Dark Matter Direct Detection

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About me:

- After a PhD in Physics, research associate at Princeton Univ.
- Work at LNGS since 2001
  - Mainly experimental activity on solar neutrinos, dark matter and low background detectors
  - Phenomenology
- On leave in 2007 as lecturer at Princeton Univ.
- On leave from 2015 to 2018 to work at LSC, Spain as lab director
- Mainly experimental activity in the framework of Borexino, DarkSide-50, and SABRE
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A few numbers to keep in mind

- $M_\odot = 1.99 \times 10^{30}$ kg
- $L_\odot = 3.828 \times 10^{26}$ W $= 2.39 \times 10^{13}$ MeV/s (no ν)
- 1 kpc $= 3.086 \times 10^{19}$ m
- $H_0 = 100 \times h$ km/s/Mpc with $h \sim 0.7$
- $m_p = 1.6726 \times 10^{-24}$ g $= 938.27$ MeV/c^2
- $M_{Pl} = 1.22 \times 10^{19}$ GeV/c^2
- $\hbar c = 197.327 \times 10^{-13}$ MeV cm
- 1 GeV^{-1} $= 0.197 \times 10^{-13}$ cm
- 1 GeV^{-1} $= 6.58 \times 10^{-25}$ s
- $\rho_c = 2.775\, h^2\, 10^{11}\, M_\odot/\mathrm{Mpc}^3 = 1.054\, h^2\, 10^{-5}$ GeV/c^2/cm^3

  $= 5\, m_p/\mathrm{m}^3 \sim 10^{-26}$ kg/m^3

Introduction

- Modern cosmology includes a non-baryonic matter component
- This component accounts for ~26% of the critical energy density in the universe and 84% of the total matter density
- This dark matter component is mainly observed by its gravitationally effects on structures in the universe

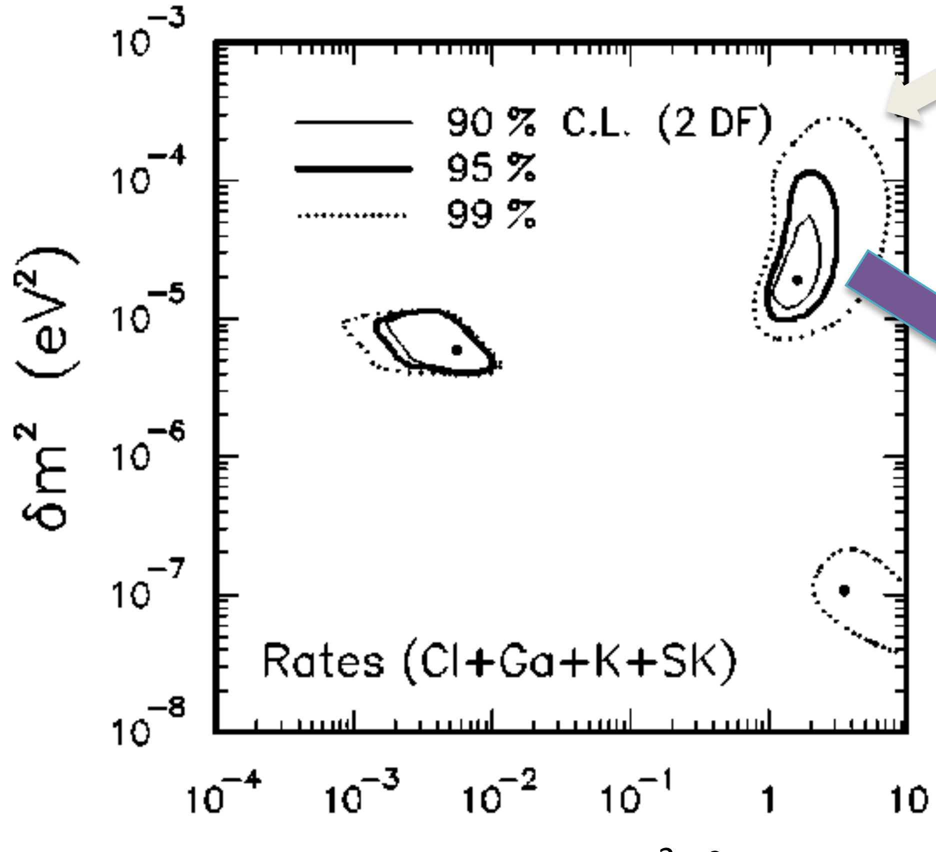
Challenges for direct search

- Lack of knowledge of kind of particle we are hunting
- Lack of knowledge of interaction process
- Space of parameter is huge

An analogy:
solar neutrinos in the late 1990s and today

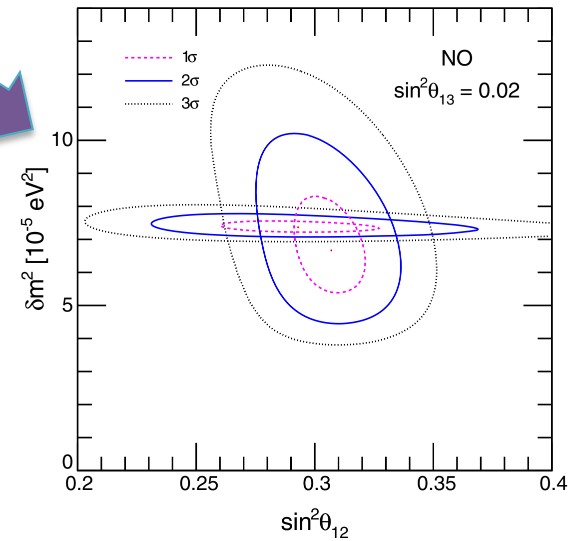
SuperKamiokande in data taking since 1996

SNO from 1999 to 2006, not in this analysis



PRD 62.013002(2000)

21 years later



PRD 104.083031(2021)

General considerations on DM

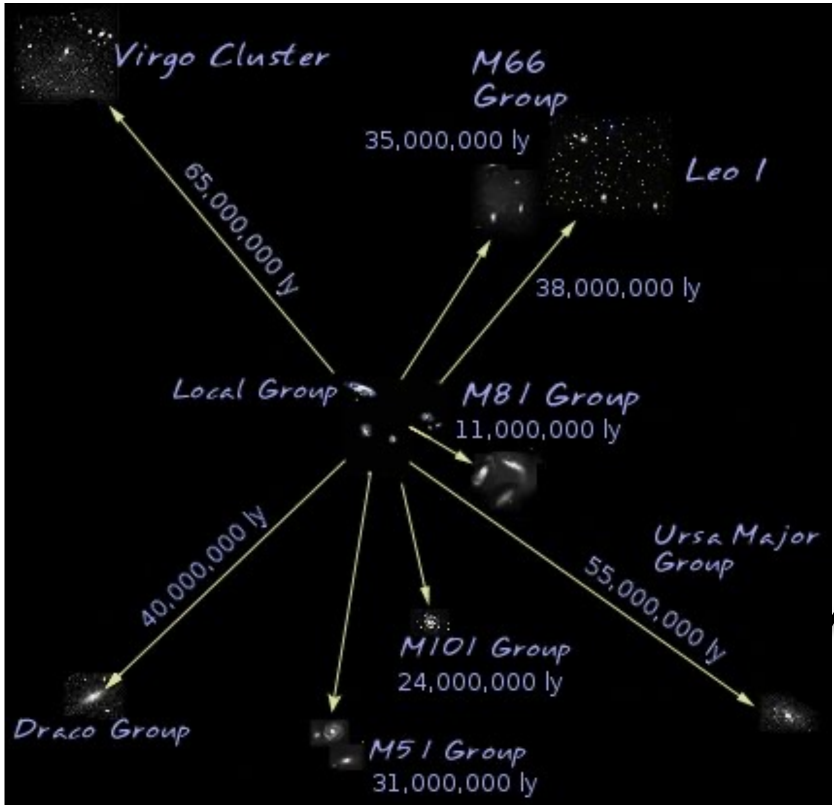
Measurements to support evidence of DM in the universe

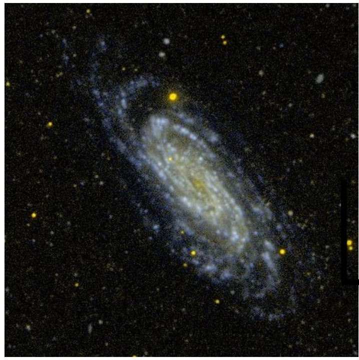
- Mass-to-Light ratio in galaxies and clusters of galaxies
  - $\Omega_m = \rho_m / \rho_c = (\rho_L / \rho_c)x(M/L)$
  - $\Omega_m = \frac{\rho_L}{\rho_c}\left(\frac{M}{M_\odot}\right)\left(\frac{L_\odot}{L}\right)$

- Temperature anisotropies in the CMB

- Gravitational lensing

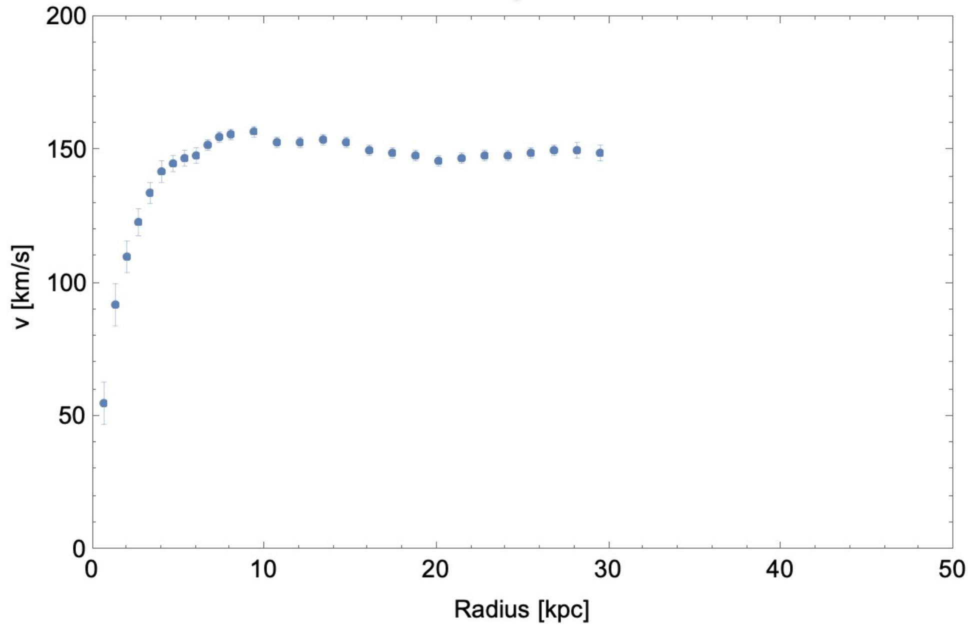
Galaxy rotation curve and DM: NGC 3198 as a case study





NGC3198

rotation curve



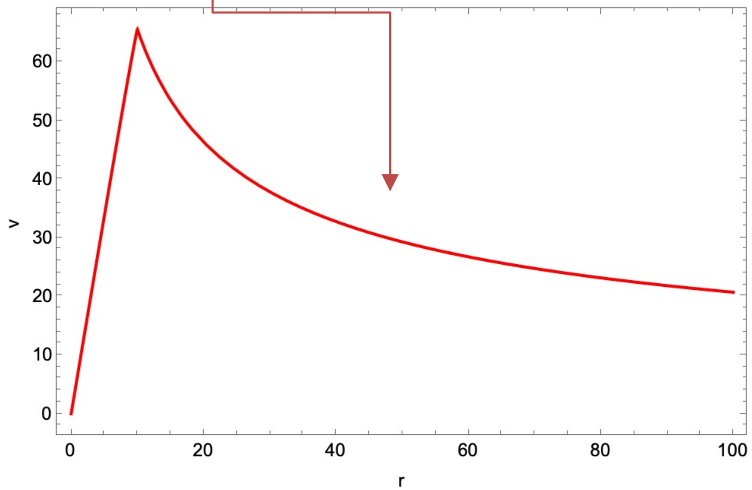
R_{disk} = 2.68 kpc
$L_V / L_\odot = (7.0\pm0.7)\times10^9$
Distance = 9.2 Mpc = 30×10^6 ly

Rotation curve: what do you expect?

$$v(r) = \sqrt{\frac{4\pi G}{r}\int_0^r dx\, \rho(x) x^2}$$

Extension of central mass is r_0

How does v changes inside and outside the central mass?



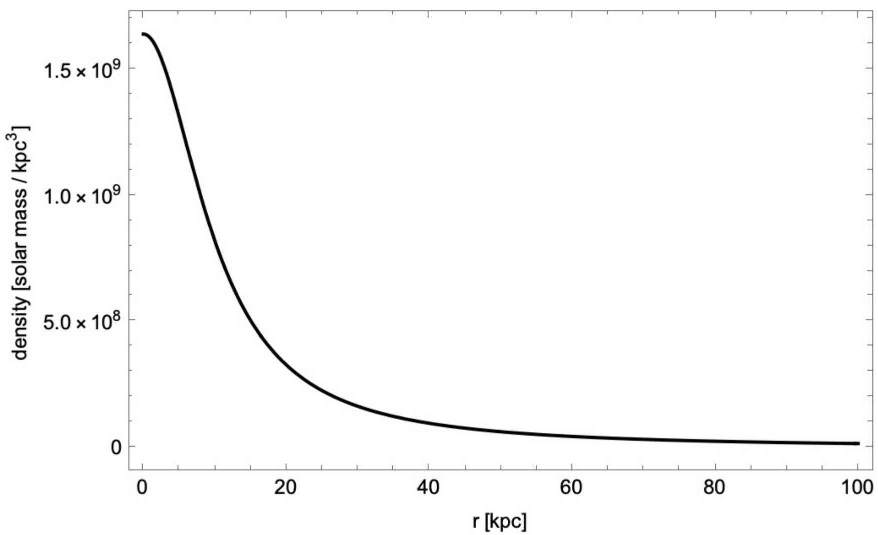
A flat curve implies M(r) = k r

$\rho(r) \sim 1/r^2$ for a spherically symmetric halo about the center of galaxy

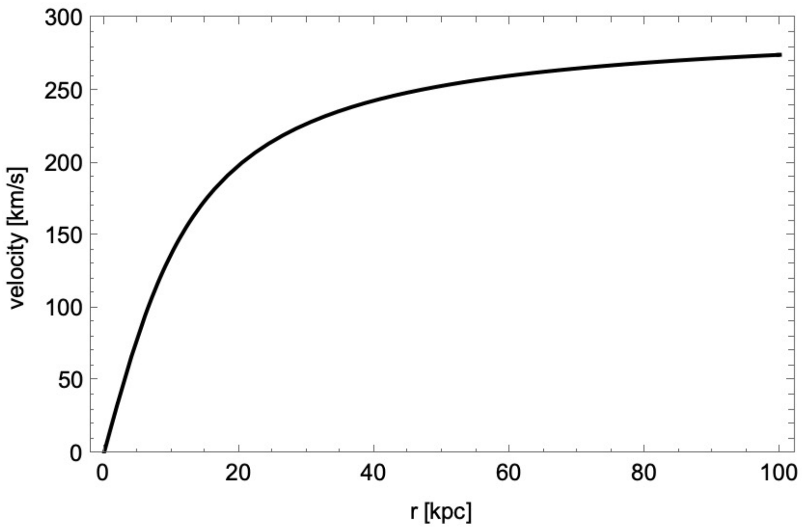
Build up a simple model

$$\rho(r) = \frac{\rho(0)}{1+\left(\frac{r}{a}\right)^g} = \left(1+\left(\frac{R_0}{a}\right)^g\right)\frac{\rho(R_0)}{1+\left(\frac{r}{a}\right)^g}$$

with g ~ 2 and R_0 ~ 8 kpc



$$v(r) = \sqrt{\frac{4\pi G}{r}\int_0^r dx\, \rho(x) x^2}$$



Exploit the model

- Use exponential surface brigthness distribution: $I(r) \propto e^{-r/R_d}$
  - P. Salucci et al., Mon. Not. R. Astron. Soc. 378, 41-47 (2007)

- $v_d^2(r) = \frac{1}{2}\frac{G\,M_d}{R_d}(3.2x)^2\big(I_0(1.6x)K_0(1.6x) - I_1(1.6x)K_1(1.6x)\big)$

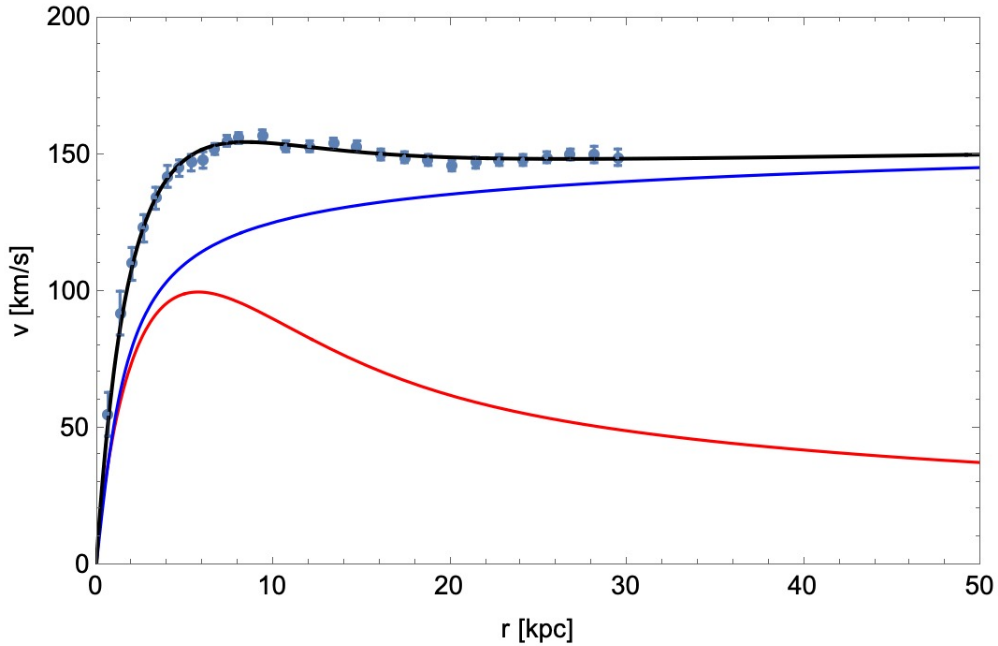
- With x=r/R_{opt}, R_{opt}=3.2R_d and I_n, K_n modified Bessel functions

- $v^2(r) = v_d^2(r) + v_h^2(r)$

- With $v_h(r) = \sqrt{\frac{4\pi G}{r}\int_0^r dx\,\rho_h(x)x^2}$

Fit result

- Constraints to fit procedure:
  - g ~ 2
  - ρ(8 kpc) ~ 0.4 GeV/c^2/cm^3 ~ 0.01 $M_\odot$/pc^3
- Salucci et al. 2010: $\rho_\odot$**=0.43±0.15 GeV/c^2/cm^3**



M_h = 5.3×10^{11} $M_\odot$

M_h / M_d = 33

M_h / M_d (<40 kpc) = 12

M / L_V (< 40 kpc) = 28

ρ(8 kpc) ~ 0.22 GeV/c^2/cm^3

Ω_m (r<40 kpc) ~ 0.02
Ω_m (r<100 kpc) ~ 0.07

How big is the DM halo?

- Simple model: $v_{rot}^2 = \begin{cases} v_0^2, r < \ r_* \\ \propto \frac{1}{r}, r > r_* \end{cases}$

- Determine the mass: $M(r) = \begin{cases} v_0^2 r/G, & r < \ r_* \\ v_0^2 r_*/G, & r > r_* \end{cases}$

How big is the DM halo?

- Consider our MW galaxy
  - R_{sun} = 8.5 kpc
  - v_0 ~ 220 km/s at ≥ $2R_{sun}$
  - v_{max} ~ 500 km/s
- Use: $\frac{dU}{dr} = \frac{GM(r)}{r^2}$
- Determine: $U(r) = \begin{cases} v_0^2 \left[ln\frac{r}{r_*} - 1 \right], & r < r_* \\ v_0^2 r_*/r, & r > r_* \end{cases}$
- Use: $\frac{1}{2} v_{max}^2 + U(R_{sun}) \leq 0$
- $\frac{1}{2} v_{max}^2 + v_0^2 \left[ln\frac{Rsun}{r_*} - 1 \right] \leq 0$ implies **r_* ≥ 41 kpc** and M_* = 4.6×10^{11} $M_\odot$
- With L_V = 1.4×10^{10} $L_\odot$, M/L ≥ 33
- Ω_m ≥ 0.03

Change halo density profile

- $$\rho(r) = \frac{\rho(0)}{\left(\frac{r_8}{a}\right)^g + \left(\frac{r}{r_8}\right)^g + 0.01\left(\frac{r}{r_8}\right)^4}$$

$M_h = 3.4 \times 10^{11}\, M_\odot$

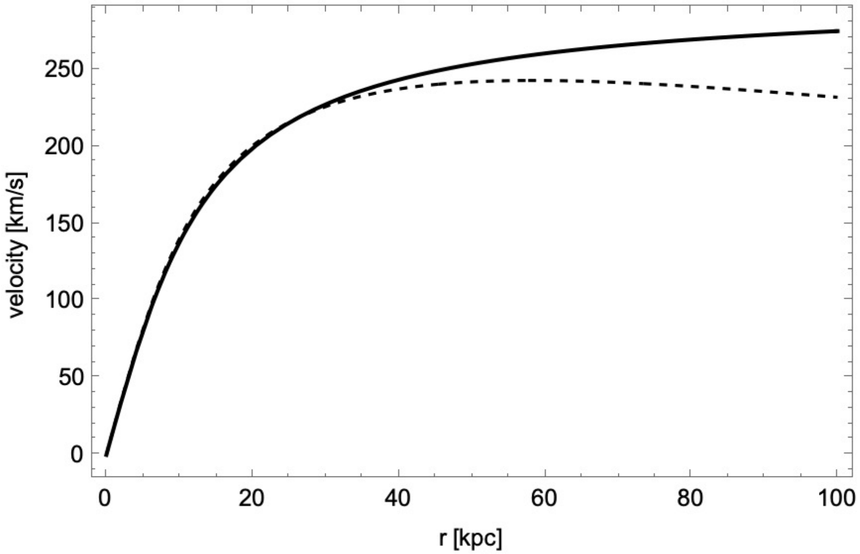
$M_h / M_d = 21$

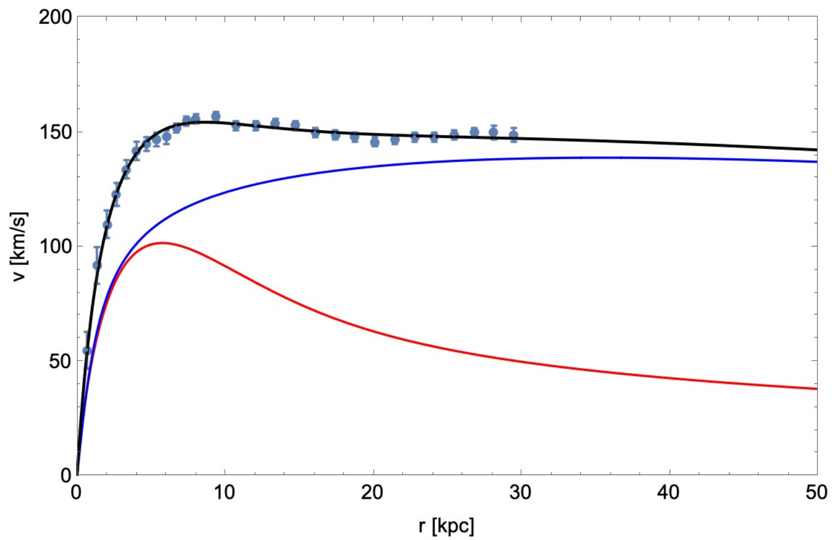
M_h / M_d (<40 kpc) = 11

M / L_V (< 40 kpc) = 28

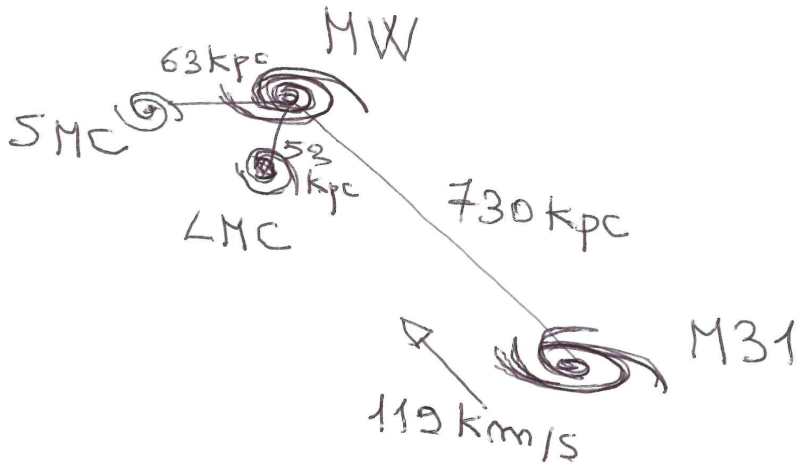
ρ(8 kpc) ~ 0.20 GeV/c^2/cm^3

Ω_m (r<40 kpc) ~ 0.02





Milky Way and Andromeda (scale < 700 kpc)



Relative velocity of MW and M31 is -119 km/s

From the relative orbit equation determine:

$$\frac{dr}{dt} = \frac{r}{t}\,\frac{\sin\eta(\eta - \sin\eta)}{(1-\cos\eta)^2} = \sqrt{\frac{GM}{a}}\,\frac{\sin\eta(\eta-\sin\eta)}{(1-\cos\eta)^2}$$

with dr/dt = -119 km/s
t = 10 Gyr
Turns out that η = 4.11
Use η to determine M

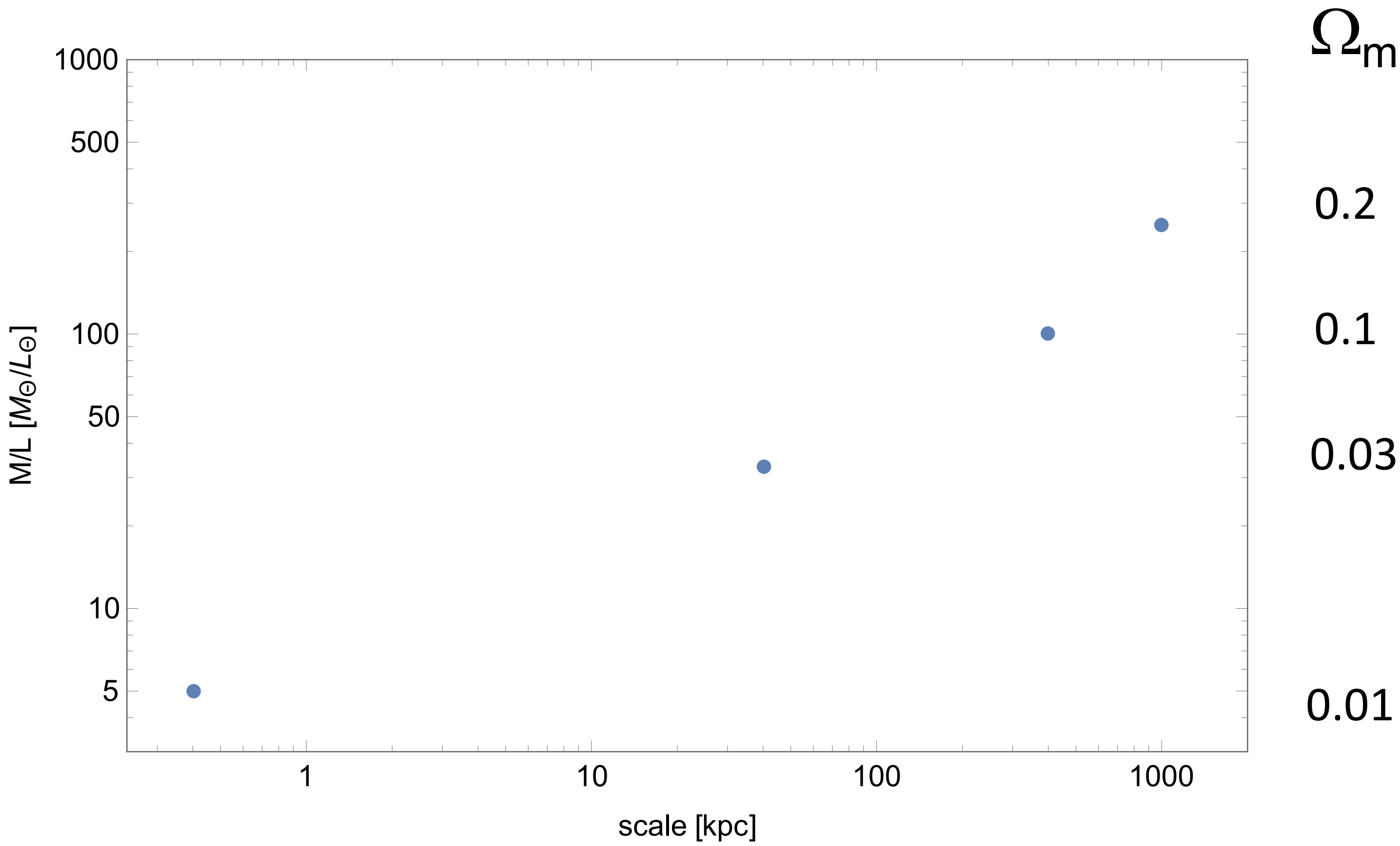
M/L ~ 100

Dark Matter in galaxy clusters

- Extension ~ 1 Mpc
- ~ 1000 galaxies
- Average velocity for member galaxy ~ 1000 km/s
- For a spherical symmetry gravitational system, using virial theorem: $2\ \frac{1}{2}M(3\bar{v}^2) = \frac{3}{5}\frac{GM^2}{R}$
- Determine: $M \sim 10^{15}\ M_\odot$
- M/L ~ 100-200 and $\Omega_m \sim$ 0.1-0.2

DM in the Universe

$$\Omega_m = \frac{1}{1630\,h}\left\langle\frac{M}{L}\right\rangle \sim 0.001 \text{ M/L for h=0.7}$$



Early universe evolution

10^{10} y, ~10^{-4} eV today

growth of structures

10^{5} y, ~0.2 eV $e^- + p \rightarrow H + \gamma$

baryogenesis

10-100 s, ~0.1 MeV $p+n \rightarrow d+\gamma$, $2p+2n \rightarrow {}^4He$

1 s, ~1 MeV ν decoupling

10^{-5} s, ~0.2 GeV QCD phase transition

quark-gluon plasma

10^{-11} s, ~10^{2} GeV electroweak phase transition

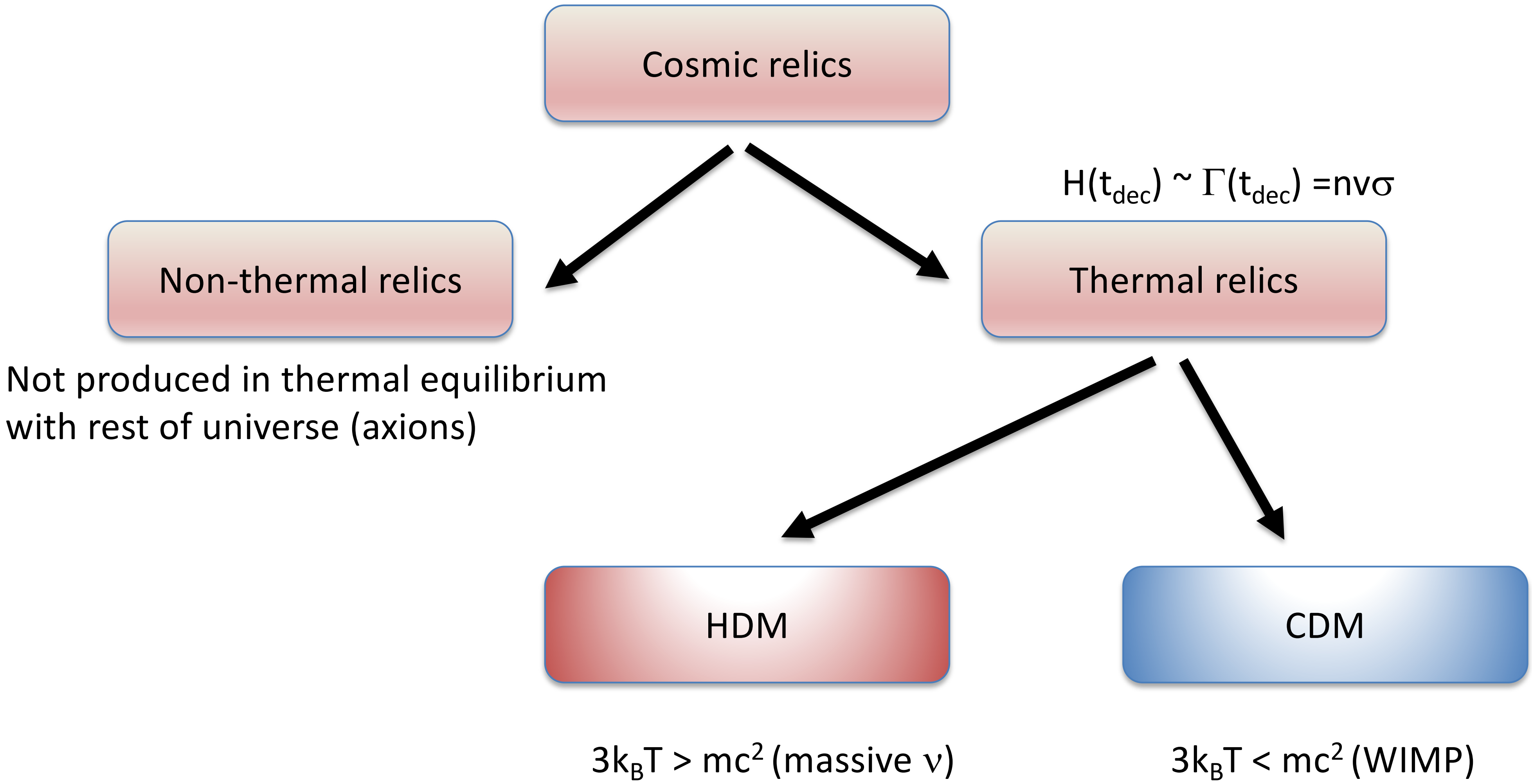
free W and Z in cosmic fluid

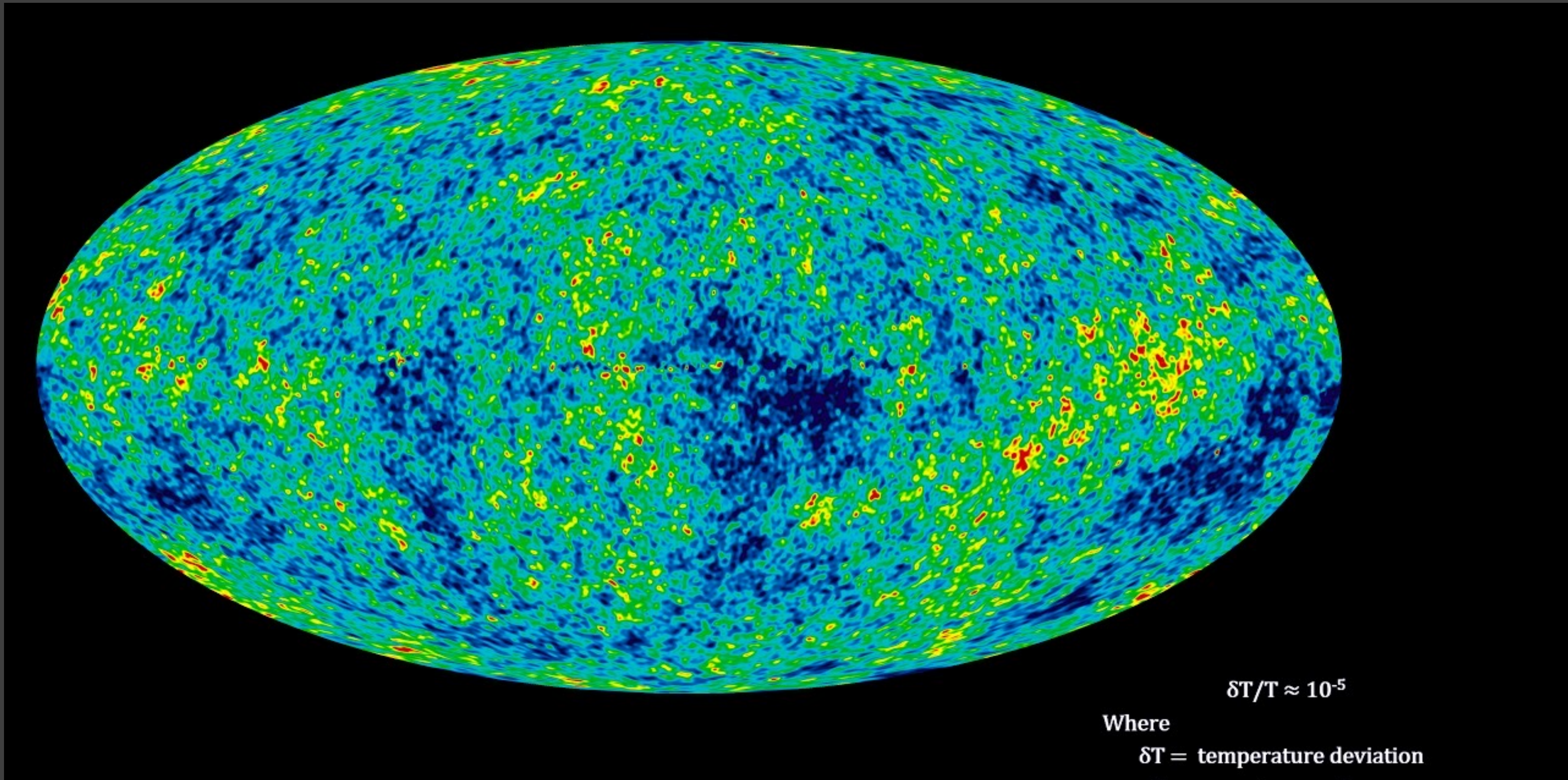
10^{-36} s, ~10^{16} GeV

Fundamental question

- What is the role of DM in the universe evolution ?

Type of DM

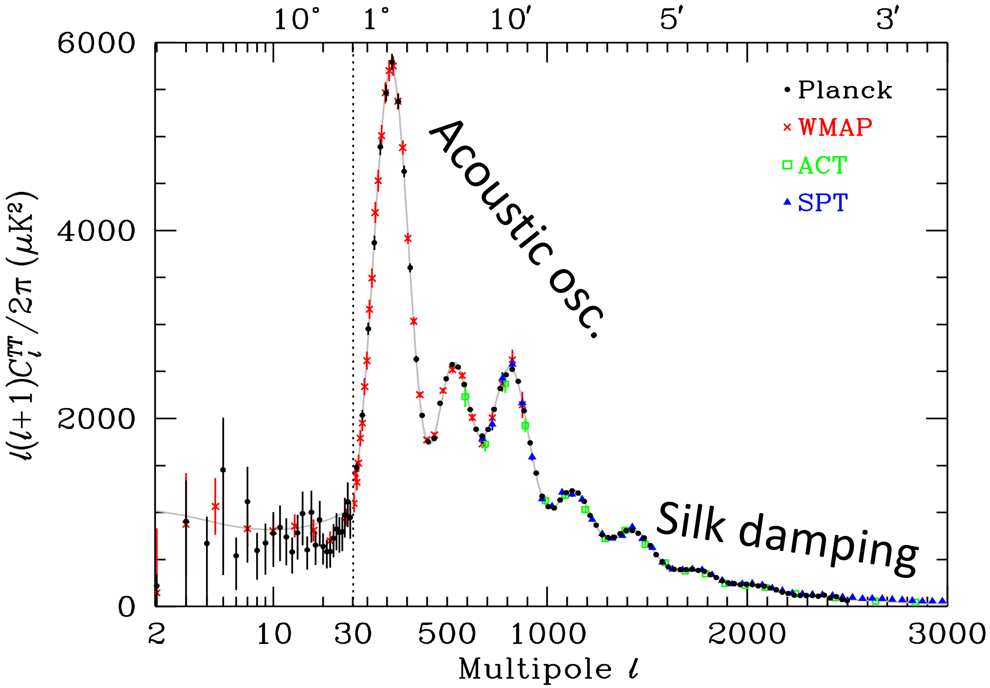

Cosmic relics
Non-thermal relics
Thermal relics
$H(t_{dec}) \sim \Gamma(t_{dec}) = nv\sigma$
Not produced in thermal equilibrium with rest of universe (axions)
HDM
CDM
$3k_BT > mc^2$ (massive ν)
$3k_BT < mc^2$ (WIMP)



CMB temperaure anysotropies

- Snapshot of the universe at rad. decoupling: p+e→H+γ
- $\frac{\Delta\rho}{\rho} = \frac{4\Delta T}{T}$ density fluctuations in CMB matches fluctuations in matter before recombination

Cosmology parameters from CMB anysotropies



- $C(\theta) = \left\langle \frac{\Delta T(\vec{n})}{T} \; \frac{\Delta T(\vec{m})}{T} \right\rangle = \sum_l (2l+1) C_l \frac{P_l(\cos\theta)}{4\pi} \quad with\ \ \vec{n}\cdot\vec{m} = \cos\theta$

- Structure of C_l is very sensitive to cosmology parameters

$\Omega = \Omega_r + \Omega_m + \Omega_\lambda + \Omega_k \sim 1$ (location of 1st acoustic peak, k ~ 0)

$\Omega_r \sim 5\text{x}10^{-5}$
$\Omega_b \sim 0.04$ (ratio 1st to 2nd acoustic peak)
$\Omega_r \sim 0.26$ (also from BBN) (ratio 2nd to 3rd acoustic peak)
$\Omega_\lambda \sim 0.7$
$\Omega_k \sim 0$

Density fluctuations in early universe

- Introduce a *density contrast*: $\delta = \Delta\rho/\rho$
- Today $\delta(0) \gtrsim 1$
- At radiation decoupling: $\delta \sim 10^{-5}$
  - $z_{dec} \sim 10^3$ and $t_{dec} \sim 3x10^5$ yr
- In a matter-dominated expanding universe
  - $\delta(t) = -\frac{3\Delta R}{R} \propto R(t) \propto 1/(1+z)$
- $\delta(0) \sim (1 + z_{dec})\, \delta(t_{dec}) \sim 10^{-2}$
- Observed fluctuations in CMB are too small to account for present structures distribution with only baryons

DM comes to the rescue

- Assume there is non-baryonic matter in the universe with $\Omega_m \sim 0.26$
- $\frac{\Omega_m(t)}{\Omega_r(t)} = \frac{\Omega_m(0)(1+z)^3}{\Omega_r(0)(1+z)^4} \approx 1$
- $\frac{0.26}{5 \cdot 10^{-5}(1+z)} \approx 1 \implies z \sim 5000$
- DM dominates on radiation earlier than baryons and will not interact with radiation
  - DM has more time and it is more efficient to achieve gravitational collapse for structures to grow
  - Baryons density contrast follows that of DM

Growth of structures

- Perturbation theory predicts that density fluctuations can produce growth, decay or oscillations in cosmic fluid

- In cosmic fluid baryon fluctuations can survive to recombination epoch (acoustic oscillations) if $M_b > 10^{13}\ M_\odot$
  - Proposed problem

- Fluctuation amplitude is reduced by photon diffusion (baryons) or by «hot DM» free-streaming damping
  - Hot DM affects fluctuations on large scales containing superclusters size mass
  - It prefers top-down structures formation
  - Observations (> 1 Mpc) agree better with bottom-up scenario, cold DM

Issues for further considerations: fluctuation amplitude damping

- For only baryonic matter
  - Silk damping will erase all fluctuations at small scale: survives only those with $M_b > 10^{13}\ M_\odot$
    - This will behave as acoustic waves ($d < \lambda_J$)
  - Top-down structure formation by fragmentation
  - Fragmentation to evolve requires $\Delta\rho/\rho \sim 10^{-3}$ at recombination
  - Not enough time to reach $\Delta\rho/\rho \sim 1$ today
- Collisionless DM
  - CDM has small velocity dispersion, zero pressure fluid
  - HDM or WDM non-small dispersion velocity, free-streaming damping
- Free-streaming damping
  - $t_{dispersion} = d/\sigma_v$ with d is the size of fluctuation, σ_v the velocity dispersion
  - Hubble time: $t_H = 1/H = \sqrt{3/8\pi G\rho}$
  - If $d < \lambda_J = \sigma_v\sqrt{\pi/G\rho}$, $t_{dispersion} \lesssim t_H$
    - dispersion in random direction for non-zero velocity dispersion produces amplitude damping

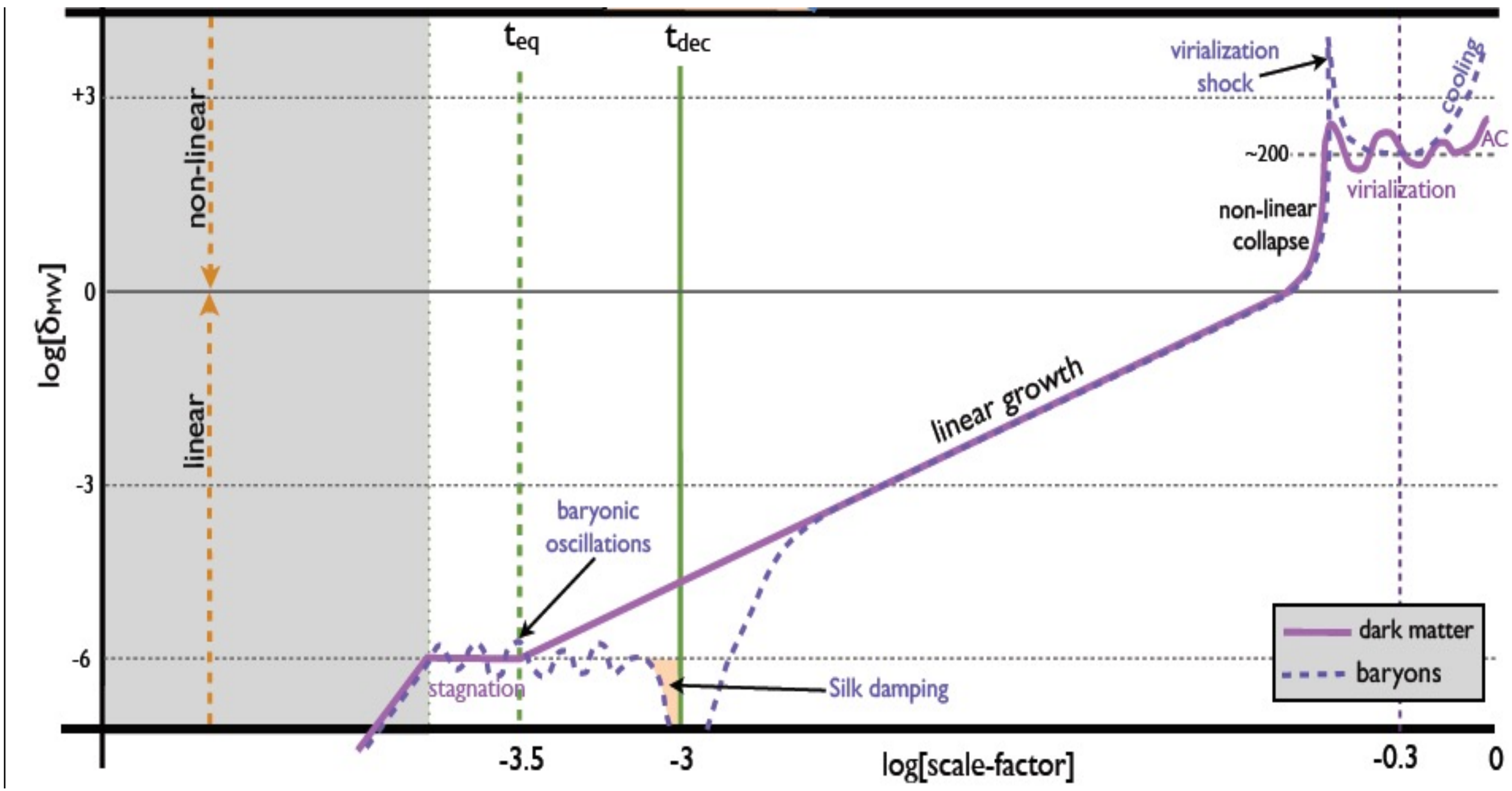
Issues for further considerations: CDM

- Characteristic time for CDM growth: free-fall time
  - $t_{FF} \propto {}^{1}/_{\sqrt{G\rho_m}}$
- Characteristic time for expansion: Hubble time
  - Hubble time: $t_H = 1/H = \sqrt{{}^{3}/_{8\pi G\rho}}$
- This implies
  - ${}^{t_H}/_{t_{FF}} \propto \sqrt{{}^{\rho_m}/_{\rho_r}} < 1$ in rad. dominated era (suppression of growth)

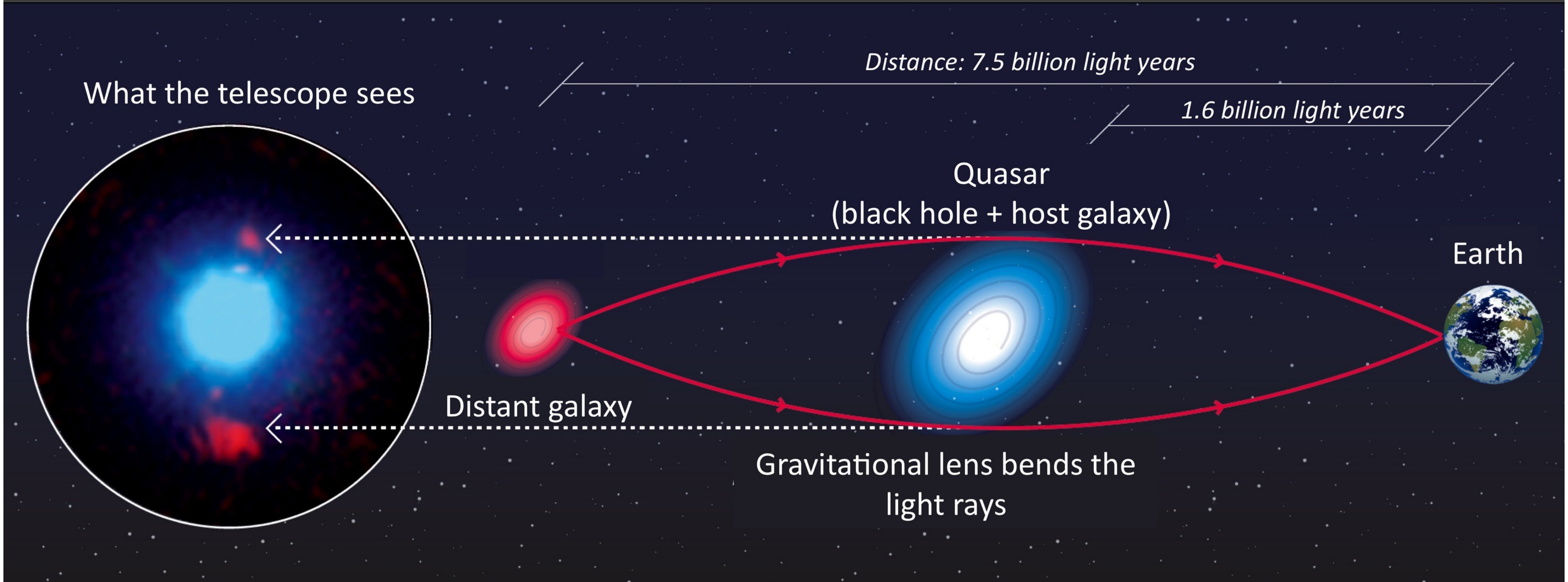
  - ${}^{t_H}/_{t_{FF}} \propto \sqrt{{}^{\rho_m}/_{\rho_r}} > 1$ in mat. dominated era

Lesson from CMB

- There should be DM in the universe to justify today density contrast
- DM dominates on baryonic matter
- DM is predominantly cold
- Structures we observe today are due to DM effect in the evolution of universe

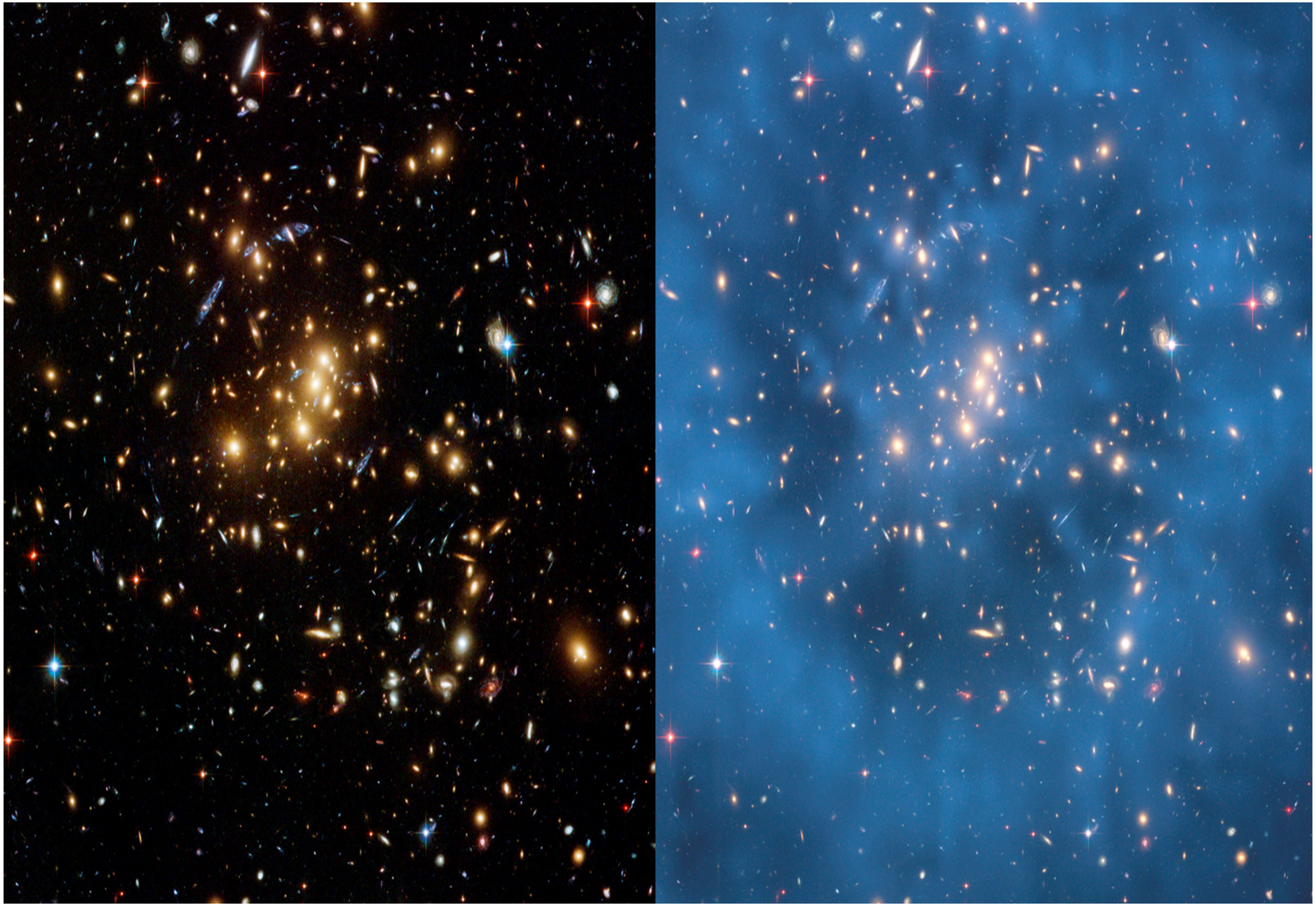


t_eq
t_dec
virialization
shock
cooling
+3
~200
AC
virialization
non-linear
collapse
non-linear
0
log[δ_MW]
linear
linear growth
-3
baryonic
oscillations
-6
stagnation
Silk damping
dark matter
baryons
-3.5
-3
log[scale-factor]
-0.3
0



Gravitational lensing

DM distribution



The bullet cluster

- Observed collision between two clusters

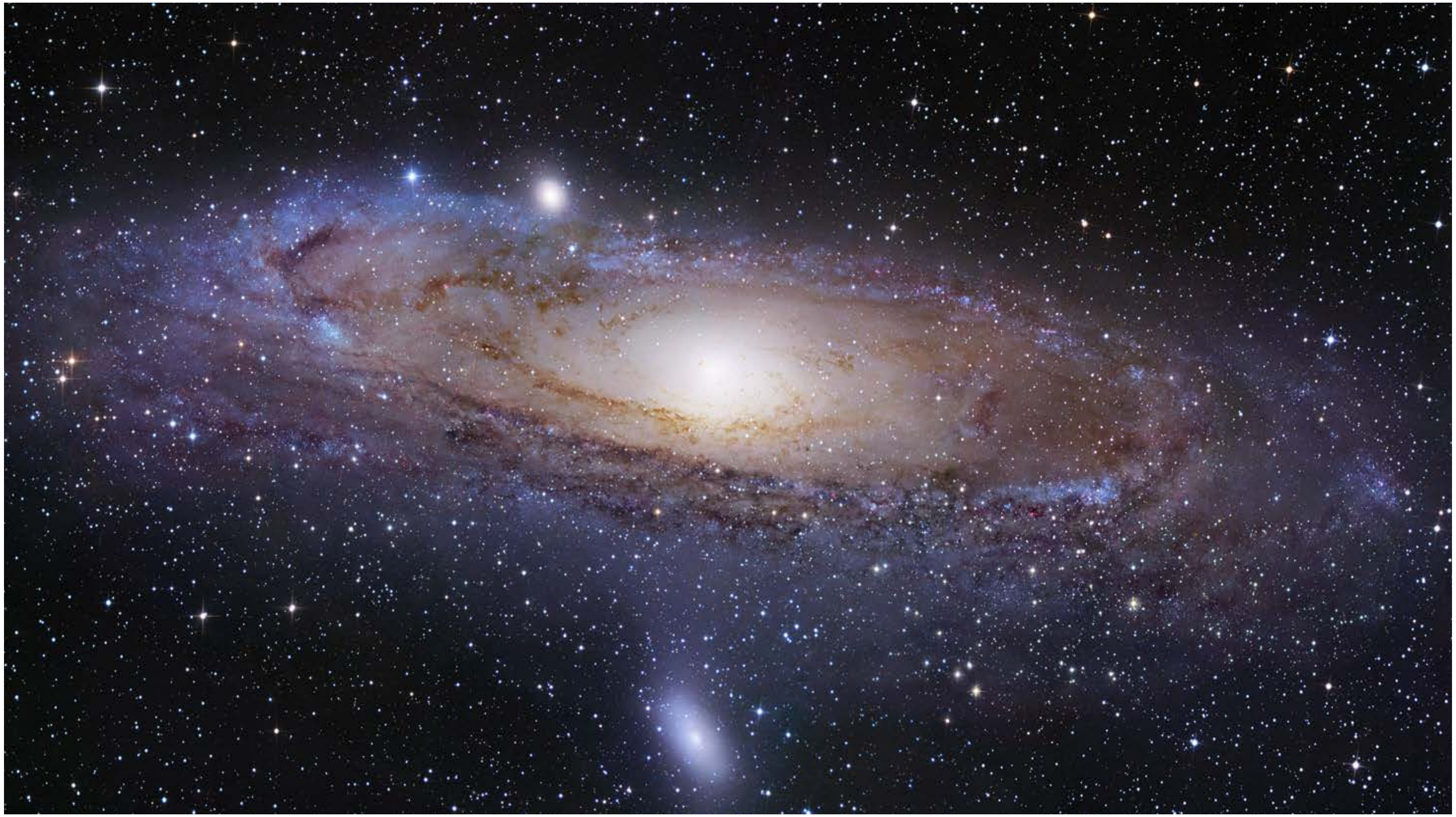
- Gas gravitationally trapped in clusters have ~10 keV temperature
  - X-ray spectrum provides gas distribution

- Gravitational lensing provide DM distribution

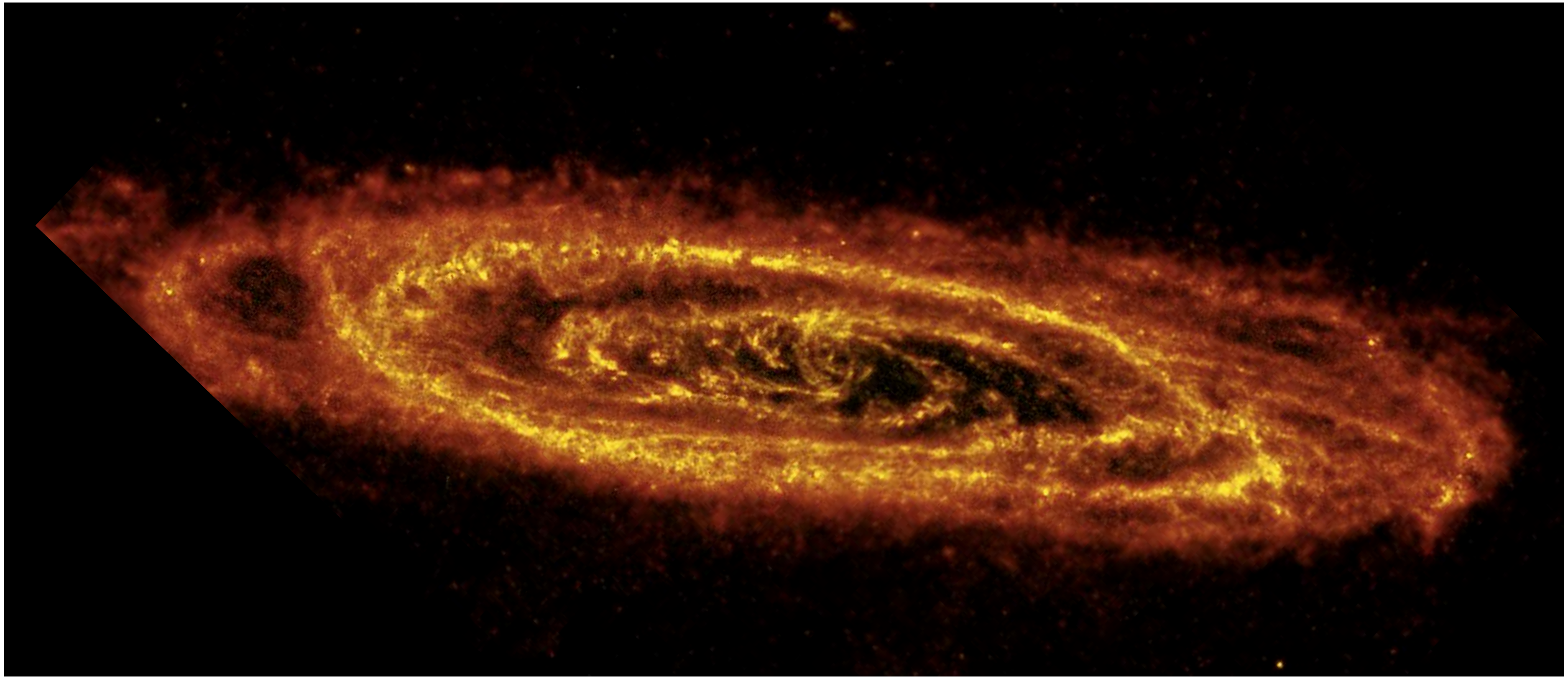
Cosmic collisions

Cosmic collisions

Andromeda galaxy in visible band



Andromeda galaxy in infrared band



Lesson from Bullet Cluster

- Determine profile of baryons from X-ray emission
  - Thermal velocity of protons ~ $(kT/m_p)^{1/2}$ ~ $v_{galaxies}$ ~ $(GM/R)^{1/2}$, implies kT ~ 10 keV
- Determine DM profile from gravitational lensing
- Compare observed distributions with simulations assuming DM self-interaction
- Result: **$\sigma/m \lesssim 1\ cm^2/g$**

Lesson from Bullet Cluster

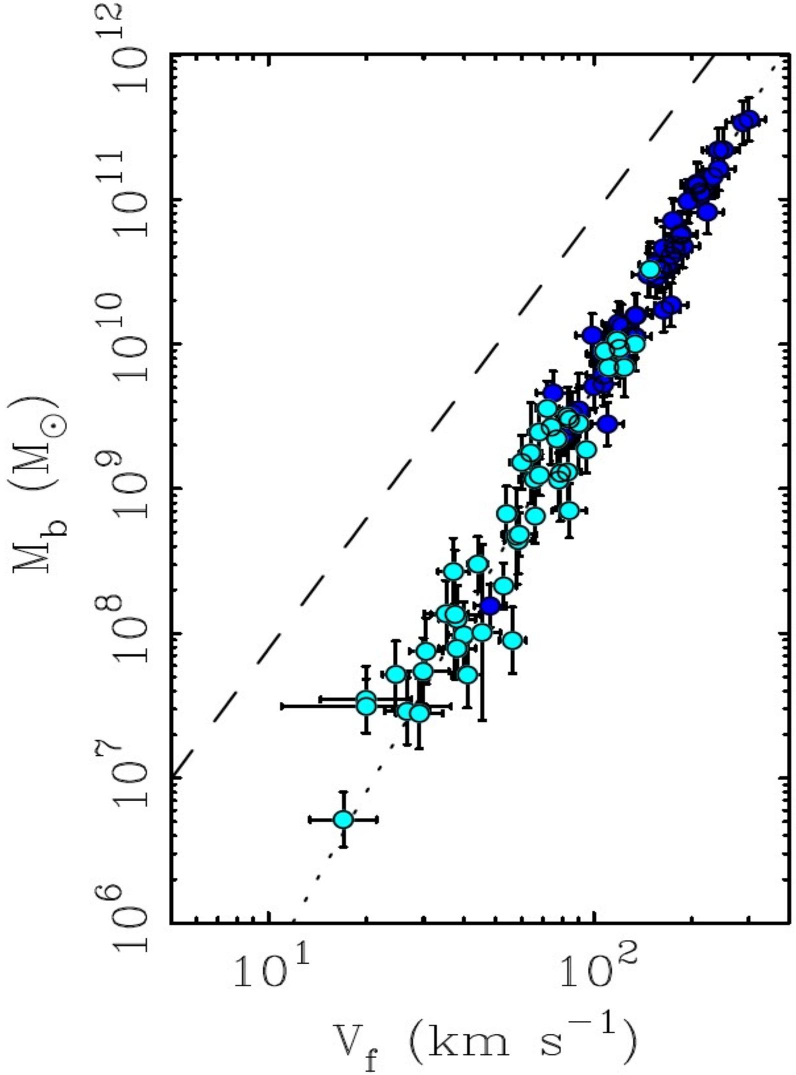
- Consider a cluster of galaxies (1 Mpc, 10^{15} $M_{\odot}$)
- Consider a DM with ρ ~ 1 GeV/cm^3 ~ 1.78x10^{-24} g/cm^3
- For σ/m ~ 1 cm^2/g, the mean free path is order of 1 Mpc
  - $\lambda = 1/n\sigma = m/\rho\sigma$
    - Proposed problem

- Consider a DM particle mass of 1 GeV/c^2
- It turns out that σ ~ 2x10^{-24} cm^2
- If $\sigma \sim G_F^2\, m^2$ ~ 10^{-10} GeV^{-2} = 4x10^{-38} cm^2

Small scale challenges to CDM paradigm

- From observations at scale < 1Mpc follows:
  - The missing satellites problem
    - Simulations of DM haloes at MW scale predicts order of 10^5 subhaloes with $M>10^7 M_\odot$
    - Order of 100 with $M \sim 300 M_\odot$ are observed
  - The cusp-core problem
    - Simulations predicts $\rho(r \sim 0) \sim r^{-1}$
    - Observation shows $\rho(r \sim 0) \sim$ constant
    - Simulations predicts more DM at the core than observed
  - The too-big-to-fail problem
    - Local universe contains fewer galaxies with core density of order $10^7 M_\odot$ wrt simulations
    - Predicted large DM haloes could have not failed to form stars, why not so many stars?
- A possible solution is given by Self-Interacting DM with $\sigma/m < 10\ cm^2/g$
  - To comply with Bullet cluster constraint this requires $\boldsymbol{\sigma \sim 1/v}$

Baryonic Tully-Fisher relation



Star dominated galaxies

Gas dominated galaxies

- - - - standard cosmology prediction

Observation: $M_b \propto v^4$

Tully-Fisher relation and MOND

- In MOdified Newtonian Dynamics one assumes:
  - $a = \begin{cases} a_N \, , a_N \gg a_0 \\ \sqrt{a_N a_0} \, , a_N \ll a_0 \end{cases}$
  - $a_0 \sim 10^{-8}$ cm/s^2
  - incidentally it turns out that $a_0 \sim c\, H_0 /6$
- Applying MOND one finds:
  - $\frac{v^2}{r} = \sqrt{\frac{G\ M_b\, a_0}{r^2}}$
  - $M_b = \frac{v^4}{G\ a_0}$

Self-Interacting DM (SIDM)

- SIDM could mitigate anomalies at < 1Mpc scale
- $R_{scat} = \frac{\rho_\chi}{m}\,\sigma\, v_{rel} = 0.1Gy^{-1}\left(\frac{\rho_\chi}{0.1\, M_\odot pc^{-3}}\right)\left(\frac{v_{rel}}{50\ km/s}\right)\left(\frac{\sigma/m}{1\ cm^2/g}\right)$
- For Dwarf galaxies R_{scat} ~ 1 in 10 Gy for $\sigma/m = 1\ cm^2/g \sim 2\text{x}10^{-24}\ cm^2/GeV$
- Compare different scale constraints on σ/m suggests $\sigma \sim 1/v$

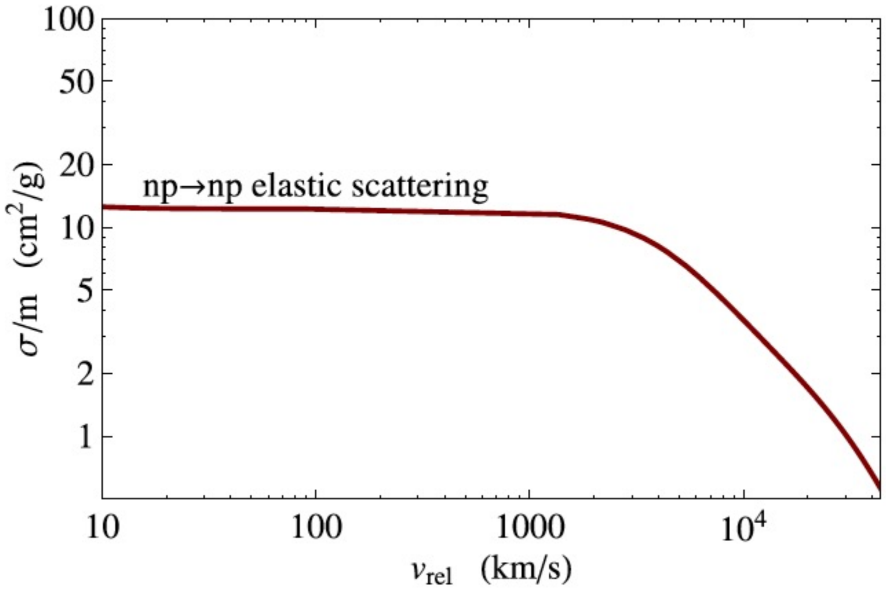
Table 1

Summary of positive observations and constraints on self-interaction cross section per DM mass. Italicized observations are based *systems*, while the rest are derived from sets of multiple systems. Limits quoted, which assume constant σ/m, may be interpreted as a fu velocity $v_{\rm rel}$ provided σ/m is not steeply velocity-dependent. References noted here are limited to those containing quoted self-inter values. Further references, including original studies of observations, are cited in the corresponding sections below.

Positive observations	σ/m	$v_{\rm rel}$	Observation
Cores in spiral galaxies (dwarf/LSB galaxies)	$\gtrsim 1\ {\rm cm}^2/{\rm g}$	30–200 km/s	Rotation curves
Too-big-to-fail problem			
Milky Way	$\gtrsim 0.6\ {\rm cm}^2/{\rm g}$	50 km/s	Stellar dispersion
Local Group	$\gtrsim 0.5\ {\rm cm}^2/{\rm g}$	50 km/s	Stellar dispersion
Cores in clusters	$\sim 0.1\ {\rm cm}^2/{\rm g}$	1500 km/s	Stellar dispersion, lensing
Abell 3827 subhalo merger	$\sim 1.5\ {\rm cm}^2/{\rm g}$	1500 km/s	DM-galaxy offset
Abell 520 cluster merger	$\sim 1\ {\rm cm}^2/{\rm g}$	2000–3000 km/s	DM-galaxy offset
Constraints			
Halo shapes/ellipticity	$\lesssim 1\ {\rm cm}^2/{\rm g}$	1300 km/s	Cluster lensing surveys
Substructure mergers	$\lesssim 2\ {\rm cm}^2/{\rm g}$	~500–4000 km/s	DM-galaxy offset
Merging clusters	$\lesssim$few ${\rm cm}^2/{\rm g}$	2000–4000 km/s	Post-merger halo survival (Scattering depth $\tau < 1$)
Bullet Cluster	$\lesssim 0.7\ {\rm cm}^2/{\rm g}$	4000 km/s	Mass-to-light ratio

A possible analogy

- Observations show a decreasing σ/m with increasing structure size



Partial summary

- DM is dominant in the universe, mainly CDM
- DM local density ~ 0.4 GeV/c^2/cm^3
- Extension of halo unknown (> 40 kpc)
- $\sigma/m \sim 1\ cm^2/g$
- $\sigma \sim 1/v$

What DM is made of ?

What DM is made of ?

- A particle confined in 10 kpc scale moving at 100 km/s:
  - De Broglie wavelength: $\lambda \leq 0.37 \left(\frac{eV}{mc^2}\right) cm$
  - $mc^2 \geq 10^{-22}$ eV
  - For a fermion: Number of states/V = $g_i\, 4\pi p^2 dp/h^3$
  - $(mc^2)^4 \geq \frac{3}{4\pi} \frac{\rho\, h^3}{g_i\, v^3} = (30\ eV)^4$
- A macroscopic object moving around
  - In order to not disrupt globular clusters:
    $< 10^3\ M_\odot \sim 10^{70}$ eV
- DM mass spread from 10^{-22} to 10^{70} eV. What is it?

Thermal decoupling

- Consider the cosmic fluid as a thermal bath at temperature T in the expanding early universe

- Particle species are in equilibrium if:
  - $\Gamma(T) = n \cdot v \cdot \sigma > H(T)$ with $n \sim R^{-3} \sim T^3$

- When $\Gamma(T) \sim H(T)$ we determine a freeze-out (FO) temperature, T_{FO}

- In early, radiation-dominated, universe:
  - $H = \sqrt{\frac{8\pi G}{3}\rho_r} \approx 2.35 \frac{T^2}{M_{Pl}}$ $with\ M_{Pl} = 1.22 \times 10^{19}\ GeV$

Asymptotic equilibrium number density

- For a thermal bath at temperature T

$$n_{eq.} \sim \begin{cases} T^3, & T \gg m \\ (mT)^{3/2} e^{-m/T}, & T \ll m \end{cases}$$

Hot relic example: neutrino decoupling

- We need to determine T_{FO} such that $\Gamma(T_{FO}) \sim H(T_{FO})$
- It turns out that: $T^3 \cdot G_F^2 \cdot T^2 \sim 2.35\, T^2/M_{Pl}$
- $T_{FO} \sim 1$ MeV
- Assuming entropy is conserved, define Y = n/s with s = entropy density and sR^3 = const and $Y \sim nR^3$
- $Y(T_{FO}) = \frac{\rho_{FO}}{m\, s_{FO}} = Y(T_0)$ for a given species
- $\frac{\rho_0}{\rho_c} = \frac{m\, n_0}{\rho_c} = \frac{m\, Y_{FO}\, s_0}{\rho_c} \propto m$
- $\frac{\rho_\nu}{\rho_c} = \frac{n_\nu\, \sum_i m_i c^2}{\rho_c} = \frac{113\ \nu/cm^3 \sum_i m_i c^2}{1.05\times10^{-5}\, h^2\ GeV/cm^3} \Rrightarrow\ \Omega_\nu h^2 \sim \frac{\sum_i m_i c^2}{93\ eV}$
  - From neutrino oscillation experiments: $m_\nu < \mathrm{eV}$

Cold relic: WIMP example

- Consider a **Weakly Interacting Massive Particle**
  - $\sigma \sim G_F^2 E^2 \sim 10^{-10} (E/GeV)^2\ GeV^{-2} \sim 4x10^{-38} (E/GeV)^2\ cm^2$
  - for comparison: $\sigma_{\overline{\nu}_e + p \longrightarrow e^+ + n} \approx 10^{-37} \left(\frac{E}{GeV}\right)^2$ cm^2
- $(mT)^{3/2} e^{-m/T}\ \sigma \sim 2.35\ \frac{T^2}{M_{Pl}}$
- Use x=m/T
- $\sqrt{x}\ e^{-x} = \frac{2.35}{m\ \sigma\ M_{Pl}} \sim 10^{-15}$
  - For m ~ 100 GeV, x ~ 35 at FO
  - For m ~ 1 GeV, x ~ 30 at FO

- $\Omega_{WIMP} = \frac{m\, n(T_0)}{\rho_c} = \frac{m\, T_0^3}{\rho_c} \frac{n(T_0)}{T_0^3} = \frac{m\, T_0^3}{\rho_c} \frac{n(T_{FO})}{T_{FO}^3}$
  - $T_0 = 2\text{x}10^{-4}$ eV
- $\Omega_{WIMP} = x_{FO} \frac{T_0^3}{\rho_c} \frac{n(T_{FO})}{T_0^2} = x_{FO} \frac{T_0^3}{\rho_c} \frac{2.35}{M_{Pl}\sigma}$
  - after using $n(T_{FO}) = 2.35 \, {}^{T_{FO}^2}/_{M_{Pl}\,\sigma}$
- $\boldsymbol{\frac{\Omega_{WIMP}}{0.3} = \frac{x_{FO}}{30} \frac{4\times10^{-9}\, GeV^{-2}}{\sigma}}$

  - $4\times10^{-9} GeV^{-2} = 1.6 \times10^{-36}$ cm^2

- Determine WIMP velocity at FO
  - $\frac{3}{2}kT = \frac{1}{2}mc^2\beta^2$
  - For $\mathrm{x} = mc^2$/kT ~ 30, v ~ 0.3c

- $\langle \sigma\, v \rangle \approx \mathbf{4} \times \mathbf{10^{-9}}\ \boldsymbol{GeV^{-2}}\ 0.3c = 1.4\times10^{-26}\ cm^3/s$

- $\sigma_{EW} \sim G_F^2 T_{FO}^2 \sim G_F^2 \left(\frac{m_{EW}}{30}\right)^2 \sim 10^{-10}$ GeV^{-4} $\left(\frac{200\ GeV}{30}\right)^2 \sim \mathbf{4}\times\mathbf{10^{-9}}\ \boldsymbol{GeV^{-2}}$

- The electroweak pair-annihilation cross section at T_{FO} gives the proper relic energy density: **WIMP miracle**!

- Is this argument peculiar to electroweak scale?

- To obtain the «right» relic density we need:
  - $\sigma \sim 10^{-8} - 10^{-9}$ GeV^{-2}
  - $x = m/T >> 1$, i.e. $m \cdot \sigma \cdot M_{Pl} >> 1$
  - From dimensional analysis: $\sigma \sim \alpha_\chi/m^2$ which needs to be of the «right» order given α_χ and m

- It turns out that with the «right» cross section one needs m > 10 meV

- On the other side σ cannot be arbitrary large ($<4\pi/m^2$):
  - $\frac{\Omega_{WIMP}}{0.3} \gtrsim 10^{-8}\, GeV^{-2}\, \frac{m^2}{4\pi} \;\; \Longrightarrow m \lesssim 120\, TeV$

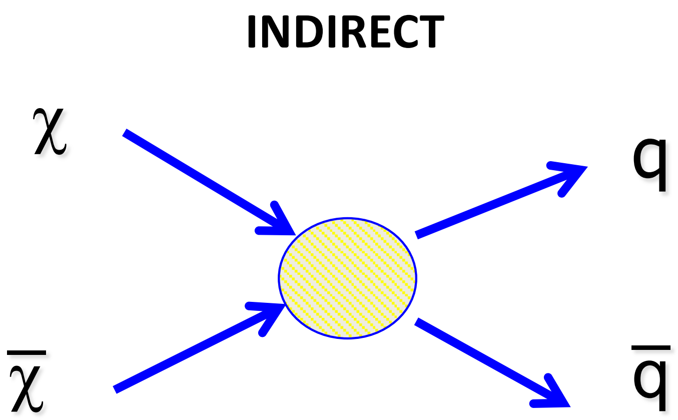
Non-thermal DM production

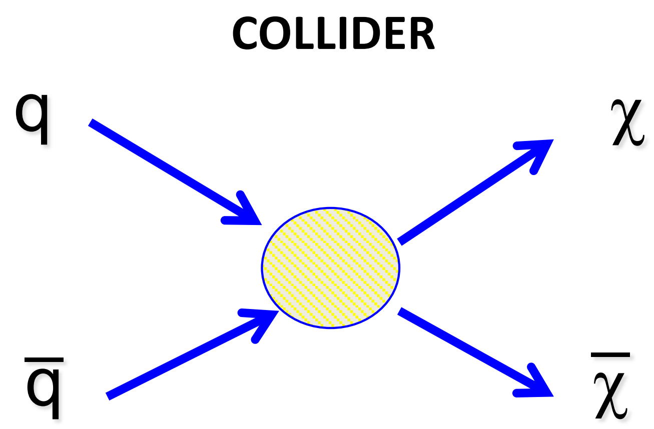
- There could be non-thermal production of DM
- A particle species ϕ with $m_\phi > m_\chi$ is produced in early universe
- ϕ decays to χ when this latter is already out of equilibrium
- $\Omega_\chi = \frac{m_\chi}{m_\phi}\, \Omega_\phi$

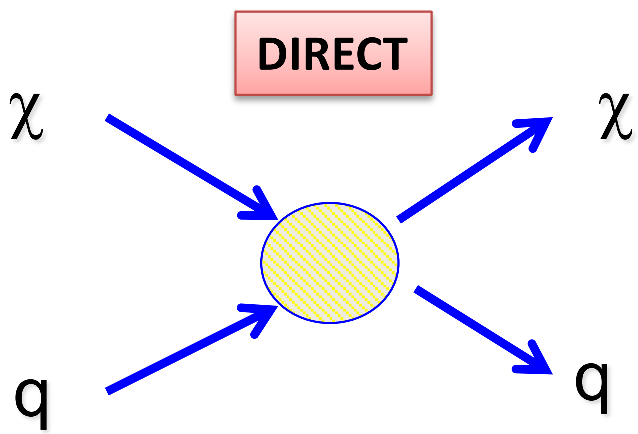
Experimental search for DM

Fundamental assumption:
DM does not only interact gravitationally

The quest for Dark Matter







χ = DM particle
q = Standard Model particle

$$\chi + (A,Z) \longrightarrow \chi' + (A,Z)^*$$

- The invariant mass:
  - $s = \left(E_\chi + E_A\right)^2 - \left(\vec{p}_\chi + \vec{p}_A\right)^2 = m_\chi^2 + m_A^2 + 2(E_\chi E_A - \vec{p}_\chi \cdot \vec{p}_A)$

- In Lab frame: $s = m_\chi^2 + m_A^2 + 2\left(T_\chi + m_\chi\right)m_A$
- $v_A \sim 10^{-3}c$
- $\left(m_\chi + m_A\right)\left(1 + \frac{m_A T}{\left(m_\chi + m_A\right)^2}\right) = m_\chi + \frac{p_{CM}^2}{2m_\chi} + m_A + \frac{p_{CM}^2}{2m_A}$
- $p_{CM}^2 = \frac{2m_\chi m_A^2 T}{\left(m_\chi + m_A\right)^2} = \mu^2 v^2$ with $\mu = {}^{m_\chi m_A}/_{(m_\chi + m_A)}$
- $E_A^{Lab} \leq \frac{(2p_{CM})^2}{2m_A} = 2\frac{\mu^2 v^2}{m_A}$
- For $m_\chi \sim m_A$ follows $E_A^{Lab} \leq \frac{Av^2}{2} \sim A\ 10^{-6}$ GeV ~ A keV

WIMPs

- Weakly Interactive Massive Particles in equilibrium with quarks and leptons in the early universe as a generic class of cold DM candidate

  for the last ~ 20 years the main scenario for DM direct detection

- Mass ~ 1 – 1000 GeV/c^2

- $<\sigma_{ann}v>$ ~ 10^{-26} cm^3s^{-1} gives the correct relic density

- Local number density ~ 10^{-1} – 10^{-4} cm^{-3}

- Flux on Earth for a 100 GeV/c^2 WIMP ~ $3x10^5$ $cm^{-2}s^{-1}$ with ρ~0.4 GeV/cm^3
  - ^{8}B solar neutrino flux $5x10^6$ cm^{-2} s^{-1}

How many WIMPs around us?

- For $\rho_\chi \sim$ 0.4 GeV/c^2·cm^3

- $n_\chi = \begin{cases} 4\times10^{-3} & m_\chi = 100\ GeV/c^2 \\ 0.4 & m_\chi = 1\ GeV/c^2 \end{cases}$

- In 1 L

- N$= \begin{cases} 4 & m_\chi = 100\ GeV/c^2 \\ 400 & m_\chi = 1\ GeV/c^2 \end{cases}$

Expected rate for WIMPs

$$R = N_t \times \sigma_{\chi A} \times \frac{\rho_\chi}{m_\chi} \times \langle \mathrm{v} \rangle$$

$$R \sim 0.2 \frac{\text{events}}{\text{kg year}} \left(\frac{100}{A} \times \frac{\sigma_{\chi A}}{10^{-38}\,\mathrm{cm}^2} \times \frac{\langle \mathrm{v} \rangle}{250\mathrm{km/s}} \times \frac{\rho_\chi}{0.4\mathrm{GeV/cm}^3} \times \frac{100\mathrm{GeV/c}^2}{m_\chi} \right)$$

Exposure = 1 ton x year

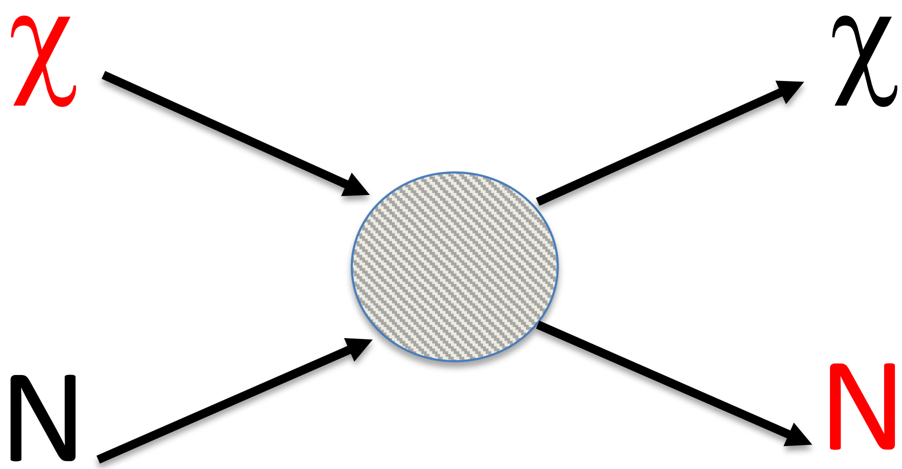
Events ~ 200, equivalent to ~**$6\text{x}10^{-3}$ μBq/kg**

1 μBq/kg of radon gives ~ 31500 decays

Need reduction factor > 200 for such a low background level!!!

Direct Search for WIMPs: nuclear recoil tagging

Goodman and Witten, PRD31, 1985



$$E_{recoil} = \frac{m_N M_\chi^2}{\left(m_N + M_\chi\right)^2} v^2 (1-\cos\theta^*)$$

$$v \sim 300 \text{ km/s} \quad \beta \sim 10^{-3}$$

$$\boxed{E_{recoil} \sim 1-100 \text{ keV}}$$

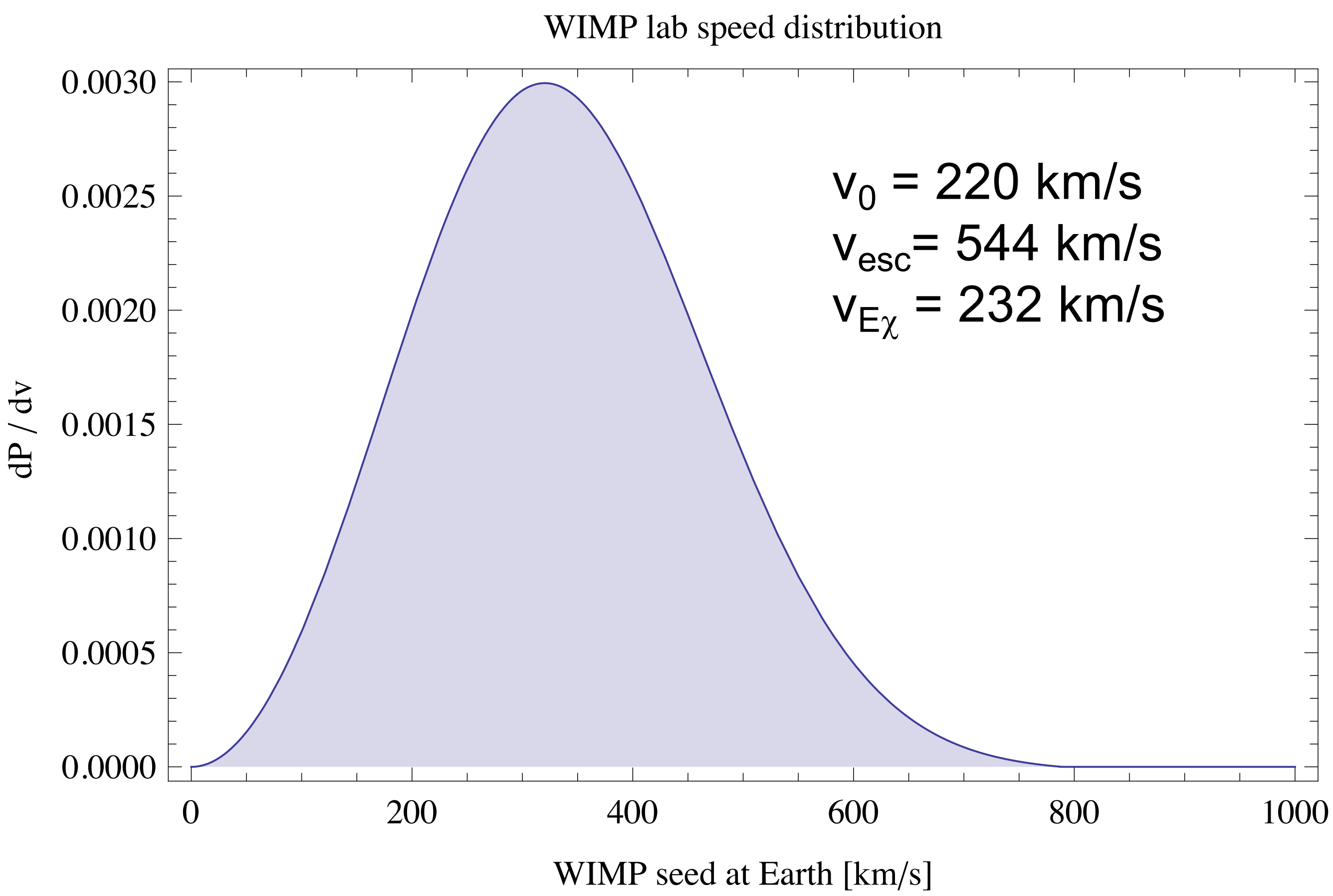
$$\boxed{\frac{\lambda}{2\pi} = \frac{h}{p} = \frac{\hbar c}{mc^2 \beta} \approx \frac{197 \cdot 10^{-13} \text{MeVcm}}{100\text{GeV } 10^{-3}} \approx 2 \cdot 10^{-13} cm}$$

$$\frac{dR}{dE} = N_t \frac{\rho_\chi}{m_\chi} \frac{m_N}{\mu_n^2} A^2 \sigma_{\chi n} F^2(E) \int_{v \geq v_{\min}(E)} d^3 v \frac{f(v)}{v}$$

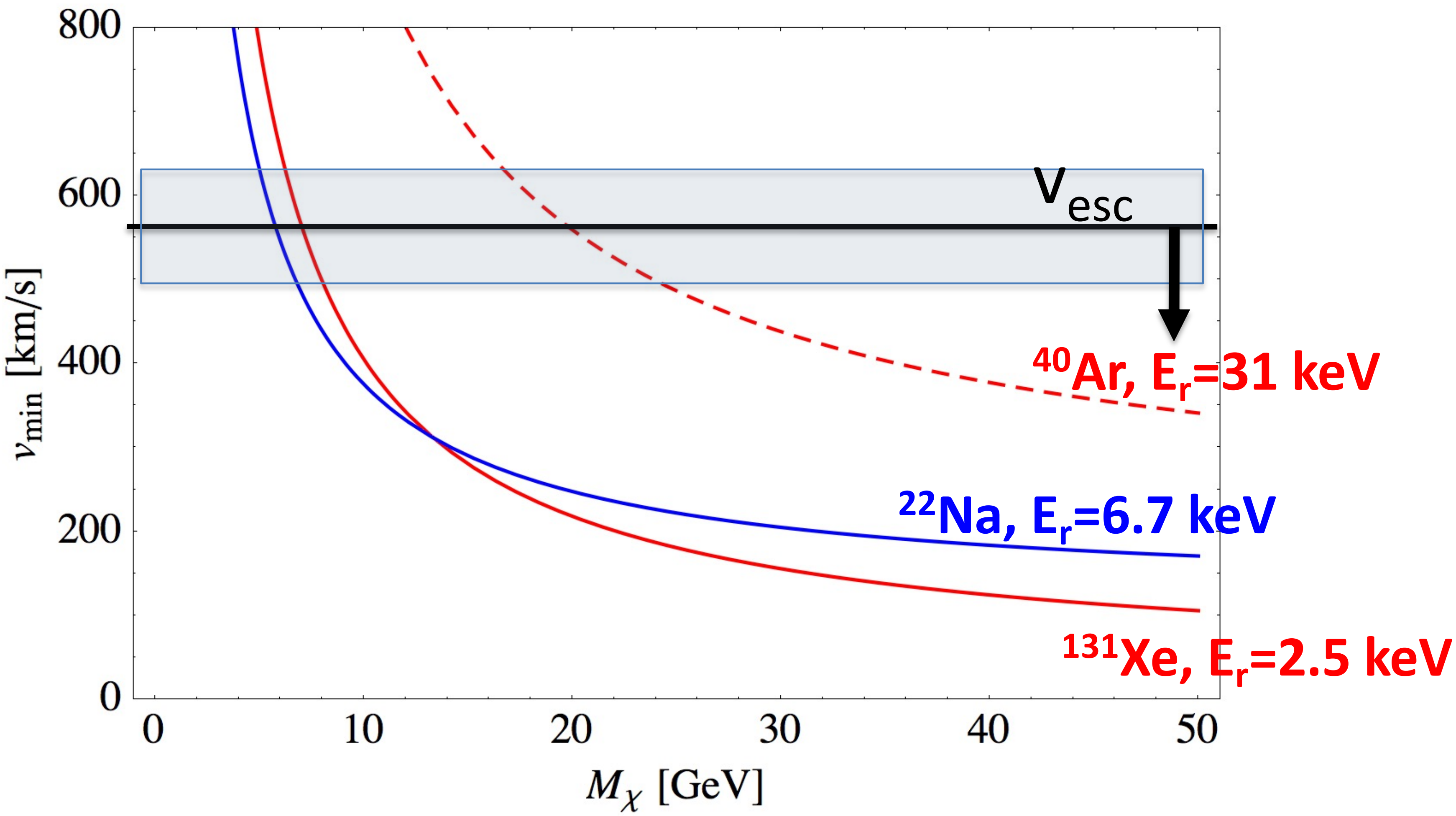
$$f(v) = \begin{cases} \frac{1}{N} e^{-\left(\frac{\left|v_\chi + v_{sun} + v_{Earth}\right|}{v_0}\right)^2}, & \left|v_\chi + v_{sun} + v_{Earth}\right| < v_{esc} \\ 0, & \text{elsewhere} \end{cases}$$

- 170 km/s < v_0 < 270 km/s
- 450 km/s < v_{esc} < 650 km/s
- ρ_χ ~ 0.4 Gev/cm^3
- F(E) = nuclear form factor
- f(v) = velocity distribution of WIMPs in the galaxy

Velocity Distribution



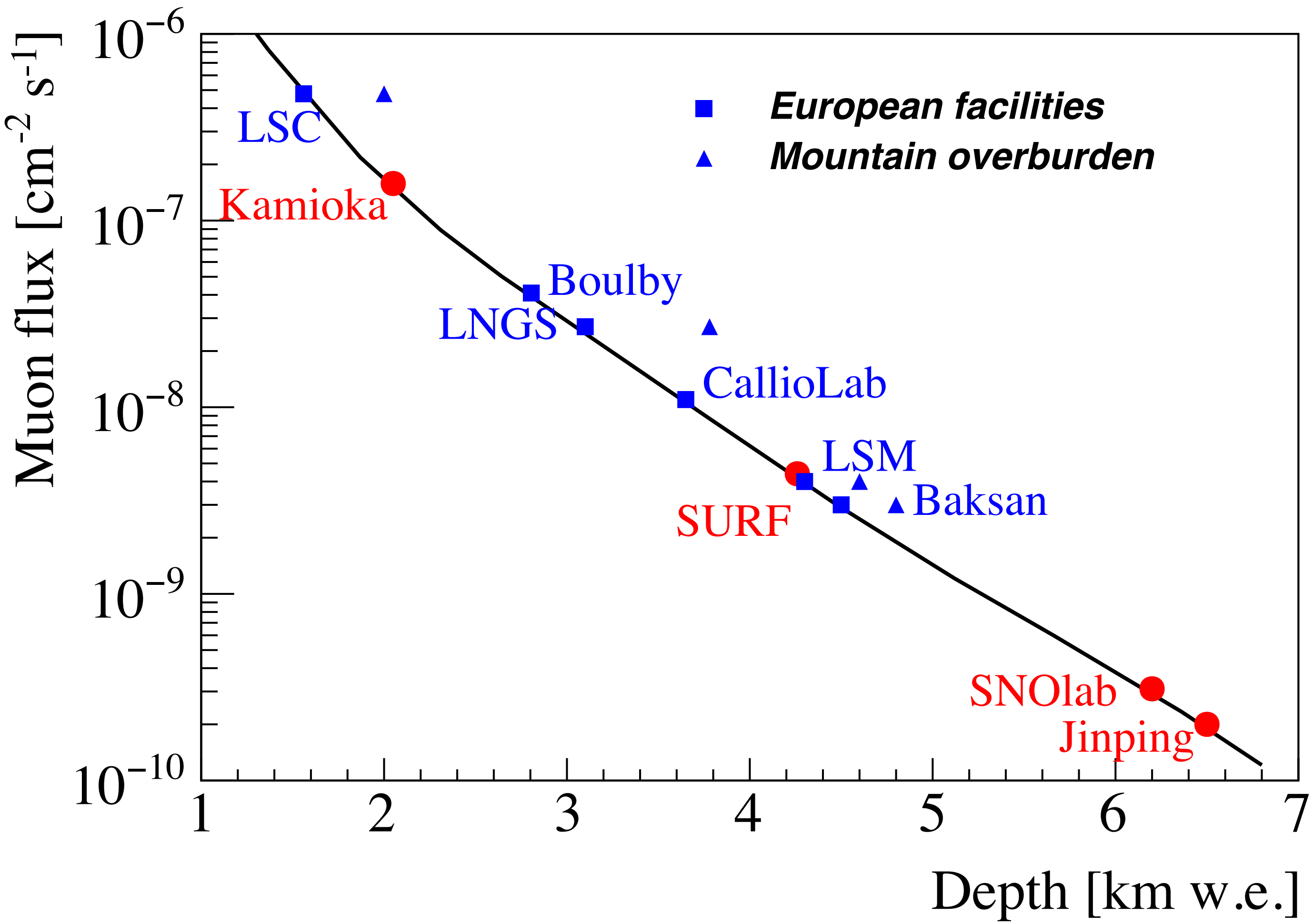
V_{min} (E_r, M_χ, A)



Recoil detection: a matter of background

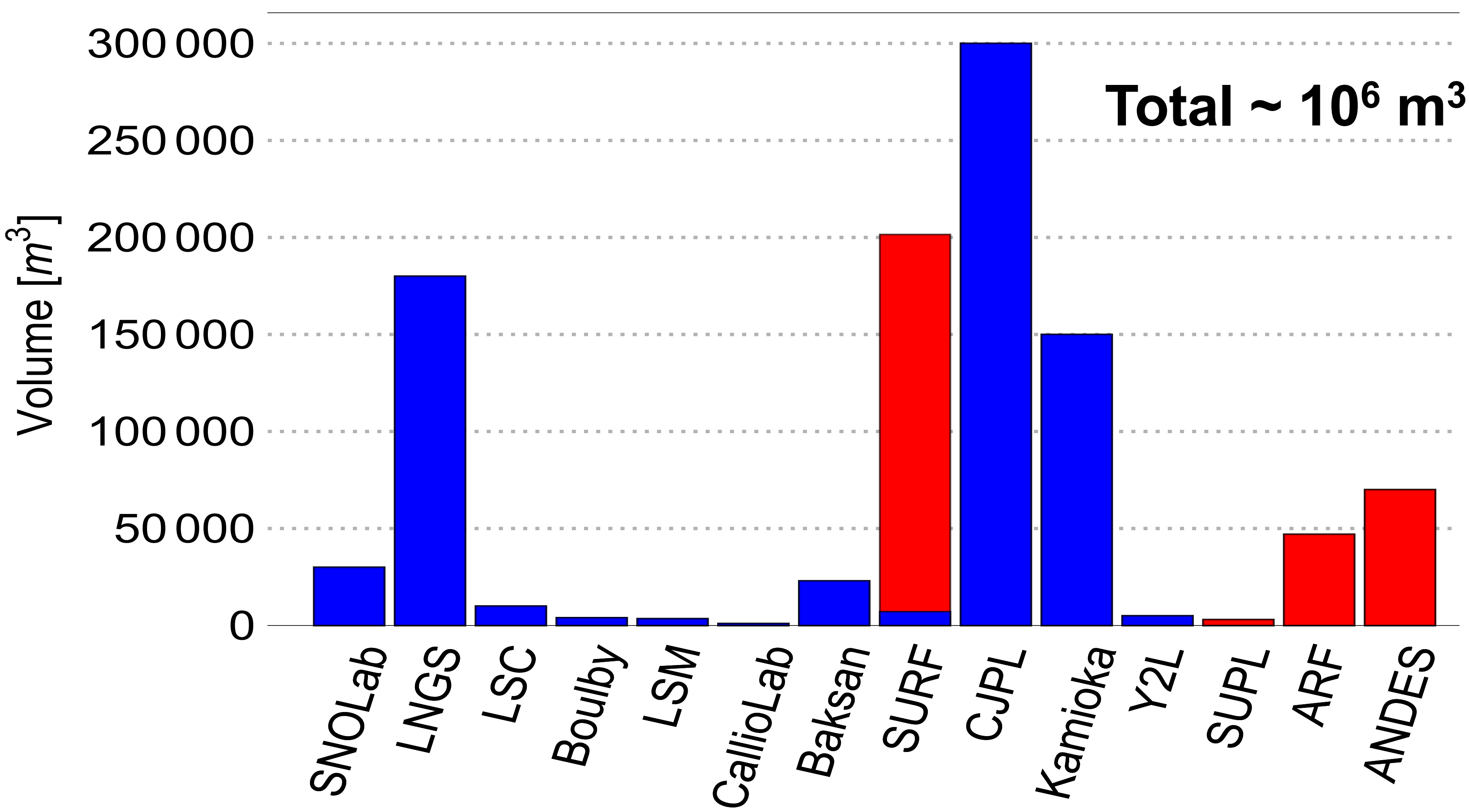
- 1ppt ^{238}U ~ 10 μBq/kg
- 1ppt ^{232}Th ~ 4 μBq/kg
- WIMP signal ~ 10^{-2} μBq/kg
- Need strong background rejection techniques

What is a Deep Underground Lab (DUL) ?

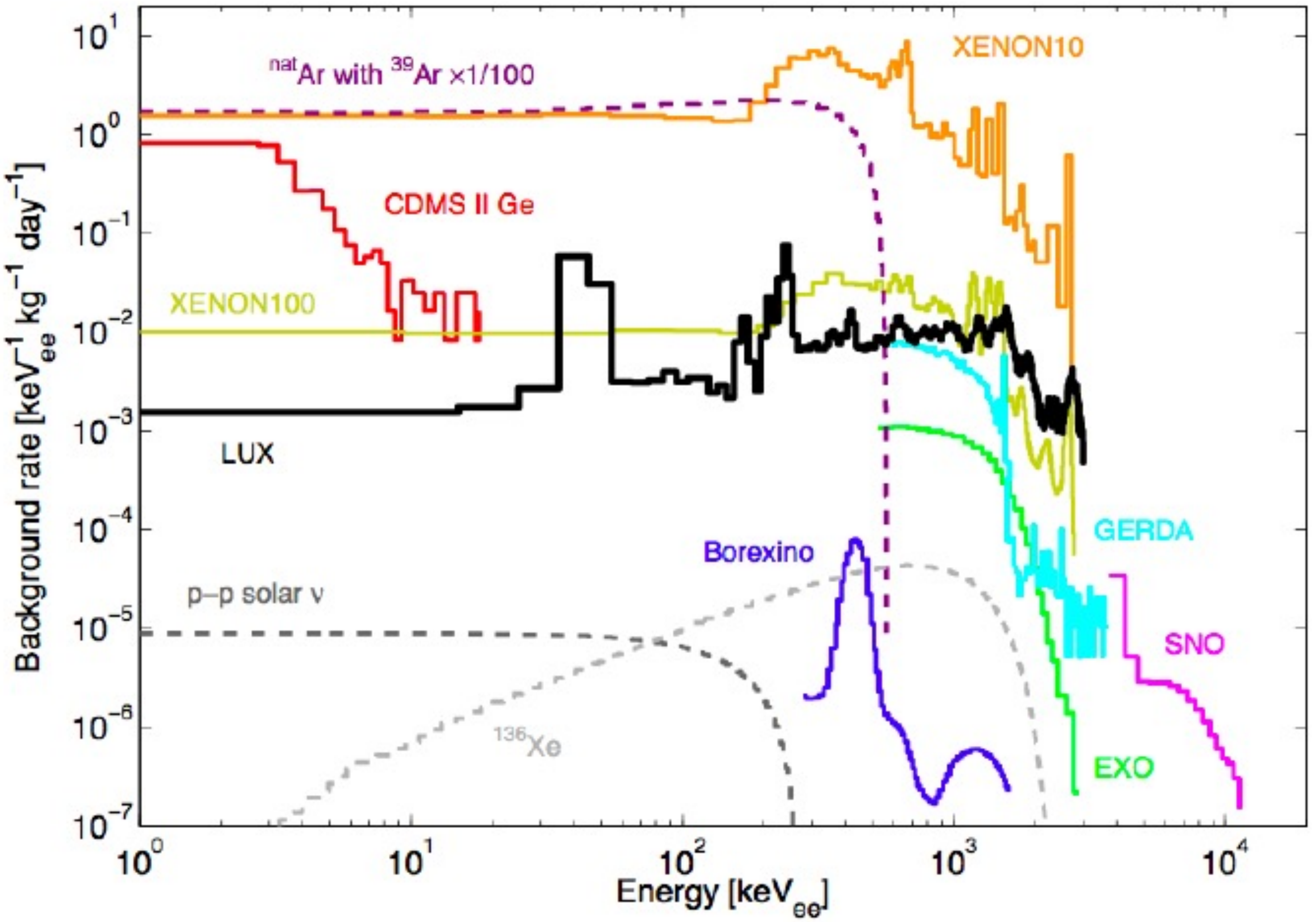


World map of DULs

Excavated volume in DULs



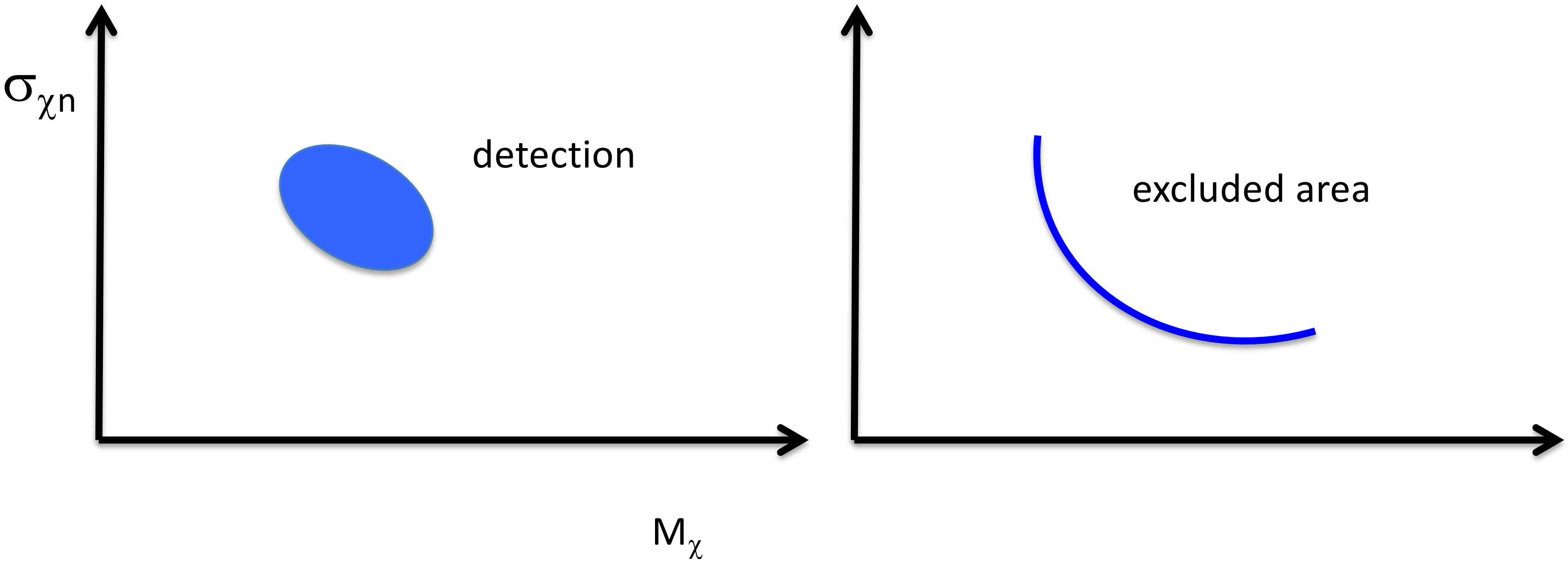
Background in DM, double beta decay and solar neutrino experiments



Plot by R. Geitskell at DM2014

What can we learn from DM Direct Search?

$$\frac{dR}{dE} = N_t \frac{\rho_\chi}{\boxed{m_\chi}} \frac{m_N}{\mu_n^2} A^2 \boxed{\sigma_{\chi n}} F^2(E) \int_{v \geq v_{\min}(E)}^{v_{esc}} d^3v \frac{f(v)}{v}$$



“Standard” WIMP cross-section

Spin Independent interaction: $$\sigma^{SI}(E_r) = \sigma_p^{SI}\left[Z + (A - Z))\frac{f_n}{f_p}\right]^2 \left(\frac{\mu}{\mu_p}\right)^2 F_{SI}^2(E_r)$$

with F(0) ~ 1. So for the “standard” case $f_p = f_n$, $\boldsymbol{\sigma^{SI} \sim A^2}$

Spin Dependent interaction: $$\sigma^{SD}(E_r) = \sigma_p^{SD}\frac{4}{3}\frac{J+1}{J}\left(\langle S_p\rangle + \langle S_n\rangle\frac{f_n}{f_p}\right)^2 \left(\frac{\mu}{\mu_p}\right)^2 F_{SD}^2(E_r)$$

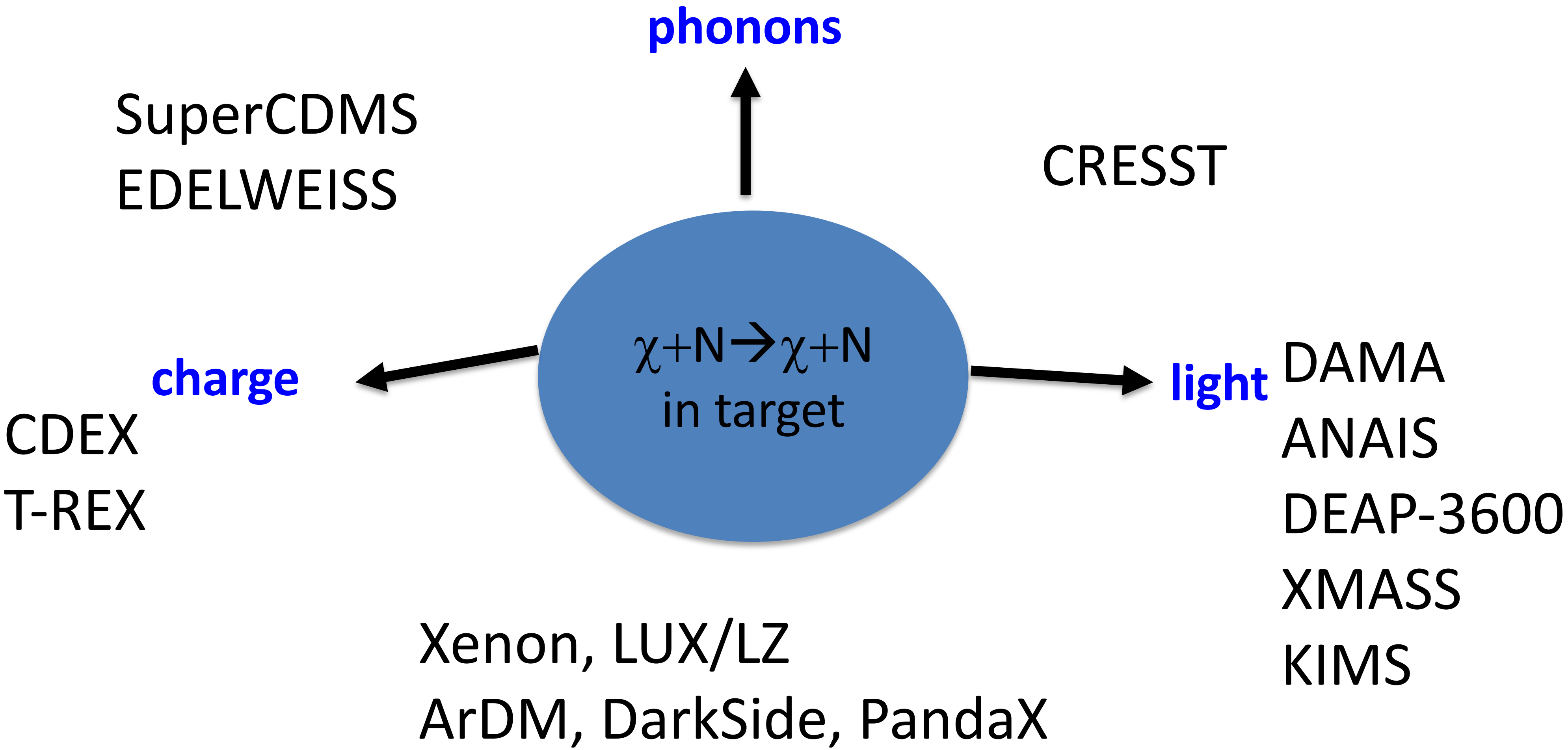
$\boldsymbol{\sigma^{SI}/\sigma^{SD} \sim A^2}$

Deviations from the “standard” scenario are considered:
Isospin Violating Interactions
    f_n/f_p ~ -0.7 reduces the coupling with Xe target (Z,N) = (54, 77)
Electromagnetic coupling
    …
Important to use different target detectors

Different target: comparison

- Both SI and SD can contribute at the same time
- Xenon:
  - (Z,N) = (54,78) BR = 26.9% $J^{\pi} = 0^{+}$ p/n = 0.69
  - (Z,N) = (54,75) BR = 26.4% $J^{\pi} = 1/2^{+}$ p/n = 0.72
  - (Z,N) = (54,80) BR = 10.4% $J^{\pi} = 0^{+}$ p/n = 0.68
- Argon:
  - (Z,N) = (18,22) BR = 99.6% $J^{\pi} = 0^{+}$ p/n = 0.82
- Na:
  - (Z,N) = (11,12) BR = 100% $J^{\pi} = 3/2^{+}$ p/n = 0.92
- I:
  - (Z,N) = (53,74) BR = 100% $J^{\pi} = 5/2^{+}$ p/n = 0.72

WIMPs Detection Methods



Technologies

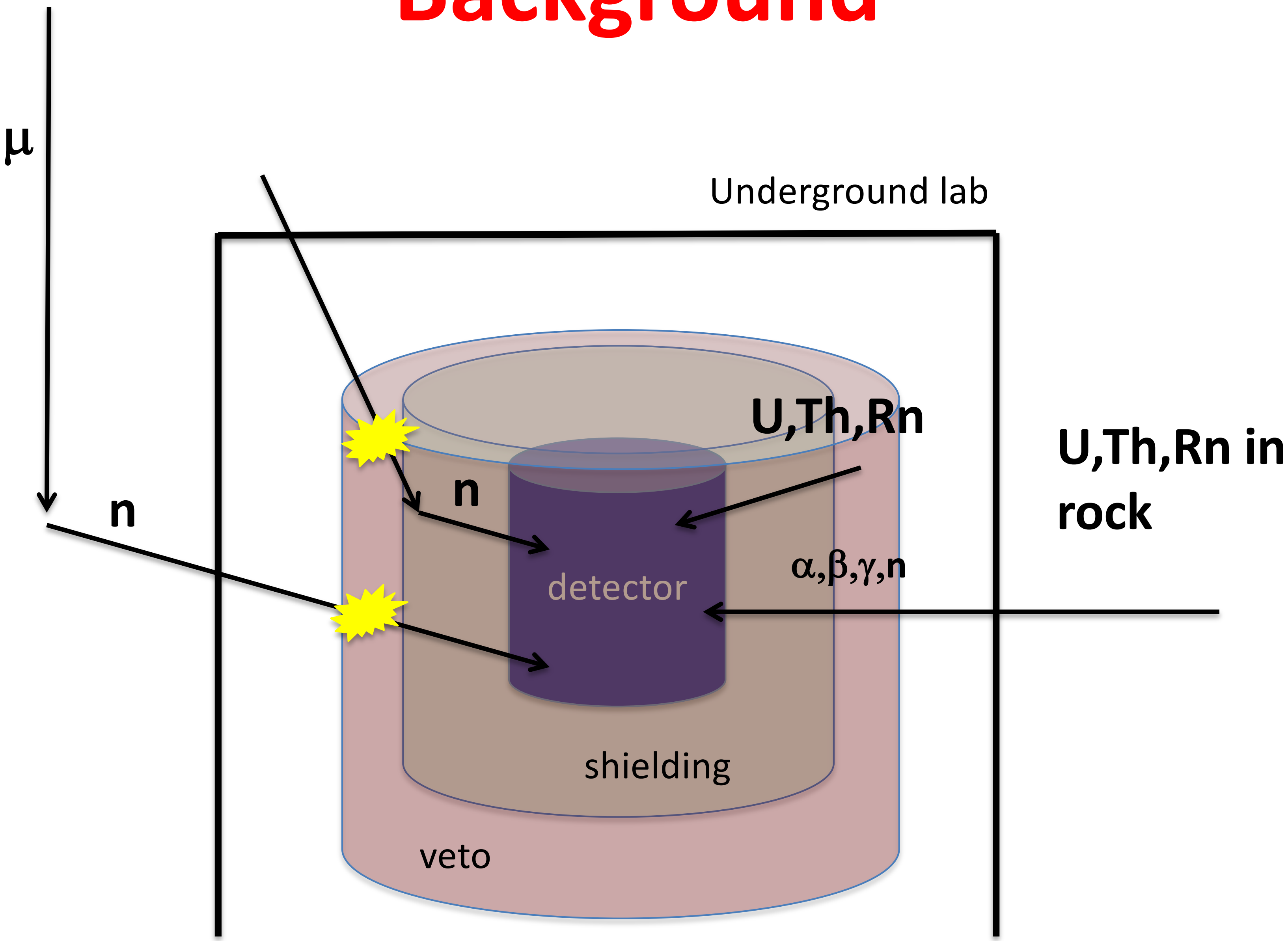
- **Cryogenic solid state**
  - Ionization spectrometer + bolometer operated at < 100mK
  - SuperCDMS(Si and Ge); CRESST(Ca); EDELWEISS(Ge)
- **Two-phase TPC with LXe** (XENON,LUX/LZ,PandaX) **or LAr** (DarkSide, ArDM, DEAP)
  - Scintillation + ionization
- **Scintillator crystal detectors**
  - DAMA/LIBRA – ANAIS - COSINE (NaI), CoGeNT (Ge),CDEX(Ge), KIMS(CsI), XMASS(LXe), DEAP(LAr)
- **Spherical gas TPC and SuperHeated detectors**

WIMPs signal and background

- **Signal**
  - Low energy nuclear recoils (1 – 100 keV)
  - Low rate (~ few counts/year/ton at 10^{-47} cm^2 SI and 100 GeV/c^2)
  - No specific features in recoil spectrum

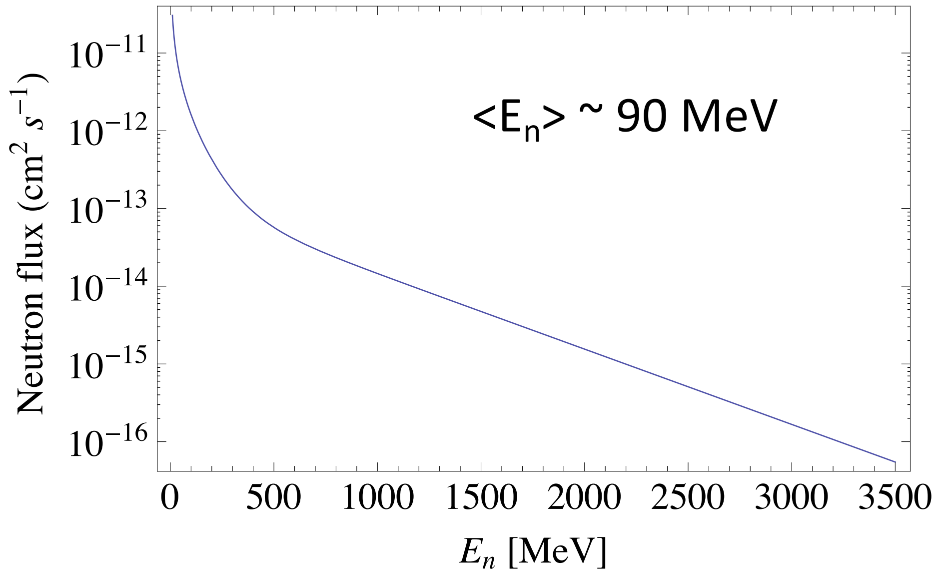
- **Background**
  - Electron Recoils (**ER**) from e, γ radioactivity
    - ✓ can be rejected by a number of discrimination cuts
  - Nuclear Recoils (**NR**) from **radiogenic and cosmogenic neutrons**
  - **Solar/Atmospheric/Relic Supernova neutrinos**:
    - ✓ Elastic Scattering interactions will limit the sensitivity depending on the ER rejection power of the experiment
    - ✓ Neutrino-nucleus coherent interactions set the limiting sensitivity

Background


μ
Underground lab
U,Th,Rn
U,Th,Rn in rock
n
n
detector
α,β,γ,n
shielding
veto

Cosmogenic Neutrons

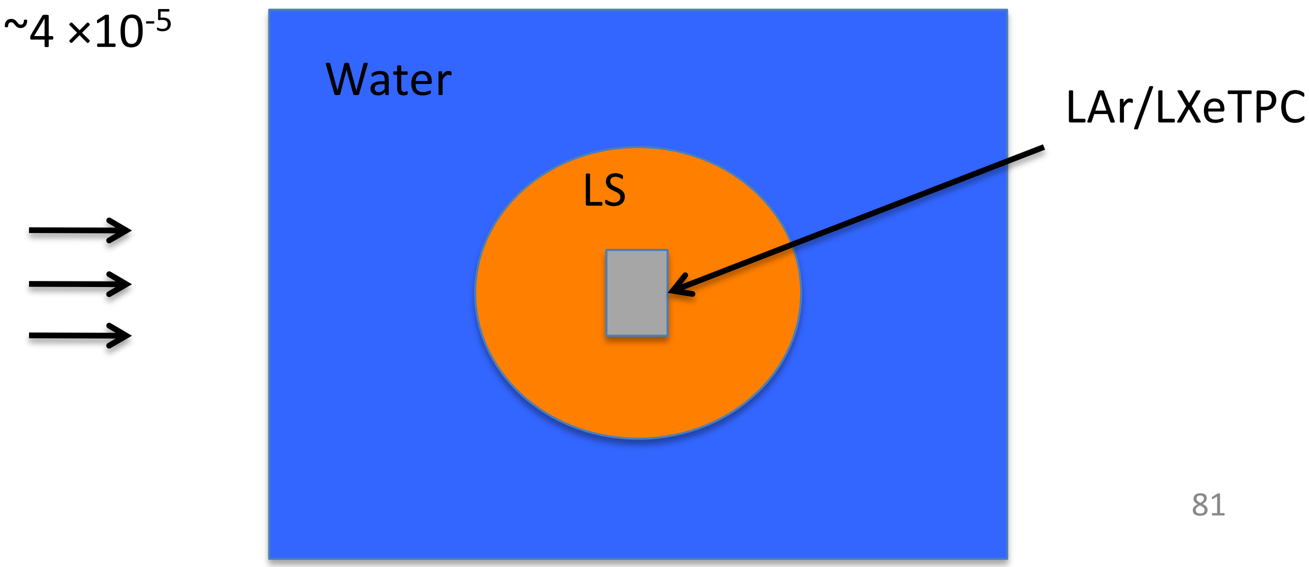
- Flux at Gran Sasso lab:
  - ✓ 2.4 m^{-2} day^{-1}
  - ✓ 0.7 m^{-2} day^{-1} for > 10 MeV
- **Expected rate ~ 3×10^{-33} /s/atom**
- **WIMPS rate ~ 10^{-34} /s/atom**



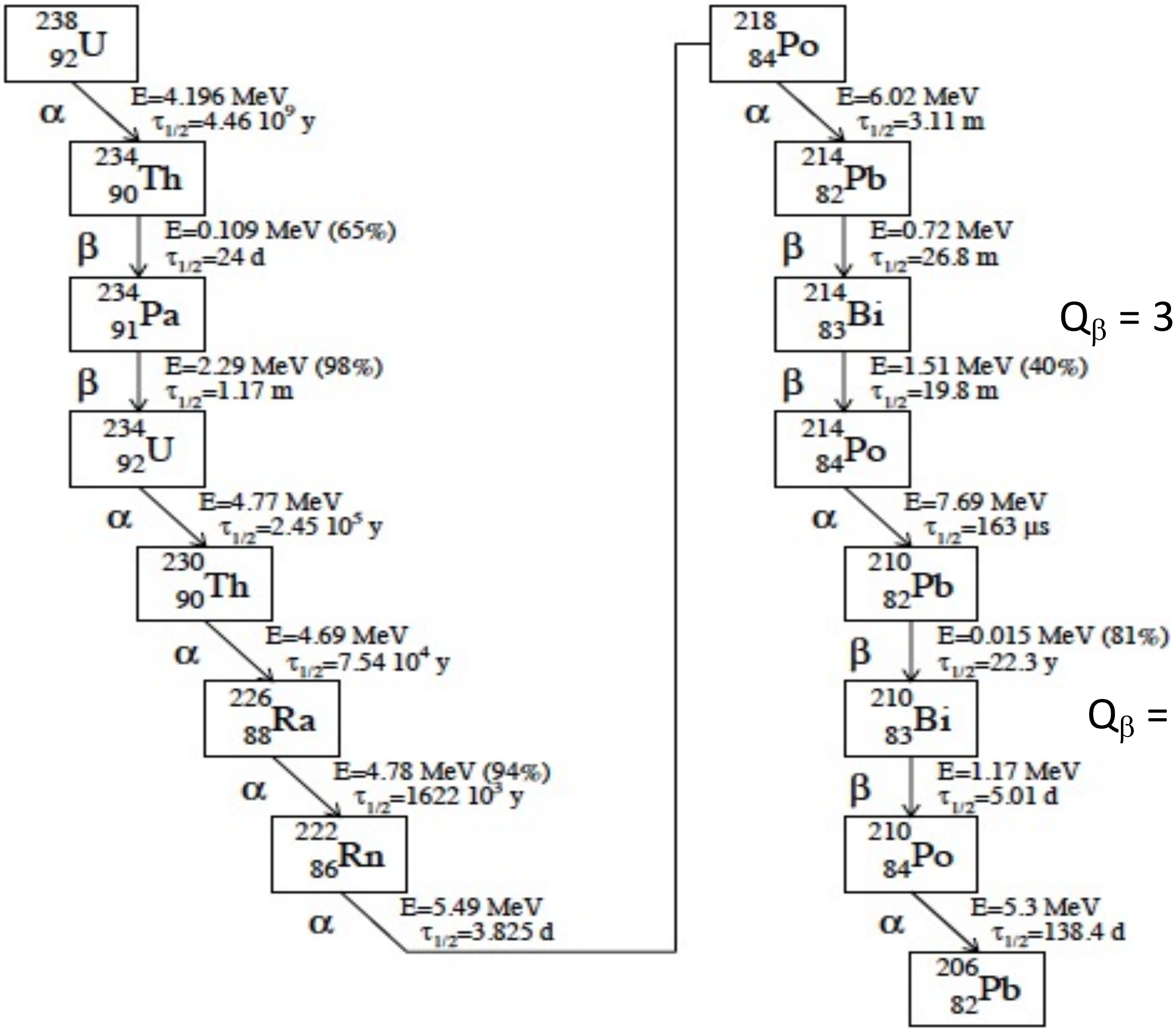
- Neutrons from surrounding rocks reduced by shielding

✓ In DS-50 3m of water ~ 10^{-3} and 0.04 from 1.5m of liquid scintillator: ~4 $\times 10^{-5}$

μ-induced neutrons



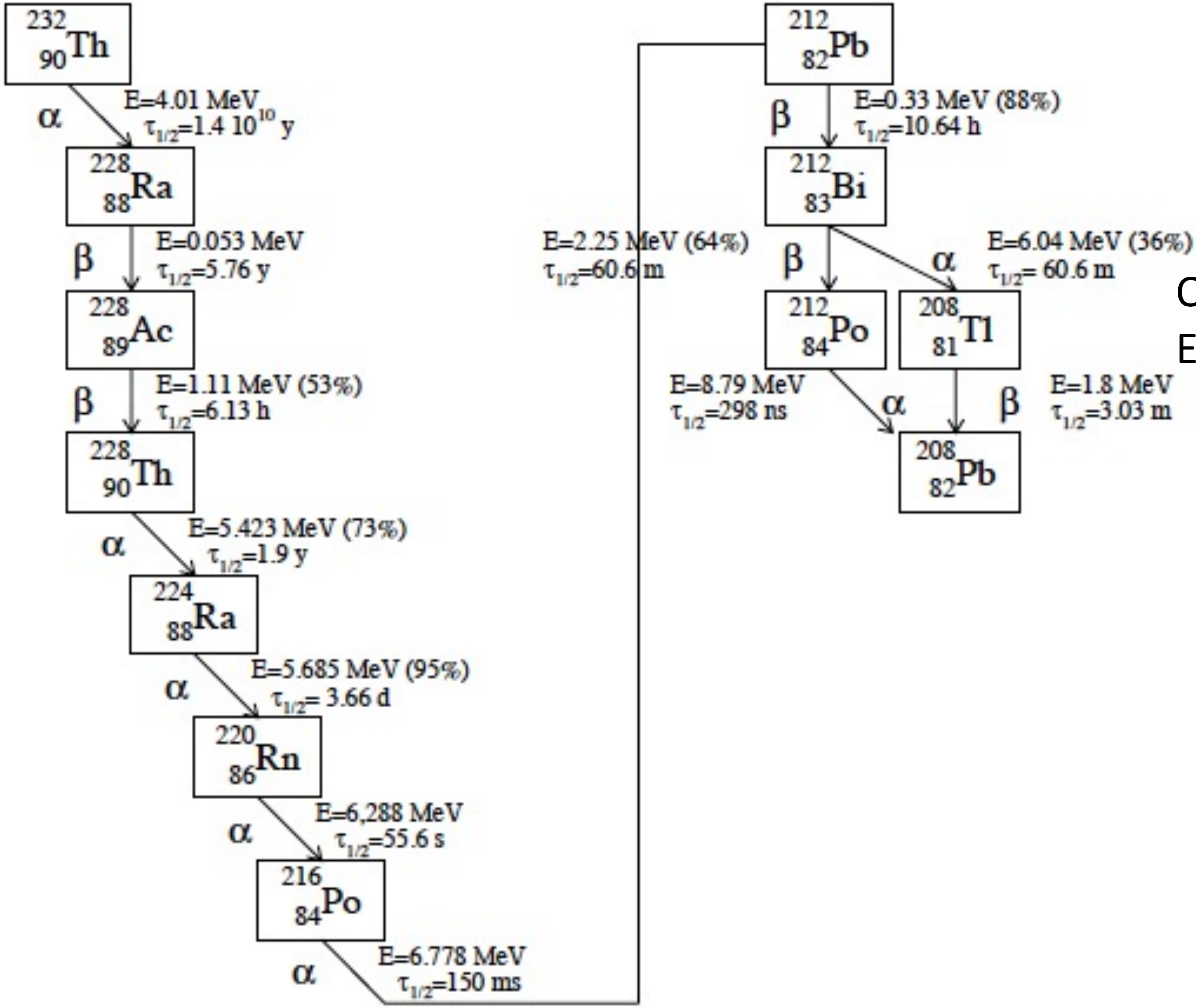
^{238}U chain



Q_β = 3.2 MeV

Q_β = 1.2 MeV

^{232}Th chain



Q_β = 5.0 MeV

E_γ = 2.6 MeV

Strategy to reduce background

- Design detector with active and passive shielding
- Advance cleaning of detector components in clean room environment
- Assemblying of detector components in radon-free environment
- Exploit offline reduction after extensive calibration campaign

Radon-free clean room (Rn < 100 mBq/m3)

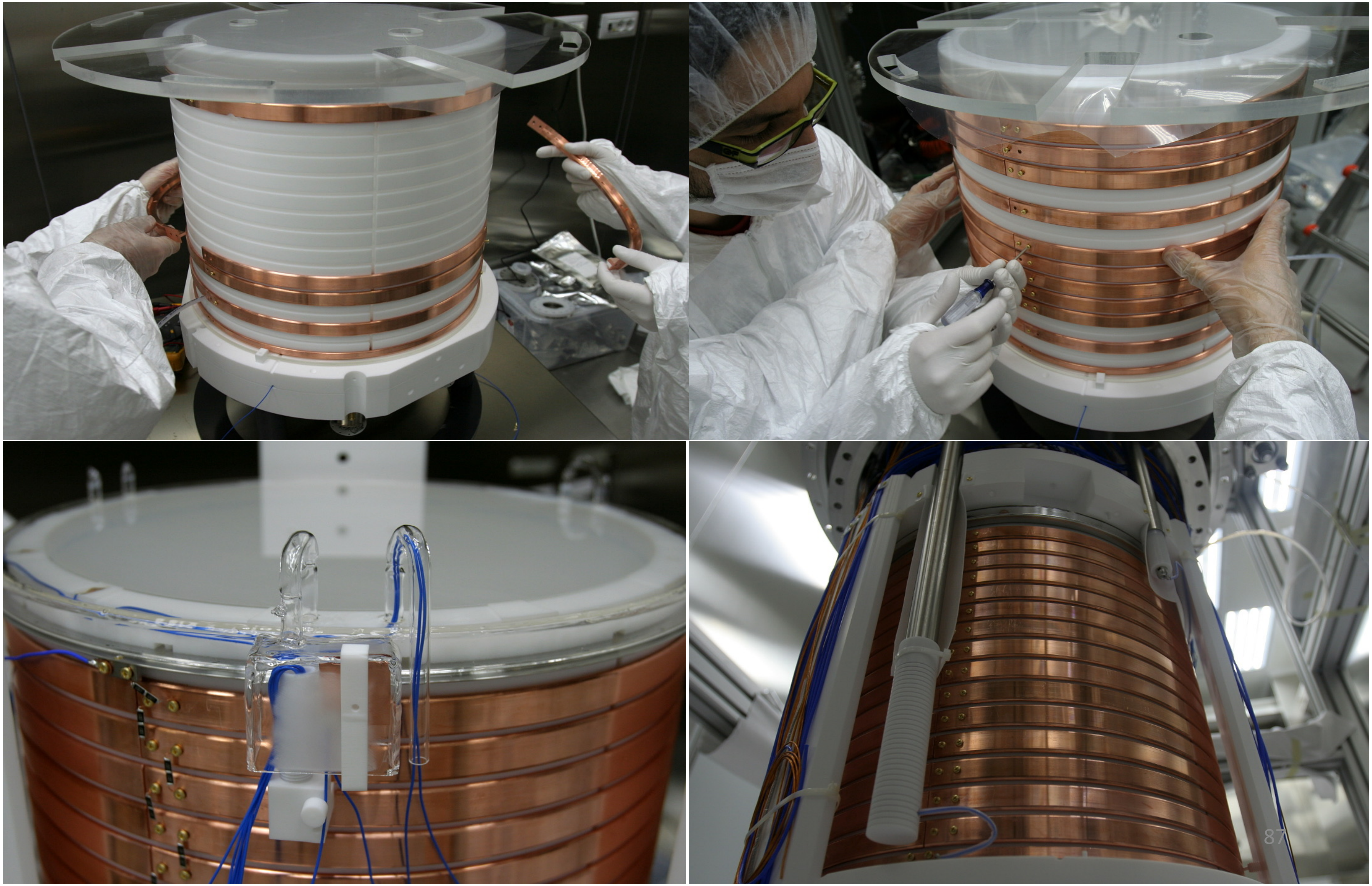
Cleaning

Inside CR: steel, copper, teflon, brass parts cleaned and baked before storing in Rn-tight bags

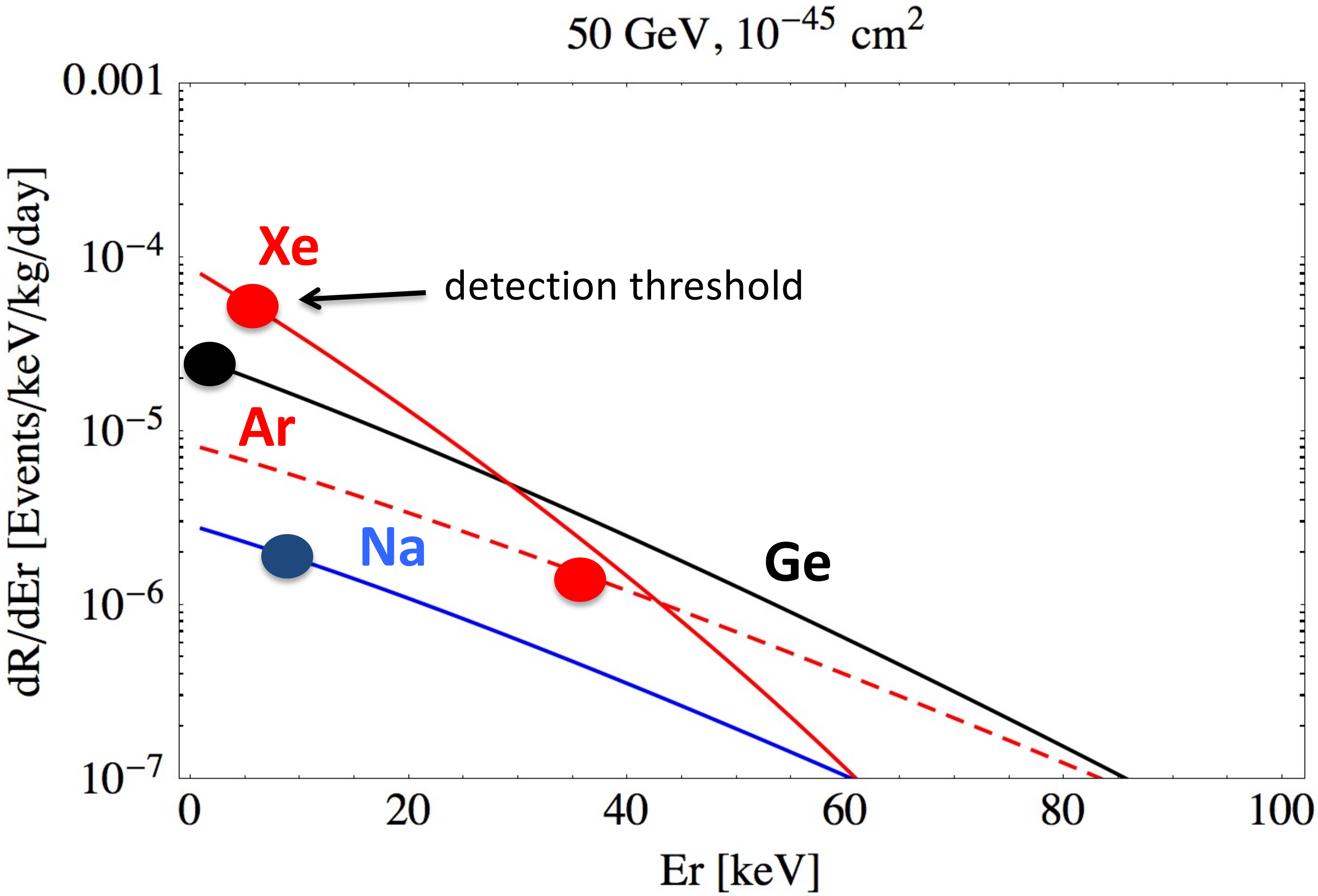
Pickling and passivation of surfaces, de-gassing

Advance cleaning of as-built large vessels and fluid handling system

DS-50 TPC

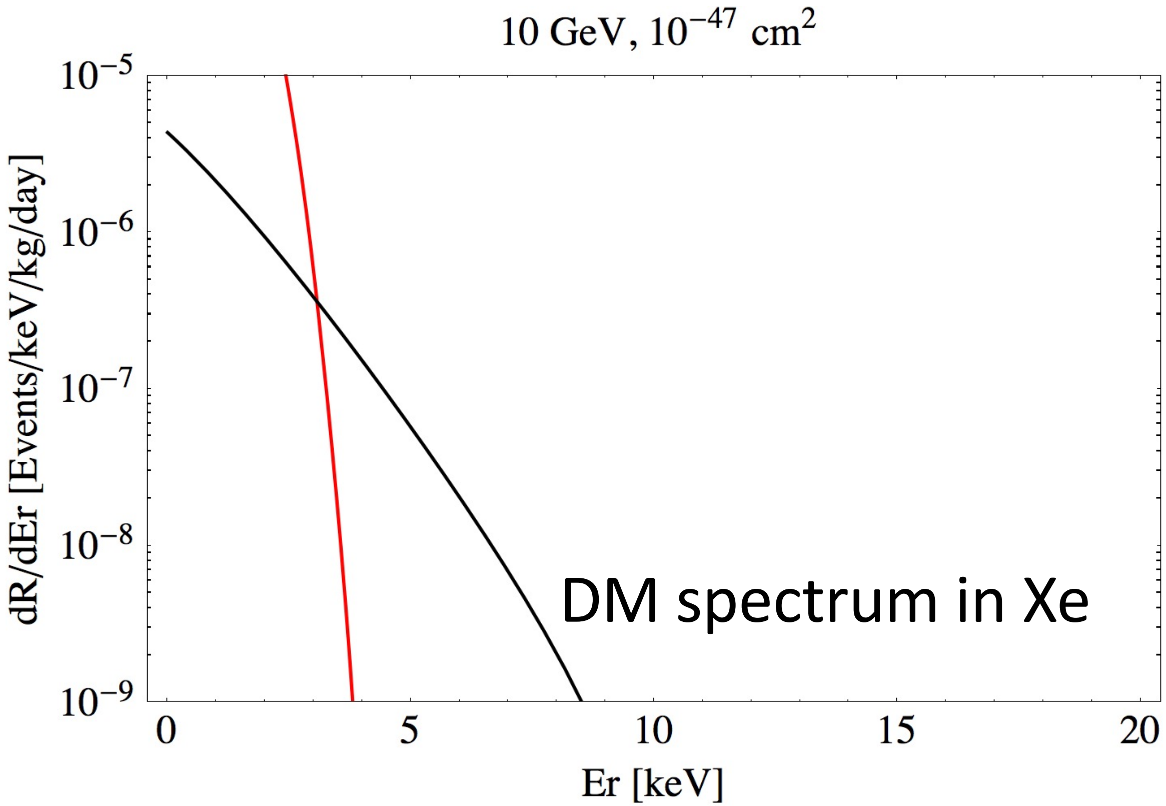


WIMPs Recoil Spectrum

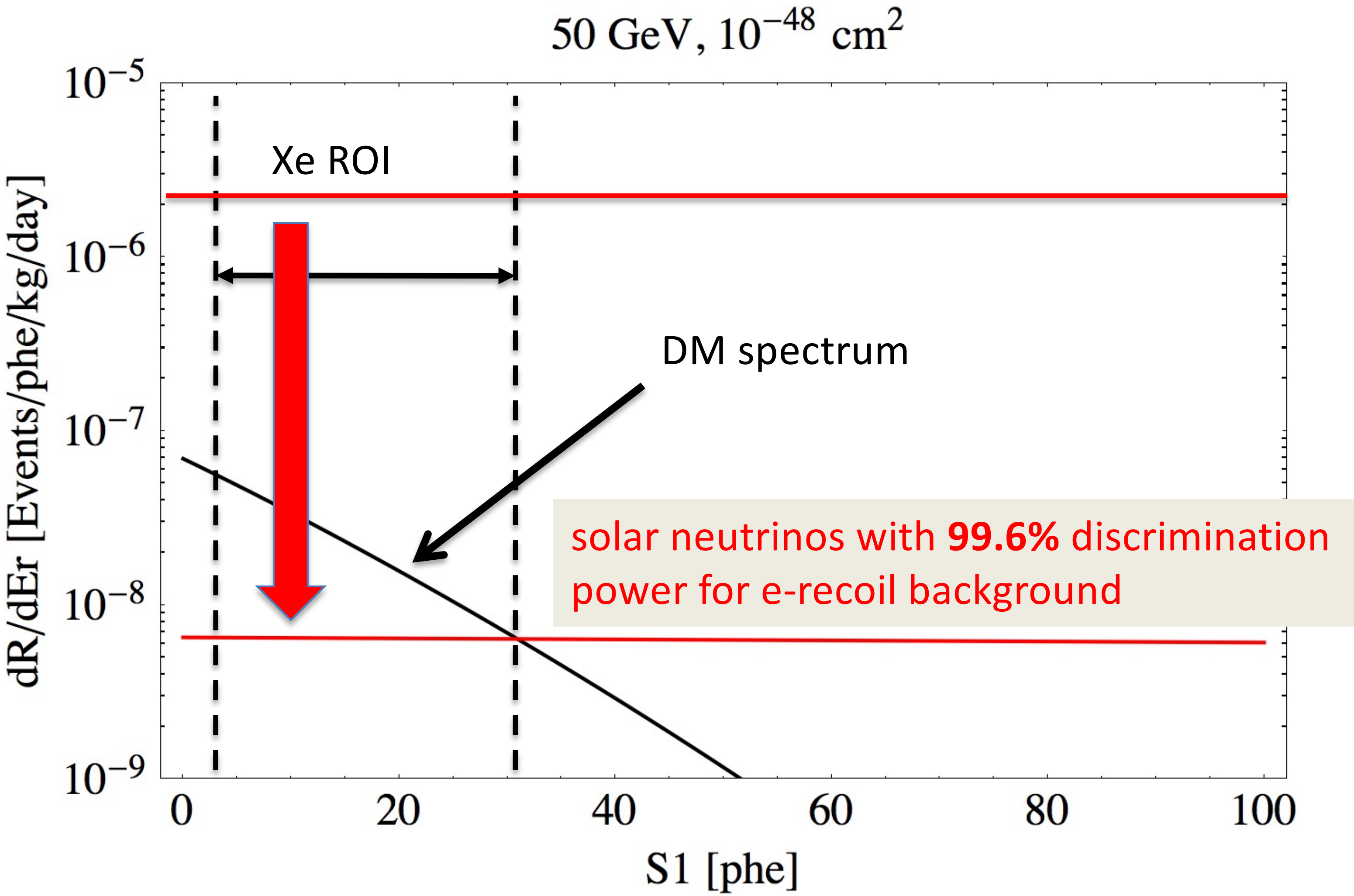


Solar Neutrinos Background in the NR channel

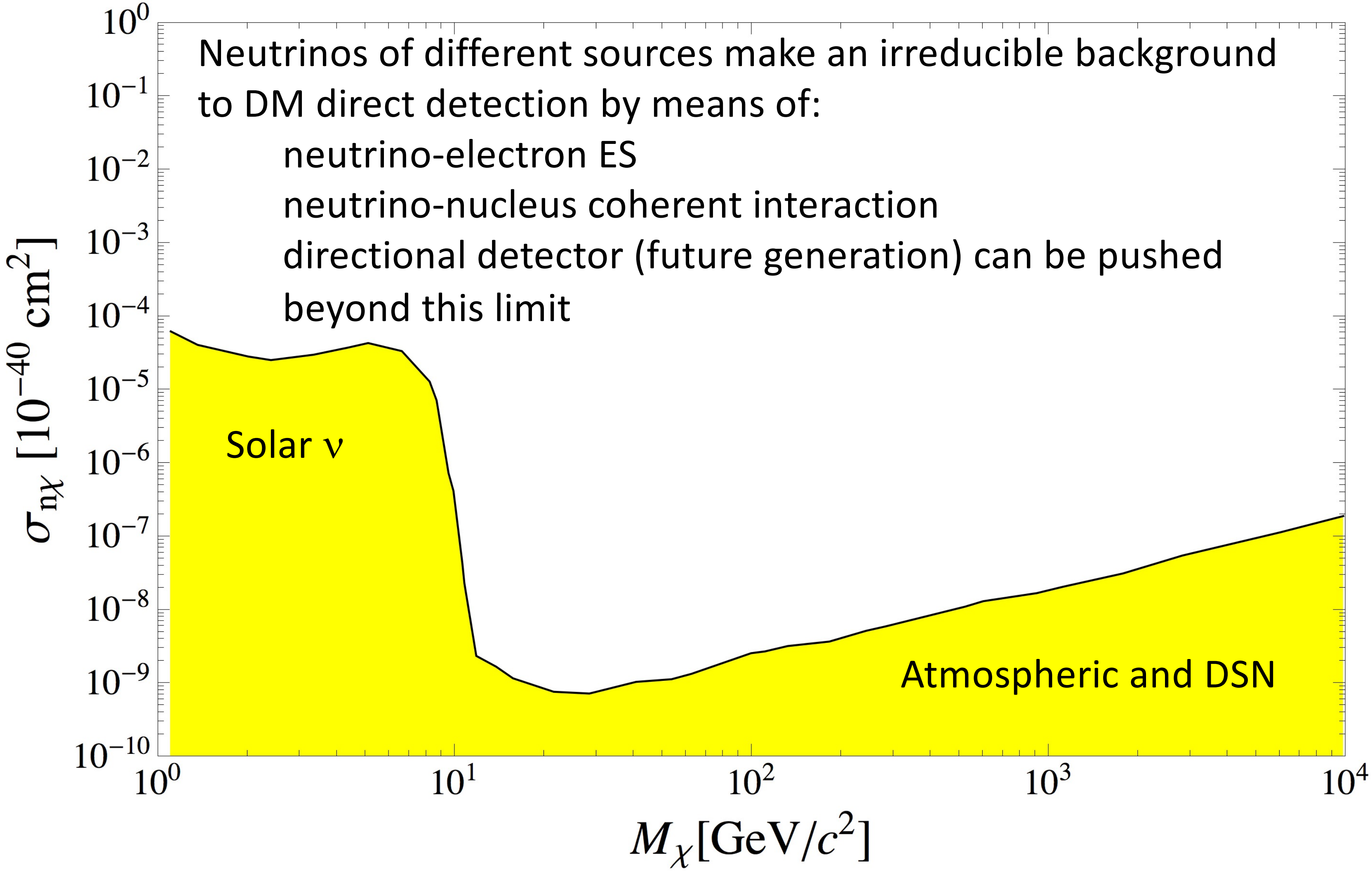
- ν-nucleus coherent scattering
  - Maximum recoil energy for ^{8}B neutrinos = 4.3 keV
  - Flux of ^{8}B ~ $5 \cdot 10^6$ cm^{-2}s^{-1}



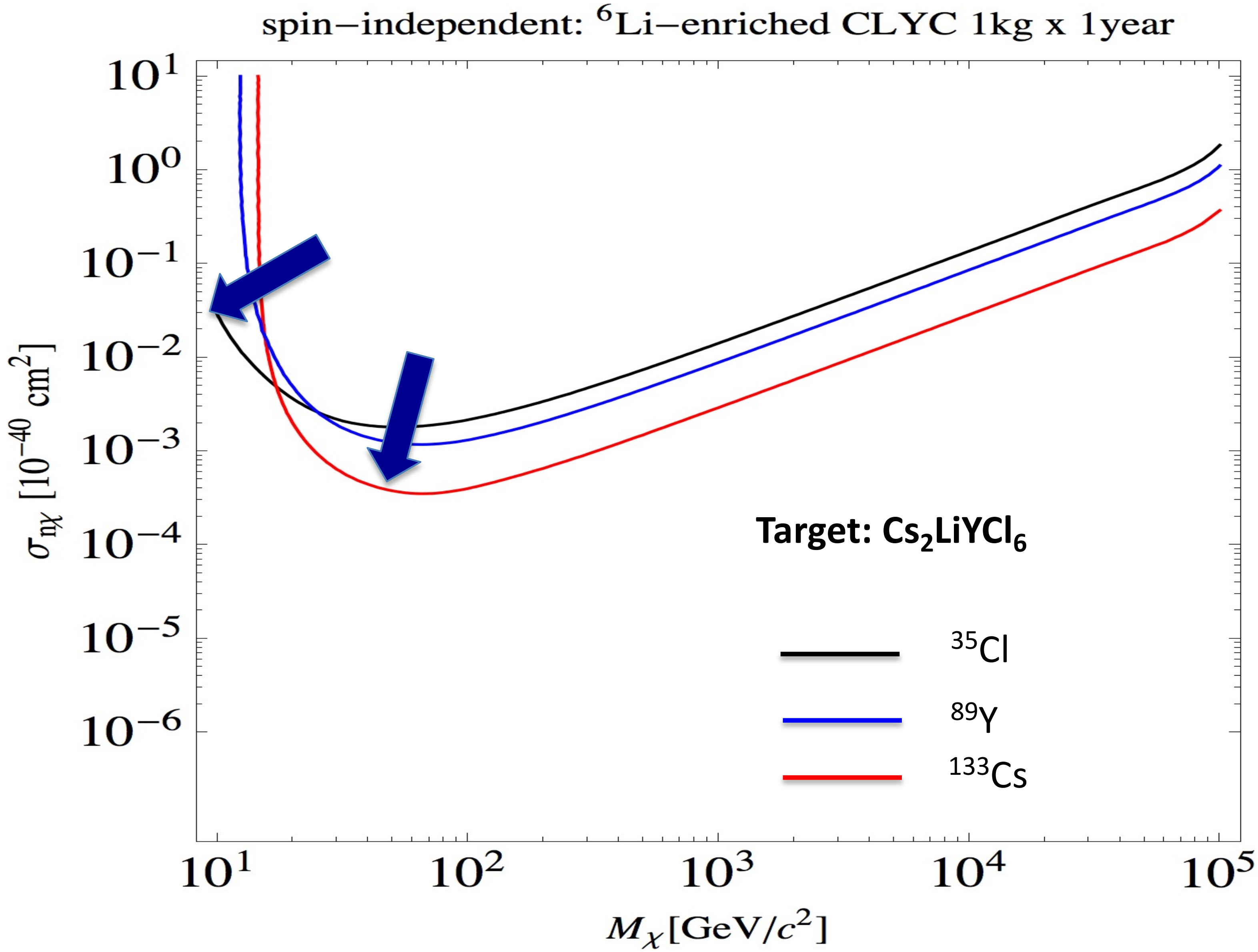
Solar Neutrinos as Background in ER channel



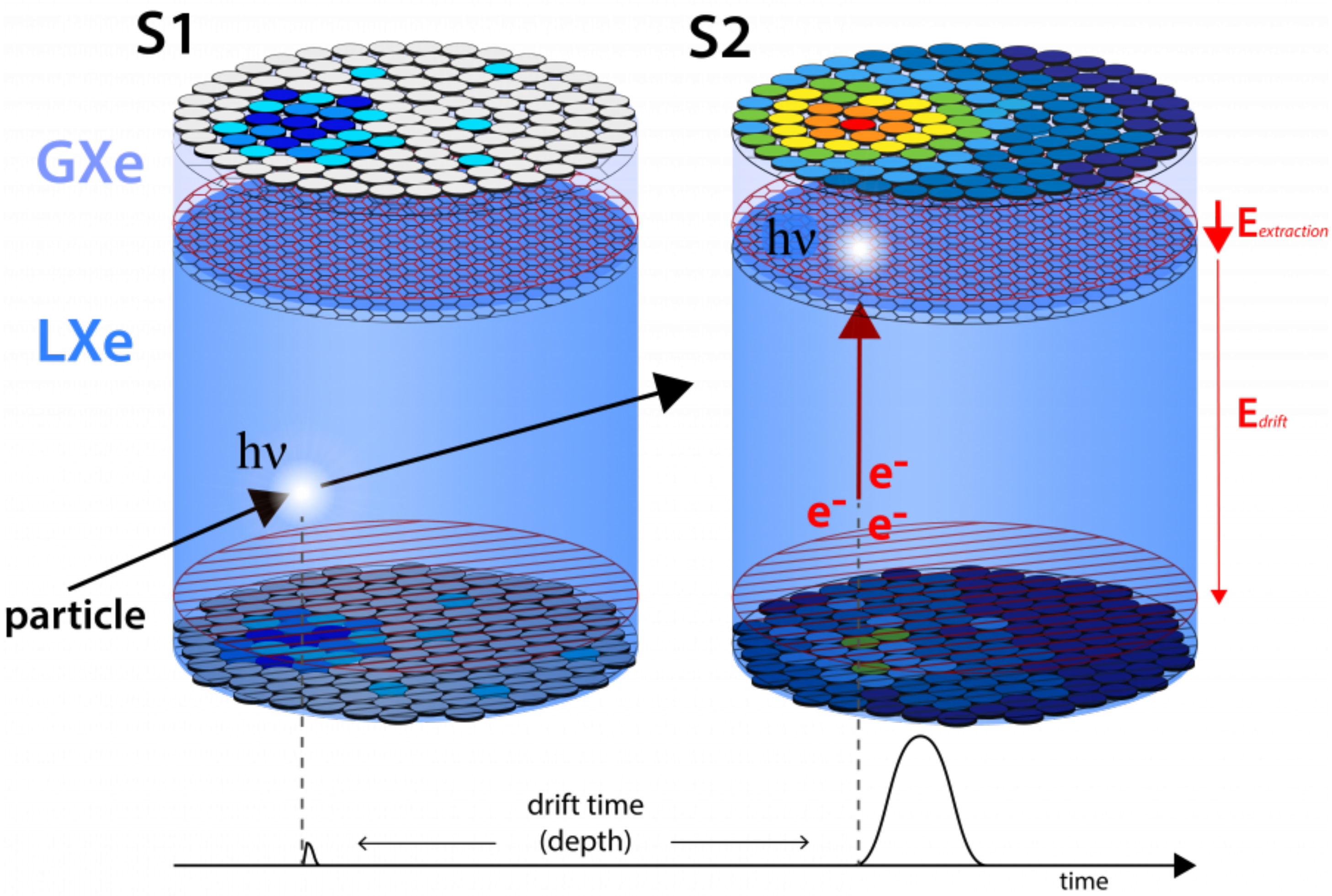
“Neutrino floor” for DM



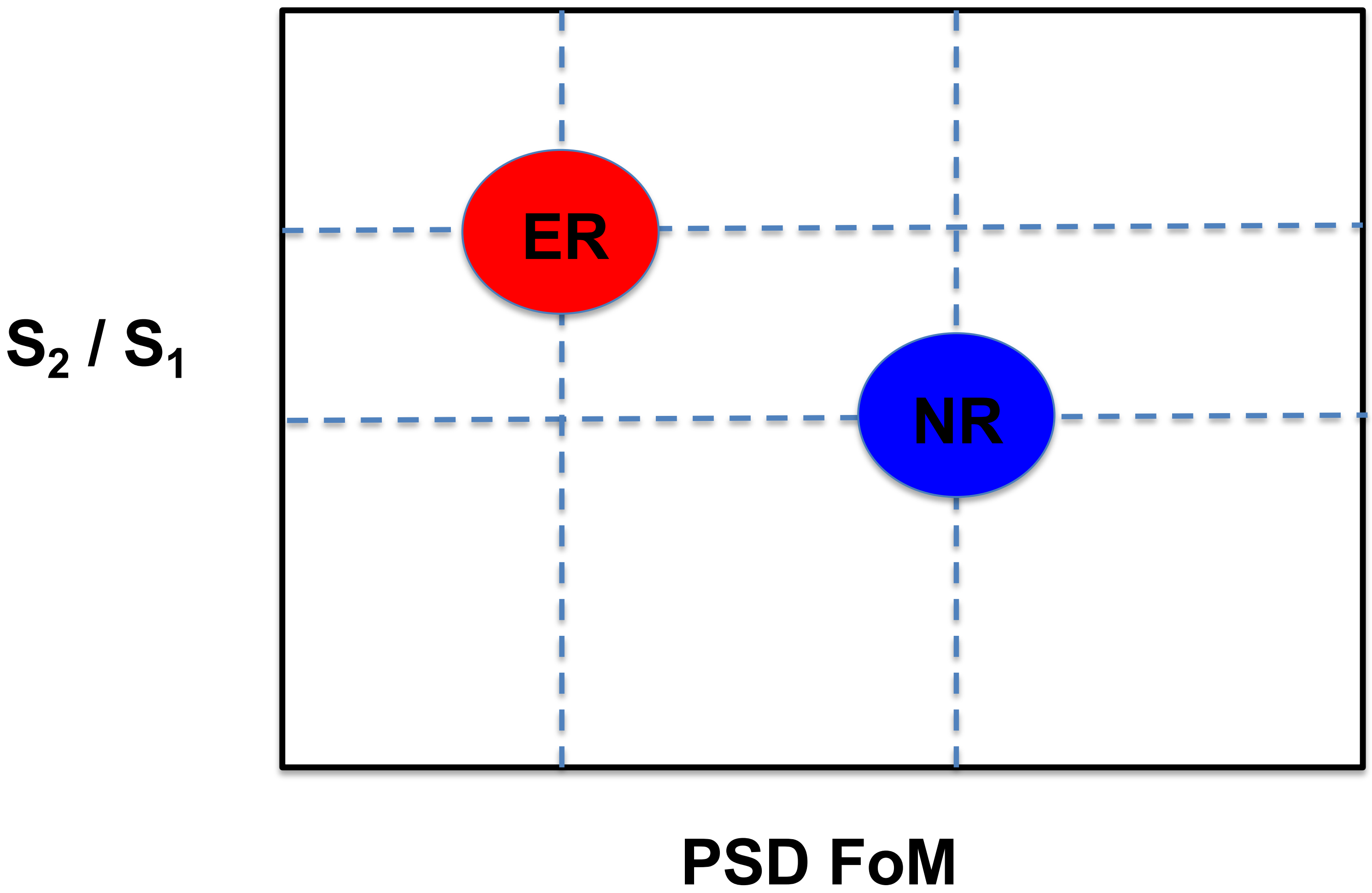
Exclusion plot: example



Two-phase TPC and background rejection

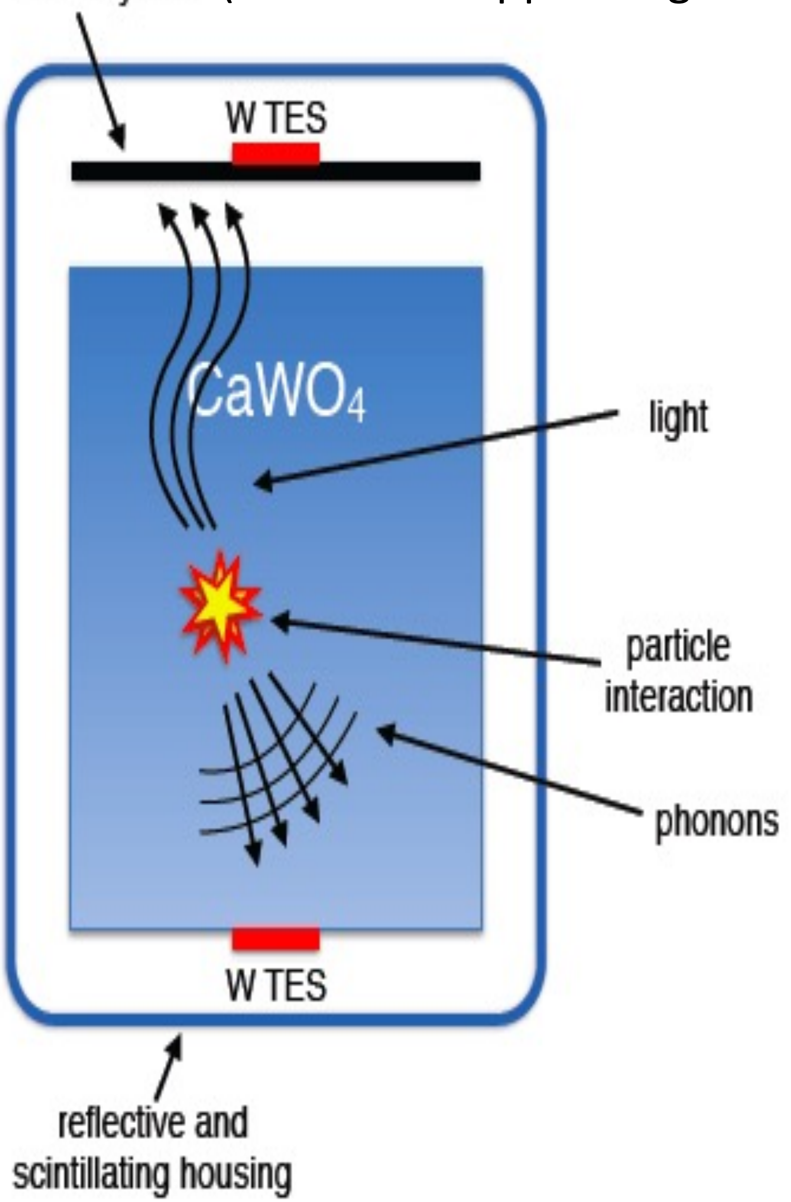


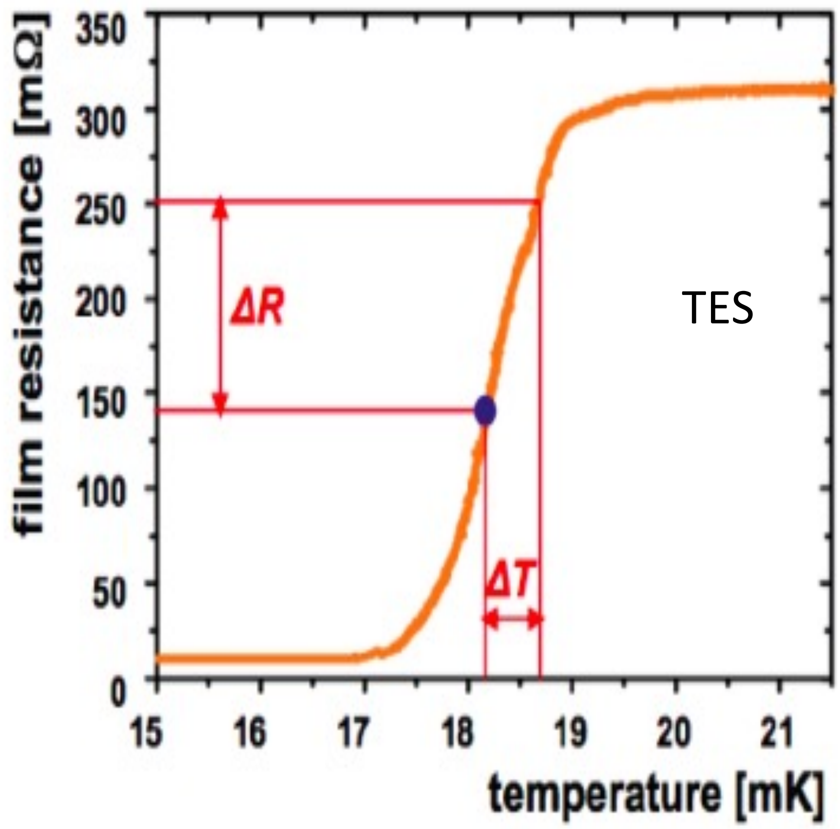
Scintillation and Ionization Discrimination



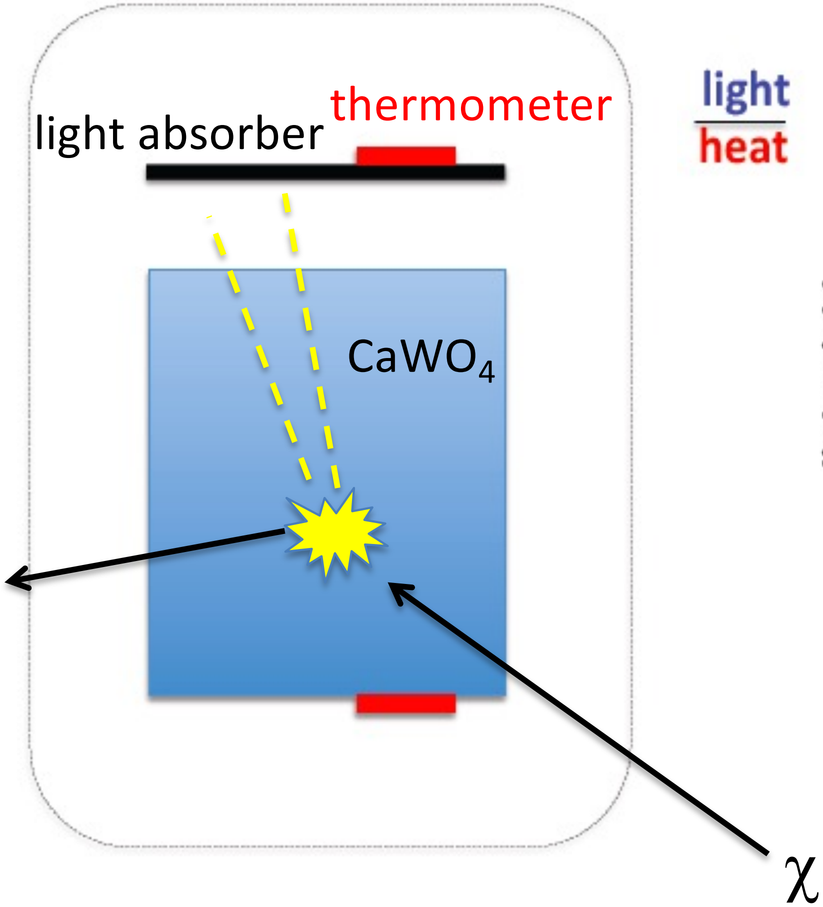
CRESST Detectors

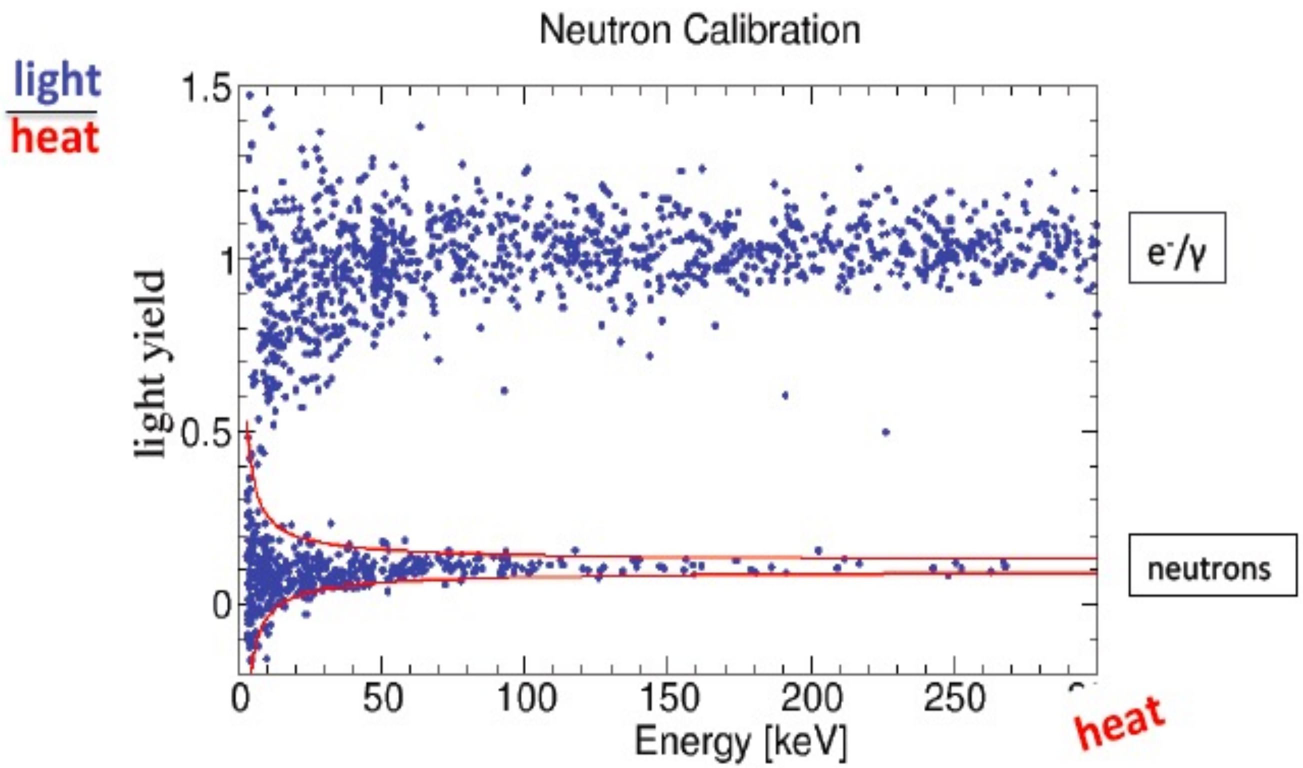
SOS crystal (Silicon on Sapphire light detector)





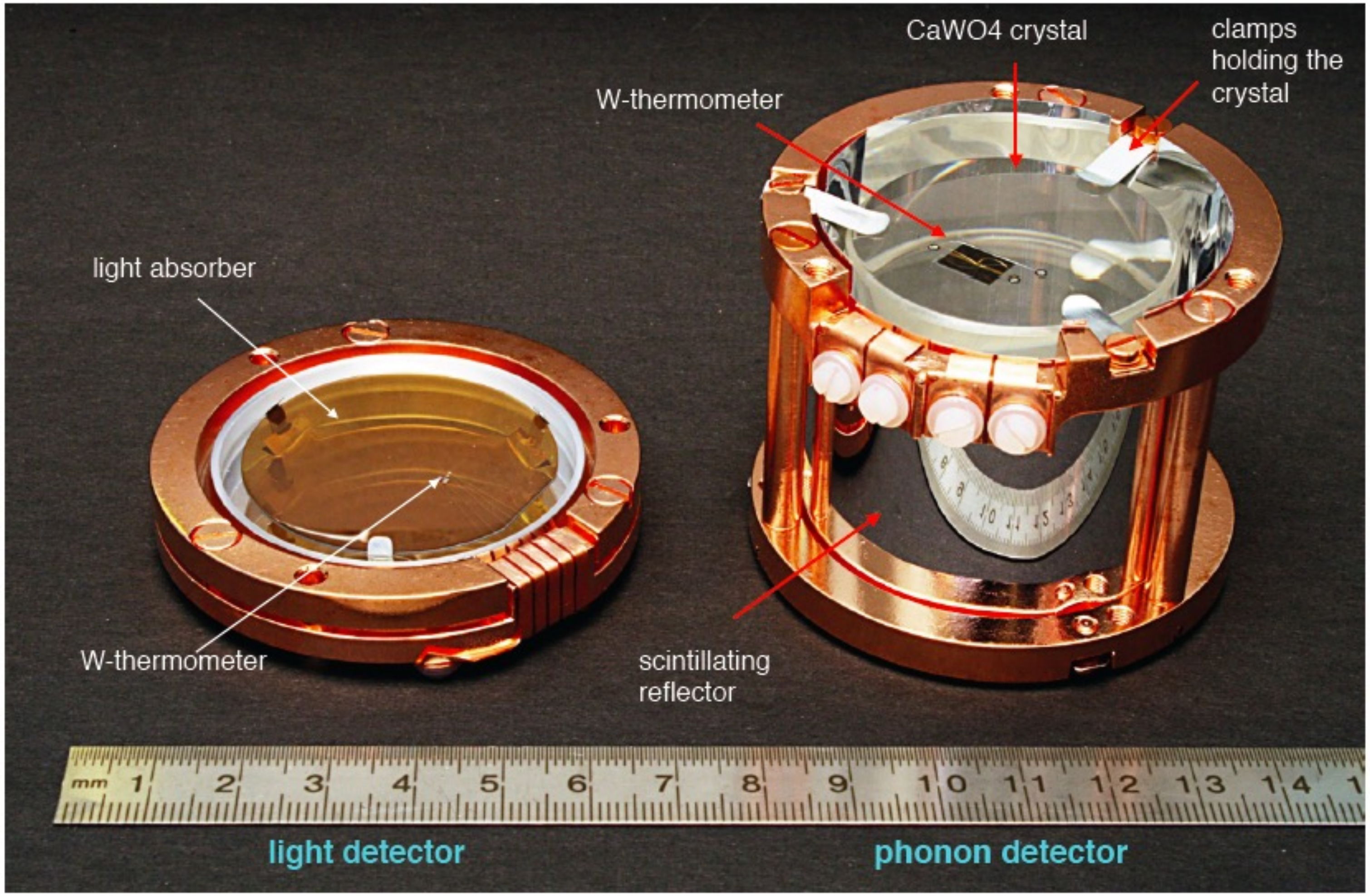
Background rejection: an example from CRESST





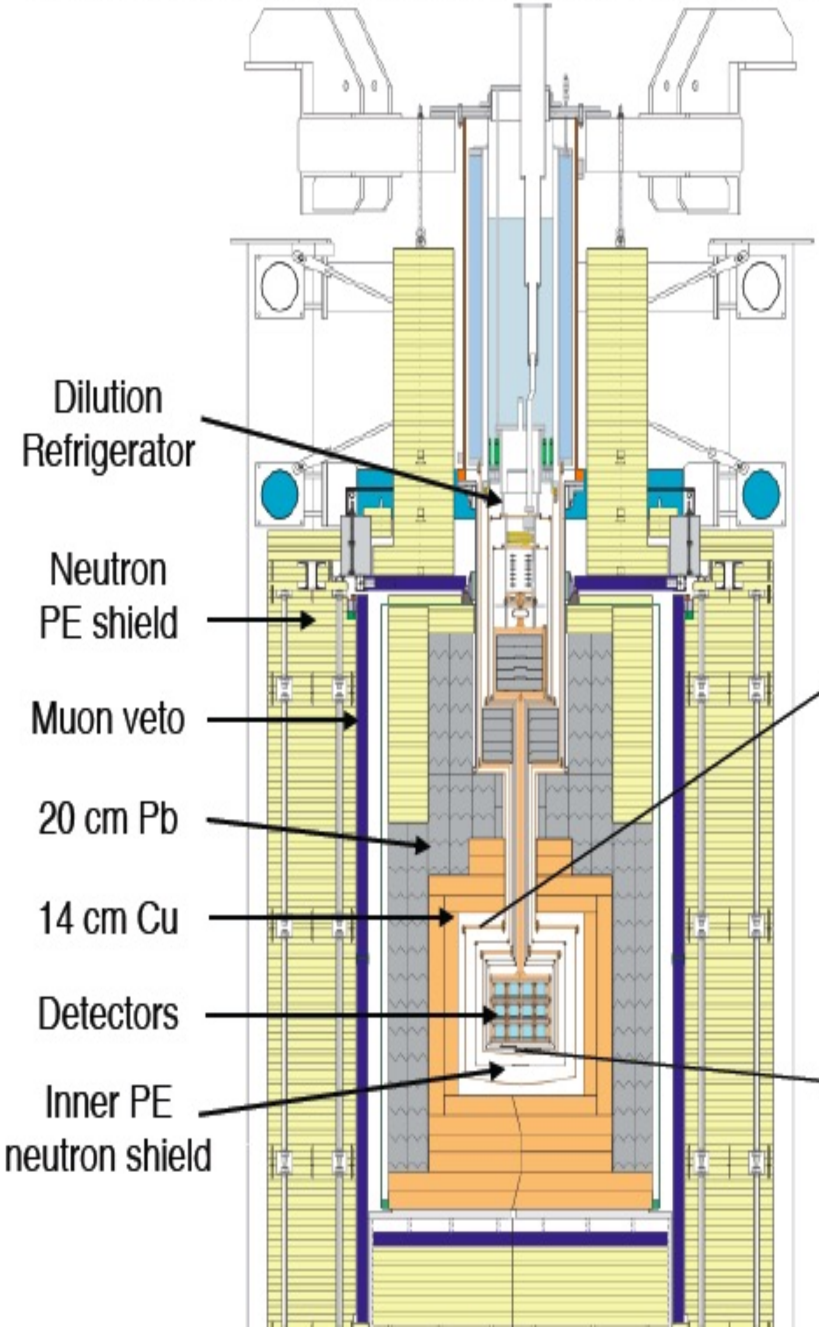
CRESST Crystal

300 g Detector Module



The CRESST Experiment

Cryogenic Rare Event Search with Superconducting Thermometers



CRESST detectors need to be operated at ~14 mK. The CRESST facility (Dilution refrigerator) provides a low background, low vibration, ~10 mK experimental volume.

Direct Dark Matter search with liquid Xe and Ar in a two-phase TPC

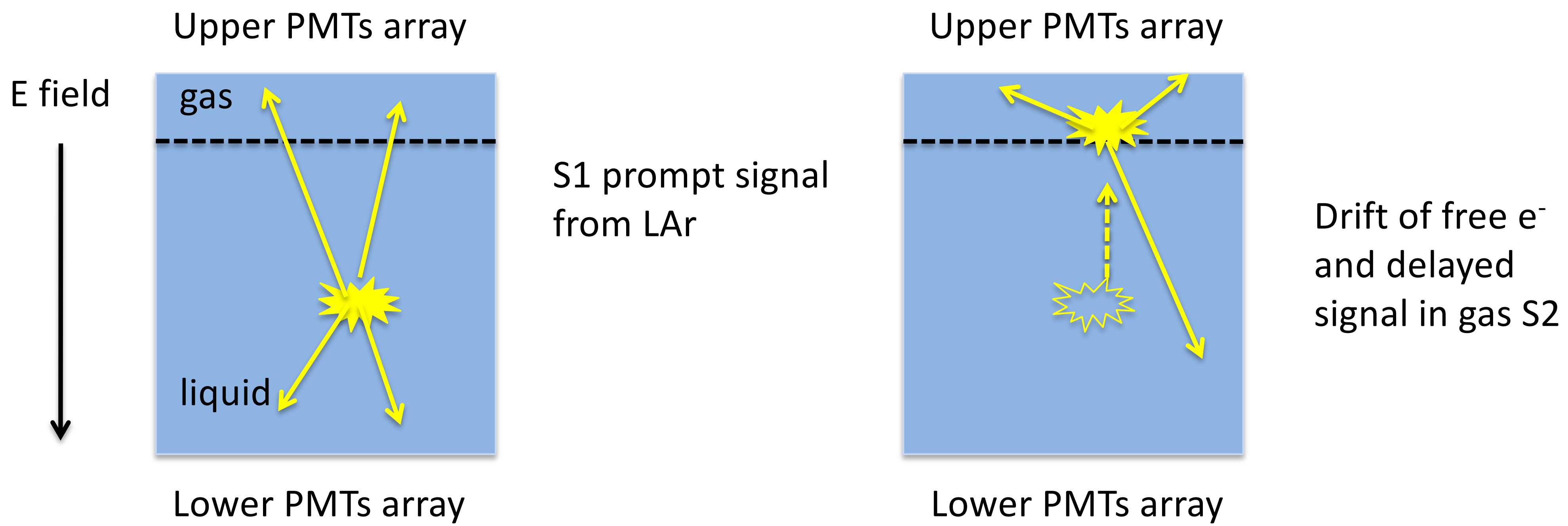
Features of LAr and LXe

- High scintillation yield (> 40000 photons/MeV)
- High intrinsic purity
- Unique capability to produce scintillation and drifting the ionization charge to > 1m length
- Possibility to extract the charge into gas phase and produce secondary scintillation

Liquified noble gases as WIMPs target

	Ar	Xe
Atomic number	18	54
Mean atomic mass	40	131.3
Boiling point @ 1atm [K]	87.3	165.0
Density for liquid [g/cm^3]	1.40	2.94
Volume fraction in atmosphere [ppm]	9340	0.09
Scintillation λ [nm]	128	178
Scint. fast component [ns]	7	3
Scint. Slow component [ns]	1600	27

Two-phase TPC at Work: basic



S1 measures energy and time of event

S2 measures position of event in LAr and is proportional to the fraction of charge that escapes recombination (this fraction depends on the drift field)

S2/S1 = f(dE/dx) important for ER vs NR discrimination

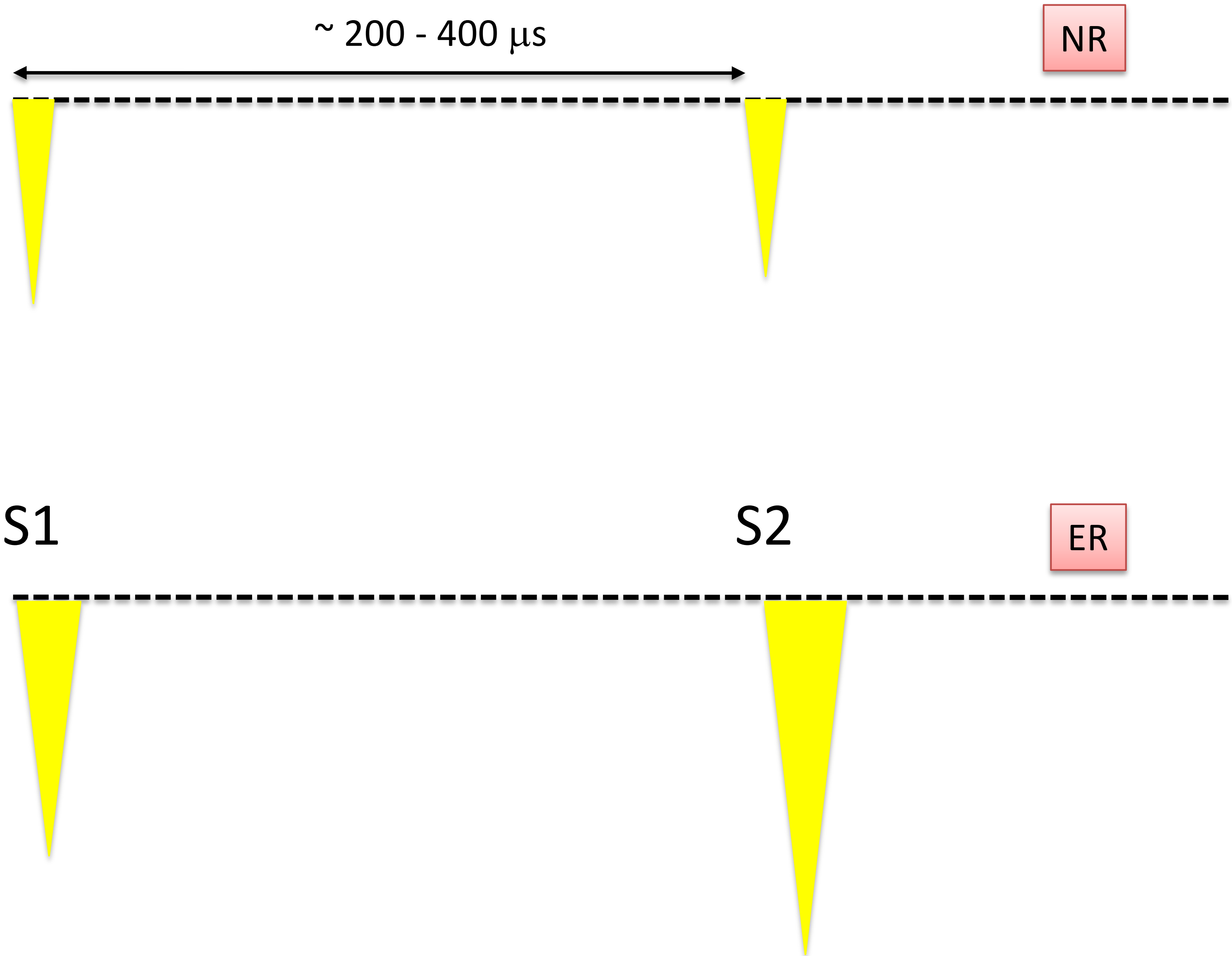
Drift time allows to measure z-coordinate at < mm level

S2 allows to measure x-y coordinates at mm level

Scintillation and charge in LAr and LXe

- In absence of electric field scintillation of NR is quenched (~0.25) wrt to ER: $keV_{NR} = 4keV_{ER}$
- With electric field the yield for ER is reduced more than for NR
- Energy deposit produces ionization and excitation
  - ionization/excitation ~ 0.2
  - excitation produces scintillation
- dE/dx larger for NR: larger density of excited atoms (directly or by ionization)
  - Increases quenching: $Ar^* + Ar^* \rightarrow Ar + Ar + heat$
  - Decreases proportional charge collected, more recombination

LAr two-phase TPC at Work: signals



Pulse Shape Discrimination in LAr

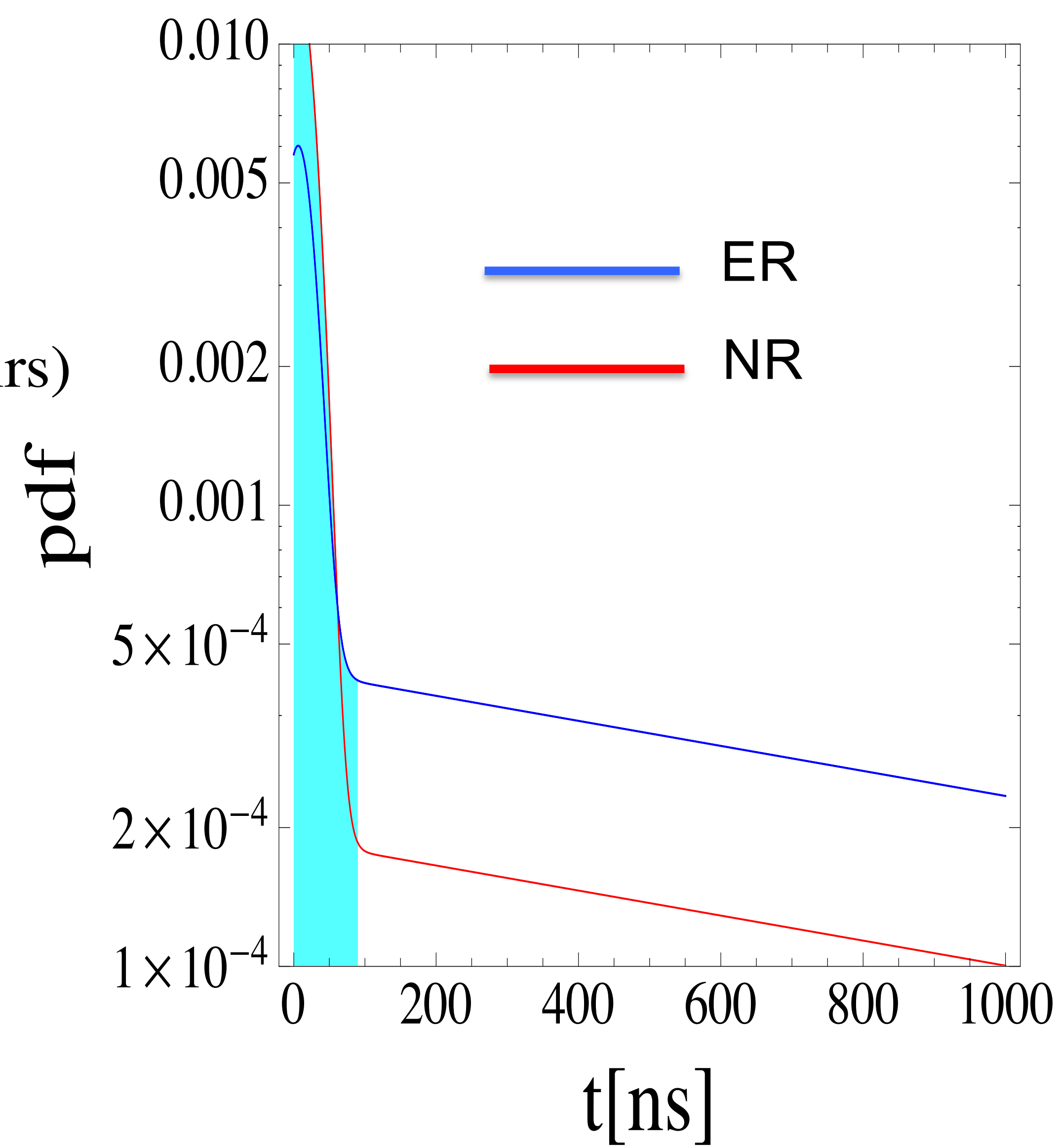
$$f(t) = \left(\frac{q}{\tau_F} e^{-t/\tau_F} + \frac{1-q}{\tau_S} e^{-t/\tau_S} \right)$$

$$\tau_F = 6ns$$

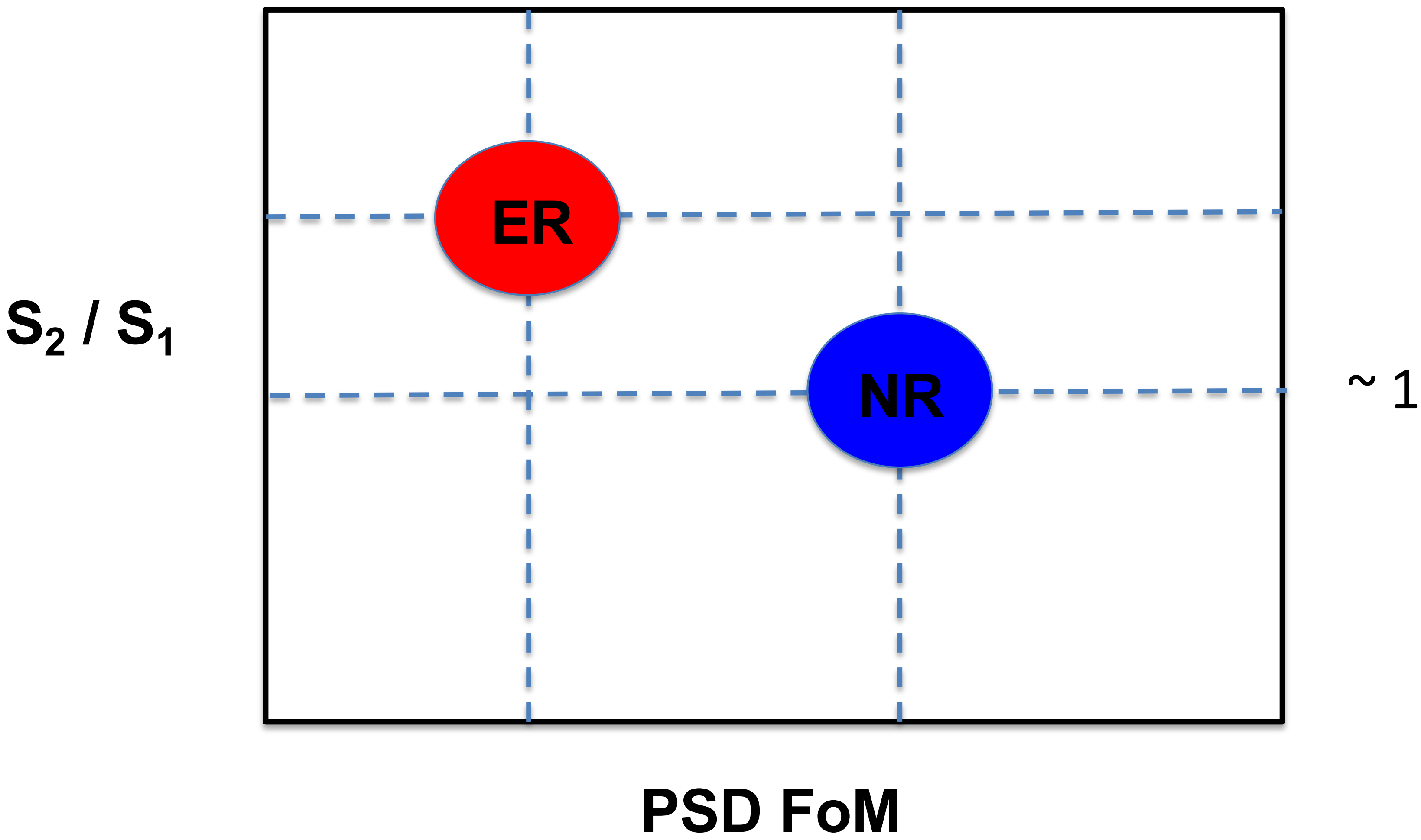
$$\tau_S = 1600ns$$

$$q = \begin{cases} 0.3 \text{ ER (low density e-ion pairs)} \\ 0.7 \text{ NR} \end{cases}$$

$$F_{90} = \frac{\int_0^{90ns} dt\, f(t)}{\int_0^{\infty} dt\, f(t)} = \begin{cases} 0.3 \text{ ER} \\ 0.7 \text{ NR} \end{cases}$$



Scintillation and Ionization Discrimination



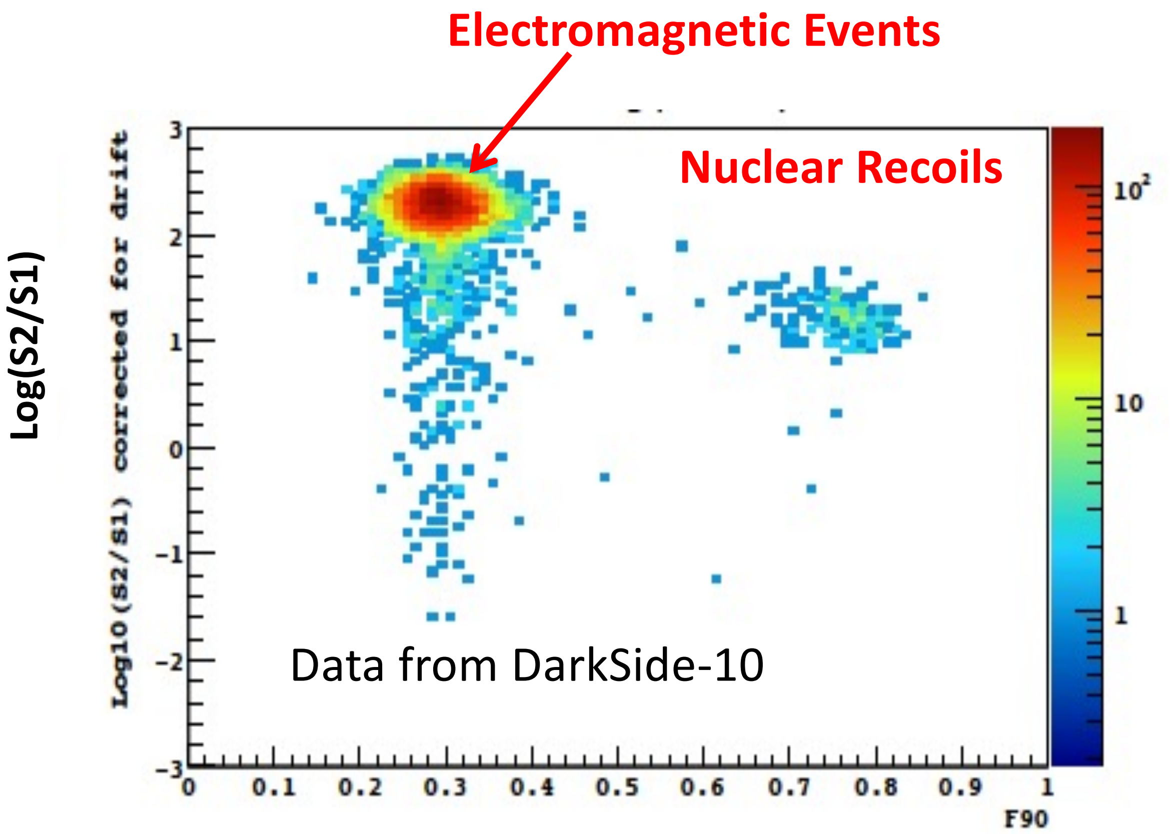
Two-phase TPC at Work: FoM for background discrimination

Background reduction performed by exploiting

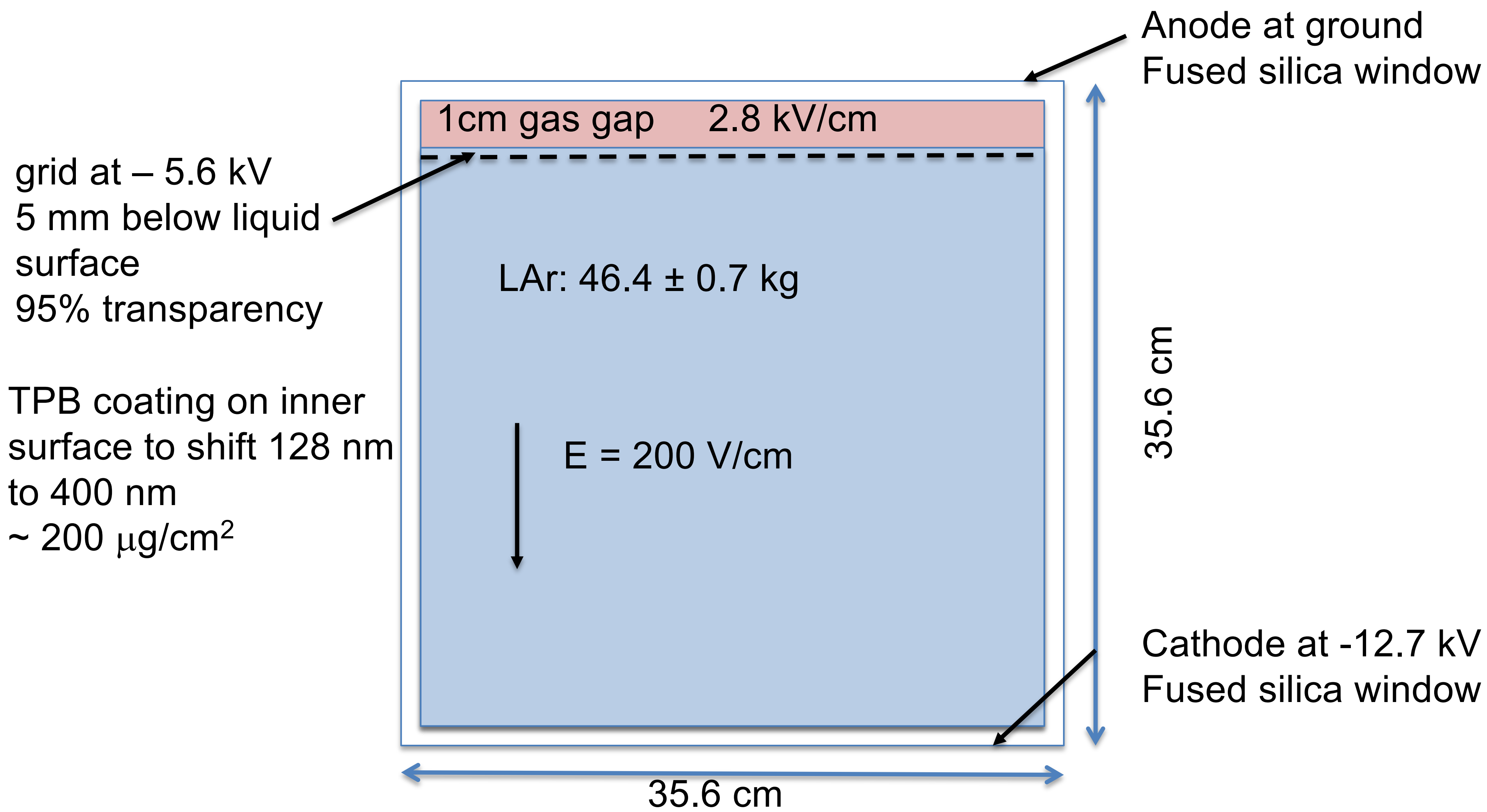
a) Pulse shape of S1 through a parameter which measures the fraction of fast to slow component in scintillation.

$$F_{90} = \frac{\int_0^{90ns} f_{S_1}(t)\,dt}{\int_0^{\infty} f_{S_1}(t)\,dt}$$

b) S2/S1: larger for e-like

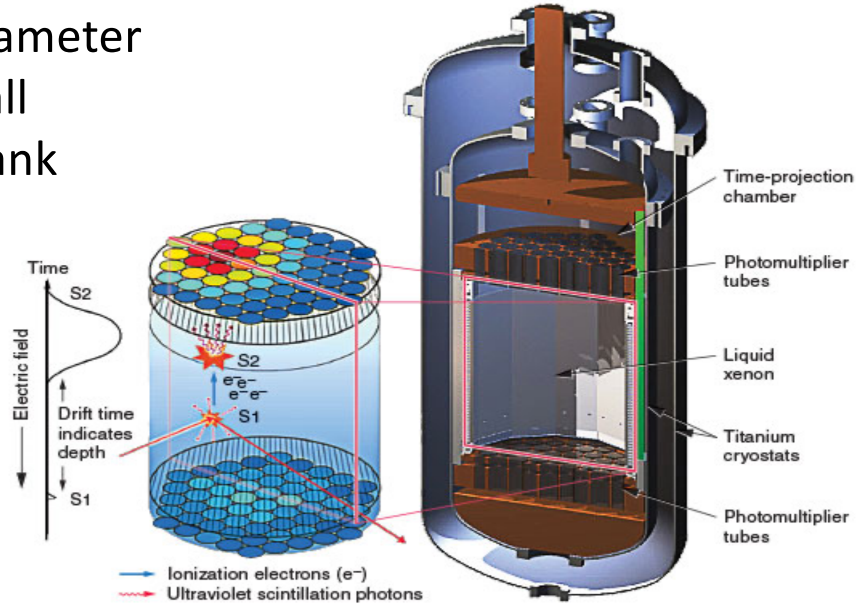


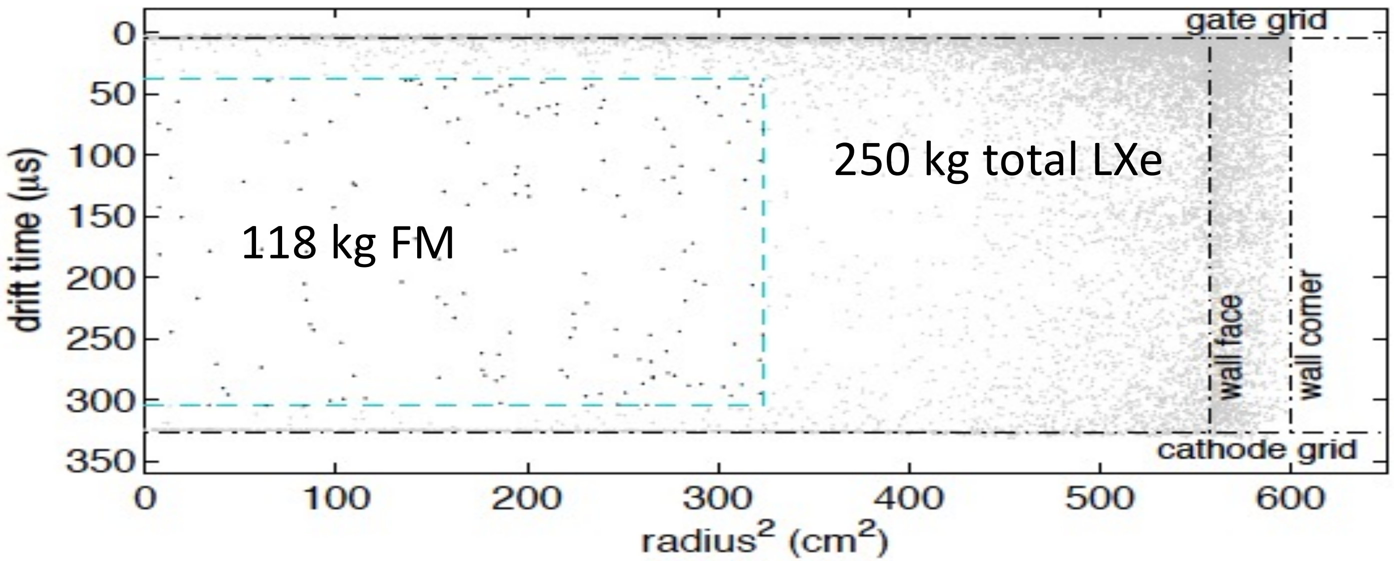
DS-50 TPC details



Fiducial Volume Selection in LUX

7.6m diameter
6.1 m tall
water tank





LUX coll., Rev. Lett. 112, 091303 (2014)

Calibrations for ER and NR response

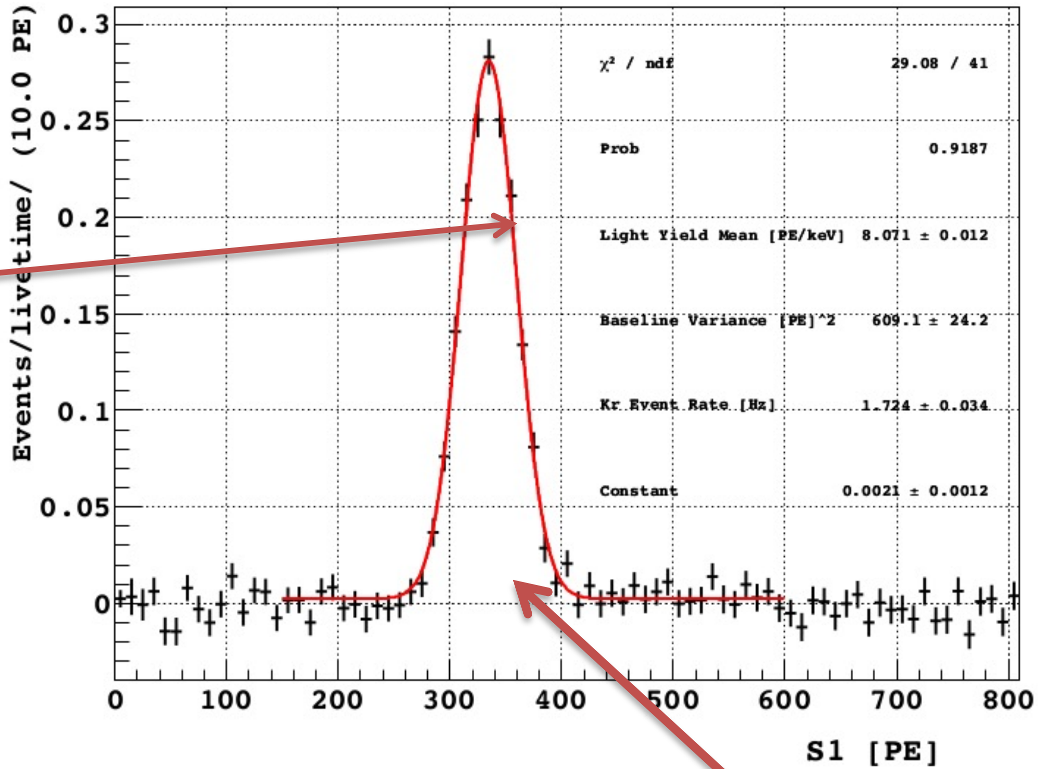
- ^{83m}**Kr**: 1.8h half-life monoenergetic, injected and uniformly distributed in FM
  - 31.5keV + 9.4keV = 41.5keV line
- **CH_3T** (tritiated methane): injected and spatially uniform, Q_β = 18.6 keV
- **Deuterium-Deuterium neutron generator**: 2.5 MeV monoenergetic (d+d→^{3}He+n)
- **AmBe** neutron source
  - ^{241}Am->α+^{9}Be->^{12}C+n+5.71MeV
- **External gamma-ray sources**

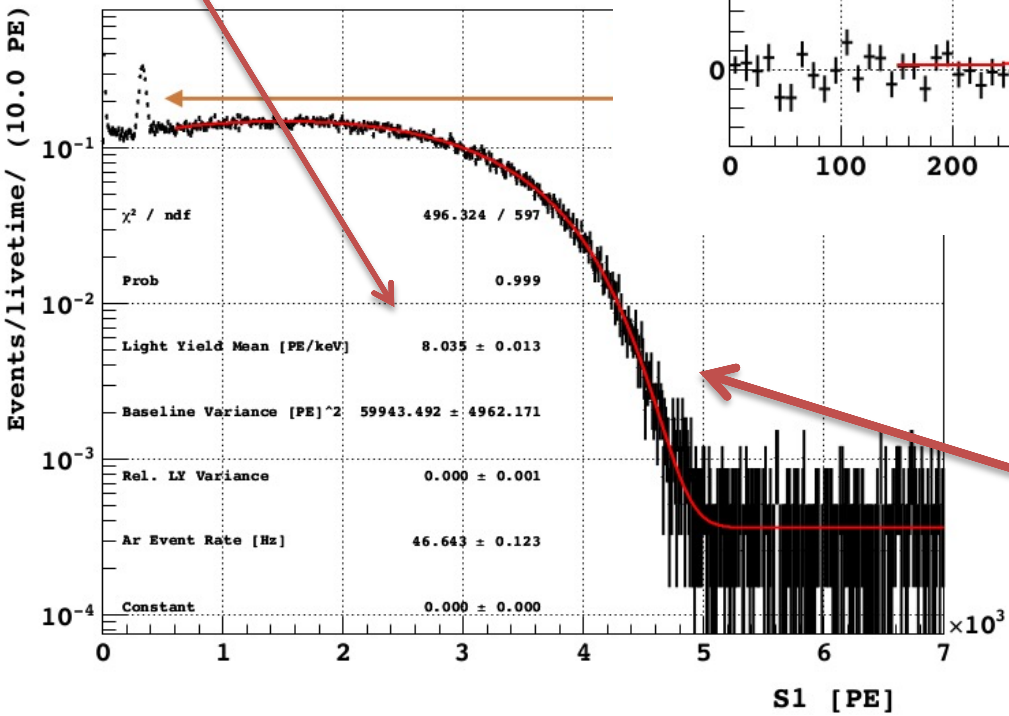
TPC energy calibration

- For LAr internal calibration performed with ^{39}Ar and with ^{83m}Kr
- ^{83m}Kr from ^{83}Rb (τ=124.4 days) prepared in form of RbCl and adsorbed on low radon (<10mBq/kg) charcol
- For DS-50 initial activity of ^{83}Rb was 8.5 kBq
- ^{83m}Kr (τ=2.64 h) escapes charcoal, passes 0.5μ filter and radon trap and goes into the TPC
- ^{83m}Kr produces a single deposition of 41.5 keV (32.1+9.4)

Light yield @ null field

Light Yield = 7.9 ± 0.4 pe/keV$_{ee}$
at **null field**

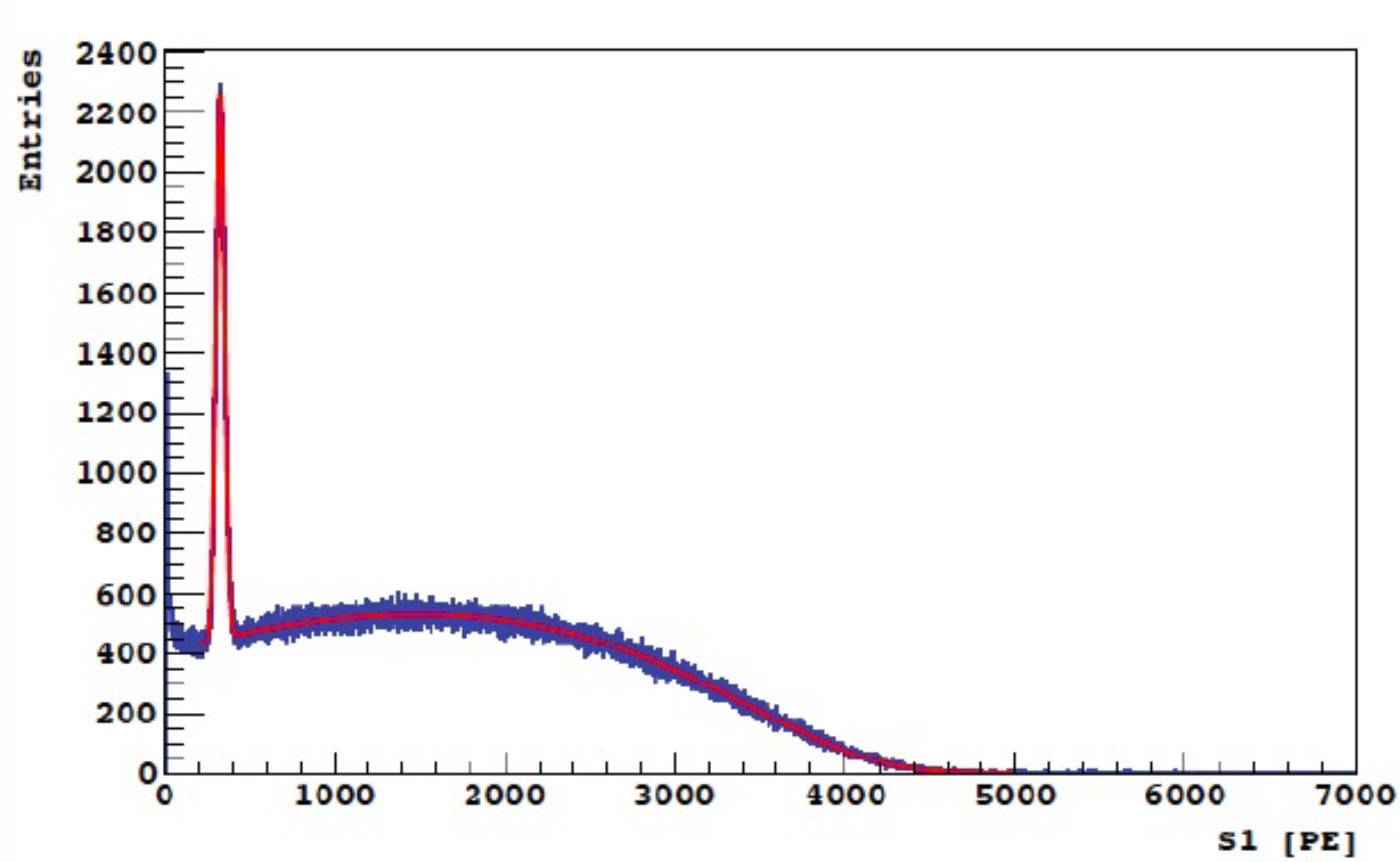




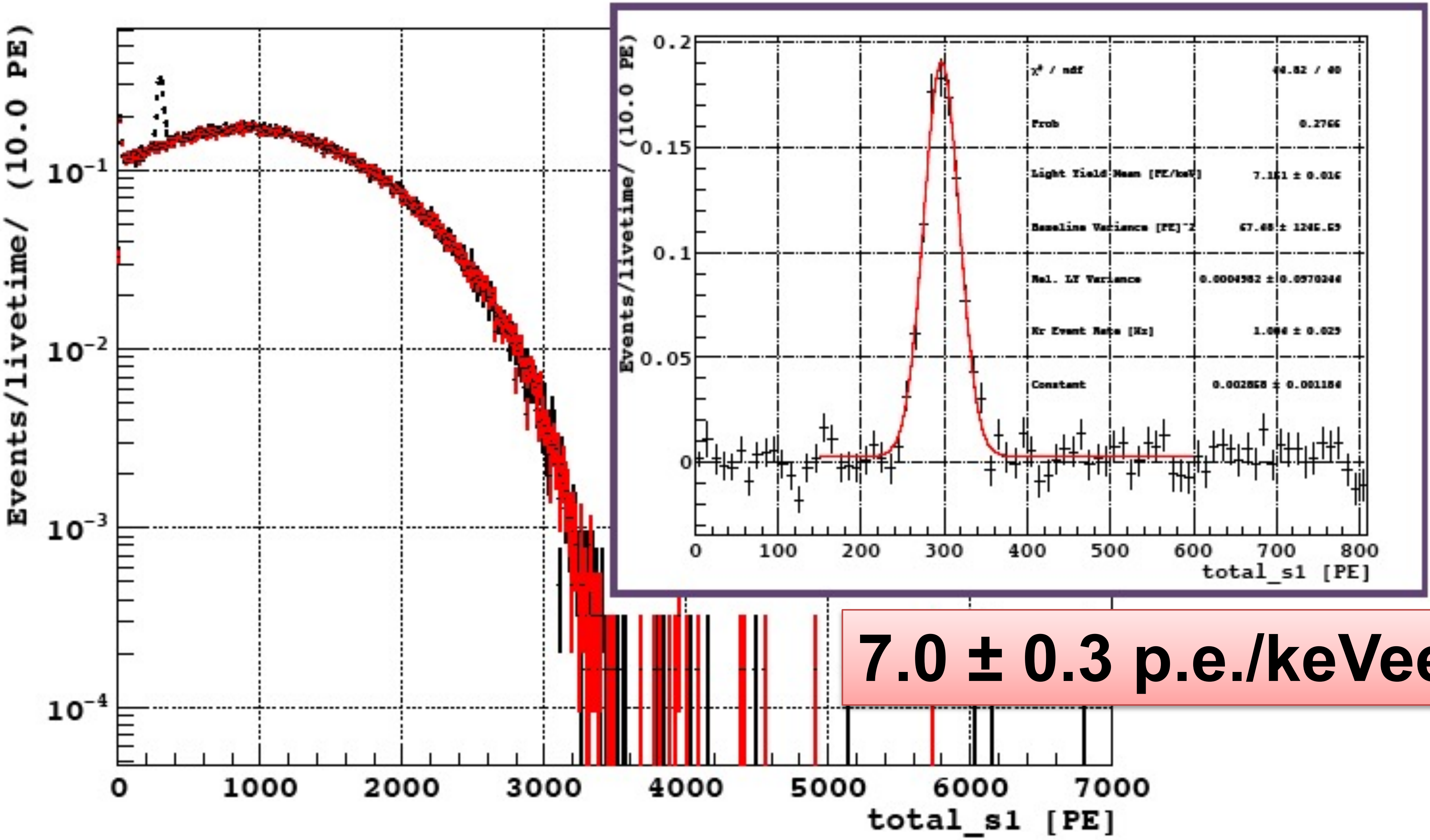
^{83m}Kr peak
41.5 keV, $T_{1/2}$=1.83h

^{39}Ar spectrum
565 keV

^{39}Ar + ^{83m}Kr energy calibration



Light Yield @ 200V/cm



7.0 ± 0.3 p.e./keVee

Calibration of the NR scale

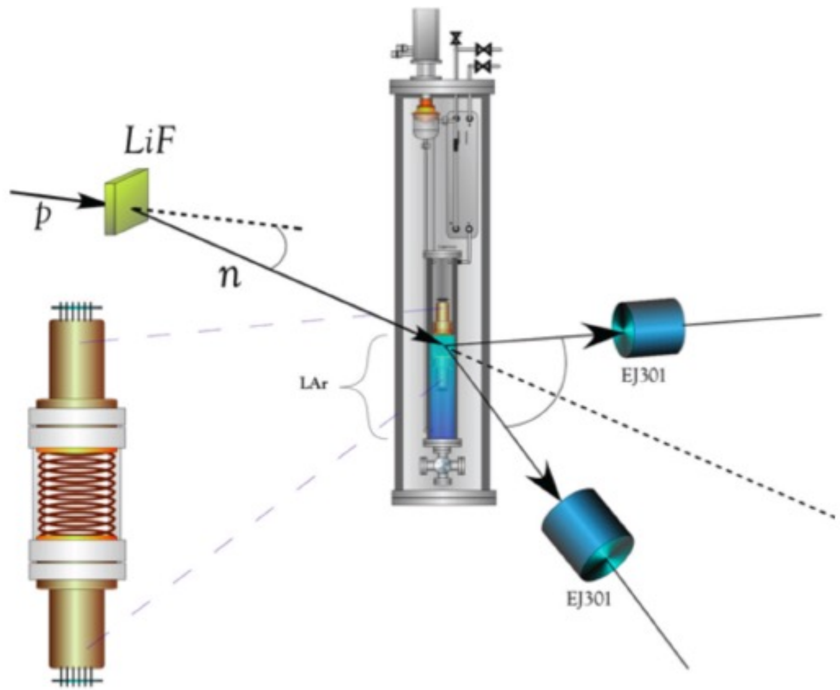
$$E_{ER} = w(n_\gamma + n_e)$$

$$E_{NR} = w(n_\gamma + n_e)\frac{1}{Q}$$ Q=quenching factor

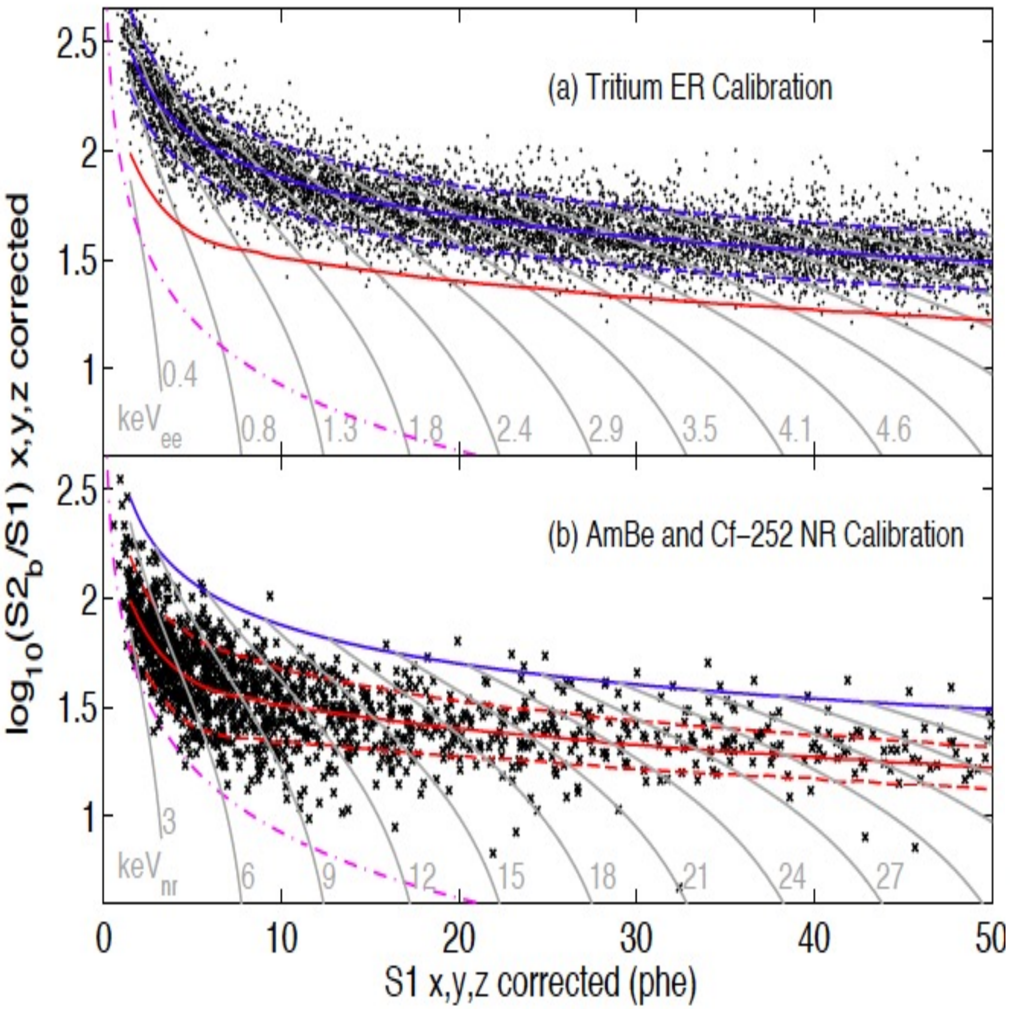
$$w_{Xe} \sim 14\text{keV} \quad w_{Ar} \sim 24\text{keV}$$

$$S_1(LAr) = L_Y \cdot E_{ER} = L_Y \cdot \boxed{Q(E_{NR})} \cdot E_{NR}$$

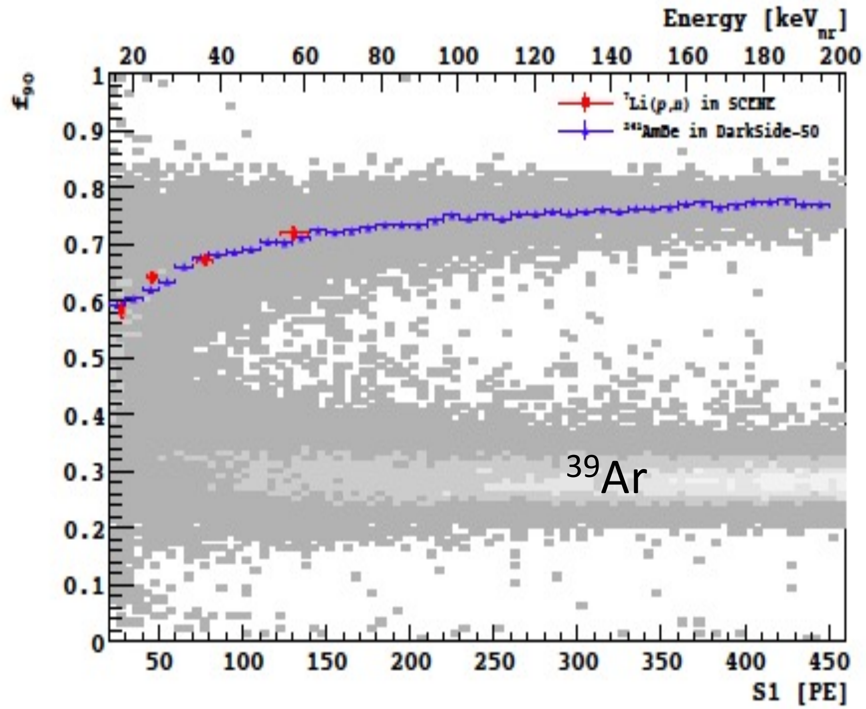
$$4E_{ER} \approx E_{NR}$$



Calibration of PSD parameters



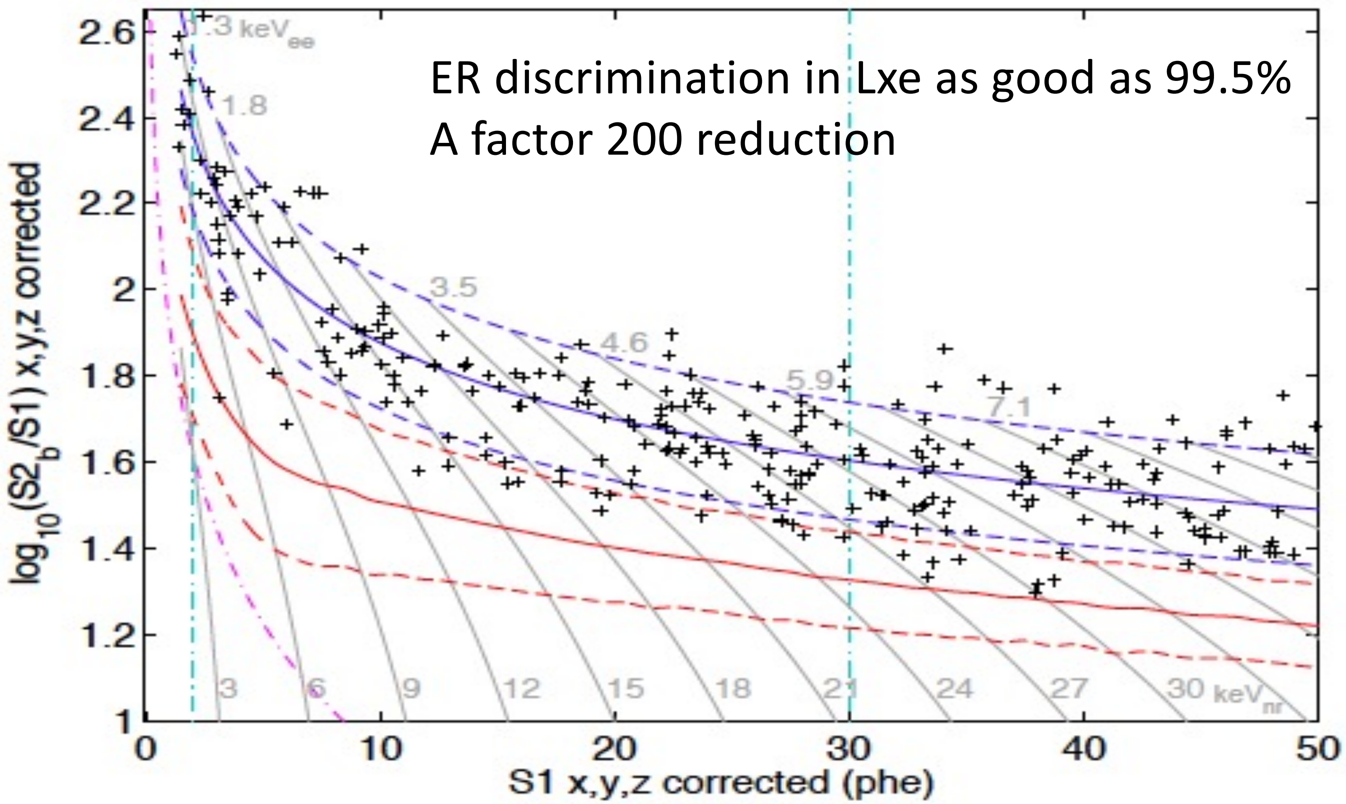
LUX coll., Rev. Lett. 112, 091303 (2014)



DS-50 coll., Phys. Rev. D 93, 081101 (2016)

LUX 2013 results

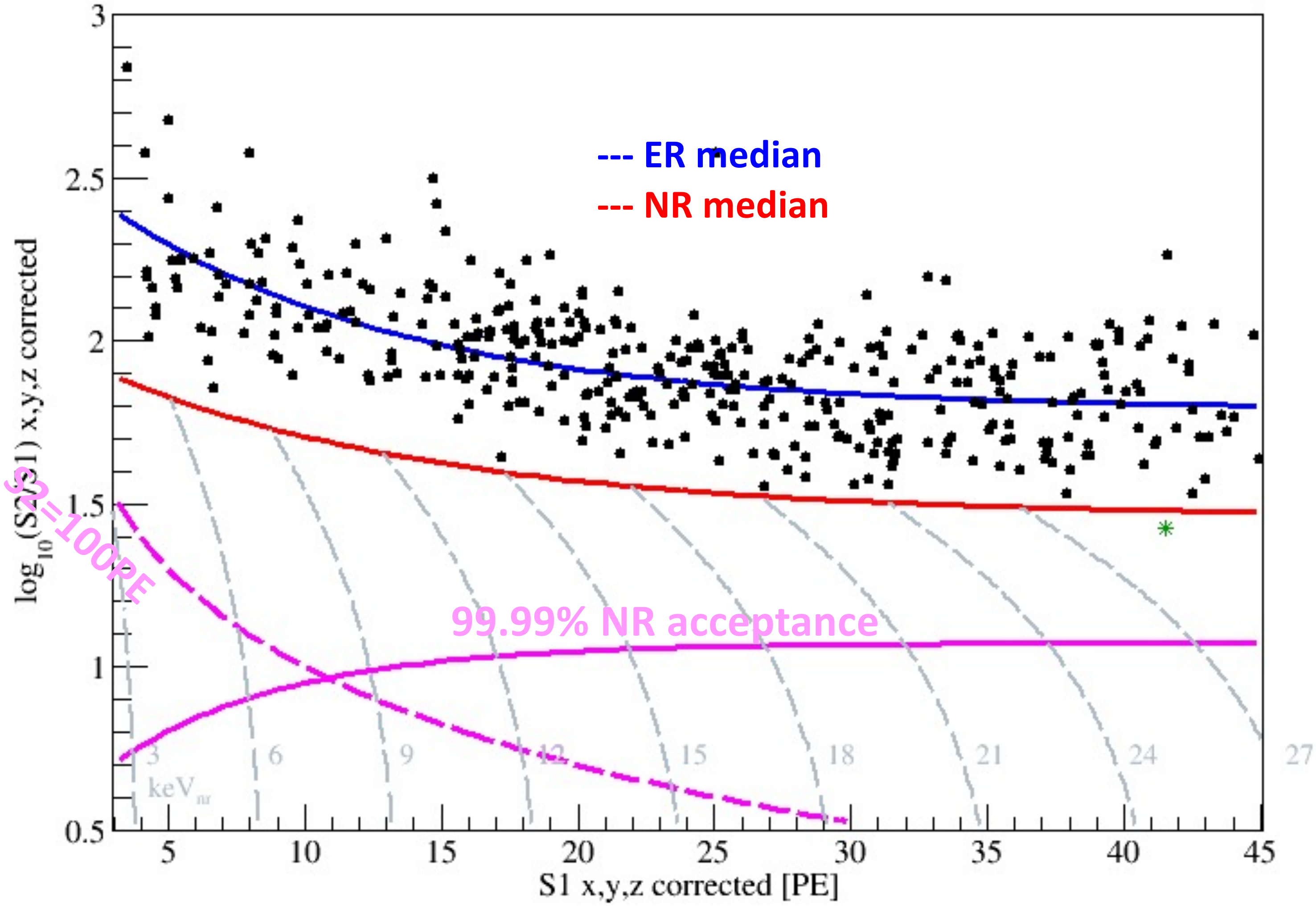
LUX data
85.3 live-days
118 kg
160 events in [2,30]phe
0.64 ER leakage with 50% NR acceptance



1DRU = 1 count/keV/kg/day

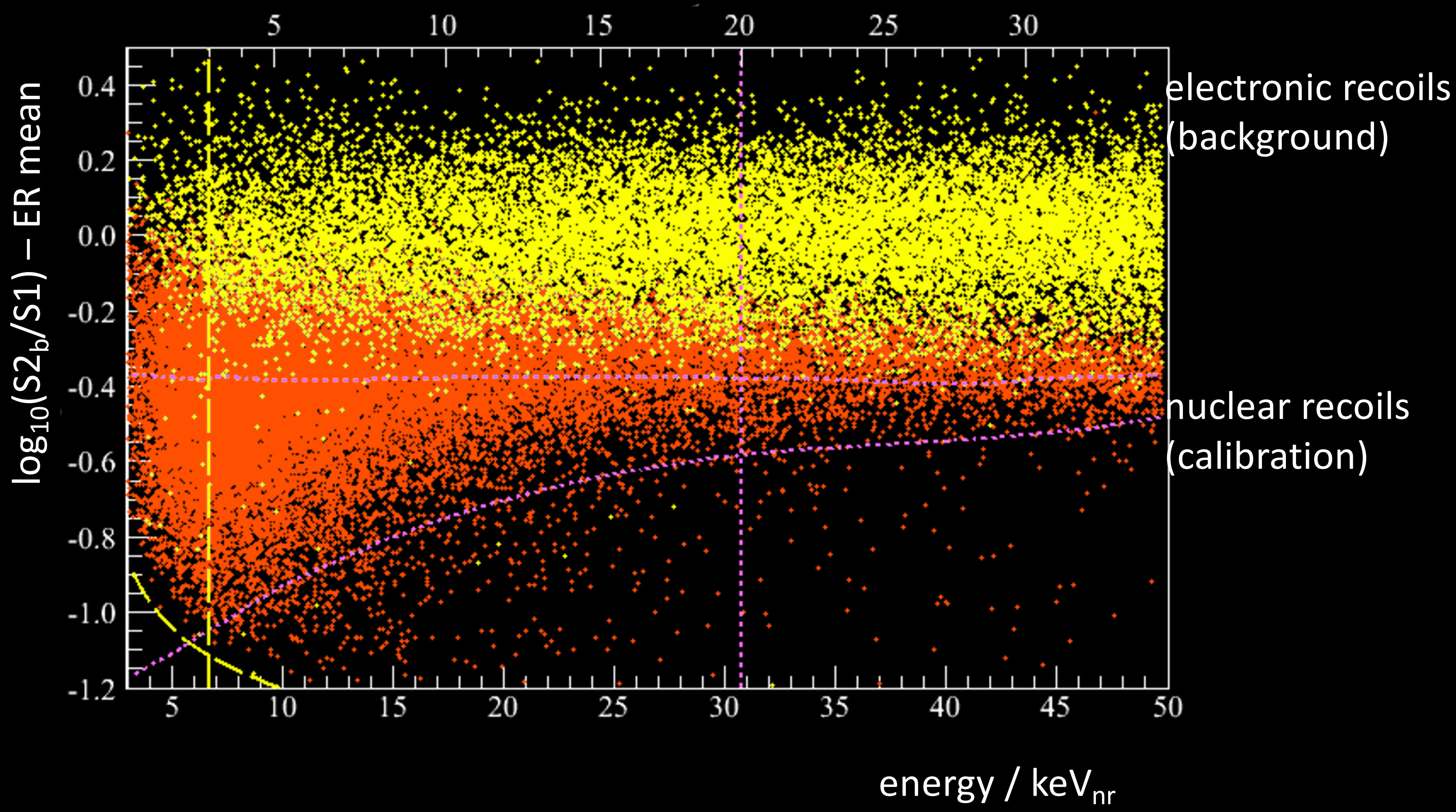
Source	Background rate [mDRU]
γ–rays	1.8±0.4
^{127}Xe	0.5±0.1
^{214}Pb	0.11-0.22 (90% C.L.)
^{85}Kr	0.13±0.07
Total predicted	2.6±0.4
Total observed	3.6±0.3

PandaX-II Run-9



Discrimination using S2/S1 in XENON100

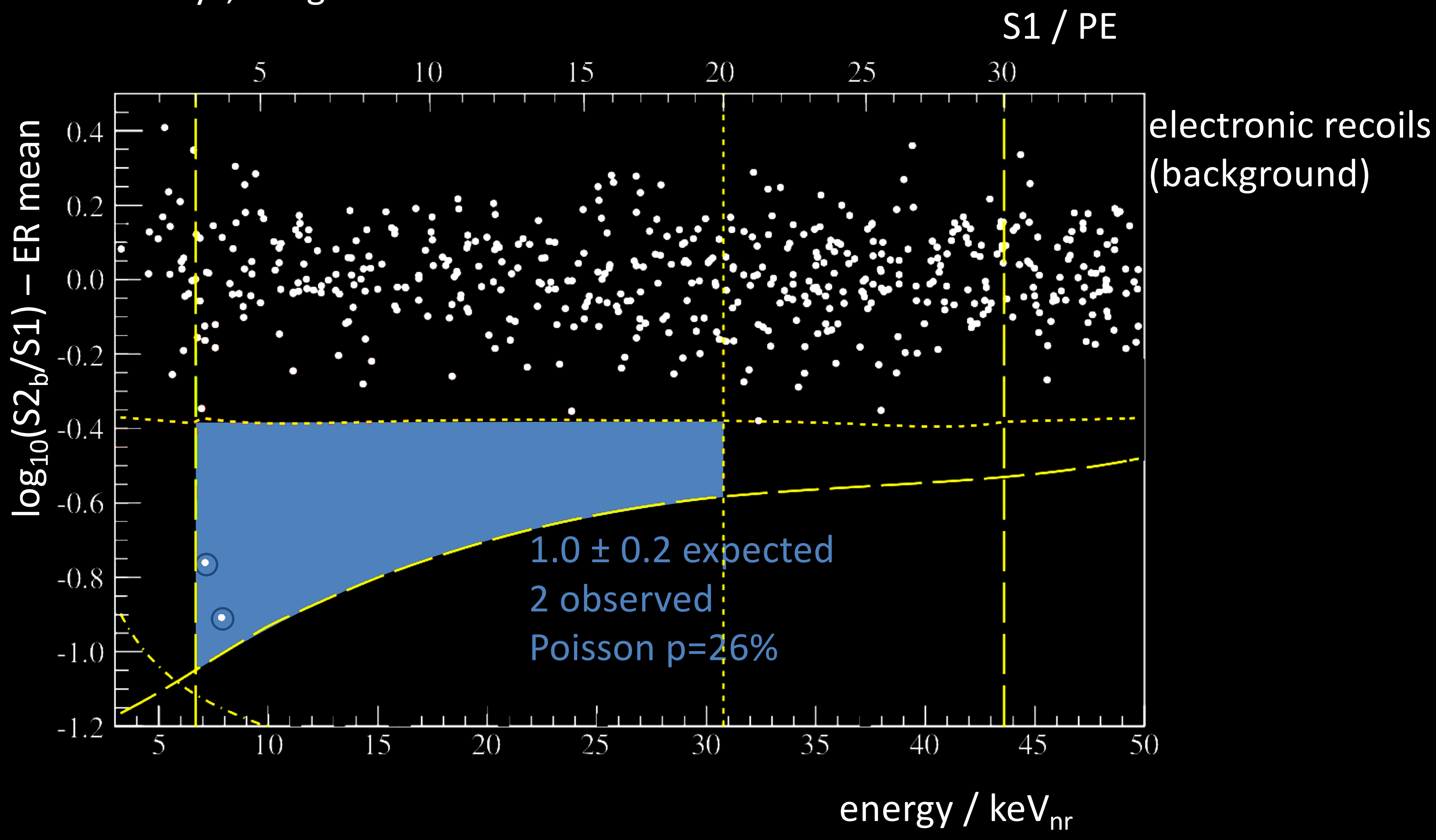
^{60}Co, ^{232}Th and ^{241}AmBe calibration



99.5% ER rejection @ 50% NR acceptance

XENON100: No Signal Observed

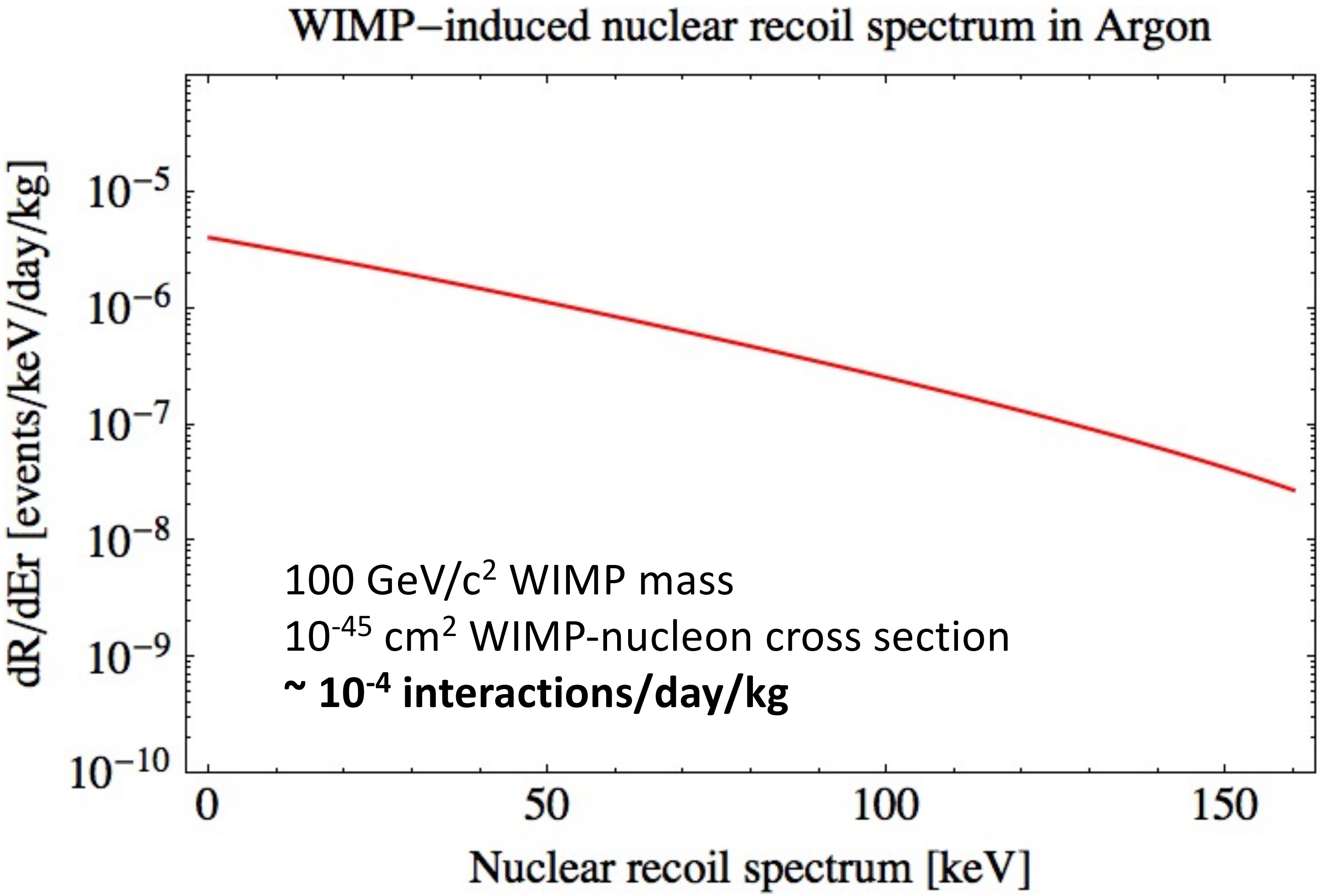
225 live days, 34kg fiducial:



likelihood analysis: background-only p-value

arXiv:1207.5988

Expected WIMPs Signal in LAr



Exposure of 1 ton-year gives about 40 events with these assumptions

The problem of ^{39}Ar

- ✓ Ar naturally present in the atmosphere at 1% level
- ✓ ^{39}Ar formed by cosmic muons interactions
  - $^{40}K(n,2n)^{39}Ar$
- ✓ ^{39}Ar is a β emitter with Q_β=565 keV and $T_{1/2}$=269 years
- ✓ In Ar from the atmosphere, ^{39}Ar is at the level of 1 Bq/kg
  - **~ 9×10^4 decays/kg/day**
  - WIMPs(100GeV, 10^{-45} cm^2) ~ **10^{-4} events/kg/day**

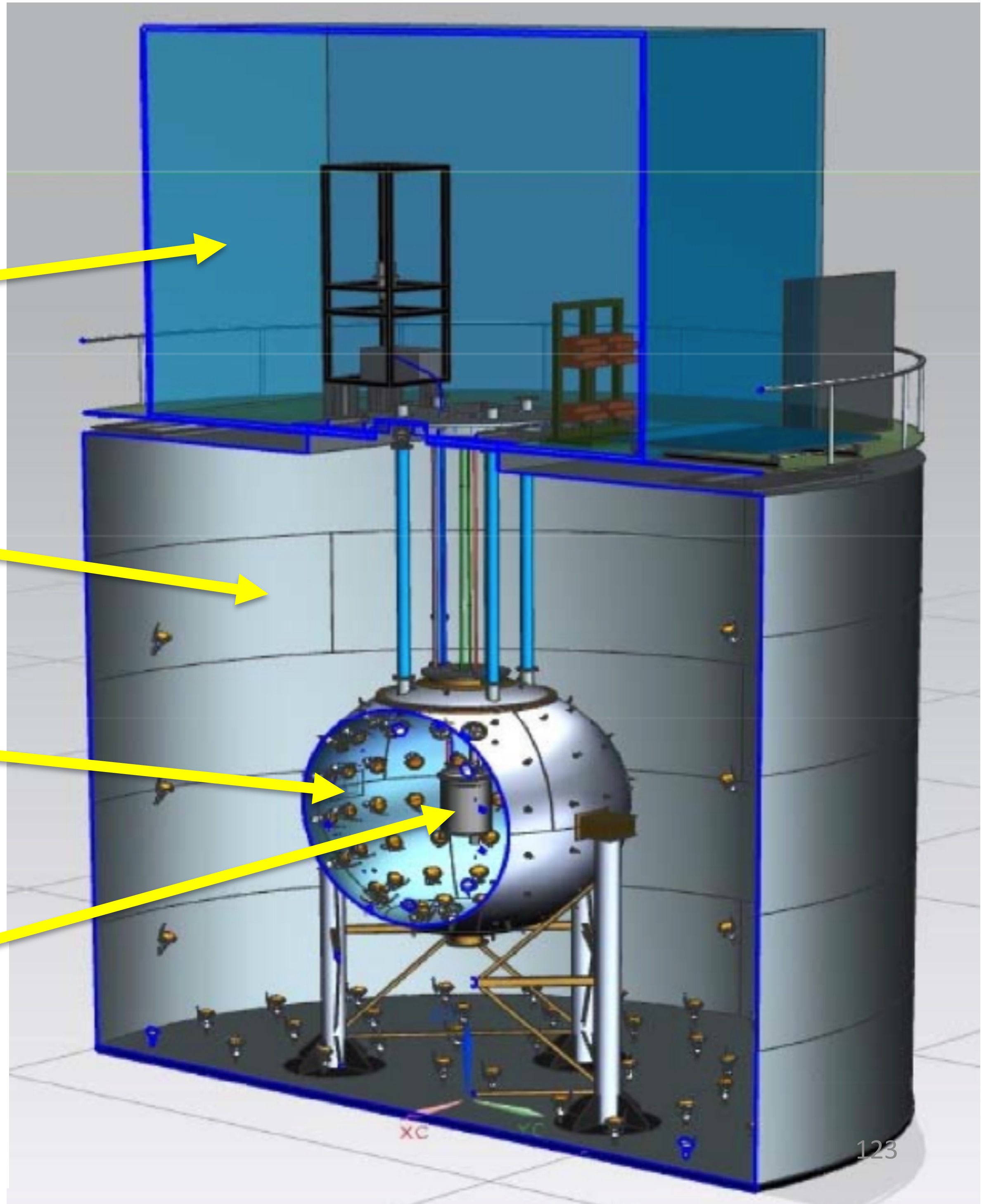
DS-50 @ LNGS

Rn-free clean room
(1-10 mBq/m^3 in 110 m^3)
Used for assembling TPC and deployment

Water Cherenkov muon veto:
10^3 m^3 H_2O with 76/80 8” PMTs

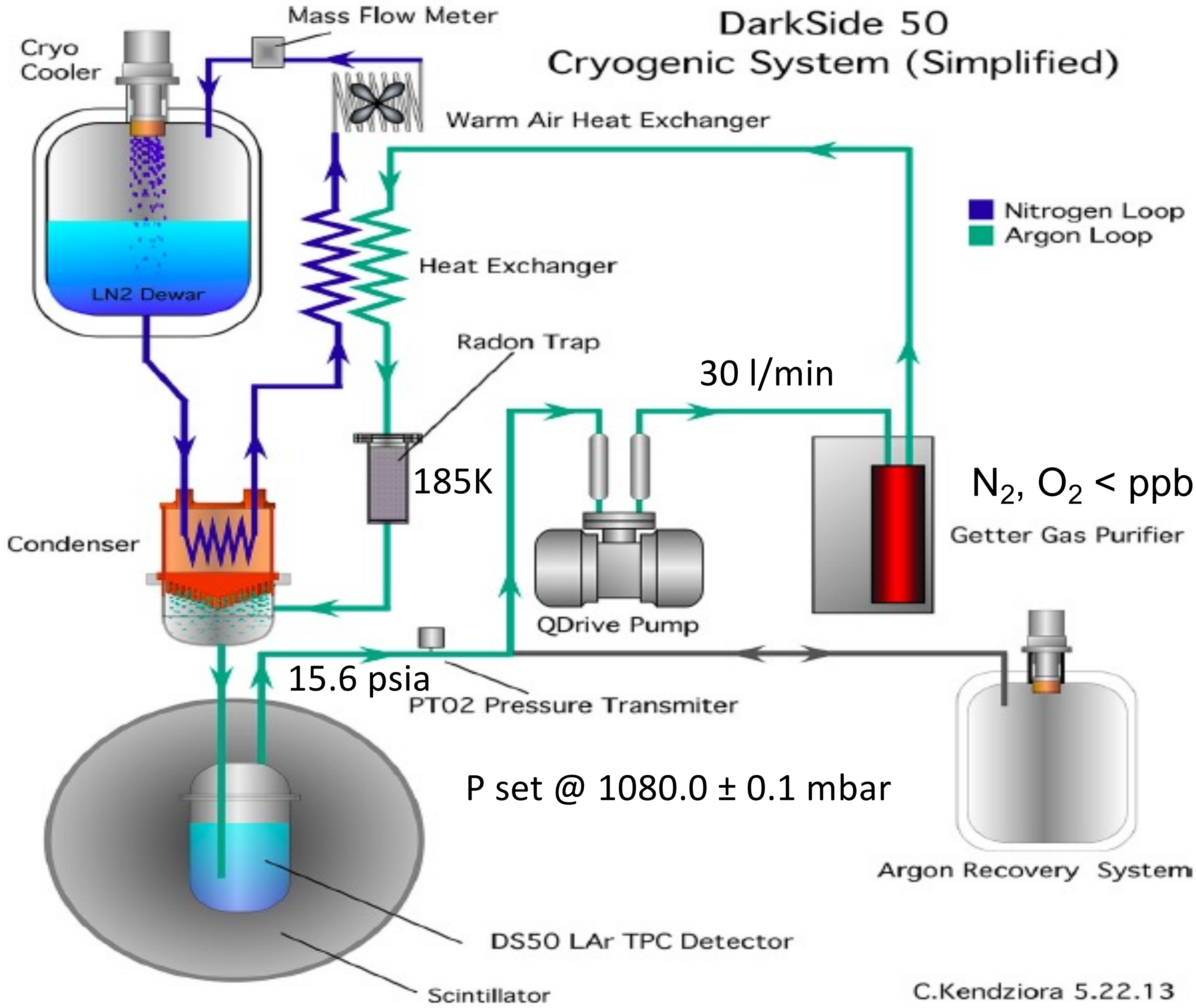
Boron-loaded liquid scintillator
(5% TMB + 95% PC) as neutron veto with 108/110 8” PMTs + 1.4 g/l PPO

150kg LAr TPC with 2 x 19 3” PMTs
AAr with 1Bq/kg ^{39}Ar
UAr with < 0.7 mBq/kg ^{39}Ar




Water Cherenkov

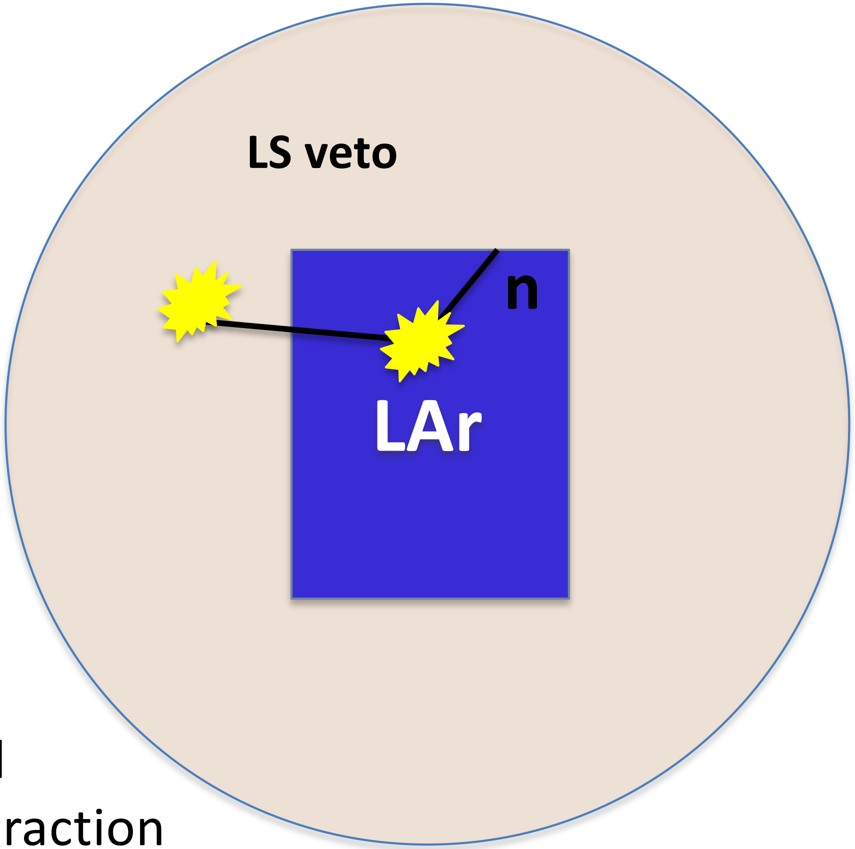
Cryogenic for DS-50 TPC



TPC hanging in LSV

Total inventory of the devices
110 new PMTs for the neutron veto
80 old PMT from CTF for the muon veto
plus a few spares

The Neutron Veto: general idea



A radiogenic neutron
from the cryostat steel
or PMTs makes an interaction
in LAr (WIMP-like) and later
is captured in the LS veto.
This type of event is rejected.

Neutron veto

- **30 tons of boron-loaded liquid scintillator**
  - 50% TMB [$B(OCH_3)_3$] + 50% PC + 3 g/l PPO

$$B(OCH_3)_3 + 3H_2O \rightarrow H_3BO_3 + 3CH_3OH$$

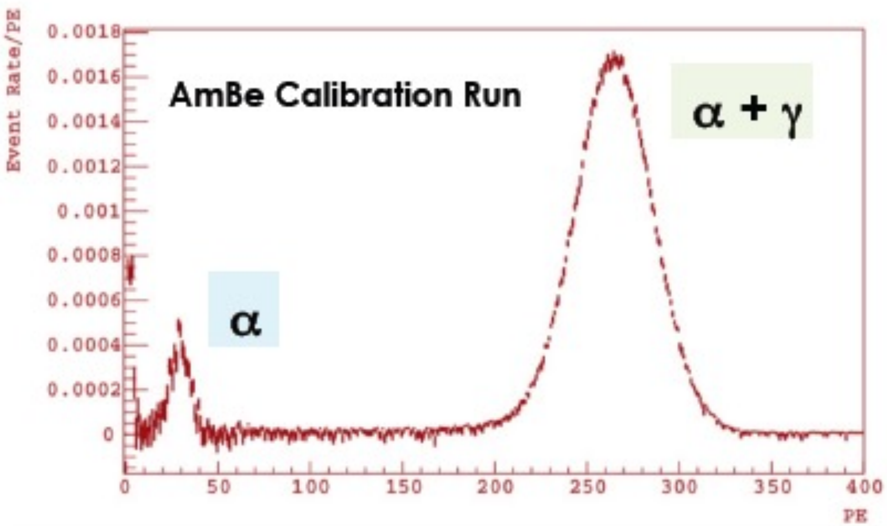
$$^{10}B(19.9\%) + n \begin{array}{l} \rightarrow \quad {}^{7}Li(\text{g.s.}) + \alpha(1775\text{ keV}),\ 6.4\% \\ \rightarrow \quad {}^{7}Li^{*} + \alpha(1471\text{ keV}),\ {}^{7}Li^{*} \rightarrow {}^{7}Li + \gamma(478\text{keV}),\ 93.7\% \end{array}$$

- 108 Hamamatsu R5912 8” PMTs with QE = 37% @ 408nm
- High reflectivity of inner surface of containment vessel
- n-veto expected performance: < 1 event in 3 years after n-veto rejection and TPC cuts

The Neutron Veto in DarkSide50

$n + {}^{10}B$ →

- ${}^{7}Li$ (1015 keV) + α (1775 keV) (6.4%)
- ${}^{7}Li^{*}$ (839 keV) + α (1471 keV) (93.7%)
  - → ${}^{7}Li$ + γ (478 keV)



Neutron Veto Efficiency

Efficiency from capture signal alone at > 99%
(from calibrations and simulations)

- ~0.6% of lost neutrons because of escaping proton capture gamma
- ~0.05% of neutrons leave no signal in LSV at all

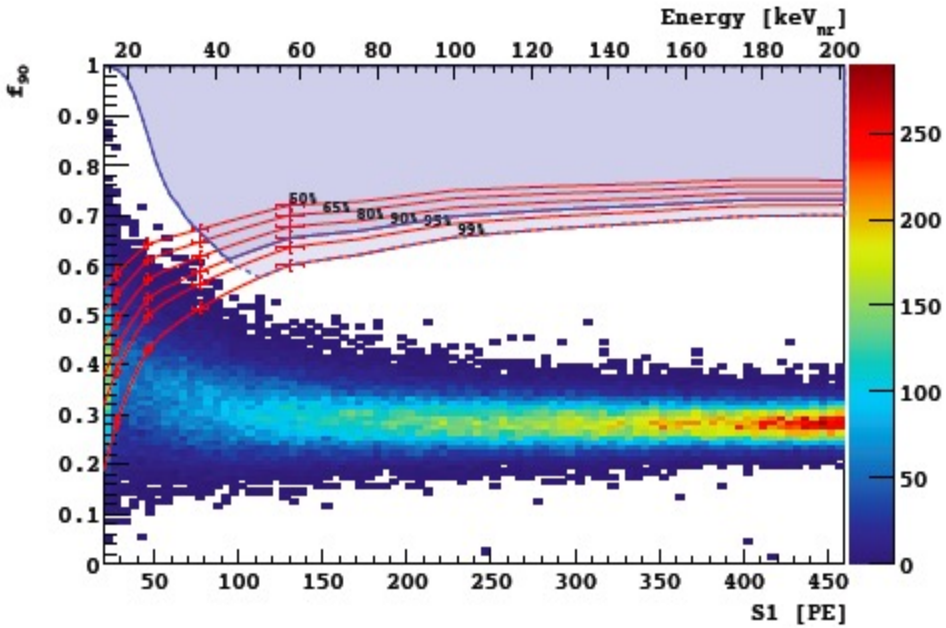
Larger total efficiency due to thermalization signal

Cut at 1 PE threshold: ~0.9% acceptance loss

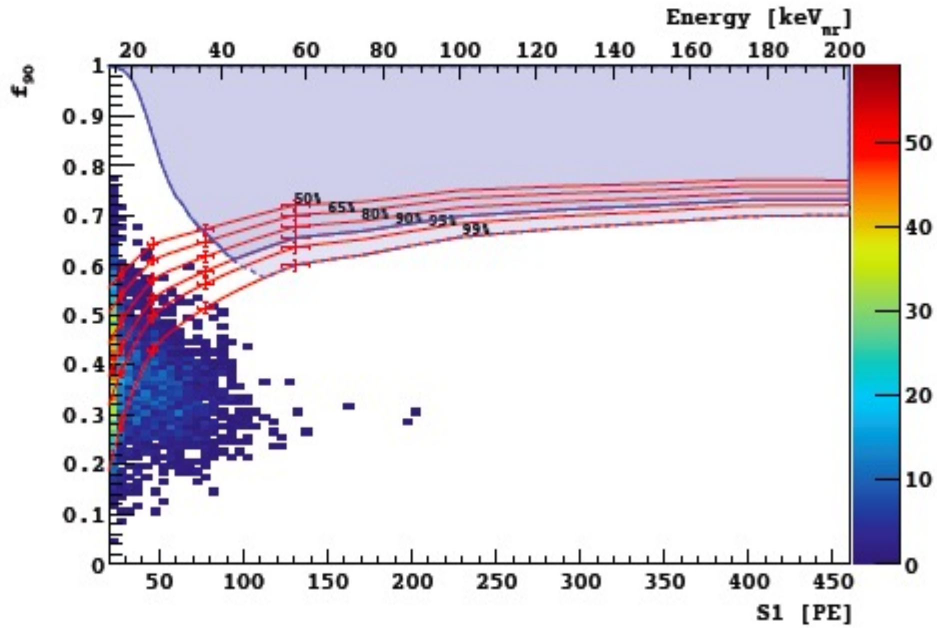
DarkSide-50 results

150 kg of LAr in cryostat with a 50 kg two-phase TPC

With Atmospheric Argon
1422 kg-day
PSD > 1.5×10^7



With Underground Argon
2616 kg-day
Depletion factor > 1400



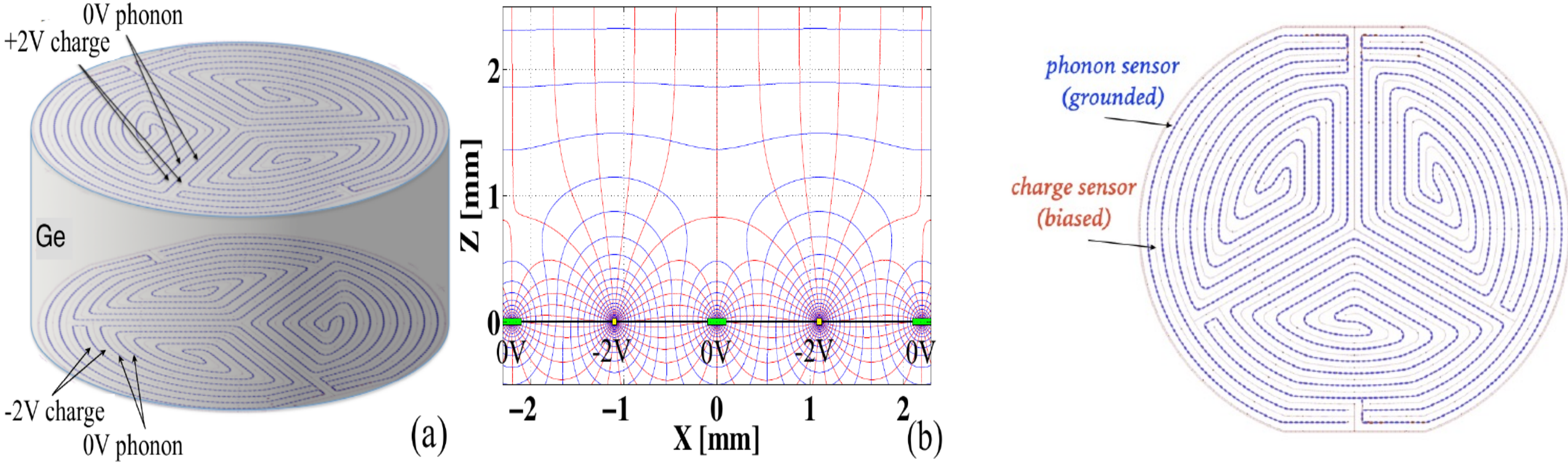
Cryogenic solid state detectors

- Need: an absorber, a refrigerator, a thermometer
- Readout both ionization and phonon signals
- High energy resolution
- Low thereshold
  - ~ 3 eV to create electron-hole pair against ~ 30 eV for scintillation photon
- Thermal and athermal sensors
  - Thermal needs thermalization of phonons within the bulk and sensor, ms timescale
  - Athermal measures non-equilibrium phonons
- Temperature change = E / C
  - 10 mK and 1 keV produces $\Delta T \sim 1\ \mu K$
- Phonon sensors: NTDs and TESs

Neutron Transmutation Doped (NTD) Ge Sensors

- Thermal sensors used as an example in CUORE
- Ge wafers are bombarded with neutrons to produce dopant impurities
- Dopant concentration determines the sensor performaces
- Strong dependence of resitance on temperature:
  - $R \sim T^{-g}$

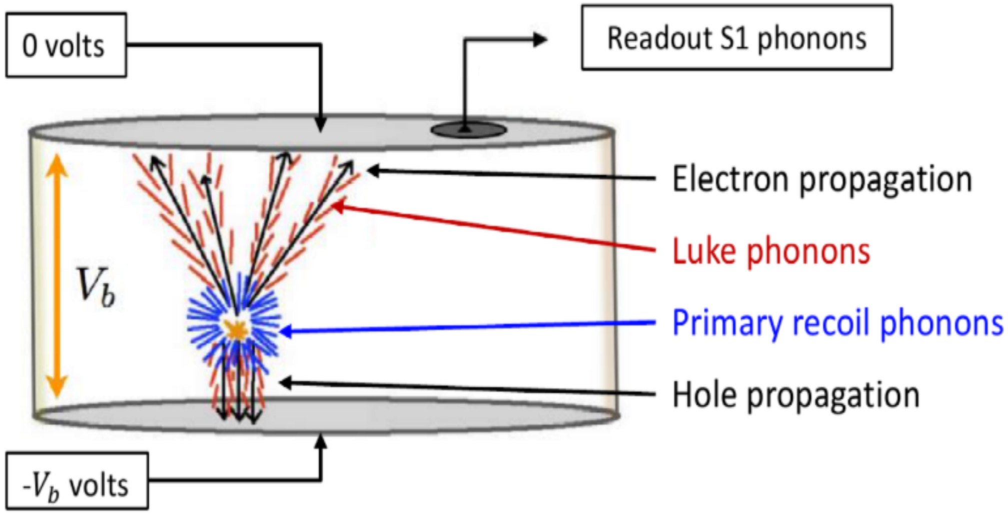
SuperSDMS at SNOLab



interleaved Z-sensitive Ionization and Phonon (iZIP) detectors for ionization and athermal phonon signals

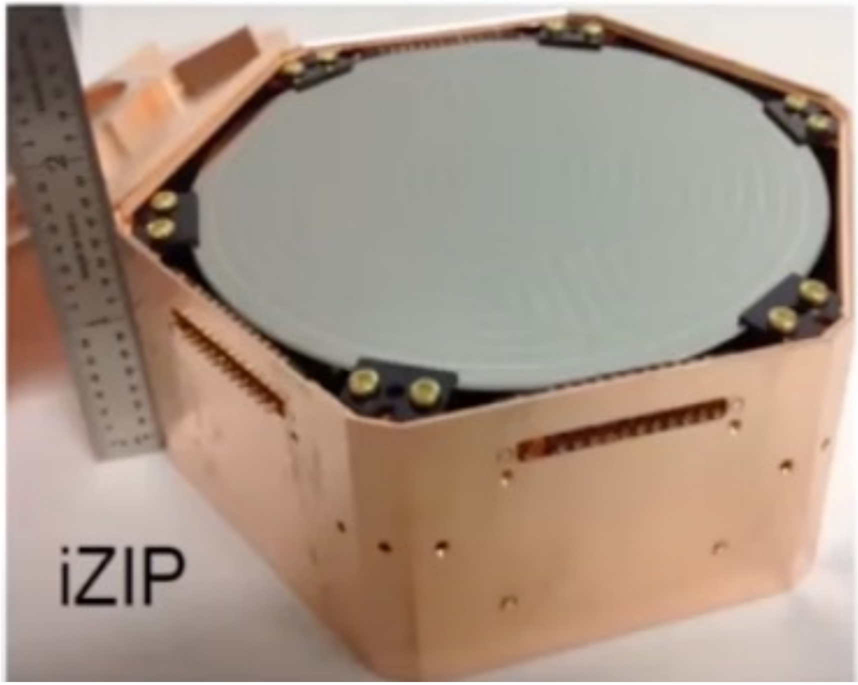
HV detectors

TES readout for athermal phonons



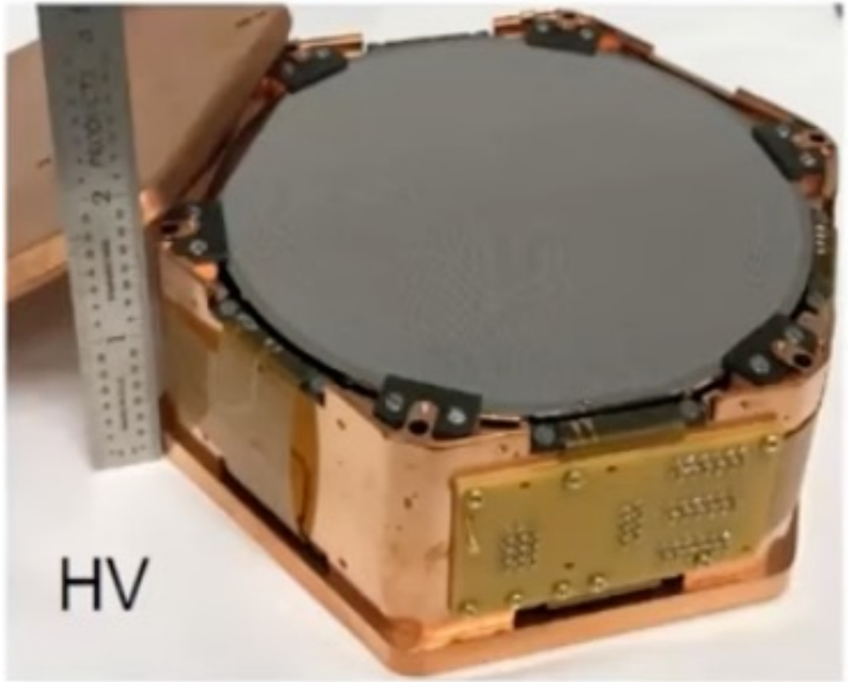
iZIP and HV detectors in SuperCDMS

Charge and phonons



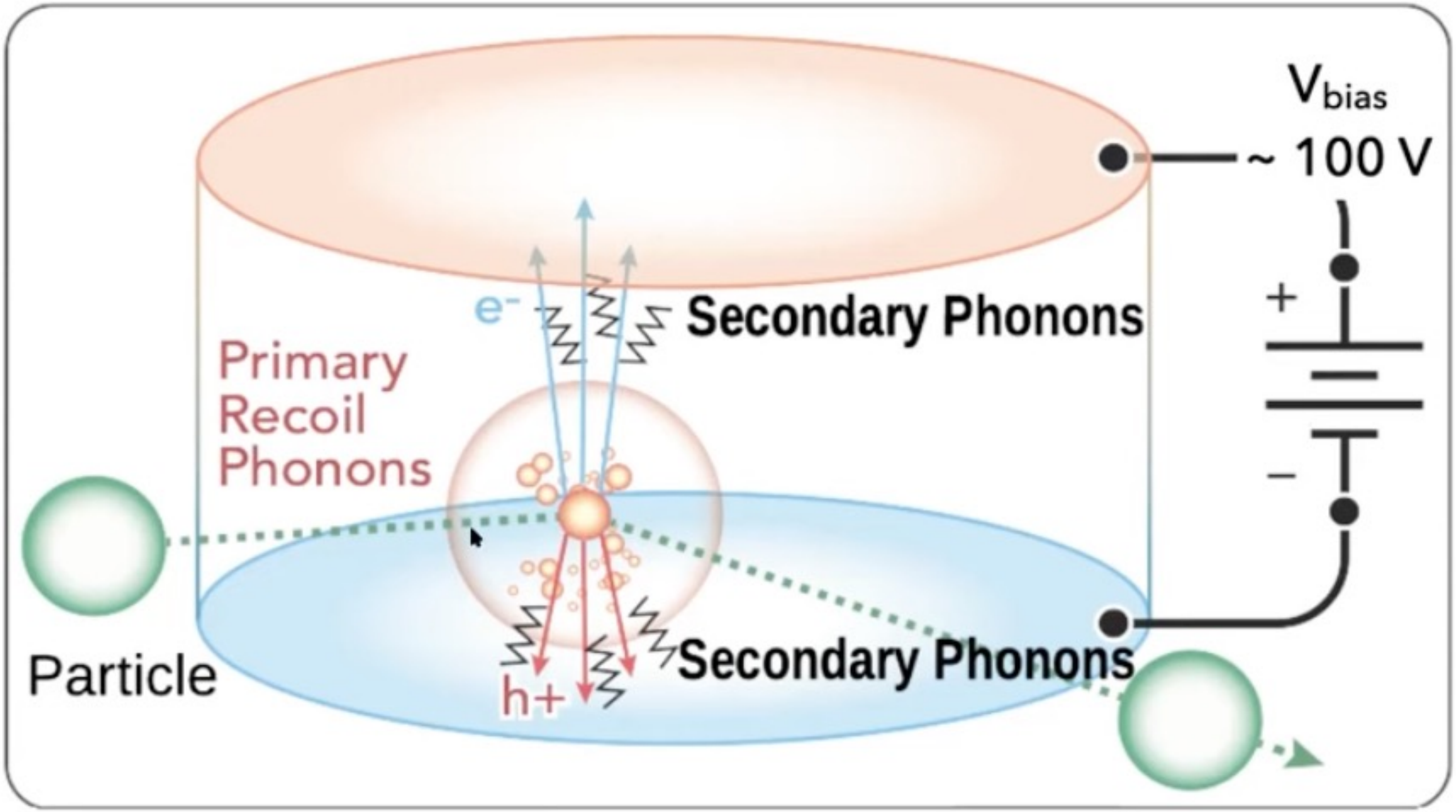
High PSD efficiency

phonons



Low threshold

Phonon amplification of ionization signal



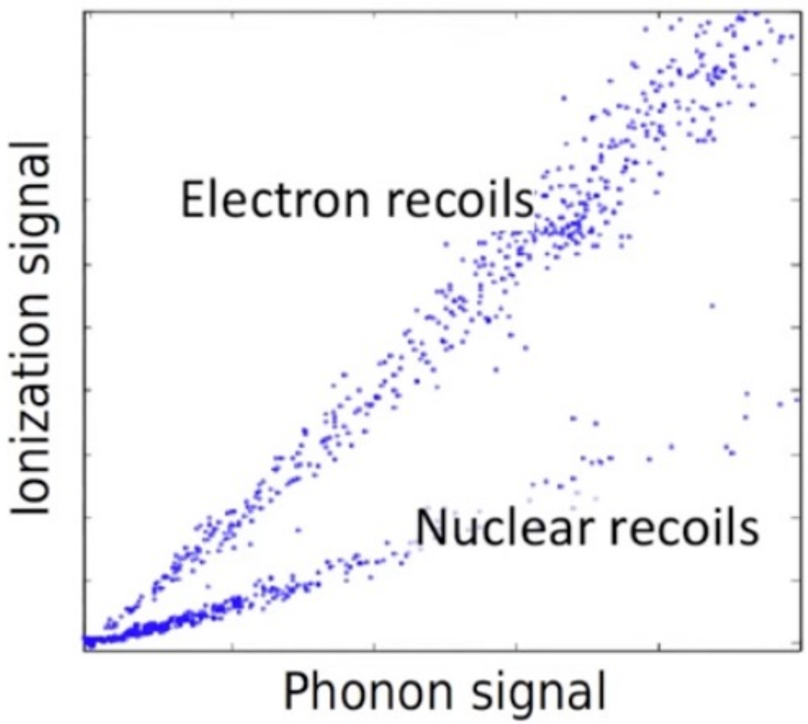
Neganov-Trofimov-Luke (NTL) effect: drifting electrons amplify phonon production

SuperCDMS

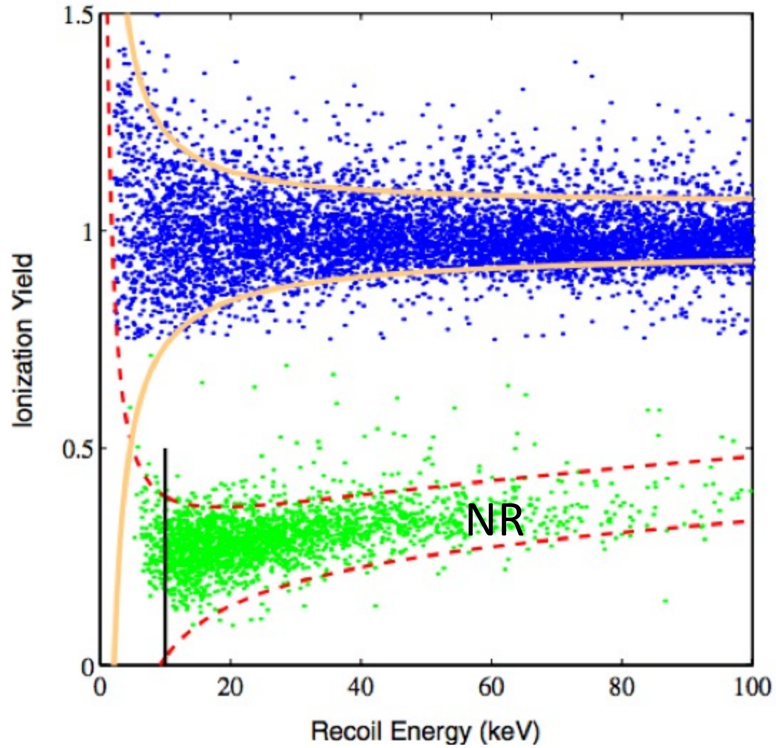
- Ge and Si target at 15 mK
- 30 kg in 24 detectors and 4 towers at SNOLab
- Each tower contains Ge (1.4kg) and Si (0.6kg) detectors
- Two towers with HV detectors to exploit NTL effect
  - $E_{NTL} = N_{eh}\, eV_b$ ($N_{eh} = E_r/\varepsilon$ with ε~3eV)
  - $E_{tot} = E_r + E_{NTL}$
- Detectors equipped to read both phonons (TES) and charge
  - Robust PSD for ER
- e,γ background ~ 0.1 dru
- Discrimination of surface background from charge distribution
  - Bulk event have symmetric distribution between top and bottom
- Sensitivity to m_χ ~ 0.3 GeV/c^2

PSD in SuperCDMS

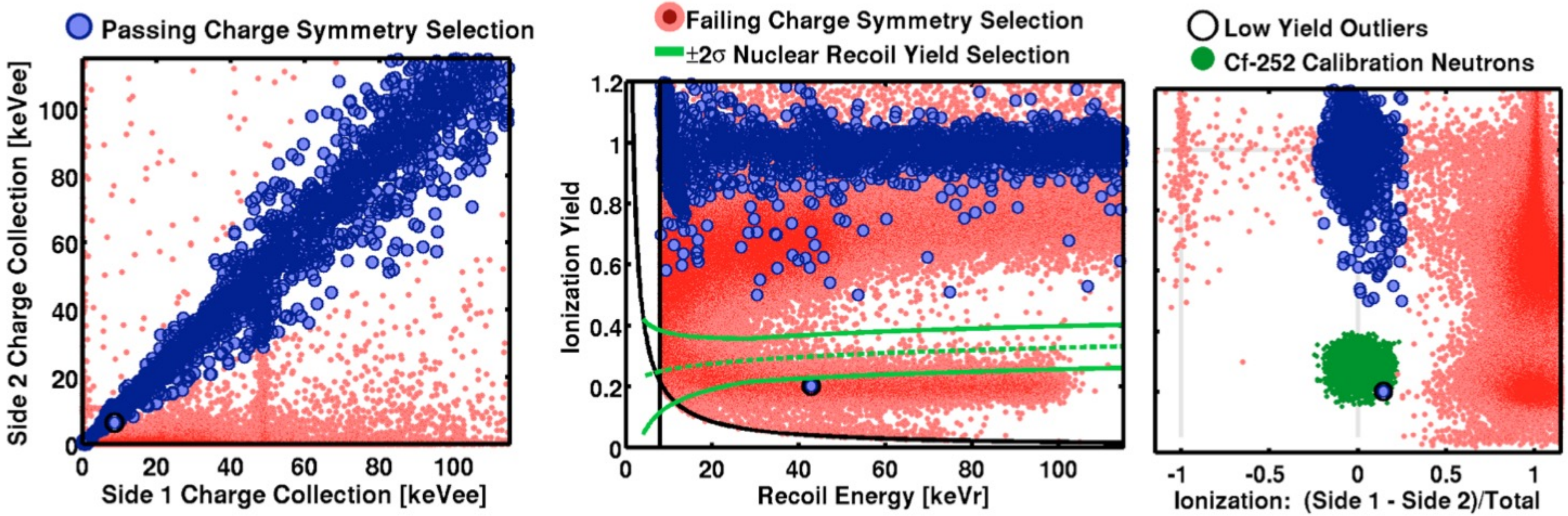
- ER produces a lot of ionization, much more than NR
  – ER gives high fraction of ionization and small fraction of phonons
- Yield = Charge / Phonon energy
- $Y_{NR} < Y_{ER}$



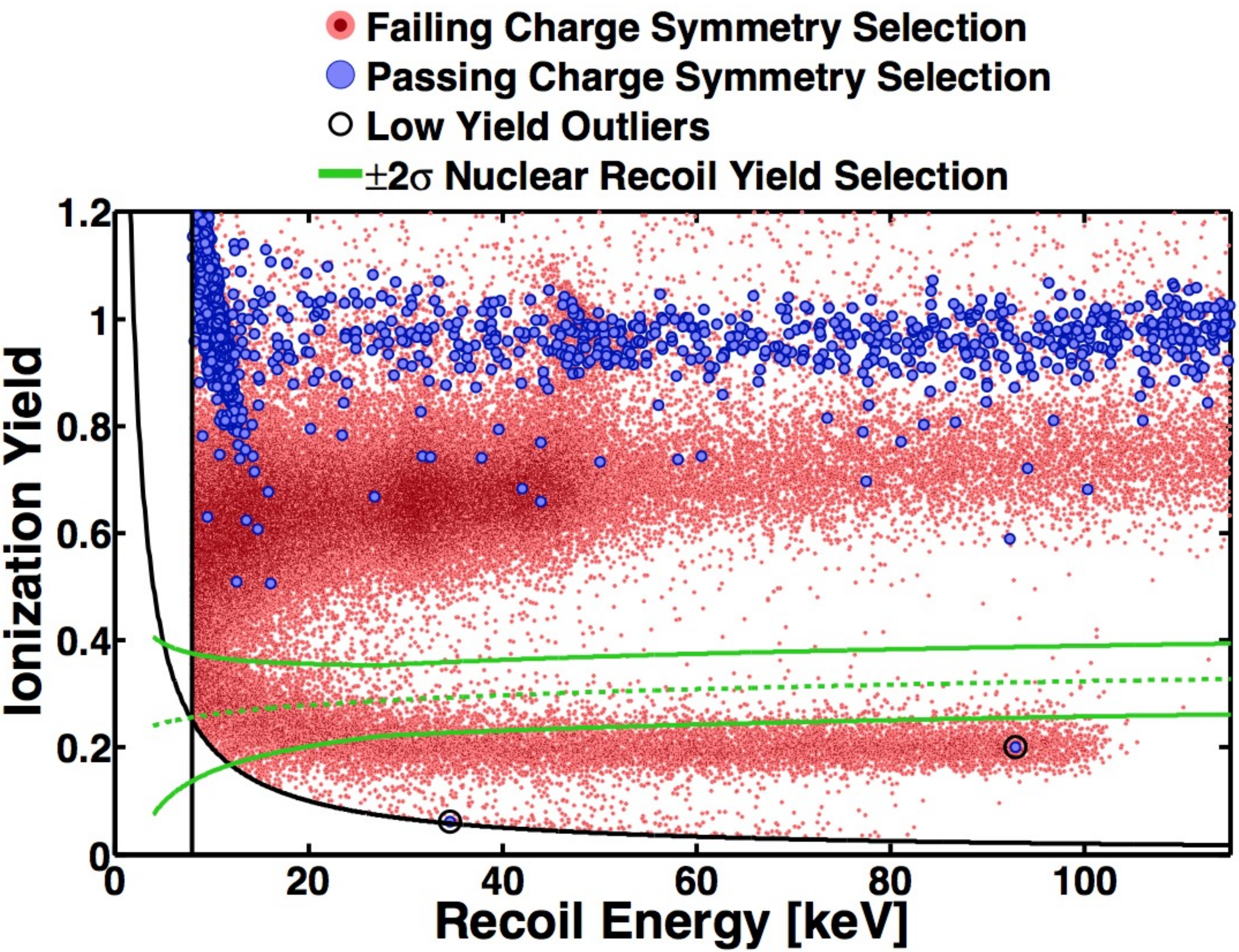
PSD at work



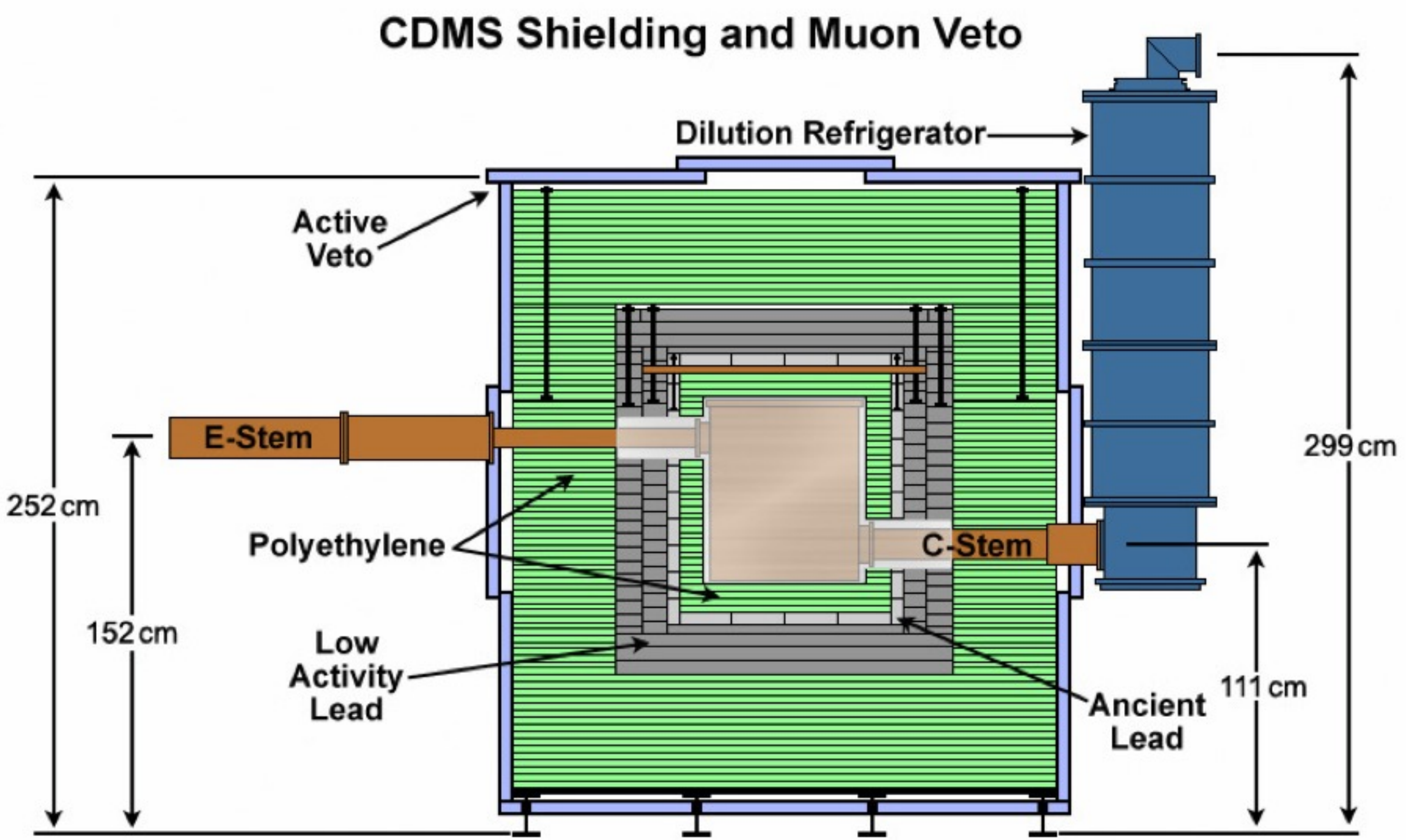
Ionization Yield
Recoil Energy (keV)
NR



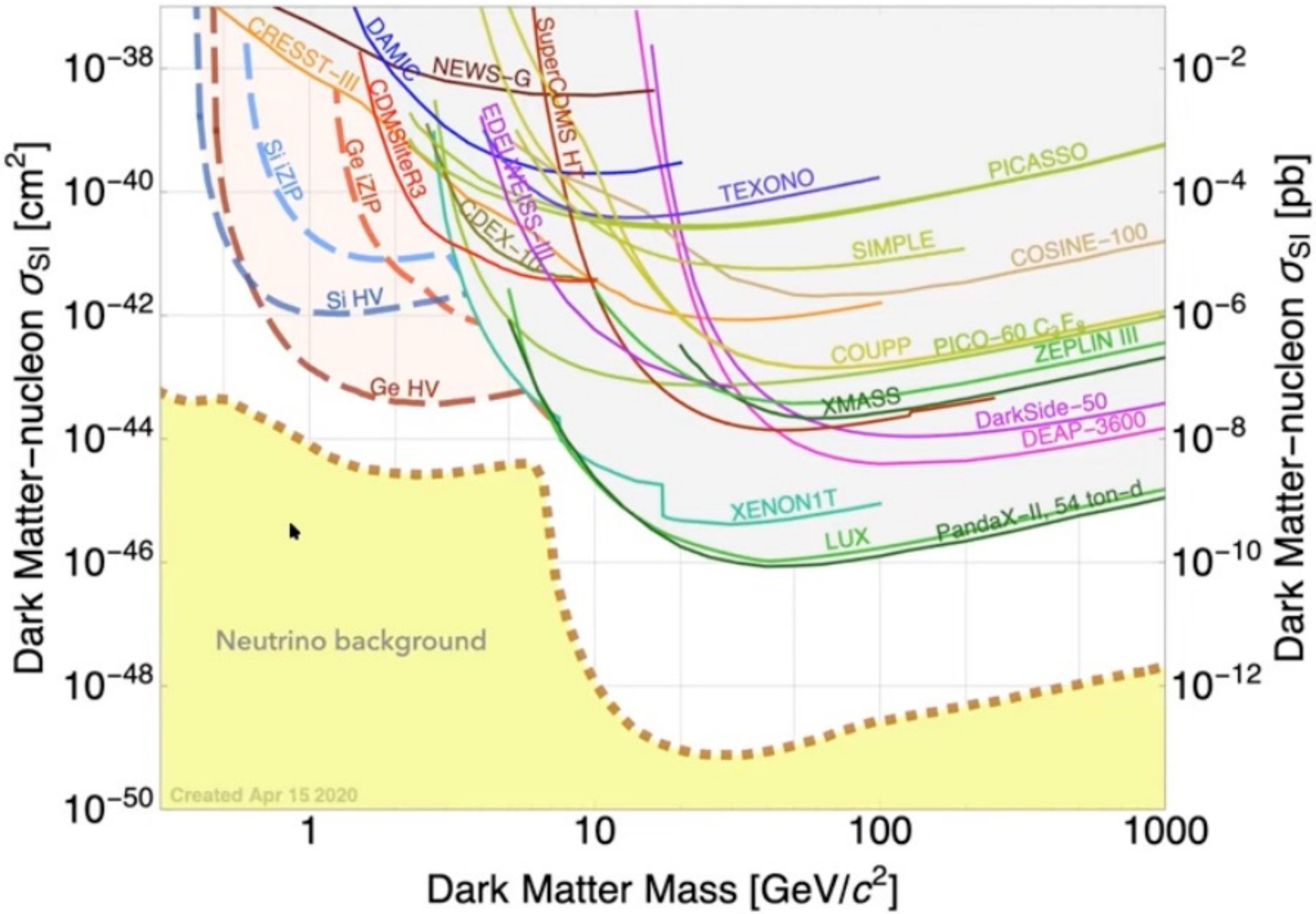
Passing Charge Symmetry Selection
Side 2 Charge Collection [keVee]
Side 1 Charge Collection [keVee]
Failing Charge Symmetry Selection
±2σ Nuclear Recoil Yield Selection
Ionization Yield
Recoil Energy [keVr]
Low Yield Outliers
Cf-252 Calibration Neutrons
Ionization: (Side 1 - Side 2)/Total



Failing Charge Symmetry Selection
Passing Charge Symmetry Selection
Low Yield Outliers
±2σ Nuclear Recoil Yield Selection
Ionization Yield
Recoil Energy [keV]
0
0.2
0.4
0.6
0.8
1
1.2
0
20
40
60
80
100

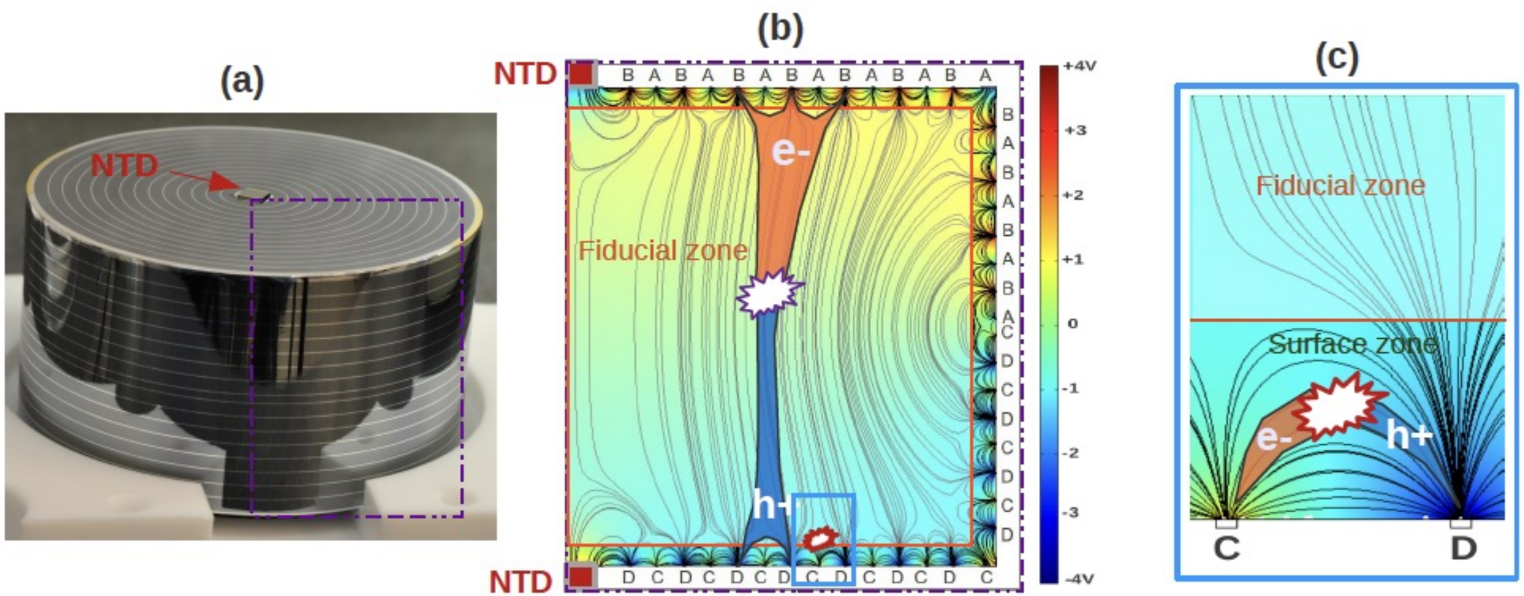

CDMS Shielding and Muon Veto
Dilution Refrigerator
Active Veto
E-Stem
252 cm
152 cm
Polyethylene
Low Activity Lead
C-Stem
299 cm
111 cm
Ancient Lead

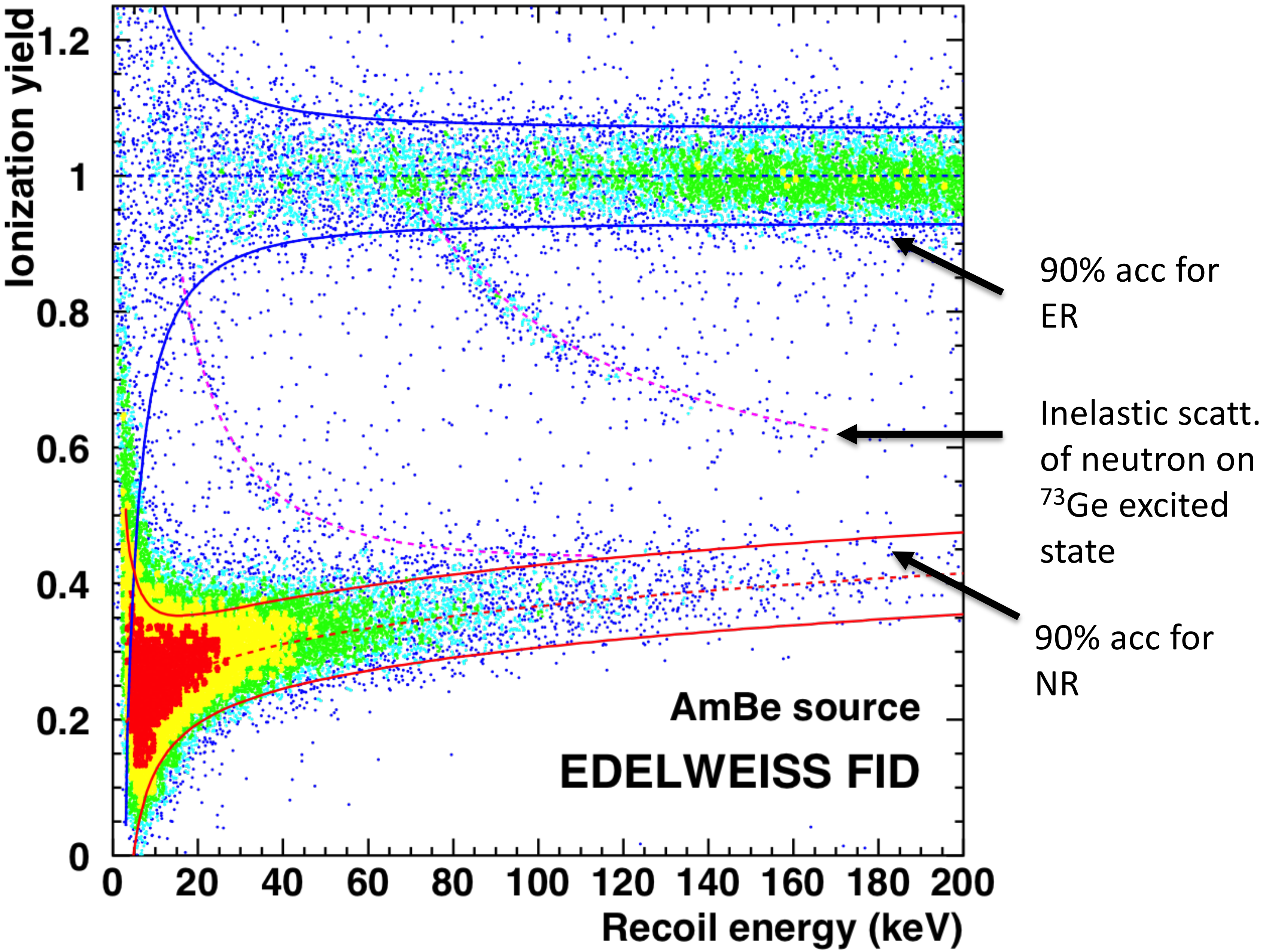
SuperCDMS 2023-2026



Edelweiss at LSM

24 Ge crystals operated at 18 mK (860 g each)
Phonons readout by two NTDs
Strong PSD down to 5 keV
Rejection power for ER events $4\text{x}10^{-5}$
WIMP search above 10 GeV/c^2 limited by n background

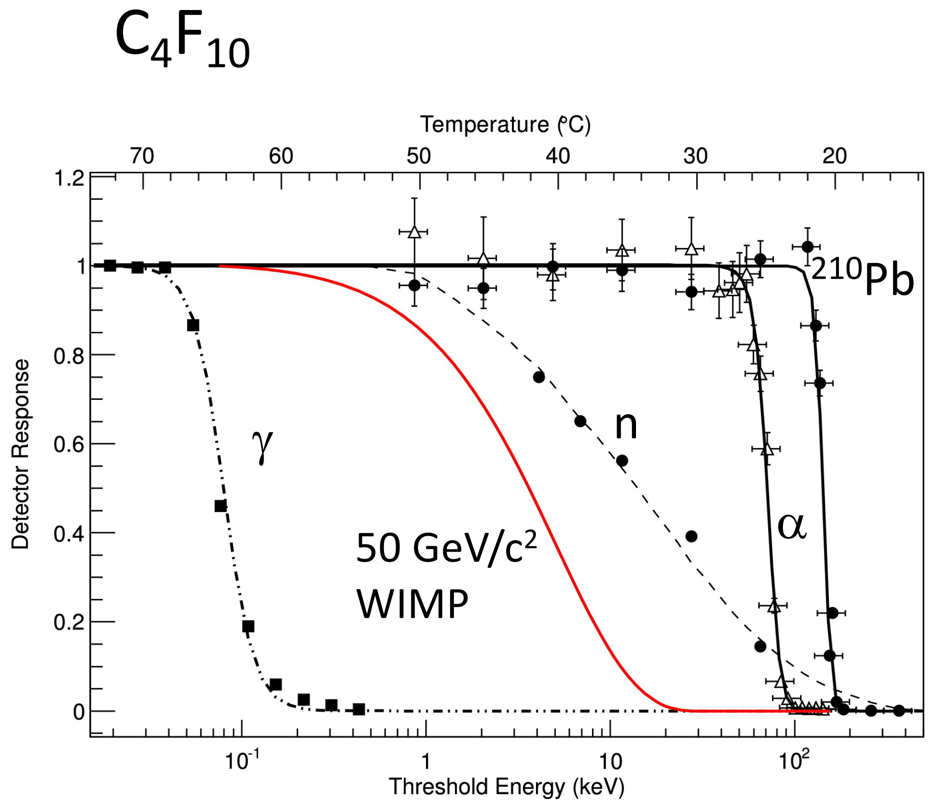




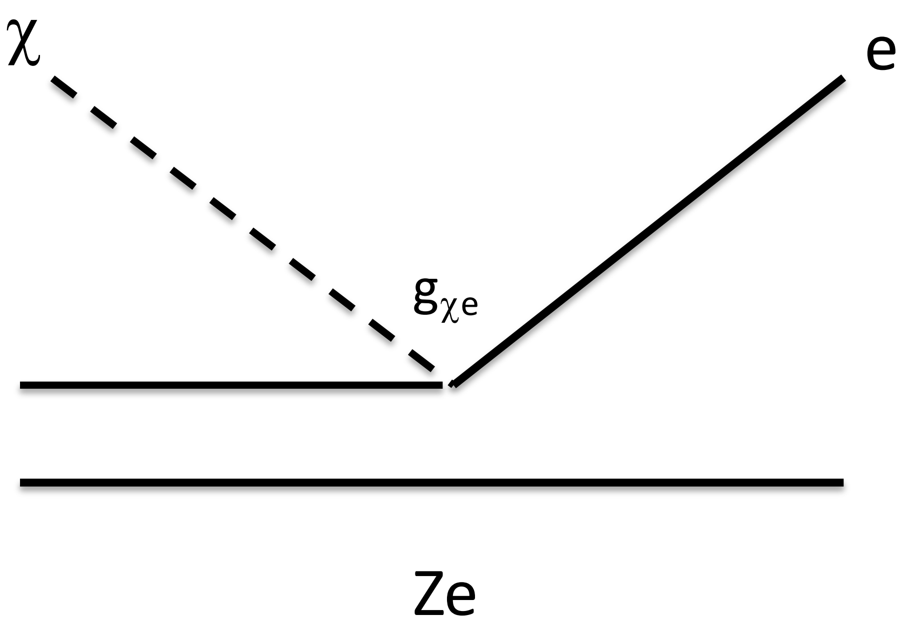
Ionization yield
Recoil energy (keV)
AmBe source
EDELWEISS FID
90% acc for ER
Inelastic scatt. of neutron on ^{73}Ge excited state
90% acc for NR

Superheated Liquids

- PICASSO, COUPP, PICO
- Sealed vessels with liquid under pressure
- Exploit bubble nucleation
  - Ionization produces gas bubbles
- Bubble grows if $P_b > P_l + P_s$
  - Bubble growth detected by acoustic sensors
- ER have much lower threshold than NR
- Alpha background can be discriminated by acoustic detector



ALP and dark photons with low threshold detectors



Electron emitted with the Incoming energy of DM particle

Probe eV scale mass

Deposited energy proportional to mass of incoming particle

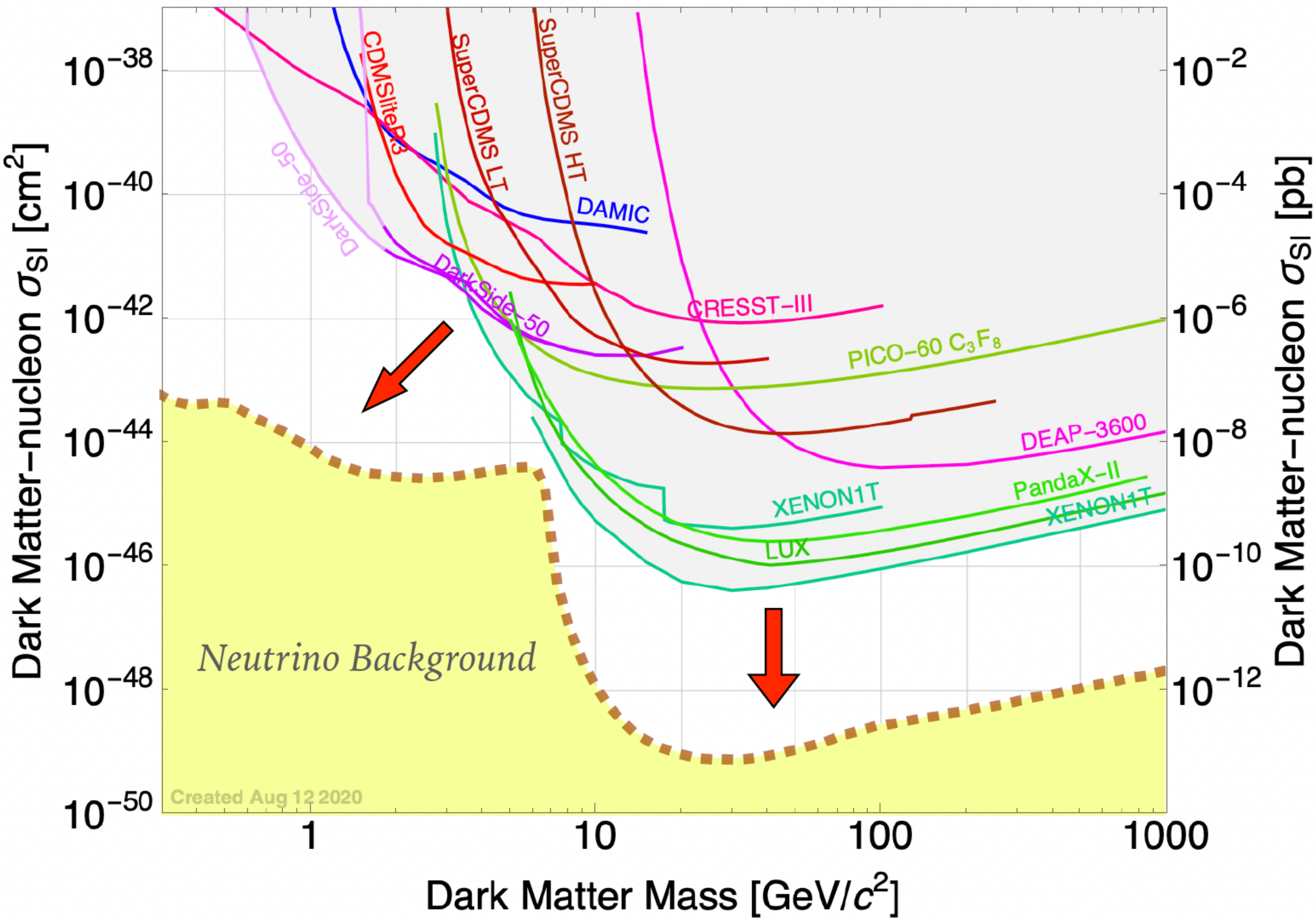
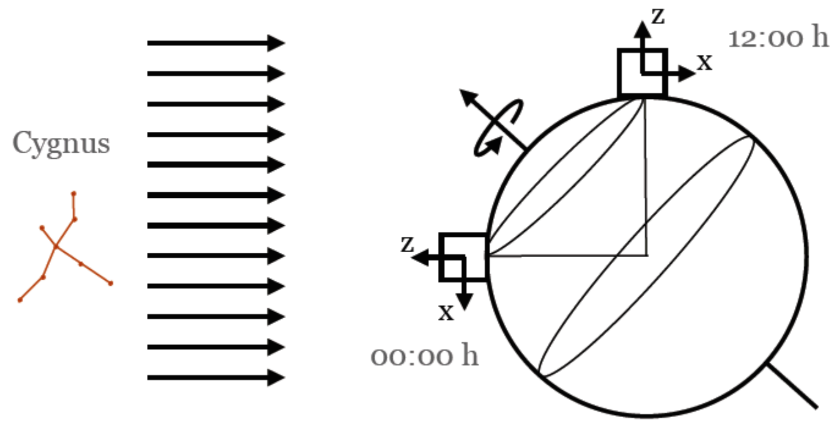


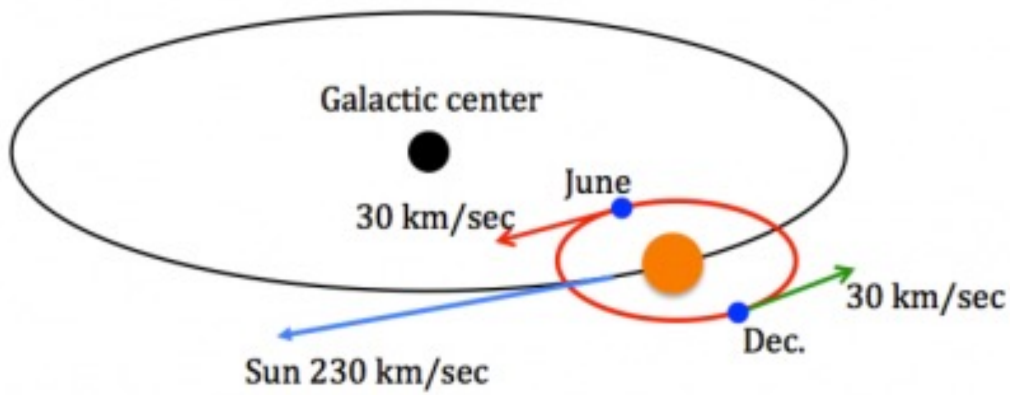
Image credit to J. Cooley

DM direct detection experimental signatures

- Daily forward/backward asymmetry due to Earth's rotation



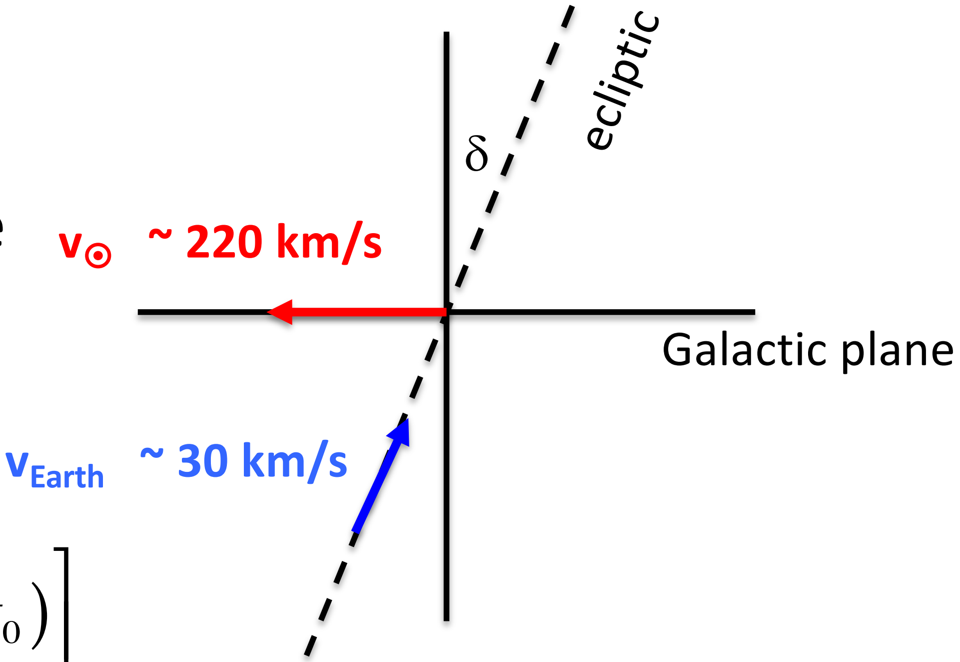
- Annual modulation



Direct Dark Matter search with NaI(Tl)

Annual Modulation of WIMP interaction rate

The WIMPs interaction rate is oscillating during one year due to the relative motion of the Sun with respect to the halo reference frame



$$v_\chi(t) = v_{sun} + v_{earth}\sin\delta\cos\left[\frac{2\pi}{T}(t-t_0)\right]$$

$$v_\chi(t) \sim 220 + 15\cos\left[\frac{2\pi}{365}(t-153)\right] \text{ km/s}$$

$$\boxed{R(E_r,t) = R_0(E_r) + R_1(E_r)\cos\left[\frac{2\pi}{365}(t-153)\right]}$$

Expected modulation (at **% level**) of

1. rate
2. spectral shape

This is a **model independent signature**

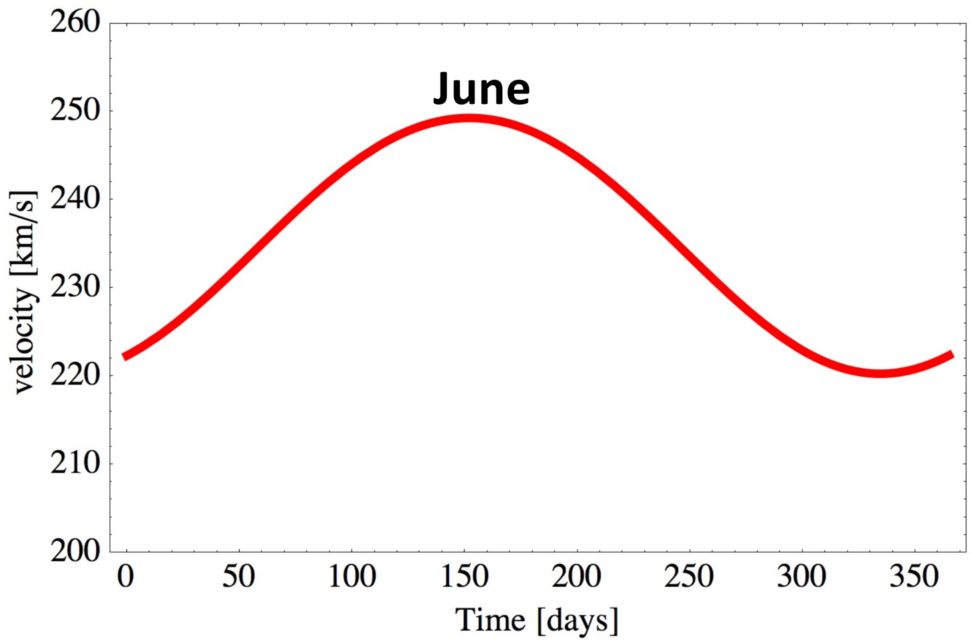
DM annual modulation

- 100 GeV/c^2 gives a flux of ~10^5 $cm^{-2}s^{-1}$

$$S(\theta,t) = S_0(\theta) + \boldsymbol{S_m(\theta)} \cos\left(\frac{2\pi}{T}(t-t_0)\right)$$

- S_m ~ few%S_0

- for a NaI target experiment
  - S_0 ~ 0.1 cpd/kg/keV in [2,6] keV
  for $\sigma=10^{-42}$$cm^2$



NaI detectors and DM direct searches

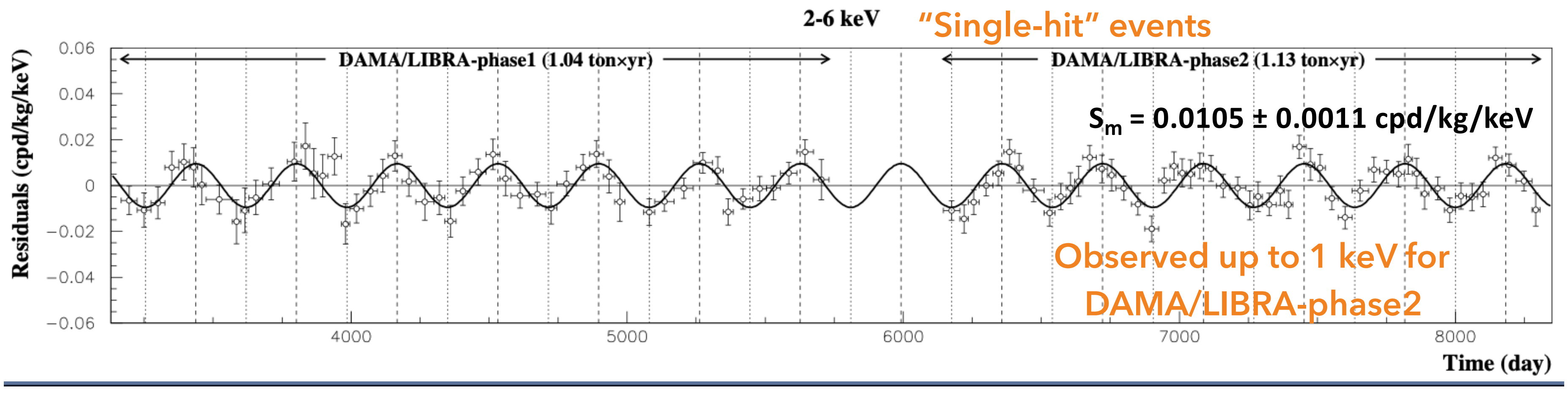
- **DAMA/LIBRA**
  - 250 kg running at LNGS since 2003
  - Upgrade in 2010 (Phase 2) running since 2011
    - Replaced PMTs, new preamplifiers and trigger
  - $S_m = 0.0105 \pm 0.0011$ cpd/kg/keV in [1,6]keV for 1.13 ton x yr (only Phase 2)
- **ANAIS**
  - 112.5 kg running at LSC since 2017
  - $S_m = -0.0034 \pm 0.0042$ cpd/kg/keV in [1,6]keV for 313.95 kg x yr
- **COSINE-100**
  - 106 kg running at Yangyang since 2016
  - $S_m = 0.0092 \pm 0.0067$ cpd/kg/keV in [2,6]keV for 97.7 kg x yr

DAMA/LIBRA

Phase 1 in [2,6] keV: ~**1 cpd/kg/keV**

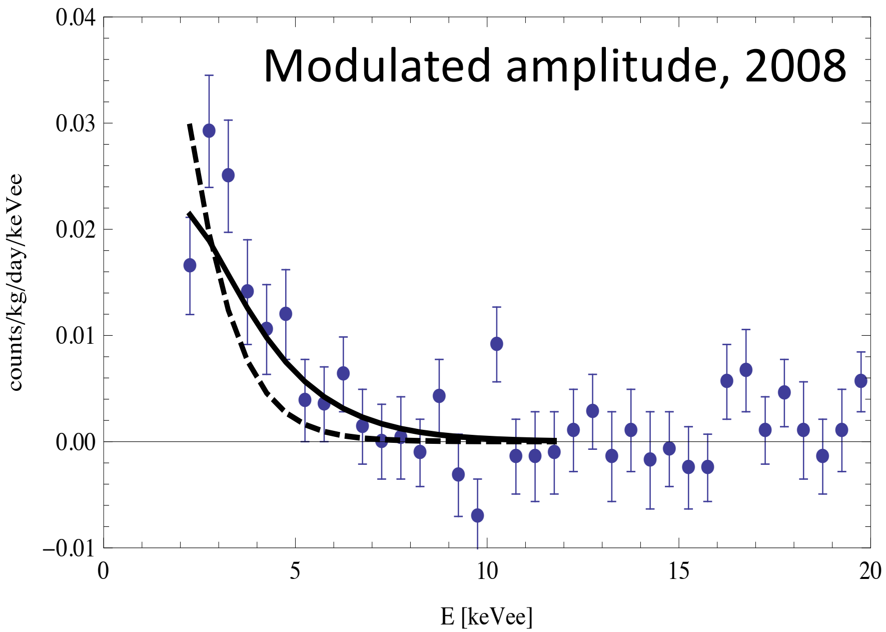
Phase 2 in [1,6] keV: ~**0.7 cpd/kg/keV**

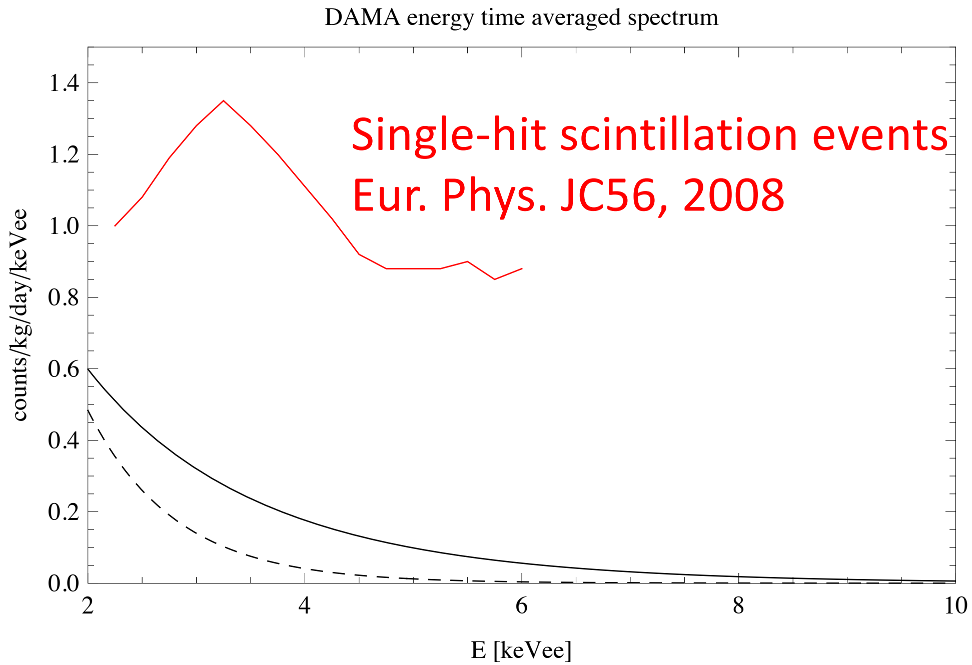
- 5x5 module matrix of NaI(Tl) detectors produced by Saint-Gobain
- No muon veto
- 20 annual cycles for 2.46 ton x yr (including DAMA/NaI)
- Average ~20 ppb of K
- Average ^{210}Pb ~ 5-30 μBq/kg
- Average ^{3}H < 90 μBq/kg
- ^{232}Th ~ 2-30 μBq/kg [0.5-7.5 ppt]
- ^{238}U ~ 9-120 μBq/kg [0.7-10 ppt]



DAMA/LIBRA phase1: WIMPs fit

Target	LY [pe/keV]	Threshold ER [pe/keV]	Threshold NR [keVr]	σ/E
NaI	5.5-7.5	2	6.7(Na) 22(I)	~7% at 60keV

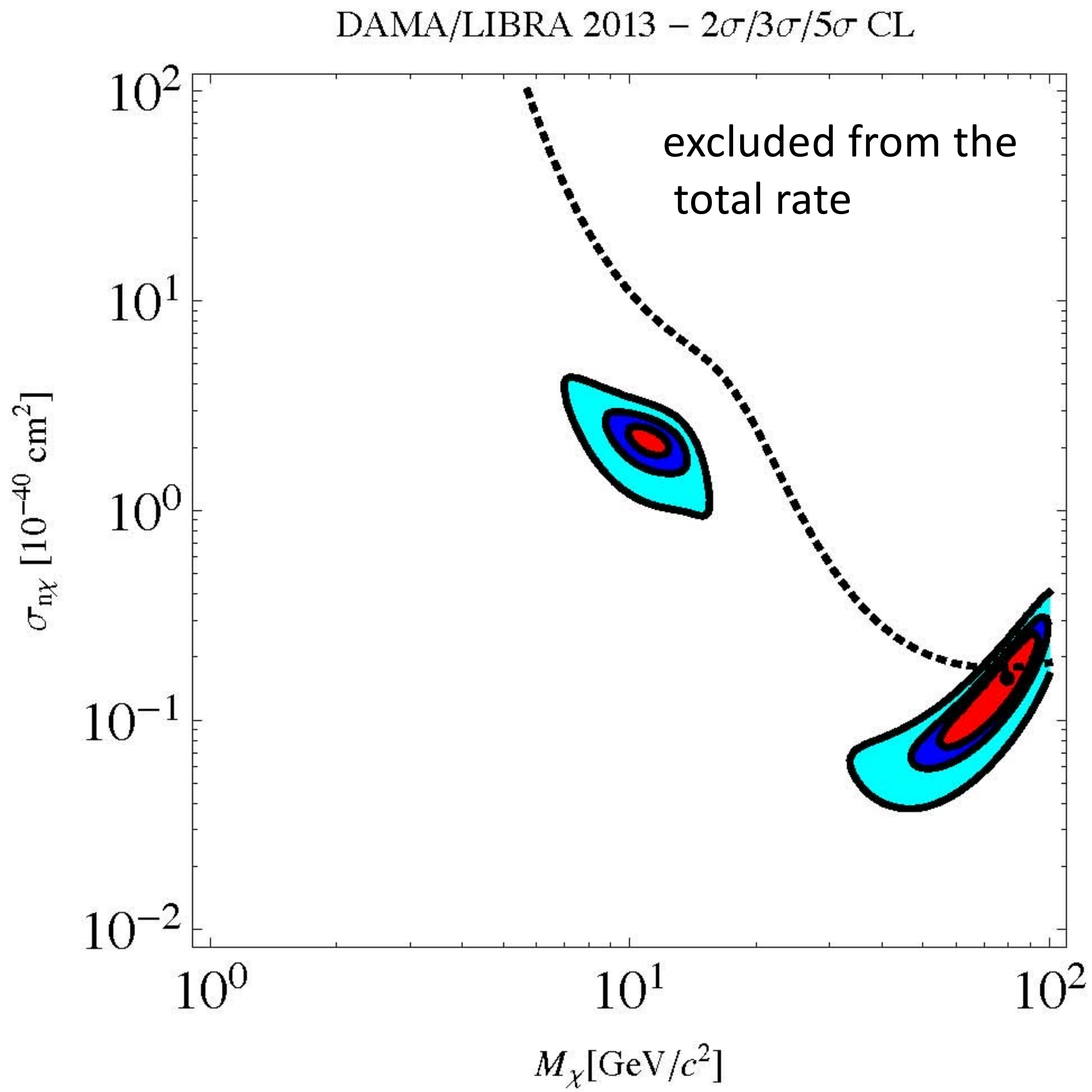




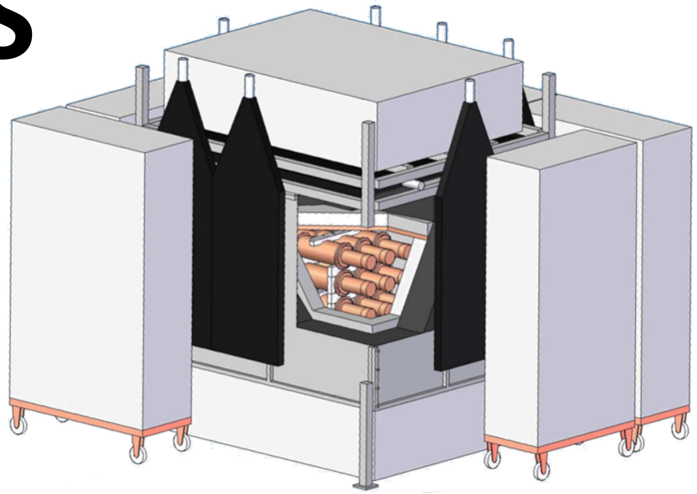
——— M_χ = 12 GeV/c^2 $\sigma_{\chi p}$ = $1.5 \cdot 10^{-41}$ cm^2 χ^2/Ndof = 1.02

- - - - M_χ = 8.6 GeV/c^2 $\sigma_{\chi p}$ = $1.9 \cdot 10^{-41}$ cm^2 χ^2/Ndof = 1.69

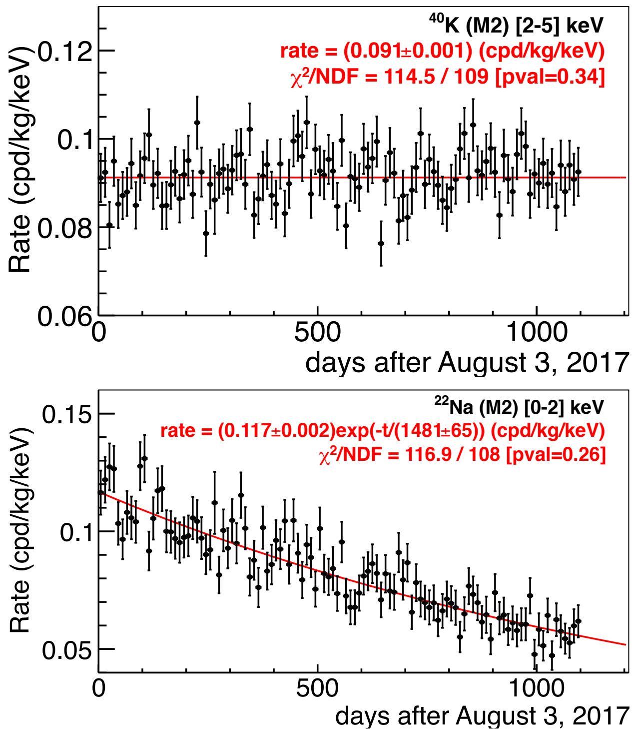
DAMA/LIBRA fit for "standard" SI WIMPs



ANAIS



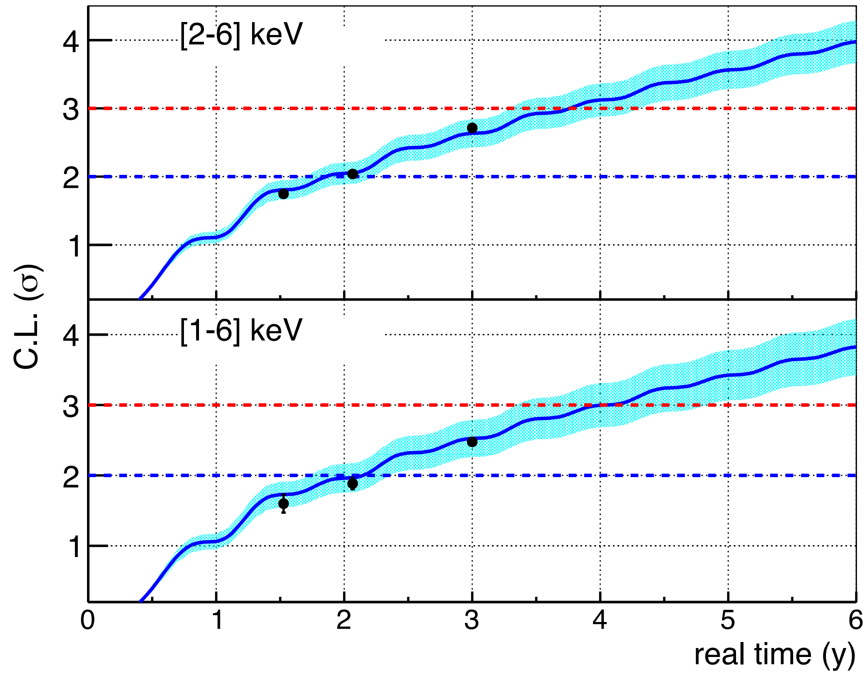
^{40}K and ^{22}Na rate time evolution



- 3x3 module matrix of NaI(Tl) detectors produced by Alpha Spectra Inc
- Muon veto
- Average **~32 ppb of K**
- Average **^{210}Pb ~0.8 mBq/kg** (2 older crystals have ~3 mBq/kg)
  - From PSA and direct counting
- Average ^{3}H ~ 0.15 mBq/kg
- ^{232}Th ~ 1.5 μBq/kg
- ^{238}U ~ 6 μBq/kg

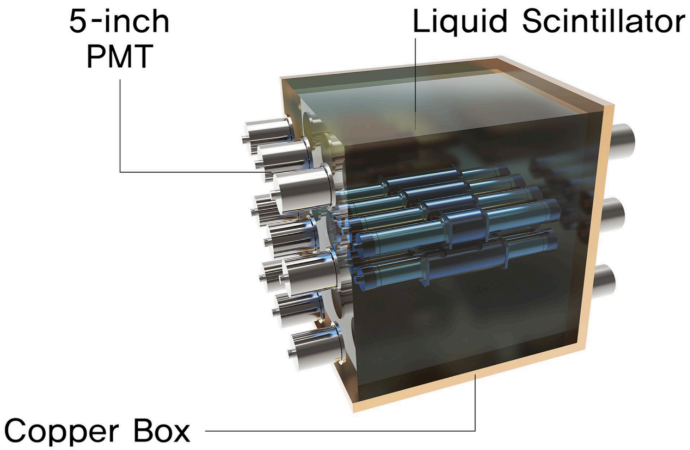
ANAIS recent result

- Sensitivity given as $S_m^{DAMA}/\sigma(S_m^{ANAIS})$
- At present
  - $\sigma(S_m^{ANAIS})$ = 0.0042 cpd/kg/keV for [1,6] keV

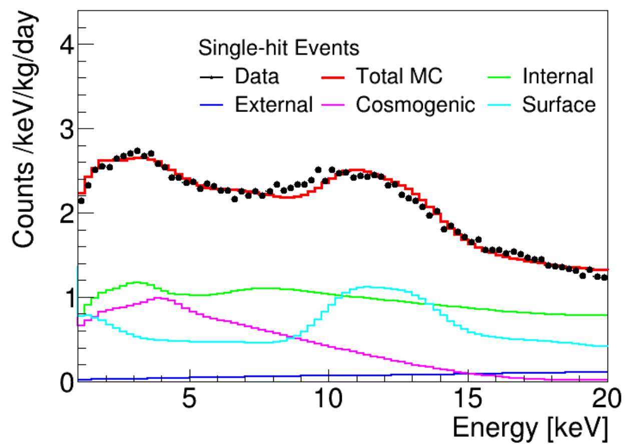


e-Print: [2103.01175](2103.01175)

COSINE



Low energy spectrum in one crystal from EPJ C 2021



- 4x2 module matrix of NaI(Tl) detectors produced by Alpha Spectra Inc
- Muon veto and 2ton active liquid scintillator veto
- Average **~25 ppb of K**
- Average **^{210}Pb ~1.3 mBq/kg**
  - From PSA and direct counting
- Average ^{3}H ~ 0.15 mBq/kg
- ^{232}Th ~ 5 μBq/kg
- ^{238}U < 1.5 μBq/kg

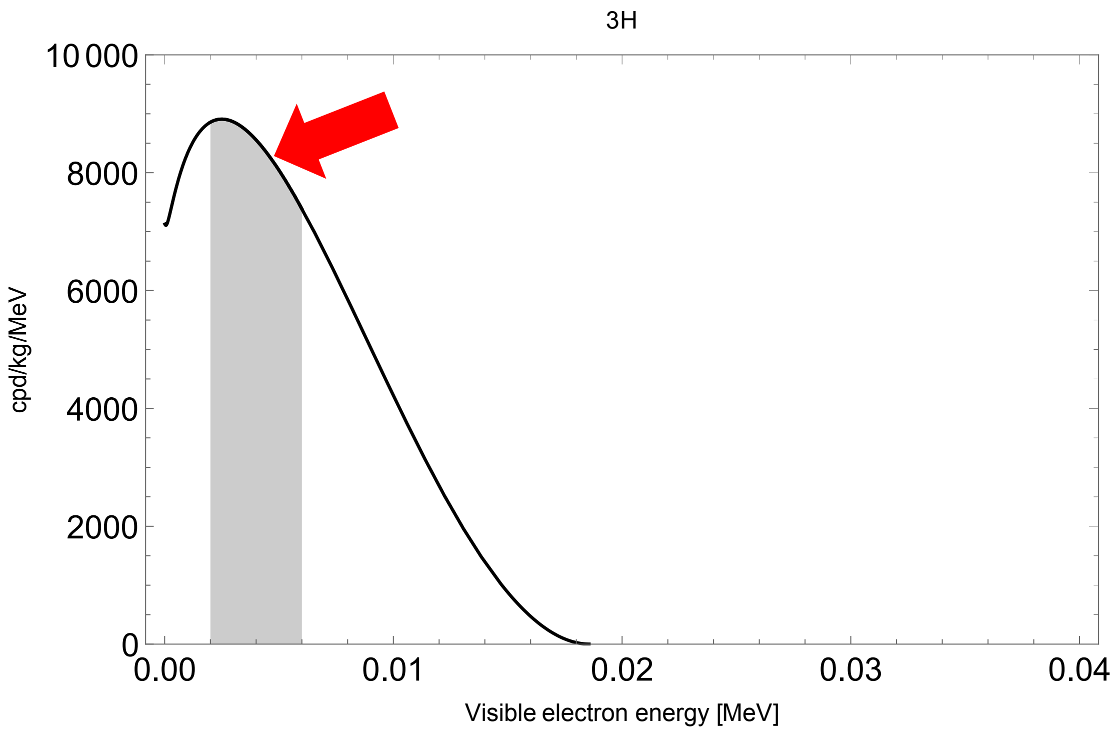
^3H background in ROI

^3H can be a main source of background in the ROI.
Contribution in ROI ~39%

$T_{1/2}$ = 12.3 years

Ultimate ultra-high radio-purity crystal must be grown in underground

A recent study from ANAIS points to a significantly higher ^3H production rate equal to **83±27 decay/kg/day**
(ANAIS coll. Astropart. Phys. 97 (2018) 96-105)

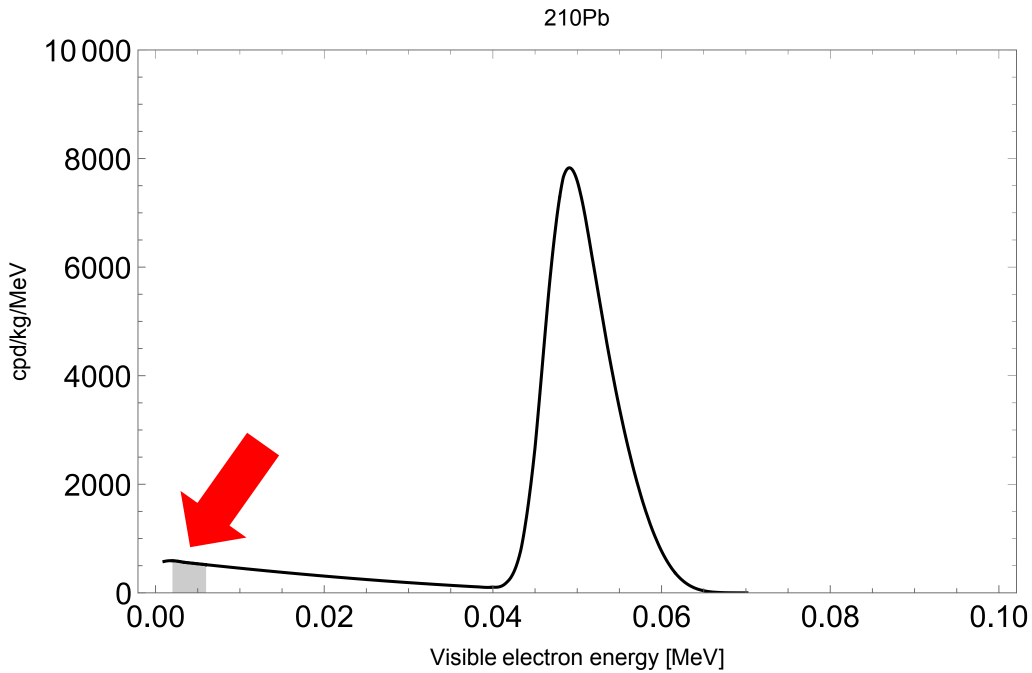


^{210}Pb background in ROI

^{210}Pb can be a main source of background in the ROI.
Contribution in ROI ~3%

In DAMA/LIBRA of order of 30 μBq/kg

In best ANAIS-COSINE crystals of order x 30 DAMA/LIBRA



SABRE

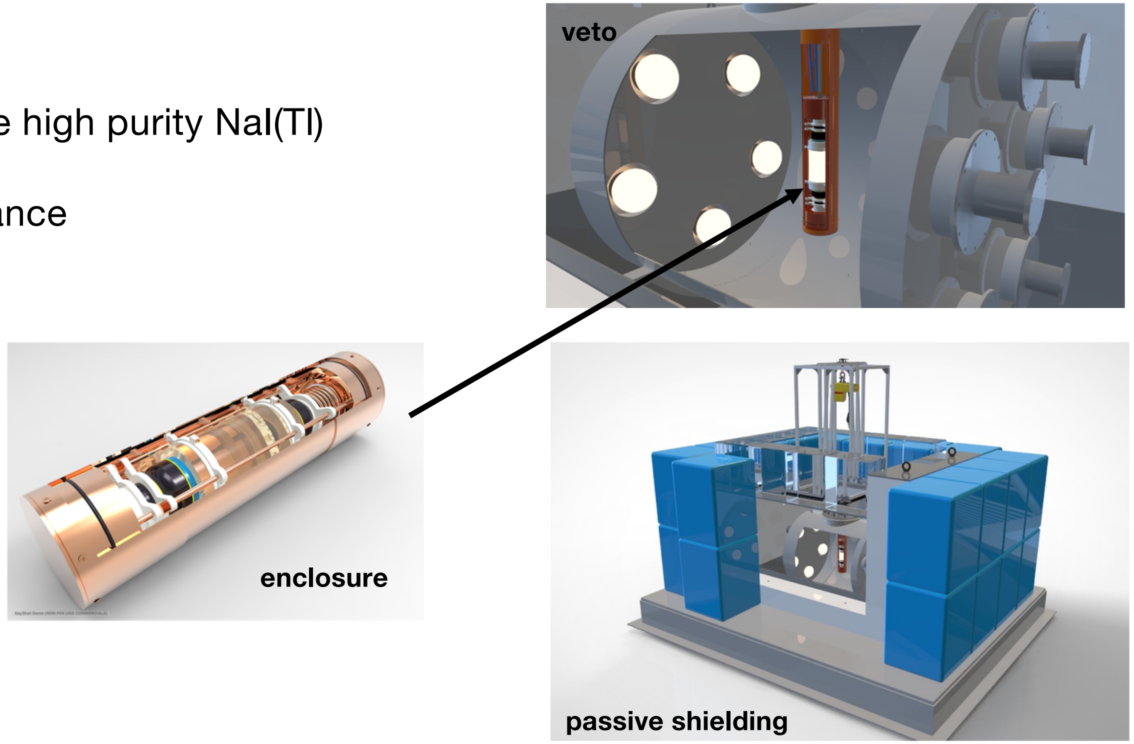
- A new NaI based detector array with two set-ups one at LNGS and one at SUPL
- Aim to obtain 0.1 dru in ROI by dedicated ultra high purity underground
- Present status: PoP at LNGS and full scale detector under construction at SUPL

The SABRE PoP @ LNGS

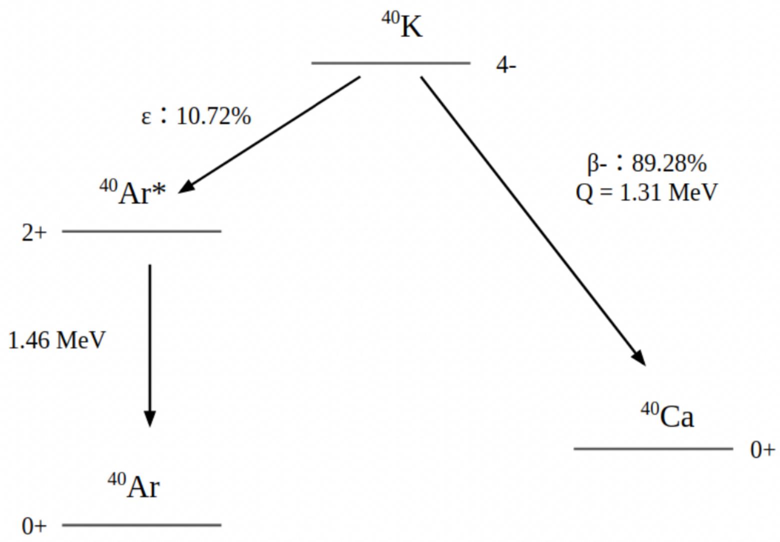
PHASE I: SABRE Proof of Principle (PoP) – ongoing @LNGS

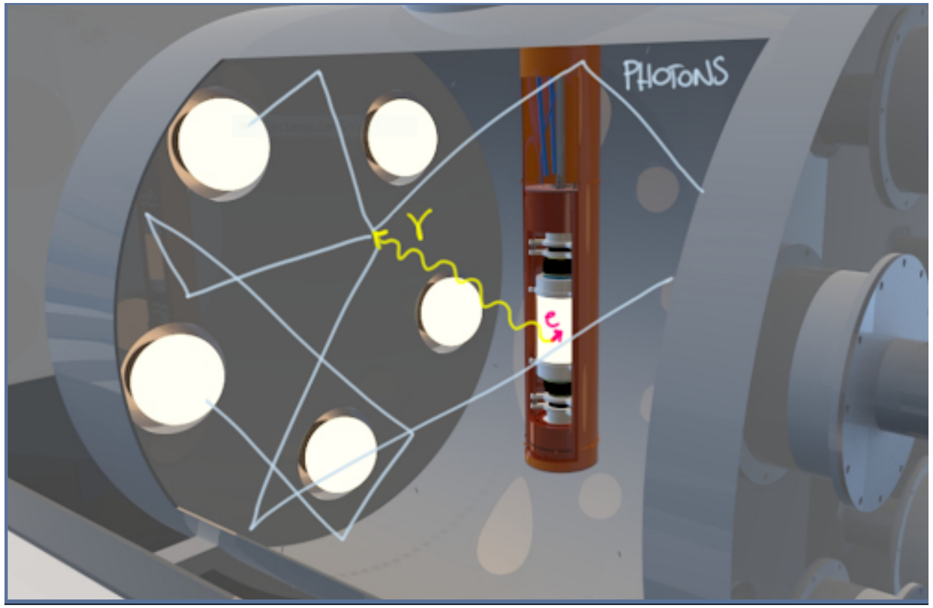
Goals

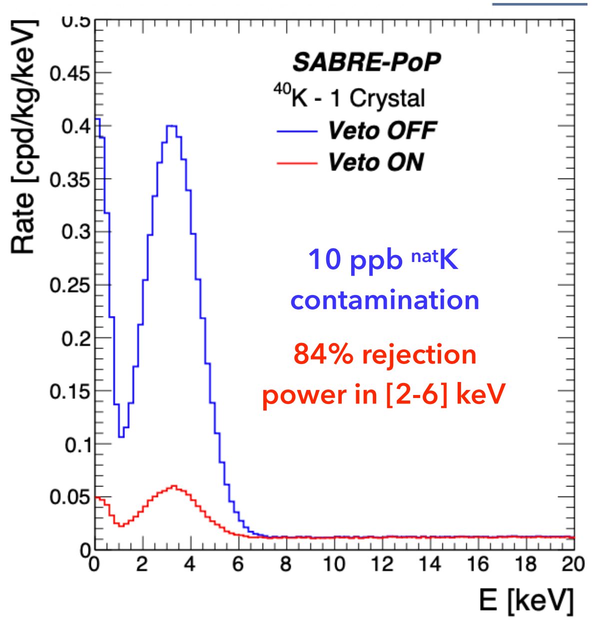
- Produce and characterize high purity NaI(Tl) detector
- Test active veto performance



SABRE active veto



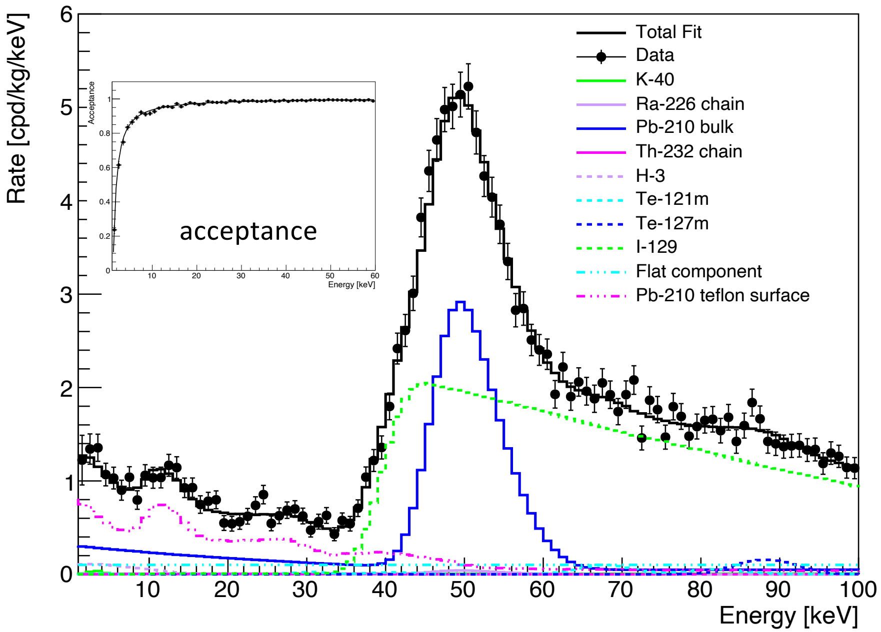




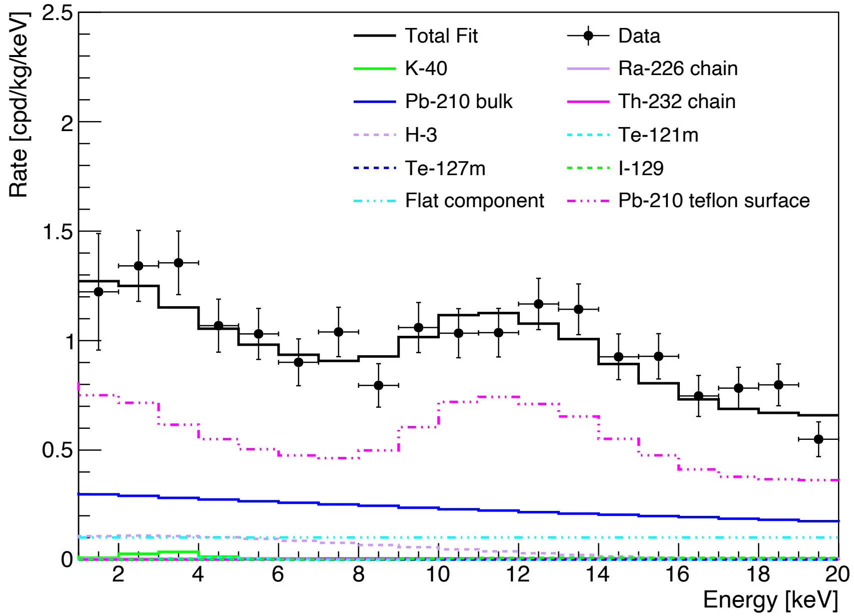
SABRE Coll. Astrop. Phys. 106 (2019) 1-9

Energy spectrum analysis

- Data: single hits spectrum
- Background components from MC
- Fit p-value = 0.26



paper to appear online soon



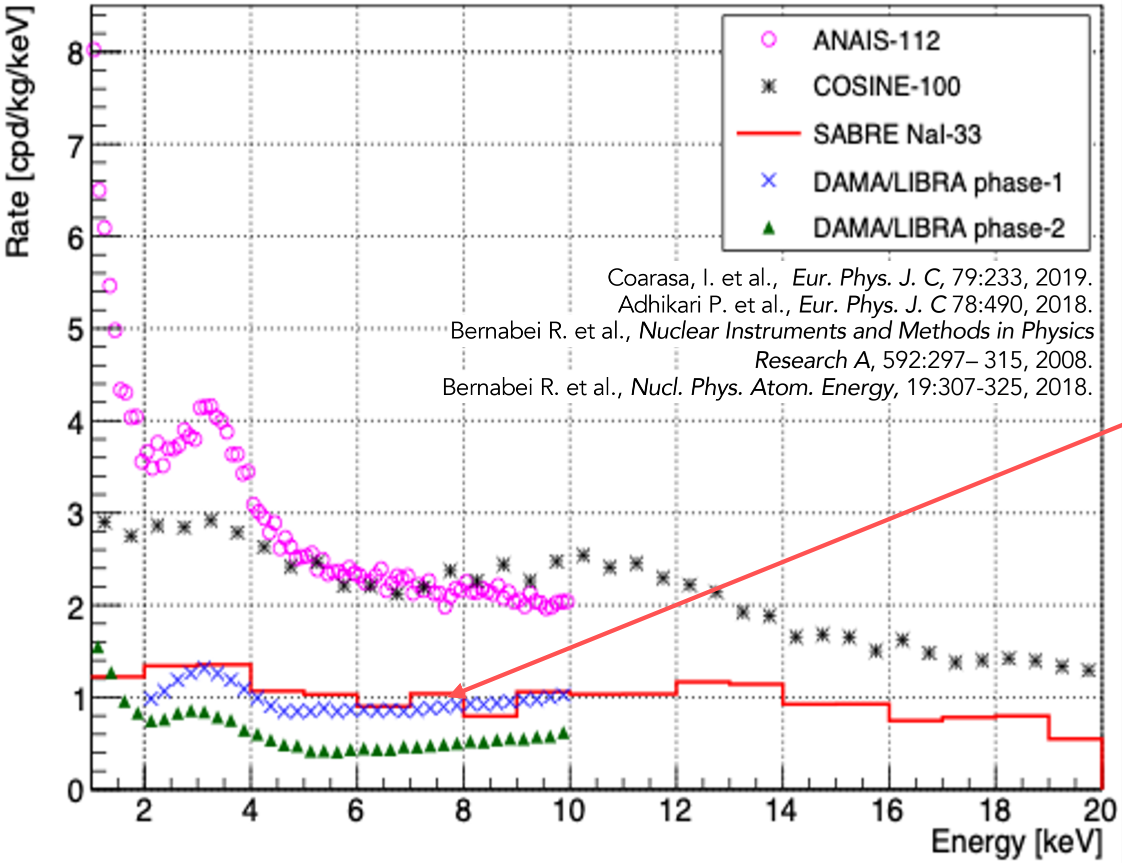
Breakdown of background components in SABRE PoP

Rate from counting data in [1,6] keV is **1.20±0.05 cpd/kg/keV**

Average ~**4 ppb of K**
Average ^{210}Pb ~**0.4 mBq/kg**
Average ^{3}H ~ 12 μBq/kg
^{232}Th ~ 1.6 μBq/kg
^{238}U ~ 6 μBq/kg

Source	Activity [mBq/kg]	Rate in ROI [cpd/kg/keV]
^{40}K	0.14±0.01	0.018±0.001
^{210}Pb (bulk)	0.41±0.02	0.28±0.01
^{226}Ra ^{232}Th	0.0059±0.0006 0.0016±0.0003	0.0044±0.0005
^{3}H	0.012±0.007	<0.12
^{121m}Te ^{127m}Te ^{129}I	<0.084 0.016±0.006 1.34±0.04	<0.011
^{210}Pb(reflector)	0.32±0.06	0.63±0.09
Other backgrounds		0.10±0.05
Total		**1.16±0.10**

SABRE PoP: Comparison with other NaI(Tl)-based experiments

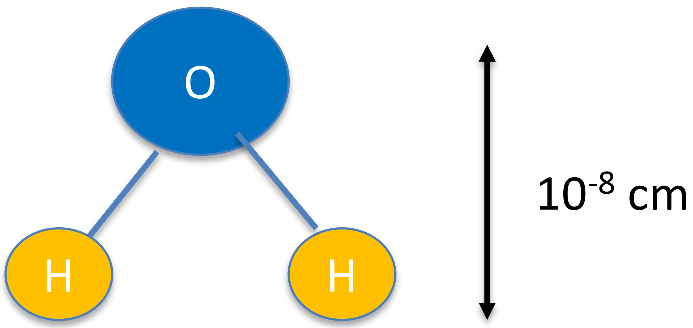


With only 1 month of data taking !

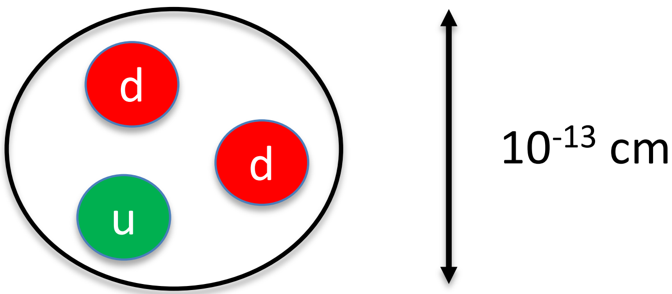
Background level comparable (for the first time) with that of DAMA/LIBRA phase-1

Axions as DM particles

Electric dipole moment of neutron



- Dipole moment of H_2O
  - estimation~ 10^{-8} e · cm
  - data ~ 5×10^{-9} e · cm



- Dipole moment of neutron
  - estimation 10^{-13} e · cm
  - theory ~ $10^{-16}\,\theta$ e · cm
  - data < 3×10^{-26} e · cm
    - $\theta \sim 10^{-10}$?

- From theory: $d_n = 2.4 \times 10^{-16}\, \theta\ e \cdot cm$
  - With θ parameter from the theory
  - Data: $\theta \sim 10^{-10}$
- Peccei, Quinn 1977, Weinberg, Wilczek 1978: a new scalar field associated to θ, **axion field**
- Axion created at some high energy scale $f_a \sim 10^{16}$ GeV
  - $m_a \approx 10^{-9}\, eV \left(\frac{10^{16}\, GeV}{f_a}\right)$
    - 10^{-12} eV < m_a < 1 MeV

Axion as DM particle

- Thermal axions would contribute to HDM:

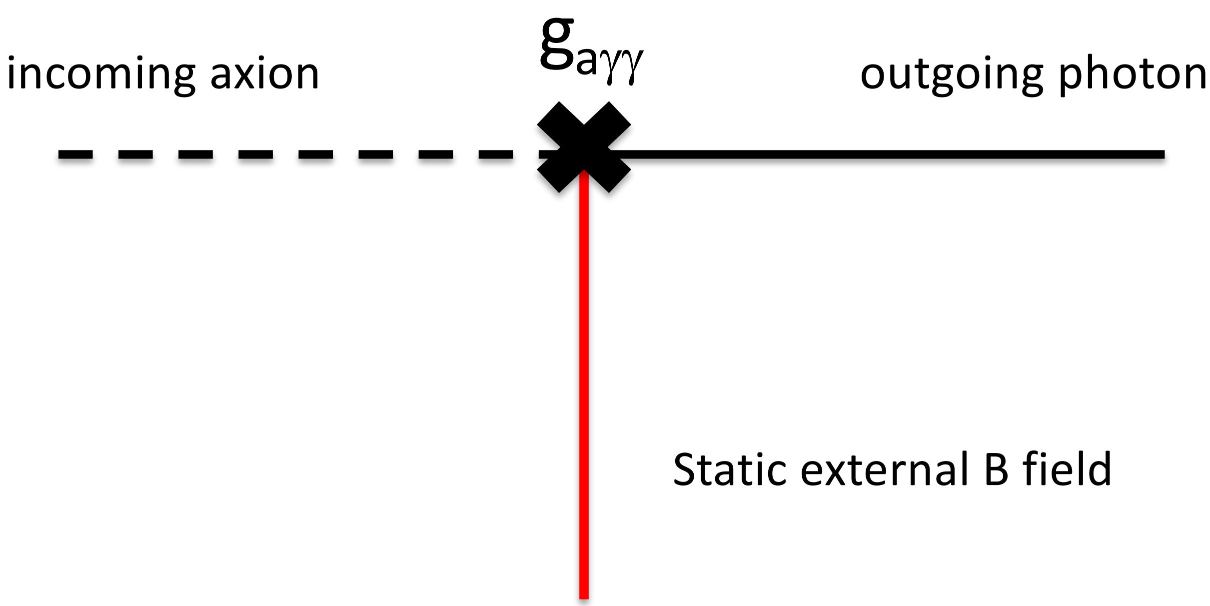
$$\Omega_a h^2 \approx 0.5 \left(\frac{m_a}{130\ eV}\right)$$

  - $m_a < 0.7$ eV for DM cannot be mainly hot
- Axion CDM: $\Omega_a h^2 \approx 0.13 \left(\frac{m_a}{10\ \mu eV}\right)^{-7/6}$
  - This depends on how θ changes with T while relaxing to 0
- With $\rho_{DM} \sim 0.4$ GeV/cm^3 and $m_a = 10\mu$eV
- $\lambda_{de\ Broglie} \sim 12$ cm
- $n_a \sim 4\mathrm{x}10^{13}$ cm^{-3}
- $\phi \sim 10^{21}$ cm^{-2} s^{-1}

From QCD axions to ALPs

- QCD axions: $m_a\ f_a \sim m_\pi f_\pi$ with $f_\pi \sim 93$ MeV (pion decay constant)
- $m_a\ f_a$ can be larger or smaller for ALPs and the space of parameters gets much larger
- These are «possible» weak interacting particles with features similar to the QCD axions

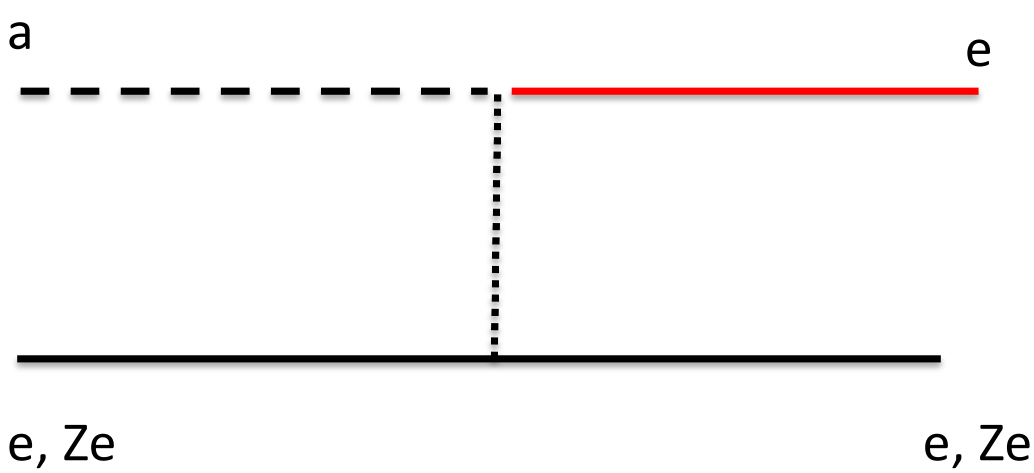
Axion-photon conversion



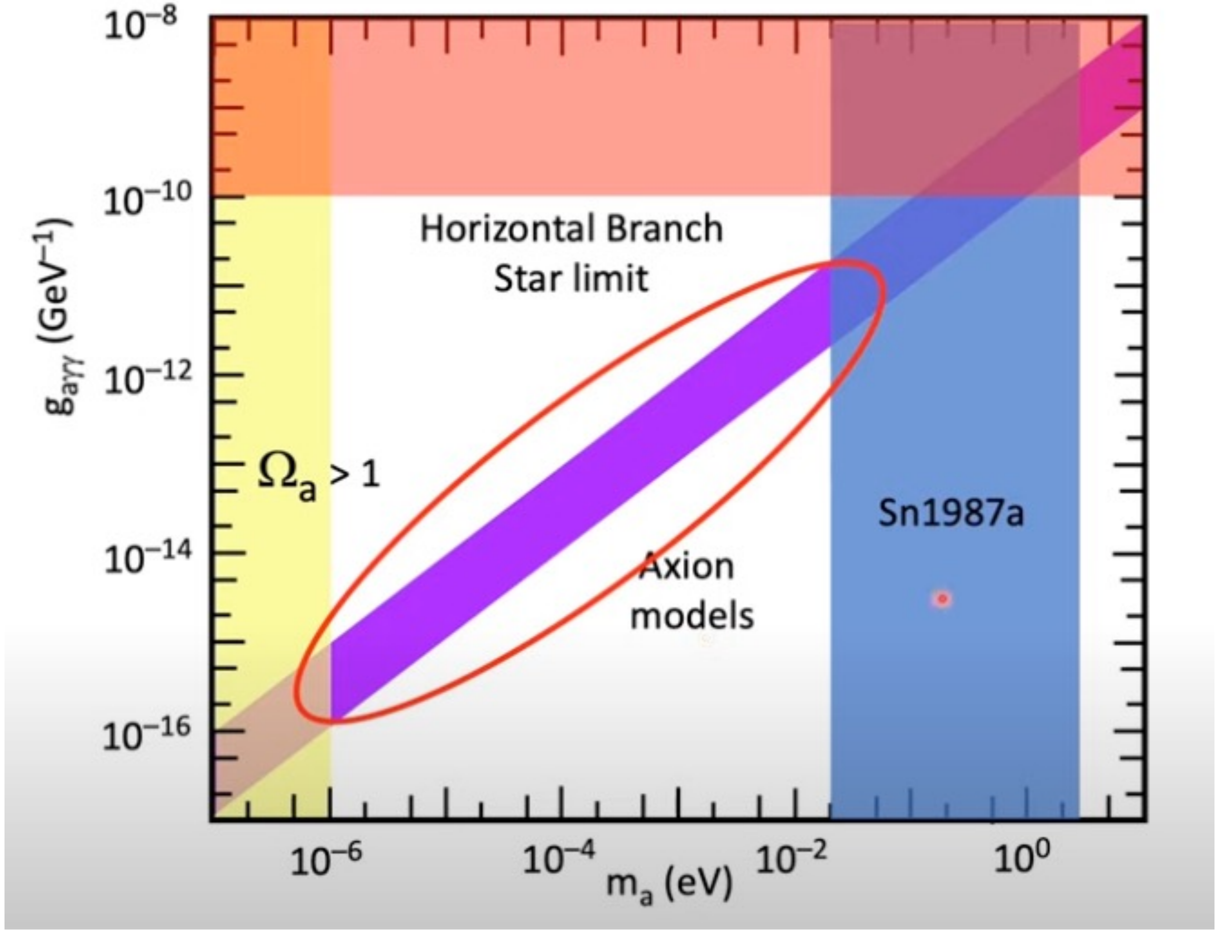
$$P_{a \to \gamma} \propto g_{a\gamma\gamma}^2 \, B^2 \, L^2$$

Axioelectric effect

- This effect can be studied as a by-product in WIMPs DM detectors with low threshold



$g_{ae} < 10^{-12}$ for 1-40 keV



$m_a \propto g_{a\gamma\gamma} \propto 1/f_a$

$\Omega_a \propto f_a^{7/6}$

Looking for axion decay in space

- Idea: $a \rightarrow 2\gamma$ with $E_\gamma = m_a / 2$ from any halo including our own

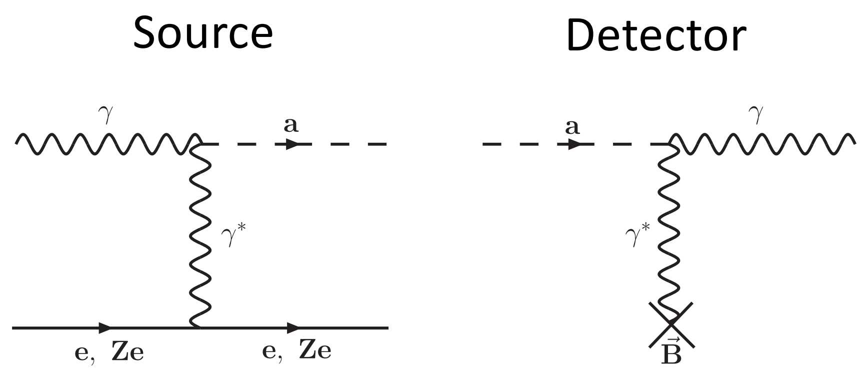
- Coupling very very small implies decay time >> universe age

Solar axions

Axions are produced in the keV plasma inside the Sun

Primakoff effect:

$\gamma + Ze \rightarrow Ze + a$

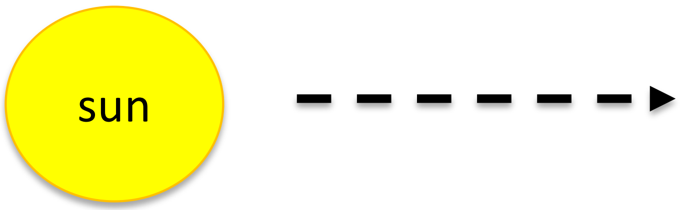


These axions can be detected on Earth

by axion-photon conversion

CAST

Conversion produces X-ray which need to be detected



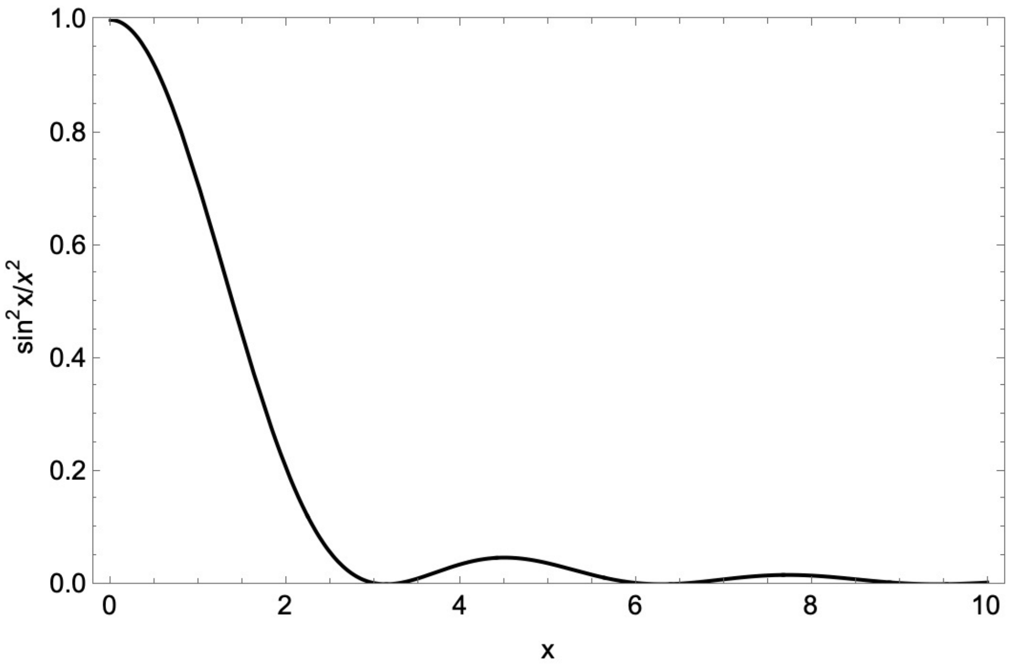
$$p_a c = \sqrt{E_a^2 - m_a^2 c^4} \approx E_a \left(1 - \frac{m_a^2 c^4}{2E_a^2}\right)$$

$$q = |p_\gamma - p_a| = \left|\frac{m_\gamma^2 - m_a^2}{2E_a}\right| \quad E_\gamma \approx E_a$$

CAST

- Solar axion:
  - $\phi_a \sim 4\times10^{11} \left(\frac{g_{a\gamma}}{10^{-10}\ GeV^{-1}}\right)\ cm^{-2}s^{-1}$
  - $\langle E_a \rangle = 4.2\ keV$
  - Energy losses limits $g_{a\gamma} < 5\times10^{-10}\ GeV^{-1}$
- Transition probability
  - $P_{a\to\gamma} = \left(\frac{g_{a\gamma}\ B\ L}{2}\right)^2 \sin\left(\frac{qL}{2}\right)^2 / \left({}^{qL}/{}_{2}\right)^2$

CAST with magnet under vacuum



Transition probability > 0 if $qL/2 < \pi$

In vacuum $m_\gamma = 0$ and

$$m_a < \sqrt{\frac{4\pi\ E_a}{L}} \sim 0.03 \text{ eV}$$

with L = 10 m

How one can probe larger masses ?

Filling the magnet with gas in CAST

- Use ^{4}He
- Photons have an effective mass
  - $m_\gamma^2 = 4\pi \frac{N_e}{V} r_e$
  - $\frac{N_e}{V} = \frac{2N_A}{R} \frac{p}{T}$
  - $m_\gamma = \sqrt{0.01997 \left(\frac{p}{mbar}\right)\left(\frac{K}{T}\right)} \approx 0.25\ eV$ for p = 5.5 mbar and T = 1.8 K
- Sensitivity to axion for $m_a \sim m_\gamma$ so that q ~ 0

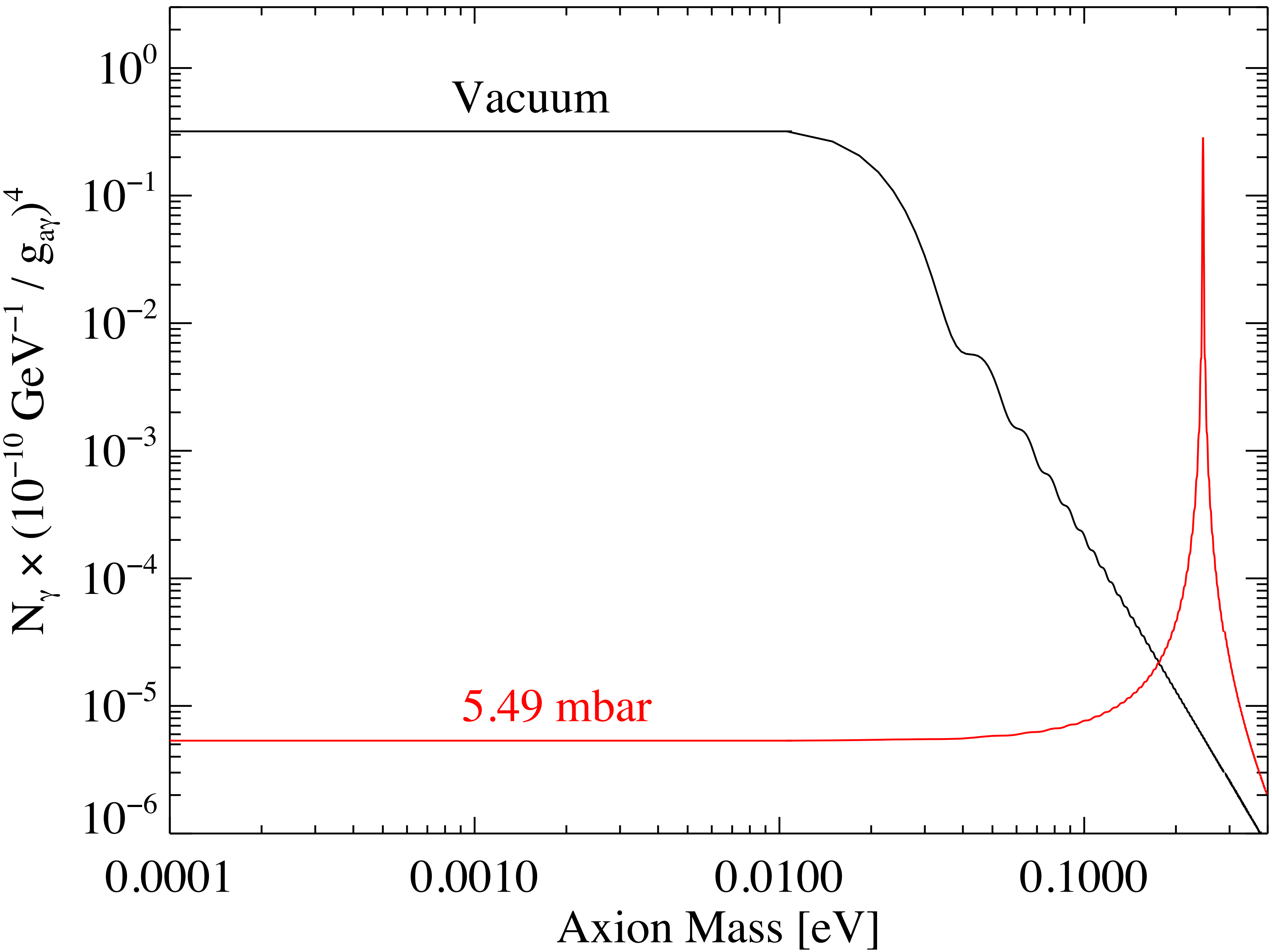
- $q = \left|\frac{m_\gamma^2 - m_a^2}{2\,E_a}\right| < \frac{2\pi}{L}$ depends on pressure and on E_a , m_a fixing T = 1.8 K and L ~ 10 m

- $\sqrt{m_\gamma^2 - \frac{4\pi E_a}{L}} < m_a < \sqrt{m_\gamma^2 + \frac{4\pi E_a}{L}}$
- with p_{max} ~ 16 mbar, m_a < 0.43 eV
- with ^{3}He goes up to 1.2 eV

- 9.26 m prototype LHC magnet with B_{max} = 9 T
- System to perform alignement to the Sun during sunrise and sunset
  2 weeks in Spring and Fall
- X-ray detector

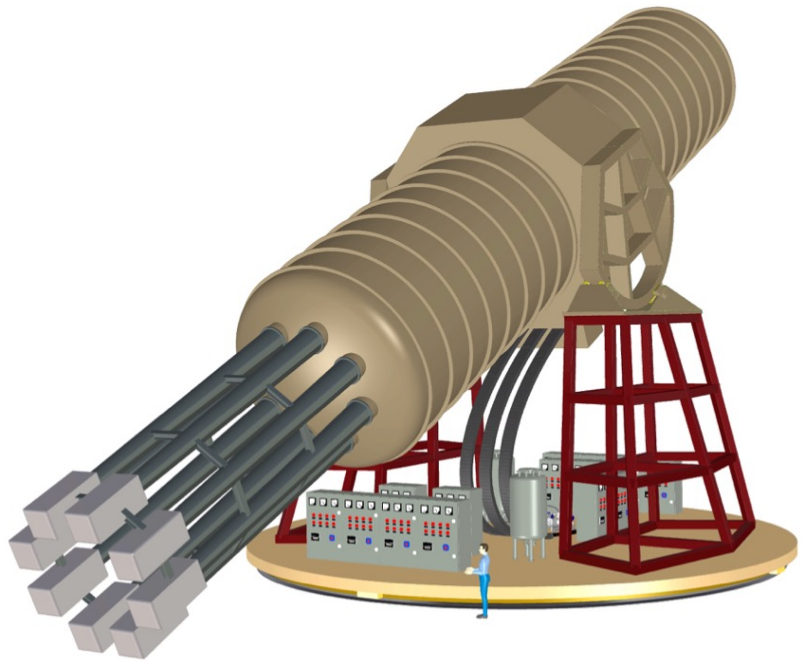
$$N_\gamma = \int_E \frac{d\Phi(E_a)}{dE_a} P_{a\to\gamma}(E_a)\,\epsilon(E_a)\,\Delta t\;A\,dE_a$$

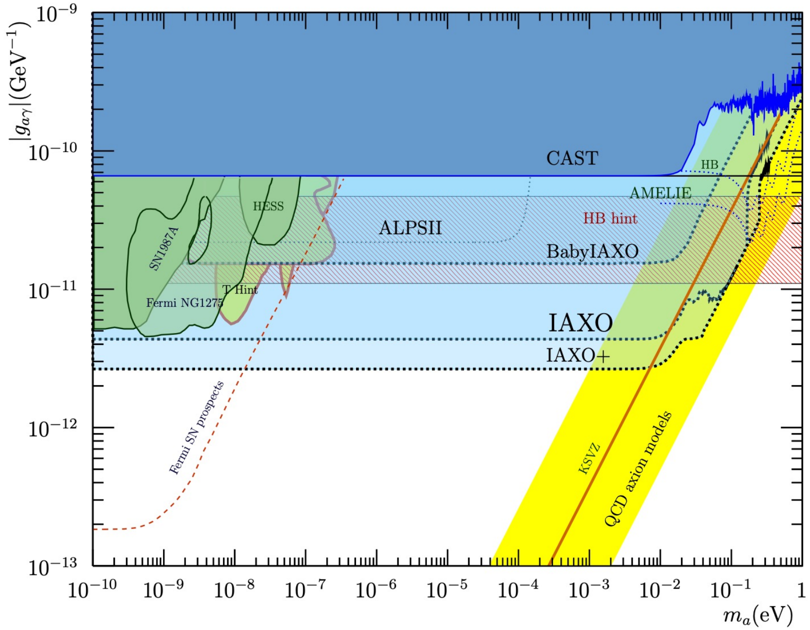
A = 14.522 cm^2 magnet bore


Vacuum
5.49 mbar
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0.0001
0.0010
0.0100
0.1000
Axion Mass [eV]
$N_\gamma \times (10^{-10}\ \mathrm{GeV}^{-1} / g_{a\gamma})^4$

IAXO

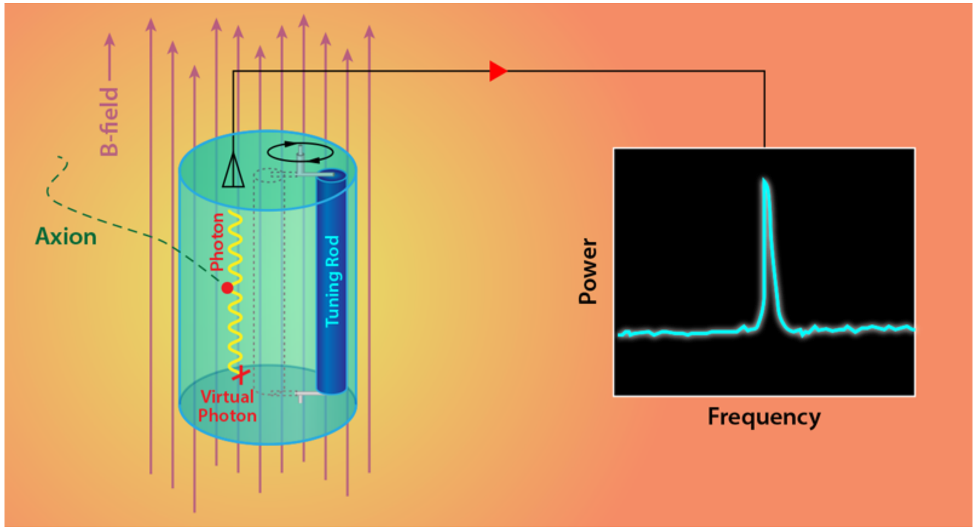
- Next generation helioscope
- L = 25 m
- 2.5 T in 8 bores
- Use MM X-ray detectors with ~ 10^{-7} cts/keV/cm^2/s background level
- Expected to improve CAST S-to-N of 10^4





Axion haloscope

- Proposed by P. Sikivie in 1983
- Tunable high-Q microwave cavity
- Axion couples with cavity producing a photon with f = E/h
- 10 μeV => 2.4 GHz
- E.m. power is extracted by an antenna



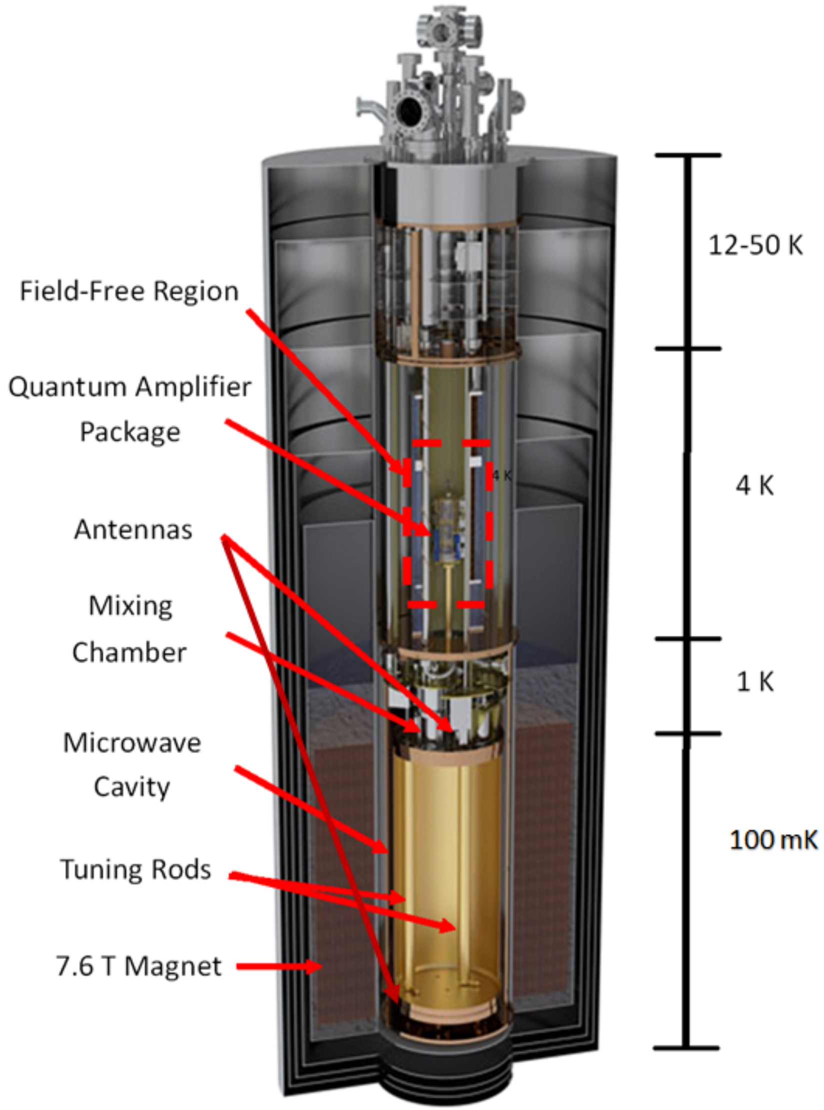
$$P \approx 10^{-22}\,W \left(\frac{V}{10\ L}\right)\left(\frac{B}{6\ T}\right)^2\left(\frac{m_a}{10\ \mu eV}\right)$$

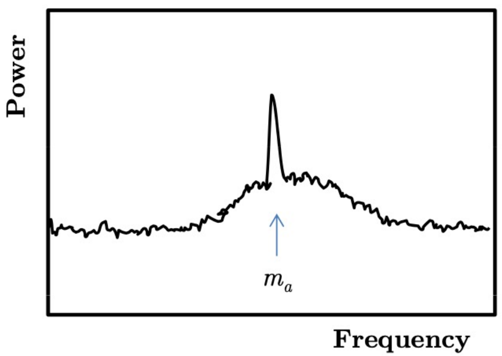
ADMX:

B = 7.6 T

V = 140 L --> 136 with tuning rods

P ~ 10^{-21} W for 10 μeV

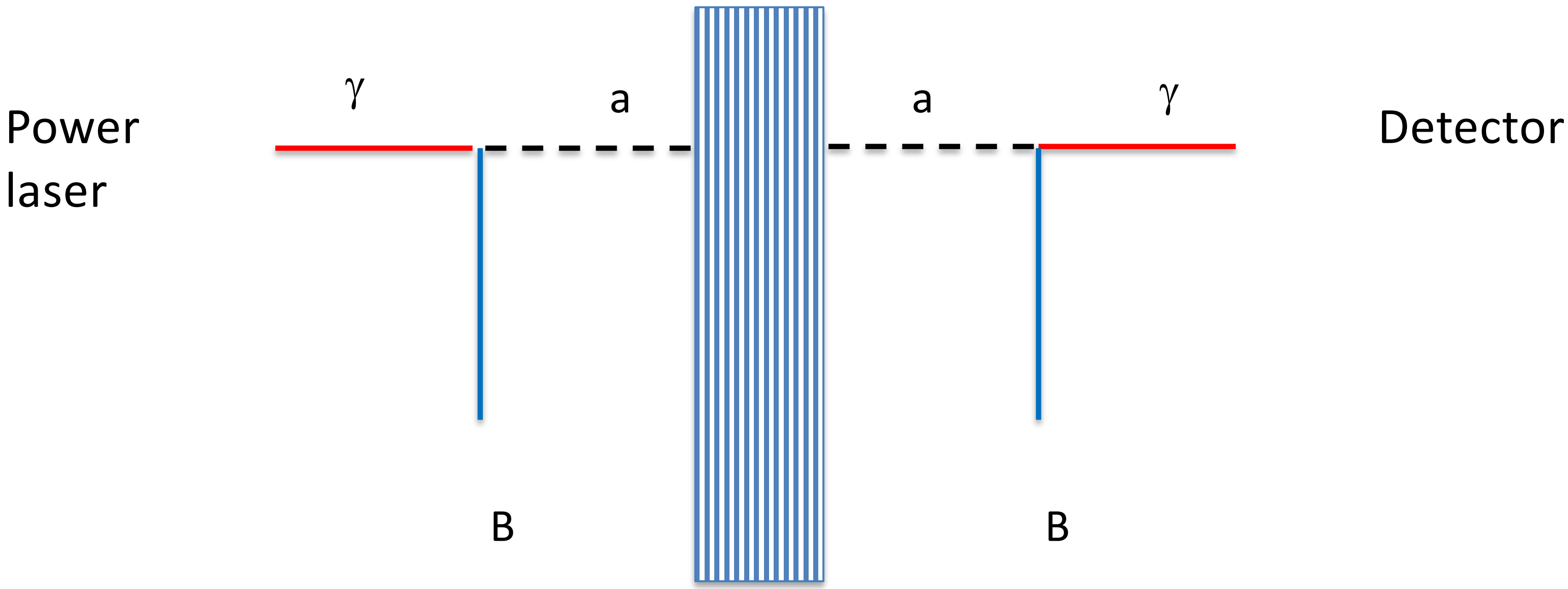




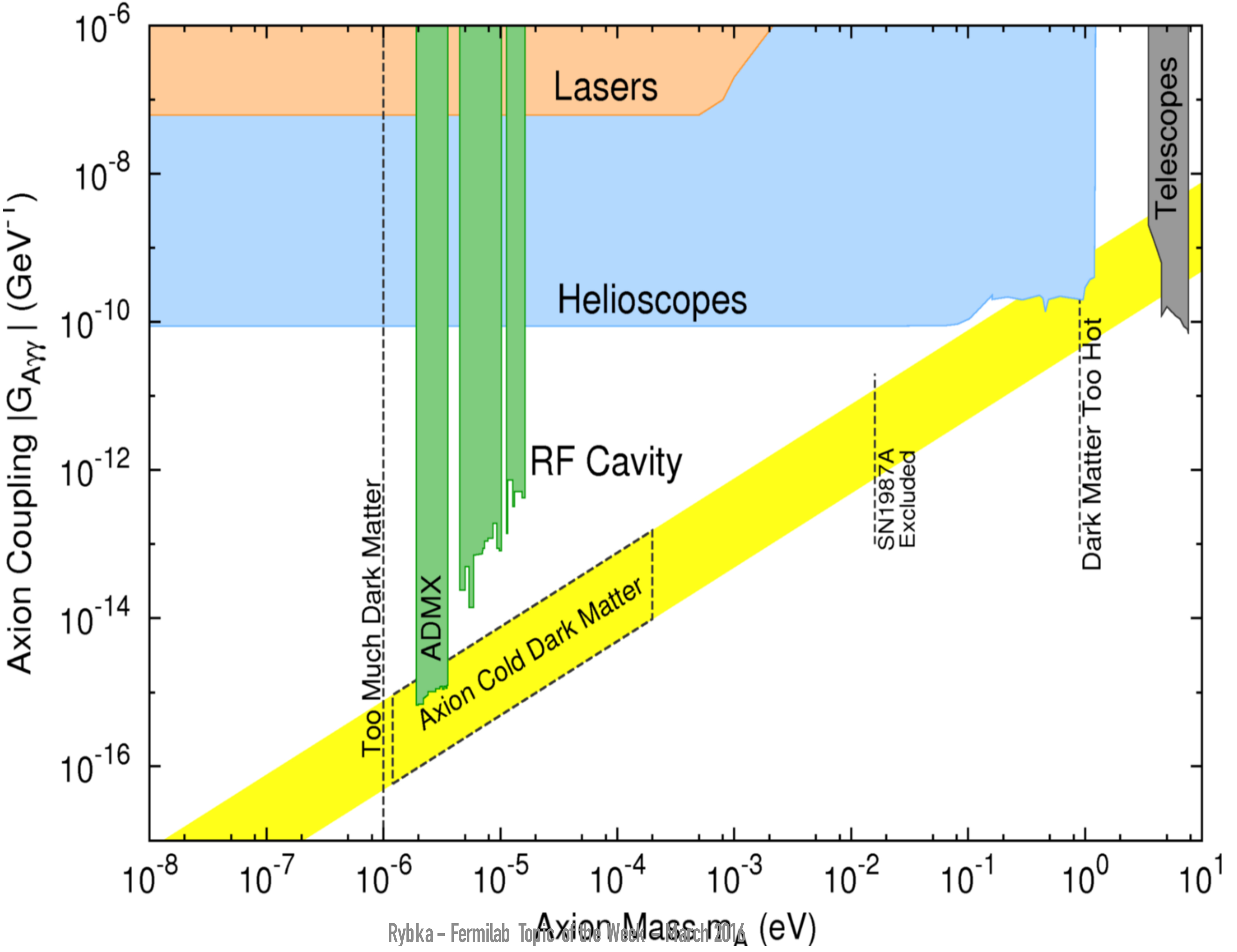
ADMX

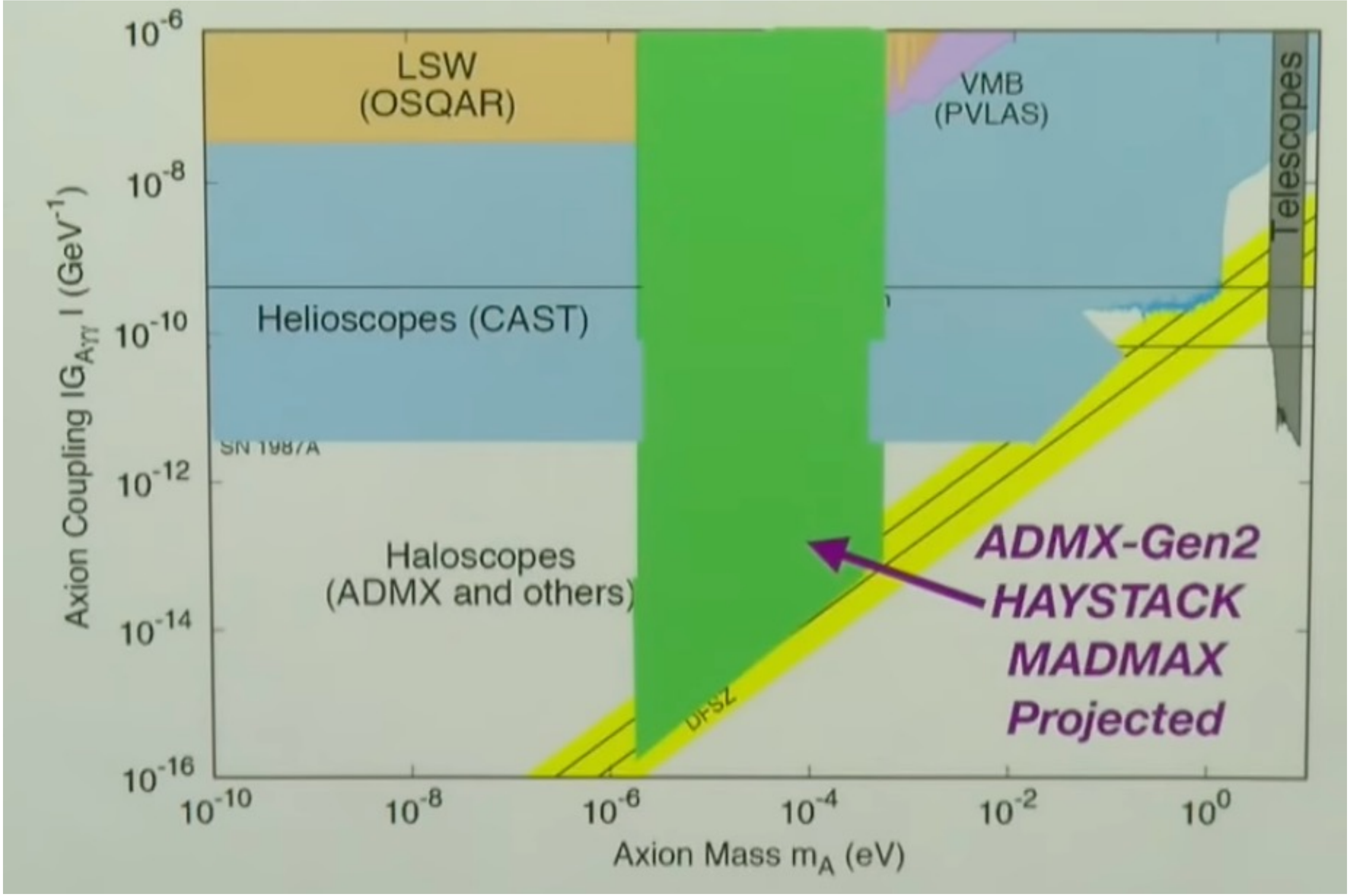
- $P \propto g_{a\gamma\gamma}^2 \left(\frac{\rho_a}{m_a}\right) B^2 Q$
- $P = 7.7 \times 10^{-23} W \left(\frac{V}{136\,L}\right) \left(\frac{B}{7.5\,T}\right)^2 \left(\frac{C}{0.4}\right) \left(\frac{\rho_a}{0.45\,GeV/cm^3}\right) \left(\frac{g_\gamma}{0.36}\right)^2 \times \left(\frac{f_a}{1\,GHz}\right) \left(\frac{Q}{8\times 10^4}\right)$
- $Q = \frac{f}{\Delta f}$
- $E_a \sim m_a (1 + O(\beta^2))$ with $\beta \sim 10^{-3}$
- $\Delta f_a / f_a \sim 10^{-6}$ and $\Delta f_c / f_c \sim 10^{-4}$
- Signal-to-Noise Ratio $= \frac{\boldsymbol{P}}{\boldsymbol{k\,Ts\,/\epsilon}} \sqrt{\frac{\boldsymbol{\Delta t}}{\boldsymbol{\Delta f}}}$
  - Ε transmission efficiency between the cavity and the Josephson parametric amplifier (JPA)
  - $kT_s = h\nu \left(\frac{1}{e^{h\nu/kT}} + \frac{1}{2}\right) + kT_A$
- Scanning f over a wide range

Light shining through wall



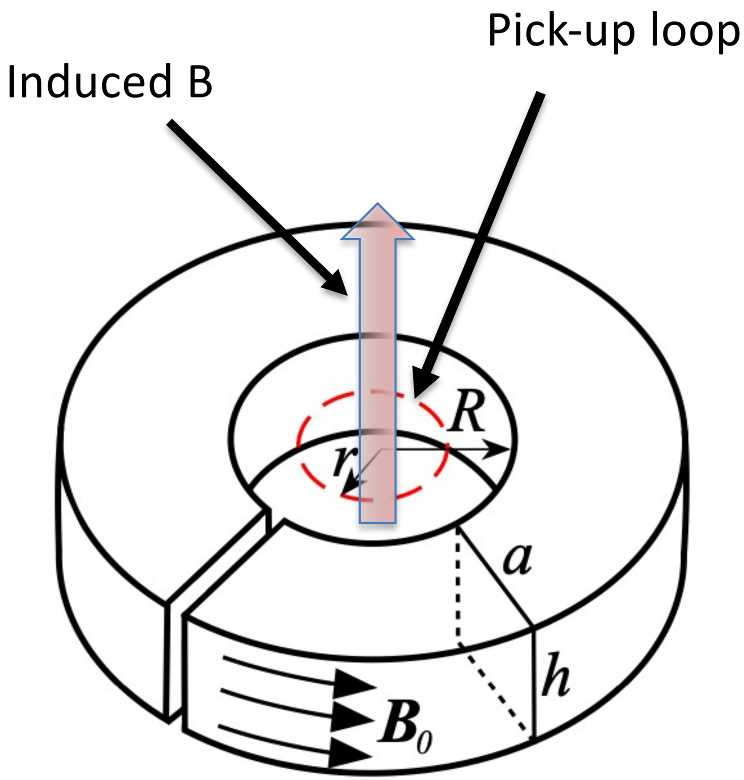
$$P(\gamma \to a \to \gamma) = P(\gamma \to a)P(a \to \gamma) \propto \left(\frac{g_{a\gamma}B}{m_a}\right)^4$$

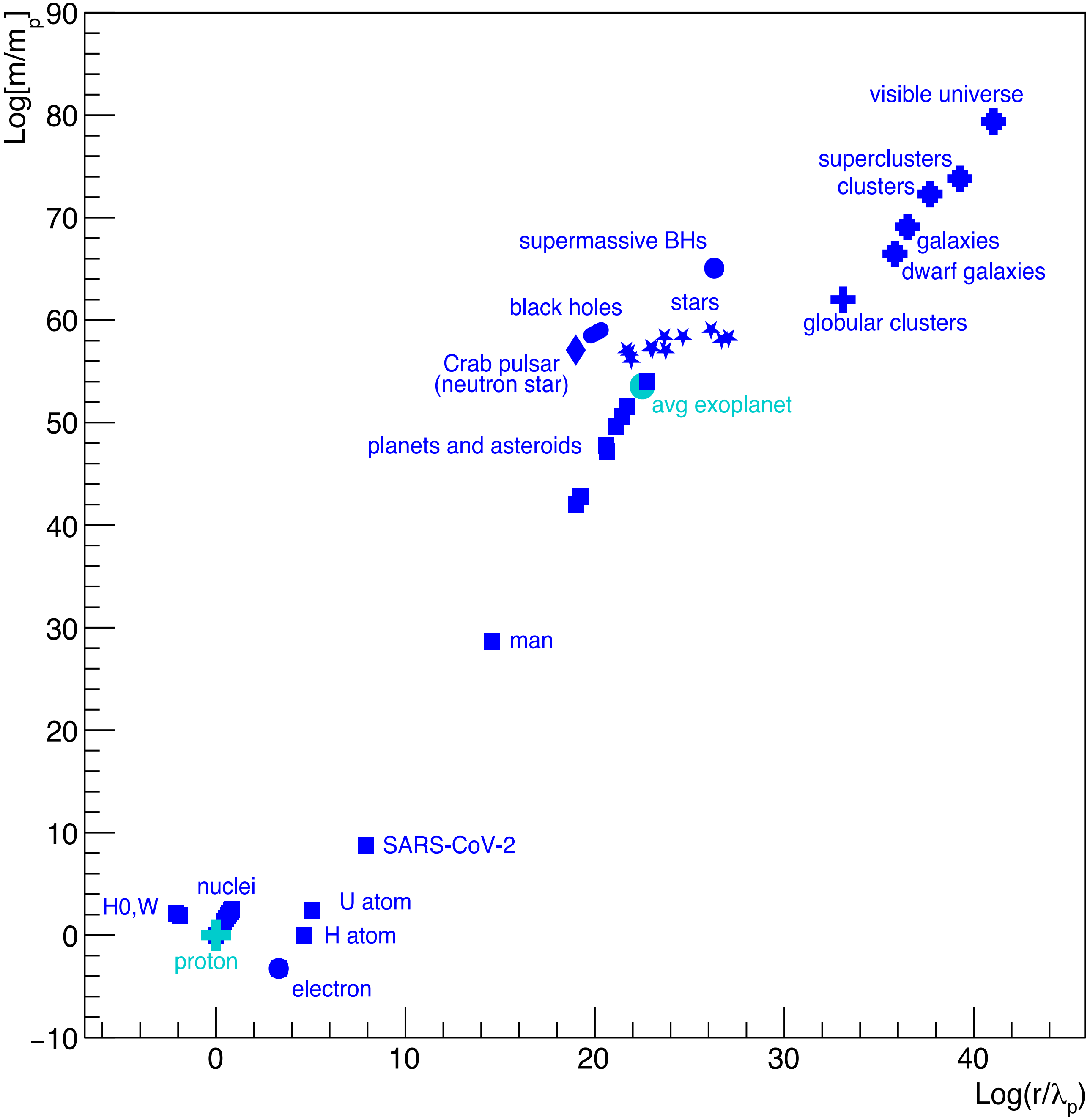

Lasers
Helioscopes
RF Cavity
ADMX
Telescopes
Too Much Dark Matter
Axion Cold Dark Matter
SN1987A Excluded
Dark Matter Too Hot
Axion Coupling $|G_{A\gamma\gamma}|$ (GeV^{-1})
Axion Mass m_A (eV)


LSW
(OSQAR)
VMB
(PVLAS)
Telescopes
Helioscopes (CAST)
SN 1987A
Haloscopes
(ADMX and others)
DFSZ
ADMX-Gen2
HAYSTACK
MADMAX
Projected
Axion Coupling |G_Aγγ| (GeV^-1)
10^-6
10^-8
10^-10
10^-12
10^-14
10^-16
10^-10
10^-8
10^-6
10^-4
10^-2
10^0
Axion Mass m_A (eV)

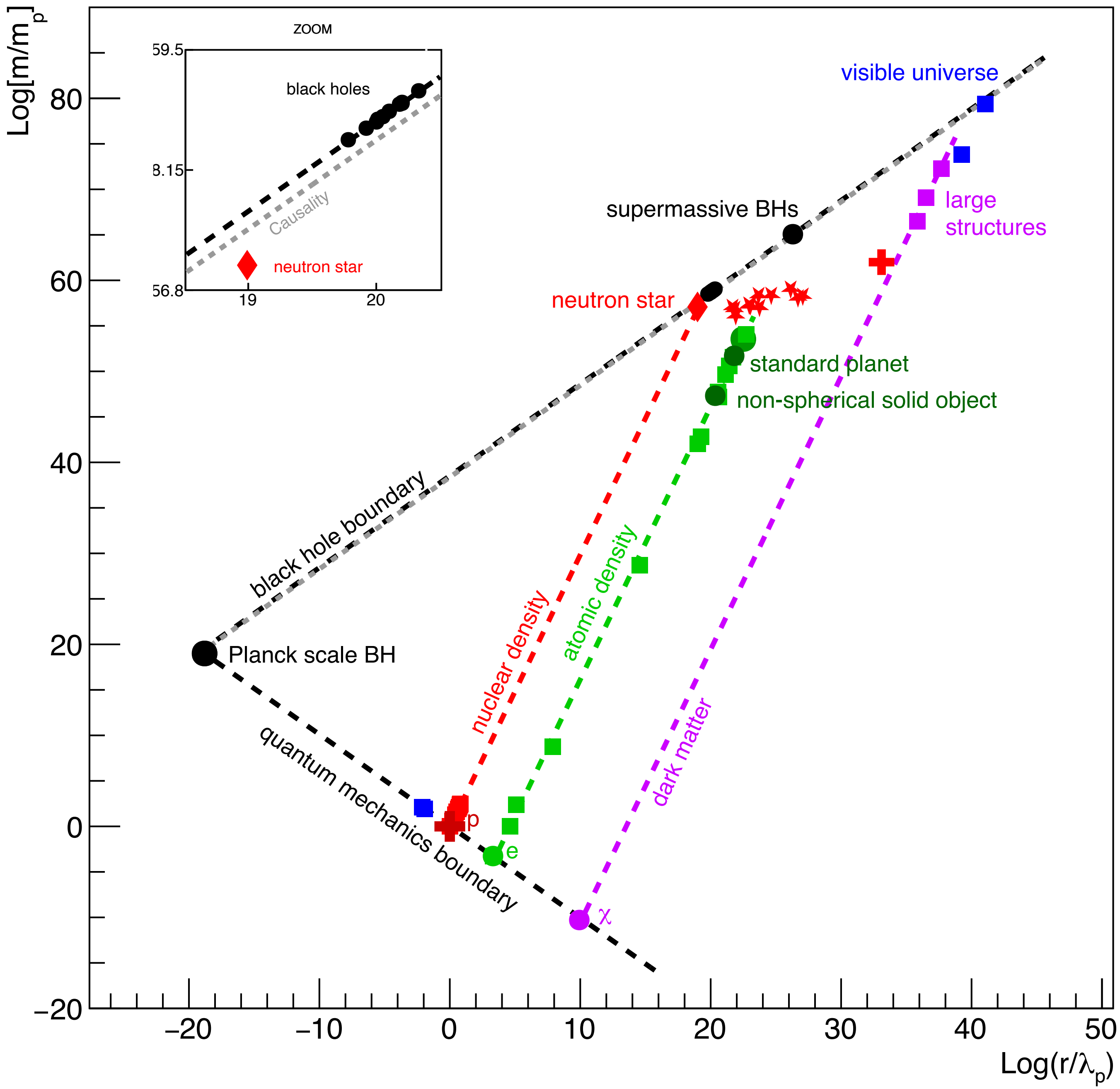
ABRACADABRA

- Axion flux induces a current in a magnet
  - $I \propto g_{a\gamma\gamma} B_0 \sqrt{\rho_a} \cos(m_a t)$
- This currect induces a not-static magnetic field which can be detected
- Aiming to probe $m_a < 10\mu eV$
- Prototype stage

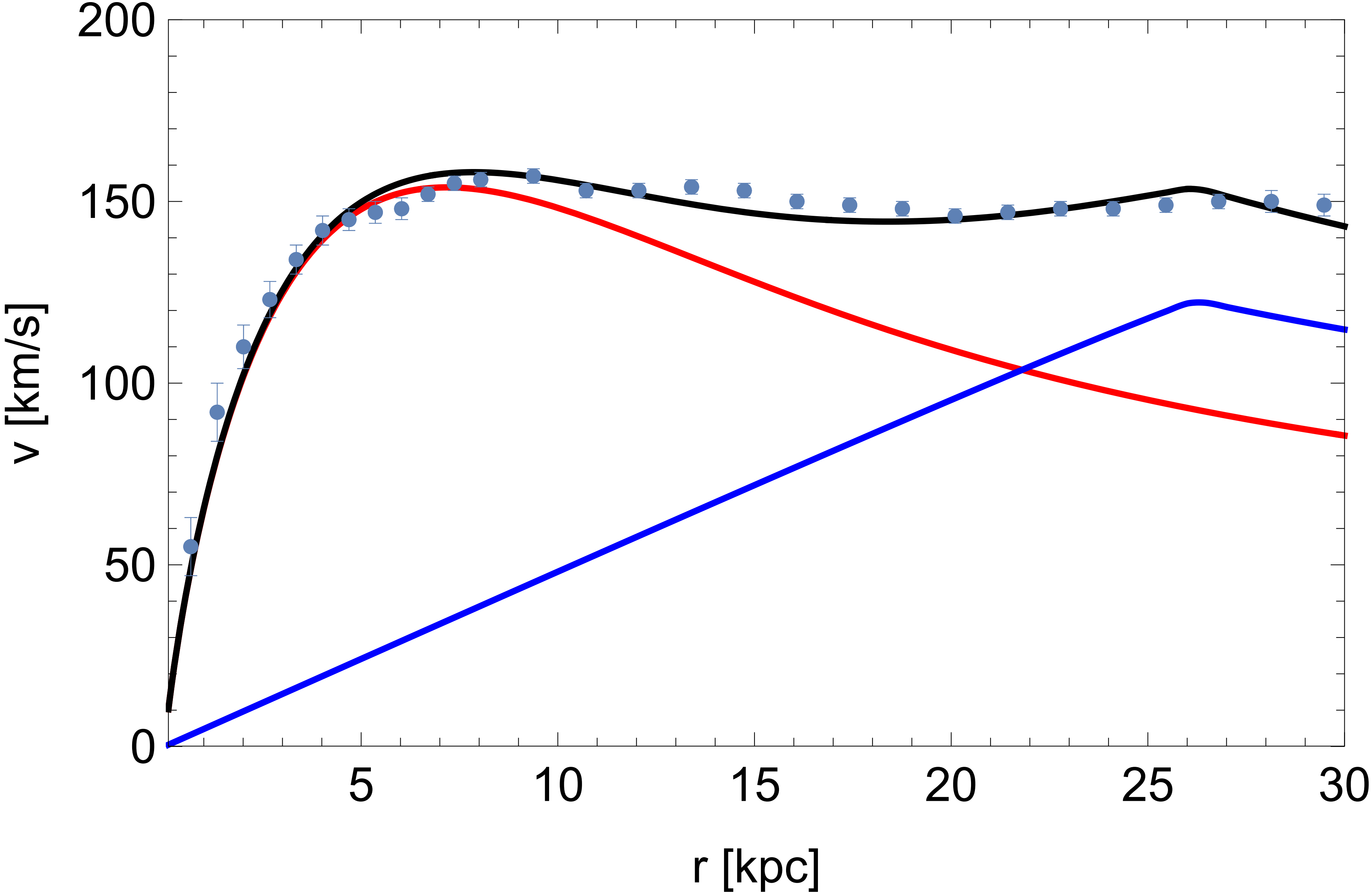




Log[m/m_p]
90
80
70
60
50
40
30
20
10
0
−10
0
10
20
30
40
Log(r/λ_p)
visible universe
superclusters
clusters
galaxies
dwarf galaxies
globular clusters
supermassive BHs
black holes
stars
Crab pulsar
(neutron star)
avg exoplanet
planets and asteroids
man
SARS-CoV-2
nuclei
H0,W
U atom
H atom
proton
electron



ZOOM
59.5
8.15
56.8
19
20
black holes
Causality
neutron star
Log[m/m_p]
80
60
40
20
0
−20
visible universe
supermassive BHs
large structures
neutron star
standard planet
non-spherical solid object
black hole boundary
atomic density
nuclear density
dark matter
Planck scale BH
quantum mechanics boundary
p
e
χ
−20
−10
0
10
20
30
40
50
Log(r/λ_p)



200
150
100
50
0
5
10
15
20
25
30
v [km/s]
r [kpc]

The end. Thank you