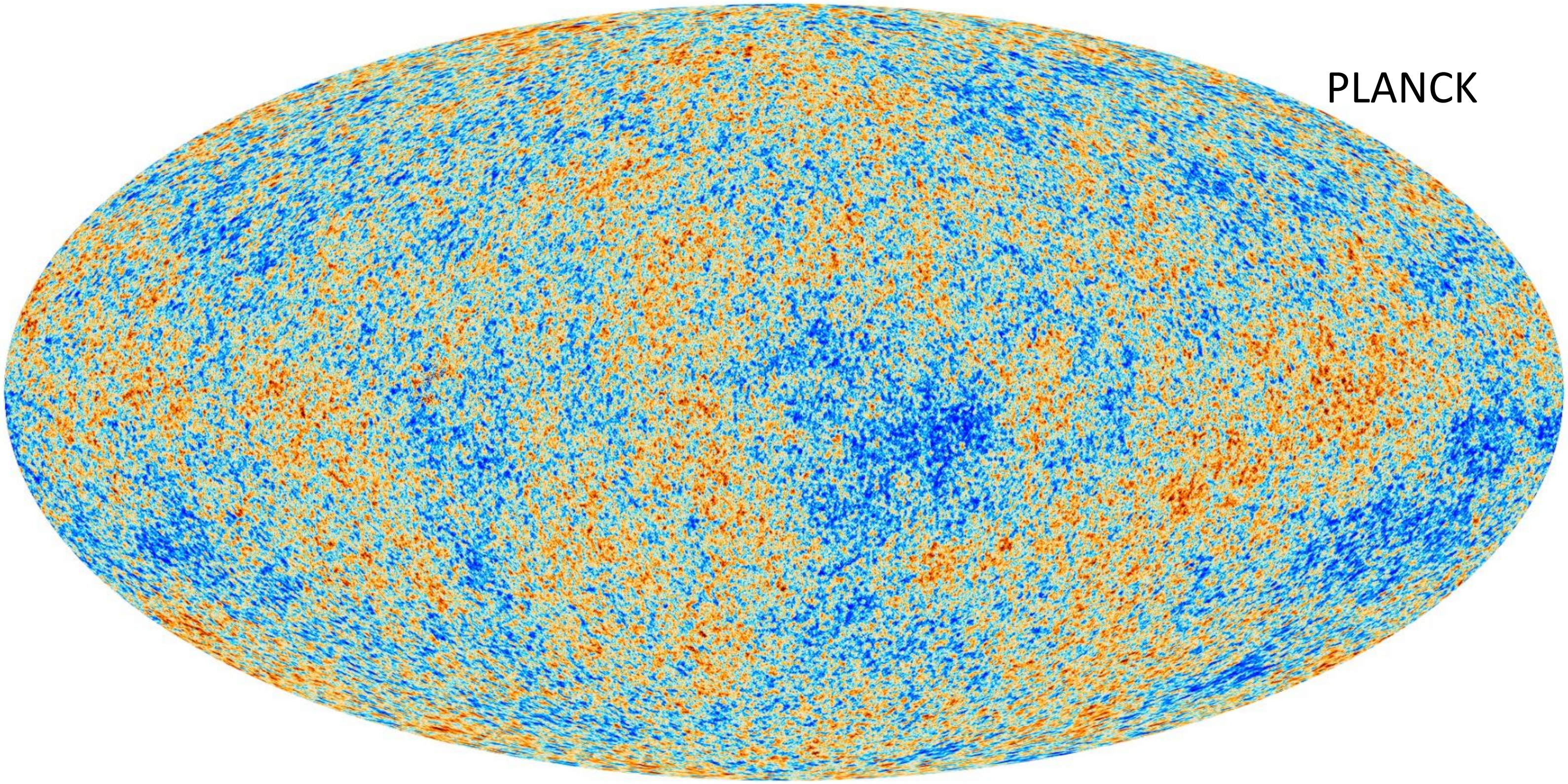
Interview with S. Sakar
https://www.youtube.com/watch?v=B1mwYxkhMe8&fbclid=IwAR2bANSv9NunxQGi8FywNfvTzQzSOZmlSAbuzte63diKIXwSrQB_Y0J0oK0

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

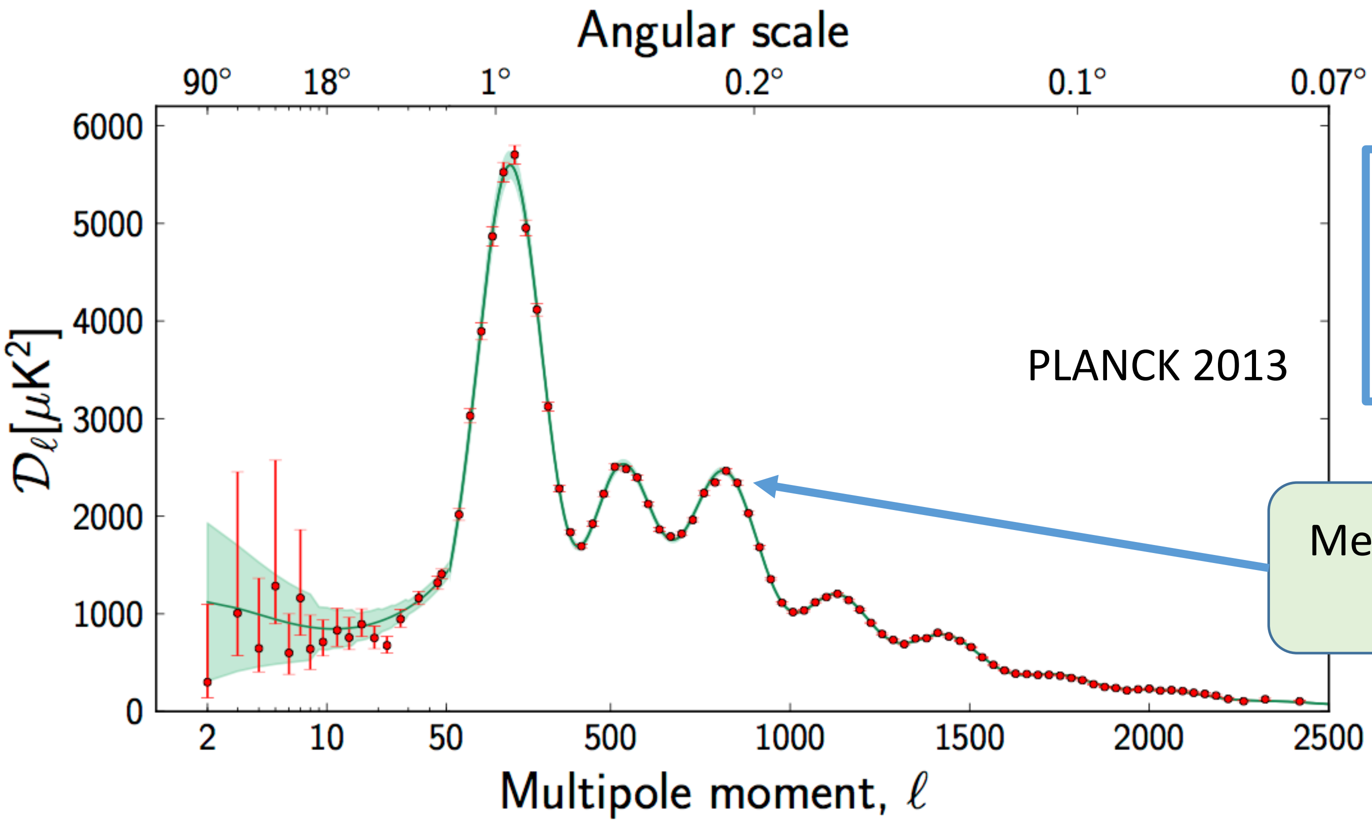
PLANCK



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)

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

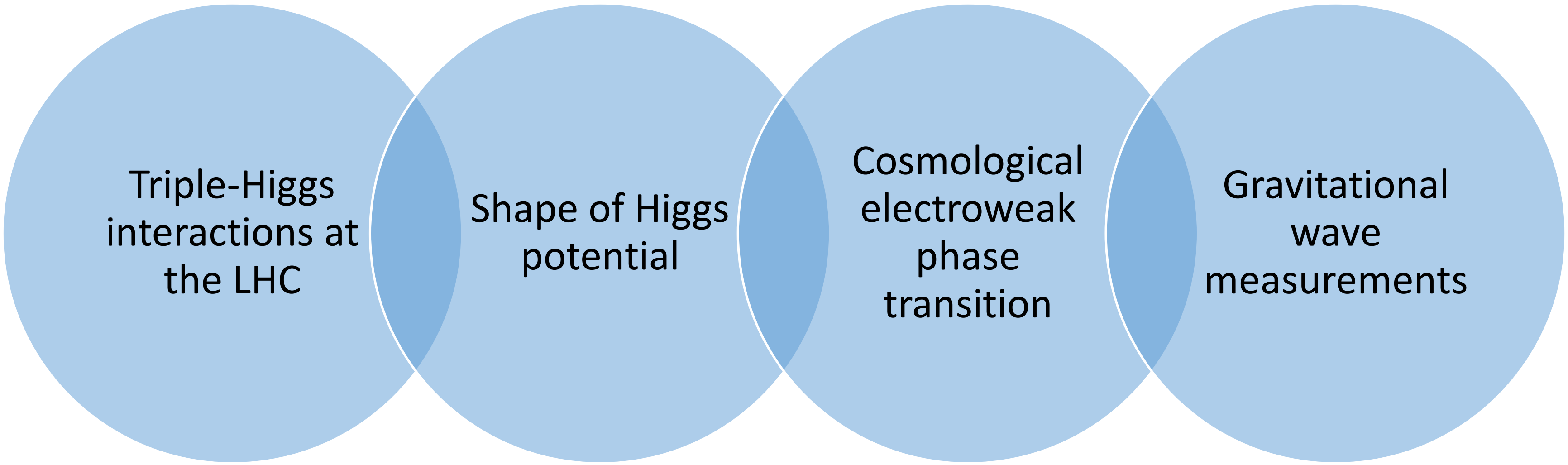


Dark Energy barely affects this picture
Dark Matter mainly indicated in 3rd peak

Measure physical density of the Dark Matter

Gravitational waves and higgs bosons?

Is there a "gravitational CMB"? Measure gravitational waves today to get information about the early Universe



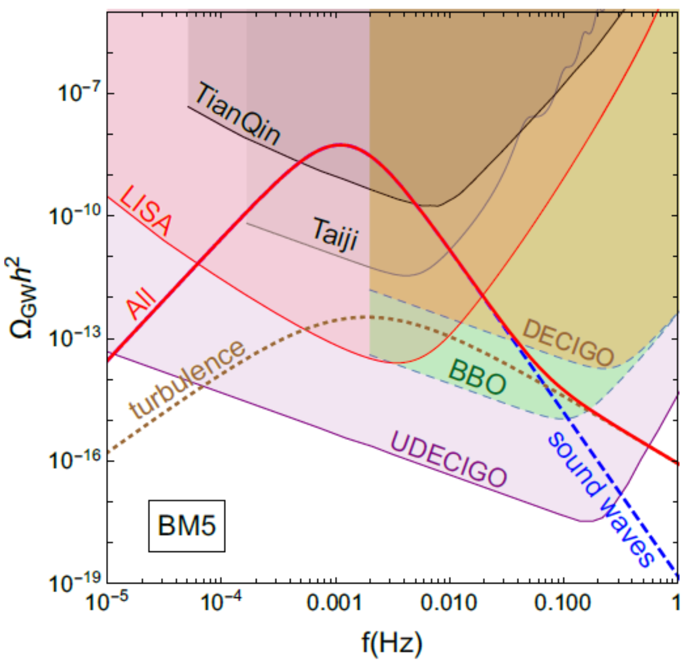
Information overlap model-dependent. For instance is it just a SM higgs, or extended higgs sector?

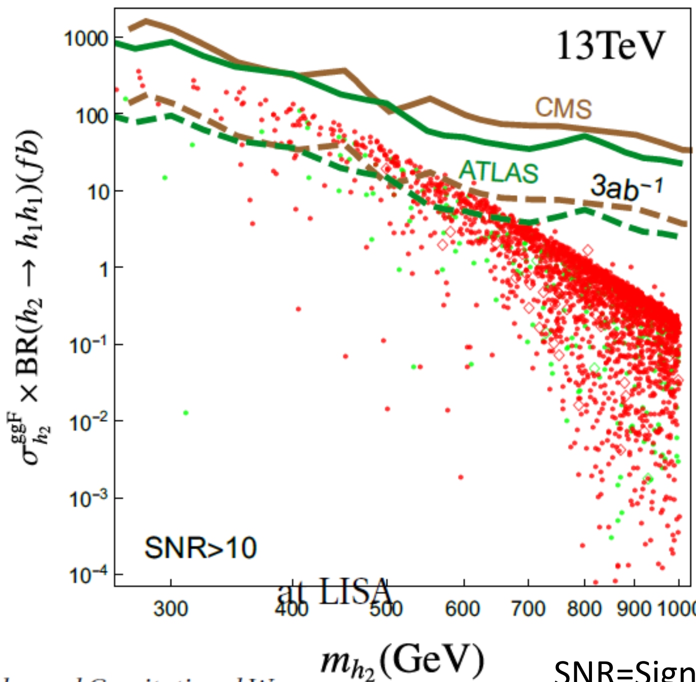
Slide from Roman Pasechnik

GWs complementarity to di-Higgs: an example

Singlet-extended SM

Gravitational wave energy density





Current

Projected

SNR=Signal-to-Noise-Ratio
Green: SNR > 10
Red: SNR >50

A. Alves, T. Ghosh, H.-K. Guo, K. Sinha, and D. Vagie, *Collider and Gravitational Wave Complementarity in Exploring the Singlet Extension of the Standard Model*, JHEP **04** (2019) 052, arXiv:1812.09333 [hep-ph].

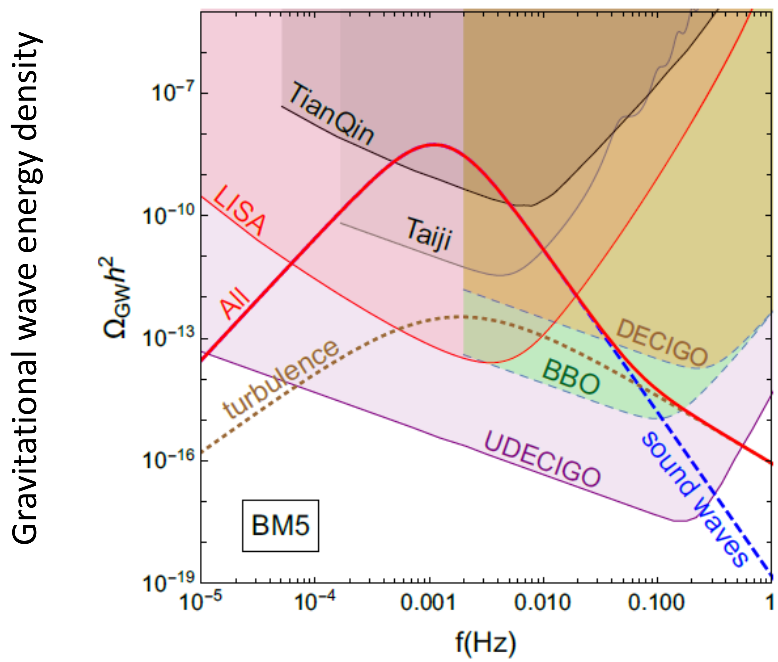
A. Alves, T. Ghosh, H.-K. Guo, and K. Sinha, *Resonant Di-Higgs Production at Gravitational Wave Benchmarks: A Collider Study using Machine Learning*, JHEP **12** (2018) 070, arXiv:1808.08974 [hep-ph].

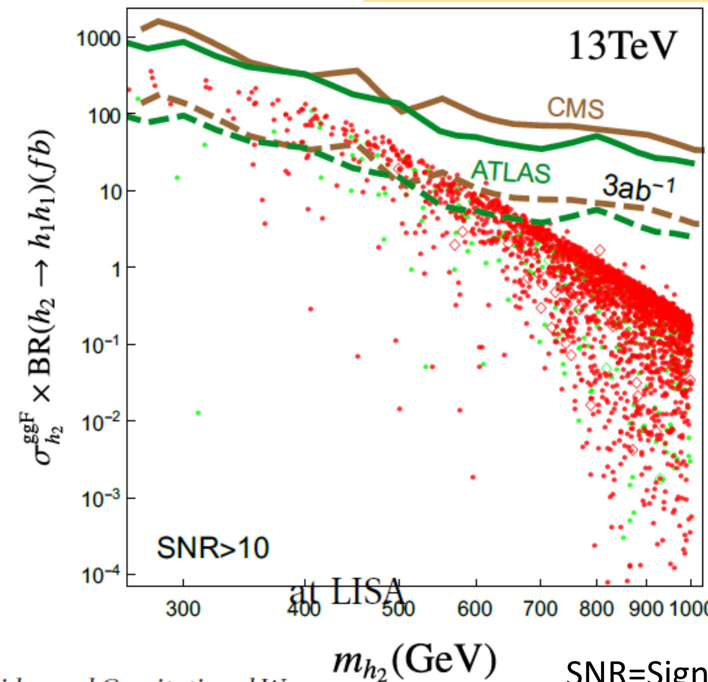
Slide from Roman Pasechnik

GWs complementarity to di-Higgs:

For low mass h2 both LISA and LHC experiments have high sensitivity!

Singlet-extended SM





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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.