Physics beyond the Standard Model 1

CHANG-SEONG MOON

CENTRE FOR HIGH ENERGY PHYSICS (CHEP), KYUNGPOOK NATIONAL UNIVERSITY (KNU)

Caveat

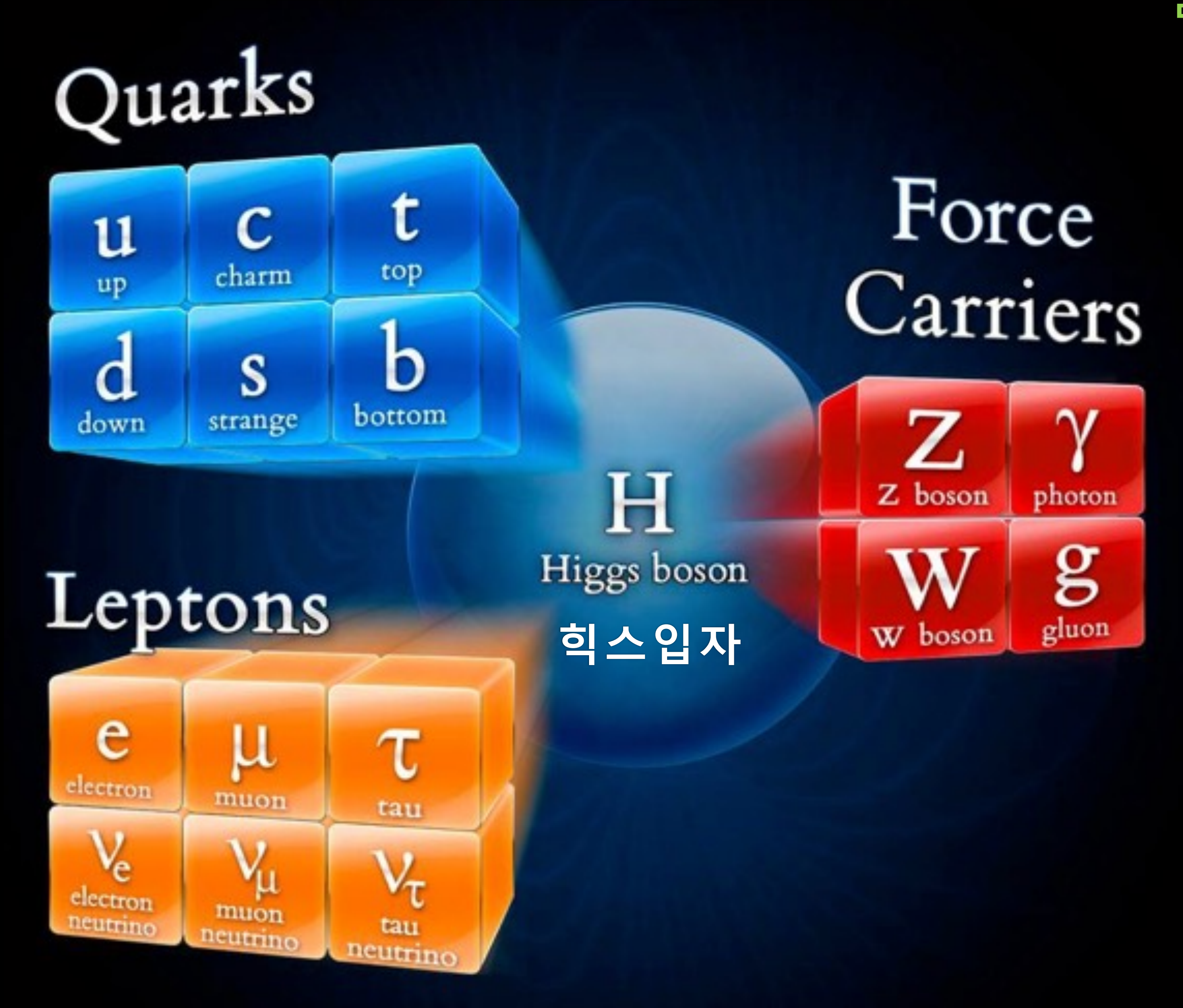
Stolen most of my slides from Jessie Shelton, Teresa Marrodán Undagoitia, Zach Marshall and others.

입자물리학의 표준 모형

2012년 힉스입자의
발견으로 표준모형 완성

쿼크

경입자



힘 매개 입자
(게이지보존)

6개의 쿼크
6개의 경입자
4개의 게이지보존
1개의 힉스보존

SUCCESS OF THE STANDARD MODEL (SM)

- Predictive power and efficiency.
  - More experimental observables than free parameters
- Unification of electromagnetic and weak forces
  - Tested to high accuracy with EWPTs (electroweak precision tests)
- CKM mechanism confirmed as dominant source of flavour decays
  - from BaBar, Belle I+II, LHCb experiments
- Higgs boson observed with ”reasonable” mass value
  - from LHC experiments

PROBLEMS OF THE STANDARD MODEL

- Origin of flavor
  - Why three generations?
  - Origin of hierarchical Yukawa couplings?
- CP violation
- SM does not include gravity
- The hierarchy problem
- Does not provide a viable Dark Matter candidate
- Dark Energy

ORIGIN OF MATTER

- tiny asymmetry between matter and antimatter:

$$\frac{n_p - n_{\bar{p}}}{n_\gamma} \approx 6 \times 10^{-10}$$

- baryogenesis requires (Sakharov):
  - baryon number violation
  - CP violation
  - departure from thermal equilibrium
- Not satisfied in SM! (* but heavy RH neutrinos might fit the bill?)

THE HIERARCHY PROBLEM

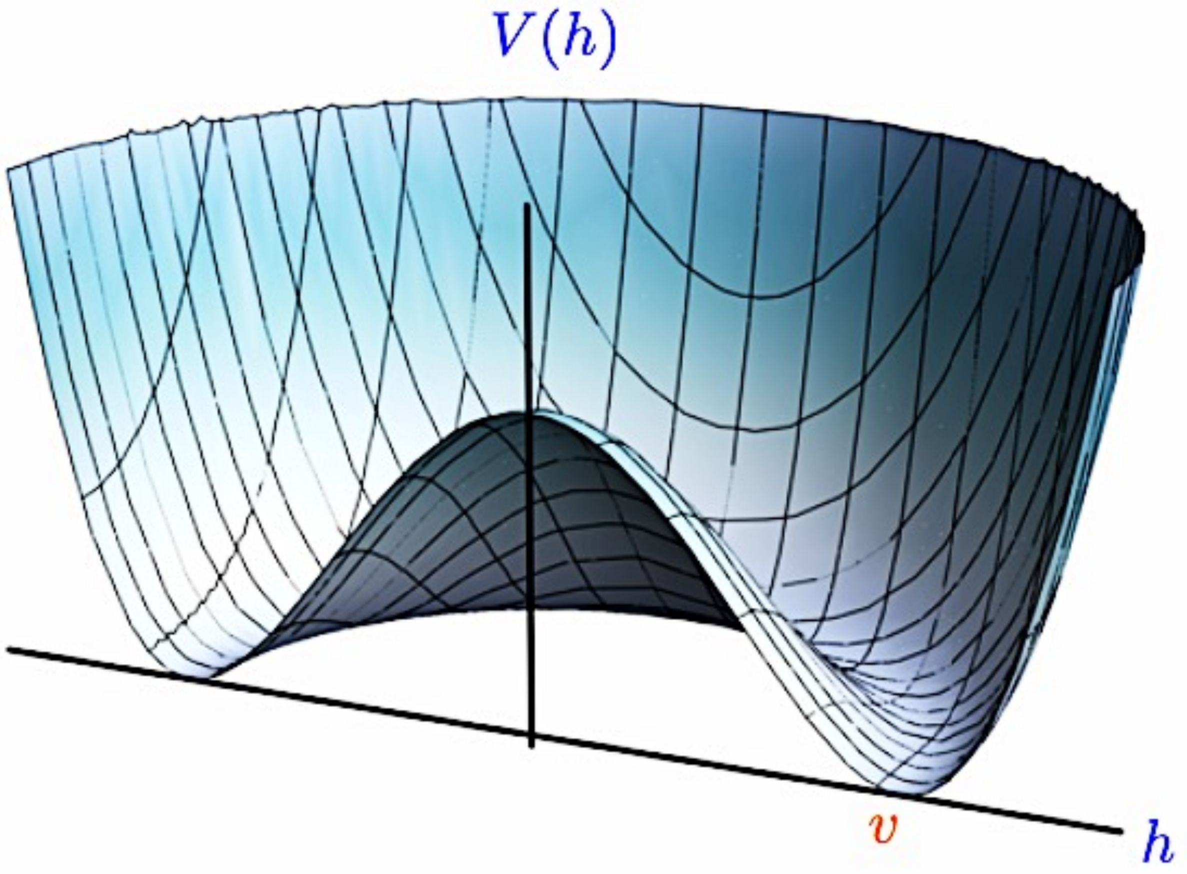
- Why is $M_{SM} \neq M_{Pl}$?
  - spontaneous electroweak symmetry breaking:

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$

  - sets mass scale of the SM

$$v = \sqrt{\frac{\mu^2}{\lambda}}$$

  - Higgs mass is equivalent to v: $m_h = \sqrt{\frac{\lambda}{2}}v$



THE HIERARCHY PROBLEM

- The problem: $\Lambda = M_{pl} \sim 10^{19}\,\text{GeV}$
  - Getting $m_h = 125\,\text{GeV}$ requires an extremely delicate cancellation:

$$\mathcal{O}(10^{19})^2 - \mathcal{O}(10^{19})^2 = \mathcal{O}(100)^2$$

  - Cancellation profoundly sensitive to physics in the UV:
    - new states $\Rightarrow$ new loops, spoil cancellation
  - The generic (natural) expectation is thus $m_h \sim \Lambda$

THE HIERARCHY PROBLEM

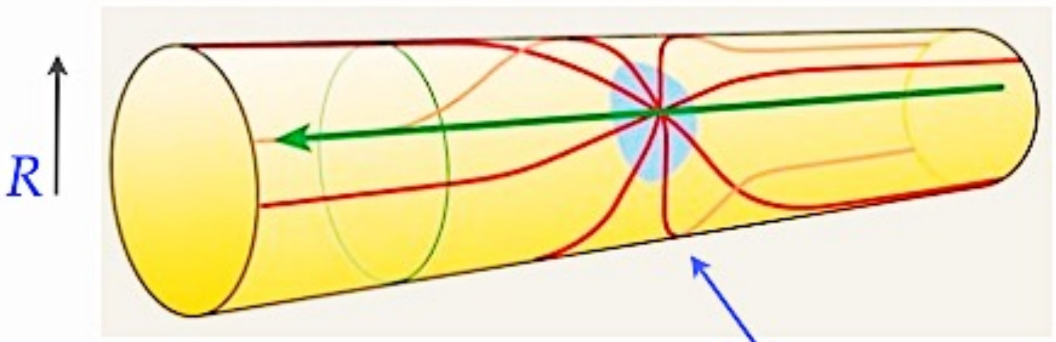
- We only have one universe. So what's wrong with setting up one cancellation?

$$\delta m^2(M) \sim M^2 \ln(M/m_h)$$

  - cancellation is between value of mass at Λ and the contribution from all intermediate scales
  - different microphysical origin!
  - no intrinsic reason to expect a cancellation of one part in 10^{36}

THE HIERARCHY PROBLEM

- consider n flat extra dimensions:



$$V(r) = \frac{m}{M_{Pl(4+n)}^{n-2}} \frac{1}{R^n} \frac{1}{r}$$

but for $r > R$, field propagation is 4-dimensional

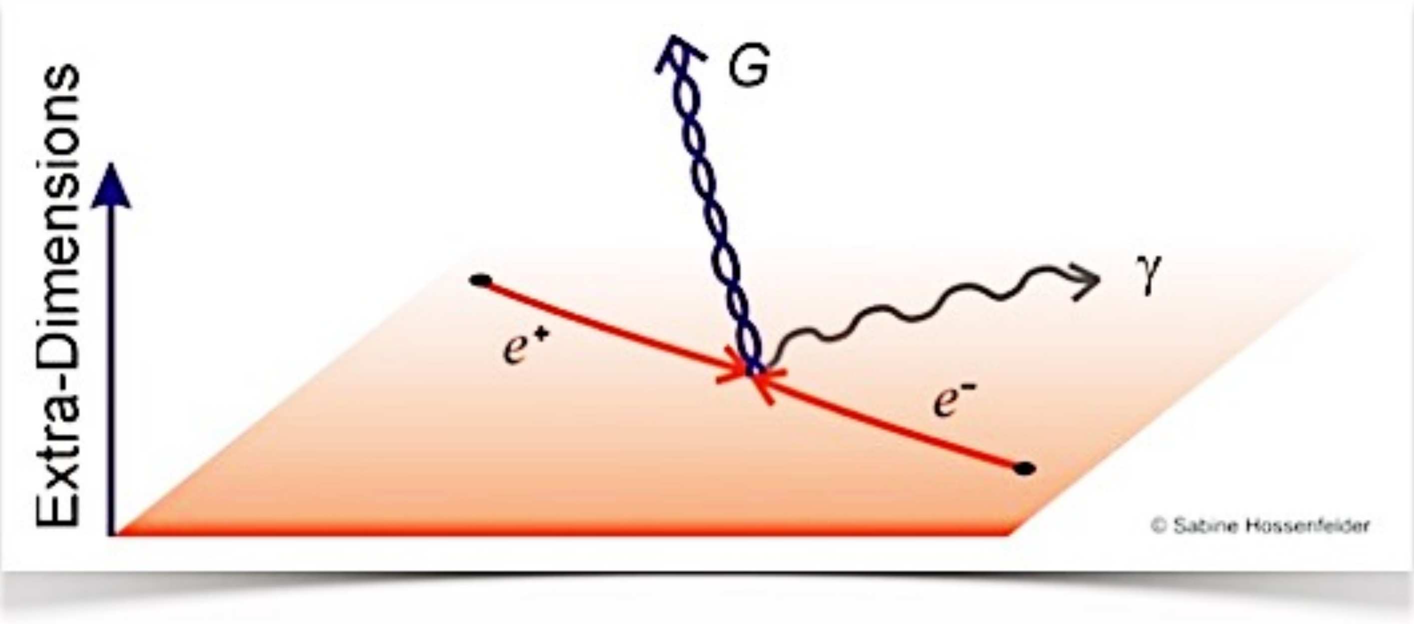
short distance behavior is 4+n-dimensional

$$V(r) = \frac{m}{M_{Pl(4+n)}^{n-2}} \frac{1}{r^{n+1}}$$

- if volume of extra dimensions is large in units of Planck length, 4D gravity appears weak: $M_{Pl(4+n)} R^n = M_{Pl(4)}$

THE HIERARCHY PROBLEM

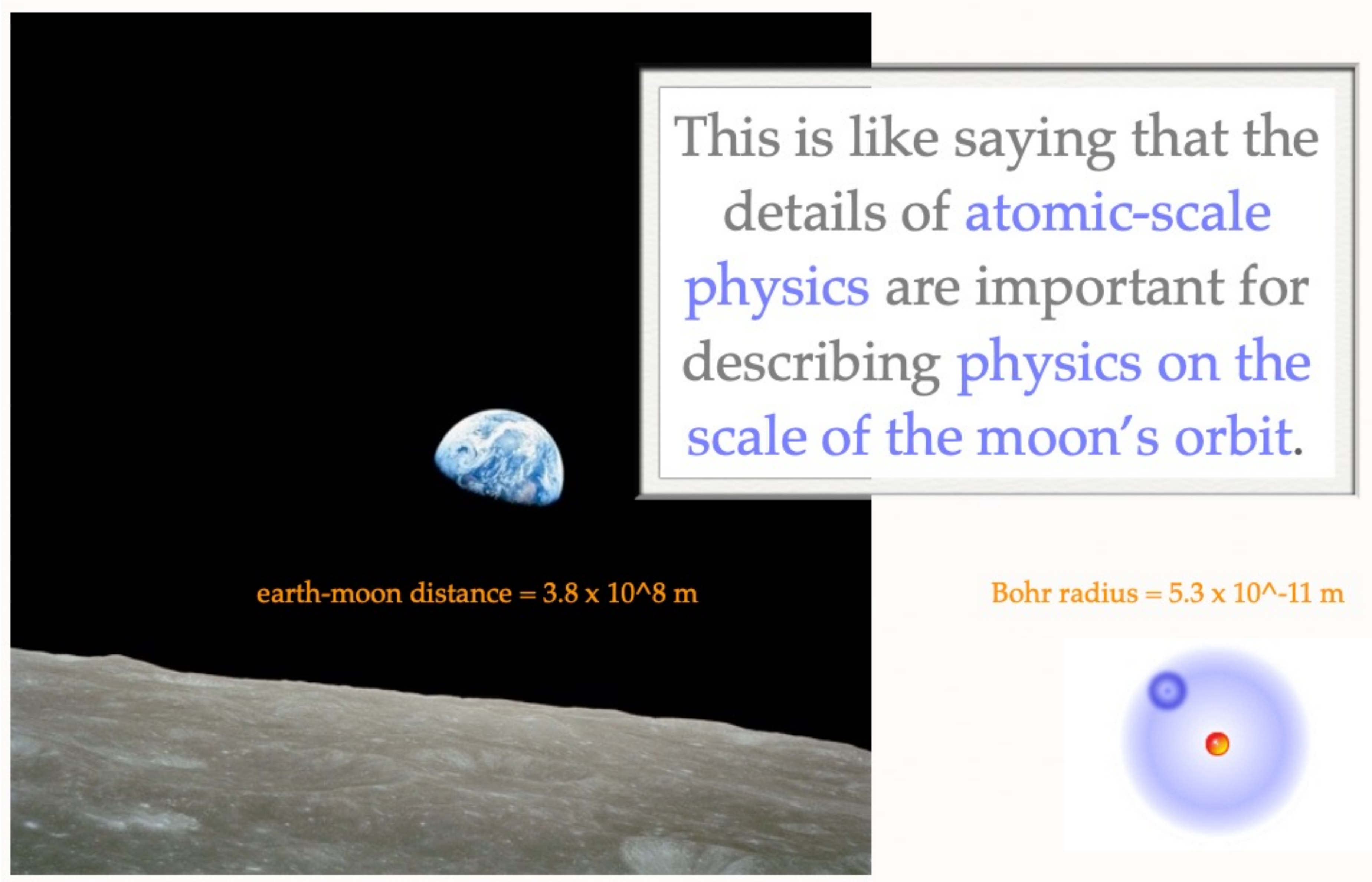
- Some collider signatures:
  - production of Kaluza-Klein gravitons:



mono-(jet, *W*, *Z*, photon) recoiling against large *MET*

  - ...maybe quantum black holes?!

THE HIERARCHY PROBLEM



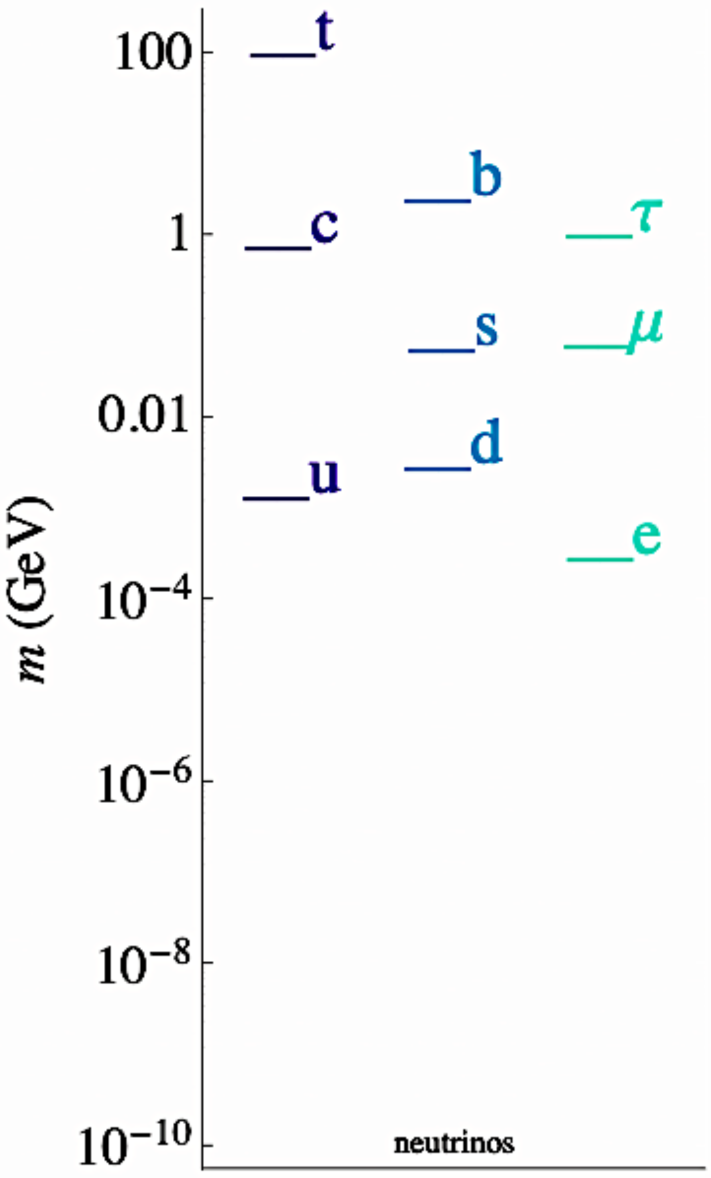
THE HIERARCHY PROBLEM

- Bottom line: if the weak scale is natural, new physics should be experimentally accessible by current and/or feasible technology

- Conversely the failure to find new physics near the electroweak scale would tell us nature is fine-tuned: qualitatively new

ORIGIN OF FLAVOR

- "Who ordered that?": flavor
  - Yukawa couplings: $Y^U_{ij} Q_i H u_j$
  - eigenvalues are hierarchical
  - and (mostly) small
- Where does this structure come from?

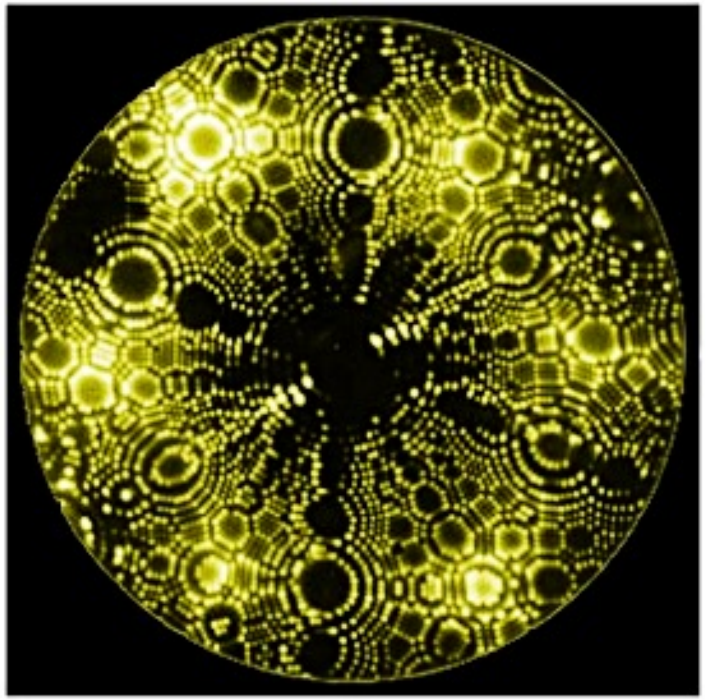


ORIGIN OF FLAVOR

- On the other hand this means no guide to scale of new physics associated with flavor:
  - Yukawa couplings are renormalizable, i.e., are dimensionless ⇒ no intrinsic mass scale
  - No fine tuning ⇒ no scale that could even subjectively point to the need for new physics
- The origin of flavor is one of the biggest mysteries with some of the fewest clues.

ORIGIN OF FLAVOR

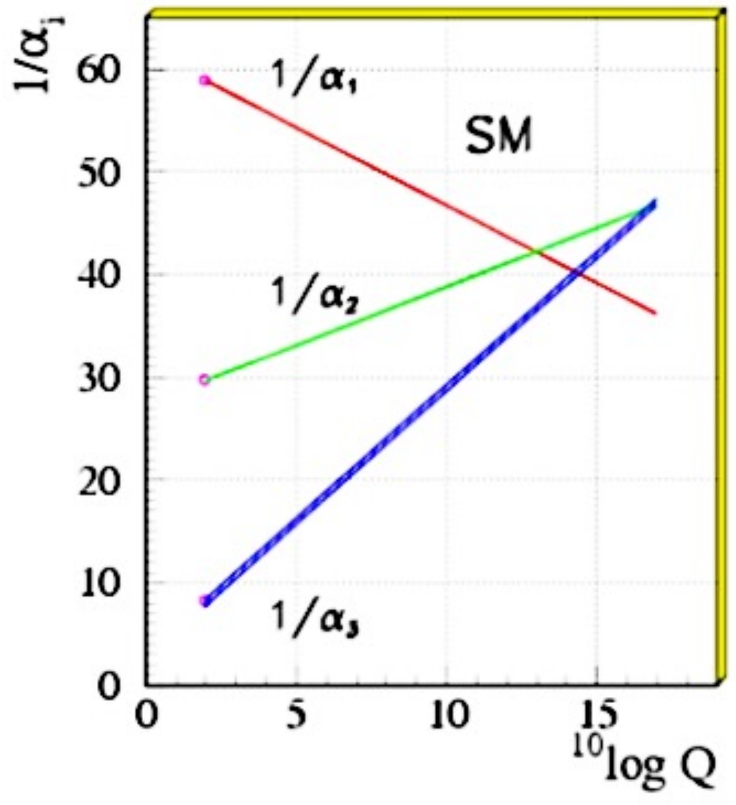
- What about the top quark?
  - only fermion with *O(1)* Yukawa coupling
  - No top mesons
  - direct clue to flavor? possible, but we would need to be very lucky
  - anomalous couplings or decays from new UV physics coupling preferentially to top?



a single top quark is as heavy as an entire tungsten atom

UNIFICATION

- Evolution of SM gauge couplings suggests a common origin at a high scale $M_{GUT} \sim 10^{15}, 10^{16}$ GeV



[plot from PDG]

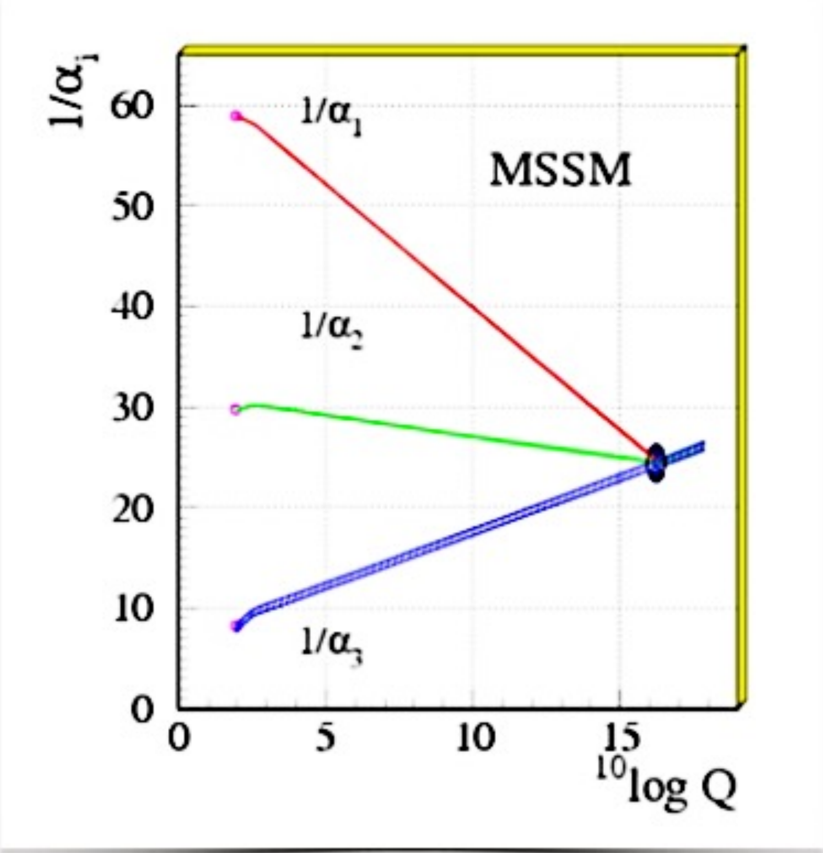
- common origin of SM gauge interactions in single interaction?

$$SU(3)_c \times SU(2)_L \times U(1)_Y \subset SO(10)$$

- Nontrivial: SM fermions have right quantum numbers to fit in single multiplet of $SO(10)$

UNIFICATION

- Adding new matter adds to the screening and changes the evolution with energy:



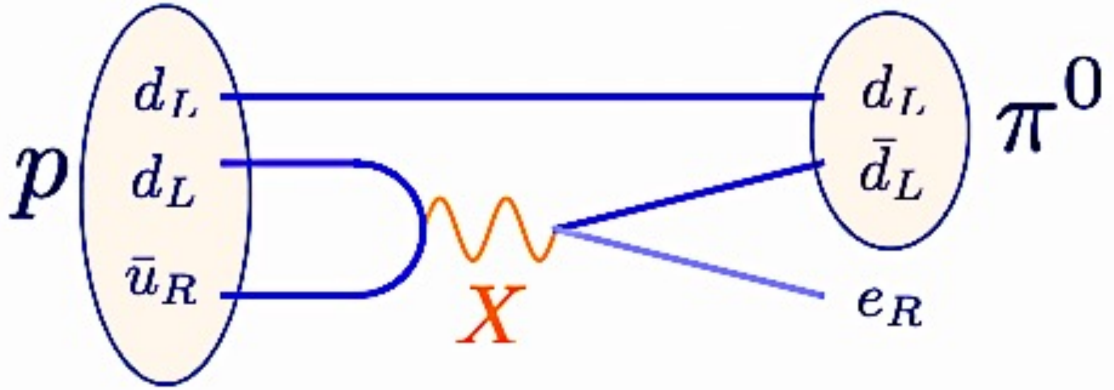
[plot from PDG]

- New charged matter in MSSM makes numerical unification work significantly better
- Precision unification requires new charged states between SM and M_{GUT}
- But unification is insensitive to exact value of this scale

UNIFICATION

- Again: look for high-scale physics indirectly in low-background processes

- Grand unified gauge bosons mediate proton decay:

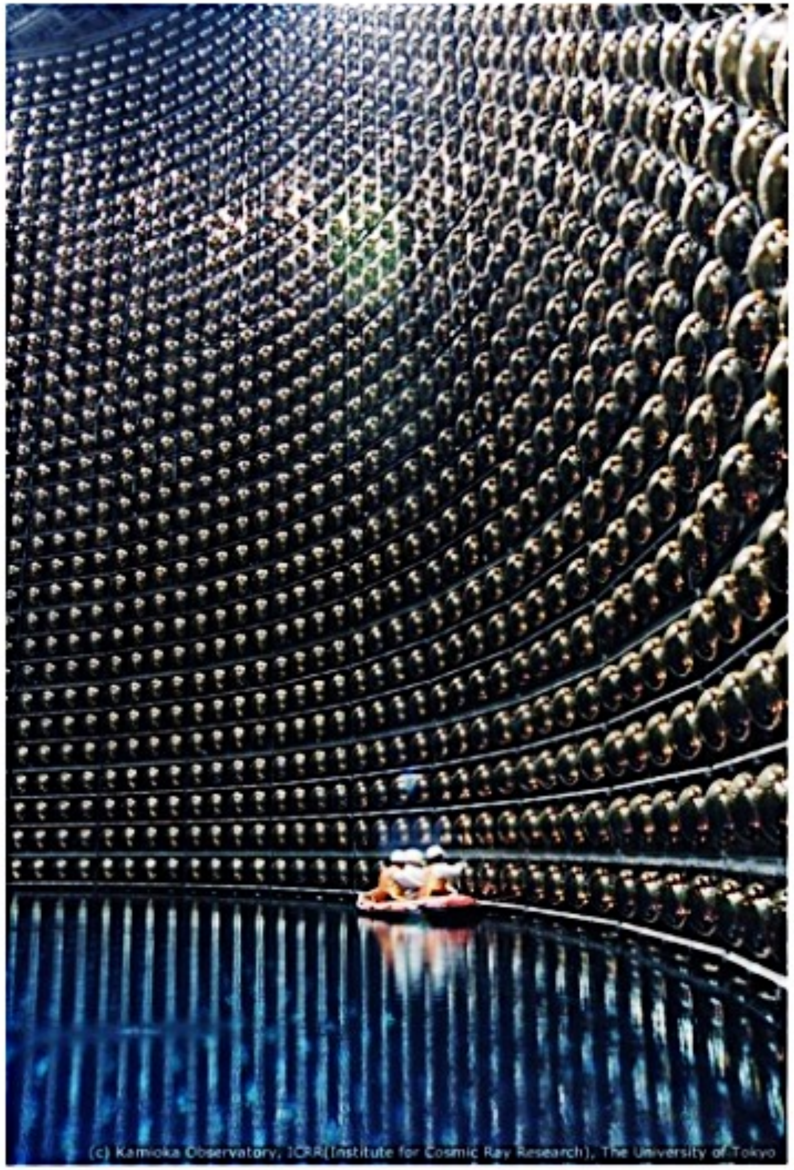


  - New four-fermi operator: $\frac{g_X^2}{M_X^2}\bar{u}_R\gamma^\mu d_L\ \bar{e}_R\gamma_\mu d_L$

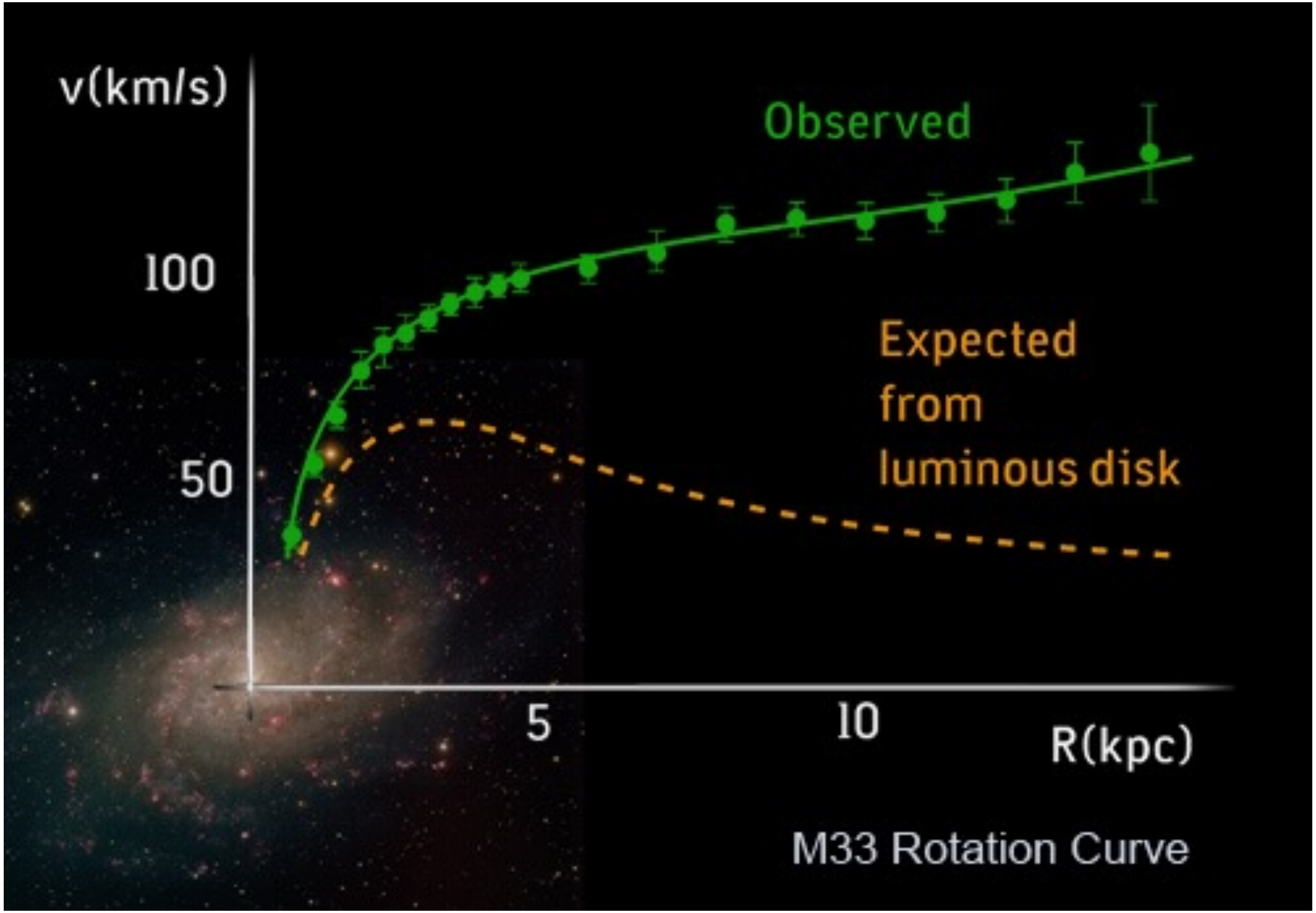
UNIFICATION

- Proton lifetime bounds
  - depend on flavor structure of decay
  - generally:

$$\tau_p \gtrsim 10^{34}\ \text{years}$$

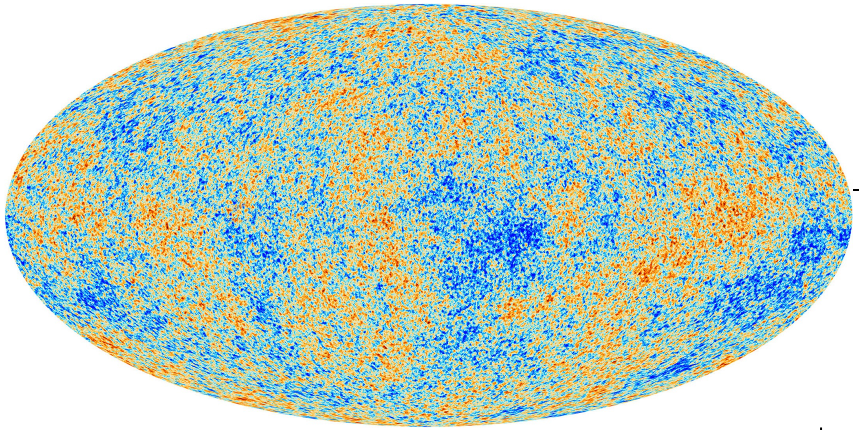


Evidence For Dark Matter

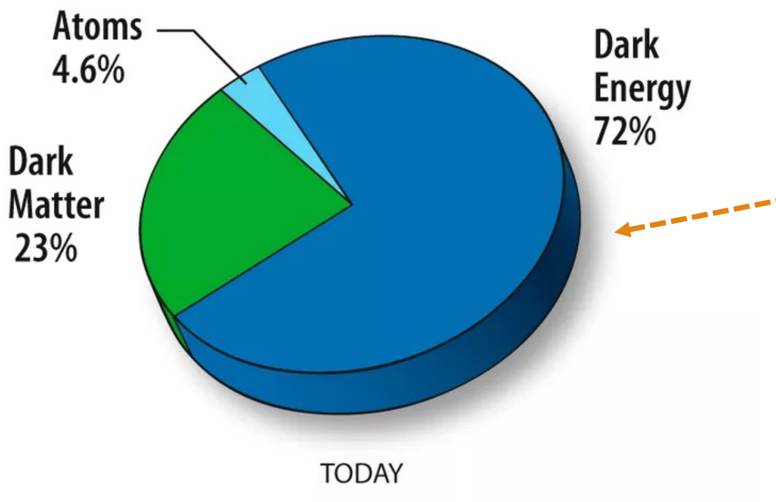


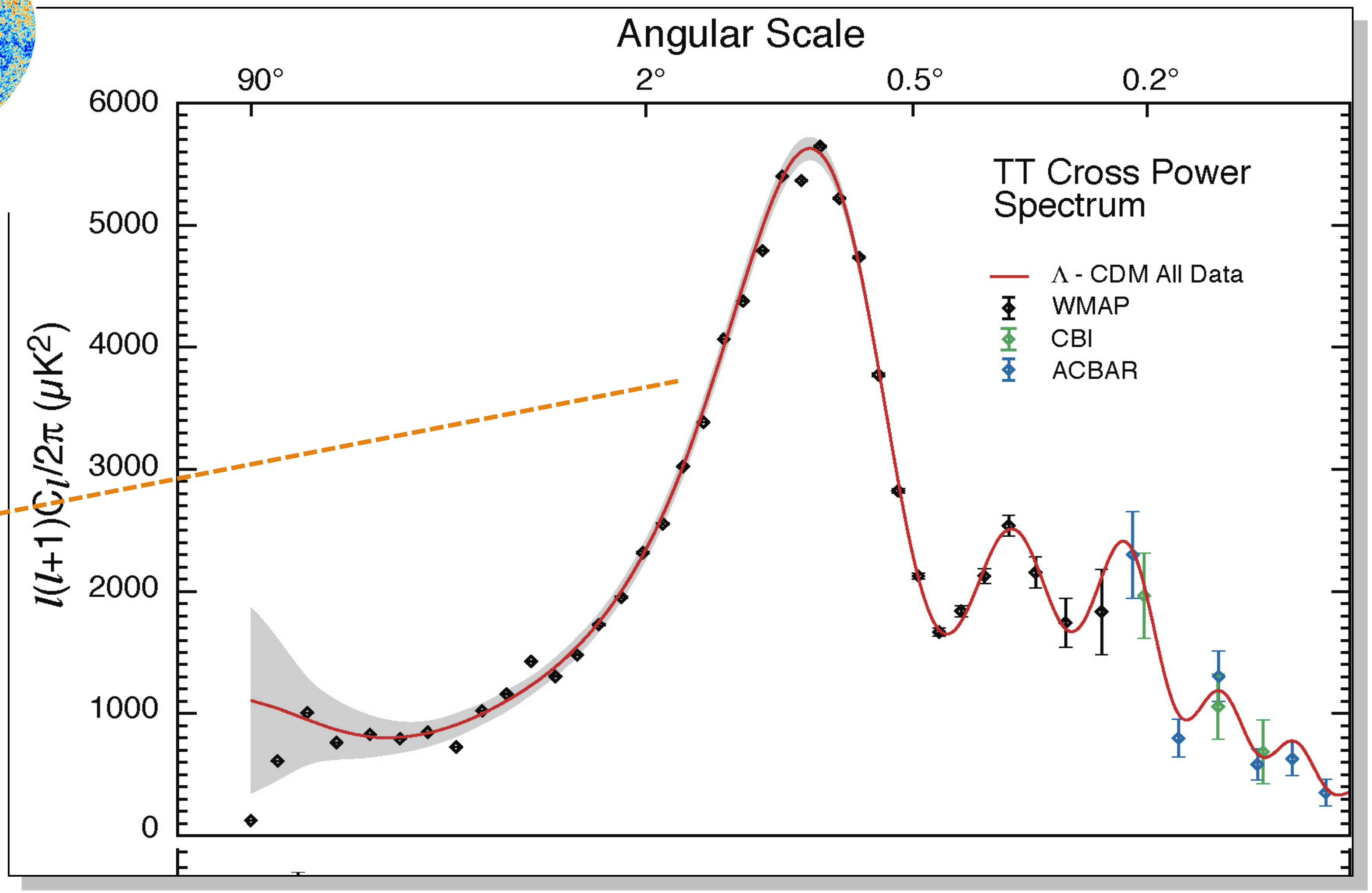
Galactic rotation curves

Evidence For Dark Matter



Cosmic microwave background anisotropies



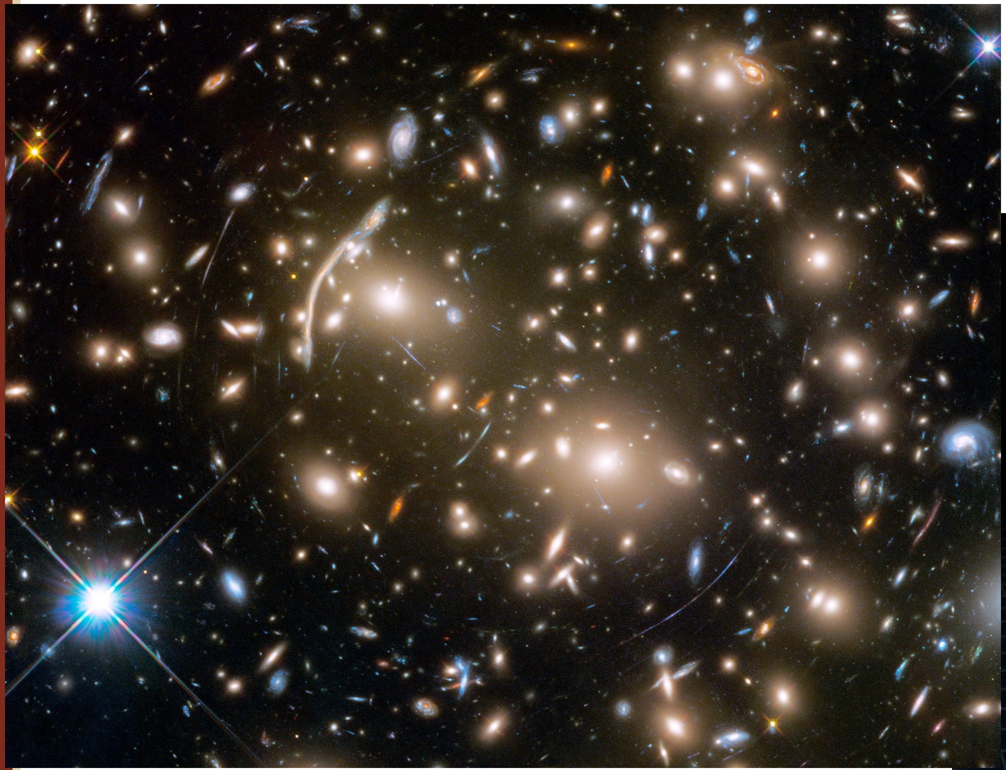


Evidence For Dark Matter

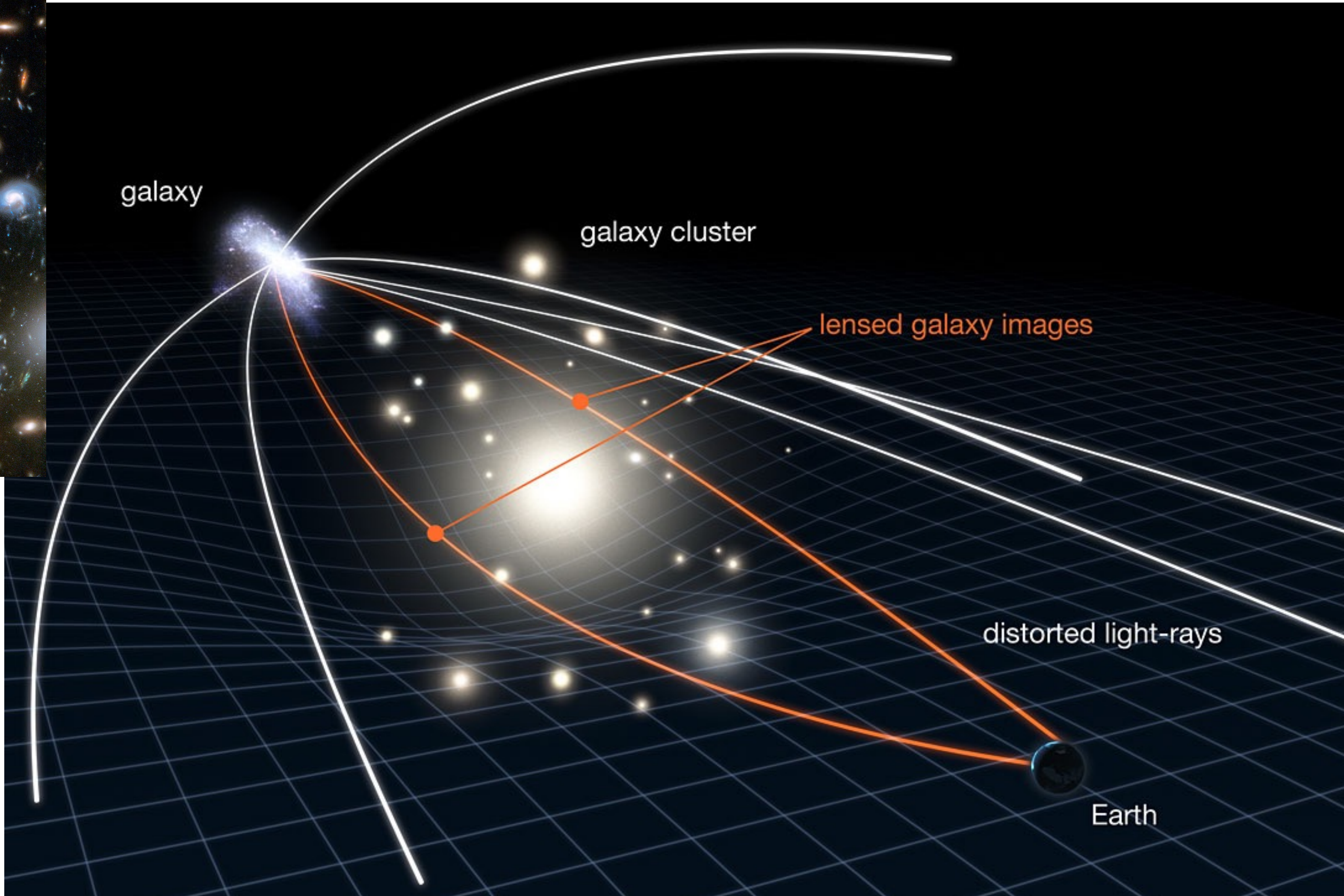
Galaxy has a visible component and a dark component which interacts only gravitationally.

Colliding galaxies show the different interactions of the neutral Dark Matter and the visible matter, which has Electromagnetic interactions.

Evidence For Dark Matter



Gravitational lensing

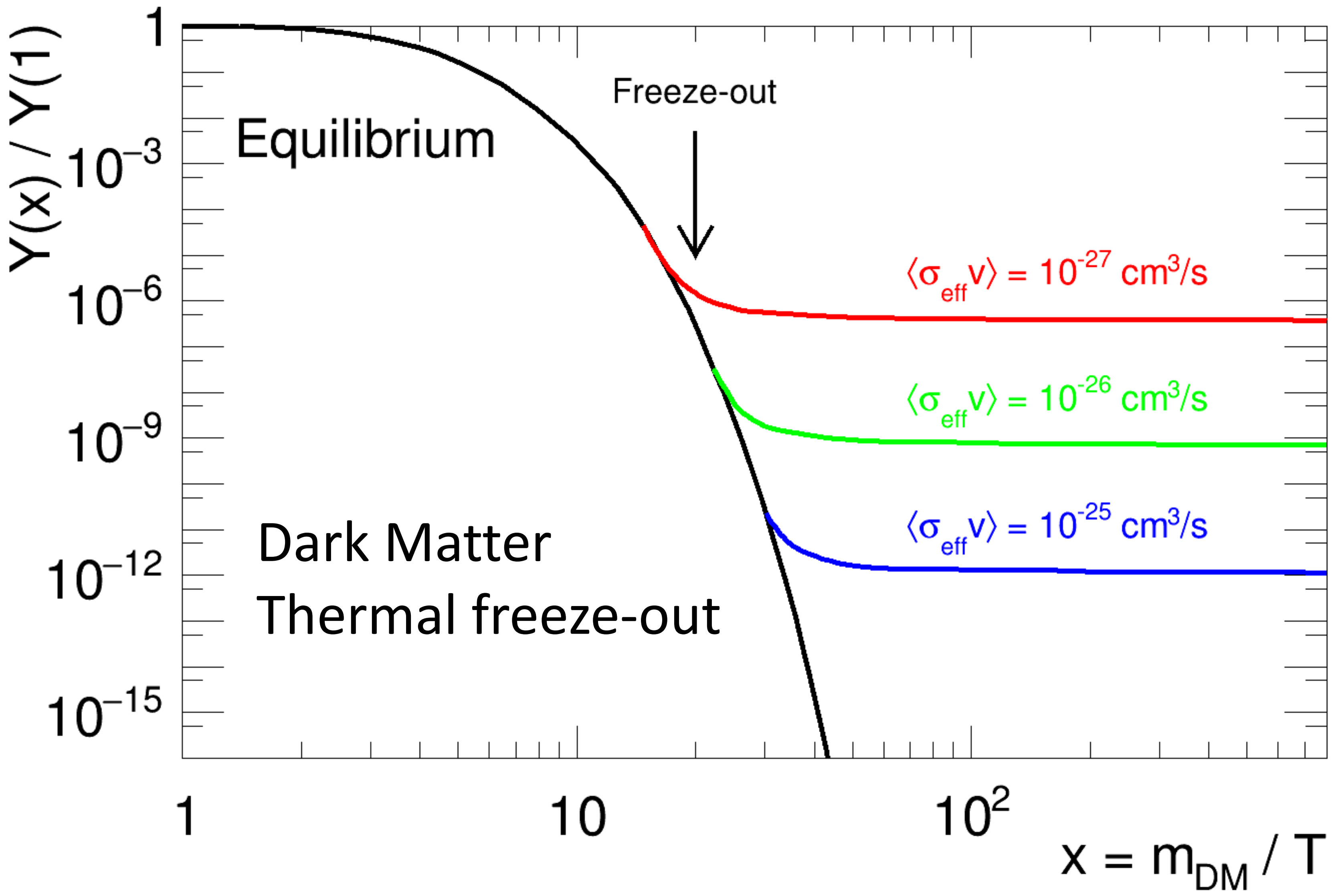


Galaxy cluster Abell 370 composed of several hundreds of galaxies. The blue arcs are distorted images of remote galaxies behind the cluster.

Dark Matter

- Thermal freezeout:
  - particles in early universe are a thermal plasma
  - equilibrium number densities
    - relativistic: $n_i \propto g_i T^3$
    - non-relativistic: $n_i \propto g_i T^3 \left(\frac{m}{T}\right)^{3/2} e^{-m/T}$
  - T decreases with adiabatic expansion of universe

Dark Matter



Dark Matter

Thermal freeze-out

Dark Matter

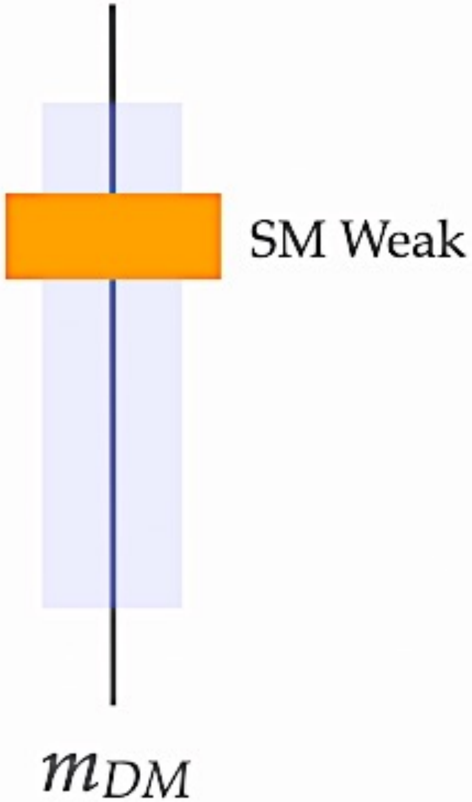
- WIMP miracle is properly a statement about perturbative thermal relics:

  - upper bound on m: $g^2 < 4\pi$

    $\Rightarrow m \lesssim 40\,\mathrm{TeV}$

  - lower bound on m: freezeout must happen when DM is relativistic

    $\Rightarrow m \gtrsim 10\,\mathrm{eV}$

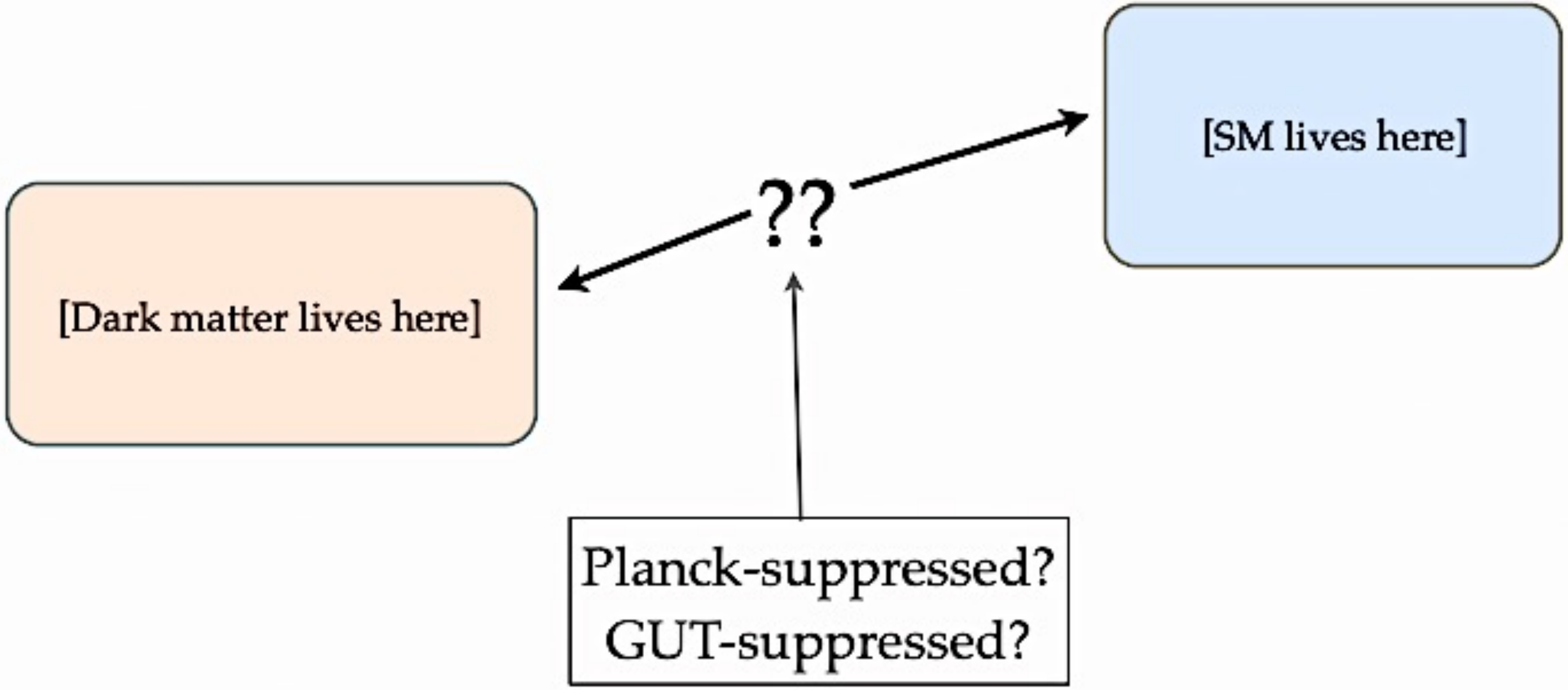


Dark Matter

- This is a broad but bounded range of mass scales
- Nontrivial: includes SM electroweak
  - SM weak interactions: only SM gauge interaction with right properties
  - Higgs interactions also fit the bill
  - Is dark matter part of extended model of EWSB?
  - Testable at current/future facilities!

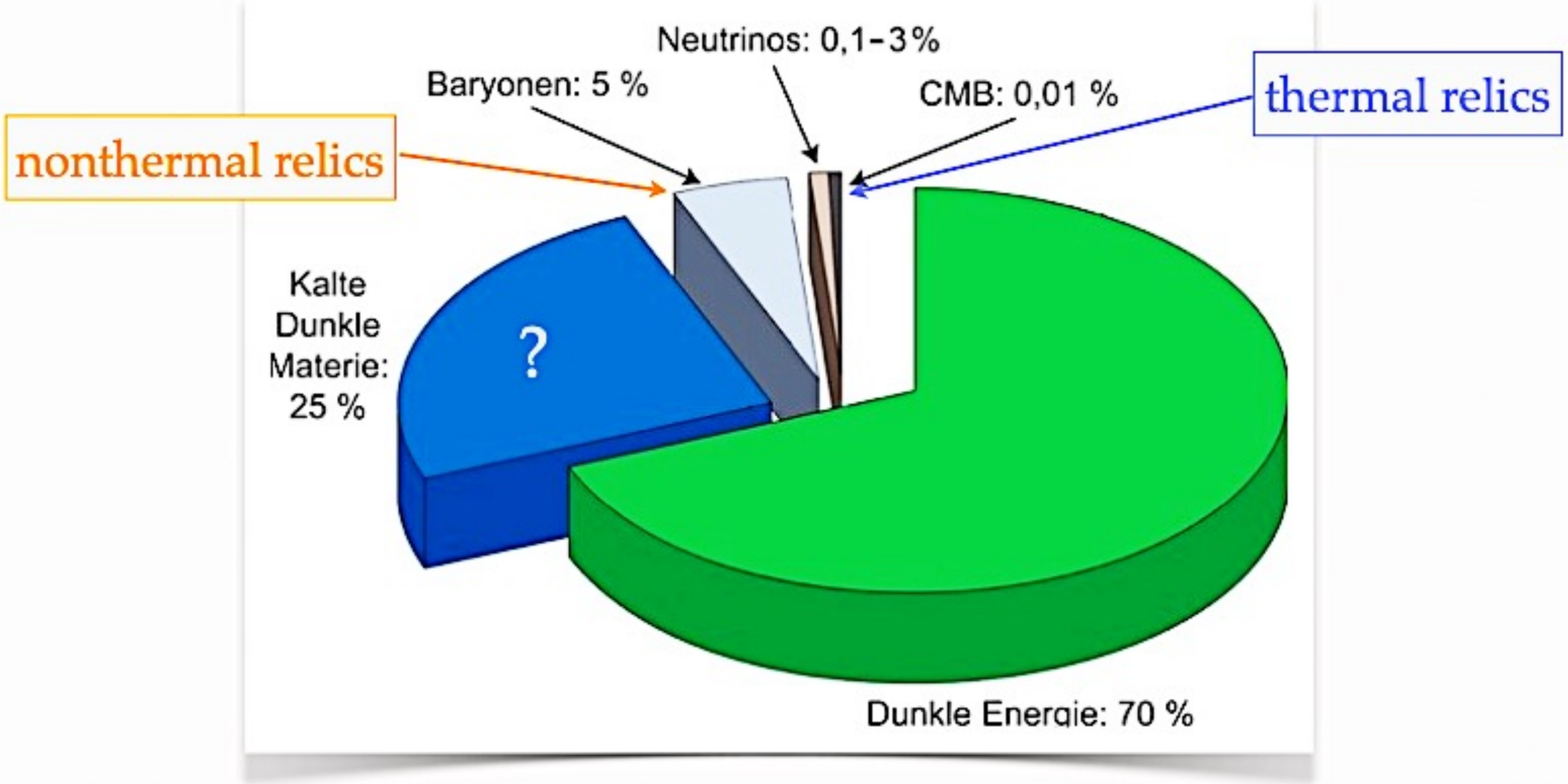
Dark Matter

- Caveat 1:
  - If freezeout happens through non-SM interactions then couplings between DM and the SM may be too feeble to see at colliders



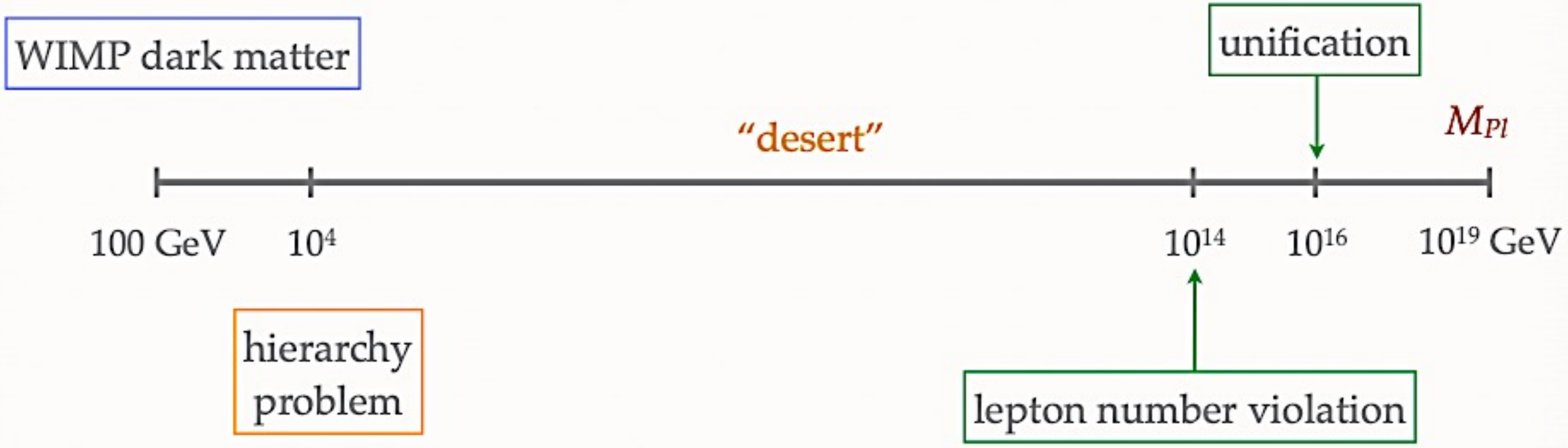
Dark Matter

- Caveat 2:
  - DM doesn't have to be a perturbative thermal relic



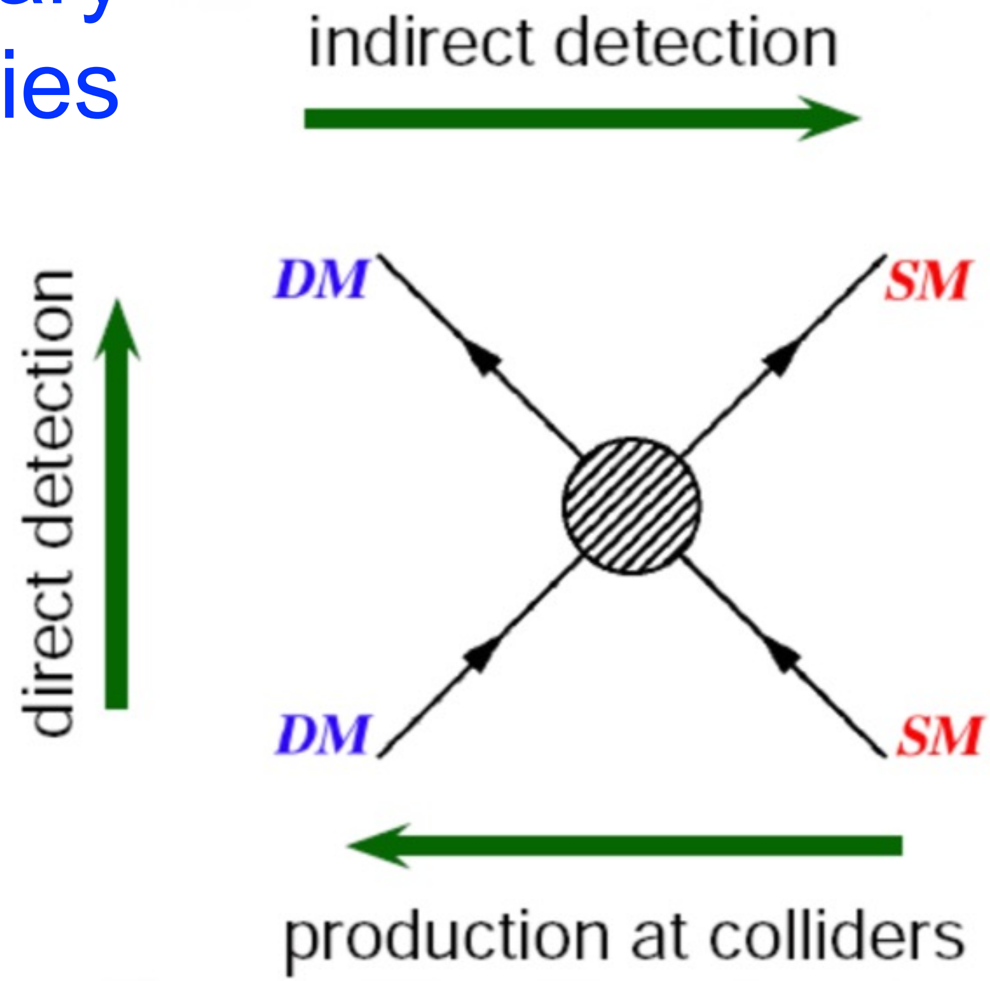
WHERE IS NEW PHYSICS?

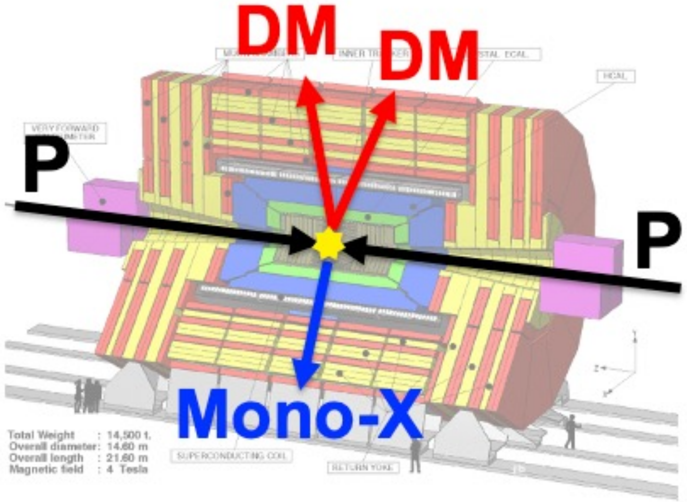
- A summary cartoon:



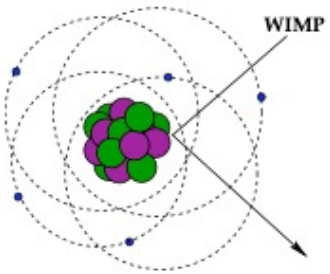
Dark matter experiments

3 complementary search strategies



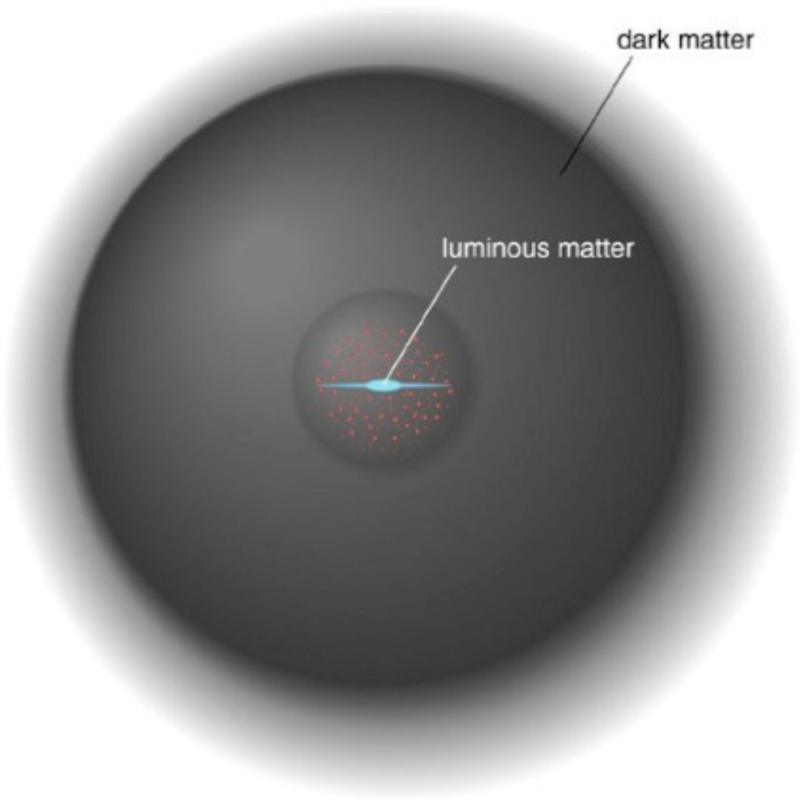


Dark matter in the Milky Way



$E_R \sim \mathcal{O}(10\,\mathrm{keV})$

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(\mathbf{v},t) \cdot \frac{d\sigma}{dE}(E,v)\, d^3v$$



Astrophysical parameters:

- ρ_0 = local density of the dark matter in the Milky Way

  'Standard' value: $\rho_\chi \simeq 0.3\,\mathrm{GeV/cm^3}$
- $f(\mathbf{v},t)$ = WIMP velocity distribution, $\langle v \rangle \sim 220\,\mathrm{km/s}$

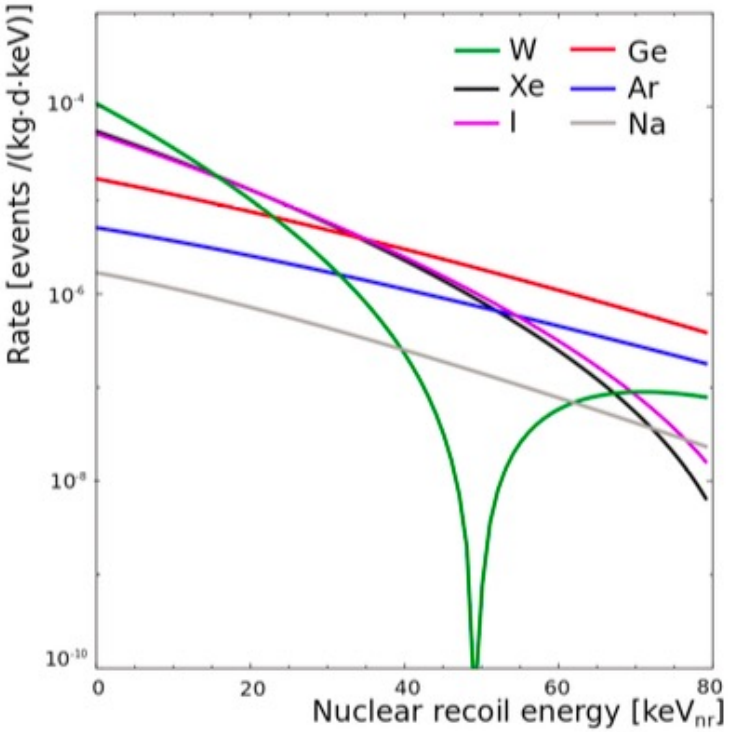
Parameters of interest:

- m_χ = WIMP mass ($\sim 100\,\mathrm{GeV}$)
- σ = WIMP-nucleus elastic scattering cross section (SD or SI)

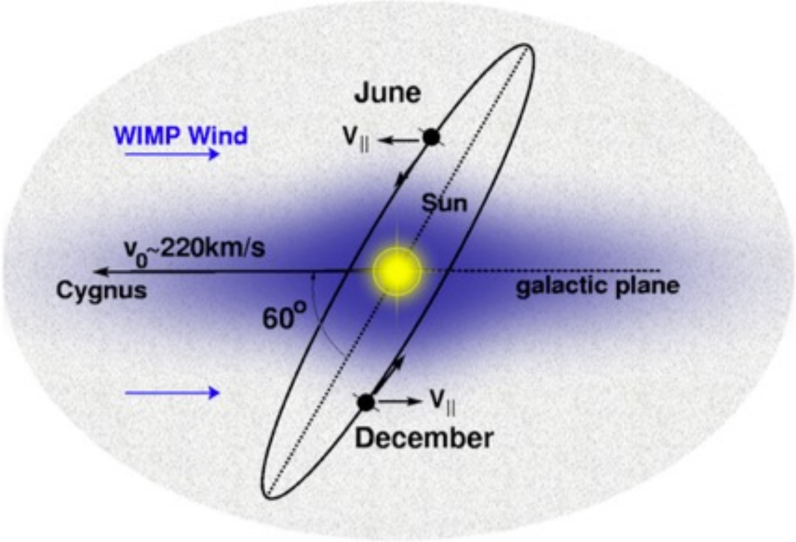
Detector requirements and signatures

- Large detector mass (grams up to several tonnes)
- Low energy threshold ~ few keV's or sub-keV
- Very low background and/or background discrimination

J. Phys. G: 43 (2016) 1 & arXiv:1509.08767



- Other signatures of dark matter
  - Annual modulated rate
  - Directional dependance

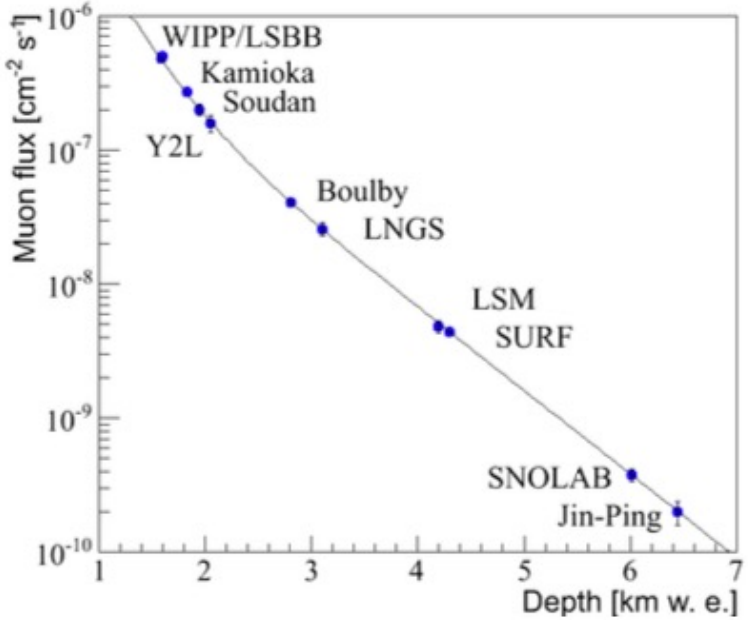


Backgrounds and reduction strategies

- External γ's from natural radioactivity:
  - Material screening & selection + Shielding

- External neutrons: muon-induced, (α, n) and from fission reactions
  - Go underground!
  - Neutron shielding
  - material selection for low U and Th concentrations

+ Neutrinos from the Sun, atmospheric and from supernovae



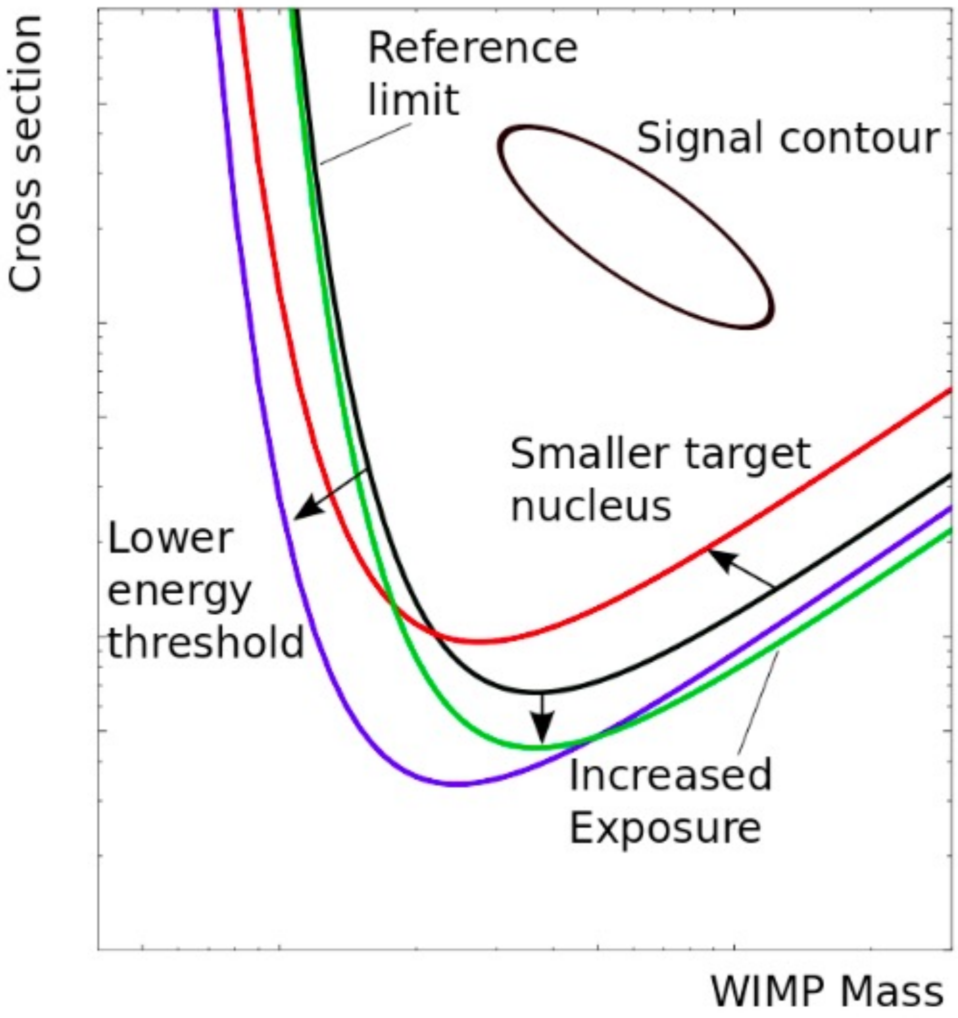
J. Phys. G: 43 (2016) 1 & arXiv:1509.08767

- Internal backgrounds:
  - Liquids/gases: Rn-emanation from surrounding materials
  - Solids: surface events from α- or β-decays
  - Cosmogenic activation important for all

Result of a direct detection experiment

→ Statistical significance of signal over expected background?

J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767



- Positive signal
  - Region in σ_χ versus m_χ
- Zero signal
  - Exclusion of a parameter region

  - Low WIMP masses: detector threshold matters
  - Minimum of the curve: depends on target nuclei
  - High WIMP masses: exposure matters $\epsilon = m \times t$

Overview of WIMP searches

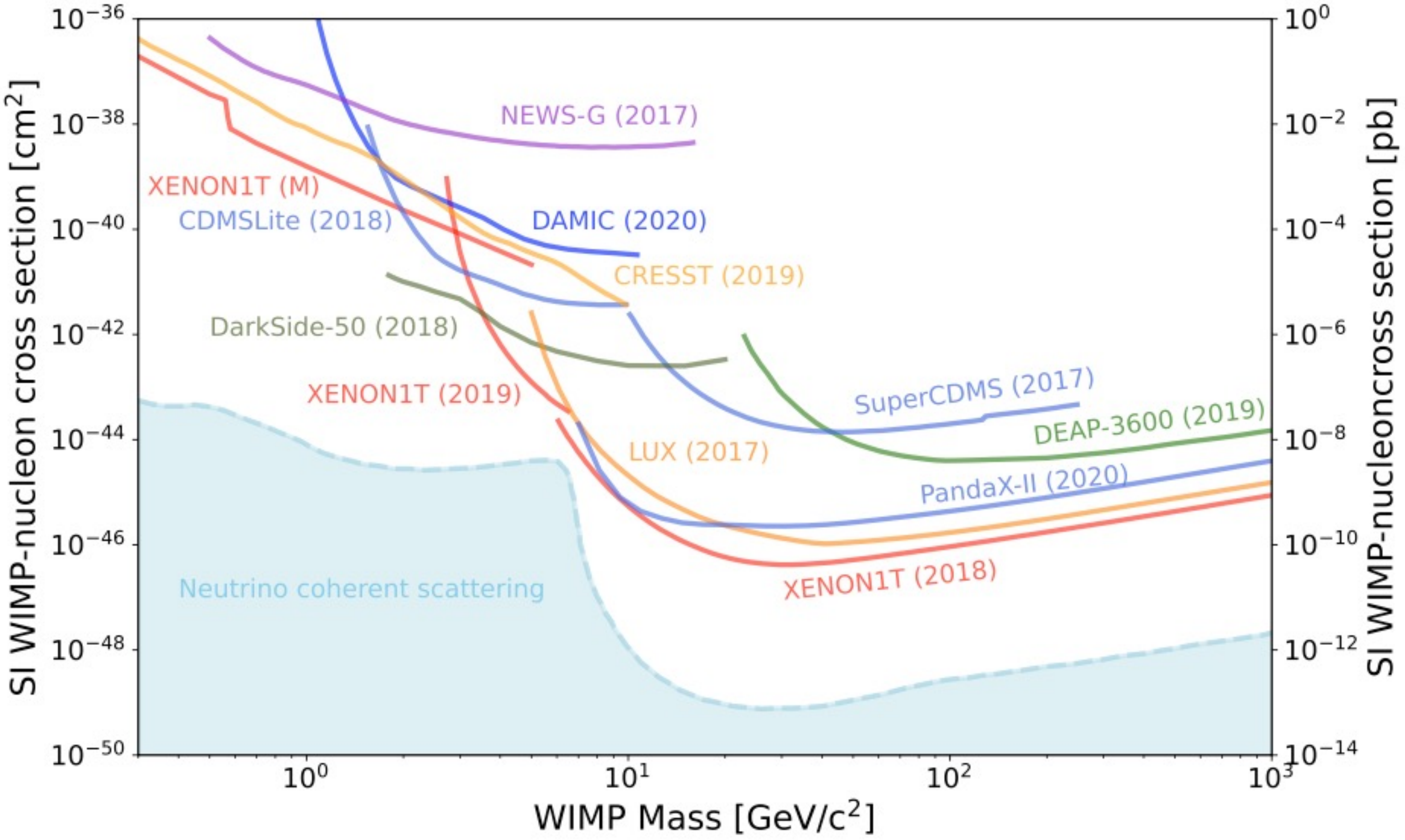
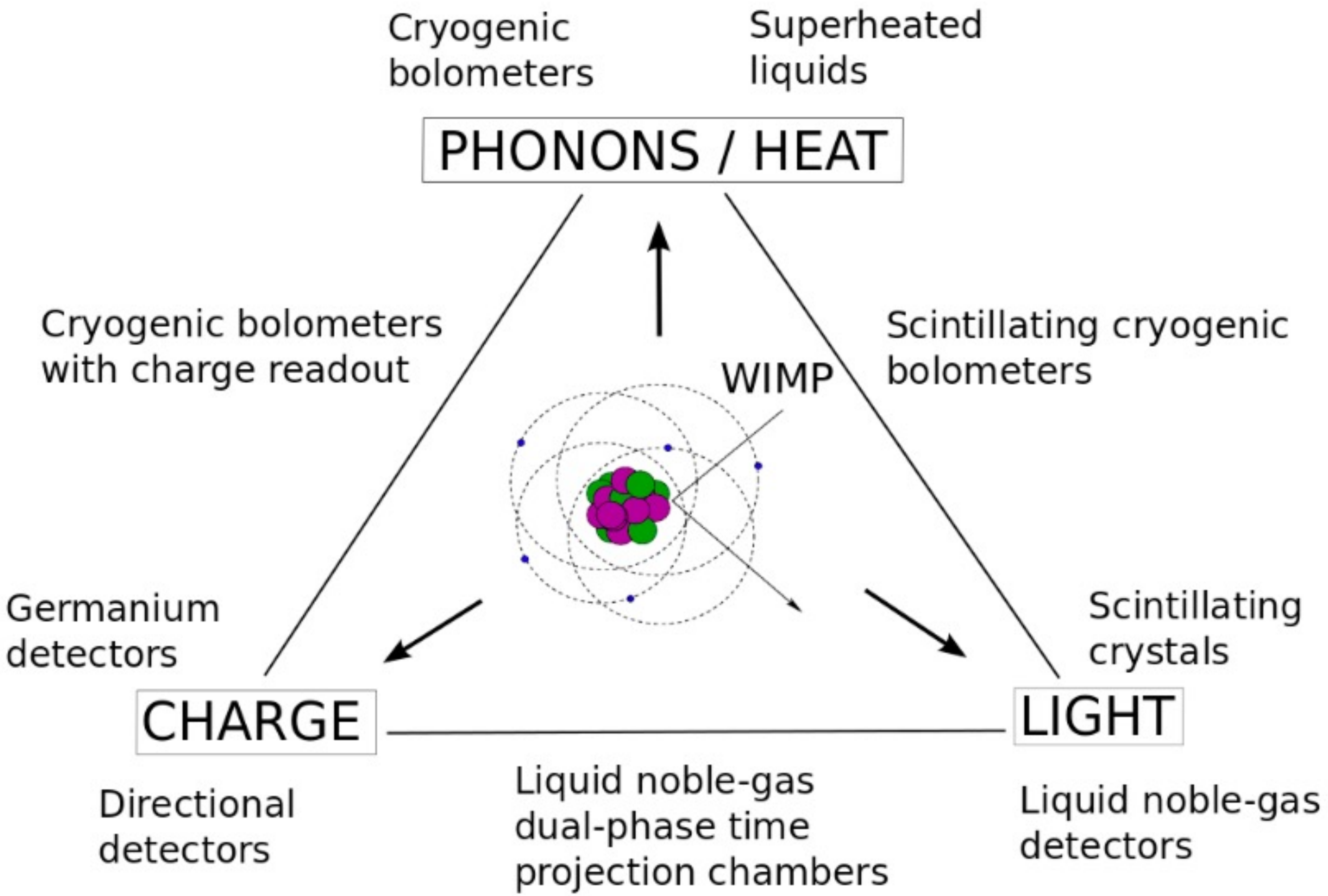


Figure updated from PDG, Prog. Theor. Exp. Phys. 2020 (2020) 083C01

Direct detection experiments

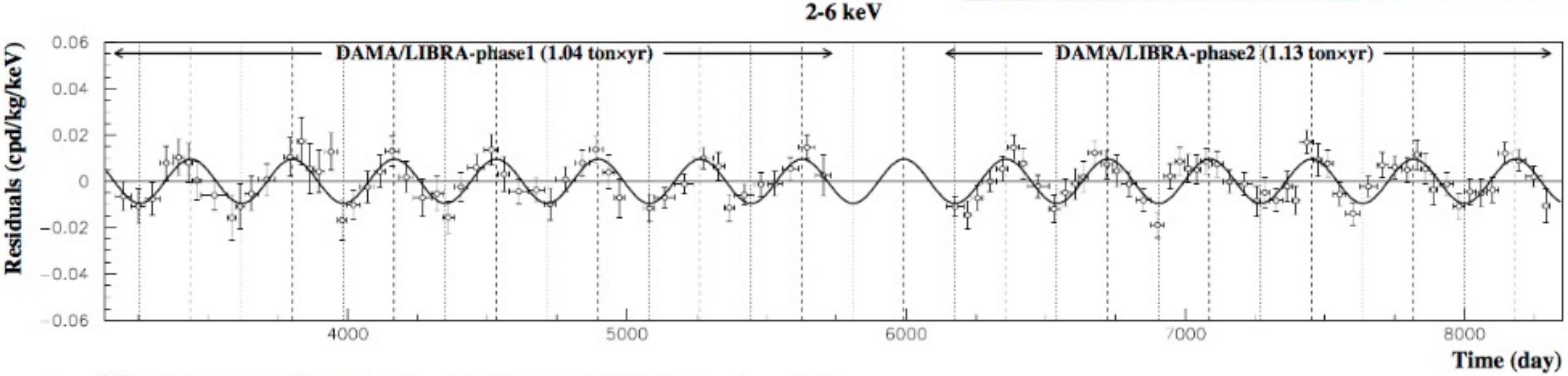


J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

DAMA annual modulation

- Ultra radio-pure NaI crystals @LNGS
- Annual modulation of the background rate in the energy region (2 – 6) keV
- Last results (2018): signal at 12.9 σ

Nucl. Phys. At. Energy 19 (2018) 307



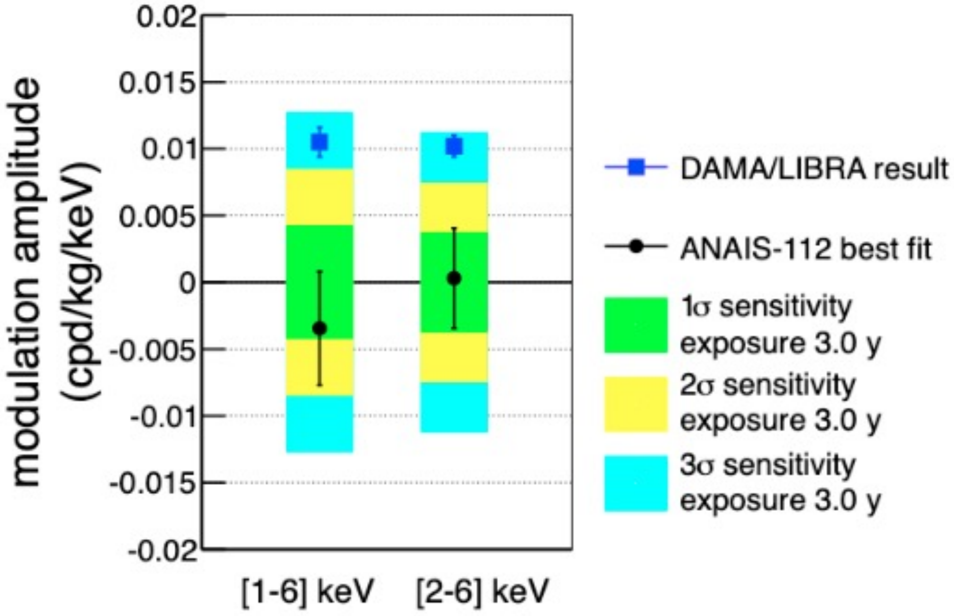
→ New results July 2021: 13.7 σ significance @EPS-HEP conference by P. Belli

WIMP interpretation in contradiction with many other results

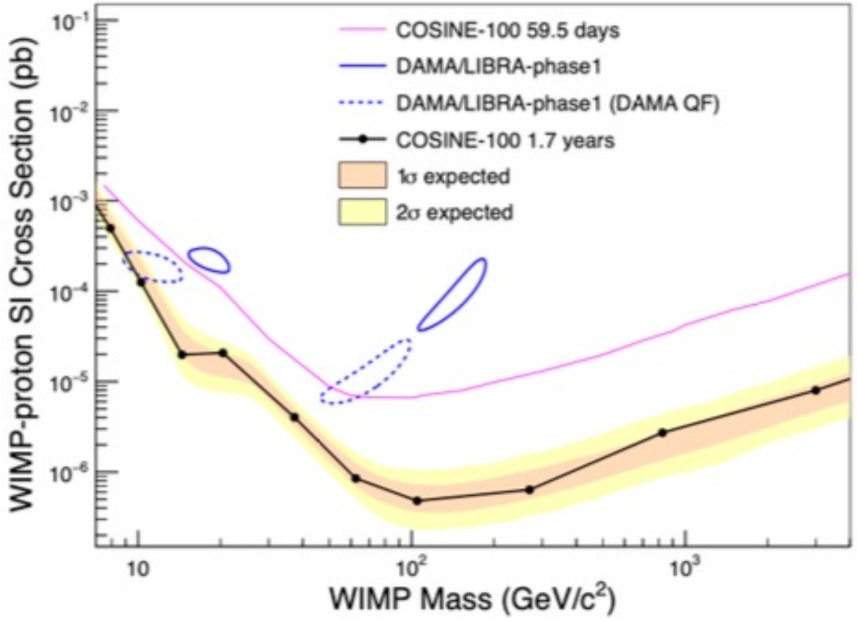
Worldwide effort to verify/refute this result

Recent results from ANAIS & COSINE-100

ANAIS, PRD 103 (2021) 102005 & arXiv:2103.01175



COSINE-100, Sci.Adv. 7 (2021) 46 & arXiv:2104.03537



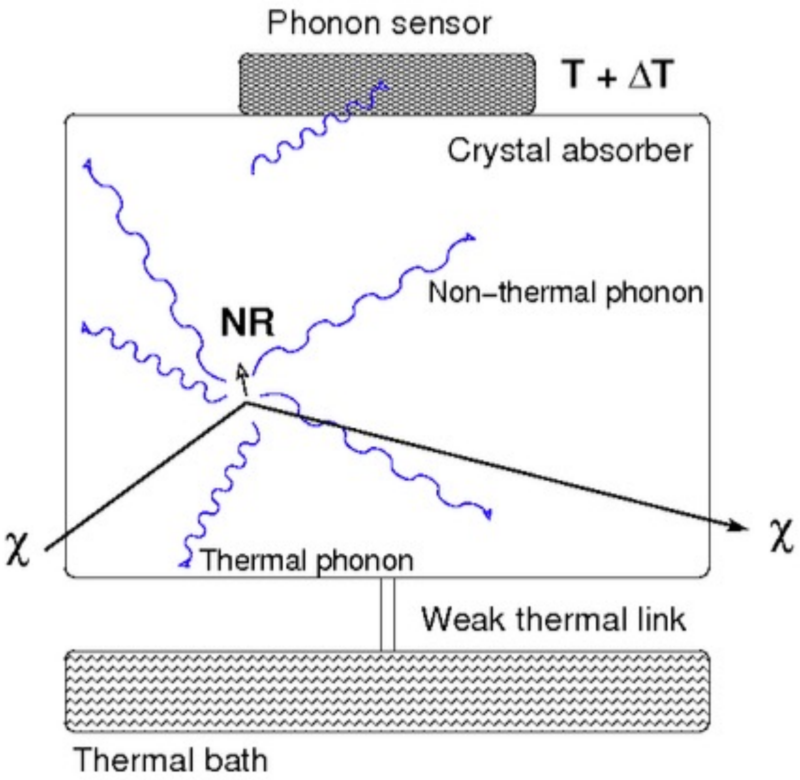
ANAIS @Canfranc:

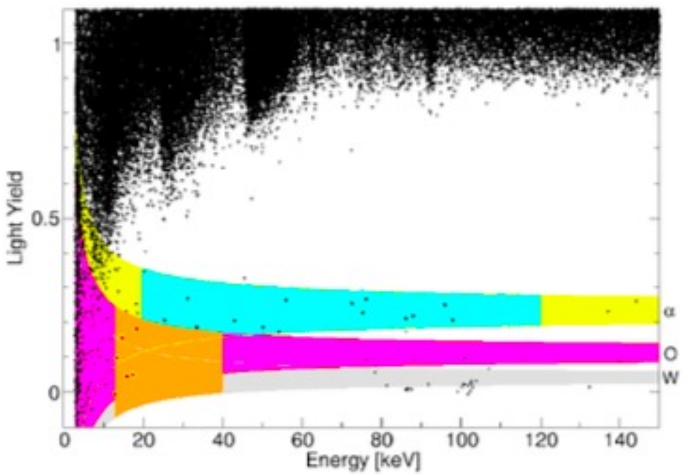
- DAMA modulation disfavoured at 3.3 σ for [1-6] keV at 2.6 σ for [2-6] keV
- Sensitivity above 3 σ within 2022

COSINE-100 @Yangyang:

- DAMA SI signal excluded
- Modulation analysis compatible with both DAMA and no modulation

Cryogenic bolometers





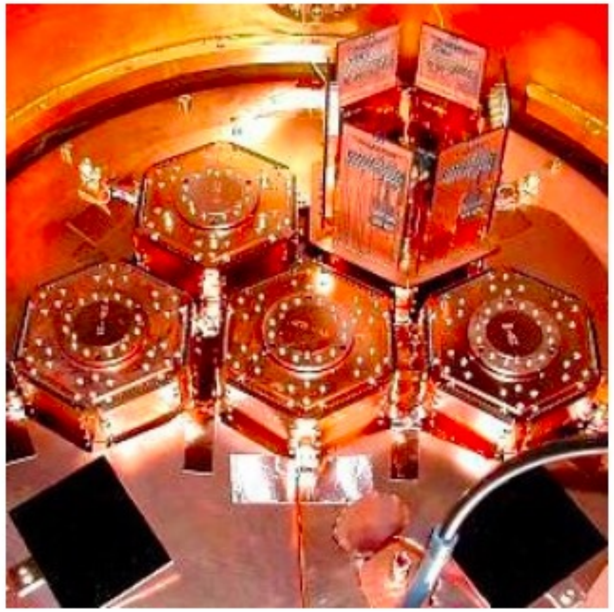
- Crystals at (10 – 100) mK
- Temperature rise:
  $\Delta T = E/C(T)$
  E.g. Ge at 20 mK, $\Delta T = 20\,\mu$K for few keV recoil
- Measurements of ΔT with NTD or TES
- Discrimination: combination with light or charge read-out
- Large separation of electronic and nuclear recoil bands

Example from CRESST, EPJC 72 (2012) 1971

Bolometer experiments


CRESST experiment


EDELWEISS experiment


Super-CDMS experiment

- Excellent sensitivities (low m_χ) due to their low energy thresholds
- CRESST: scintillating bolometer
  CRESST, PRD 100 (2019) 102002 (E_{th} = 30 eV)
- CDMS/EDELWEISS: germanium bolometers
  CDMS-Lite, PRD 99 (2019) 062001 (E_{th} = 70 eV)
- New CDMS HVeV 0.93 g silicon crystal with E_{th} = 9.2 eV V. Novati @TAUP2021

Results from cryogenic bolometers

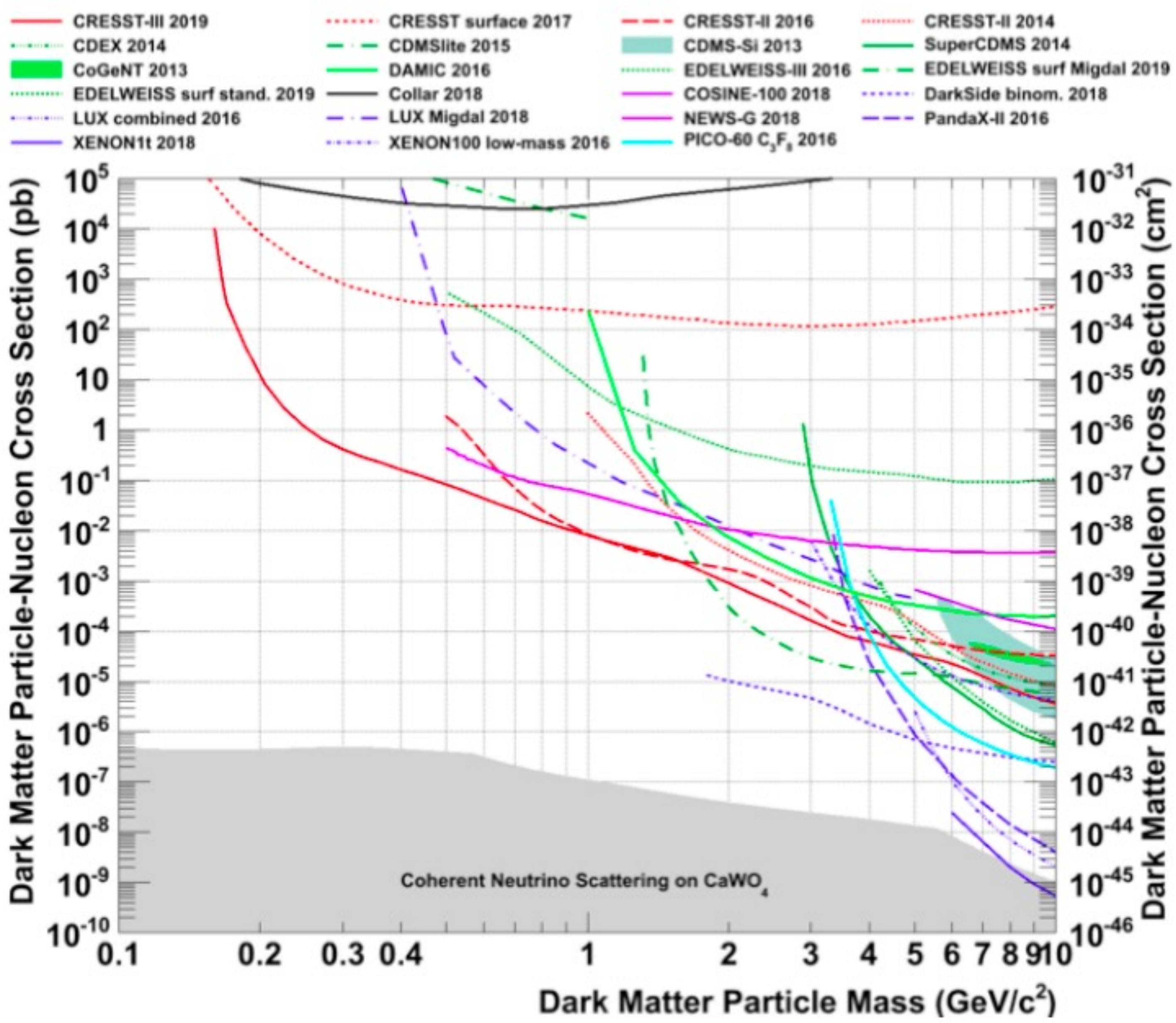
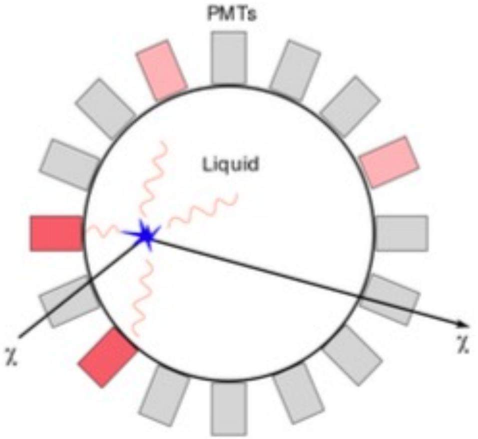


Figure from CRESST, Phys.Rev.D 100 (2019) 102002 & arXiv:1904.00498

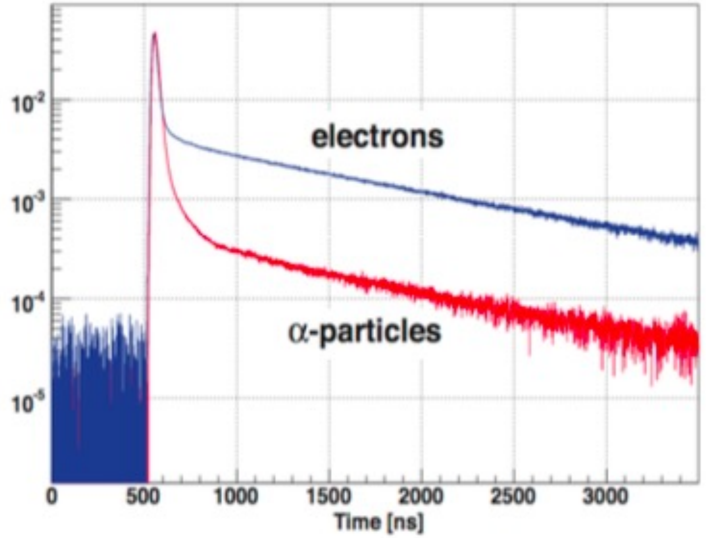
Advantages of liquid noble gases

- Large masses and homogeneous targets (LNe, LAr & LXe)
- 3D position reconstruction → fiducialization



Single phase (liquid) -type of detector:

- High light yield using 4π photosensor coverage
- Pulse shape discrimination (PSD) from scintillation



Scintillation decay constants of LAr by ArDM

- Very different singlet and triplet lifetimes in argon & neon
- Relative amplitudes depend on particle type → discrimination

10^{-8} by DEAP-I above 25 keV_{ee} (50% acceptance)

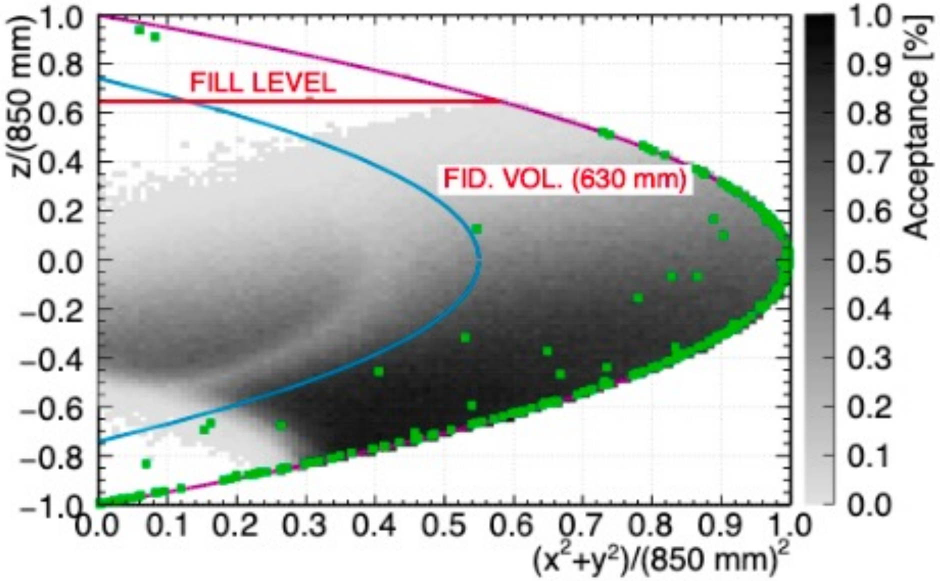
M. G. Boulay *et al.*, arXiv:0904.2930

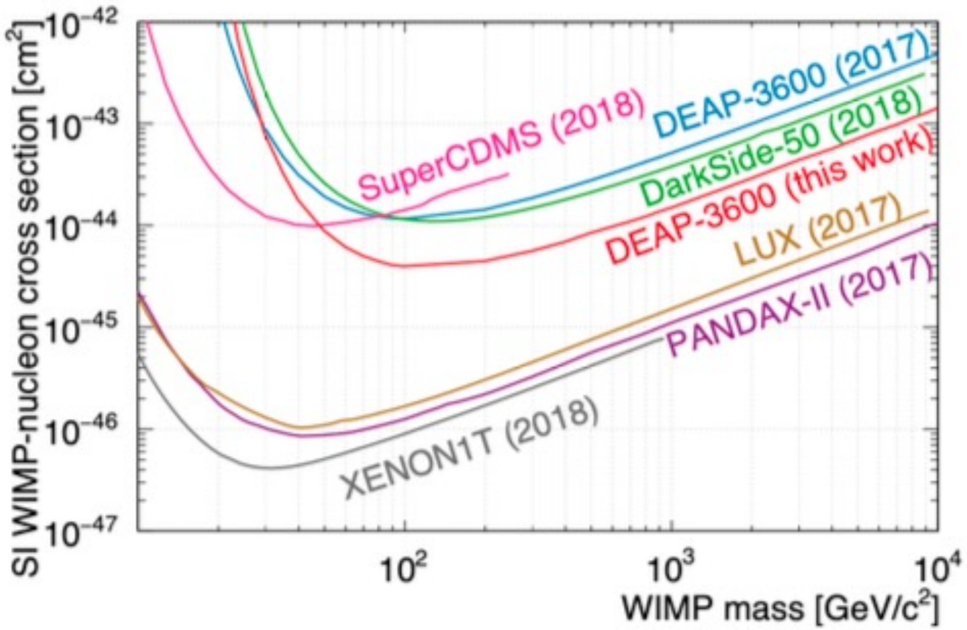
Single phase detectors

DEAP - LAr detector at SNOLAB, Canada

Dark matter **E**xperiment with **A**rgon and **P**ulse shape discrimination

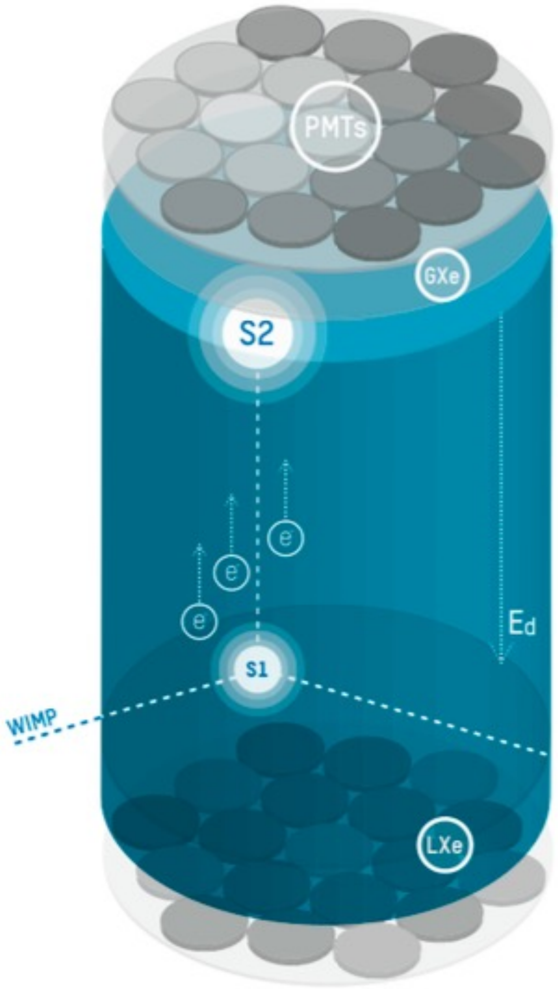
- 3 600 kg total mass & 3 280 kg fiducial volume
- Results of 231 d DEAP, PRD 100 (2019) 022004
- Most competitive liquid argon results





From Jan. 2018 to Mar. 2020: blind data taking → analysis on-going!

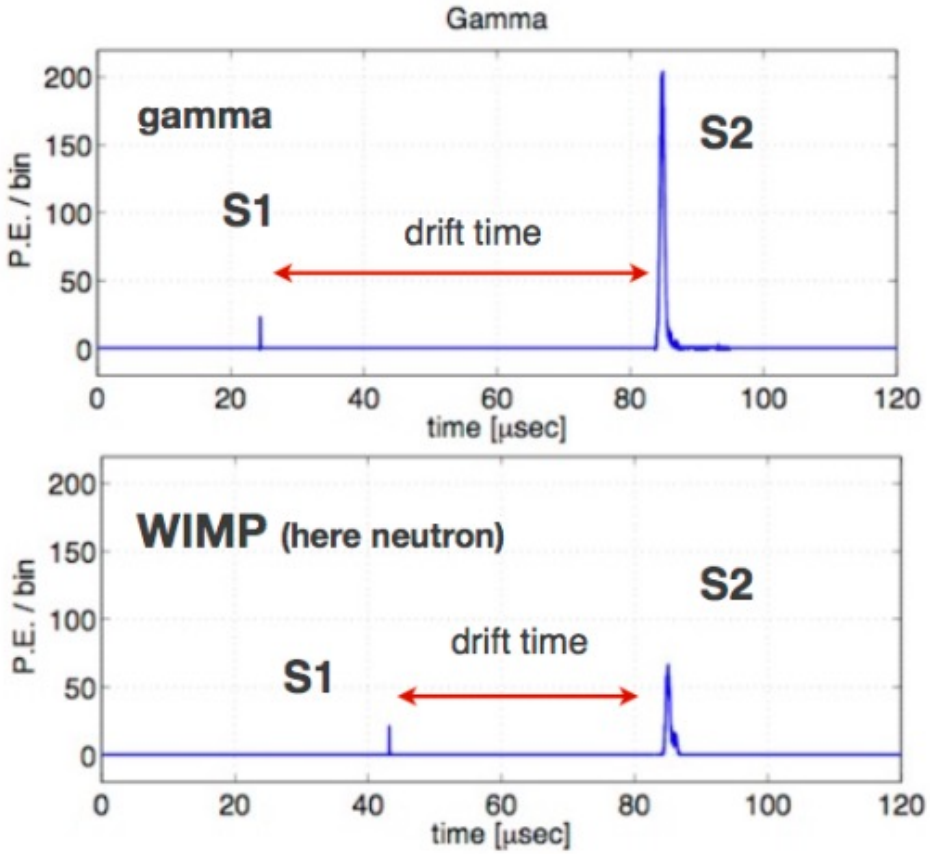
Two phase noble gas TPC



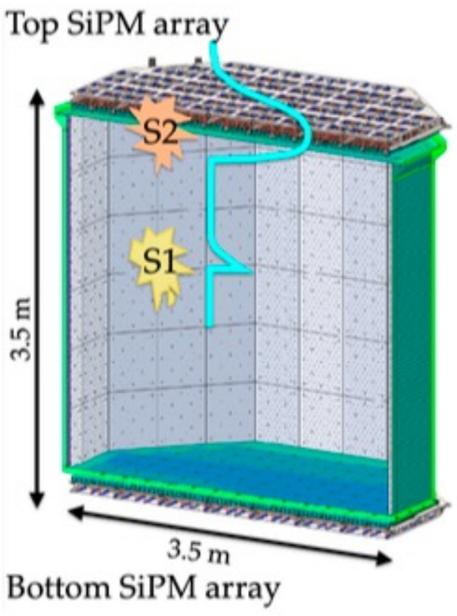
- Position resolution
  → XY from PMT pattern
  → Z from drift time

- Scintillation signal (S1)
- Charges drift to the liquid-gas surface
- Proportional signal (S2)

→ Electron- /nuclear recoil discrimination



The DarkSide experiment



- DarkSide-50 run @LNGS with 50 kg mass
  DarkSide, PRD 98 (2018) 102006 & PRL 121 (2018) 8, 081307
- DarkSide-20K: new global LAr collaboration
  - 50 t total target mass
  - TPC inside a sealed acrylic vessel
  - SiPM for light read-out (~ 19 m^2)

- Underground Ar from URANIA plant (Colorado)
  Depletion factor (in ^{39}Ar) measurement @Canfranc
  Shipment to distillation in ARIA @Sardinia
- Aiming at high mass dark-matter search
  ROI (20 – 200) keV_{nr} → operation in 2025
  E. Pantic @TAUP 2021 conference

Beyond DarkSide-20K

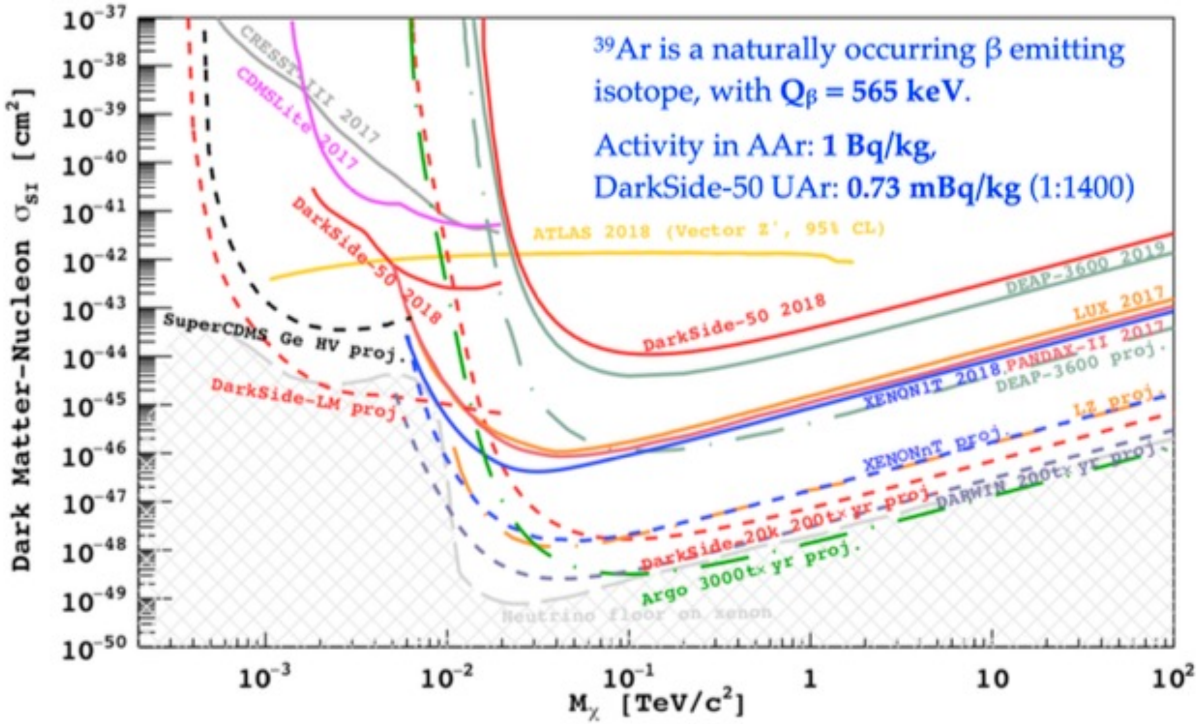
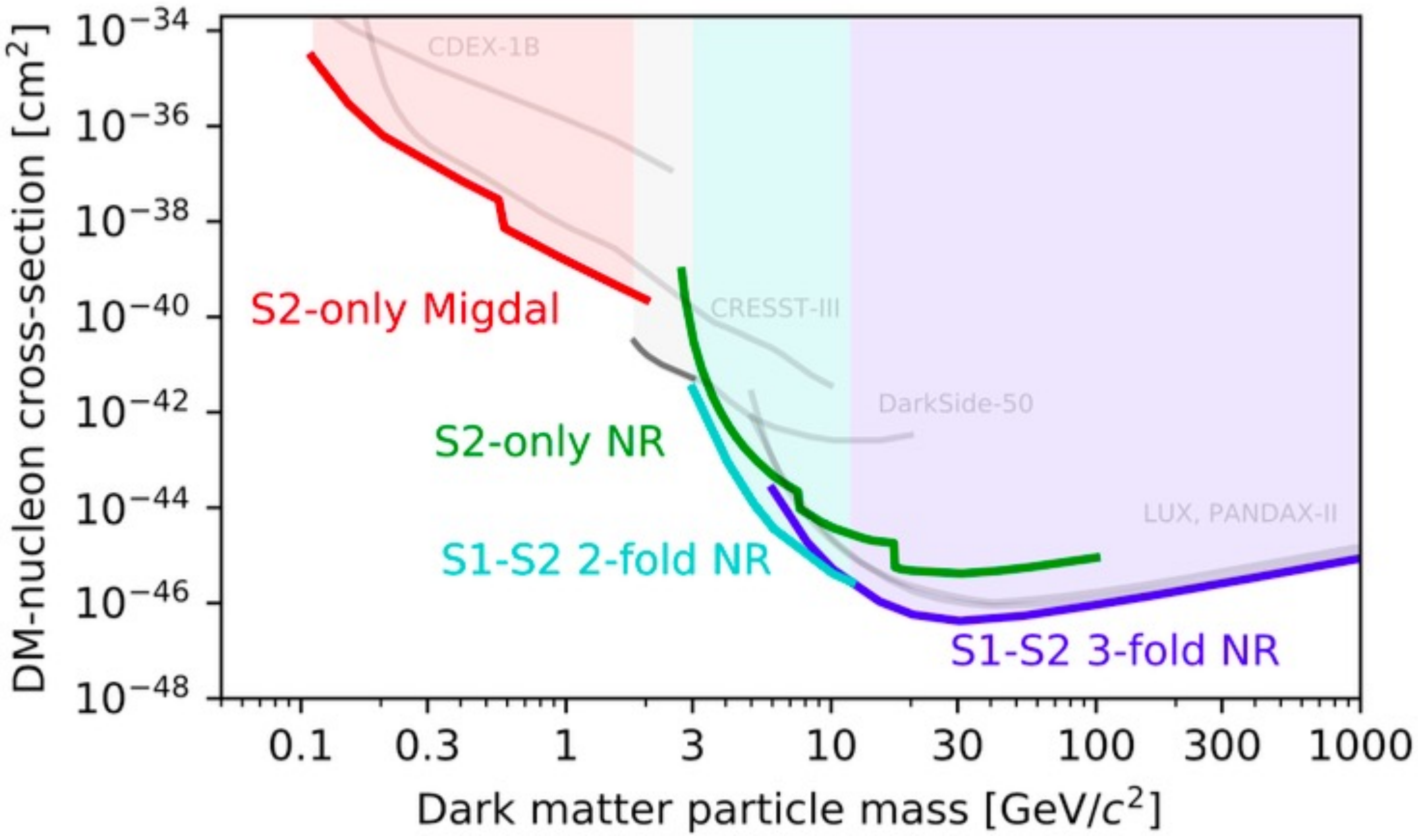


Figure from W. M. Bonivento @Canfranc SC 2021

- ARGO@SNOLAB (conceptual study)
  - Reach atmospheric neutrino floor with ~ 360 t (fiducial) UAr
  - Single- or dual-phase detector with photodetectors (~ 100 m^2)
- DarkSide-LowMass (conceptual study)
  - Reach solar neutrino floor with ~ 1 t (fiducial) in 1 y
  - Depleted underground argon & ionization channel only

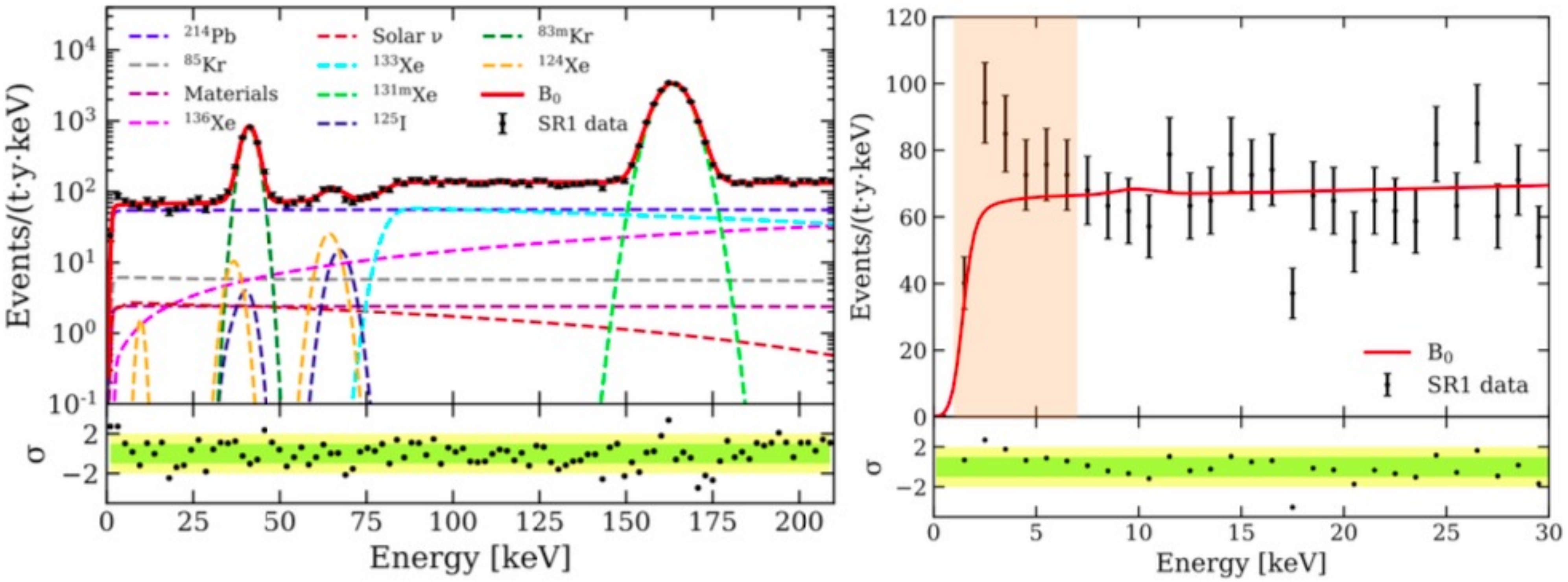
XENON 1T results



XENON1T, PRL121 (2018) 111302, PRL123 (2019) 241803, PRL123 (2019) 251801, PRL126 (2021) 091301

- XENON1T operated at LNGS from 2016 to 2019
- Best upper limits for WIMP masses above 3 GeV/c^2
- Migdal result: depends on the experimental confirmation of this effect

Interesting signal from XENON 1T



XENON1T, Phys. Rev. D 102 (2020) 072004 & arXiv: 2006.09721

Excess of events in (1-7) keV in the background region

- ~ 3.3 σ statistical significance
- A lot of excitement (> 350 citations since June 2020)
- Unclear origin: Tritium? or Axion signal? or something else?

Next generation: LZ, PandaX-4T and XENONnT

LZ:
- 7 T target mass
- Currently commissioning

PANDAX-4T:
- 4 T target mass
- First data released in July 2021

XENONnT:
- 6 T target mass
- Currently taking data

→ A race to measure WIMPs down to $\sigma \sim 10^{-48}$ cm^2

Released data from current LXe detectors

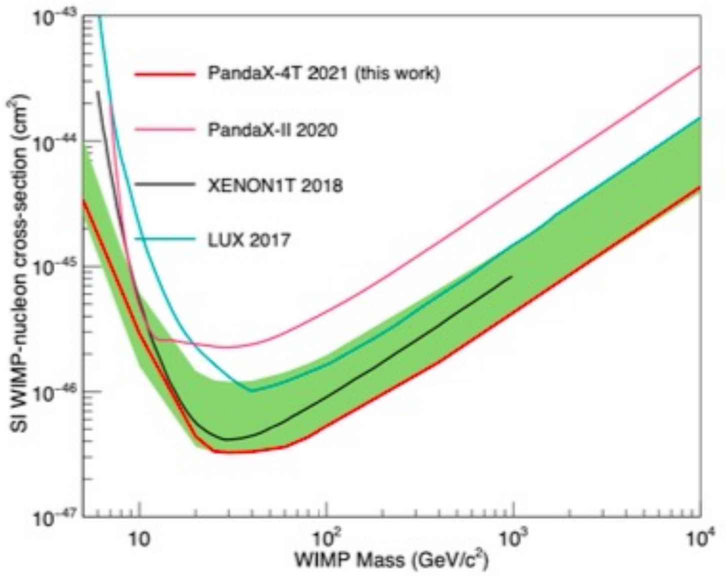


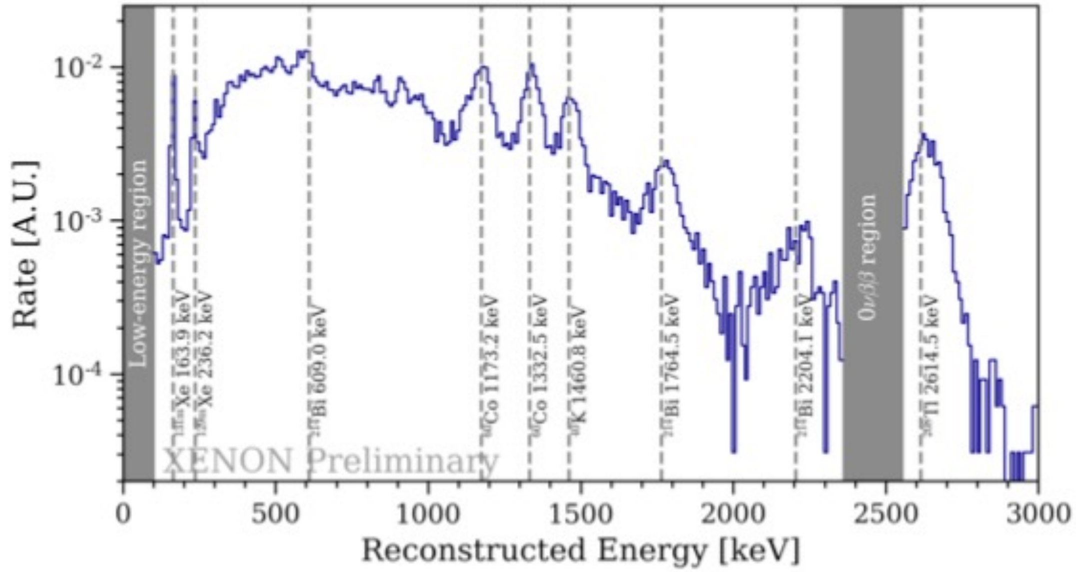
Figure from arXiv:2107.13438

- First results of PandaX-4T@CJPL (non blind analysis)
- Contamination with ^3H

→ no check of XENON1T excess possible

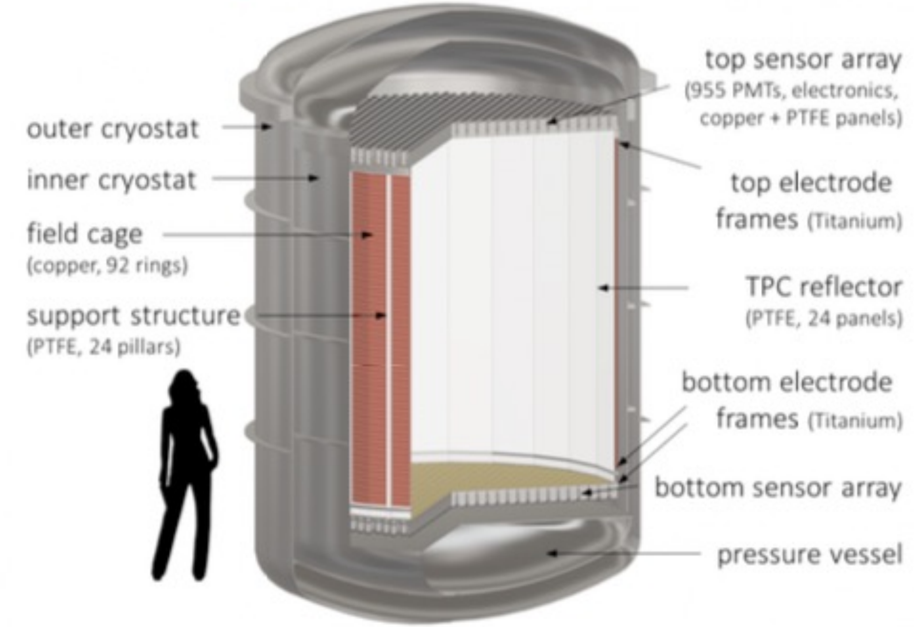
- Rn level at 4.2 μBq/kg similar to XENON1T

- XENONnT @LNGS, first performance data
- Background goal in reach (Rn ~ 1.7 μBq/kg)
- Test low ER excess

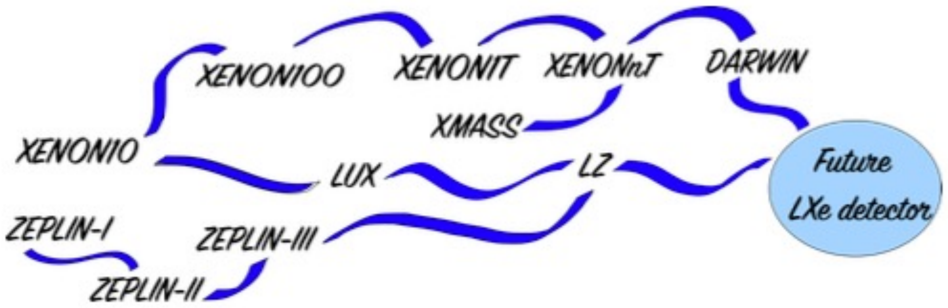


DARWIN: the ultimate WIMP detector

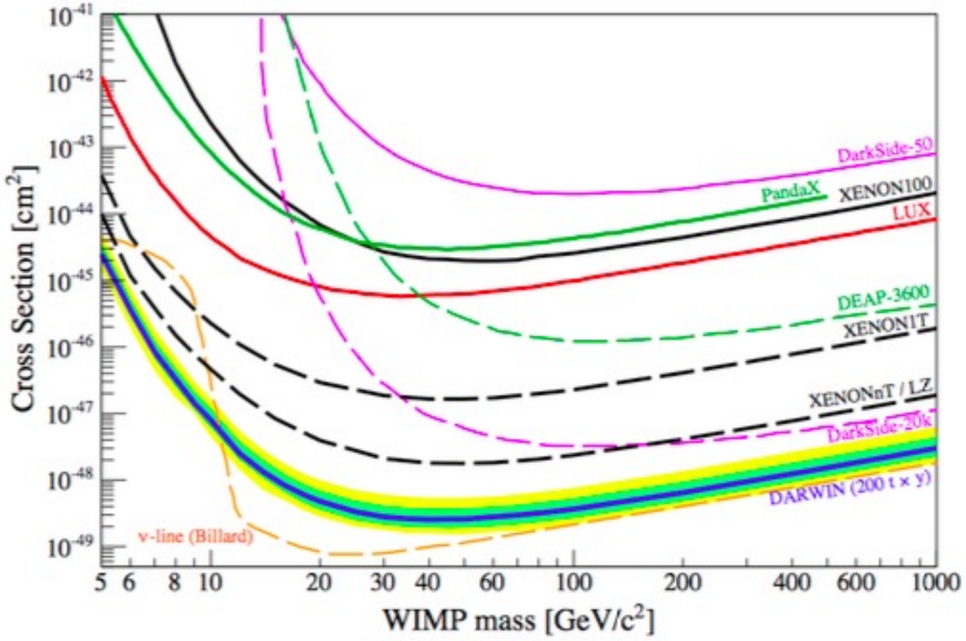
dark matter wimp search in noble liquids
DARWIN



50 t LXe total (40 t in the TPC)



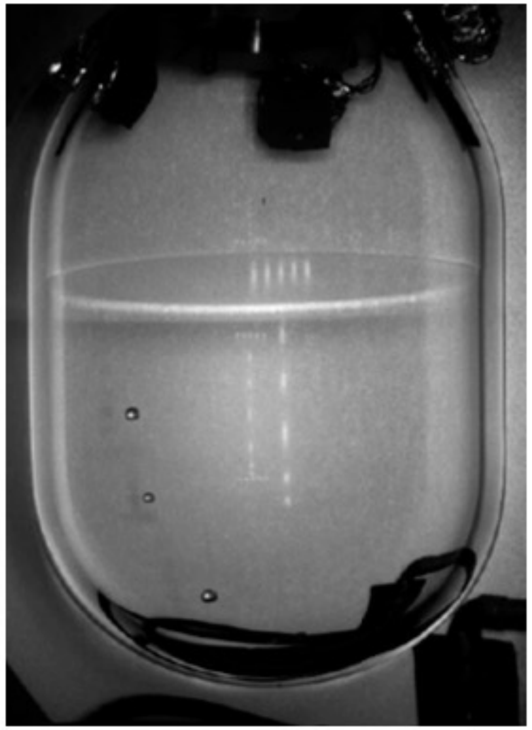
- Goal: measure WIMP properties / ultimate cross-section sensitivity
- Additional physics channels:
  - Solar & supernova ν's
  - CEνNS, proton decay, DEC & neutrinoless $\beta\beta$-decay ...



DARWIN, JCAP 1611 (2016) no.11, 017, arXiv:1606.07001

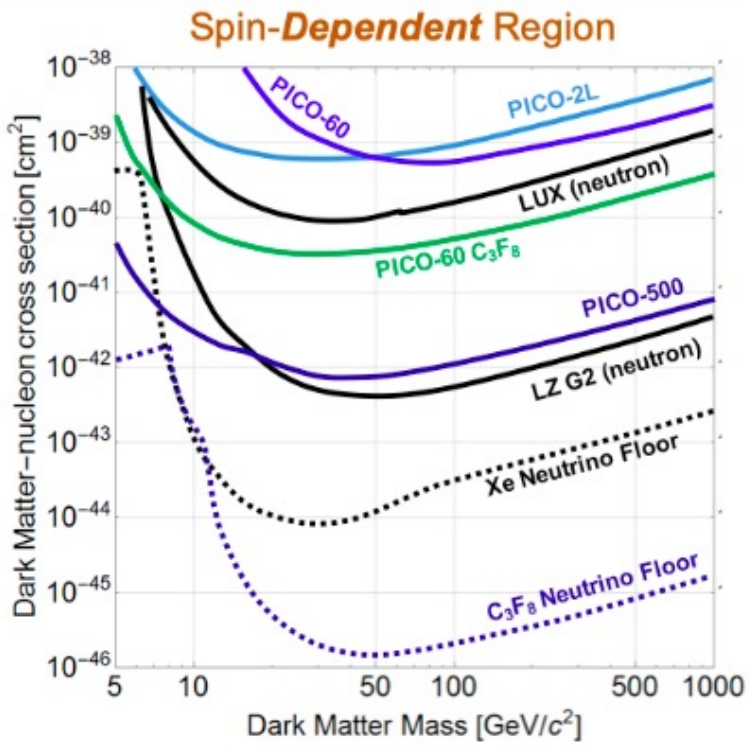
Superheated fluid detectors

COUPP experiment



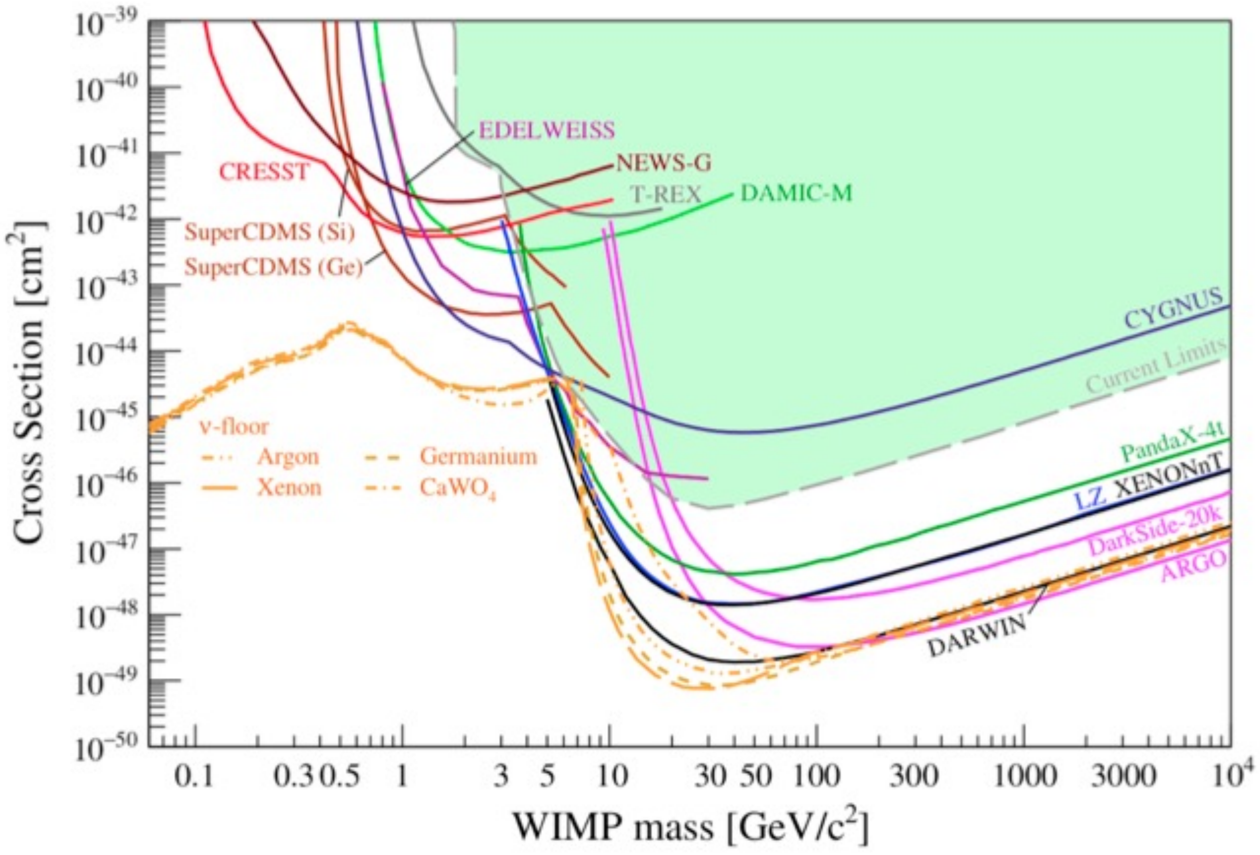
- Energy depositions > E_{th} → expanding bubble detected with cameras + piezo-acoustic sensors

- A bubble chamber filled with superheated fluid (C_3F_8) in meta-stable state
- Great sensitivity to spin-dependent σ



- PICO-500: detector to be installed in the miniCLEAN space @SNOLAB (TDR planned for early 2022)

Prospect for the future



Sensitivity projections from the APPEC report, J. Billard et al., (2021) arXiv:2104.07634

- DD covers a large range in mass and cross section
- Exploring WIMPs but also light DM, ALPs, dark photons ...
- We hope for a dark matter discovery ideally in various detectors!