Prospects in Low Mass Dark Matter, MPP Colloquium, Max-Planck-Institut fuer Physik, Munich, 1st Nov., 2015

Prospects in Low Mass Dark Matter

Antonio Masiero

INFN and Univ. of Padova

2012: the conquest of a new energy scale in physics

- ~1900 **ATOMIC SCALE** 10^{-8} cm. $1/(\alpha m_e)$
- ~1970 **STRONG SCALE** 10^{-13} cm. $Me^{-2\Pi/\alpha_s b}$
- ~2010 **WEAK SCALE** 10^{-17} cm. TeV^{-1}

FUNDAMENTAL OR **DERIVED SCALE**?

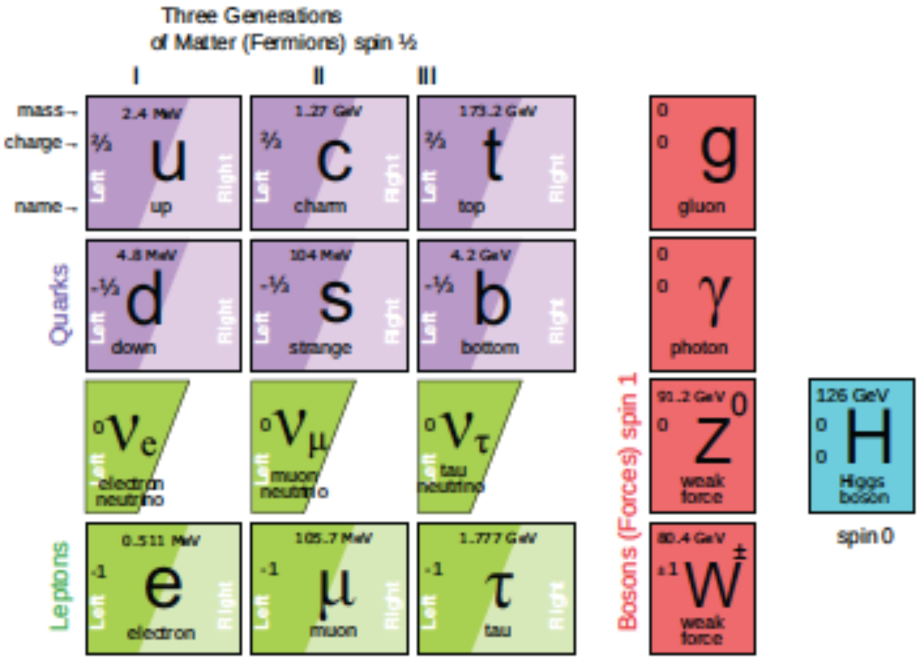
EX. **EXTRA-DIMENSIONS**
or
TeV STRING THEORY

EX.: **TECHNICOLOR** or
SUSY with ELW RAD. BREAKING

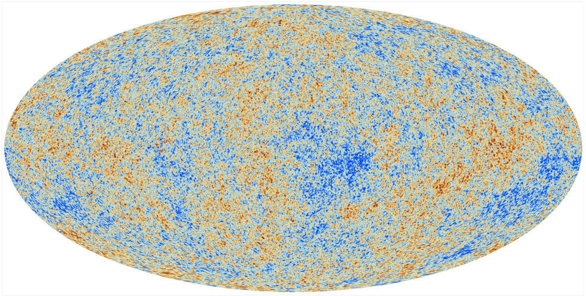
NEW PARTICLES AT THE TEV SCALE?

2013: the thiumph of the STANDARD

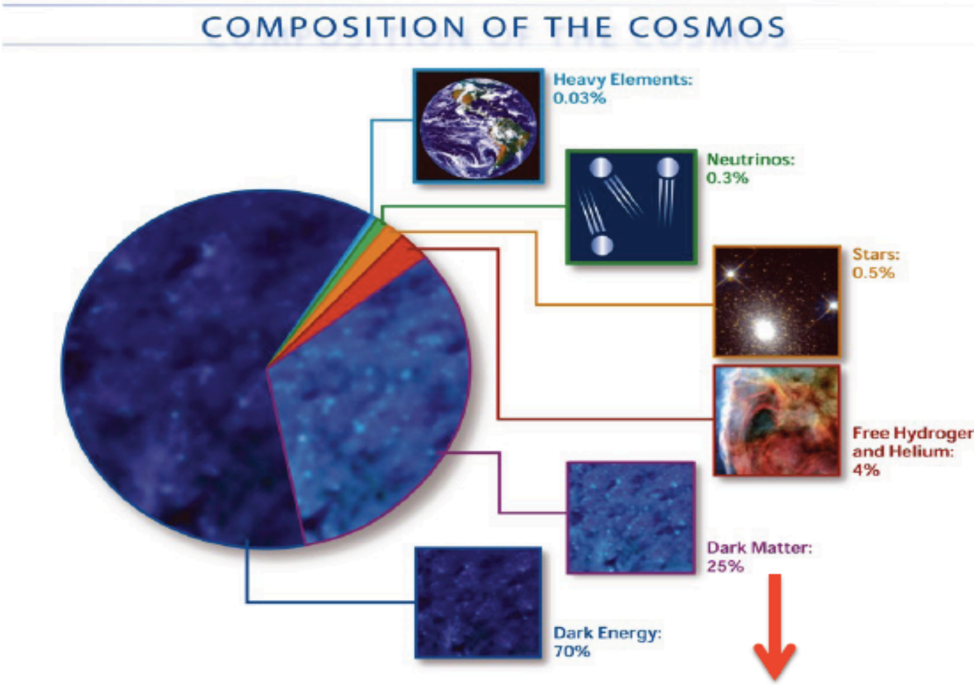
- **PARTICLE STANDARD MODEL**

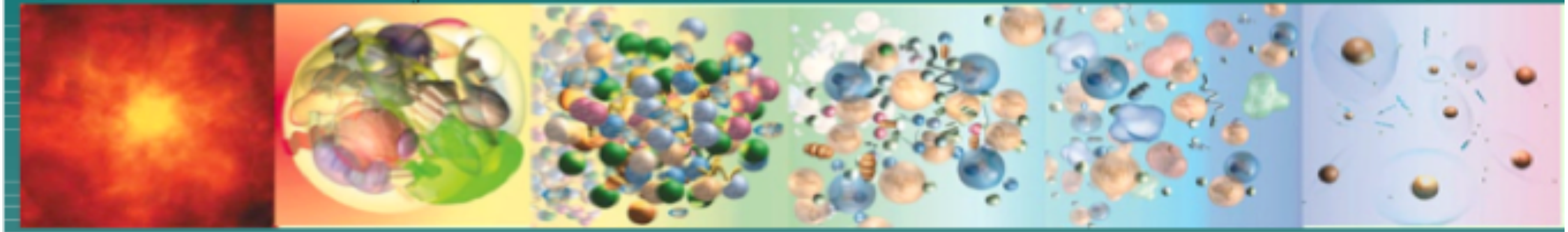


- **COSMOLOGY STANDARD MODEL**

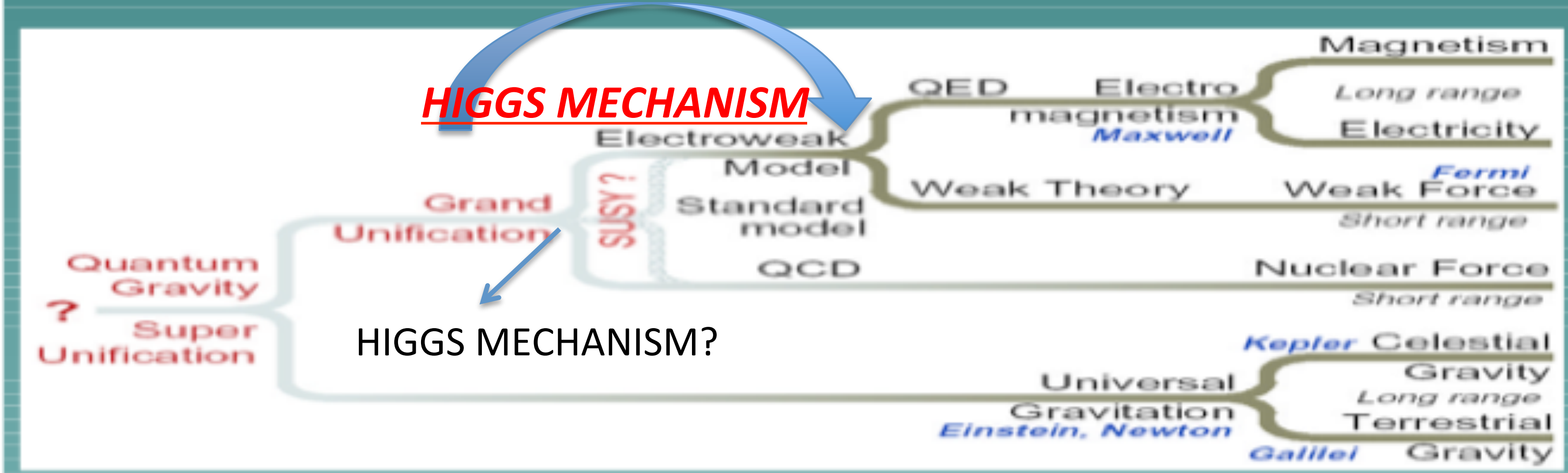


ΛCDM + "SIMPLE" INFLATION





Big Bang	Quark-Gluon Plasma		Protoni e neutroni	Protoni e Nuclei leggeri	Atomi →Galassie →Molecole→DNA
Gravità	*Nucleare forte*	*Nucleare debole*			
10^{-43} sec	10^{-32} sec	10^{-10} sec	10^{-4} sec	100 sec	300KY → 15GY
10^{-35} m	10^{-32} m	10^{-18} m	10^{-16} m	10^{-15} m	10^{-10} m
10^{19} GeV	10^{16} GeV	10^{2} GeV	1 GeV	1 Mev	10 eV
???	LHC	LEP			Astronomia→



HIGGS MECHANISM

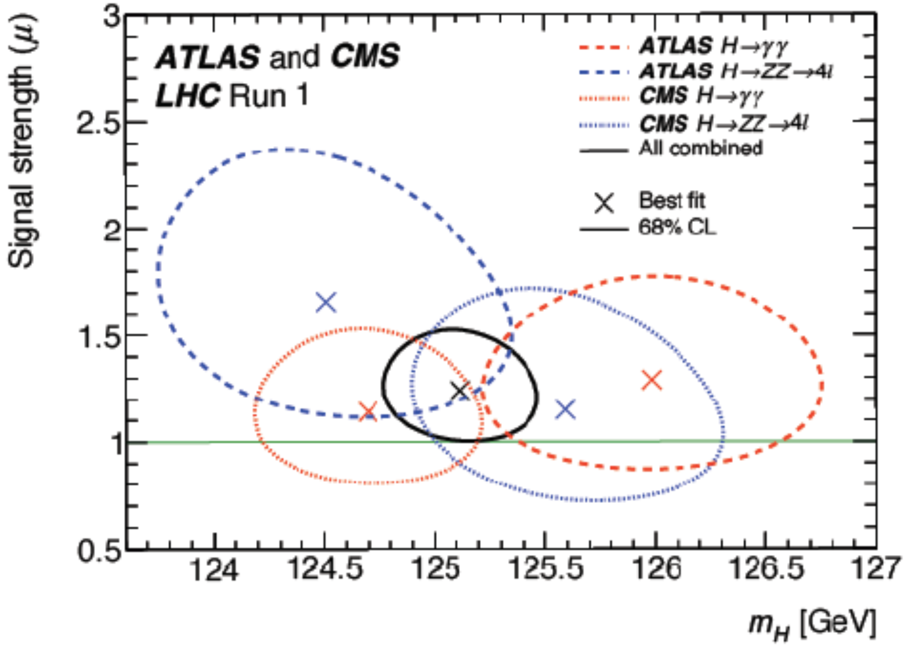
HIGGS MECHANISM?

Theories:

STRINGS? RELATIVISTIC/QUANTUM CLASSICAL

Higgs Mass measurements

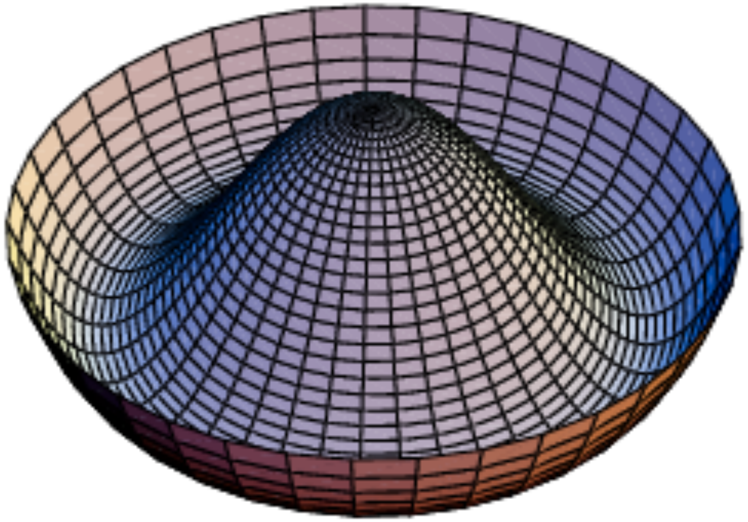
ATLAS + CMS ZZ* and γγ final states

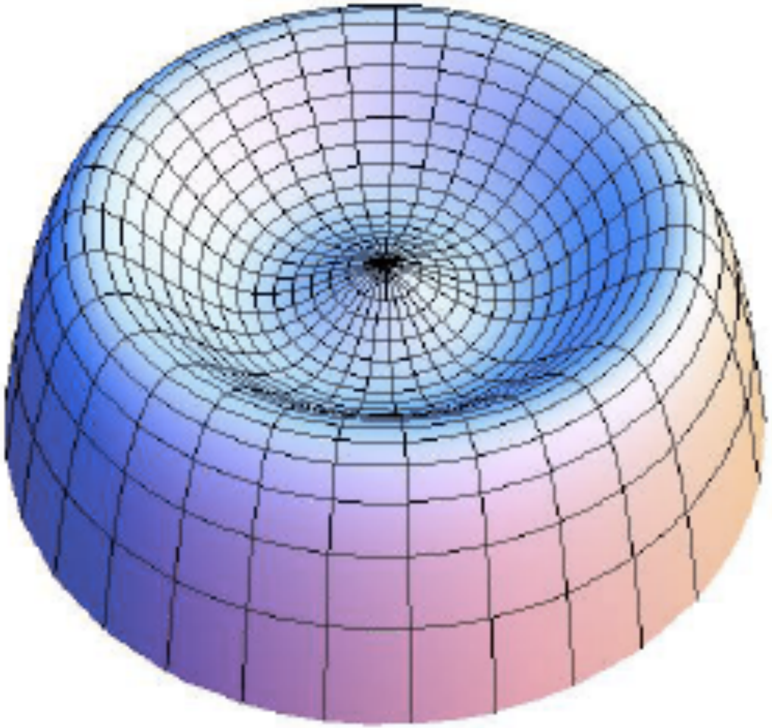


$$125.09 \ \pm 0.21\ (\text{stat}) \ \pm 0.11\ (\text{syst})$$

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

STABILITY ↔ **INSTABILITY**



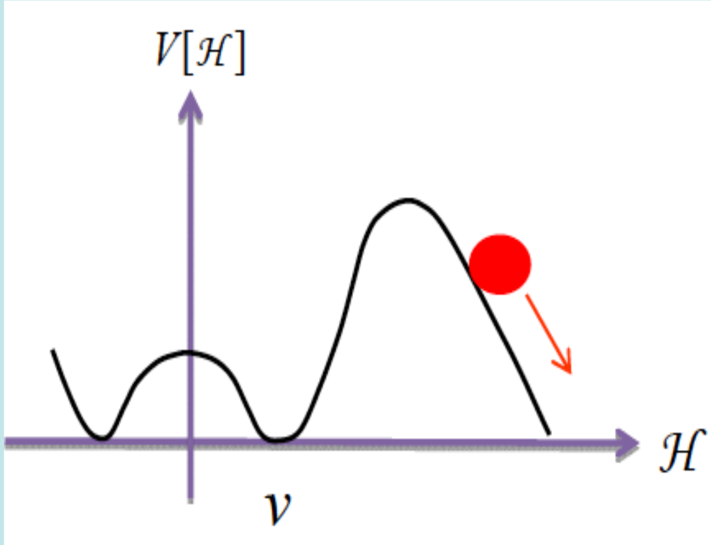


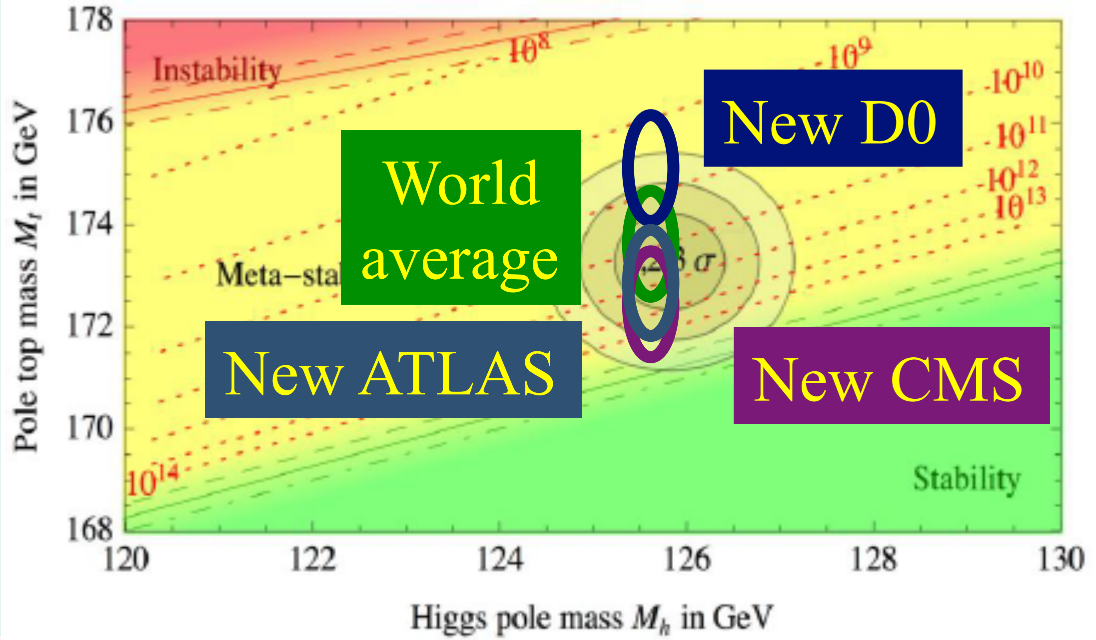
ON THE IMPORTANCE OF PRECISELY MEASURING HIGGS and TOP MASSES

Vacuum Instability in the Standard Model

- Very sensitive to m_t as well as M_H

Melnikov, Meyer





J. Ellis, LP 2015

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

- Instability scale:

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

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

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?

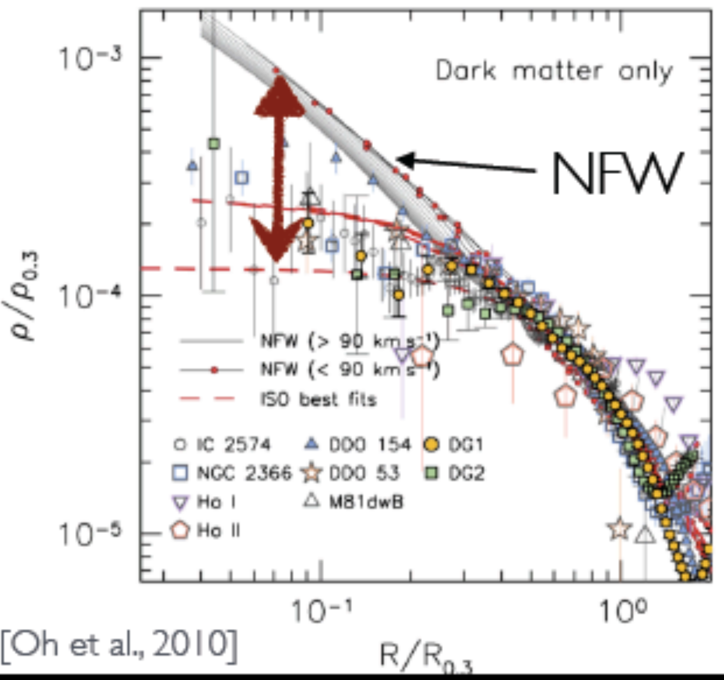
- Several discrepancies between N-body simulations and astrophysical observations:

1. 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: $\rho(r) \xrightarrow{r\to 0} \mathrm{const}$
- Problem exists in:
  (field and satellite) dwarfs,
  LSBs, Clusters

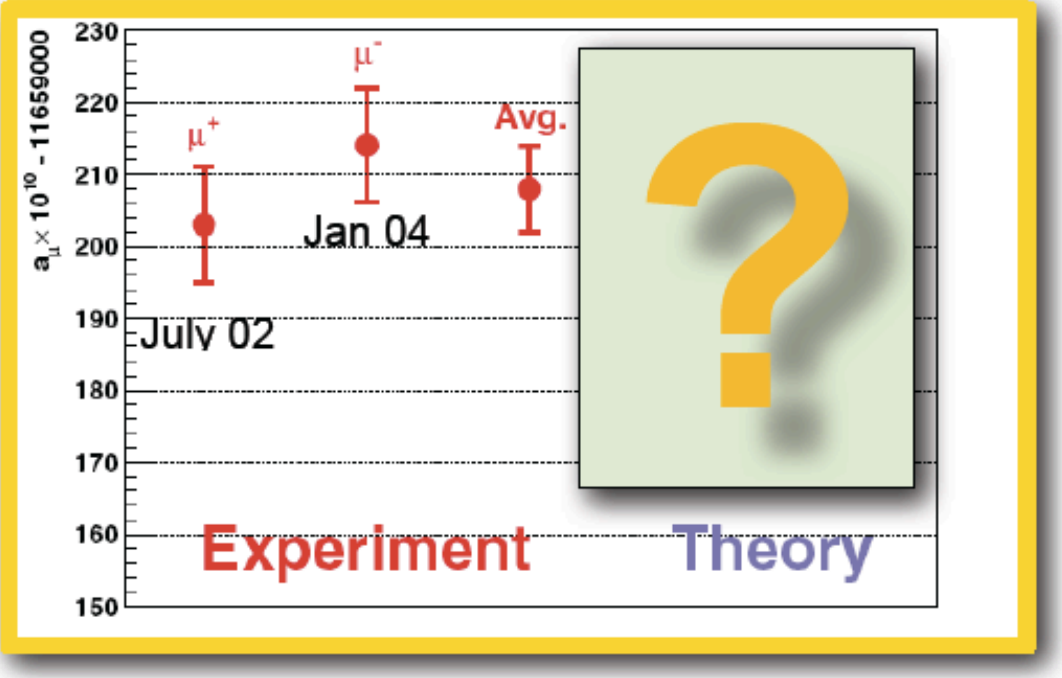
[Walker, Penarrubia, 2011; de Blok, Bosma, 2002; Kuzio de Naray et al., 2007; Kuzio de Naray, Spekkens, 2011; Newman et al. 2012; Oh et al. 2015;…]



[Oh et al., 2010]

T. VOLANSKY at this meeting

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 ± 16×10^{-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

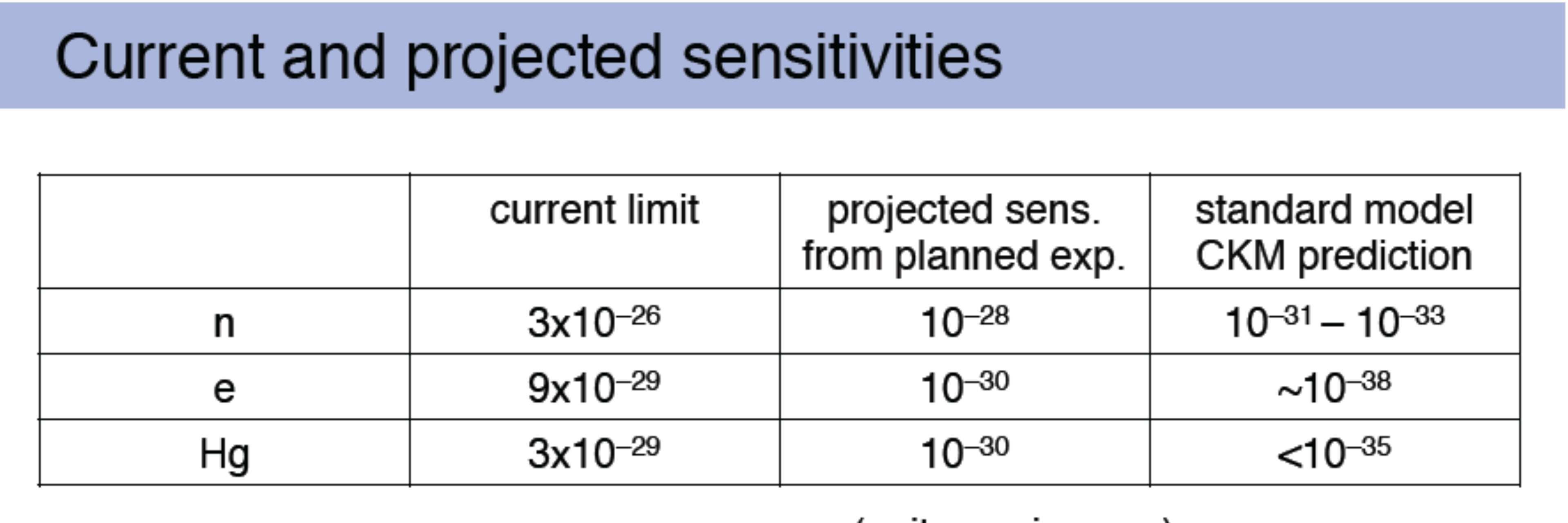
$a_\mu^{\mathrm{SM}} \times 10^{11}$	$\Delta a_\mu = a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}}$	σ
$116\,591\,795\ (56)$	$296\ (86) \times 10^{-11}$	3.5 [1]
$116\,591\,815\ (57)$	$276\ (85) \times 10^{-11}$	3.2 [2]
$116\,591\,841\ (58)$	$250\ (86) \times 10^{-11}$	2.9 [3]

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

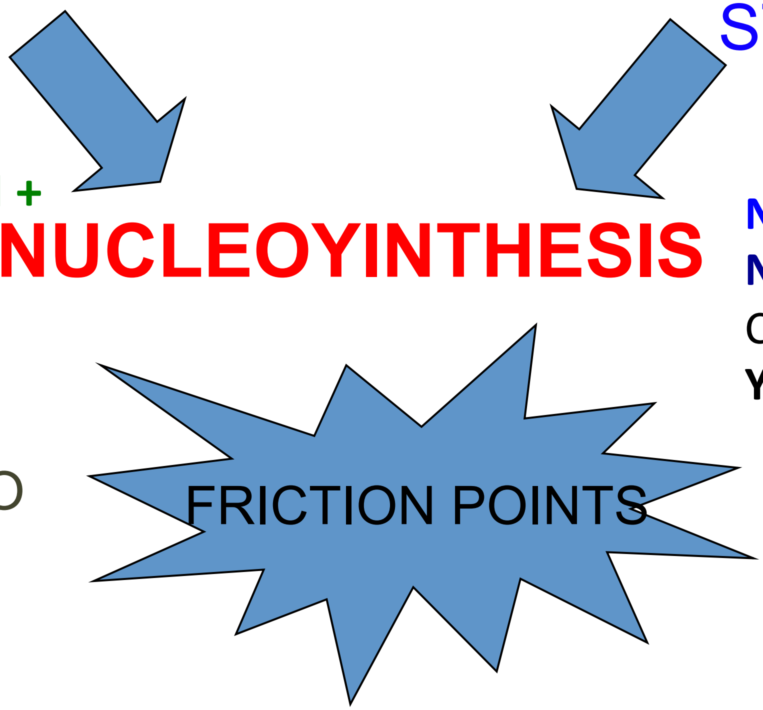
	current limit	projected sens. from planned exp.	standard model CKM prediction
n	$3\mathrm{x}10^{-26}$	10^{-28}	$10^{-31} - 10^{-33}$
e	$9\mathrm{x}10^{-29}$	10^{-30}	$\sim 10^{-38}$
Hg	$3\mathrm{x}10^{-29}$	10^{-30}	$<10^{-35}$

MICRO

GWS STANDARD MODEL

MACRO

HOT BIG BANG STANDARD MODEL



UNIVERSE EXPANSION +
WEAK INTERACTIONS
1 sec. after BB

NUCLEOYINTHESIS

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

BUT ALSO

FRICTION POINTS

☺☺ **-COSMIC MATTER-ANTIMATTER ASYMMETRY**

☺ **-INFLATION ???**

☺☺☺ **- DARK MATTER + DARK ENERGY**

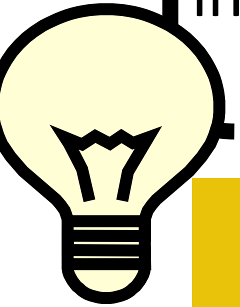
OBSERVATIONAL EVIDENCE OF NEW PHYSICS

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**

+

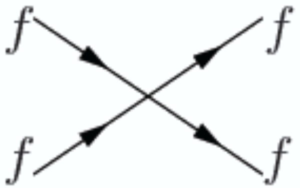
★ **CORRECT GRAND UNIFICATION “CALLS” FOR NEW PARTICLES AT THE ELW. SCALE**

No-Lose Theorems

A. Wulzer, BSM What Next 2015

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

Beyond the Fermi Theory:

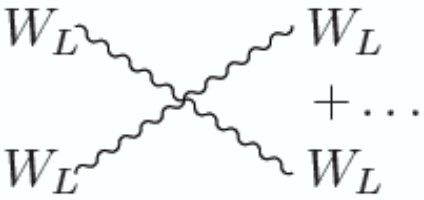


$$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \Longrightarrow m_W < 4\pi v$$

Beyond the Bottom Quark:

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

Beyond the (Higgsless) EW Theory:



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

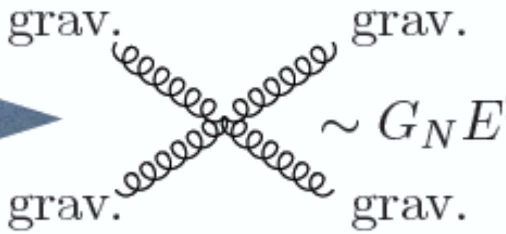
Each (secretly) due to d=6 non-renormalizable operators, signalling nearby new physics.

No-Lose Theorems

A. Wulzer, BSM What Next 2015

Only one d>4 is left after Higgs discovery …

$$\frac{1}{G_N}\sqrt{g}R \longrightarrow$$



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

… 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:

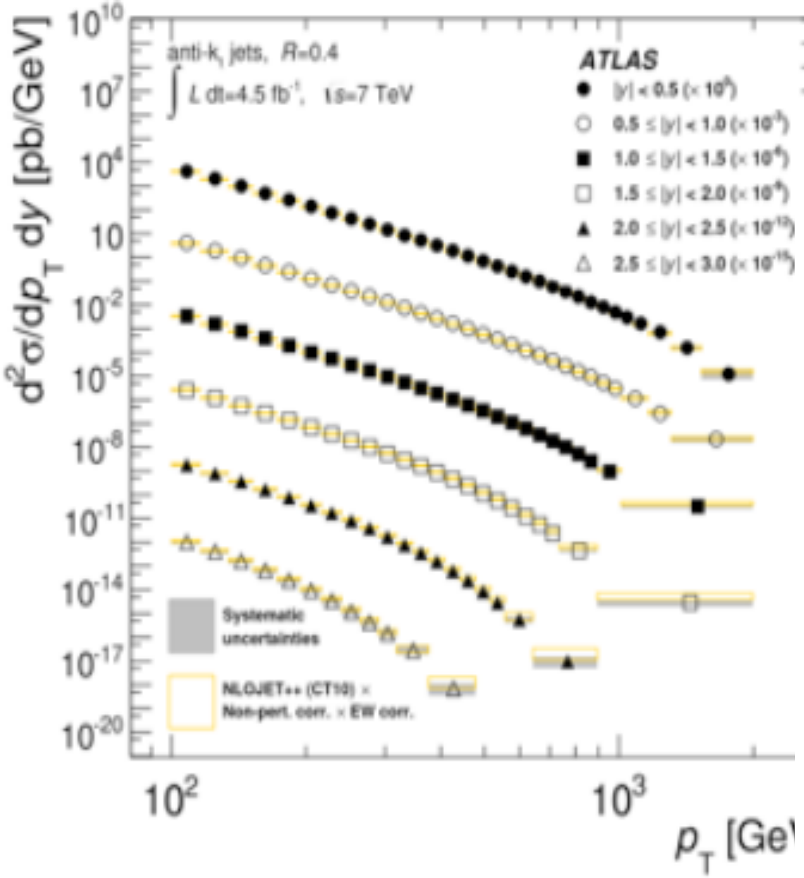
“No guaranteed discoveries” $=$ “post-Higgs depression”

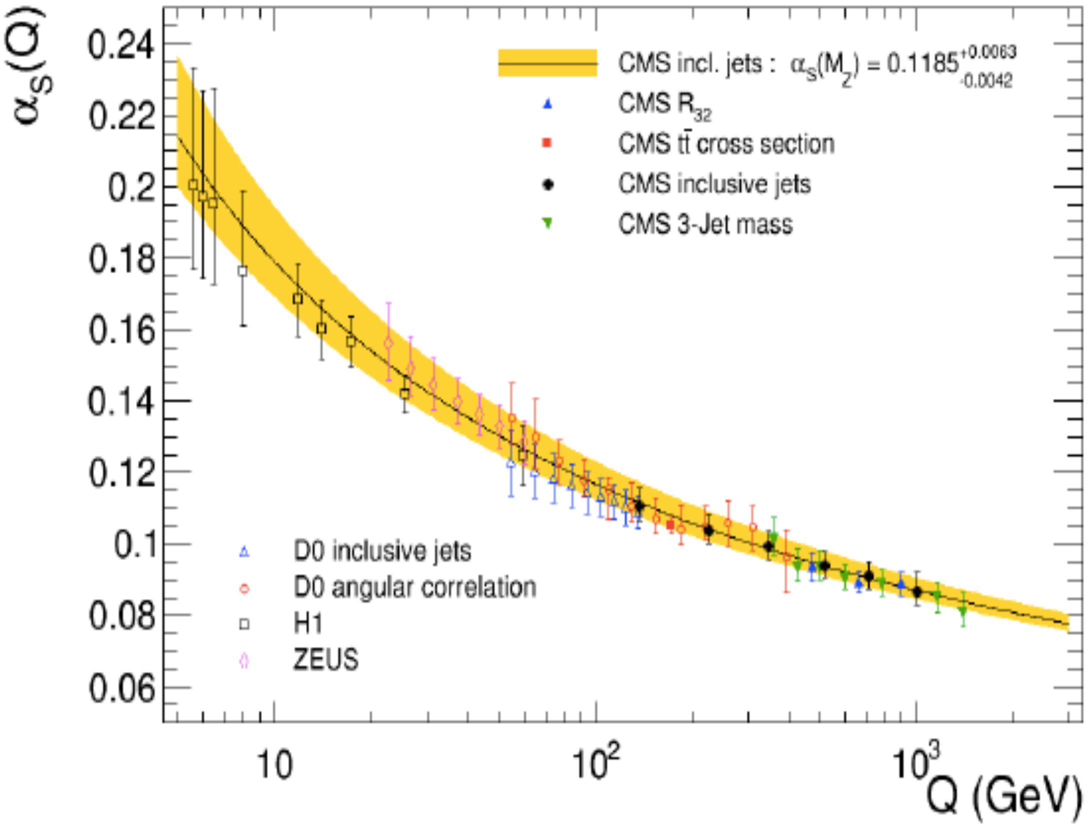
However, one **d<4** comes with the Higgs discovery:

$$\frac{m_H^2}{2}H^\dagger H \longrightarrow$$

The **Naturalness Problem:**

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

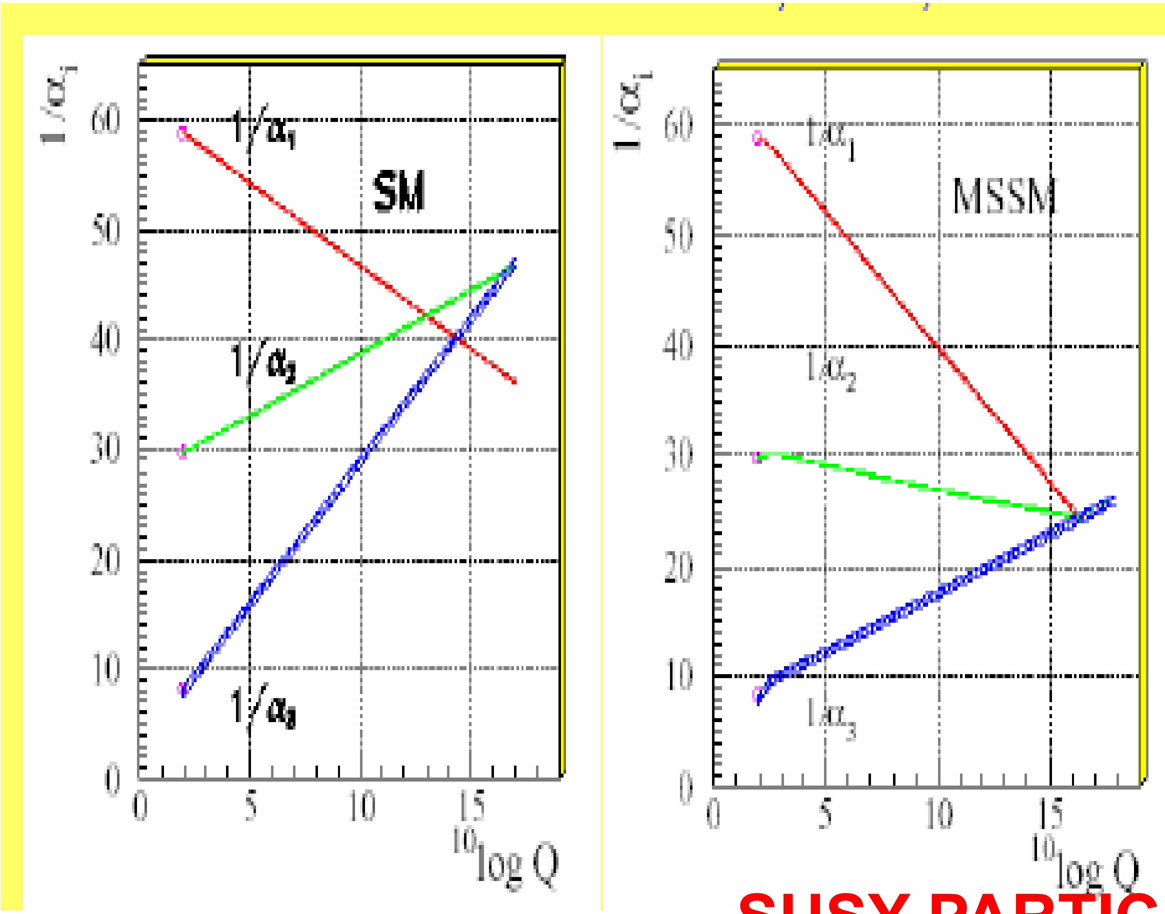




- QCD predictions successful over many orders of magnitude
- **α_s runs beyond the TeV scale**: into a GUT?
- Consistent with world average

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

$M_{SUSY} = 10^{3.4\pm0.9\pm0.4}$ GeV

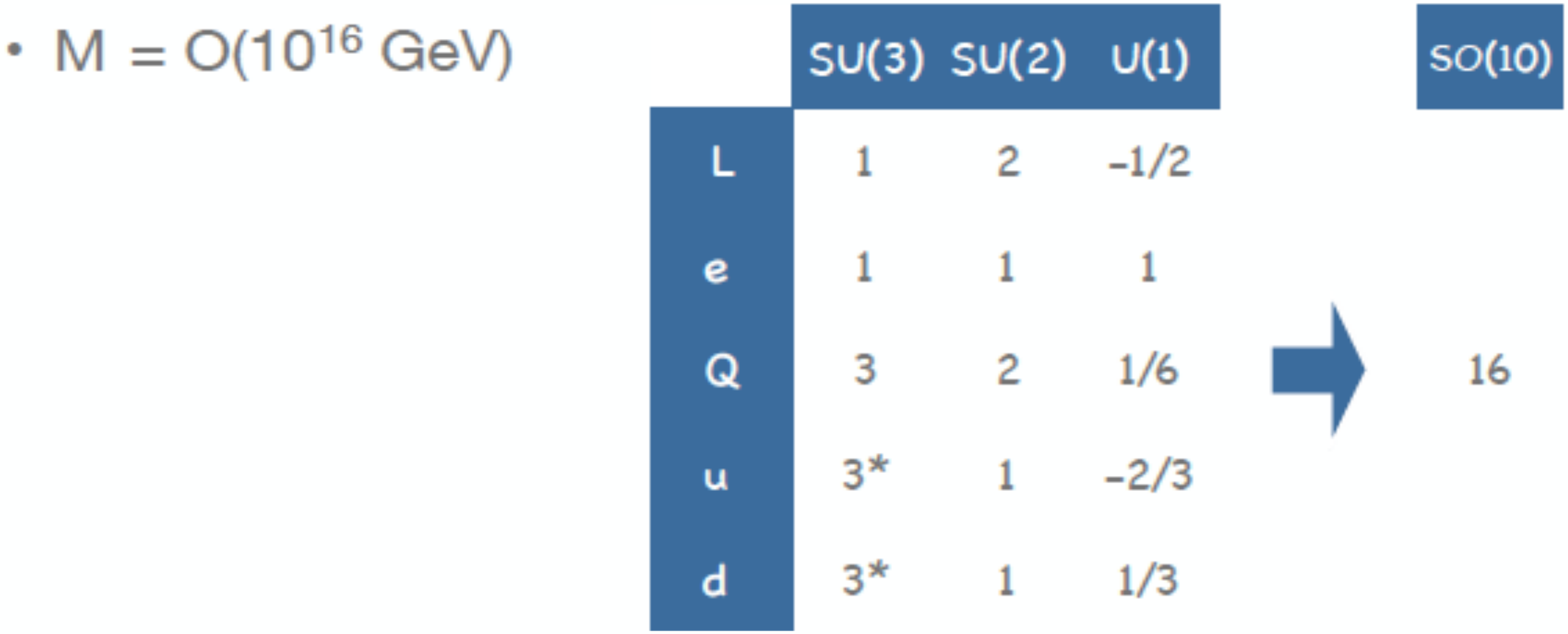
$M_{GUT} = 10^{15.8\pm0.3\pm0.1}$ GeV

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

SUSY PARTICLES AT THE TEV SCALE !

THE "COMPREHENSION" OF THE ELECTROWEAK SCALE

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



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

	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

$$m_{NP} \ll M$$

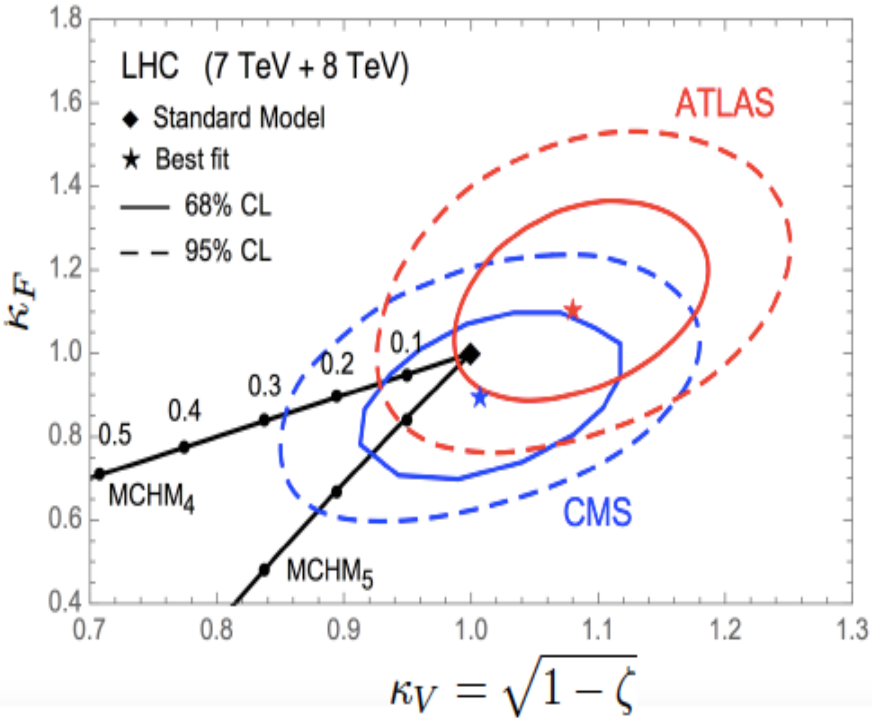
Low-energy **SuperSymmetry**

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

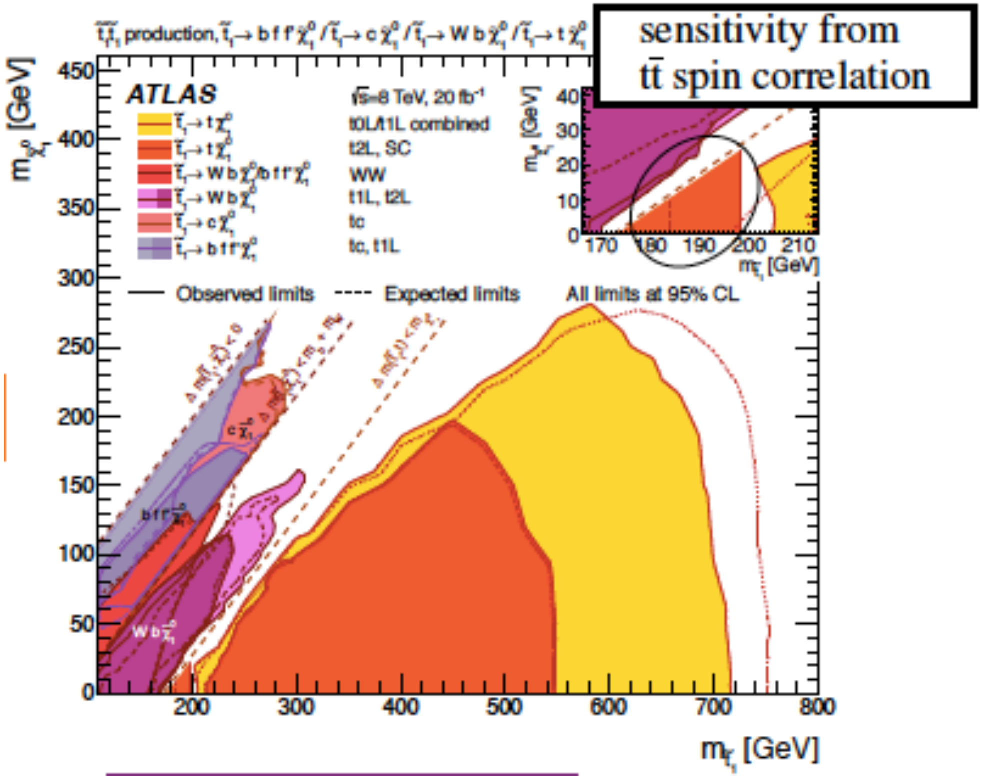
- **COMPOSITE HIGGS** : the Higgs is a pseudo-Goldstone boson (pion-like) → new interaction getting strong at $m_{NP} \ll M$

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

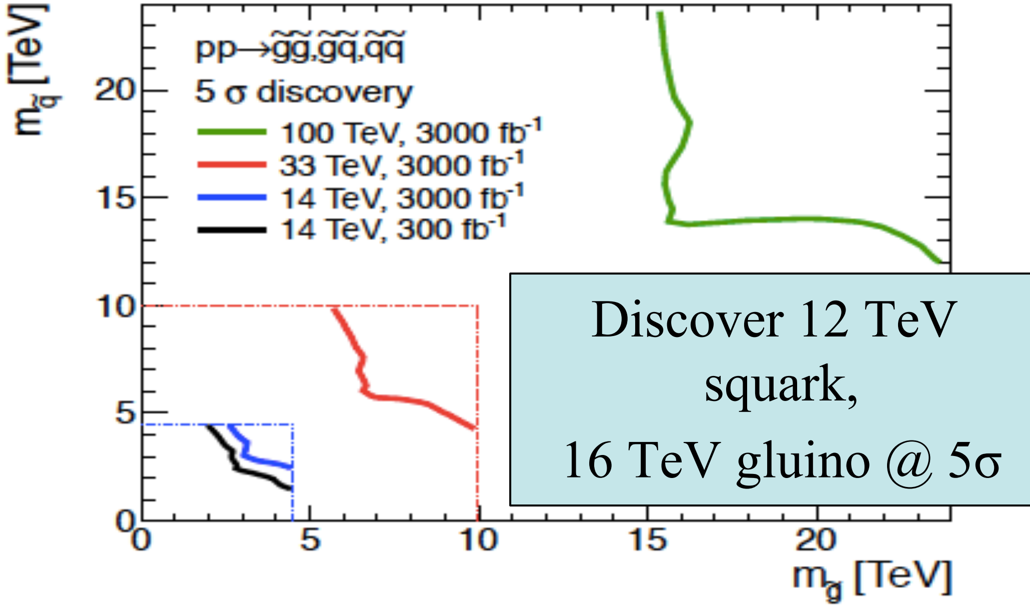
- **H is a fundamental (elementary) particle → we live in a universe where the fine-tuning at M arises (anthropic solution, multiverse, Landscape of string theory)**



Current bound $\zeta < 0.12$ → 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 BIG and the SMALL- dim[m] ≠ 0

- $V = \mu^2 |H|^2 + \lambda |H|^4$ what is the value of the energy of its vacuum, i.e. the SM **vacuum energy**? → $V_o = \mu^2 <H>^2 + \lambda <H>^4 \sim (100\ \mathrm{GeV})^2$

observed vacuum energy, i.e. dark energy accelerating the expansion of the Universe O(10^{-3} eV)

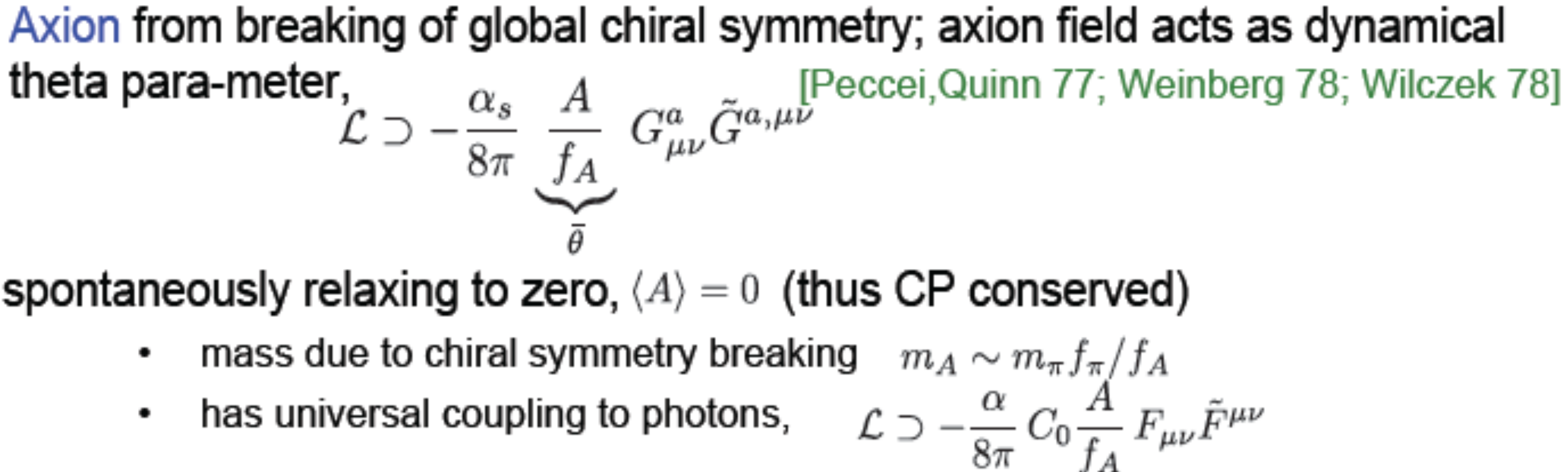
- V defined up to a constant → choose such constant to **cancel** the O ($100\ \mathrm{GeV})^2$ contribution
- **10^{-3} eV 10^{2} GeV 10^{16} GeV 10^{19} GeV**

- **Why** so different mass scales ?

- **How** to guarantee their separation → symmetry vs. multiverse

The BIG and the SMALL – dim[m]=0

- h_t – h_e **flavour** issue
- L_{SM} no symmetry prevents to add a term violating **CP in the strong interactions** whose size depends on a **dimensionless** parameter θ → the bound on the neutron EDM → $\theta < 10^{-10}$
- **The θ – problem** : the symmetry solution



Axion from breaking of global chiral symmetry; axion field acts as dynamical theta para-meter, [Peccei,Quinn 77; Weinberg 78; Wilczek 78]

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\underbrace{\frac{A}{f_A}}_{\bar\theta} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

spontaneously relaxing to zero, $\langle A \rangle = 0$ (thus CP conserved)

- mass due to chiral symmetry breaking $m_A \sim m_\pi f_\pi / f_A$
- has universal coupling to photons, $\mathcal{L} \supset -\frac{\alpha}{8\pi} C_0 \frac{A}{f_A} F_{\mu\nu}\tilde{F}^{\mu\nu}$

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)

DM and ELW. SYMMETRY BREAKING

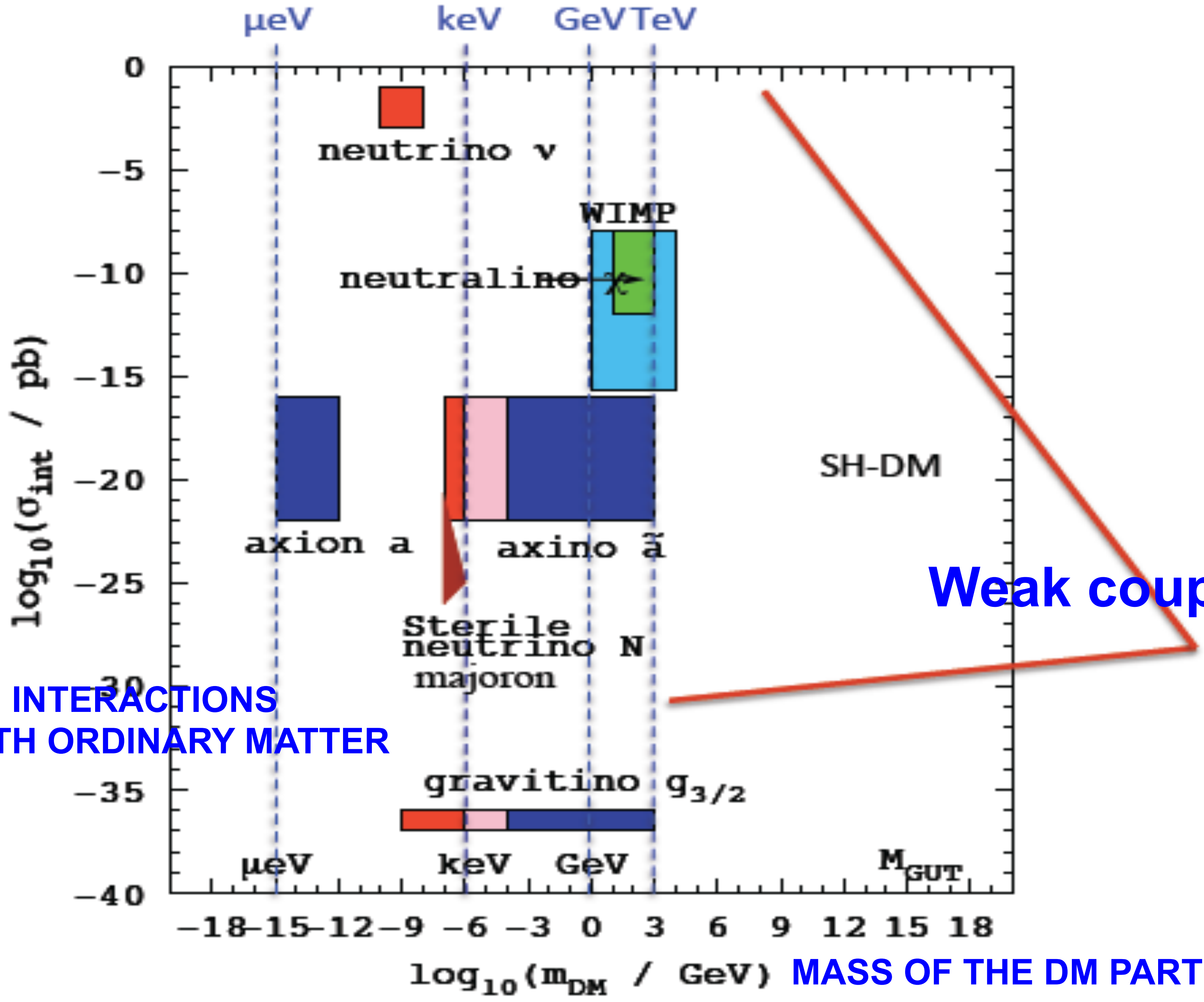
THE DM ROAD TO NEW PHYSICS BEYOND THE SM:

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”**



Weak couplings

DM INTERACTIONS WITH ORDINARY MATTER

MASS OF THE DM PARTICLE

THE “*WIMP MIRACLE*”

Bergstrom

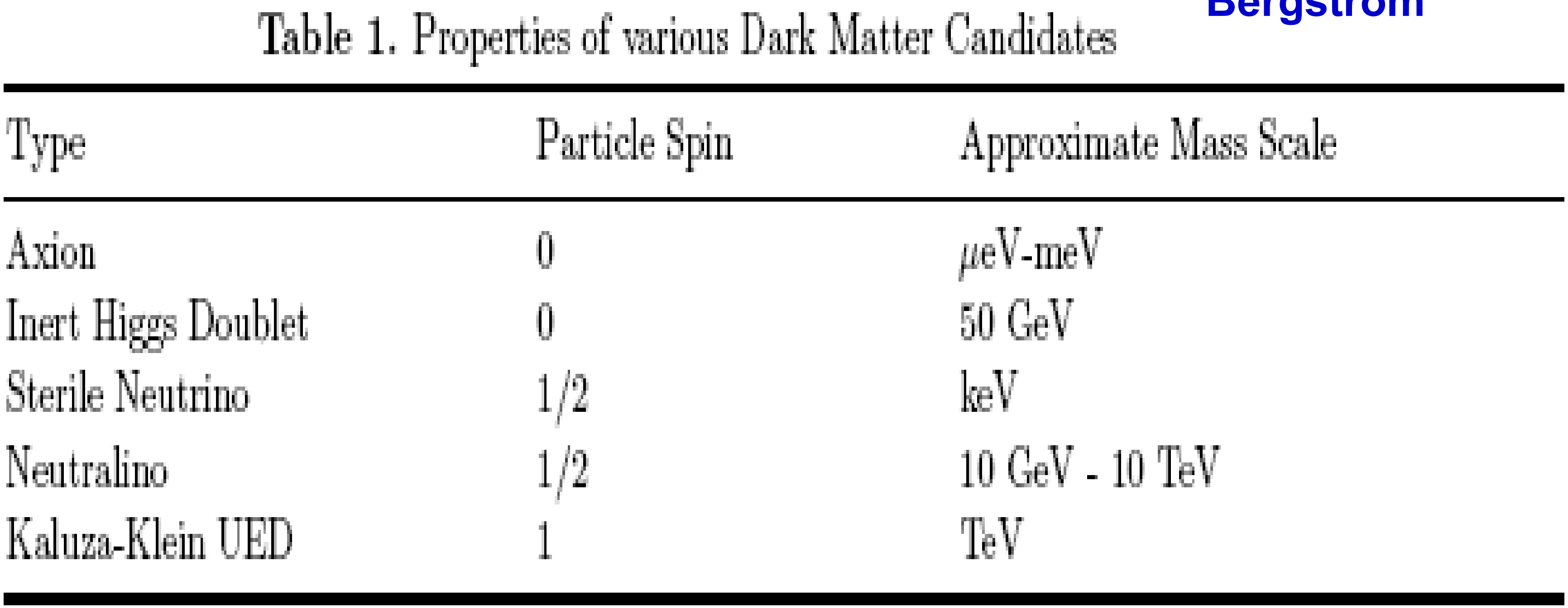
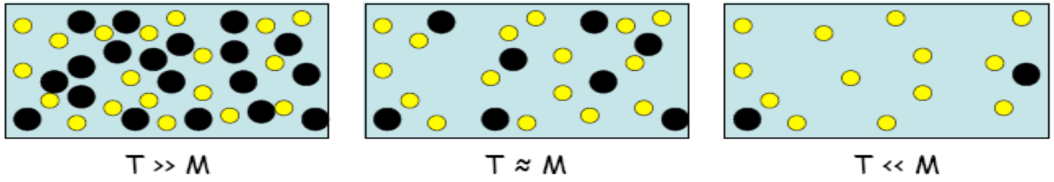


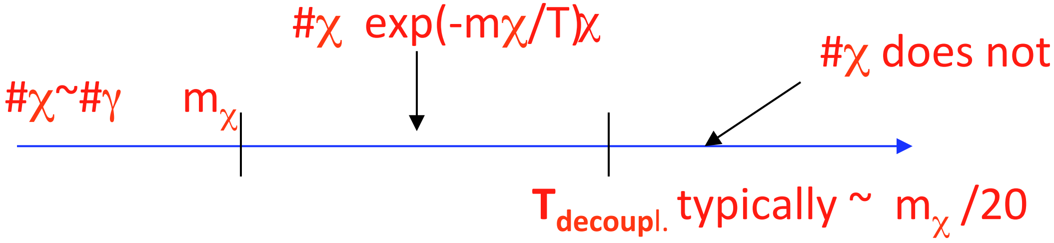
Table 1. Properties of various Dark Matter Candidates

Type	Particle Spin	Approximate Mass Scale
Axion	0	μeV-meV
Inert Higgs Doublet	0	50 GeV
Sterile Neutrino	1/2	keV
Neutralino	1/2	10 GeV - 10 TeV
Kaluza-Klein UED	1	TeV

Many possibilities for DM candidates, but WIMPs are really special: peculiar coincidence between particle physics and cosmology parameters to provide a VIABLE DM CANDIDATE AT THE ELW. SCALE


T >> M
T ≈ M
T << M

WIMPS (Weakly Interacting Massive Particles)


#χ exp(-mχ/T)χ

#χ does not change any more

#χ~#γ m_χ

$T_{decoupl.}$ typically ~ m_χ /20

Ω_χ depends on particle physics ($\sigma_{annih.}$)χ and "cosmological" quantities (H, T_0, …

$$\Omega_\chi h^2 \simeq \frac{10^{-3}}{\underbrace{\langle(\sigma_{annih.})\, V \chi\rangle}_{\sim\, \alpha^2 / M^2_\chi} \ \text{TeV}^2}$$

COSMO – PARTICLE

CONSPIRACY

TeV² → From T^0 M_{Planck}

$\Omega_\chi h^2$ in the range 10^{-2} -10^{-1} to be cosmologically interesting (for DM)

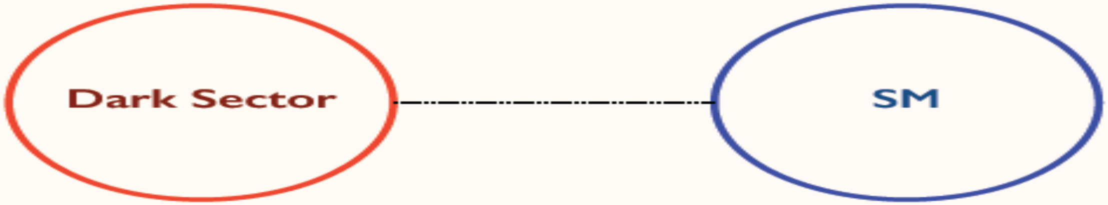
$m_\chi \sim 10^2 - 10^3$ GeV (weak interaction) $\Omega_\chi h^2 \sim 10^{-2}$ -10^{-1} !!!

THERMAL RELICS (WIMP in thermodyn.equilibrium with the plasma until $T_{decoupl}$)

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.



T. VOLANSKY at this meeting

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

Very different from the WIMP paradigm!!

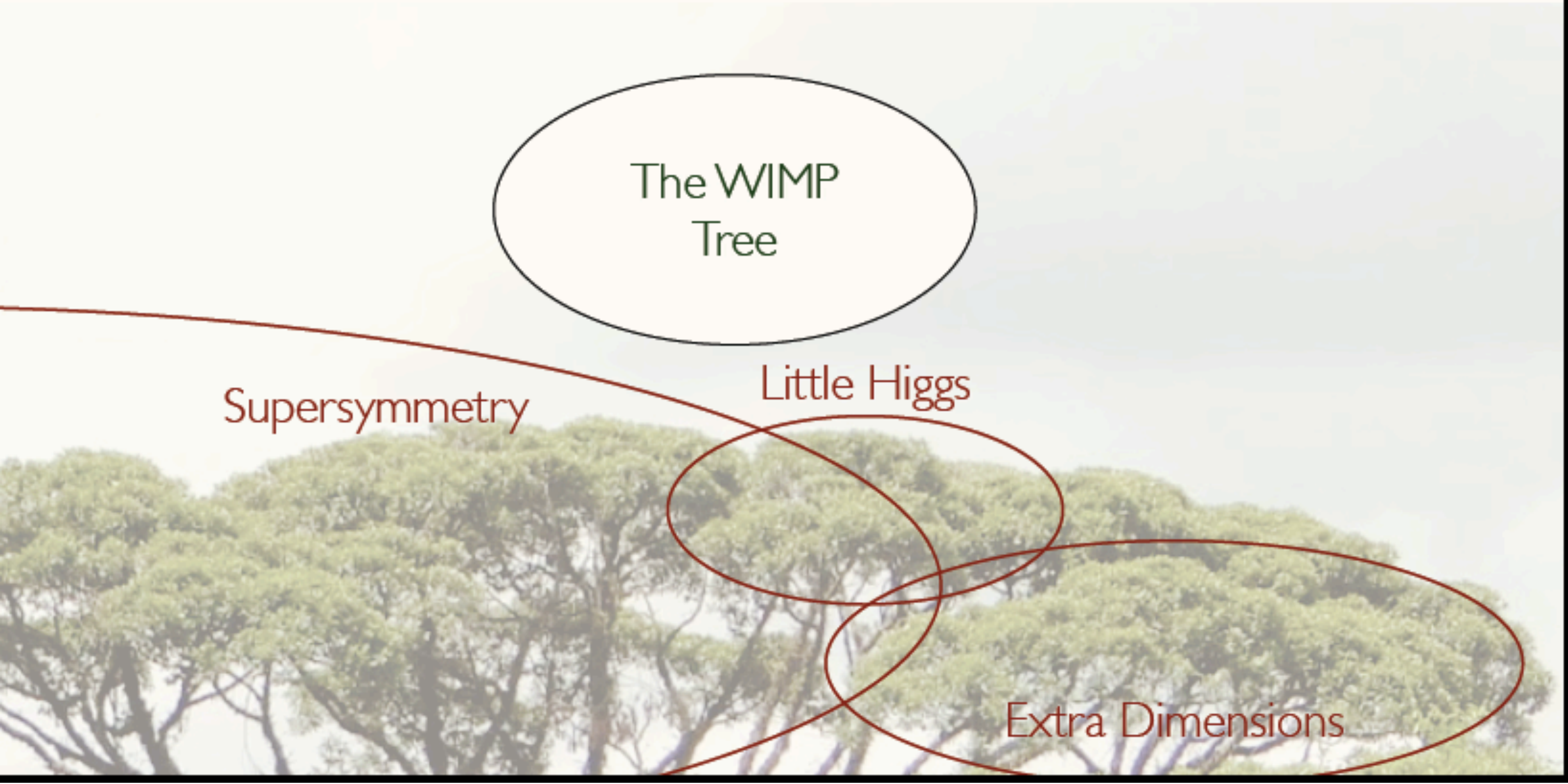
CONNECTION DM – ELW. SCALE

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** → **DISCRETE SYMM.** → **STABLE NEW PART.**	***R-PARITY LSP*** Neutralino spin 1/2	***KK-PARITY LKP*** spin1	***T-PARITY LTP*** spin0
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

The Dark Matter Tree

T. VOLANSKY at this meeting

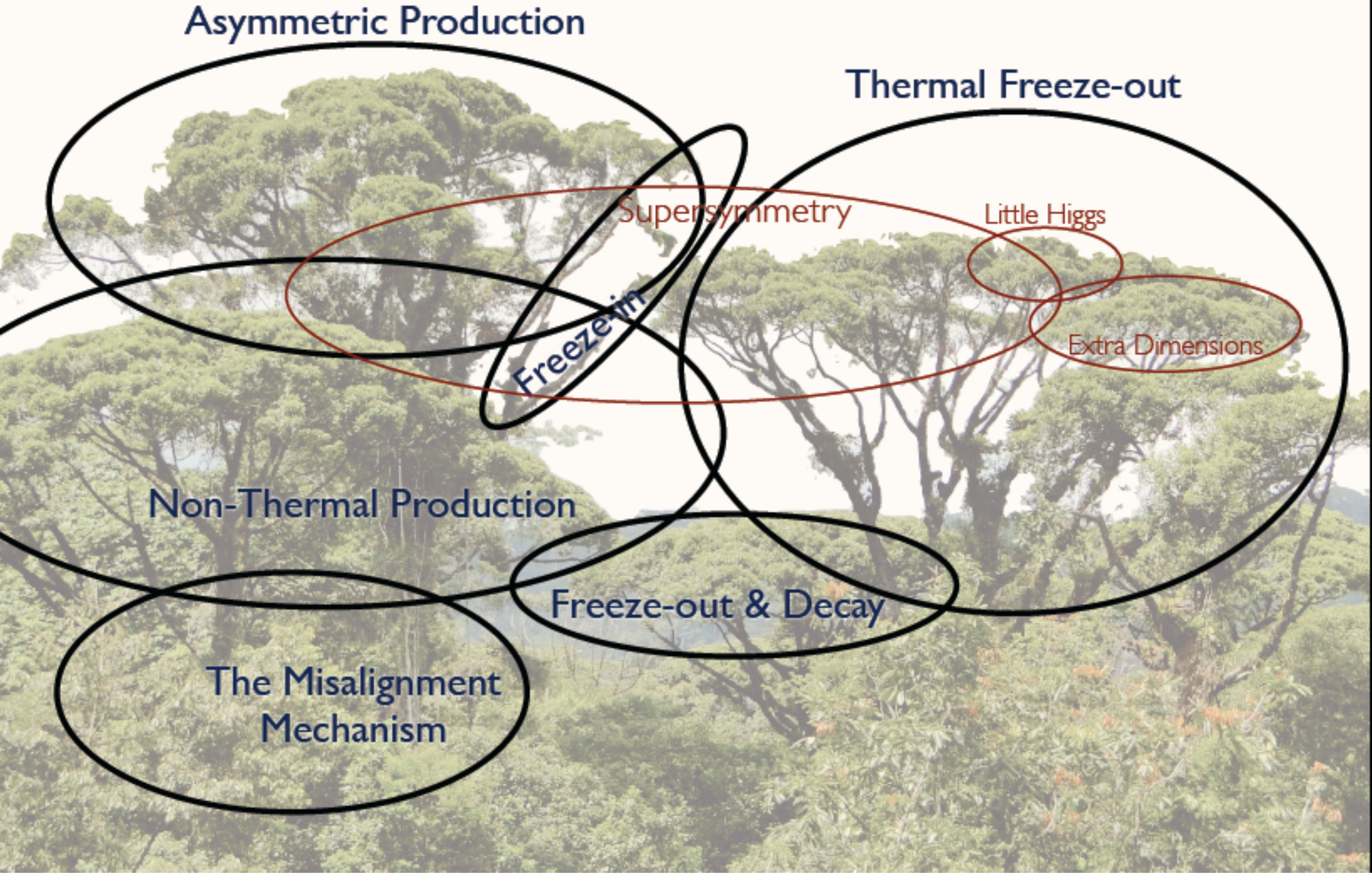


The WIMP Tree

Little Higgs

Supersymmetry

Extra Dimensions



Asymmetric Production

Thermal Freeze-out

Supersymmetry

Little Higgs

Extra Dimensions

Freeze-in

Non-Thermal Production

Freeze-out & Decay

The Misalignment
Mechanism

SUSY & DM : a successful marriage

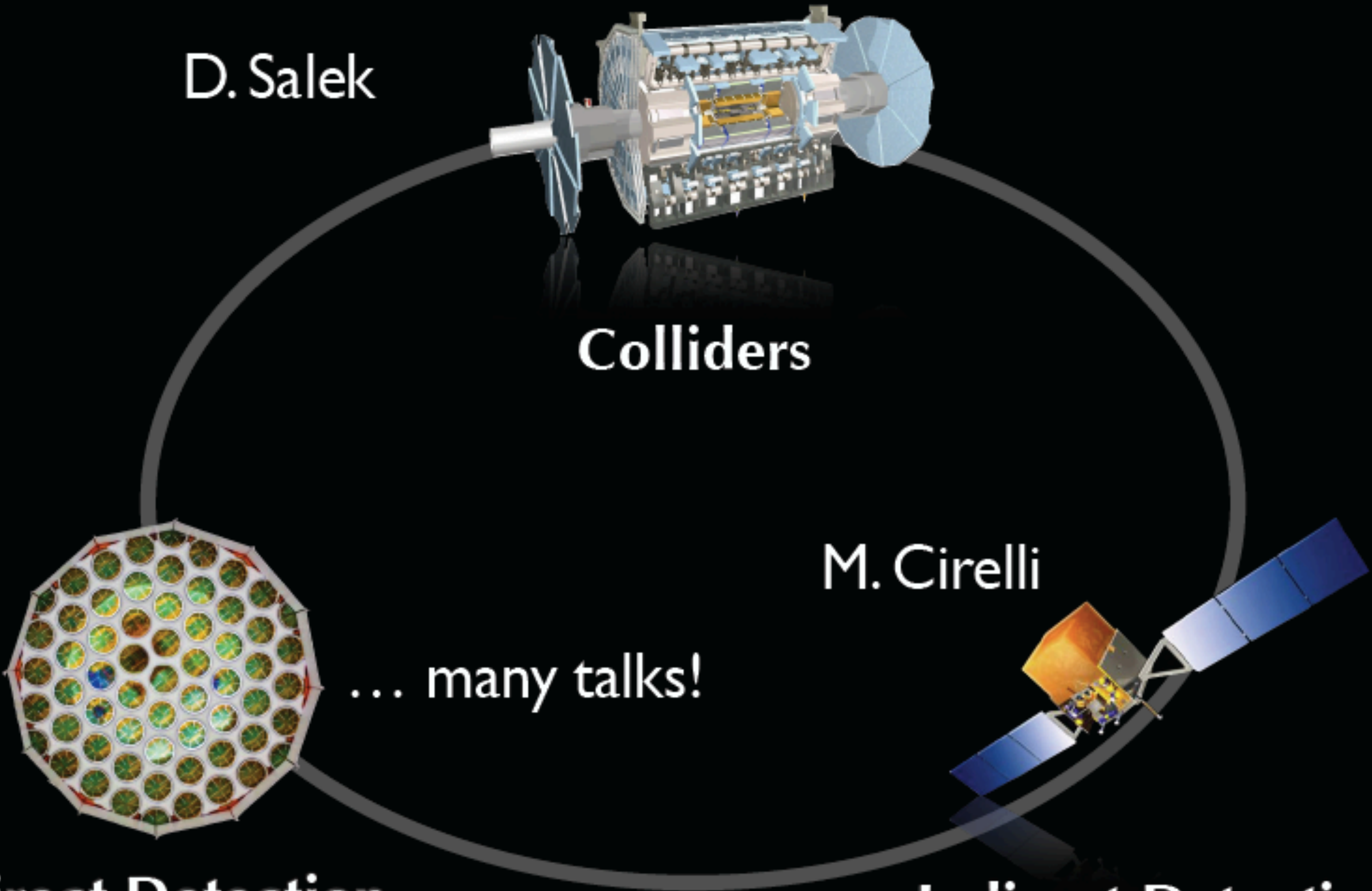
- Supersymmetrizing the SM does not lead necessarily to a stable SUSY particle to be a DM candidate.
- However, the mere SUSY version of the SM is known to lead to a too fast p-decay. Hence, necessarily, the SUSY version of the SM has to be **supplemented with some additional (ad hoc?) symmetry to prevent the p-decay catastrophe.**
- Certainly the simplest and maybe also the most attractive solution is **to impose the discrete R-parity** symmetry
- MSSM + R PARITY → LIGHTEST SUSY PARTICLE (LSP) IS STABLE .
- The LSP can constitute an interesting DM candidate in several interesting realizations of the MSSM (i.e., with different SUSY breaking mechanisms including gravity, gaugino, gauge, anomaly mediations, and in various regions of the parameter space).

DESPERATELY SEEKING (SUSY)

WIMPS

The quest for Dark Matter

G. BERTONE, at this meeting



D. Salek

Colliders

M. Cirelli

… many talks!

Direct Detection

Indirect Detection

Indirect Detection

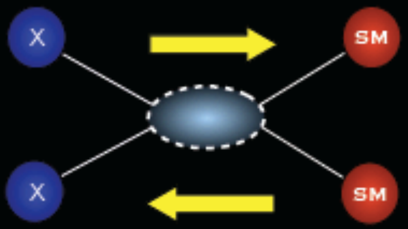
WHY “ANNIHILATIONS”?

BERTONE

X = DARK MATTER

SM = STANDARD MODEL PARTICLE

EARLY UNIVERSE



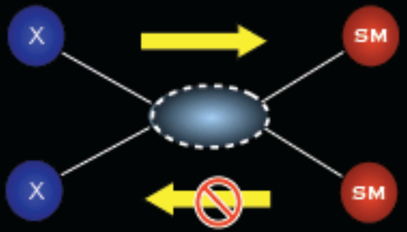
$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle\sigma v\rangle \left[n_\chi^2 - (n_\chi^{eq})^2\right]$$

RELIC DENSITY (NR FREEZE-OUT)

$$\Omega h^2 \approx \frac{3\times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{<\sigma v>}$$

Electroweak-scale cross sections can reproduce correct relic density.

TODAY



$$\frac{dn_\chi}{dt} = -(\sigma v)_o n_\chi^2$$

ANNIHILATION FLUX

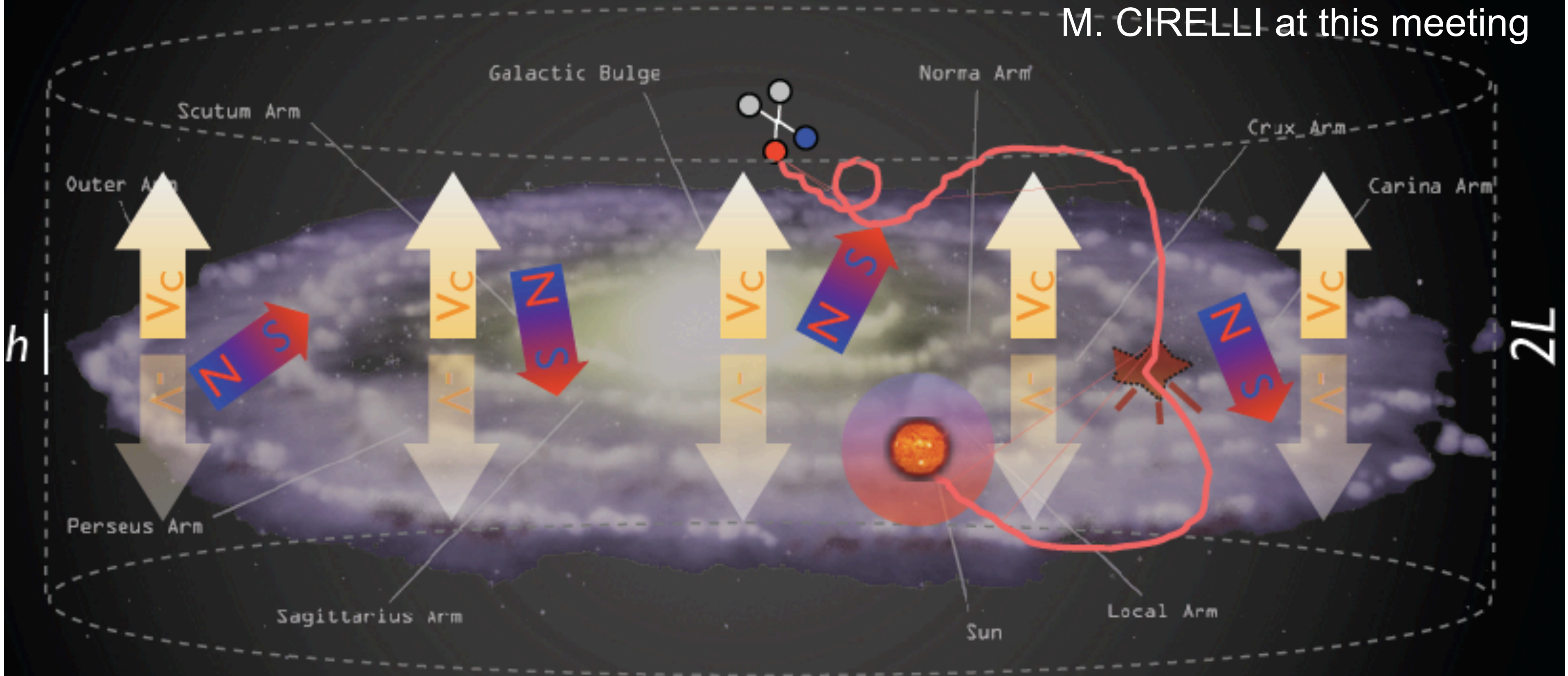
$$\Phi_i(\Omega, E_i) = \frac{dN}{dE_i}\frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\int_{los}\rho_\chi^2(\ell,\Omega)d\ell$$

Particle physics input from extensions of the Standard Model. Need to specify distribution of DM along the line of sight.

Indirect Detection: charged CRs

$\bar{p}$ and e^+ from DM annihilations in halo

M. CIRELLI at this meeting



spectrum

$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}\left(b(E)f\right) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

diffusion energy loss convective wind source spallations

Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maur
Brun... '90s, '00s

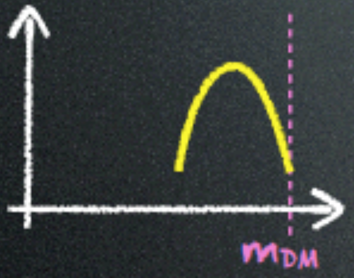
[uncert]

How does DM produce γ-rays?

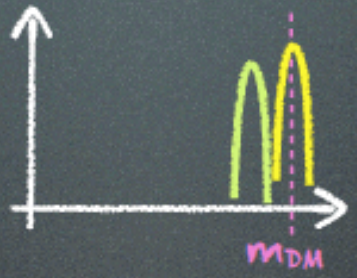
environment-independent

1. prompt emission

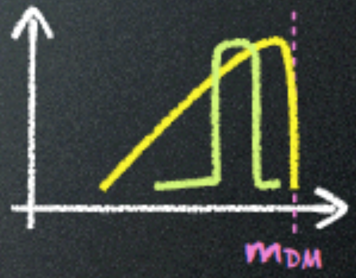
1a. continuum



1b. line(s)



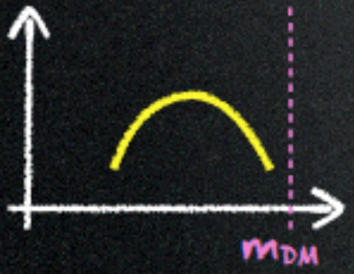
1c. sharp features



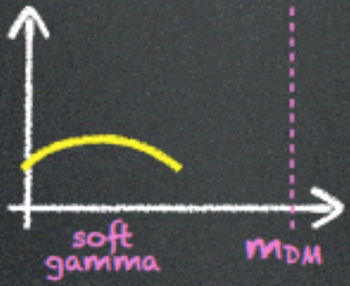
environment-dependent

2. secondary emission

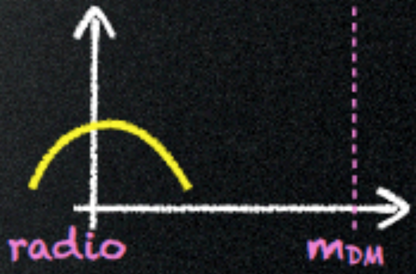
2a. ICS



2b. bremsstrahlung

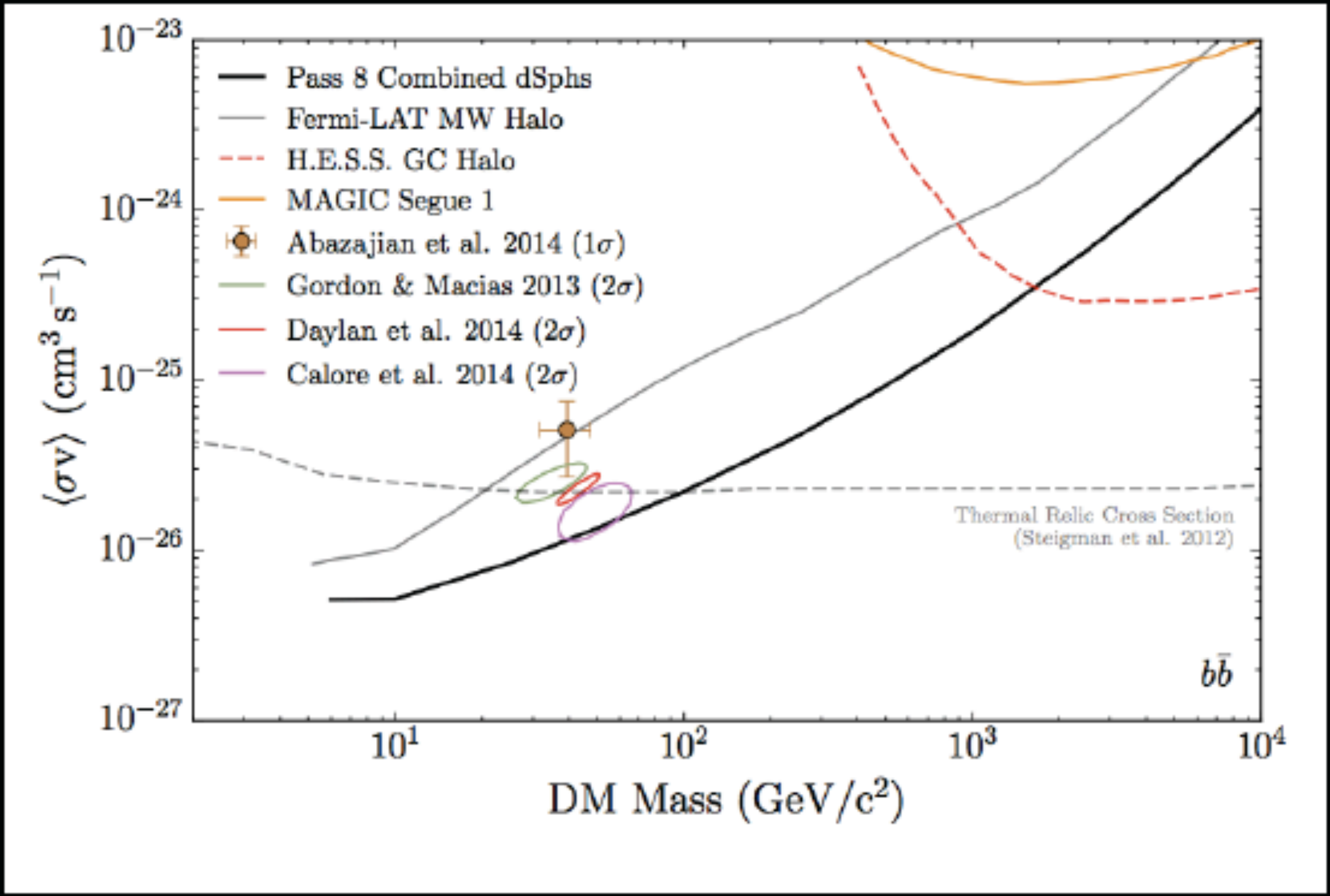


2c. synchrotron



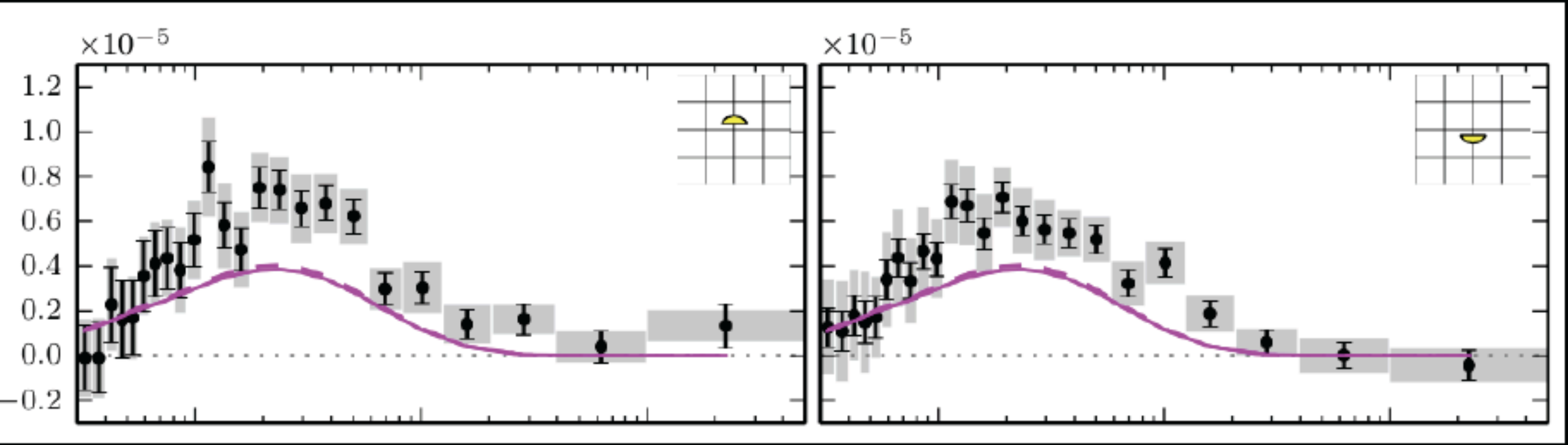
M. CIRELLI at this meeting

Stringent constraints from dwarf galaxies



Fermi LAT coll. 1507.03530

The GeV excess

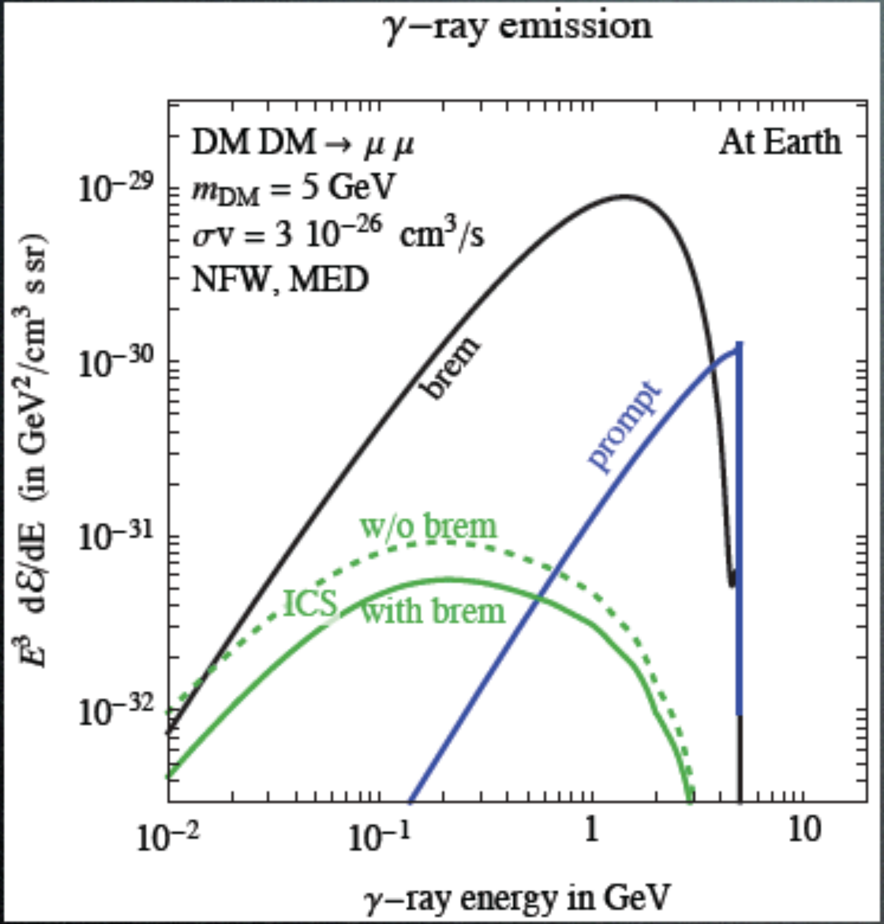


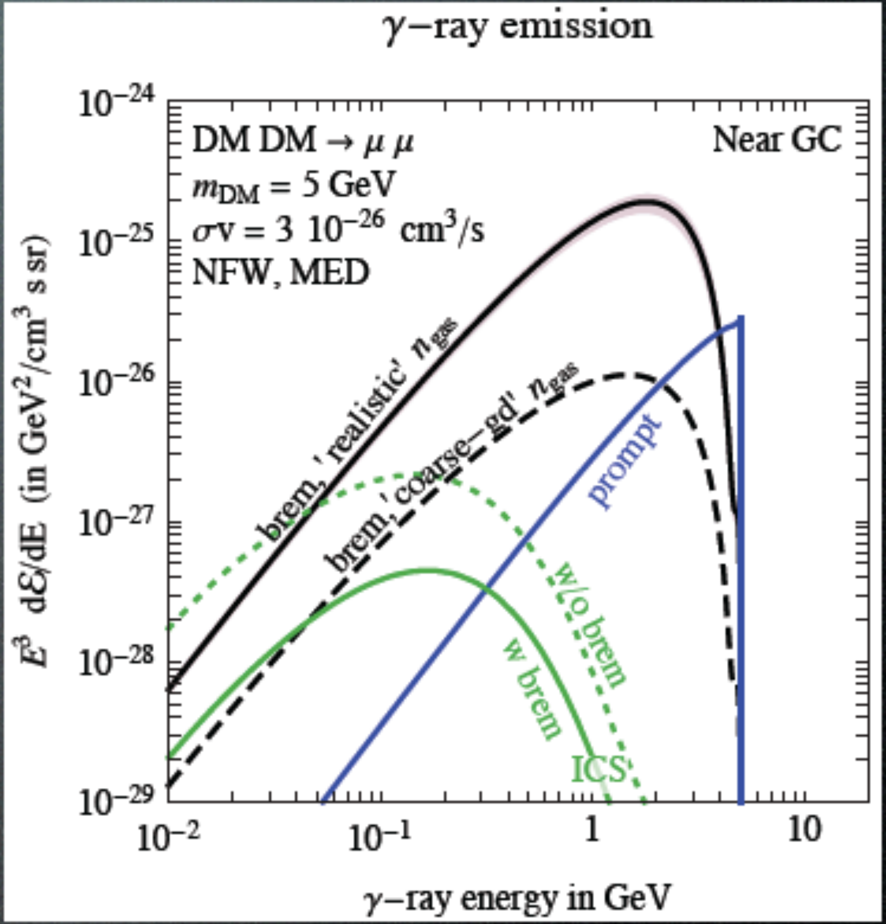
Calore, Bozorgnia, GB+ arXiv:1509.02164

High resolution simulated haloes (Eagle sim.) that satisfy observational constraints exhibit, in the inner few kiloparsecs, dark matter profiles shallower than those required to explain the GeV excess via dark matter annihilation.

Results

The total γ ray spectrum





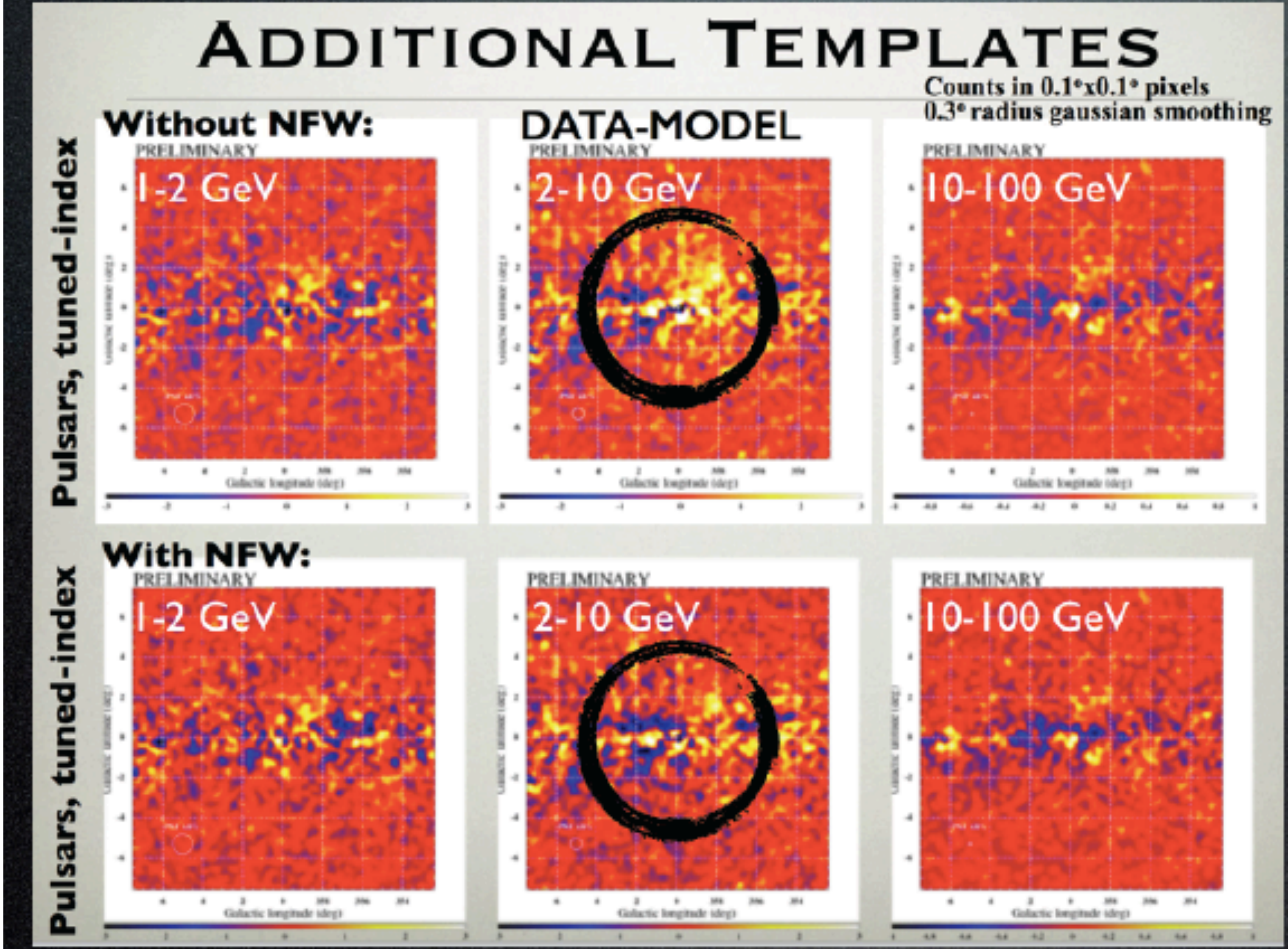
- brem is dominant
- ICS is affected

- uncertainty ▭ is somewhat reabsorbed:

large n_{gas} ⇨ more loss **and** more emission

GC GeV excess

Dark Matter interpretation:



ADDITIONAL TEMPLATES

Counts in 0.1°x0.1° pixels
0.3° radius gaussian smoothing

Without NFW:

DATA-MODEL

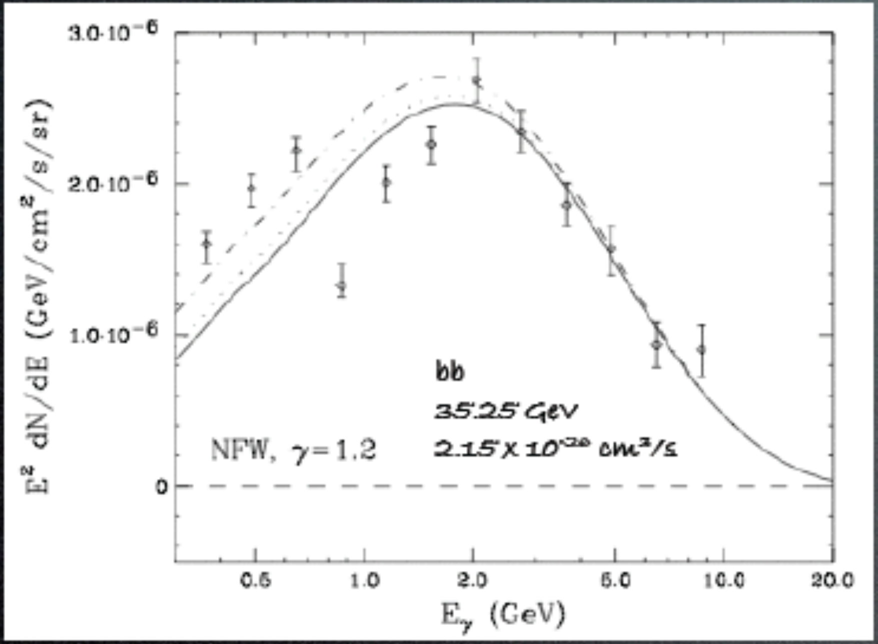
With NFW:

S. Murgia + T. Porter for FERMI-LAT - ICRC 2015
FERMI-LAT Coll., 1511.02938

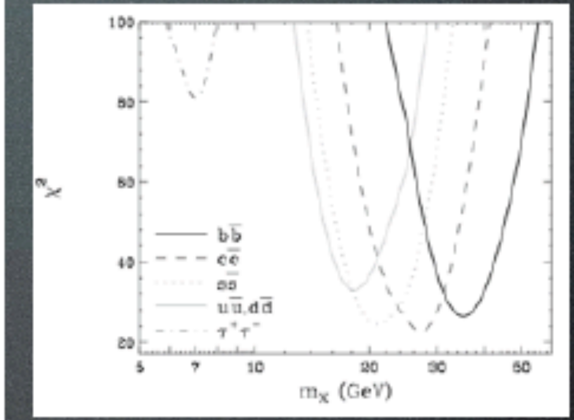
GC GeV excess

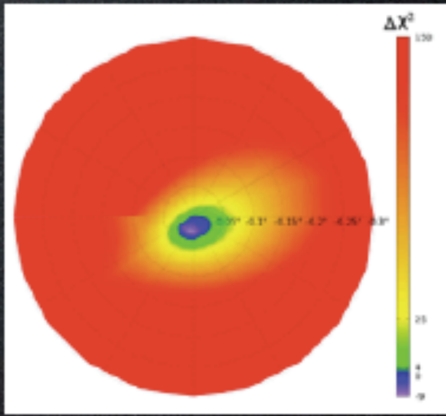
Dark Matter interpretation:

Best fit:
~35 GeV, quarks, ~thermal σv



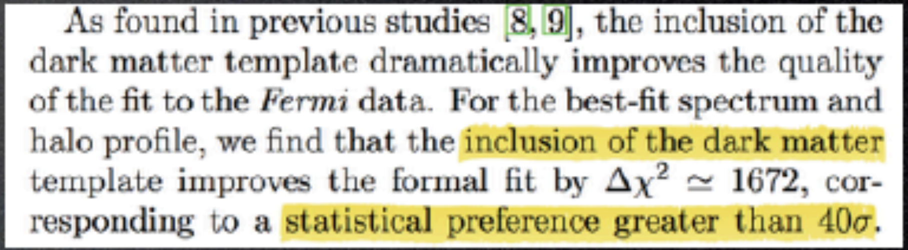
Using events with accurate directional reconstruction





A compelling case for annihilating DM

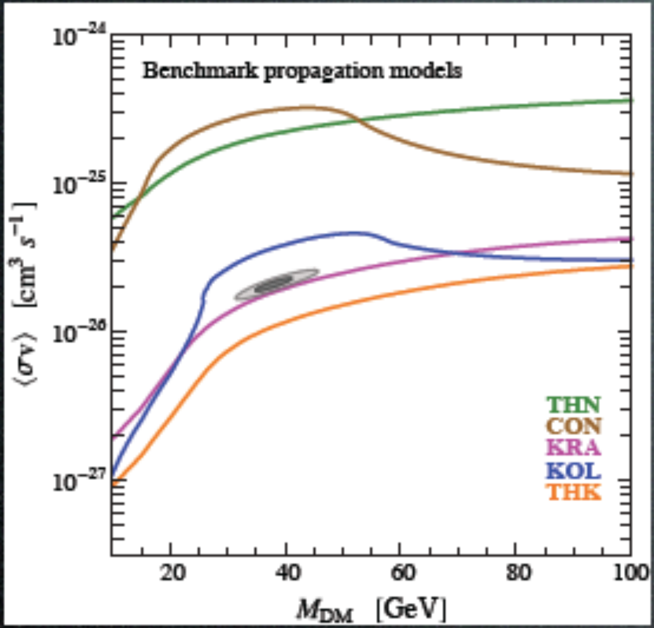
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703



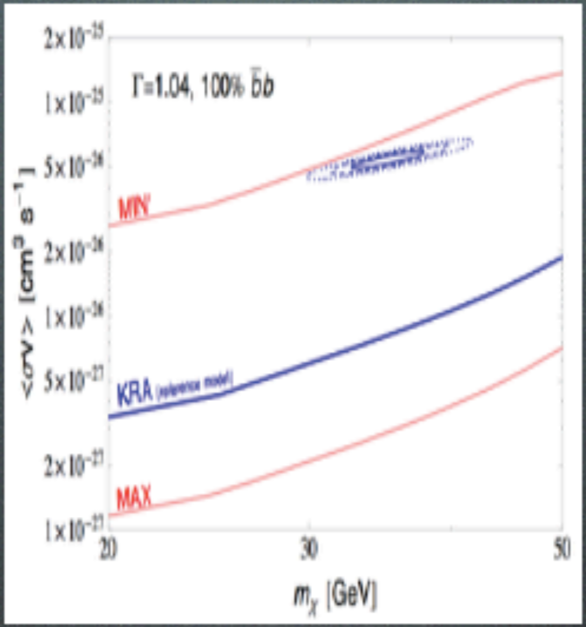
As found in previous studies [8, 9], the inclusion of the dark matter template dramatically improves the quality of the fit to the *Fermi* data. For the best-fit spectrum and halo profile, we find that the inclusion of the dark matter template improves the formal fit by $\Delta\chi^2 \simeq 1672$, corresponding to a statistical preference greater than 40σ.

GC GeV excess

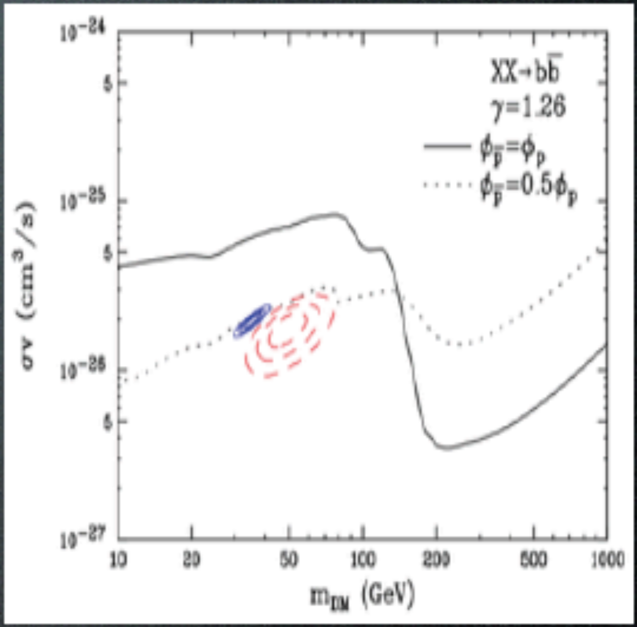
Antiproton constraints compared:



Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173



Bringmann, Vollmann, Weniger 1406.6027



Hooper, Linden, Mertsch 1410.1527

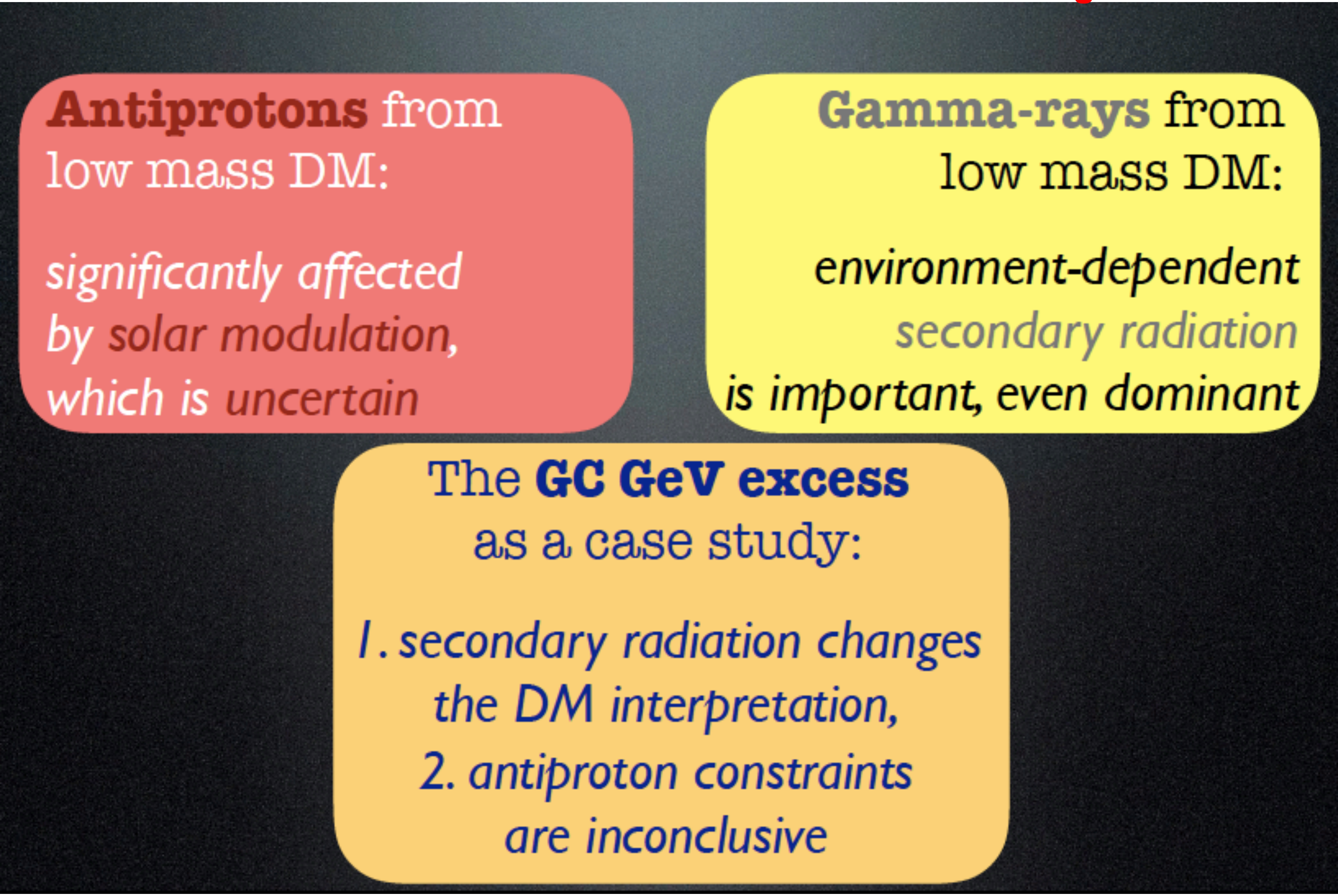
May be very relevant!
But not robust.

'Rule out' or
'considerable tension'.

'Significantly less stringent'.

How come?!?

M. CIRELLI at this meeting



Antiprotons from
low mass DM:

significantly affected
by solar modulation,
which is uncertain

Gamma-rays from
low mass DM:

environment-dependent
secondary radiation
is important, even dominant

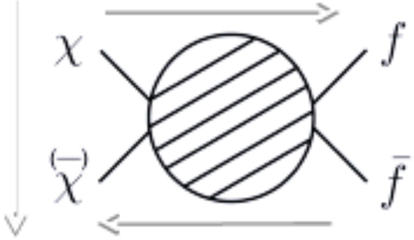
The **GC GeV excess**
as a case study:

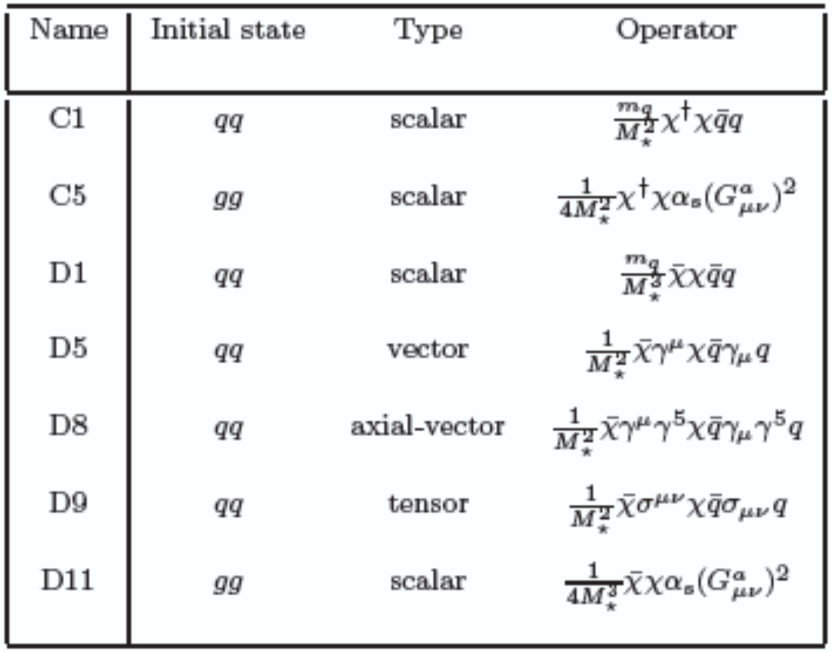
1. secondary radiation changes
the DM interpretation,
2. antiproton constraints
are inconclusive

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

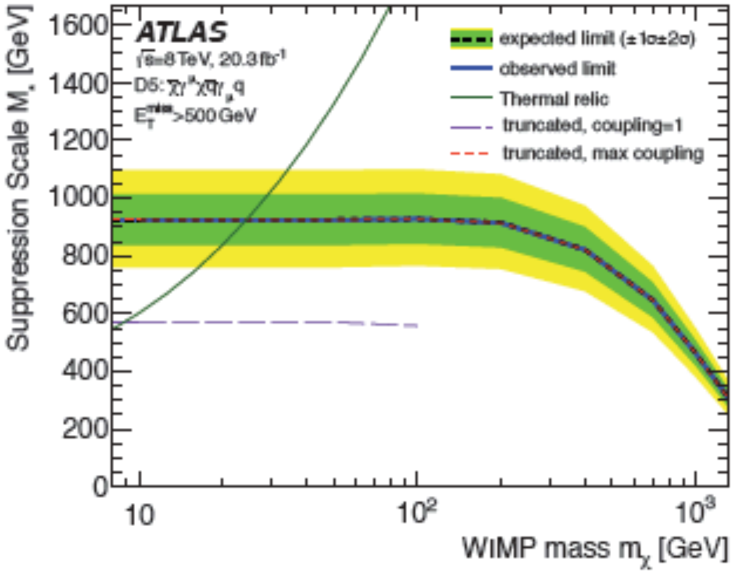
Dark Matter EFT operators

- 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)





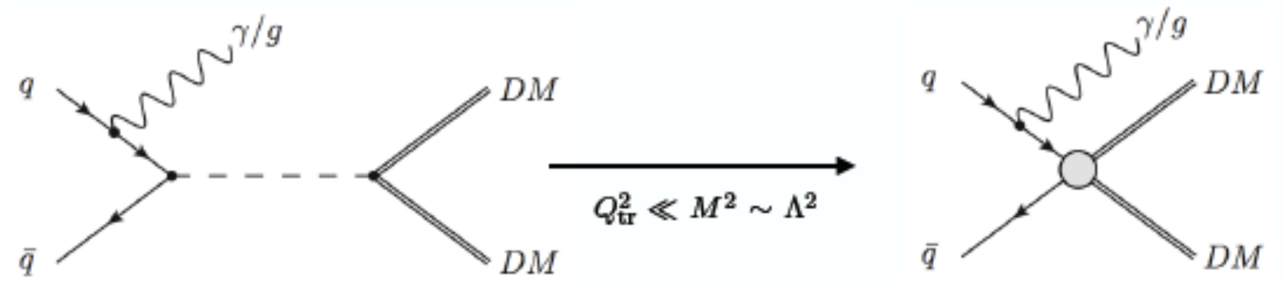
Name	Initial state	Type	Operator
C1	qq	scalar	$\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$
C5	gg	scalar	$\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu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



1008.1783

1307.2253

Contact interactions



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

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

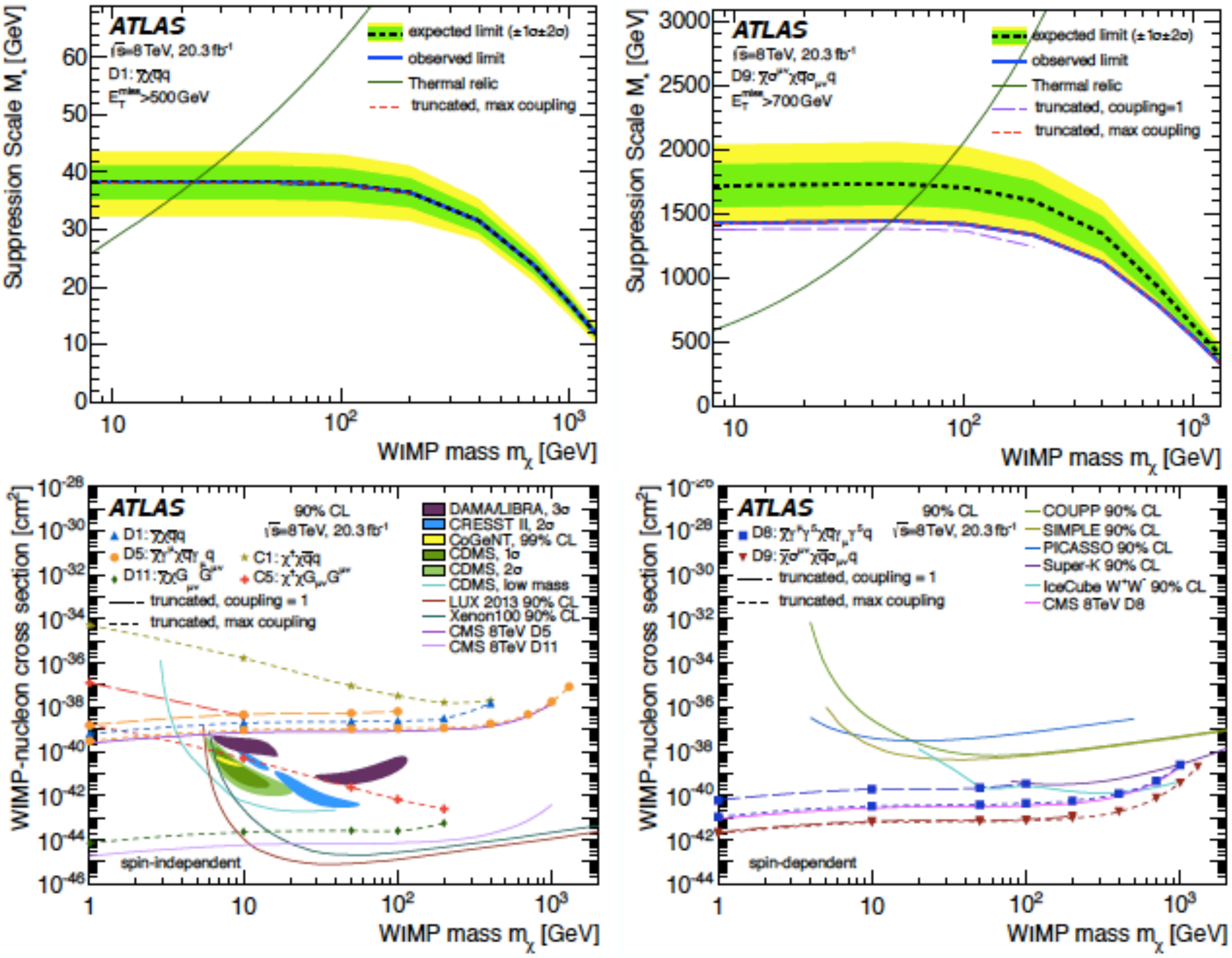
It is safe to use EFT when the mediator can be integrated out.

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

Salek at this meeting

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

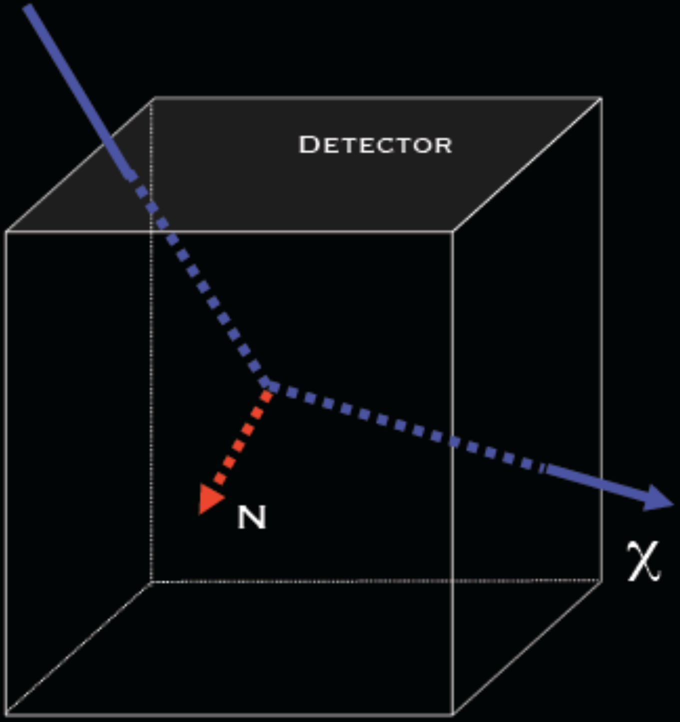
DM interpretation



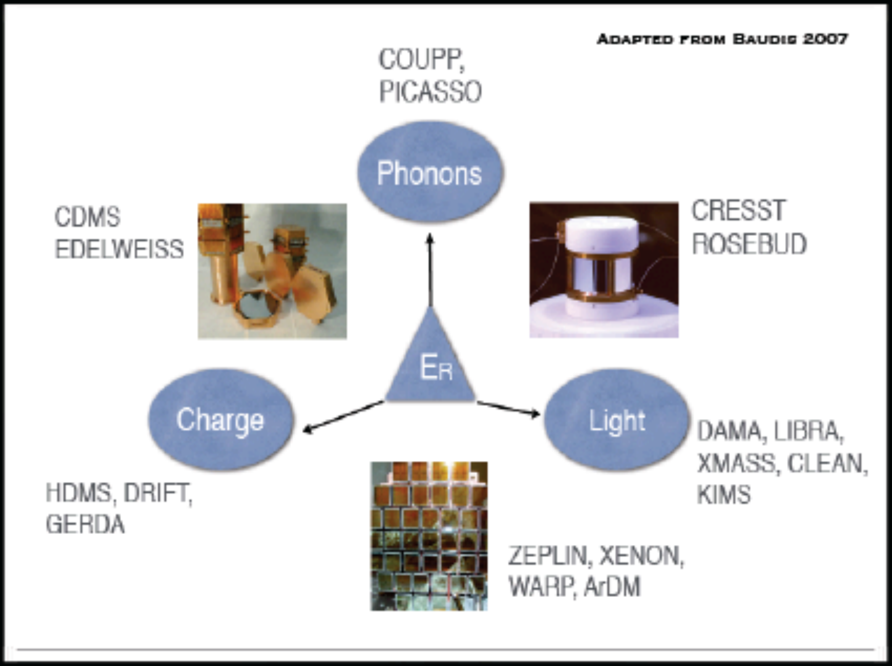
Direct Detection

Principle and Detection Techniques

G. BERTONE, at this meeting



DM Scatters off nuclei in the detector



Detection of recoil energy via ionization (charges), scintillation (light) and heat (phonons)

Info to extract from the **direct searches**

$$\boxed{\frac{dR}{dE_R} = \frac{\rho_\chi \sigma_n}{2 m_\chi \mu_{n\chi}^2} N_A m_n C_T^2(A,Z) \int dE'_R G(E_R, E'_R)\,\epsilon(E'_R) F^2(E'_R) \overbrace{\int_{v_{min}(E'_R)}^{\infty} \frac{f(\mathbf{v}+\mathbf{v}_E)}{v} d^3v}^{= g(v_{min})}}$$

DM model — detector properties — nuclear physics — DM halo model

$v_{min}(E'_R)$: min. DM velocity required for nuclear recoil E'_R

Usual method: DM model + halo model → limits/preferred values in $m_\chi - \sigma_n$ space

Kahn, McCullough, Fox 2014

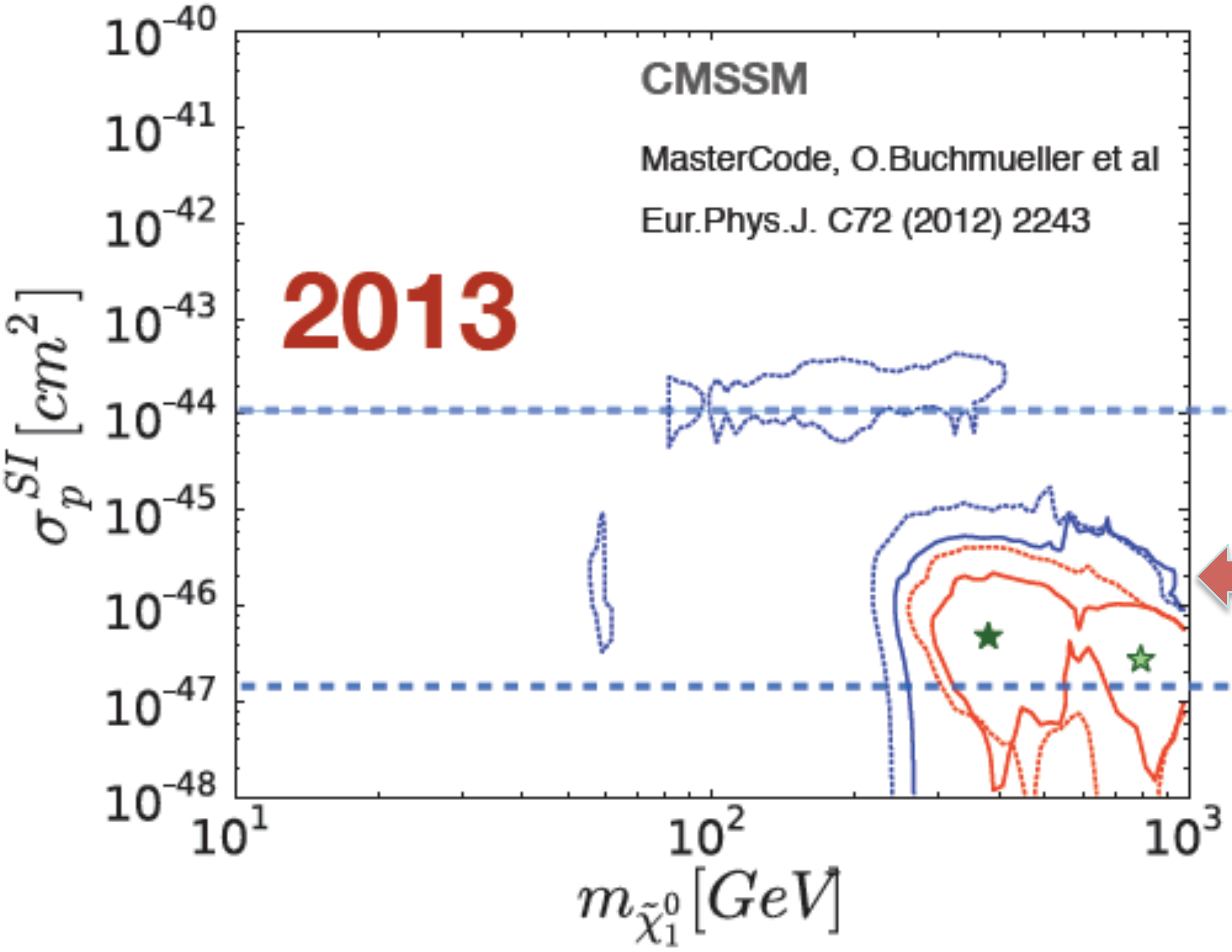
Halo-independent: DM model → limits/preferred values in $v_{min} - g(v_{min})$ space

No assumptions about DM halo, easy to compare multiple experiments (esp. signal vs. exclusion)

INTERACTION RATE FOR ELASTIC SCATTERING

after integrating over WIMP velocity distribution

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



MasterCode, O.Buchmueller et al

Eur.Phys.J. C72 (2012) 2243

2013

~ 1 event kg^{-1} yr^{-1}

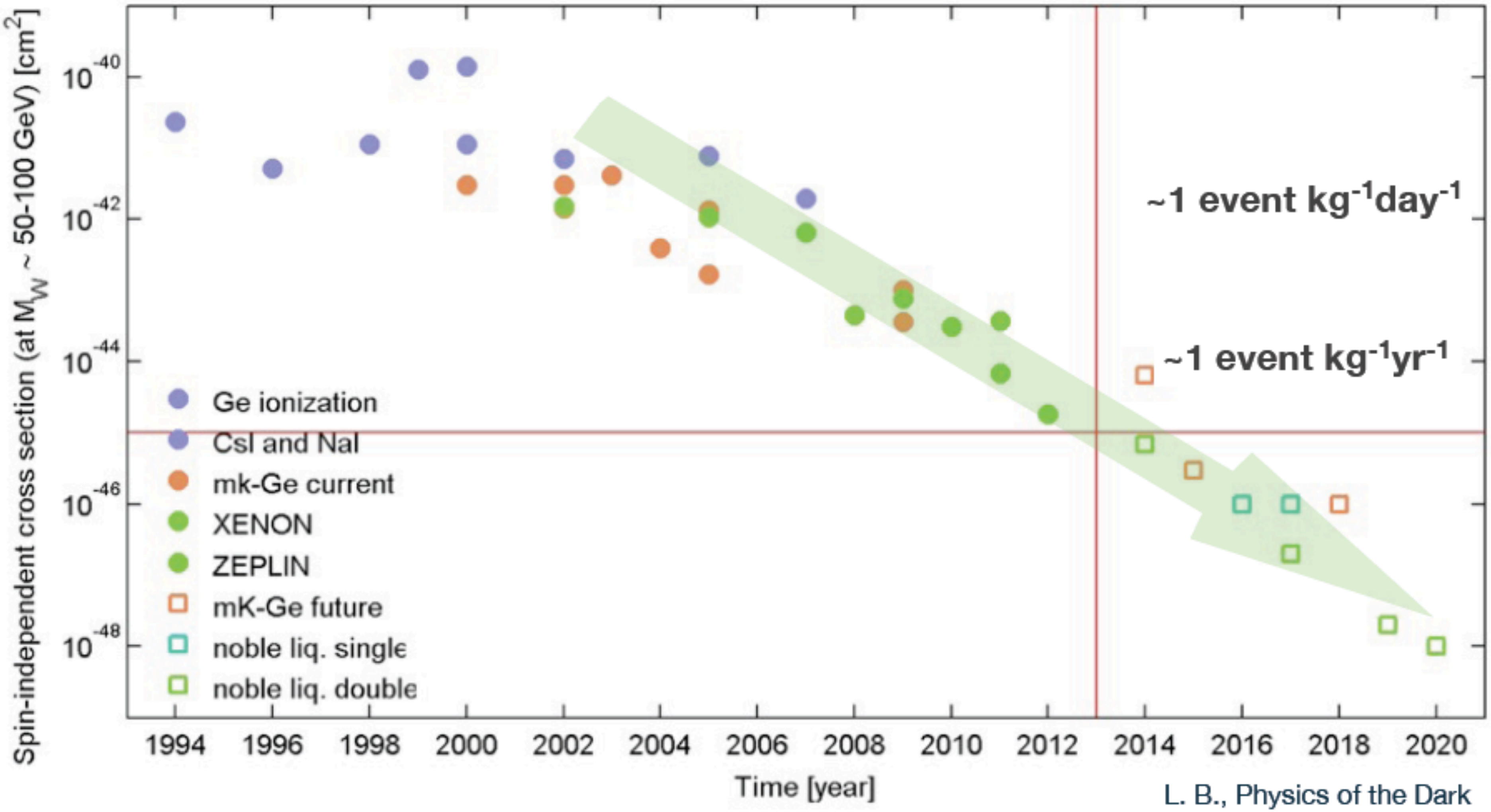
Examples of SUSY predictions

~ 1 events t^{-1} yr^{-1}

Direct detection: sensitivity versus time

Factor ~ 10 every two years!

L. BAUDIS



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

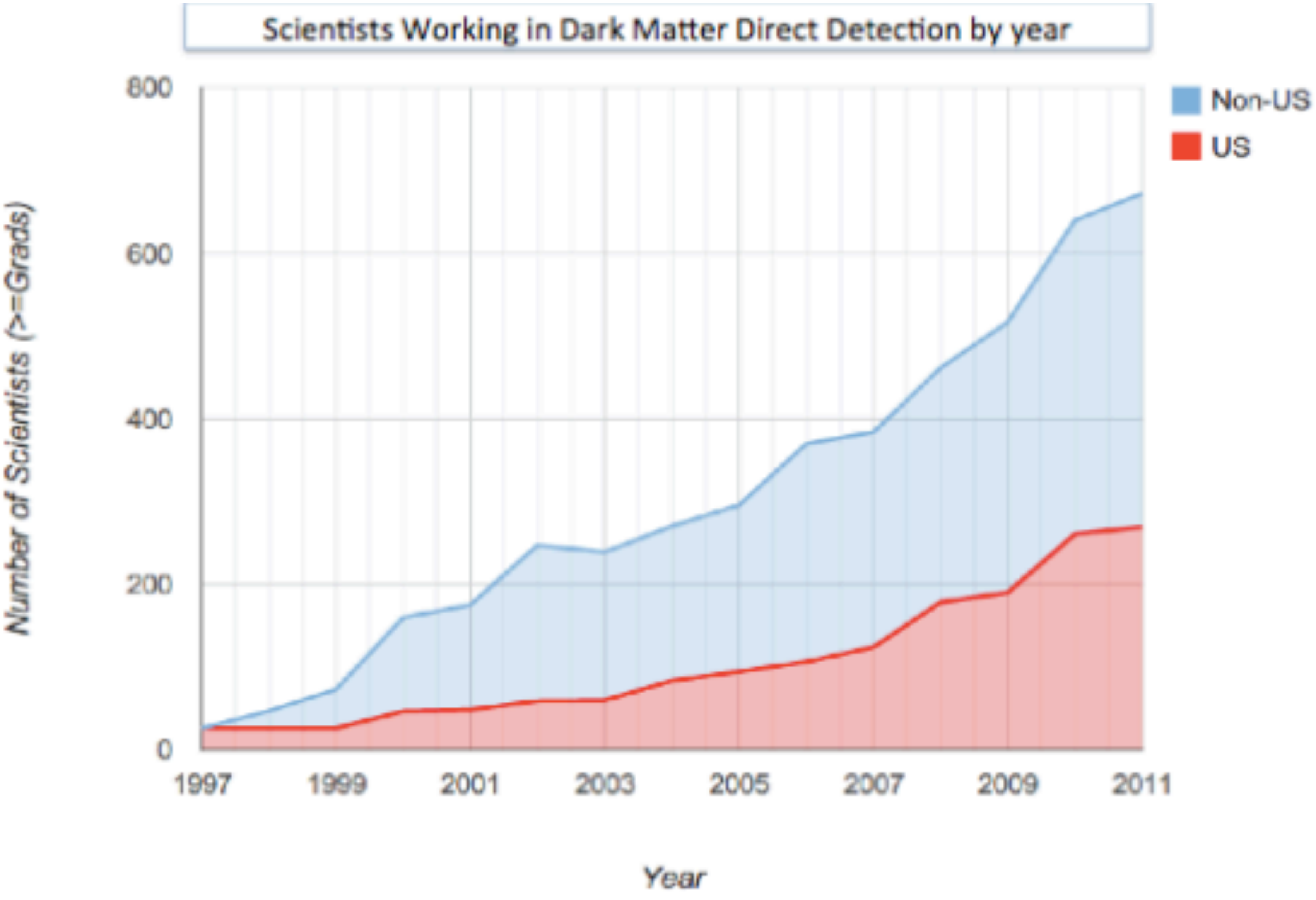
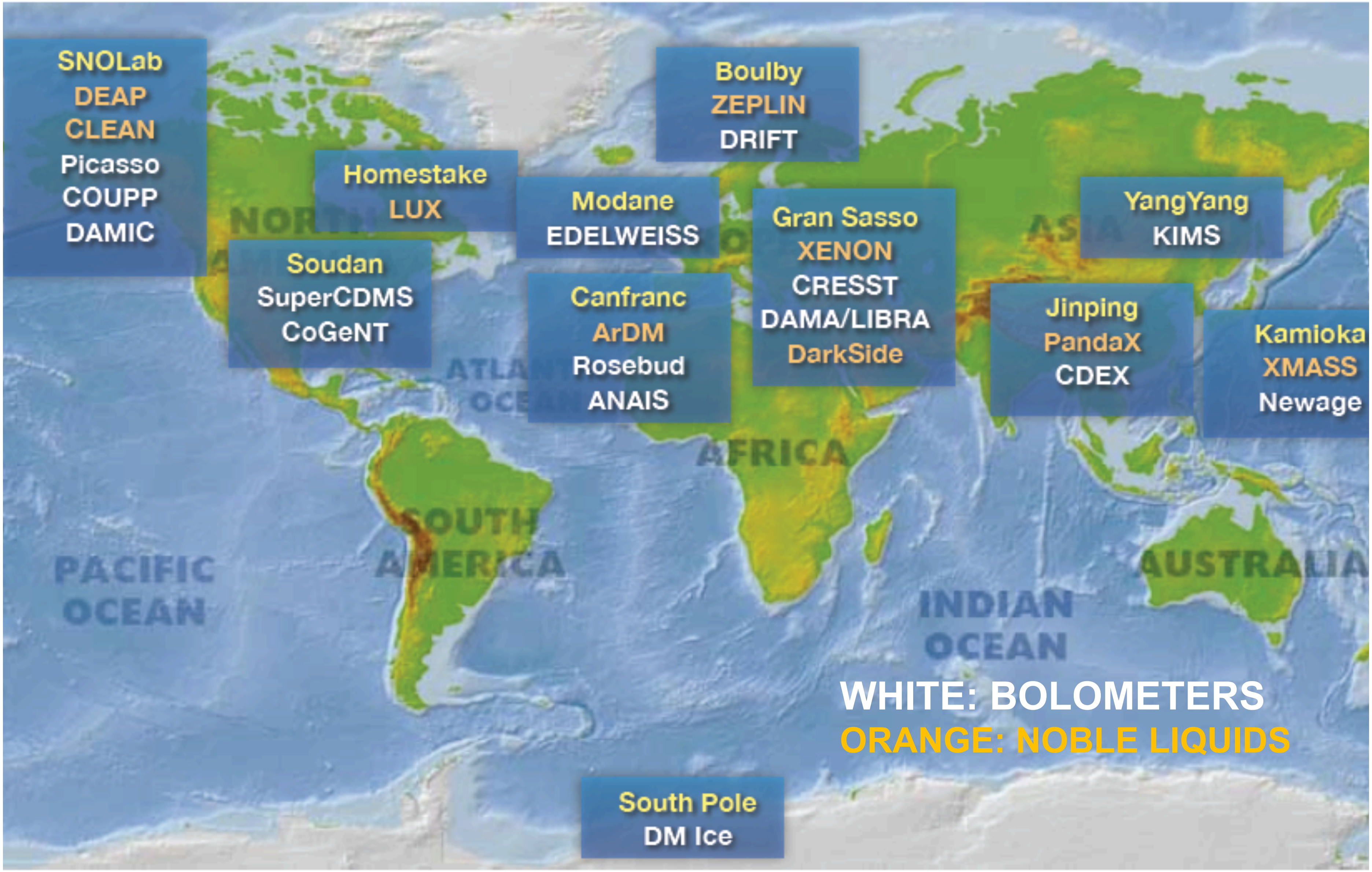


Figure 4. *Dark matter direct detection experiment demographics.*

arXiv:1310.8327

IMPRESSIVE EFFORT TO LOOK FOR WIMPS WORLDWIDE

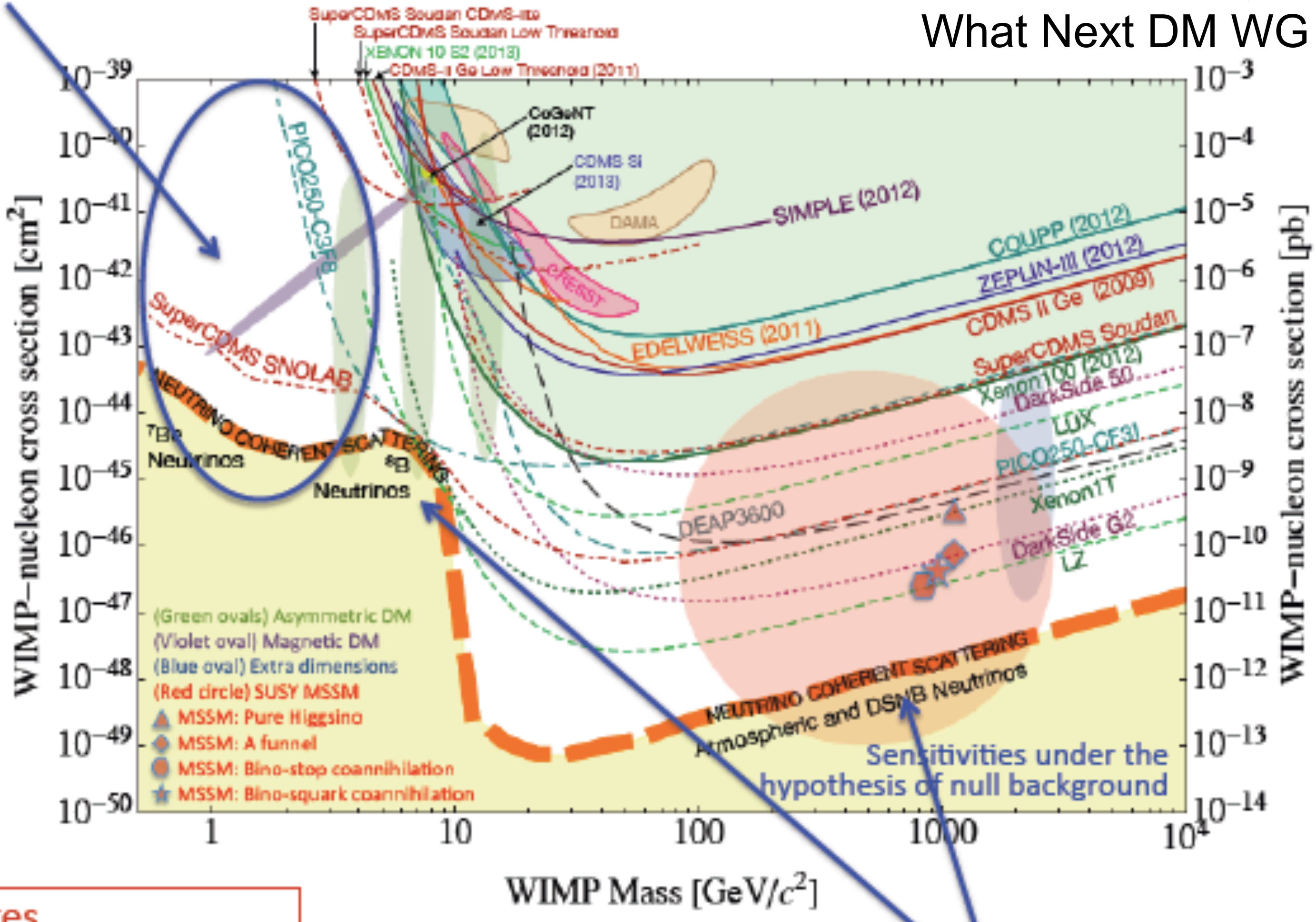


WHITE: BOLOMETERS
ORANGE: NOBLE LIQUIDS

Direct detection

N. FORNENGO,
What Next DM WG 2015

Light WIMPs window



Sensitivities under the hypothesis of null background

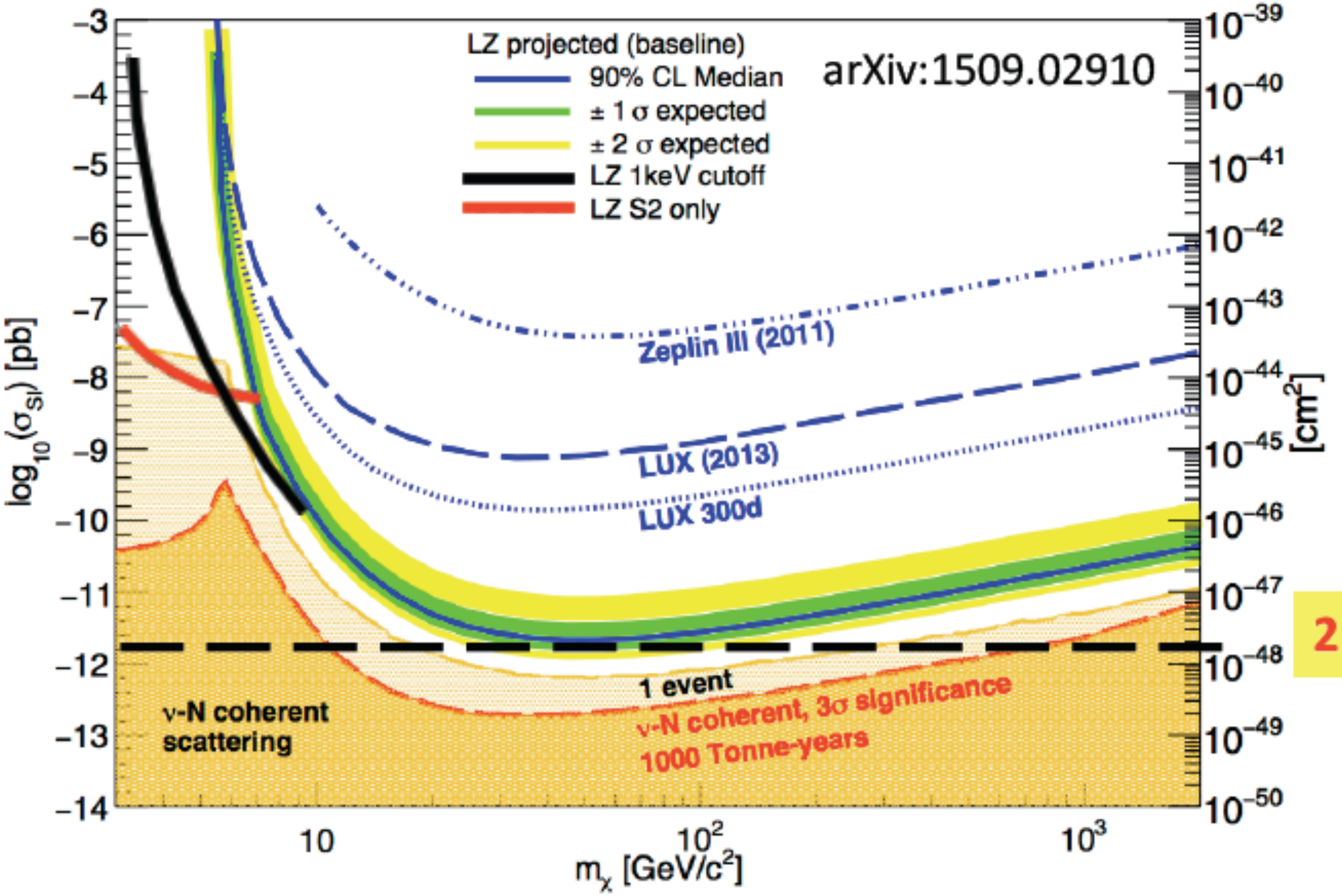
"Neutrino floor"

Signatures
- Annual modulation
- Diurnal modulation
- Directionality

Full set of effective operators (15)

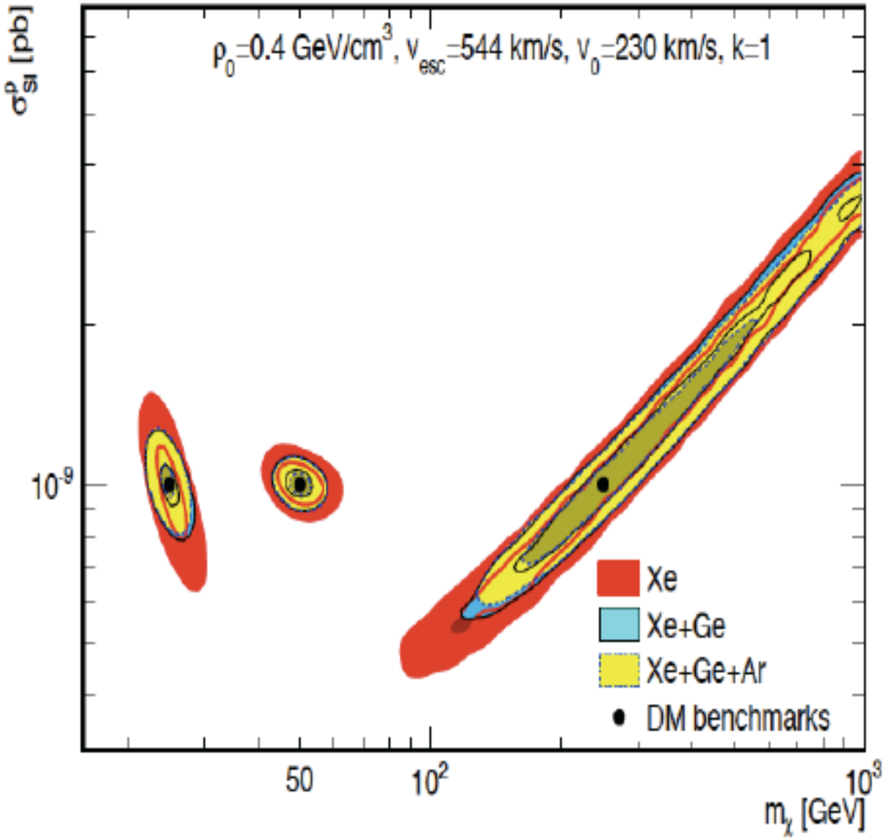
WIMP

- S1+S2 WIMP SI sensitivity: 2 x 10^{-48} cm^2: 5.6t x 1d
- Lower energy threshold: 1 keV
- S2-only: 2.5 e$^-$ (100 photons detected), 1t x 1000d



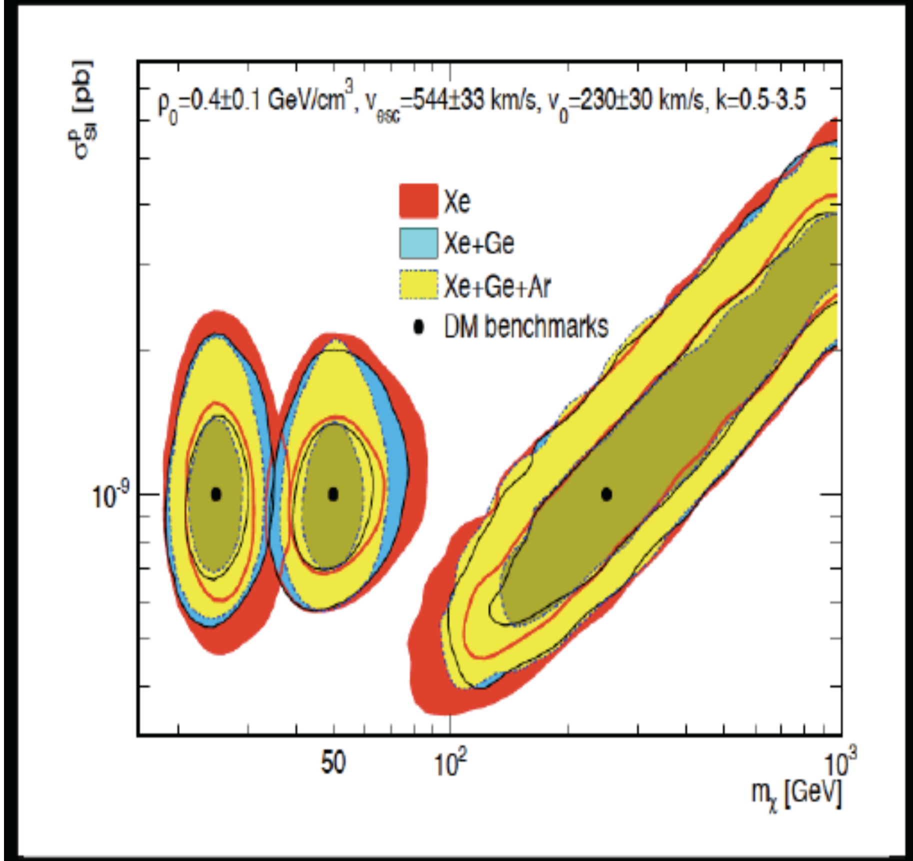
2×10^{-48} cm^2

What do we learn in case of detection? (assuming the newly discovered particles are THE DM

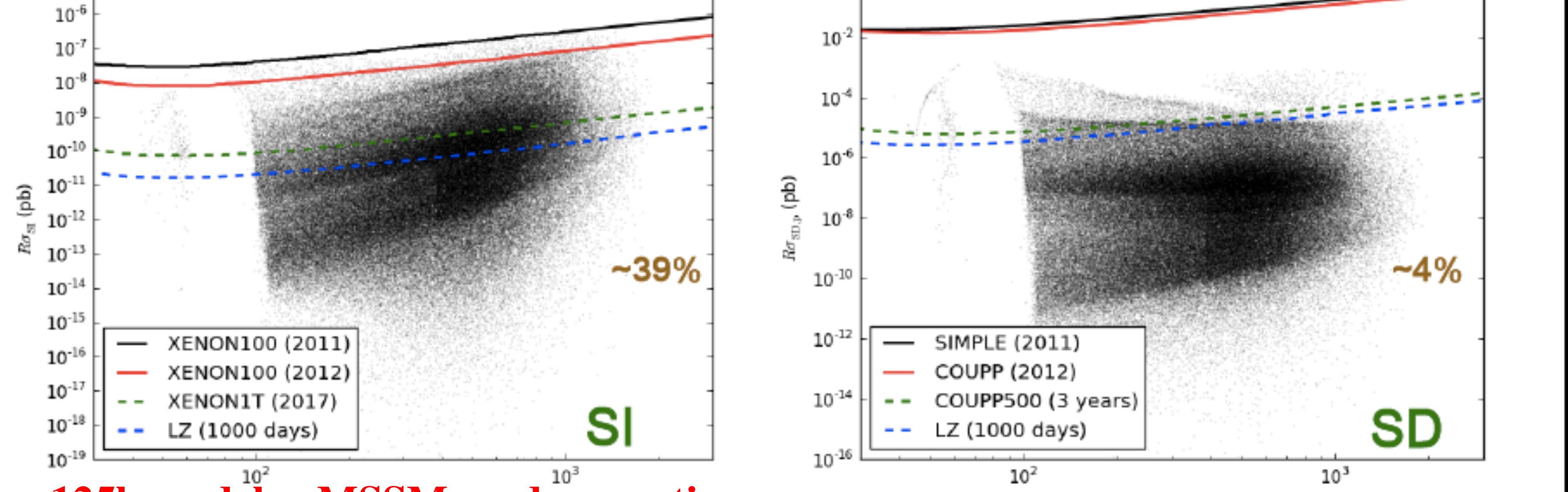


Pato, Baudis, GB, Ruiz, Strigari, Trotta, arXiv:1012.3458

Effect of including
the astrophysical uncertainties

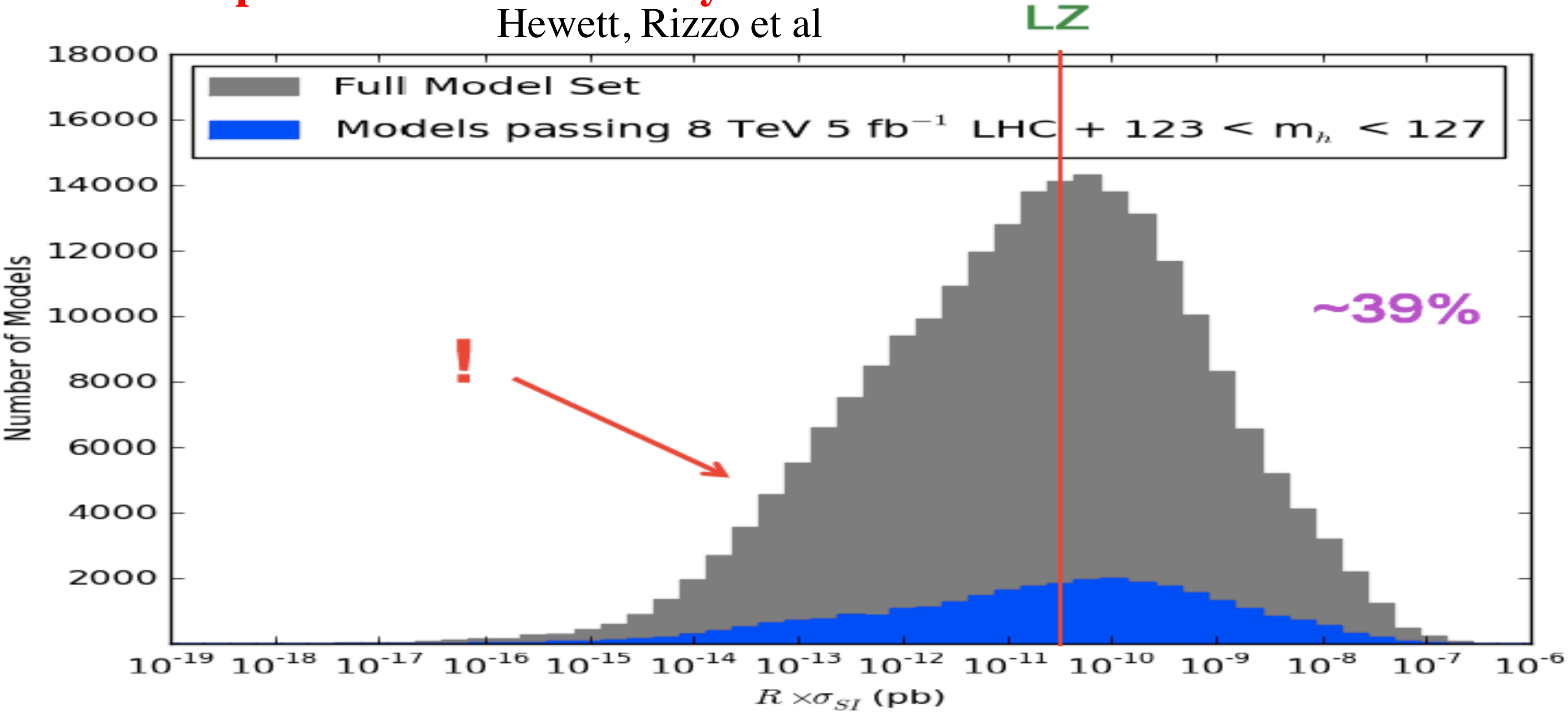


Pato, Baudis, GB, Ruiz, Strigari, Trotta, arXiv:1012.3458

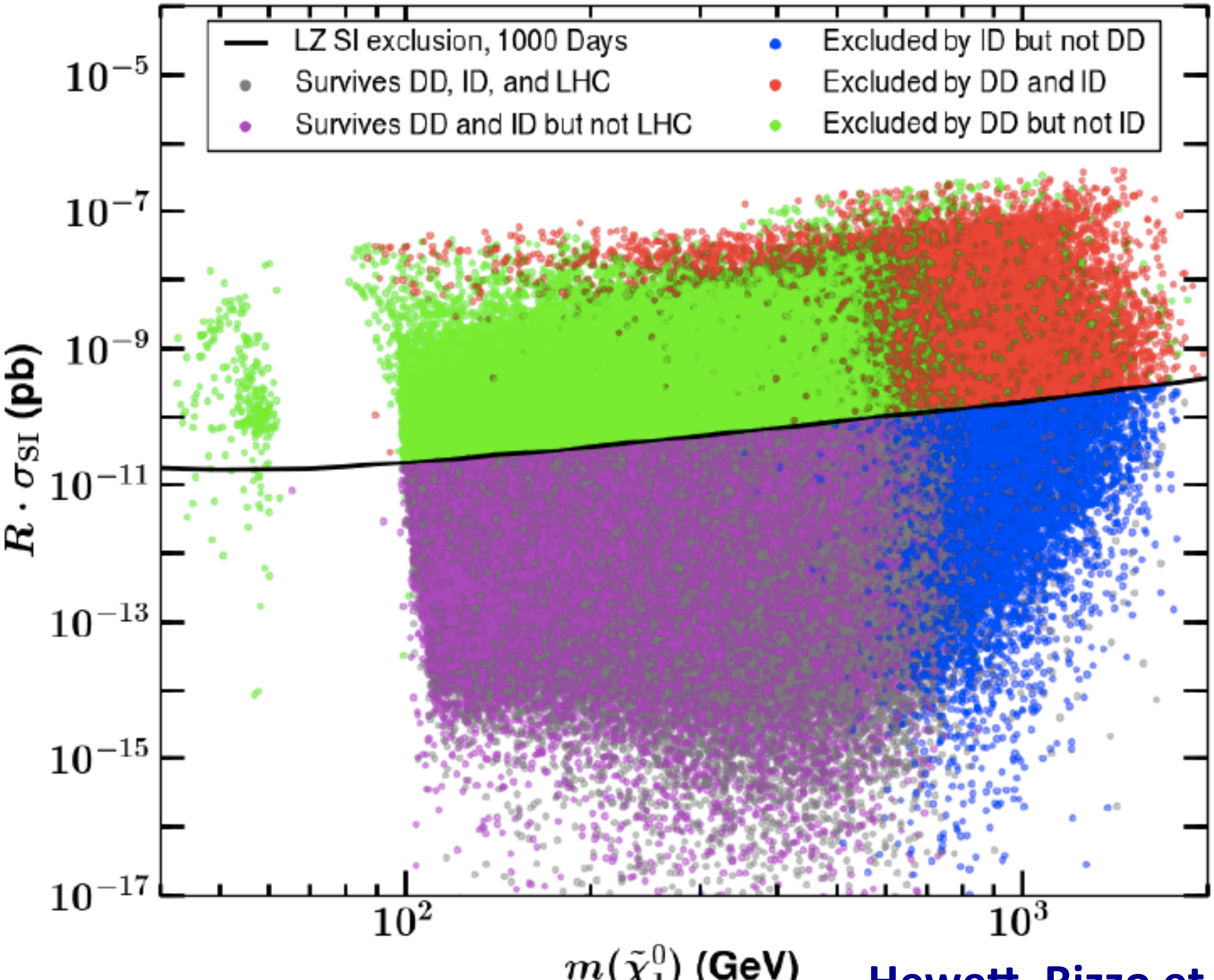


125k models pMSSM under scrutiny

Hewett, Rizzo et al



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



11.4%
29.2%
7.2%
27.5%
24.7%

Hewett, Rizzo et al. 2013

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 …

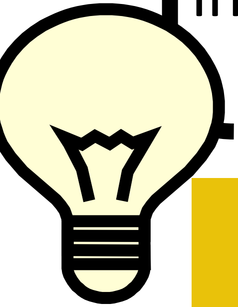
Overall, **in the next few years the APPEC agencies will need to take a decision on**

- **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.**

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

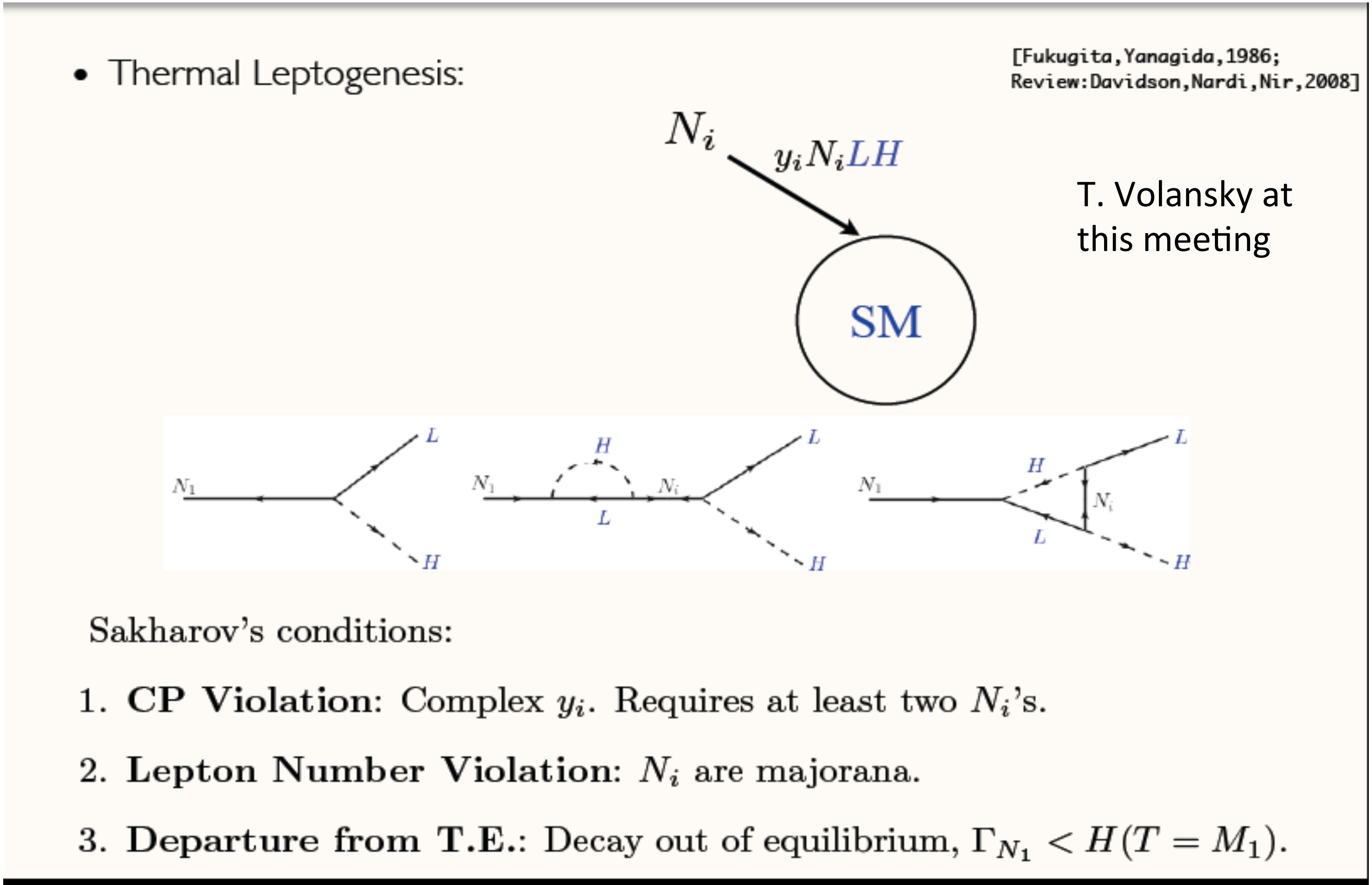


The Energy Scale from the "Theoretical" New Physics

★ ★ ★ **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**

Linking neutrino masses, matter-antimatter-asymmetry and DM



- Thermal Leptogenesis:

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

T. Volansky at this meeting

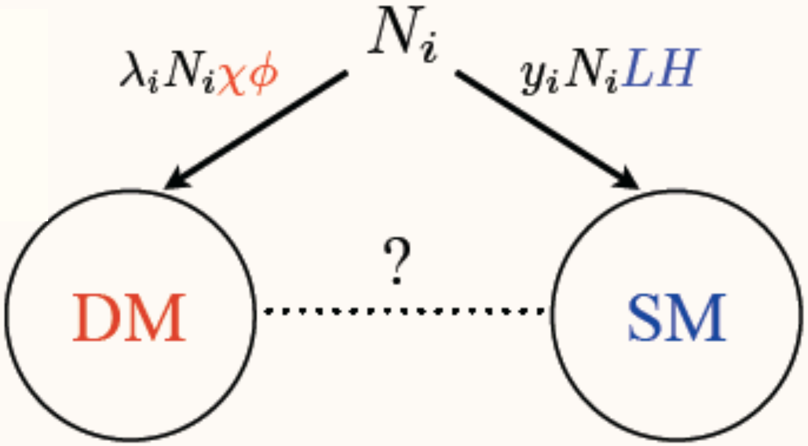
Sakharov's conditions:

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, $\Gamma_{N_1} < H(T = M_1)$.

- Simple scenario: 2-sector leptogenesis.

[Falkowski,Ruderman,TV, 2011]

$$\Omega_{\rm DM} \simeq 5\Omega_b$$

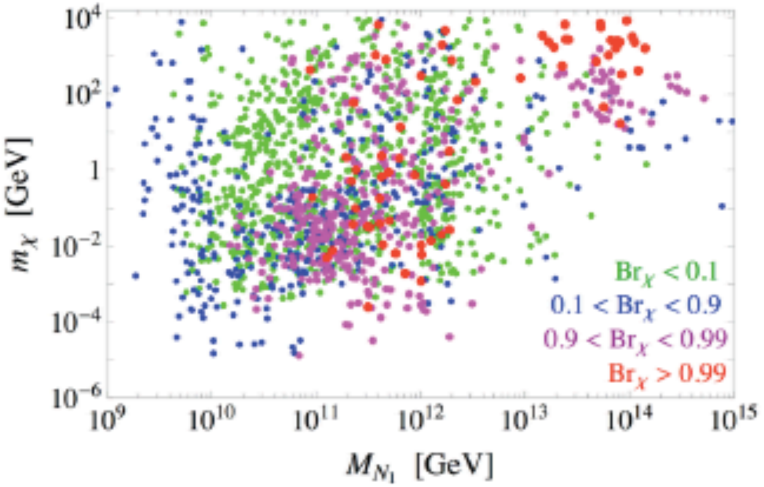


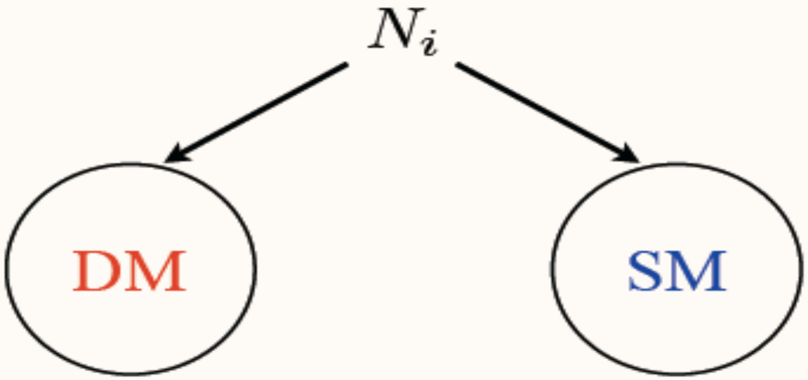
T. Volansky

- The number densities in the two sectors depend on the ratio of branching fractions and washout effects.

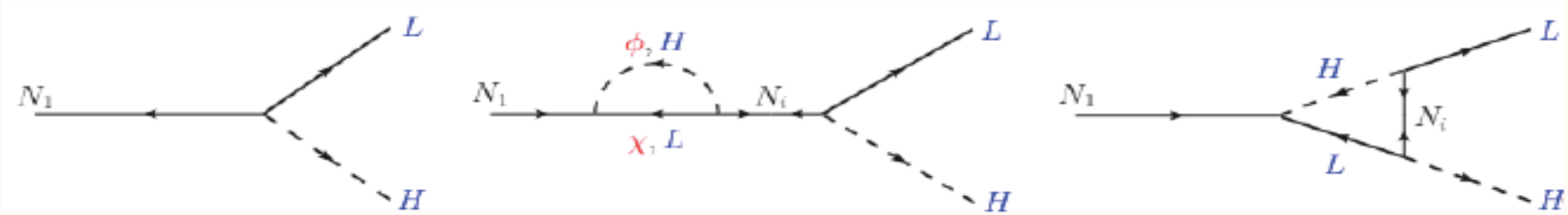
Wide range of DM masses:

keV - 100 TeV

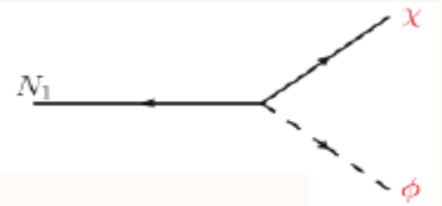




- When N decays it produces the baryon asymmetry through CP violation (loops):



- Symmetric DM produced through tree level:



- Consequently, DM number density is generically larger than number baryon density.

- To have the same mass density, $\Omega_i \propto m_i n_i$, this requires $m_{DM} < m_{proton}$

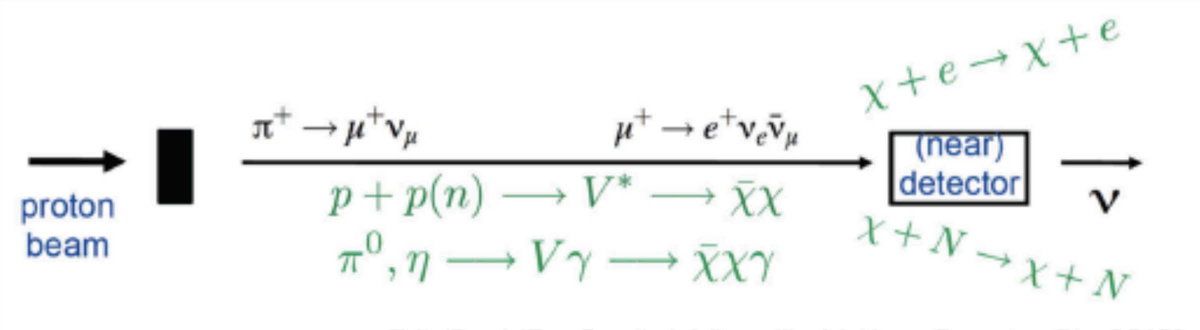
See also, **Weakly Interacting Sub-eV Particles**, WISPs by **Redondo** at this meeting

Light DM.

[Falkowski,Kuflik,Levi,TV, work in progress]

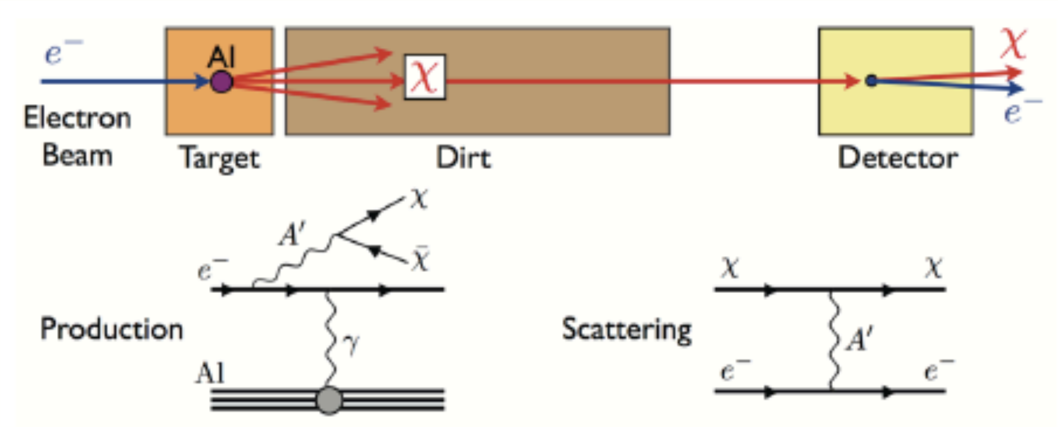
Beam-dump Experiments: A Dark Matter Beam

Neutrino Experiments



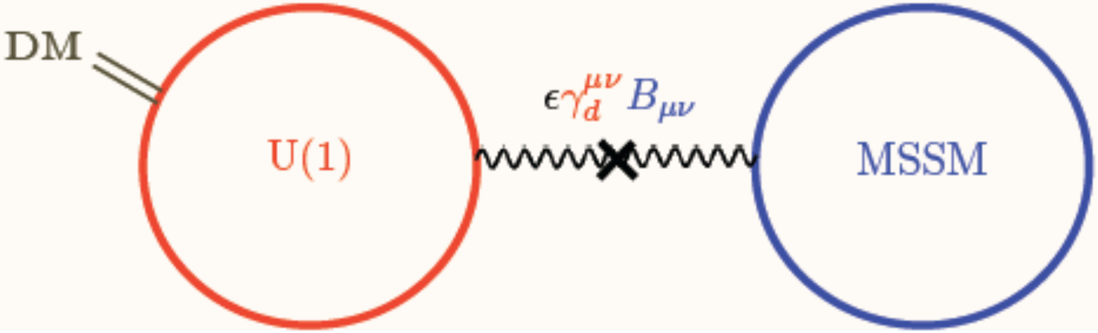
[MiniBooNE + Batell, deNiverville, McKeen, Pospelov, Ritz 2012]

Electron Beam-dumps

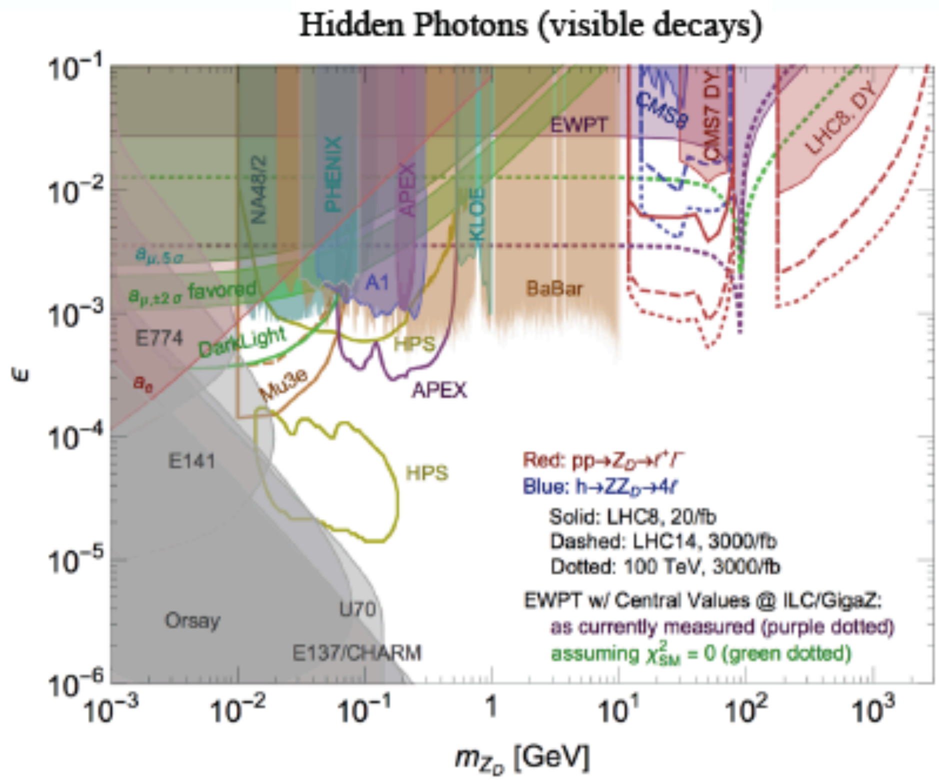


[Batell, Essig, Surujon 2014]

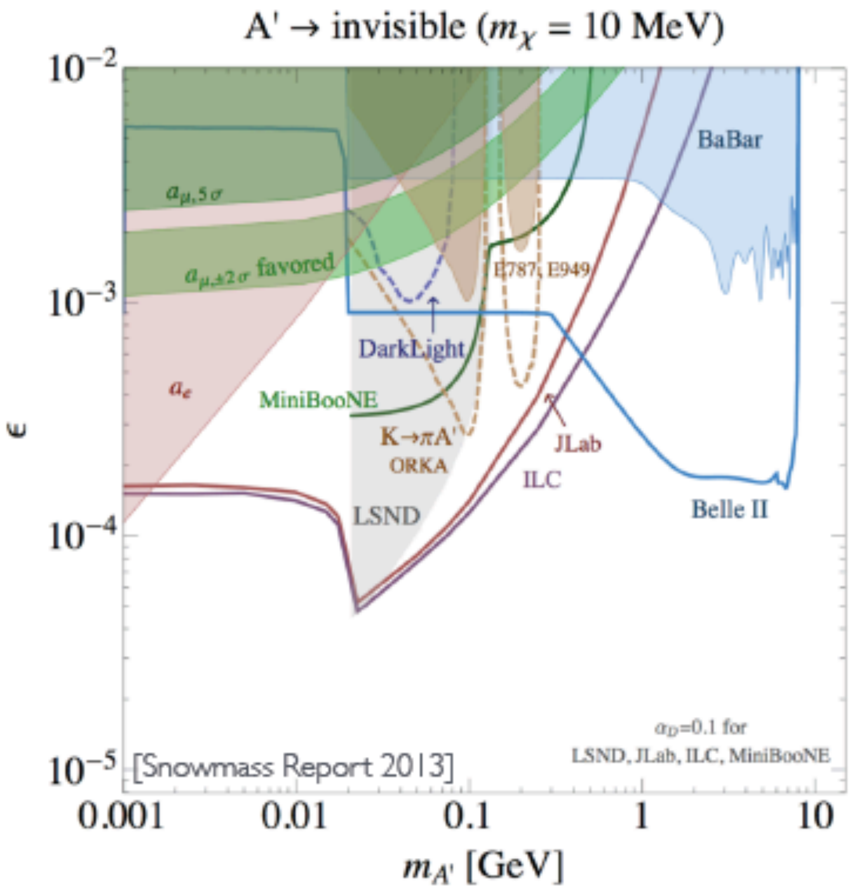
Collider and Beam-dumps: Selected Results



T. Volansky

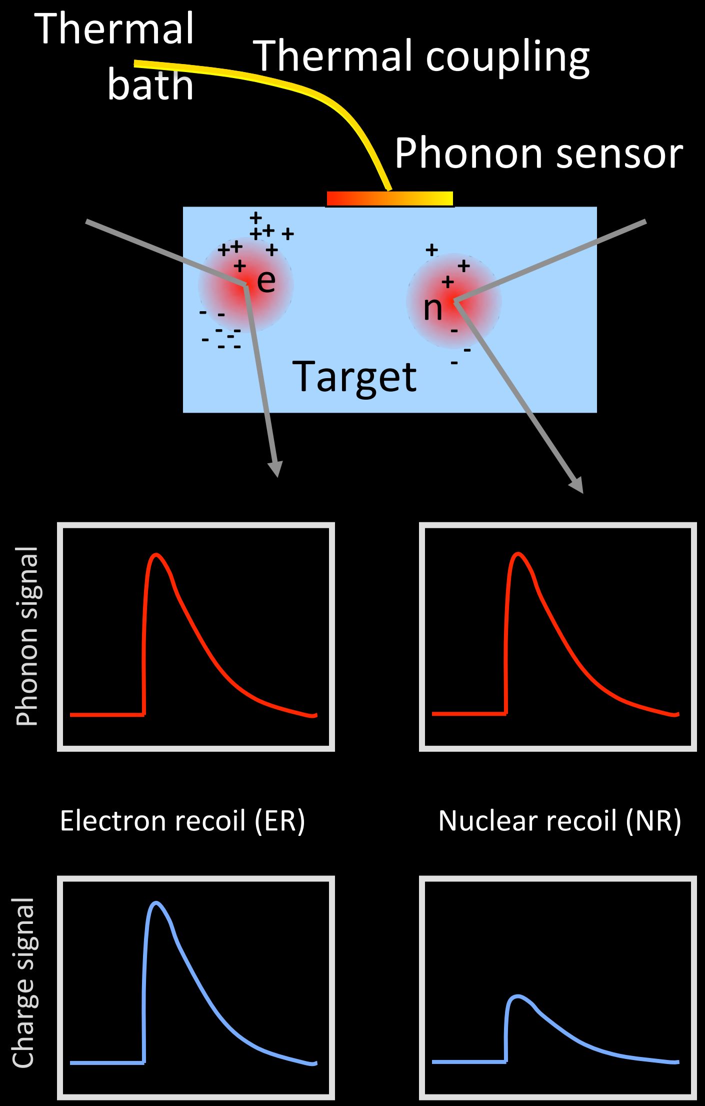


[Curtin, Essig, Gori, Shelton, 2014]

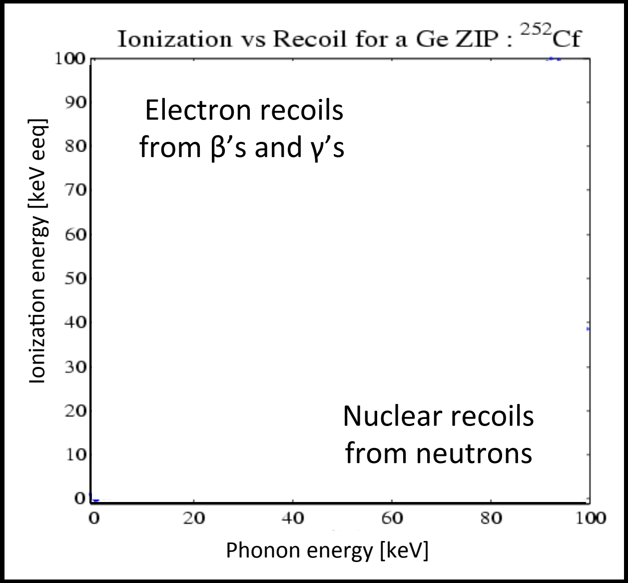


[Snowmass Report 2013]

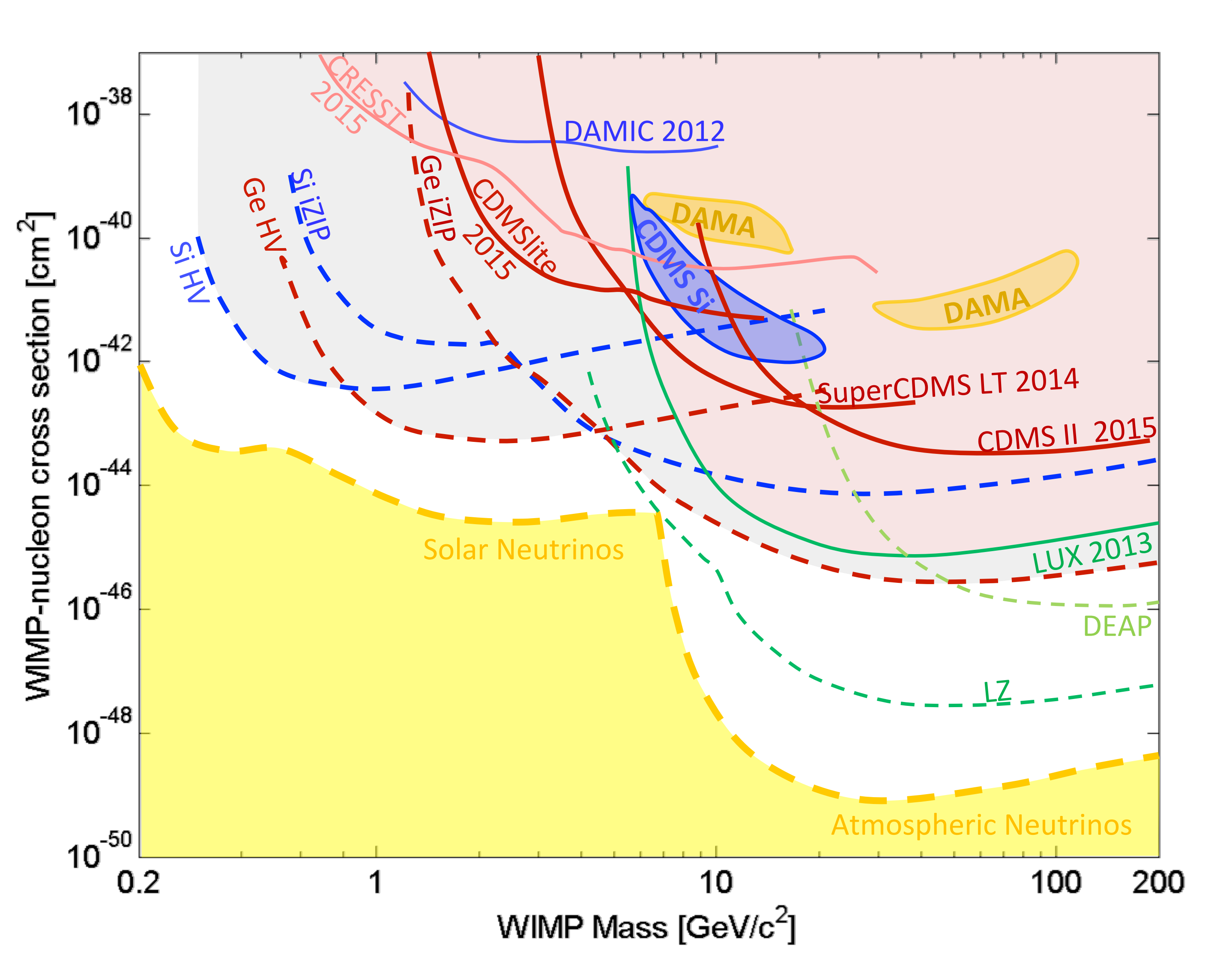
Cryogenic Dark Matter Detection



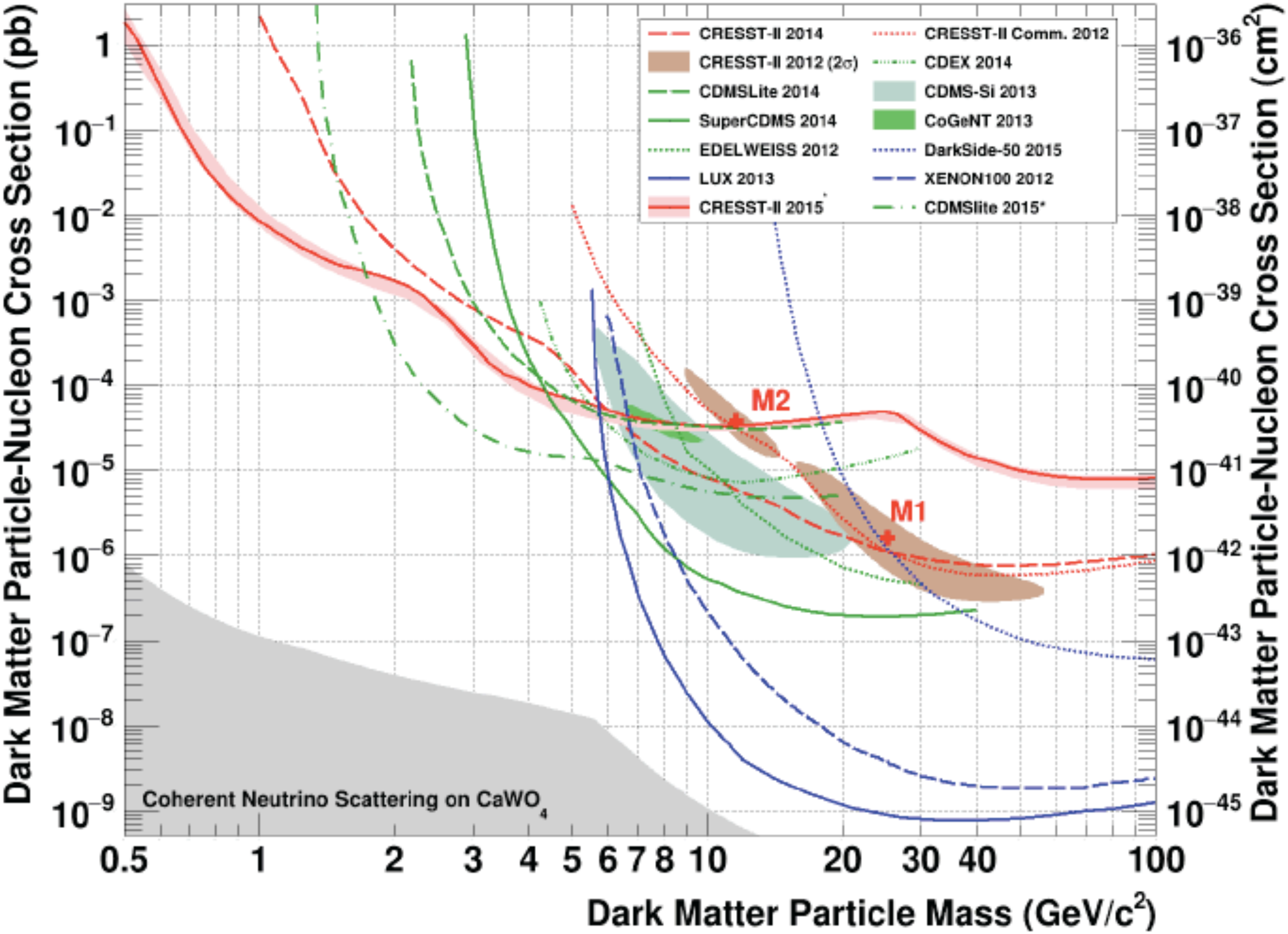
- Phonon signal (single crystal): measures energy deposition
- Ionization/scintillation signal: quenched for nuclear recoils (lower signal efficiency)
- Combination: efficient rejection of electron recoil background



SuperCDMS at SNOLAB Goal Sensitivity

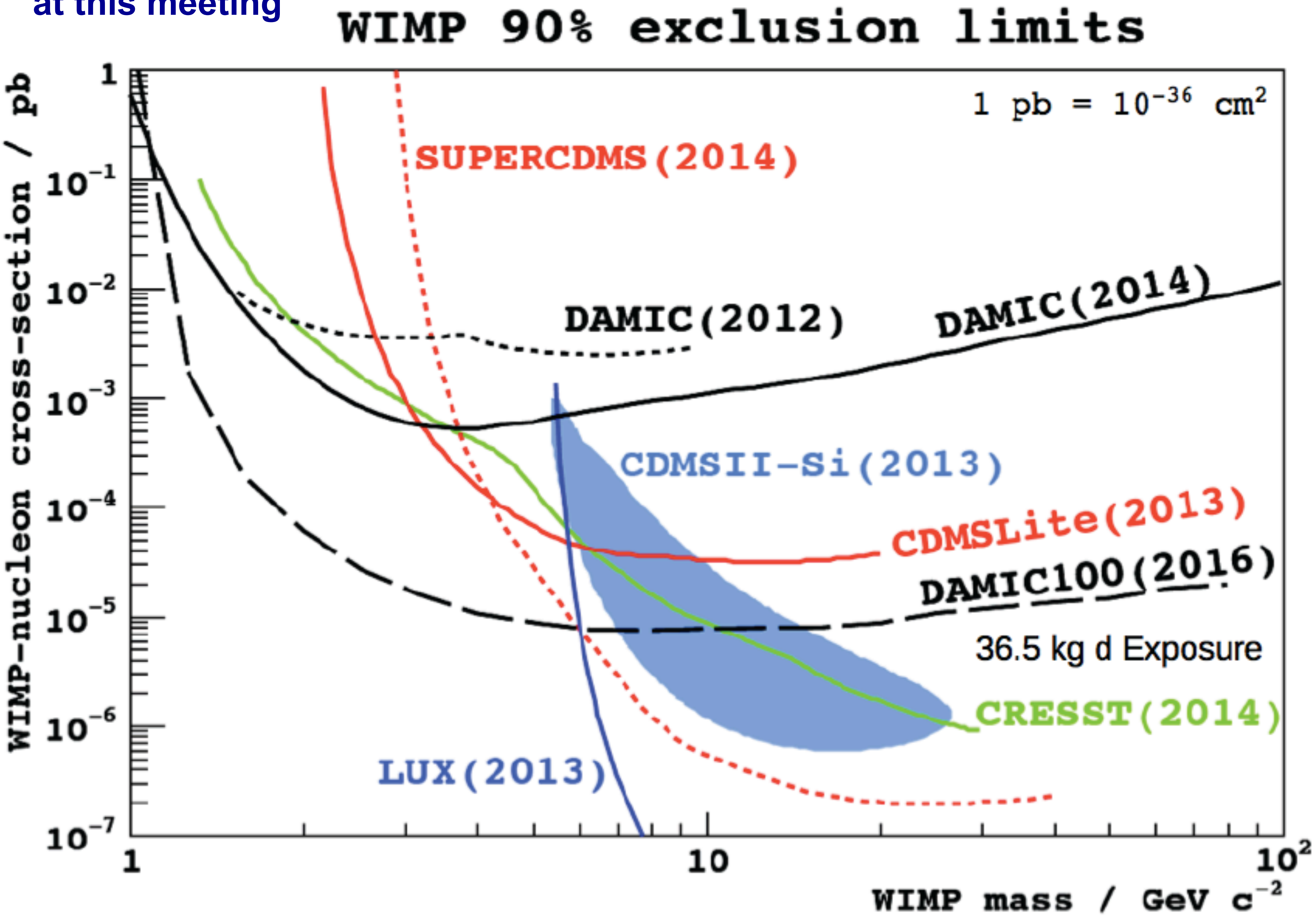


Current Status of Direct Dark Matter Searches



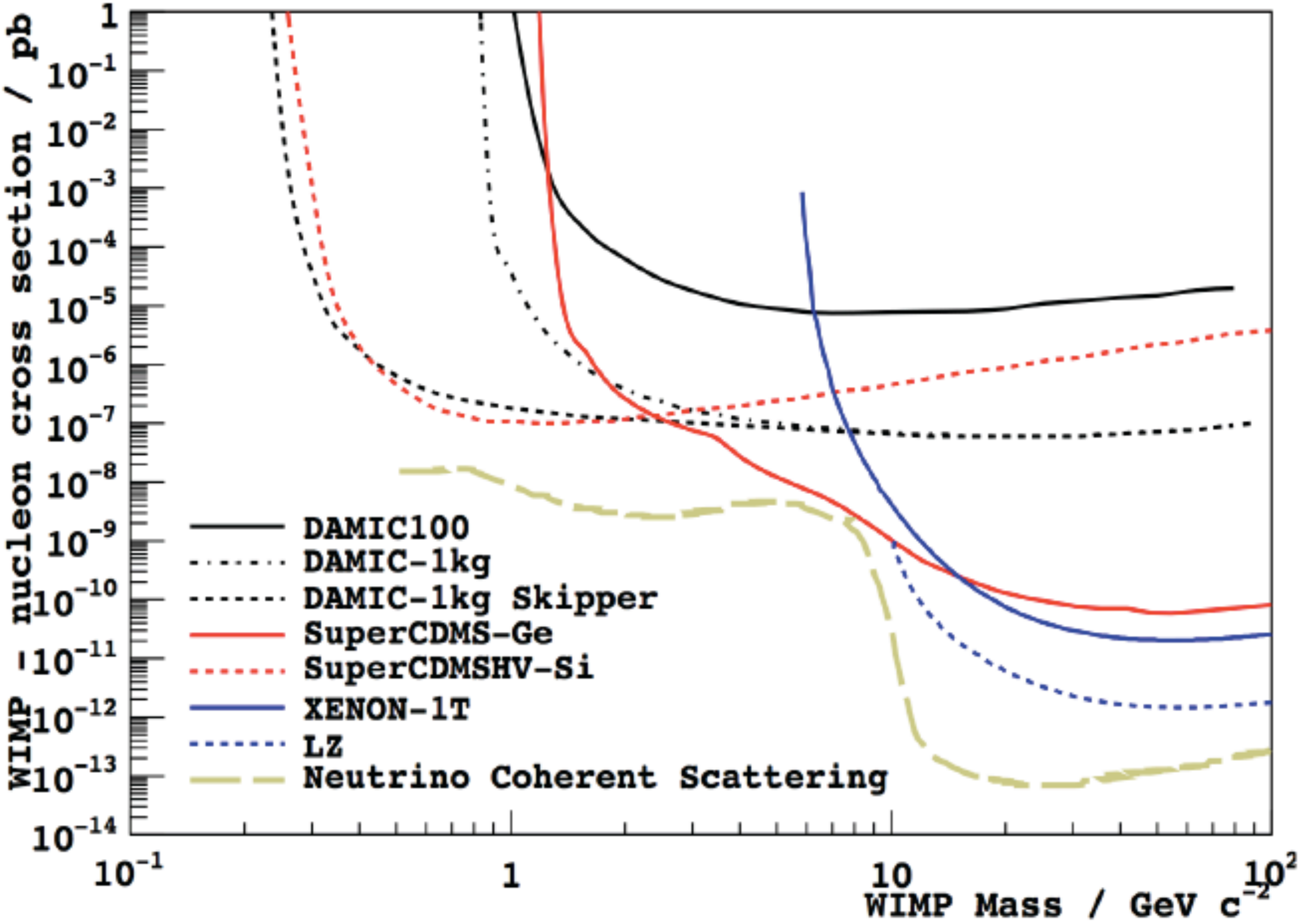
Ben Kilminster
at this meeting

DAMIC sensitivity

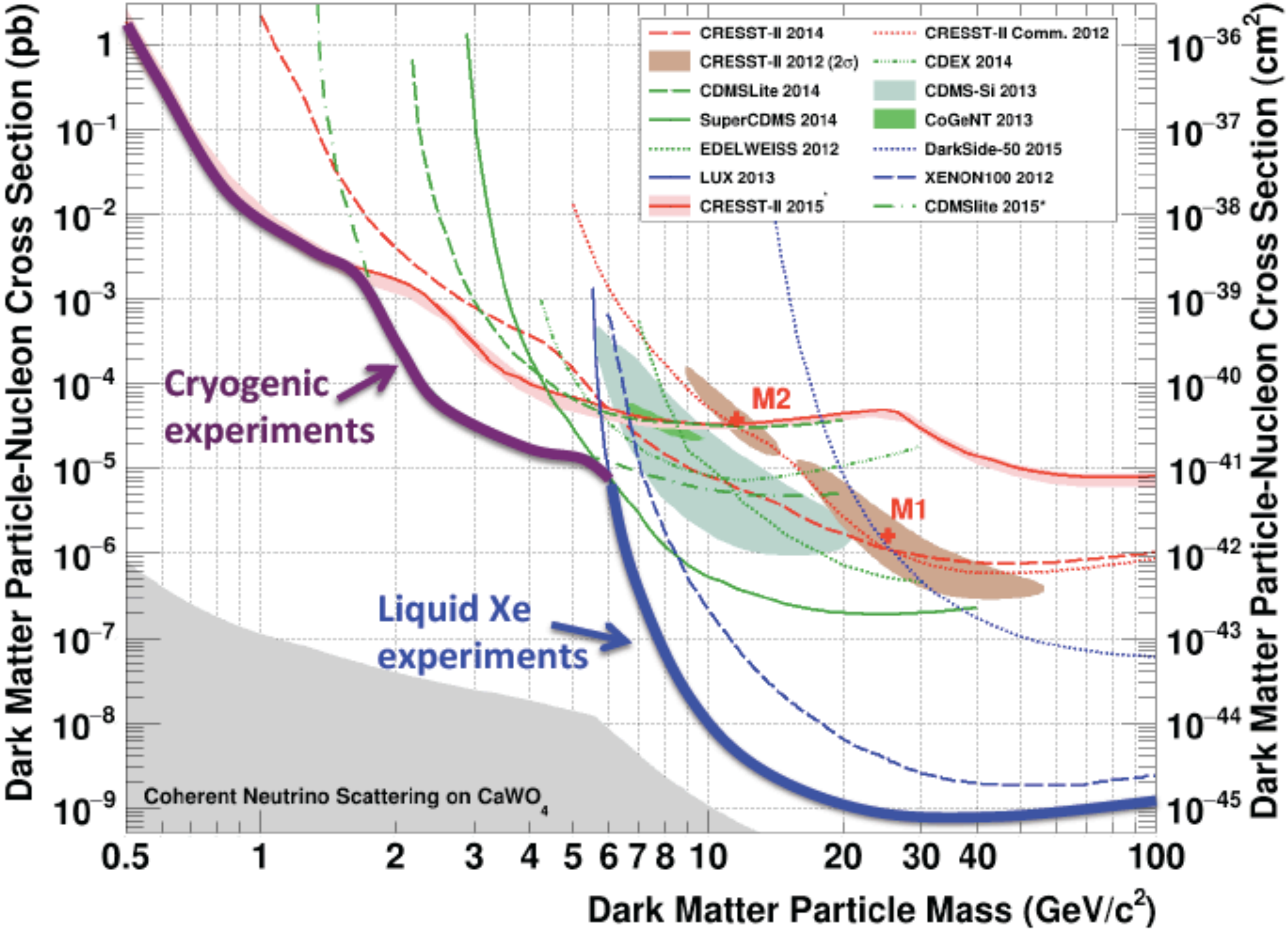


DAMIC 1 kg

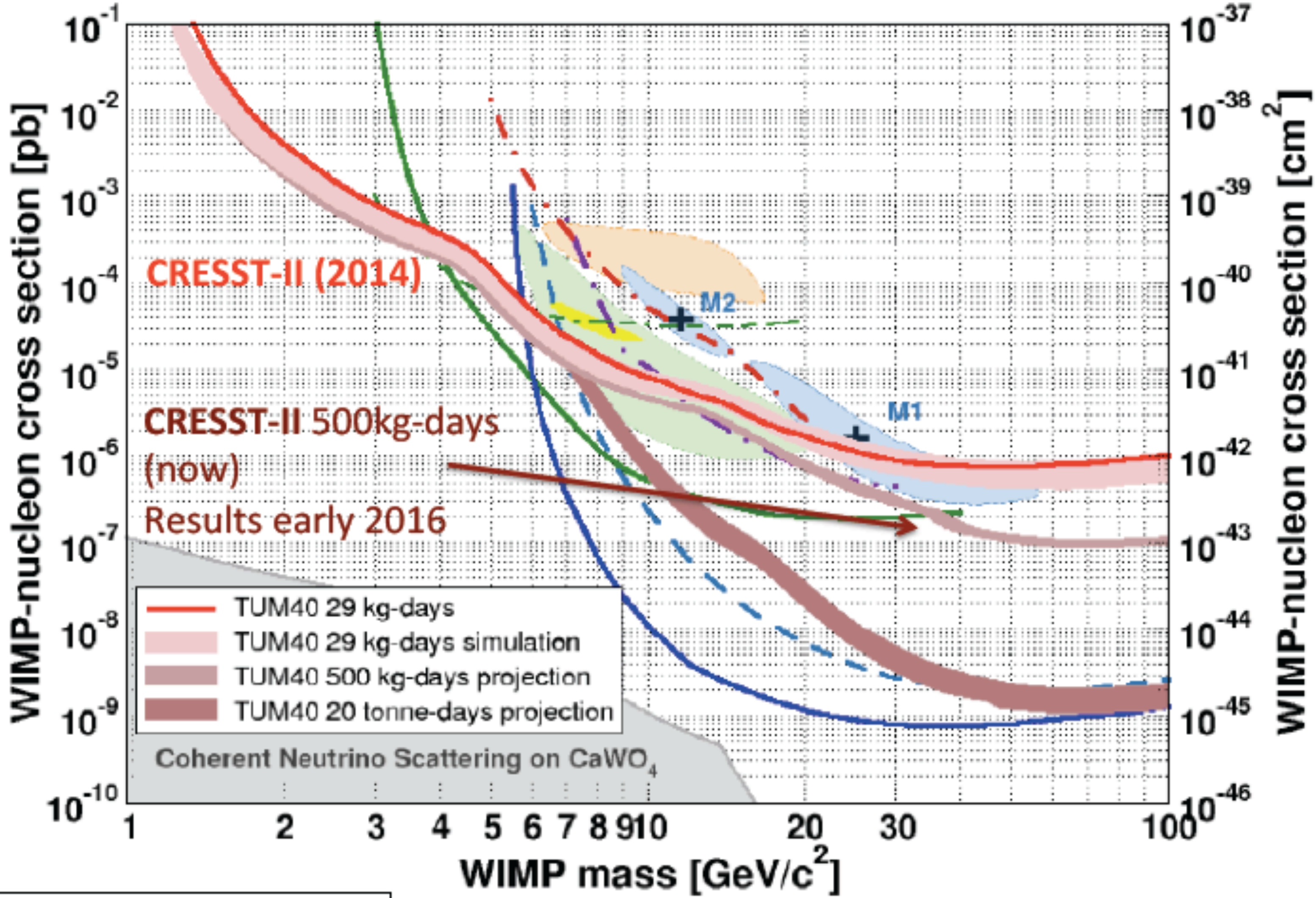
Potential of a 1 kg Si detector



Current Status of Direct Dark Matter Searches



Final Data Release: Projections

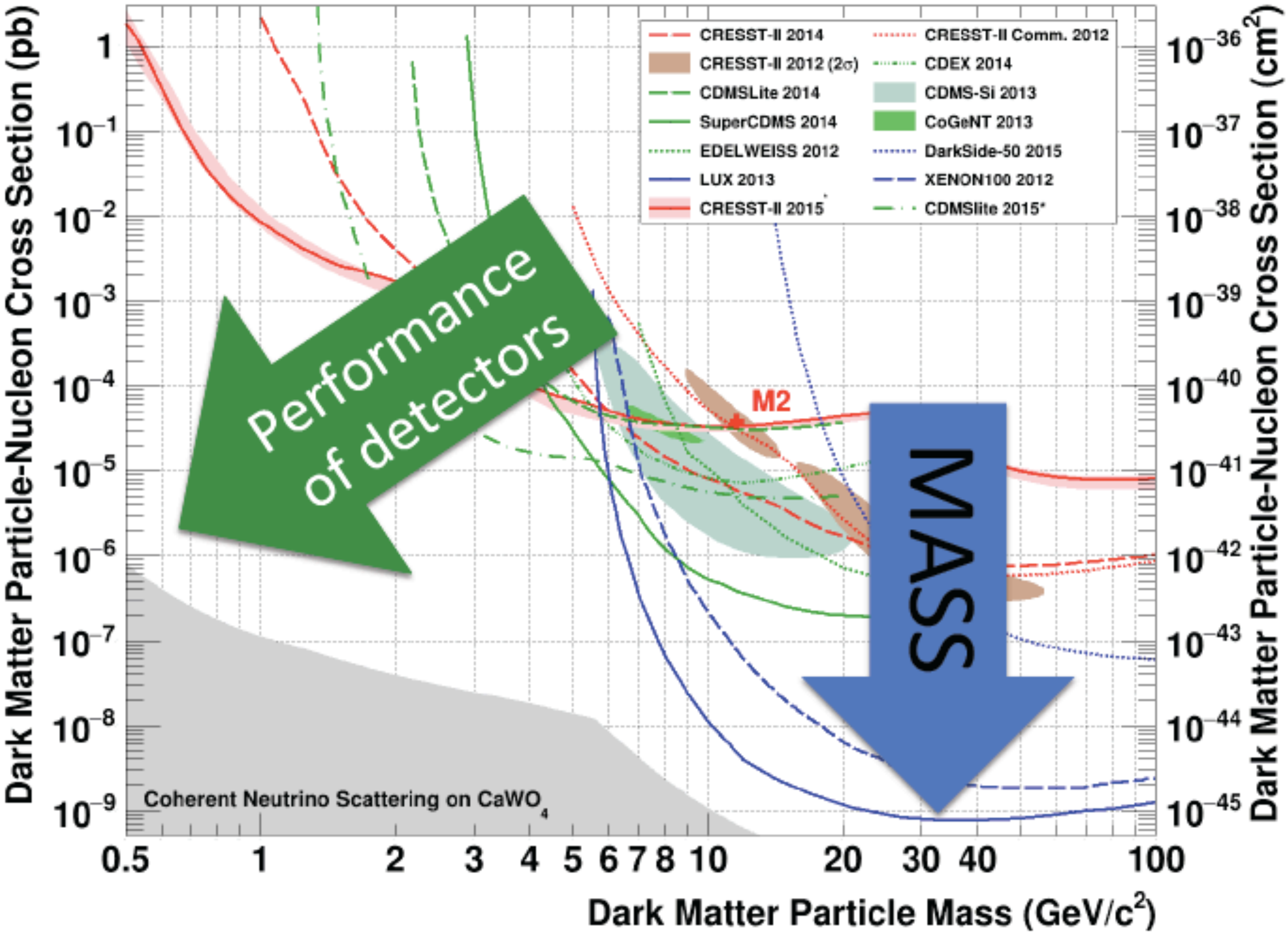


CRESST-II (2014)

CRESST-II 500kg-days
(now)
Results early 2016

G. Angloher et al. arXiv:1503.08065

Future of Dark Matter Searches



CRESST-III: Low-Mass Dark Matter Search

Straight-forward approach for near future: **CRESST-III** Phase 1

Status quo

m = 250g
V = 32x32x40 mm^3

Phonon threshold: $E_{th} \lesssim 500$eV

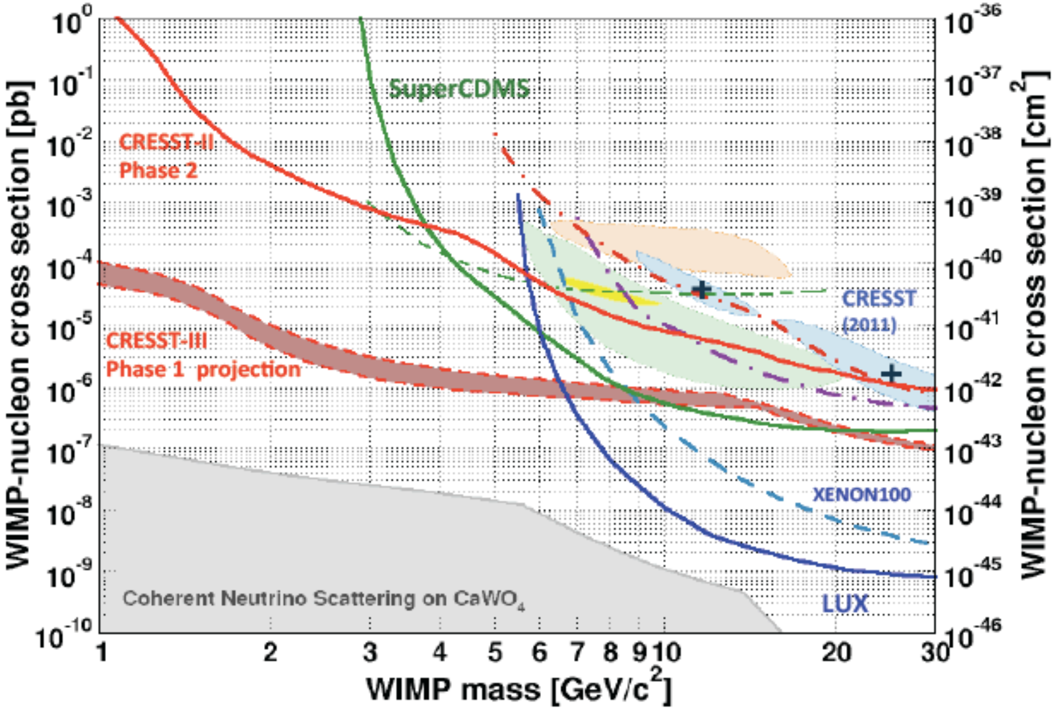
improvement by a factor of 5-10

Light-detector res.: $\sigma \approx 5$ eV

CRESST-III Phase 1

Assumptions:

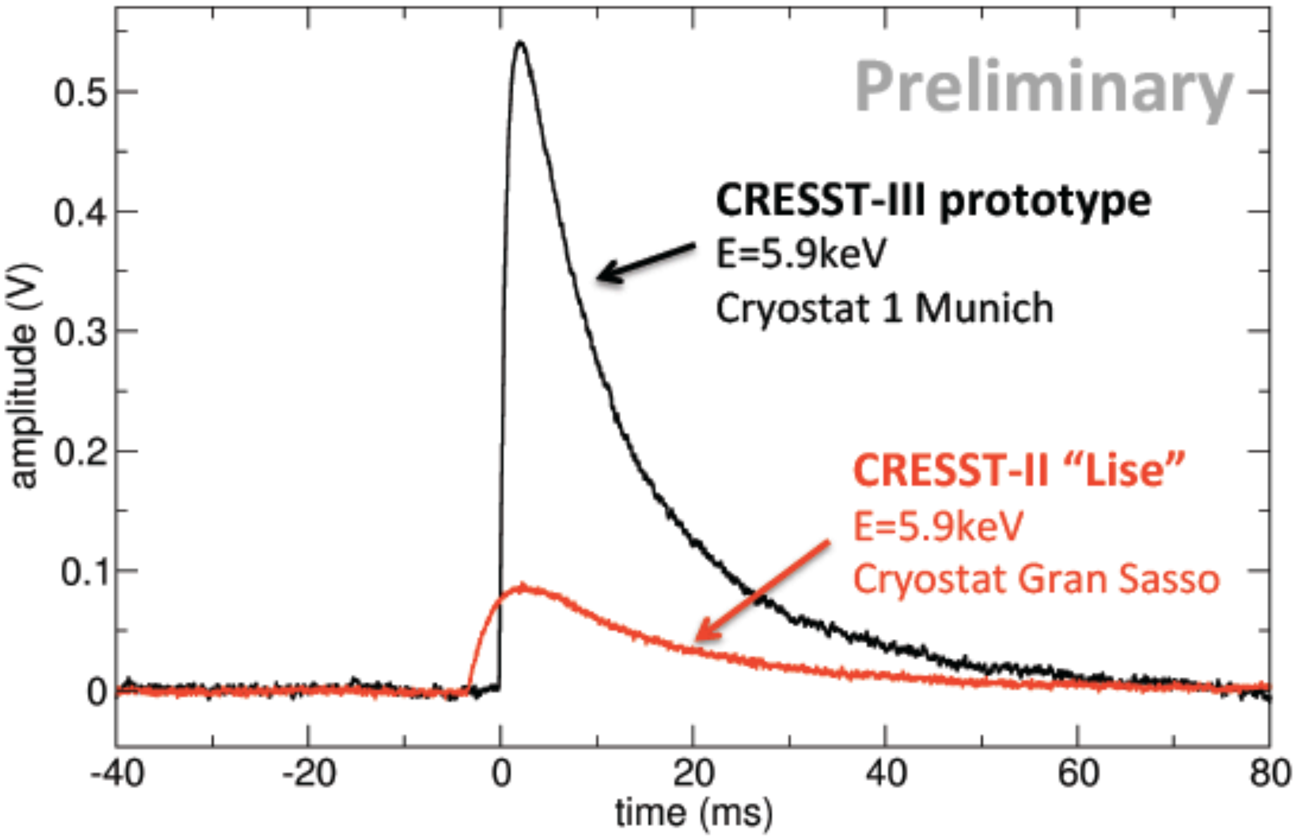
- 24g $CaWO_4$ crystal
- **E_{th} = 100eV**
- Light detector improved by factor 2 (due to smaller volume)
- 2x more detected light: due to thin crystal
- **CRESST-II radiopurity**



See: CRESST collab. G. Angloher et al. arXiv:1503.08065

10 x 24g detectors operated for one year ≈ **50 kg-days** (net)

First Results of CRESST-III Detector



Promising results:

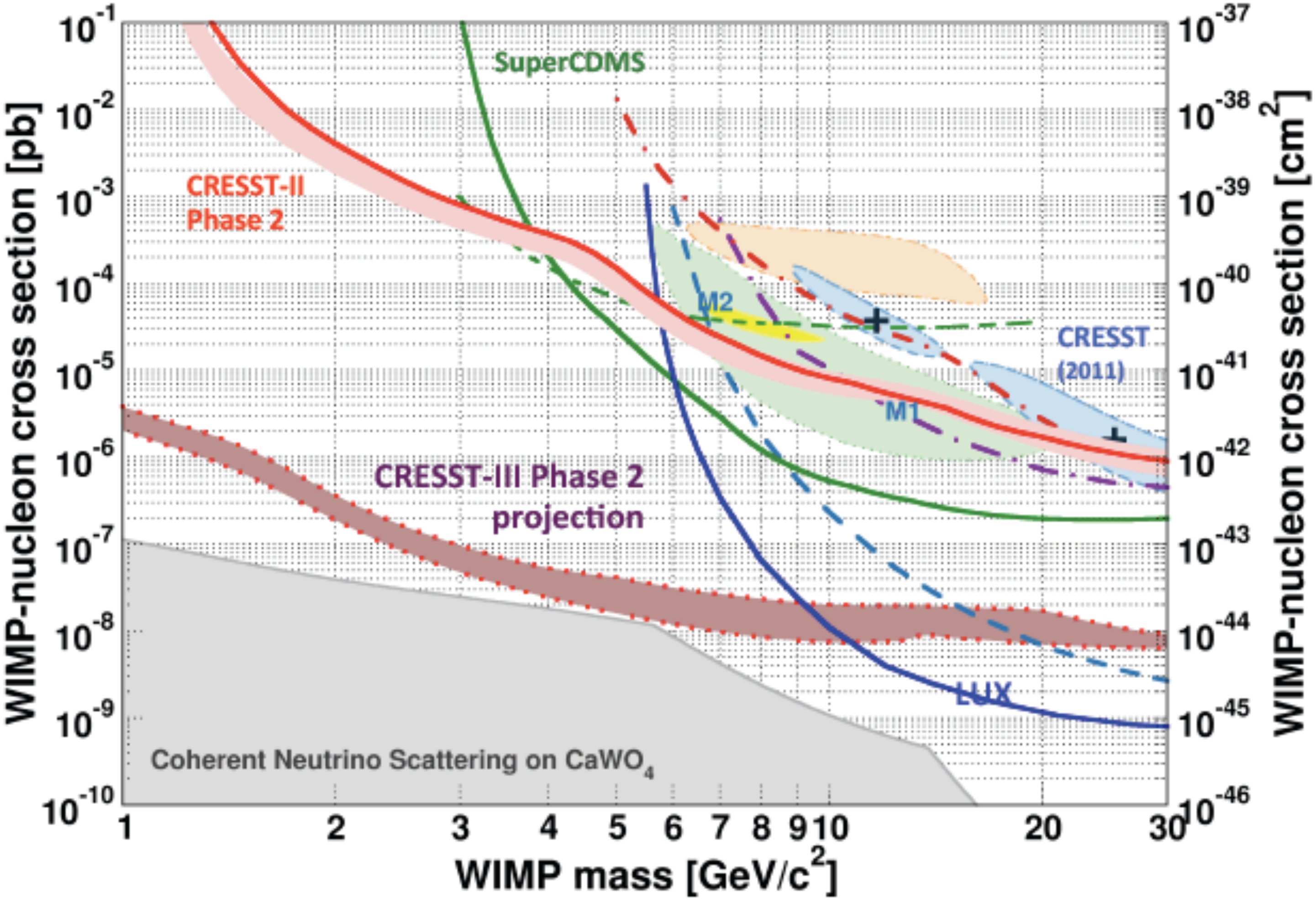
Improvement by **factor 6.2** compared to best CRESST-II detector (E_{th} = 298eV)

→ Baseline noise @GS 1.8-3.0mV RMS

→ **Threshold: E_{th}= 45-60eV**

Design goal (E_{th}=100eV) for **CRESST-III** Phase 1 exceeded!

CRESST-III Phase 2



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

CRESST-III: Low-Mass Dark Matter Search

Straight-forward approach for near future: **CRESST-III** Phase 1

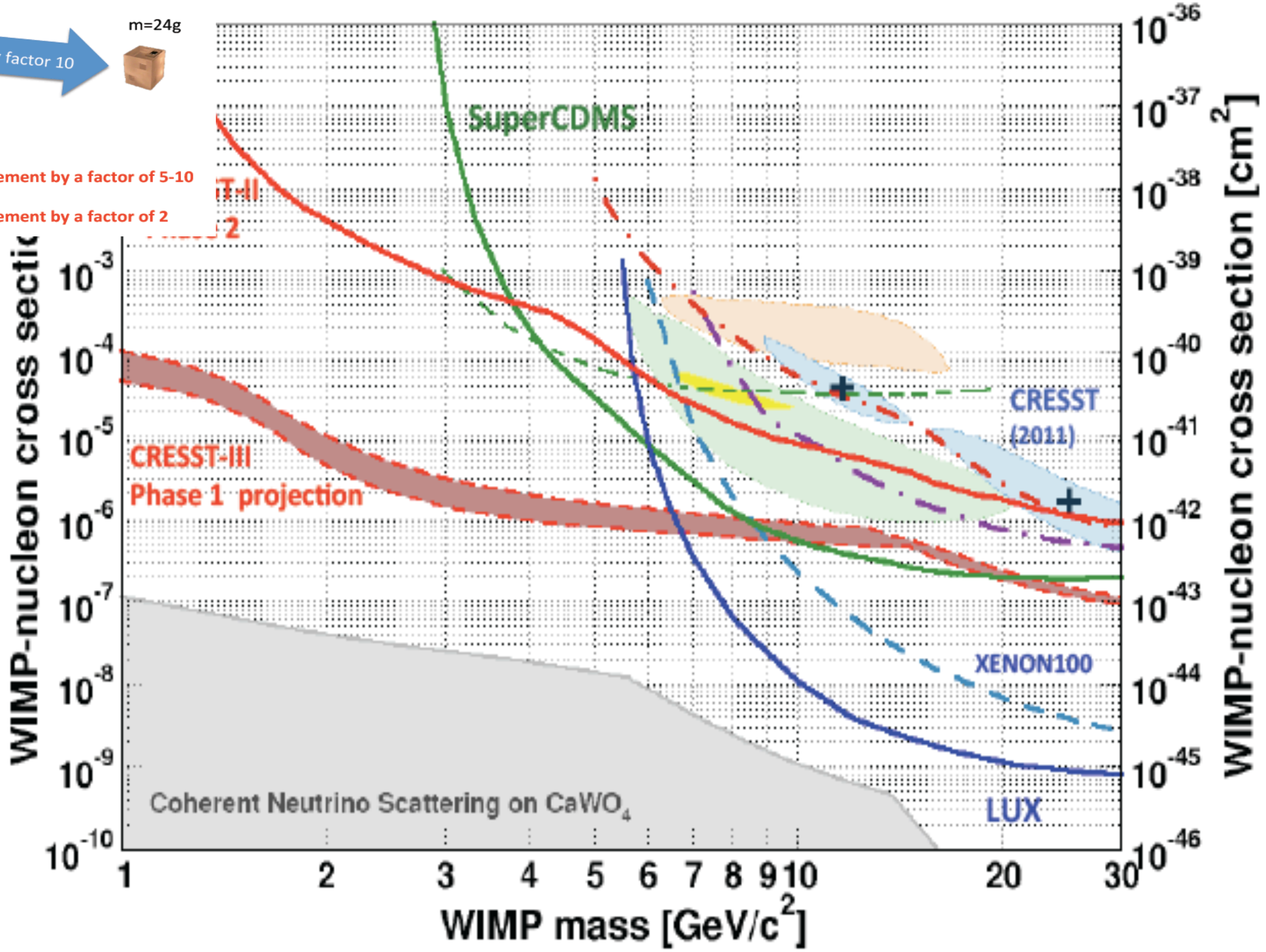
Status quo

m = 250g
V = 32x32x40 mm³

Phonon threshold:	$E_{th} \lesssim 500$eV	improvement by a factor of 5-10
Light-detector res.:	$\sigma \approx 5$ eV	improvement by a factor of 2

ST-III Phase 1

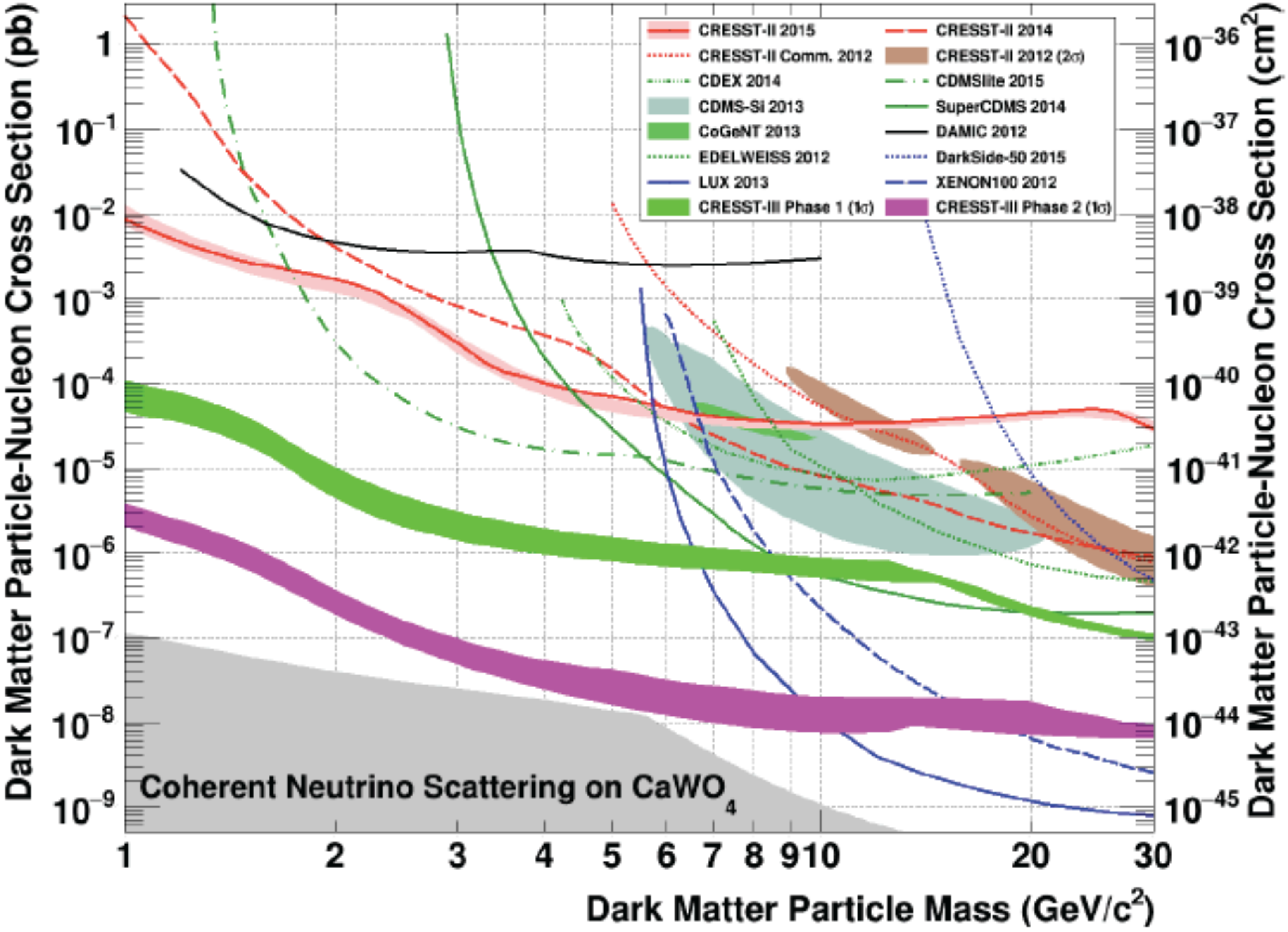
- **E_{th} = 100eV**
- Light detector improved by factor 2 (due to smaller volume)
- 2x more detected light: due to thin crystal
- **CRESST-II radiopurity**



10 x 24g detectors operated for one year ≈ **50 kg-days** (net)

See: CRESST collab. G. Angloher et al. arXiv:1503.08065

Projections for CRESST-III



Hunting for
GRAVITATIONAL WAVES:
DISCOVERY AND ASTRONOMY

2^{nd} generation detectors:

Advanced Virgo, Advanced LIGO

GOAL:

sensitivity 10x better →

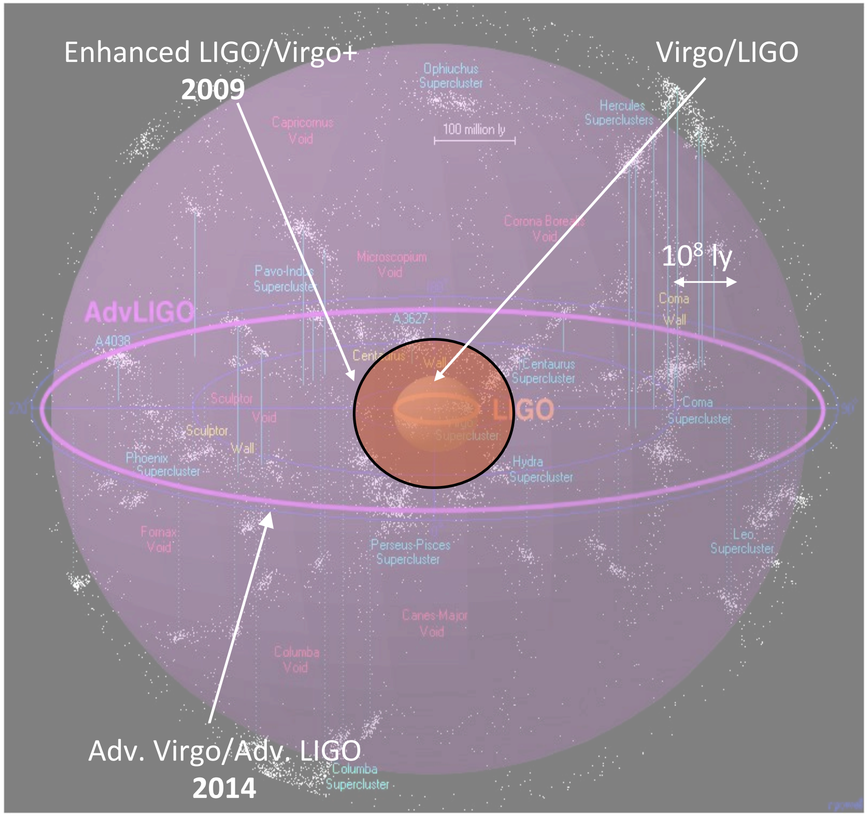
look 10x further →

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

**Advanced LIGO has already started taking data,
Adv Virgo is going to start in a few months –
the 2 collaborations are working together**

LISA Pathfinder is going to be launched in a few hours from now …

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, new prospects in the low-mass DM
- **Neutrinoless double β** → ν mass degenerate region; enter IH region
- **SBN** → sterile ν ?
- **Gravitational waves** → discovery
- **DE**: BOSS →DESI; DES → LSST
- **CMB**: final PLANCK; B-modes of the polariz.+ black-body spectrum : EU exps. QUBIC, LSPE, QIJOTE + many others on

The importance of being **SMALL**

My recommendation: beware the temptation of going ONLY for LARGE enterprises

The protective shield of large, Big Science: too big to fail!

Richness of small, “unorthodox” projects based more on clever ideas than on muscular, managerial strength!

- 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

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** problem could be our black-body and photoelectric problems of the beginning of the XXI century