# Status and Perspectives of Direct Dark Matter Detection

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**INTERNATIONAL SCHOOL OF SUBNUCLEAR PHYSICS**

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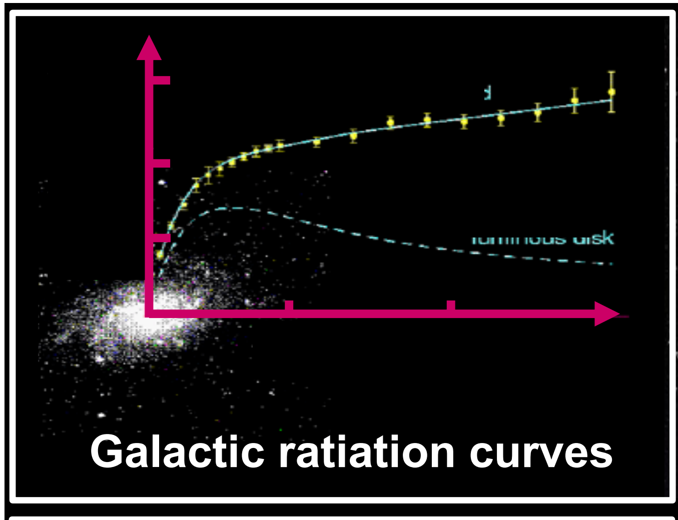
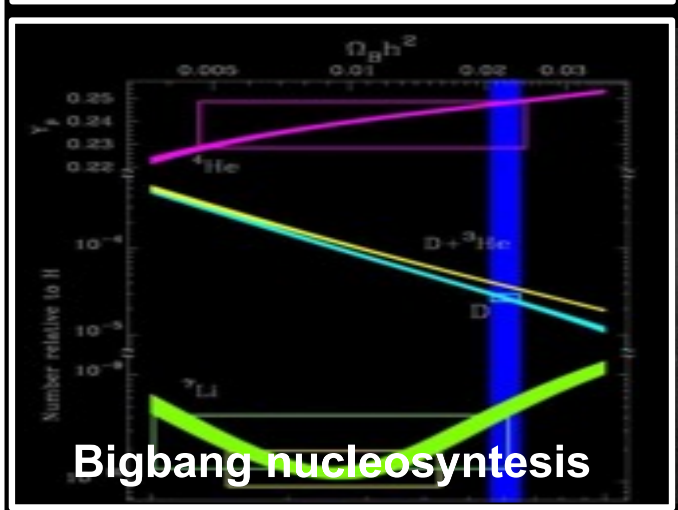
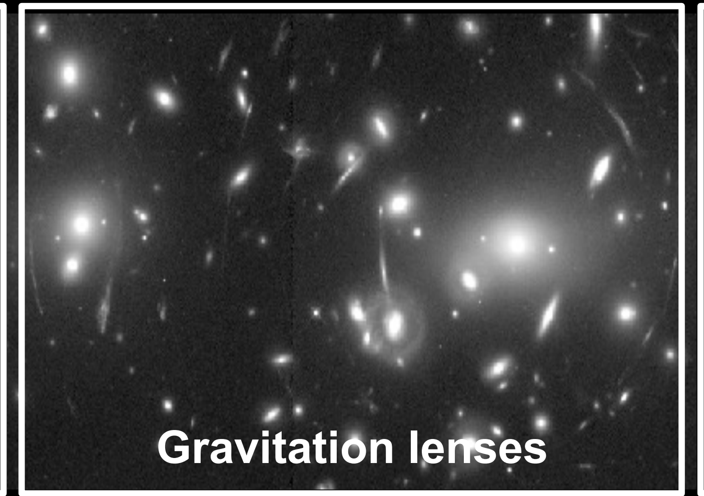
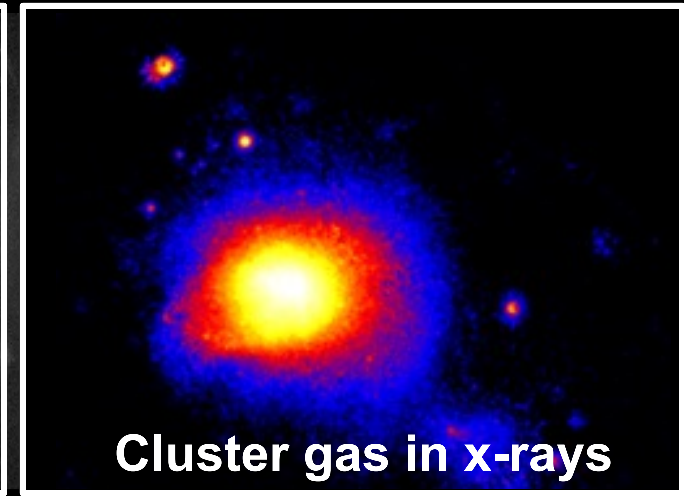
# Evidence for Dark Matter

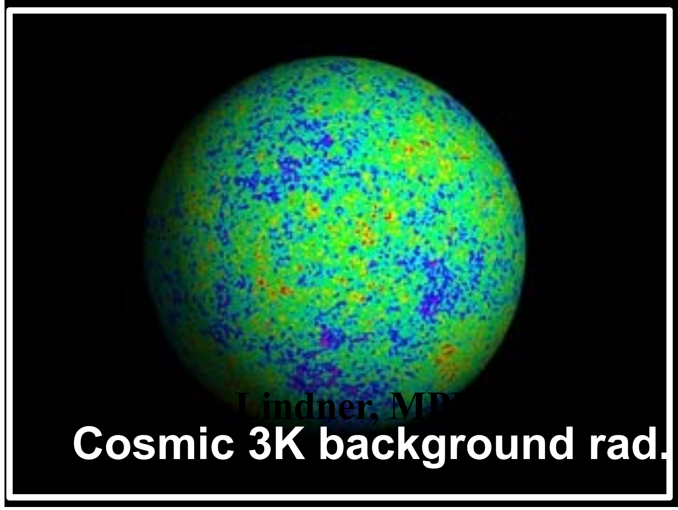


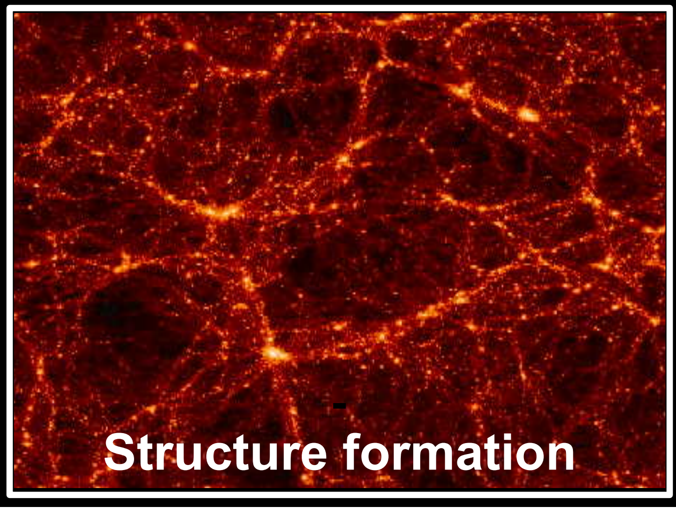


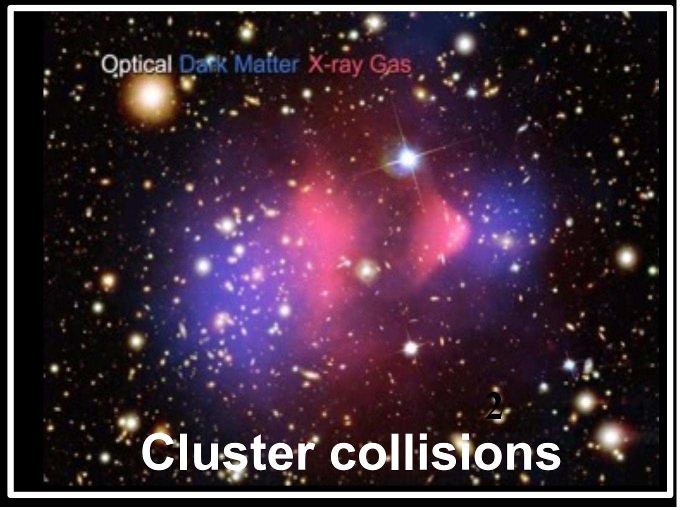



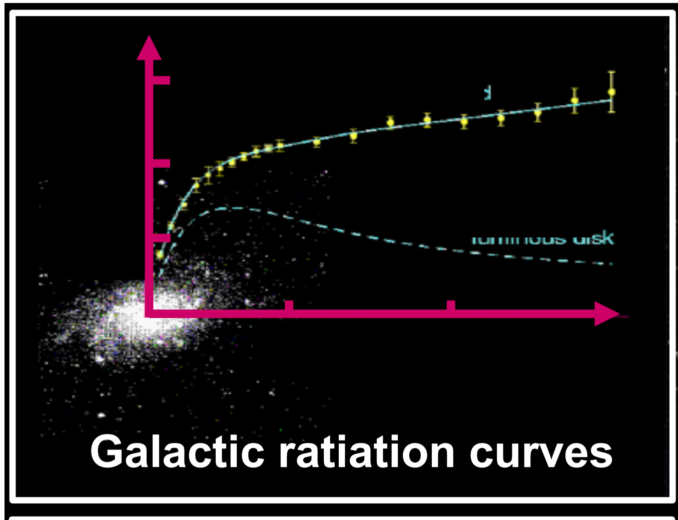



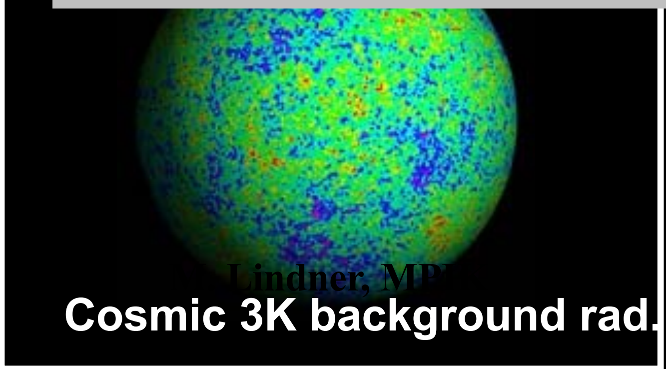
# Evidence for Dark Matter

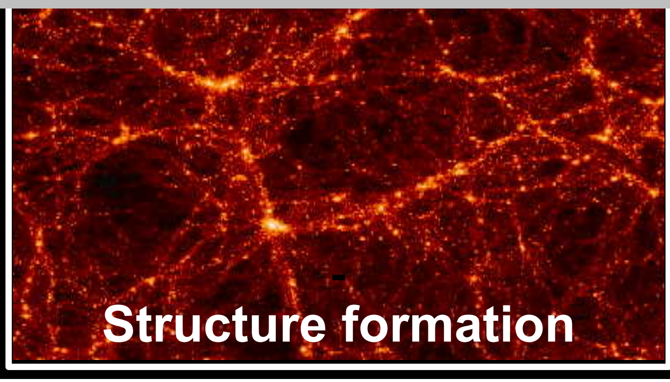

Galactic ratiation curves


Dwarf galaxies


Cluster dynamics

an impressive variety of arguments:
GR-dynamic, GR-static, radiation, …
vastly different scales and times: galactic to cosmology
**➔ something going beyond**
**- Standard Model of particle physics ➔ BSM**
**- General Relativity (GR) & standard cosmology**


Cosmic 3K background rad.


Structure formation


Cluster collisions

# Competing Dark Matter Directions

## Gravity

**Something wrong with GR?**

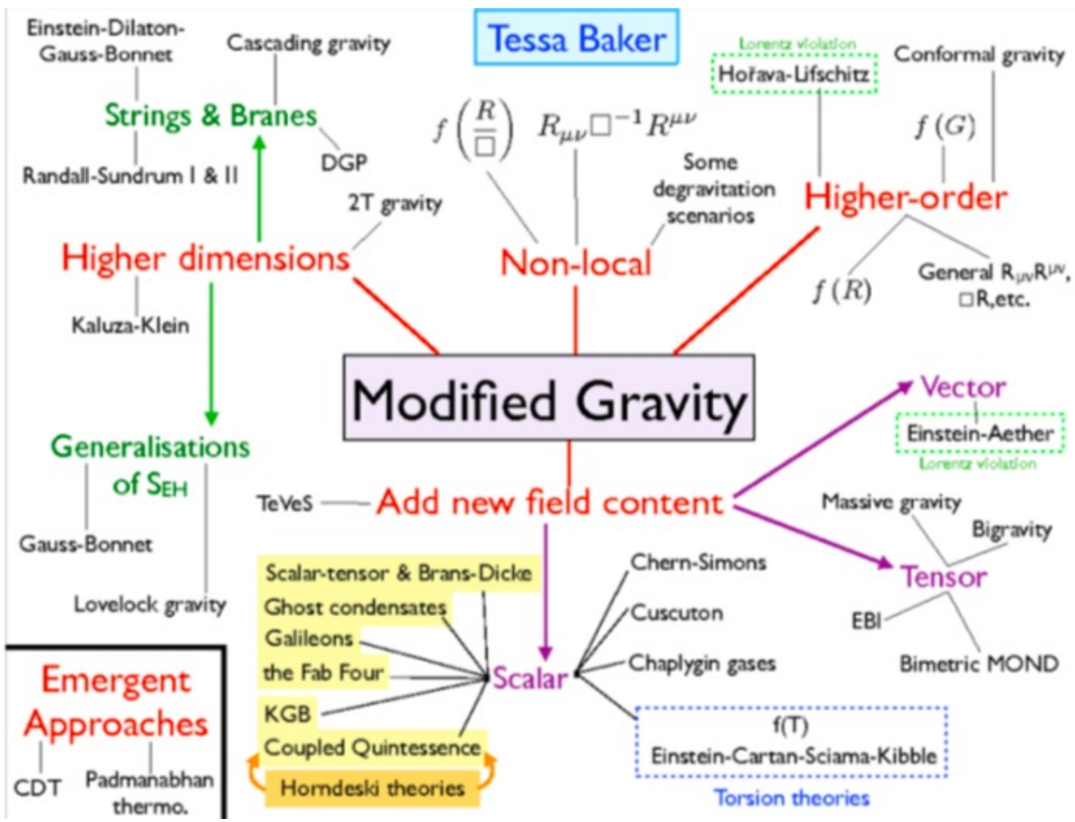
Einstein Field Equations:

1) From line element: metric, Bianchi identities, Riemann tensor, Ricci scalar

2) Hilbert-Einstein action
→ variation →field equations

$$I_{HE} = \frac{1}{2\kappa}\int d^4x\sqrt{-g}[R + \mathcal{L}_m].$$

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$




Credit: J. Chagoya

# Competing Dark Matter Directions


## Particles

**DM candidates should**

- have no EM interaction
- not couple to QCD
- may have weak interaction
- must couple to gravity
- must not spoil things:
  - BBN
  - ...
- must not be excluded:
  - LHC, $\nu$-experiments, DM searches, ...

➔ **solve known problems**

➔ **convincing extensions** (not probabilistic)

# Competing Dark Matter Directions

## Gravity

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

### Other
more elaborate GR modifications

or

a suitable population (mass, number) of black holes

## Particles

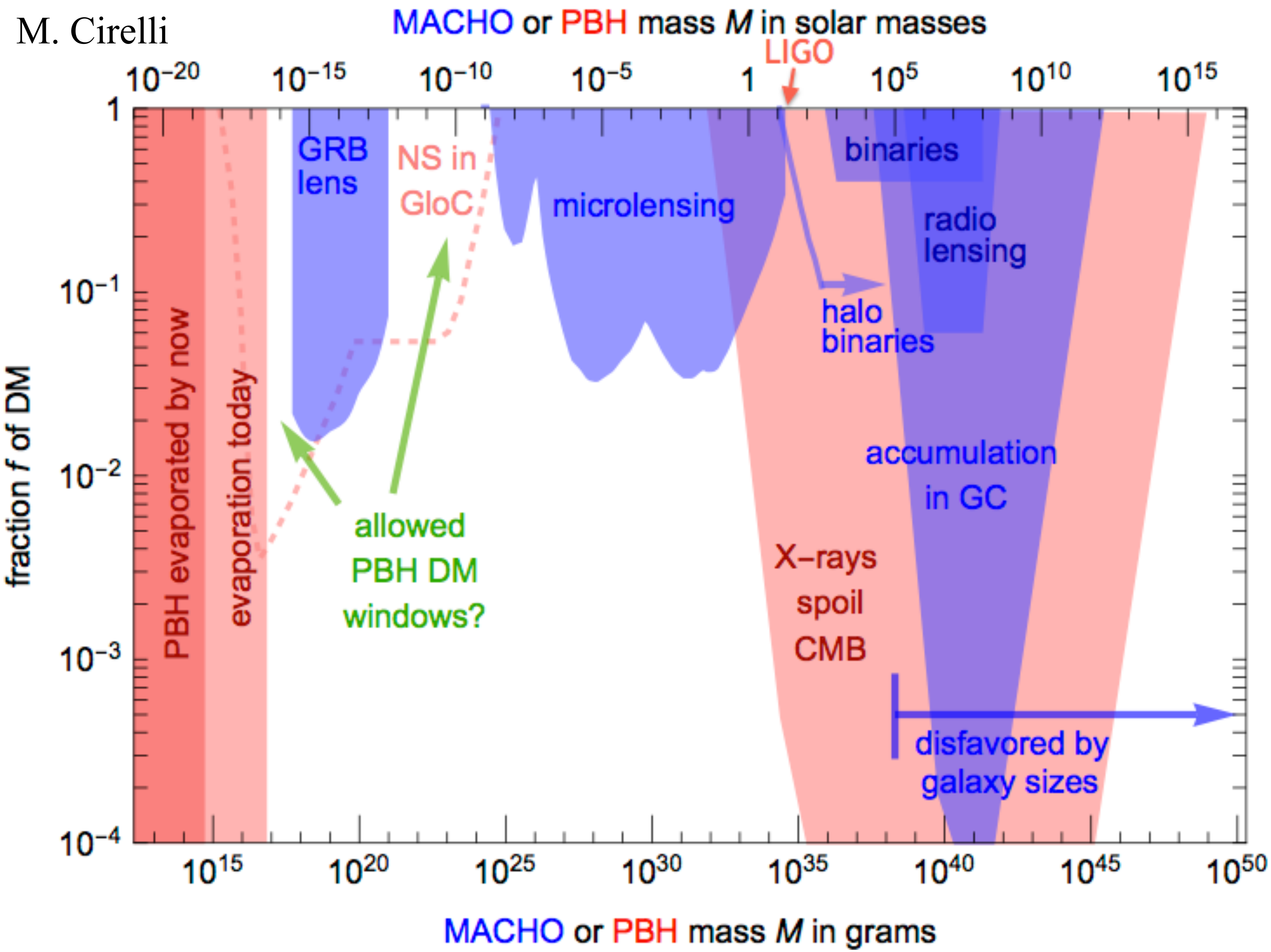
### BSM physics motivated by SM problems
+ WIMPs (neutralinos)
+ axions
+ sterile $\nu$'s
- …

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

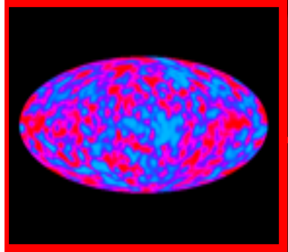
**WIMPs combine both aspects in an attractive way: BSM + abundance**

# Black Holes as Dark Matter

M. Cirelli



# The cosmic Matter Balance



radiation:
0.005%

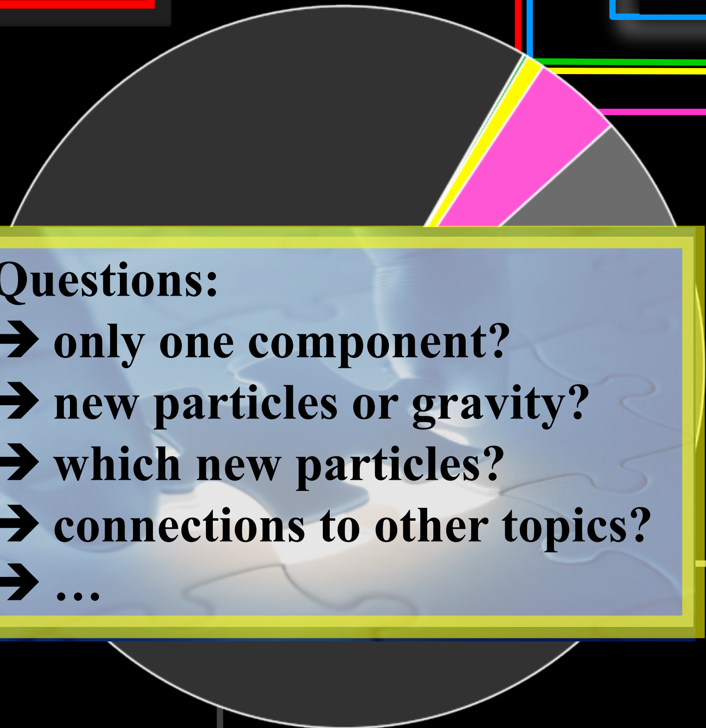
chemical elements:
(not H & He) 0.025%

neutrinos = CνB:
0.17%

$\nu_e$ $\nu_\mu$ $\nu_\tau$

stars:
0.8%

H & He:
gas 4%



Questions:
→ only one component?
→ new particles or gravity?
→ which new particles?
→ connections to other topics?
→ …

?

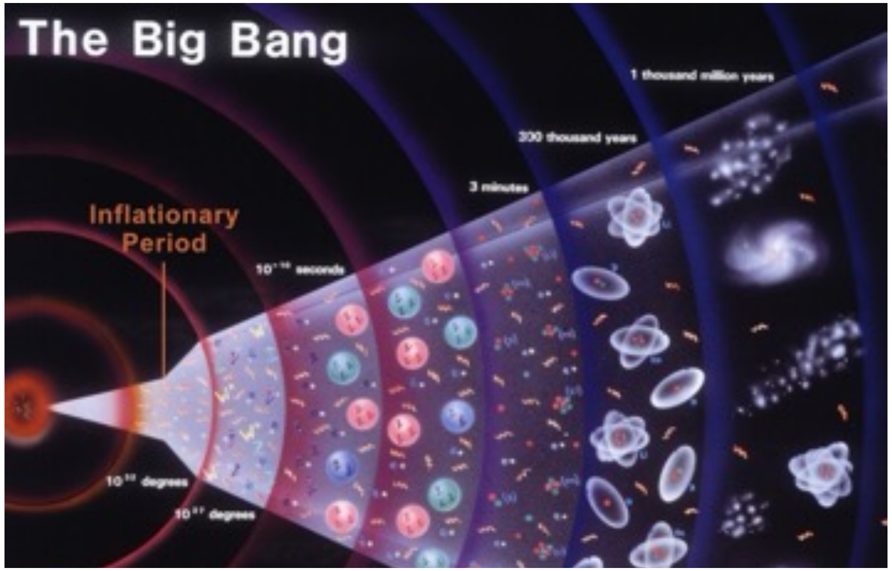
dark matter: 26.8%
→ something invisible
in addition to CνB

?

dark energy: 68.3%

# The WIMP Miracle

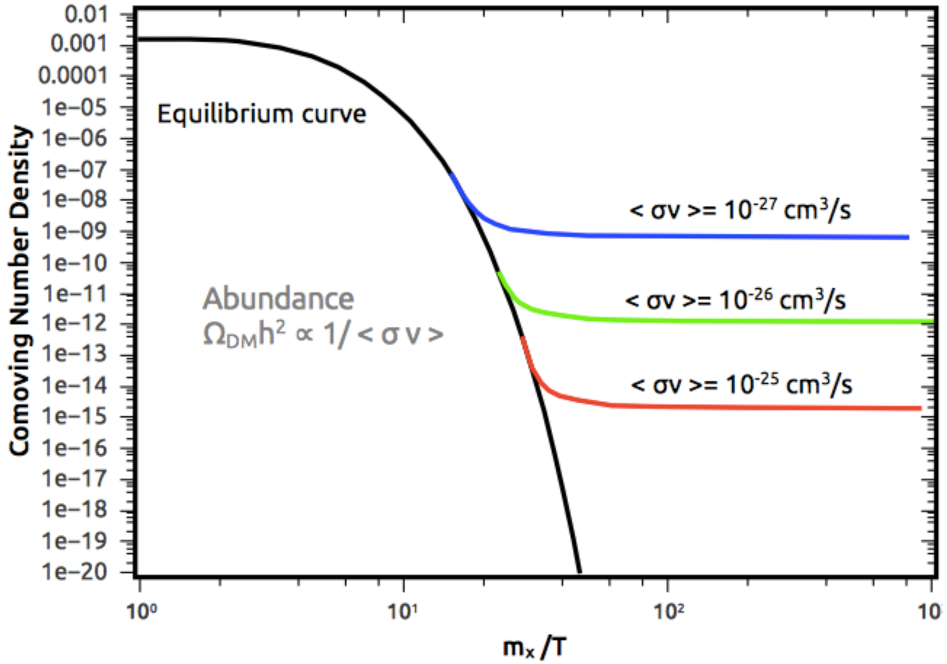
- **Inflation ➔ many e-folds**
- **Reheating ➔ all particle types produced**
- **Evolution of original plasma by:**
  - expansion (dilution)
  - decays
  - interactions → conversion processes




**Evolution of original DM density:**

➔ Boltzmann equation

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




**Remarkable coincidence:**

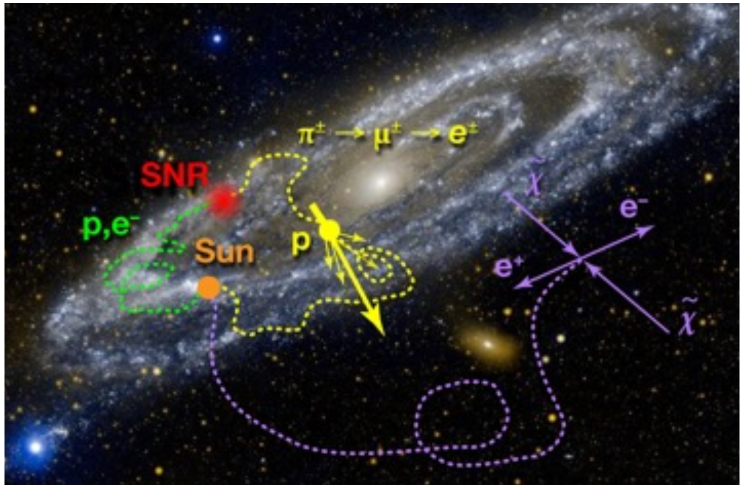
- **Correct (cold) DM abundance**
  → WIMP masses O(10-1000 GeV)
- **SM hierarchy problem**
  → TeV BSM physics
  → BSM motivated DM candidates

➔ Automatically ~ correct abundance

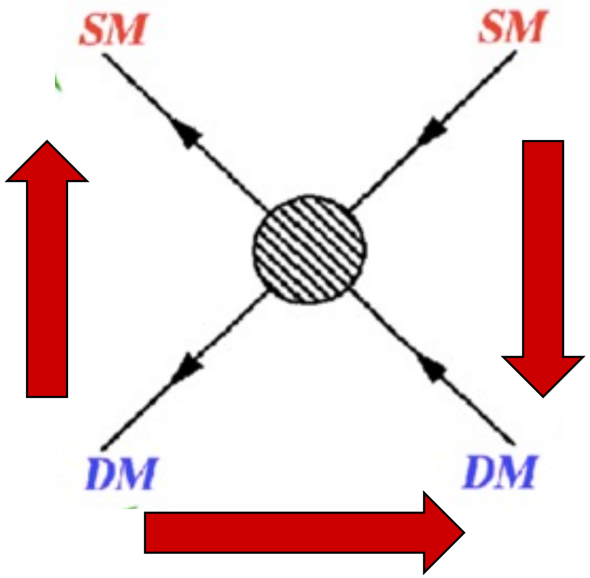
# Hunting WIMPS in different Ways

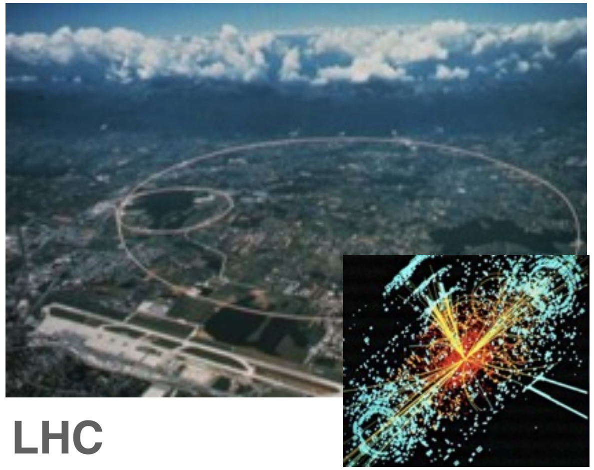
**known Standard Model (SM) particles interact with WIMPs: assumptions…**

**indirect detection**



**colliders**



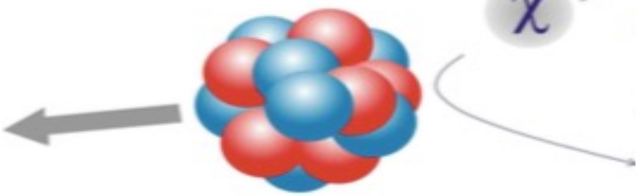



LHC

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

- astronnomical uncertainties...
- signal without doubt from DM?

**direct detection**




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

WIMP wind : 220km/s from Cygnus
➔ see the DM in the Universe

# 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**

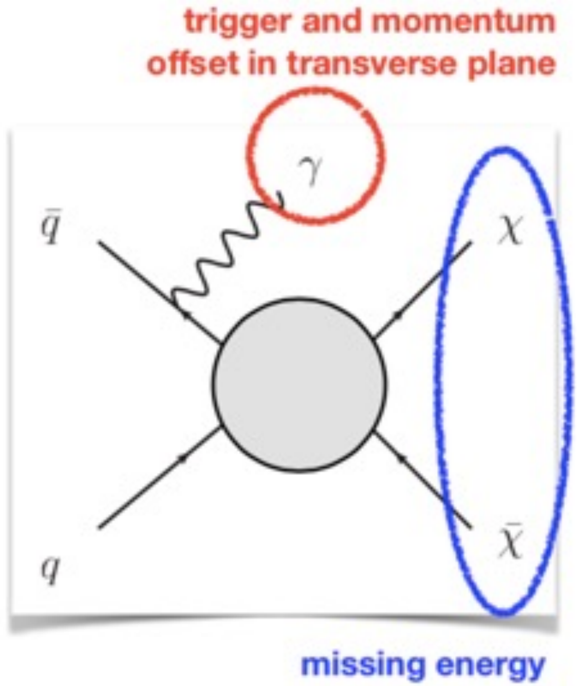
annihilation of standard model particles into a pair of DM particles

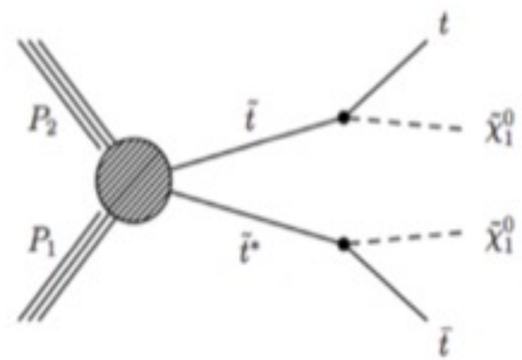
**2) indirect production of DM particles**

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 $M_{med}$

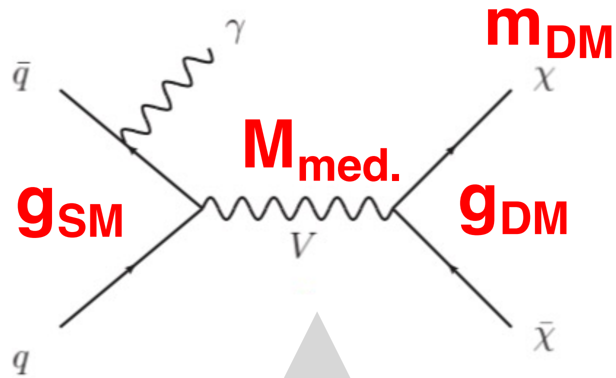
**➔Interaction described by M* and $m_{DM}$**

type of interaction ➔ different operators

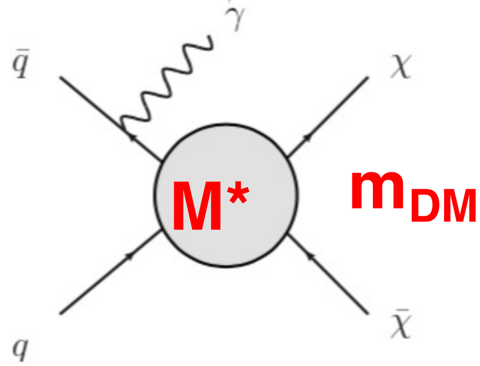
most common:

| 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




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




**Mediator induces also SM➔SM processes**

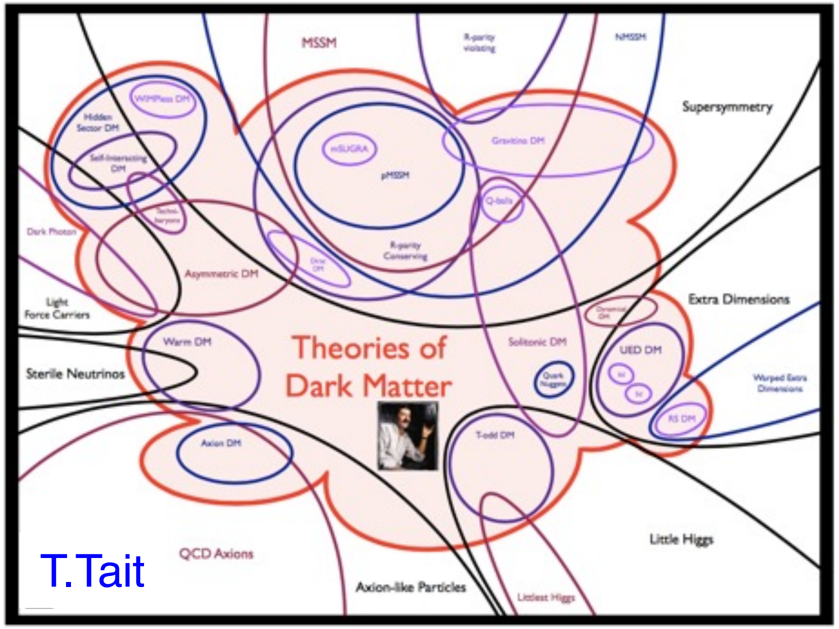
➔ LHC sets limits on $g^2_{SM}/M^2_{med}$ (mod. $m_{DM}$)

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

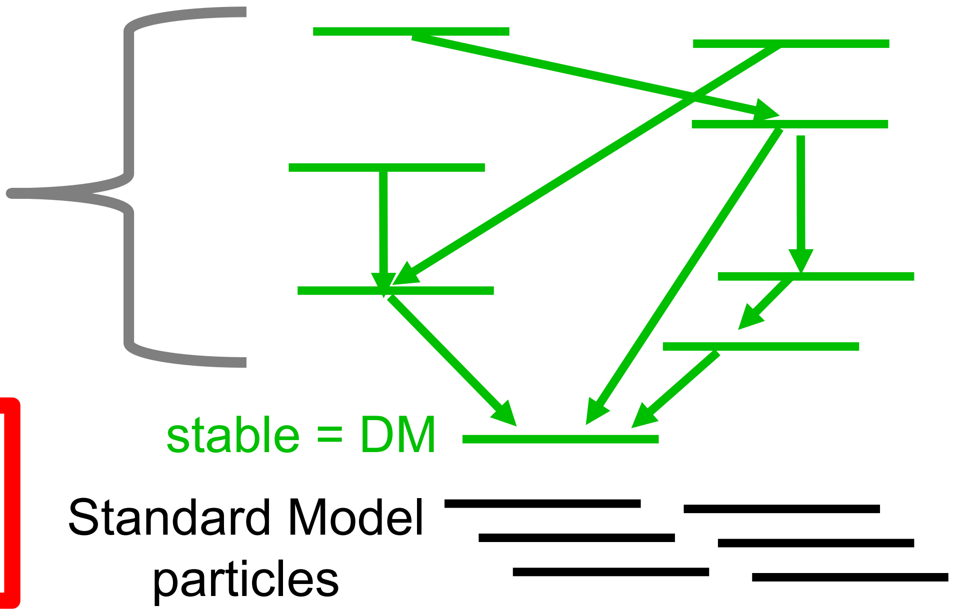
**$g_{DM}$ =1 is an assumption** ➔ could be tiny ➔ weaker DM limits

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

# DM motivated Extensions have other Consequences



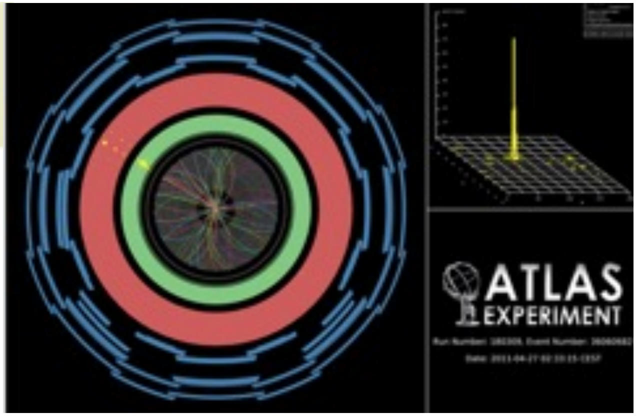

- More particles…
- All existing particles produced in Big Bang and later (decays, …)
- Some particles may be stable
- Very long-lived due to small parameters → natural?
- Effects of unstable states +/-
  → on the early Universe
  → on collider physics



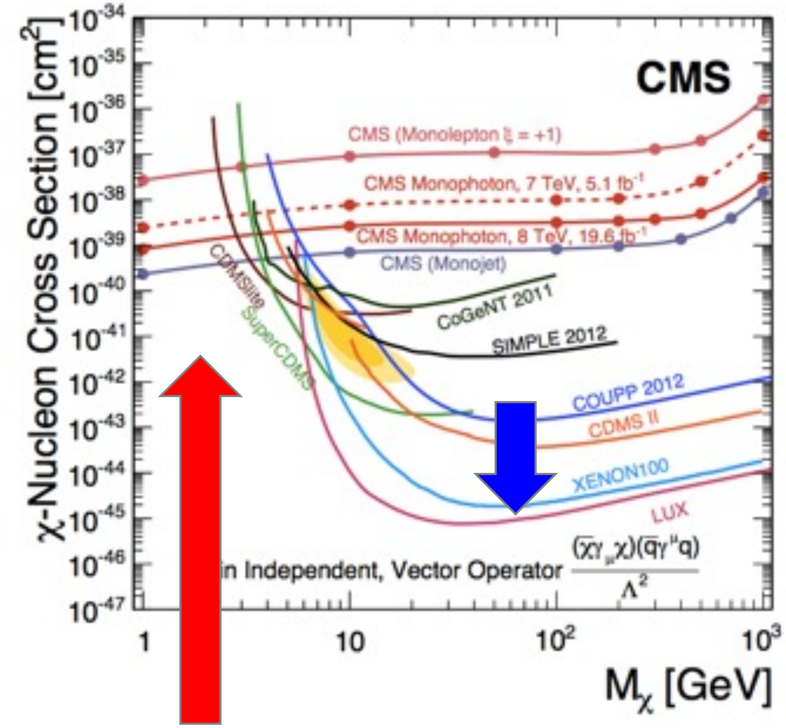

**Warning: Your DM model may affect many other known things!**

# 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

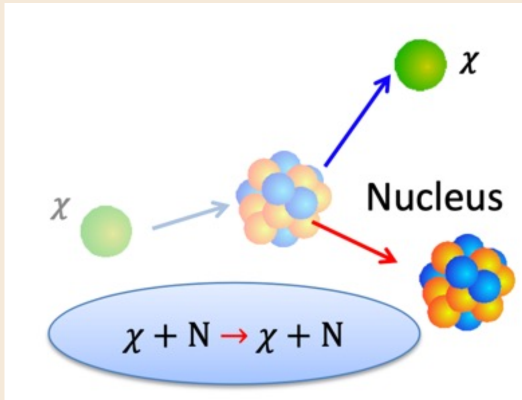
heavy WIMPS
➔ direct searches

←→ 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: Billard with invisible Balls

- WIMPs scatter off atoms in a detector → **detect the signal…**
- Maximal momentum transfer → $M_{WIMP} \sim M_{atom}$
  **Additionally: clean, transparent, high density, no free charges,**
  → **liquid Xenon** (ca. -100 degree)
  ←→ rarest stable element

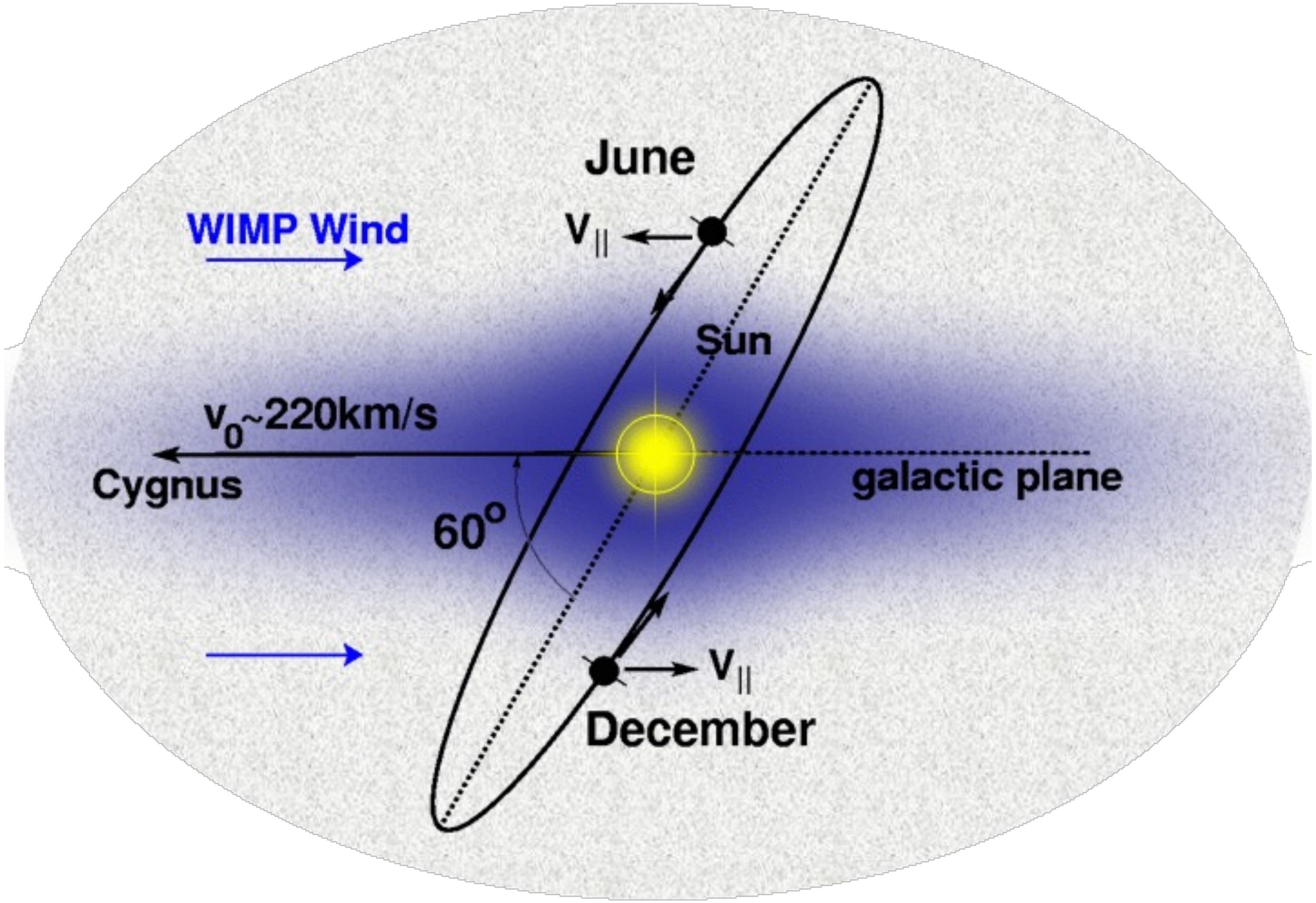



**1) Maximize signal**
→ big detector

**2) Minimize background**
→ extremely low radioactive background requirements

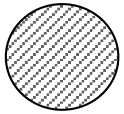
# The WIMP Wind

- Solar system is about 8.5 kpc from galactic center
- Is pulled towards the Cygnus-Cluster ➔ ~ 220 km/s
  ➔ flow of DM particles from Cygnus ➔ WIMP wind



# The generic WIMP Cross-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, …

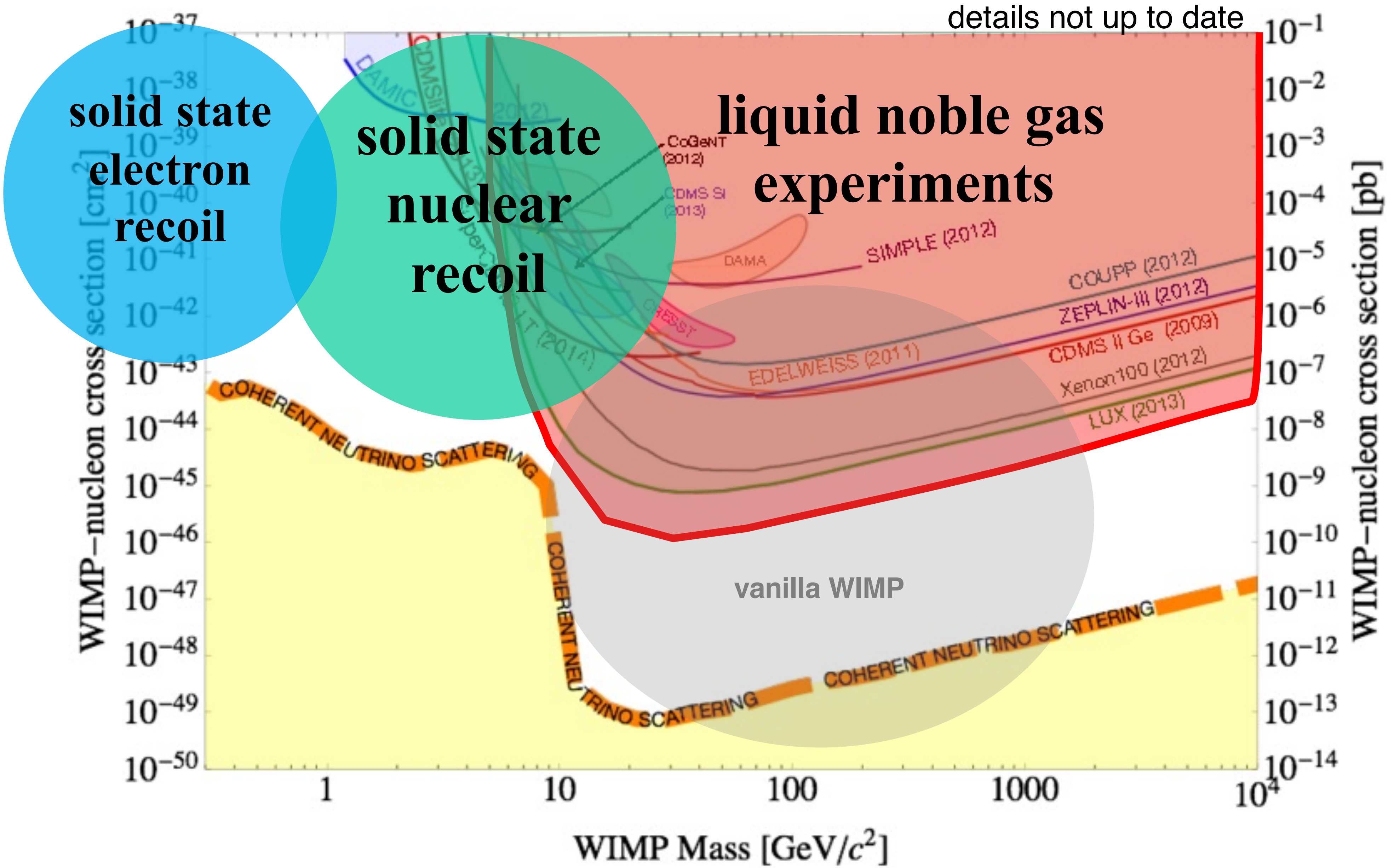
←→ abundance

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

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

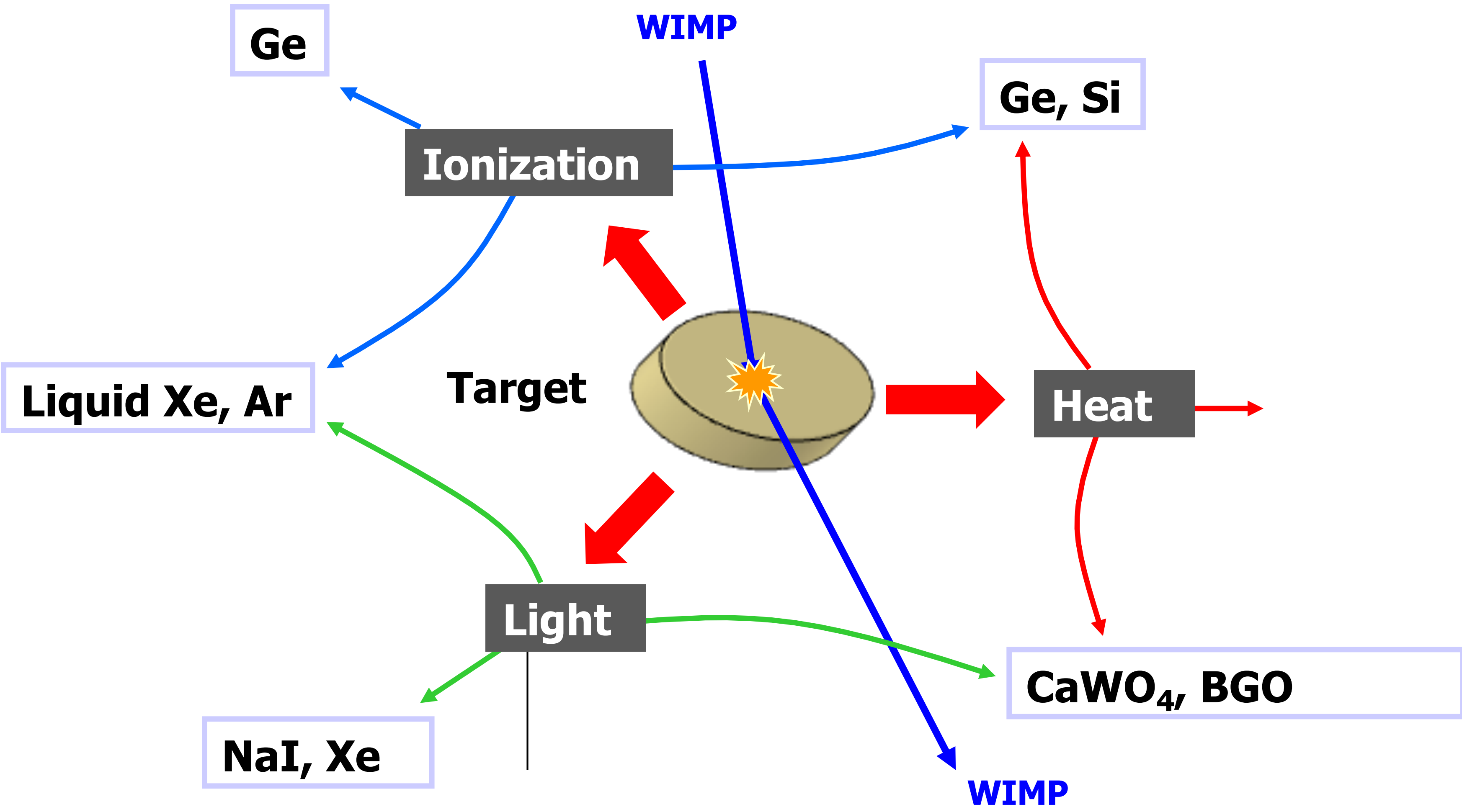
➔ we know size/sensitivity of a detector which can cover the most interesting natural WIMP space

# The Players and their main Territory



# Direct Detection Techniques (WIMPs)

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

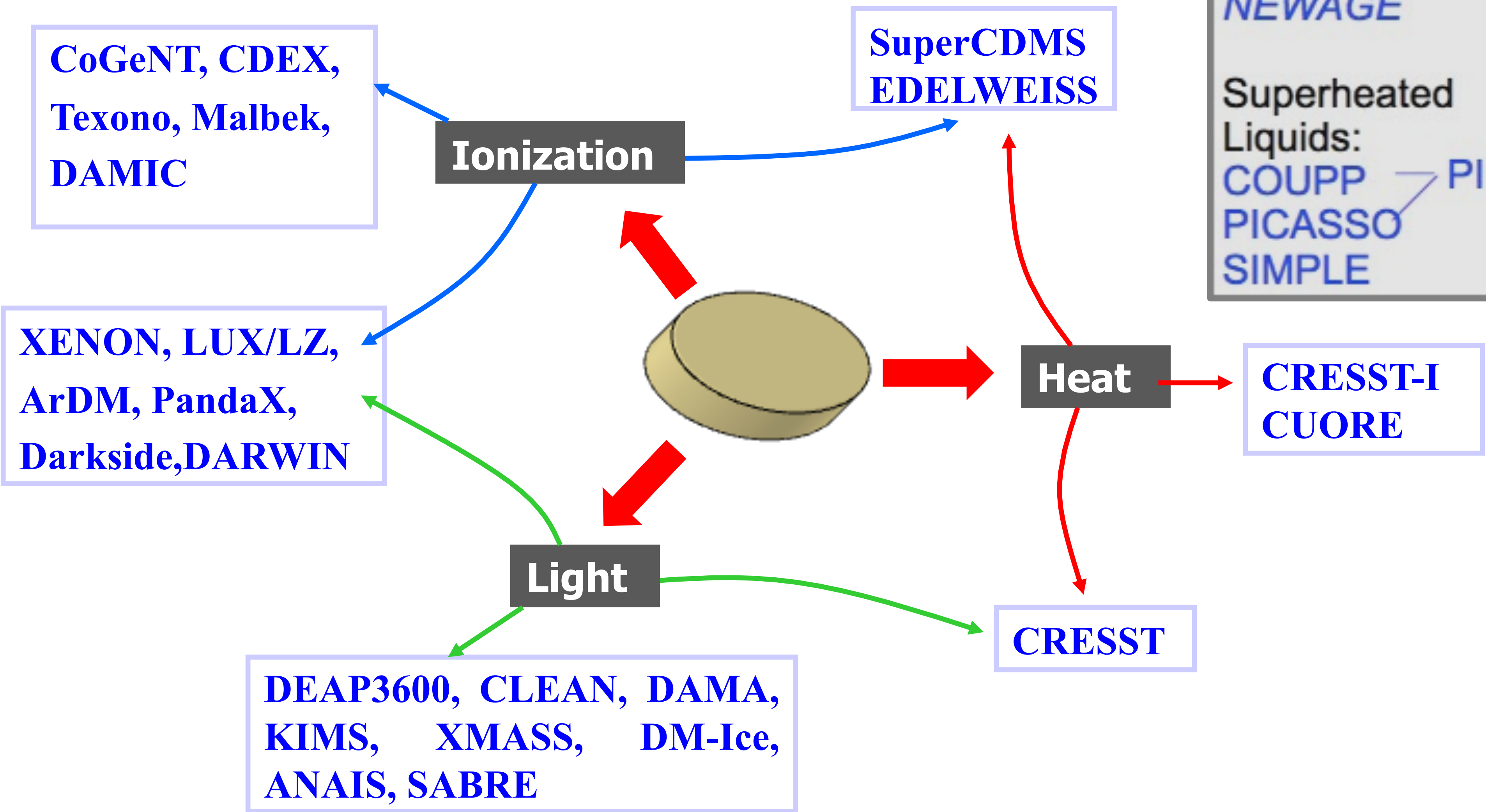


# Direct Detection Experiments

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

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

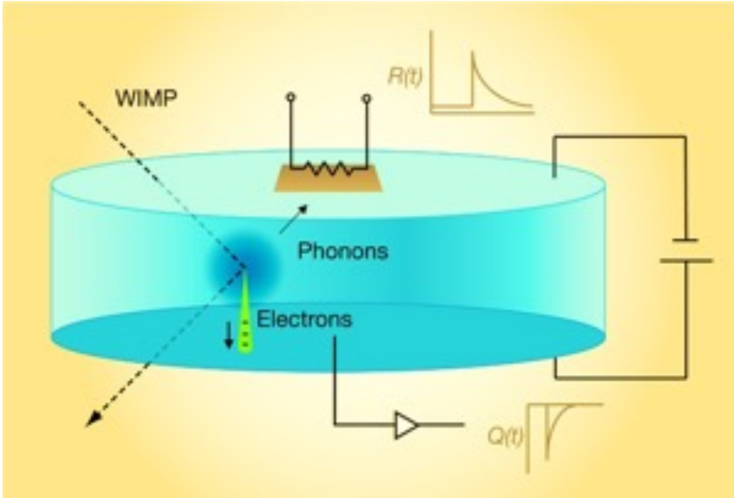
Superheated Liquids:
COUPP → PICO
PICASSO
SIMPLE

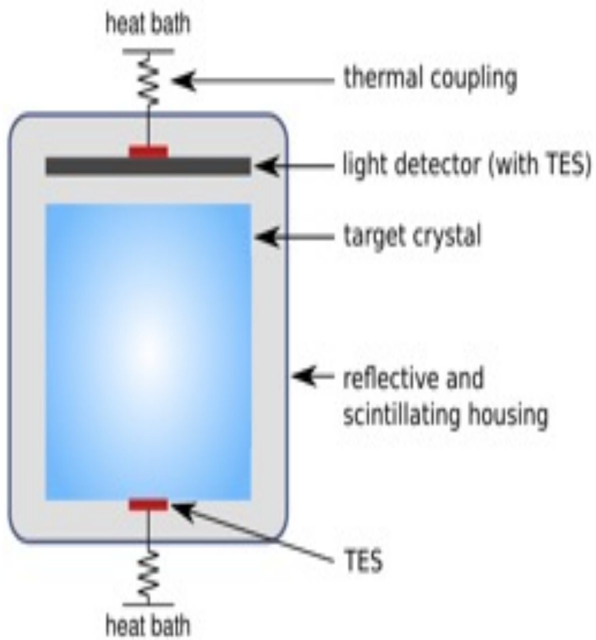


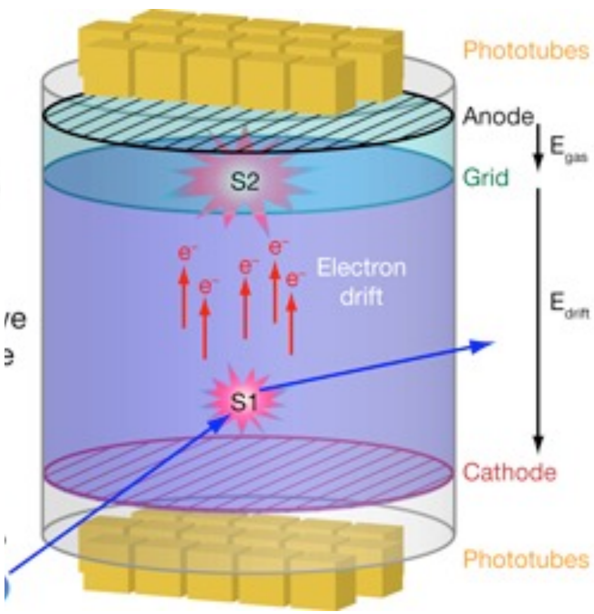
# Converting WIMP Scattering into Signals

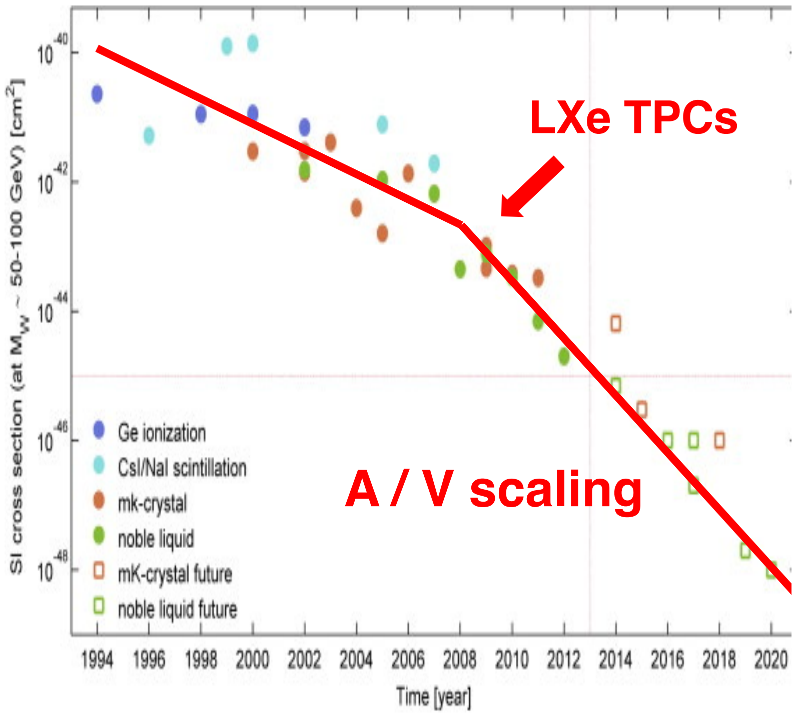
## Light – ionization – heat: 3 examples

- semiconductors (Ge)
  → ionization → pulses
- crystals (e.g. $CaWO_4$)
  → heat + light
- liquid noble gases @TPC's
  → light + ionization



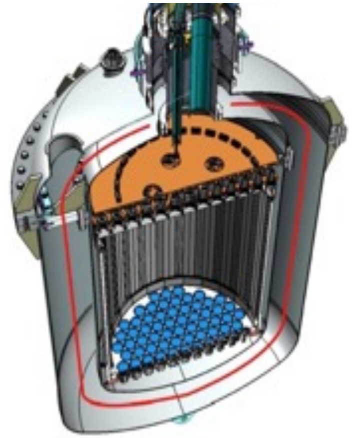



# The XENON Dark Matter Program

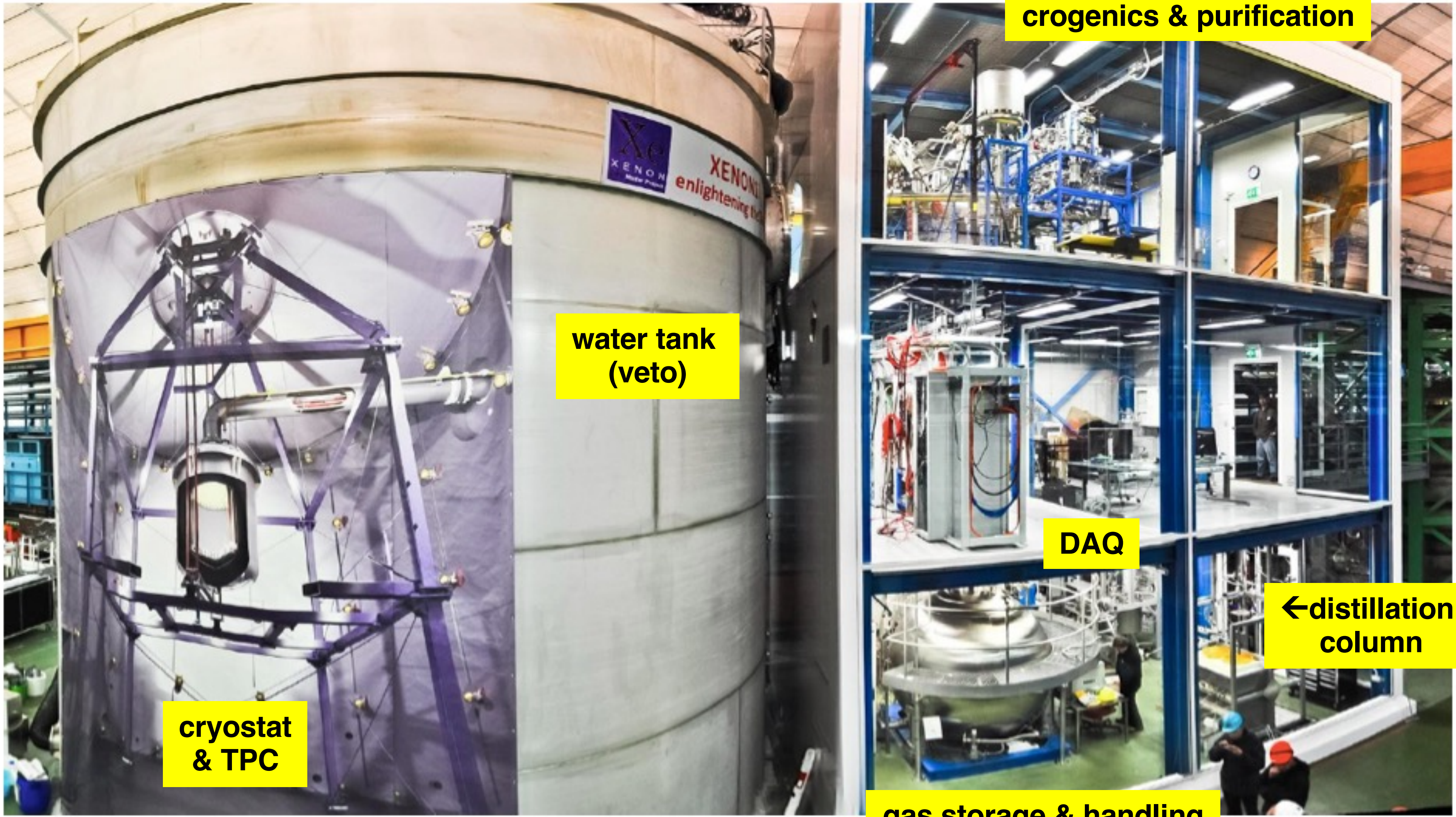
**The XENON program at Gran Sasso, Italy (3600 mwe)**

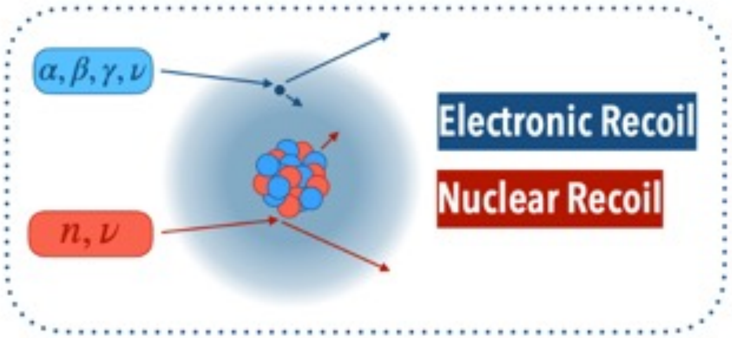
| | XENON10 | XENON100 | XENON1T | XENONnT |
|---|---|---|---|---|
| Period | 2005-2007 | 2008-2016 | 2012-2018 | → 2019-202n |
| Total (active) mass | 25 kg (14kg) | 161 kg (62 kg) | 3200 kg (2t) | ~8400 kg (5.9t) |
| Drift length | 15 cm | 30 cm | 100 cm | 150 cm |
| Status | Completed (2007) | Completed (2016) | Completed (2019) | Running |
| $\sigma_{SI}$ limit (@50 GeV/c²) | $8.8 \times 10^{-44}$ cm² | $1.1 \times 10^{-45}$ cm² | $1.6 \times 10^{-47}$ cm² | $\sim 10^{-48}$ cm² |

**XENONnT prepared while XENON1T was running**
**➔ switching gears**

# XENON1T @ LNGS



# Direct Dark Matter Detection




## Background reduction

**→ extremely challenging:**

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

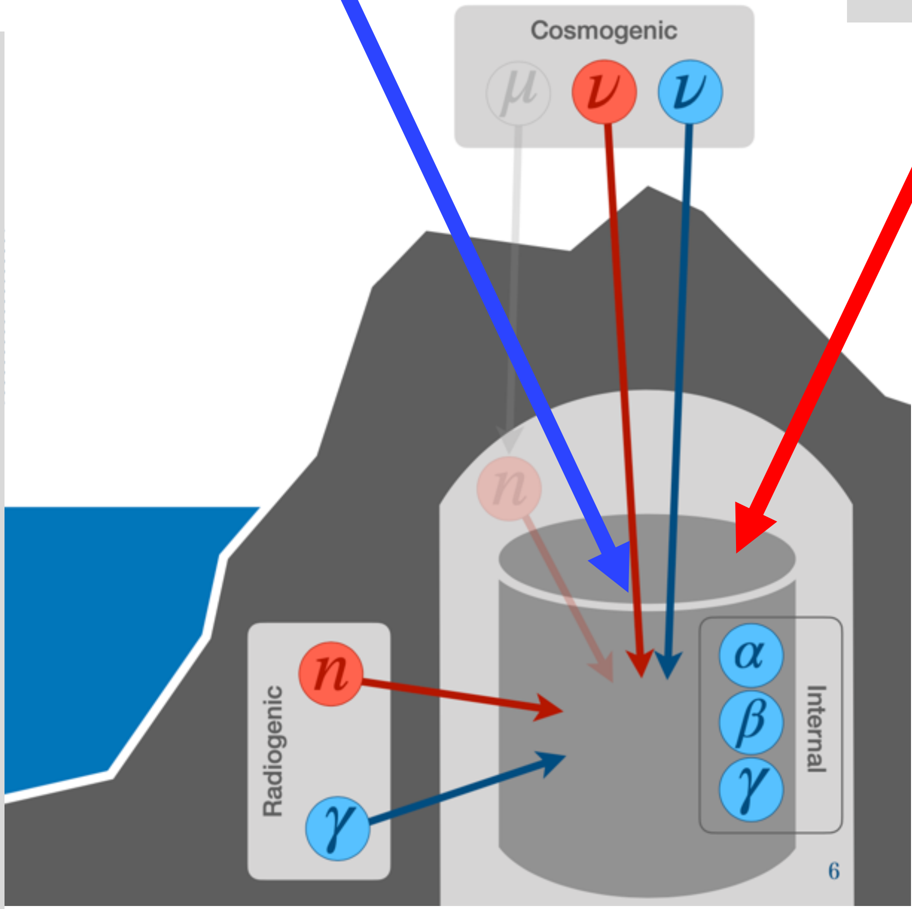
**WIMPs**

→ nuclear recoils

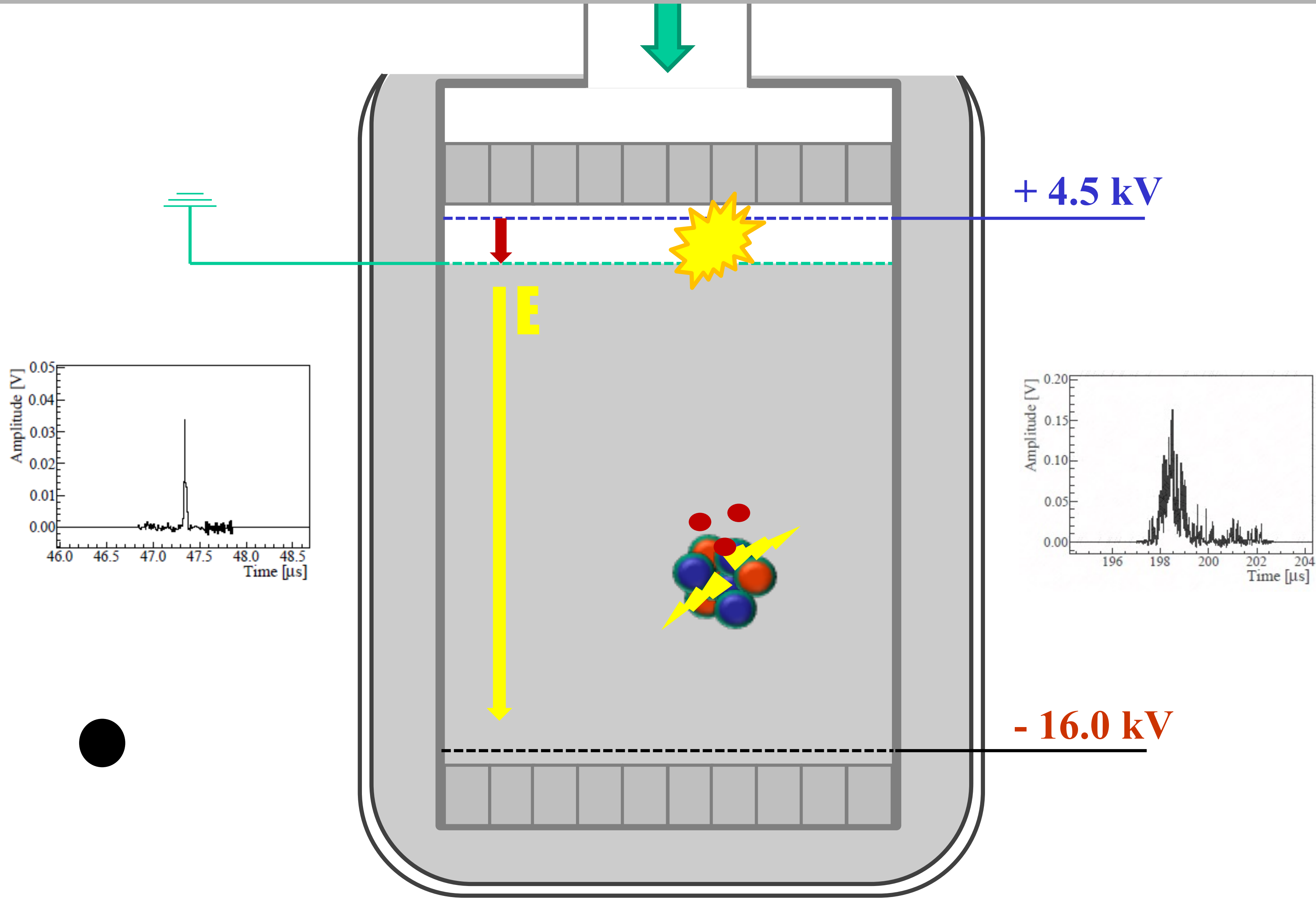
**Sun:**

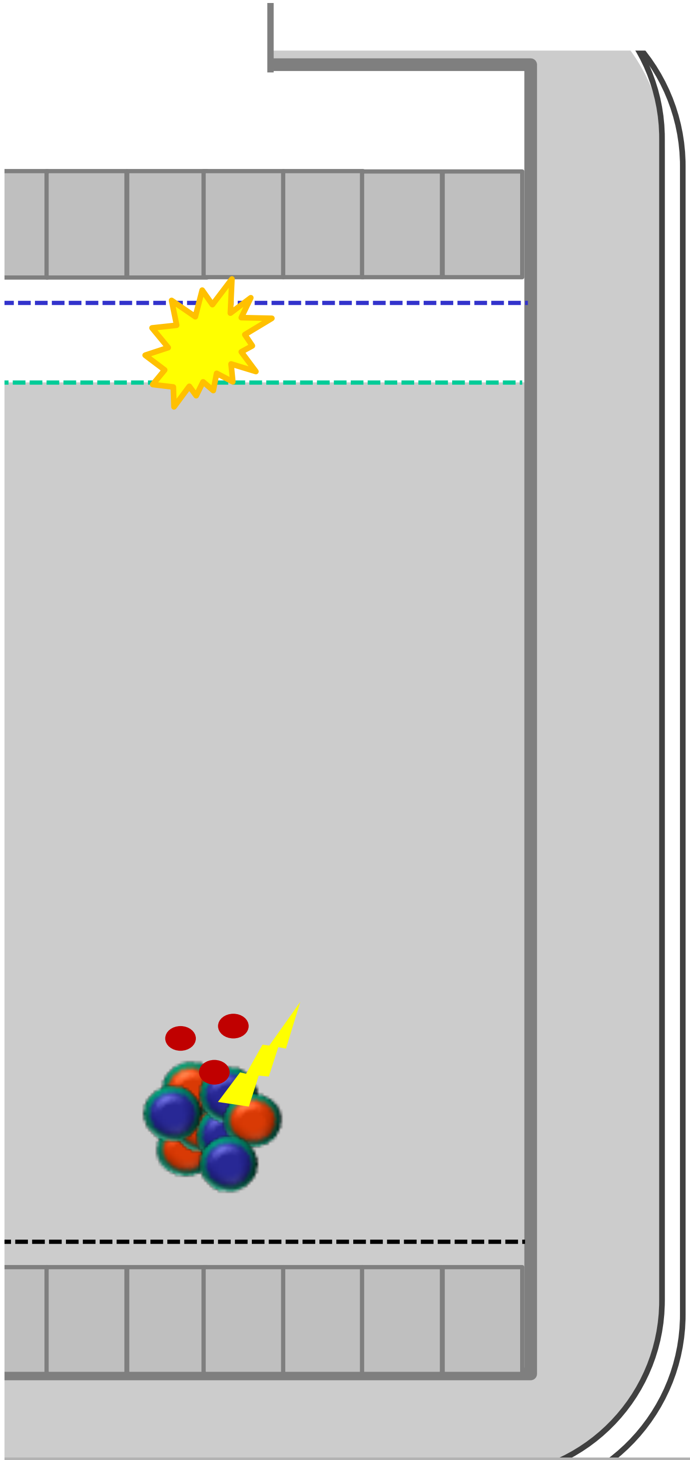
- Neutrinos
- Axions ?
- ???

SM: too weak
→ should
not show up



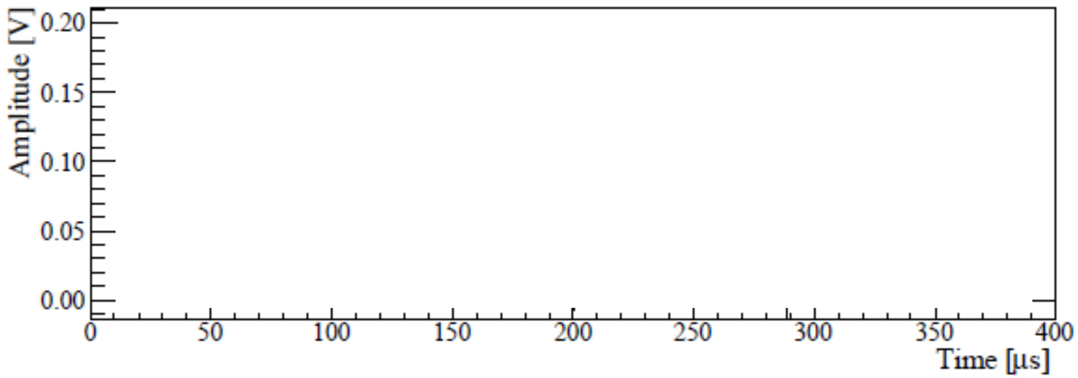
# Dual Phase LXe TPC





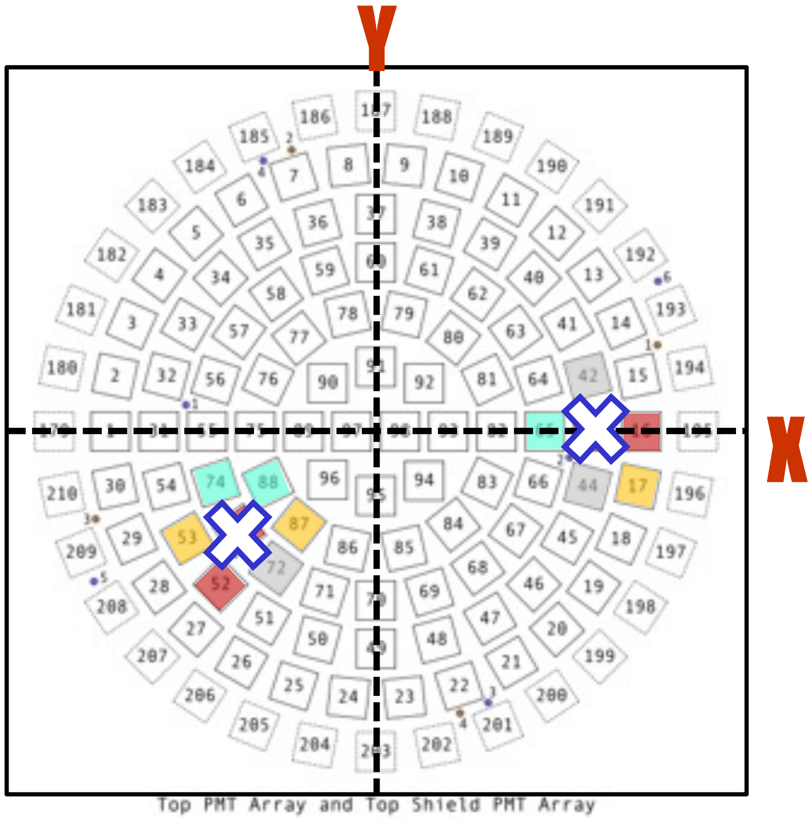
● **Rec**

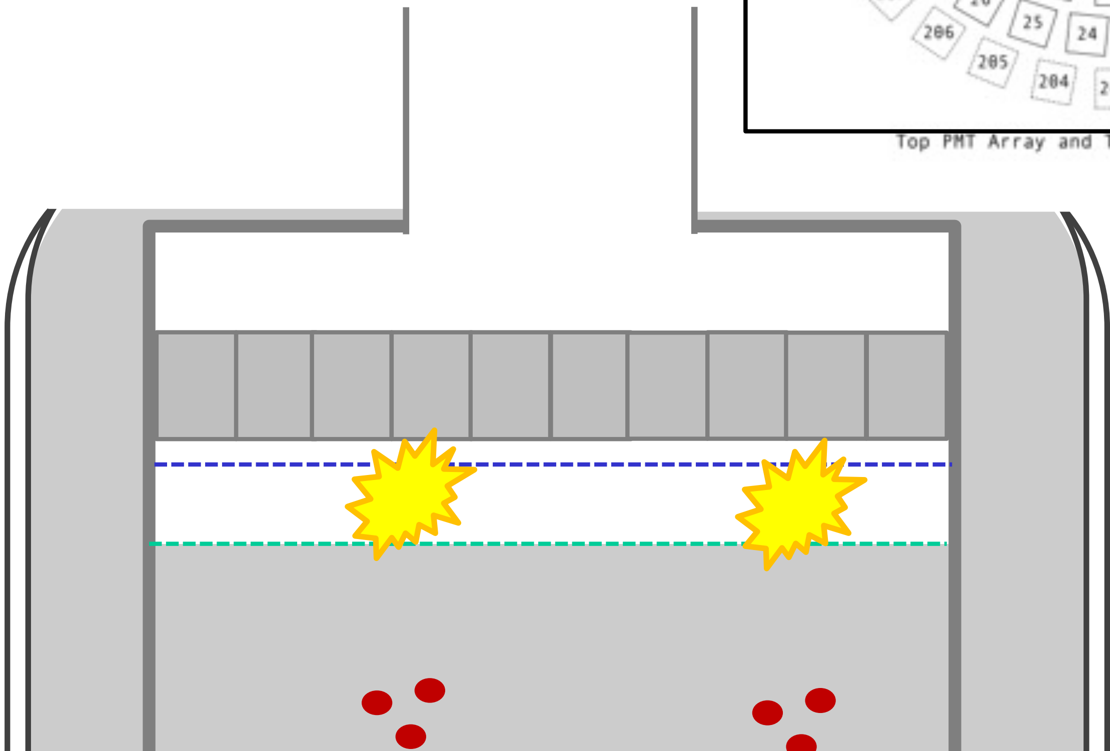
**Slow motion**

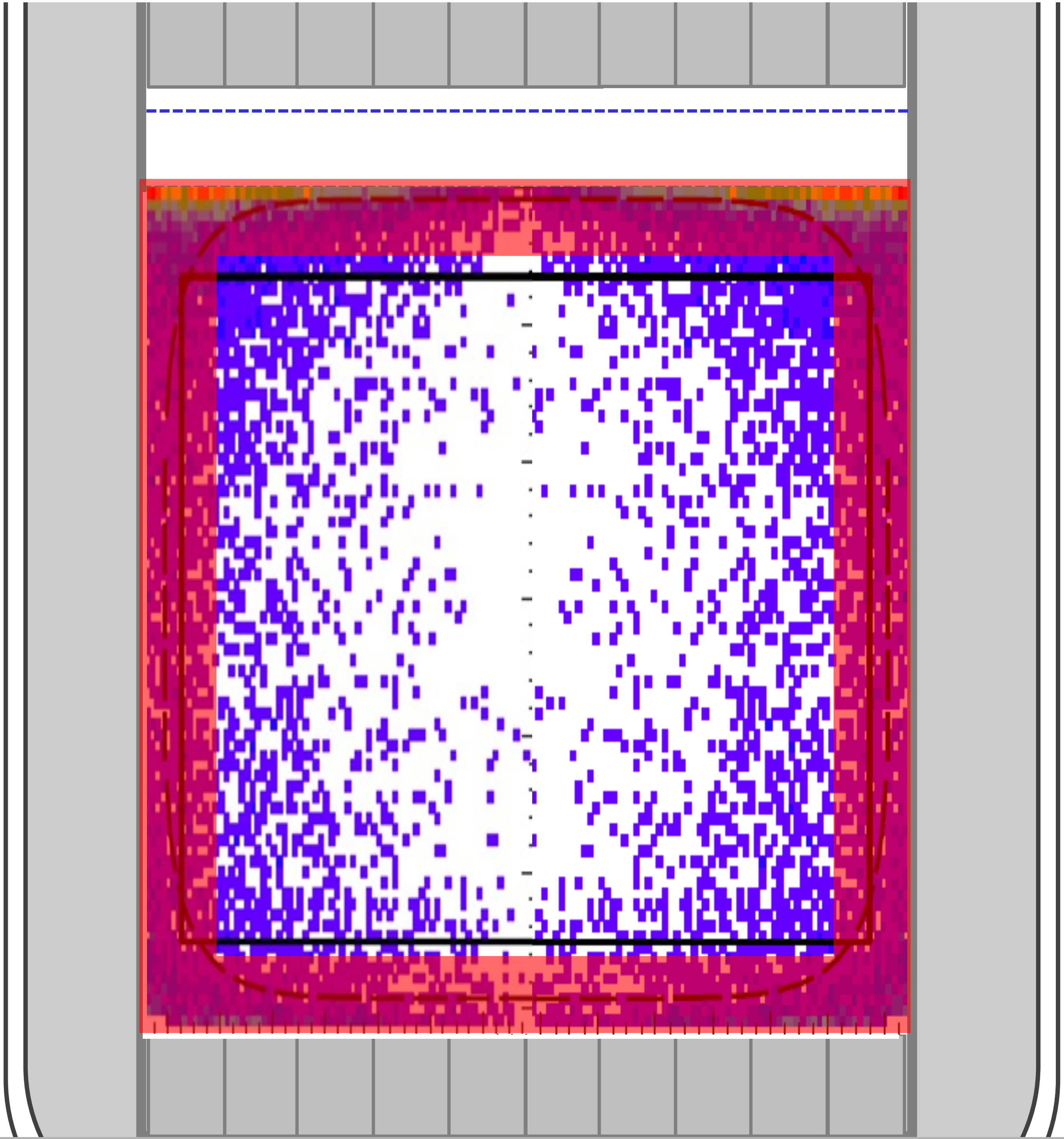



$$z(dt) = vDrift \cdot dt$$

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


Y
X
Top PMT Array and Top Shield PMT Array

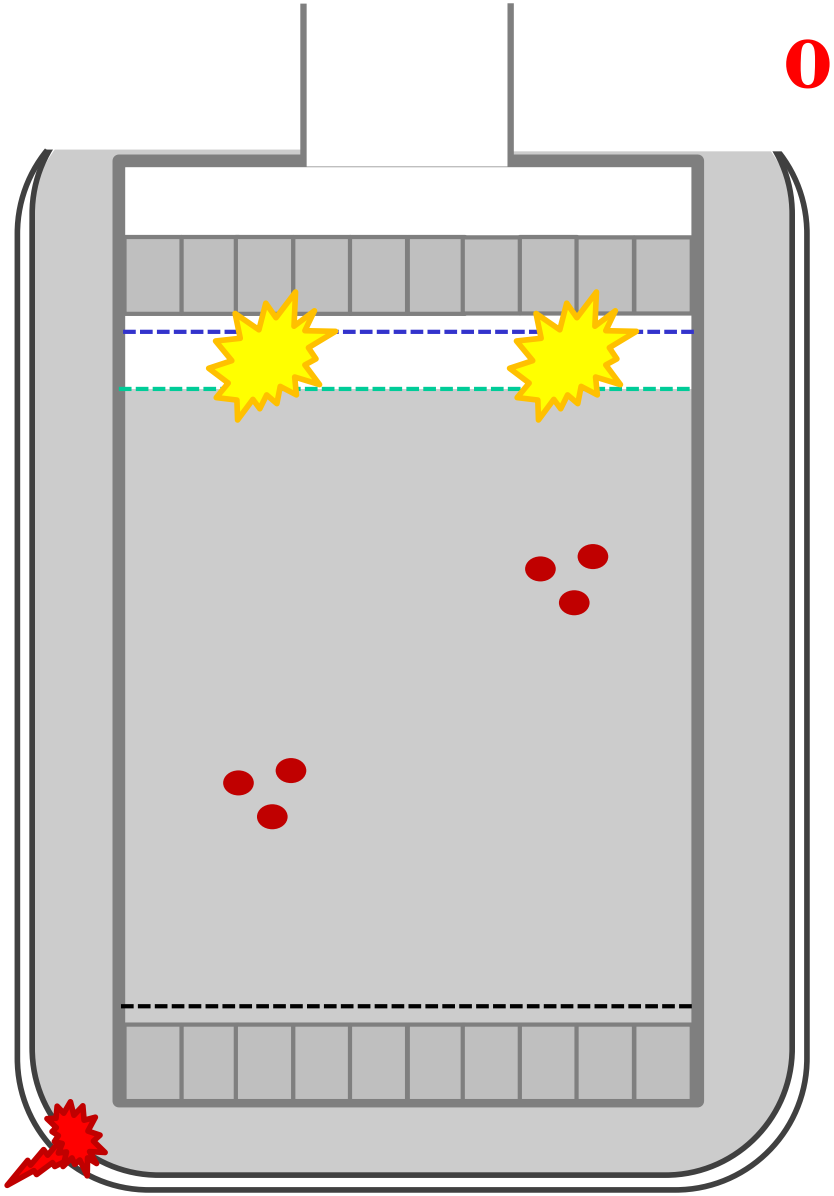


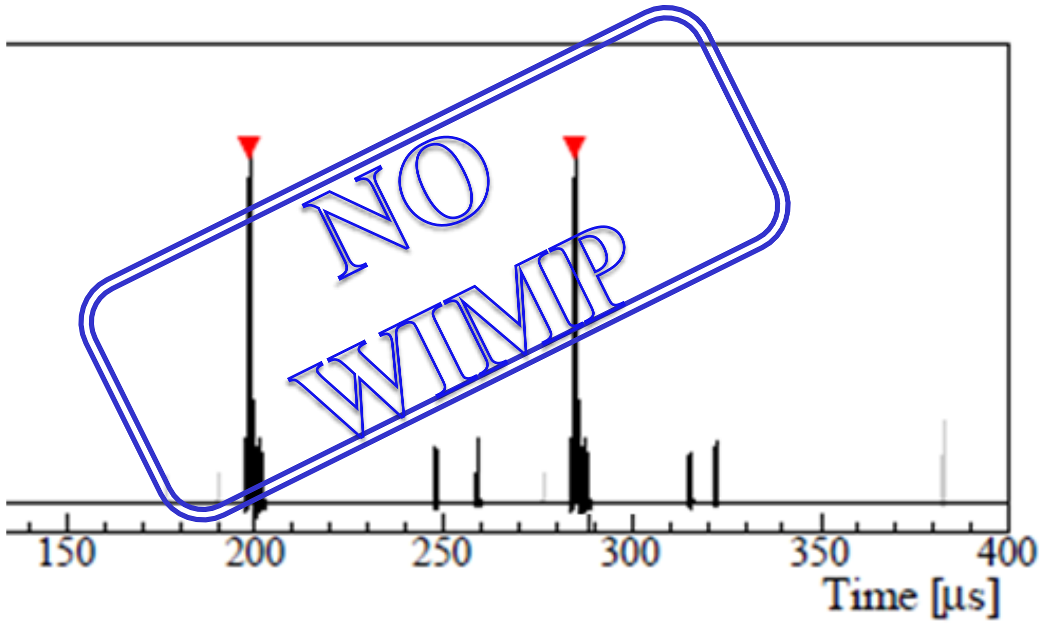


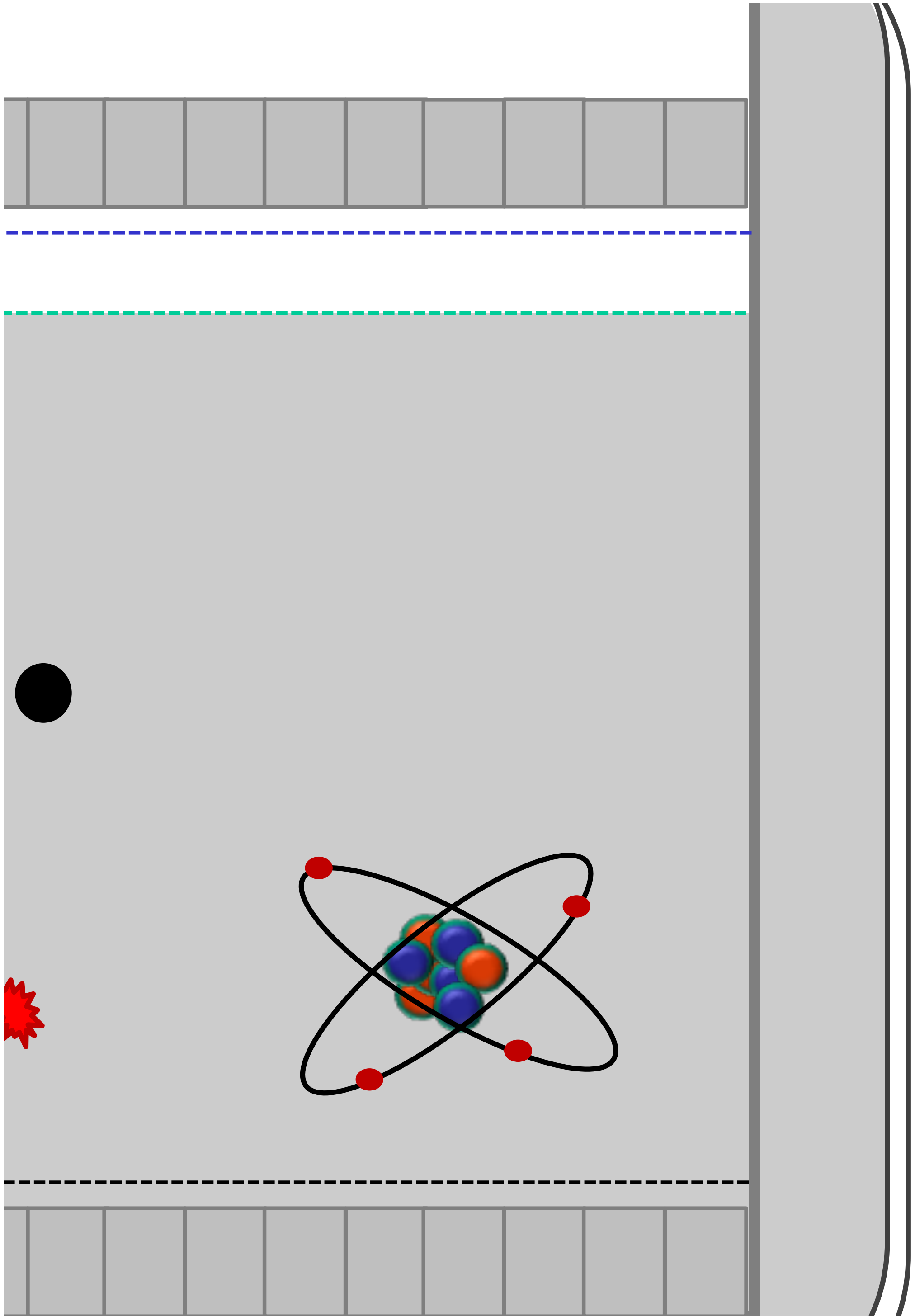
- reconstruct x,y,z

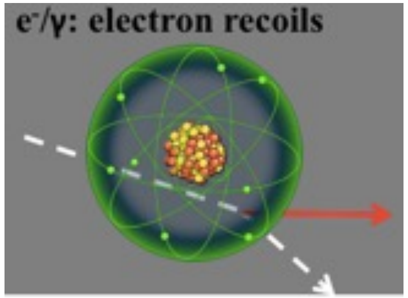
Next:
- fiducialize
- remove bg events

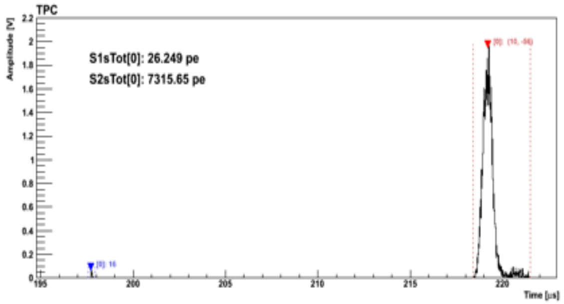
# A WIMP scatters only once (if at all)

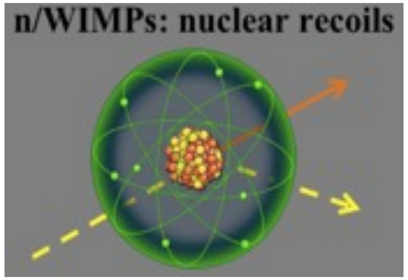


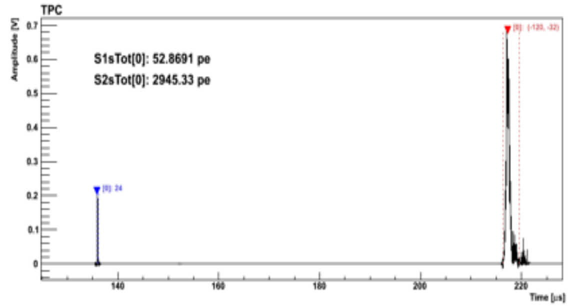




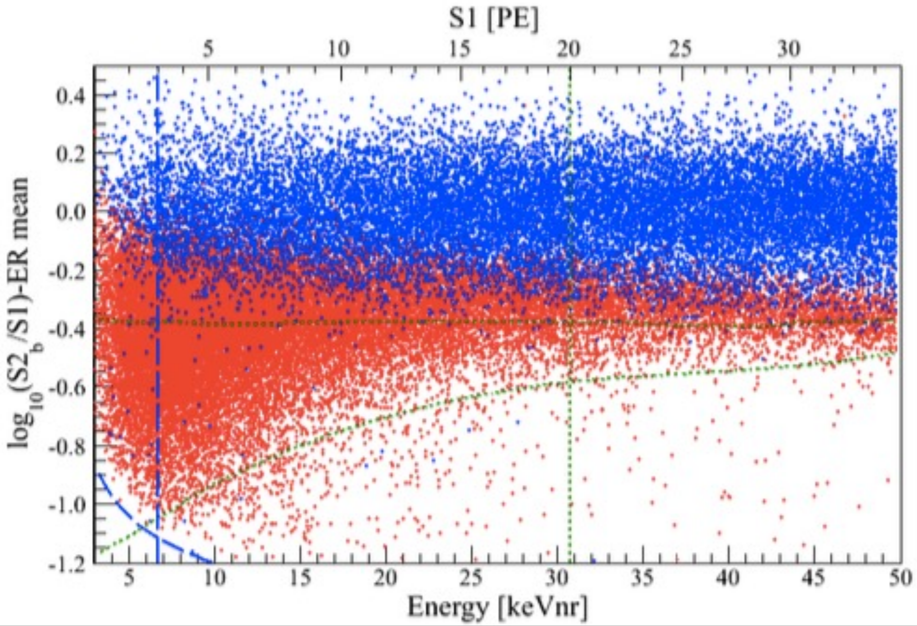


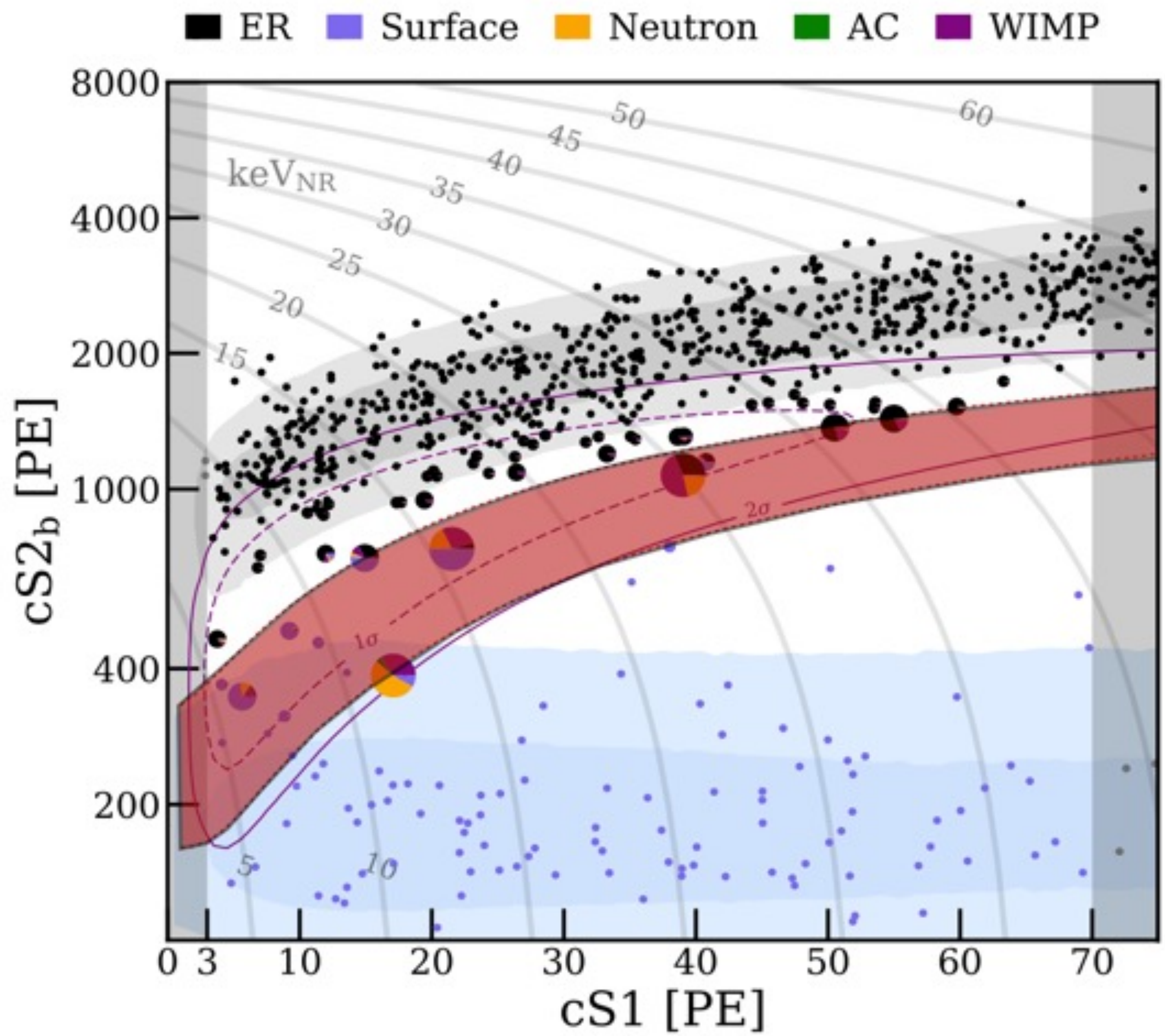



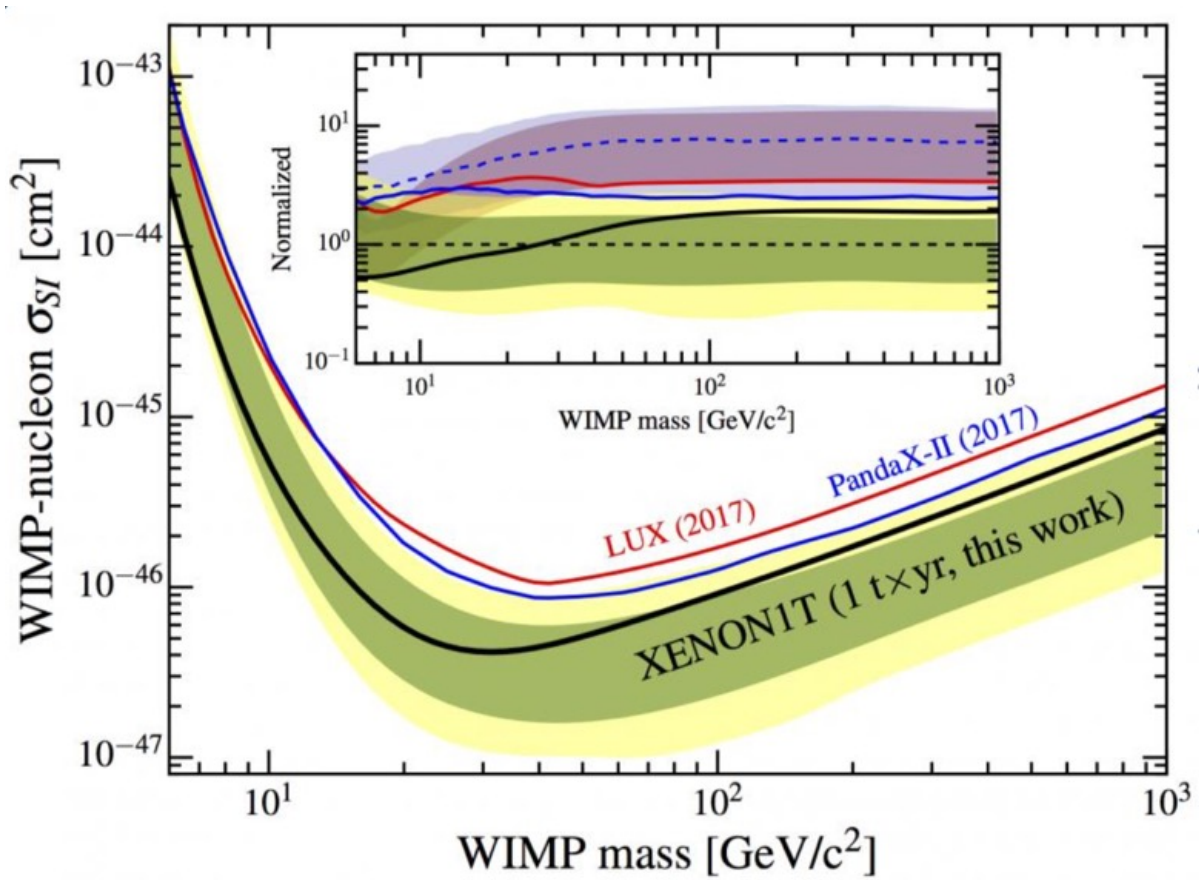

➔ **Distinguish: electronic recoils (ER)**
**nuclear recoils (NR)**



# XENON1T: NR Search for WIMPs

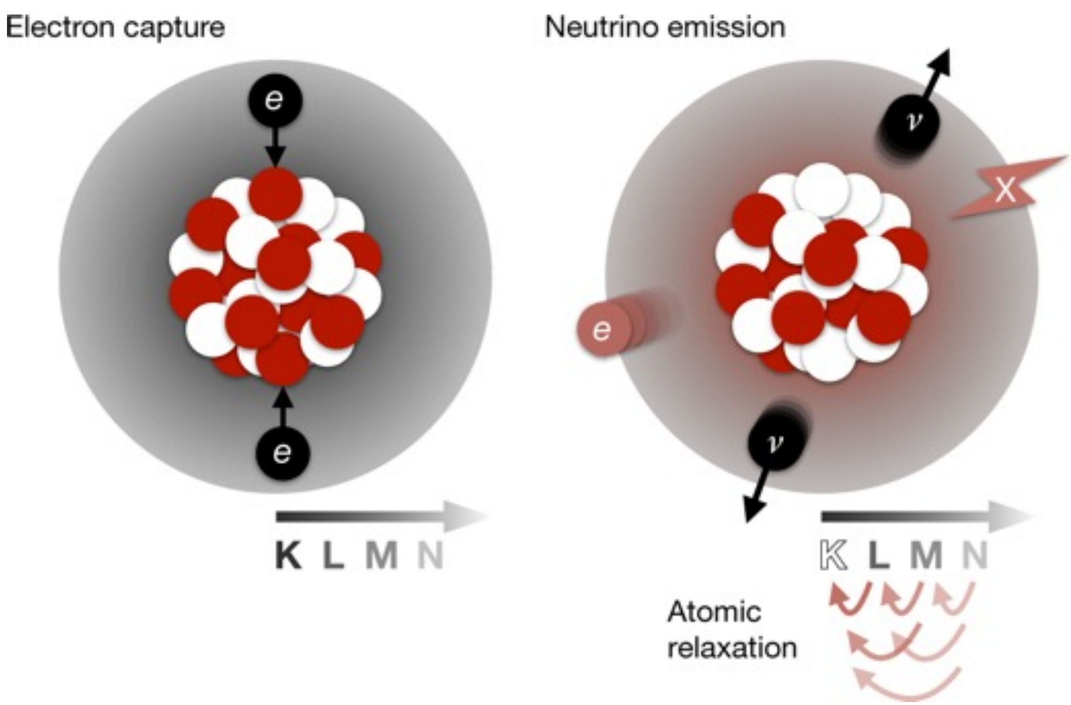


# XENON1T: Results on WIMPs




**➔ Most stringent result on SI scattering of WIMP Dark Matter down to 3 GeV/c² masses** [PRL 121, 111302 + PRL 123, 251801]

# Double Electron Capture of $^{124}Xe$





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

No rejection significane: $4.4\sigma$

**➔ about one trillion times the age of the Universe**

**➔ longest half-life ever measured directly**

Nature 568 (2019) 7753, 532-535

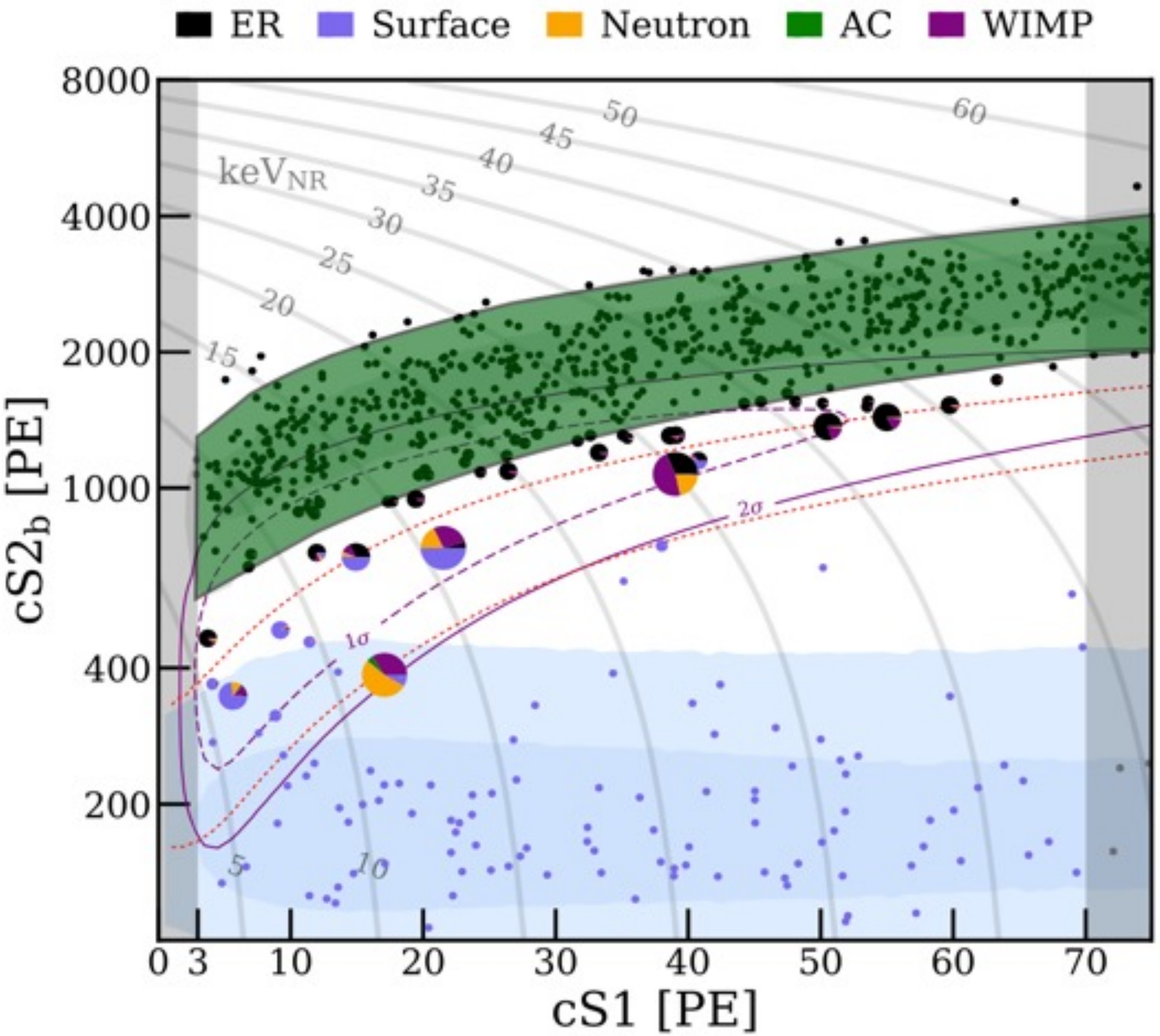
# Search for New Physics with ER Events

Phys. Rev. D 102, 072004

**Large exposure:**
**0.65 tonne-years**

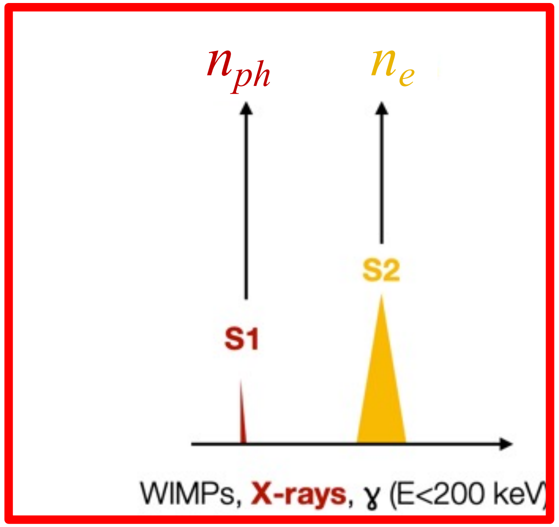
**Unprecedented low background:**
**76 ± 2 events/t/yr/keV**

**Low threshold:**
**1 $keV_{ee}$**



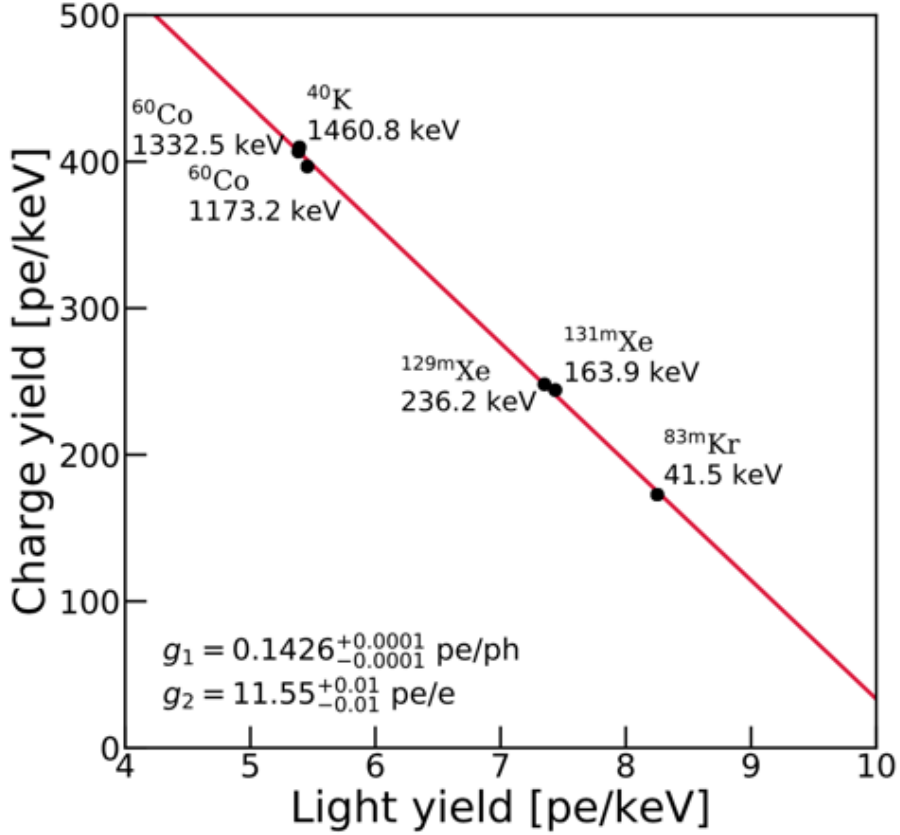
# Energy Reconstruction and Resolution

**Combine light and charge**




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

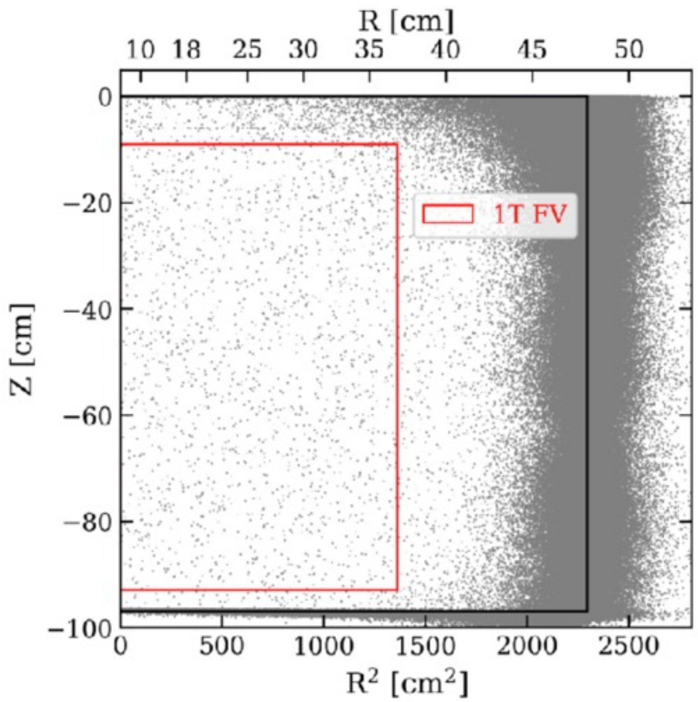
➔ **detector constants $g_1$ and $g_2$**

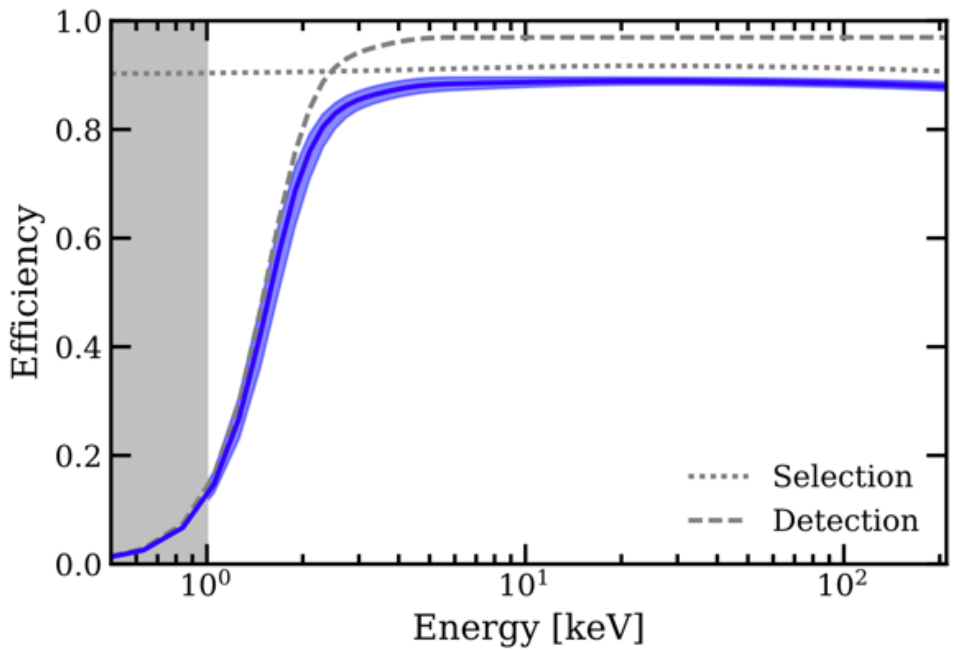



- Anti-correlation between light and charge
  ➔ checked with calibration sources
- Energy resolution < 5 % at 50 keV

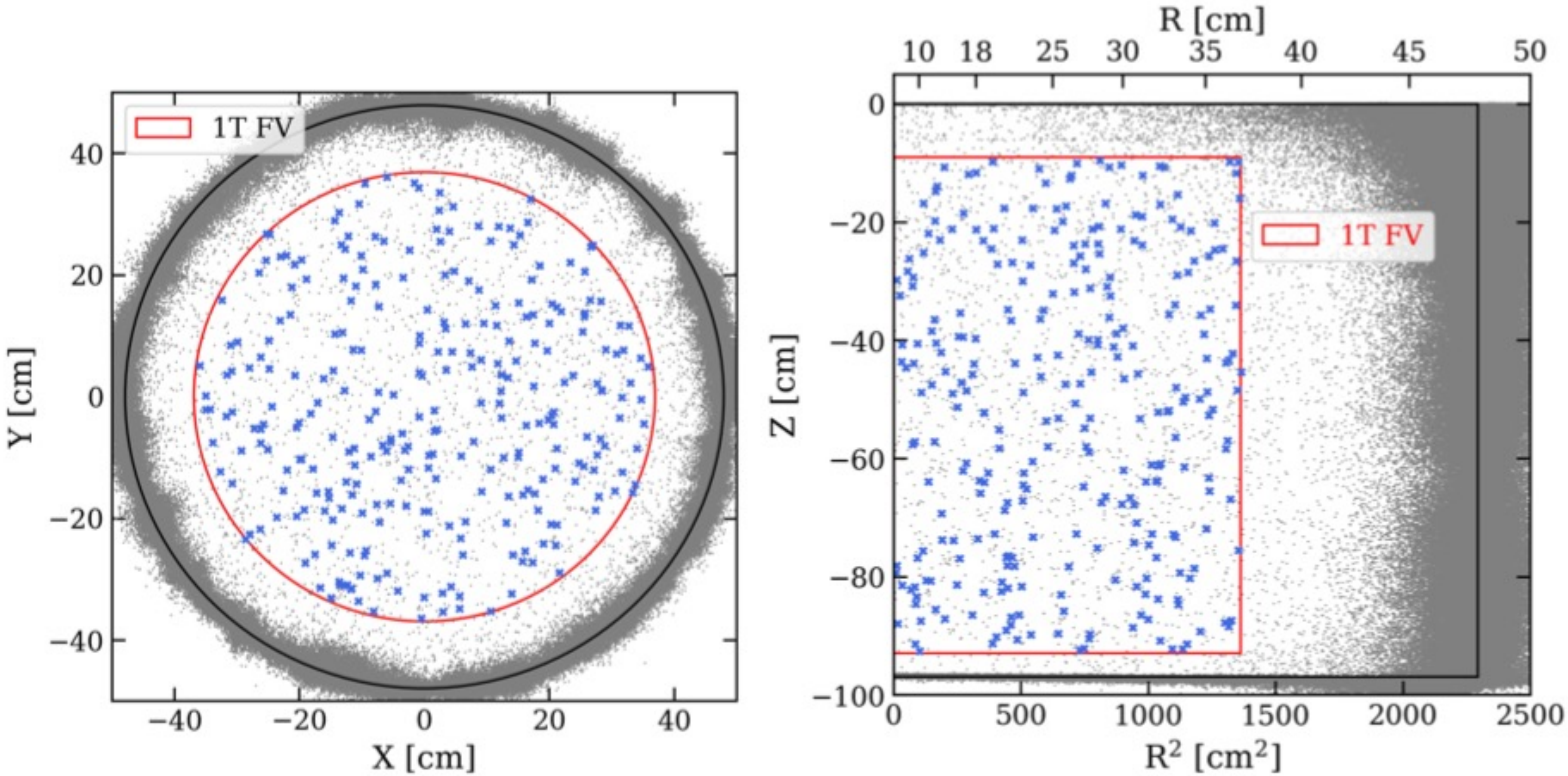
# Data Selection ands Detection Efficiency

- **Science Run I:** Feb. 2017 - Feb. 2018 ➔ 226.9 live days
- Fiducial volume: 1 tonne
- Energy range for single scatter events: [1,210] $keV_{ee}$
- Data quality cuts
- Include reconstruction efficiency & threshold at 10% detection efficiency



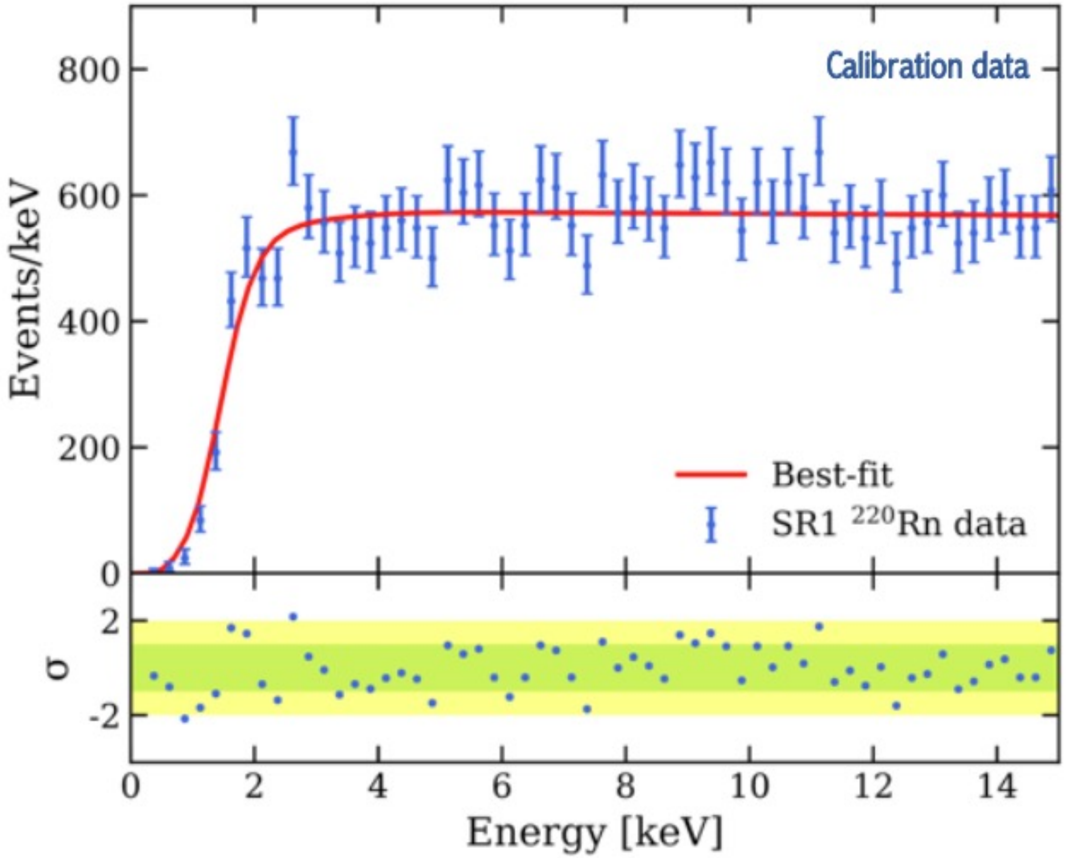
# Distribution of Events




- [1 - 120] keV
- [1 - 7 ] keV

# Detector Calibration

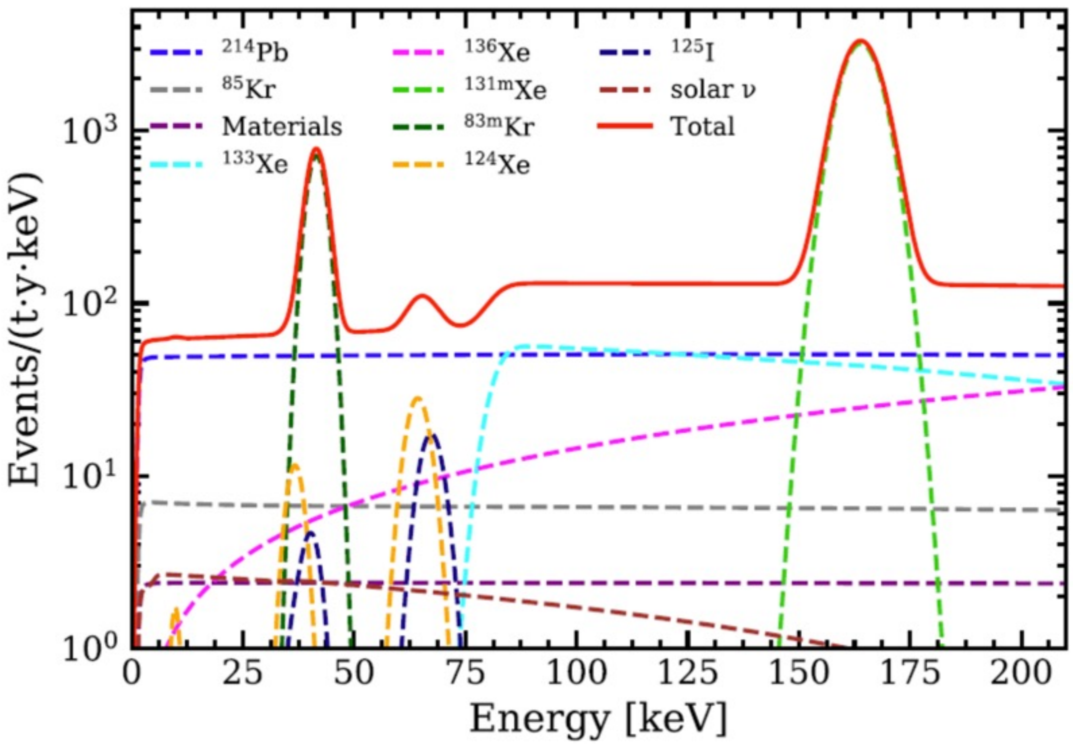
- $^{220}$Rn ($^{212}$Pb, β-decay ) calibration data validates our model even below 1keV
- No threshold excess
- No large systematics
- Uses the aame un-binned likelihood framework as in the main analysis



# Background Model

Background prediction in [1,210] keV interval based on:

- knowledge from material screening and control measurements
- GEANT4 simulations smeared with detector effects
- 10 components




**Internal (uniform in volume)**

**$^{214}$Pb (main contribution)**

**$^{85}$Kr (distilled out)**

**$^{136}$Xe, $^{124}$Xe** [Nature 568,532]

**$^{83m}$Kr** (calibration source issue)

**Neutron induced**

**$^{131m}$Xe, $^{133}$Xe, $^{125}$I**

**Solar neutrinos**

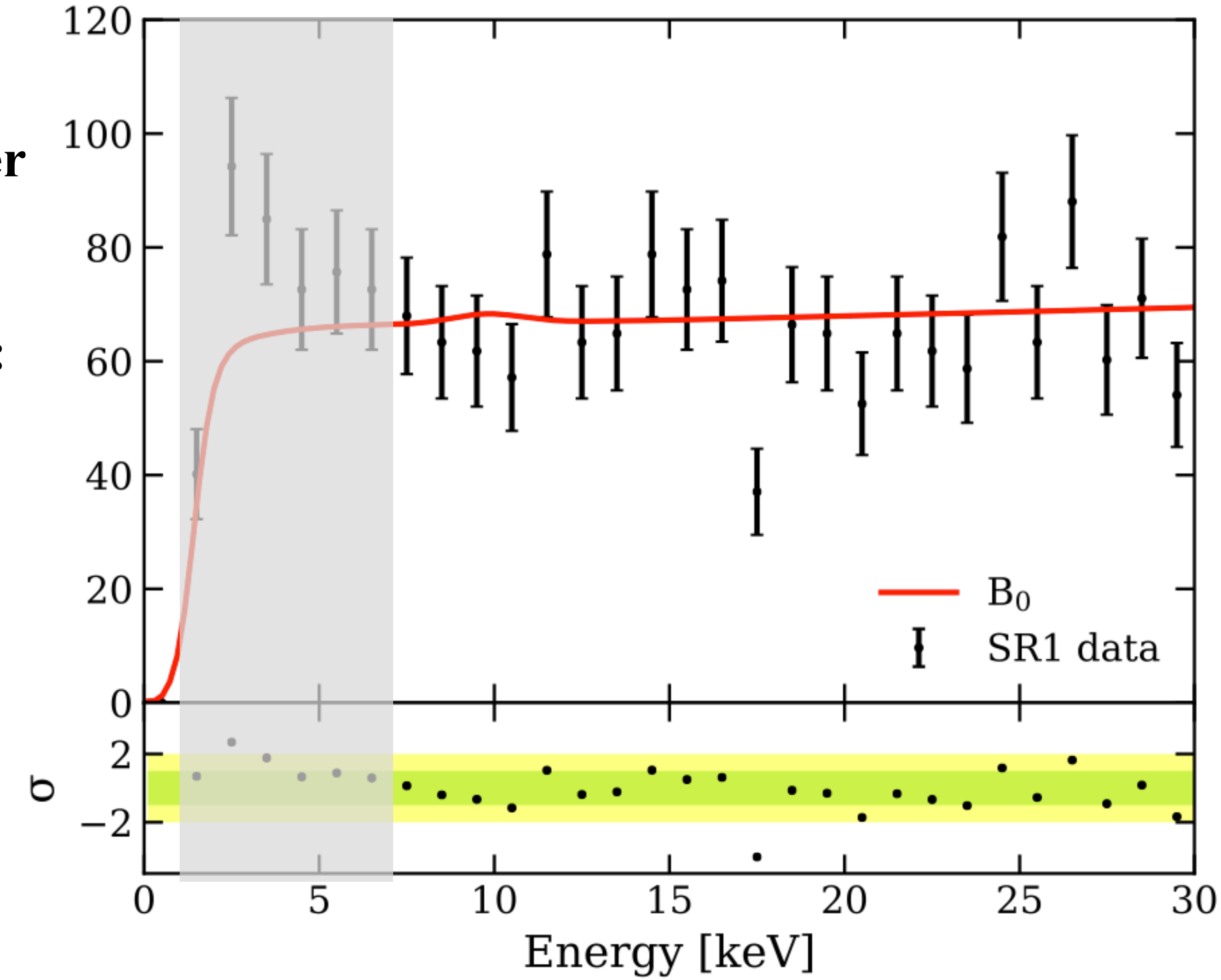
**Materials←→radio-essay & GEANT4**

**Time-dependency**

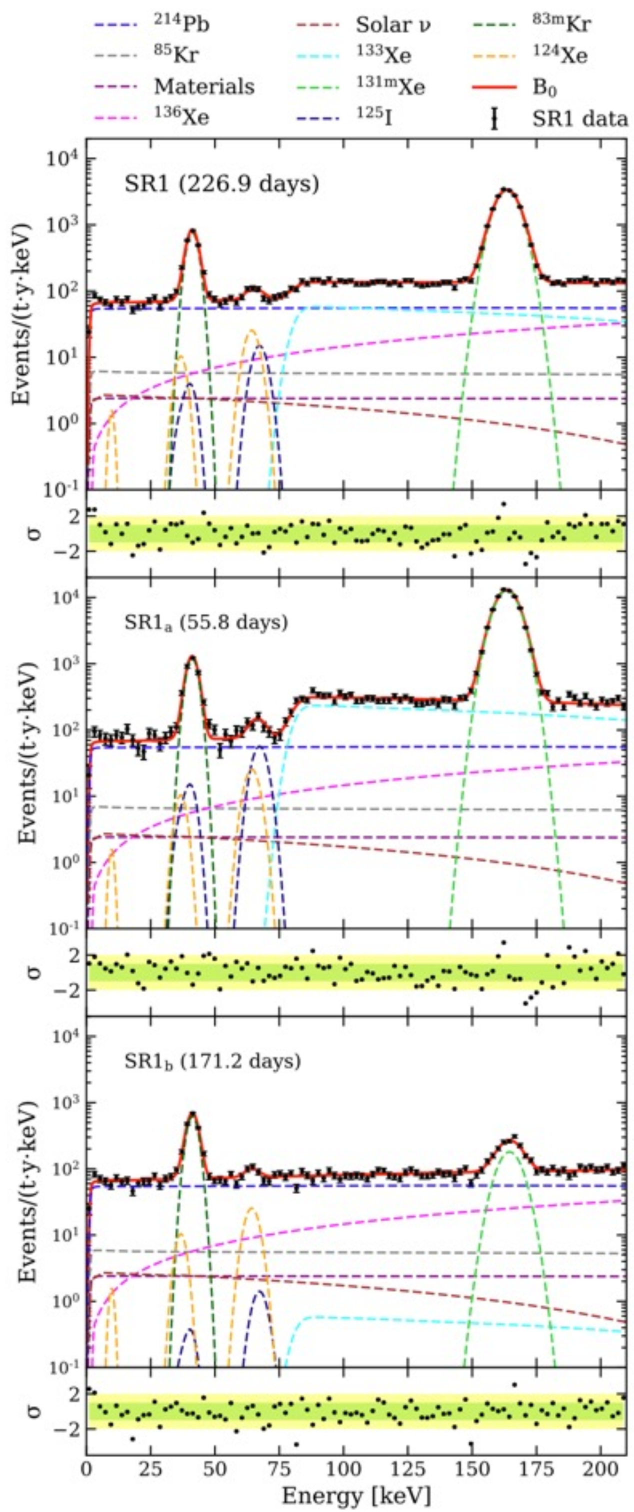
# The Result

- **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**

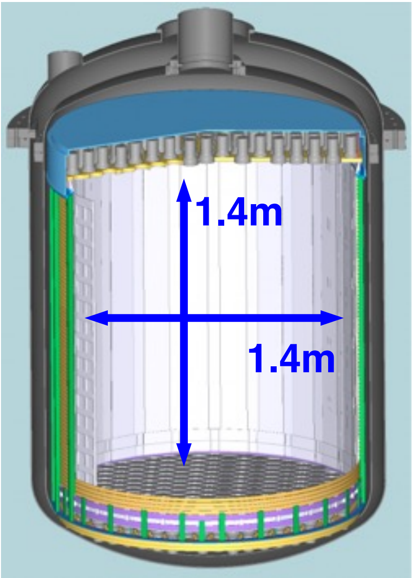
**<u>Explanation #2:</u>**
**Some unexpeccted new background?**

# Explanation #3: New Physics

- 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
- 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

Many papers which try to explain the XENON1T result
→ mostly 3 main directions: Axions, ν's, light bosons
→ stay tuned: analysis of 1st run of XENONnT is on-going...

# XENON1T → XENONnT

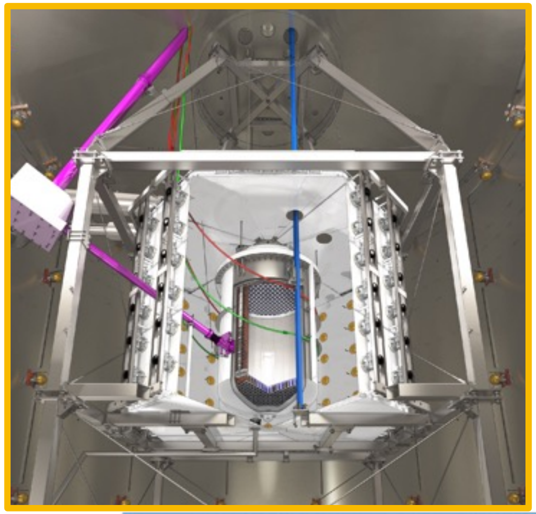




being prepared while XENON1T runs → switching gears

# Main changes for XENONnT

## Larger TPC

- Total 8.4 t LXe
- 5.9 t in TPC
- ~ 4 t fiducial
- 248 → 494 PMTs



## Neutron veto

- Inner region of existing muon veto
- optically separate
- 120 additional PMTs
- Gd in the water tank
- 0.5 % $Gd_2(SO_4)_3$

## $^{222}Rn$ distillation

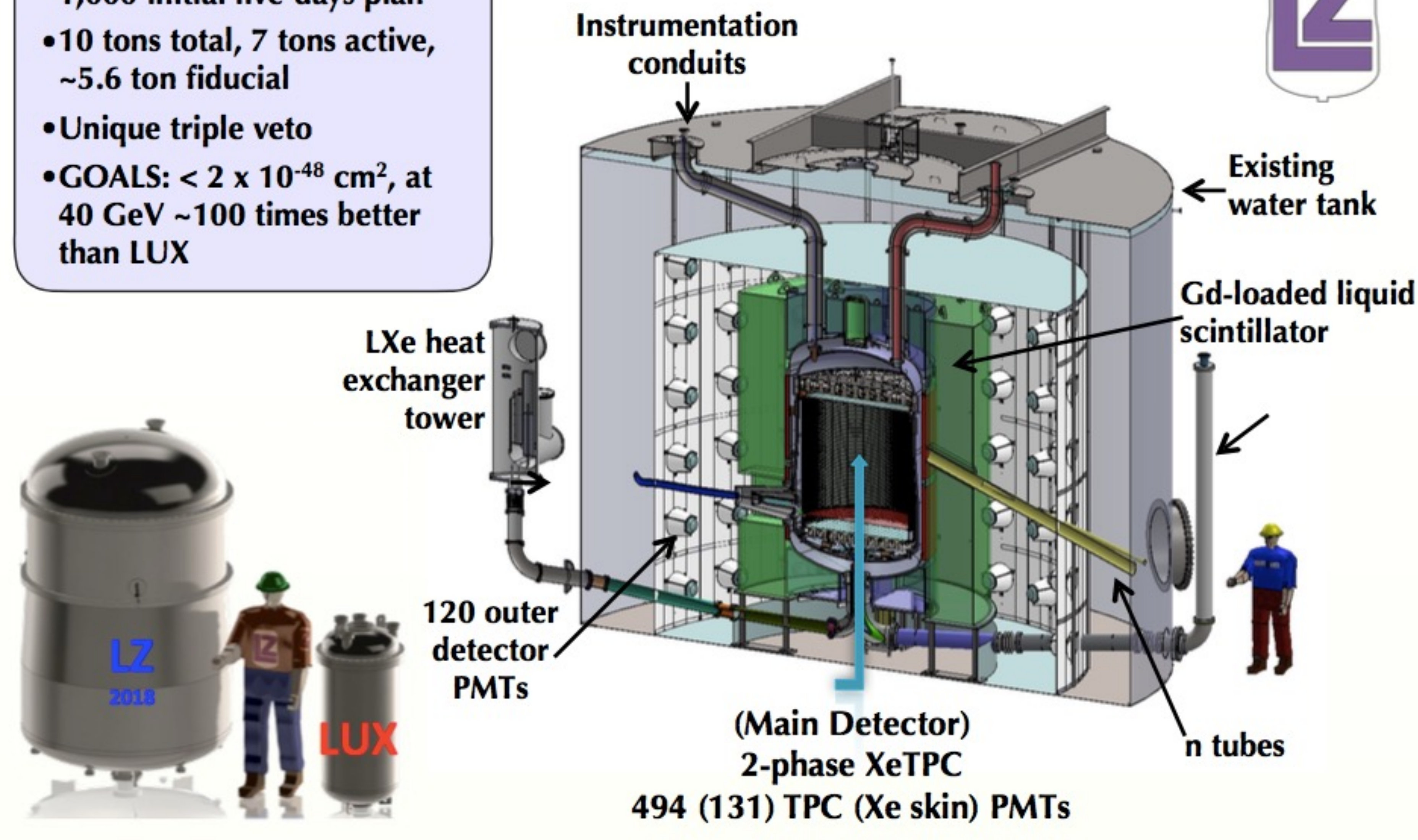
- Reduce Rn ($^{214}Pb$) from pipes, cables, cryogenic system
- New system, PoP in XENON1T

## LXe purification

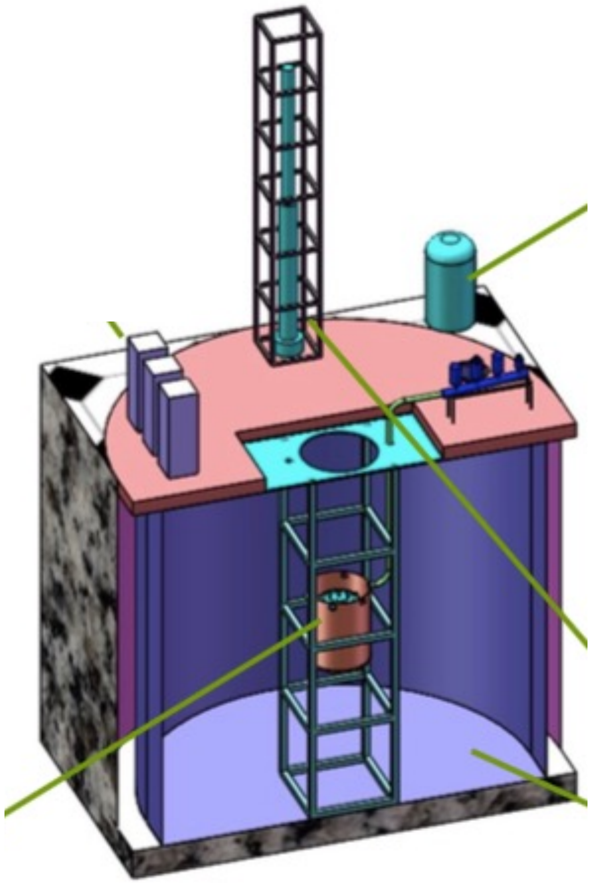
- Faster xenon cleaning
- 5 L/min LXe (2500 slpm)
- XENON1T ~ 100 slpm

# LUX-ZEPLIN (LZ)

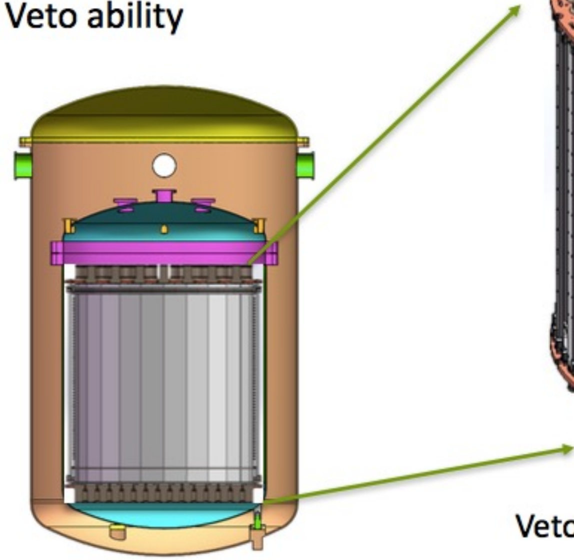
- Turning on by 2022 with 1,000 initial live-days plan
- 10 tons total, 7 tons active, ~5.6 ton fiducial
- Unique triple veto
- GOALS: < 2 x $10^{-48}$ $cm^2$, at 40 GeV ~100 times better than LUX

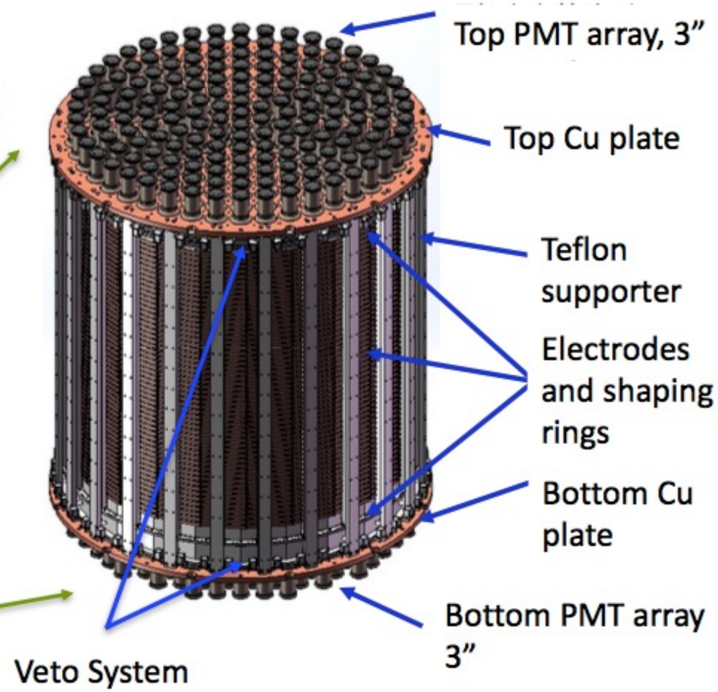


# PandaX-4T at CJPL



- 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

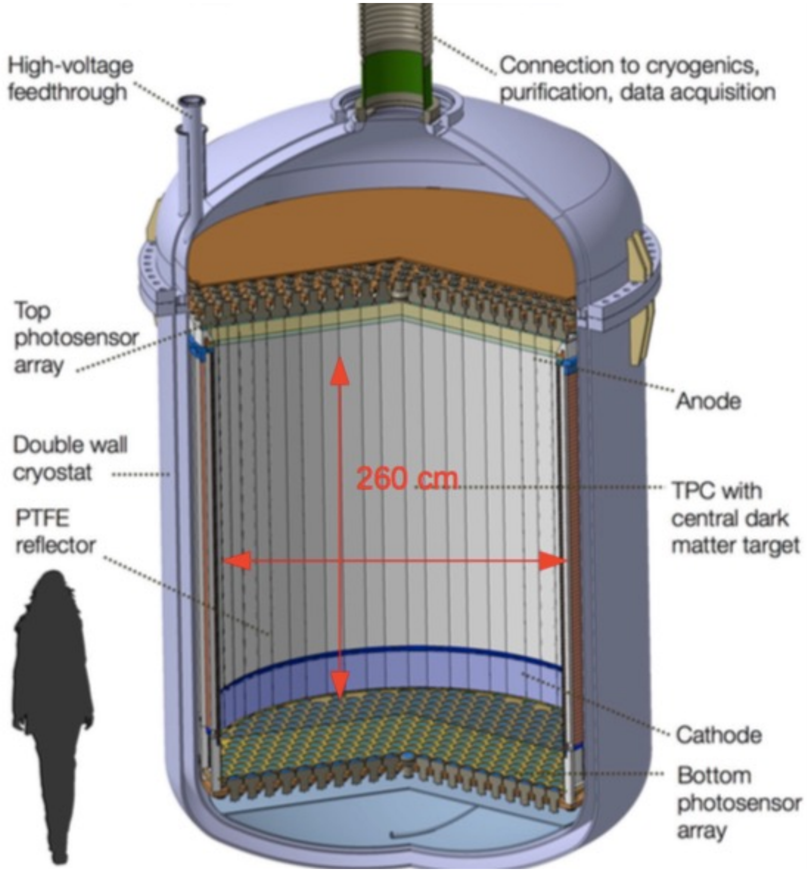





- 2017-2018:Produce all components and test
- 2019-2020:On-site assembling and commissioning
- 2021-2022:Data-taking
- eventual goal: ~30 t at CJPL to reach neutrino floor sensitivity

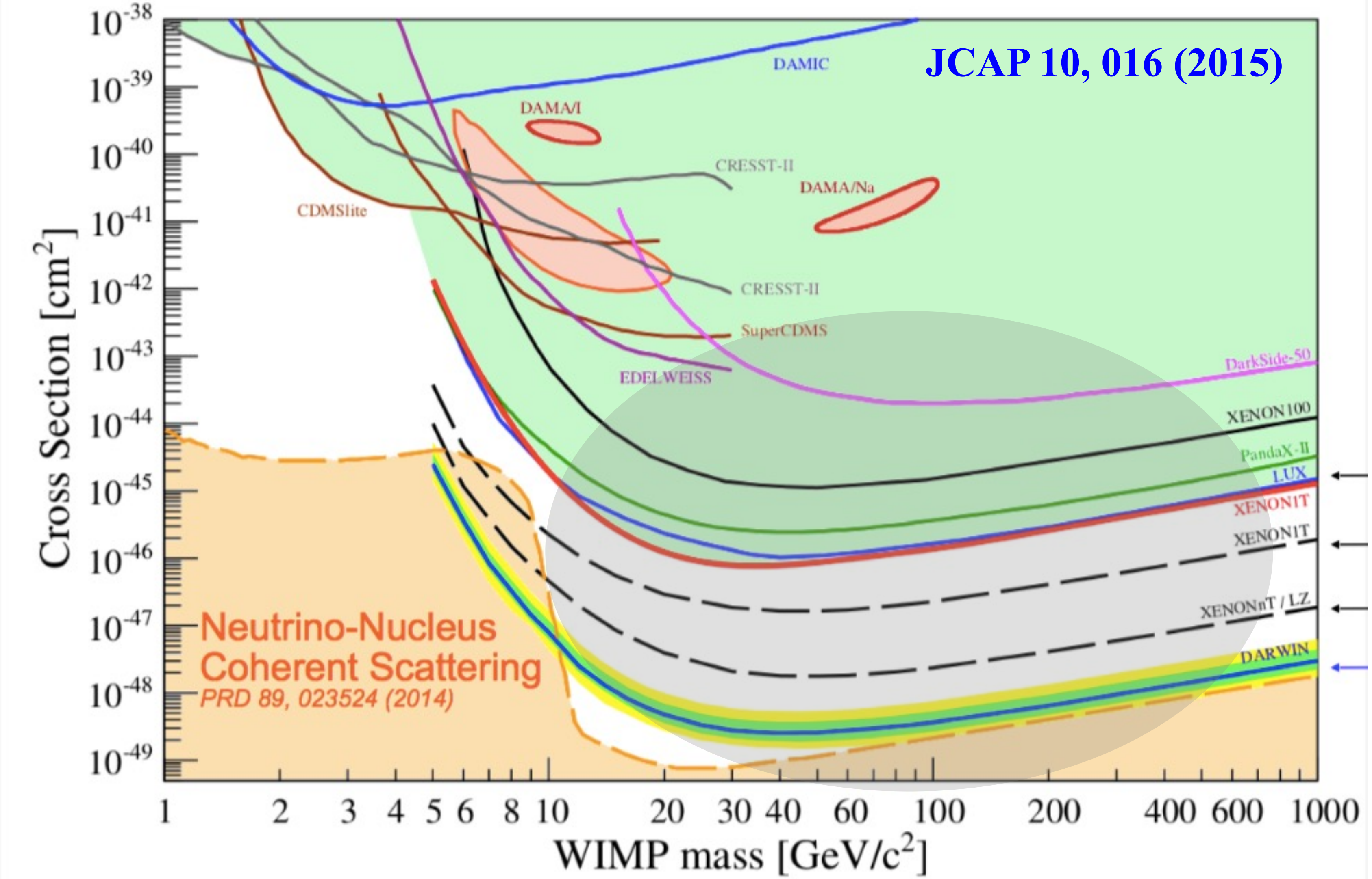
# Overall Status and Plans

- **XENONnT is analyzing data from 1st science run → stay tuned!**
- **2nd science run started**
- **LZ (similar size) is also operational**
  → competition
- **DARWIN (XENON + few more) →**
  50t target mass
- **DARWIN-LZ-consortium:**
  - merge expertise, ...




**JCAP 11, 017 (2016)**
www.darwin-observatory.org

# Spin Independent (SI) WIMP Interaction




**tests the generic WIMP space ➔ find a WIMP or a paradigm change**

**➔ solar neutrino signal & CEνNS**

**➔ supernova neutrinos**

} ➔ **neutrino phase**

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

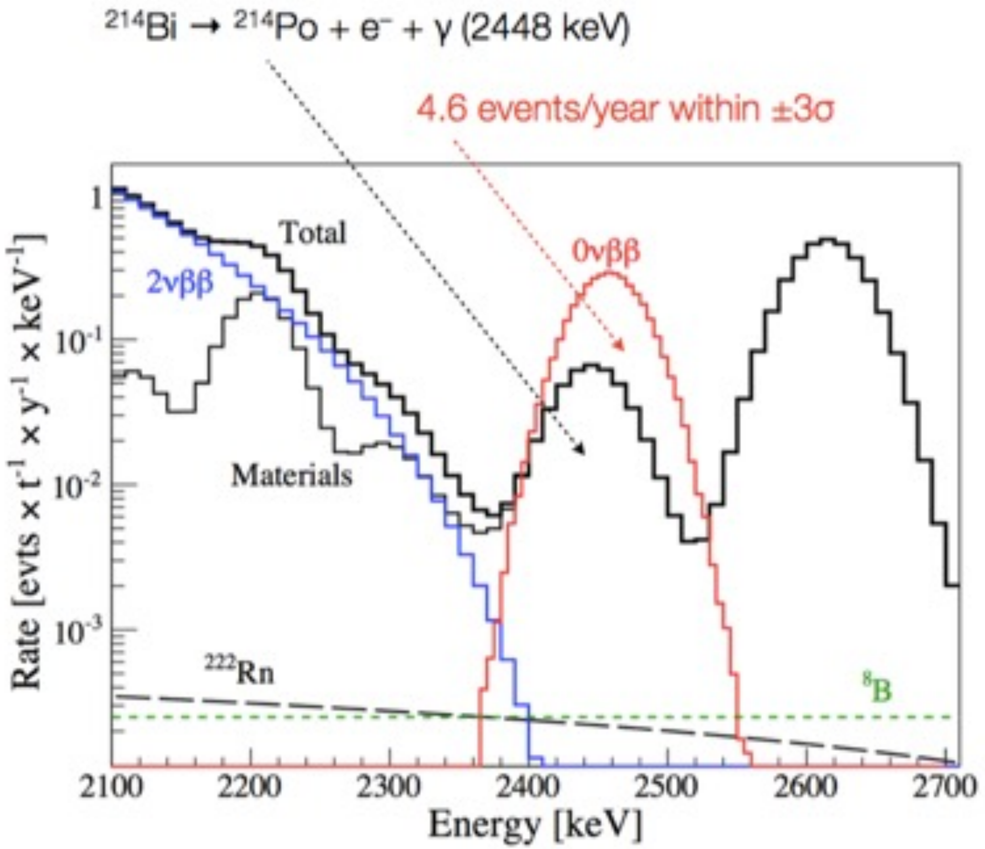
**8.9% natural abundance**

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

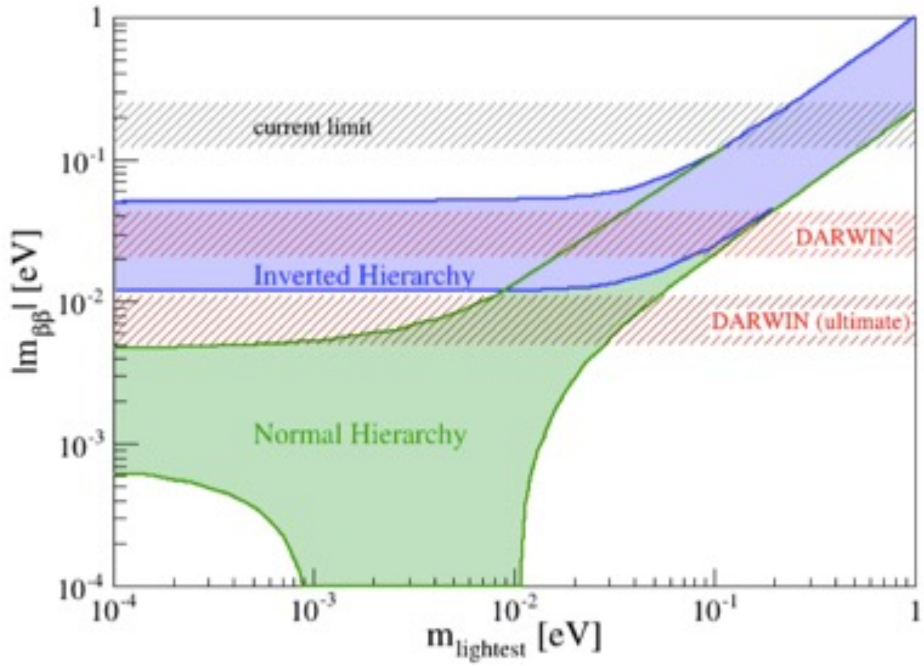
**$Q_{\beta\beta}$ = (2458.7 ± 0.6) keV**

**Assume:**

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




JCAP 01, 044 (2014)



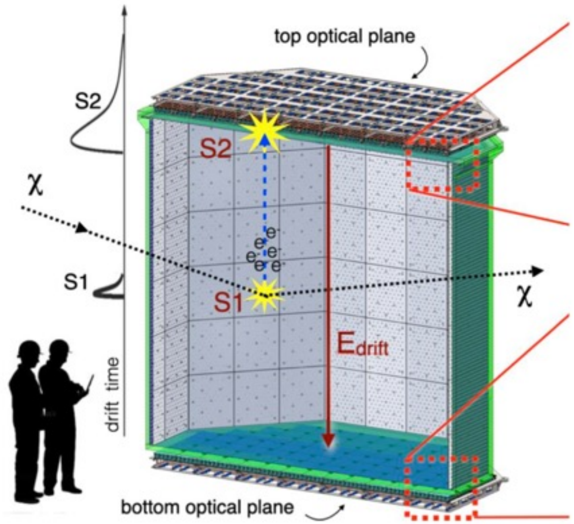

**Sensitivity @ 95% CL:**

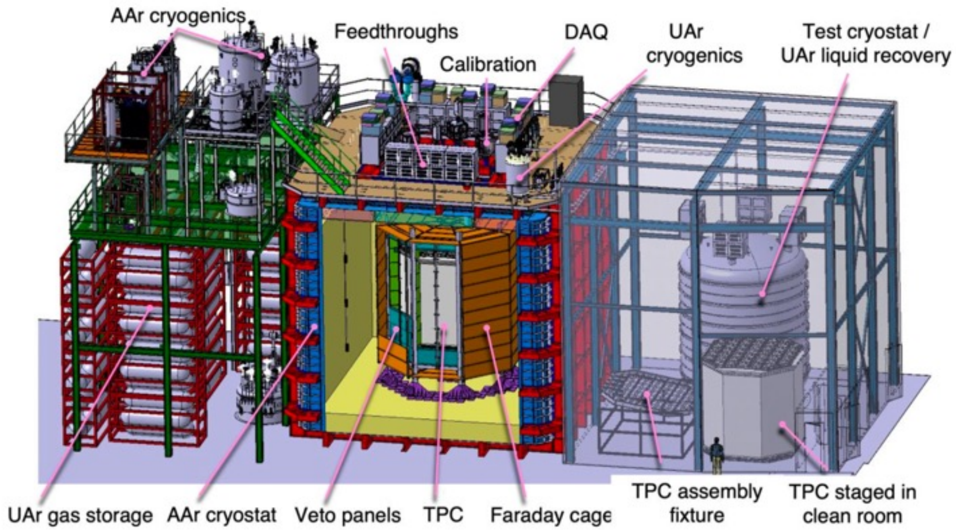
- 30 t*yr → $T_{1/2} > 5.6 \times 10^{26}$ yr
- 140 t*yr → $T_{1/2} > 8.5 \times 10^{27}$ yr

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

# LAr based TPCs

**Darkside 20k @LNGS: 40 t LAr** – see talk byA. Zoccoli




- DarkSide
- DEAP
- ArDM
- MiniCLEAN

→ DS-20K @LNGS → ARGO @SNOLAB

➔ **300 t of underground argon**

# Conclusions

- Direct detection of dark matter <u>is essential</u> for proving that it is made of particles
- Many candidates... ←→ spectrum of theoretical ideas
- WIMPs, axions, sterile ν's appear best motivated
  ➔ find them or paradigms will change!
- Strong competition → impressive sensitivity gain/time
- New results expected...
- Exciting longer term projects...
- Options for the discovery of other new physics (ν's, ...)
  ➔ will remain an exciting field