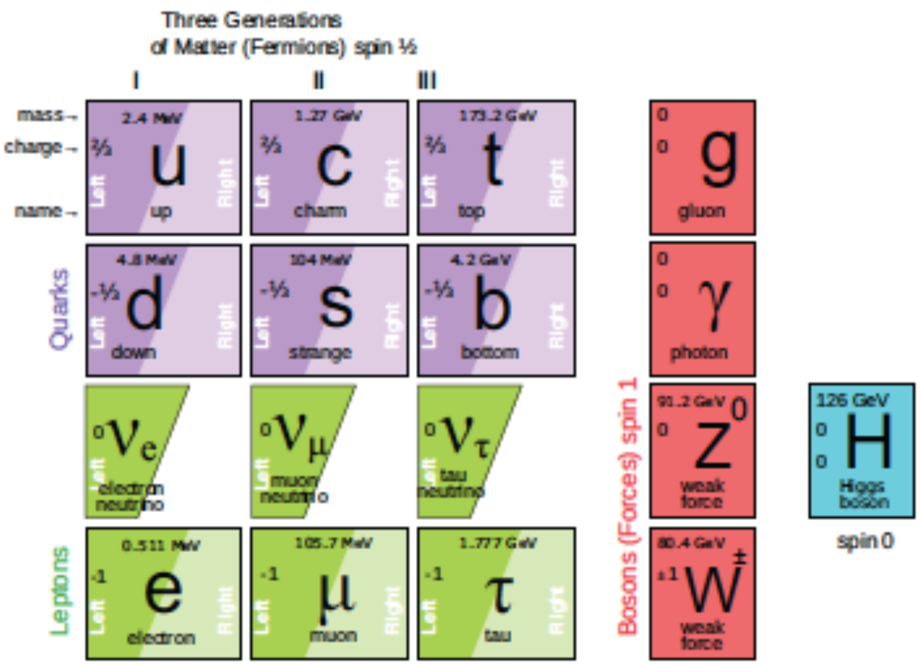
NA62 Handbook Workshop, MITP, Mainz, Jan. 18, 2016

Where are we going in Particle Physics

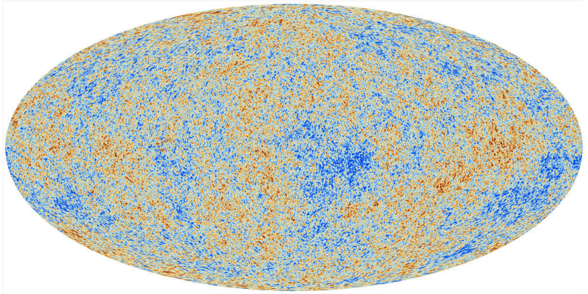
Antonio Masiero
INFN e Univ. of Padova

2013: the thiumph of the STANDARD

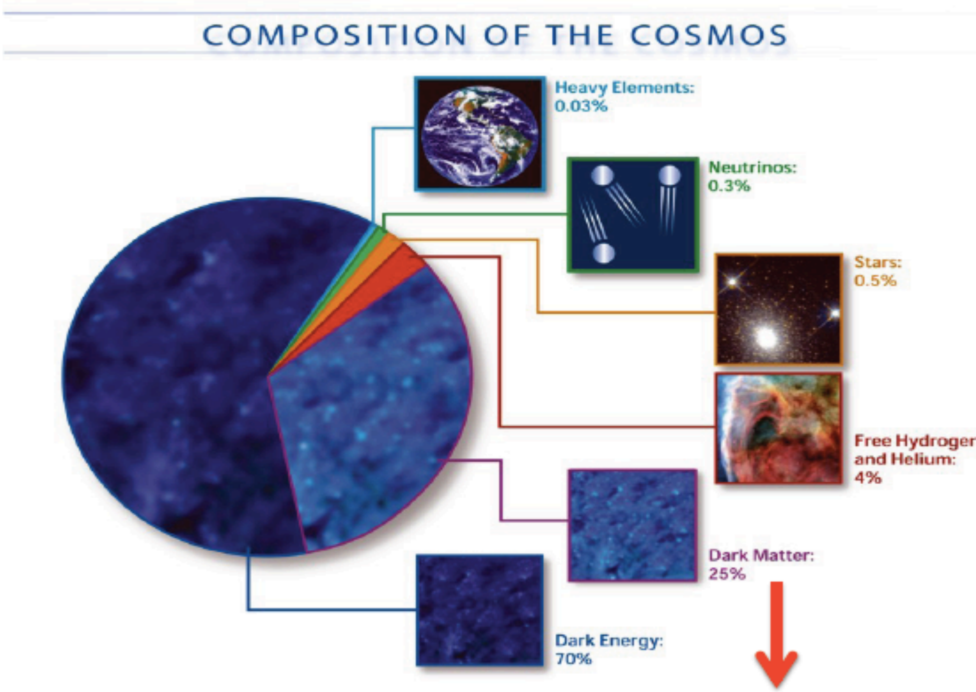
- **PARTICLE STANDARD MODEL**

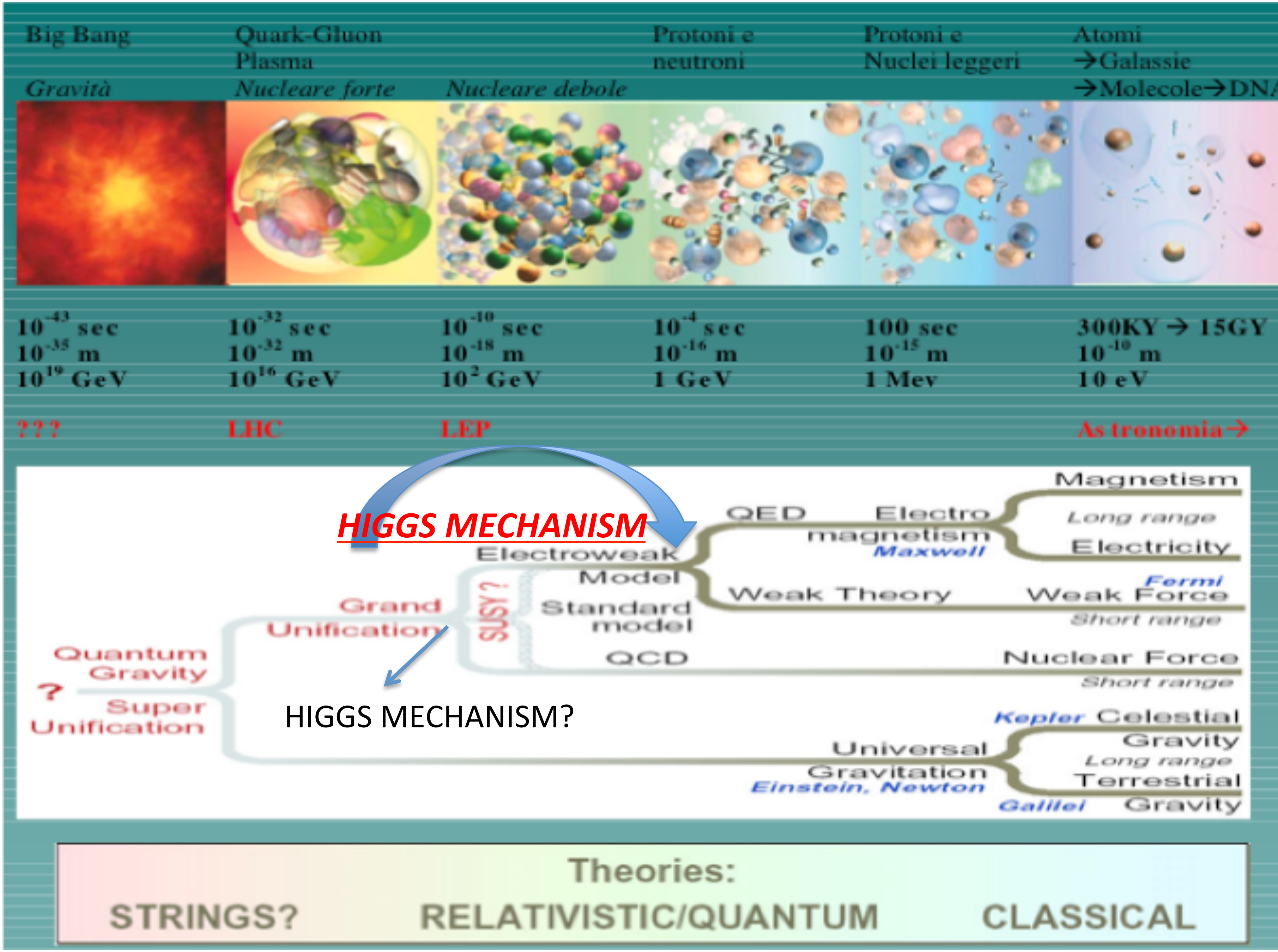


- **COSMOLOGY STANDARD MODEL**



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
As tronomia→
HIGGS MECHANISM
Electroweak
Model
Standard model
SUSY ?
Grand Unification
Quantum Gravity
?
Super Unification
HIGGS MECHANISM?
QED
Electro magnetism
Maxwell
Magnetism
Long range
Electricity
Weak Theory
Fermi
Weak Force
Short range
QCD
Nuclear Force
Short range
Kepler
Celestial Gravity
Long range
Universal Gravitation
Einstein, Newton
Terrestrial Gravity
Galilei
Theories:
STRINGS?
RELATIVISTIC/QUANTUM
CLASSICAL

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) exception: **the anomalous magnetic moment of the muon**

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

Problems with Cold Dark Matter?

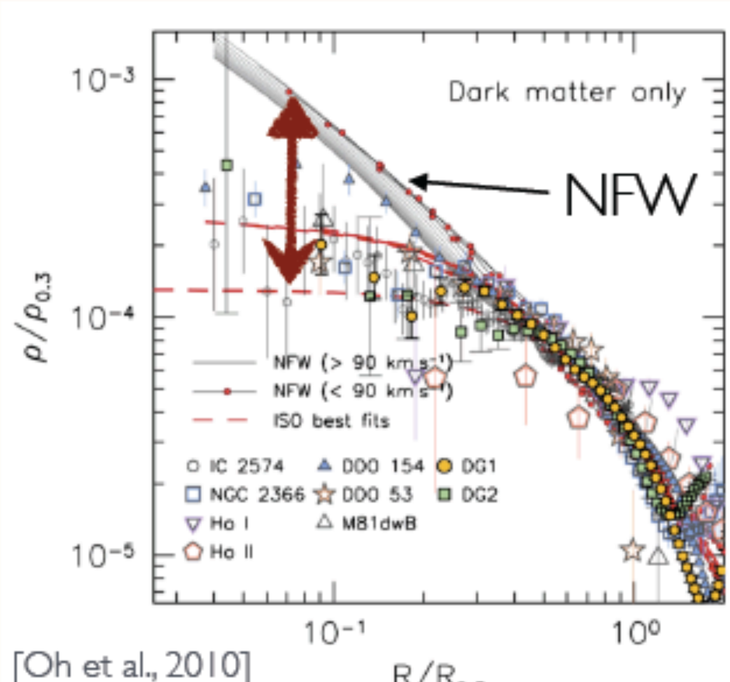
- Several discrepancies between N-body simulations and astrophysical observations:

  I. Core vs. Cusp

  [Moore 1994; Flores,Primack 1994]

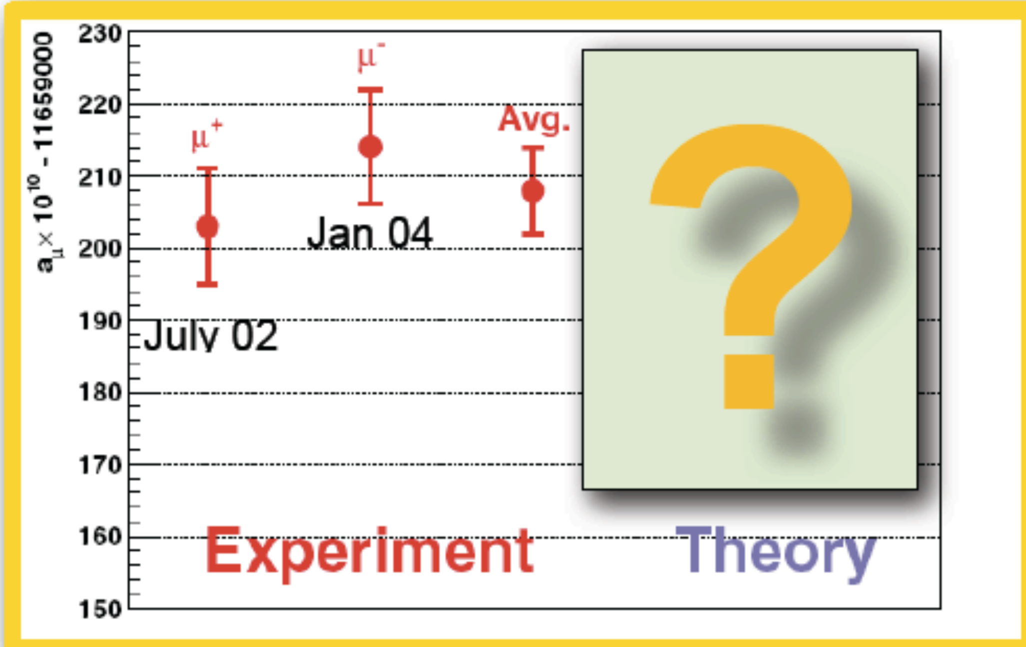
  - N-body simulations typically predict: $\rho(r) \xrightarrow{r\to 0} \frac{1}{r^{\alpha}}$
  - Measurements suggest a core: $\rho(r) \xrightarrow{r\to 0} \text{const}$
  - Problem exists in:
    (field and satellite) dwarfs,
    LSBs, Clusters

[Walker, Penarrubia, 2011; de Blok, Bosma, 2002; Kuzio de Naray et al., 2007; Kuzio de Naray, Spekkens, 2011; Newman et al. 2012; Oh et al. 2015;…]



[Oh et al., 2010]

The muon g-2: the experimental result



- **Today:** $a_\mu^{EXP} = (116592089 \pm 54_{stat} \pm 33_{sys}) \times 10^{-11}$ [0.5ppm].
- **Future:** new muon g-2 experiments at:
  - Fermilab E989: aiming at $\pm 16 \times 10^{-11}$, ie 0.14ppm. Beam expected in 2017. First result expected in 2018 with a precision comparable to that of BNL E821.
  - J-PARC proposal: aiming at 2019 Phase 1 start with 0.4ppm.
- Are theorists ready for this (amazing) precision? No(t yet)

The muon g-2: SM vs. Experiment

Adding up all SM contributions we get the following theory predictions and comparisons 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
$116\,591\,795\ (56)$	$296\ (86) \times 10^{-11}$	3.5 [1]
$116\,591\,815\ (57)$	$276\ (85) \times 10^{-11}$	3.2 [2]
$116\,591\,841\ (58)$	$250\ (86) \times 10^{-11}$	2.9 [3]

with the very recent "conservative" hadronic light-by-light $a_\mu^{HNLO}(lbl) = 102\ (39) \times 10^{-11}$ of F. Jegerlehner arXiv:1511.04473, and the hadronic leading-order of:

[1] Jegerlehner, arXiv:1511.04473 (includes BaBar, KLOE10-12 & BESIII 2π)
[2] Davier et al, EPJ C71 (2011) 1515 (includes BaBar & KLOE10 2π)
[3] Hagiwara et al, JPG38 (2011) 085003 (includes BaBar & KLOE10 2π)

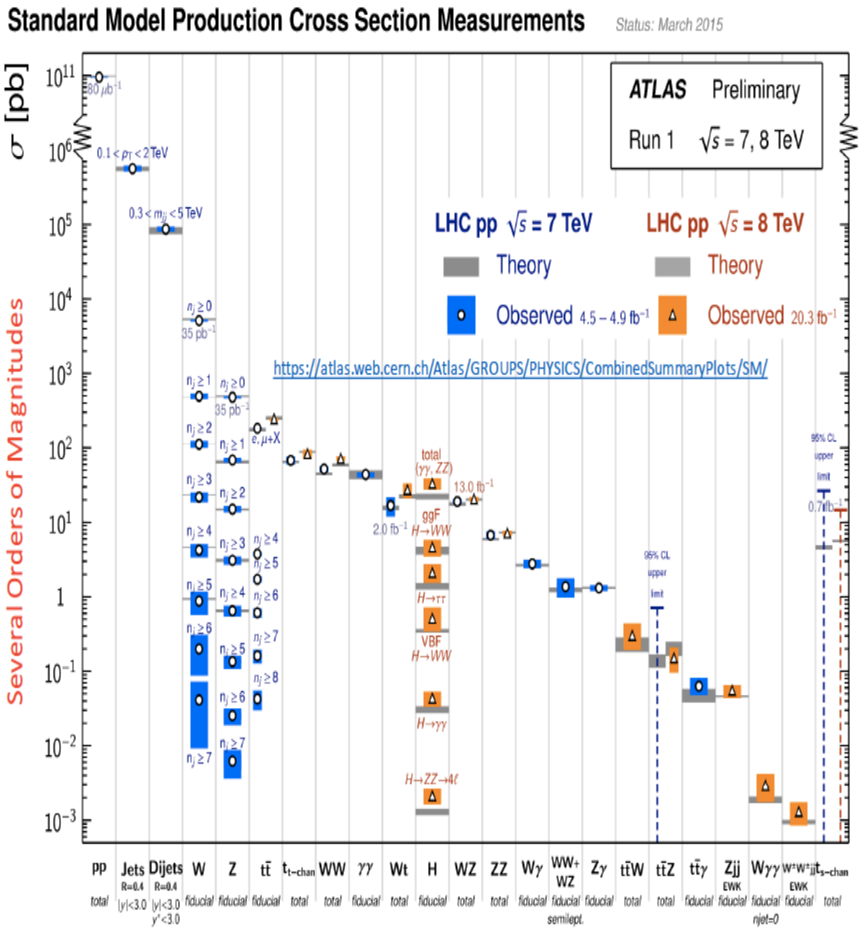
THE EDM CHALLENGE

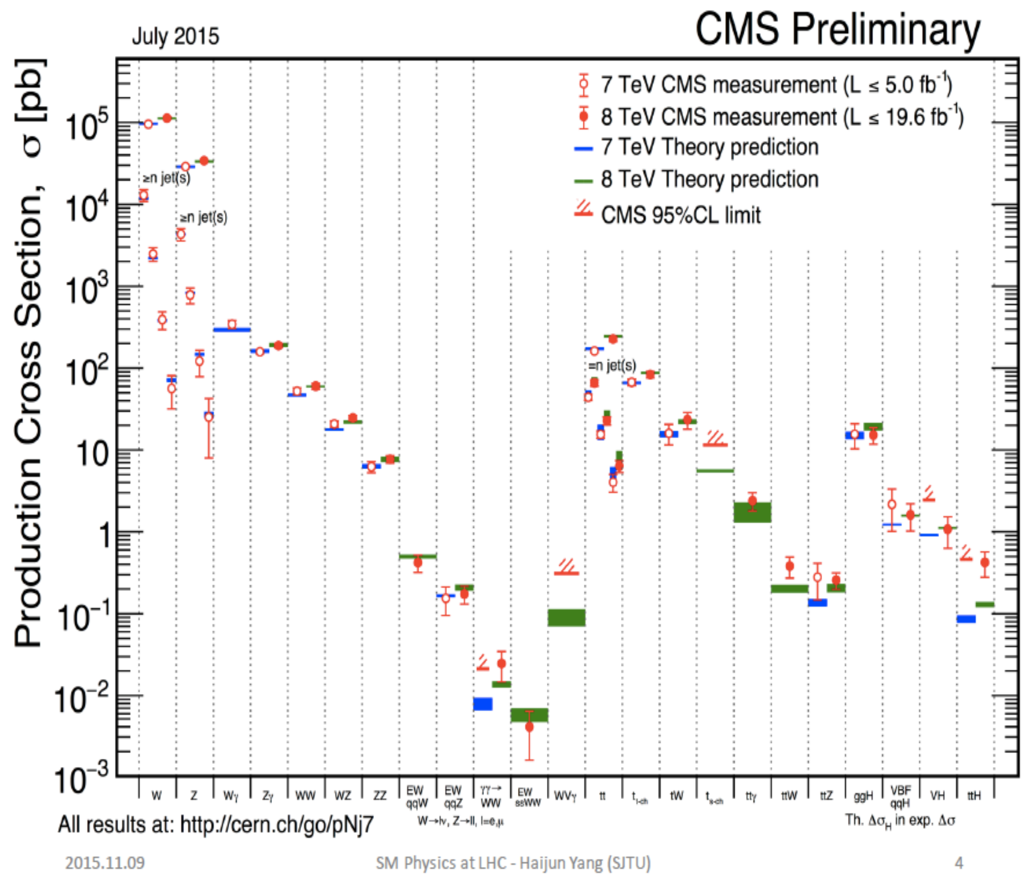
FOR **ANY** **NEW PHYSICS AT THE TEV SCALE** WITH **NEW SOURCES OF CP VIOLATION** → NEED FOR **FINE-TUNING** TO PASS THE EDM TESTS OR SOME **DYNAMICS TO SUPPRESS THE CPV** IN FLAVOR CONSERVING EDMS

Current and projected sensitivities

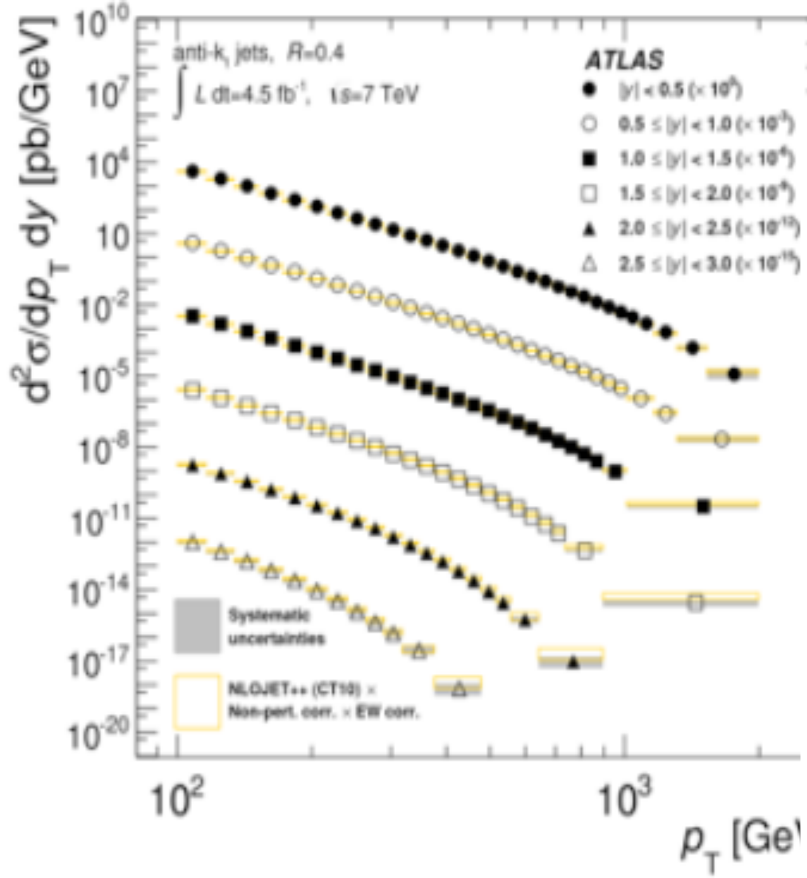
	current limit	projected sens. from planned exp.	standard model CKM prediction
n	3×10^{-26}	10^{-28}	$10^{-31} - 10^{-33}$
e	9×10^{-29}	10^{-30}	$\sim10^{-38}$
Hg	3×10^{-29}	10^{-30}	$<10^{-35}$

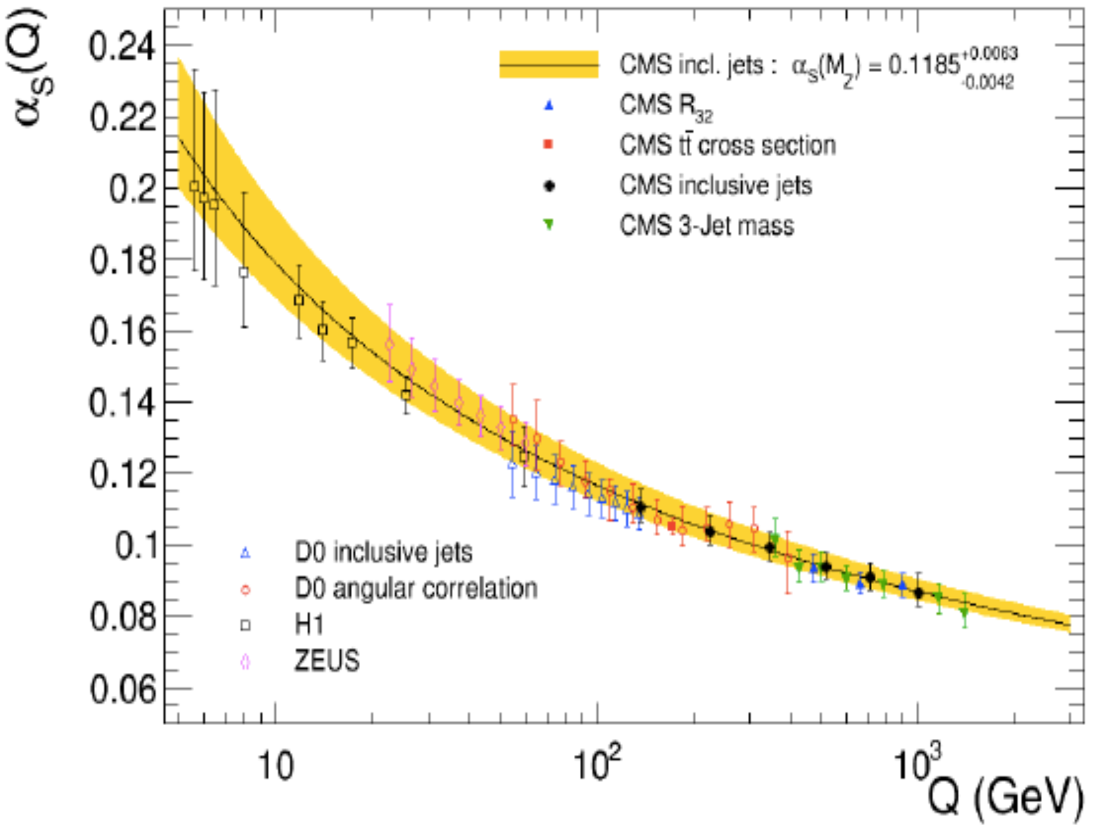
NEW ERA IN PRECISION HIGGS PHYSICS





- State-of-the-art calculation NNLO, NLO EW
- NNNLO Higgs cross sections
- NNLO kinematic contributions

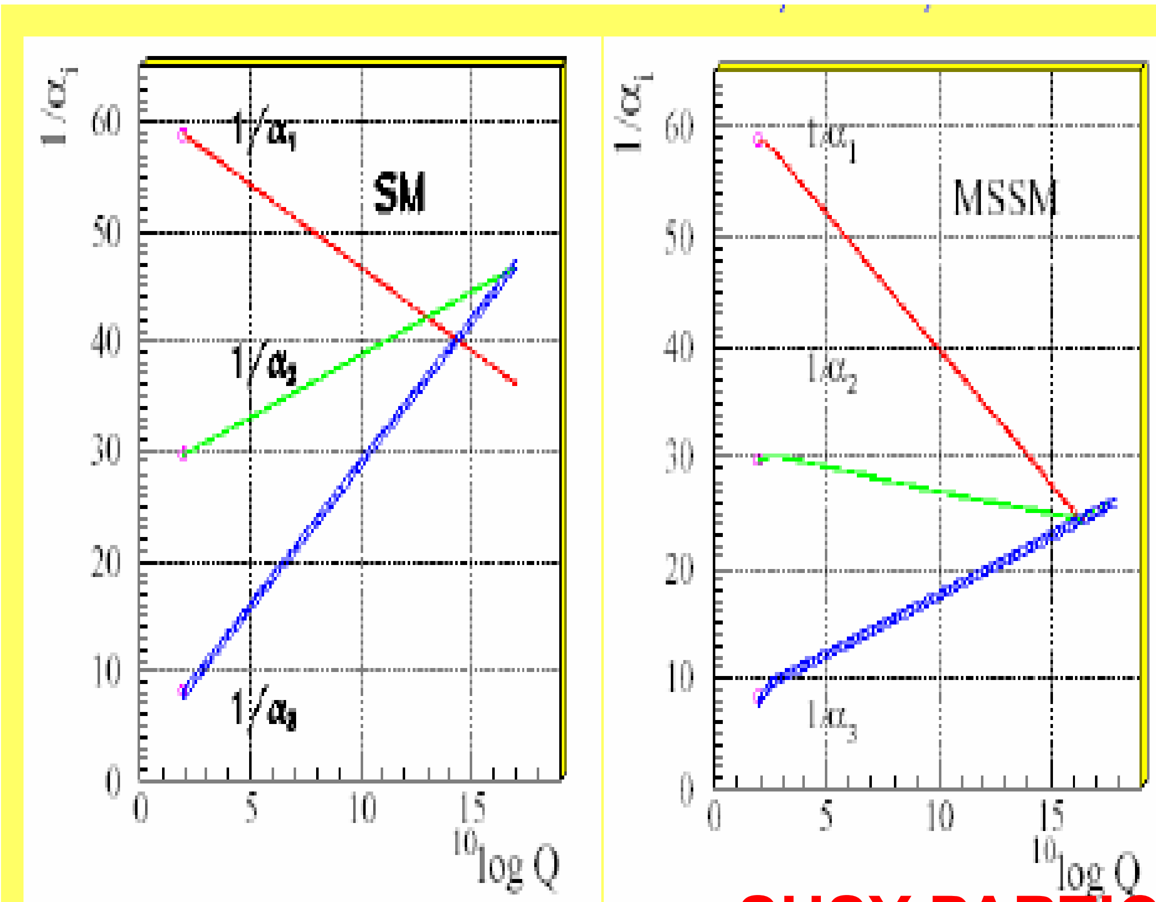




- QCD predictions successful over many orders of magnitude
- **α_s runs beyond the TeV scale**: into a GUT?
- Consistent with world average

J. Ellis, LP 2015

LOW-ENERGY SUSY AND UNIFICATION



Input

$\alpha^{-1}(M_Z) = 128.978 \pm 0.027$

$\sin^2 \theta_{\overline{MS}} = 0.23146 \pm 0.00017$

$\alpha_s(M_Z) = 0.1184 \pm 0.0031$

Output

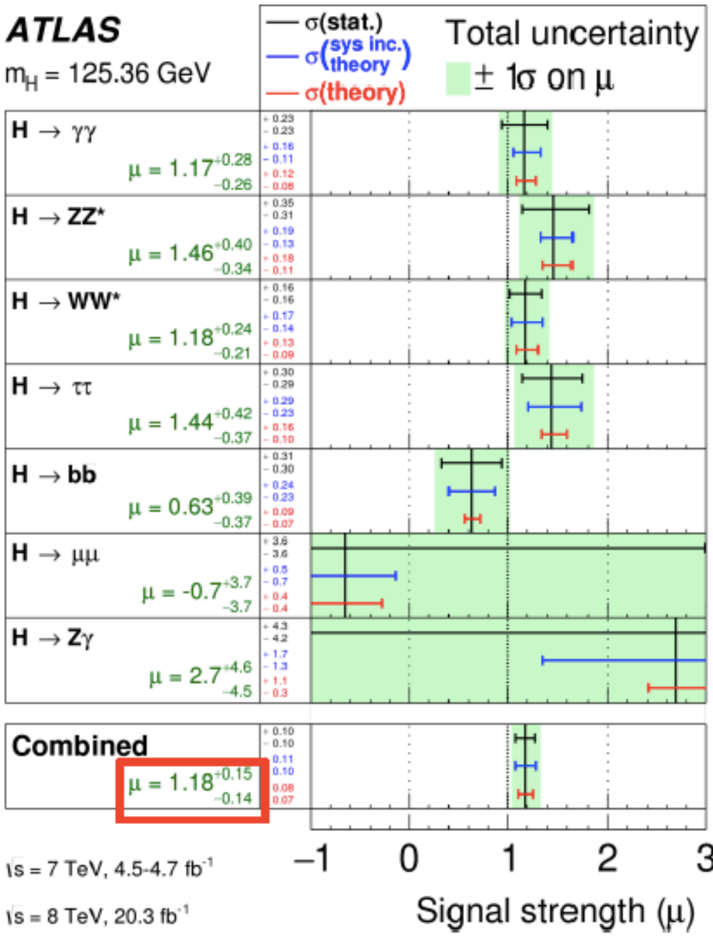
$M_{SUSY} = 10^{3.4 \pm 0.9 \pm 0.4}$ GeV

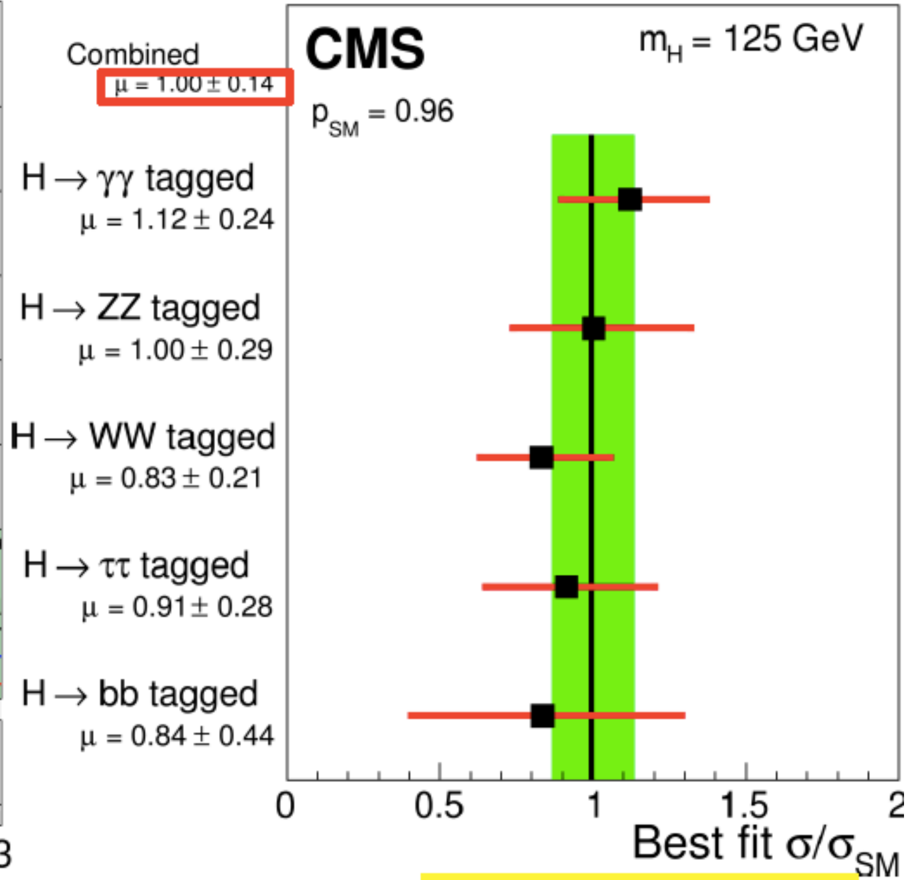
$M_{GUT} = 10^{15.8 \pm 0.3 \pm 0.1}$ GeV

$\alpha^{-1}_{GUT} = 26.3 \pm 1.9 \pm 1.0$

SUSY PARTICLES AT THE TEV SCALE !

Higgs Signal Strengths





EPJC 75 (2015) 212

Globally the SM is OK @ 10% level

What remains to be learnt on the SM from LHC and future accelerators

- **Higgs boson couplings to bosons and fermions**: precisions ≤ 10% attainable with 300 fb^{-1} ;

  precisions 2% - 5% in the High Luminosity phase

  uncertainties O(1%) at ILC and <1% at FCC-ee

- **Higgs total width**: too narrow (~4 MeV) to be measured at LHC – at HL-LHC try using the interference of a specific mode with the continuum; at ILC/FCC-ee through HZ

- **Higgs boson rare production and rare decay modes**: HH production important → related to Higgs self-couplings → need full HL-LHC phase

Coupling $\sqrt{s}$ (TeV)→ L (fb^{-1}) →	LHC 14 3000(1 expt)	CepC 0.24 5000	FCC-ee 0.24 +0.35 13000	ILC 0.25+0.5 6000	CLIC 0.38+1.4+3 4000	FCC-hh 100 40000
K_W	2-5	1.2	0.19	0.4	0.9	
K_Z	2-4	0.26	0.15	0.3	0.8	
K_g	3-5	1.5	0.8	1.0	1.2	
K_γ	2-5	4.7	1.5	3.4	3.2	< 1
K_μ	~8	8.6	6.2	9.2	5.6	~ 2
K_c	--	1.7	0.7	1.2	1.1	
K_τ	2-5	1.4	0.5	0.9	1.5	
K_b	4-7	1.3	0.4	0.7	0.9	
$K_{Z\gamma}$	10-12	n.a.	n.a.	n.a.	n.a.	
Γ_h	n.a.	2.8	1%	1.8	3.4	
BR_{invis}	<10	<0.28	<0.19%	<0.29	<1%	
K_t	7-10	--	13% ind. tt scan	6.3	<4	~ 1 ?
K_{HH}	?	35% from K_Z model-dep	20% from K_Z model-dep	27	11	5-10

Units are %

Few preliminary estimates available
SppC : similar reach

from K_γ/K_Z, using K_Z from FCC-ee

rare decays → pp competitive/better

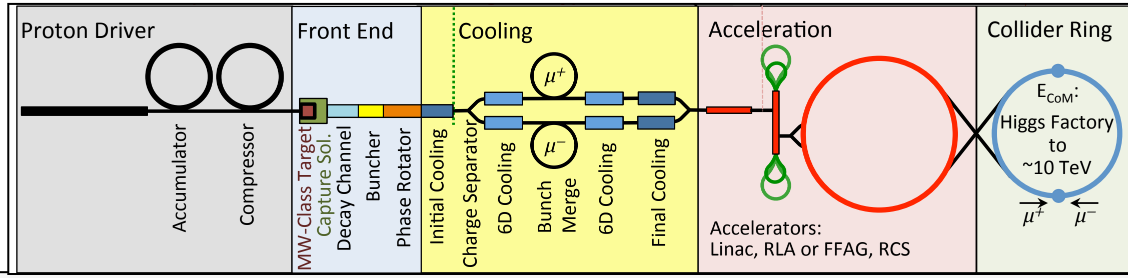
from ttH/ttZ, using ttZ and H BR from FCC-ee

- LHC: ~20% today → ~ 10% by 2023 (14 TeV, 300 fb^{-1}) → ~ 5% HL-LHC
- HL-LHC: -- first direct observation of couplings to 2nd generation (H→ μμ)
  -- model-independent ratios of couplings to 2-5%
- Best precision (few 0.1%) at FCC-ee (luminosity !), except for heavy states (ttH and HH) where high energy needed → linear colliders, high-E pp colliders
- Complementarity/synergies between ee and pp

F. Gianotti, EPS '15

Theory uncertainties (presently few percent e.g. on BR) need to be improved to match expected superb experimental precision

Muon colliders



Synergies with neutrino factories

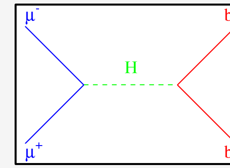
F. Gianotti, EPS '15

Main advantage compared to e^+e^- colliders: $m_\mu \sim 200\ m_e$

→ negligible SR → can reach multi-TeV with (compact !) circular colliders: 300 m ring for $\sqrt{s}$ = 125 GeV, 4.5 km for $\sqrt{s}$ = 3 TeV

→ negligible beamstrahlung → much smaller E spread

→ σ (μμ → H) ~ 20 pb (s-channel resonant production) → H factory

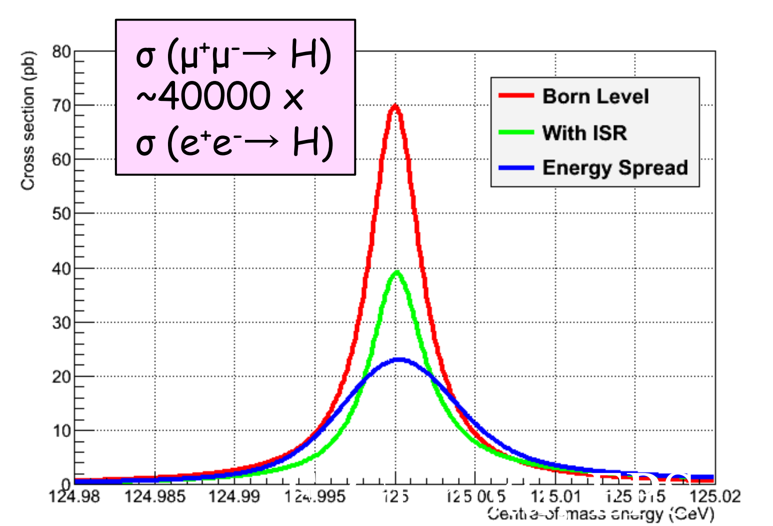


Main challenge: produce high-intensity, low E-spread beams:

- ❑ $m_\mu \sim 200\ m_e$ → SR damping does not work → novel cooling methods (dE/dx based) needed to reach beam energy spread of ~ 3×10^{-5} (for precise line shape studies) and high L
- ❑ $\tau_\mu \sim 2.2\ \mu s$ → production, collection, cooling, acceleration, collisions within ~ ms

Beam spread of ~ 3×10^{-5} would allow Γ_H measurement from line shape to 5% (0.2 MeV) → resolve (possible) resonances

However, with currently projected L (~10^{32}): ~ 20000 H/year → not competitive with e^+e^- colliders for coupling measurements (except Hμμ ~ 1%)

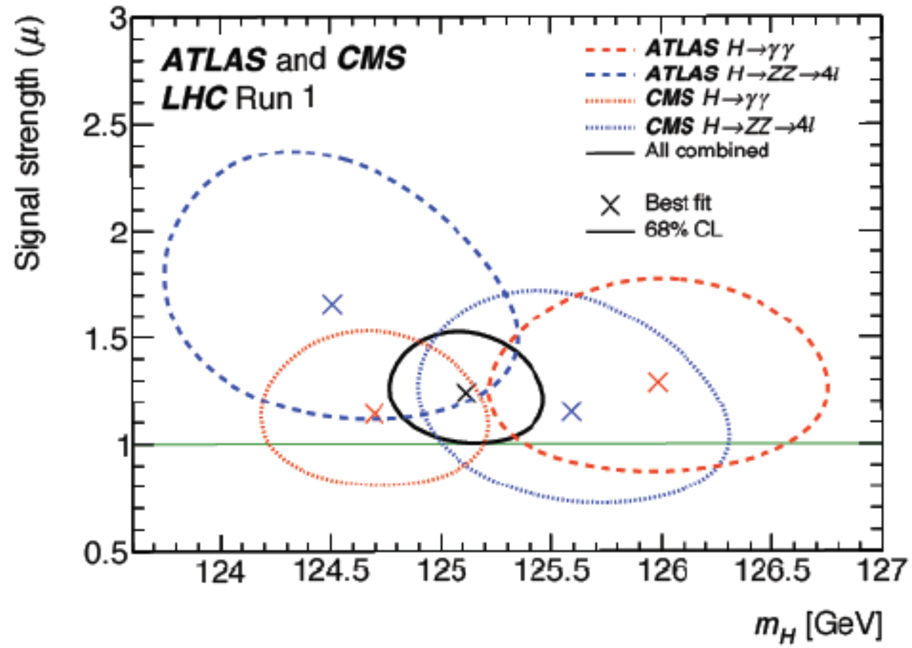


More R&D needed to demonstrated feasibility, in particular cooling:

linear systems (MICE at RAL), rings (recently re-ignited by C.Rubbi

Higgs Mass measurements

ATLAS + CMS ZZ* and γγ final states

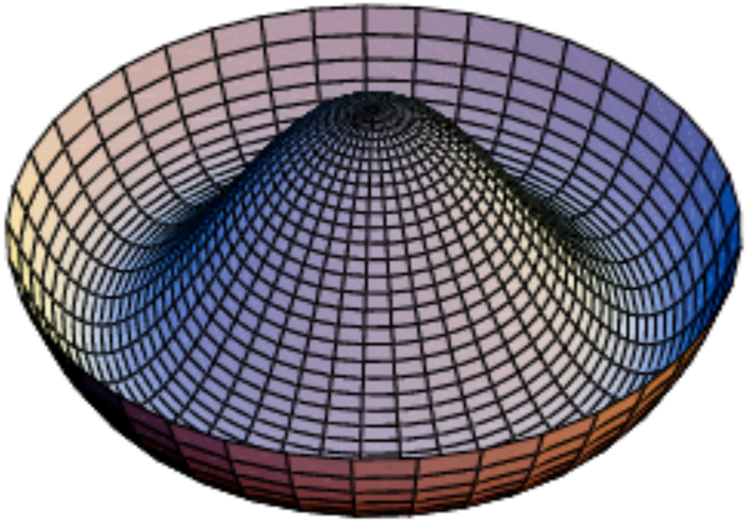


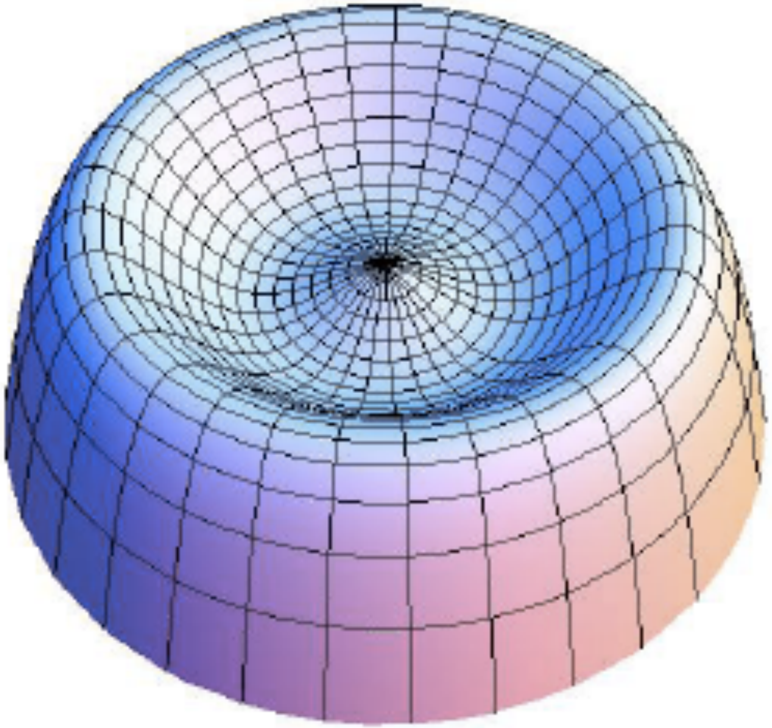
$125.09 \pm 0.21\,(\text{stat}) \pm 0.11\,(\text{syst})$

The values of the **TOP and HIGGS masses** are crucial to establish the stability of the

ELECTROWEAK VACUUM

STABILITY ⟷ INSTABILITY

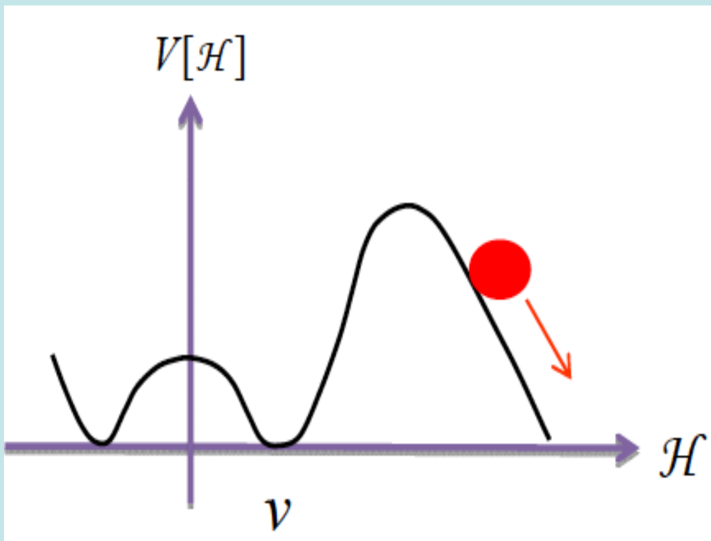




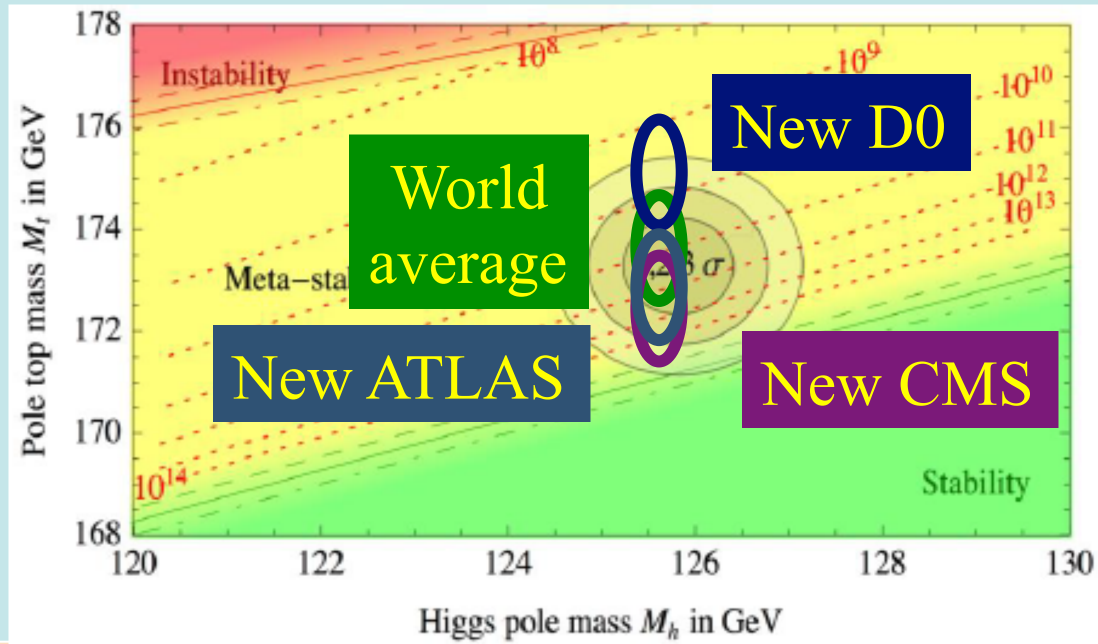
ON THE IMPORTANCE OF PRECISELY MEASURING HIGGS and TOP MASSES

Vacuum Instability in the Standard Model

- Very sensitive to m_t as well as M_H



J. Ellis, LP 2015



Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

- Instability scale:

$$\log_{10}\frac{\Lambda_I}{\mathrm{GeV}} = 11.3 + 1.0\left(\frac{M_h}{\mathrm{GeV}} - 125.66\right) - 1.2\left(\frac{M_t}{\mathrm{GeV}} - 173.10\right) + 0.4\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

$m_t = 173.3 \pm 1.0$ GeV ➔ $\log_{10}(\Lambda/\mathrm{GeV}) = 11.1 \pm 1.3$

THE FLAVOUR PROBLEMS

FERMION MASSES

What is the rationale hiding behind the spectrum of fermion masses and mixing angles (our "**Balmer lines**" problem)

→ **LACK OF A FLAVOUR "THEORY"**

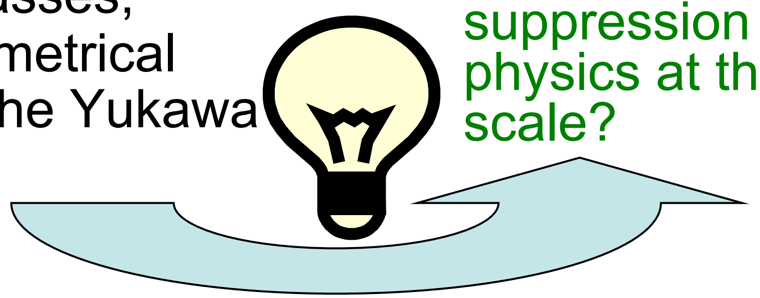
(new flavour – horizontal symmetry, radiatively induced lighter fermion masses, dynamical or geometrical determination of the Yukawa couplings, …?)

FCNC

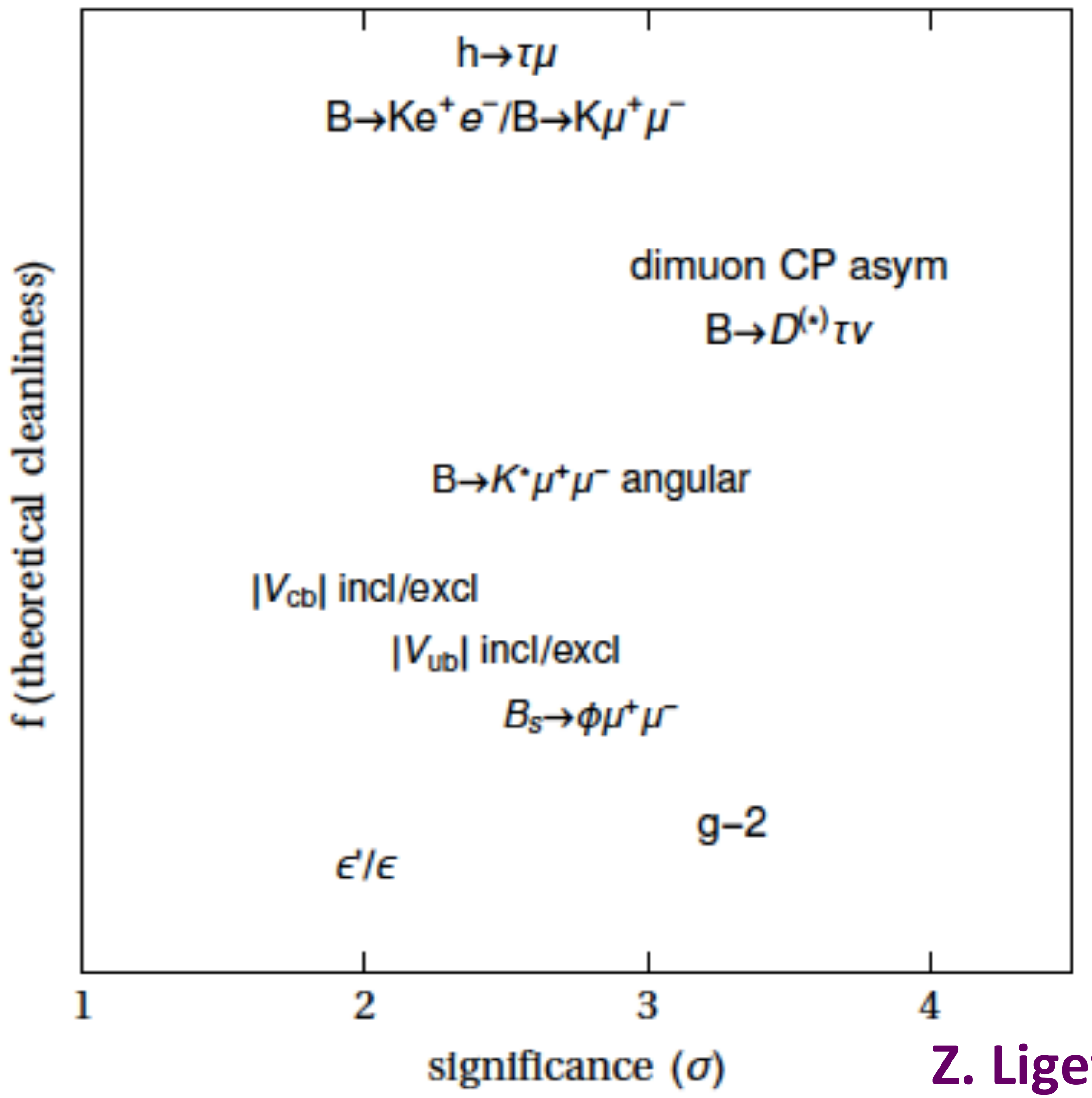
Flavour changing neutral current (FCNC) processes are suppressed.

In the SM two nice mechanisms are at work: the **GIM mechanism** and the structure of the **CKM mixing matrix.**

How to cope with such delicate suppression if the there is new physics at the electroweak scale?



Deviations from the SM expectations: significance of such deviations vs. their theoretical cleanliness



Z. Ligeti, LP 2015

Puzzling deviations: $R(D^{(*)}) = BR(\bar{B} \to D^{(*)}\tau\bar{\nu}) / BR(\bar{B} \to D^{(*)} l\bar{\nu})$

New HFAG average of R(D*) and R(D):

HFAG averages:

R(D*) = 0.322 ±0.018±0.012

R(D) = 0.391 ±0.041±0.028

Correlation (D,D*) = -0.29

SM predictions:

R(D*) = 0.252 ± 0.003

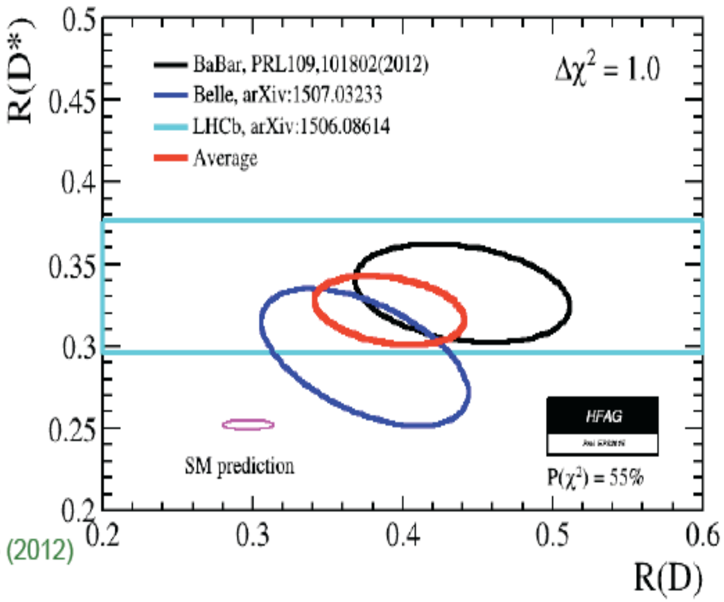
PRD 85 (2012) 094025

R(D) = 0.300 ±0.010

FNAL/MILC, arXiv:1503.07237

H. Na at al., arXiv:1505.03925

S. Fajfer et al., PRD 85, 094025 (2012)

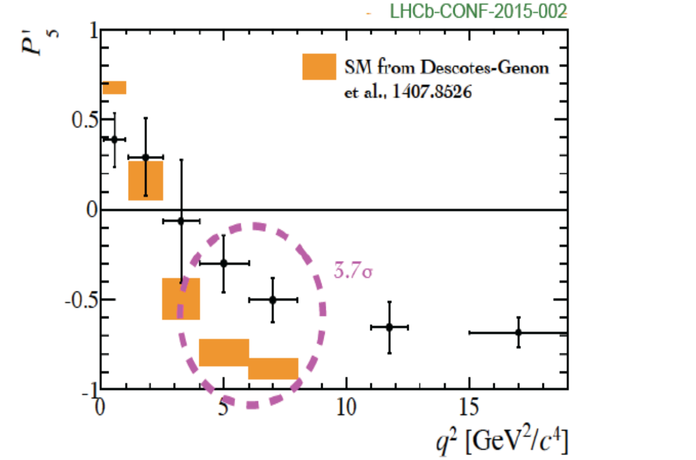


Difference with SM predictions at 3.9 σ level.

G. Lanfranchi, LP 2015

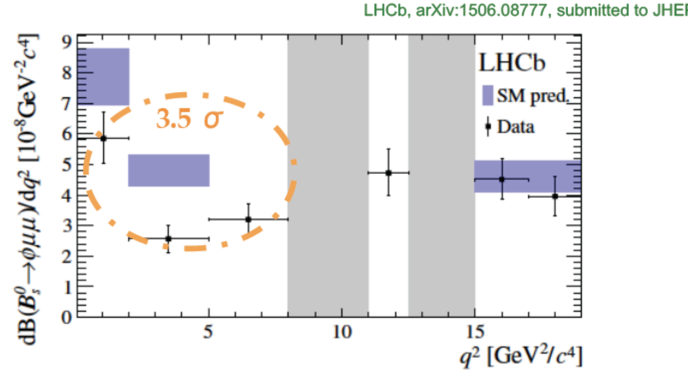
Puzzling deviations: P'_5 in $B^0 \to K^{*0} \mu^+ \mu^-$

Recently confirmed by LHCb with the full Run I dataset (3 fb^{-1})



..and recently also in the differential BR of $B^0_s \to \phi \mu^+\mu^-$ with full Run I dataset (3 fb^{-1})

LHCb, arXiv:1506.08777, submitted to JHEP



SM predictions based on W. Altmannshofer and D. Straub, arXiv:1411.3161

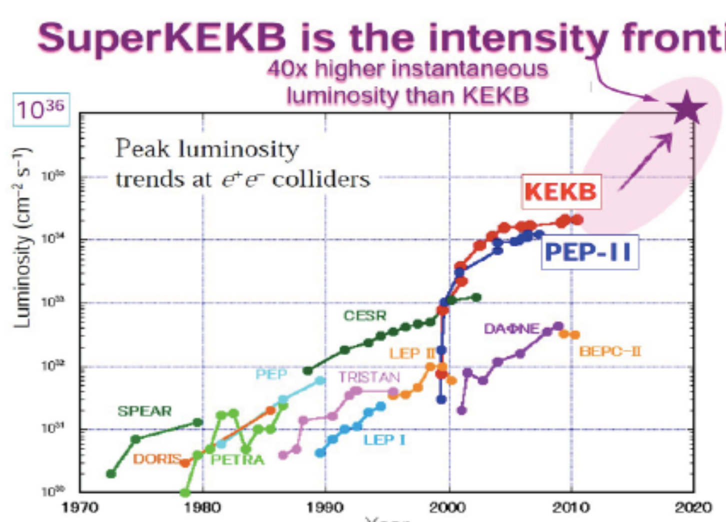
A. Bharucha, D. Straub, R. Zwicky: arXiv:1503.05534

BELLE2 @ SuperKEKB:

data taking starting with full detector in 2018 → expected 50 ab^{-1} by 2025

	Belle	BaBar	Global Fit CKMfitter	LHCb Run-2	Belle II 50 ab^{-1}	LHCb Upgrade 50 fb^{-1}	Theory
φ_1: ccs	0.9°		0.9°	0.6°	0.3°	0.3°	v. small.
φ_2: uud	4° (WA)		2.1°		1°		~1-2°
φ_3: DK	14°		3.8°	4°	1.5°	1°	negl.
$\lvert V_{cb}\rvert$ inclusive	1.7%		2.4%		1.2%		
$\lvert V_{cb}\rvert$ exclusive	2.2%				1.4%		
$\lvert V_{ub}\rvert$ inclusive	7%		4.5%	7.2%	3.0%		
$\lvert V_{ub}\rvert$ exclusive	8%				2.4%		
$\lvert V_{ub}\rvert$ leptonic	14%				3.0%		

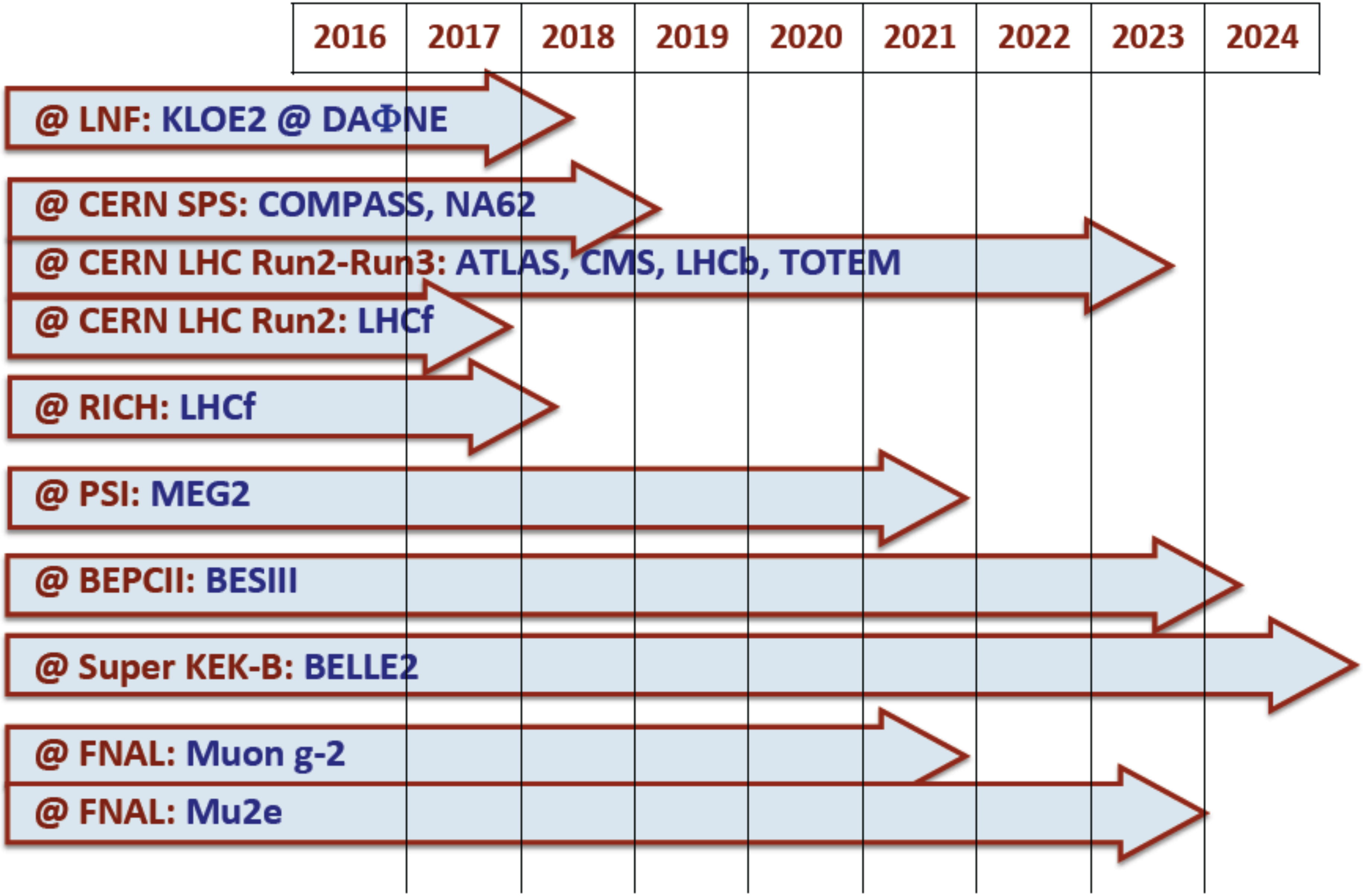
Experiment	Theory
No result	
Moderate precision	Moderate precision
Precise	Clean / LQCD
Very Precise	Clean



Hadronic parameter	L.Lellouch ICHEP 2002 [hep-ph/0211359]	FLAG 2013 [1310.8555]	2025 [What Next]
$f_+^{K\pi}(0)$	- First Lattice result in 2004 [0.9%]	[0.4%]	[0.1%]
$\hat{B}_K$	[17%]	[1.3%]	[0.1-0.5%]
f_{Bs}	[13%]	[2%]	[0.5%]
f_{Bs}/f_B	[6%]	[1.8%]	[0.5%]
$\hat{B}_{Bs}$	[9%]	[5%]	[0.5-1%]
B_{Bs}/B_B	[3%]	[10%]	[0.5-1%]
$F_{D^*}(1)$	[3%]	[1.8%]	[0.5%]
$B\rightarrow\pi$	[20%]	[10%]	[>1%]

C. Tarantino
LTS1
Elba 2014

Complete data taking plans with approved detectors



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

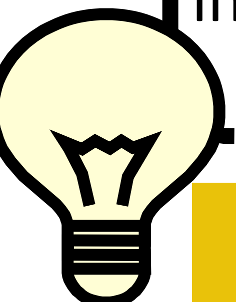
OBSERVATIONAL EVIDENCE OF NEW PHYSICS

BEYOND THE STANDARD

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

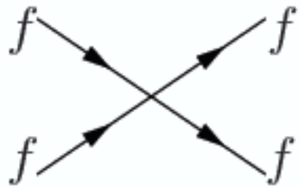
★ ★ ★ **Stabilization of the electroweak symmetry breaking at M_W calls for an ULTRAVIOLET COMPLETION of the SM already at the TeV scale** +

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

No-Lose Theorems

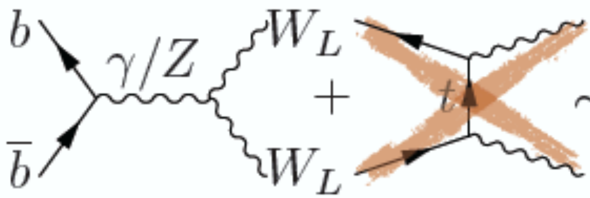
A number of **guaranteed** discoveries in the history of HEP

Beyond the Fermi Theory:



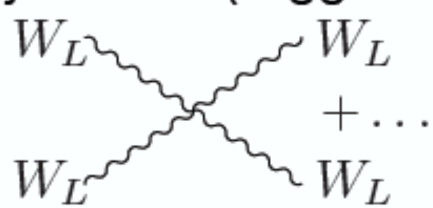
$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \Rightarrow m_W < 4\pi v$

Beyond the Bottom Quark:



$\sim g_W^2 E^2/m_W^2 < 16\pi^2 \Rightarrow m_t < 4\pi v$

Beyond the (Higgsless) EW Theory:



$\sim g_W^2 E^2/m_W^2 < 16\pi^2 \Rightarrow m_H < 4\pi v$

Each (secretly) due to d=6 non-renormalizable operators, signalling nearby new physics.

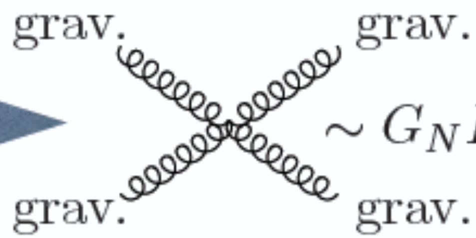
A. Wulzer 2015

No-Lose Theorems

A. Wulzer

Only one d>4 is left after Higgs discovery …

$\frac{1}{G_N}\sqrt{g}R$ ⟶



$\sim G_N E^2 \simeq E^2/{M_{\rm P}}^2 < 16\pi^2$ ⟶ $\Lambda_{\rm SM} \lesssim M_{\rm P}$

… the last, impractical, No-Lose Theorem is Q.G. at $M_{\rm P}$!

We do have exp. evidences of BSM, but none necessarily pointing to light/strongly-coupled enough new physics:

“No guaranteed discoveries” $=$ “post-Higgs depression”

However, one **d<4** comes with the Higgs discovery:

$\frac{m_H^2}{2} H^\dagger H$ ⟶

The **Naturalness Problem:**

Why $m_H \ll \Lambda_{\rm SM}$?

THE "COMPREHENSION" OF THE ELECTROWEAK SCALE

$$V = \mu^2|H|^2 + \lambda|H|^4$$ **μ ~ 10^2 GeV**

Romanino

- M = O(10^{16} GeV)

	SU(3)	SU(2)	U(1)		SO(10)
L	1	2	-1/2		
e	1	1	1		
Q	3	2	1/6	⇒	16
u	3*	1	-2/3		
d	3*	1	1/3		

$$m_H^2 \sim -2\mu^2 + \frac{g^2}{(4\pi)^2}M^2$$

ONLY FOR SCALARS; SM FERMIONS AND GAUGE BOSON MASSES ARE PROTECTED BY THE SU(2) × U(1) SYMMETRY !

To comprehend (i.e. stabilize) the elw. scale need NEW PHYSICS (NP) to be operative at a scale $m_{NP} \ll M$

Naturalness or Un-naturalness?

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

$$m_{NP} \ll M$$

Low-energy **SuperSymmetry**

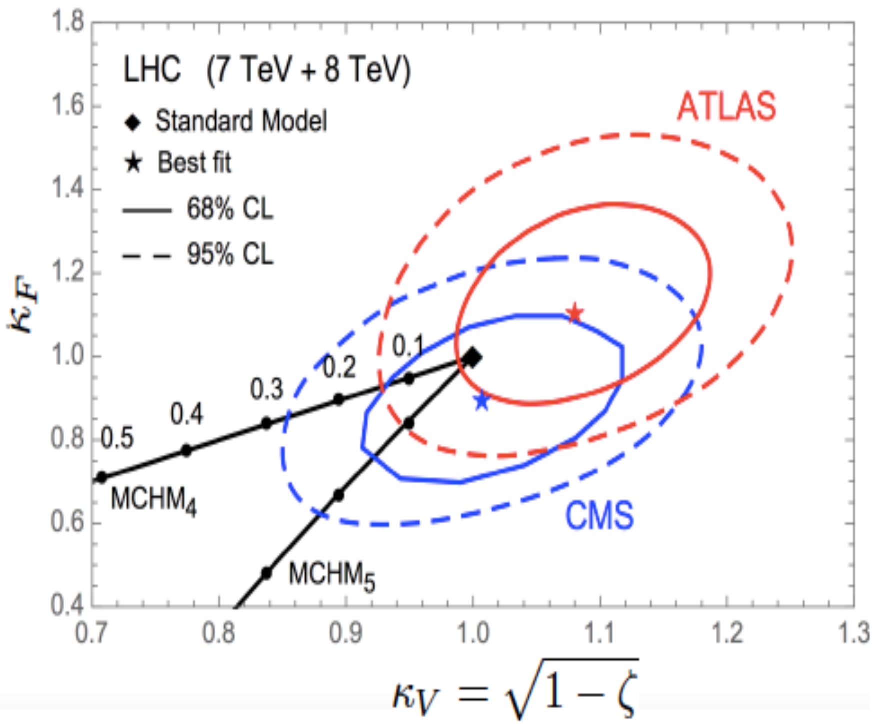
- **Space-time modification (extra-dim., warped space)**

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

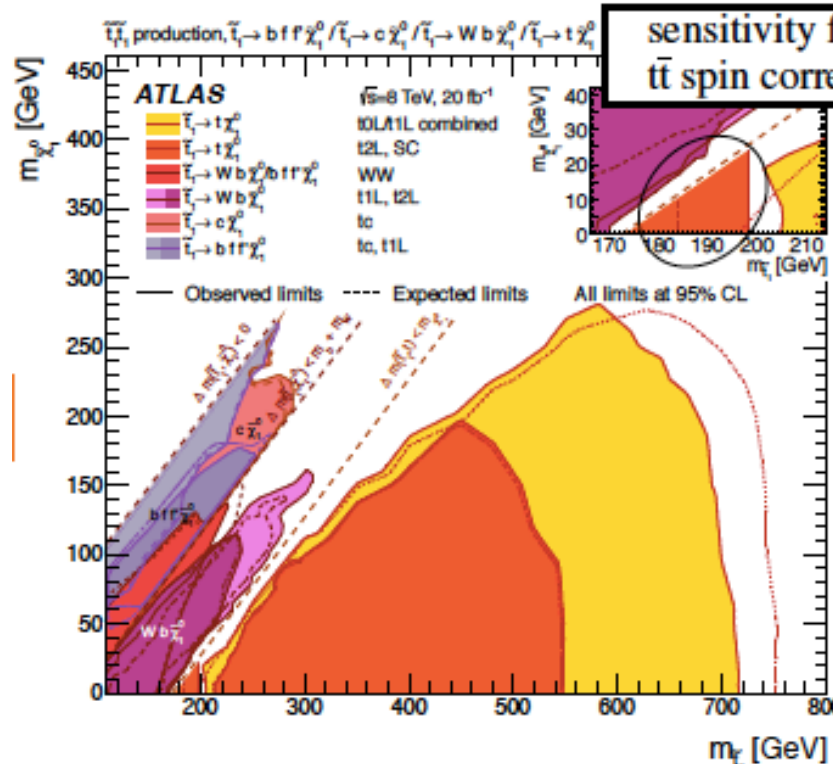
- **The scale at which the electroweak symmetry is spontaneously broken by <H> results from COSMOLOGICAL EVOLUTION**

- **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)**

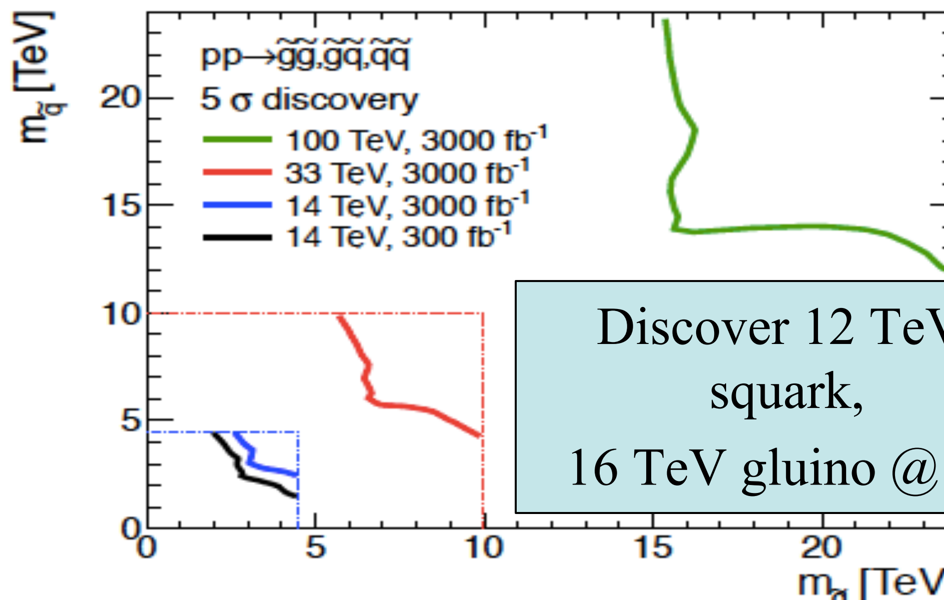
Higgs boson: elementary or composite?



Current bound ζ < 0.12 → already some tuning on the **composite** models to look like SM



sensitivity from $t\bar{t}$ spin correlation



Discover 12 TeV squark,
16 TeV gluino @ 5σ

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

DM and ELW. SYMMETRY BREAKING

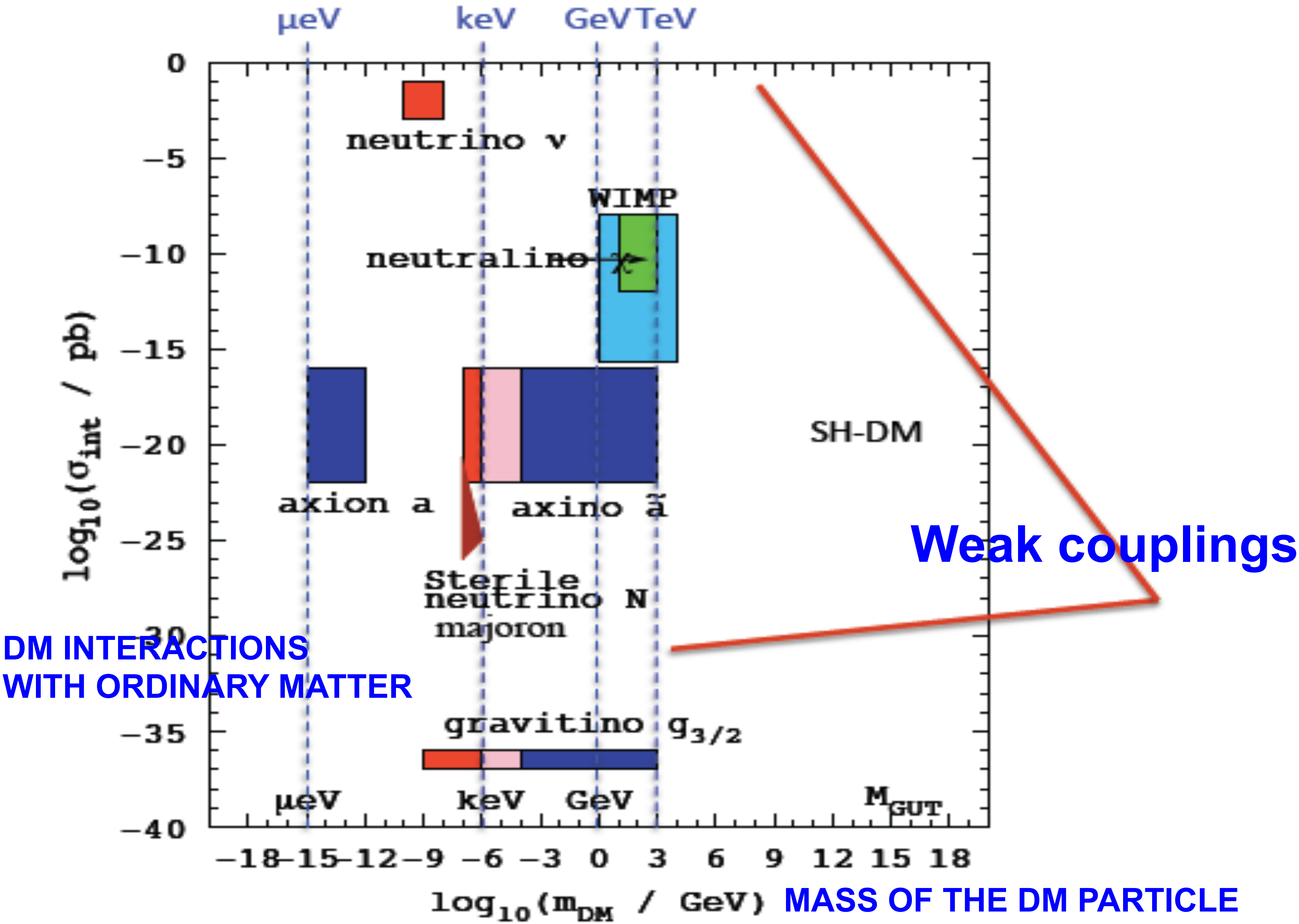
THE DM ROAD TO NEW PHYSICS BEYOND THE SM:

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

TEN COMMANDMENTS TO BE A "GOOD" DM CANDIDATE

BERTONE, A.M., TAOSO

- **TO MATCH THE APPROPRIATE RELIC DENSITY**
- **TO BE COLD**
- **TO BE NEUTRAL**
- **TO BE CONSISTENT WITH BBN**
- **TO LEAVE STELLAR EVOLUTION UNCHANGED**
- **TO BE COMPATIBLE WITH CONSTRAINTS ON SELF – INTERACTIONS**
- **TO BE CONSISTENT WITH DIRECT DM SEARCHES**
- **TO BE COMPATIBLE WITH GAMMA – RAY CONSTRAINTS**
- **TO BE COMPATIBLE WITH OTHER ASTROPHYSICAL BOUNDS**
- **"TO BE PROBED EXPERIMENTALLY"**

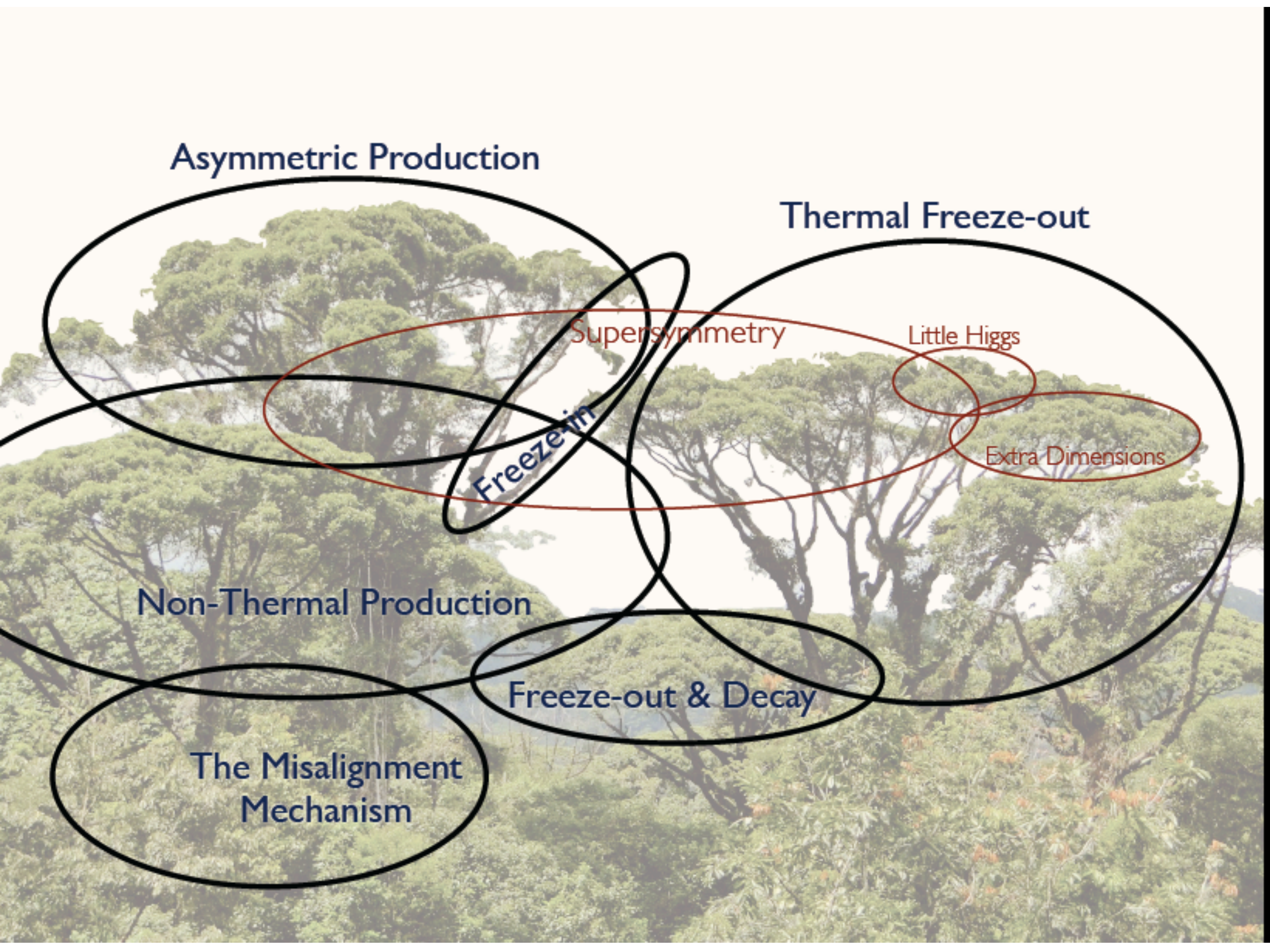


μeV
keV
GeV
TeV
0
−5
−10
−15
−20
−25
−30
−35
−40
neutrino ν
WIMP
neutralino χ
SH-DM
axion a
axino ã
Sterile
neutrino N
majoron
gravitino g3/2
μeV
keV
GeV
MGUT
−18
−15
−12
−9
−6
−3
0
3
6
9
12
15
18
log10(σint / pb)
log10(mDM / GeV)
Weak couplings
DM INTERACTIONS
WITH ORDINARY MATTER
MASS OF THE DM PARTICLE

CONNECTION DM – ELW. SCALE

THE WIMP MIRACLE :STABLE ELW. SCALE WIMPs

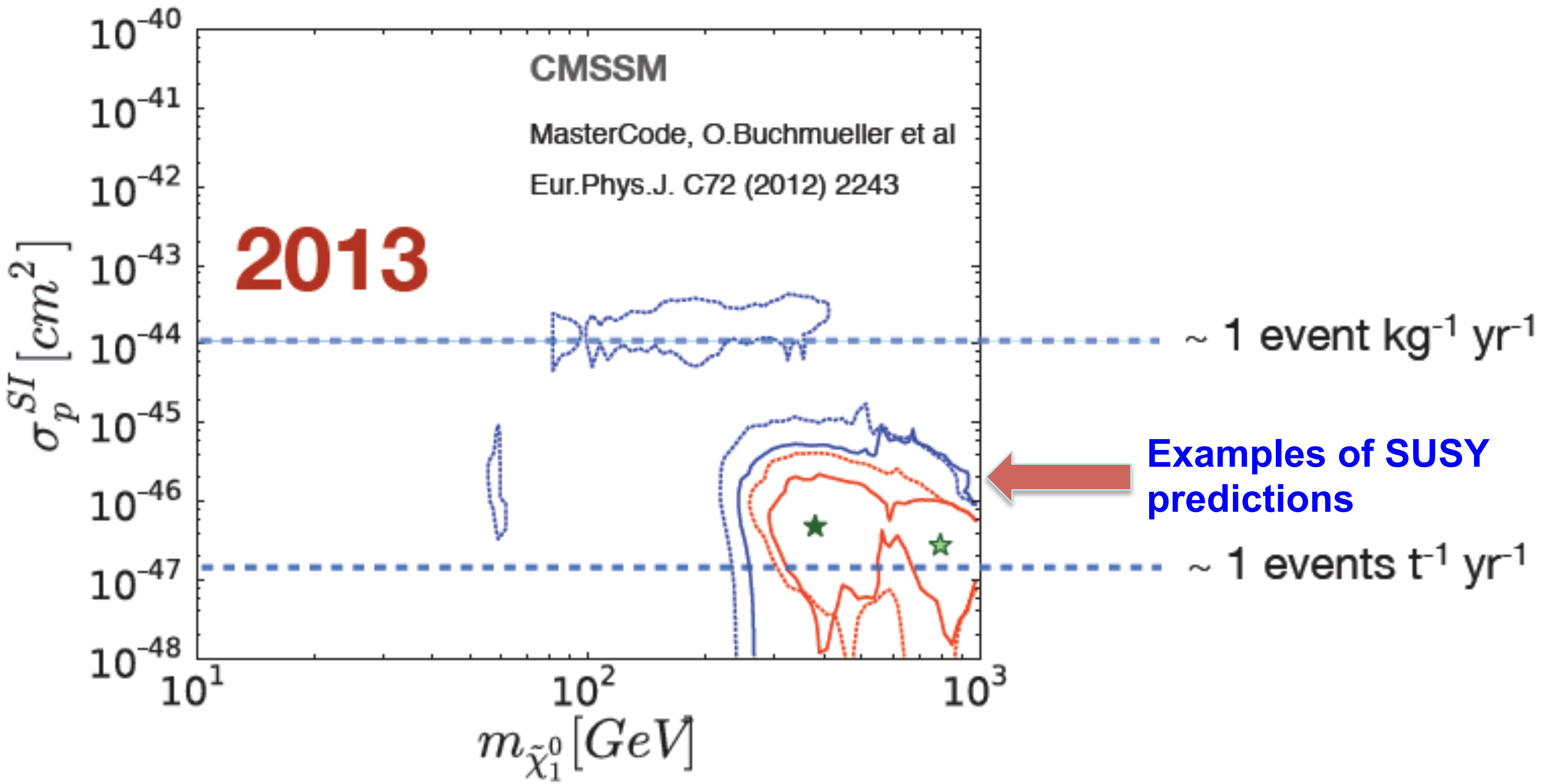
	SUSY	EXTRA DIM.	LITTLE HIGGS.
1) **ENLARGEMENT OF THE SM**	(x^{μ}, θ)	(x^{μ}, j^{i})	SM part + new part
	Anticomm. Coord.	New bosonic Coord.	to cancel Λ^2 at 1-Loop
2) **SELECTION RULE**	***R-PARITY LSP***	***KK-PARITY LKP***	***T-PARITY LTP***
→ **DISCRETE SYMM.**	Neutralino spin 1/2	spin1	spin0
→ **STABLE 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


Asymmetric Production
Thermal Freeze-out
Supersymmetry
Little Higgs
Extra Dimensions
Freeze-in
Non-Thermal Production
Freeze-out & Decay
The Misalignment
Mechanism

INTERACTION RATE FOR ELASTIC SCATTERING

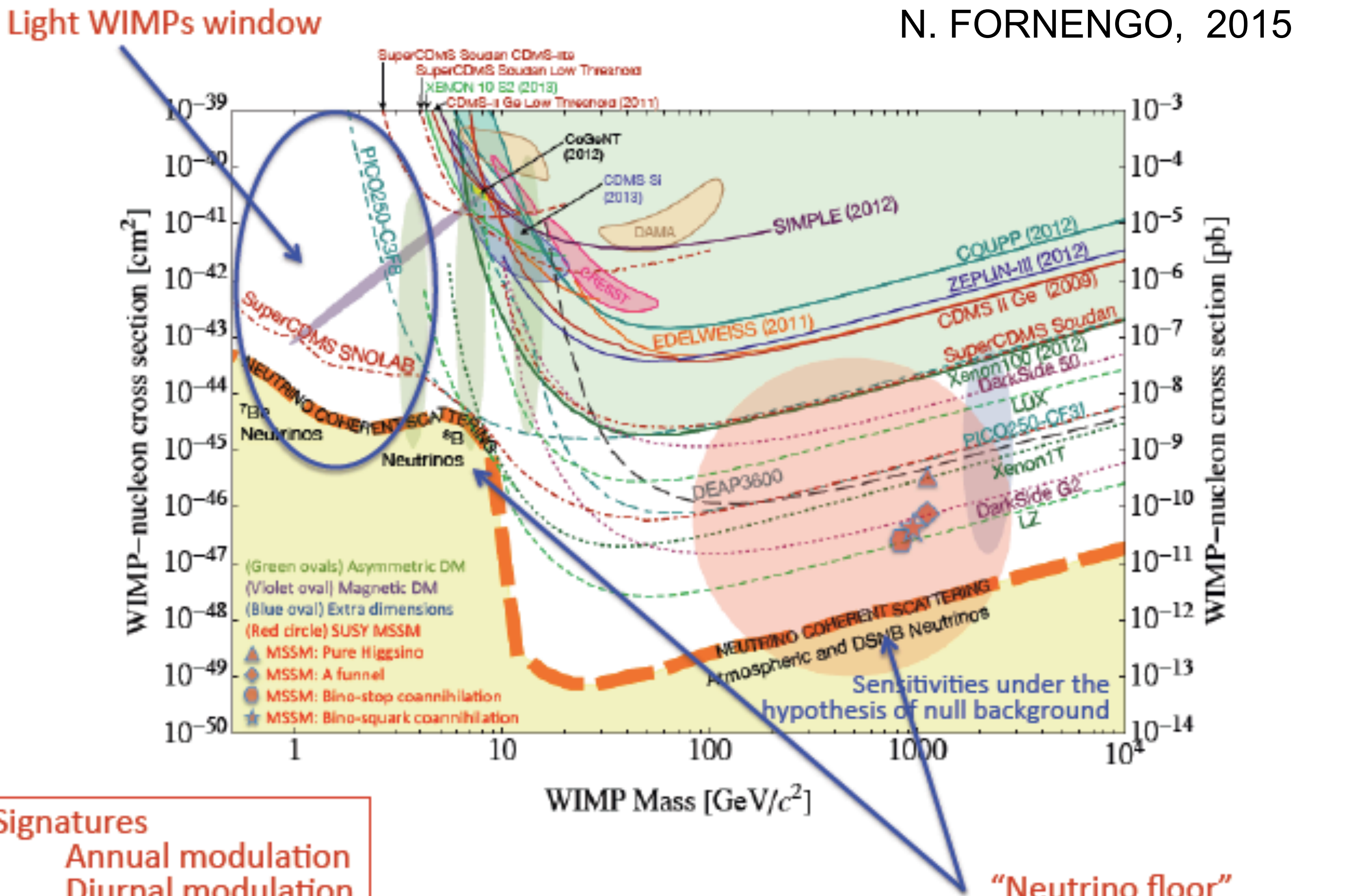
after integrating over WIMP velocity distribution

$$R \sim 0.13 \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$



Direct detection

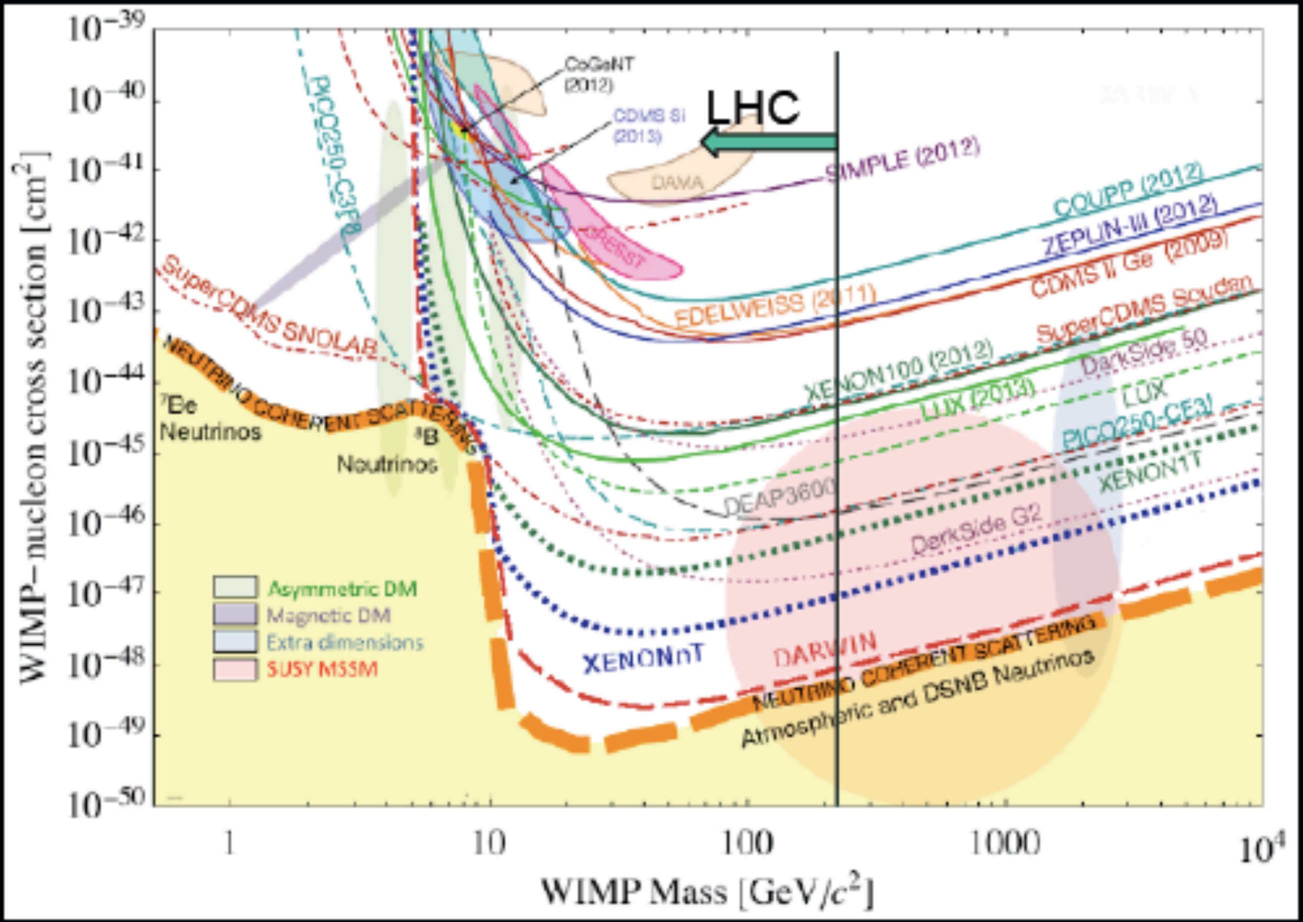
N. FORNENGO, 2015



Signatures
- Annual modulation
- Diurnal modulation
- Directionality

Full set of effective operators (15)

Direct Dark Matter direct detection II



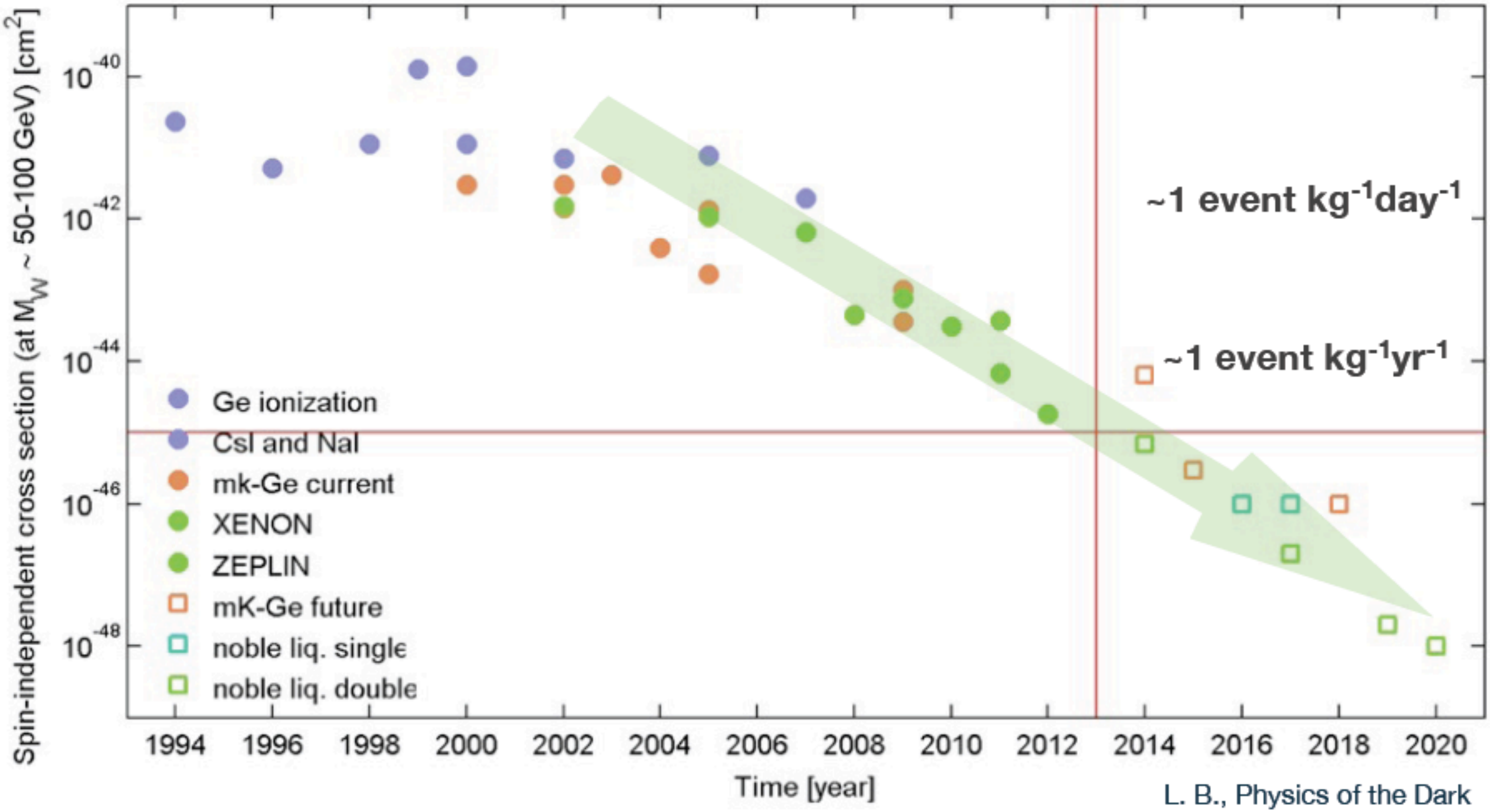
- ✓ *Complementarity: Low masses → bolometers , High masses → Noble liquids*
- ✓ *Complementarity with LHC but also in case of high WIMP masses rationale for FCC*
- ✓ *Reaching the neutrino background → directional R&D*
- ✓ *Place for 1-2 in the world, with large international collaborations*
- ✓ *APPEC SAC → Decide after 3 years the (G3) multi-ton experiment.*
- ✓ *P5 similar conclusions*

J. MONROE

Direct detection: sensitivity versus time

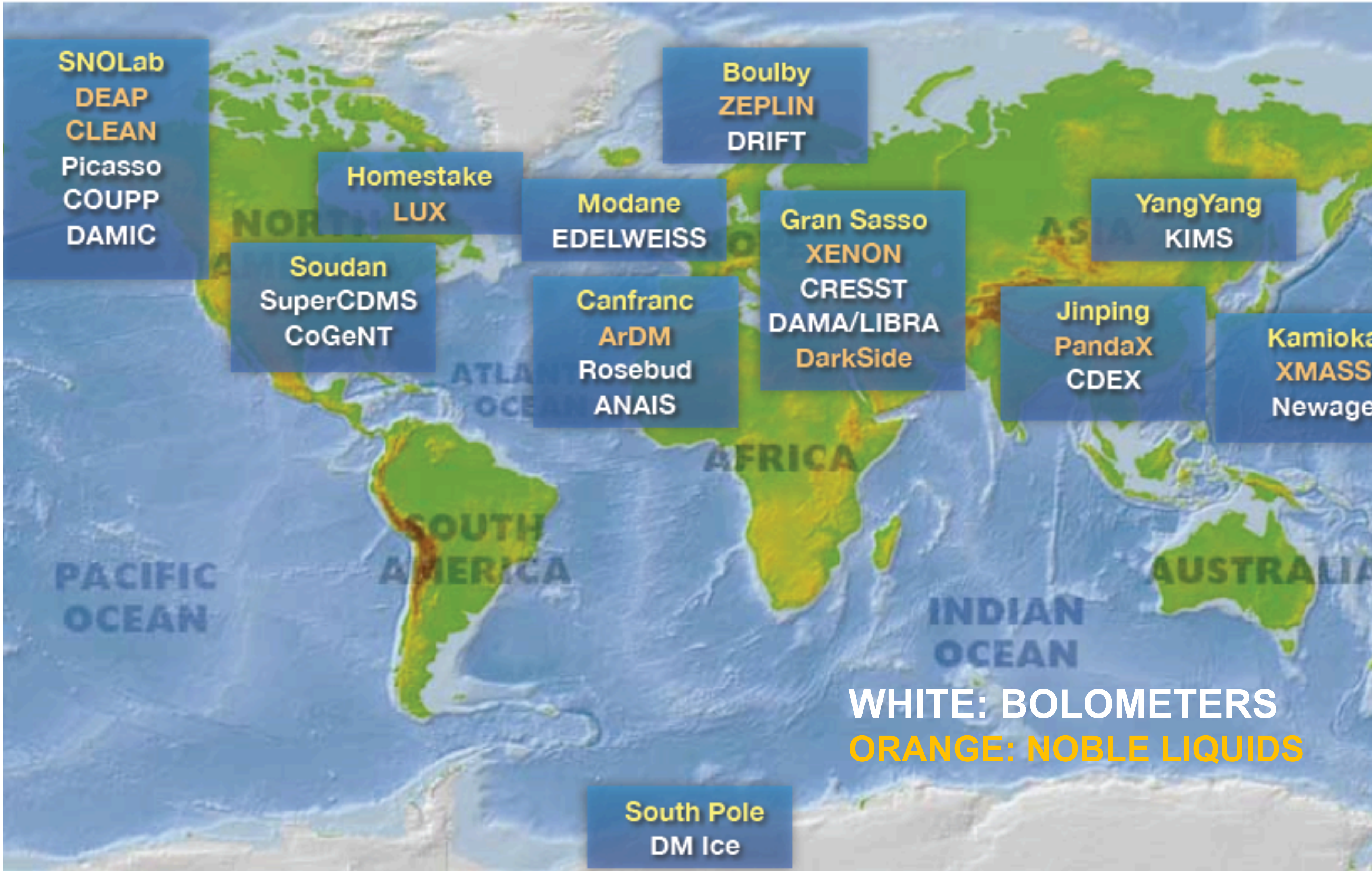
Factor ~ 10 every two years!

L. BAUDIS

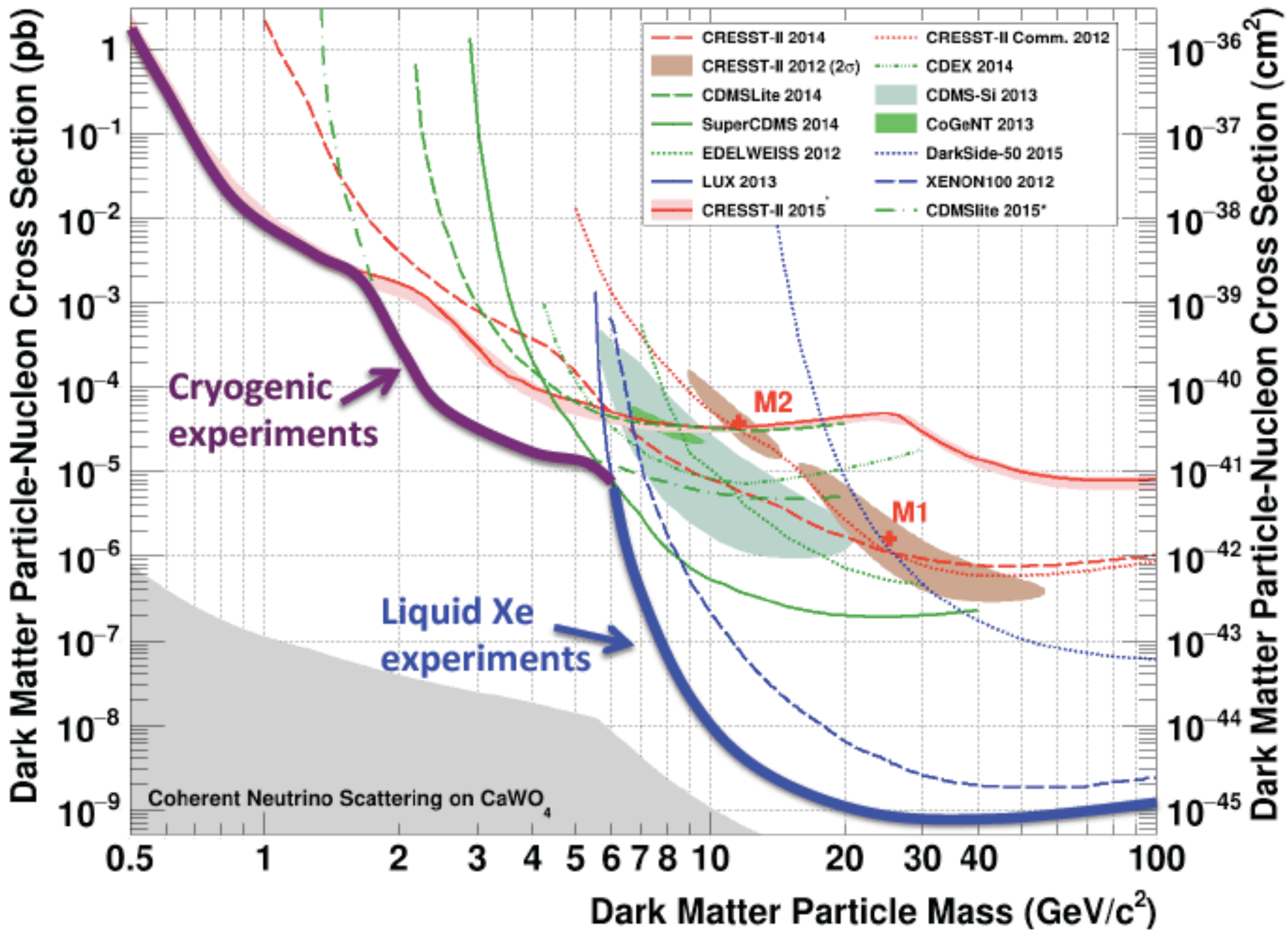


L. B., Physics of the Dark Universe 1, 94 (2012)

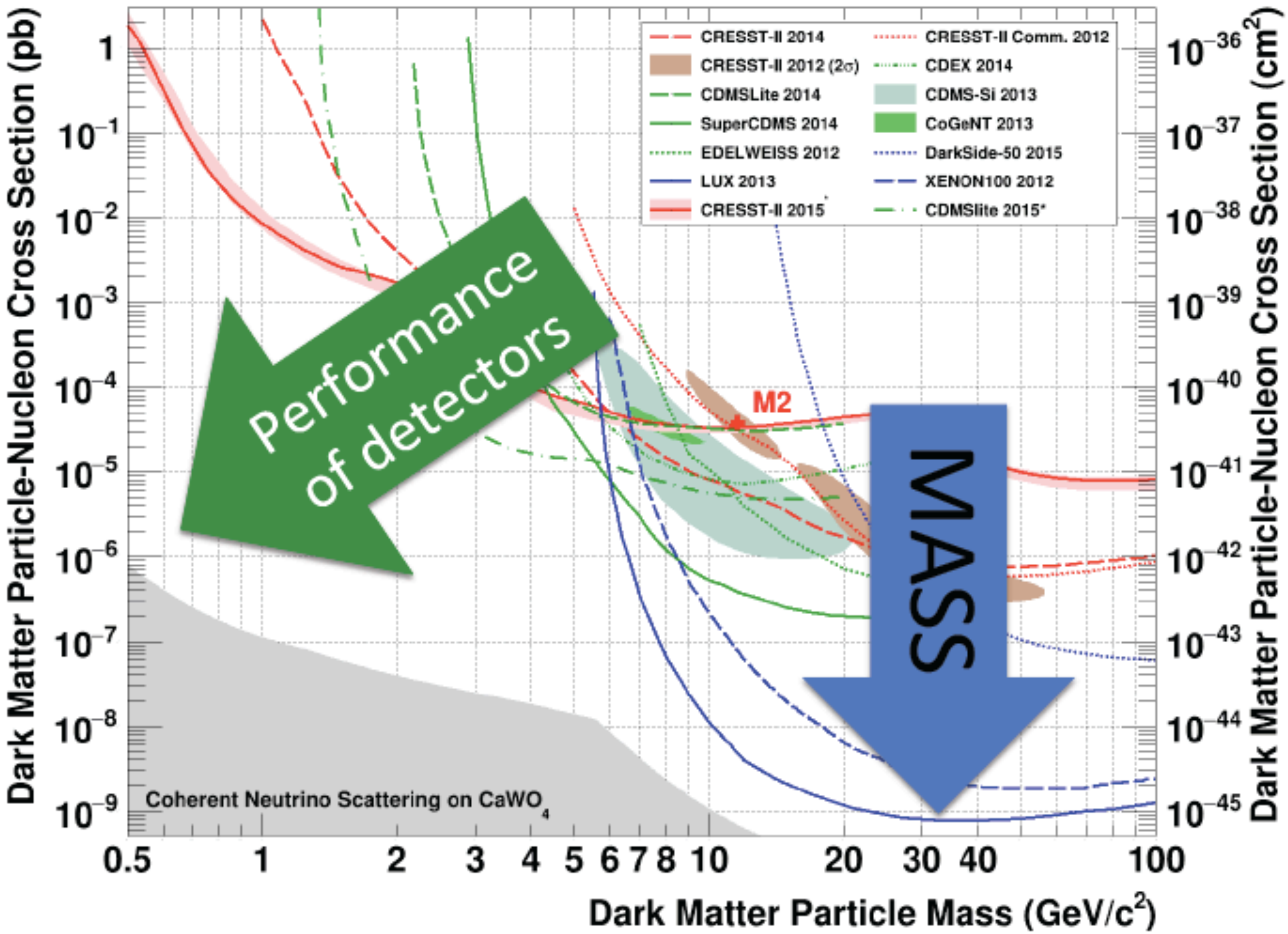
IMPRESSIVE EFFORT TO LOOK FOR WIMPS WORLDWIDE



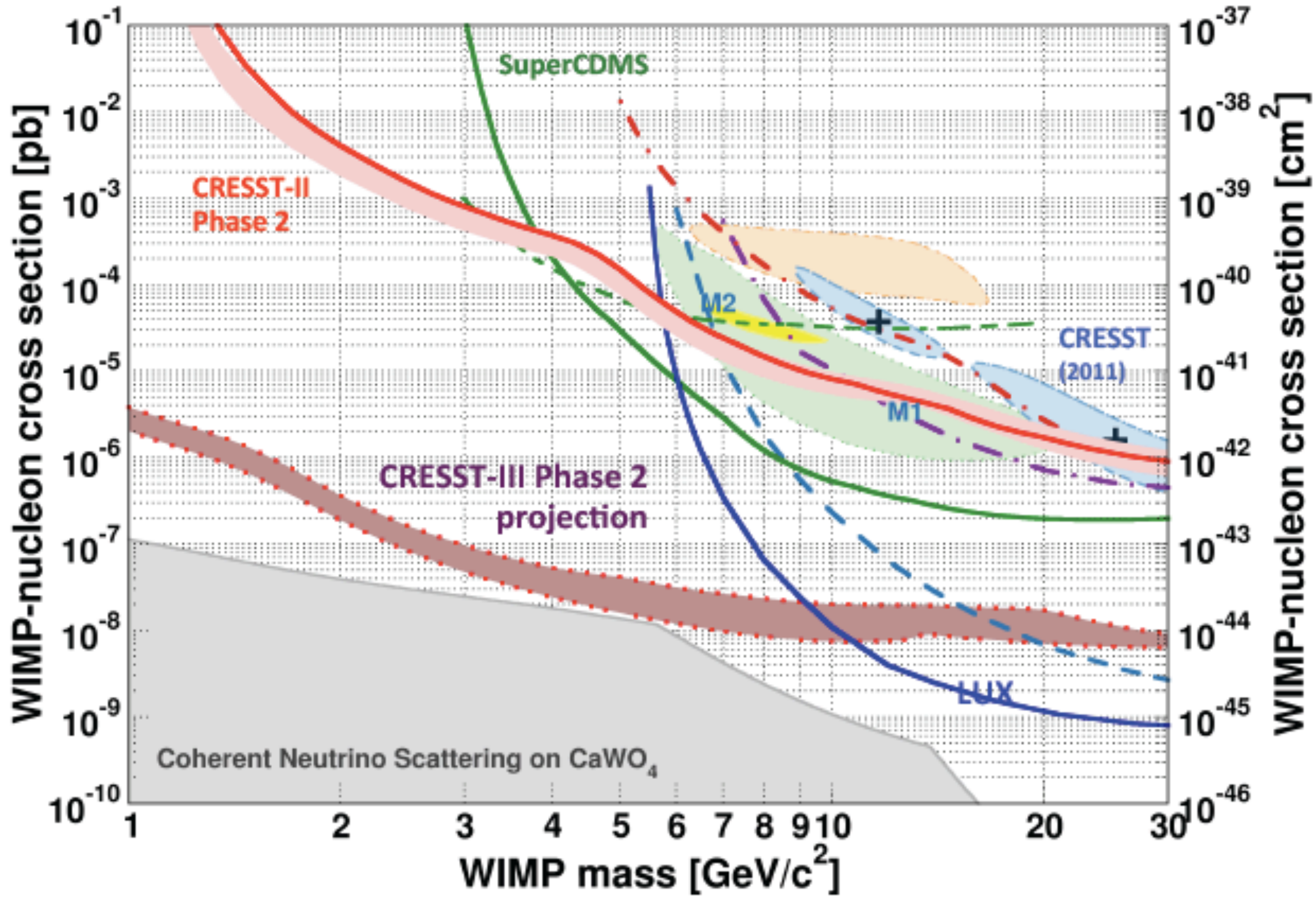
Current Status of Direct Dark Matter Searches



Future of Dark Matter Searches



CRESST-III Phase 2

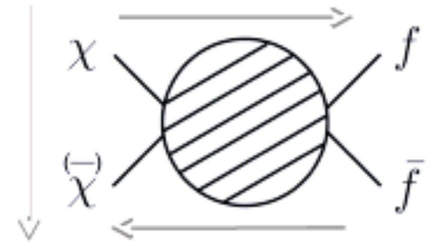


100 x 24g detectors of improved quality operated for 2 year ≈ 1000 kg-days (net)

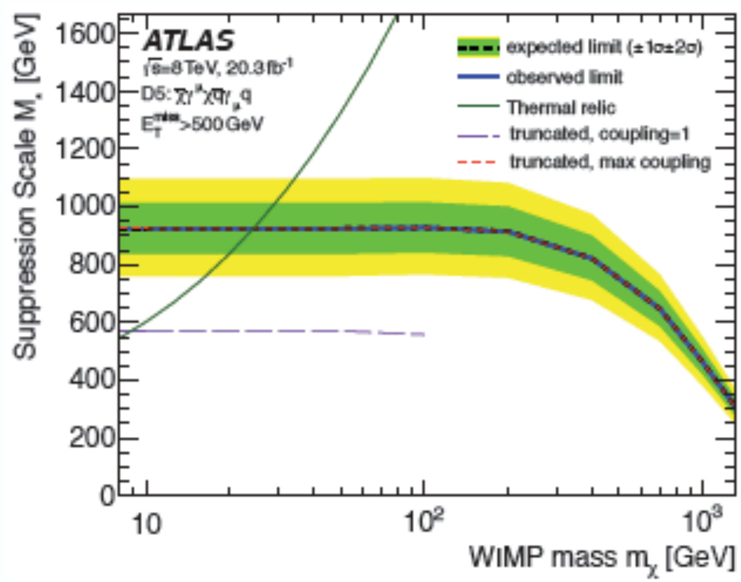
Eur. Phys. J. C (2015) 75:299

Dark Matter EFT operators

- Contact interactions (dimension-6 operator) form a simple framework for the description of the collider and astro-particle experimental results and were widely used in Run-1 by both ATLAS and CMS.
- EFT has two parameters (mDM and suppression scale Λ)

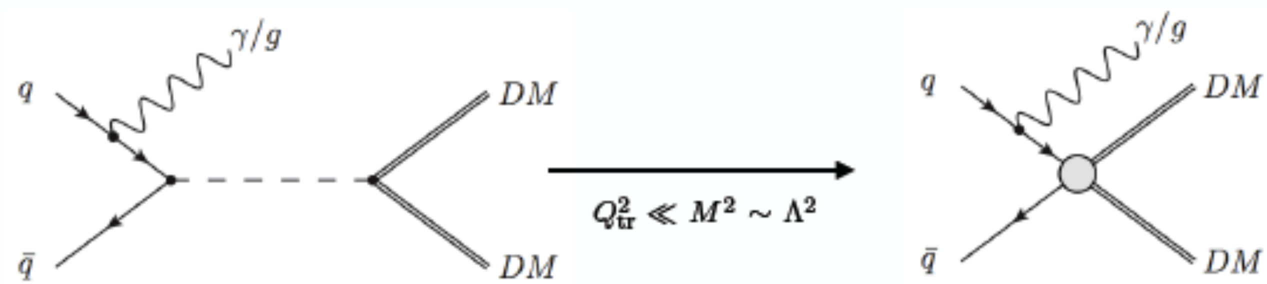


Name	Initial state	Type	Operator
C1	qq	scalar	$\frac{m_q}{M_*^2}\chi^\dagger\chi\bar{q}q$
C5	gg	scalar	$\frac{1}{4M_*^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
D1	qq	scalar	$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_*^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$



1008.1783

Contact interactions



$$\frac{1}{Q_{tr}^2 - M^2} = -\frac{1}{M^2}\left(1+\frac{Q_{tr}^2}{M^2}+\mathcal{O}\left(\frac{Q_{tr}^4}{M^4}\right)\right)$$

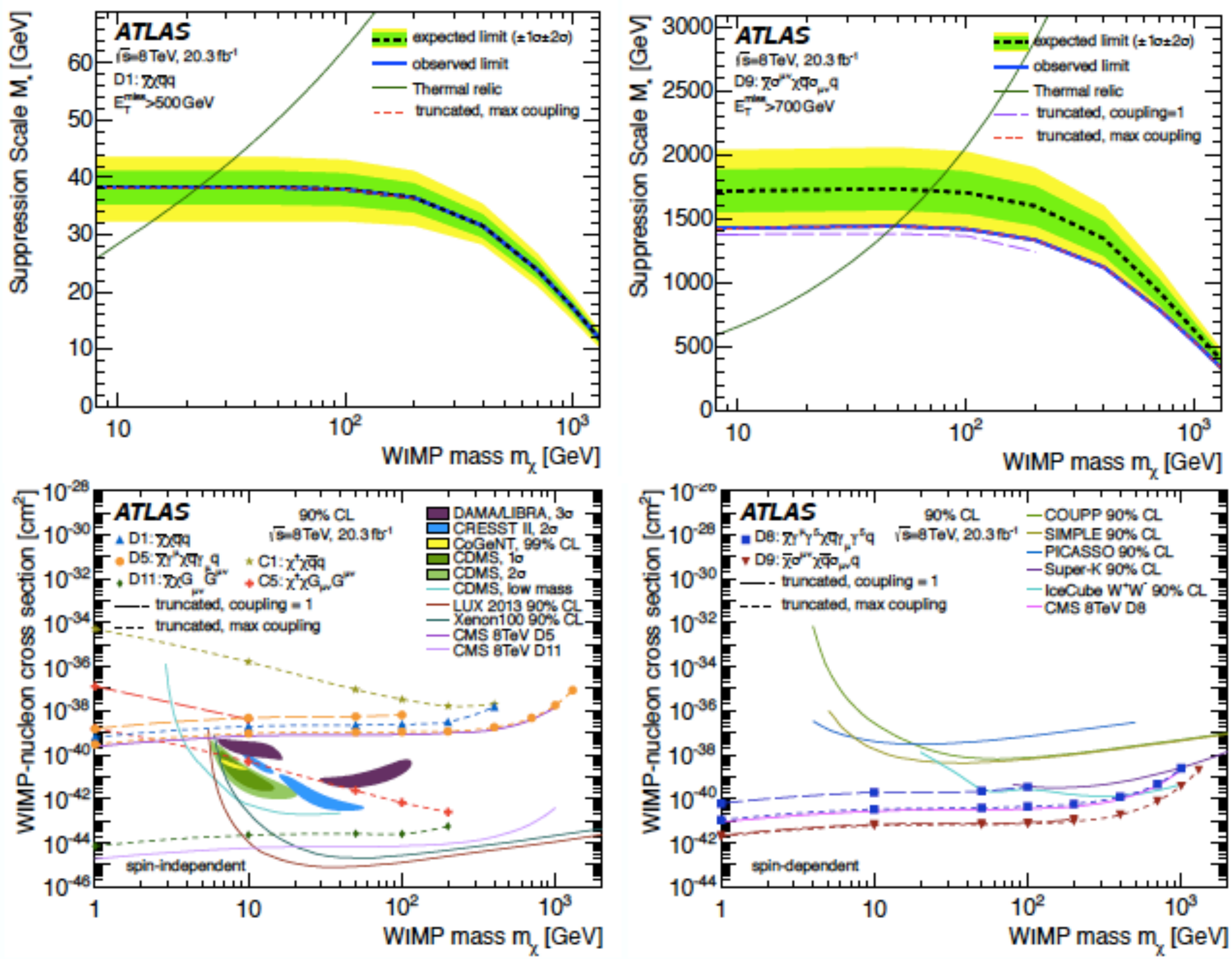
$$\mathcal{O}_S = \frac{1}{\Lambda^2}(\bar{\chi}\chi)(\bar{q}q) \qquad \frac{1}{\Lambda^2} = \frac{g_\chi g_q}{M^2}$$

It is safe to use EFT when the mediator can be integrated out.

However, at the LHC energies, the limits on the suppression scale are comparable to the momentum transfer!

Eur. Phys. J. C (2015) 75:299

DM interpretation



DE

- A :**Cosmological Constant** → constant vacuum energy
- B : **Varying vacuum energy** → varying potential energy of a scalar field rolling down to its zero minimum asymptotically
- **A or B?** → study the history of the expansion rate of the Universe and/or the history of the rate of growth of the large-scale structures in the Universe
- Techniques: **spectroscopic galaxy surveys** and **photometric (imaging) galaxy surveys**

DE

On ground

- Spectroscopic → DESI from redshift 3.5 up to now
- Photometric → DES up to redshift 1.5 → LSST deeper, wider, faster than any other optical survey to date

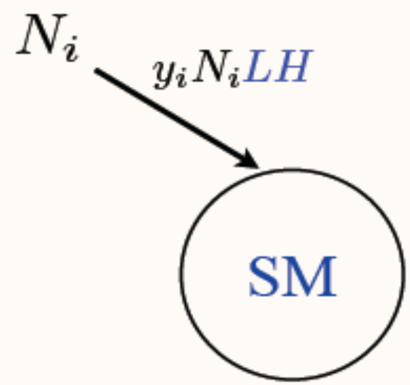
In space

- EUCLID (M-class **ESA mission** to be launched in 2020 → combines the virtues of DESI and LSST → 10^9 galaxies to be observed

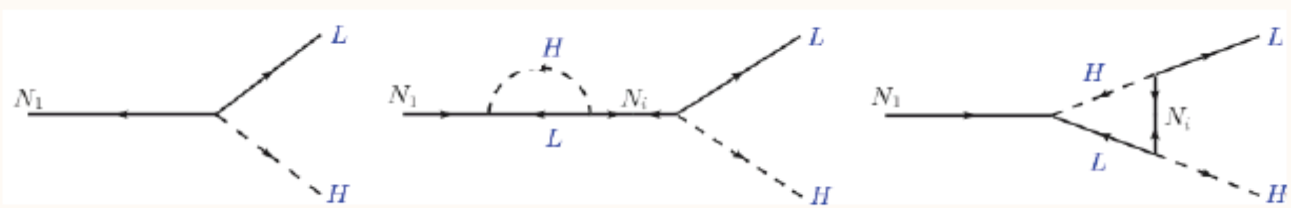
Linking neutrino masses, matter-antimatter-asymmetry and DM

- Thermal Leptogenesis:

[Fukugita,Yanagida,1986;
Review:Davidson,Nardi,Nir,2008]



T. Volansky, Prospects for Low Mass DM, MPP, Dec. 1, 2015



Sakharov's conditions:

1. **CP Violation**: Complex y_i. Requires at least two N_i's.
2. **Lepton Number Violation**: N_i are majorana.
3. **Departure from T.E.**: Decay out of equilibrium, $\Gamma_{N_1} < H(T = M_1)$.

Going beyond the SM:
the NEUTRINO MASS

A. GIULIANI, SAC APPEC

Cosmology, **single** and **double β decay** measure different combinations of the neutrino mass eigenvalues, constraining the **neutrino mass scale**

In a standard three active neutrino scenario:

$$\Sigma \equiv \sum_{i=1}^{3} M_i$$

← **cosmology**
simple sum
pure kinematical effect

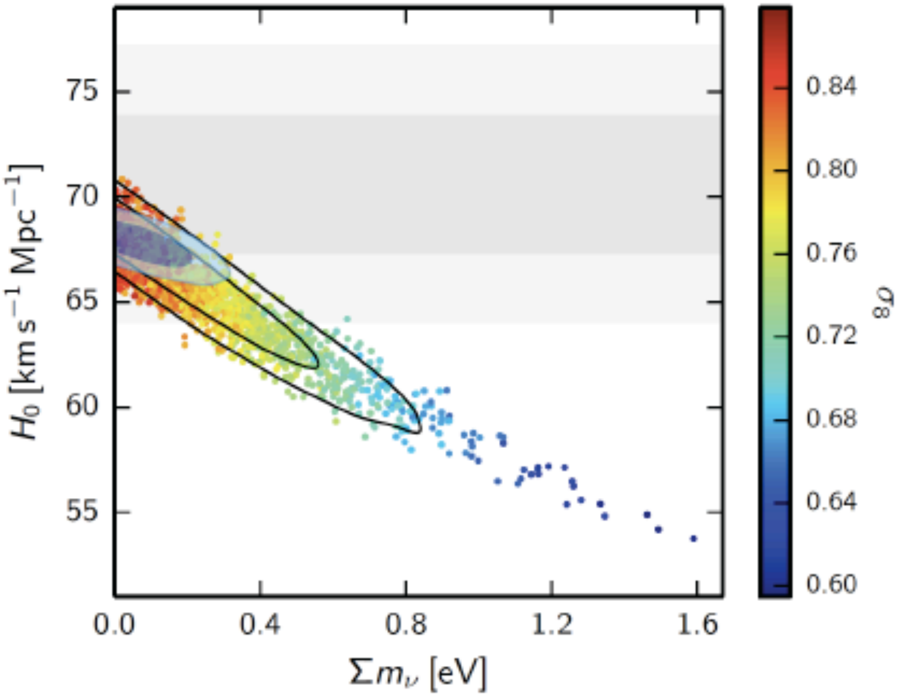
$$\langle M_\beta \rangle \equiv \left(\sum_{i=1}^{3} M_i^2 \, |U_{ei}|^2 \right)^{1/2}$$

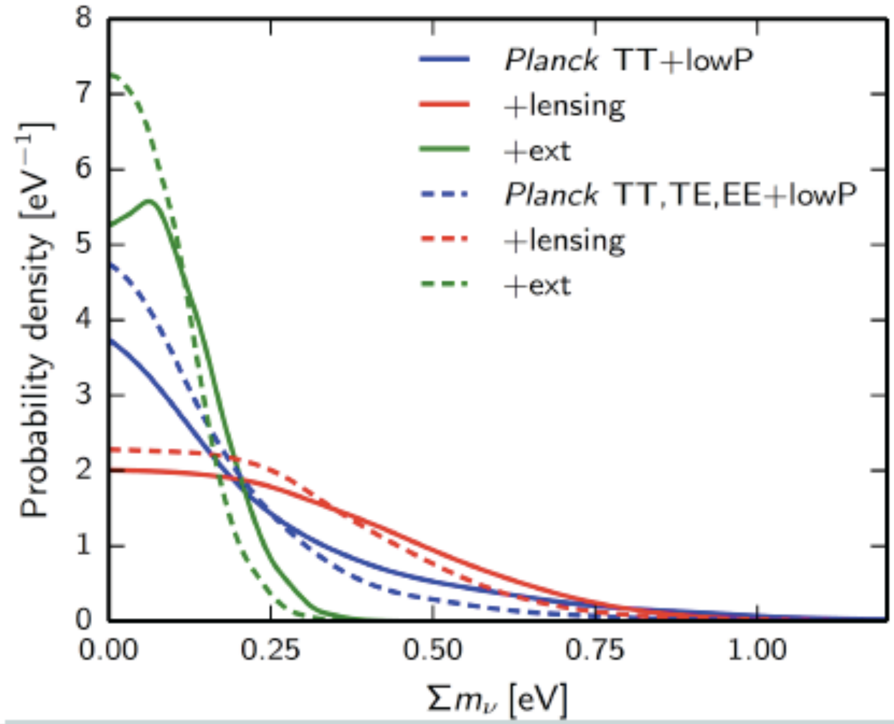
← **β decay**
incoherent sum
real neutrino

$$\langle M_{\beta\beta} \rangle \equiv \left| \sum_{i=1}^{3} M_i \, |U_{ei}|^2 \, e^{i\alpha_i} \right|$$

← **double β decay**
coherent sum
virtual neutrino
Majorana phases

Planck constraints on neutrino masses

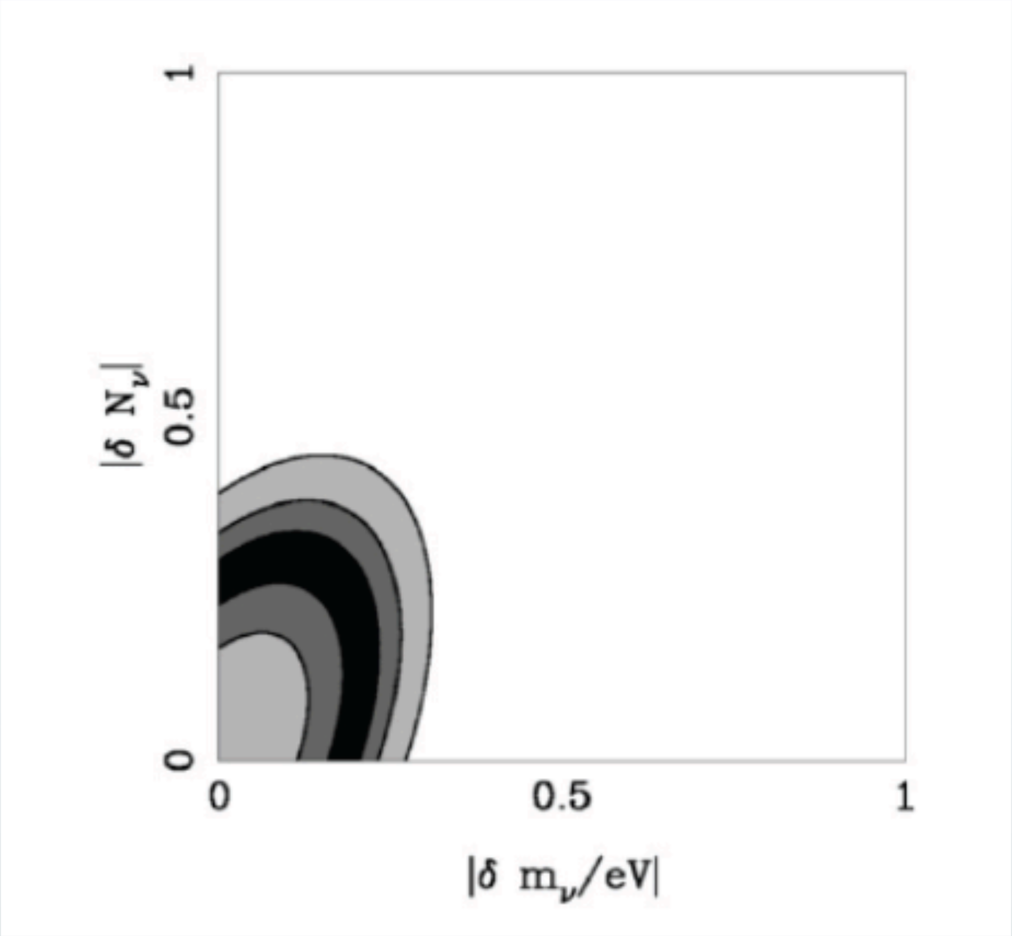




$\Sigma m_\nu < 0.23$ eV (95% CL)

$N_{eff} = 3.15 \pm 0.23$

Example: Euclid and neutrino physics



Planck+Euclid
(Kitching et al.2008)

Δm_ν~0.03 eV & ΔN_ν~0.08

Decay modes for Double Beta Decay

① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$

2ν Double Beta Decay
allowed by the Standard Model
already observed – $\tau \sim 10^{18} - 10^{21}$ y

② $(A,Z) \rightarrow (A,Z+2) + 2e^-$

neutrinoless Double Beta Decay (0ν-DBD)
never observed (except a discussed claim)
$\tau > 10^{25}$ y

③ $(A,Z) \rightarrow (A,Z+2) + 2e^- + \chi$

Double Beta Decay
with Majoron (light neutral boson)
never observed – $\tau > 10^{22}$ y

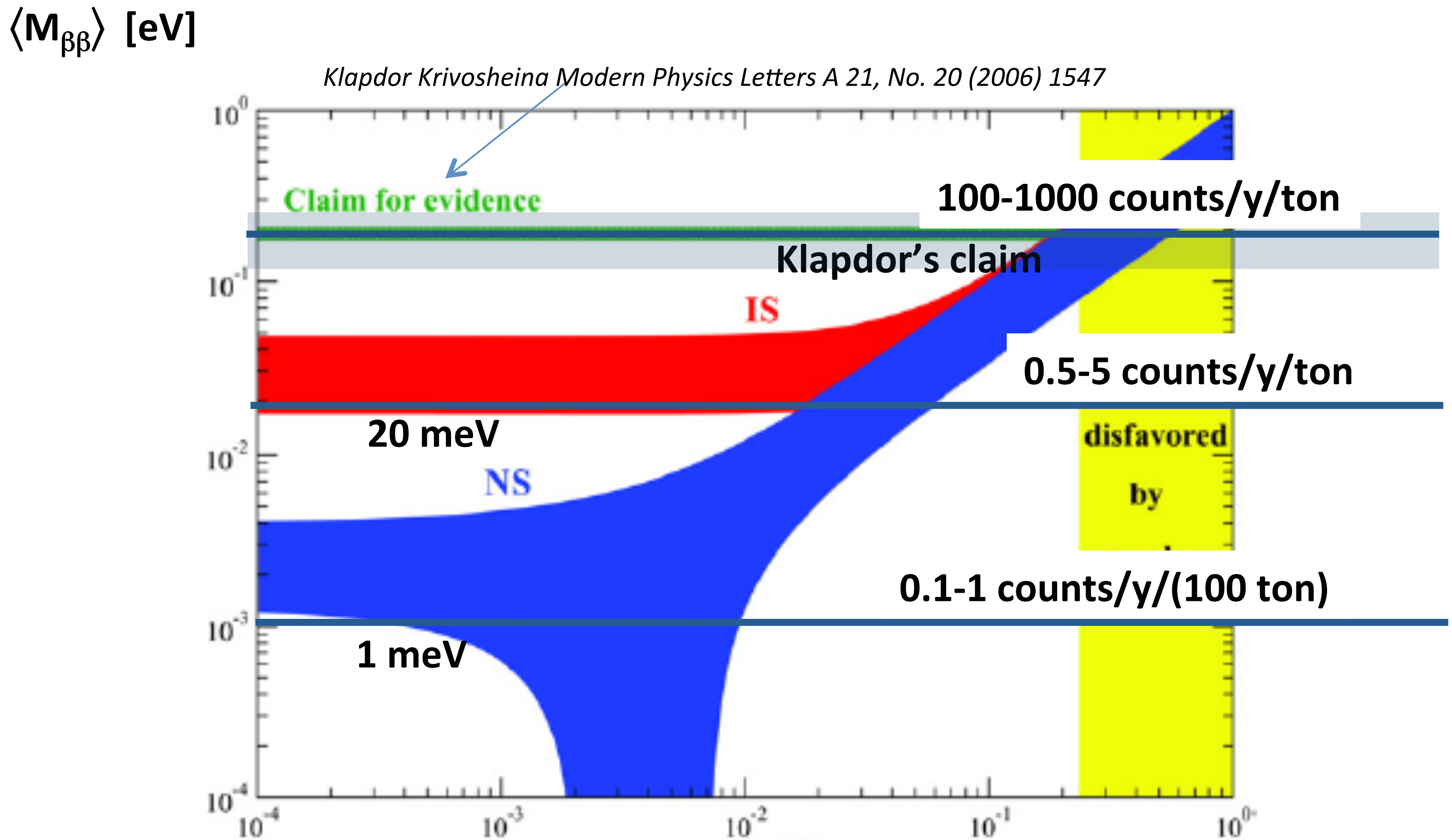
Processes ② and ③ would imply new physics beyond the Standard Model

violation of total lepton number conservation

Why is neutrinoless Double Beta Decay important

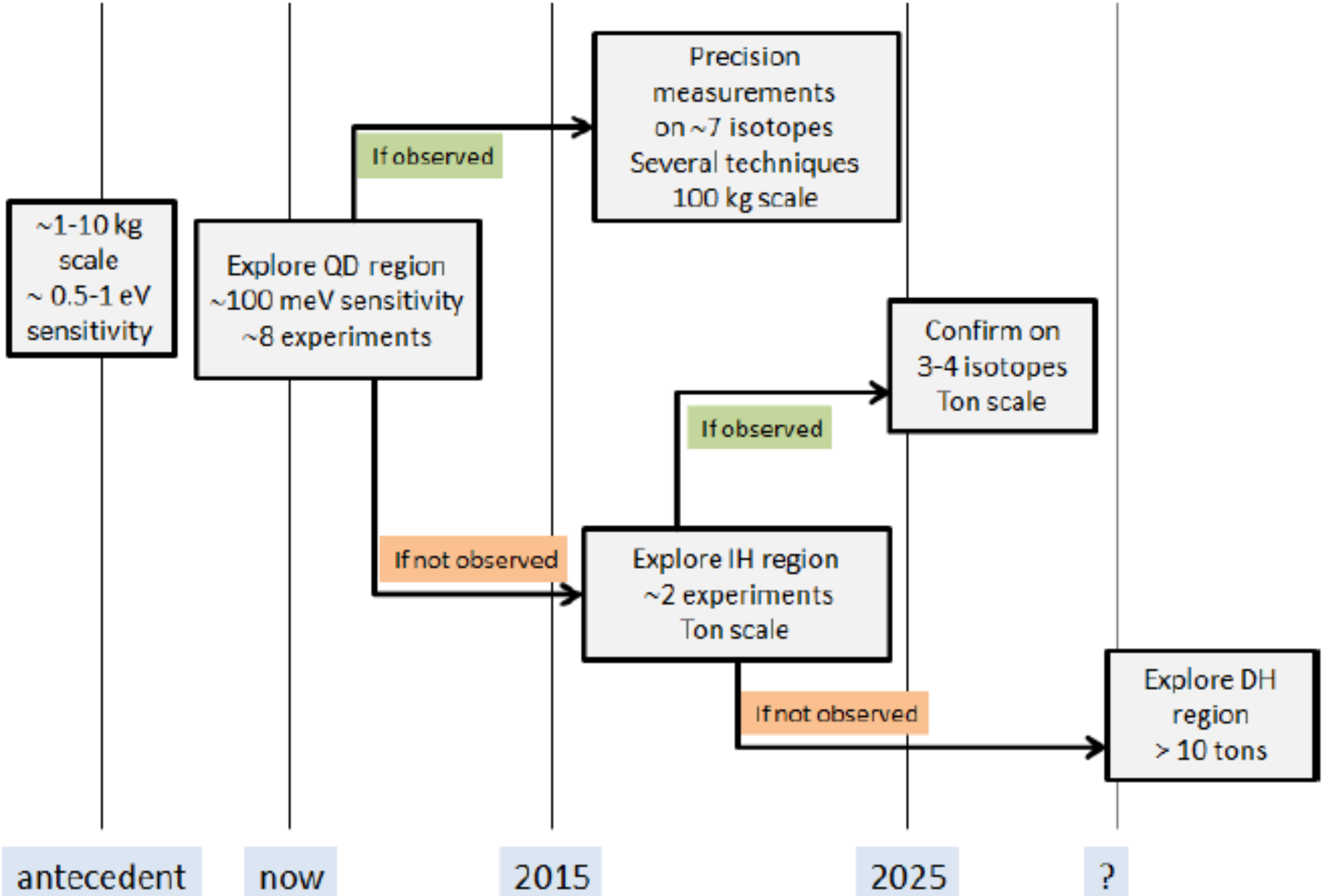
- Majorana nature of neutrino (irrespectively of the mechanism)
- See-saw mechanism ⇒ naturalness of small neutrino masses
- Leptogenesis and matter-antimatter asymmetry in the Universe

Three challenges for 0ν-DBD search

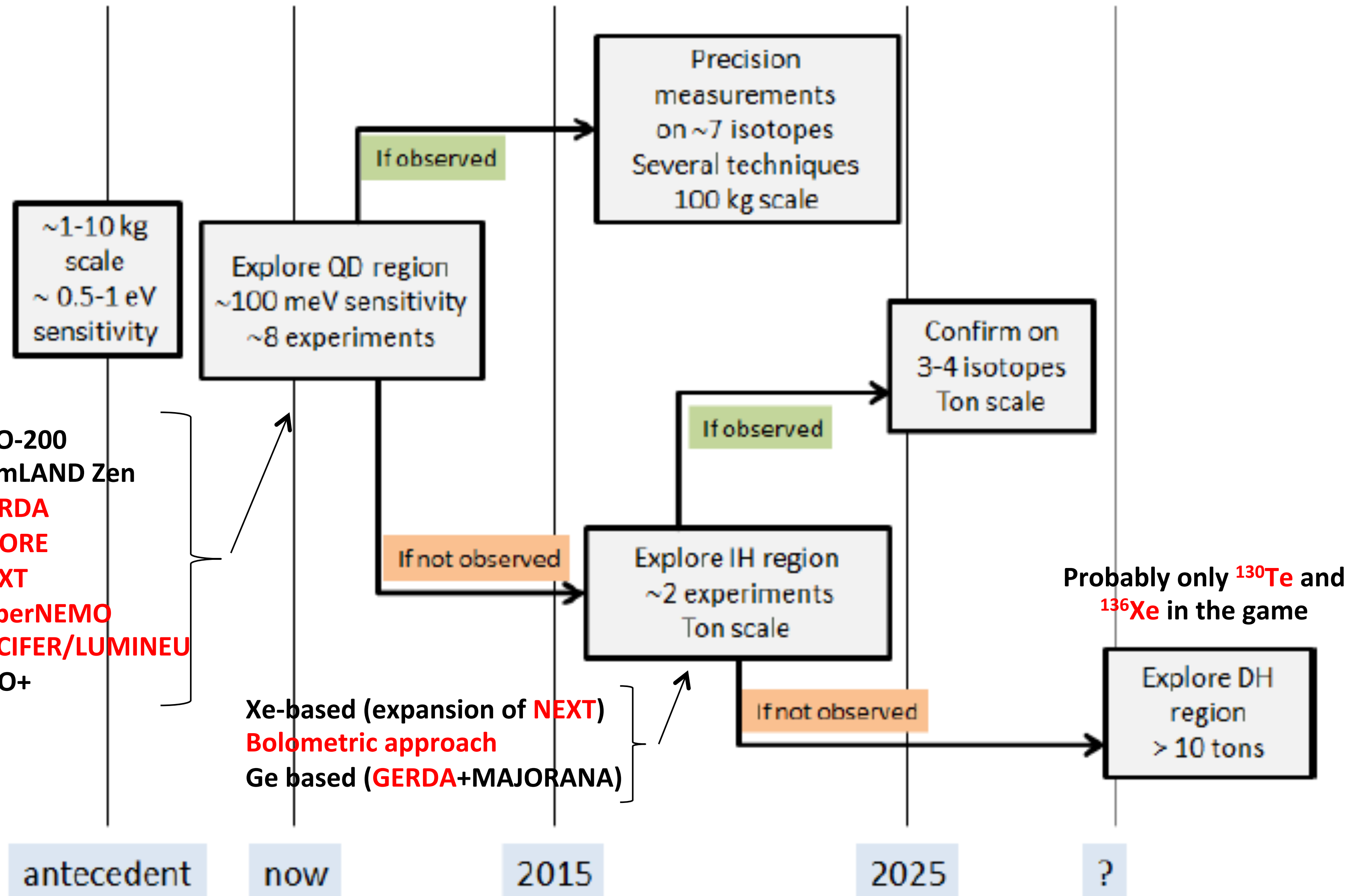


Looking into the crystal ball

GIULIANI

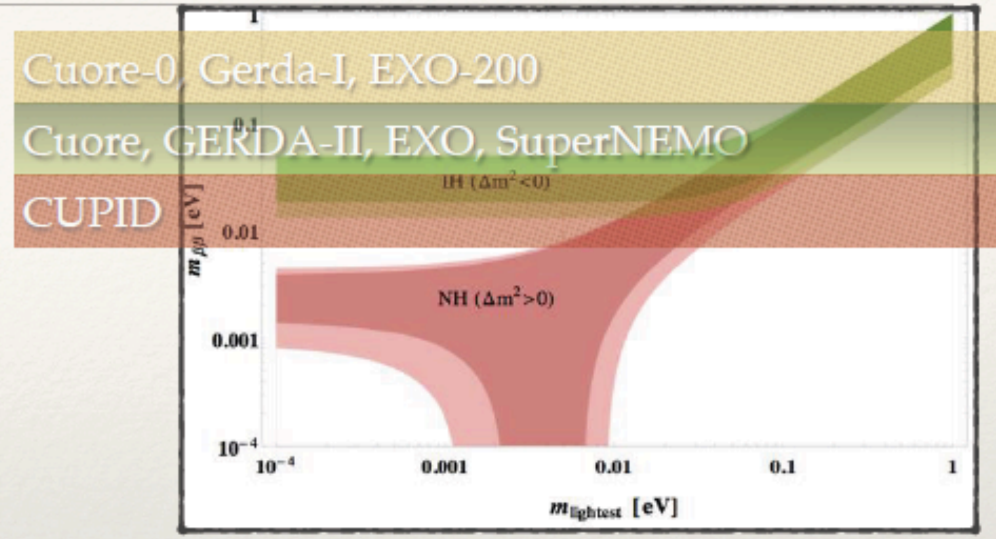


Looking into the crystal ball



0νββ strategy

- **What next CUORE and GERDA-II ?**
  - CUORE is ***background limited:*** simple mass scaling is useless and probably also very difficult to do
  - GERDA has lower background.
    - However: can we increase to ton scale ?
    - Not easily. Very expensive, and probably US based.



- **GOAL:** *seek for a zero background experiment* at **ton scale** to **explore inverse hierarchy region**
  - if g_a is not a show stopper
  - if direct hierarchy is not discovered first or ν mass is not measured by EUCLID first

- **Answer: CUPID R&D**

Challenges for next DM, ββ frontiers; Challenges for LNGS

- **Attack and cover the IH region → 1-ton neutrinoless ββ**
- **WIMPS DM : Reach the neutrino background → n-ton exps. n= 20, 50 ?**

LNGS → largest ultra low-background facility …

Current 3ν picture in just one slide (with 1-digit accuracy)

Flavors = e μ τ

LISI, 2014

Terra Cognita:

$\delta m^2 \sim 8 \times 10^{-5}$ eV^2
$\Delta m^2 \sim 2 \times 10^{-3}$ eV^2
$\sin^2\theta_{12} \sim 0.3$
$\sin^2\theta_{23} \sim 0.5$
$\sin^2\theta_{13} \sim 0.02$

Terra Incognita:

δ (CP)
sign(Δm^2)
octant(θ_{23})
absolute mass scale
Dirac/Majorana nature

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\beta/2} \end{bmatrix}$$

[only if Majorana]

Terra Cognita

Mixing angles θ_{23}, θ_{13}, θ_{12} : known ✔

Terra Incognita I

CP-violat. phase(s) δ (α, β) : unknown ✗

Mass-squared spectrum (up to absolute scale)

"Normal" Hierarchy

"Inverted" Hierarchy

[+ contribution in matter ~ $G_F \cdot E \cdot$ density]

Terra Cognita

δm^2, Δm^2: known ✔ **Matter effects (solar ν): ✔**

Terra Incognita I

Hierarchy : unknown ✗

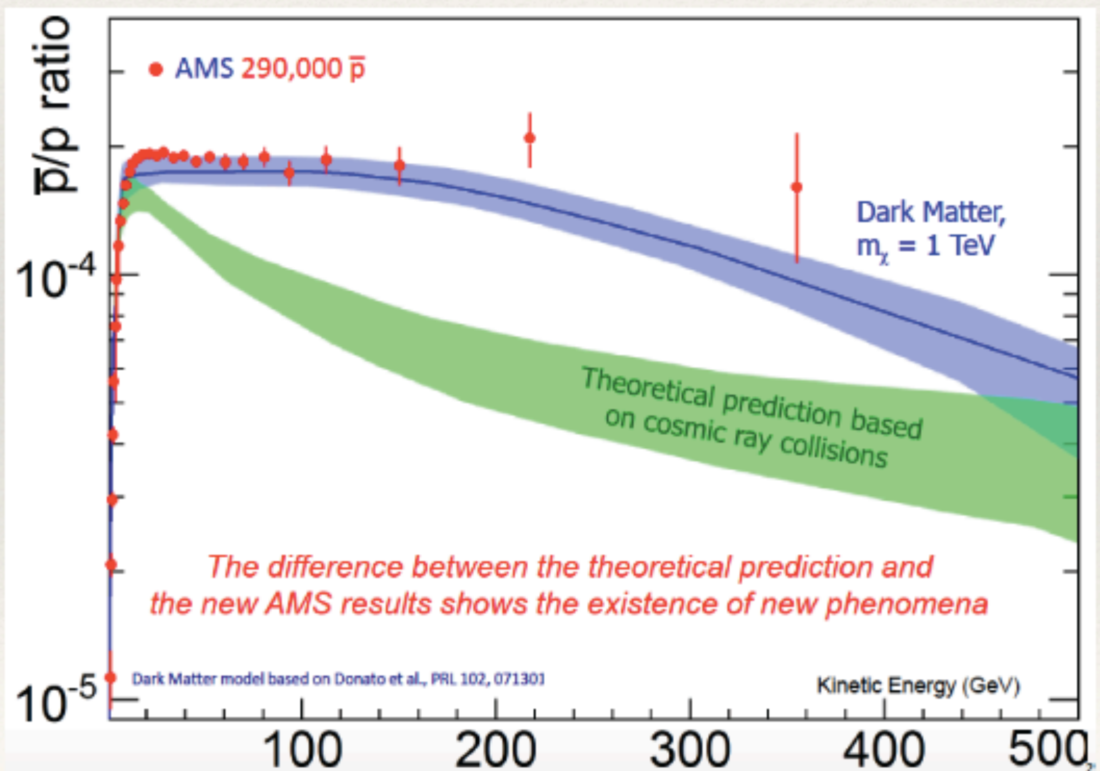
F. Lisi (C2, 11/2014)

A) Multimessenger astronomy, B) neutrino properties, C) dark side of the Universe and CMB

- A) **Photon**, **cosmic ray**, **neutrino** , **gravitational** astronomies (some in their maturity, some in their youth, some just baby or even still to be born
- B) **neutrino mass** and its relation to the global symmetry of the SM, **Lepton number** (Dirac vs. Majorana natur of the neutrinos); measuring the full neutrino mass parameters (neutrino mass hierarchy, CP violation)
- C) **Dark Matter**; **Dark Energy** and **their role in the evolution of the Universe** (primordial inflation, elw. Phase transition, quark-hadron phase transition, nucleosynthesis, matter-antimatter cosmic asymmetry)

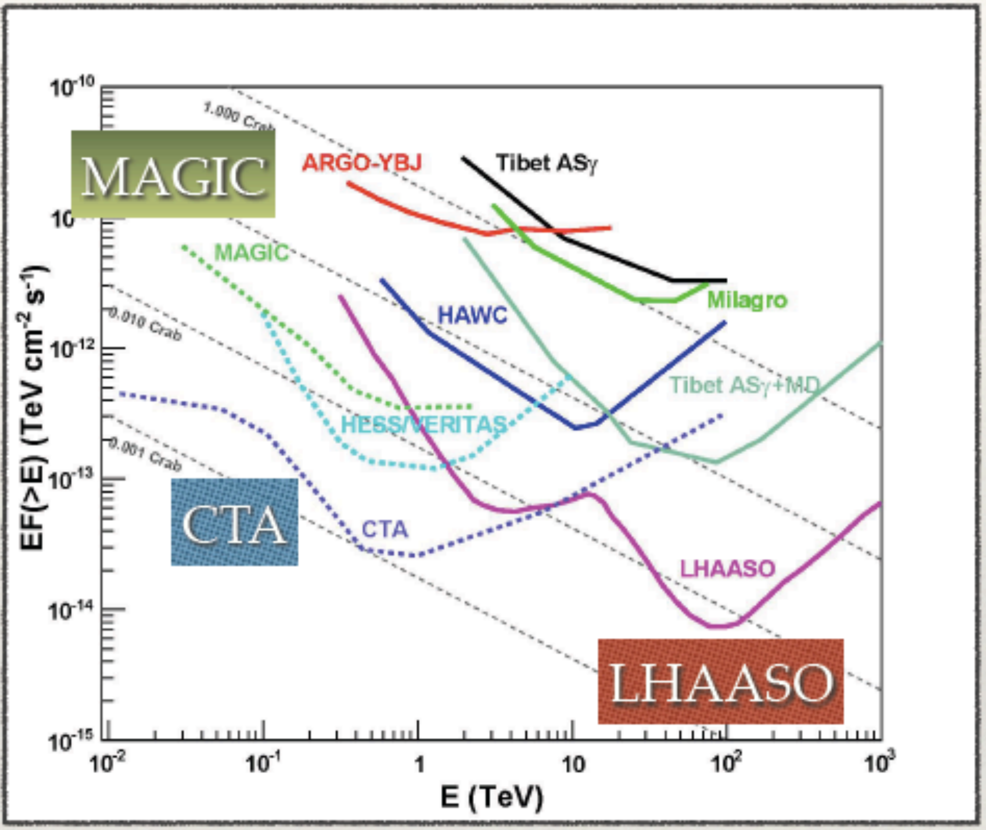
AMS-02 (2)

- Anti-protons
  - Clear deviation from current propagation and diffusion models
  - Dark matter a suggestive possibility, but astrophysical explanations are possible



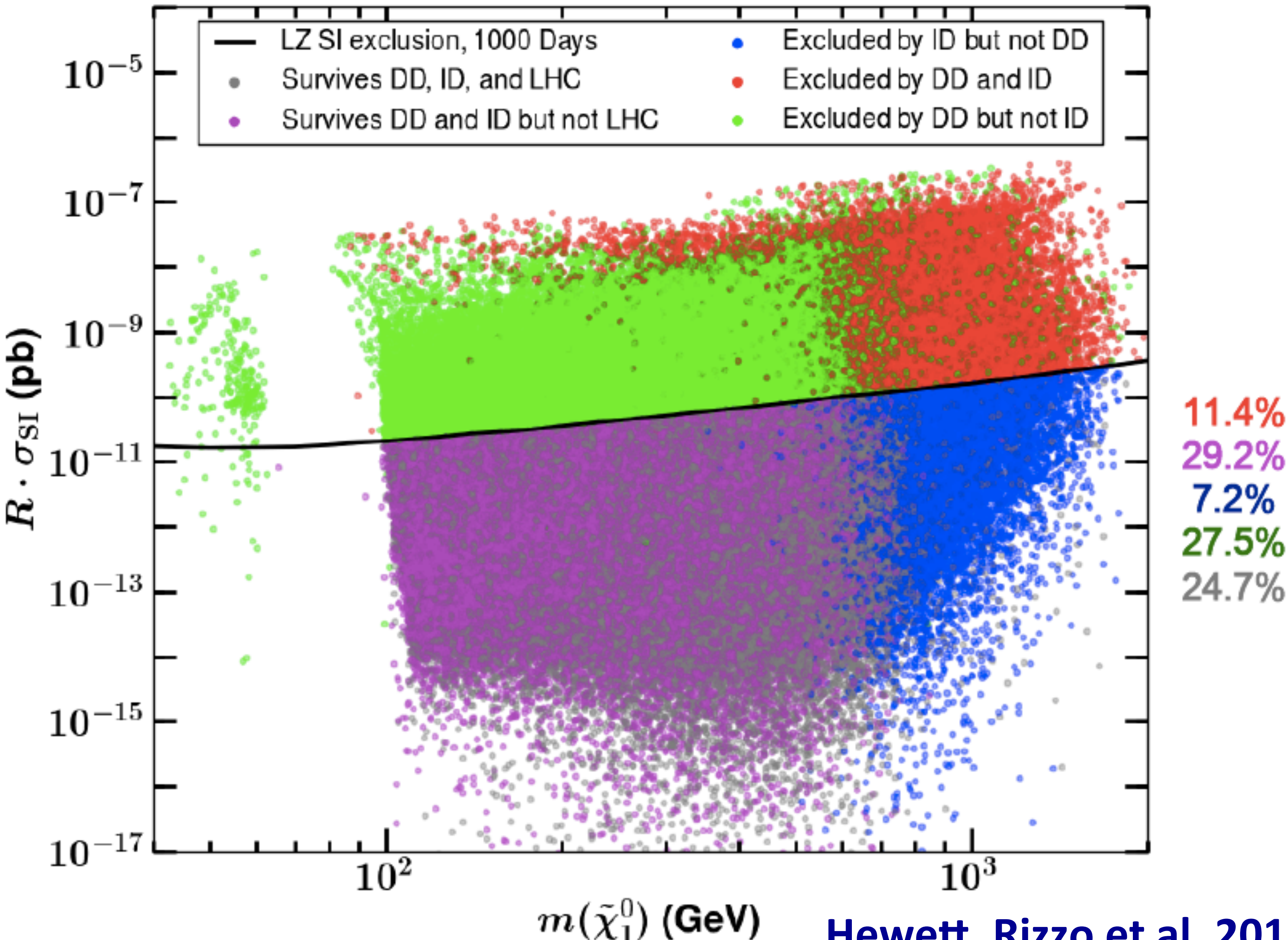
H.E. γs from ground detectors

- **MAGIC**
  - **Running,** recently improved trigger, threshold down to 35 GeV
  - INFN support till beginning of CTA
- **CTA**
  - Pointing observatory 100 GeV - 100 TeV
  - Coordination with INAF
  - INFN scope: trigger, electronics for LT
  - Building on MAGIC experience: **Canary Islands site approved besides Chile !**



- **LHAASO**
  - **Large FoV and duty cycle.** More sensitivity above 10 TeV and knee CR physics too
  - Complementary with CTA with better sensitivity at high energy and transient detection capability
  - Scope: physics, simulations, analysis: **building on ARGO experience**

pMSSM models DD = LZ both SI + SD ID = FERMI + CTA



Hewett, Rizzo et al. 2013

Overall, **in the next few years the APPEC agencies will need to take a decision on**

a) **the construction of the phase 1.5 of KM3Net,**

b) **a major investment as a contribution to a neutrino long baseline program in US or Japan,**

c) **a European-led dark matter multi-ton experiment**

d) **a ton-scale neutrino mass detector (double beta decay technique)**

e) **a major contribution on ground and/or space to the cosmology program probing the param. of inflation.**

Hunting for **GRAVITATIONAL WAVES**: DISCOVERY AND ASTRONOMY

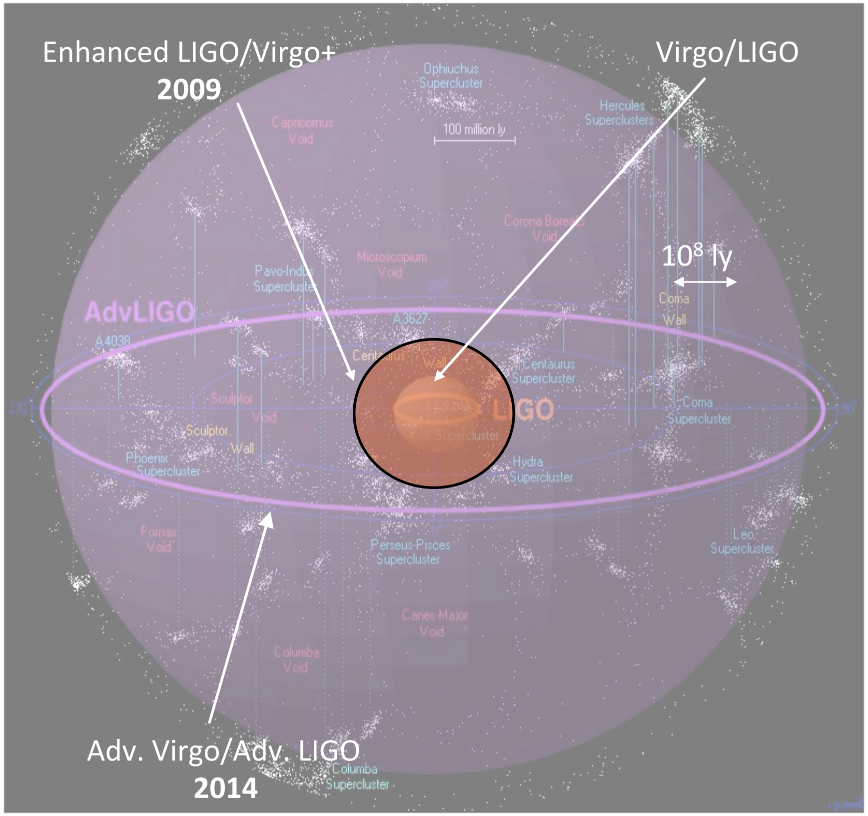
2^{nd} generation detectors:
Advanced Virgo, Advanced LLIGO

GOAL:

sensitivity 10x better →
look 10x further →
Detection rate 1000x larger

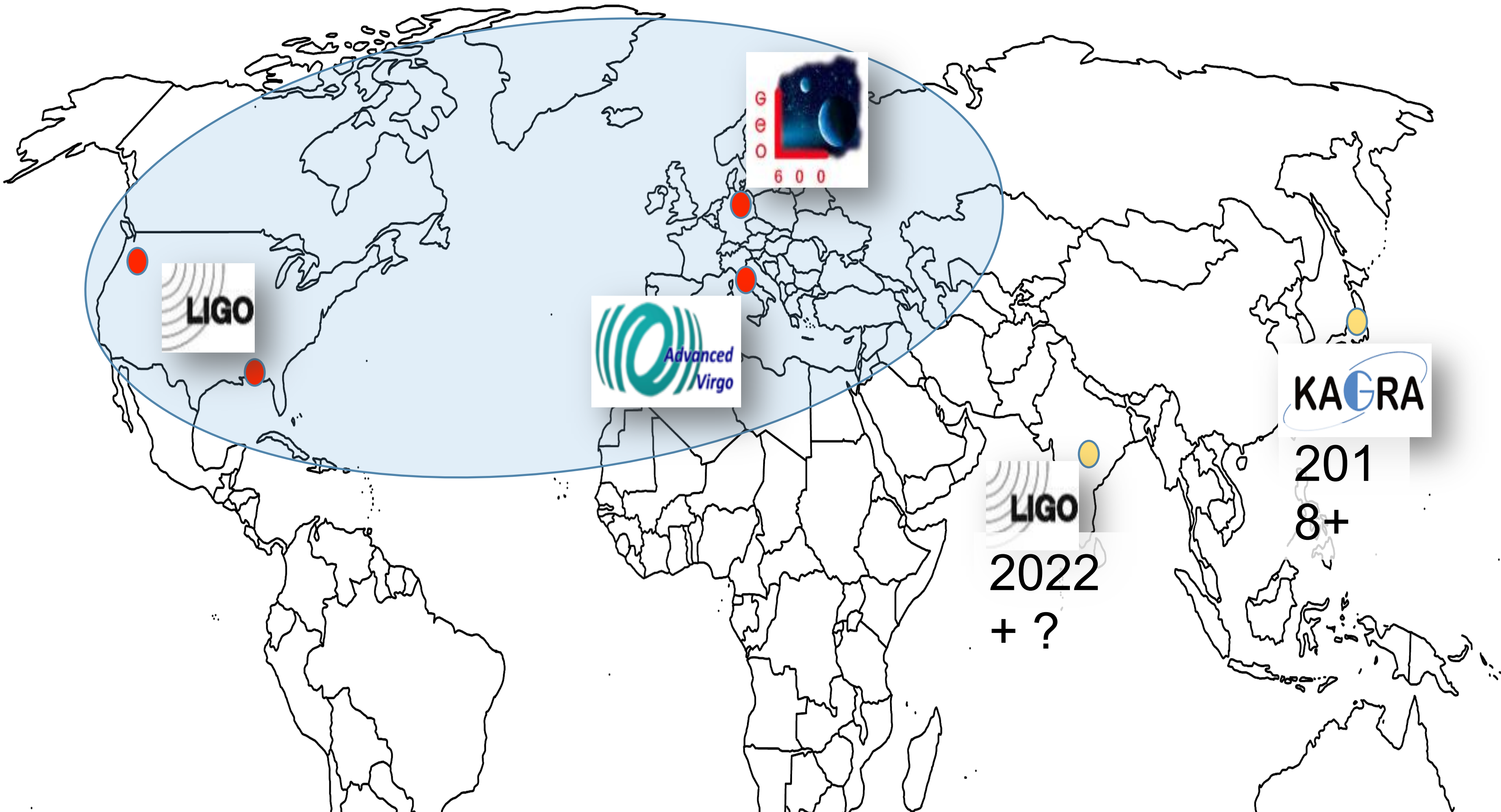
NS-NS detectable as far as 300 Mpc
BH-BH detectable at cosmological distances

10s to 100s of events/year expected!



Credit: R.Powell, B.Berger

WORLDWIDE NETWORK OF GW DETECTORS

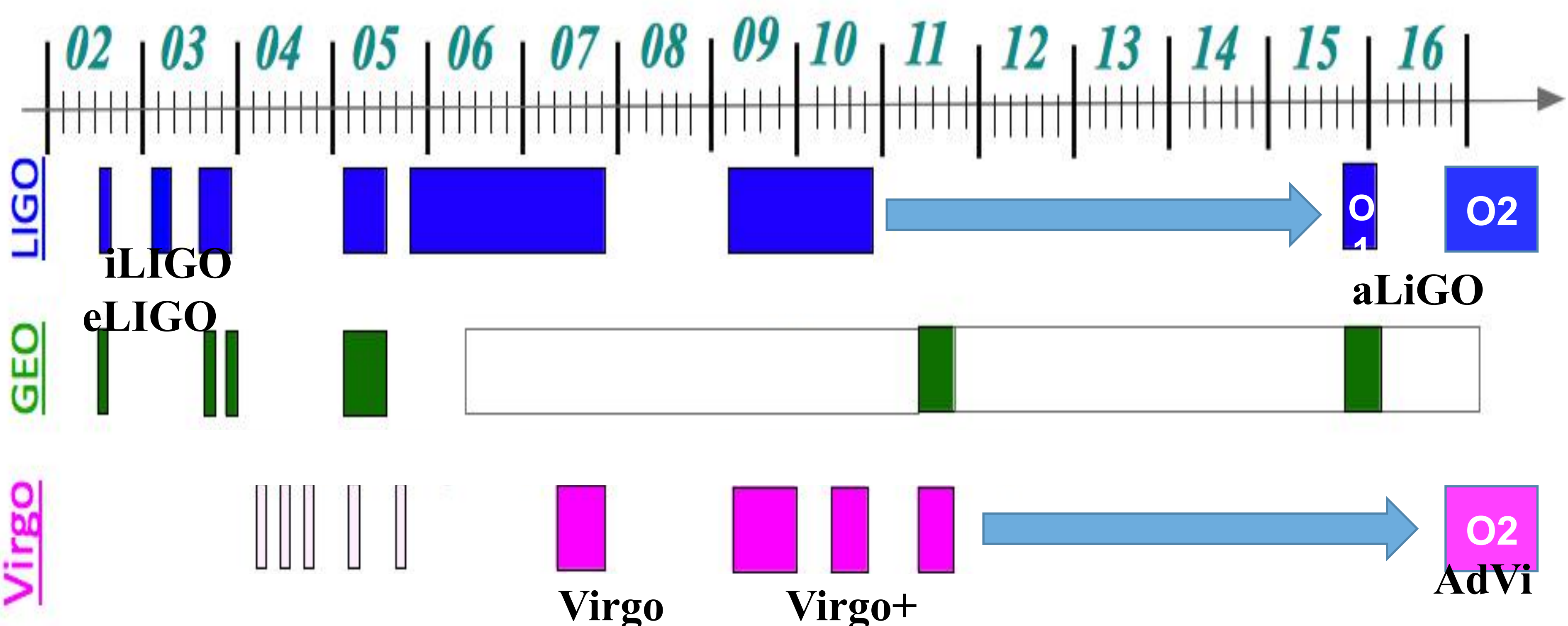


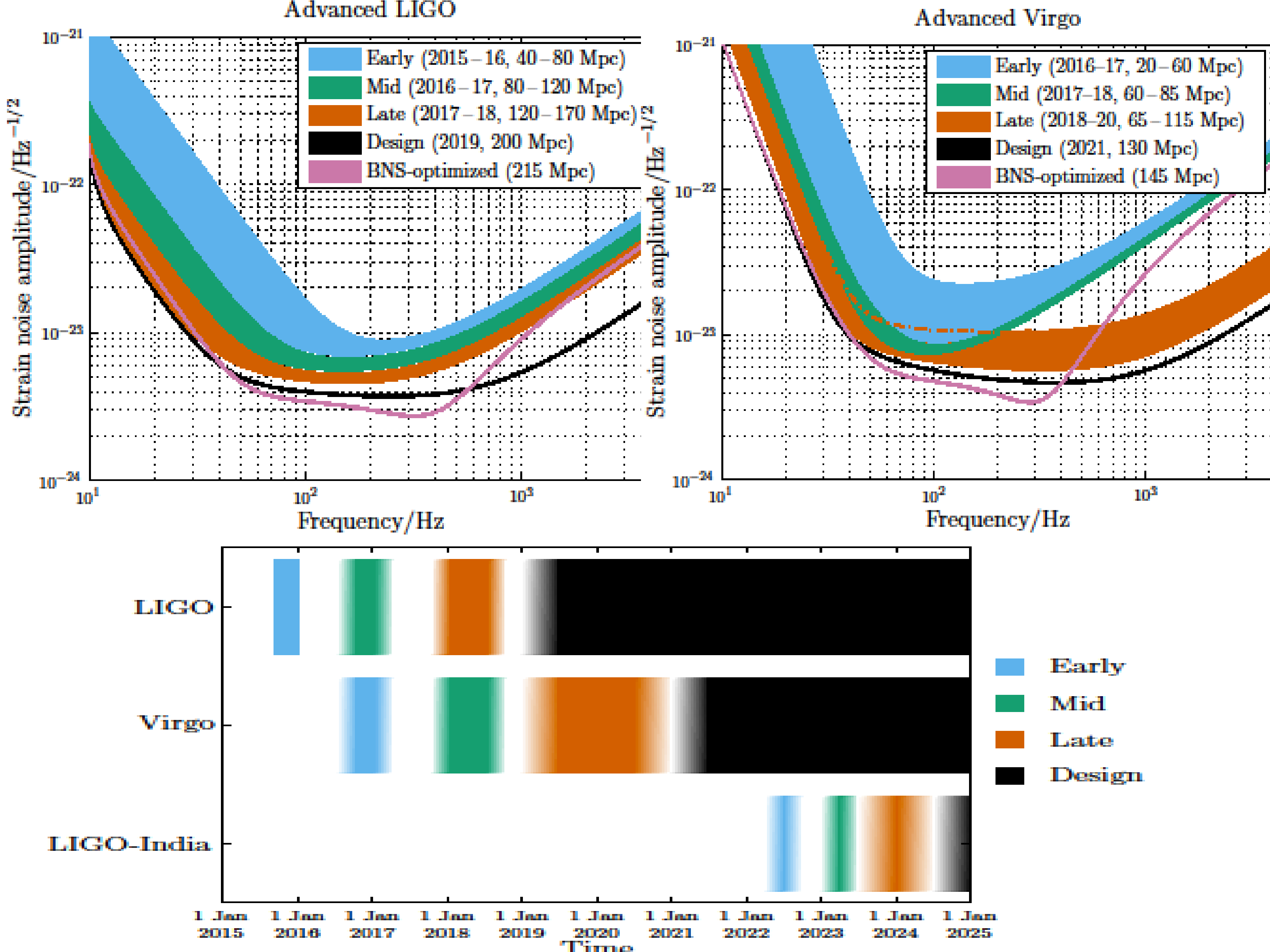
ADVANCED LIGO (aLIGO)

- ✓ Project funded: April 2008
- ✓ Project start: 2010
- ✓ Funding: >205 M$
- ✓ Installation completed: June 2014
- ✓ First science run: O1 Aug 2015

ADVANCED VIRGO (AdV)

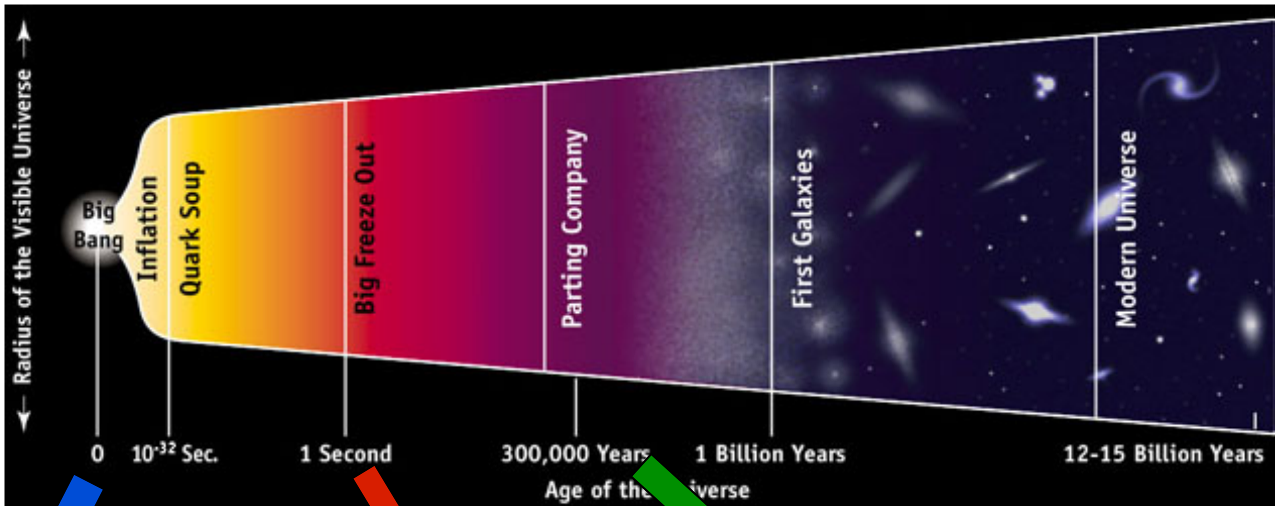
- ✓ Project funded: Dec 2009
- ✓ Project start: 2012
- ✓ Funding: 23 M€
- ✓ Installation completed: early 2016
- ✓ First science run: O2 ~Sep 2016





Advanced LIGO
Early (2015 – 16, 40 – 80 Mpc)
Mid (2016 – 17, 80 – 120 Mpc)
Late (2017 – 18, 120 – 170 Mpc)
Design (2019, 200 Mpc)
BNS-optimized (215 Mpc)
Strain noise amplitude /Hz$^{-1/2}$
Frequency/Hz
Advanced Virgo
Early (2016–17, 20 – 60 Mpc)
Mid (2017–18, 60 – 85 Mpc)
Late (2018–20, 65 – 115 Mpc)
Design (2021, 130 Mpc)
BNS-optimized (145 Mpc)
LIGO
Virgo
LIGO-India
Early
Mid
Late
Design
1 Jan 2015
1 Jan 2016
1 Jan 2017
1 Jan 2018
1 Jan 2019
1 Jan 2020
1 Jan 2021
1 Jan 2022
1 Jan 2023
1 Jan 2024
1 Jan 2025
Time

Relic Stochastic Background



Relic gravitons

Relic neutrinos

CMBR

- Imprinting of the early expansion of the universe
- Correlation of at least two detectors needed

much depends on the next 5 years …

- **LHC14** (high energy: ATLAS, CMS; flavor: LHCb; quark-hadron phase transition: ALICE)
- **Flavor**: NA62; upgraded MEG, Mu-e; BELLEII; EDMs; g-2
- **DM** 1-ton exps. → $10^{-10} – 10^{-11}$ pb
- **Neutrinoless double β** → ν mass degenerate region; enter IH region
- **SBN** → sterile ν ?
- **Gravitational waves** → discovery to pave the way to gravitationalwave astronomy
- **DE**: BOSS →DESI; DES → LSST
- **CMB**: final PLANCK; B-modes of the polariz.+ black-body spectrum : EU exps. QUBIC, LSPE, QIJOTE + many others on

- By the end of the 20^{th} 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

BUT …

Certainly the two Standard Models are an **extraordinary step forward in our knowledge** of the Universe:

but, beware, Nature is rich of "unknown unknown"

→ after all Physics had already produced a "comprehensive, fundamental theory of all observed forces of nature" at the end of the XIX century…

Maybe the **Dark Matter** (or the **FLAVOR**) problem could be our black-body and photoelectric problems of the beginning of the XXI century