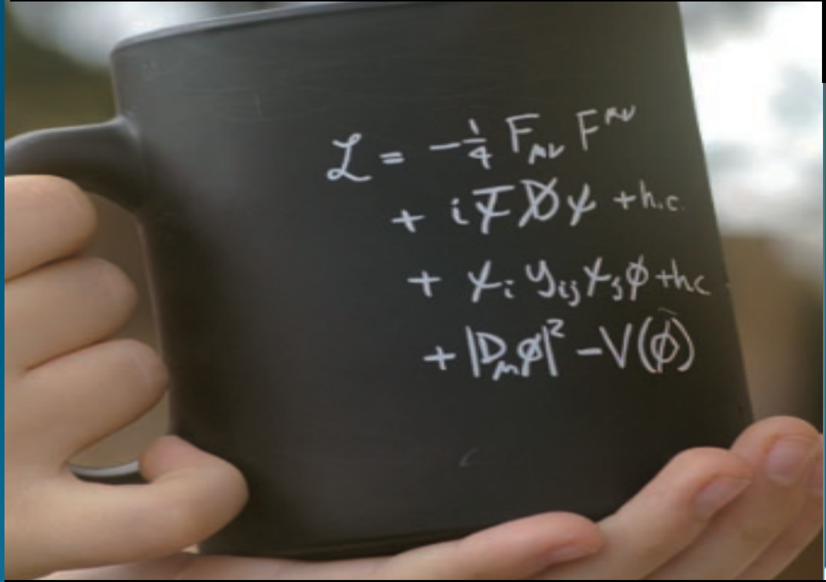
Outlook

Fabio Zwirner
University and INFN – Padova

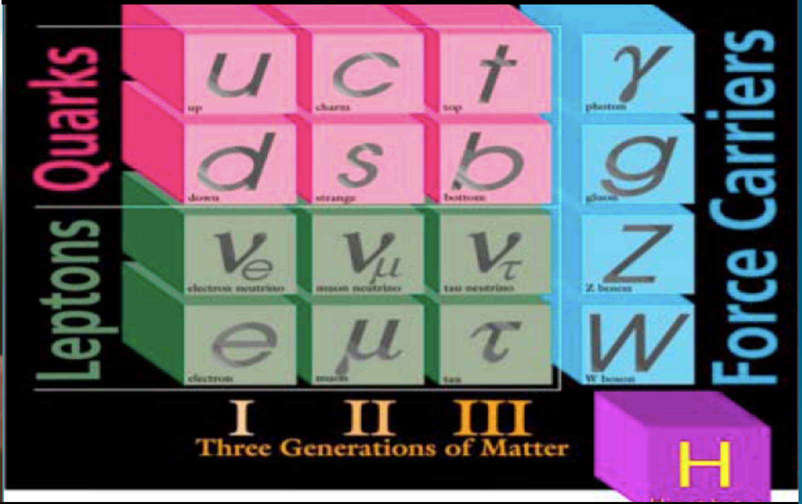
EPS-HEP 2017

The triumph of the Standard Model

TH "completed" in 1973



EXP "completed" in 2012



5 years later, no crack in the construction found
in the realm of accelerator-based HEP (LHC)

The triumph of the Standard Model

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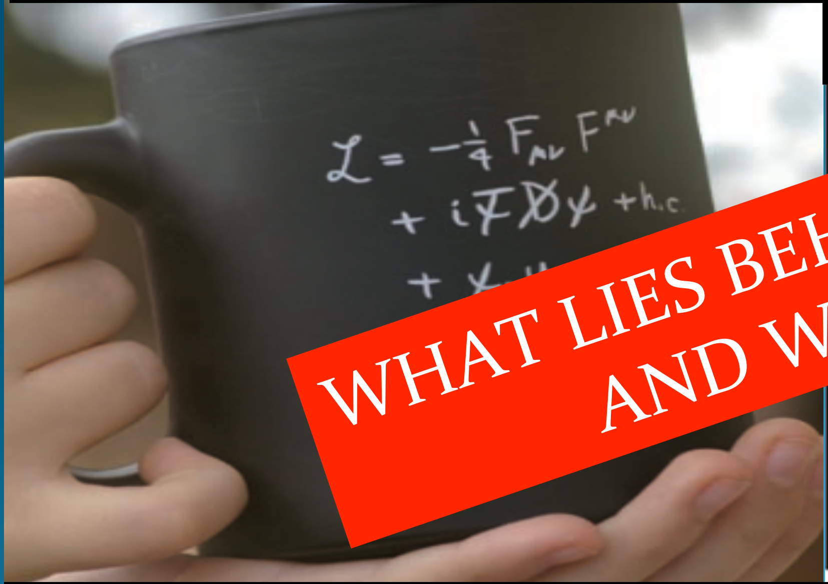

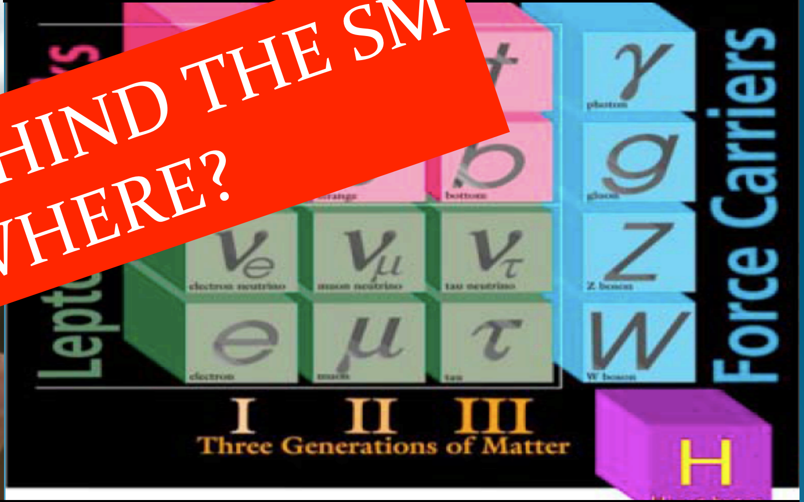

WHAT LIES BEHIND THE SM AND WHERE?

5 years later, no crack in the construction found in the realm of accelerator-based HEP (LHC)

Today's feeling in HEP

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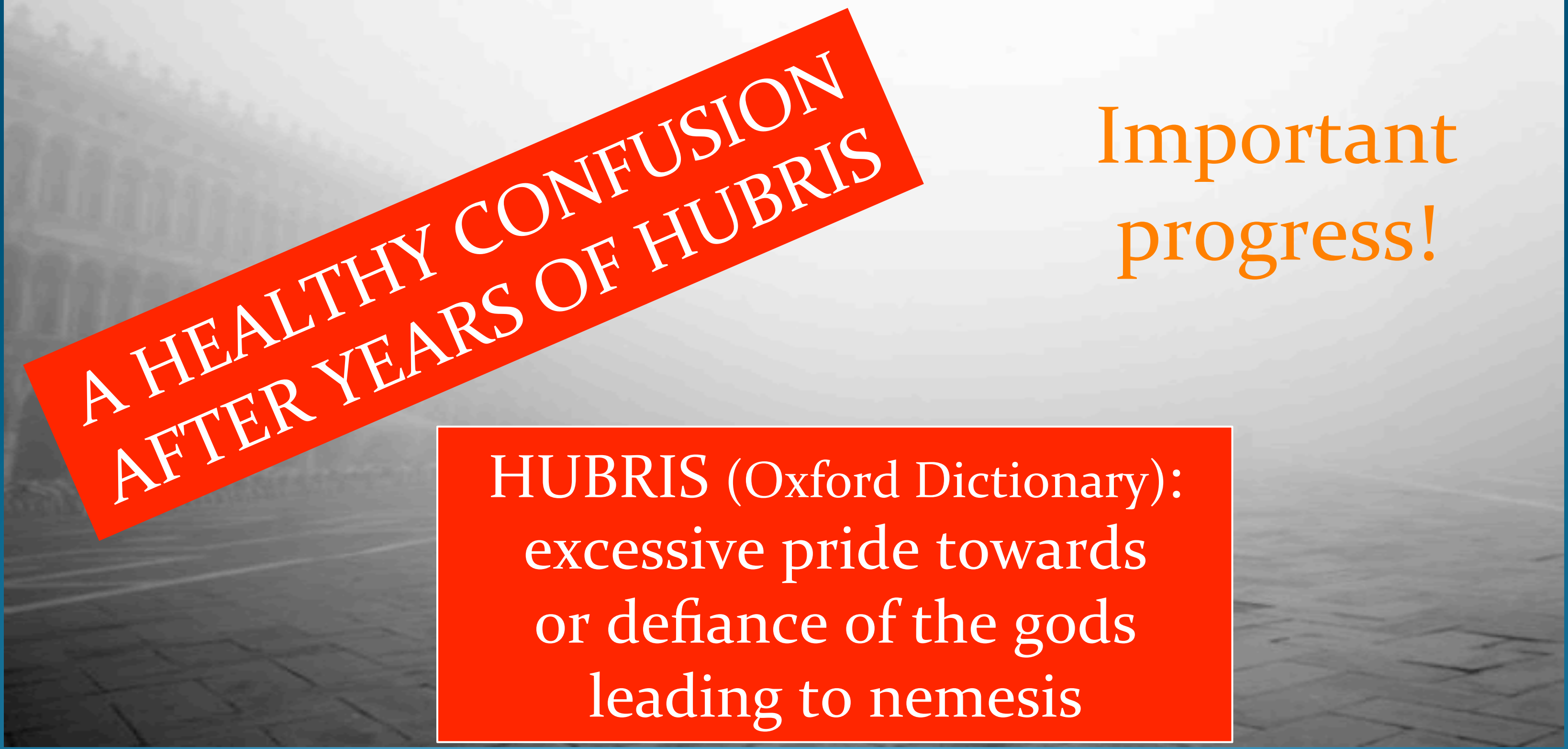
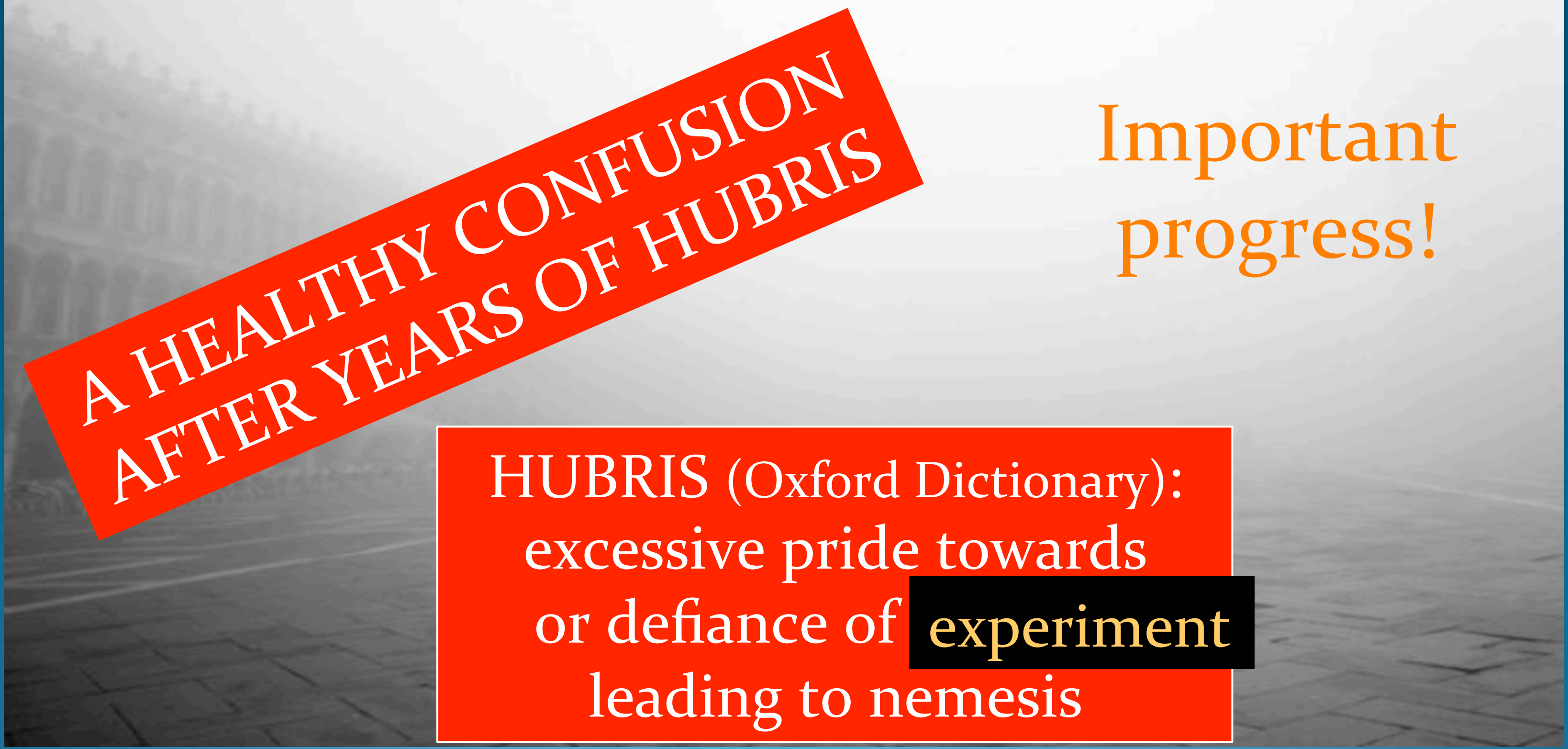


A HEALTHY CONFUSION
AFTER YEARS OF HUBRIS

Important progress!

HUBRIS (Oxford Dictionary): excessive pride towards or defiance of the gods leading to nemesis

Today's feeling in HEP



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excessive pride towards
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Any reference points in the fog?

Some reference points

EMPIRICAL, CONCEPTUAL, OR BOTH:

- Neutrino oscillations: **call so far for minor modifications (νSM), though potentially may be much more disruptive**
- **Stronger exceptions with** astrophysics & cosmology once SM is effectively coupled to Einstein's gravity: Dark Matter and Energy, Inflation, Baryon asymmetry
- Inclusion of quantum gravity
- Naturalness of the EW scale
- The strong CP problem

Gravity (classical) (more in Punturo)

A recent monumental breakthrough
DIRECT DETECTION OF GRAVITATIONAL WAVES
Honoured (also) by Giuseppe & Vanna Cocconi Prize

Test of classical GR in highly non-linear regime

Obvious extraordinary impact on astrophysics
very rich forthcoming experimental program:
A-LIGO, A-Virgo, KAGRA, LIGOIndia, Einst.Tel, LISA

Limited consequences so far for our understanding
of the fundamental interactions at the quantum level

Gravity (quantum)

SM + GR consistent as quantum EFT at low-energy
But: new physics must appear before $M_P \sim 10^{18}$ GeV

We miss a microscopic theory of Quantum Gravity

String theory still insufficiently predictive for HEP
important theoretical tools: amplitudes, AdS/CFT

(latter used also by Papadodimas in his talk on the BH information paradox)

Coupling SM to gravity reveals the
cosmological constant (dark energy) problem:
origin/stability of $\langle V \rangle \sim (10^{-3}\,\text{eV})^4 \ll (M_P)^4$
No understanding, link with the EW naturalness problem?

The EW naturalness problem

Small parameters only because of symmetries

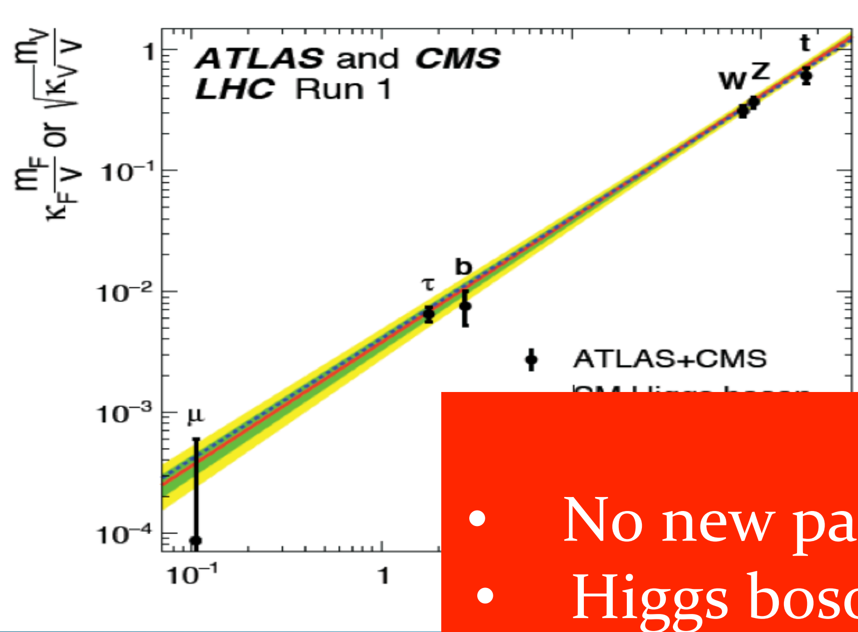
No quantum SM symmetry recovered for $m_H \rightarrow 0$
Unprotected ratio m_H/Λ for any NP scale $\Lambda >> m_H$

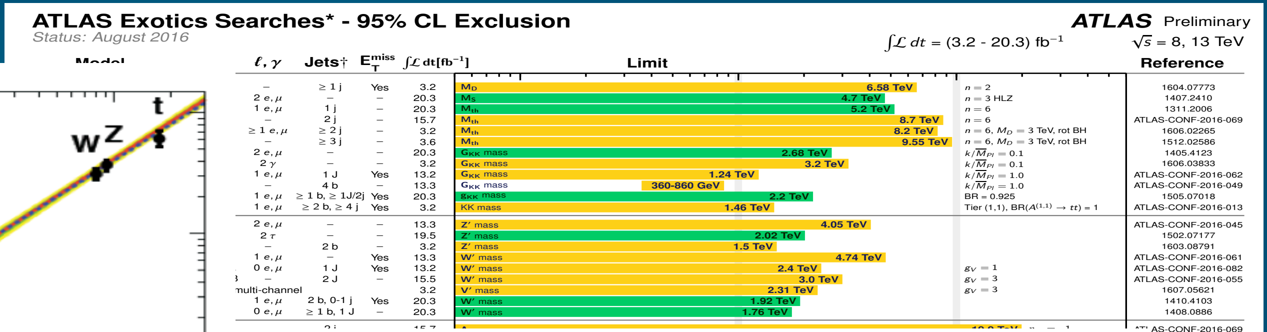
SM unnatural unless New Physics at the TeV

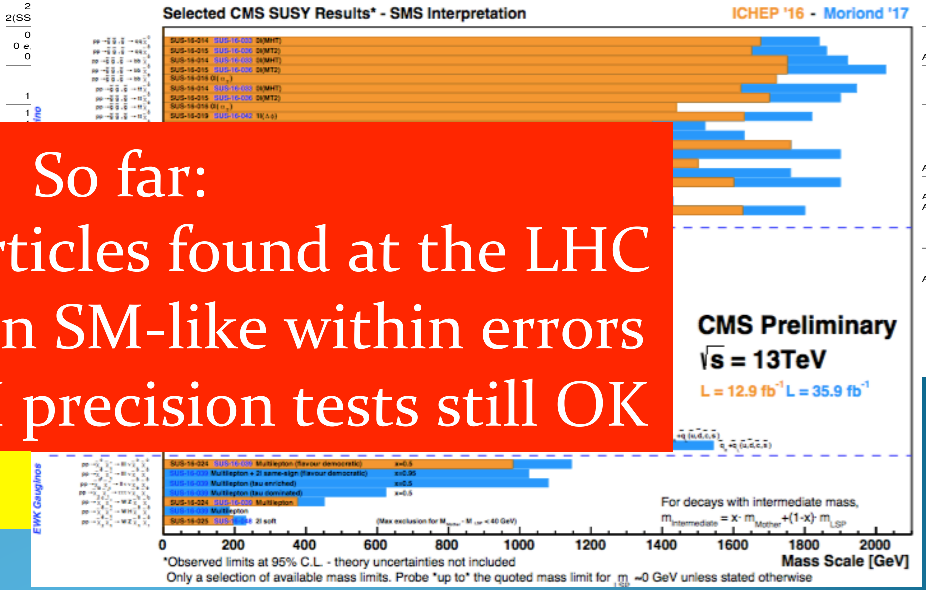
Superficially (too superficially?):

$$\delta m_H^2 \sim -\frac{3\,h_t^2}{8\,\pi^2}\,\Lambda^2 < O(m_H^2) \quad \rightarrow \quad \Lambda < O(500\ \text{GeV})$$

The failure of simple-minded solutions







So far:

- No new particles found at the LHC
- Higgs boson SM-like within errors
- Further SM precision tests still OK

(more in D'Onofrio, Meridiani, Shapiro)

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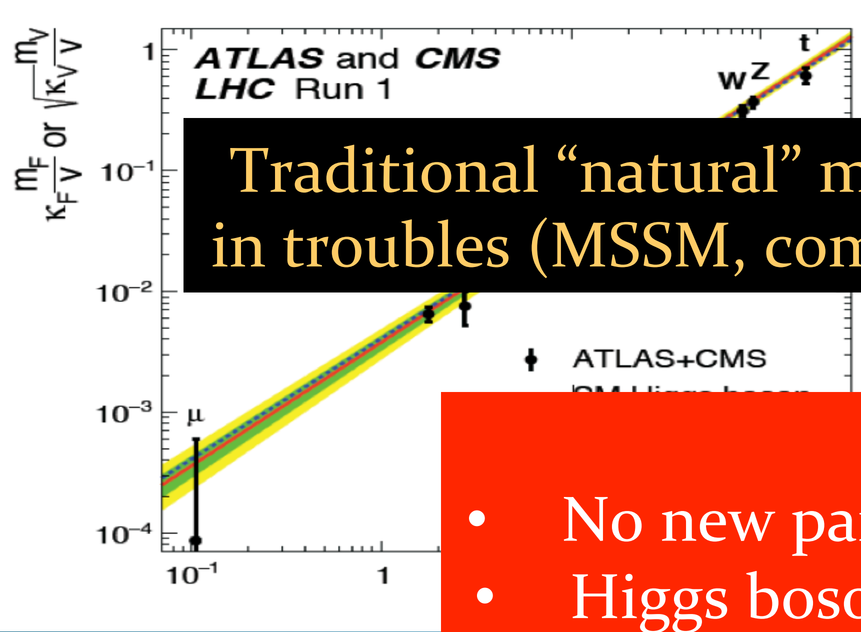

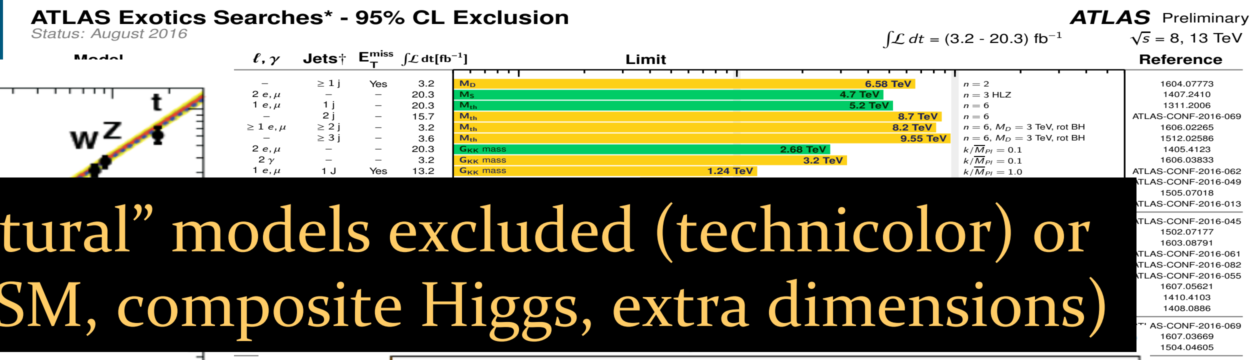

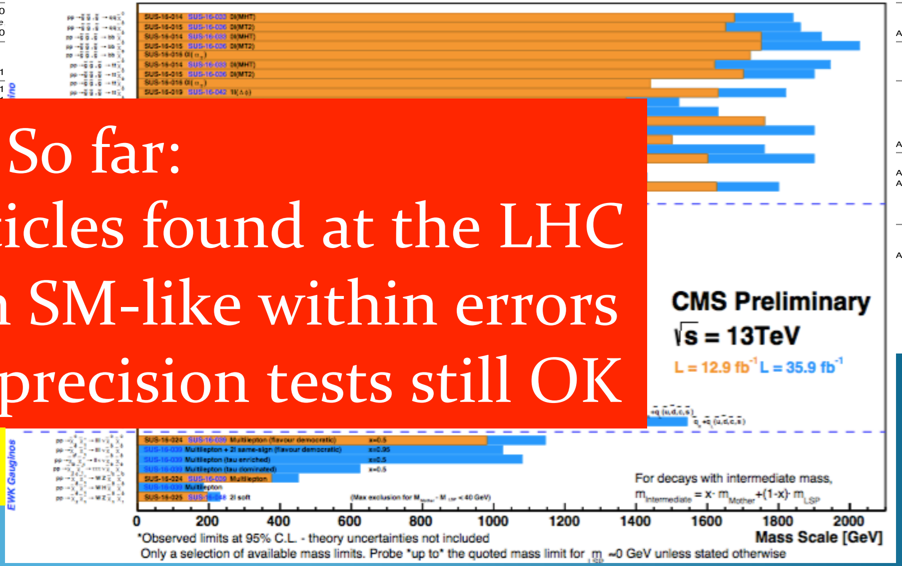

Traditional "natural" models excluded (technicolor) or in troubles (MSSM, composite Higgs, extra dimensions)

So far:

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(more in D'Onofrio, Meridiani, Shapiro)

Other attempts (more in Craig)

1. More complicated models to minimize tuning

Neutral naturalness, Twin Higgs, …

Some tuning, possible LHC signatures, a bit ad hoc

2. Meso-tuning to keep the models simple/motivated

Mini-split supersymmetry, partial compositeness, …

Direct LHC signatures not guaranteed. Elsewhere?

3. Radical revision of naturalness: "conformality"?

[Bardeen 1995; Shaposhnikov et al; Nicolai et al; 't Hooft; Strumia et al; …]

Spontaneous generation of all mass scales, including M_P

No fully consistent/convincing formulation known

So far model-dependent hints more than predictions

Wrapping up on EW naturalness

Central issue for today's particle physics

final answer can only come from experiment

Two main options for what we did not understand:

- Some detail ➔ NP signals at the LHC or later will guide us to understand what we missed
- The whole point ➔ experiment must confirm it beyond doubt to reshape theory on a new basis

In both cases, a fundamental lesson to be learnt

WAY TOO EARLY TO CONCLUDE NOW!

Still a role to play for SUSY? (more in Craig)

Much more in SUSY than MSSM vs hierarchy problem

Phenomenologically:

- Best hint at the unification of gauge couplings
- Flavour and h-SM improve with heavier spectrum
- LSP still viable (although tuned) candidate for DM

Theoretically:

- Most general symmetry of relativistic D=4 QFT
- Special UV properties of extended SUSY/SUGRA
- Plays a crucial role in superstring theories

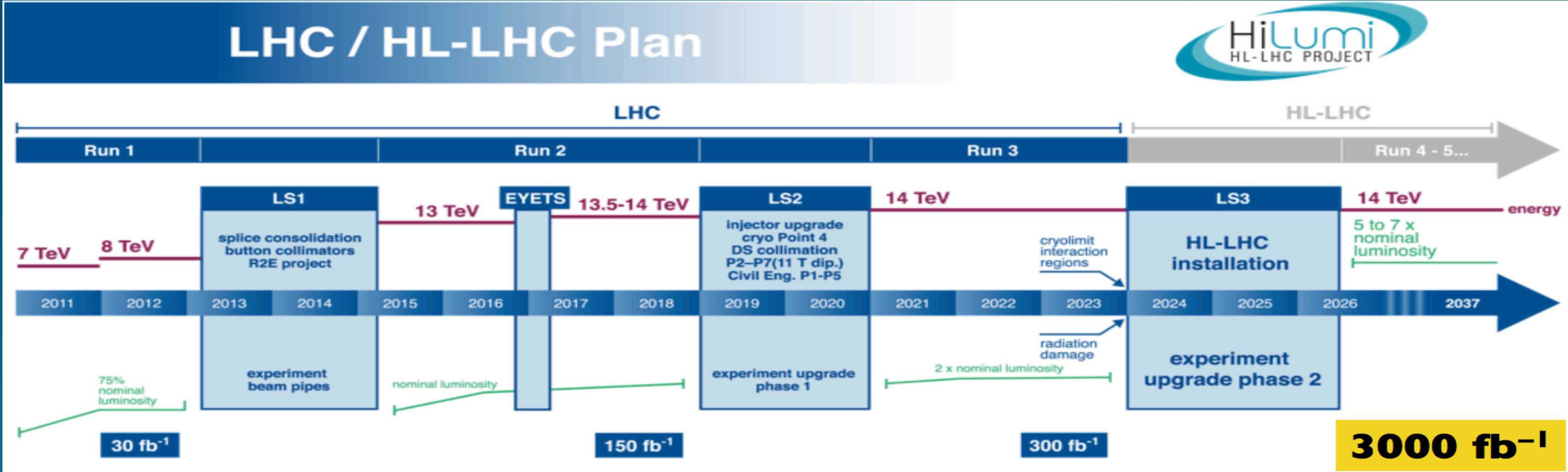
May eventually fit the picture, but how?

Need new ideas more than studies of parameter spaces

Beyond the SM with energy

Energy frontier: direct searches for new particles

$\sqrt{S_{LHC}}/\sqrt{S_{Tev}} \sim 6.5$ (~7 Run≥3) but $s=x_1x_2S$ & PDFs count



Data collected so far < 2% of the final statistics:
still (moderate) room for new particles at the LHC
Another factor of 2 with 16T magnets at HE-LHC?

Beyond the SM with accuracy

No more four fundamental (gauge) forces:
Gravity (spin-2) + Strong & Weak & EM (spin-1)

Different forces involving the spin-0 Higgs boson

$Y_{ij}\ \psi_i\ \psi_j\ H$ ➔ Yukawa interactions

$\lambda\ |H|^4$ ➔ Higgs self-interactions

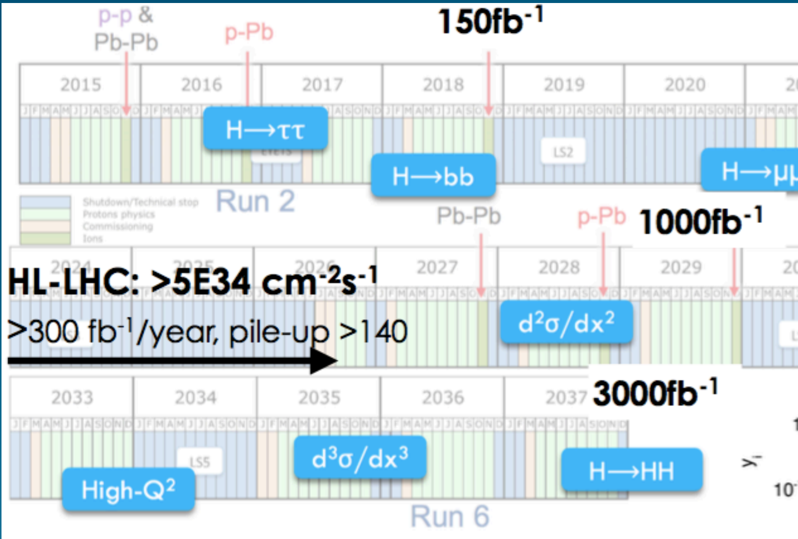
We must study them as precisely as possible

Knowledge is not only discovering new particles

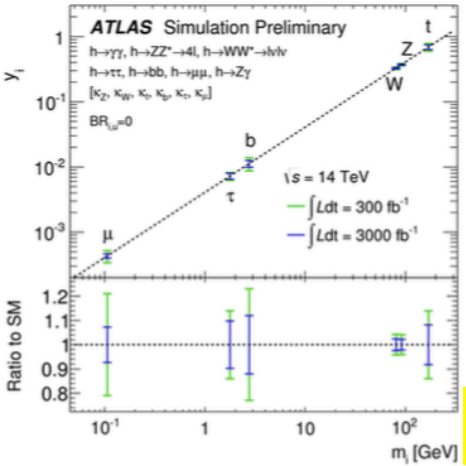
it is also finding out about their interactions

with the highest possible precision

Forthcoming Higgs physics at the LHC



Careful with the gap
from evidence/observation
to precision measurement



from Meridiani

Precision physics at colliders

In this respect, the SM is still unfinished job:
long way from SM Lagrangian to precise predictions
as beautifully shown by the QCD/EW/top talks

(see Dittmaier, Czakon, Shapiro)

expect continuing progress in pQCD, PDFs, MCs

Interesting observation [Panico et al, 1609.08157]
Non-trivial EW precision tests possible at the LHC
exploiting d=6 EFT operators with $\Delta\Theta/\Theta \sim E^2/\Lambda^2$
e.g.: oblique parameters W and Y from Drell-Yan
LHC can beat LEP thanks to its much higher energy

Flavour physics

(more in Gori, Egede, Serrano, Schwanda)

Still many opportunities for a SM crisis:
$B_{d,s} \to \mu\mu$, $\tau \to \mu\gamma$, $\mu N \to eN$, $K \to \pi\nu\nu$, EDMs, ...

Indirect access to scales >> TeV

Today's hot topic: "anomalies" in s.l. B decays

NC b→sll [SM 1-loop]

$$R_{K^*}^{\mu/e} = \left.\frac{\mathcal{B}(B \to K^*\mu\bar{\mu})_{\rm exp}}{\mathcal{B}(B \to K^*e\bar{e})_{\rm exp}}\right|_{q^2\in[1.1,6]\rm GeV} = 0.685^{+0.113}_{-0.069} \pm 0.047$$

LHCb 1705.05802

$$R_{K}^{\mu/e} = \left.\frac{\mathcal{B}(B \to K\mu\bar{\mu})_{\rm exp}}{\mathcal{B}(B \to Ke\bar{e})_{\rm exp}}\right|_{q^2\in[1,6]\rm GeV} = 0.745^{+0.090}_{-0.074} \pm 0.036\ ,$$

LHCb 1406.6482

CC b→clν [SM tree]

$$R_{D^*}^{\tau/\ell} = \frac{\mathcal{B}(B \to D^*\tau\bar{\nu})_{\rm exp}/\mathcal{B}(B \to D^*\tau\bar{\nu})_{\rm SM}}{\mathcal{B}(B \to D^*\ell\bar{\nu})_{\rm exp}/\mathcal{B}(B \to D^*\ell\bar{\nu})_{\rm SM}} = 1.23 \pm 0.07$$

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HFAG avg. of Babar, Belle,LHCb

Potential message: R≠1 → LFU violation → New Physics

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LHCb 1705.05802

06.6482

Not so easy to fit both effects in a single model
Special role of the third generation for NP effects?
Additional features in other channels in many models
Wait and see (remember the di-photon story in 2016!)

CC b→c
[SM tree]

$$R_D^{\tau/\ell} = \frac{\mathcal{B}(B \to D\tau\bar{\nu})_{\rm exp}/\mathcal{B}(B \to D\tau\bar{\nu})_{\rm SM}}{\mathcal{B}(B \to D\ell\bar{\nu})_{\rm exp}/\mathcal{B}(B \to D\ell\bar{\nu})_{\rm SM}} = 1.34 \pm 0.17\,,$$

AG avg.
Babar,
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Potential message: R≠1 → LFU violation → New Physics

Extreme precision at low energies

A long-standing "anomaly" of the SM: $(g\text{-}2)_\mu$

a_μ^{EXP}= 116592091 (63) x 10^{-11} [BNL-E821 (2006)]

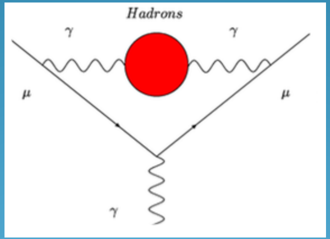
$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM}$= 250-330 (85) x 10^{-11} [2.9-3.9 σ]

a_μ^{SM} uncertainty dominated by hadronic LO a_μ^{HLO}

Fermilab E989 starting Nov 2017 aims at ± 16 x 10^{-11}

Recent idea:

Carloni-Calame, Passera, Trentadue, Venanzoni, ...



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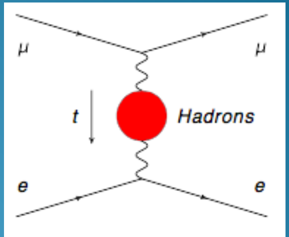


could aim at ±20x10^{-11} in a_μ^{HLO} with μe scattering exp after further studies of systematics and TH NNLO calculation

Beyond the SM with neutrinos?

(see Smirnov, Lisi, Kopp)

Minimal embedding of ν masses in the SM:

1. Dirac (include ν_R , impose B-L)
2. Majorana (do not impose B-L)

A wide open chapter of SM flavour physics
many questions will be answered "soon":

-mass ordering and absolute scale
-more precise determination of ϑ_{23}
-CP violation (δ) in neutrino sector

(see Lasserre, Nakaya)

Rich and structured experimental programme
important input also from cosmology

Beyond the SM with neutrinos!

With a combination of luck and ingenuity
much more radical discoveries possible

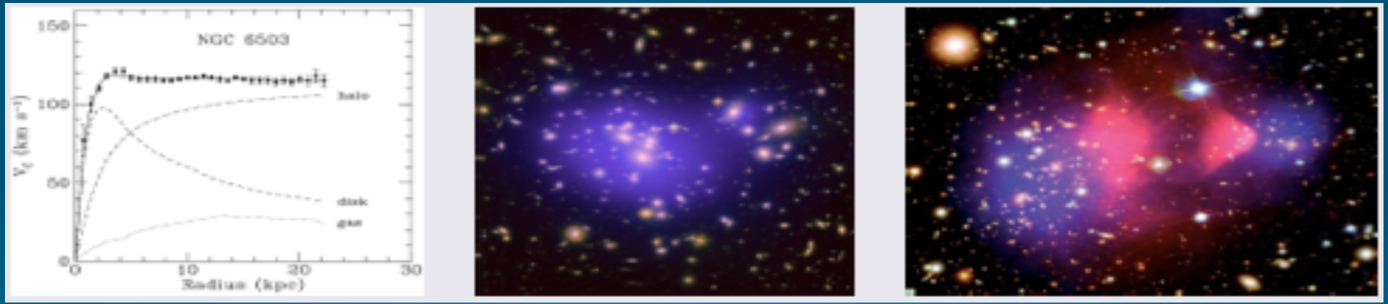
"tickets to Stockholm of neutrino physics"

-neutrino-less double beta decay
is B-L a broken symmetry of Nature?

-direct detection of relic neutrinos
formidable experimental challenge
another crucial cosmic connection

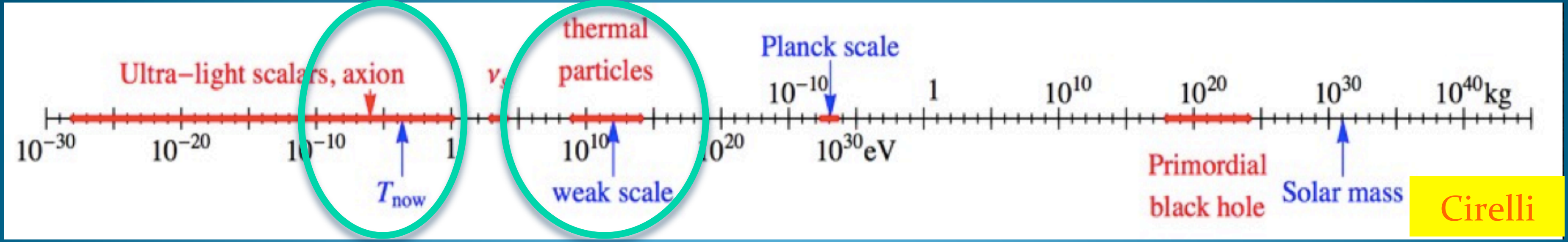
-breakdown of standard 3-neutrino picture
weaker motivation, potentially disruptive

Beyond the SM with Dark Matter?



Convincing (gravitational) evidence for DM

No compelling option in a wide spectrum



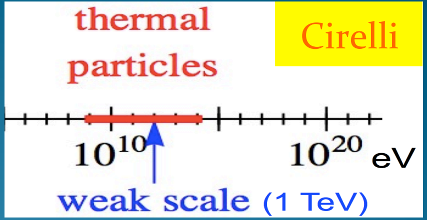
Lampost principle: focus on motivated detectable candidates

Beyond the SM with DM: WIMPs

The WIMP miracle: DM of weak-scale mass and interactions

For a thermal relic:

$<\sigma_\chi v> \sim 0.12\ \text{pb}/(\Omega_\chi h^2)$



Very roughly: $<\sigma_\chi v> \sim (\alpha/m_\chi)^2$

Natural WIMPs: $\alpha \sim \alpha_W$ $m_\chi \sim m_W$

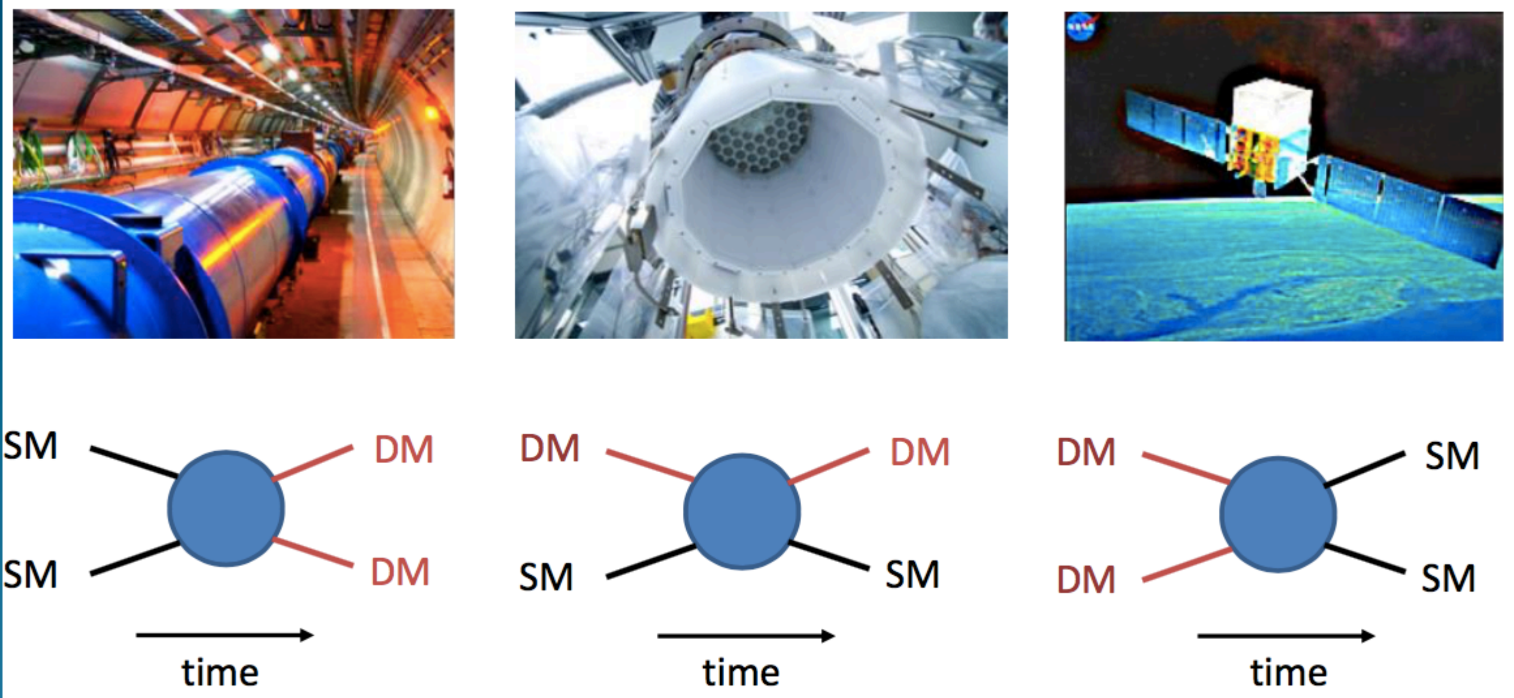
Weakened by failure of naïve naturalness
(not to mention single specific realizations!)
still motivated, worth exploring more broadly

TeV-scale WIMPs: $\alpha \sim 1$ $m_\chi \sim$ TeV

Weakly coupled WIMPs: $\alpha < \alpha_W$ $m_\chi < m_W$

WIMP collider/direct/indirect searches

A massively advertised "complementarity":



Hochberg

Comments on WIMP searches (I)

Indirect:

- Backgrounds still poorly understood: more and better data →progress in understanding physics astrophysics and MC modeling of Cosmic Rays

- There are "dirty" and "clean" channels: most promising those with sharp spectral features

- Should be as broad as possible in energy range

Comments on WIMP searches (II)

Collider:

- Conceptualy difficult to organize DM searches "per se": limitations of EFT with NR operators vs. proliferation of models (simplified or not)
- At the LHC, positive info more likely as spin-off from discovery of other resonances (messengers)

Direct:

- Towards the ultimate ν background with multi-ton experiments (and attempts to overcome it)

Beyond the SM with DM: axions

(more in Redondo)

Motivated by the strong CP problem

$\theta = \theta_{QCD} + N_f\,\delta$ why $\theta < 10^{-10}$?

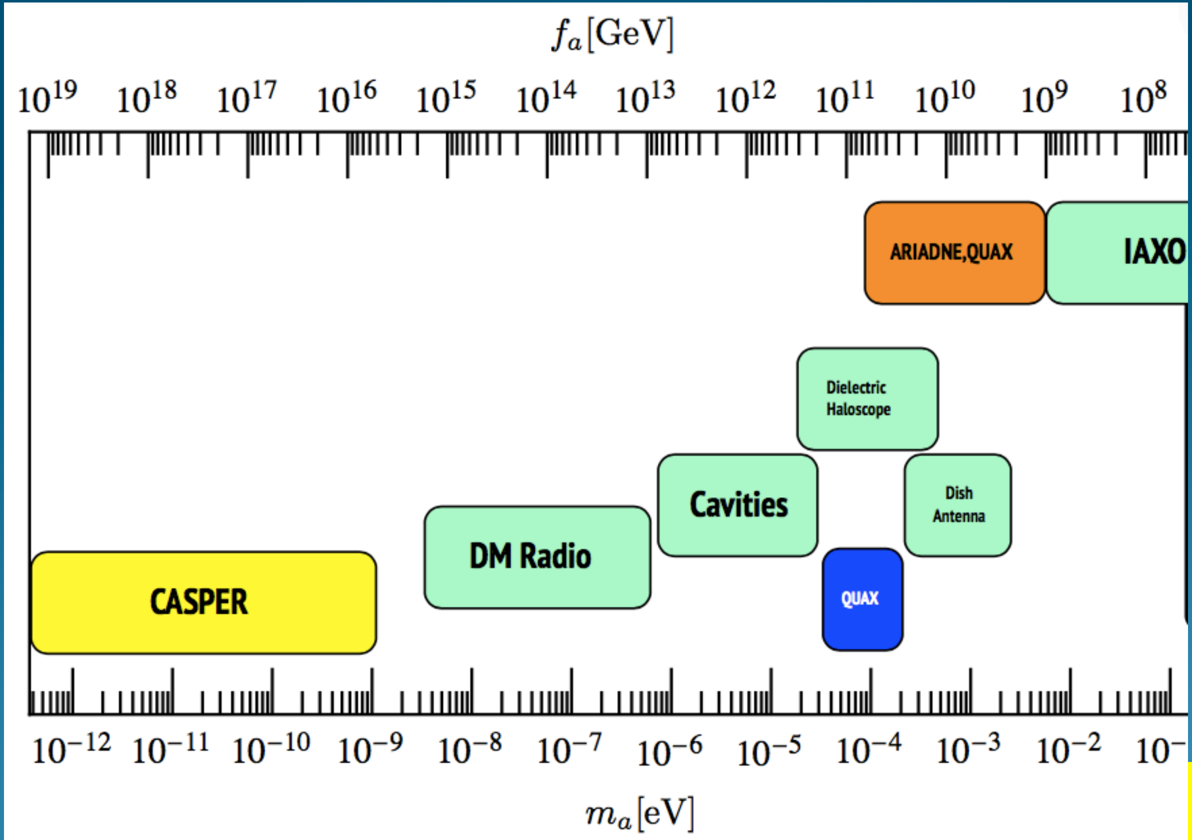
Automatic candidate for DM (with subtleties in the theoretical estimate of the relic density)

$m_a = \sqrt{\chi} / f_a$ with $\sqrt{\chi} \approx (75.5\ \text{MeV})^2$

Intensification of axion search experiments

More generally, new low-energy frontier also connected to other very light DM candidates: very light particles, very weakly coupled to SM

Some axion search experiments

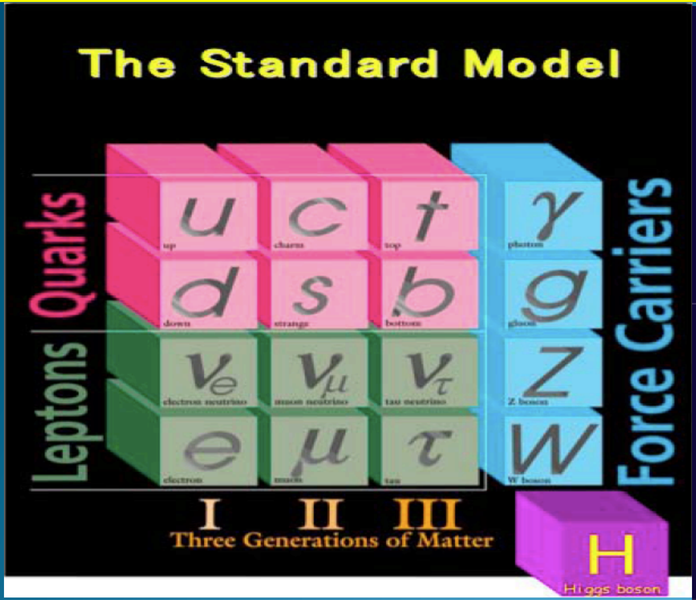


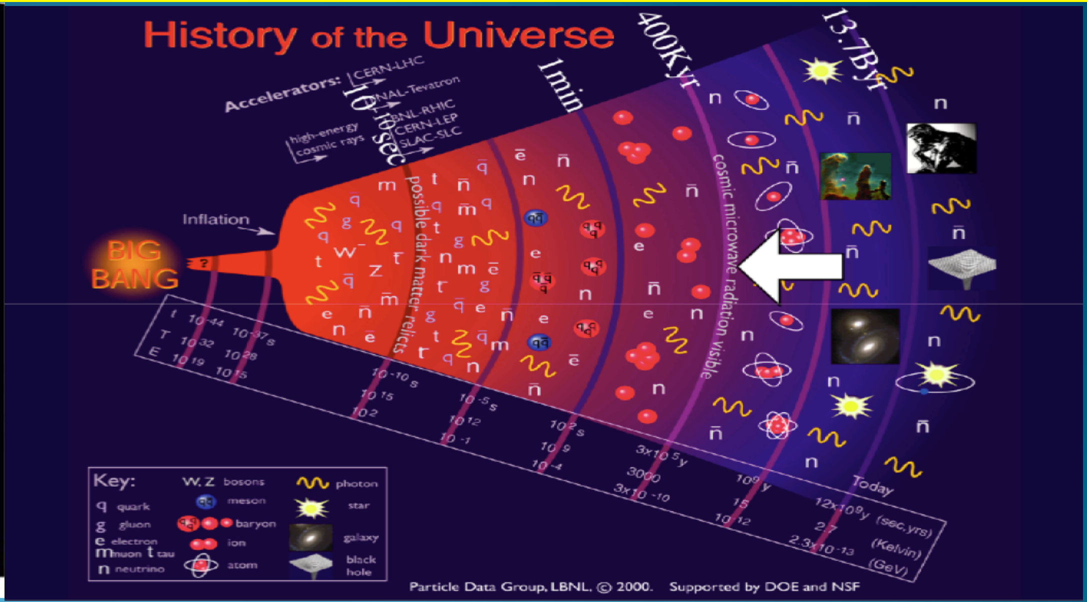
Redondo

The importance of connections

Boundaries between HEP, astro and cosmo are fading away

(see Lebedev, Bertucci, Hofmann, DeJong, Lasserre, Lindner, Bouchet, Krause, Riotto)





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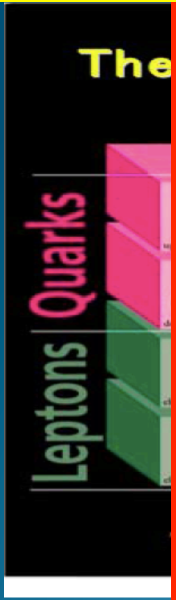
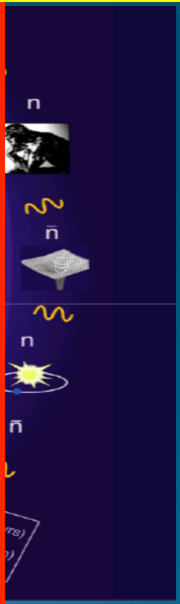


Neutrinos, DM, baryo-/lepto-genesis, inflation

Increasing emphasis on Higgs role in cosmology: instabilities, relaxation mechanisms, inflation

Another big boost could come from the detection of the B-mode of the CMB polarization (after the 2014 false alarm on r~0.2 from BICEP2): sensitivity down to $r \sim 10^{-3}$ seems within reach



Wrapping up: a change of perspective

From the 80s on, all collider discoveries (W/Z, t, H)
strongly "guided" by theory: no-lose theorems
we won't be again in such a condition for some time

Experiment now leading in the search for new phenomena
plenty of open problems to address, limited resources
diversify efforts to maximize chances
(until new discovery or new compelling theory)

- Ballistic projects with guaranteed return
- High-risk high-gain exploratory projects

(including detector, accelerator and data analysis R&D)

Sooner or later the fog will clear up

But it will not come by itself:
we must work hard for that!

Sooner or later the fog will clear up

Big discoveries often required patience and very long-term commitment, e.g.:

- Neutrino oscillations
- Higgs boson
- Gravitational waves

WE CAN EXPECT MANY MORE

WHAT WILL COME NEXT, AND WHEN?

But it will not come by itself:

we must work hard for that!

Thank you for your attention!