# Direct Searches for Dark Matter

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# A long List of Evidences for Dark Matter…

+ Galactic rotation curves
+ Galaxy clusters & GR lensing
+ Bullet Cluster
+ Velocity dispersions of galaxies
+ Cosmic microwave background
+ Sky Surveys and Baryon Acoustic Oscillations
+ Type Ia supernovae distance measurements
+ Big Bang Nucleosynthesis (BBN)
+ Lyman-alpha forest
+ Structure formation
+ …

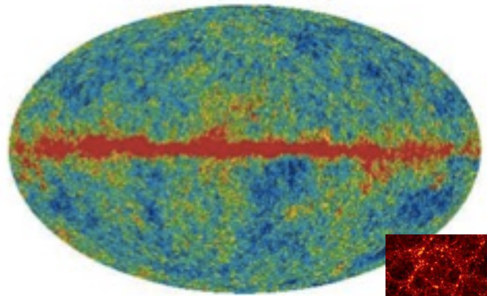
➔ **strong evidence for a large dark sector**

➔ **evidences: GR-dynamic, GR-static, radiation, …**

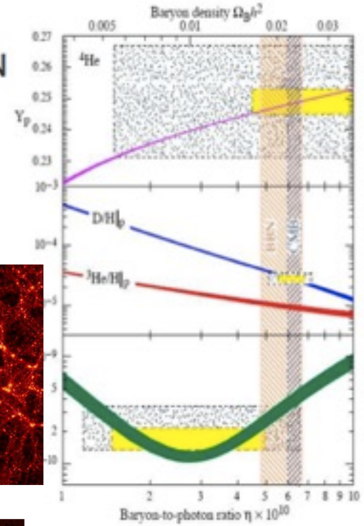
➔ **cannot be explained by ordinary matter**

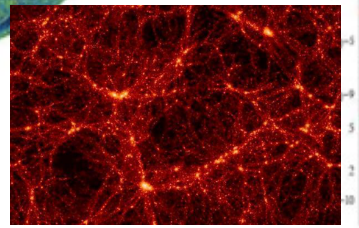
➔ **strong astronomy / cosmology groups in cluster!**

CMB (WMAP)

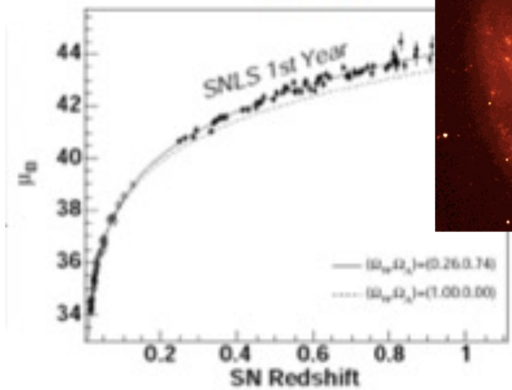


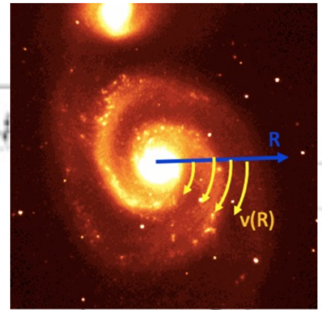
BBN



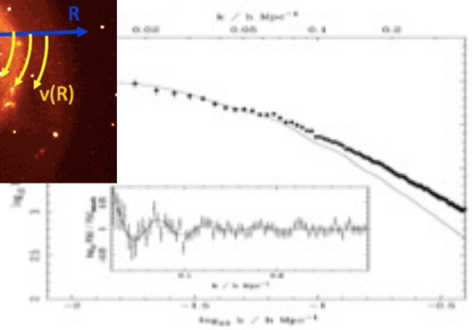


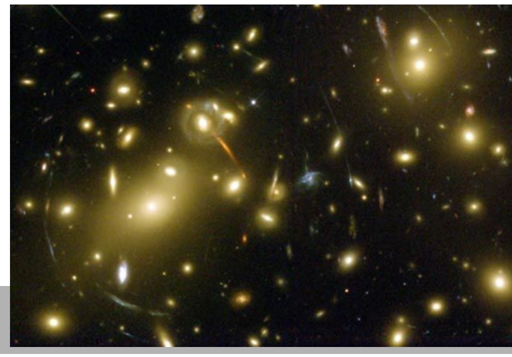
SN 1a



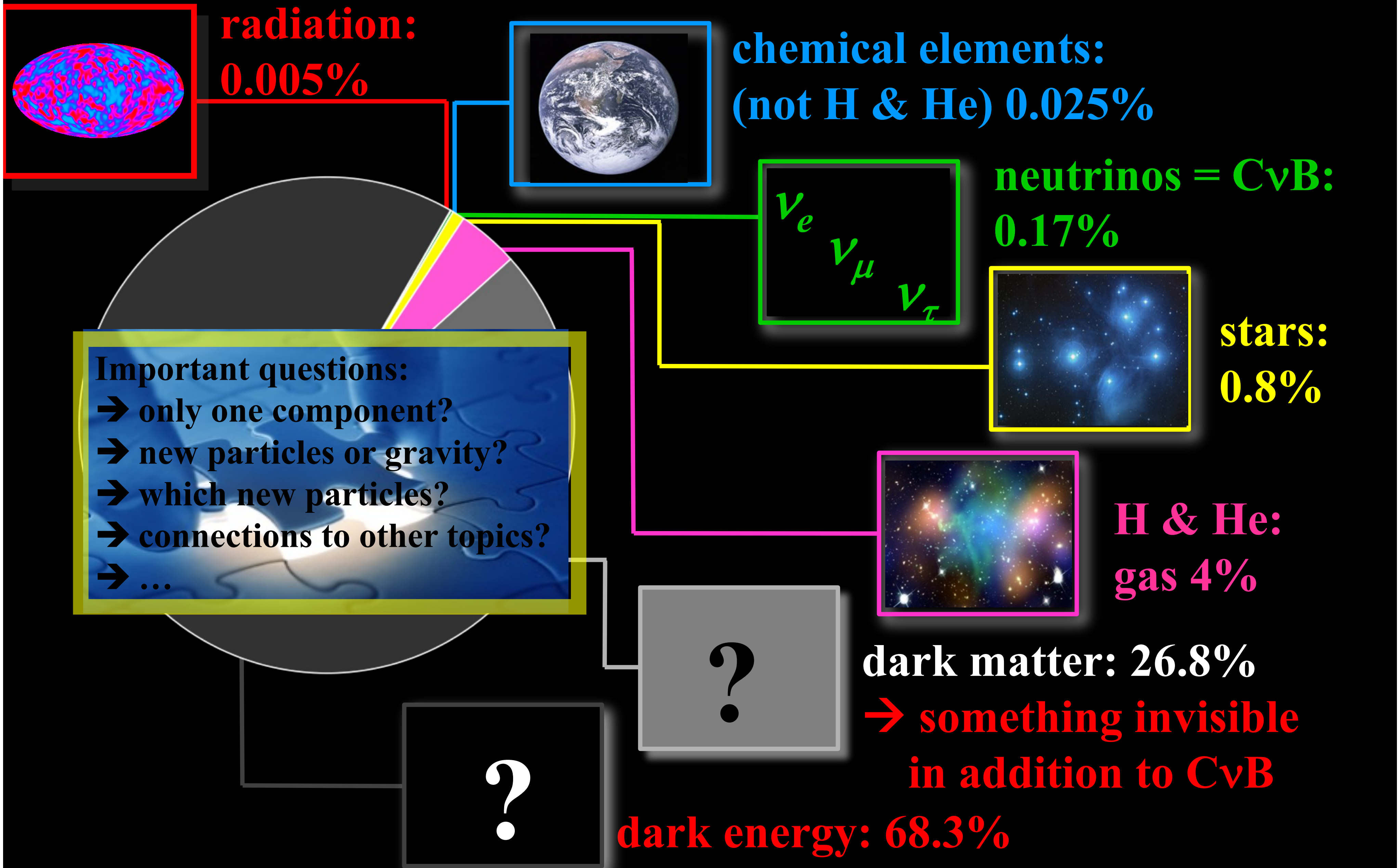




BAO

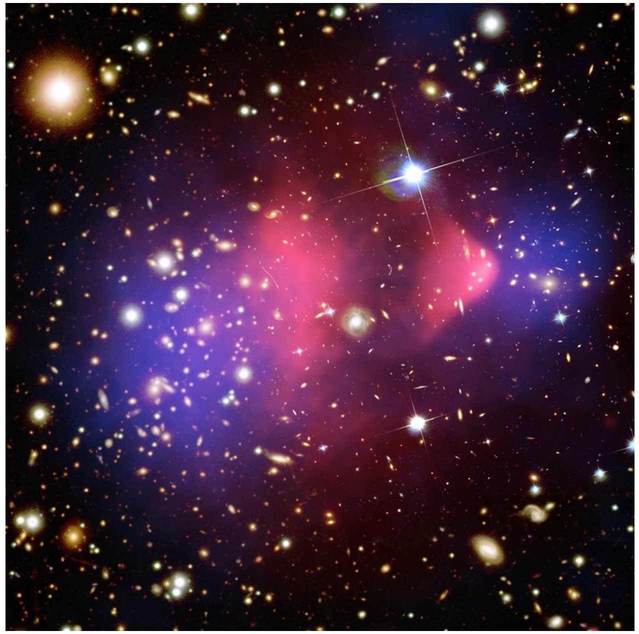




# The cosmic Matter Balance

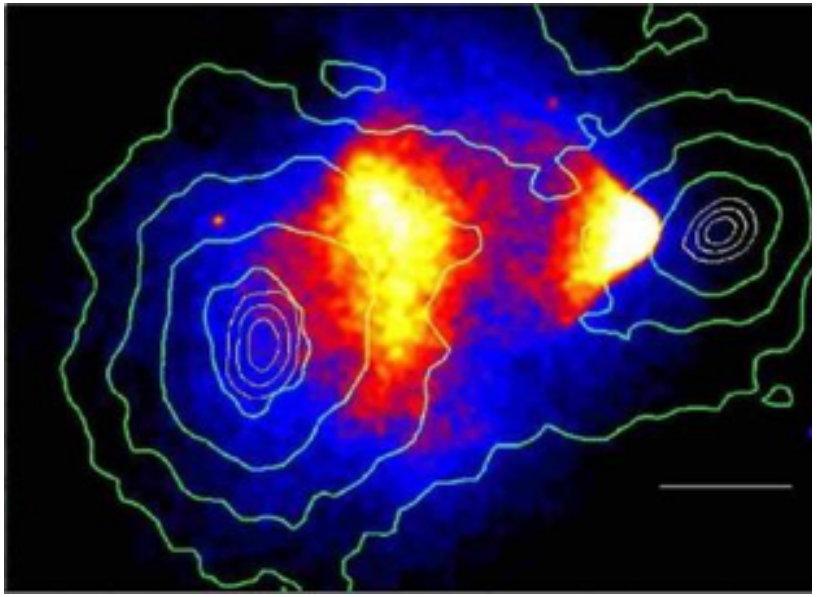


# Is it Particles?



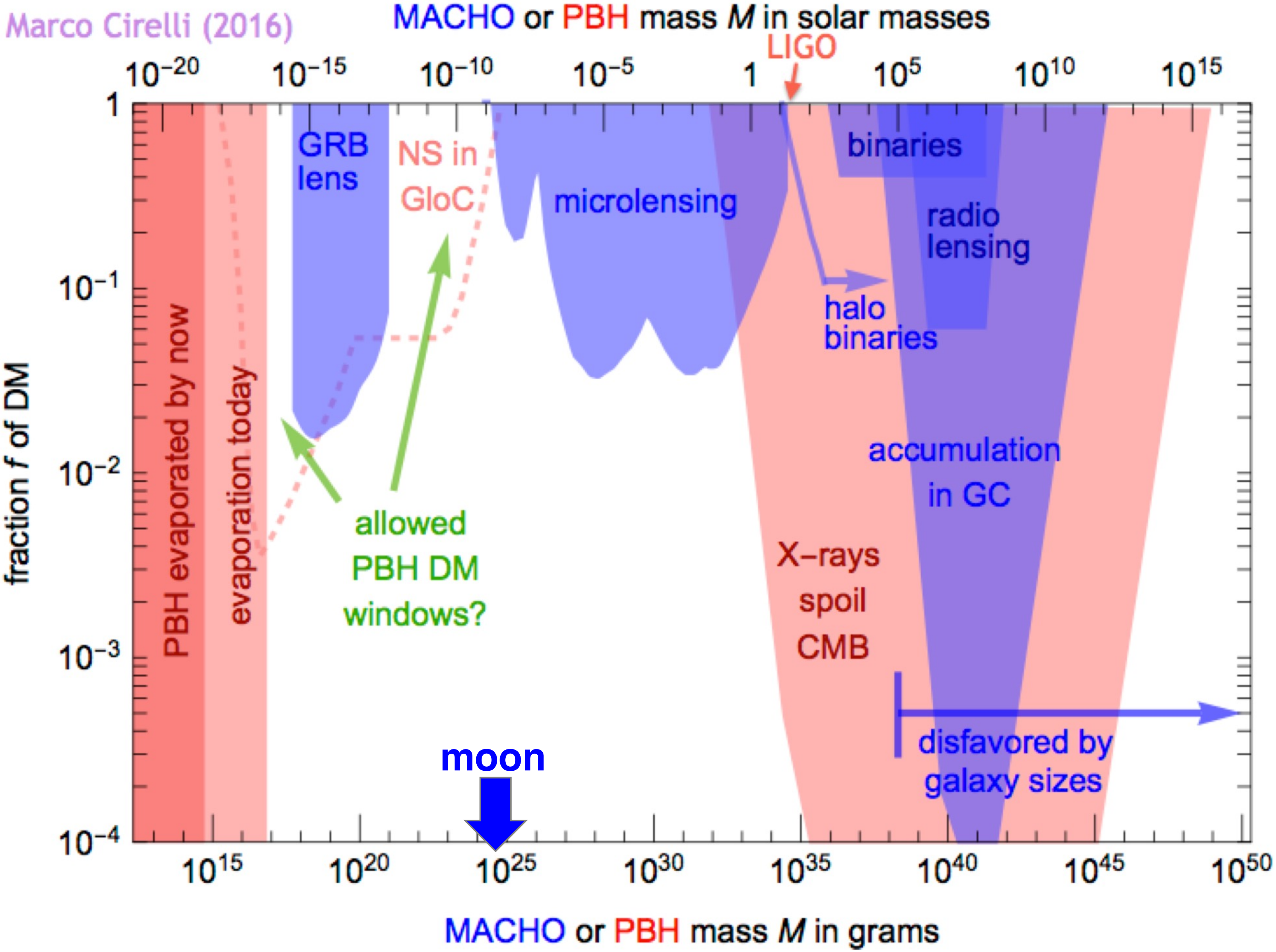
- **bullet cluster (1E 0657-56)**
  - colliding galaxy clusters
    = stars, gas, DM ; up to $10^6$ km/h
  - x-rays from charged particle interactions
  - Dark Matter just traverses w/o scattering
  ➔ displacement of visible matter
     and GR potential = all matter (~ 8σ)

- **Shows that normal particles scatter, but NOT that DM is particles**



- **<u>What is needed:</u>**
  - gravitates ←→ mass
  - non-baryonic
  - SM neutral
  - no or very limited self-interaction
  - no coupling to massive particle
  - stable or long lived

# Black Holes as Dark Matter



# Competing Dark Matter Directions

## Gravity

**MOND**
a simple one scale modification
→ fails badly

**Other**
new GR modifications

or

a suitable population (mass, number) of black holes

## Particles

**BSM physics motivated by SM problems**
+ WIMPs (neutralinos)
+ axions
+ sterile ν's
- …

**Correct thermal abundance**
+ WIMPs
- dark photons
- ALPs
? other new particles

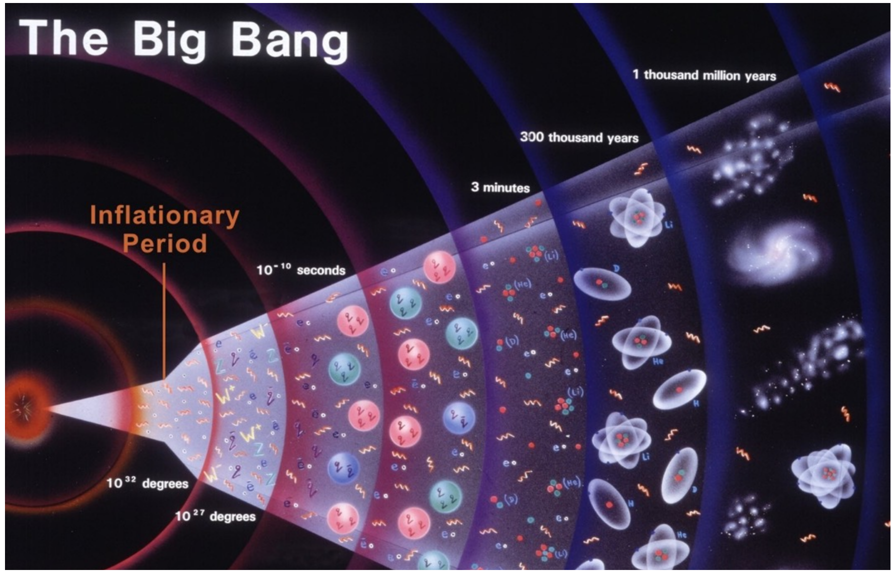
**WIMPs** combine both aspects in an attractive way: **BSM + abundance**

# The WIMP Miracle

**inflation ➔ many e-folds**

**Reheating ➔ all particle types produced**

**Evolution of original plasma by:**
**- expansion (dilution)**
**- decays**
**- interactions ➔ conversion processes**

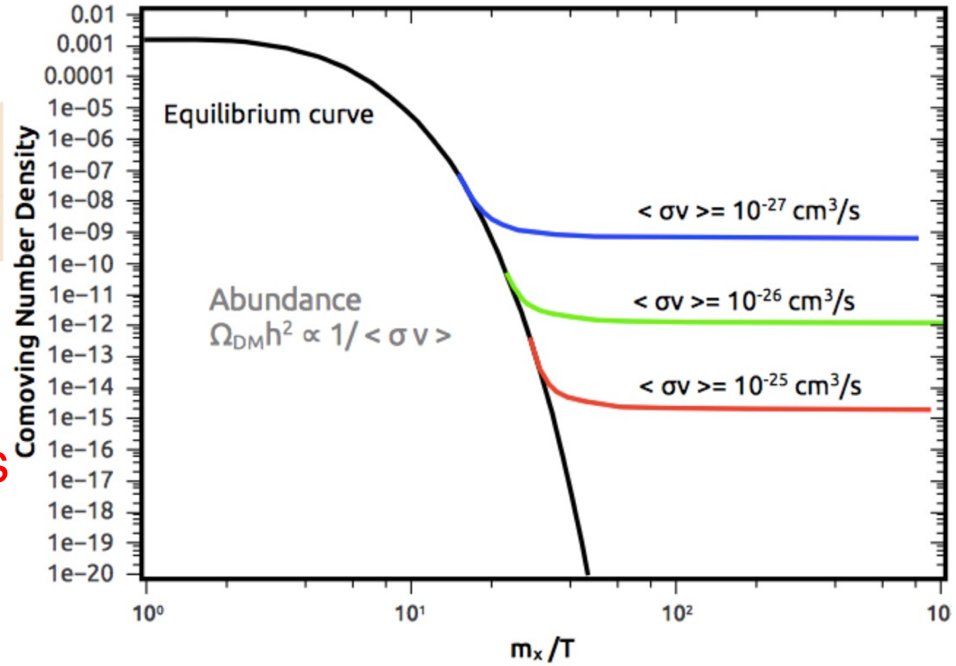



## Evolution of original DM density:

➔ Boltzmann equation

$$\frac{dn_\chi}{dt} + 3H(T)n_\chi = -\langle\sigma v\rangle(n_\chi^2 - n_{\chi,eq}^2)$$

➔ thermal freez-out

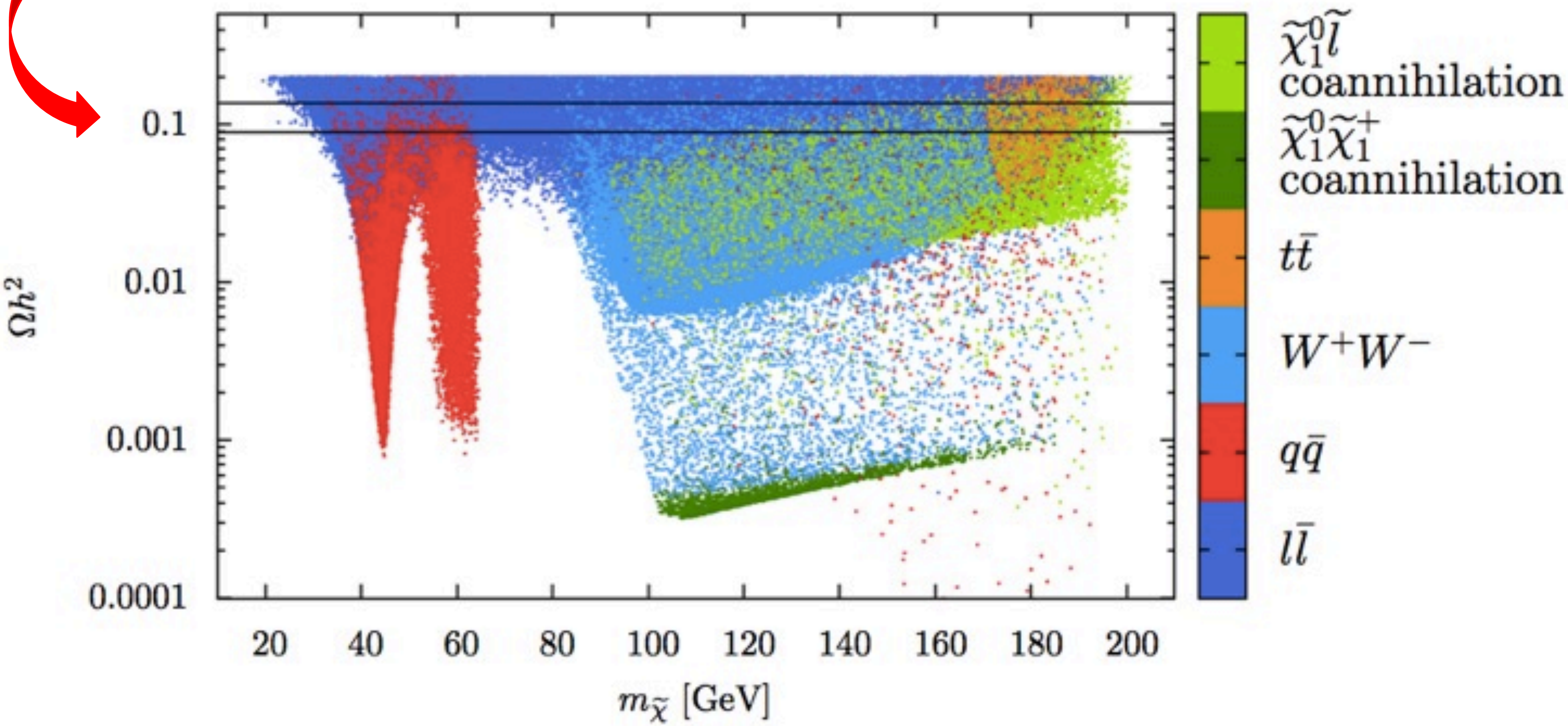



BSM motivated new physics @TeV scales
➔ Automatically ~ correct abundance

# Hierarchy Problem ➔ MSSM ➔ Vanilla WIMP

- **LSP=Neutralino ➔ WIMP miracle ➔ correct abundance**

**Scan parameter space for different annihilation channels ➔ $\Omega h^2$**
**Note: we will not argue for equal probability in parameter space!**

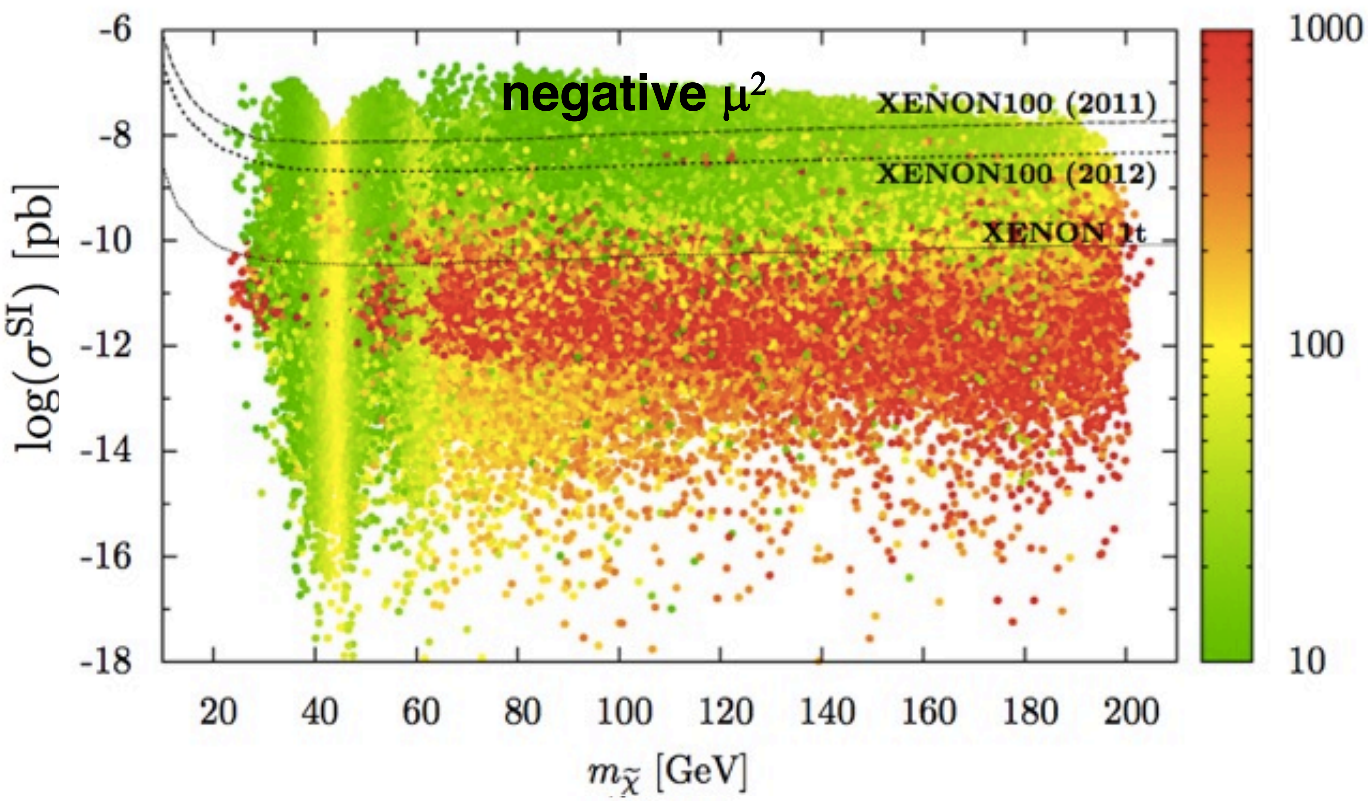



**➔ Select correct range of $\Omega h^2$ ➔ constrains parameter ranges**

# How fine-tuned are the paramaters?

- **MSSM neutralino: Level of fine-tuning → $\Delta_{tot}$**

$$\Delta p_i \equiv \left| \frac{p_i}{M_Z^2} \frac{\partial M_Z^2(p_i)}{\partial p_i} \right| = \left| \frac{\partial \ln M_Z^2(p_i)}{\partial \ln p_i} \right| \qquad \Delta_{tot} \equiv \sqrt{\sum_{p_i=\mu^2, b, m_{H_u}^2, m_{H_d}^2} \{\Delta p_i\}^2}$$




→ XENON100-2010
→ XENON100-2012
→ XENON1T

- **XENON100 cuts already into expected space**
- **XENON1T covers a much larger part**

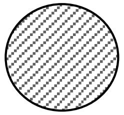
* **XENONnT covers most**
   ➔ **high potential**
   ➔ **be first!**

**LMSSM: x-section down**

Grothaus, ML, Takanishi: full MSSM, not CMSSM, pMSSM, NMSSM…⇔ **WIMP miracle?**

# Generic WIMP Cros Section

- Quantum mechanics: wavelength $\lambda \sim 1/\text{mass}$



"size = area" of a particle: $\pi\lambda^2 = \pi/m^2$

➔ cross section: area ✖ coupling strength

$\sigma \sim O(0.001\text{-}1.0)^2 \quad g_2^2 \quad \pi/m^2$

model parameters — some weak coupling — area

or tuning, symmetry, …

←→ abundance

➔natural range for a 50GeV WIMP: $\sigma \sim 10^{-42} - 10^{-48}\ \text{cm}^2$

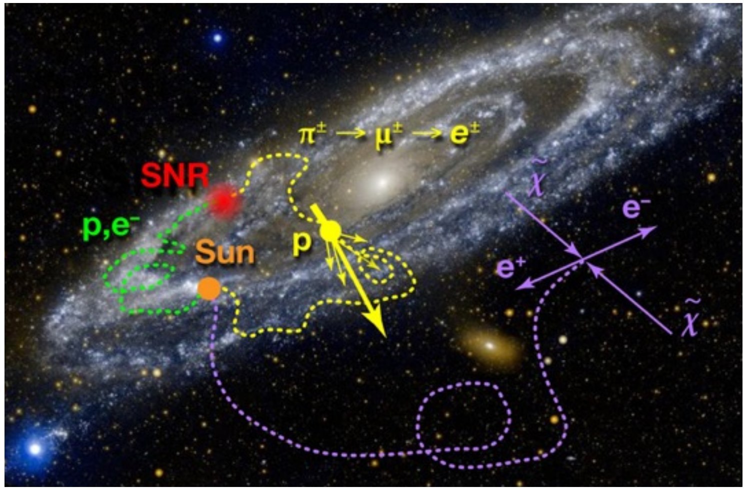
known amount of DM ➔~WIMP flux ➔ rate@direct.det.

➔ we know size/sensitivity of a detector which can cover the most interesting natural WIMP space

# Hunting WIMPS in different Ways

**known Standard Model (SM) particles interact with WIMPs: assumptions…**

**indirect detection**

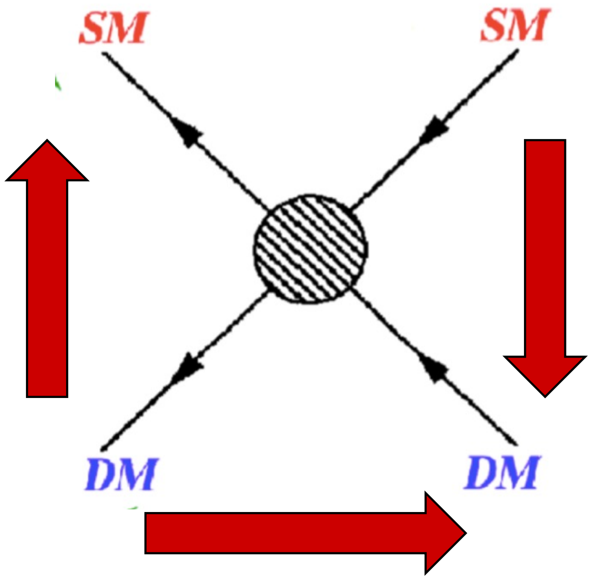



FERMI, PAMELA, AMS, HESS, IceCube, CTA, HAWC…

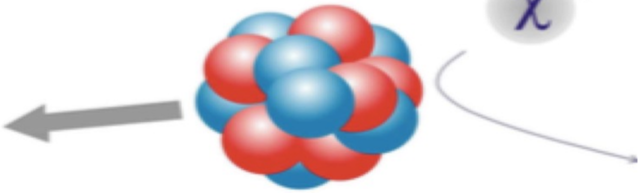
astronnomical uncertainties...

→ is the signal without doubt from DM?

keV lines ←→ atomic physics




**direct detection**

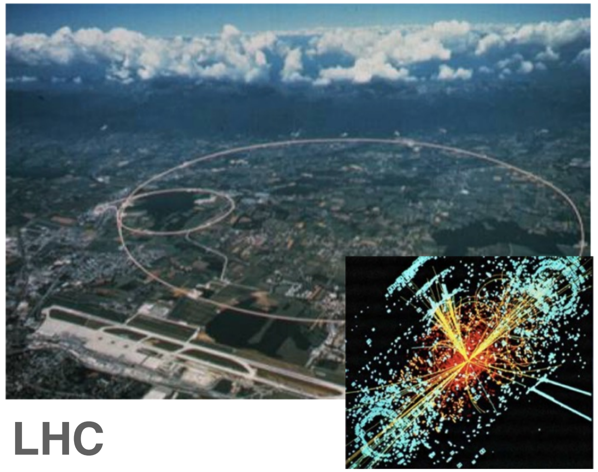



WIMP wind : 220km/s from Cygnus

→ modelling

→ rare event backgrounds

**colliders**



LHC

may detect new particles, but is it DM (lifetime, abundance)?

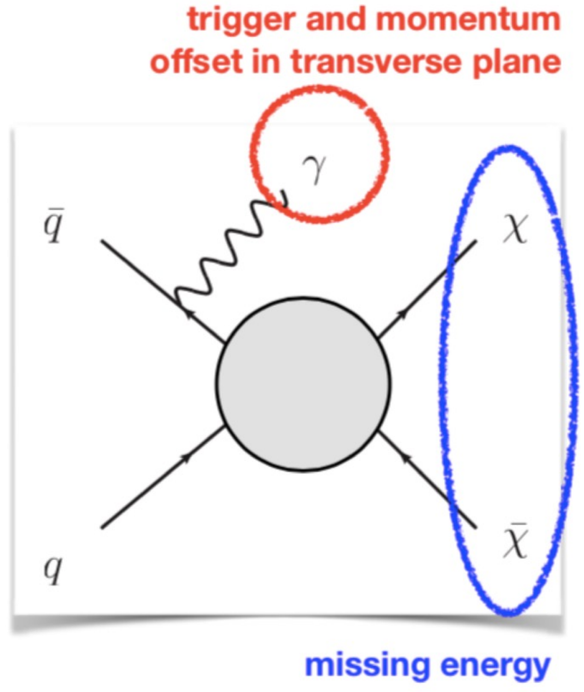
So far nothing seen…

- → impact on theory…
- → SUSY → higher scale
- → other SB motivated WIMPs
- → new ideas/candidates

# Dark Matter Production at Colliders

DM particles do not interact via electromagnetic interaction
➔ **no DM tracks in a detector**

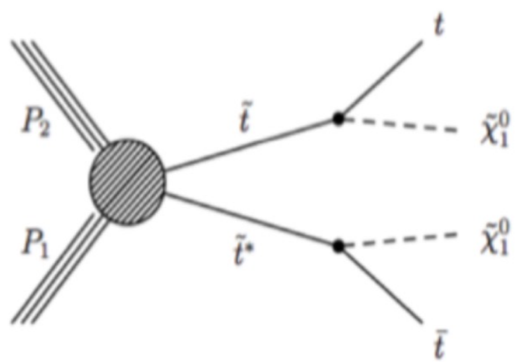
DM particles carry energy & momentum
➔**missing energy**




**two approaches at colliders for DM search:**

**1) direct production of DM particles**
annihilation of standard model particles into a pair of DM particles

**2) indirect production of DM particles**
search for dedicated decay chains with DM-like particles using a dedicated model (e.g. SUSY)

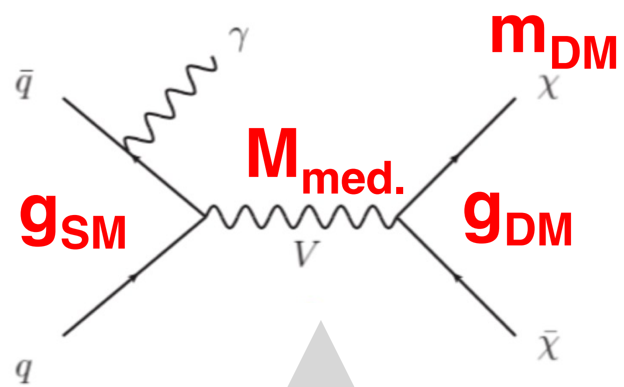



**Drawbacks:**
- a signal does not guarantee a long life-time
- unrelated to DM density in the Universe

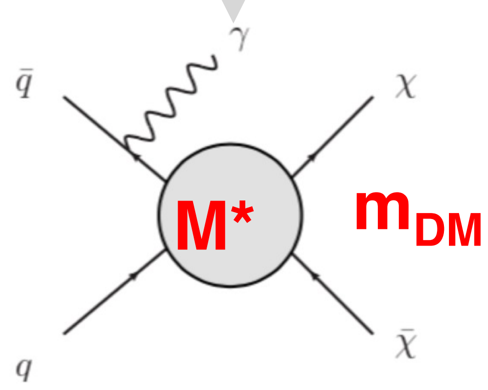
# EFT Interpretation

For q << mediator mass $M_{med}$

**➔Interaction described by $M^*$ and $m_{DM}$**




$$\frac{g^2}{(q^2+M^2_{Med.})} \xrightarrow{q^2 \ll M^2_{Med.}} \frac{g^2}{M^2_{Med.}}$$




type of interaction ➔ different operators

most common:

| Name | Initial state | Type | Operator |
|---|---|---|---|
| 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 | $\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^\mu q$ |
| D9 | $qq$ | tensor | $\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$ |
| D11 | $gg$ | scalar | $\frac{1}{4M_*^3}\bar{\chi}\chi\alpha_s(G^s_{\mu\nu})^2$ |

D1, D5, D11 spin independent (SI), D8, D9 = SD

**Mediator induces also SM➔SM processes**

➔ LHC sets limits on **$g^2_{SM}/M^2_{med}$** (mod. $m_{DM}$)

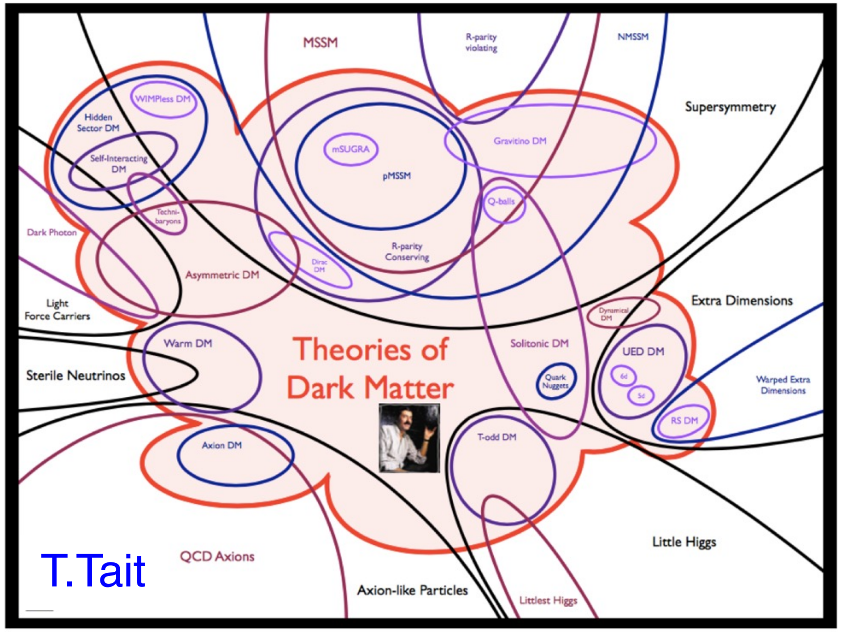
➔Unless $g_{SM}$ is tiny TeV-ish limits on **$M_{med.}$**

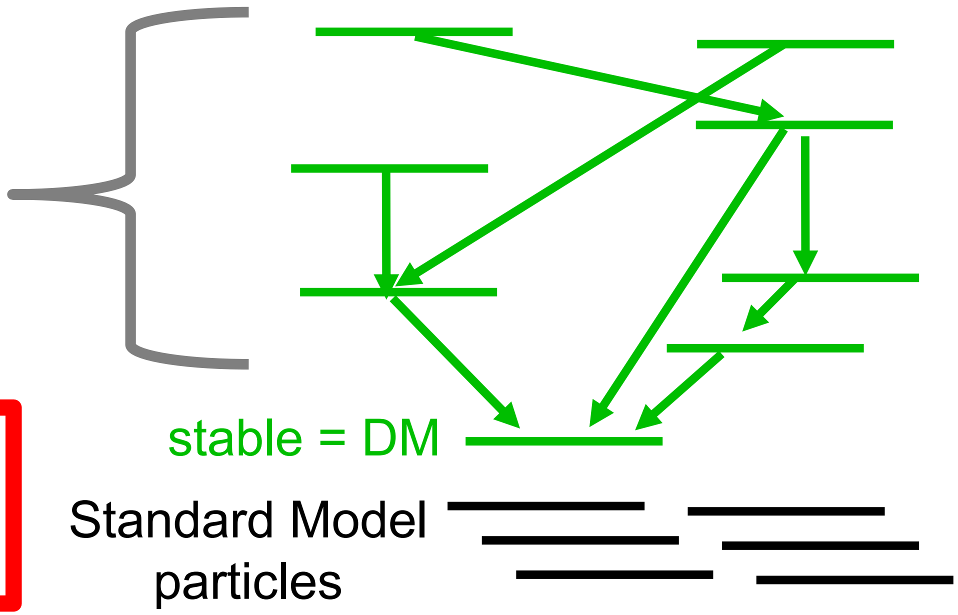
**$g_{DM}$ =1 is an assumption** ➔ could be tiny ➔ weaker DM limits

***or* a full model** ➔more signatures/effects & constraints

# DM motivated Extensions have other Consequences

- More particles…
- All existing particles produced in Big Bang and later (decays, …)
- Some particles may be stable
- Very long-lived due to small parameters → natural?
- Effects of unstable states +/-
  ➔ on the early Universe
  ➔ on collider physics

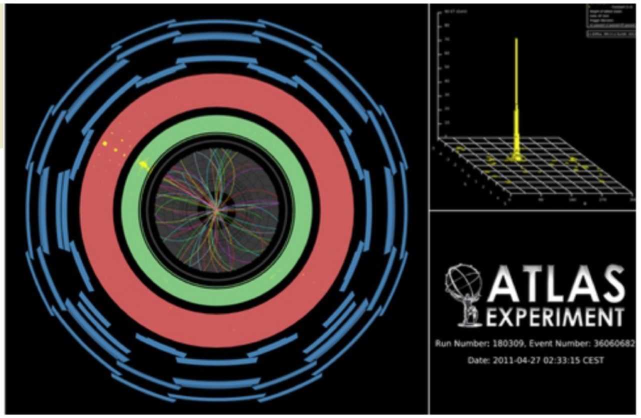


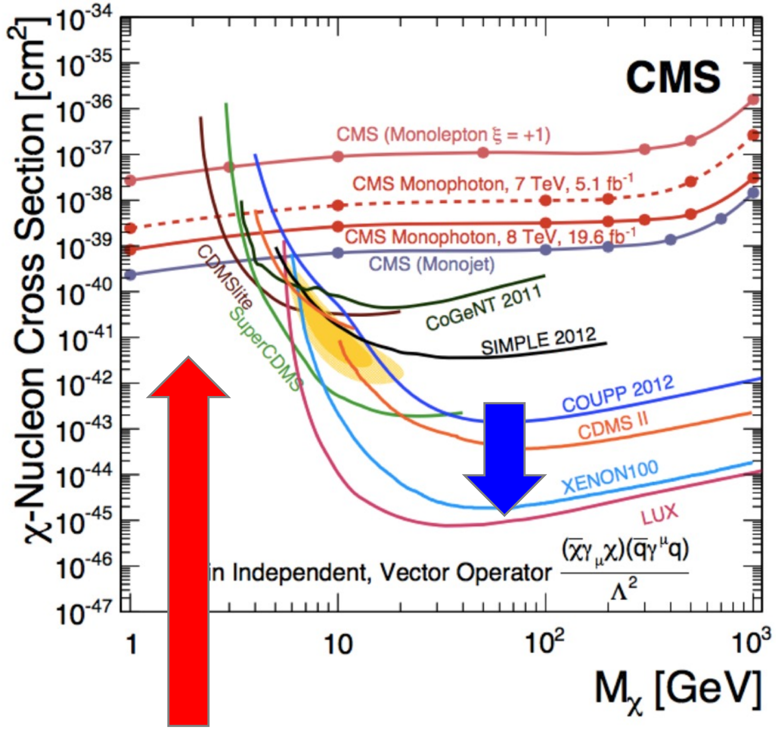




**Warning: Your DM model may affect many other known things!**

# Dark Matter at the LHC

- **Generic signature** $pp \rightarrow \not{E}_T + X$
- **Generic kinematics:** weak dependence on WIMP mass for $m_{DM} \ll$ beam energy




**light WIMPs**
$\mathcal{L}$ ➔ **timing**

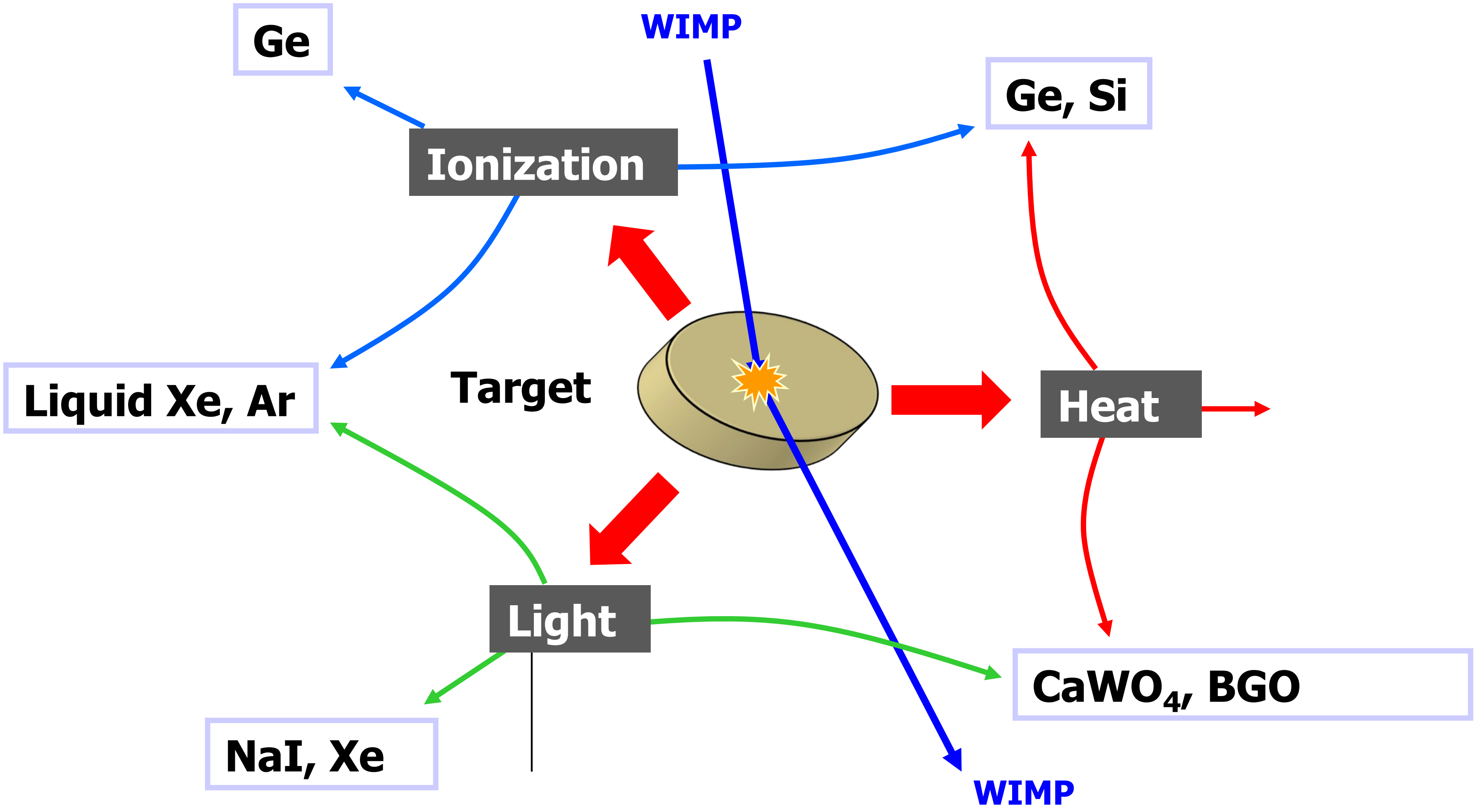
**heavy WIMPS**
→ **direct searches**

**←→ CRESST-III, SuperCDMS ➔ GeMMC**

- **Life is more complex…**
  - many conceivable candidates
  - detection efficiencies, ...
  - ➔ EFT or simplified models =parametrizion – not always appropriate
  - $g_{DM}$ = assumptions *or* full model +...
- **LHC:**
  - can exclude a DM candidate
  - can establish a candidate
  - does not test if it is DM in Univ.: long lived? abundance?

# Direct Detection Techniques (WIMPs)

- **Detection of DM = see what the Universe is made of**
  **➔ WIMP wind (known flux) scatters on target atoms ➔ signal…**

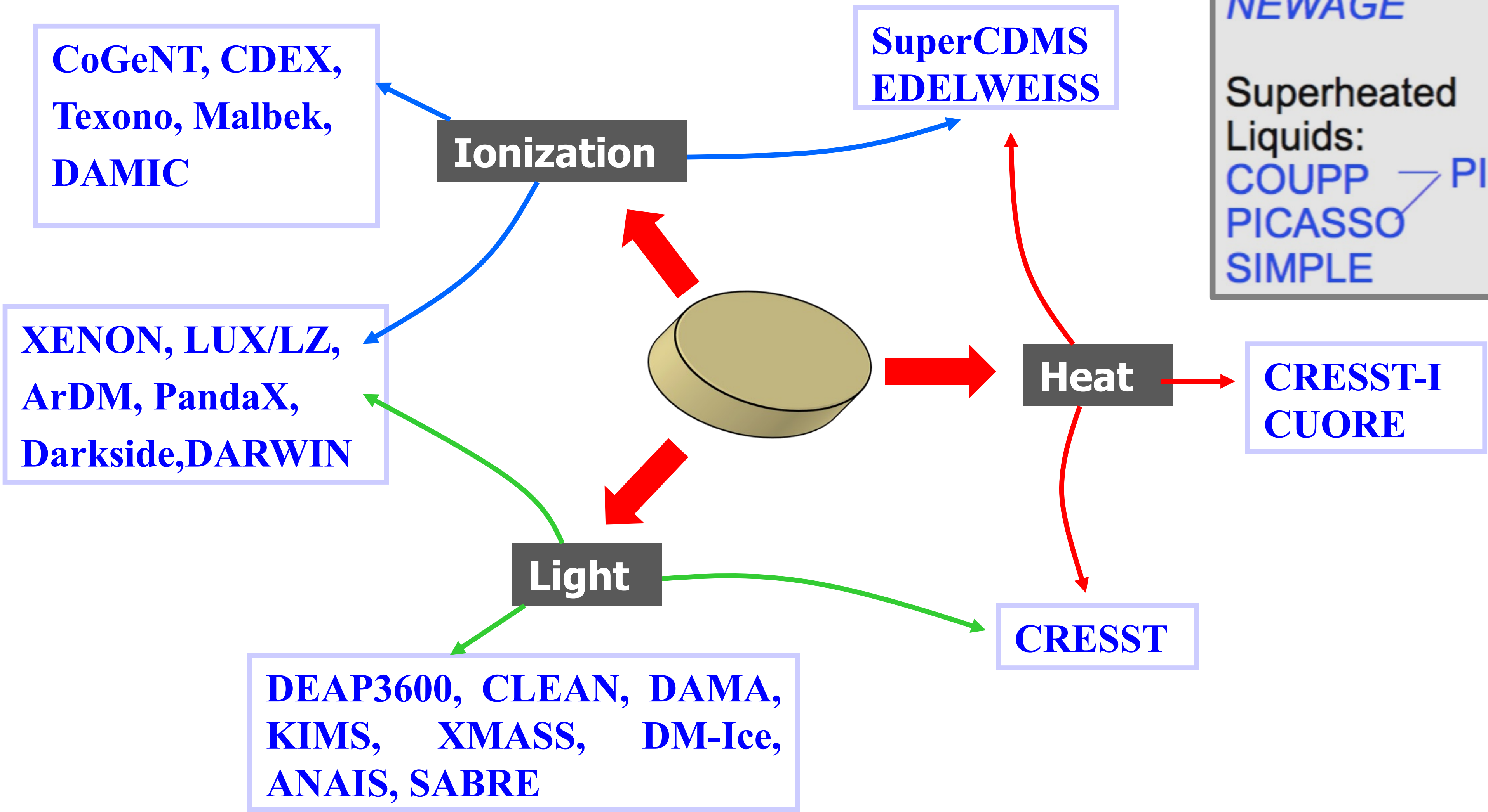


# Direct Detection Experiments

**Detection metods:** Crystals (NaI, Ge, Si), Cryogenic Detectors, Liquid Noble Gases

Tracking:
*DRIFT, DMTPC*
*MIMAC*
*NEWAGE*

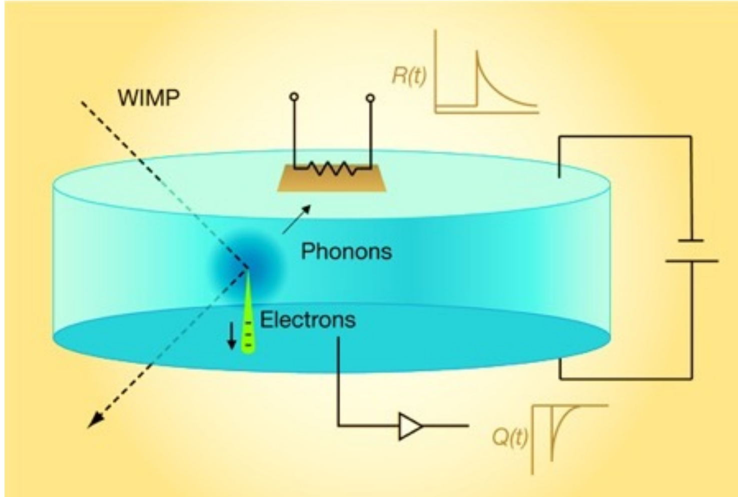
Superheated Liquids:
COUPP → PICO
PICASSO → PICO
SIMPLE

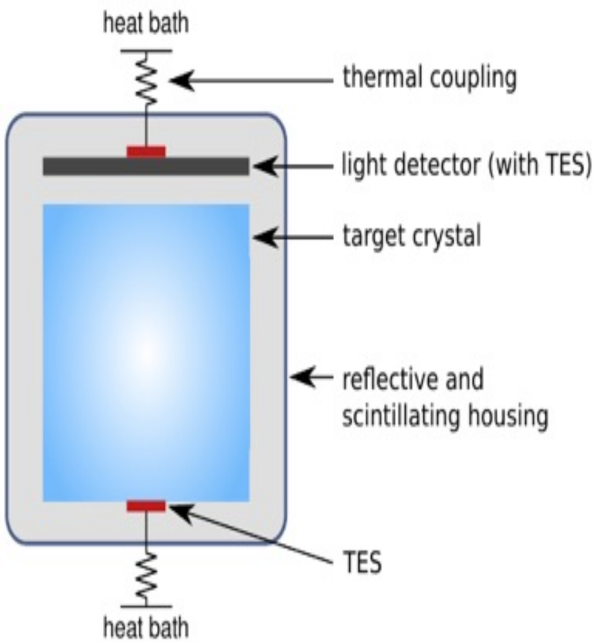


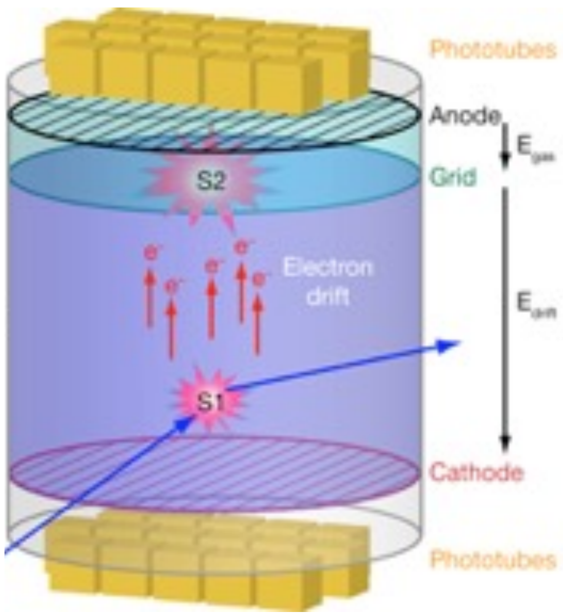
# Converting WIMP Scattering into Signals

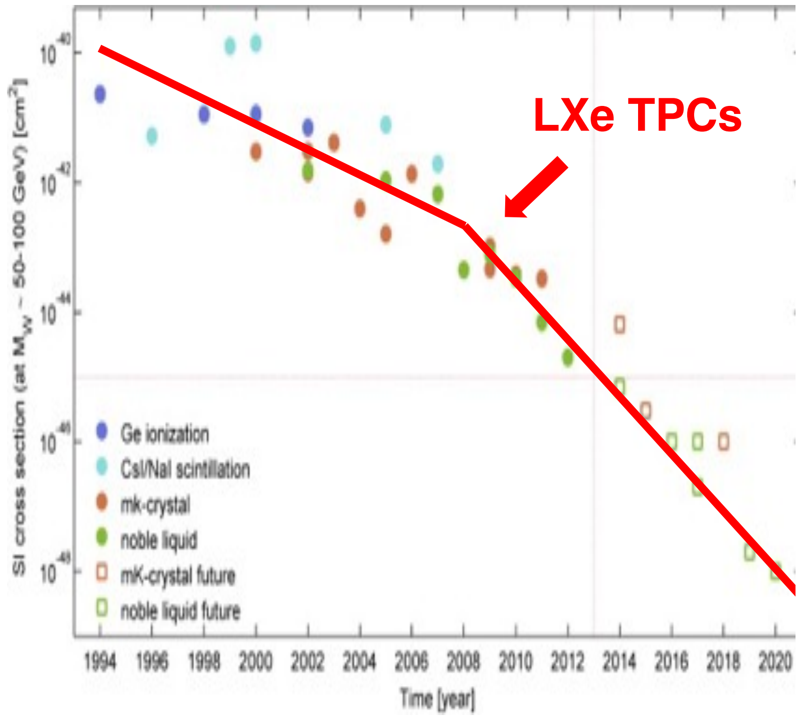
## Light – ionization – heat: 3 examples

- semiconductor Crystals (Ge)
  → pulses
- in crystals (e.g. $CaWO_4$)
  → heat +light signal
- liquid noble gases
  → light and ionization @TPC



# Extreme Low Background Conditions

- typical environmental number: 100 Bq/kg

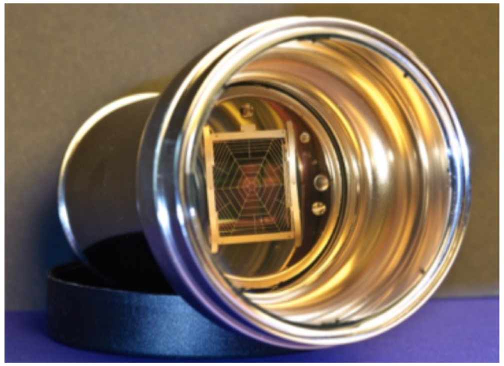
- avoid cosmogenic backgrounds
  → underground labs and detector shielding
- radiopurity of detector & shielding material
  - down to a few μBq/kg = $10^{-6}$/kg/s
  ←→ typical envirnomental 10/kg/s - $10^{3}$/kg/s

1) find clean materials (expertise…; GeRn DB)
2) screening – e.g. MPIK facilities:
   - γ screening → GEMPIs (10μBq/kg)
   - $^{222}$Rn emanation of detector materials
     → single atom counting
     → Auto-Ema – automatized screening system

   Nylon (Borexino) < 1μBq/m², Copper (Gerda): 2μBq/m²
   stainless steel (Borexino): 5μBq/m²
   Titanium: (100±30) μBq/m²

# Example: Radio-pure PMTs for XENON1T

**Hamamatsu R11410-21**
**3", 248 pcs**

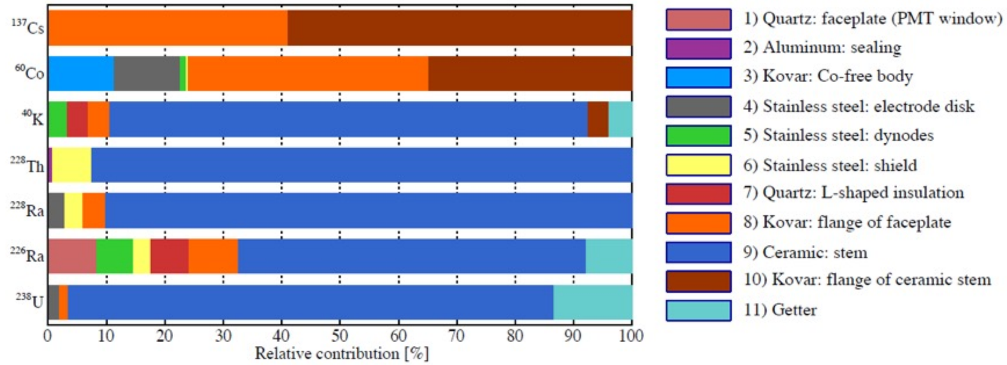


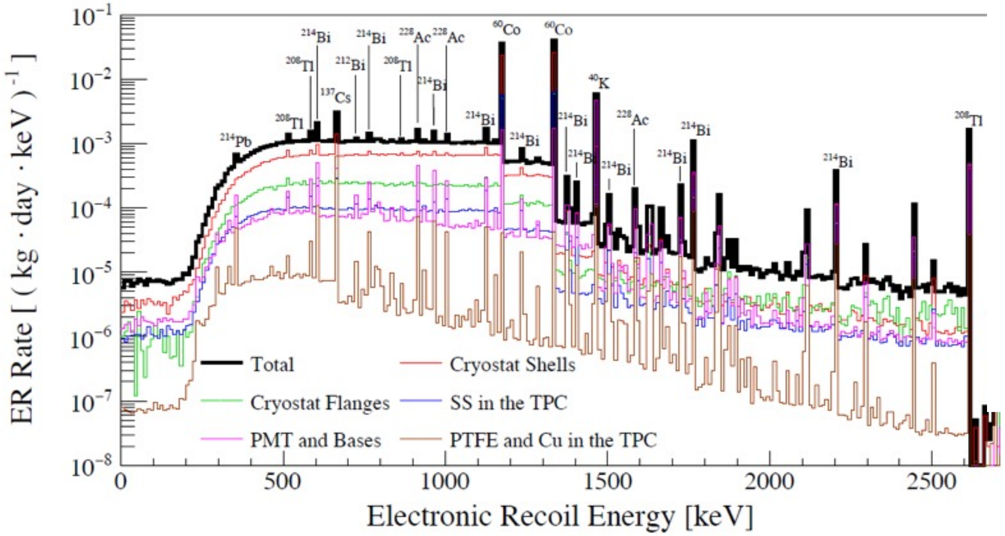
- careful material selection,
- screening of materials
- screening of final PMTs

  **< 1mBq/PMT in U/Th**

**Intensive cooperation:**

- **improvements & optimization**
- **radio-purity**




- **extensive testing at room temperature and cold**

**high QE: 35% @ 175nm**
**stability, tightness, …**
**30% single PE resolution**
**JINST 12 P01024 (2017)**

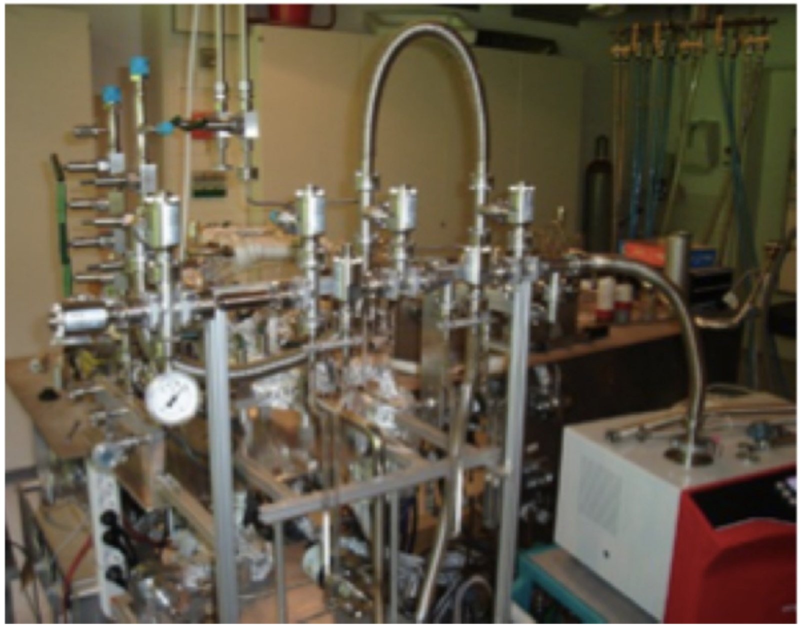
**← electronic recoil BG from materials**
**JCAP 04 (2016) 027**

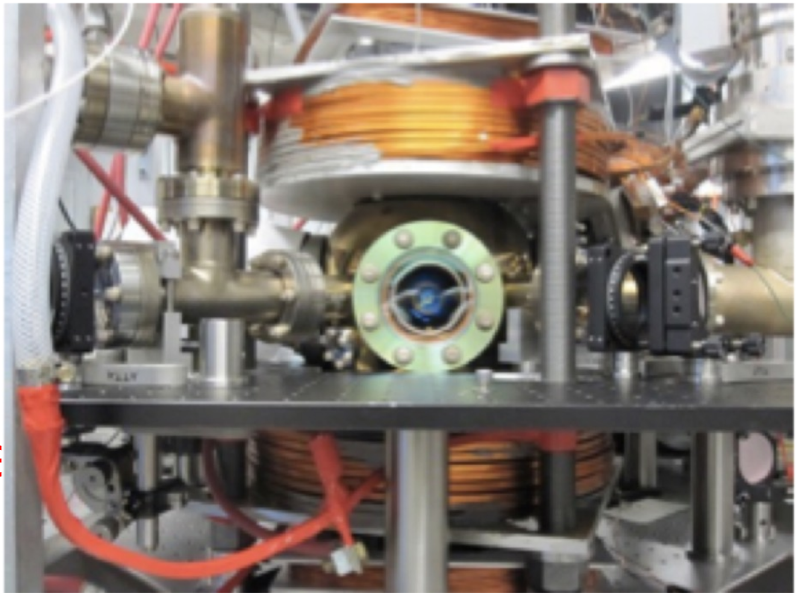
# Krypton Analytics

**unstable $^{85}$Kr in air** → impurity in Xenon gas
- active removal by distillation
- control by precise measurements

**Kr measurements:**
**- with gas chromatography**
**- Rare Gas Mass Spectroscopy (RGMS @MPIK)**
→ measure $^{nat}$Kr to ppt level
→ extrapolate: $^{85}$Kr from atmospheric abundance
→ RGMS down to ppq level

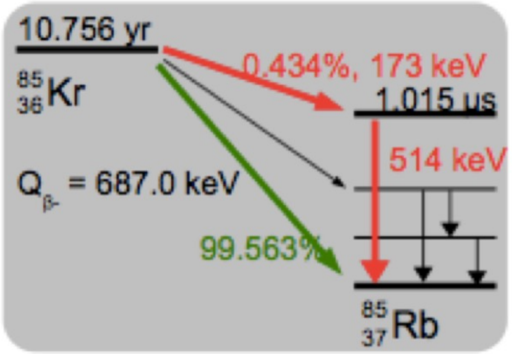
**- $^{84}$Kr measurement with atomic trap (ATTA @ Columbia U)**
→ measurement of $^{84}$Kr to ppt level
→ extrapolate: $^{85}$Kr from atmospheric abundance
→ atom trap operational and efficient for Ar*





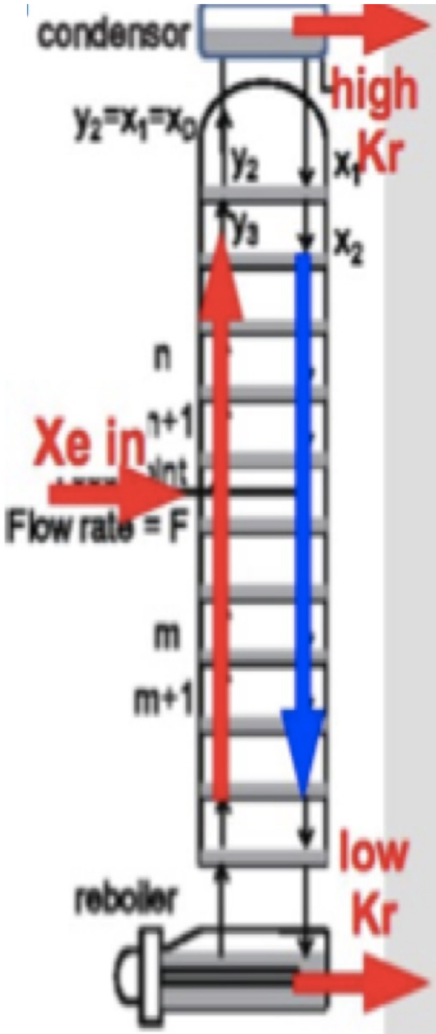
# Krypton Removal by cryogenic Distillation

- commercial Xenon contains 1 ppm – 10 ppb of Kr
- $^{85}$Kr is unstable




- goal: reduce Kr to sub ppt
- XENON100 achieved (19 ± 1) ppt

**XENON1T distillation column:**
- through-put up to 6.5 kg/hr
- separation factor > 6.4 $10^5$
- final Kr/Xe < 1 ppt
- capable to obtain an output concentration < 48 ppq
  Eur. Phys. J. C77 (2017) 275
- also operated for Rn removal




# WIMP Detection

$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

detector | astrophysics | particle physics

**axial-vector**

$$\mathcal{L} \supset \alpha_q^A (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)$$

$\frac{(J+1)}{J}$ (Angular mom)

Spin-Dependent (SD)

**scalar**

$$\mathcal{L} \supset \alpha_q^S \bar{\chi}\chi\bar{q}q$$

$A^2$ (Nucleon #)

Spin-Independent (SI)

**Vector**

$$\mathcal{L} \supset \alpha_q^V \bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$

$A^2$

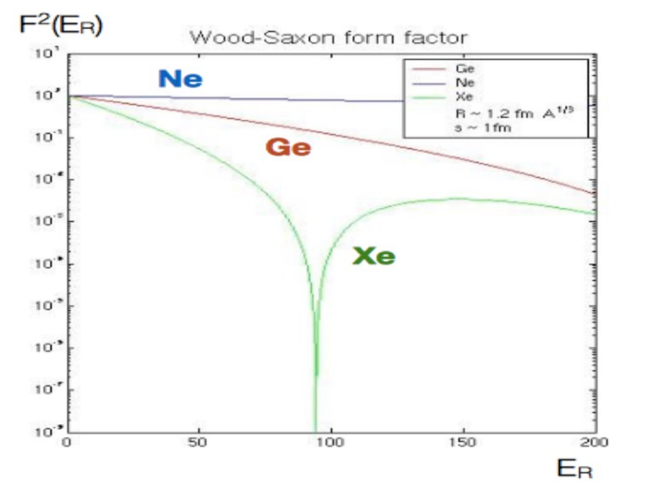
Only for non-Majorana WIMPs

Spin-Independent (SI)

**SI is coherently enhanced**

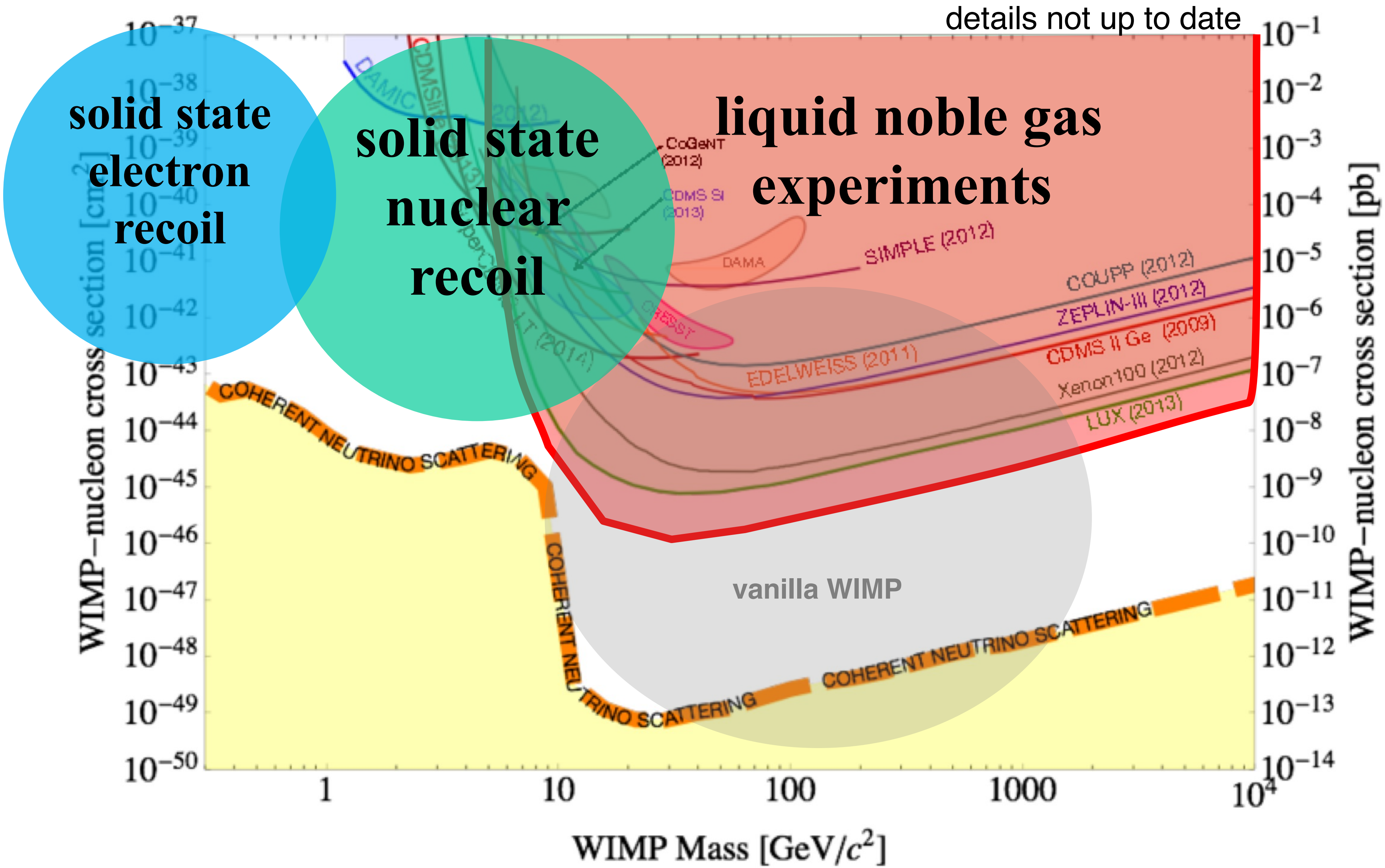
$$F(qr_n) = \frac{3[\sin(qr_n) - qr_n\cos(qr_n)]}{(qr_n)^3} e^{-(qs)^2/2}$$

**form factor = FT of nucleus**




**Larger momentum transfer probes smaller scales**
**➔ loss of coherence**

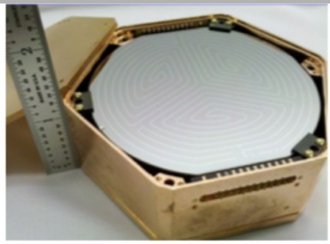
# The Players and their main Territory



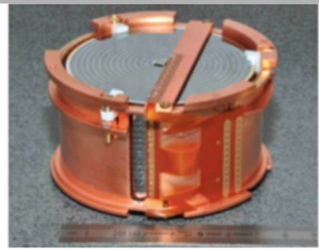
# Solid State Experiments

- **nuclear recoils**
  - CRESST
  - EDELWEISS
  - SuperCDMS
  - DAMIC
- **electron recoils**
  - SENSEI
  - DANAE
- **annual modulations / signal in NaI(Tl)**
  - DAMA/LIBRA
  - ANAIS
  - COSINE
  - PICOLON
  - SABRE
  - COSINUS

# Spin Independet (SI) limits for low $M_{WIMP}$



SuperCDMS: Ge, Si



EDELWEISS-III (Ge)

CRESST ($CaWO_4$)

**phonons (heat) + ionization** **heat + light**

**SuperCDMS @SNOLAB**

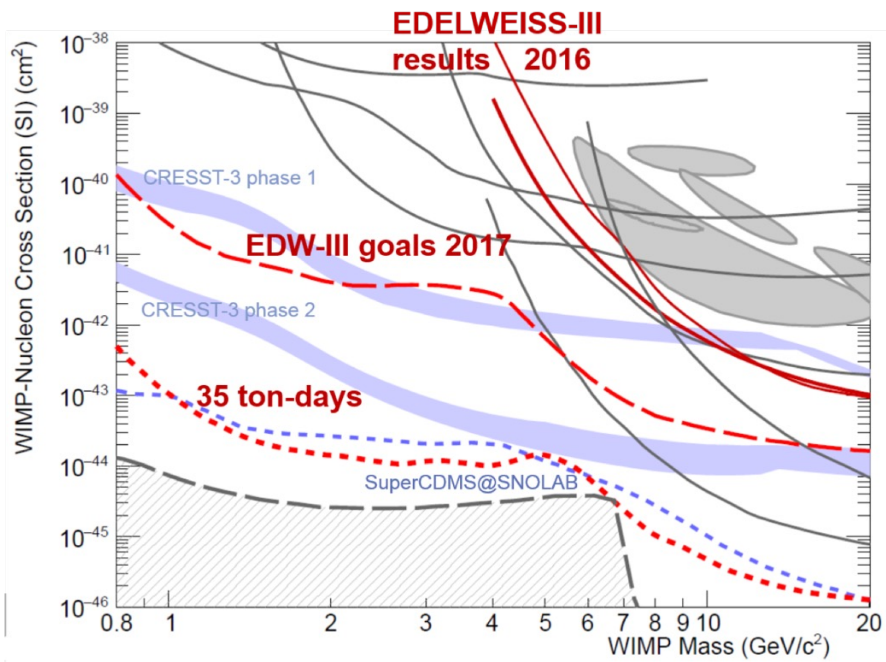
Aim: 50 kg-scale (cryostat up to 400kg)
low threshold, less bg: deeper, cleaner,
upgraded electronics, data taking 2020+

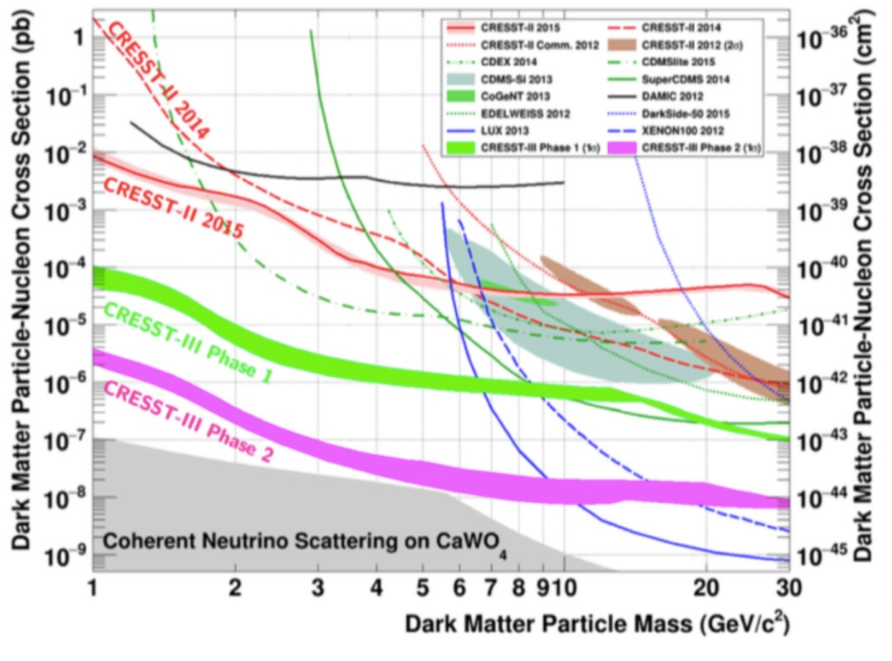
**EDELWEISS @LSM**

2016: 20 kg Ge array
2017: 350 kgd in HV mode
optimize 1-10 GeV sensitivity
future: ton scale together with
CDMS (EURECA) **+GeMMC**

**CRESST @LNGS**

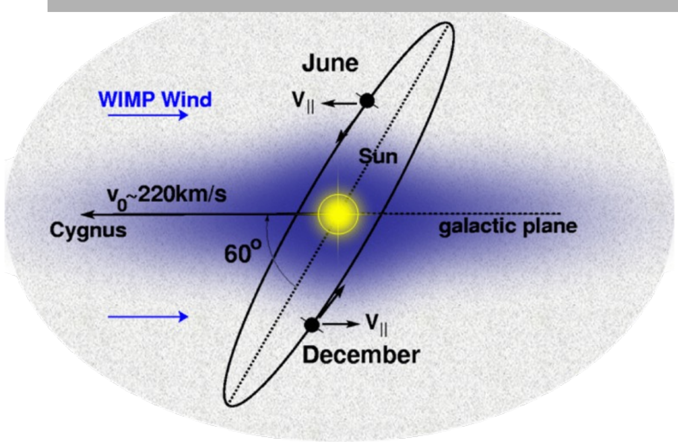
2013-2015, 52 kg × d
now: best threshold 300 $eV_{nr}$
excellent sensitivity
for small WIMP mass
**➔ CRESST-III ←→ bg?**



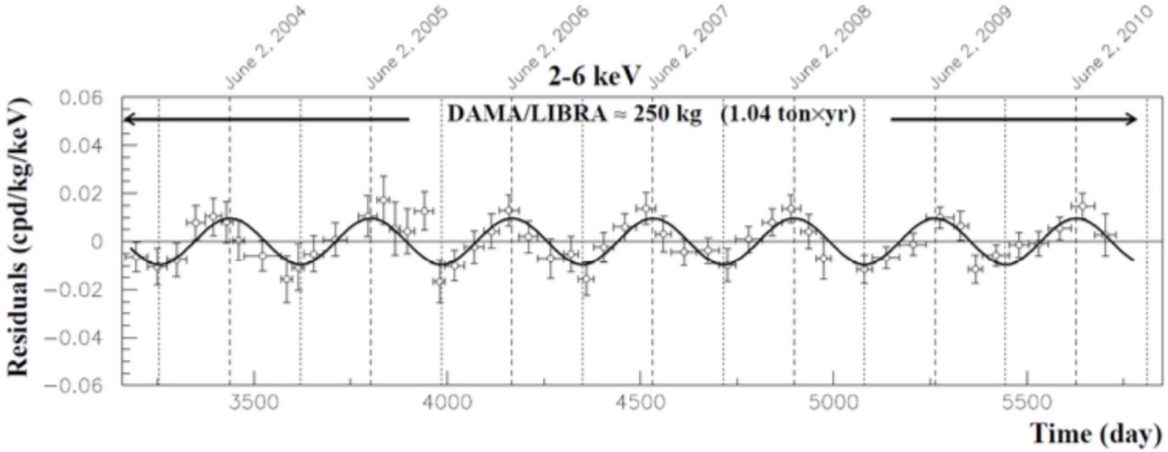

-

# The DAMA/LIBRA annual Modulation




moving thru the WIMP wind around the sun
➔ small annual modulation on top of average rate

DAMA/LIBRA
1.33 t*year exposure of NaI crystals (13 annual cycles)




Recently: 9.2σ modulation signal improved to 12.9σ
DM or something else?

Various periodic backgrounds (atmosphere ←→ μ flux, water levels ←→n, Rn, …)

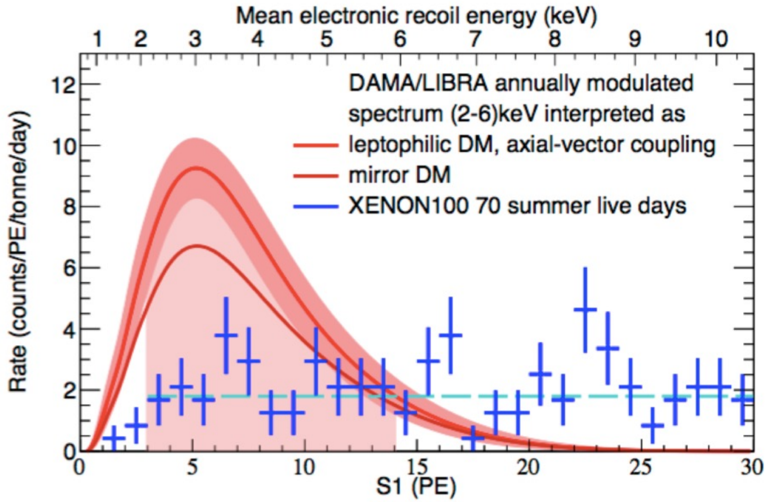
**Problem:**

- Backgrounds: So far no accepted explanation
- Signal: Other detectors (direct detection, indirect detection, LHC) do not see the corresponding overall rate which matches to the modulation

Proposed way out: DM particles which scatter on electrons (leptophilic...)
➔ would be seen by DAMA/LIBRA, but not by others

# Modulation of Electronic Recoils in XENON100

**477 life days (48kg*year) aquired 2010-2014; improved signal & bckg. modelling**

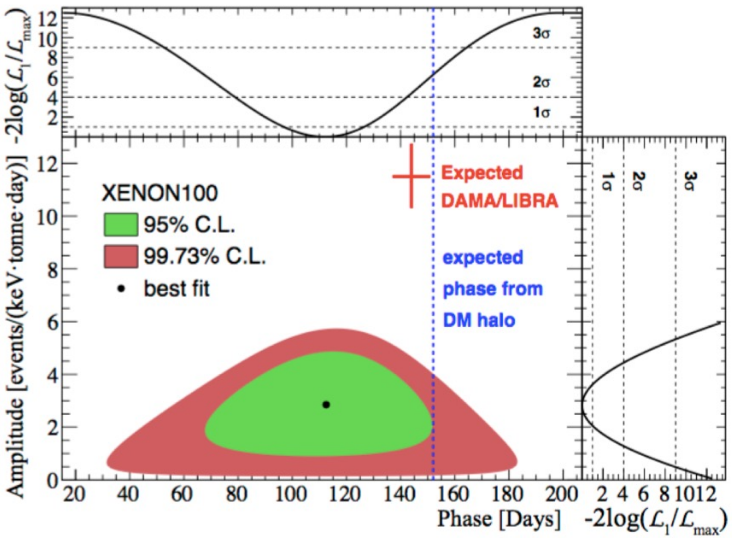



➔ **DAMA signal excluded @5.7σ**
XENON100: PRL 118, 101101 (2017)

➔ **XMASS @3σ** arXiv:1801.10096

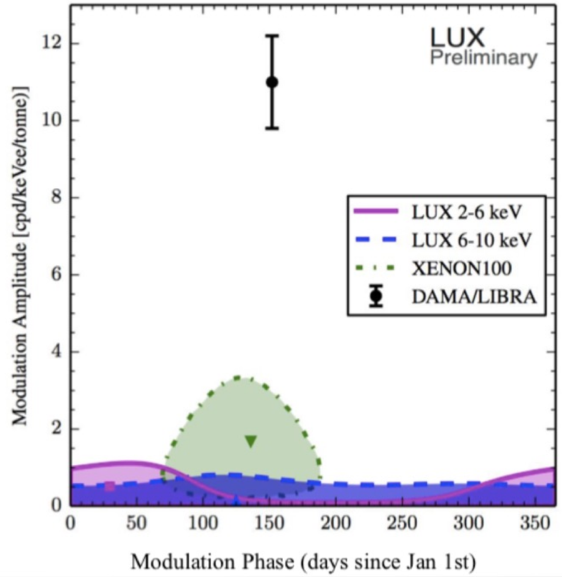
➔ **leptophilic models excluded**

➔ **DAMA modulation not understood**




**LUX: J. Xu @UCLA DM**

➔ also no modulation



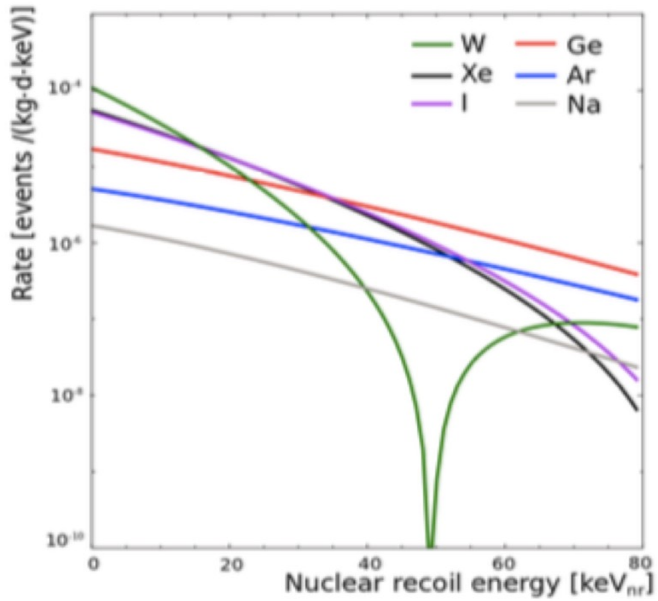

Future: New NaI Projects to directly check DAMA ➔ clarify modulation

➔ new projects: **SABRE, COSINUS, COSINE-100, ANAIS, KIMS-NaI, DM-Ice**

# Liquid Noble Gas Experiments

- **Single phase (liquid Ar and Xe) detectors**
  - DEAP
  - XMASS
- **Dual phase LAr experiments**
  - DarkSide 50, DarkSide-20k, 300 t detector
  - ArDM experiment (@Canfranc, Spain)
- **Dual phase LXe experiments**
  - PandaX, PandaX-II, PandaX-xT
  - LUX, LZ
  - XENON10, XENON100, XENON1T,XENONnT
  - DARWIN - the ultimate WIMP detector

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



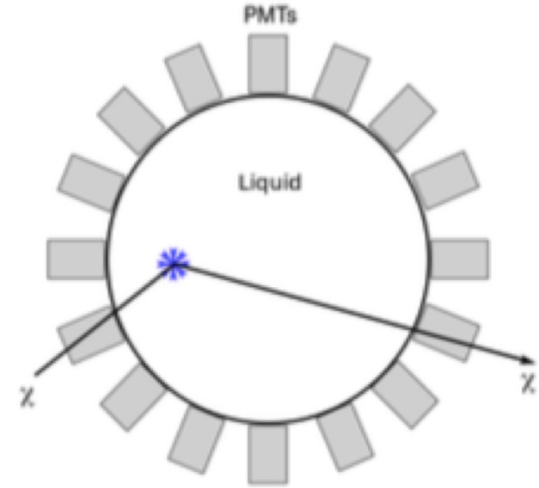

**Comparing of target masses:**

- 5*LXe $\simeq$ LAr  or in numbers: 1t LXe $\simeq$ 5t LAr
- cost: Ar << Xe  *but* $Ar^{39}$ free Ar >> Ar from air

# Single Phase (liquid) Detectors

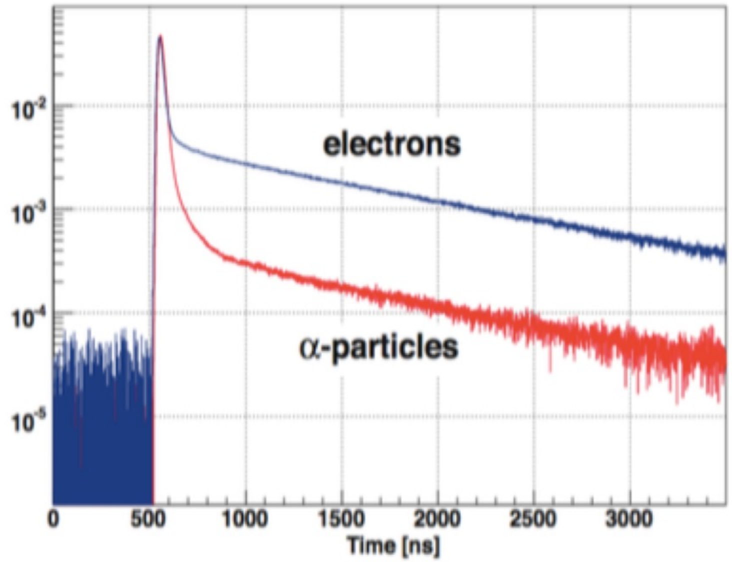
## Generic advantages of liquid noble gas det

- Large masses & homogeneous targets
  LNe, LAr, LXe
- 3D position reconstruction ➔ fiducialization
  ➔ optimize S/B by using inner volume
- Transparent to their own scintillation light




## Specific for single phase detectors:

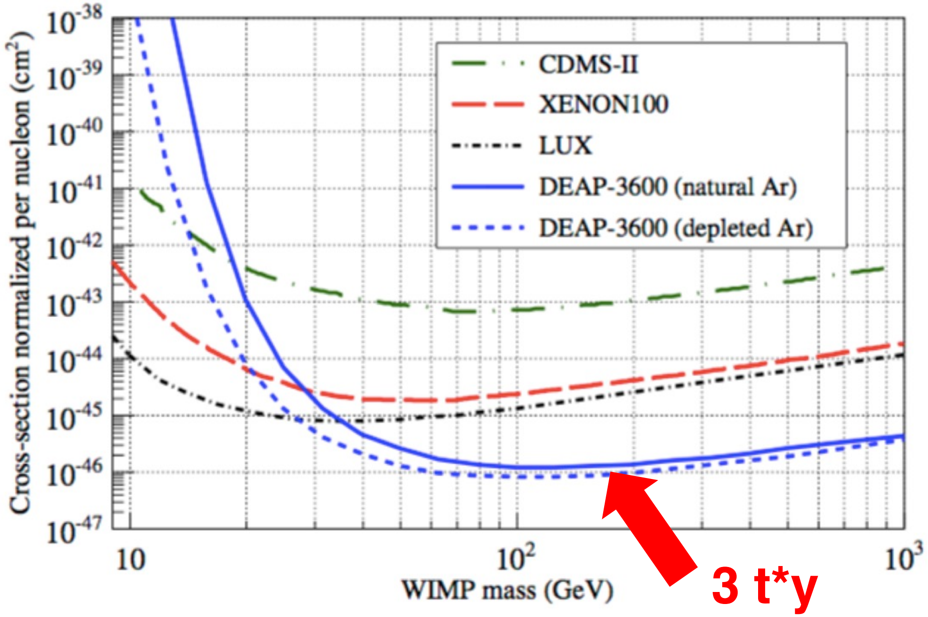
- High light yield using 4π PMT coverage
- Position resolution in the cm range
- Pulse shape discrimination (PSD)
  from scintillation
- Relative amplitudes depend on
  particle type ➔ discrimination

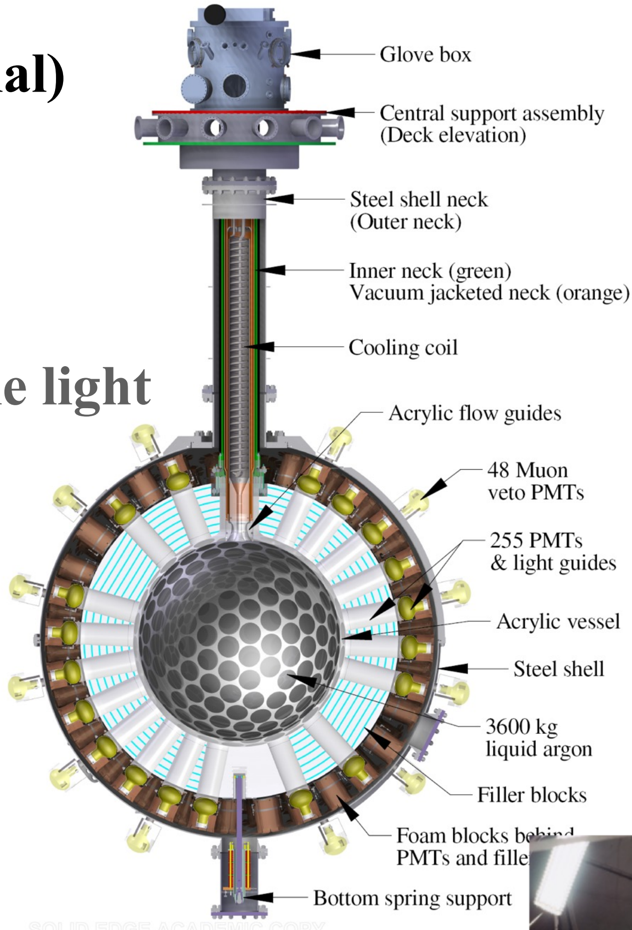



Scintillation decay constants of argon measured by ArDM

# DEAP @ SNOLAB

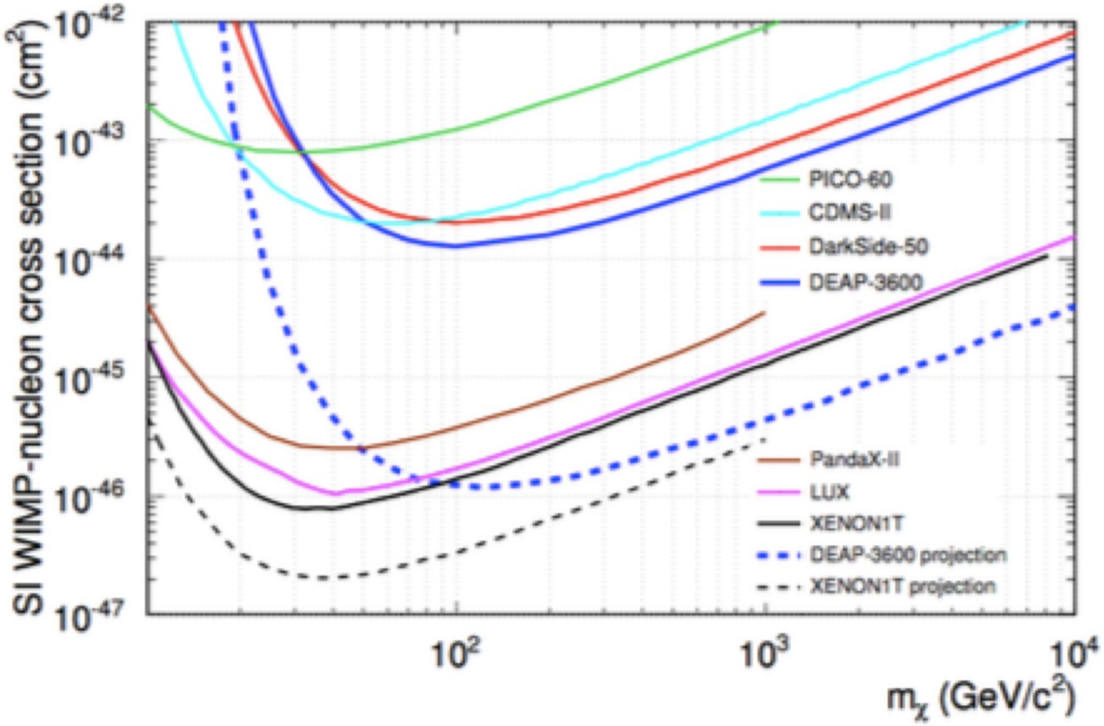
- **Single phase LAr TPC, 3.6t (1t fiducial)**
- **Spherical ultra pure acrylic vessel**
- **255 PMTs, extra shielding (foam, PE)**
- **TPB wavelength shifter**
  **➔ 128nm scintillation light into visible light**
- **Water tank + veto PMTs**
- **Projected sensitivity**




# DEAP Results and Status

- First result arXiv:1707.08042: 4.4d , 2223 kg fiducial mass

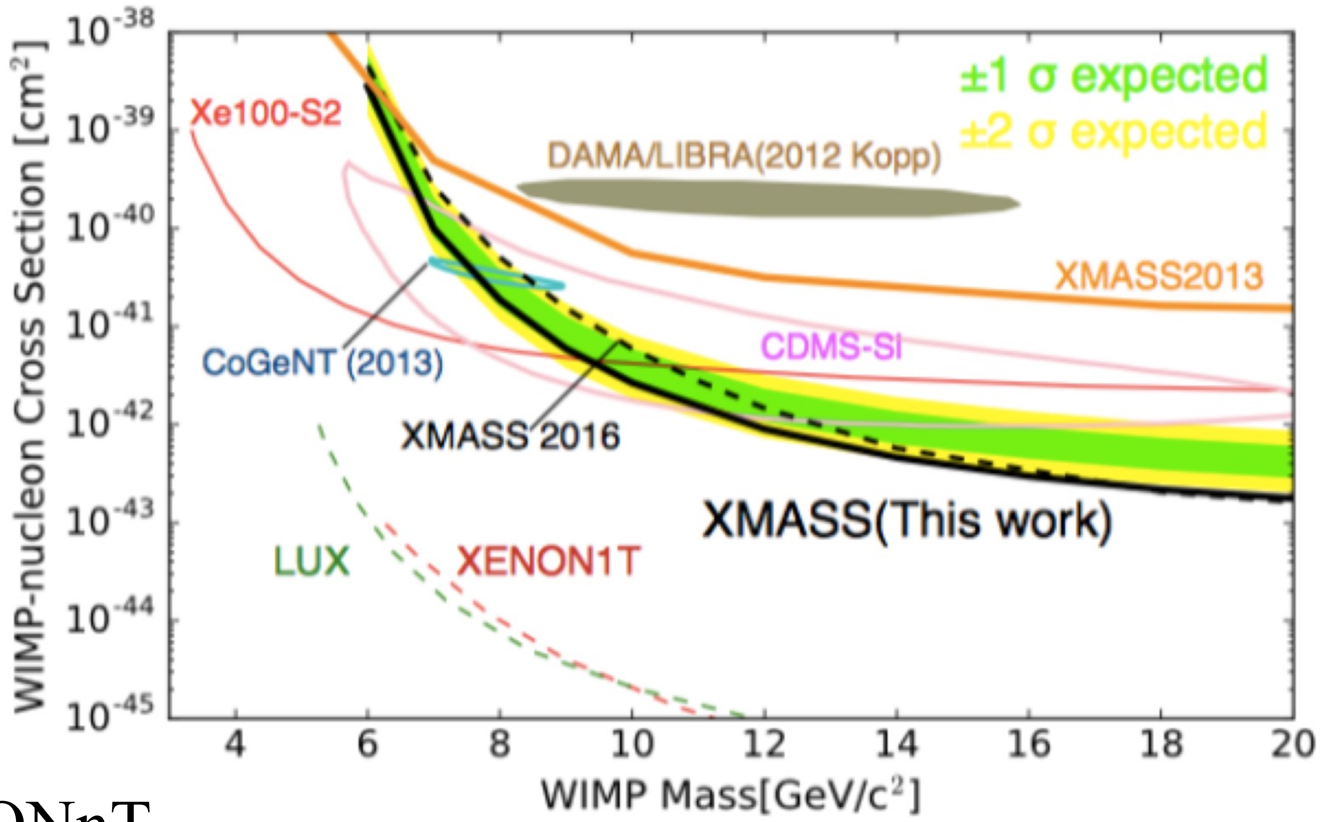



- Most sensitive running LAr dark matter detector
- Next steps:
  - working on a second data release (about 1y of data)
  - aim at 3 t*y exposure
  - next generation: join DarkSide-20k

# XMASS @ Kamioka

**1t total LXe mass & 800kg FV**

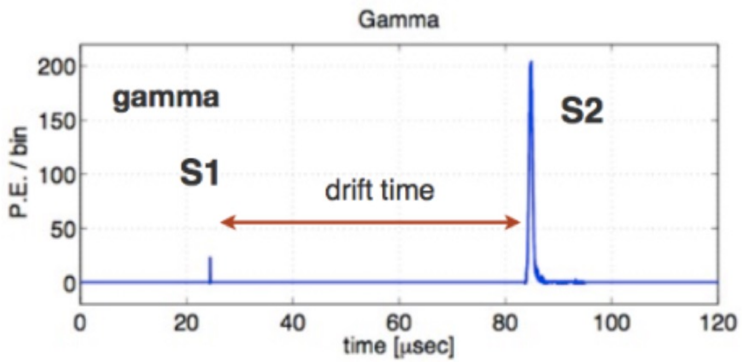
- Ultra-clean PMTs directly in contact with the LXe target
- High light yield measured: 14.7 PE/keVee, $E_{th} = 0.3$ keV$_{ee}$
- Improved analysis: arXiv:1801.10096

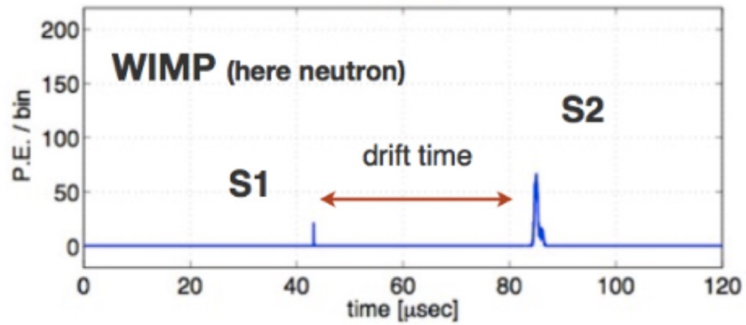


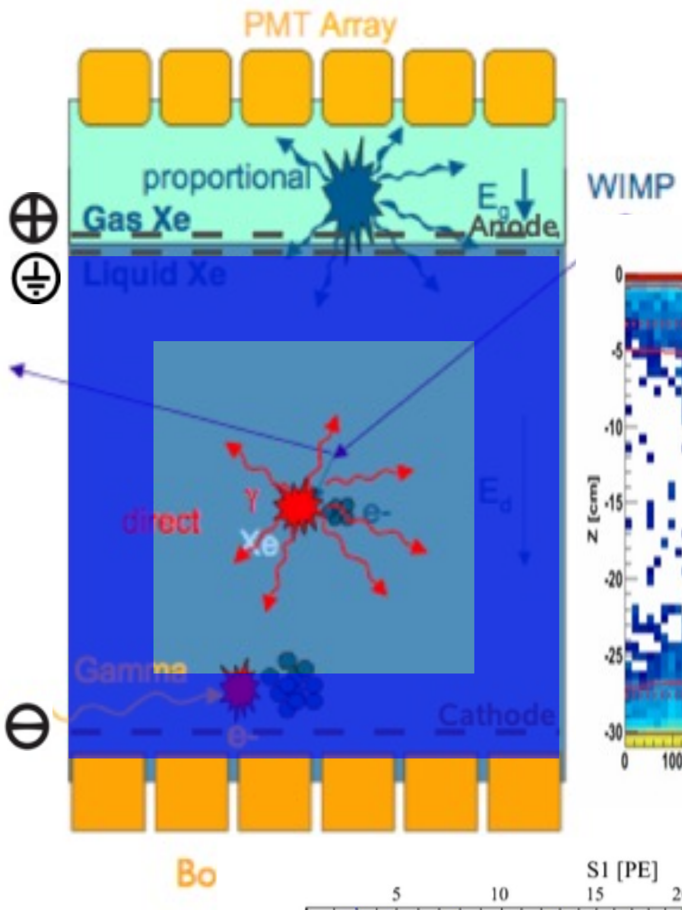

- Future: Join XENONnT...

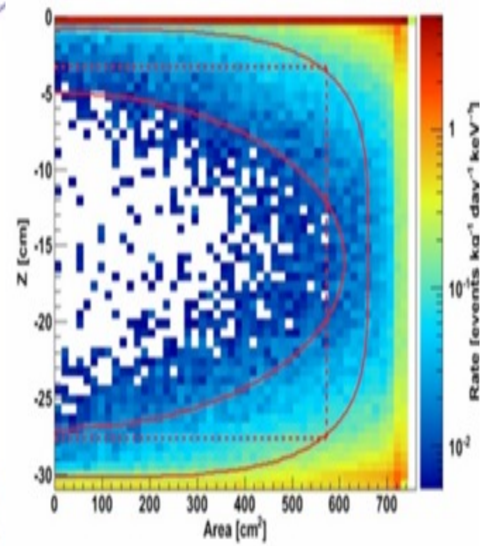
# Powerful Devices: Dual-Phase TPCs

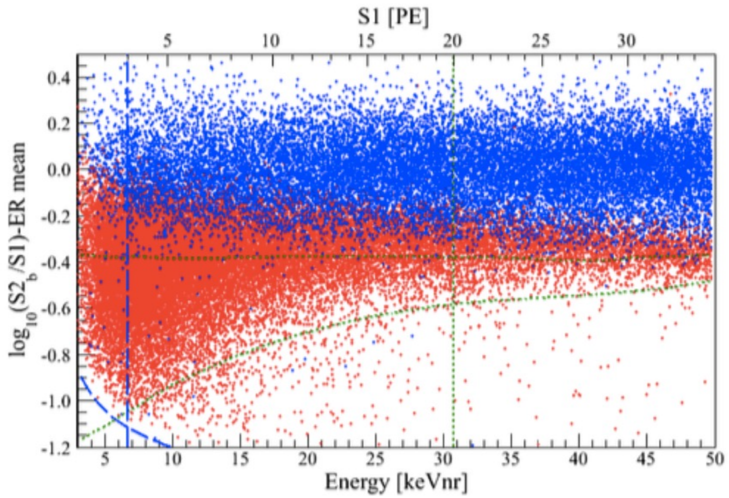
1) direct light singal → S1
2) drift of electrons to gas phase
3) 2nd light signal → S2




→ **excellent 3D position reconstruction**
→ **fiducialization** = exclude known backgrounds from 'dirty' surfaces
→ **S2/S1 discrimination of ER / NR**

# Sensitivity Evolution for DM Detectors

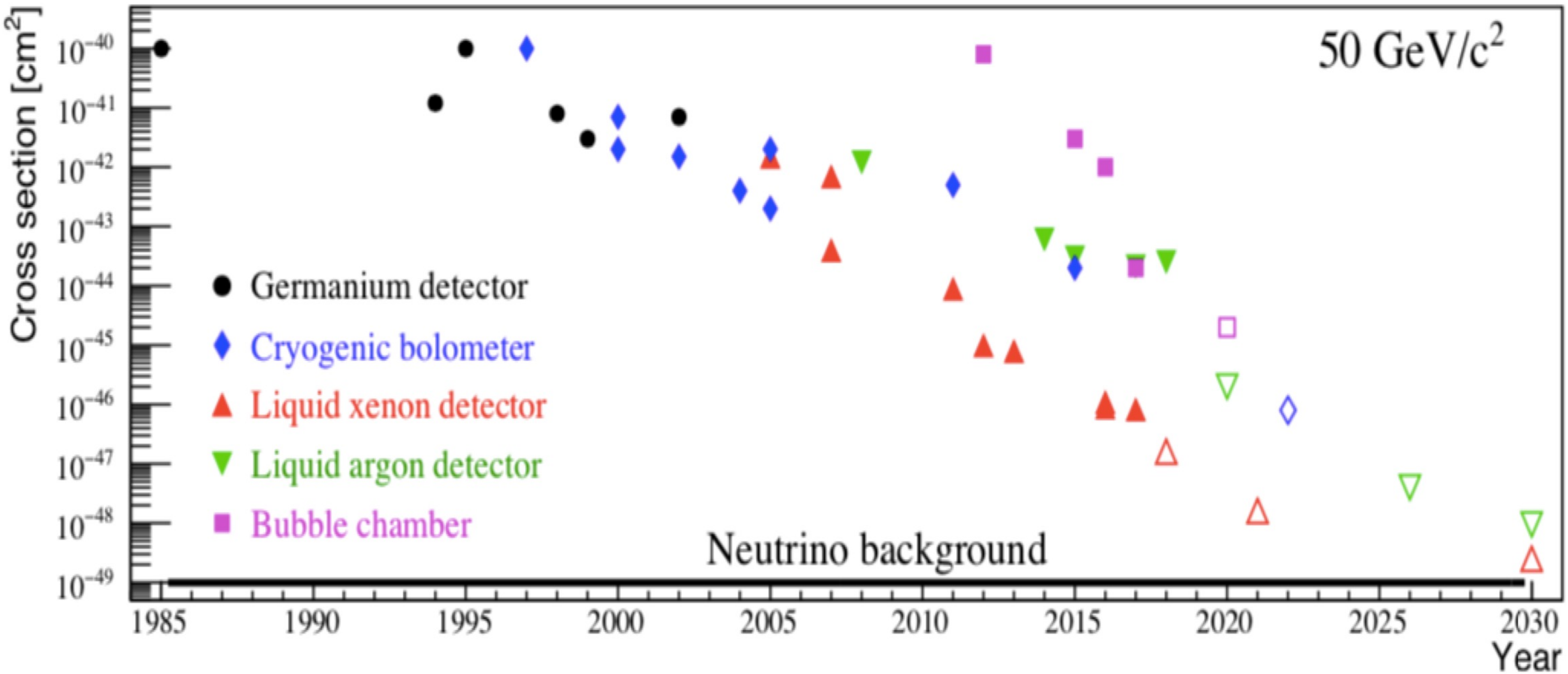



Figure updated from J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

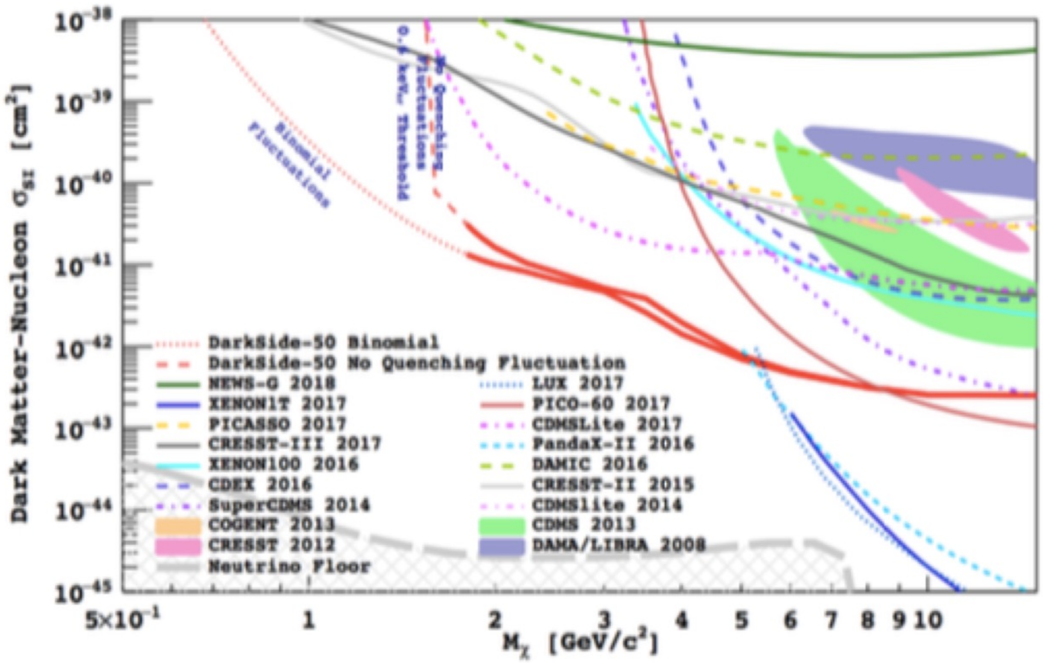
# Dual phase LAr experiments

**Other targets are important:**
➔ **different backgrounds, physics, consistency**
**Liquid Argon: Excellent target**
**Future: Must avoid $^{39}Ar$**
➔ **production from UG oil/gas wells**

## Running: DarkSide-50 @ LNGS

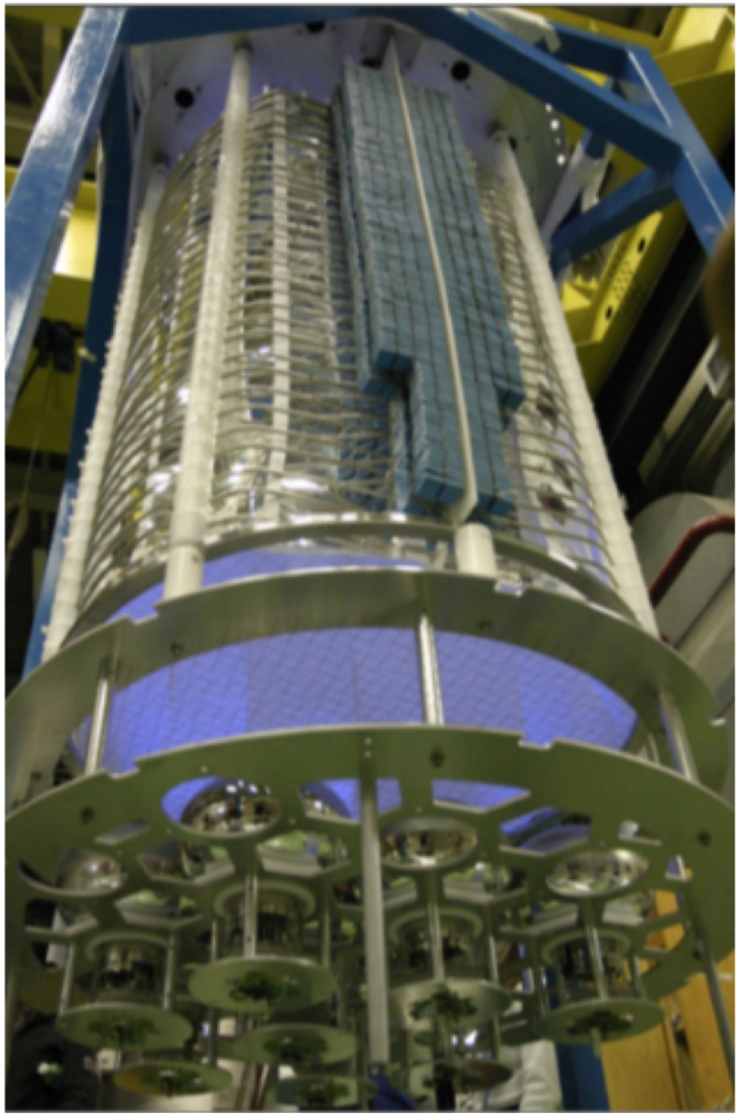
- **50 kg depleted**
- **pulse shape for particle discrimination**
  ➔ **separation > $10^7$**
- **energy threshold at 4 $e^-$**
  ➔ **equivalent to 0.1 $keV_{ee}$**

- **recent result: arXiv:1802.06998**



# ArDM @ Canfranc

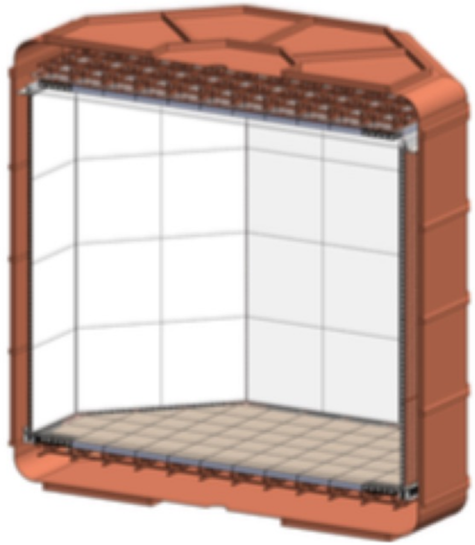
- 850 kg LAr (in target)
- technology demonstrator
- installed at Canfranc (Spain)
- a year long operation of 2 t of LAr in single phase
- run 2: operation in dual-phase started Jan 2018
- purification and data analysis on-going

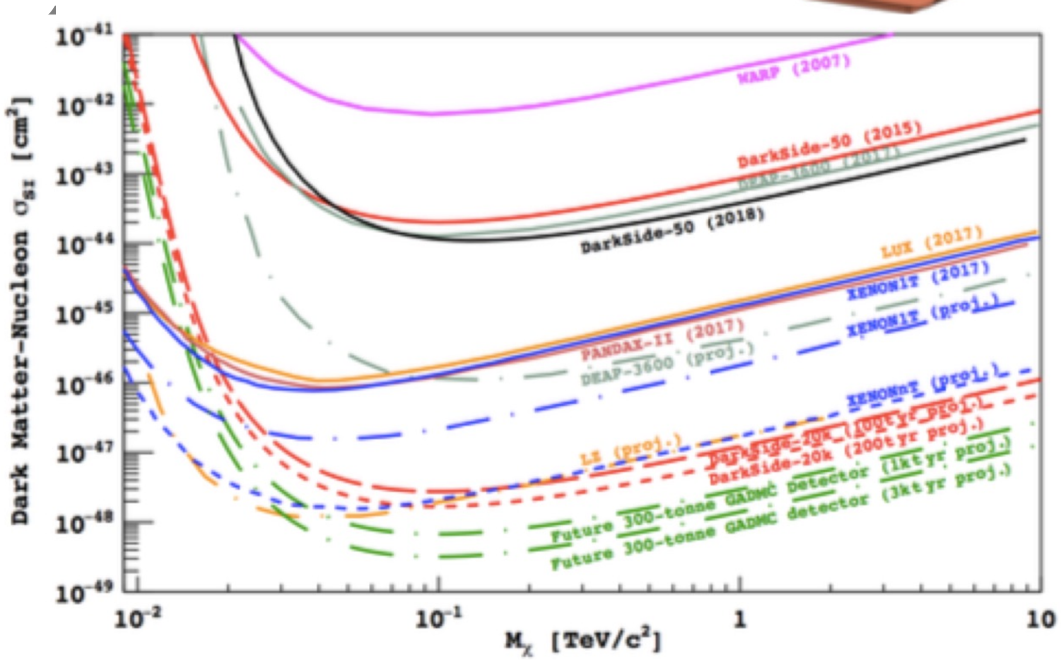


# DarkSide-20k & future LAr Program

**Next step:** DarkSide-20k @ LNGS (2021)

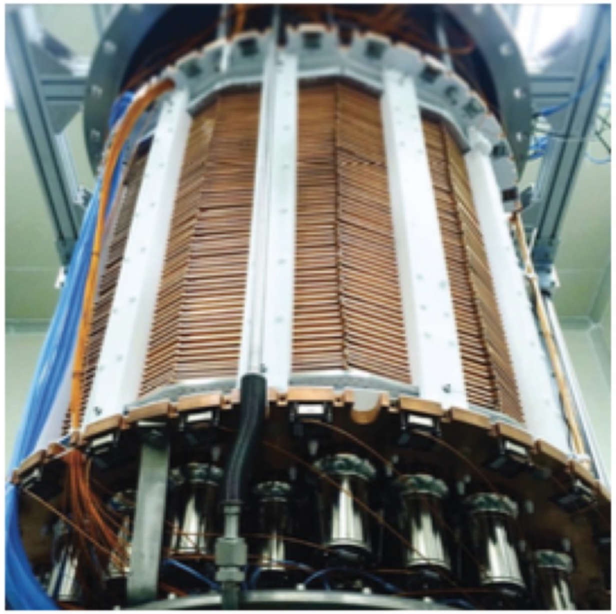
- 30 t (20 t fiducial) aiming at 100 t*yr
  ➔ $10^{-47}$ cm$^2$ at 1 TeV/c$^2$
- plant to extract large amounts of argon from underground
- isotopic separation ($^{39}$Ar from $^{40}$Ar) via cryogenic distillation
- 14 m$^2$ of SiPM for light read-
- a global collaboration: ArDM+DarkSide +DEAP+MiniCLEAN





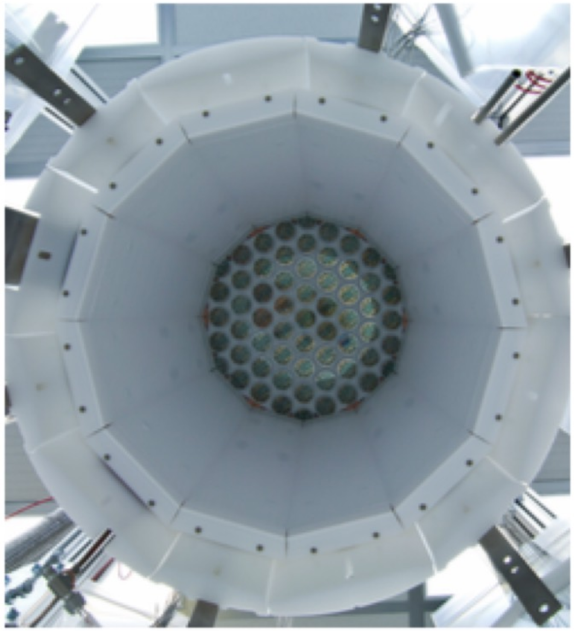

**Then:** Argo = 300 t @???
2027-...
➔ 1kton*yr exposure

# The LXe TPC Competition



**PANDAX-II:**

370 kg fiducial
(1.2 t total)
latest results 2017
54 t*d exposure
PRL 119, 181302 (2017)
**currently running**



**LUX:**

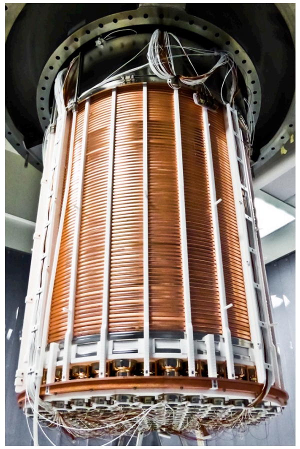
100 kg fiducial mass
(370 kg total)
latest results 2016
33.5 t*d exposure
PRL 118, 021303 (2017)
**decommissioned**

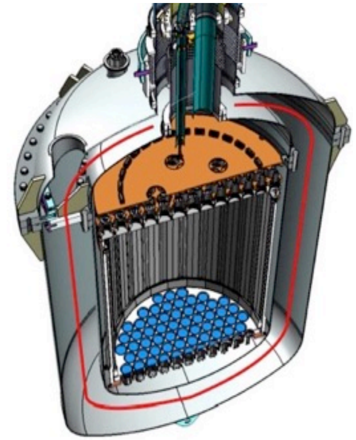
**XENON1T:**

~1.3t LXe fiducial
(3.2 t total)
largest existing det.
first results 33.6 t*d
PRL 119 (2017) 181301
**new results soon!**

# The current XENON Dark Matter Program

**The XENON program at Gran Sasso, Italy (3600 mwe)**

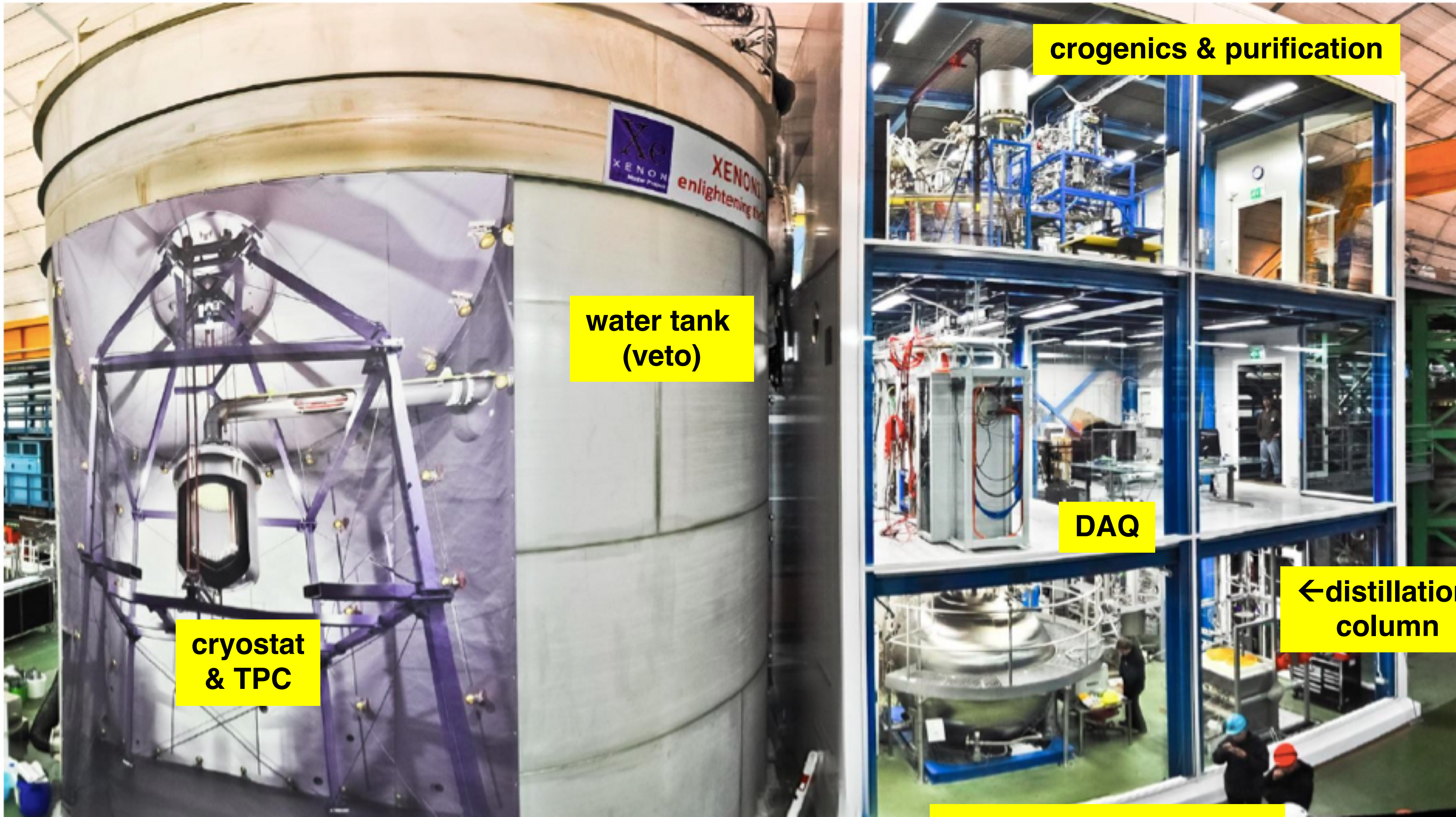


| | XENON10 | XENON100 | XENON1T | XENONnT |
|---|---|---|---|---|
| **Period** | **2005-2007** | **2008-2016** | **2012-2018** → | **2019-2023** |
| **Total mass** | 25 kg | 161 kg | 3200 kg | ~8000 kg |
| **Drift length** | 15 cm | 30 cm | 100 cm | 150 cm |
| **Status** | Completed (2007) | Completed (2016) | Running | Construction |
| **$\sigma_{SI}$ limit** (@50 GeV/c$^2$) | $8.8 \times 10^{-44}$ cm$^2$ | $1.1 \times 10^{-45}$ cm$^2$ | $1.6 \times 10^{-47}$ cm$^2$ (2018) | $1.6\times10^{-48}$ cm$^2$ (2023) |

**XENONnT being prepared while XENON1T runs → switching gears**

# The near Future: XENON1T

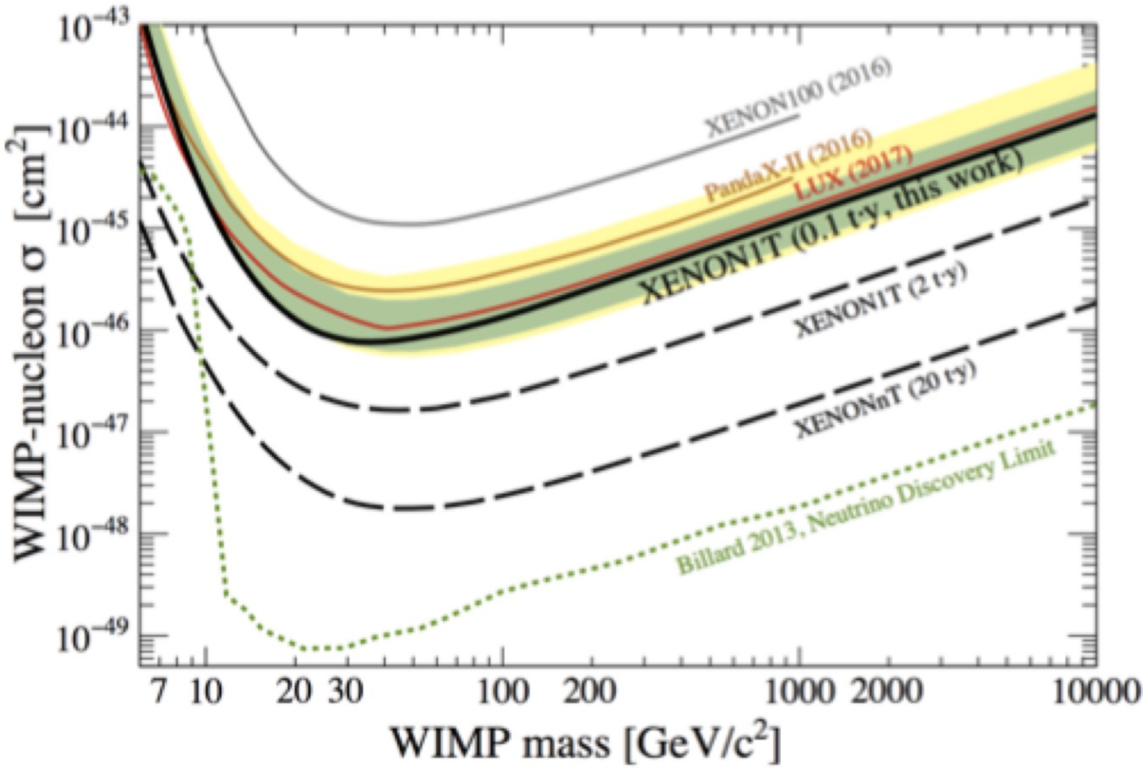
→ Goal: two orders of magnitude improvement in sensitivity with respect to XENON100 → commissioning in 2016 → data taking



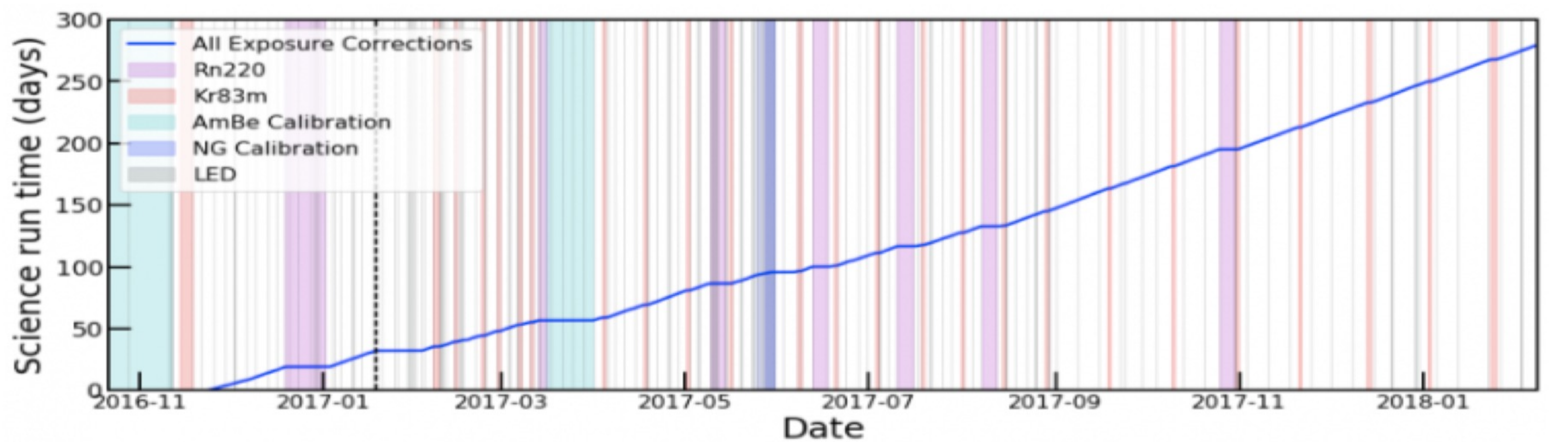
# XENON1T: Results and new Data

**2017: SR0**
**34.2 live days**
**➔ PRL 119 (2017) 181301**

**2018: SR1**
**247 additional live days**
**analysis being finalized**
**~ 1.3 t fiducial volume**

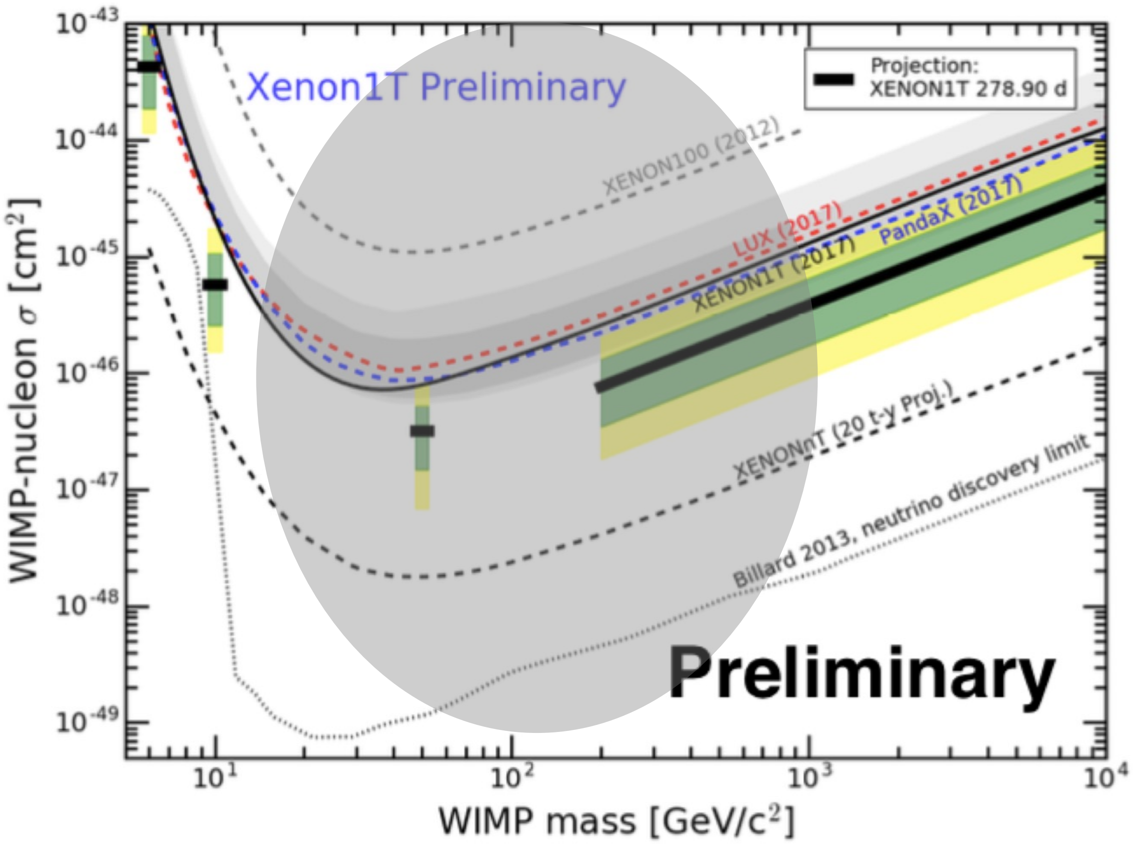



(new PandaX-II result is missing)



# Spin Independent (SI) Projection

**New XENON1T results will come soon…**



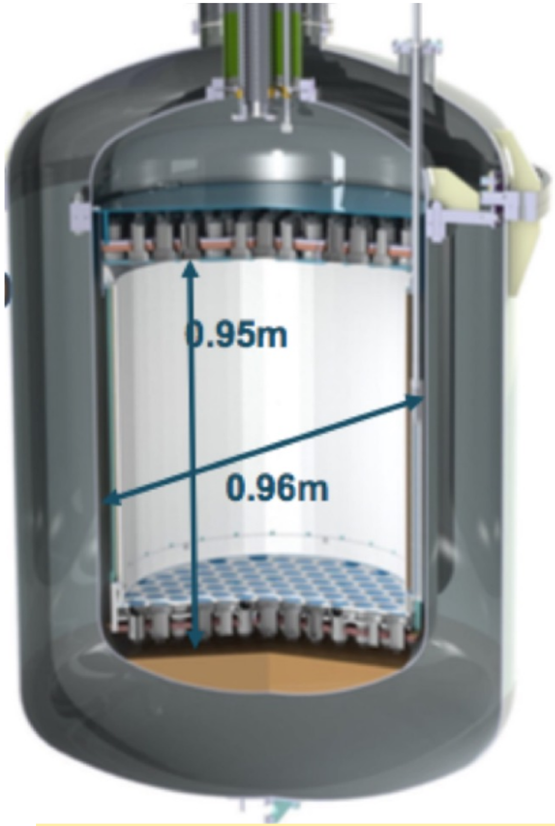

- Expected sensitivity generated from toy MC at 4 typical WIMPs masses: 6, 10, 50, 200 GeV
- For a 50 GeV WIMP a factor of 3 sensitivity increase compared to SR0
- If WIMP cross-section close to our SR0 limit we expect a signal with 3-sigma significance

**Covers more and more of the generic WIMP space…**

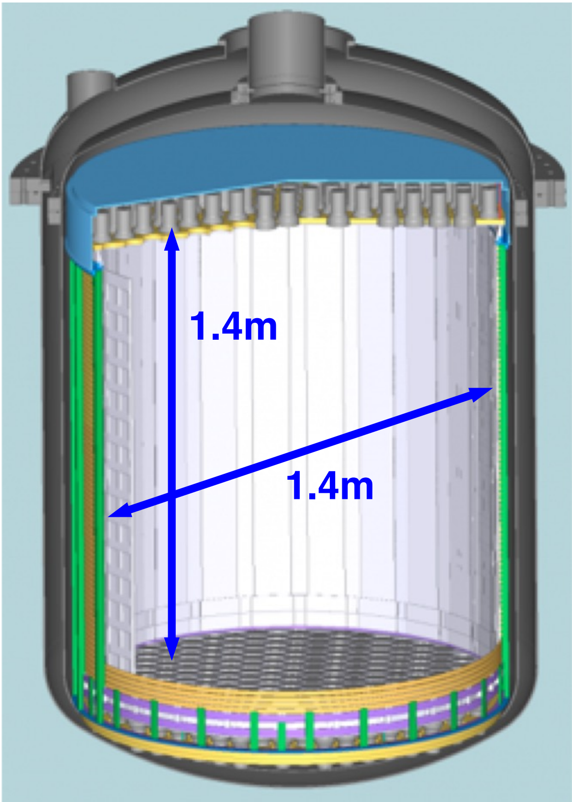
**… but don't forget: it is a log scale ➔ lot's of parameter space left!**

# The XENONnT Upgrade

**XENON1T**




**XENONnT**




**2012-2018**
**3.2t LXe**
**running**

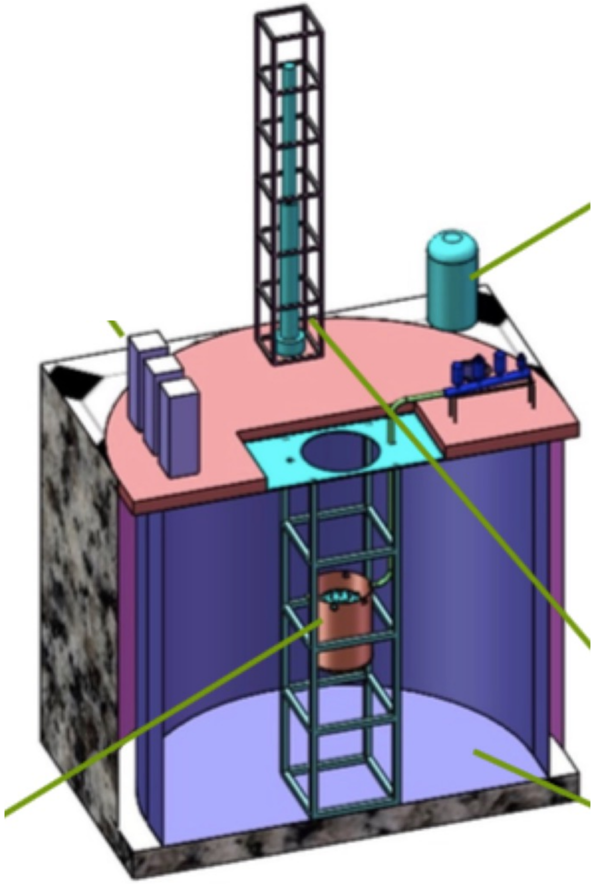
**2019-2023**
**ca. 8t LXe**
**under preparation**
**goal @50GeV: $1.6 \cdot 10^{-48}$ cm$^2$**

**being prepared while XENON1T runs ➔ switching gears**

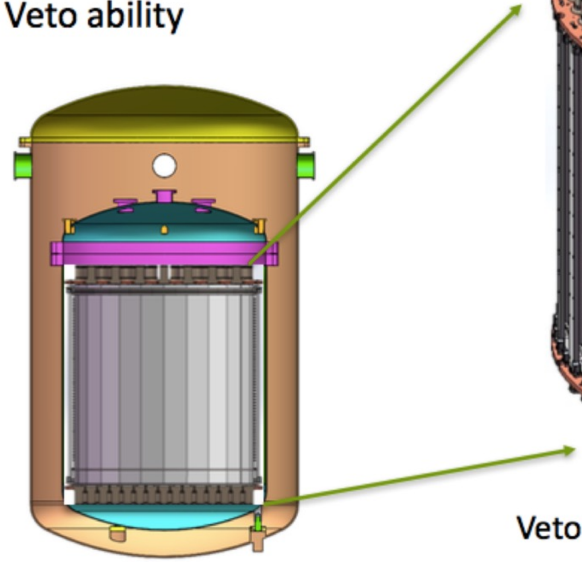
**Existing/operational/tested:**
muon veto
cryostat support
outer cryostat
in-LXe cabeling
LXe storage system (Restox)
cryogenic system
purification system
Kr removal
DAQ & 95% electronics
slow control system
calibration system
> 8t of Xenon gas & 260 PMTs
screening facilities

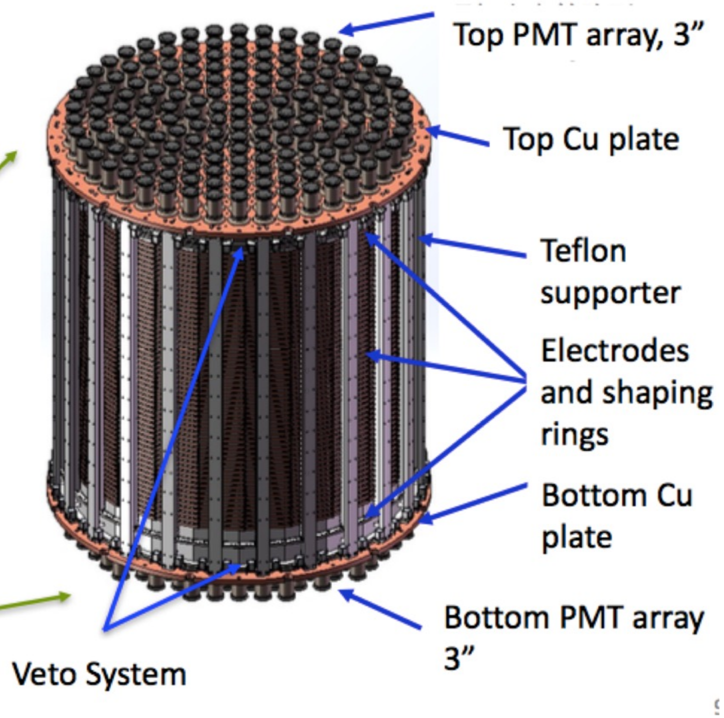
**Started/design/on-going:**
230 more PMTs ordered
➔ being delivered & tested
TPC & inner cryostat design
n-veto studies
material orders
$\gamma$ and Rn screening
Rn reduction system
improved purification
2nd Restox & more Xe gas

# PandaX-4T at CJPL



- Drift region: $\Phi$~1.2m， $H$~1.2m
  - Xenon in sensitive region～4ton
- Design goal:
  - High signal efficiency
  - Large and uniform electric field
  - Veto ability

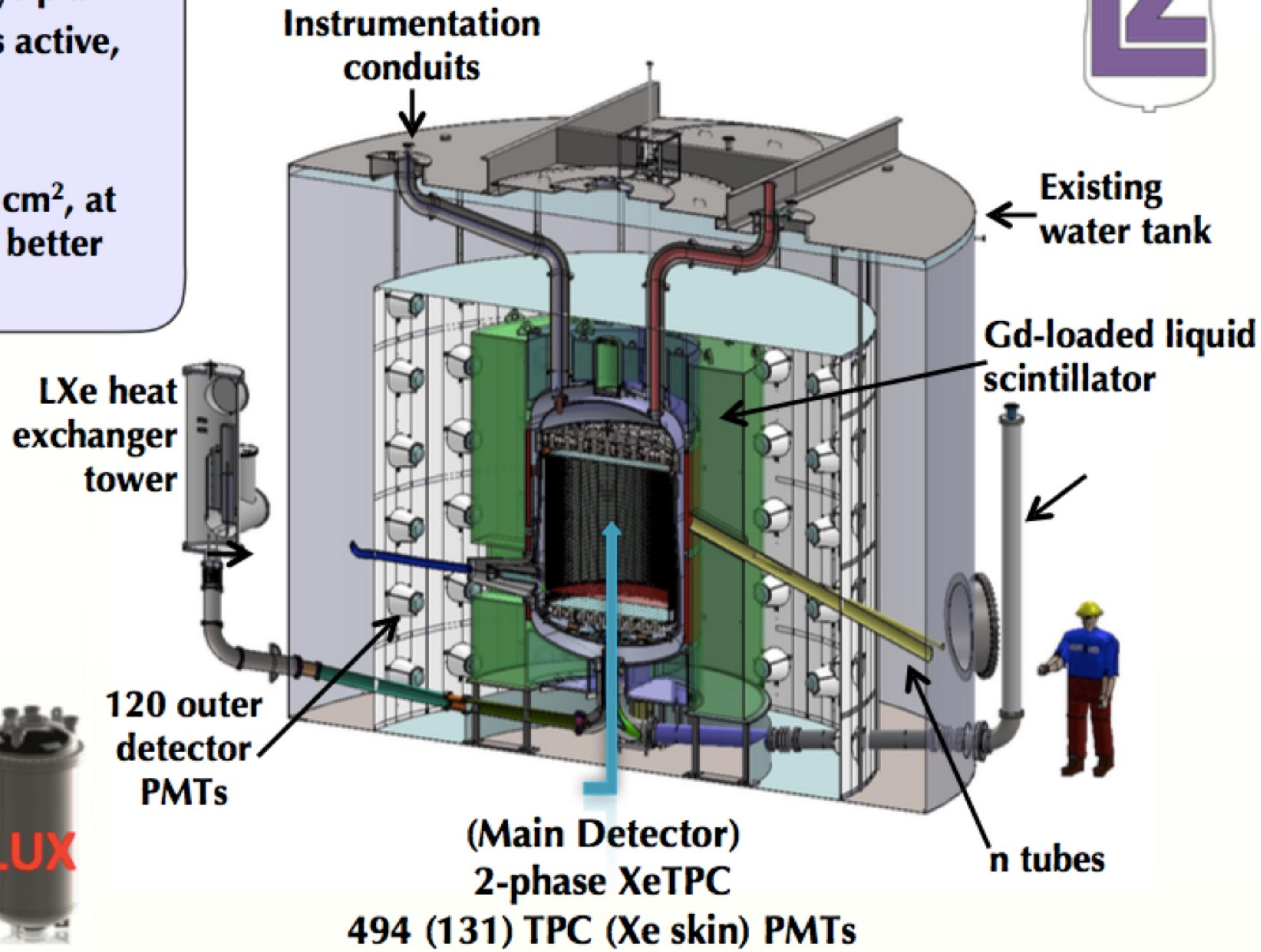




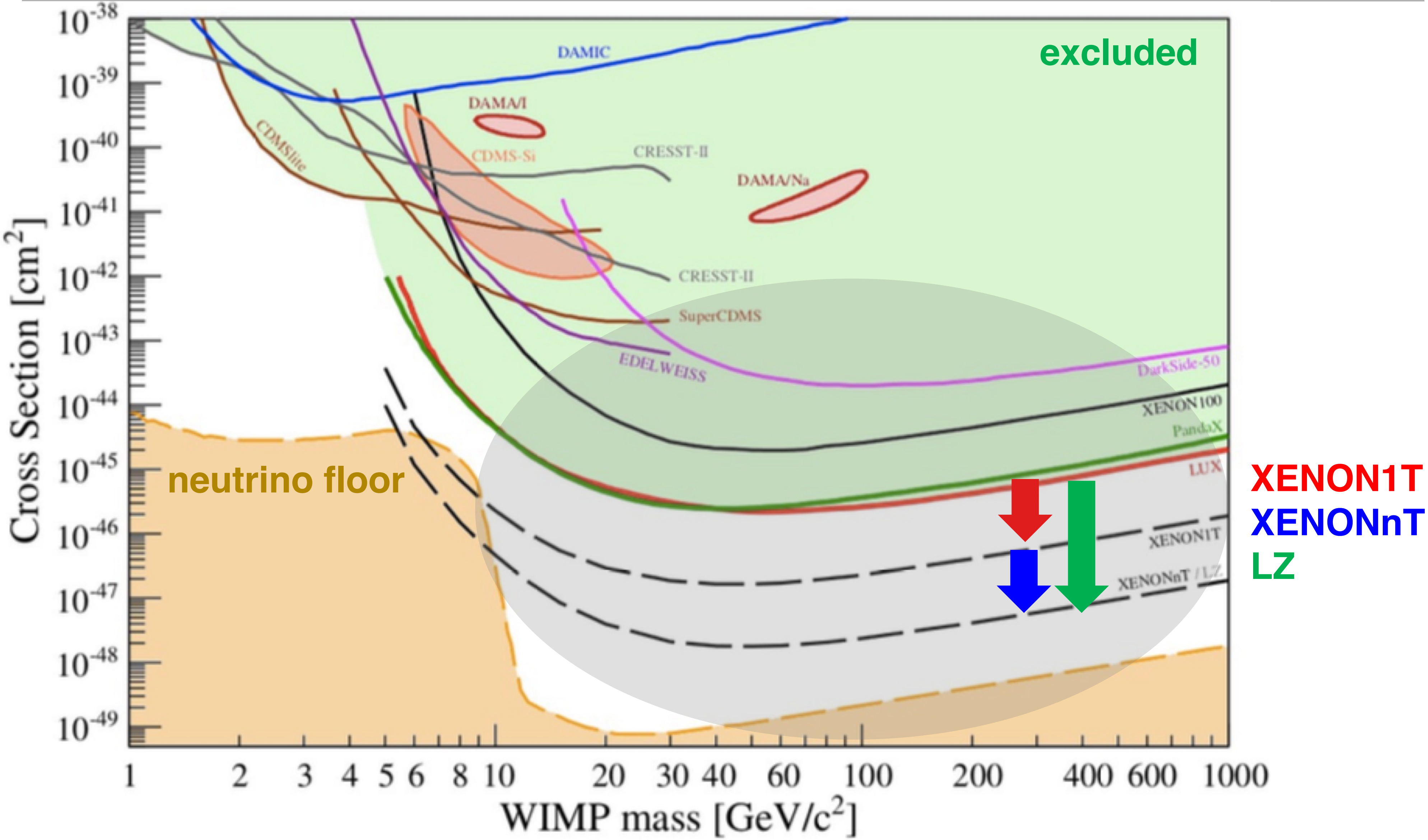

- 2017-2018:Produce all components and test
- 2019-2020:On-site assembling and commissioning
- 2021-2022:Data-taking
- eventual goal: ~30 t at CJPL to reach neutrino floor sensitivity

# LUX-ZEPLIN (LZ)

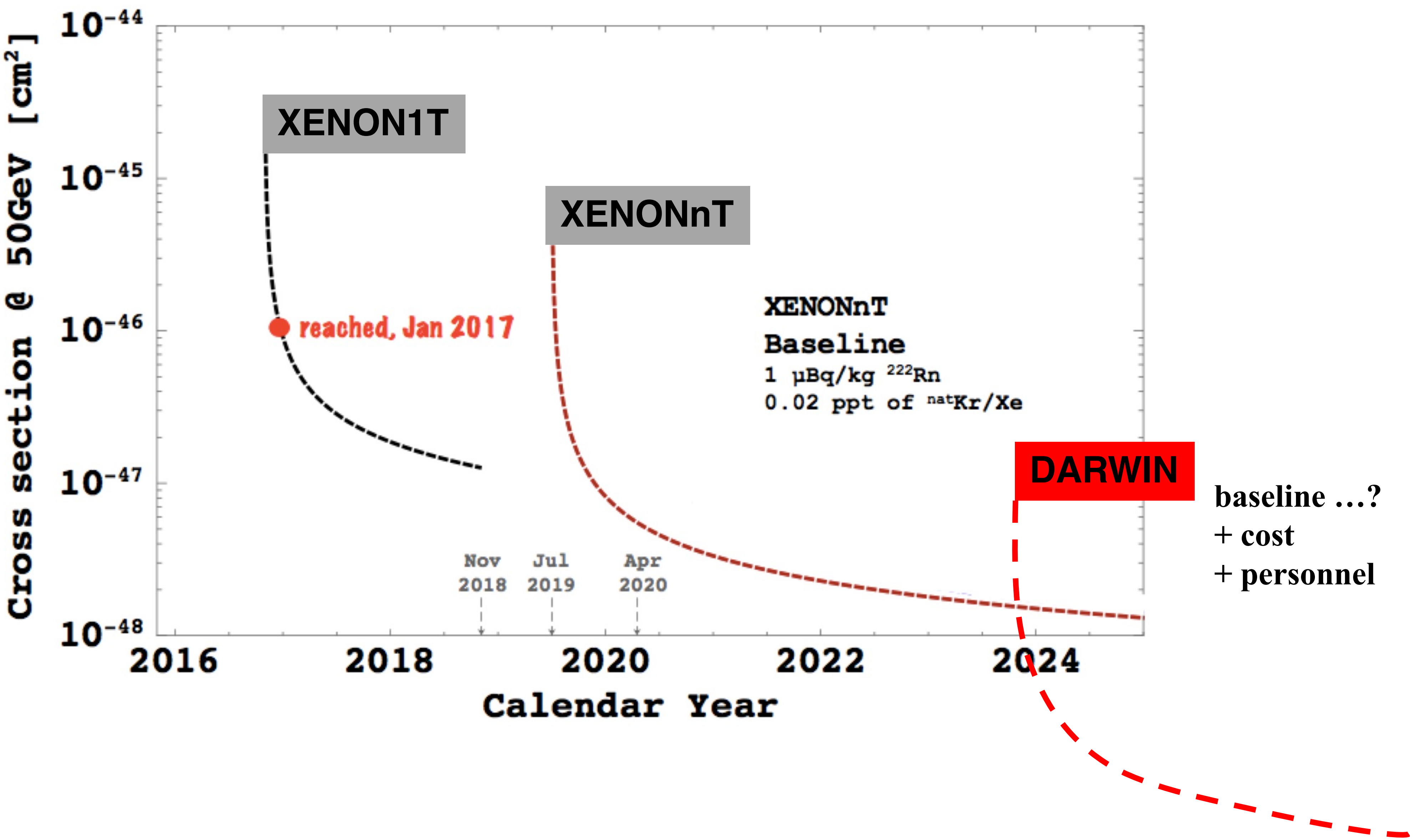
- Turning on by 2019 with 1,000 initial live-days plan
- 10 tons total, 7 tons active, ~5.6 ton fiducial
- Unique triple veto
- GOALS: < 2 x $10^{-48}$ $cm^2$, at 40 GeV ~100 times better than LUX

# Direct Detection Future

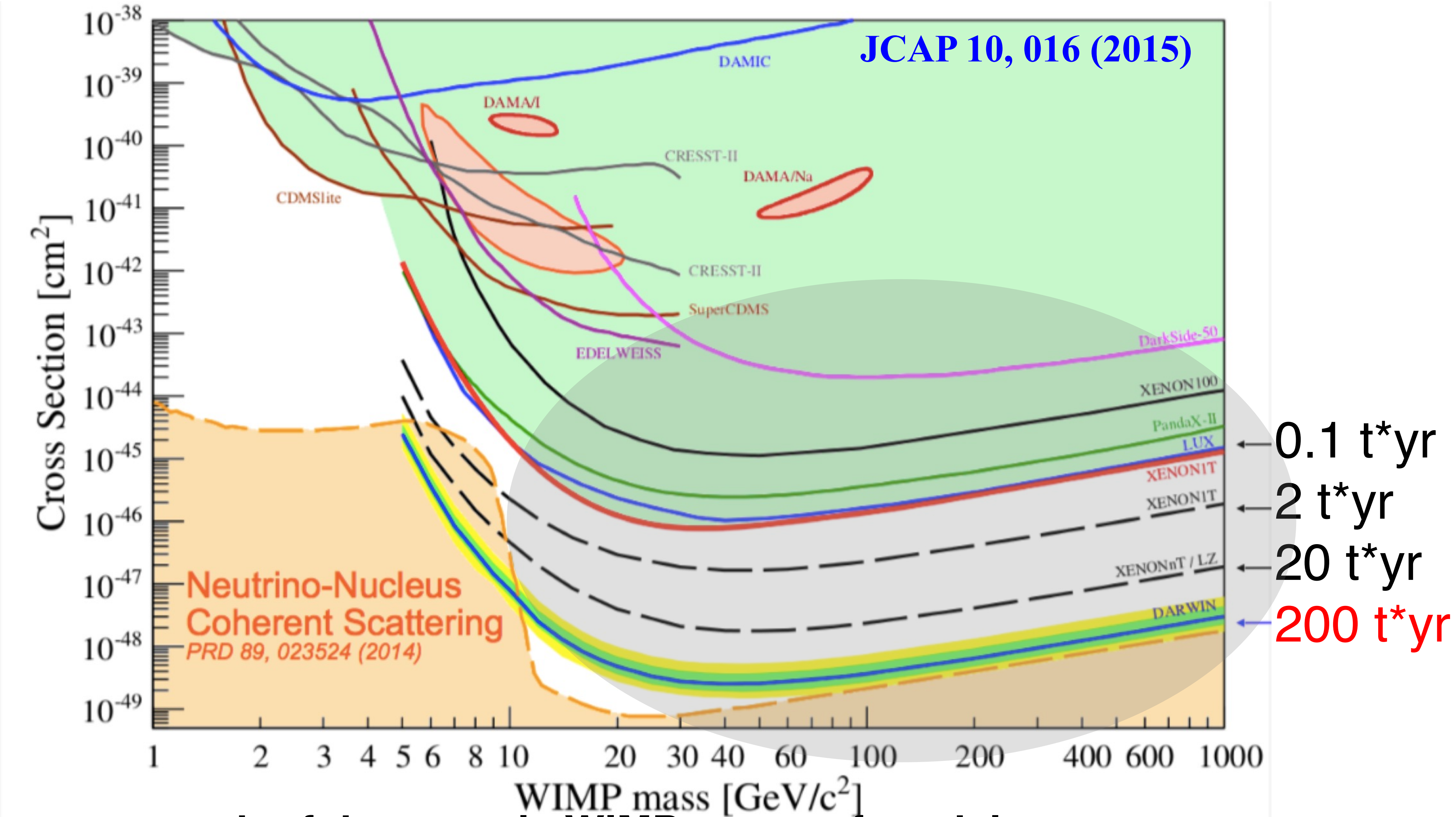


# DARWIN: The ultimate Dark Matter Detector




baseline …?
+ cost
+ personnel

# Spin Independent (SI) WIMP Interaction




**tests much of the generic WIMP space of models**

**➔ a declining WIMP case w/o discovery?**

**➔ solar neutrino signal & CNNS: 200 t*yr**

# $0\nu\beta\beta$ with $^{136}Xe$

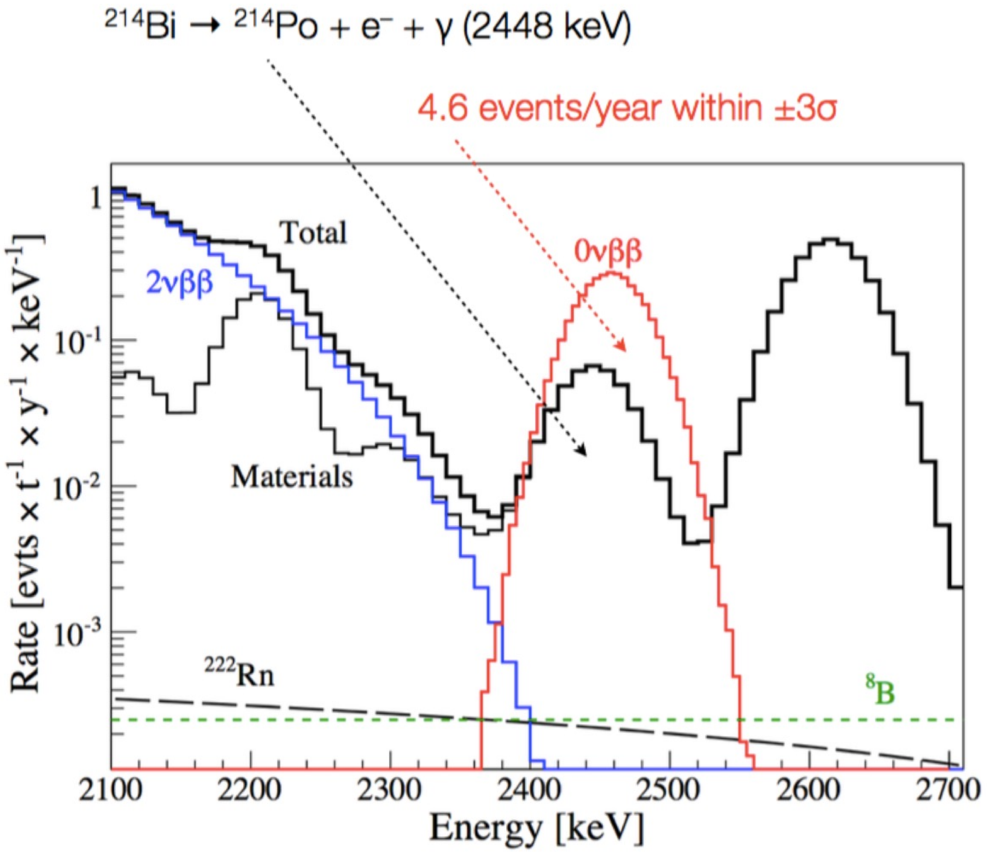
**8.9% natural abundance**

**➔ 3.5 t $^{136}Xe$ in 40t without enrichment!**

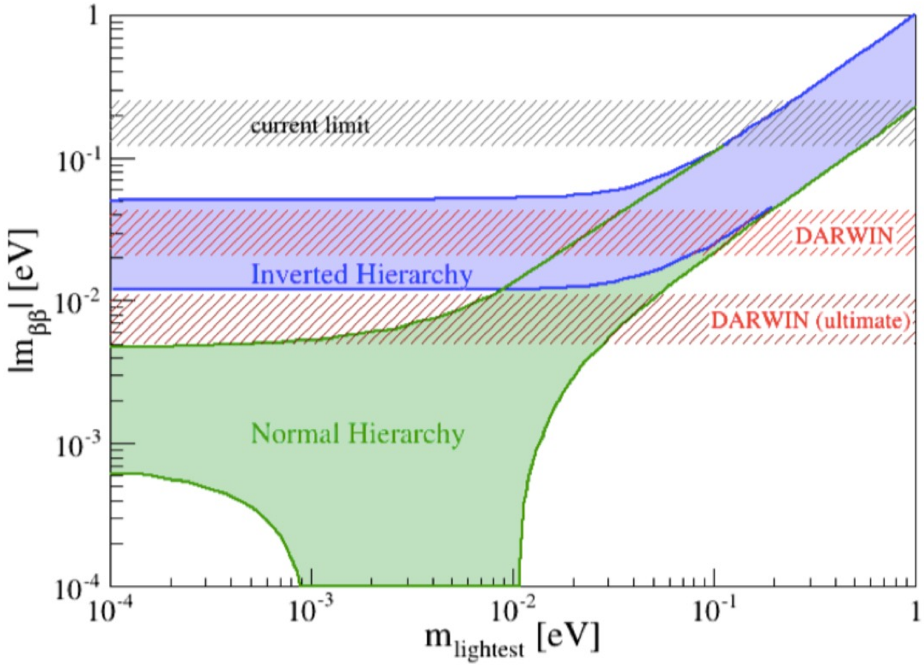
**$Q_{\beta\beta}$ = (2458.7 ± 0.6) keV**

**Assume:**

- 6t fiducial
- energy resolution at $Q_{\beta\beta} \simeq 1\%$




JCAP 01, 044 (2014)

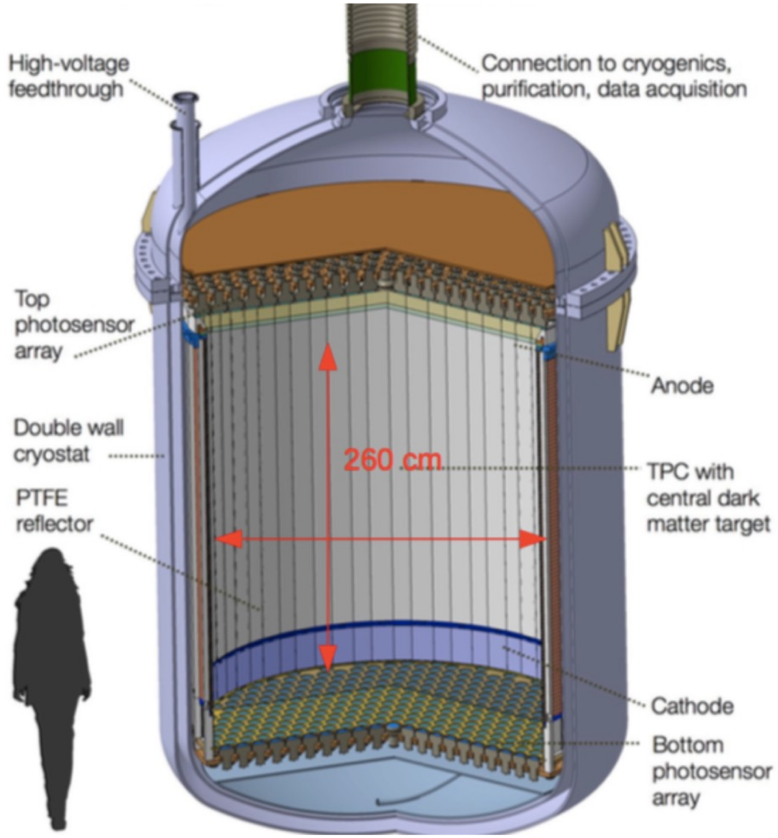



**Sensitivity @ 95% CL:**

- 30 t*yr → $T_{1/2} > 5.6 \times 10^{26}$ yr
- 140 t*yr → $T_{1/2} > 8.5 \times 10^{27}$ yr

**IMPORTANT: DARWIN might become a powerful, cost effective and time-wise competitive $0\nu\beta\beta$ experiment (no enrichment!)**

# DARWIN Conceptual Design




- **Baseline: 50t LXE**
- **40t LXe TPC, aim at 200 t*yr**
- **TPC dimension 2.6m x 2.6m**
- ~1800 * 3” PMTs (or ~1000 4” PMTs)
- Low-background cryostat
- PTFE reflector panels
- Copper E-field shaping rings
- Water Cherenkov shield (~14m diameter)
- Liquid scintillator neutron veto under study
- Possible location LNGS
- **aim at sensitivity of a few $10^{-49}$ cm$^2$, limited by irreducible ν-backgrounds**
- R&D and initial design now
- **Timescale: after XENONnT**
- **Cost effective:**
  - use existing Xe gas; buy more & re-sell
  - no enrichment (also faster)

**JCAP 11, 017 (2016)**

DARWIN

www.darwin-observatory.org

# The DARWIN Collaboration

**France:**
- Subatech
- LAL
- LPNHE

**Germany:**
- University of Münster
- MPIK, Heidelberg
- University of Freiburg
- KIT, Karlsruhe
- University of Mainz
- TU Dresden
- Heidelberg University

**Great Britain:**
- Imperial College London

**Italy:**
- INFN, Sezione LNGS
- INFN, Sezione di Bologna

**Israel:**
- Weizmann Institute of Science

**The Netherlands:**
- Nikhef, Amsterdam

**Portugal:**
- University of Coimbra

**Sweden:**
- Stockholm University

**Switzerland:**
- University of Zürich

**USA:**
- Columbia University
- UCLA
- Arizona State University
- Purdue University
- Rice University
- UCSD
- University of Chicago
- Rensselaer Polytechnic Institute

**Abu Dhabi:**
- New York UniversityAbu Dhabi


– **seed funding**
– **2 approved ERC grants**
– **ExIn application**

# Summary

- **There is clear evidence for DM in the Universe**

**Direct detection of Dark Matter is the crucial test to prove that the Universe is full of new particles**

- **Different options/candidates:**

➔ **WIMPs seem best motivated**

➔ **Excellent opportunity to find or exclude WIMPs in the next years in the natural parameter space**

➔ **Axions, sterile neutrinos and ... other candidates**

➔ **Interplay of indirect & direct detection & LHC**

➔ **Exciting perspectives for the next few years!**