DMDE2019, Mainz, 3-7 June, 2019

Muon g-2 and DM

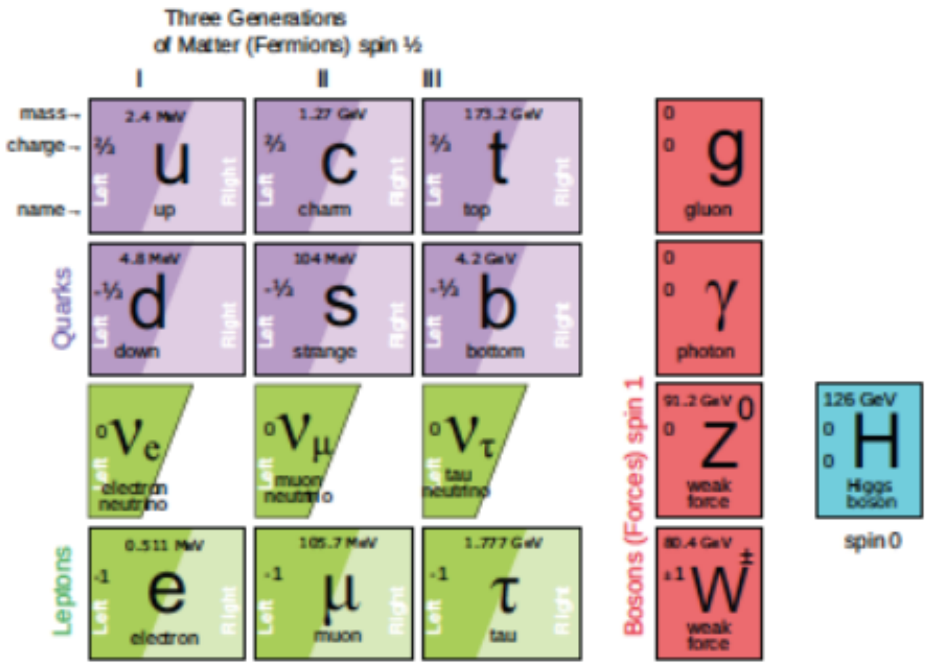
as windows of New Physics beyond the SM

Antonio Masiero

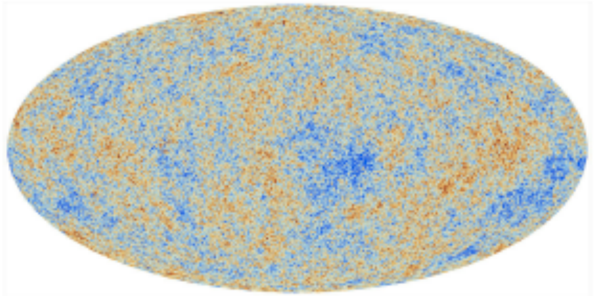
INFN and Univ. of Padova

2013 – 2016 : the triumph of the STANDARD

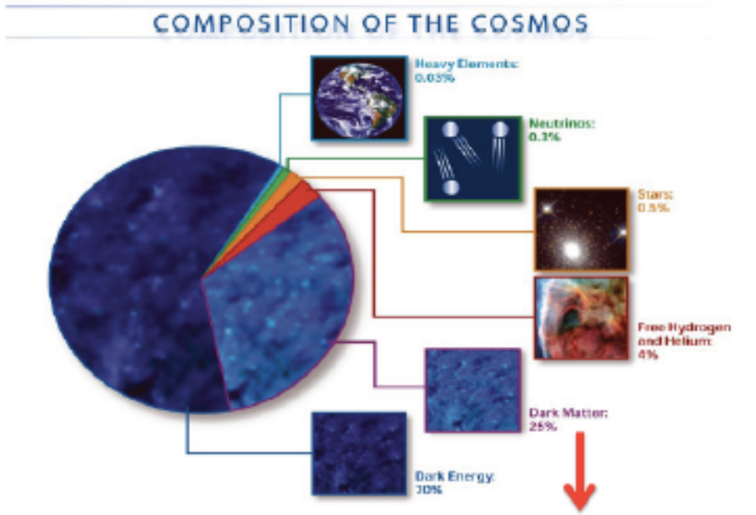
- **PARTICLE STANDARD MODEL**

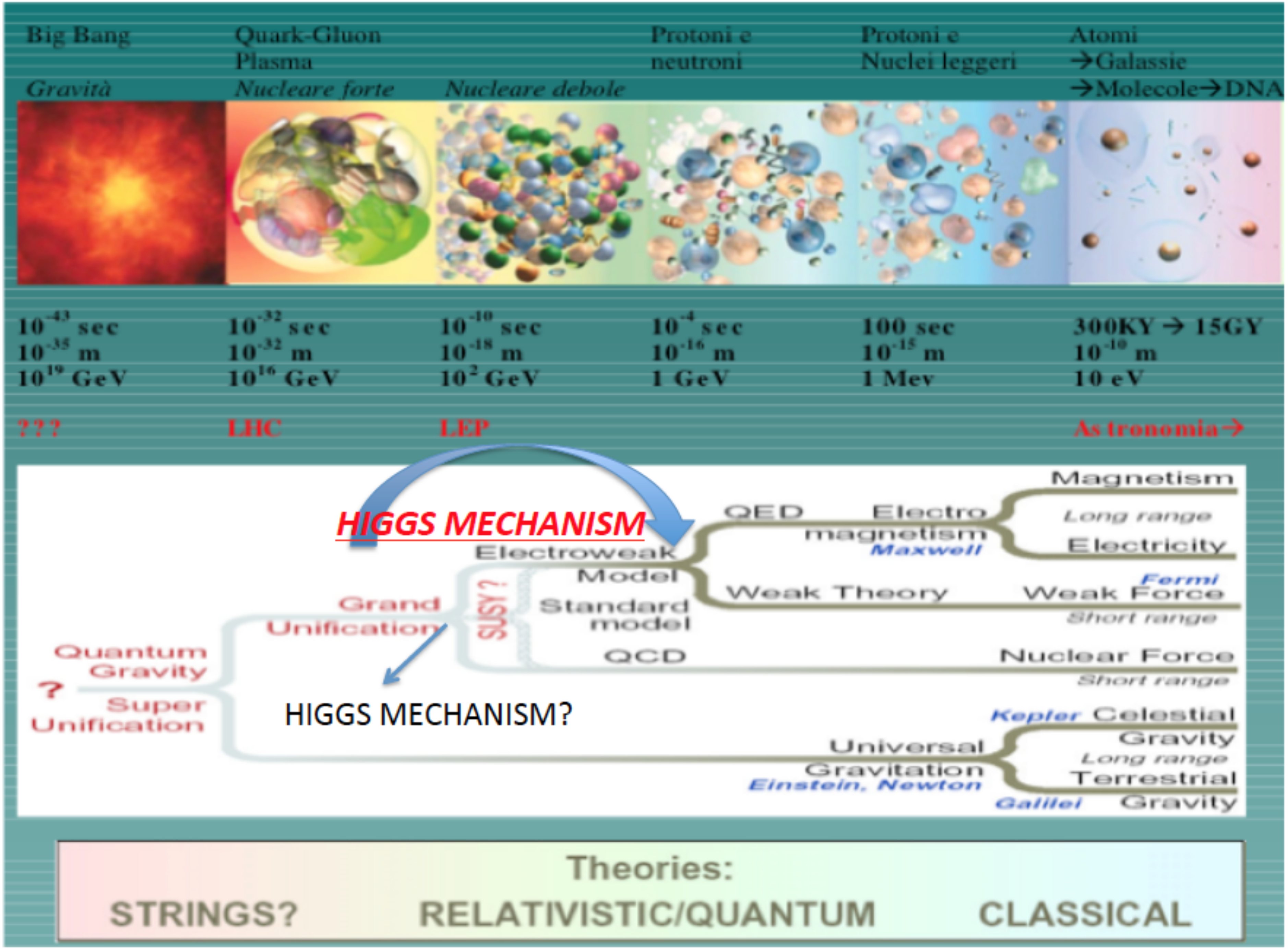


- **COSMOLOGY STANDARD MODEL**



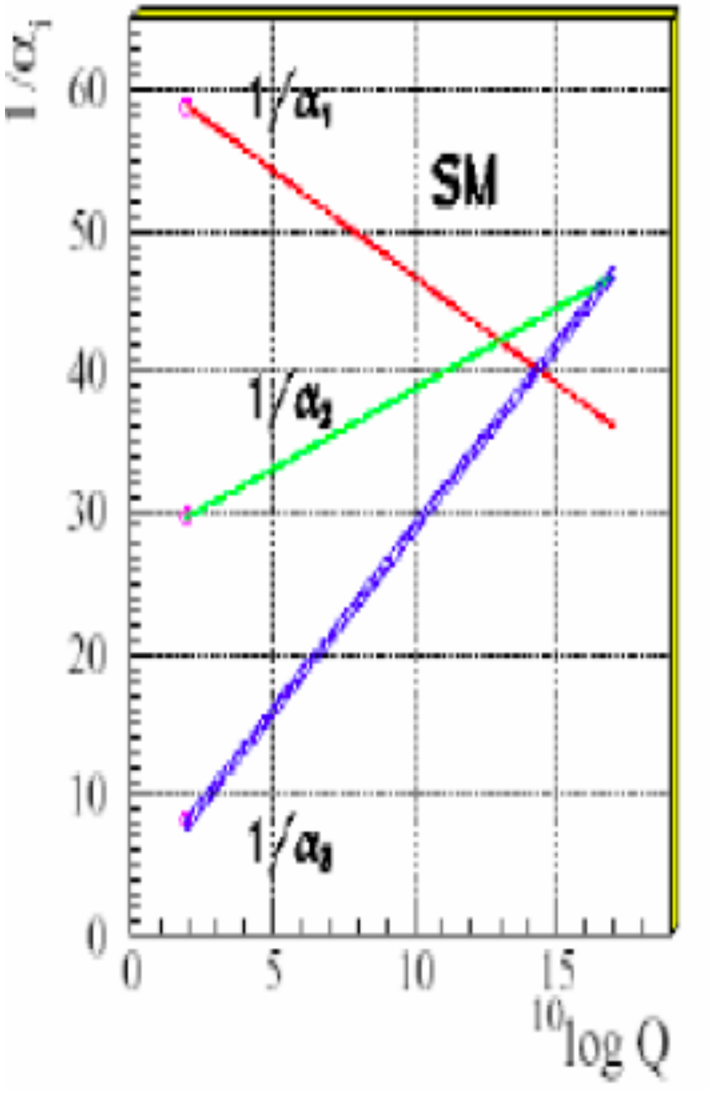
ΛCDM + "SIMPLE" INFLATION

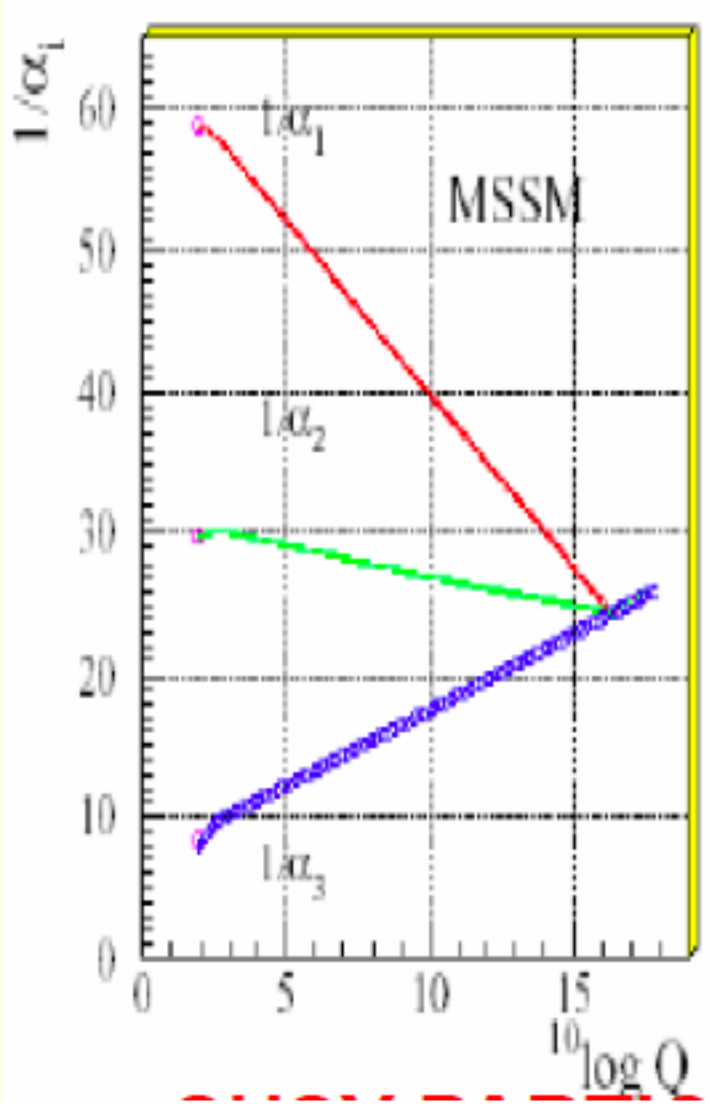




Big Bang
Gravità
Quark-Gluon Plasma
Nucleare forte
Nucleare debole
Protoni e neutroni
Protoni e Nuclei leggeri
Atomi →Galassie →Molecole→DNA
10^{-43} sec 10^{-35} m 10^{19} GeV
10^{-32} sec 10^{-32} m 10^{16} GeV
10^{-10} sec 10^{-18} m 10^{2} GeV
10^{-4} sec 10^{-16} m 1 GeV
100 sec 10^{-15} m 1 Mev
300KY → 15GY 10^{-10} m 10 eV
???
LHC
LEP
Astronomia→
HIGGS MECHANISM
Magnetism
QED
Electro magnetism
Maxwell
Long range
Electricity
Electroweak
Model
Fermi
Weak Theory
Weak Force
Short range
Grand Unification
SUSY ?
Standard model
QCD
Nuclear Force
Short range
Quantum Gravity
?
Super Unification
HIGGS MECHANISM?
Kepler
Celestial Gravity
Long range
Universal Gravitation
Einstein, Newton
Terrestrial Gravity
Galilei
Theories:
STRINGS?
RELATIVISTIC/QUANTUM
CLASSICAL

Only one fundamental interaction?





Are the SMs really STANDARD?

G-W-S SM

- **All the experimental results** of both **high-energy particle physics** and **high-intensity flavor physics** are surprisingly (and embarrassingly) in **very good agreement** with the predictions of the GSW SM

- Only (possible) exceptions:

  -- **the anomalous magnetic moment of the muon (3.6 σ discrepancy w.r.t. the SM prediction);**

  -- **hints of violation of the lepton flavor universality in semileptonic B decays**(??)

ΛCDM SM

- **All the cosmic observations are in agreement** with the ~25% CDM, ~70% cosmological constant **Λ ,** ~5% ordinary matter of the **ΛCDM SM**

- (Possible) exception: **troubles with pure Cold DM** from absence proto-galaxies, non-existence of spikes in DM density at the centre of the galaxies

- …**Value of the Hubble constant** measured today or inferred from the Planck results on the CMB

MICRO

GWS STANDARD MODEL

MACRO

HOT BIG BANG STANDARD MODEL

UNIVERSE EXPANSION +
WEAK INTERACTIONS **NUCLEOYINTHESIS**
1 sec. after BB

NUMBER OF BARYONS and OF NEUTRINO SPECIES → CONFIRMED FROM CMB 350000 YEARS AFTER BB

Independent confirmation from the study of the CMB

BUT ALSO

FRICTION POINTS

- -COSMIC MATTER-ANTIMATTER ASYMMETRY
- -INFLATION ???
- - DARK MATTER + DARK ENERGY

OBSERVATIONAL EVIDENCE OF NEW PHYSICS

BEYOND THE STANDARD

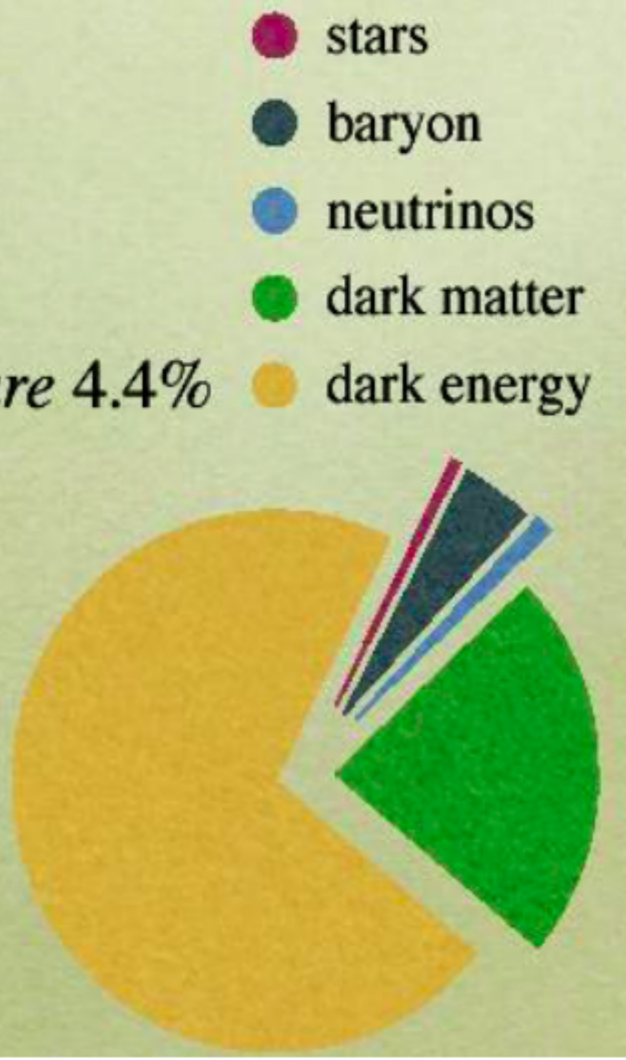
WHY BSM

Theoretical reasons (of dissatisfaction towards the SM as a "final" theory rather than actual problems for the SM)

- Lack of the theory of **Flavor** (why three fermion families, why hierarchical mass spectrum, why mixing angles so different)
- **CPV in strong interactions**, i.e. the θ-problem
- **Unification** of the fundamental interactions (running the SM gauge couplings → clear trend for unification of the interactions, but "pure SM" fails) – gravitational interactions as an external classical field
- **Gauge hierarchy** – twofold puzzle: why M_{GUT} or M_{planck} >>> M_W; stabilization of the higgs mass at M_W at any order in perturbation theory

5 numbers, 5 indications of physics beyond the Standard Models of Particle Physics and Cosmology: NEUTRINO MASSES, DARK MATTER, DARK ENERGY, ANTIMATTER and VACUUM ENERGY

- *Stars and galaxies are only ~0.5%*
- *Neutrinos are* **> 0.1 %**
- *Rest of ordinary matter (electrons, protons & neutrons) are 4.4%*
- *Dark Matter* **~ 27%**
- *Dark Energy* **~ 68 %**
- *Anti-Matter* **0 %**
- *Higgs Bose-Einstein condensate* ~ **10^{62} %** ??



thanks to H. Murayama

The Energy Scale from the "Observational" New Physics

- neutrino masses
- dark matter
- baryogenesis
- inflation

→ NO NEED FOR THE NP SCALE TO BE CLOSE TO THE ELW. SCALE

The Energy Scale from the "Theoretical" New Physics

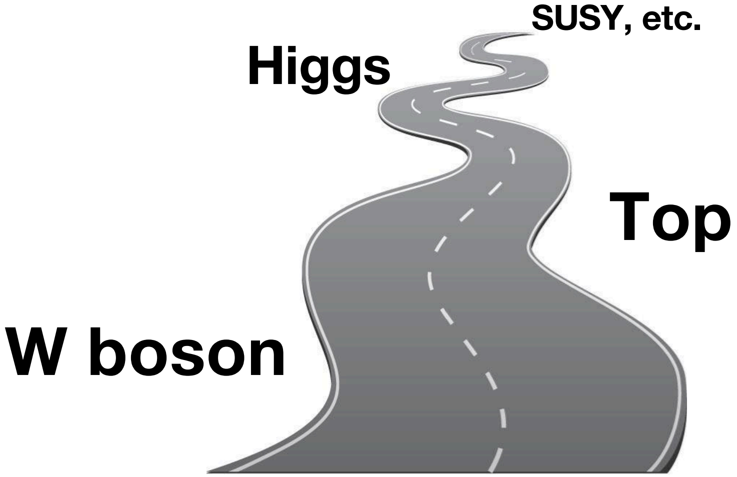
★ ★ ★ **Stabilization of the electroweak symmetry breaking at M_W calls for an ULTRAVIOLET COMPLETION of the SM already at the TeV scale**

\+

★ **CORRECT GRAND UNIFICATION "CALLS" FOR NEW PARTICLES AT THE ELW. SCALE**

Ideology

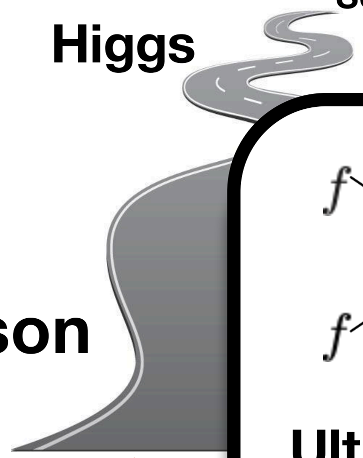
HEP before the LHC



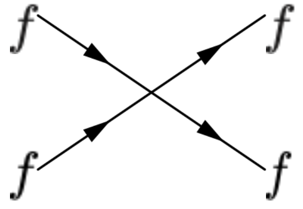
HEP before the F.C.

Ideology

HEP before the LHC



HEP before the F.C.

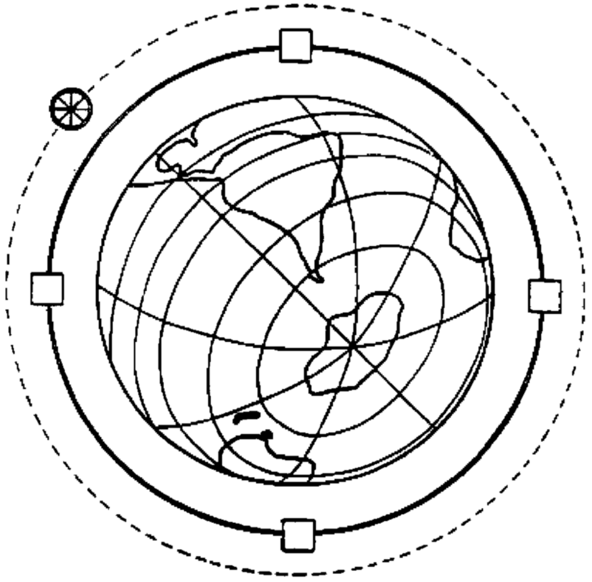


$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \rightarrow m_W < 4\pi v$

Ultimate Accelerator.

Drawn by Fermi in the '50 to reach 3 TeV.

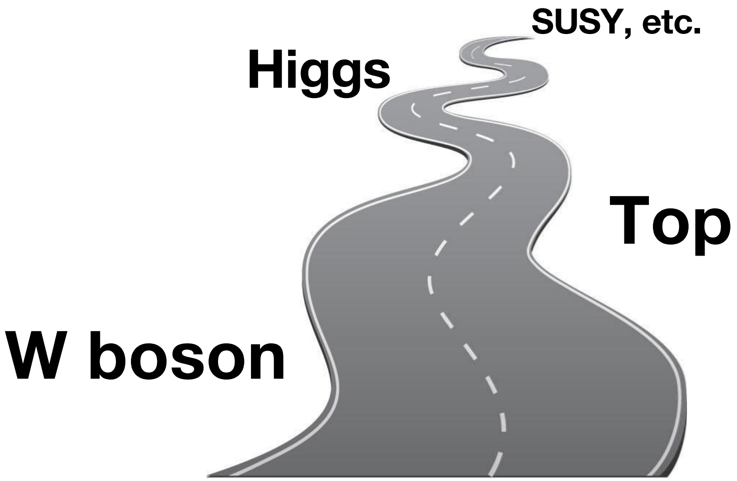
The manifesto of HEP!



A. Wulzer 2019 at the Town Meeting of EU Particle Strategy in Granada, 13-16 May 2019

High Energy Physics before and after the LHC

HEP before the LHC



HEP after the LHC

Particle physics is not **validation** anymore, rather it is **exploration of unknown territories**

This is **good:**
next discovery will be **revolutionary**

This is **bad:**
F.C. potential cannot be evaluated on few uniquely identifiable benchmarks (e.g., Higgs for LHC). Selection made in what follows.

A. Wulzer 2019 at the Town Meeting of EU Particle Strategy in Granada

Naturalness or Un-naturalness?

Naturalness

- **New SYMMETRY** giving rise to a cut-off at

  $$m_{NP} \ll M$$

  Low-energy **SuperSymmetry**

- **Space-time modification (extra-dim., warped space)**

- **COMPOSITE HIGGS** : the Higgs is a pseudo-Goldstone boson (pion-like) → new interaction getting strong at $m_{NP} \ll M$

Un-naturalness?

- **The scale at which the electroweak symmetry is spontaneously broken by <H> results from COSMOLOGICAL EVOLUTION**

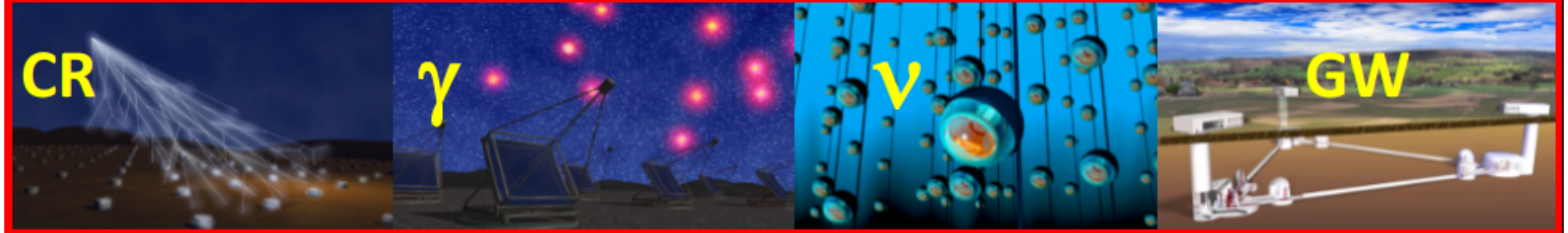
- **H is a fundamental (elementary) particle → we live in a universe where the fine-tuning at M arises (anthropic solution, multiverse, Landscape of string theory)**

or the SM **cannot** be considered an **EFFECTIVE THEORY**

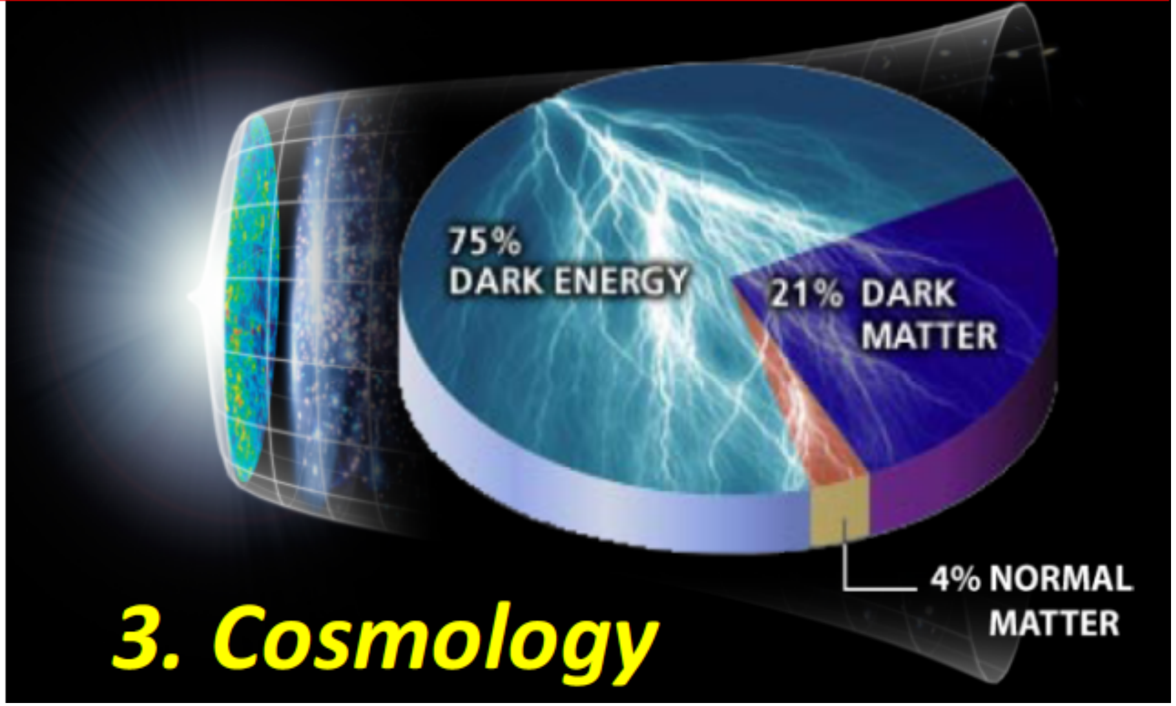
- In physics **properties at an energy scale m << M do not strictly depend on the detailed knowledge (of the parameters) at M** where a “more fundamental” theory sets in (for instance, **to study atomic physics you don’t need a detailed knowledge of the nuclear physics inside the nucleus of the atom**, or to explore nuclear physics you don’t need a detailed knowledge of the QCD (Quantum Chromo-Dynamics) ruling the dynamics of the quarks, etc.) → at each energy scale we consider the effective theory holding at that scale removing all the degrees of freedom related to the physics at a much larger scale (or much smaller distance)
- On the contrary, **the dynamics of the SM**, in particular the scale at which the electroweak symmetry breaking occurs, **would strictly depend on the relations of parameters of a fundamental theory setting in at a scale 16 orders of magnitude larger than the elw. energy scale !**

Going beyond the physics of the Standard Models: the APP 3-pronged approach

1. *High-energy Universe: multi-messengers*



2. *Neutrino's*



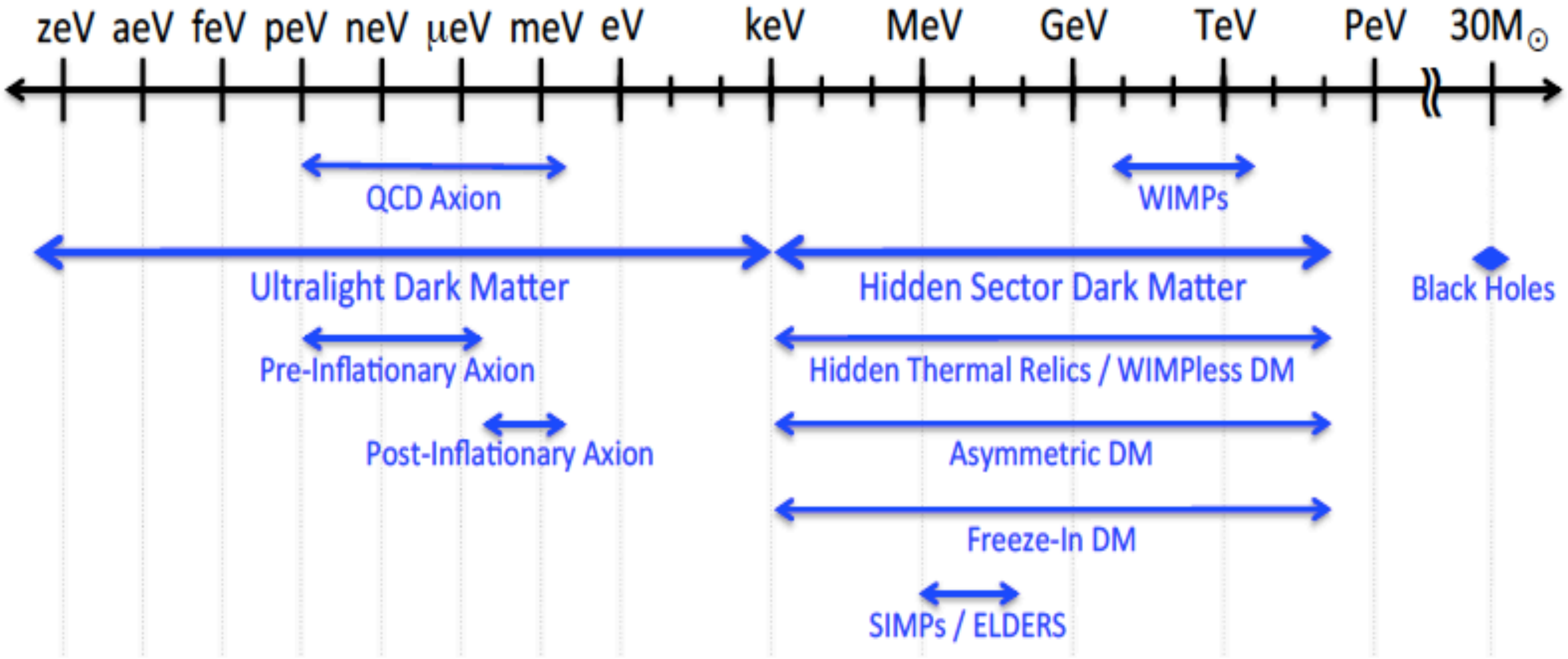
J. de Kleuver

DM and ELW. SYMMETRY BREAKING

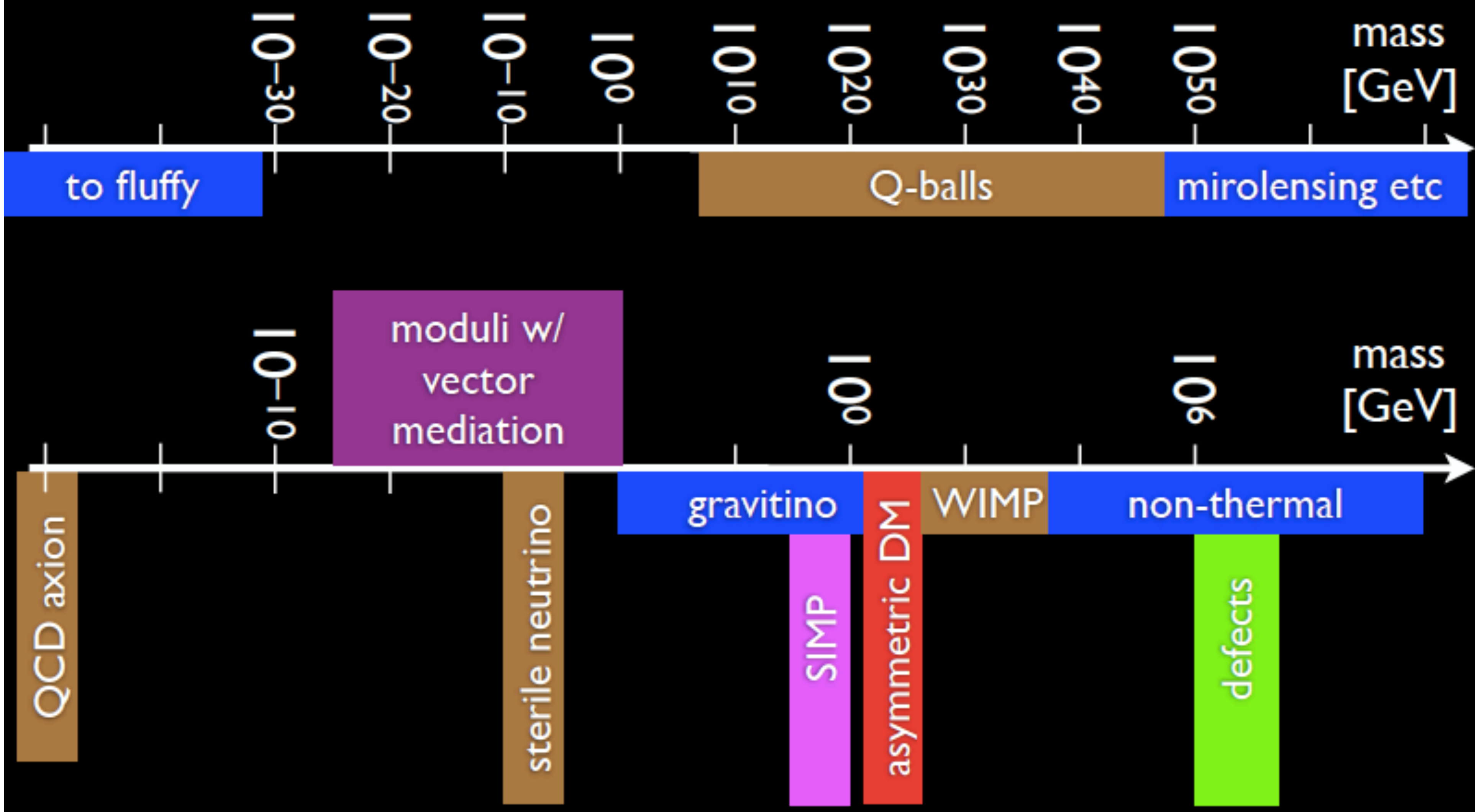
***THE DM ROAD TO NEW PHYSICS BEYOND THE SM*:**

IS **DM** A PARTICLE OF THE ***NEW PHYSICS AT THE ELECTROWEAK ENERGY SCALE*** **?**

Too small mass
⇒ won't "fit"
in a galaxy!



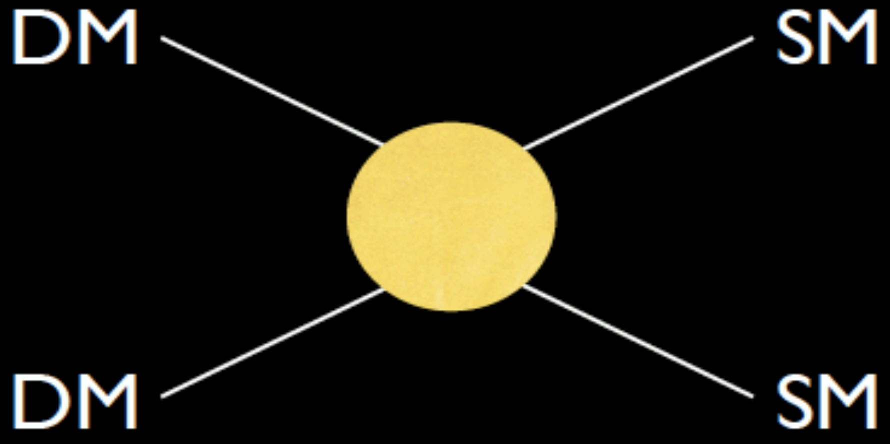
From MACHOs
searches



mass [GeV]
10^{-30}
10^{-20}
10^{-10}
10^{0}
10^{10}
10^{20}
10^{30}
10^{40}
10^{50}
to fluffy
Q-balls
mirolensing etc
mass [GeV]
10^{-10}
moduli w/ vector mediation
10^{0}
10^{6}
QCD axion
sterile neutrino
gravitino
SIMP
asymmetric DM
WIMP
non-thermal
defects

$$\frac{n_{\rm DM}}{s} = 4.4 \times 10^{-10} \frac{\rm GeV}{m_{\rm DM}}$$

WIMP Miracle



$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

$$\alpha \approx 10^{-2}$$

$$m \approx 300 \text{ GeV}$$

"weak" coupling
"weak" mass scale
→ correct abundance

We want new particles for naturalness anyway

Miracle²

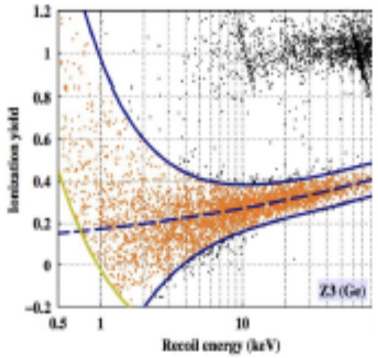
CONNECTION DM – ELW. SCALE

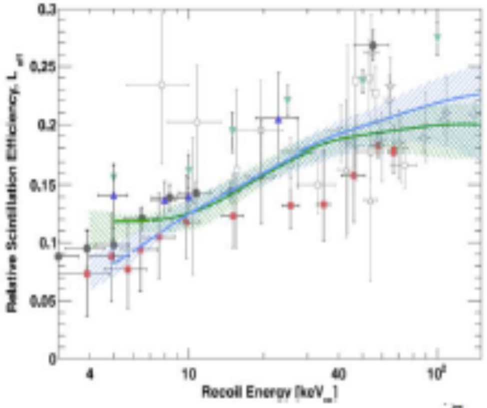
THE WIMP MIRACLE :STABLE ELW. SCALE WIMPs

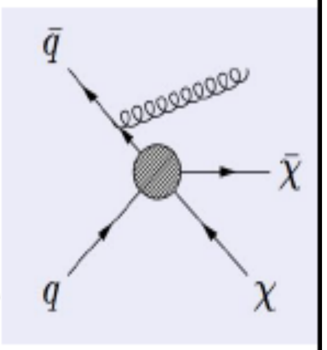
	SUSY	EXTRA DIM.	LITTLE HIGGS.
1) **ENLARGEMENT OF THE SM**	(x^{μ}, θ)	(x^{μ}, j^{i})	SM part + new part
	Anticomm. Coord.	New bosonic Coord.	to cancel Λ^2 at 1-Loop
2) **SELECTION RULE**	***R-PARITY LSP***	***KK-PARITY LKP***	***T-PARITY LTP***
→ **DISCRETE SYMM.**	Neutralino spin 1/2	spin1	spin0
→ **STABLE NEW PART.**	↓	↓	↓
3) FIND REGION (S) PARAM. SPACE WHERE THE “L” NEW PART. IS NEUTRAL + $\Omega_L h^2$ OK	m_{LSP} ~100 - 200 GeV	m_{LKP} ~600 - 800 GeV	m_{LTP} ~400 - 800 GeV

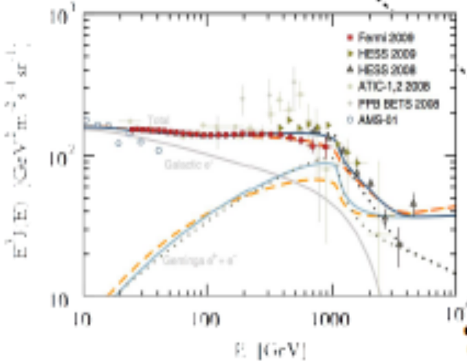
- Uncertainties associated with each technique:

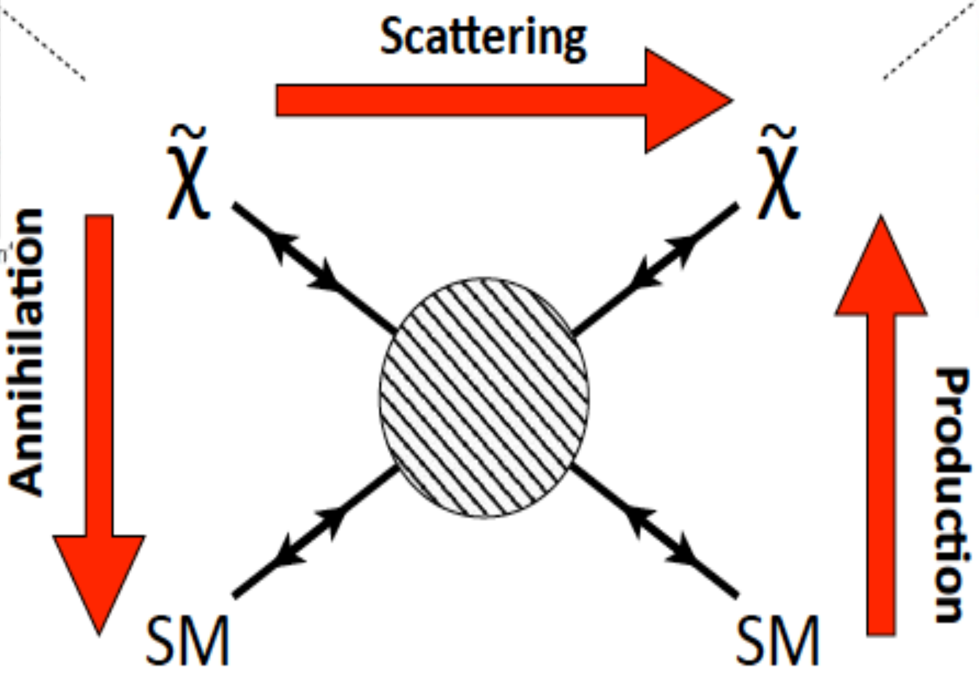
- Backgrounds
- Rate of events
- Local DM distribution

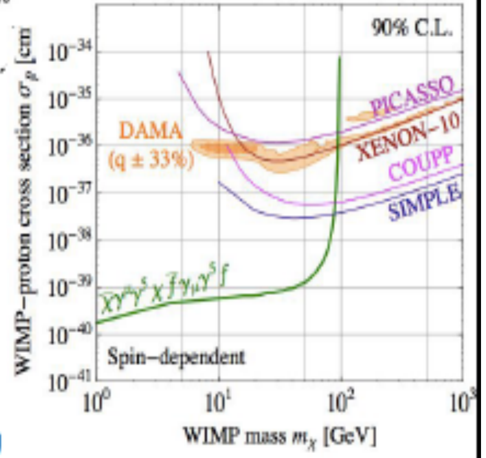






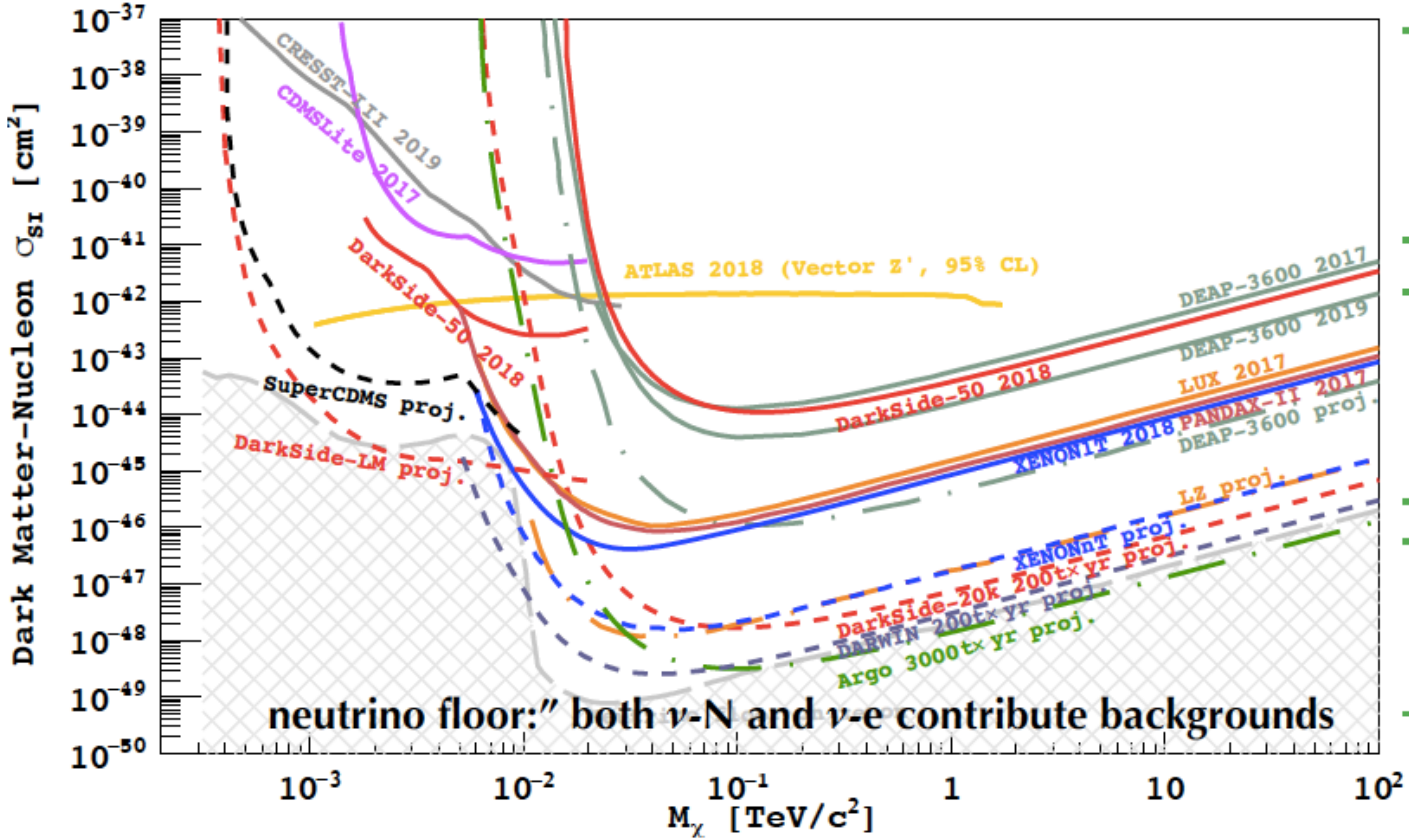






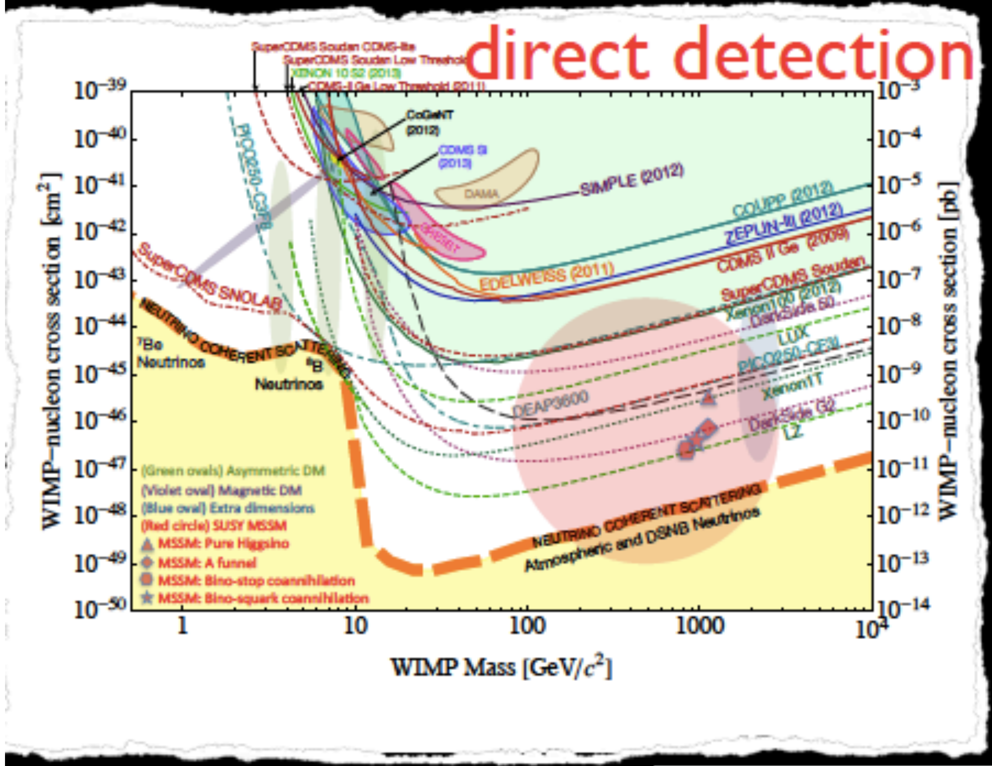
- Astrophysics sources
- Galactic DM distribution
- Annihilation product propagation

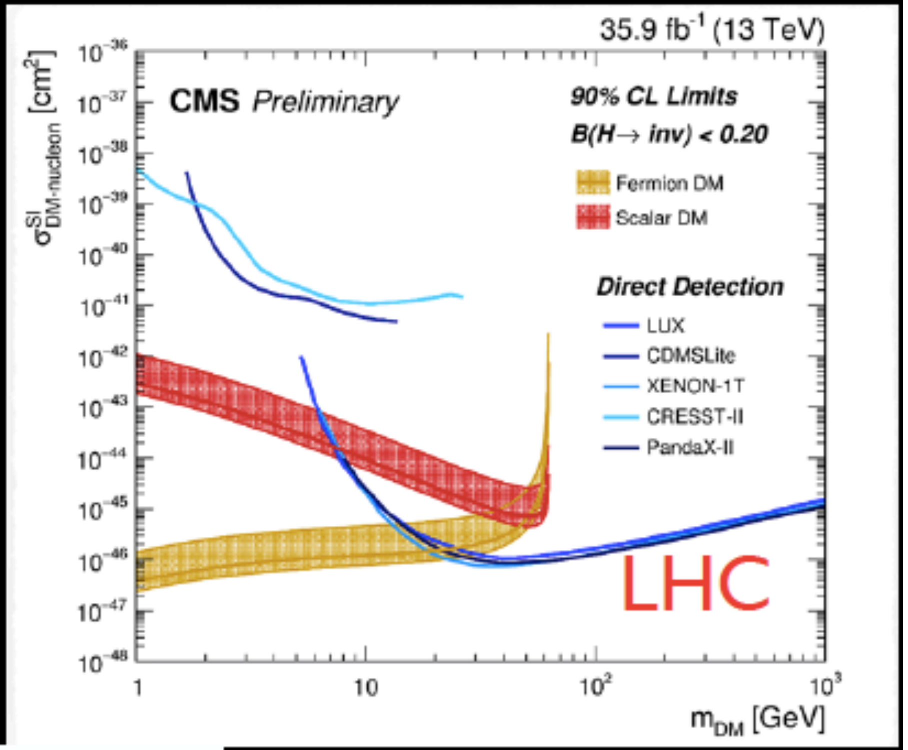
- PP Model assumptions
- Production of Candidates, not DM



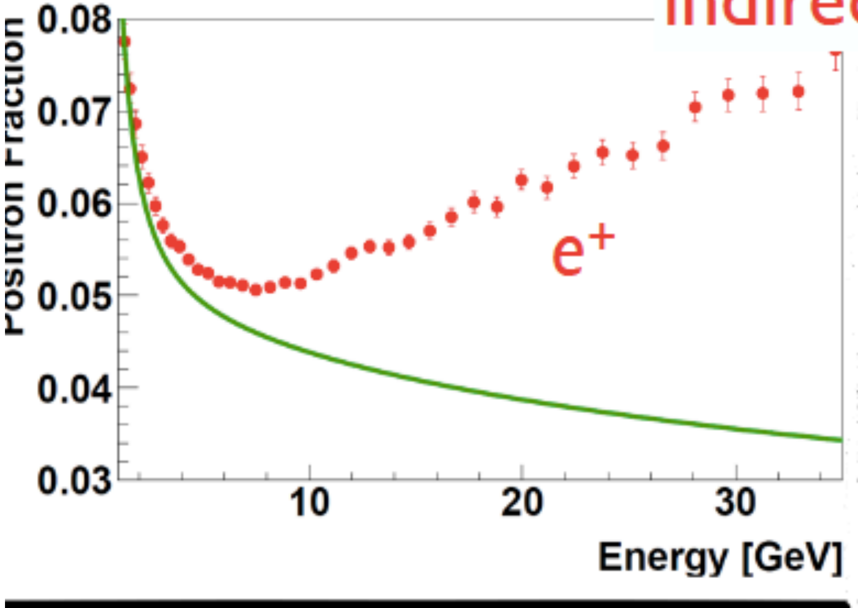
Dark Matter-Nucleon σ_{SI} [cm^2]
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
M_χ [TeV/c^2]
CRESST-III 2019
CDMSLite 2017
DarkSide-50 2018
ATLAS 2018 (Vector Z', 95% CL)
DEAP-3600 2017
DEAP-3600 2019
SuperCDMS proj.
DarkSide-50 2018
LUX 2017
PANDAX-II 2017
DEAP-3600 proj.
XENON1T 2018
DarkSide-LM proj.
LZ proj.
XENONnT proj.
DarkSide-20k 200t× yr proj.
DARWIN 200t× yr proj.
Argo 3000t× yr proj.
neutrino floor:" both ν-N and ν-e contribute backgrounds

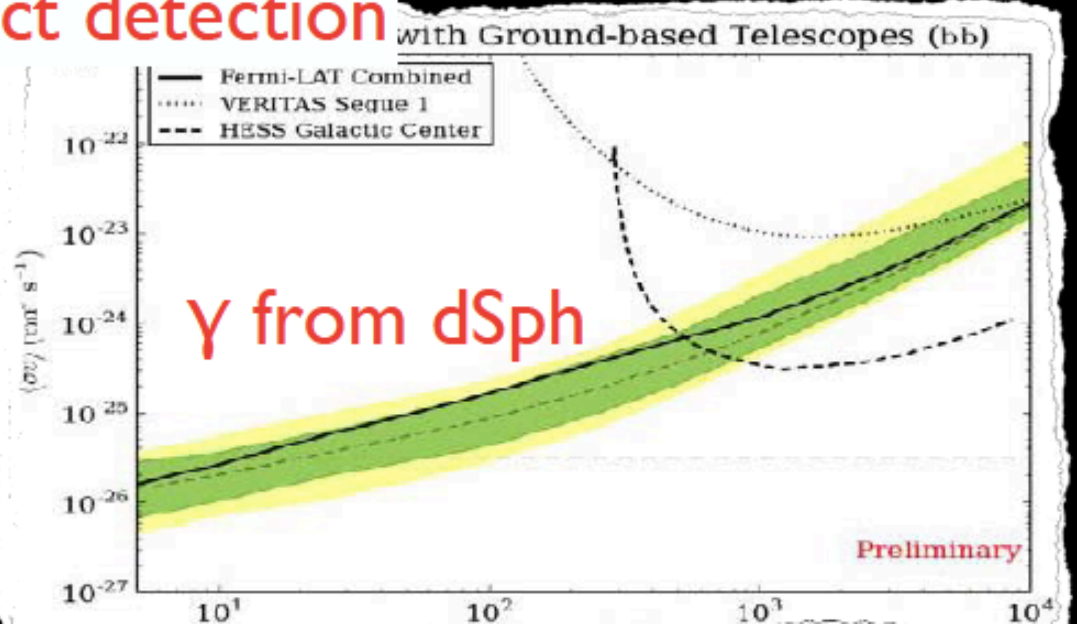
direct detection

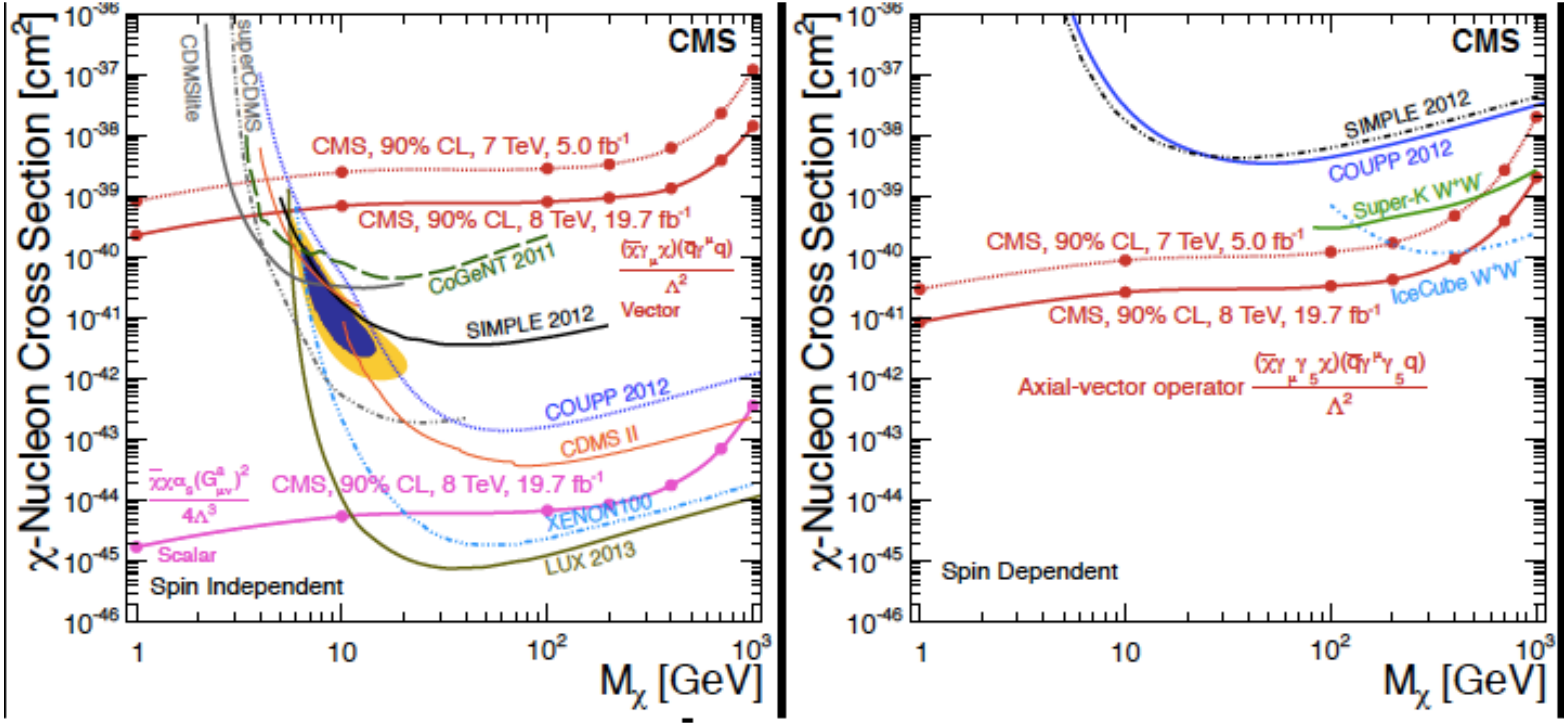




indirect detection







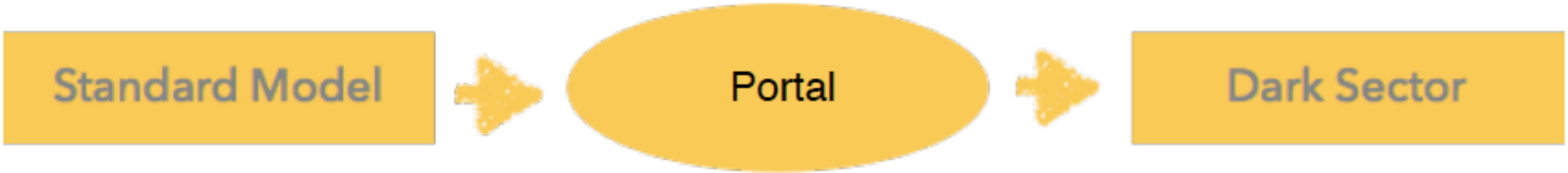
χ-Nucleon Cross Section [cm²]
CMS
CDMSlite
superCDMS
CMS, 90% CL, 7 TeV, 5.0 fb⁻¹
CMS, 90% CL, 8 TeV, 19.7 fb⁻¹
CoGeNT 2011
SIMPLE 2012
Vector
COUPP 2012
CDMS II
XENON100
LUX 2013
Scalar
Spin Independent
Mχ [GeV]
χ-Nucleon Cross Section [cm²]
CMS
SIMPLE 2012
COUPP 2012
Super-K W⁺W⁻
IceCube W⁺W⁻
CMS, 90% CL, 7 TeV, 5.0 fb⁻¹
CMS, 90% CL, 8 TeV, 19.7 fb⁻¹
Axial-vector operator
Spin Dependent
Mχ [GeV]

- WIMP should be explored at least down to the neutrino floor
  - heavier? e.g., wino @ 3TeV
- dark matter definitely exists
  - naturalness problem may be optional?
- need to explain dark matter on its own
- perhaps we should decouple these two
- do we really need big ideas like SUSY?
- perhaps not necessarily heavier but rather lighter and weaker coupling?

Summary talk by Asai and Catena of the DM WG at the EU Strategy Granada Symposium

Dark Sectors

What is meant by a dark sector ?
A Hidden sector, with Dark matter, that talks to us through a Portal



Portal can be the Higgs boson itself or New Messenger/s

Dark sector has dynamics which is not fixed by Standard Model dynamics
→ New Forces and New Symmetries
→ Multiple new states in the dark sector, including Dark Matter candidates

Interesting, distinctive phenomenology
Long-Lived Particles
Feebly interacting particles (FIP's)

Summary talk by Asai and Catena of the DM WG at the EU Strategy Granada Symposium

For the last ~30 years we have been focusing on the WIMP scenario

Our experimental effort is strongly focused on the WIMP!

New production mechanisms and mediation schemes often imply a hidden dark sector. Possibly with complex dynamics.

DARK PHOTON ?

Such hidden sectors often include low scale particles, below the GeV scale.

Very different from the WIMP paradigm!!

Or **very light axions**, or axion-like particles (**ALPs**) or **very heavy**, macroscopic objects DM, for instance **primordial Black Holes**

The muon g-2: the QED contribution

$$a_\mu^{QED} = (1/2)(\alpha/\pi)$$ Schwinger 1948

$$+\ 0.765857426\ (16)\ (\alpha/\pi)^2$$

Sommerfield; Petermann; Suura&Wichmann '57; Elend '66; MP '04

$$+\ 24.05050988\ (28)\ (\alpha/\pi)^3$$

Remiddi, Laporta, Barbieri ... ; Czarnecki, Skrzypek; MP '04;
Friot, Greynat & de Rafael '05, Mohr, Taylor & Newell 2012

$$+\ 130.8780\ (60)\ (\alpha/\pi)^4$$

Kinoshita & Lindquist '81, ... , Kinoshita & Nio '04, '05;
Aoyama, Hayakawa,Kinoshita & Nio, 2007, Kinoshita et al. 2012 & 2015;
Steinhauser et al. 2013, 2015 & 2016 (all electron & τ loops, analytic);
Laporta, PLB 2017 (mass independent term). COMPLETED^2!

$$+\ 750.80\ (89)\ (\alpha/\pi)^5$$ **COMPLETED!**

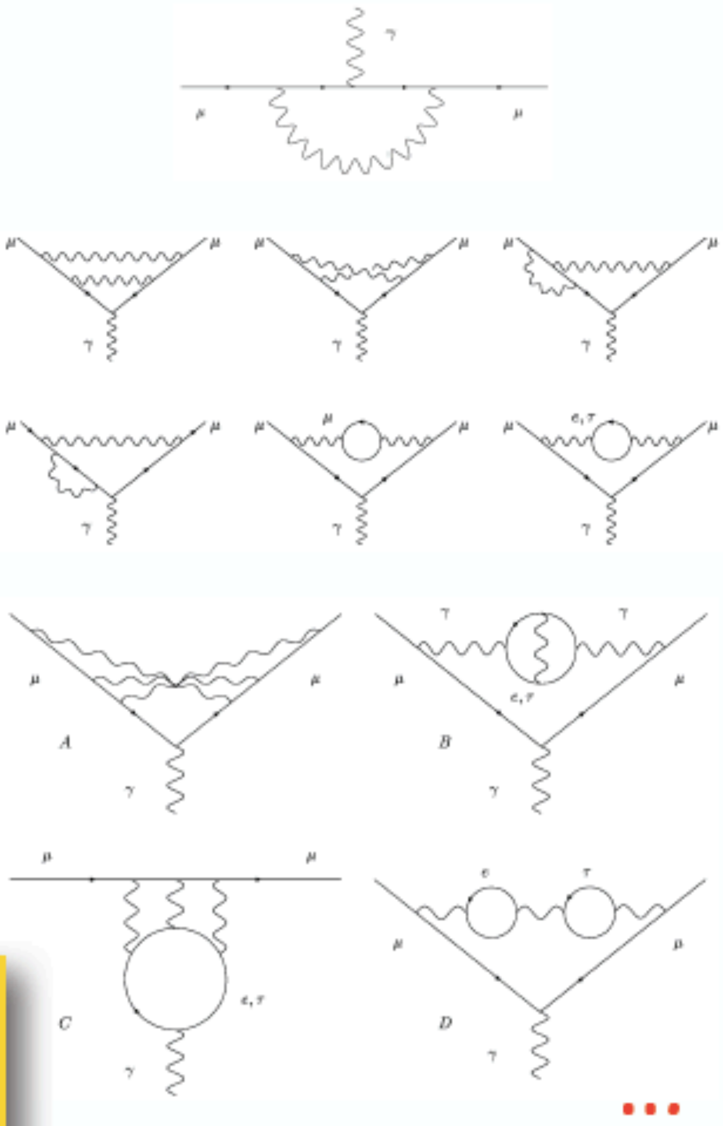
Kinoshita et al. '90, Yelkhovsky, Milstein, Starshenko, Laporta,...
Aoyama, Hayakawa, Kinoshita, Nio 2012 & 2015 & 2017.
Volkov 1905.08007: $A_1^{(10)}$[no lept loops] at variance, but negligible Δ.

Adding up, I get:

$$a_\mu^{QED} = 116584718.932\ (20)(23) \times 10^{-11}$$

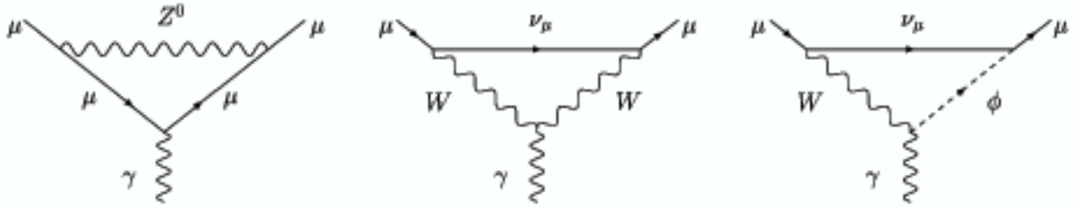
from coeffs, mainly from 4-loop unc ↲ ↳ from α (Cs)

with α=1/137.035999046(27) [0.2ppb] 2018



The muon g-2: the electroweak contribution

- **One-loop term:**



$$a_\mu^{\text{EW}}(\text{1-loop}) = \frac{5 G_\mu m_\mu^2}{24\sqrt{2}\pi^2}\left[1 + \frac{1}{5}\left(1 - 4\sin^2\theta_W\right)^2 + O\left(\frac{m_\mu^2}{M_{Z,W,H}^2}\right)\right] \approx 195\times 10^{-11}$$

1972: Jackiv, Weinberg; Bars, Yoshimura; Altarelli, Cabibbo, Maiani; Bardeen, Gastmans, Lautrup; Fujikawa, Lee, Sanda;

Studenikin et al. '80s

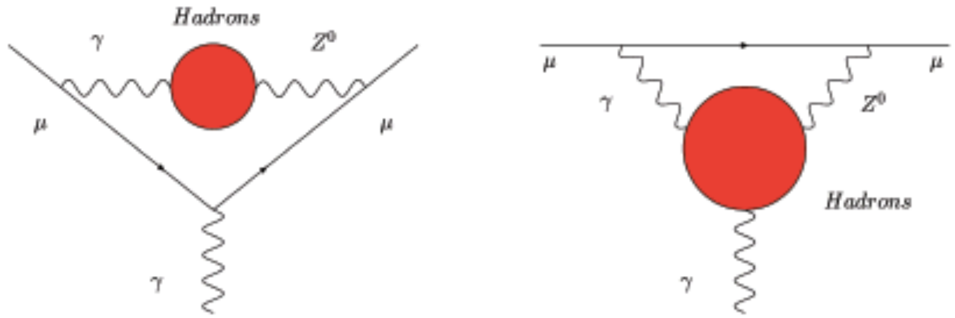
- **One-loop plus higher-order terms:**

a_μ^{EW} = 153.6 (1) x 10^{-11}

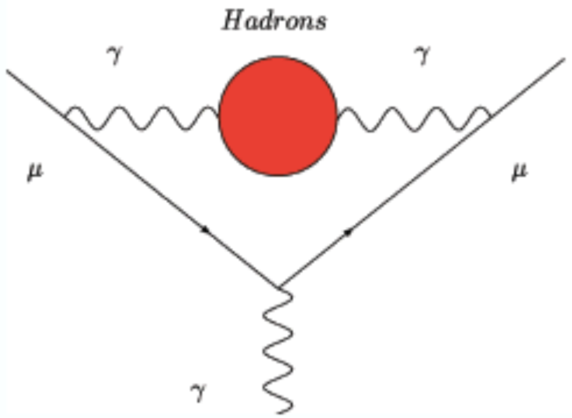
with M_{Higgs} = 125.6 (1.5) GeV

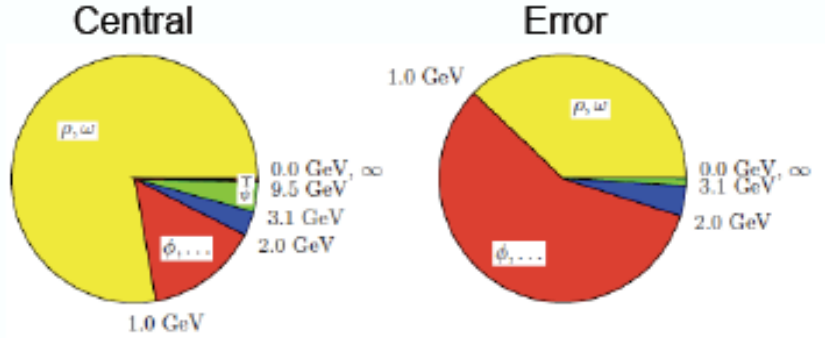
Hadronic loop uncertainties and 3-loop nonleading logs.

Kukhto et al. '92; Czarnecki, Krause, Marciano '95; Knecht, Peris, Perrottet, de Rafael '02; Czarnecki, Marciano and Vainshtein '02; Degrassi and Giudice '98; Heinemeyer, Stockinger, Weiglein '04; Gribouk and Czarnecki '05; Vainshtein '03; Gnendiger, Stockinger, Stockinger-Kim 2013.



The muon g-2: the Hadronic LO contribution (HLO)





F. Jegerlehner and A. Nyffeler, Phys. Rept. 477 (2009) 1

$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2 + (1-x)(s/m^2)} \qquad a_\mu^{\text{HLO}} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma^{(0)}(s) = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} \frac{ds}{s} K(s) R(s)$$

$a_\mu^{\text{HLO}} = 6894.6\ (32.5) \times 10^{-11}$ — F. Jegerlehner, arXiv:1711.06089

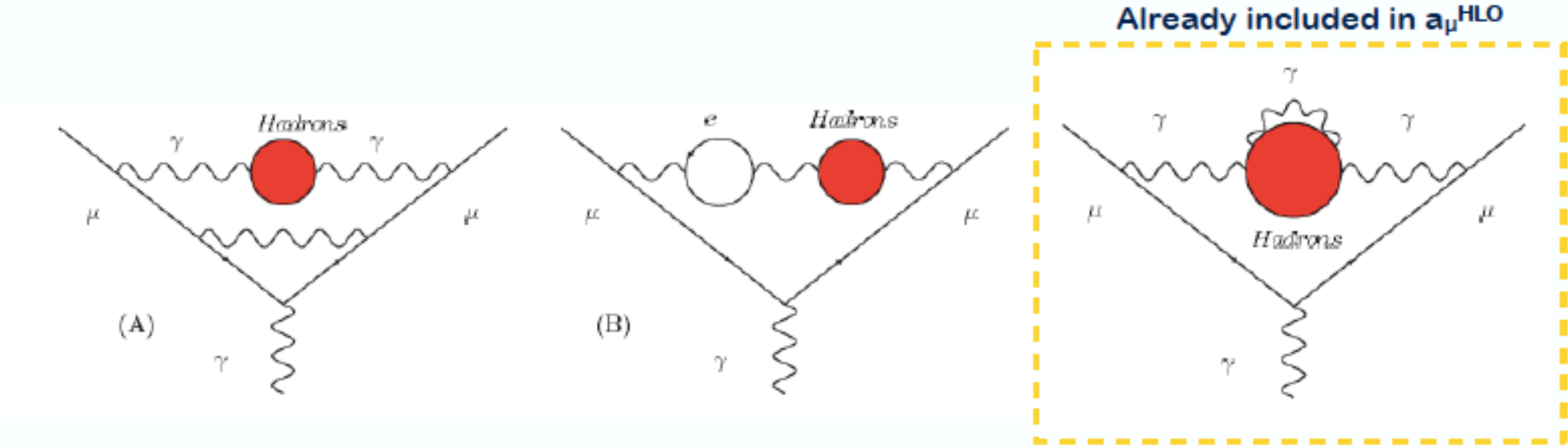
$= 6931\ (34) \times 10^{-11}$ — Davier, Hoecker, Malaescu, Zhang, arXiv:1706.09436

$= 6932.7\ (24.6) \times 10^{-11}$ — Keshavarzi, Nomura, Teubner, arXiv:1802.02995

- **Radiative Corrections are crucial.** S. Actis et al, Eur. Phys. J. C66 (2010) 585
- **Lots of progress in lattice calculations.** Muon g-2 Theory Initiative

See Colangelo's talk

- **HNLO: Vacuum Polarization**



O(α^3) contributions of diagrams containing hadronic vacuum polarization insertions:

$$a_\mu^{HNLO}(vp) = -99.27\ (67) \times 10^{-11}$$

Krause '96, Alemany et al. '98, Hagiwara et al. 2011, Jegerlehner 2017

The muon g-2: SM vs. Experiment

Comparisons of the SM predictions with the measured g-2 value:

$a_\mu^{EXP} = 116592091\ (63) \times 10^{-11}$

E821 – Final Report: PRD73 (2006) 072 with latest value of $\lambda = \mu_\mu/\mu_p$ from CODATA'10

$a_\mu^{SM} \times 10^{11}$	$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM}$	σ
116 591 783 (44)	$308\ (77) \times 10^{-11}$	4.0 [1]
116 591 820 (45)	$271\ (77) \times 10^{-11}$	3.5 [2]
116 591 821 (38)	$270\ (74) \times 10^{-11}$	3.7 [3]

with the hadronic light-by-light $a_\mu^{HNLO}(lbl) = 100\ (29) \times 10^{-11}$ of F. Jegerlehner arXiv:1705.00263, and the hadronic leading-order of:

[1] F. Jegerlehner, arXiv:1711.06089.
[2] Davier, Hoecker, Malaescu, Zhang, arXiv:1706.09436.
[3] Keshavarzi, Nomura, Teubner, arXiv:1802.02995.

The SM prediction of the electron g-2

- The SM prediction is:

$$a_e^{SM}(\alpha) = a_e^{QED}(\alpha) + a_e^{EW} + a_e^{HAD}$$

- The EW (1&2 loop) term is: Czarnecki, Krause, Marciano '96, Jegerlehner 2017

$$a_e^{EW} = 0.3053\,(23) \times 10^{-13}$$

- The Hadronic contribution, at LO+NLO+NNLO, is:

Nomura & Teubner '12, Jegerlehner 2017; Krause'97; Kurz, Liu, Marquard & Steinhauser 2014

$$a_e^{HAD} = 16.93\,(12) \times 10^{-13}$$

$$a_e^{HLO} = +\,18.490\,(108) \times 10^{-13}$$

$$a_e^{HNLO} = [-2.213(12)_{vac} + 0.37(5)_{lbl}] \times 10^{-13}$$

$$a_e^{HNNLO} = +\,0.28\,(1) \times 10^{-13}$$

- Which value of α should we use to compute a_e^{SM}?

$(g-2)_e$ no longer gives the best value of α

e

- The 2008 measurement of the electron g-2 is:

  $a_e^{EXP} = 11596521807.3\ (2.8) \times 10^{-13}$ Hanneke et al, PRL100 (2008) 120801

  vs. old (factor of 15 improvement, 1.8σ difference):

  $a_e^{EXP} = 11596521883\ (42) \times 10^{-13}$ Van Dyck et al, PRL59 (1987) 26

- Equate $a_e^{SM}(\alpha) = a_e^{EXP}$ → "g_e-2" determination of alpha:

$$\alpha^{-1} = 137.035\,999\,149\,(33) \quad [0.24 \text{ ppb}]$$

- Compare it with the best determination of alpha:

$$\alpha^{-1} = 137.036\,999\,046\,(27) \quad [0.20 \text{ ppb}]$$ Science 360 (2018) 191 (Cs)

(was α^{-1} =137.035 998 995 (85) [0.62 ppb] PRL106 (2011) & CODATA 2016)

2.4 sigma discrepancy

The electron g-2: SM vs Experiment

- Using α = 1/137.036 999 046 (27) [Cs 2018], the SM prediction for the electron g-2 is:

$$a_e^{SM} = 115\,965\,218\,16.0\,(0.1)\,(0.1)\,(2.3) \times 10^{-13}$$

δC_5^{qed} δa_e^{had} from $\delta\alpha$

- The (EXP - SM) difference is:

$$\Delta a_e = a_e^{EXP} - a_e^{SM} = -\,8.7\,(3.6) \times 10^{-13}$$

i.e. 2.4 sigma difference. Note the negative sign!
(the 5-loop contrib. to a_e^{QED} is 4.5 x 10^{-13})

- The present sensitivity is $\delta\Delta a_e = 3.6 \times 10^{-13}$, ie ($10^{-13}$ units):

$$\underbrace{(0.1)_{\text{QED5}}, \quad (0.1)_{\text{HAD}},}_{(0.2)_{\text{TH}}} \quad (2.3)_{\delta\alpha}, \quad (2.8)_{\delta a_e^{\text{EXP}}}$$

- The $(g\text{-}2)_e$ exp. error may soon drop below 10^{-13} and work is in progress to further reduce the error induced by $\delta\alpha$ →

sensitivity below 10^{-13} may be reached with ongoing exp work

- In a broad class of BSM theories, contributions to a_l scale as

$$\frac{\Delta a_{\ell_i}}{\Delta a_{\ell_j}} = \left(\frac{m_{\ell_i}}{m_{\ell_j}}\right)^2$$

This Naive Scaling leads to:

$$\Delta a_e = \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 0.7 \times 10^{-13}; \qquad \Delta a_\tau = \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 0.8 \times 10^{-6}$$

Giudice, Paradisi & MP, JHEP 2012

Testing new physics with the electron g-2 (2)

- The sensitivity in Δa_e may soon be 10^{-13} or better! This will bring a_e to play a pivotal role in probing new physics in the leptonic sector.

- NP scenarios exist which violate Naive Scaling. They can lead to larger effects in Δa_e and contributions to EDMs, LFV or lepton universality breaking observables.

Giudice, Paradisi & MP, JHEP 2012
Crivellin, Hoferichter, Schmidt-Wellenburg, PRD 2018

- One real scalar with a mass of ~ 250−1000 MeV could explain the deviations in a_μ and a_e, through one- and two-loop processes, respectively.

Davoudiasl & Marciano, PRD 2018

New physics Λ energy scale and $(g-2)_\mu$

If New Physics (NP) at a scale Λ gives the contribution δm_μ to the muon mass, then such NP leads to a loop contribution to the muon magnetic moment a_μ :

$$a_\mu(\mathrm{N.P.}) = \mathcal{O}(1) \times \left(\frac{m_\mu}{\Lambda}\right)^2 \times \left(\frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}\right)$$

Czarnecky and Marciano, 2001; Stockinger 2010

$\frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}$ ~ O(α/4π) if perturbative contributions to the muon mass

$\frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}$ ~ O (1) if the muon mass is radiatively induced

$$\Delta a_\mu = a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = 2.87\,(80) \times 10^{-9}$$

If the g-2 discrepancy between exp. and SM expectation is a real fact and if we invoke NP to account for it, then

Λ NP has to be at or below the TeV scale !

Minimal extensions of the SM to account for the $(g-2)_\mu$ anomaly

Addition of a **SINGLE NEW FIELD**:

i) The addition of a **single fermion** cannot explain this anomaly ;

(C. Biggio 2008; Freitas, Lykken, Kell, Westhoff 2014; Biggio, Bordone 2014)

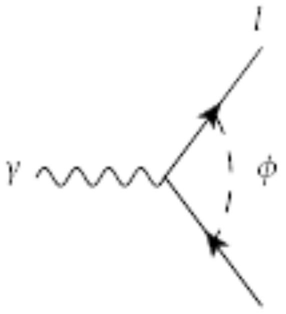
ii) The addition of a **single scalar** can account for the discrepancy if the new scalar is:

a **new Higgs doublet**; (Freitas, Lykken, Kell, Westhoff 2014; Broggio, Chun, Passera, Patel, Vempati 2014; Biggio, Bordone 2014; Cherchiglia, Kneschke, Stockinger, Stockinger-Kim 2017)

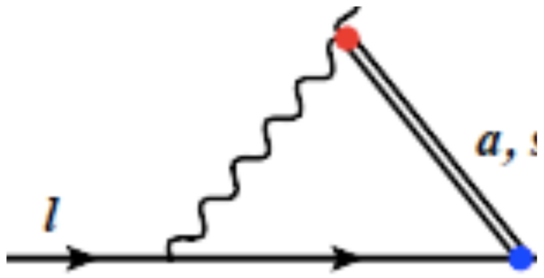
one of the two **leptoquarks**: $S^{1/3}(3, 1, -1/3; Q= -1/3)$; $D^{7/6}(3,2, 7/6; Q = 5/3, 2/3)$ Chakraverty, D. Choudhuri, Datta 2001; Biggio, Bordone 2014; Queiroz, Shepherd 2014; Coluccio Leskow, D'Ambrosio, Crivellin, Muller 2017

- **iii)** one massive **vector boson**: only possibility → abelian gauge extensions – Z’, dark photon (Biggio, Bordone, Di Luzio, Ridolfi 2016; Davoudiasl, H.-S.Lee, Marciano 2014; Altmannshofer, C.-Y. Chen, Dev, Soni 2016;)
- **iv) ALPs (ALP-photon photon + ALP Yukawa interactions with leptons)**

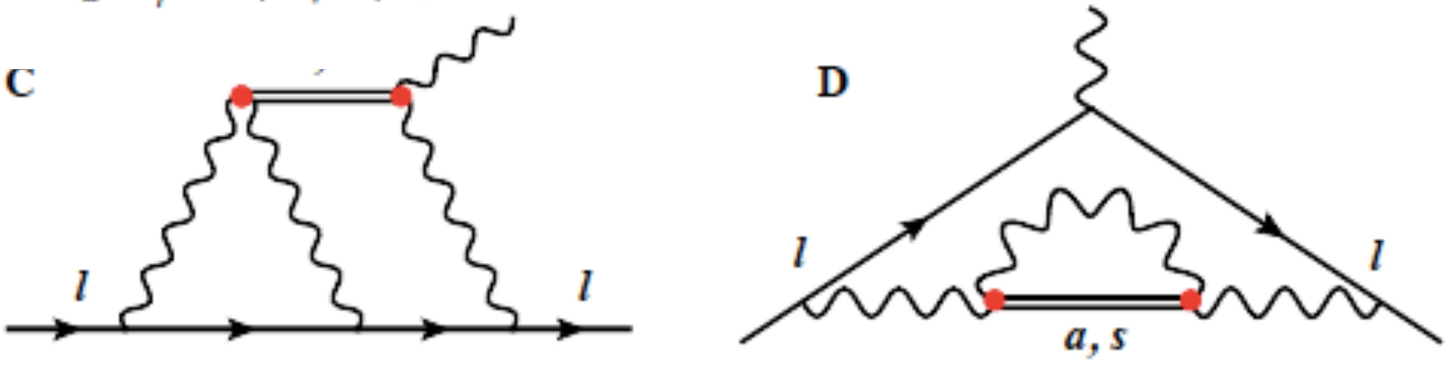
$$\mathcal{L} = \frac{1}{4} g_{a\gamma\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + i\, y_{a\psi}\, a\, \bar{\psi}\gamma_5\psi$$



Chen, Davoudiasl, Marciano, Zhang 2016



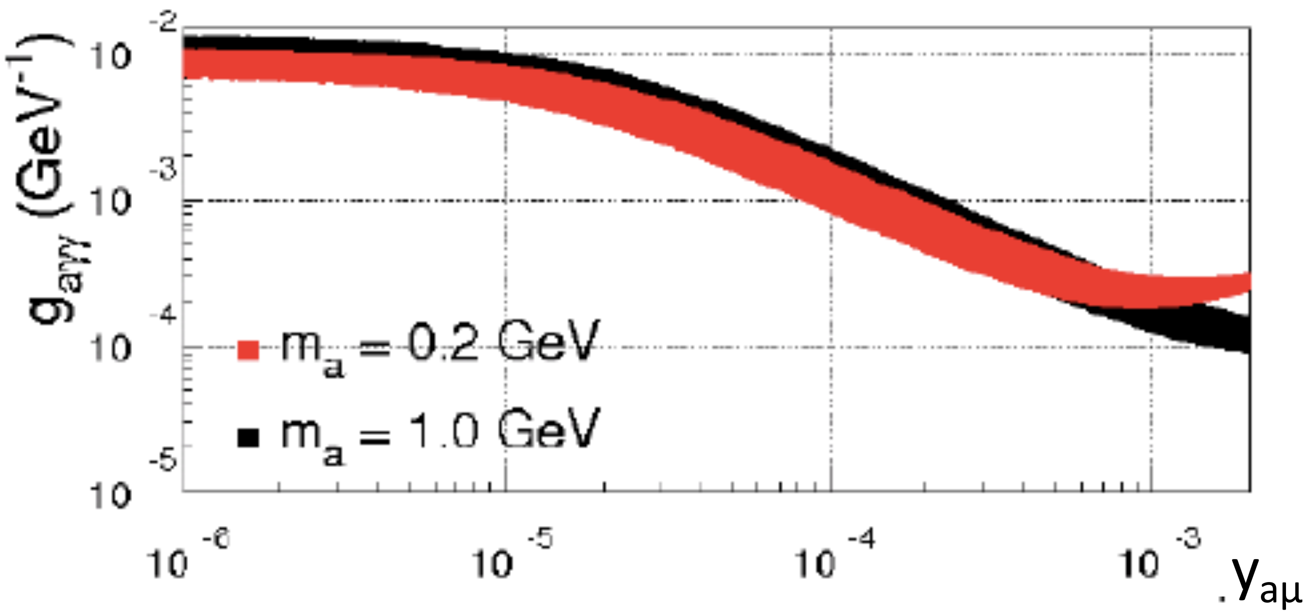
One-loop contribution



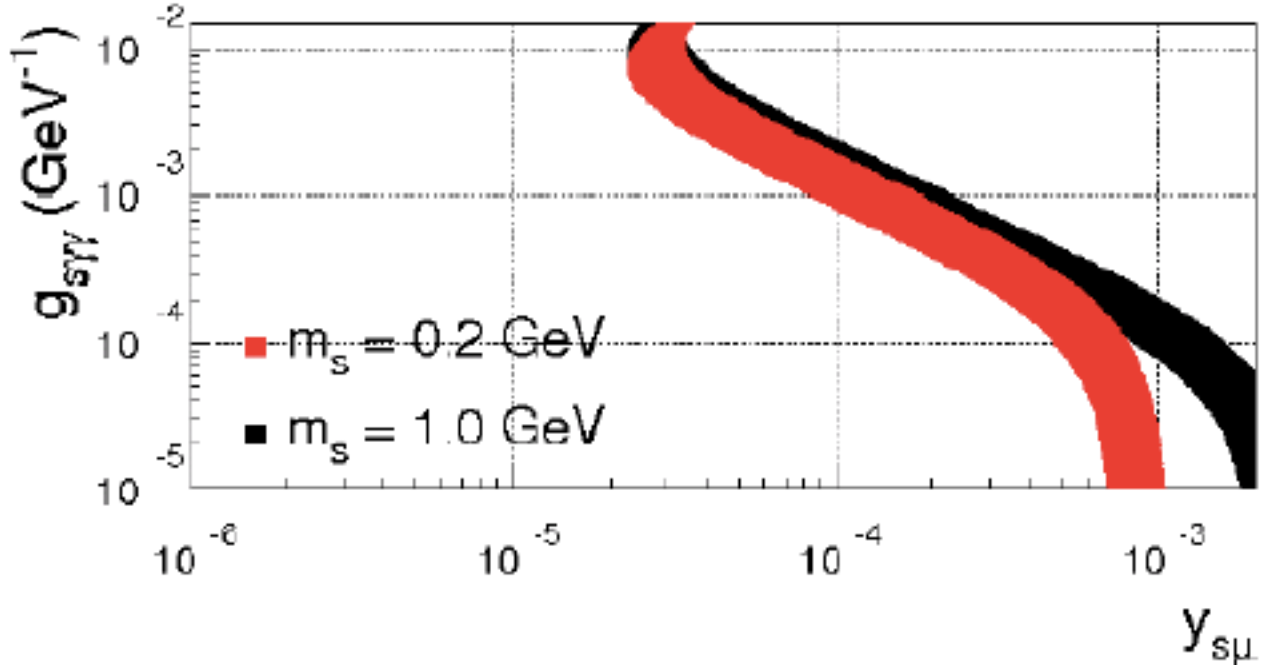
Two-loop contributions

Marciano, Masiero, Paradisi, Passera 2016

Marciano, Masiero, Paradisi, Passera 2016



Pseudoscalar 1σ solution bands to the g-2 muon anomaly taking Λ = 1 TeV



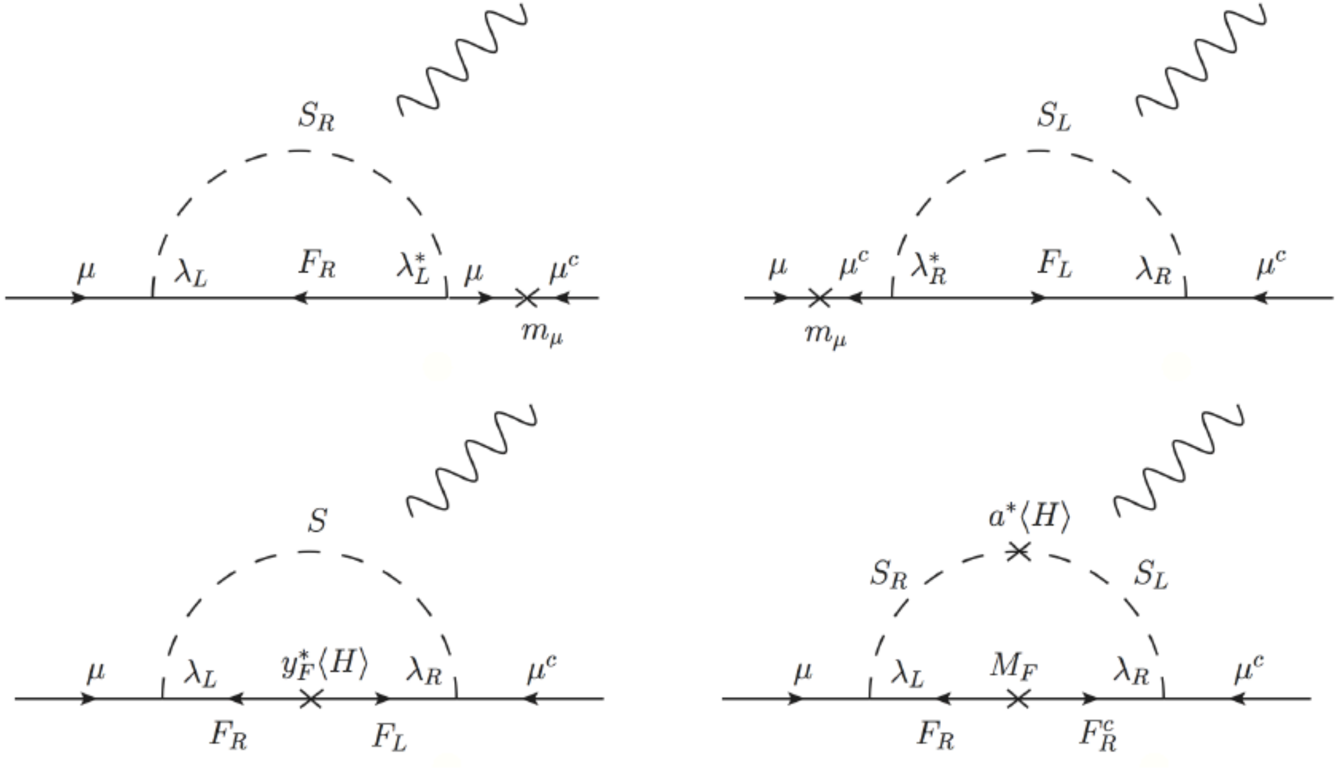
Scalar 1σ solution bands to the g-2 muon anomaly taking Λ = 1 TeV

DM and g-2 as windows to New Physics

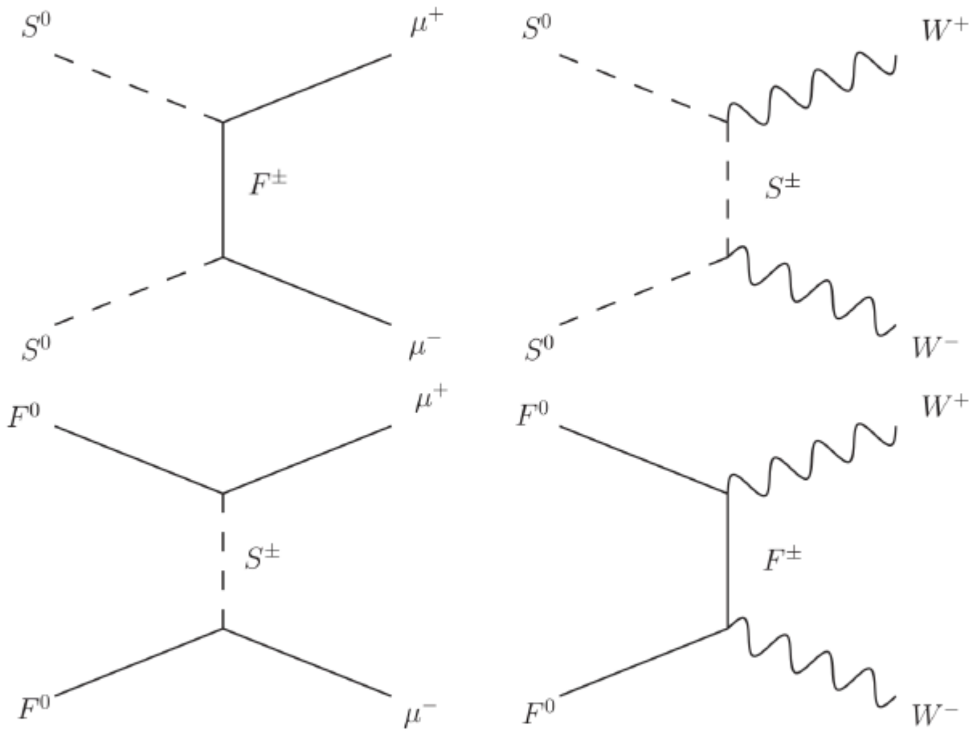
- **Minimal extensions of the SM to account for the DM**: one additional field that being neutral and stable might have been in thermal equilibrium interacting with ordinary matter and today have the correct density to account for the DM
- **Minimal extensions of the SM to account for the g-2 anomaly**: one single additional field (leptoquark or additional Higgs doublet or ALPs) coupling sizeably to leptons and/or photons
- Is it possible to have just one single additional field to account for both the DM **and** the g-2 anomaly? No, the DM fields in these minimal SM extensions decay too quickly to ordinary matter particles. **One needs at least two new fields** (for instance one additional fermion and one additional scalar)

Calibbi, Ziegler, Zupan 2018

Models without and with Higgs insertion

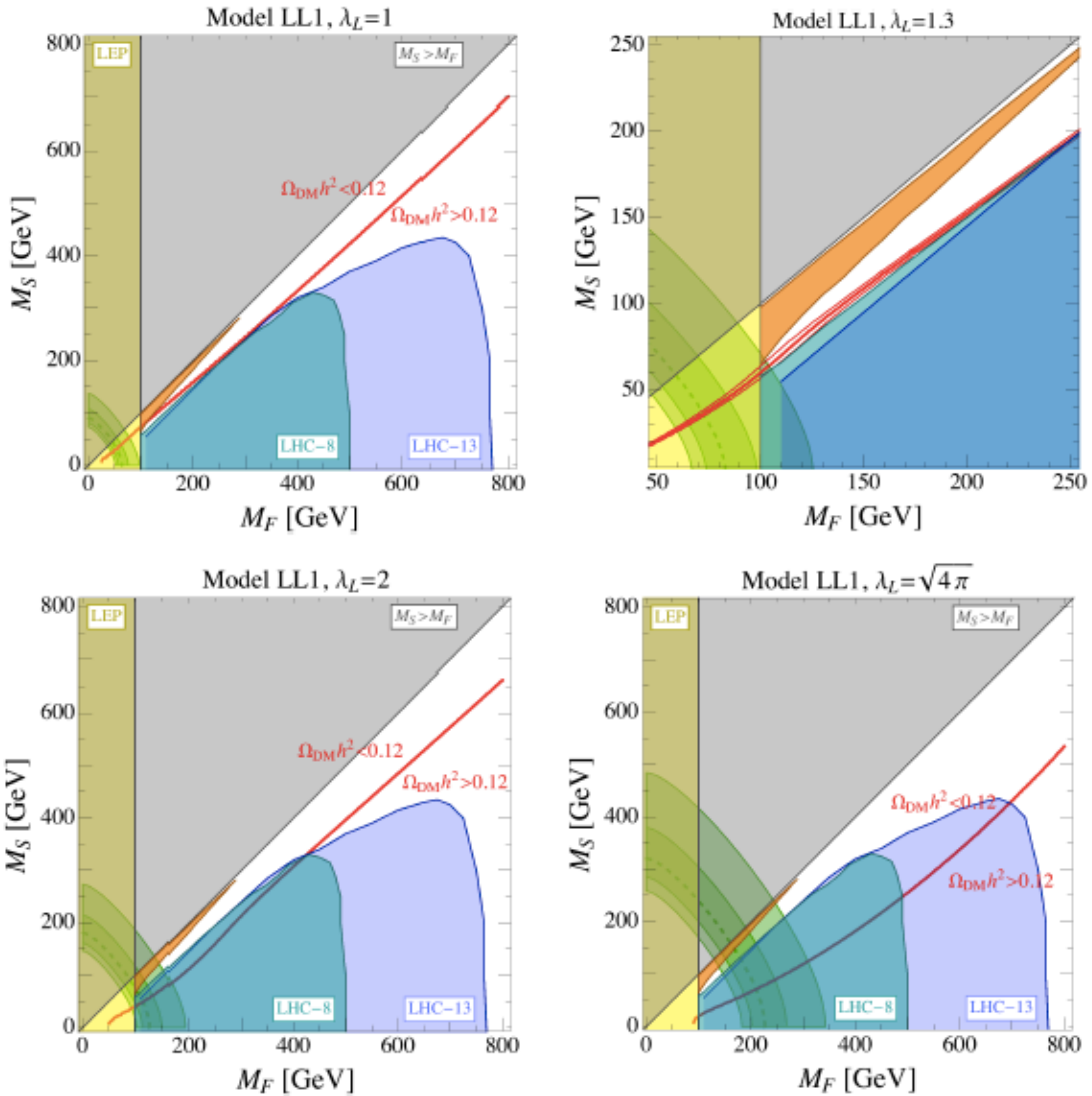


F-S one-loop contribution to g-2



DM annihilations into ordinary matter

Calibbi, Ziegler, Zupan 2018

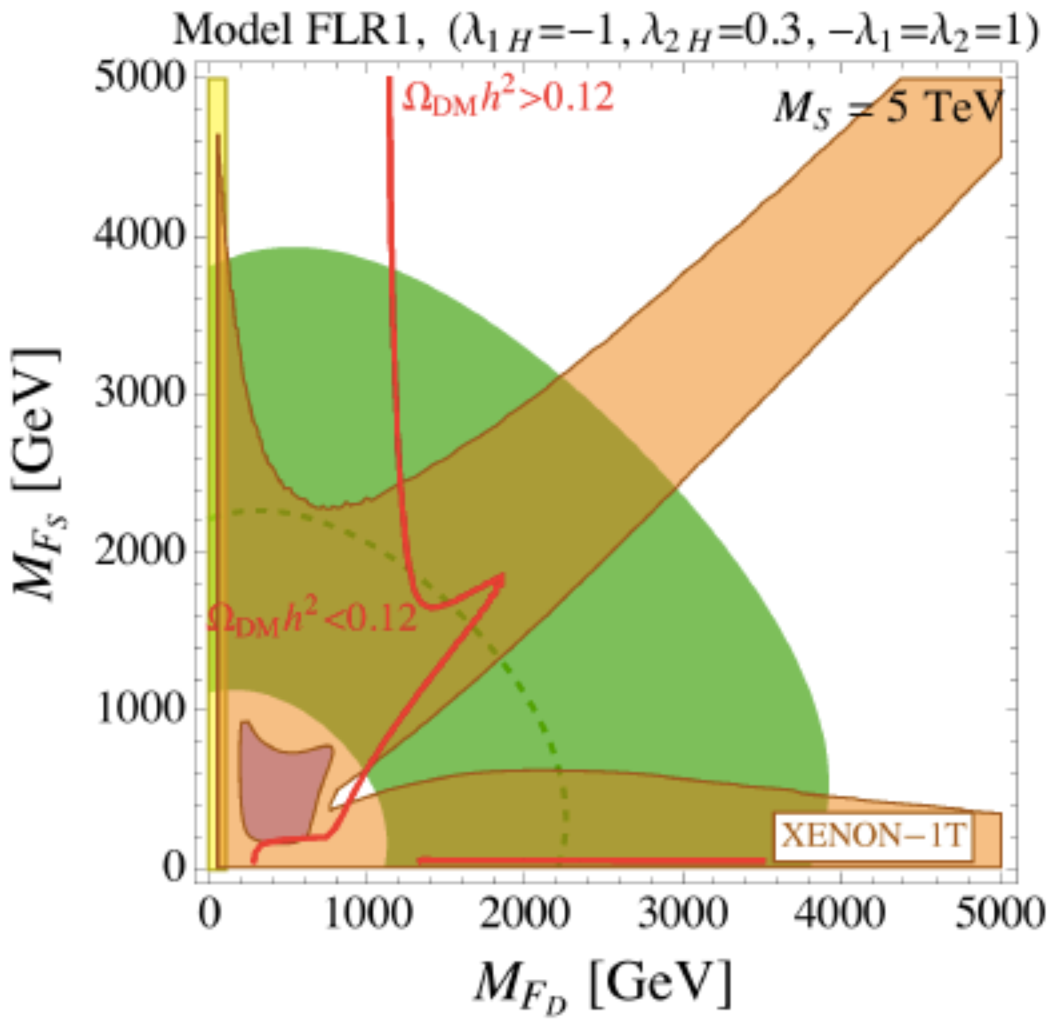


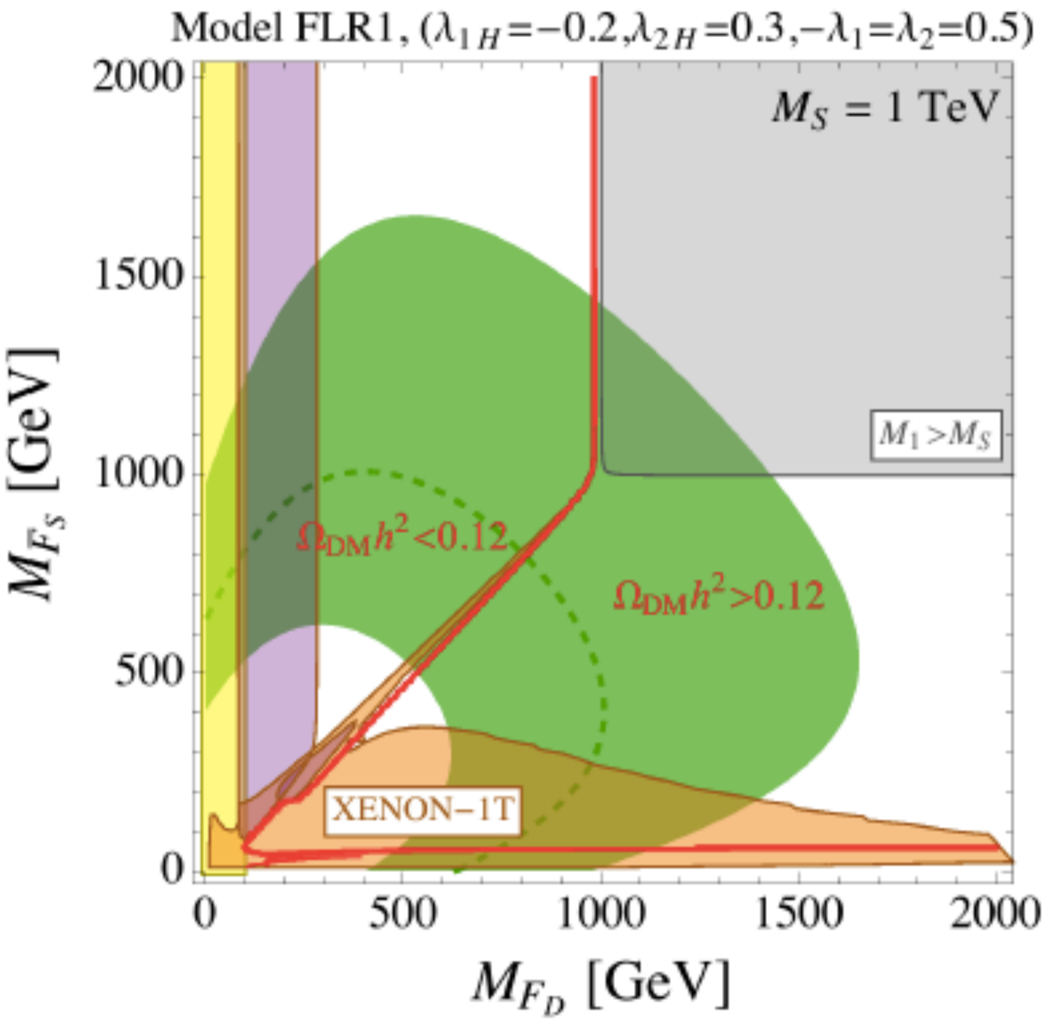
Models without Higgs insertion

Dark (light) green region → total contribution to g-2 compatible at 1 (2) σ with the experimental result

Calibbi, Ziegler, Zupan 2018

Models with Higgs insertion





Calibbi, Ziegler, Zupan 2018

Two leptonic g-2 anomalies ?

Recent (Parker et al. 2018) more precise determination of the fine structure constant

$$\alpha^{-1}(\mathrm{Cs}) = 137.035999046(27)$$

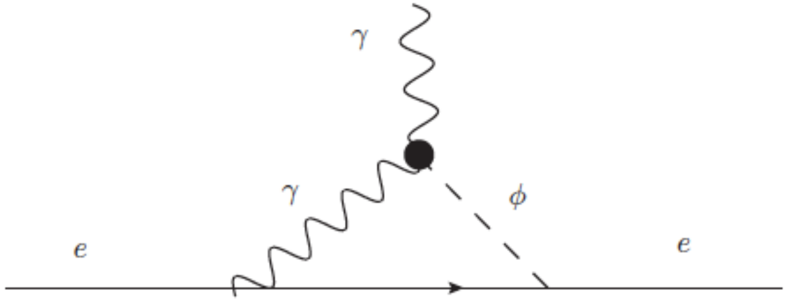
2.4 σ discrepancy (opposite in sign w.r.t. to the muon case)

$$\begin{aligned} \Delta a_e &\equiv a_e^{\mathrm{exp}} - a_e^{\mathrm{SM}} \\ &= [-87 \pm 28\,(\mathrm{exp}) \pm 23\,(\alpha) \pm 2\,(\mathrm{theory})] \\ &\times\ 10^{-14}, \end{aligned}$$

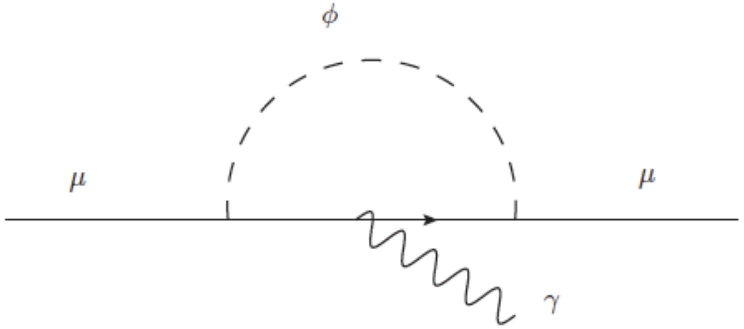
$$\Delta a_e = (-87 \pm 36) \times 10^{-14}$$

A single scalar solution to both anomalies?

Yes, if the the **two-loop Barr-Zee diagrams**



dominate over the one loop scalar contributions to the $(g\text{-}2)_e$



with relatively large couplings to the electron and the two photons

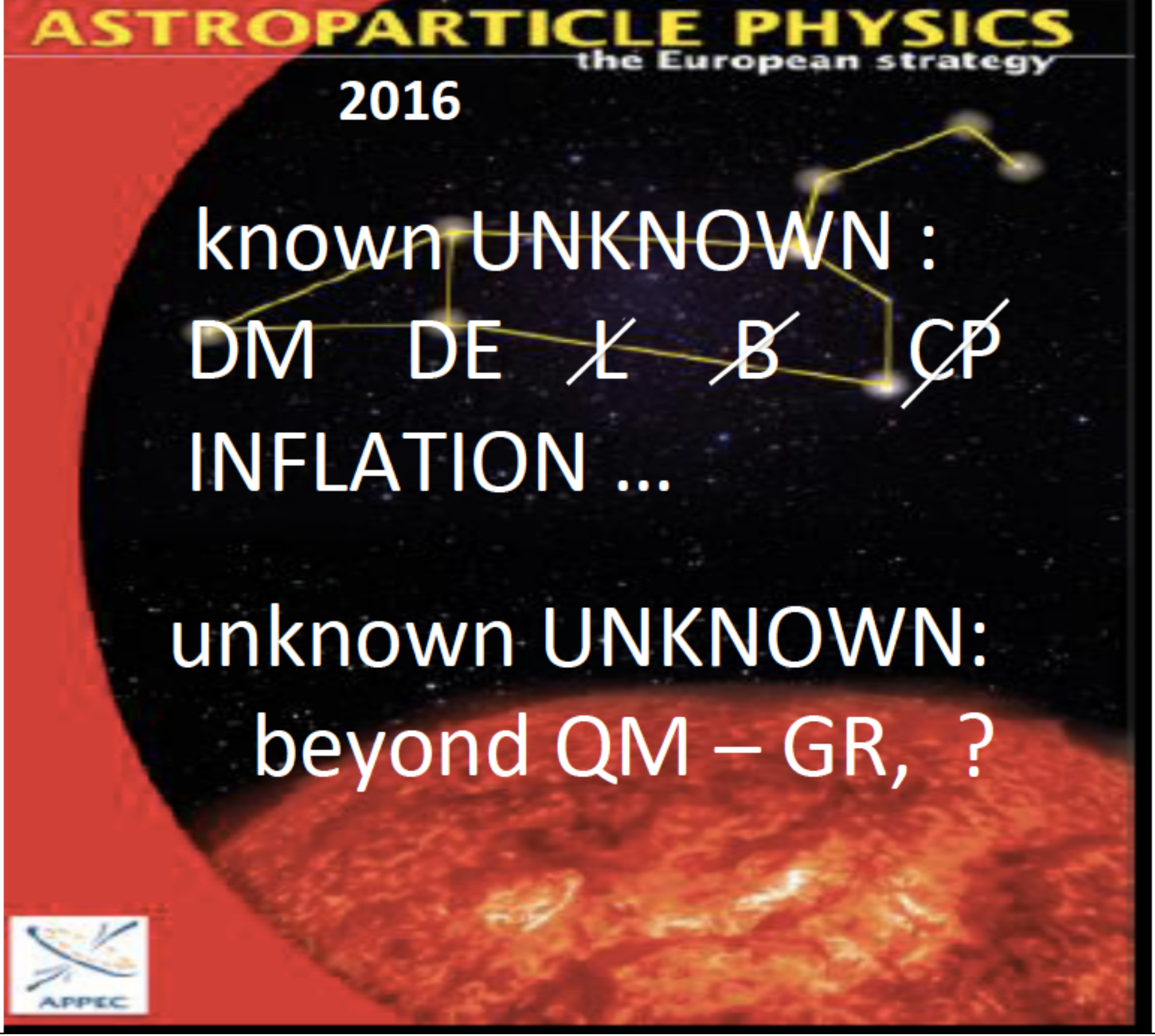
Davoudiasl and Marciano 2018

Combined explanation of $(g\text{-}2)_e$ AND $(g\text{-}2)_\mu$ with a large muon EDM

- EFT analysis (Crivellin and Hoferichter, May 2019)

Simultaneous explanation possible in models with chiral enhancement But, very important, one needs a **DECOUPLING** of the electron and muon BSM sectors to avoid the very stringent limit on **BR ($\mu \rightarrow e + X$)**

Such decoupling entails that **there is no correlation between the EDMs of the electron and muon**, i.e. the very stringent bound on d_e does not necessarily imply a very small d_μ


ASTROPARTICLE PHYSICS
the European strategy
2016
known UNKNOWN :
DM DE ~~L~~ ~~B~~ ~~CP~~
INFLATION ...
unknown UNKNOWN:
beyond QM – GR, ?
APPEC

Post – LHC physics