GIORNATE DI STUDIO SUL PIANO TRIENNALE 2020-2022 DELL'INFN
Bari, 8 -9 novembre 2019

NUOVA FISICA, dove sei ??

Antonio Masiero
INFN e Univ. di Padova

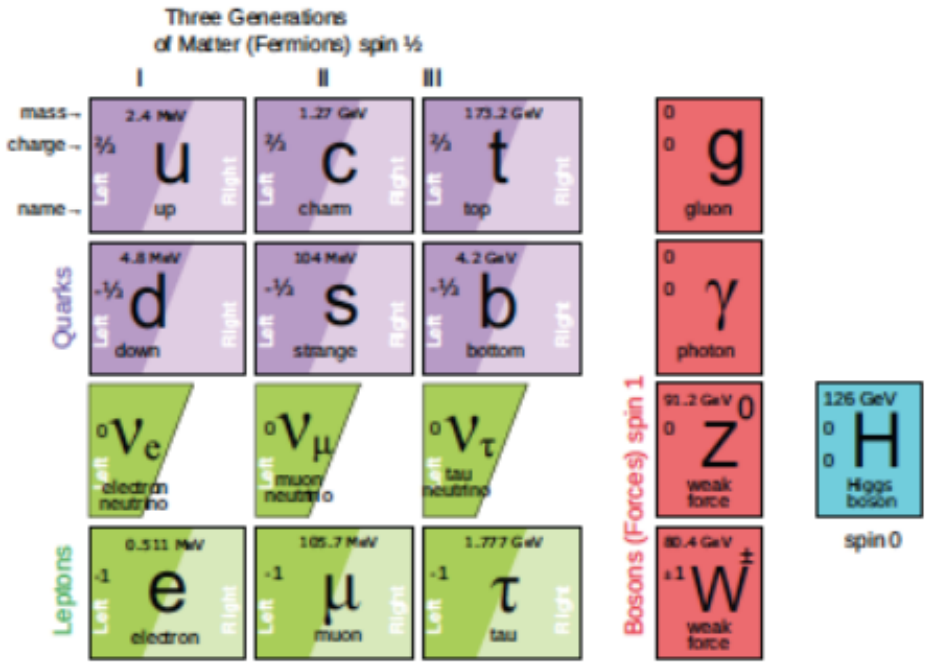
NUOVA FISICA:

NUOVA RISPETTO

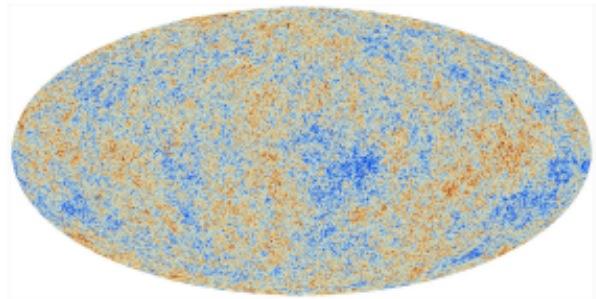
A CHE COSA?

2013 – 2016 : the triumph of the STANDARD

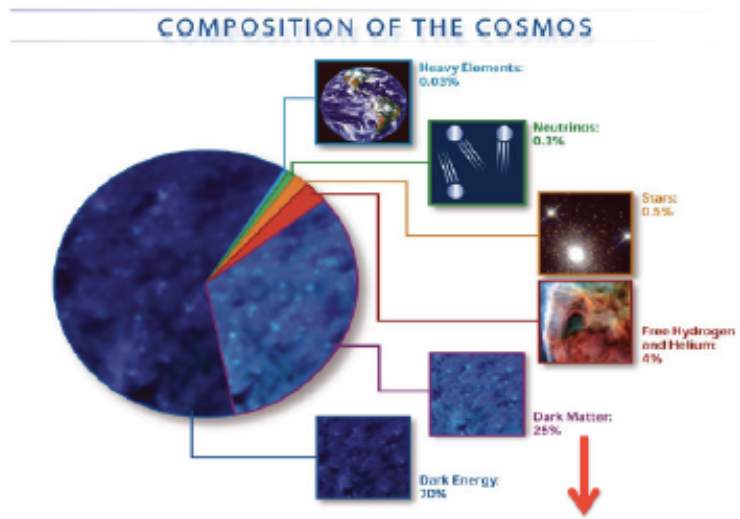
- **PARTICLE STANDARD MODEL**



- **COSMOLOGY STANDARD MODEL**



ΛCDM + "SIMPLE" INFLATION



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**(??)

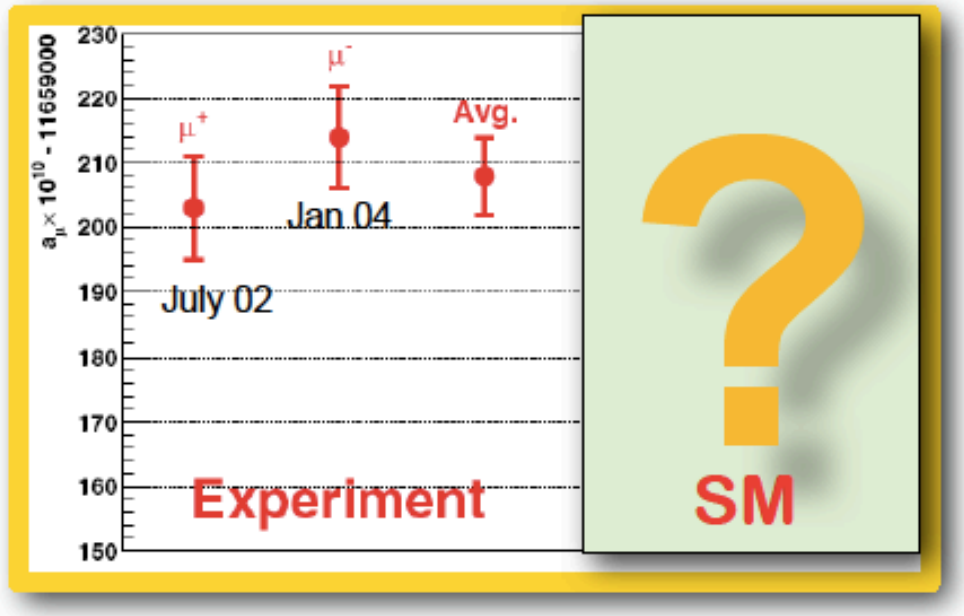
ΛCDM SM

- **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

The muon g-2: experimental status



- BNL 821: $a_\mu^{EXP} = (116592089 \pm 54_{stat} \pm 33_{sys}) \times 10^{-11}$ [0.5ppm].
- New muon g-2 experiments at:
  - Fermilab E989: aims at $\pm 16 \times 10^{-11}$, ie 0.14ppm.
    First two data taking completed. Analysis in progress.
    First result expected very soon with ~ BNL E821 precision.
  - J-PARC proposal: phase-1 start with 0.46ppm (TDR 2017).
- Are theorists ready for this (amazing) precision? Not yet!

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

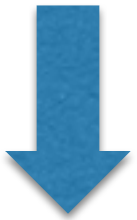
$a_\mu^{SM} \times 10^{11}$	$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM}$	σ
116 591 784 (44)	$307\ (77) \times 10^{-11}$	4.0 [1]
116 591 829 (49)	$262\ (80) \times 10^{-11}$	3.3 [2]
116 591 822 (38)	$269\ (74) \times 10^{-11}$	3.6 [3]

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:1908.00921.
[3] Keshavarzi, Nomura, Teubner, arXiv:1802.02995.

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

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



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 !

Czarnecky and Marciano, 2001; Stockinger 2010

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

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

  $a_e^{EXP} = 1596521807.3\ (2.8) \times 10^{-13}$ Hanneke et al, PRL100 (2008) 120801

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

  $a_e^{EXP} = 1596521883\ (42) \times 10^{-13}$ Van Dyck et al, PRL59 (1987) 26

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

$$\alpha^{-1} = 137.035\ 999\ 150\ (33) \quad [0.24\ \text{ppb}]$$

- Compare it with the present best determination of alpha:

$$\alpha^{-1} = 137.035\ 999\ 046\ (27) \quad [0.20\ \text{ppb}]$$ Science 360 (2018) 191 (Cs)

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

2.4 sigma discrepancy

Vicini al grande sogno di una
teoria completa delle interazioni fondamentali
dal MICRO- al MACRO- COSMO?

- By the end of the 20th century …
  we have a comprehensive, fundamental theory of all observed forces of nature which has been tested and might be valid from the Planck length scale [10^{-33} cm.] to the edge of the universe [10^{+28} cm.]

D. Gross 2007

Il “baco” di fondo dei due Modelli Standard

- MS del **micro-cosmo**: **teoria di campo QUANTISTICA** basata su simmetrie di gauge (locali) “RELATIVISTICA” solo nel senso che rispetta la **relativita’ ristretta** di Einstein che descrive solo le interazioni elettrodeboli e forti, ma **non la gravita**’ (campo gravitazionale nel MS particellare e’ un campo classico “esterno”

- MS del **macro-cosmo**: teoria che si basa sulla **RELATIVITA’ GENERALE** che descrive la **forza gravitazionale** vero motore dell’universo su grande scala

- Due laboratori eccezionali in cui in cui mettere sotto test (e stress) i 2 MS: i **buchi neri** (campo grav. forte) e **primi istanti dell’universo dopo BB**

- Importante esplorare **scenari teorici di gravita’ quantistica** (supergravità, teoria di stringa, loop gravity,…) tenendo conto (ma senza l’assillo) delle loro possibili implicazioni cosmologiche o fenomenologiche particellari.

Ideology

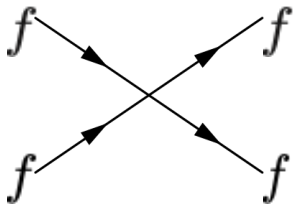
HEP before the LHC

HEP before the F.C.

SUSY, etc.

Higgs

W boson

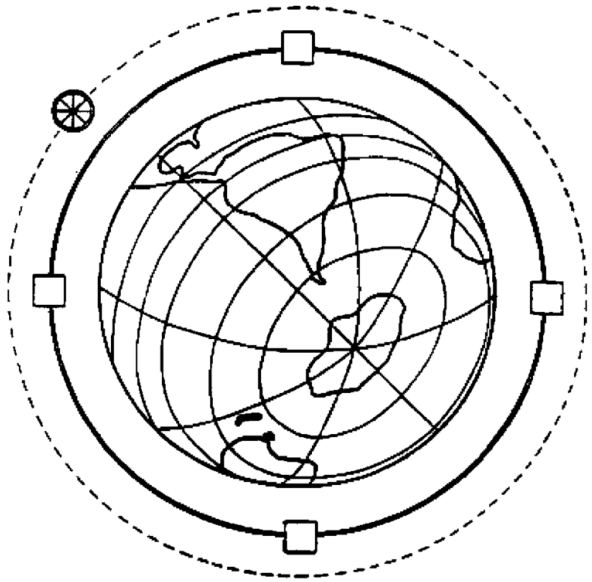


$$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \rightarrow m_W < 4\pi v$$

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

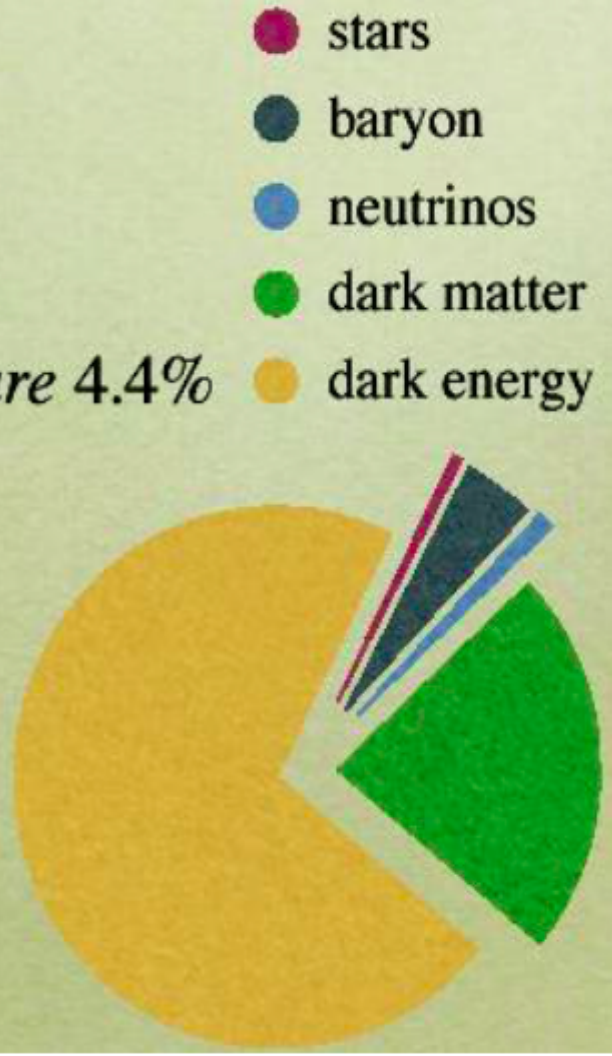
NUOVA FISICA:
REALTA' O PREGIUDIZIO?

***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

What the SM does not account for...

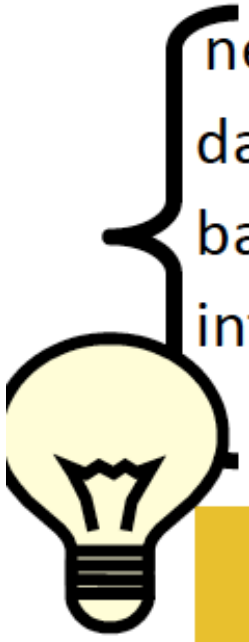
- neutrino masses
- dark matter
- baryogenesis
- inflation

→ **OBSERVATIONAL REASONS**

- $M_{HIGGS} / M_{PLANCK} \sim 10^{-16}$
- $E_{VACUUM}\,(DE) / M_{HIGGS} \sim 10^{-14}$
- $\Theta_{CPV\ in\ STRONG\ INTERAC.} < 10^{-9}$

→ **THEOR. REASONS**

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**

Naturalness or Un-naturalness?

- New SYMMETRY giving rise to a cut-off at

$$m_{NP} \ll M$$

Low-energy **SuperSymmetry**

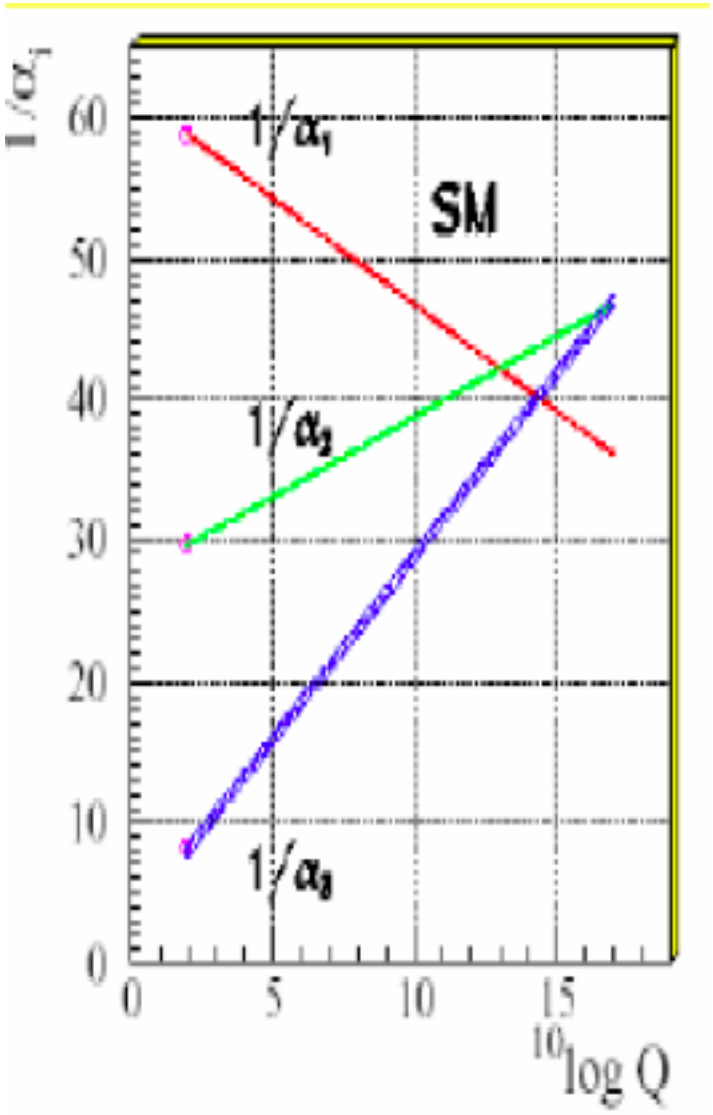
- **Space-time modification (extra-dim., warped space)**

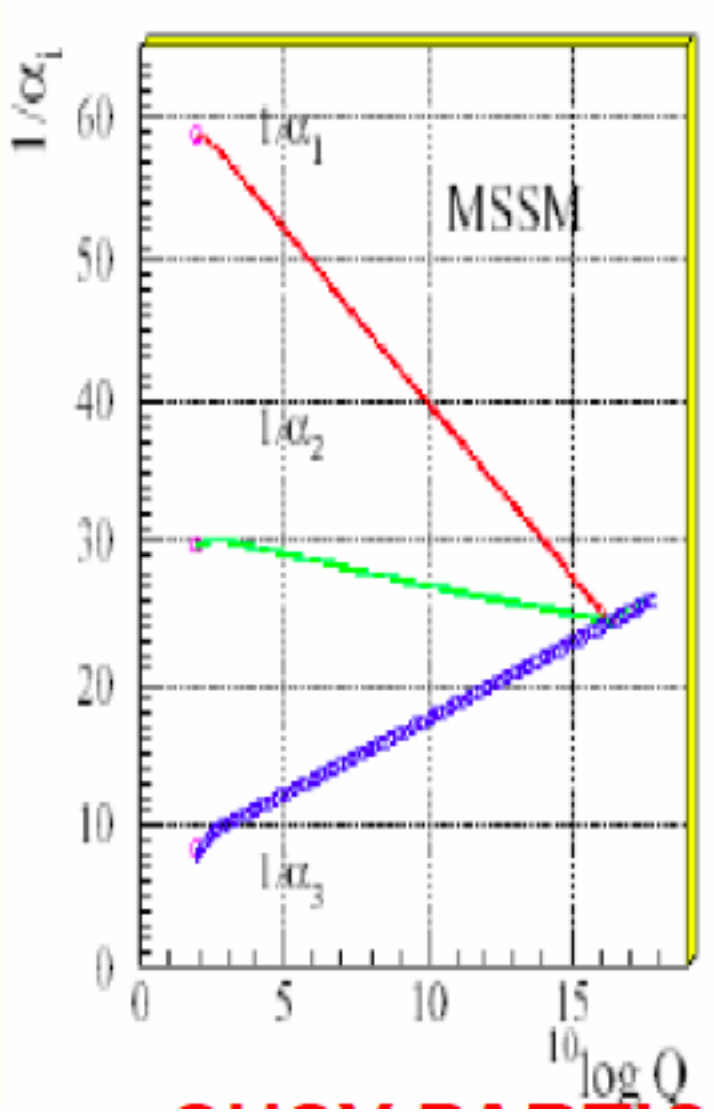
- **COMPOSITE HIGGS** : the Higgs is a pseudo-Goldstone boson (pion-like) → new interaction getting strong at $m_{NP} \ll M$

- **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)**

Only one fundamental interaction?





MASSA DEL NEUTRINO

E

SIMMETRIE DELL'UNIVERSO

L’importanza di essere un neutrino con massa

- Il ragionamento (**sbagliato**):
- a) dato che non si era (e ancor oggi non lo si è) mai visto un neutrino destrogiro e dato che allora (ma non oggi) si riteneva che il neutrino potesse essere senza massa, i padri fondatori GWS del MAS hanno introdotto **solo** il neutrino levogiro e pertanto hanno **”forzato” il neutrino a non aver massa**;
- b) pertanto, **si può dar massa al neutrino senza bisogno di ’vera’ Nuova Fisica,** basta **aggiungere alle particelle SM un neutrino destrogiro e accoppiarlo a quello levogiro mediante un accoppiamento di Yukawa molto piccolo (< O(10^{-12}))**

- Il ragionamento **corretto**:

- È possibile dare **massa ad un neutrino a 2 componenti** (solo levogiro), ma il termine $\nu_L \nu_L$ non puo' essere accoppiato all'ordinario bosone di Higgs (doppietto di $SU(2)_L$) --> introduzione di nuovi campi scalari oltre all'Higgs 'solito' → **nuova fisica "non banale"**

- Si può introdurre un **neutrino levogiro N** (singoletto di gauge) → il termine (di Majorana) NN e' gauge e Lorentz invariante → nessuna simmetria lo impedisce e questo termine introduce **una nuova scala di fisica M** nel termine di massa MNN → **nuova fisica "non banale"**

- M puo' essere messa a zero lasciando il solo termine che accoppia ν_L a N → imposizione della **simmetria GLOBALE numero leptonico L** → **nuova fisica "non banale"**

LEPTON NUMBER and ***LEPTON FLAVOR NUMBERS*** ***CONSERVATION*** in the ***SM***

- *BARYON (B) AND LEPTON (L) numbers are **AUTOMATICALLY** conserved in the SM* (at all orders of the perturbation expansion), i.e. with the fields of the SM particle spectrum it is not possible to write any **operator of dim. ≤ 4** which respects the SM gauge symmetry and violates B or L

but *B and L are NOT conserved at the QUANTUM LEVEL in the SM*

- **B and L are NOT conserved at the quantum (non-perturbative) level.**
- **no visible implications (like proton decay) at zero (or low – like the Universe today)) temperature**
- **But at** early epochs when such temperature exceeded the electroweak energy scale (i.e. T > 100 GeV) the "tunneling toll" could be avoided so that **B and L violating transitions could proceed at large rates possibly larger than the expansion rate of the Universe at that time.**

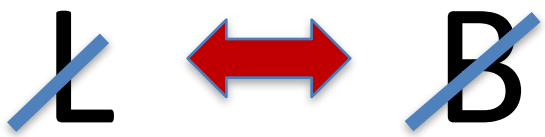
ν mass in the

SM as an **EFFECTIVE** low-energy **theory**

LLHH dim 5 → $\mathbf{M^{-1}}$LL<H><H>

$\mathbf{m_\nu \rightarrow \langle H \rangle^2 / M}$

$m_\nu < 100$ meV → **$M > 10^{14}$ GeV**



- **Simmetria numero leptonico L violata alla scala di energia**
  $M >> M_W$ ($m_\nu \sim 1/M$)
- Se soddisfatte le condizioni di Sakharov → violazione L → asimmetria tra numero di leptoni e antileptoni **ΔL**
- **Anche se il numero barionico non e' violato** esplicitamente (quindi no decadimento del protone), gli **effetti quantistici** che violano separatamente B e L (preservando B-L) a temperature > scala elettrodebole **convertono ΔL in una asimmetria tra barioni e anti-barioni ΔB**

ESISTENZA DELLA MATERIA

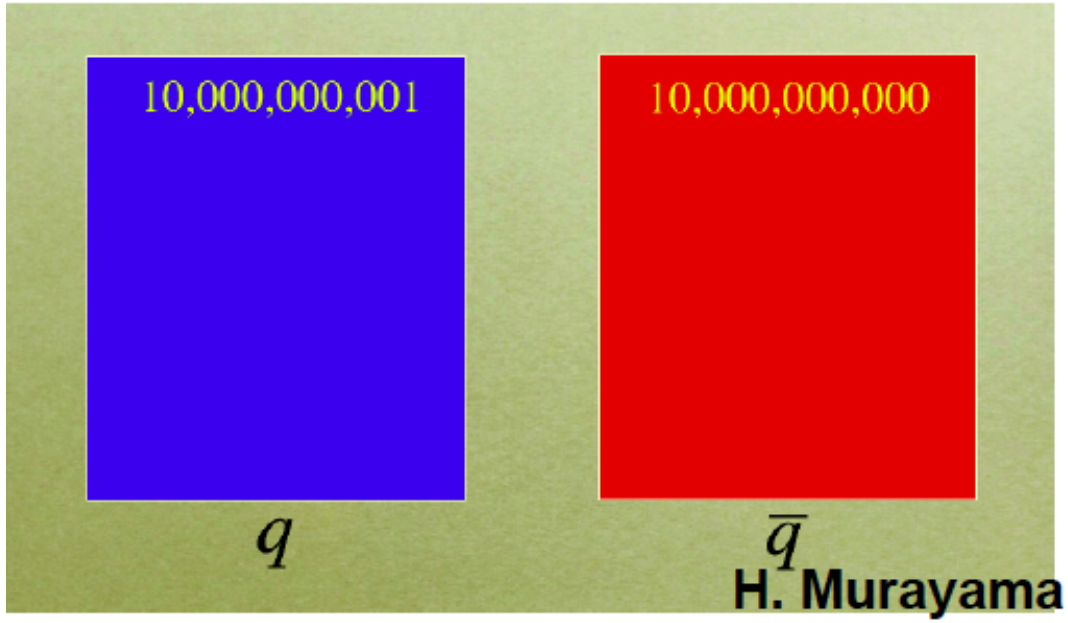
E

SIMMETRIE DELL’ UNIVERSO

THE COSMIC MATTER-ANTIMATTER ASYMMETRY PUZZLE:

-why only baryons

-why $N_{baryons}/N_{photon} \sim 10^{-10}$



Peculiar initial conditions?

Or is there a **dynamics** allowing for matter to prevail over antimatter starting from a perfectly **symmetric situation in matter – antimatter** content of the plasma after inflation?

SM FAILS TO GIVE RISE TO A SUITABLE COSMIC MATTER-ANTIMATTER ASYMMETRY

- **NOT ENOUGH CP VIOLATION IN THE SM**

  NEED FOR ***NEW SOURCES OF CPV IN ADDITION TO THE PHASE PRESENT IN THE CKM MIXING MATRIX***

- FOR M_{HIGGS} > 80 GeV THE ELW. PHASE TRANSITION OF THE SM IS A SMOOTH CROSSOVER

NEED *NEW PHYSICS BEYOND SM*. IN PARTICULAR, FASCINATING POSSIBILITY: THE ENTIRE MATTER IN THE UNIVERSE ORIGINATES FROM THE SAME MECHANISM RESPONSIBLE FOR THE EXTREME SMALLNESS OF m_ν

MATTER-ANTIMATTER ASYMMETRY ⟷ NEUTRINO MASSES CONNECTION: BARYOGENESIS THROUGH LEPTOGENESIS

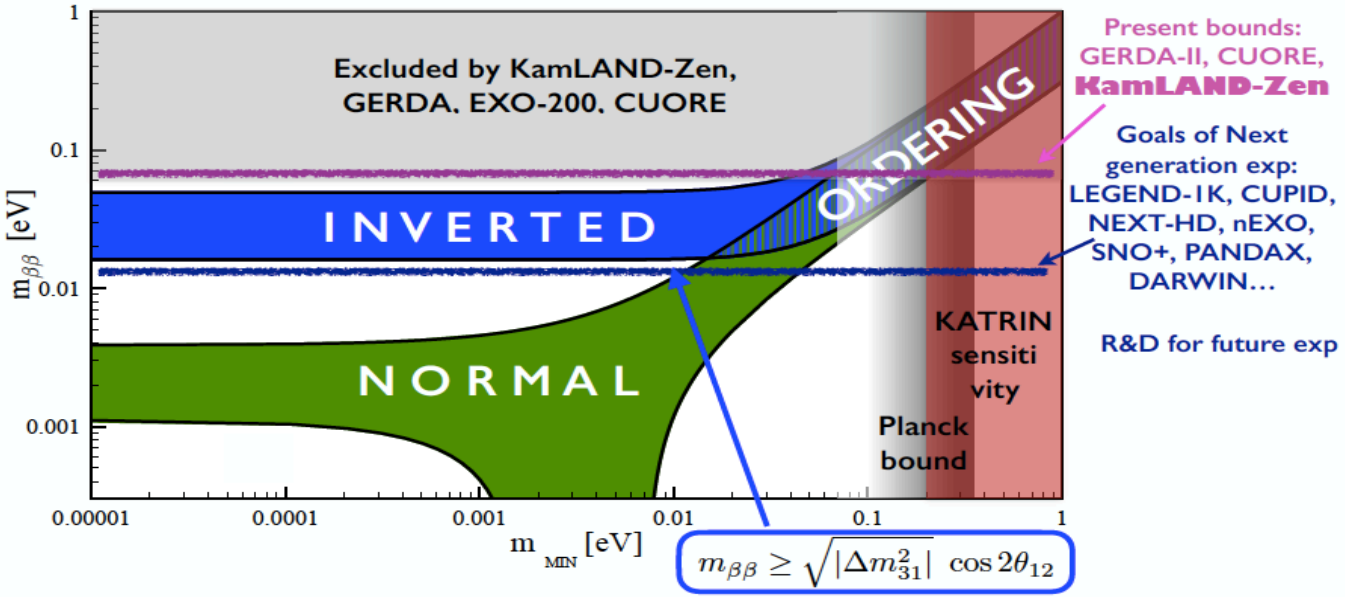
- Key-ingredient of the SEE-SAW mechanism for neutrino masses: **large Majorana mass for RIGHT-HANDED neutrino**
- In the early Universe the heavy RH neutrino decays with Lepton Number violatiion; if these decays are accompanied by a new source of CP violation in the leptonic sector, then

VANILLA LEPTOGENESISIS !

→ it is possible to create a lepton-antilepton asymmetry at the moment RH neutrinos decay. Since SM interactions preserve Baryon and Lepton numbers at all orders in perturbation theory, but violate them at the quantum level, such **LEPTON ASYMMETRY** can be converted by these purely quantum effects into a BARYON-ANTIBARYON ASYMMETRY (**Fukugita-Yanagida mechanism for leptogenesis**)

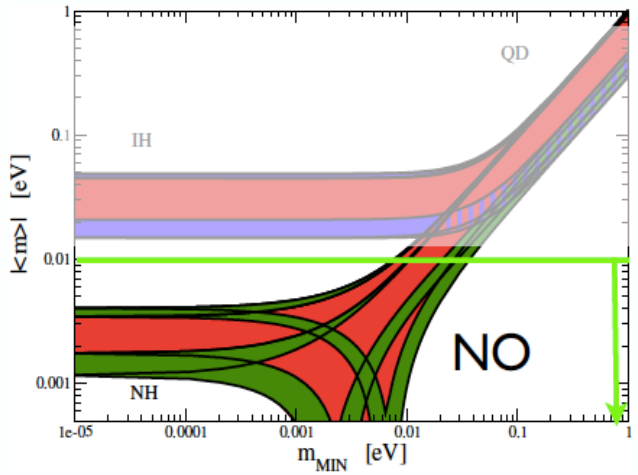
Predictions for betabeta decay

The predictions for m_{bb} depend on the neutrino masses:



Wide experimental program which is ongoing. The next generation is well into planning and R&D for future.

A positive signal would indicate L violation!



- If no signal for |<m>|~10 meV, then only NO is allowed for Majorana nus.
- If LBL experiments find IO, neutrino are Dirac particles (without fine-tuned cancellations).

S. Pascoli, APPEC Community Meeting on Neutrinoless Double Beta Decay, London, Oct. 31, 2019

ESISTENZA DELLA **MATERIA OSCURA**

E

SIMMETRIE DELL’ UNIVERSO

The DM dilemma: to be or not to be related to the electroweak symmetry breaking?

The question can be rephrased into:

DM a good honest **weakly** (but not too weakly) **interacting** (with the SM particles) **massive** (typically O(100 GeV)) **particle**, i.e. a "traditional" **WIMP** part of an extension of the SM accounting for a (possibly natural) **explanation of the (incredibly small) electroweak symmetry breaking scale M_W (as compared to the Planck scale M_{Pl}) ;**

OR

DM a (very) **light** particle coupling **very weakly** to the SM particles being part of a **new dark sector** of the theory communicating with the SM particles only through a specific "**portal**", i.e. one or more particles **bridging the "dark world" with "our" SM world** (in this case it is likely that the DM sector has nothing to do with the SM elw. breaking mechanism)

Pros and cons to be a WIMP DM (I)

Pros:

- i) the WIMP coincidence or emphatically dubbed "**WIMP miracle**" (namely: take a **weakly interacting O(100 GeV)** particle once in **thermal equilibrium** and compute its number density today – result: typically one ends up with $n_{WIMP} \sim 10^{-8}$ cm^{-3} leading to the **correct DM amount** ! ;
- ii) such WIMP DM typically constitutes a form of **COLD DM** (hence correctly accounting for the main bulk of observations on large scale structures distribution)
- iii) remarkably enough, the main SM extensions envisaged to cope with **"natural" explanation** of the gauge hierarchy puzzle $M_W << M_{Pl}$ entail the presence of a **stable particle**, typically the **lightest of the new particles** characterizing such SM extension, which is a potentially good **WIMP DM candidate**.

CONNECTION DM – ELW. SCALE

THE WIMP MIRACLE :STABLE ELW. SCALE WIMPs

	SUSY	**EXTRA DIM.**	**LITTLE HIGGS.**
1) **ENLARGEMENT OF THE SM**	(x^μ, θ) Anticomm. Coord.	(x^μ, j^i) New bosonic Coord.	SM part + new part 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

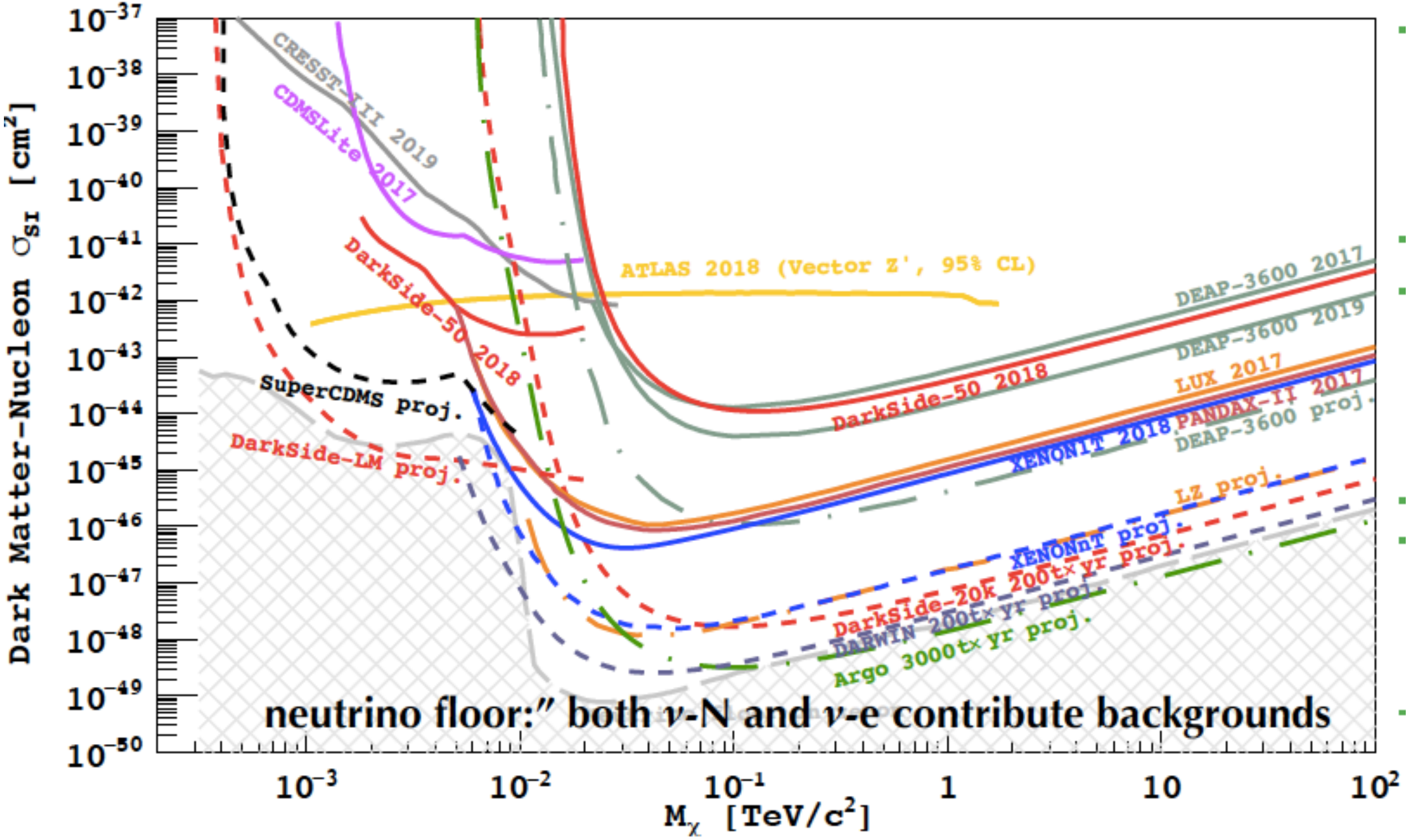
Pros and cons to be a WIMP DM (II)

The **cons**:

i) In spite of constituting the most "wanted" particle candidate for DM, **no WIMP signal** (or at least hint) has ever emerged with searches reaching sensitivities to WIMP-nuclei cross sections down to 10^{-10} pb;

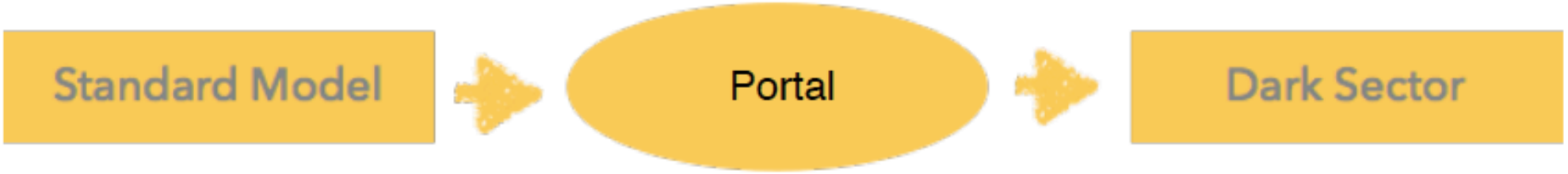
ii) The negative results coming from high-energy and flavour physics (in particular LHC) searches of new physics particles around the corner, i.e. in the O(1TeV) mass range, have (largely) **reduced our enthusiasm for a TeV new physics directly linked to a natural solution of the $M_W << M_{Pl}$ gauge hierarchy problem**. And, as a consequence, **the lightest TeV new physics particle has lost its appeal as "natural" candidate for DM**

iii) The main "victim" of this lost connection DM – TeV new physics is undoubtedly the **Lightest SUSY Particle**, LSP, typically the lightest **neutralino** in SUSY models with R parity


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)
SuperCDMS proj.
DarkSide-LM proj.
DEAP-3600 2017
DEAP-3600 2019
DarkSide-50 2018
LUX 2017
XENON1T 2018
PANDAX-II 2017
DEAP-3600 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

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

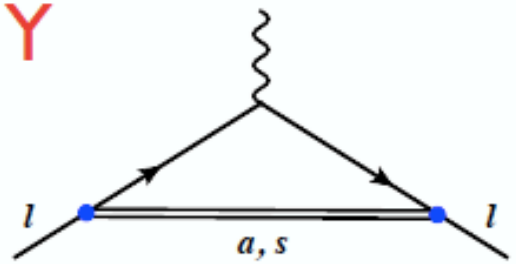
Dark sector has dynamics which is not fixed by Standard Model dynamics
→ New Forces and New Symmetries
→ Multiple new states in the dark sector, including Dark Matter candidates

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

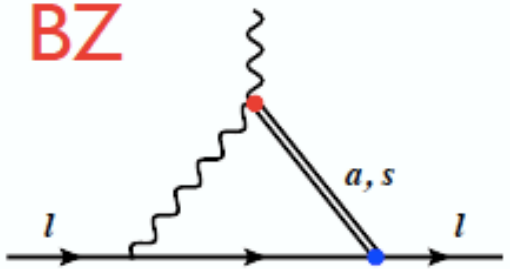
Summary talk by Asai and Catena of the DM WG at the EU Strategy Granada Symposium

ALPs contributions to the muon g-2?

Y

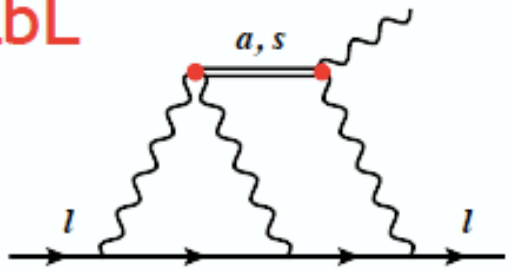


BZ

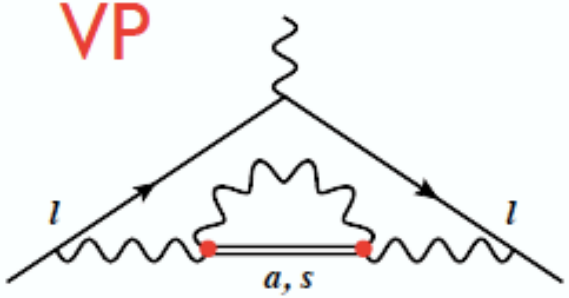


Marciano, AM, Paradisi, Passera

LbL



VP



- Both scalar and pseudoscalar ALPs can solve Δa_μ for masses ~ [100MeV-1GeV] and couplings allowed by current experimental constraints.

- They can be tested at present low-energy e^+e^- experiments, via dedicated $e^+e^- \to e^+e^-$+ALP & $e^+e^- \to \gamma$+ALP searches.

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

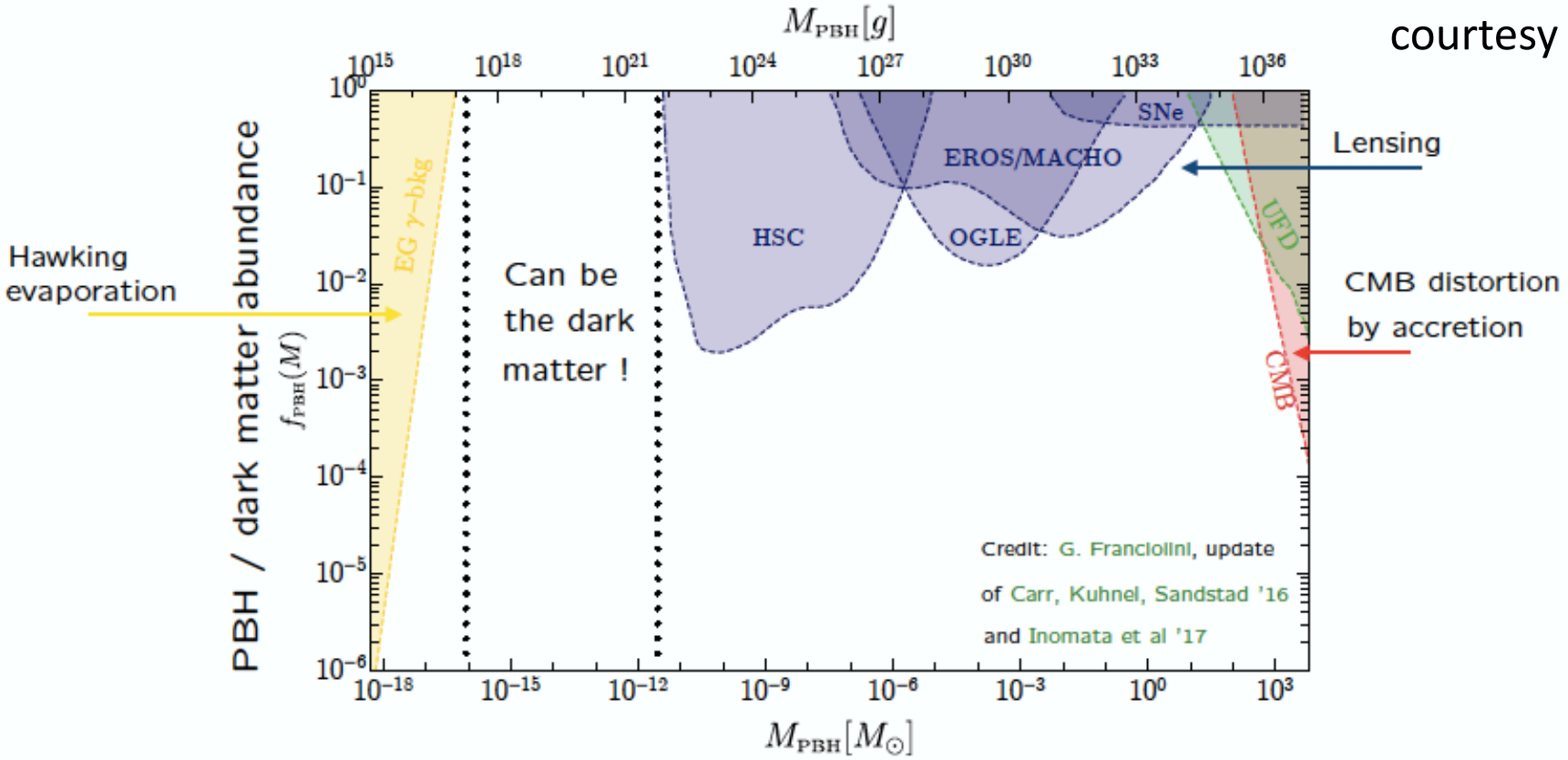
- Importanza **esperimenti di precisione** (es. Flavour fisica K, B, EDMs, MDMs …)

La **“nostra” Materia**, la **Materia Oscura** e le **Simmetrie** dell’Universo

- La sopravvivenza della Materia di cui noi siamo fatti e’ frutto di un delicato “meccanismo” (tuning?) di violazione delle simmetrie **CP, numero barionico, numero leptonico**, altre possibili simmetrie legate ad una transizione di fase di 1a specie
- La **Materia Oscura** frutto (apparentemente) di **altre simmetrie**, in particolare una simmetria che garantisca la sua (quasi) stabilita’ su scala cosmica
- E’ una **coincidenza** che alla fine il risultato di due meccanismi completamente diversi produca quasi lo stesso risultato? **La densita’ DM e’ circa 4-5 volte quella della “nostra” Materia**…

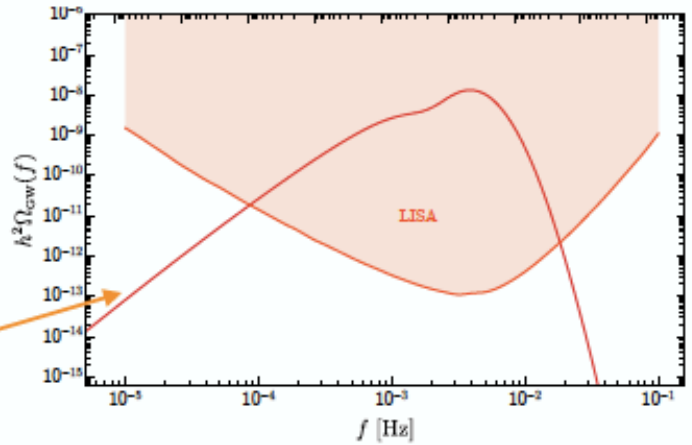
Primordial Black Hole dark matter

courtesy of Marco Peloso



In the $10^{17} - 10^{22} g$ window:

- No lensing limits since $R_{\rm PBH} < \lambda_\gamma$
- Limits from PBH capture affected by astrophysical uncertainties
- PBH accompanied by GW signal @ LISA



Subtle is the Lord, but malicious He is not

- Per ora la Nuova Fisica rimane una primula rossa: sappiamo che esiste, ma non sappiamo **ne' dove sia ne' che forma abbia** (legame tra NP e simmetria elettrodebole? Se no, fisica 'leggera' settore nascosto o fisica 'pesante' regione multi-TeV oppure? **Colombo parte per le Indie perche' sa che ci sono, ma poi trova …**

- **La ricerca deve essere a tutto campo**. Grandi progetti, grandi IRs cruciale esserci e contare, altresi' lasciare spazio a una fisica à la What Next …

- **L'INFN (come ente in tutte le sue componenti, non solo I ricercatori) ha un formidabile potenziale sia sul versante teorico che sperimentale per affrontare la sfida della caccia a questa primula rossa**