Die Jagd nach Dunkler Materie mit dem XENON1T-Detektor

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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
+ …

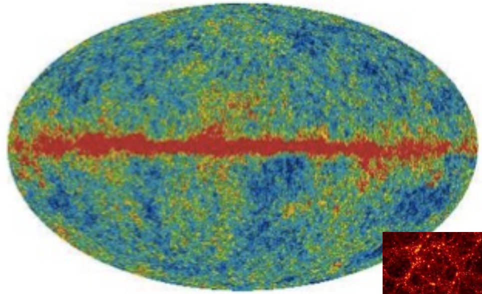
➔ **strong evidence for a large dark sector**

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

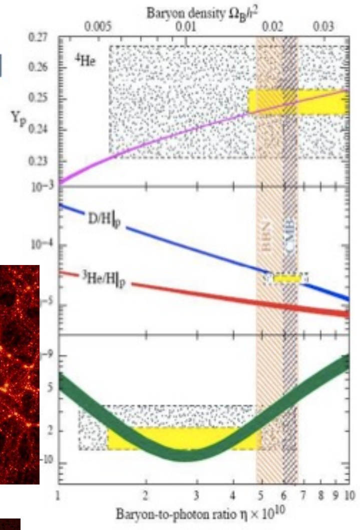
➔ **cannot be explained by ordinary matter**

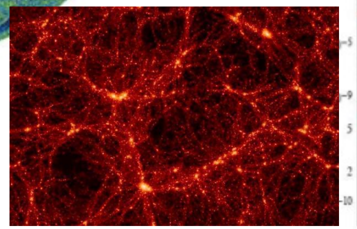
➔ **strong astronomy / cosmology groups in cluster!**

CMB (WMAP)

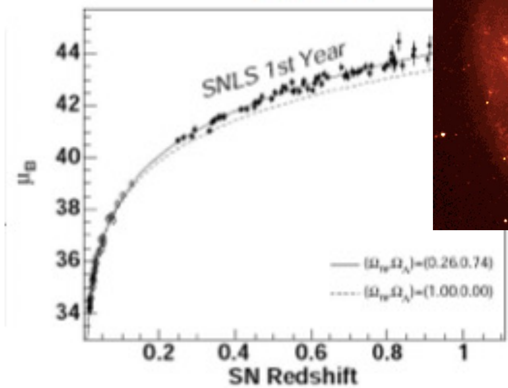


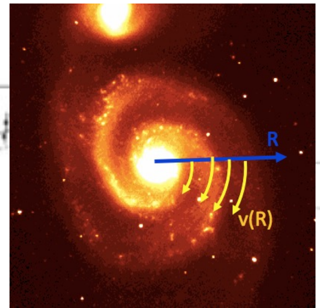
BBN



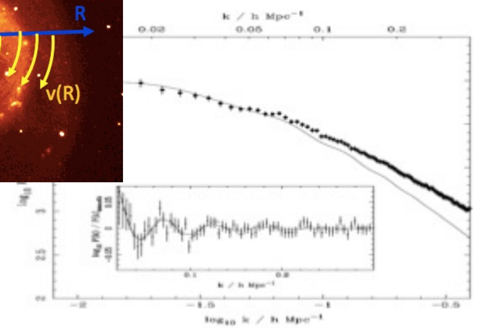


SN 1a

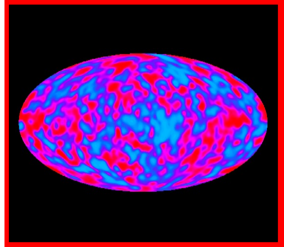




BAO



The cosmic Matter Balance



radiation: 0.005%

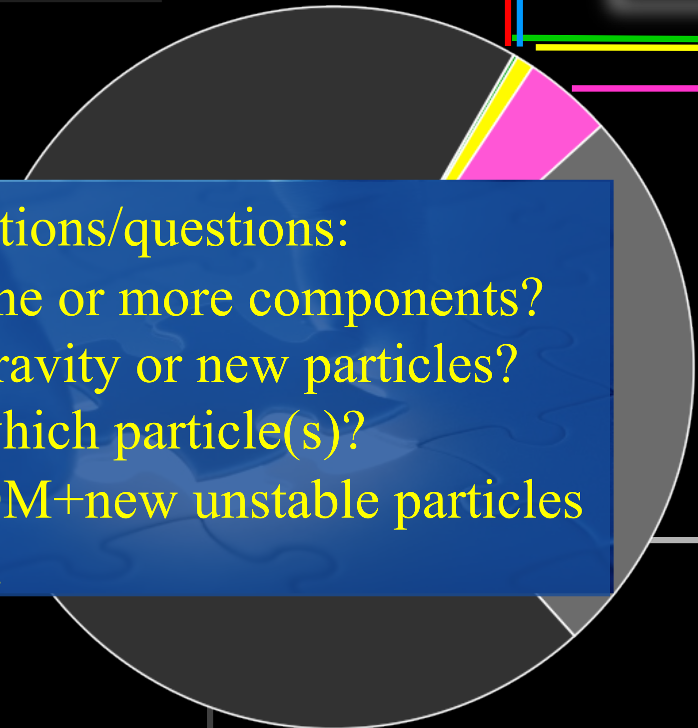
chemical elements: (not H & He) 0.025%

ν_e ν_μ ν_τ

neutrinos = CνB: 0.17%

stars: 0.8%

H & He: gas 4%



Options/questions:
- one or more components?
- gravity or new particles?
- which particle(s)?
- DM+new unstable particles
- ...

?

dark matter: 26.8%
→ something invisible in addition to CνB

?

dark energy: 68.3%

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

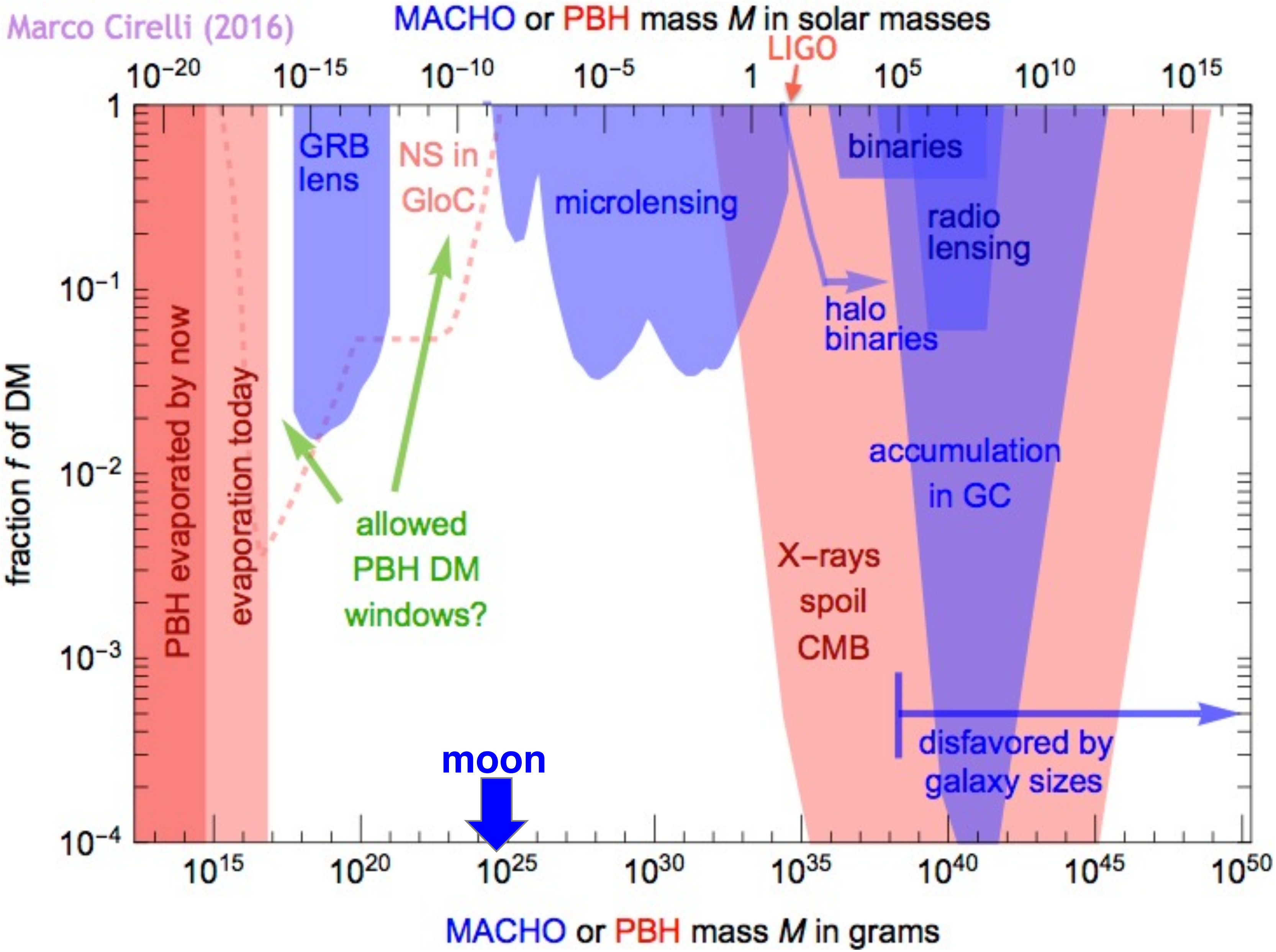
Particles

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

Models with correct abundance
- WIMPs
- dark photons
- ALPs
- other new particles

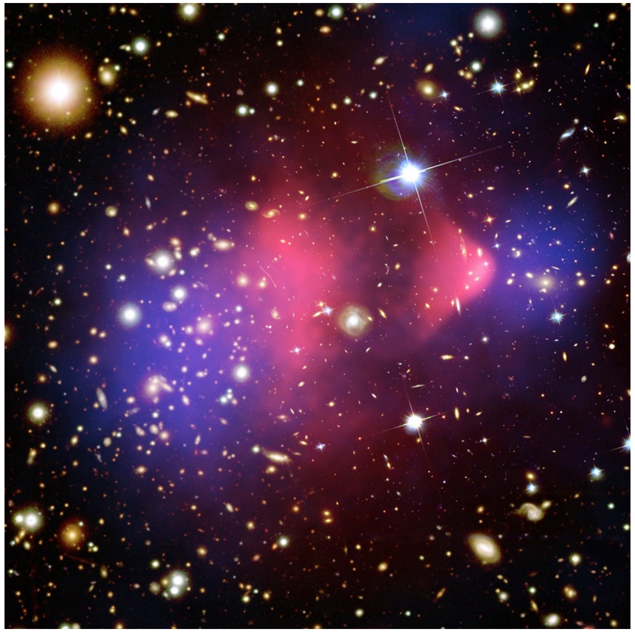
WIMPs combine both aspects in an attractive way: BSM + abundance

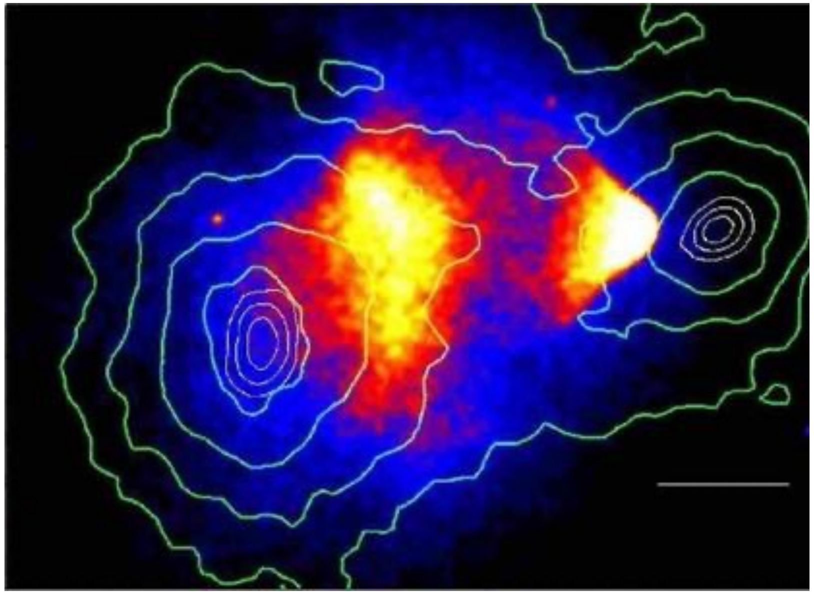
Black Holes as Dark Matter



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)



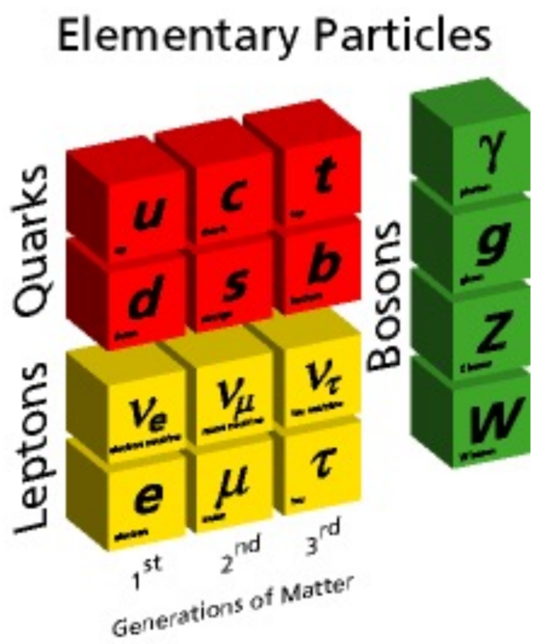


- **Shows that normal particles scatter, but NOT that DM is particles**
- **What is needed:**
  - gravitates ←→ mass
  - non-baryonic
  - SM neutral
  - no or very limited self-interaction
  - no coupling to massive particle
  - stable or long lived

Back to the Roots: The Standard Model

→ success of renormalizable local quantum field theories in d=4

QED	→ QCD	→ SM
$U(1)_{em}$	$SU(3)_C$	$SU(3)_C \times SU(2)_L \times U(1)_Y$



Symmetry, renormalizability, no anomalies

→ particle content (representations)

gauge sector – fixed by gauge group
scalar sector – must break EW symmetry, $\sim 2_L$
fermions – anomaly free combinations

- **various conceptual ingredients = questions:**

quantum fields
chiral fermions, anomaly free combinations
gauge group, d=4, three generations = copies

- **many unexplained parameters ... but it works extremely well**
- **massive neutrinos could have been DM**

→ too light, hot DM → something else → ???

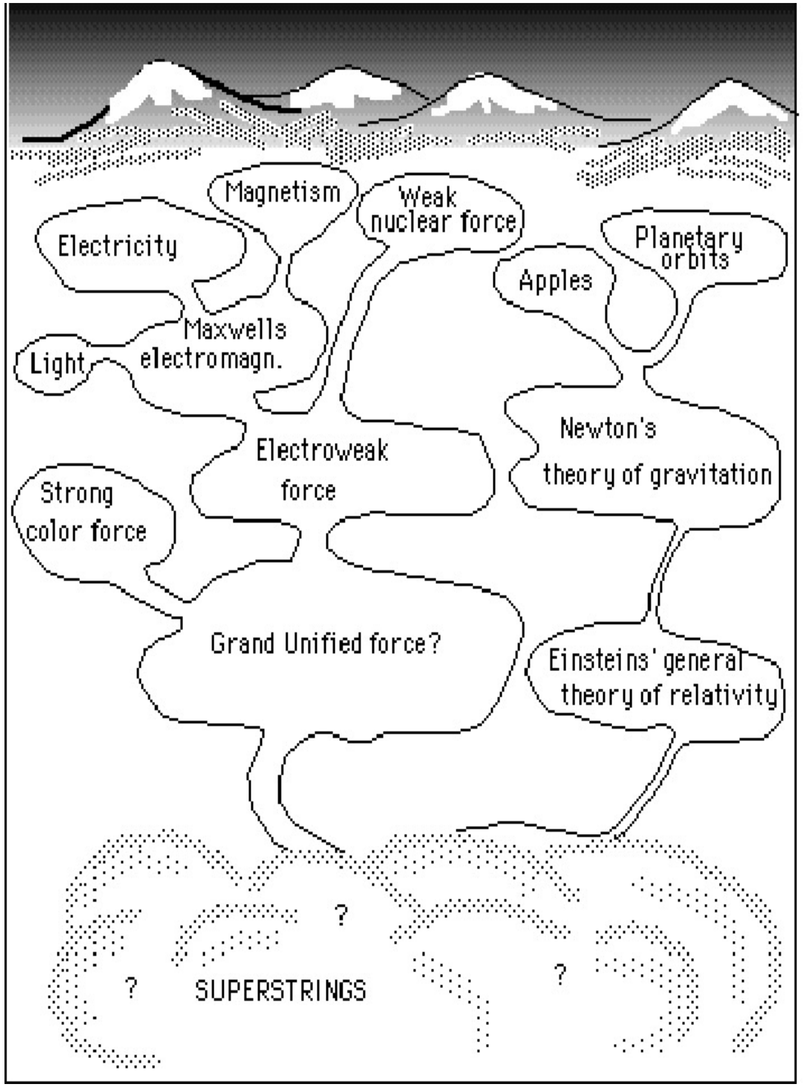
Reasons to go Beyond the Standard Model

Theoretical arguments:

SM does not exist without cutoff
(triviality, vacuum stability)
Gauge hierarchy problem
Gauge unification, charge quantization
Strong CP problem
Unification with gravity
Global symmetries & GR anomalies
Why: 3 generations, representations, d=4,
many parameters (flavour probelm)

Experimental facts:

- Electro-weak scale << Planck scale
- Gauge couplings almost unify
- Neutrino masses & large mixings
- Flavour: Patterns of masses & mixings
- Baryon asymmetry of the Universe
- Dark Matter
- Inflation
- Dark Energy

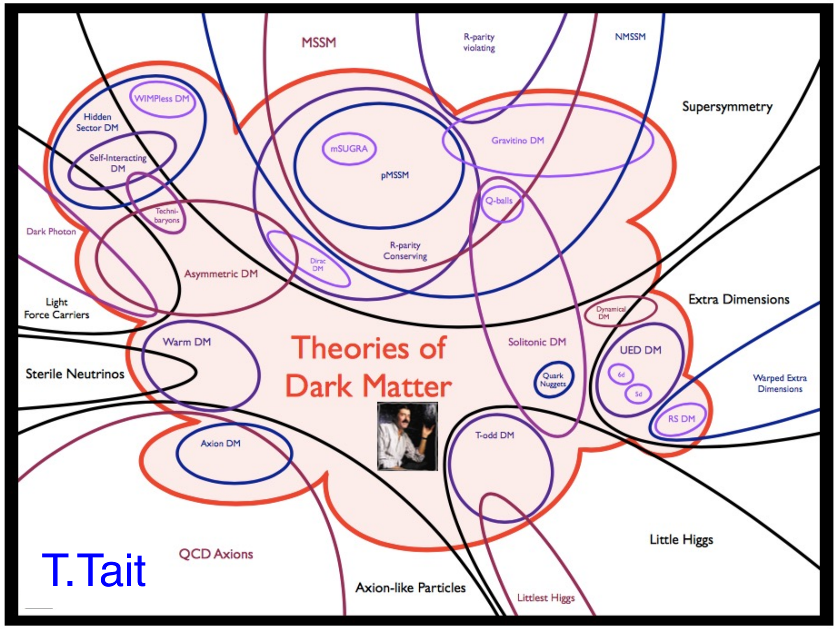


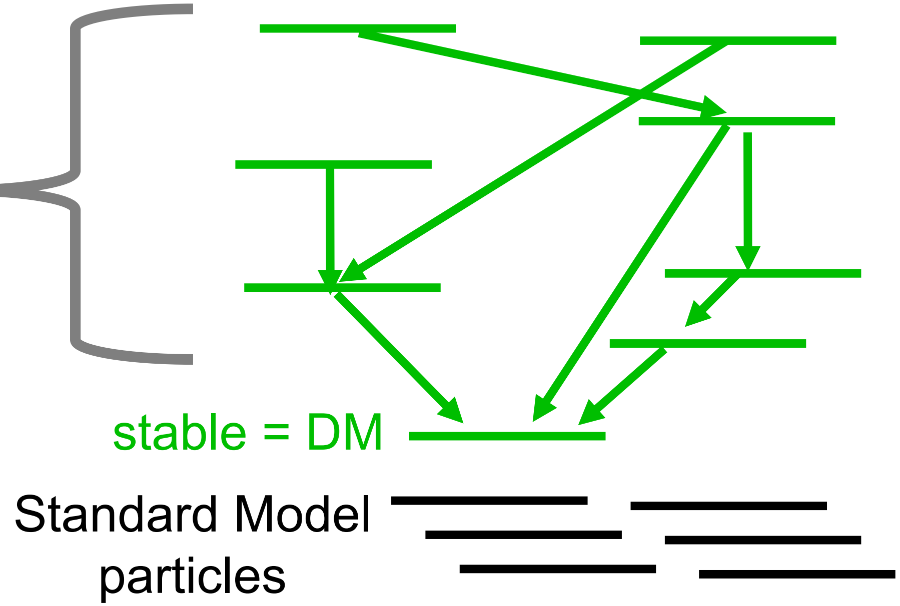
➔ many options for DM

DM motivated Extensions have other Consequences

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

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





WIMPs seem best motivated: WIMP Miracle

- **WIMPs with masses O(100 GeV)←→ many BSM models ←→ HP**
- **miracle: ~ correct abundance:**

1) **Assume a new (heavy) particle χ is initially in thermal equilibrium:**

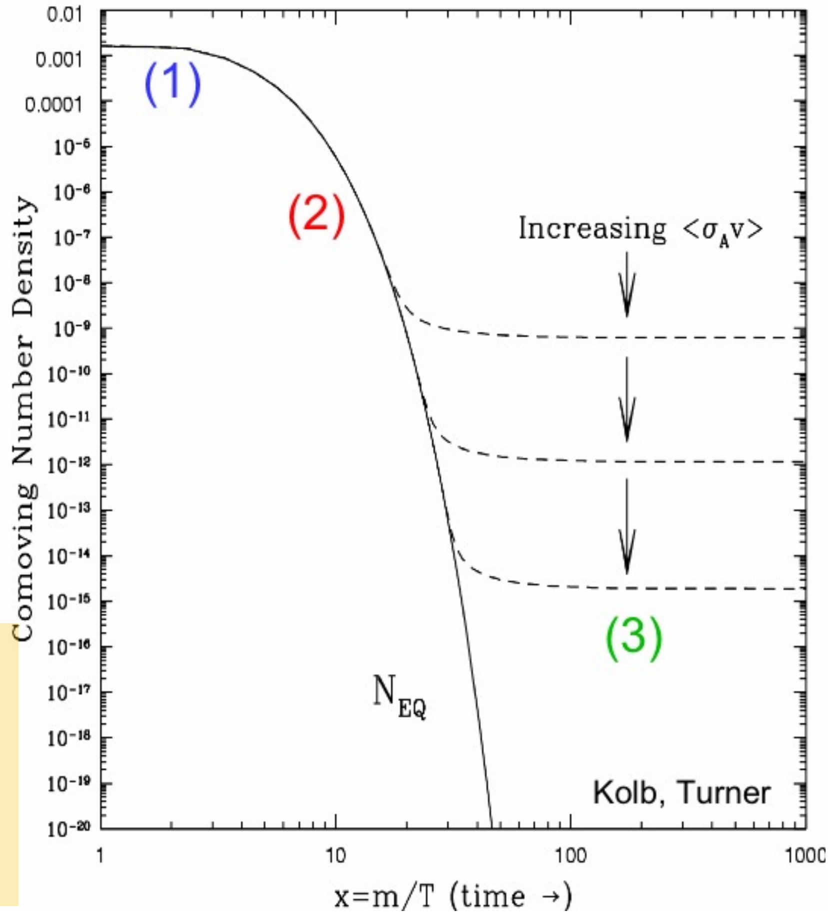
$$\chi\chi \leftrightarrow f f$$

2) **Universe cools:**

$$\chi\chi \;\substack{\rightarrow \\ \not\leftarrow}\; f f$$

1) **"freeze out"**

$$\chi\chi \;\substack{\not\rightarrow \\ \not\leftarrow}\; f f$$



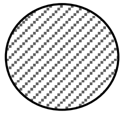
- **amount of DM ~ (x-section)$^{-1}$**
- **natural x-section ~ 1/m^2**
  → correct abundance from EW scale

→ remarkable coincidence: Ω_{DM} ~ 0.2 for m_{WIMP} ~ 100-1000 GeV

→ BSM arguments AND abundance point in the same direction

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: $\sigma \sim 10^{-42} - 10^{-48}\ \text{cm}^2$

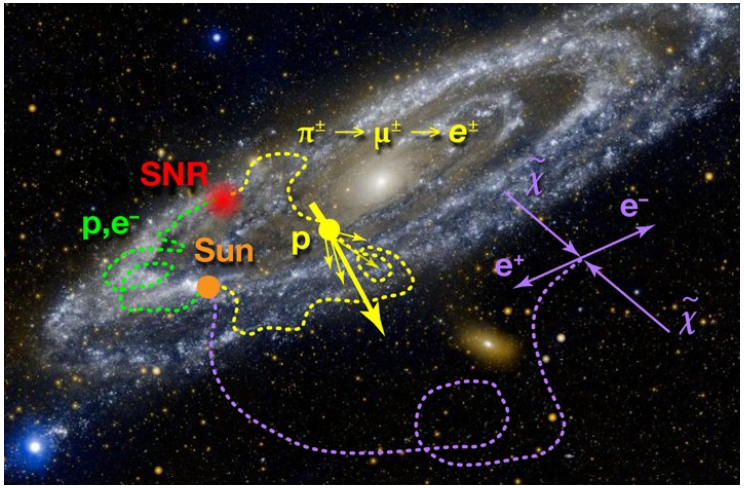
known amount of DM ➔~WIMP flux ➔ rate@direct.det.

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

Hunting WIMPS in different Ways

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

indirect detection

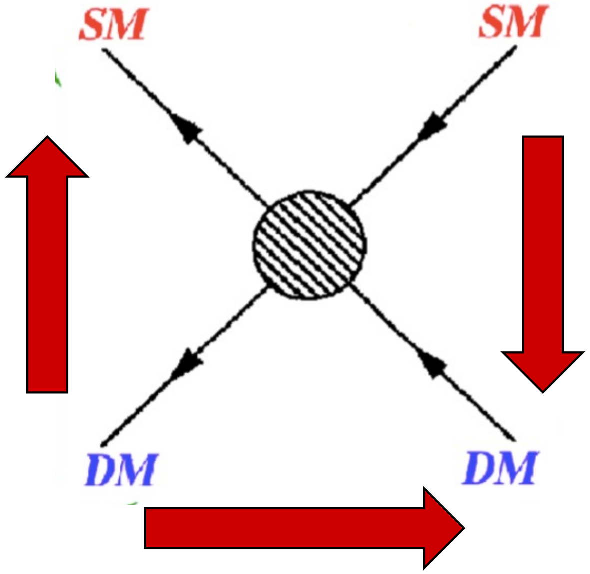


FERMI, PAMELA, AMS, HESS, IceCube, CTA, HAWC…

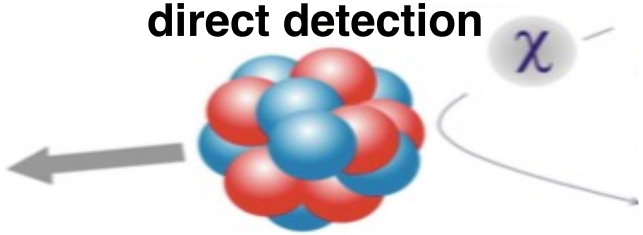
astronnomical uncertainties...

→ is the signal without doubt from DM?

keV lines ←→ atomic physics



direct detection

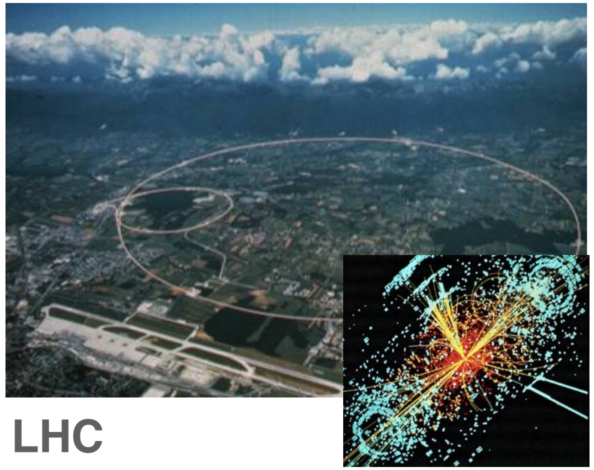


WIMP wind : 220km/s from Cygnus

→ modelling

→ rare event backgrounds

colliders



LHC

may detect new particles

- is it DM (lifetime, abundance)?

So far nothing seen…

→ impact on theory…

→ SUSY → higher scale

→ other SB motivated WIMPs

→ new ideas/candidates

Direct DM Detection: Billard with invisible Balls

- WIMPs scatter off atoms in a detector → **detect the signal… or set limits**
- Maximal momentum transfer → $M_{WIMP} \sim M_{atom}$
  Additionally: clean, transparent, high density, no free charges, …

  → **liquid Xenon** (ca. -100 degree) ←→ rarest stable element

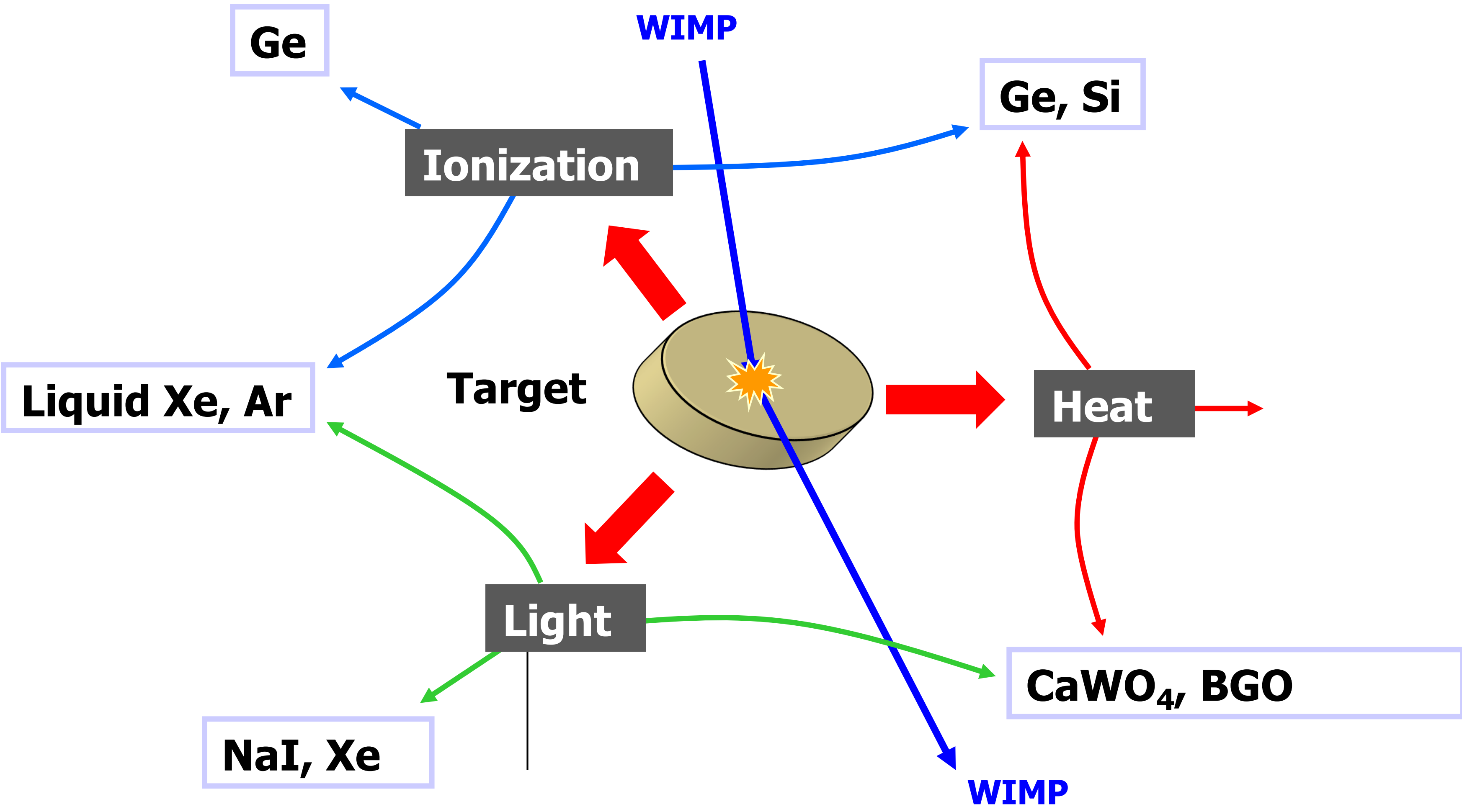
Goal:

1) **Maximal signal** ←→ rare process
   → many atoms → big detector
2) **Minimal background**
   → requires extremely low radioactive background

→ **Signal/limits for WIMPs, axions, ...**
→ **room for surprises!**

Direct Detection Techniques (WIMPs)

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

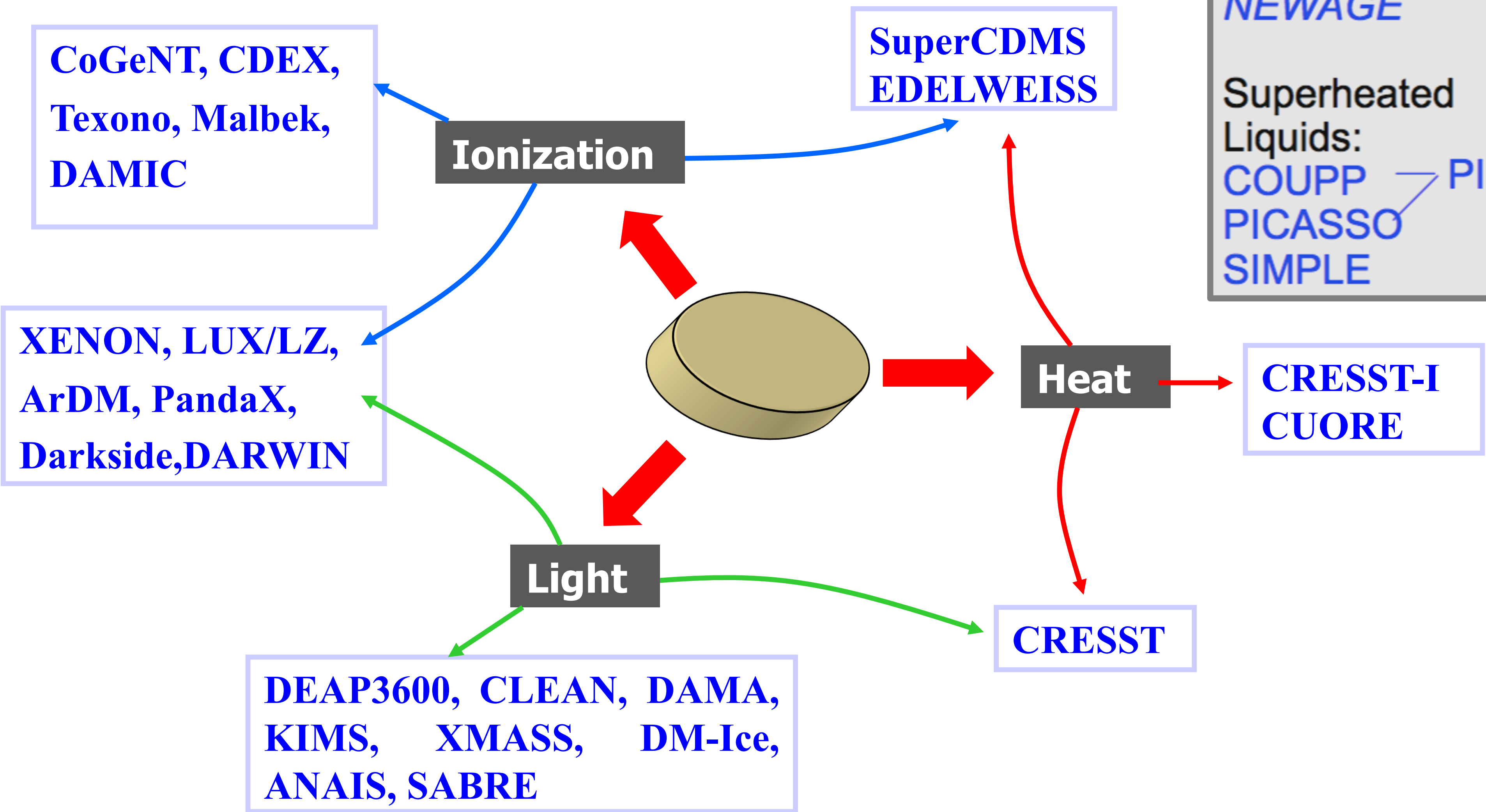


Direct Detection Experiments

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

Tracking:
DRIFT, DMTPC
MIMAC
NEWAGE

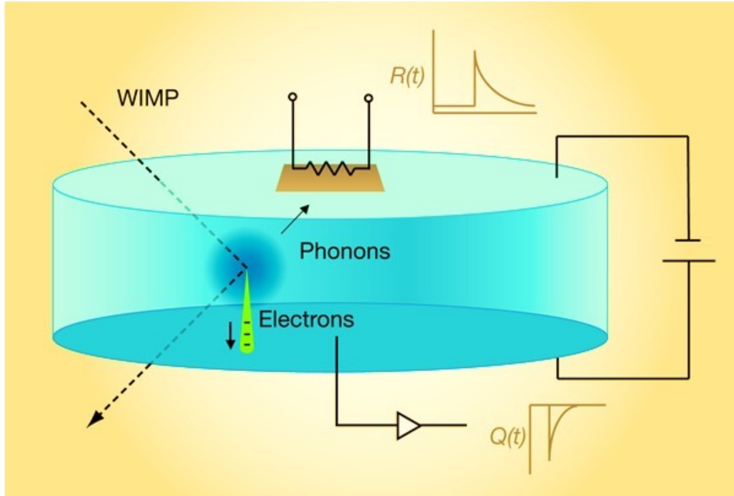
Superheated Liquids:
COUPP → PICO
PICASSO
SIMPLE

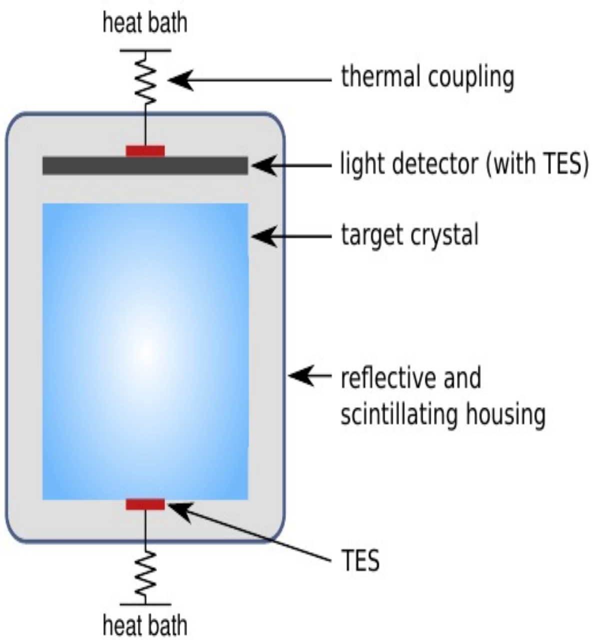


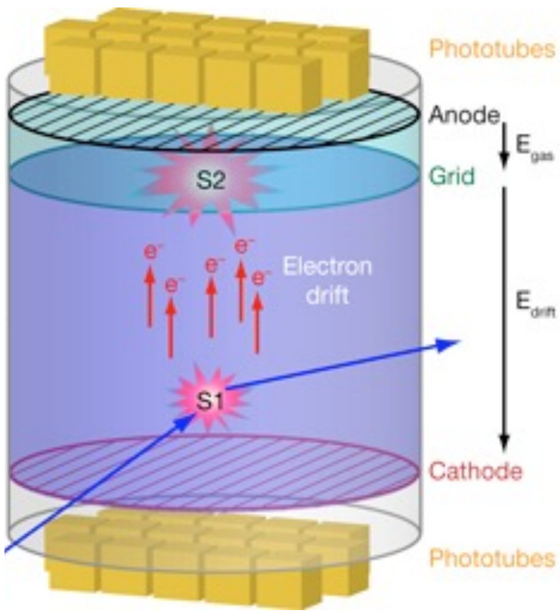
Converting WIMP Scattering into Signals

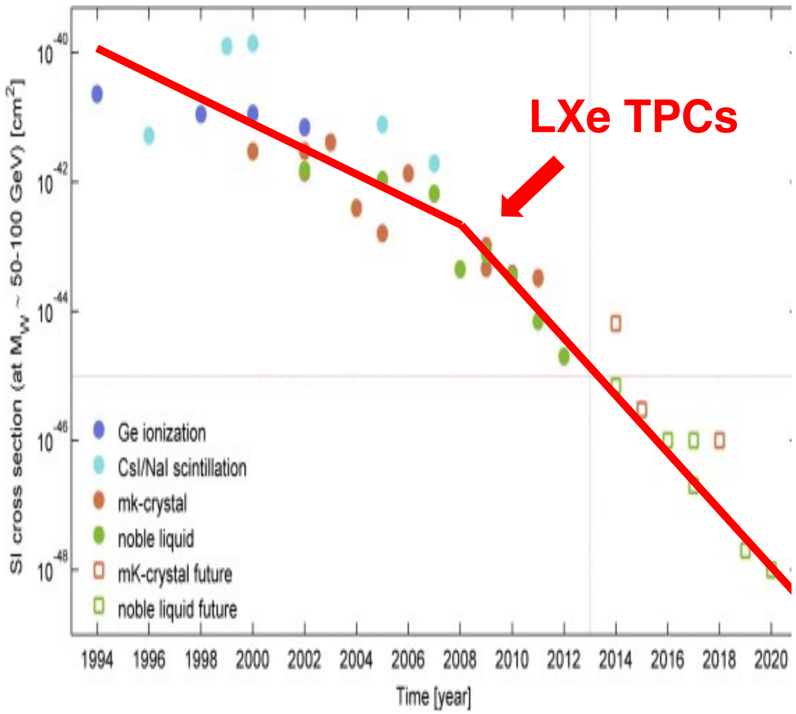
Light – ionization – heat: 3 examples

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

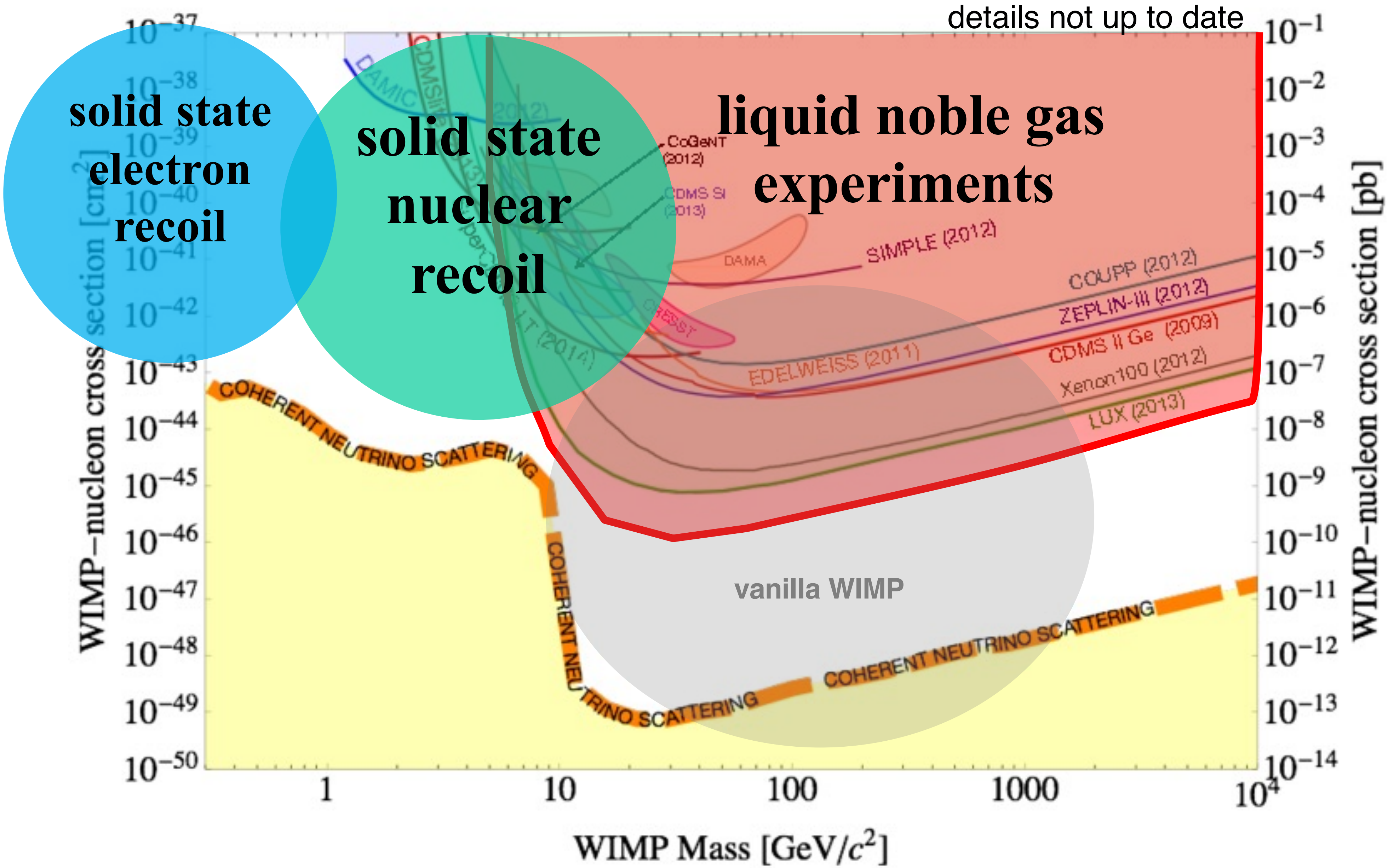








Technologies and their main Territory



The XENON Collaboration

Columbia | KIT | Nikhef | Muenster | Stockholm | Mainz | MPIK, Heidelberg | Freiburg | Zurich | Tsinghua

Chicago

UCSD

Rice

Purdue

Tokyo

Nagoya

Kobe

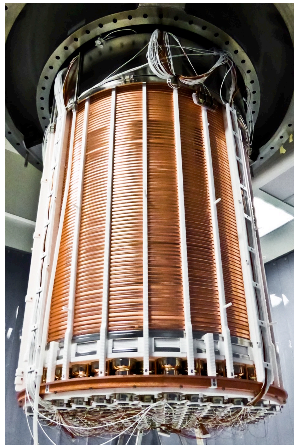
NYUAD

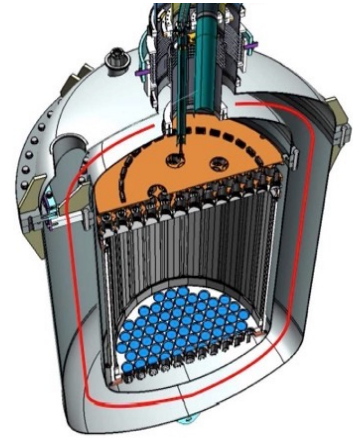
Subatech | Coimbra | LPNHE | IJCLab | Torino | Bologna | L'Aquila | LNGS | Napoli | Weizmann

XENON Collaboration: ~170 scientists

The XENON Dark Matter Program

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



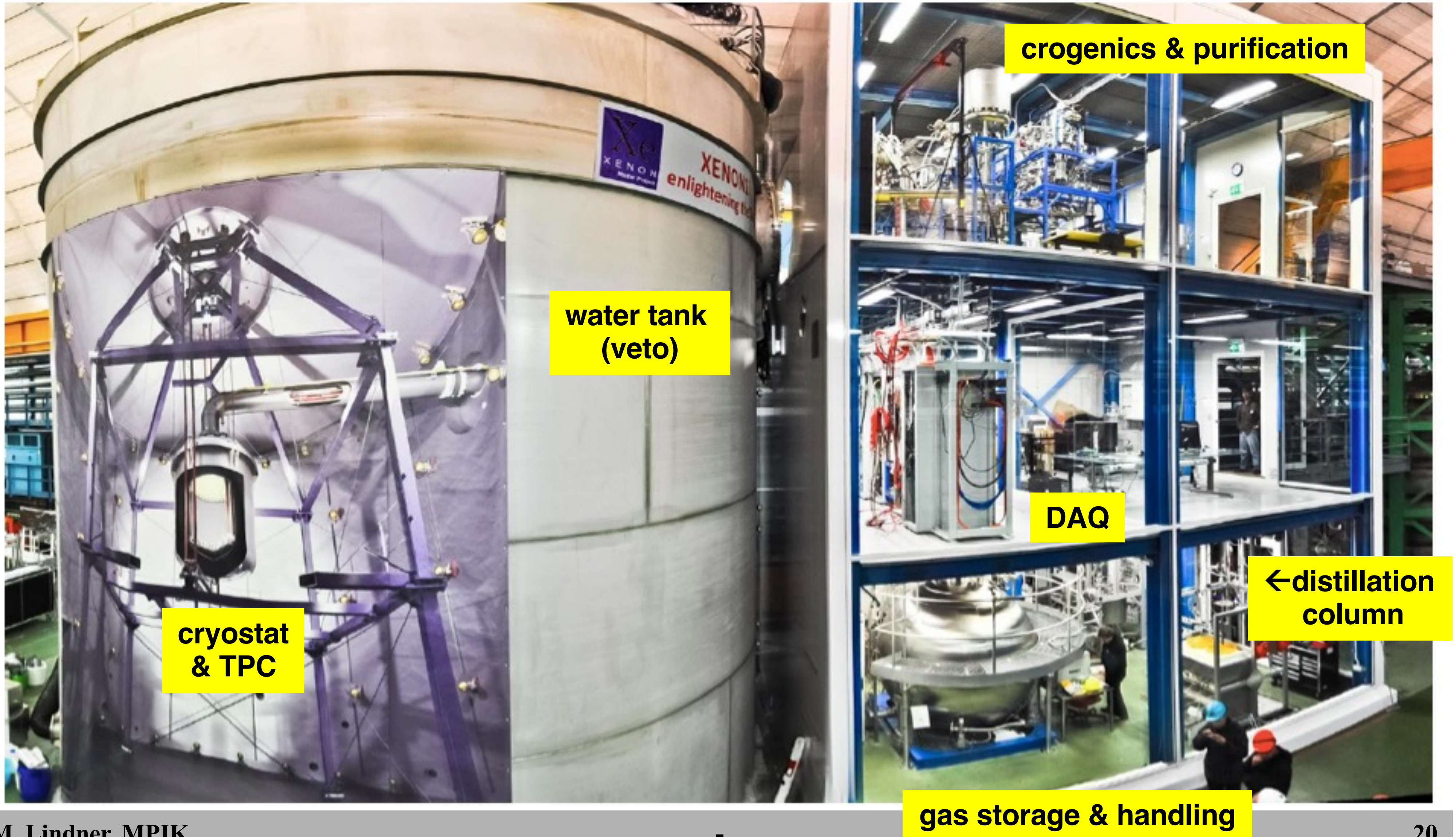


	XENON10	XENON100	XENON1T	XENONnT
Period	**2005-2007**	**2008-2016**	**2012-2018** →	**2020-2024**
Total mass	25 kg	161 kg	3200 kg	~8000 kg
Drift length	15 cm	30 cm	100 cm	150 cm
Status	Completed (2007)	Completed (2016)	Running	Construction
σ_{SI} limit (@50 GeV/c²)	8.8×10^{-44} cm²	1.1×10^{-45} cm²	1.6×10^{-47} cm² (2018)	1.6×10^{-48} cm² (2023)

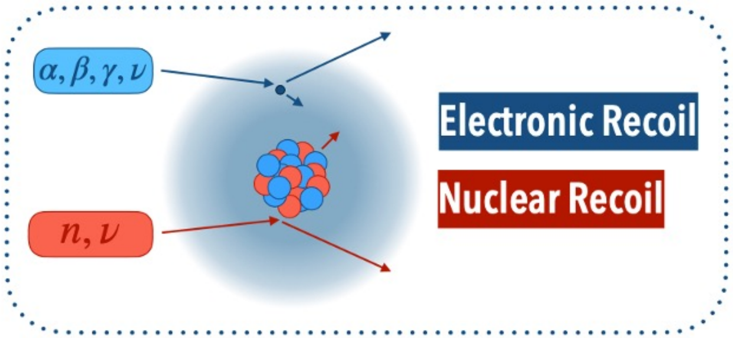
XENONnT was prepared while XENON1T took data
➔ switching gears ➔ filling started recently

XENON1T @ LNGS: Running until 12/2018

→ Goal: two orders of magnitude improvement in sensitivity with respect to XENON100



Dark Matter Detectors in UG Laboratoties



Background reduction

➔ extremely challenging:

- material selection
- screening (γ, Rn, …)
- graded shielding
  - deep underground
  - veto systems
  - water
- cryogenic distillation
- pulse shape analysis
- …

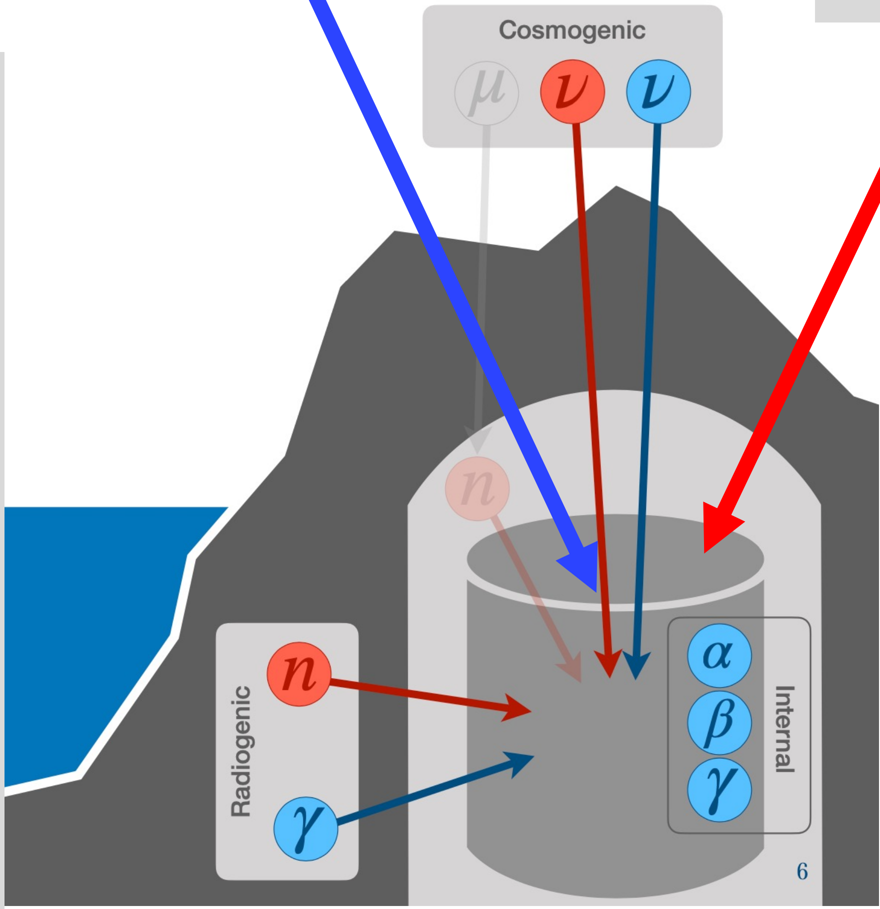
WIMPs

→ nuclear recoils

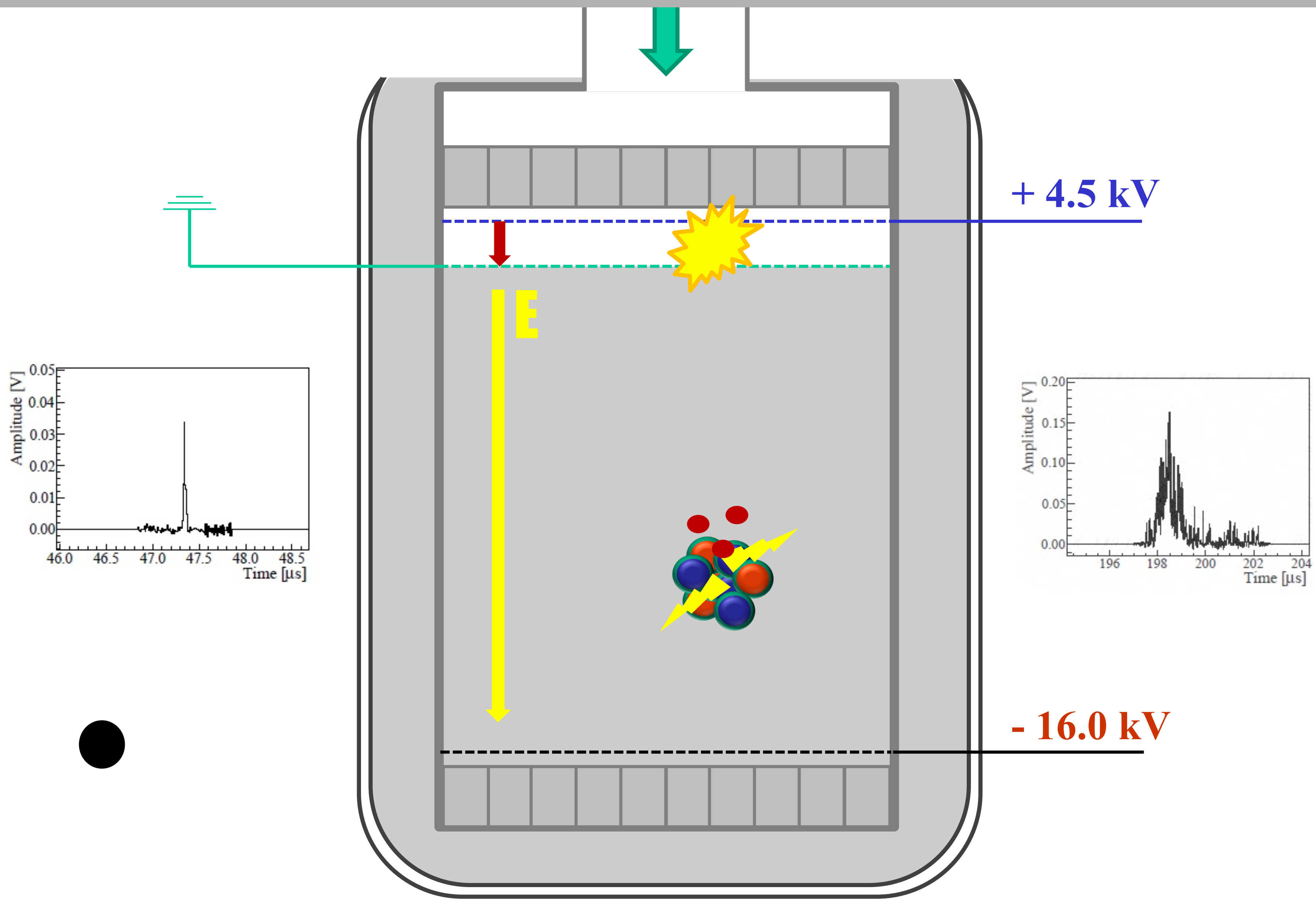
Sun:

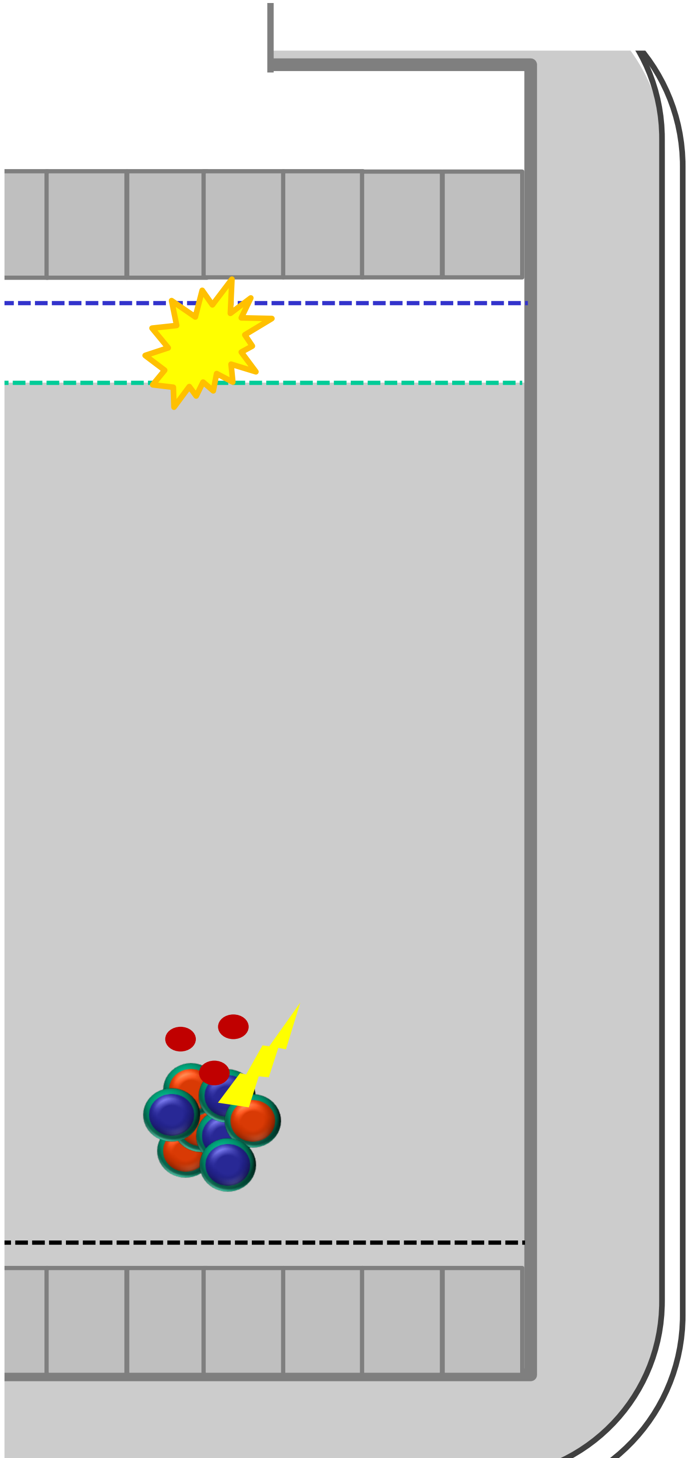
- Neutrinos
- Axions ?
- ???

SM: too weak
→ should
not show up



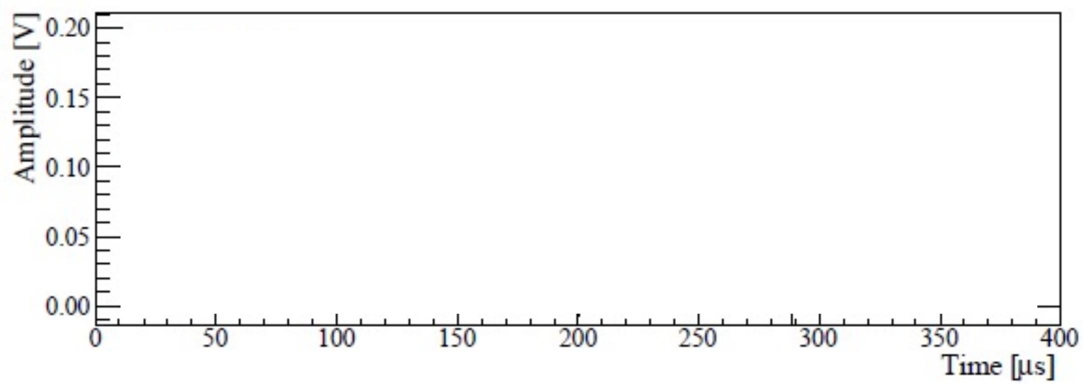
Dual Phase LXe or LAr TPCs





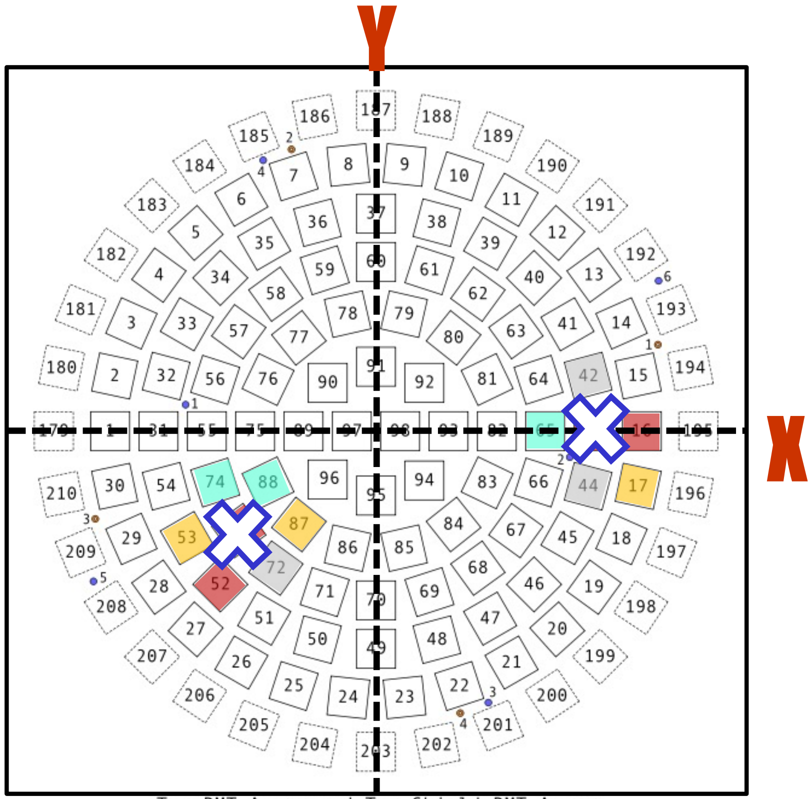
● **Rec**

Slow motion

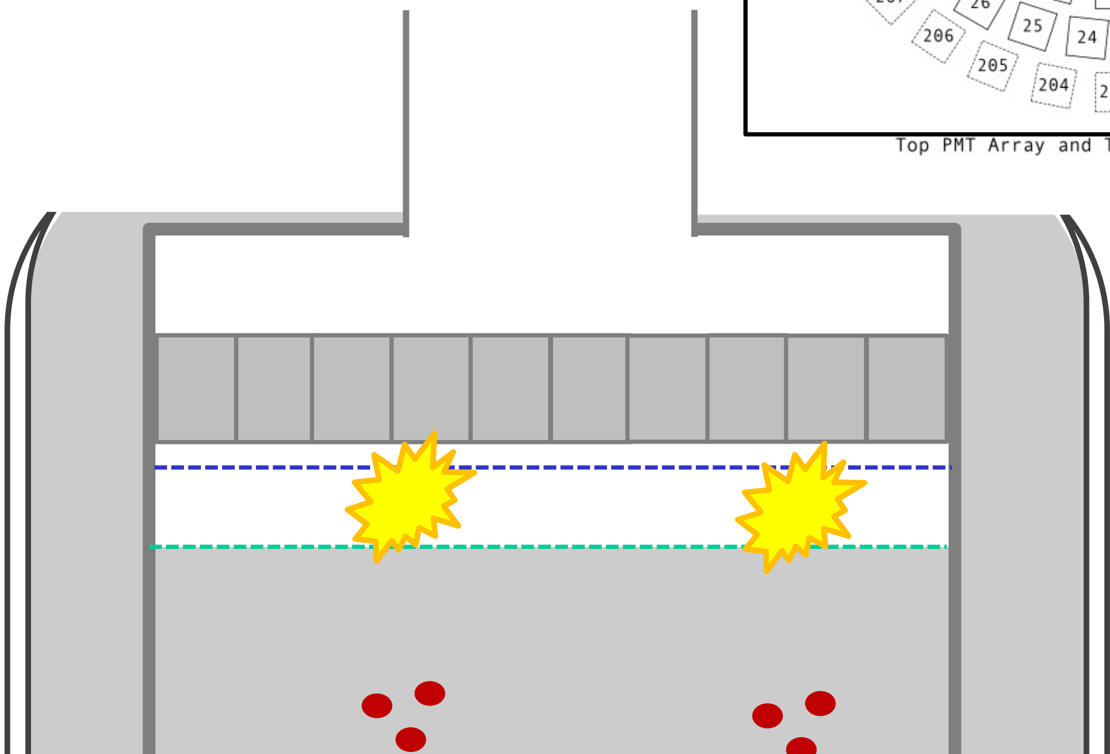


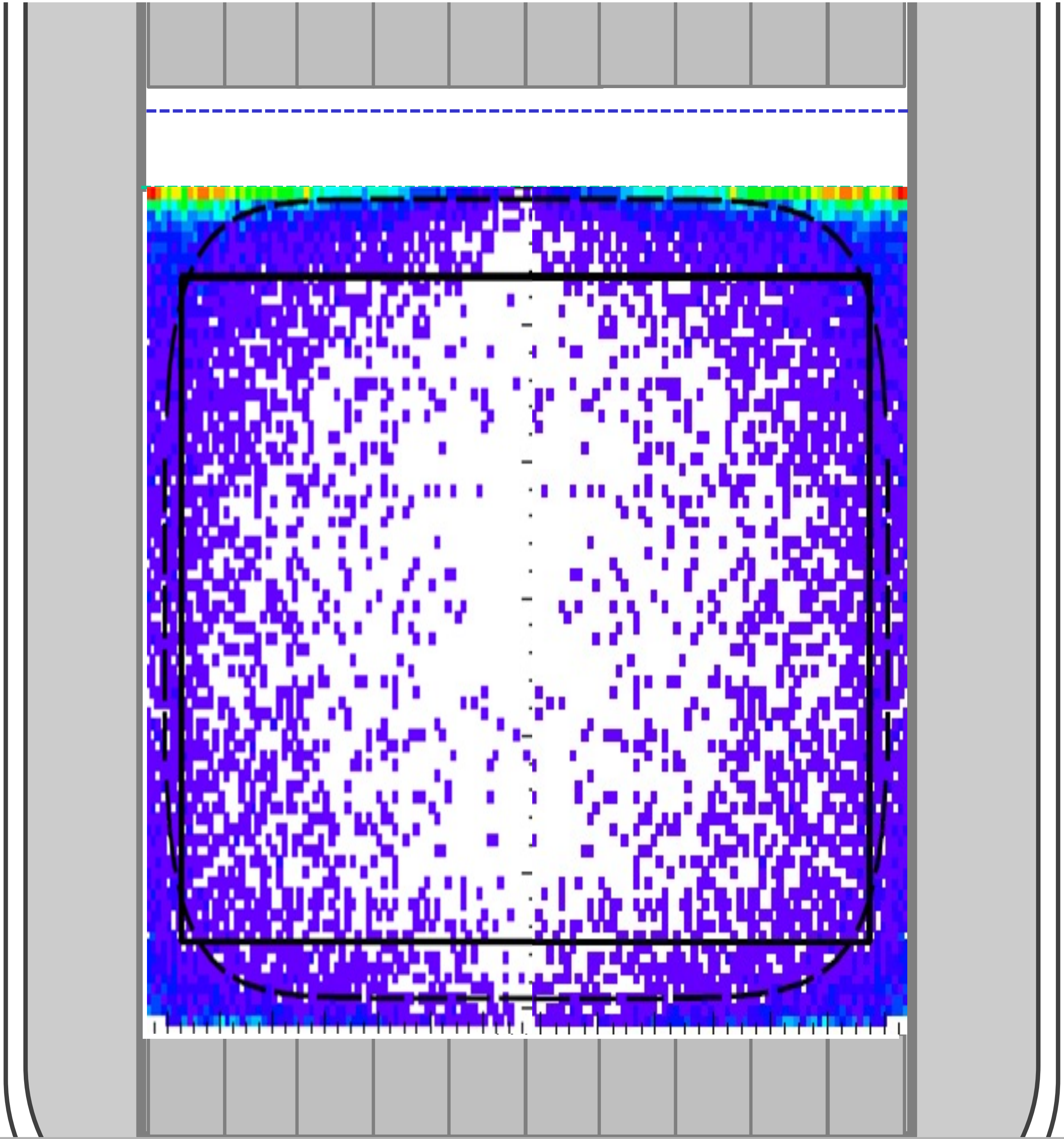
$$z(dt) = vDrift \cdot dt$$

$$vDrift \approx 1{,}74\ mm/\mu s$$



Top PMT Array and Top Shield PMT Array

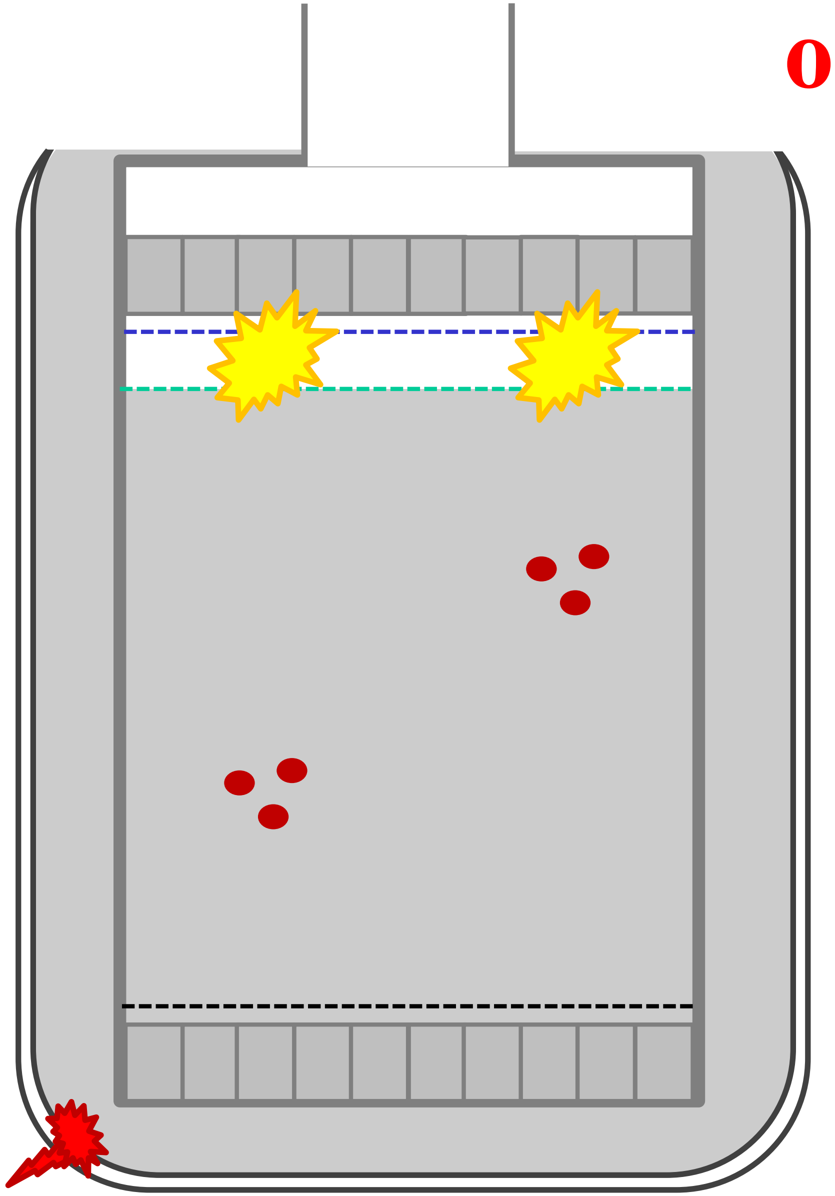


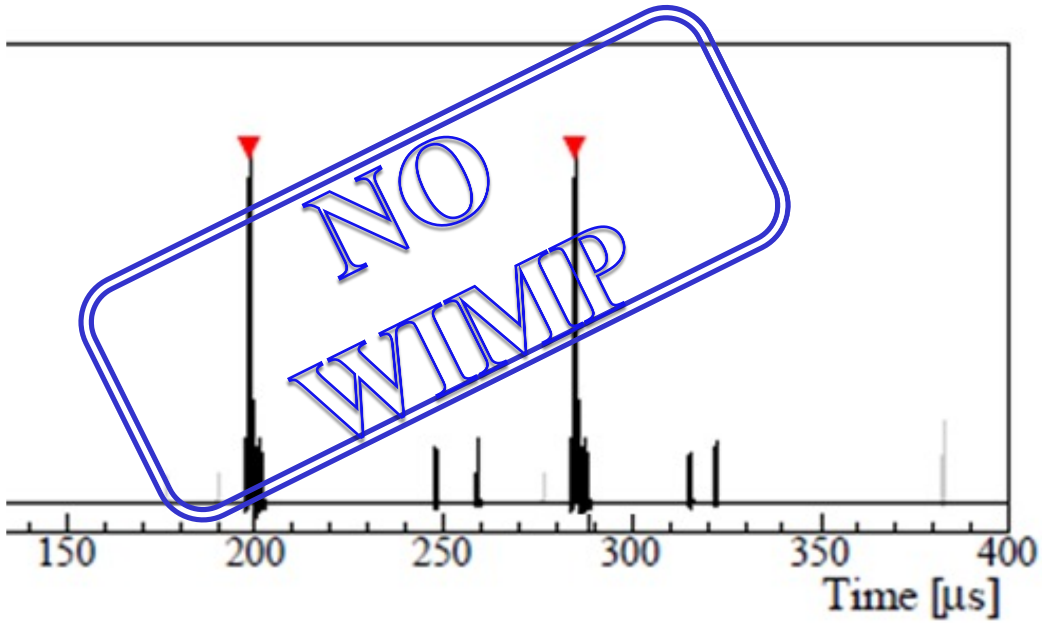


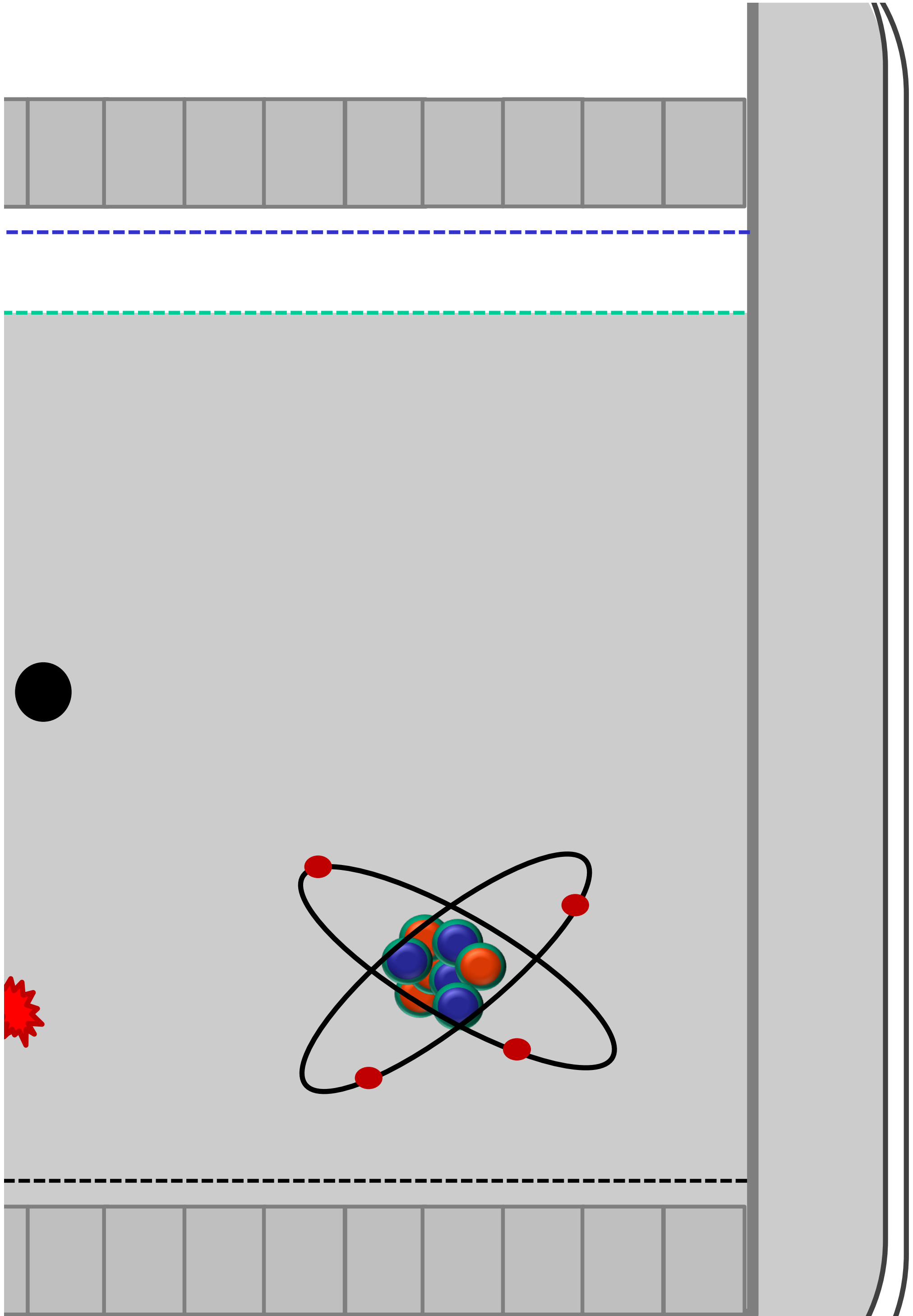
- reconstruct x,y,z

Next:
- fiducialize
- remove bg events

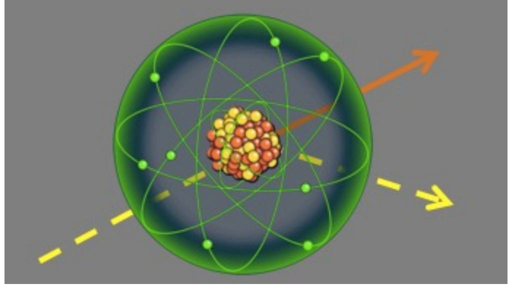
A WIMP scatters only once (if at all)

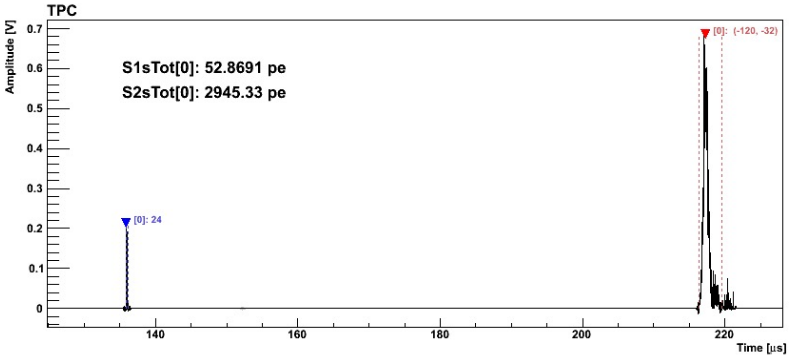




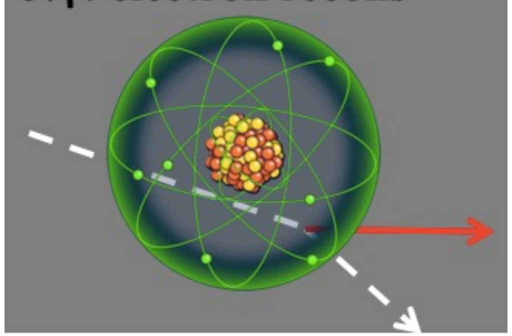


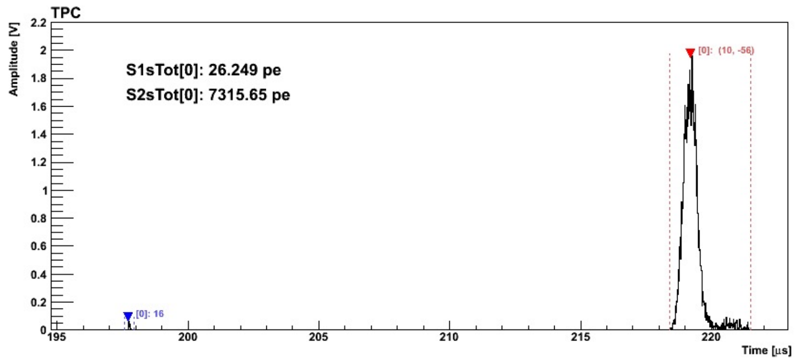
n/WIMPs: nuclear recoils





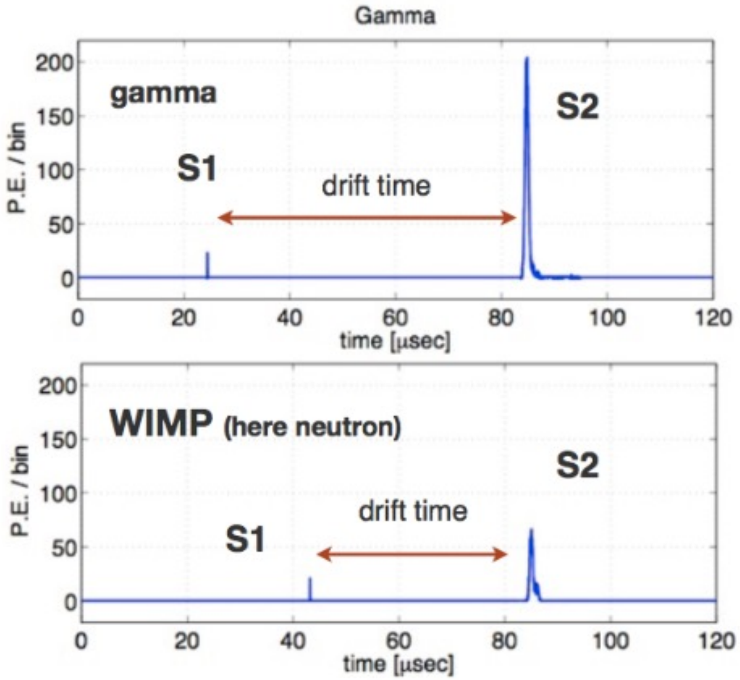
e⁻/γ: electron recoils

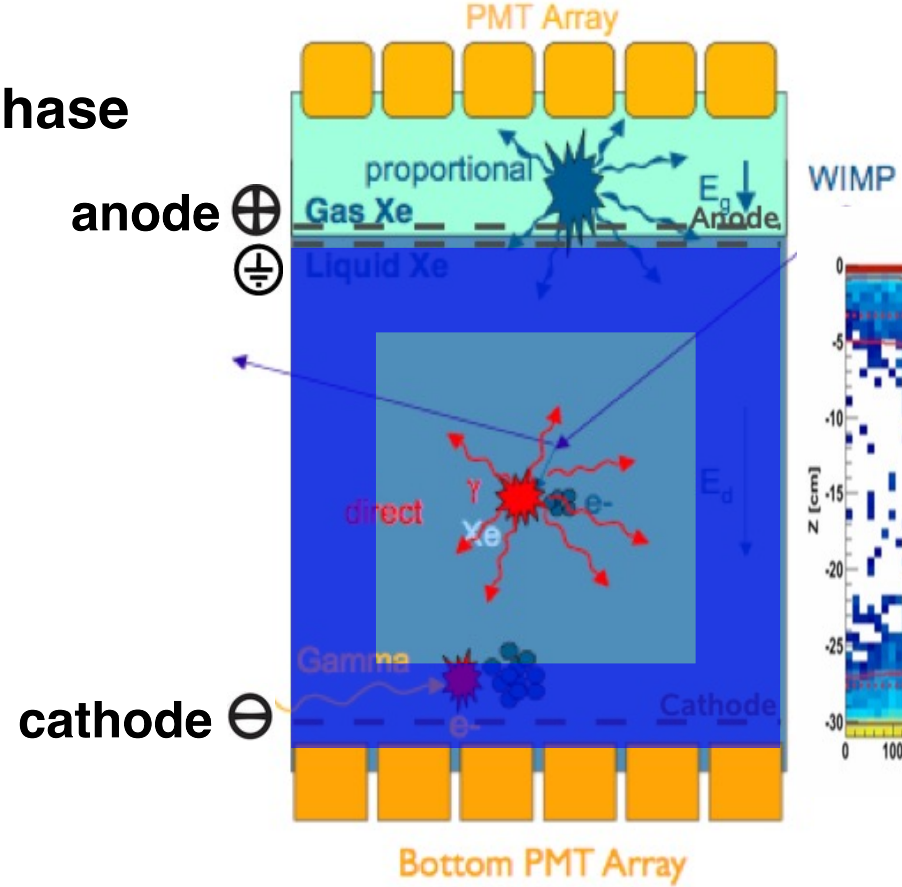


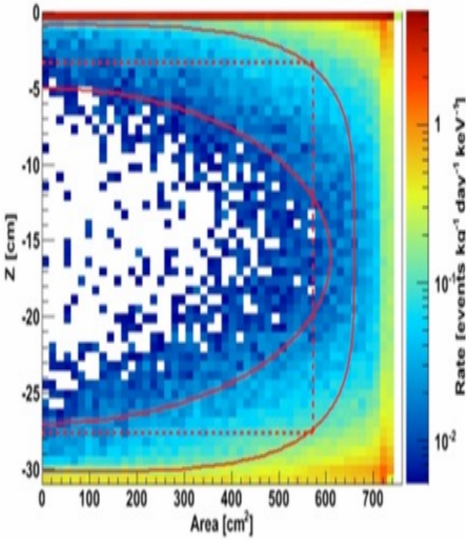


A powerful Device: Dual-Phase TPC

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



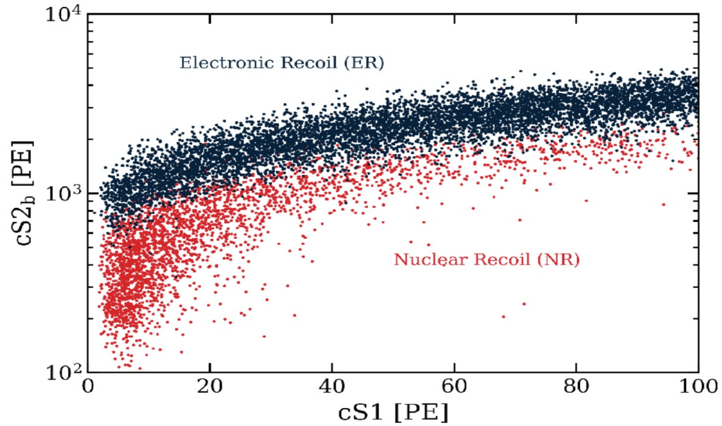




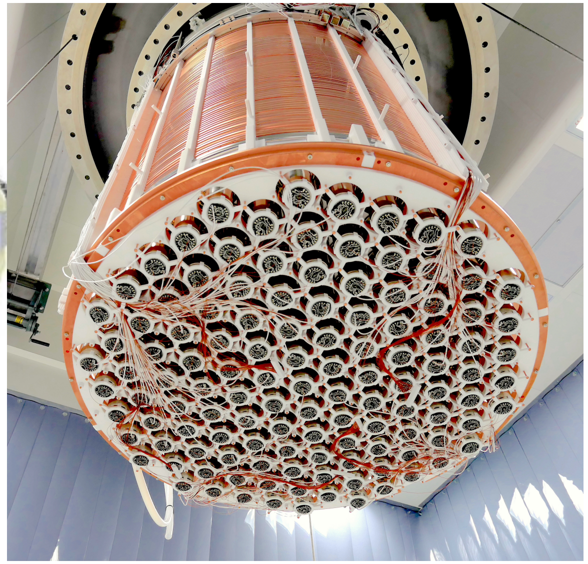
→ **excellent 3D position reconstruction**

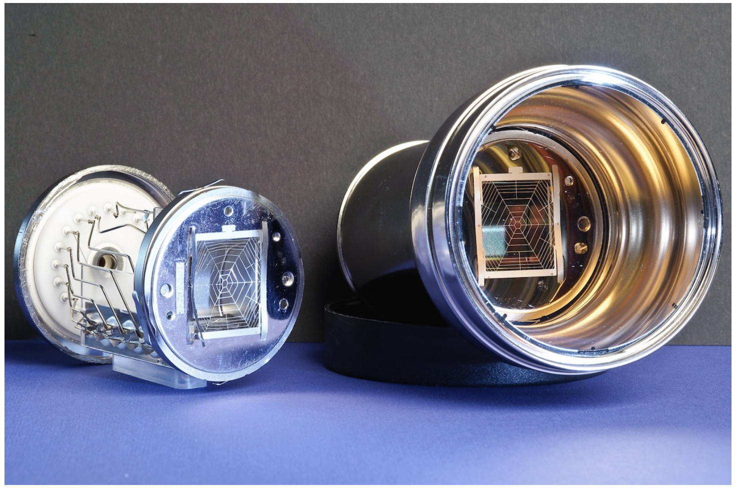
→ **fiducialization** = exclude known backgrounds from 'dirty' surfaces

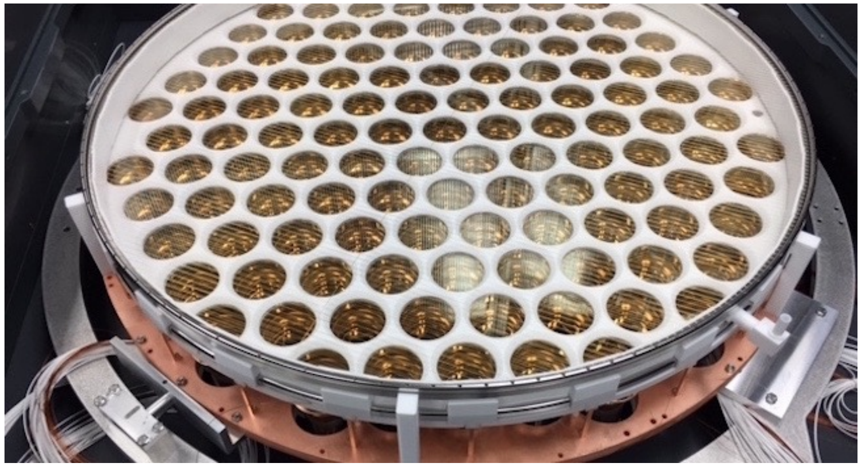
→ **S2/S1 discrimination of ER / NR**



The XENON1T TPC

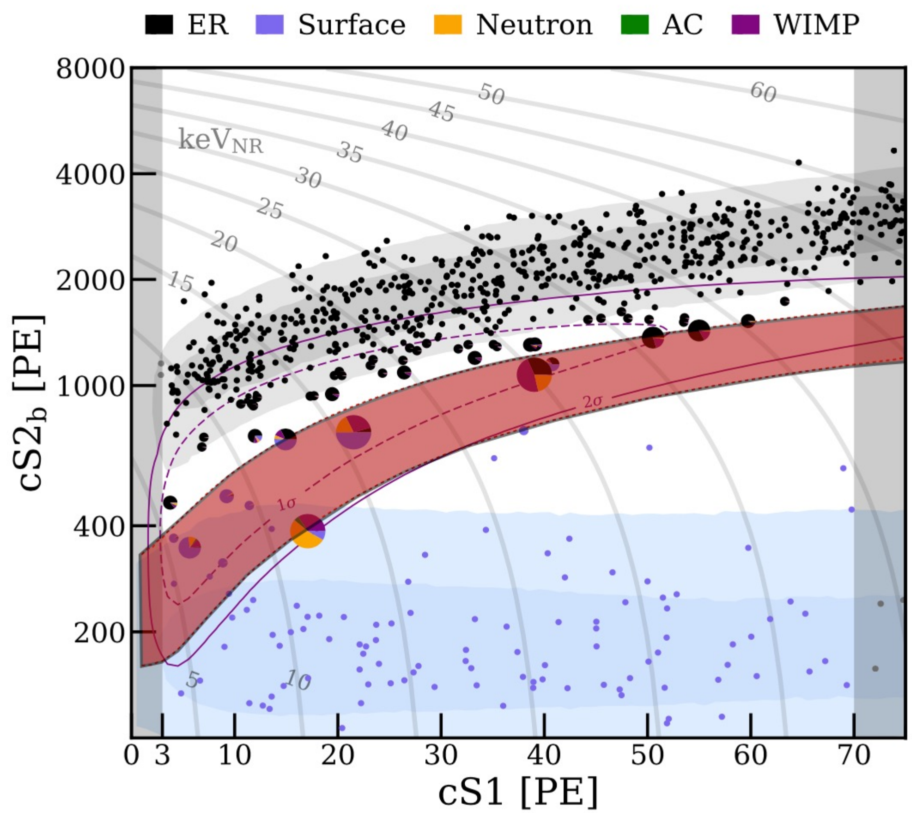


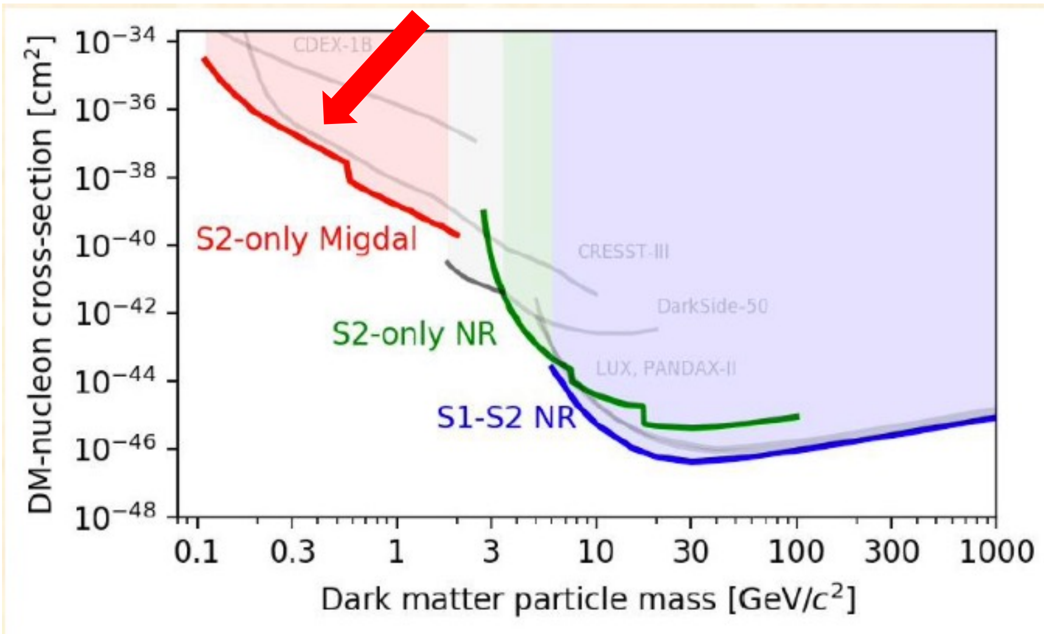




+ many other sophisticated sub-systems based on lot's of R&D

XENON1T: Nuclear Recoil Searches





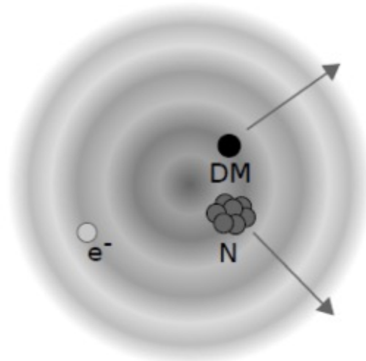
PRL 121, 111302 and PRL 123 251801- Main WIMP search

➔ **Most stringent result on SI scattering of WIMP Dark Matter down to 3 GeV/c^2 masses**

PRL 123, 241803 - Migdal effect

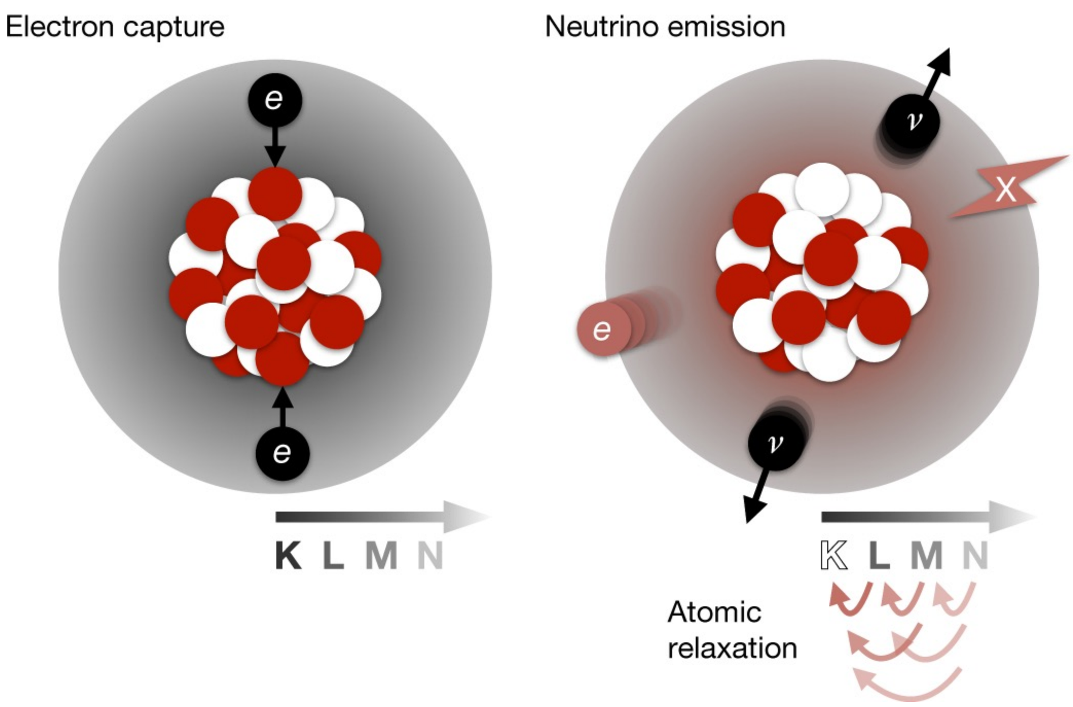
PRL 123, 251801 - light dark matter

➔ **Extends sensitivity to lower WIMP masses**



Migdal: ...it takes time for the electron to catch up

Double Electron Capture of ^{124}Xe



$T = 1.8 \pm 0.5_{stat} \pm 0.1_{sys} \times 10^{22}\, yr$

No rejection significane: 4.4σ

➔ about one trillion times the age of the Universe

➔ longest half-life ever measured directly

Nature 568 (2019) 7753, 532-535

Search for New Physics with ER Events

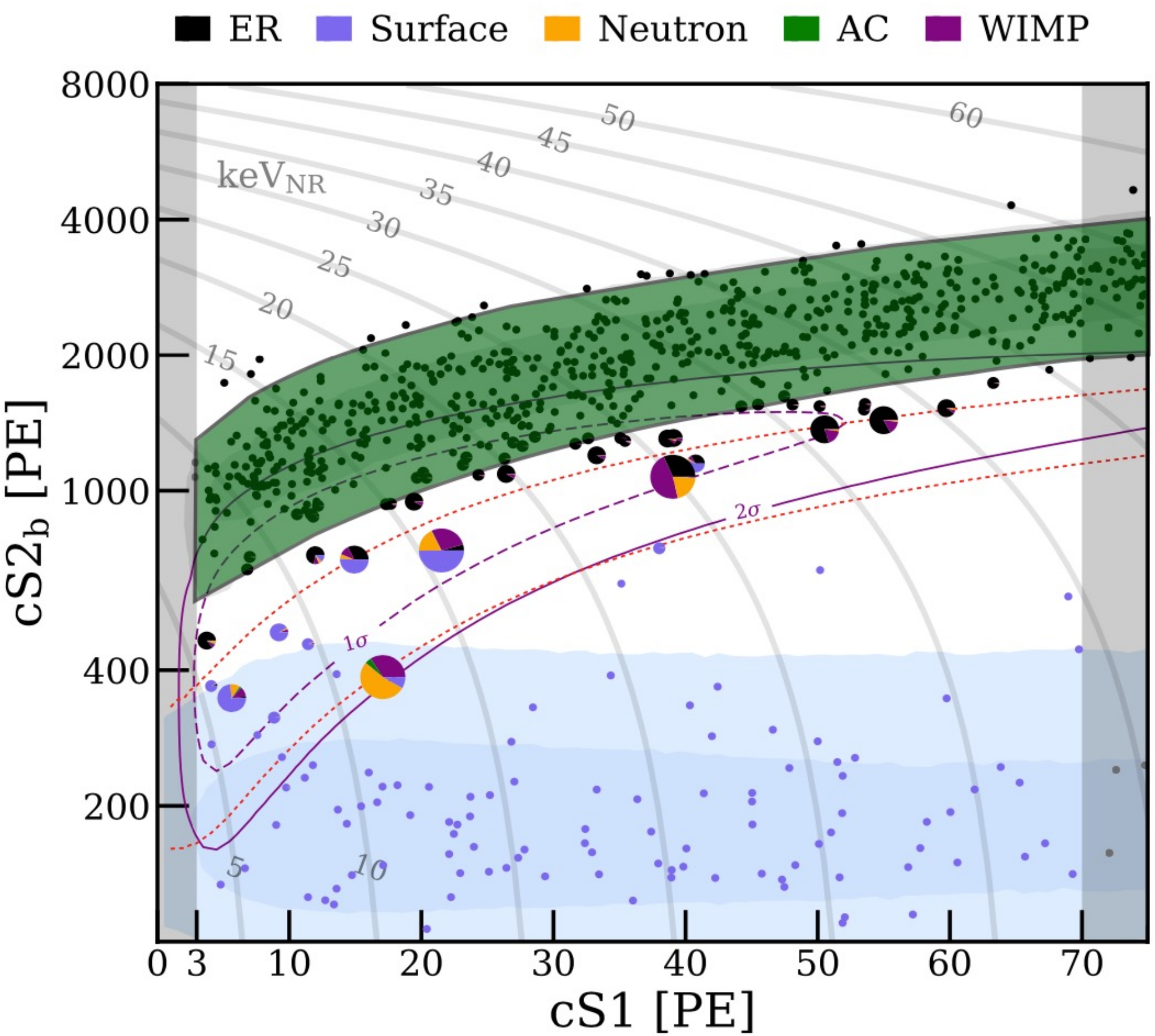
Phys. Rev. D 102, 072004

Large exposure:
0.65 tonne-years

Unprecedented low background:
76 ± 2 events/t/yr/keV

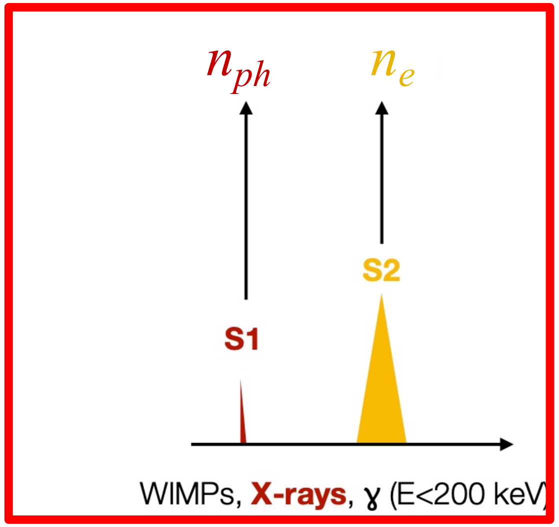
Low threshold:
1 keV_{ee}

➔ excess events!?



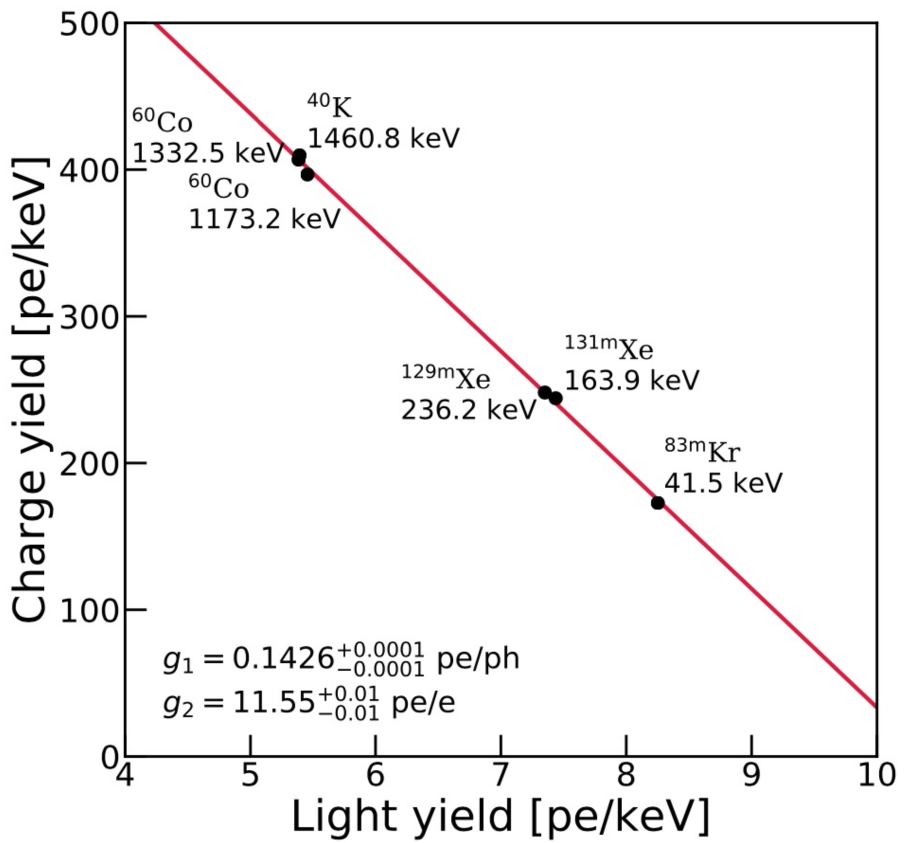
Energy Reconstruction and Resolution

Combine light and charge

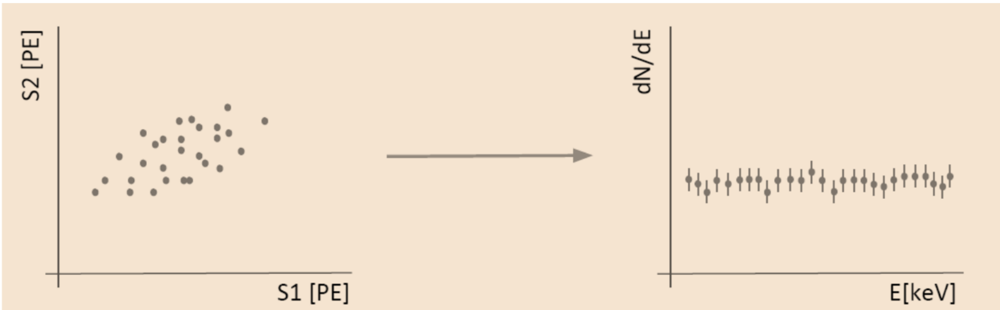


$$E = W \cdot (n_{ph} + n_e)$$
$$= W \cdot \left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)$$

➔ **detector constants g_1 and g_2**



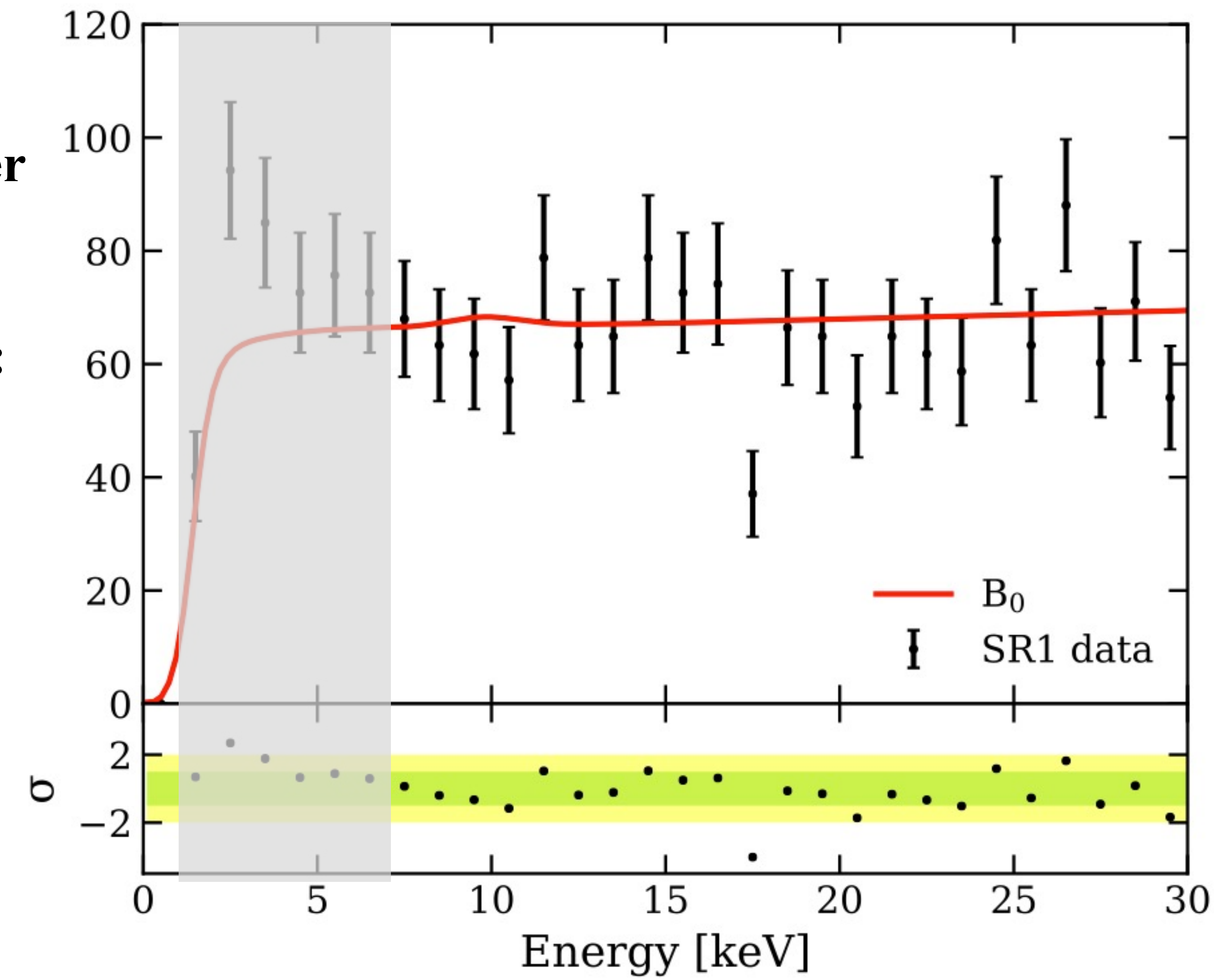
- Anti-correlation between light and charge
  ➔ checked with calibration sources
- Energy resolution < 5 % at 50 keV



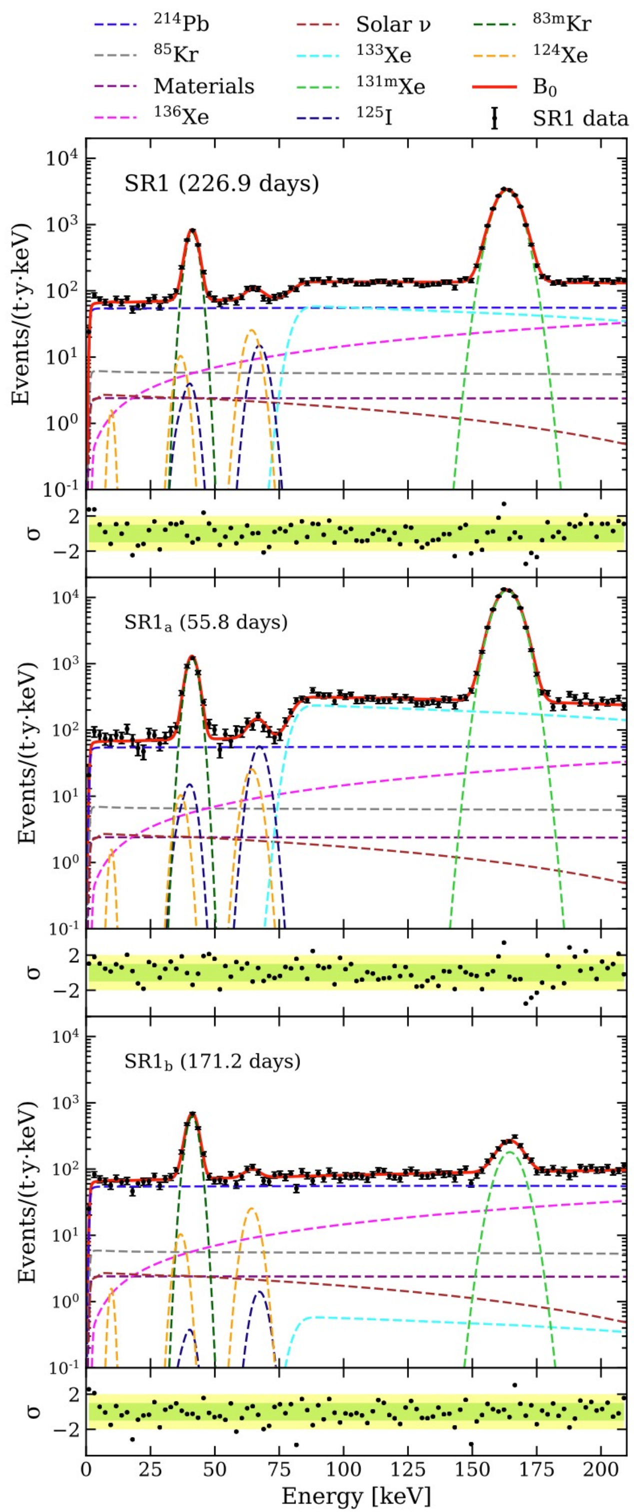
The Result

- **Exposure: 0.65 t*y**
- **Single scatter events within [1,210] keV$_{ee}$**
- **Nice agreement at higher recoil energies**

➔ **Excess between 1-7 keV:**
285 events observed
(232 ±15) expected from best-fit



Explanation #1:
3.5σ fluctuation



- Good fit observed over most of the energy range
- Consistent with expectations
- Unbinned maximum likelihood fit profiling over nuisance parameters:

$$\mathcal{L}(\mu_s, \boldsymbol{\mu_b}, \boldsymbol{\theta}) = \text{Poiss}(N|\mu_{tot}) \times \prod_i^N \left(\sum_j \frac{\mu_{b_j}}{\mu_{\text{tot}}} f_{b_j}(E_i, \boldsymbol{\theta}) + \frac{\mu_s}{\mu_{\text{tot}}} f_s(E_i, \boldsymbol{\theta}) \right) \times \prod_m C_{\mu_m}(\mu_{b_m}) \times \prod_n C_{\theta_n}(\theta_n),$$

$$\mu_{\text{tot}} \equiv \sum_j \mu_{b_j} + \mu_s,$$

➔ (76 ± 2) events / (t*y*keV) in [1,30] keV window

Lowest bg rate ever achieved in this energy range

<u>Explanation #2:</u>
Some unexpeccted new background?

Explanation #3: New Physics

More than O(200) papers in a few months which explain the XENON1T result

- **A singal from where?**
- **Sun:**

  - neutrinos (exist, but CEνNS too small ←→ neutrino floor)
  → some non-standard ν interaction with electrons
  - axions or ALPS produced in the sun ←→ other axion bounds?

- **DM density/flow**

  - some new particle
  → not WIMPs
  → light and not hot DM? A new light boson?

- **Diffuse background of invisible particles**

  ←→ consistency with other searches/limits

→ mostly 3 main directions:
Axions (non-standard), large neutrino magnetic moment, light (dark) bosons

Summary of the current Situation

Excess between 1-7 keV:

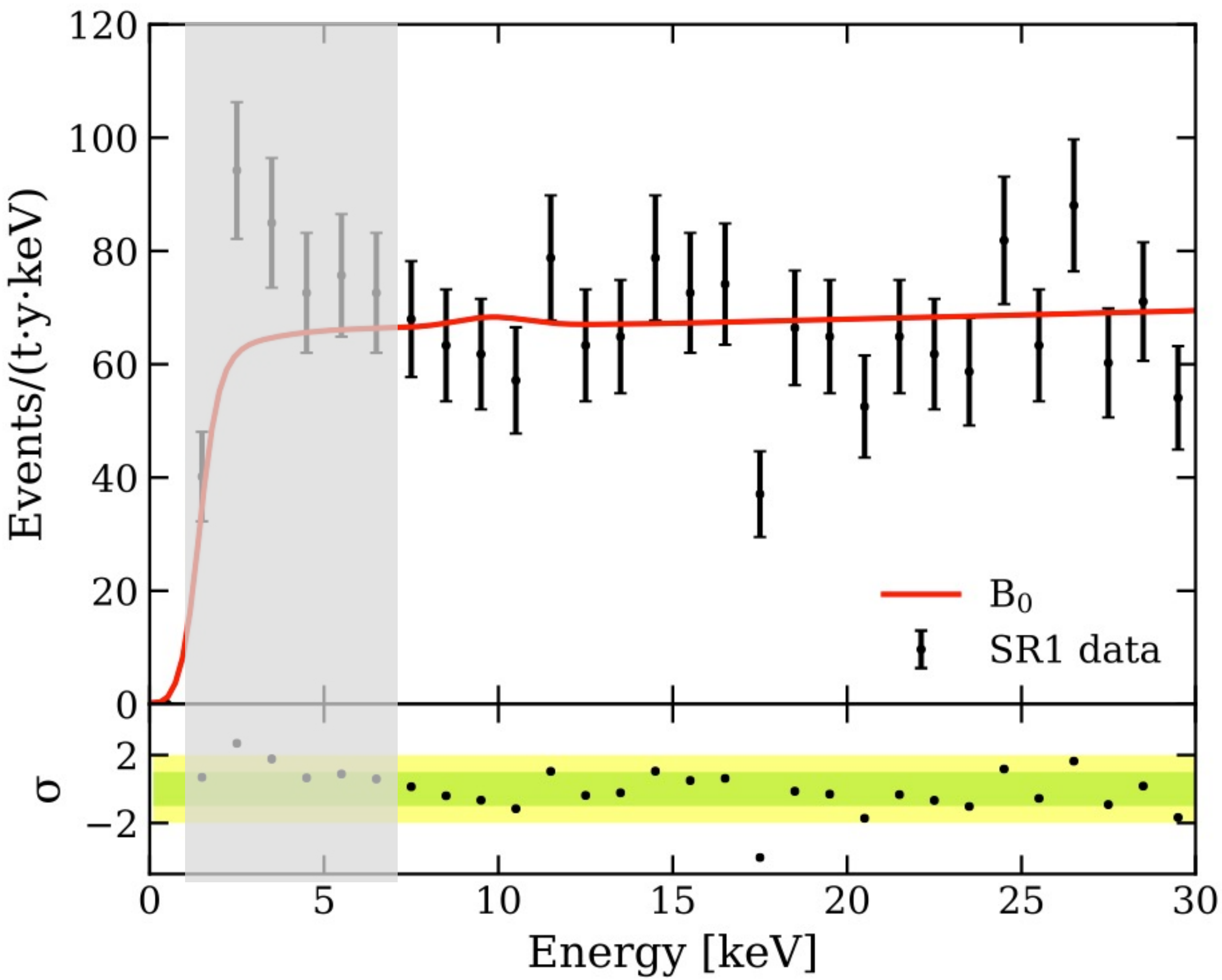
285 events observed
(**232 ±15**) expected
from best-fit

Interpretations :

a) A fluctuation

b) Some new backgrou
- Tritium
- ^{37}Ar
- ...

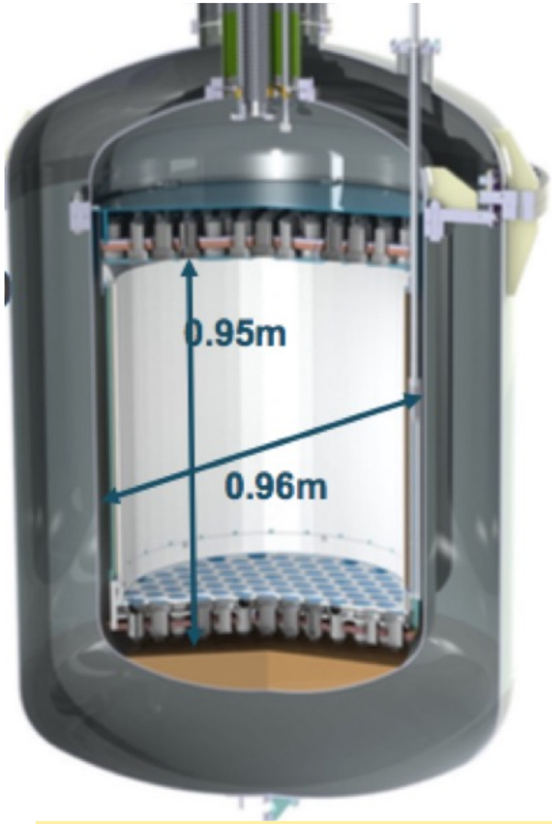
c) New physics
- solar axions
- large ν magnetic mom
- bosonic DM, dark Z, ...



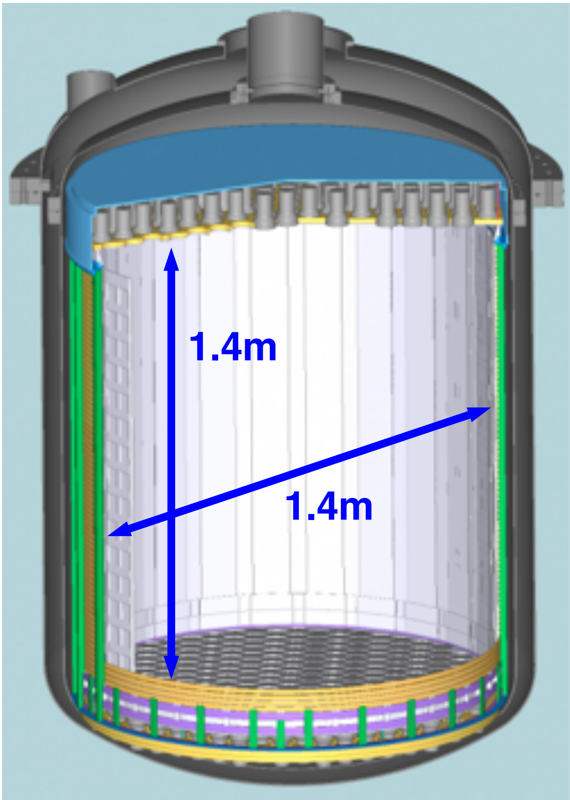
All ~3σ ➔ Collect more data with XENONnT

The XENONnT Upgrade

XENON1T



XENONnT



2012-2018
3.2t LXe
running

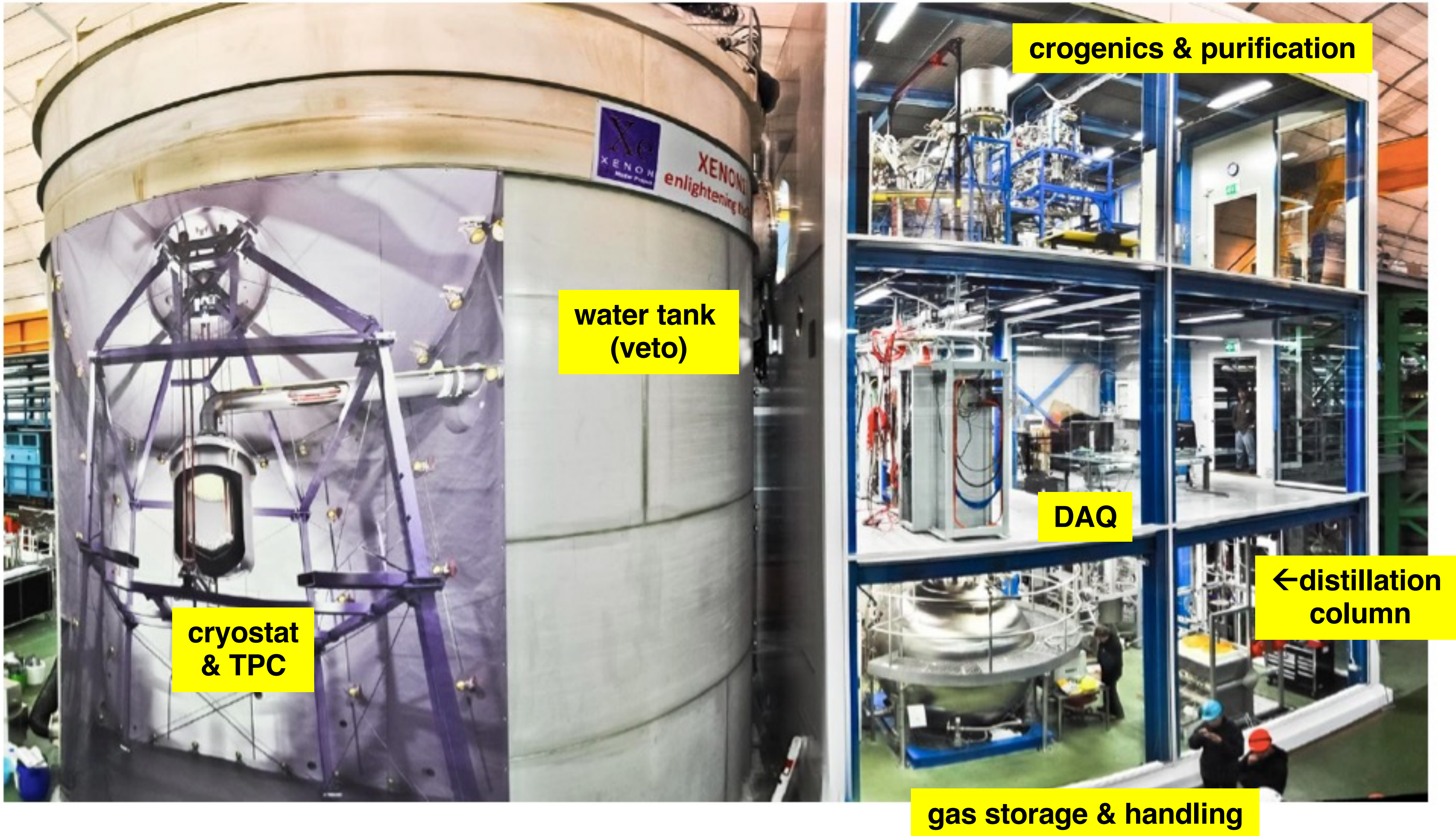
2019-2023
ca. 8t LXe
under preparation
goal @50GeV: $1.6*10^{-48}$ cm^2

Existed/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

Added:
230 more PMTs ordered
➔ being delivered & tested
new materials
TPC & inner cryostat design
n-veto
γ and Rn screening
Rn reduction system
improved purification
2nd Restox & more Xenon gas

being prepared while XENON1T runs ➔ switching gears
XENONnT assembled and started during COVID times!

XENON1T → XENONnT



Conclusions

- **The WIMP search will continue**
  - XENONnT is getting ready...
- **Direct detection will make good progress soon (XENONnT, LZ, ...)**
  - even better WIMP sensitivity
  - sensitivity to axions, neutrino physics (DEC, $0\nu\beta\beta$, solar ν's, SN, coherent scattering,…)
  - low E_R excess may be statistics, background or new physics
    ➔ more pronounced with more data from XENONnT?
    ➔ annual modulation?
    ➔ ...
- **Substantial impact even if nothing will be found**