Direct Dark Matter Detection

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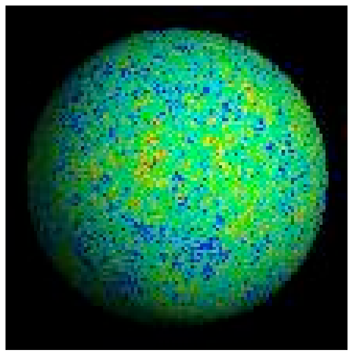
Outline

- Part 1: General Principles
  - Rates, backgrounds, signals, etc
- Part 2: Direct Detection Searches
  - Liquid Nobles
  - Cryogenic Detectors
  - Other Novel Technologies

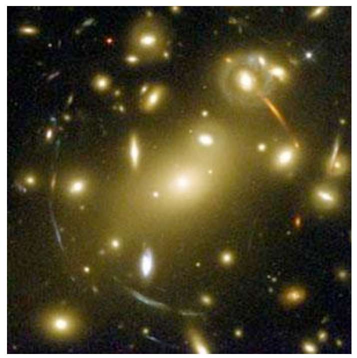
Further Reading

- Classic Papers on specific calculations
  - Lewin, Smith, Astroparticle Physics 6 (1996) 87-112
  - Kurylov and Kamionkowski, Physical Review D 69, 063503 (2004)
  - G. Jungman, M. Kamionkowski, K. Griest, Phys. Rep. 267 (1996) 195-373, arXiv:hep-ph/9506380
- Books/Special Editions that Overview the Topic of Dark Matter
  - Bertone, Particle Dark Matter Observations, Models and Searches, Cambridge University Press, 2010. ISBN 978-0-521-76368-4
  - Physics of the Dark Universe, vol 1, issues 1-2, Nov. 2012 (http://www.journals.elsevier.com/physics-of-the-dark-universe/)

Properties of Dark Matter

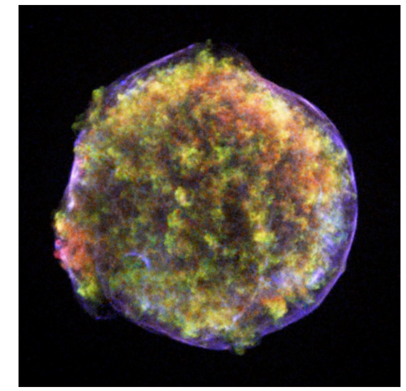


Microwave background

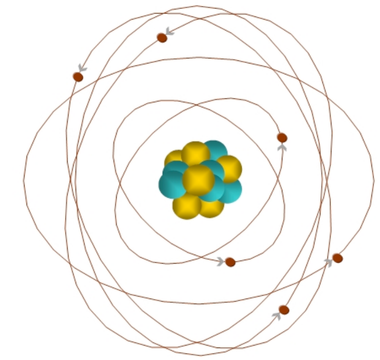


Gravitational lensing

Galaxy clusters



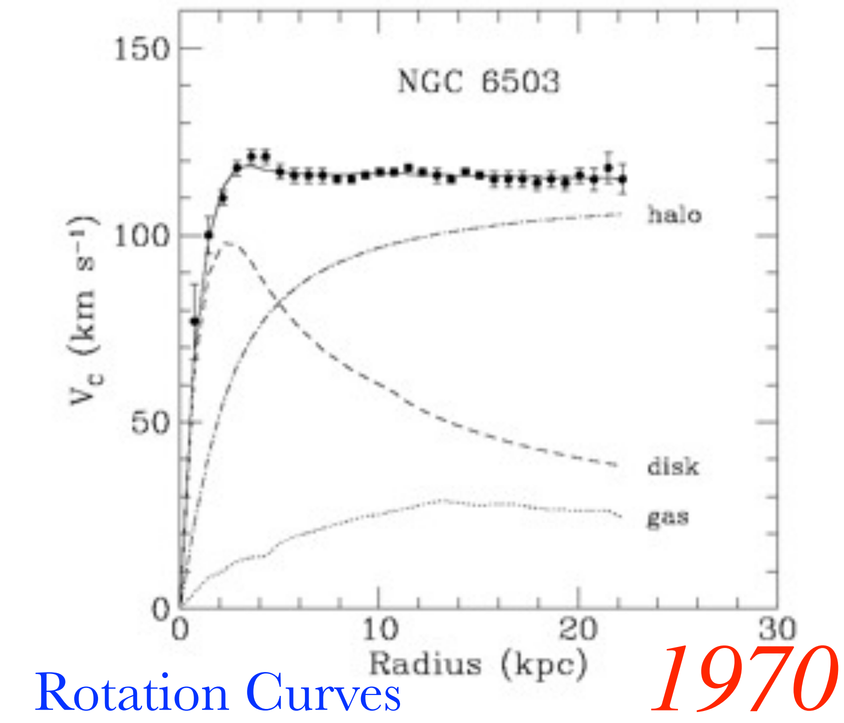
Supernovae Ia

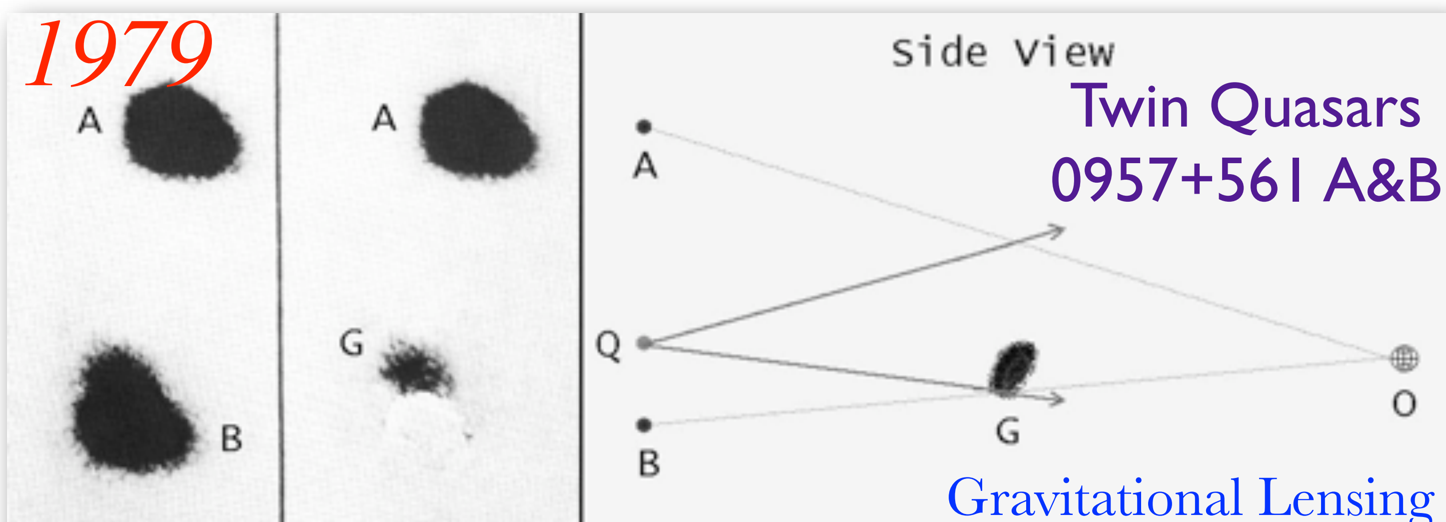


Big Bang nucleosynthesis

Approximately a quarter of our Universe is composed of non-baryonic, cold dark matter

Evidence of Existence





Evidence of the existence of dark matter comes from it's gravitational effects.

Particle Nature

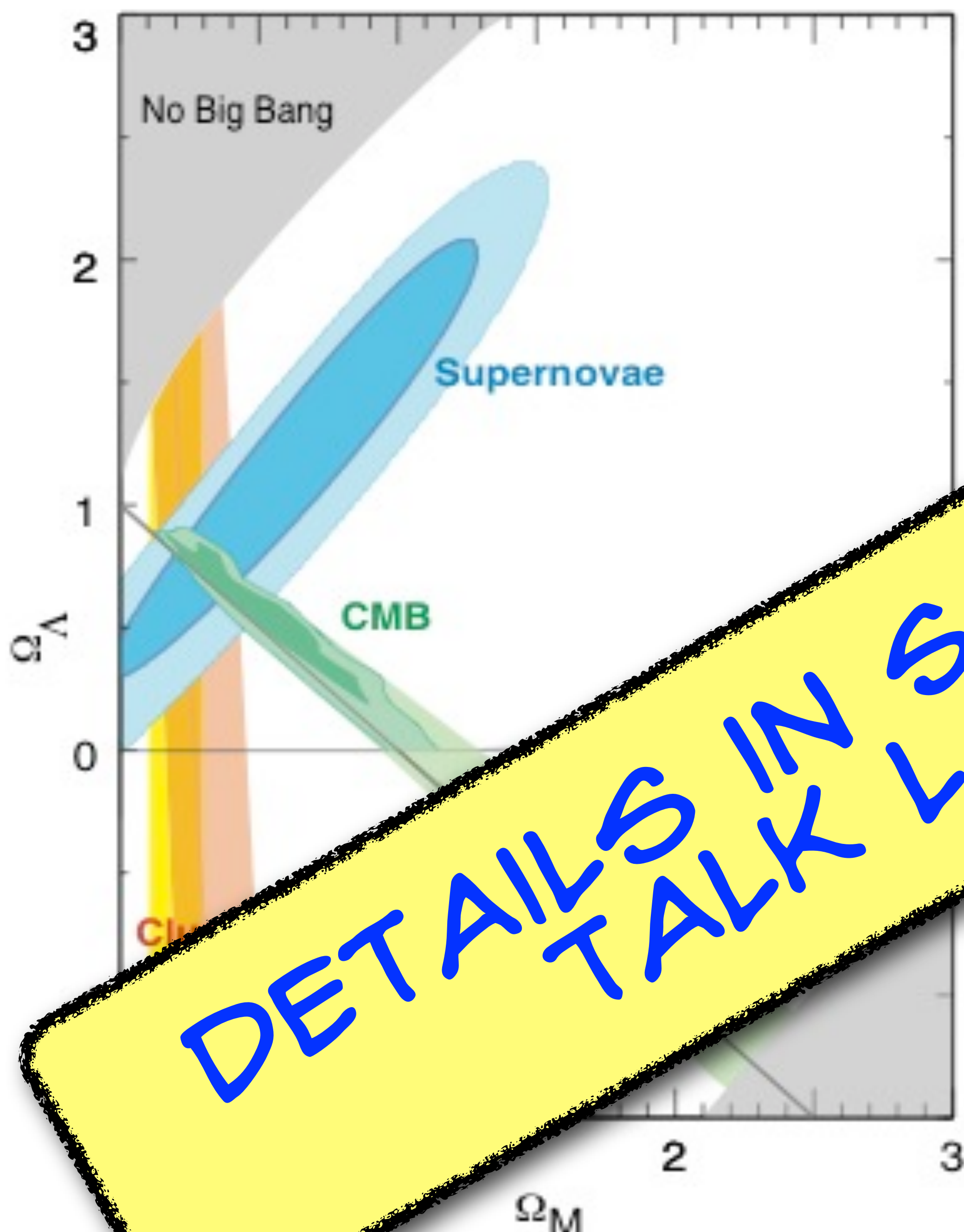
- Observations of the Bullet Cluster in the optical and x-ray fields combined with gravitational lensing provide compelling evidence that the dark matter is particles.

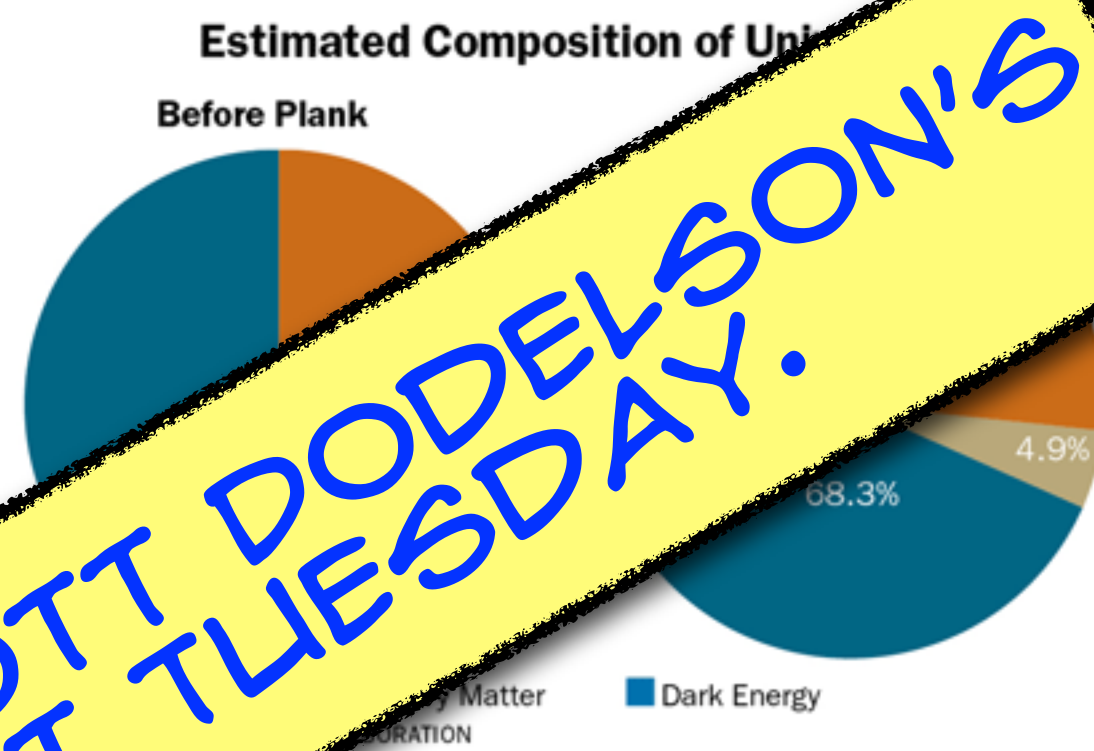
- Gravitational lensing tells us mass location
  - No dark matter = lensing strongest near gas
  - Dark matter = lensing strongest near stars

Clowe et al., ApJ, 648, 109

blue = lensing
red = x-rays

Cosmic Pie

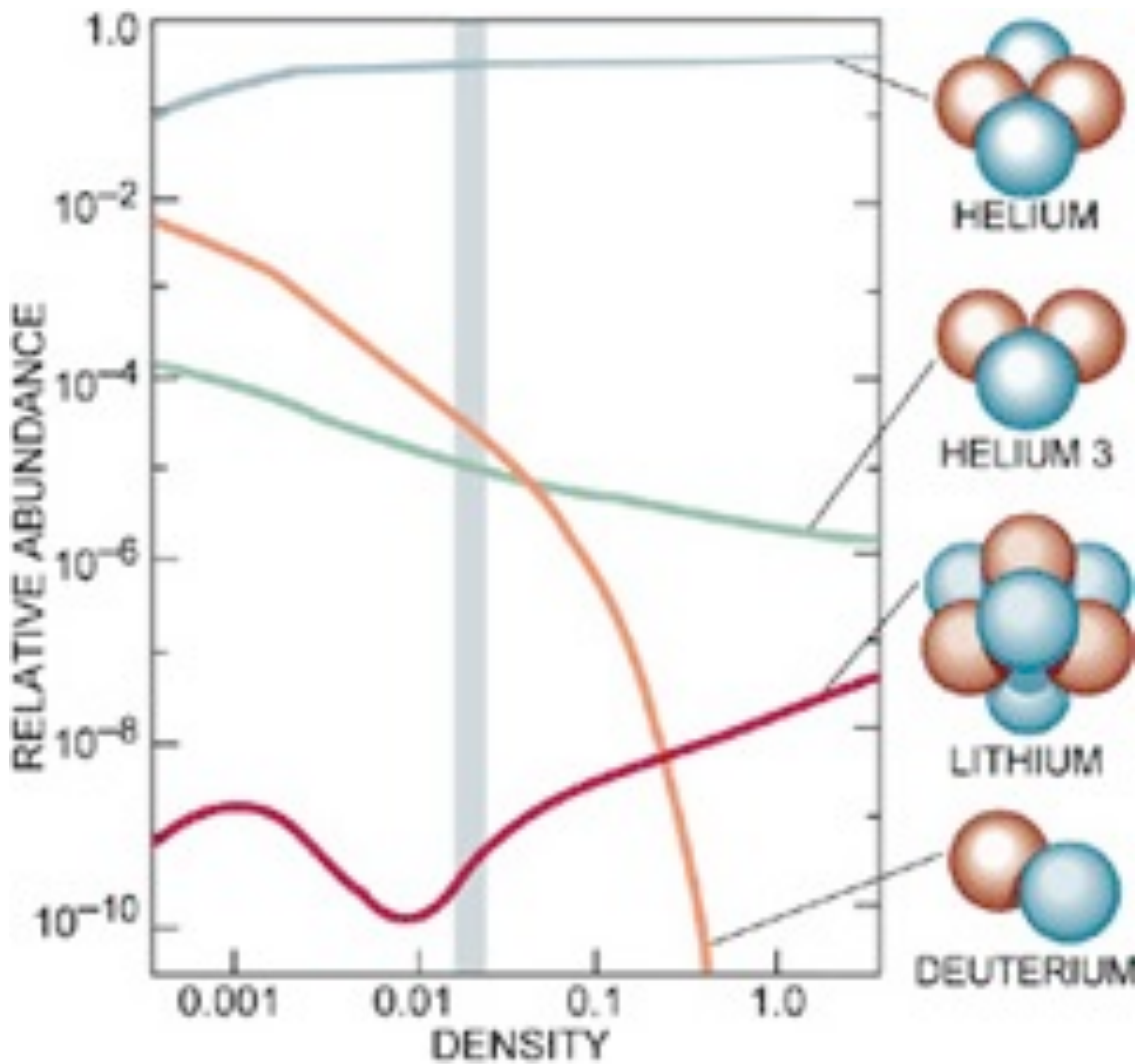




DETAILS IN SCOTT DODELSON'S TALK LAST TUESDAY.

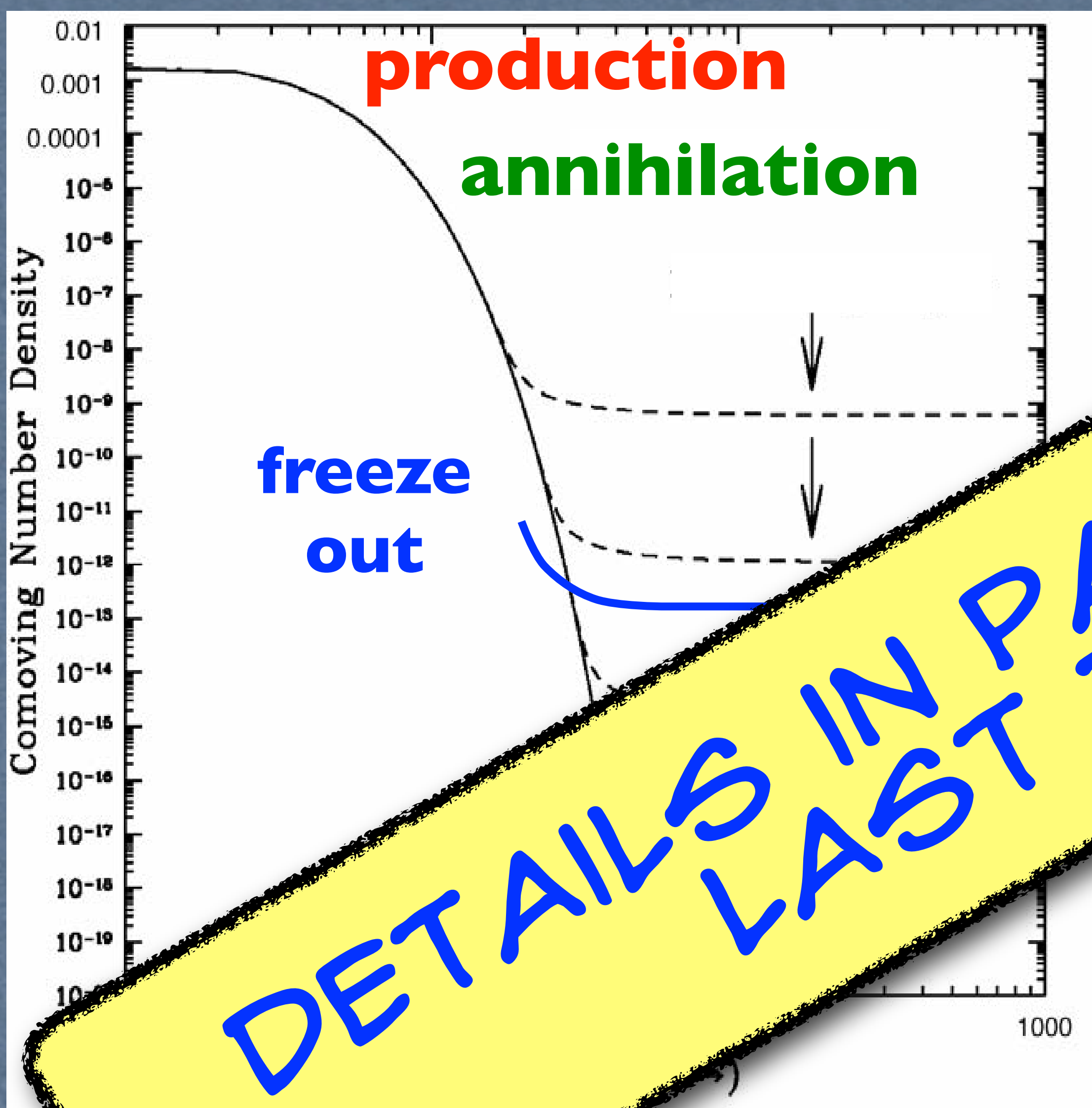
Measurements from CMB + supernovae + LSS indicate that ~ a quarter of our Universe is composed of dark matter.

What Could Dark Matter Be?



- Warm or **Cold**?
  - ordinary vs can not make up LSS of universe
- Baryonic or **Non-Baryonic**?
  - to avoid skewing formation of light elements in BBN

Motivated Candidate



$$\approx \frac{3 \times 10^{-27}}{< \sigma_\chi v >}$$

DETAILS IN PATTY FOX'S TALK
LAST THURSDAY

Weakly

M ... es

particle produced

early universe

scale cross-section gives observed

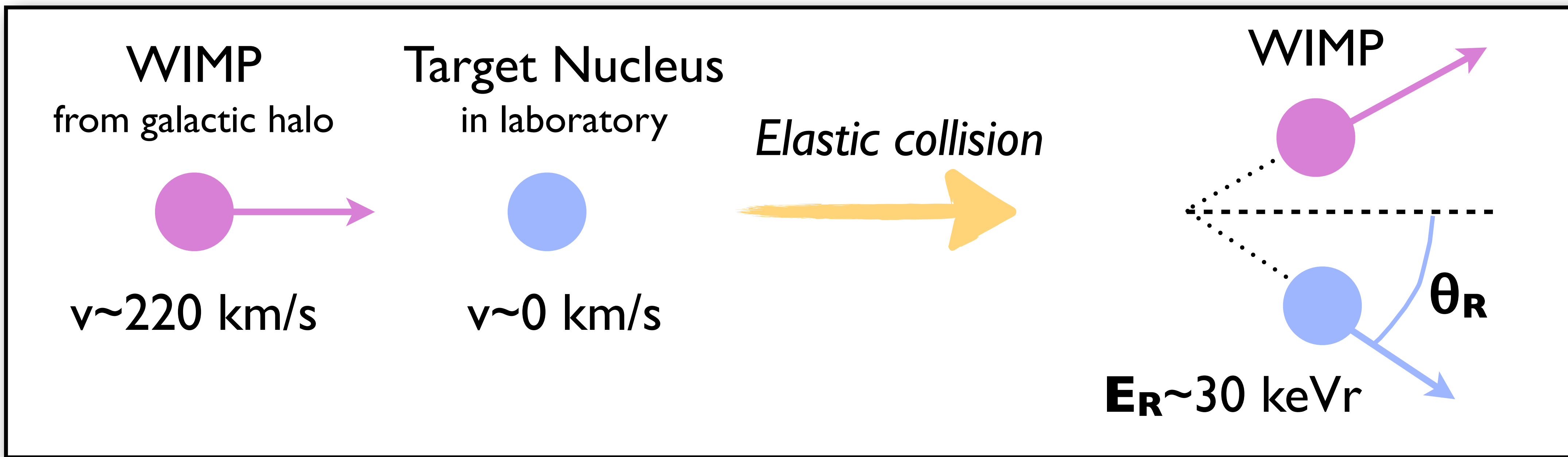
relic density

WMAP $0.095 < \Omega h^2 < 0.129$

$$\sigma_\chi \approx 10^{-37} cm^2$$

Direct Detection Rates

Assume that the dark matter is not only gravitationally interacting (WIMP).



- Elastic scatter of a WIMP off a nucleus
  - Imparts a small amount of energy in a recoiling nucleus
  - Can occur via spin-dependent or spin-independent channels
  - Need to distinguish this event from the overwhelming number of background events

Event Rate: Simplified WIMP

The differential event rate for simplified WIMP interaction is given by:

event rate

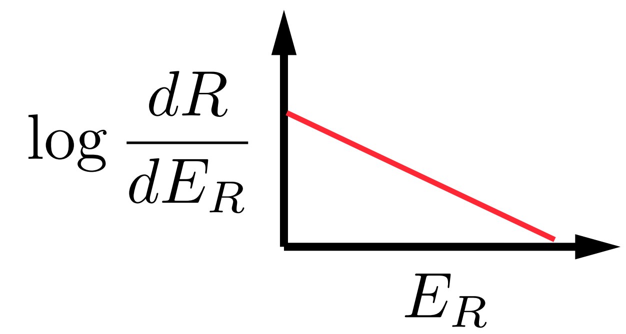
total event rate

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} e^{-E_R/E_0 r}$$

recoil energy

most probable incident energy

kinematic factor



$$r = \frac{4M_\chi M_N}{(M_\chi + M_N)^2}$$

If we integrate

$$\int_0^\infty \frac{dR}{dE_R} dE_R = R_0$$

and

$$< E_R >= \int_0^\infty E_R \frac{dR}{dE_R} dE_R = E_0 r$$

Event Rate: Calculation

Let's plug in some numbers and see what we get.

$$M_X = M_N = 100 \text{ GeV}/c^2$$

The resulting kinematic factor is

$$r = \frac{4M_\chi M_N}{(M_\chi + M_N)^2} = \frac{4(100)(100)}{(100+100)^2} = 1$$

For a WIMP with velocity 220 km/s

$$\beta = v/c \sim 0.73 \times 10^{-3}$$

Recoil Energy is then given by

$$E_R = E_0 r = \frac{1}{2} M_\chi \beta^2 c^2 = \frac{1}{2}(100\frac{GeV}{c^2})(0.73 \times 10^{-3})^2 c^2$$

$$E_R = 27 \text{ keV}$$

Event Rate

The differential event rate:

[counts kg^{-1} day^{-1}] ⟶ (dru = differential rate unit)

need input from astrophysics, particle physics and nuclear physics

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

- local WIMP density (ρ_0)
- WIMP-nucleon scattering cross section ($d\sigma/dE_R$)
- nucleus mass (m_N)
- WIMP mass (m_χ)
- WIMP speed distribution in detector frame ($f(v)$)

Minimum WIMP velocity which can cause a recoil of energy E_R.

$$v_{min} = \sqrt{\frac{E_R m_N}{2\mu^2}}$$

Elastic scattering happens in the extreme non-relativistic case in the lab frame

$$E_R = \frac{\mu_N^2 v^2 (1 - \cos\theta^*)}{m_N}$$

where

$$\mu = \frac{m_\chi m_N}{m_\chi + m_N}$$

reduced mass

WIMP-Nucleon Interaction

Event rate is found by integrating over all recoil:

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

Minimum WIMP velocity which can cause a recoil of energy E_R.

$$v_{min} = \sqrt{\frac{E_R m_N}{2\mu^2}}$$

The WIMP-nucleon cross section can be separated

$$\frac{d\sigma}{dE_R} = \left(\frac{d\sigma}{dE_R}\right)_{SI} + \left(\frac{d\sigma}{dE_R}\right)_{SD}$$

Spin-independent Spin-dependent

SI arise from scalar or vector couplings to quarks.

SD arise from axial vector couplings to quarks.

To calculate χ-N cross section, add coherently the spin and scalar components:

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2\mu^2 v^2}\left[\sigma_{SI} F_{SI}^2(E_R) + \sigma_{SD} F_{SD}^2(E_R)\right]$$

Spin-independent term Spin-dependent term

$F(E_R)$ = Form Factor encodes the dependence on the momentum transfer

WIMP-Nucleon Interaction

WIMP-nucleus cross sections:

$$\sigma_{SI} = \frac{4\mu^2}{\pi}\left[Z f_p + (A-Z) f_n\right]^2 \propto A^2$$

$$\sigma_{SD} = \frac{32\mu^2}{\pi} G_F^2 \frac{J+1}{J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2$$

best sensitivity with high A

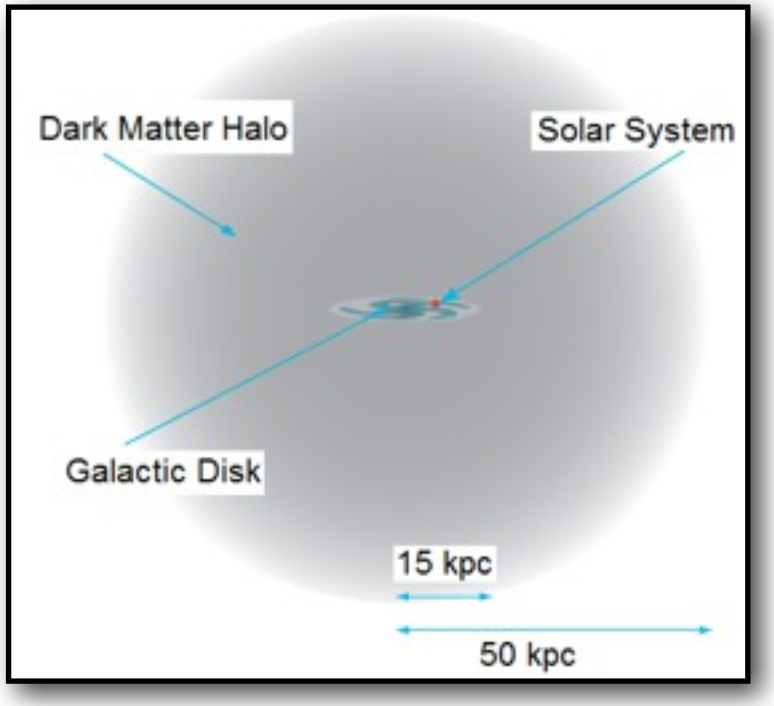
need a nucleus with spin

Nucleus	Z	Odd Nucleon	J	$\langle S_p\rangle$	$\langle S_n\rangle$	C_A^p/C_p	C_A^n/C_n
^{19}F	9	p	1/2	0.477	-0.004	9.10×10^{-1}	6.40×10^{-5}
^{23}Na	11	p	3/2	0.248	0.020	1.37×10^{-1}	8.89×10^{-4}
^{27}Al	13	p	5/2	-0.343	0.030	2.20×10^{-1}	1.68×10^{-3}
^{29}Si	14	n	1/2	-0.002	0.130	1.60×10^{-5}	6.76×10^{-2}
^{35}Cl	17	p	3/2	-0.083	0.004	1.53×10^{-2}	3.56×10^{-5}
^{39}K	19	p	3/2	-0.180	0.050	7.20×10^{-2}	5.56×10^{-3}
^{73}Ge	32	n	9/2	0.030	0.378	1.47×10^{-3}	2.33×10^{-1}
^{93}Nb	41	p	9/2	0.460	0.080	3.45×10^{-1}	1.04×10^{-2}
^{125}Te	52	n	1/2	0.001	0.287	4.00×10^{-6}	3.29×10^{-1}
^{127}I	53	p	5/2	0.309	0.075	1.78×10^{-1}	1.05×10^{-2}
^{129}Xe	54	n	1/2	0.028	0.359	3.14×10^{-3}	5.16×10^{-1}
^{131}Xe	54	n	3/2	-0.009	-0.227	1.80×10^{-4}	1.15×10^{-1}

Tovey et al., PLB488 17 (2000)

Standard Halo Model

- Energy spectrum and rate depend on details of WIMP distribution in the dark matter halo.



- Local Dark Matter Density

$$\rho_0 \equiv \rho(r = R_0) = 0.3 \;\; \mathrm{GeV/cm^3}$$

- Speed Distribution - isotropic, Maxwellian

$$f(\vec{v}) = \frac{1}{\sqrt{2\pi}\sigma} exp(-\frac{|\vec{v}|^2}{2\sigma^2})$$

where

$$\sigma = \sigma_{rms} = \sqrt{\frac{3}{2}} v_0 = 270 \; \mathrm{km/s} \quad \text{and} \quad v_0 = 220 \; \mathrm{km/s}$$

This corresponds to an isothermal sphere with density profile

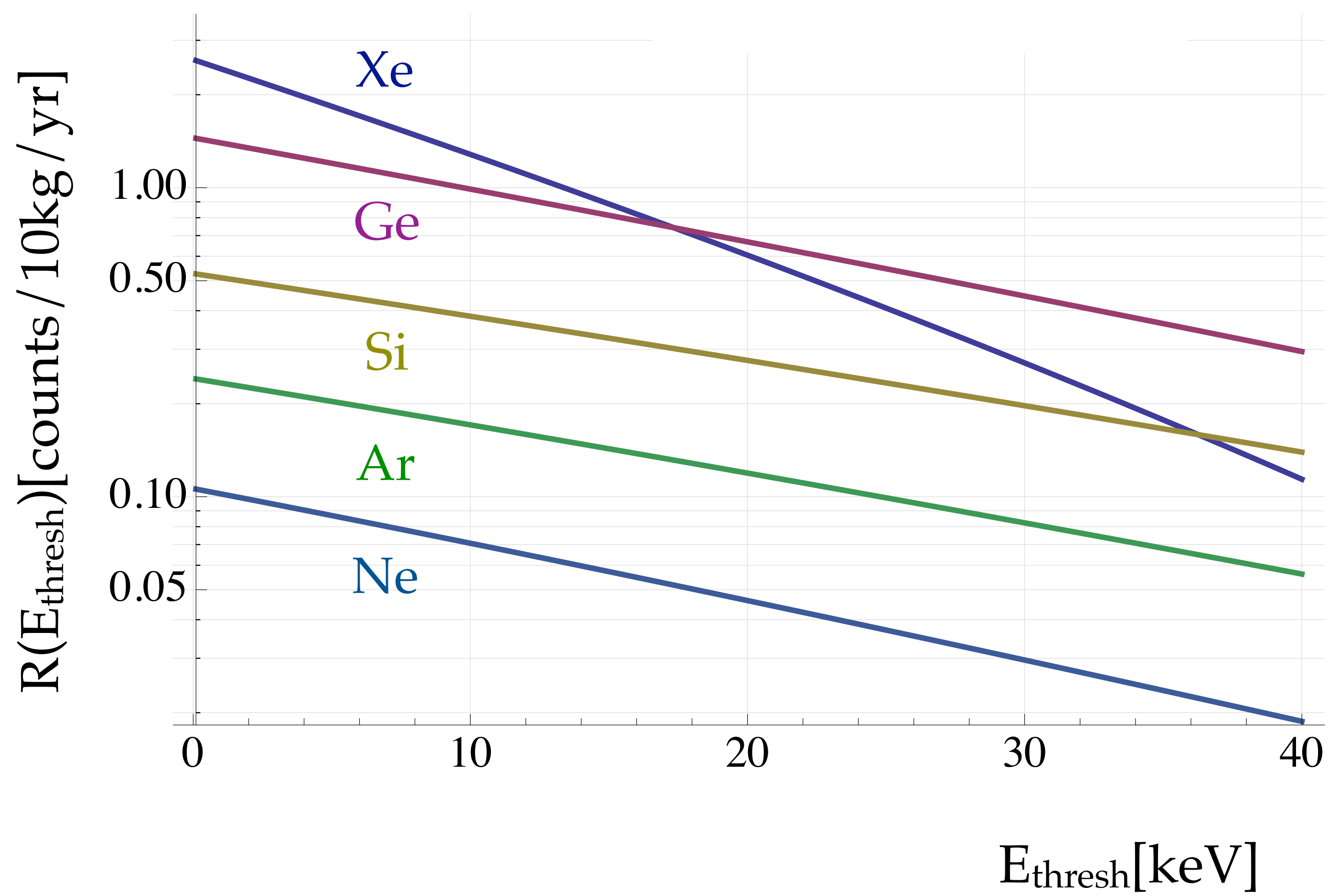
$$\rho \propto r^{-2}$$

- Note Particles with speed greater than the local escape speed are not gravitationally bound. The standard halo extends out to infinite radii and thus the speed distribution in this model must be truncated "by hand". We take v_{esc} = 650 km/s.

Event Rates

- Elastic scattering of WIMP deposits small amounts of energy into a recoiling nucleus (~few 10s of keV)
- Featureless exponential spectrum with no obvious peak, knee, break ...
- Event rate is very, very low.
- Radioactive background of most materials is higher than the event rate.

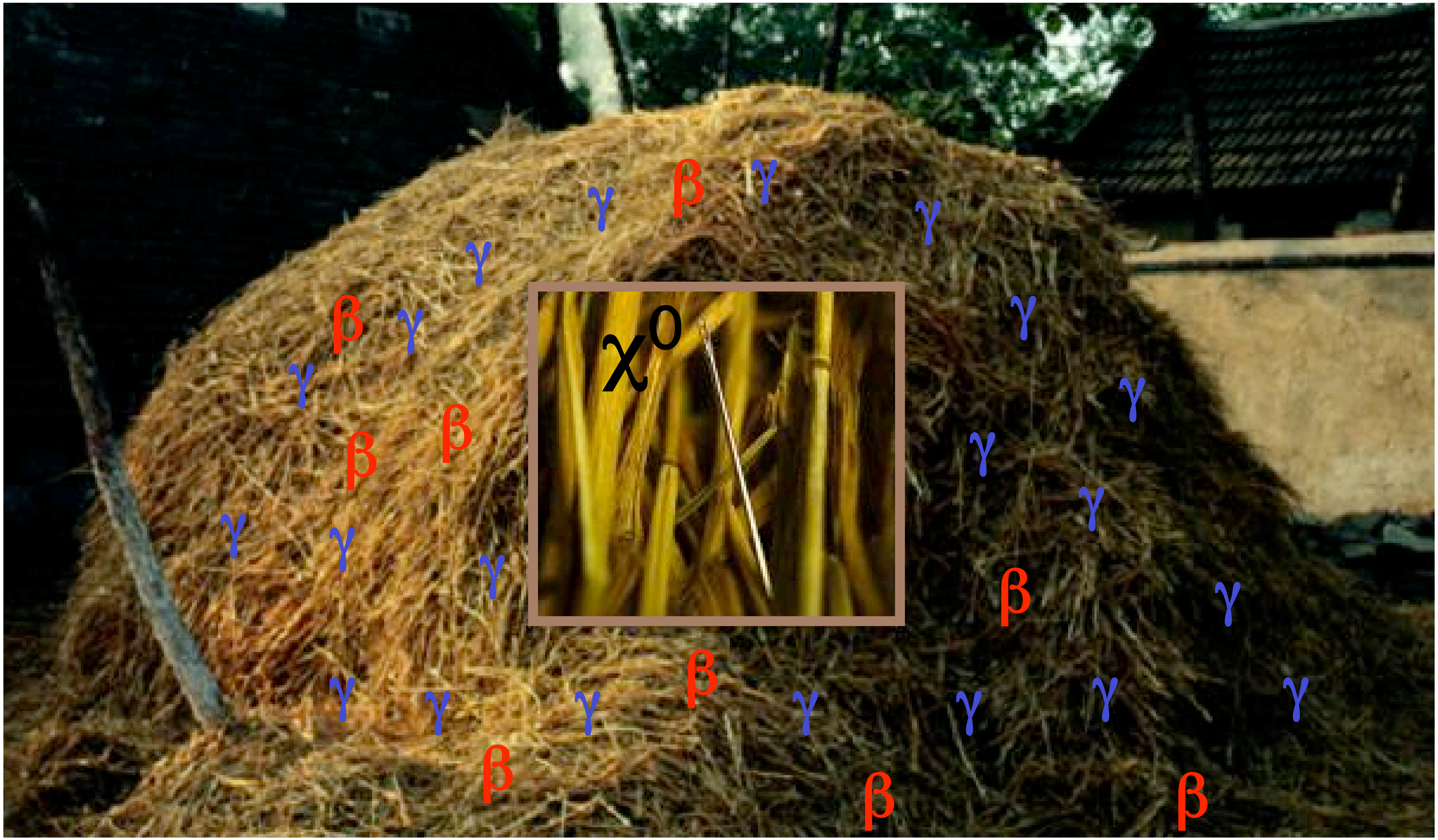
Total Event Rate
($m_\chi = 100$ GeV / c^2, $\sigma_{\chi\text{-}n} = 10^{-45}$ cm^2)



Detection Principles

- Various experimental methods exist for measuring such an energy deposition
    - Scintillation in crystals/liquids
    - Ionization in crystals/liquids
    - Thermal/athermal heating in crystals
    - Bubble formation in liquids/gels
- Easy in principle, hard in practice
    - Significant uncertainties/unknowns in estimating DM event rates and energy spectrum
    - Background rates overwhelm the most optimistic DM scattering rates.
    - And did I forget to mention - neutrons look just like the DM in our detectors.

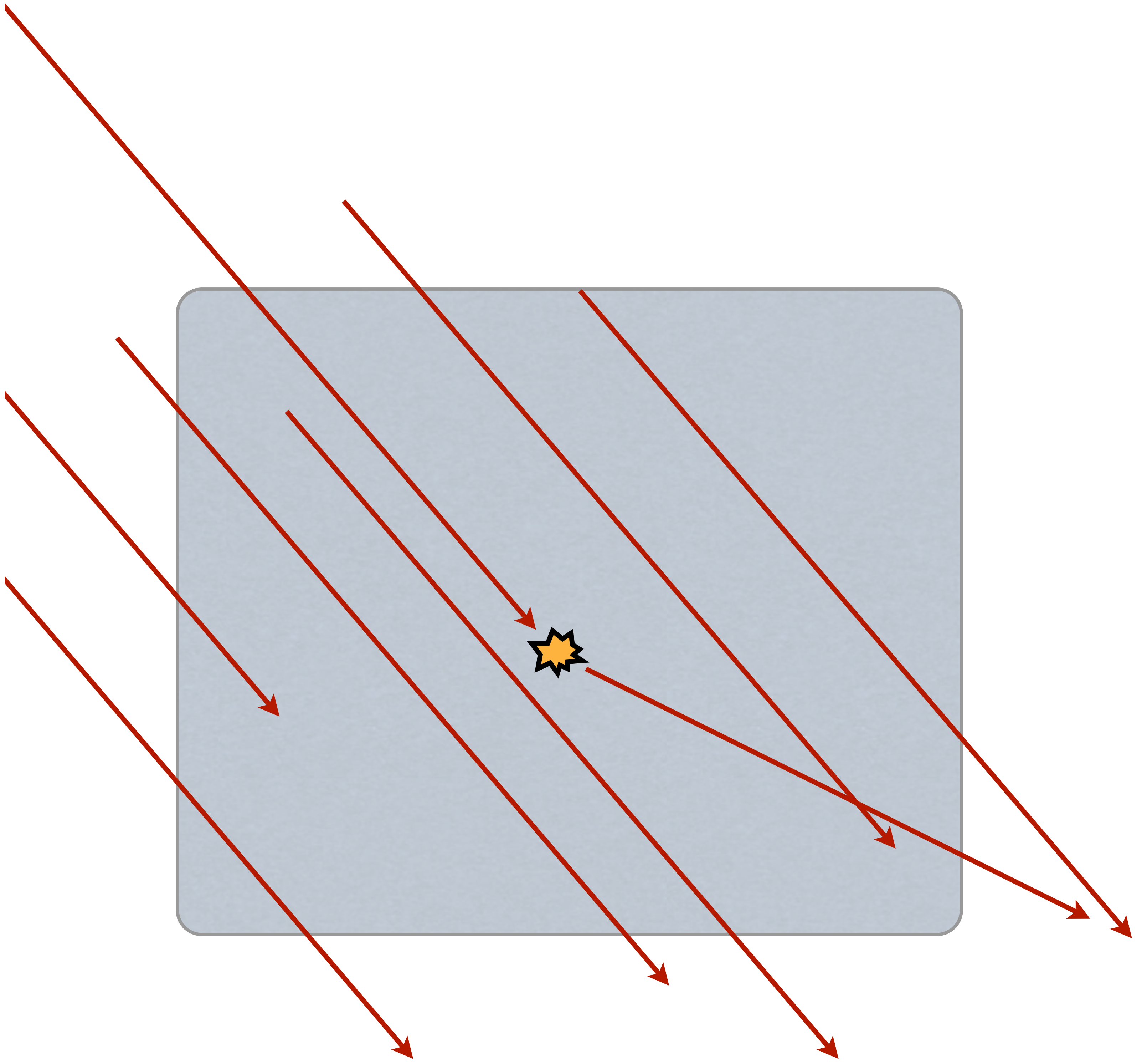
Looking for a Small Needle in a Very Large Haystack



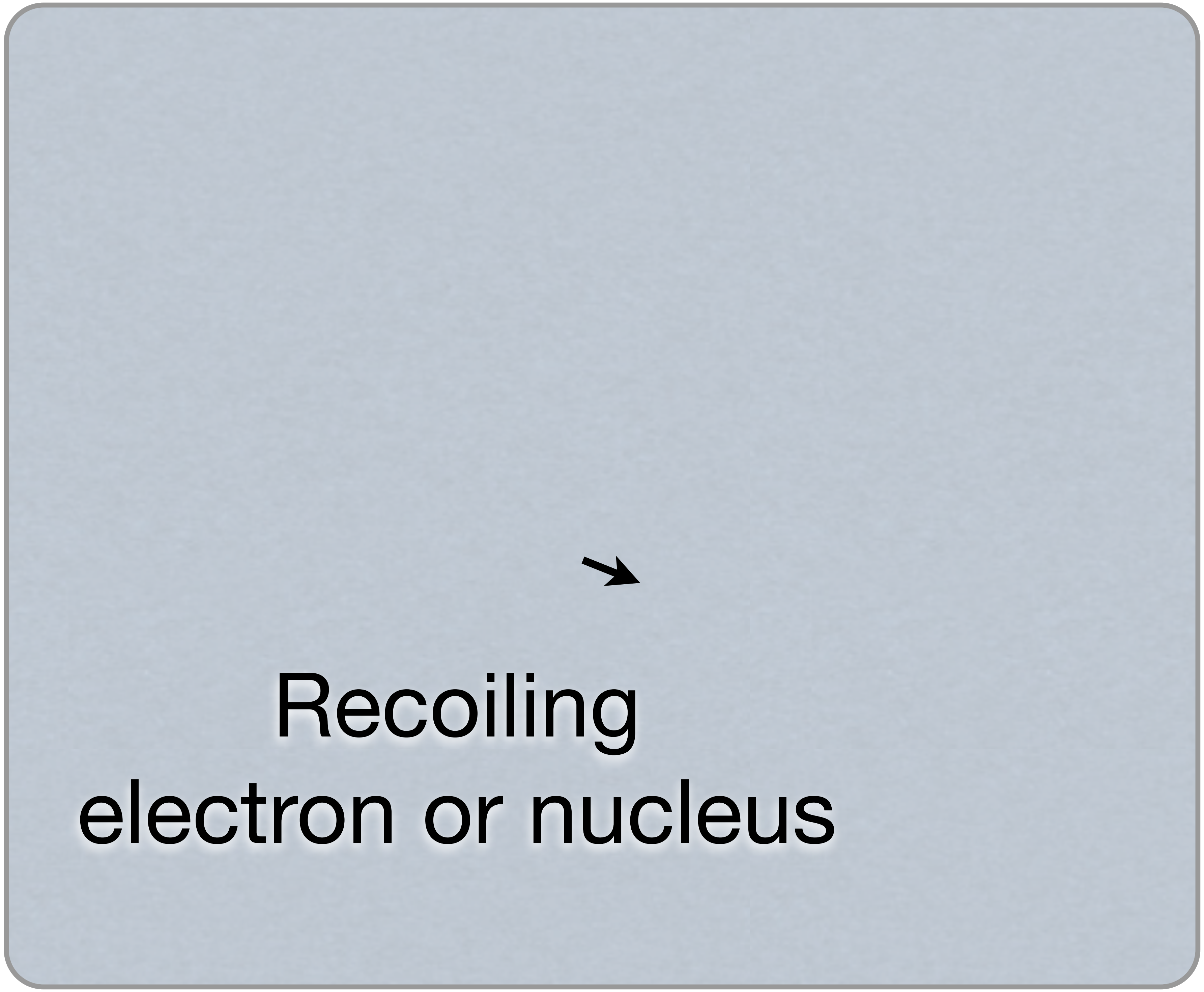
Looking for a Small Needle in a Very Large Haystack

Somewhere in the Midwest!

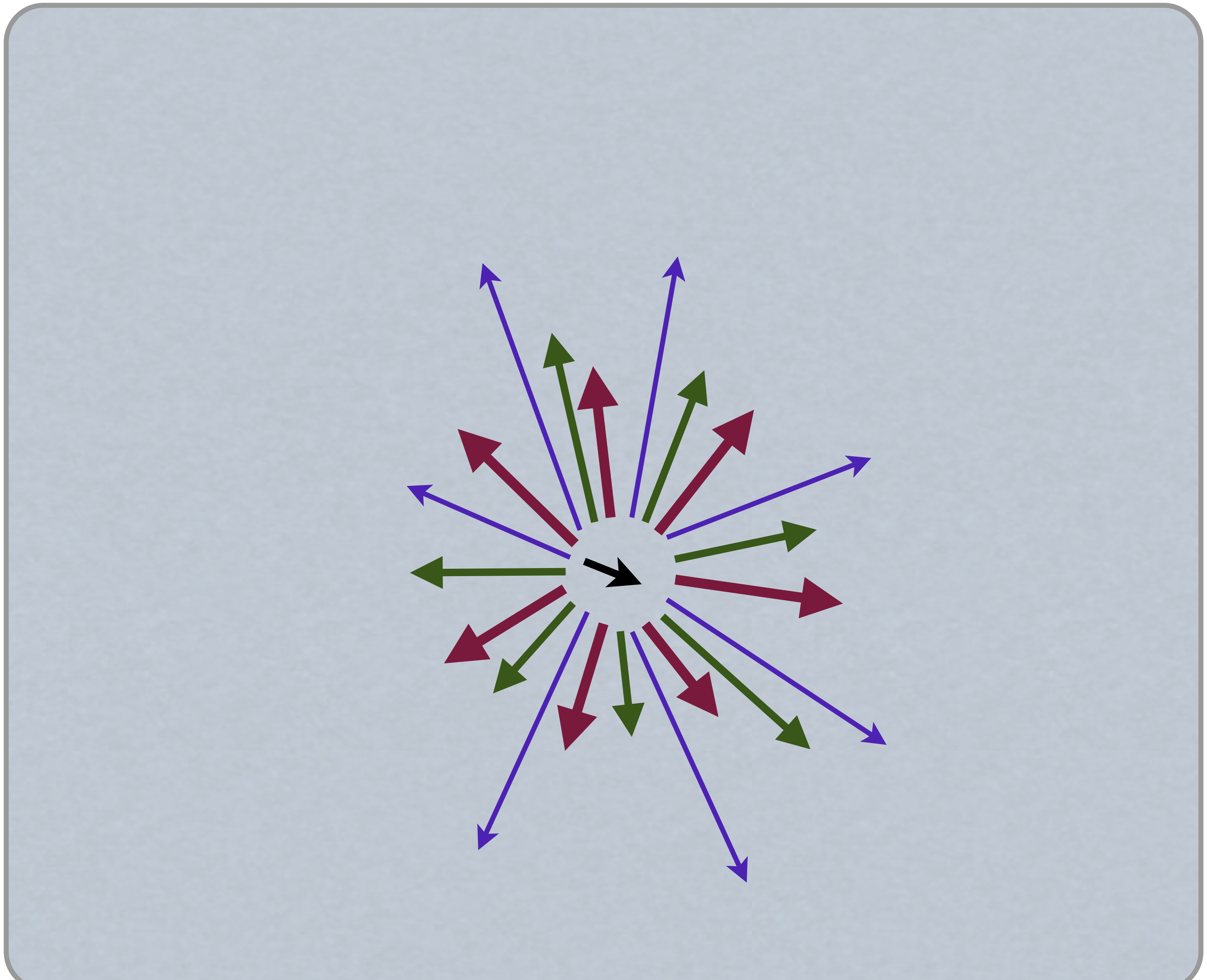
General Detection Principles



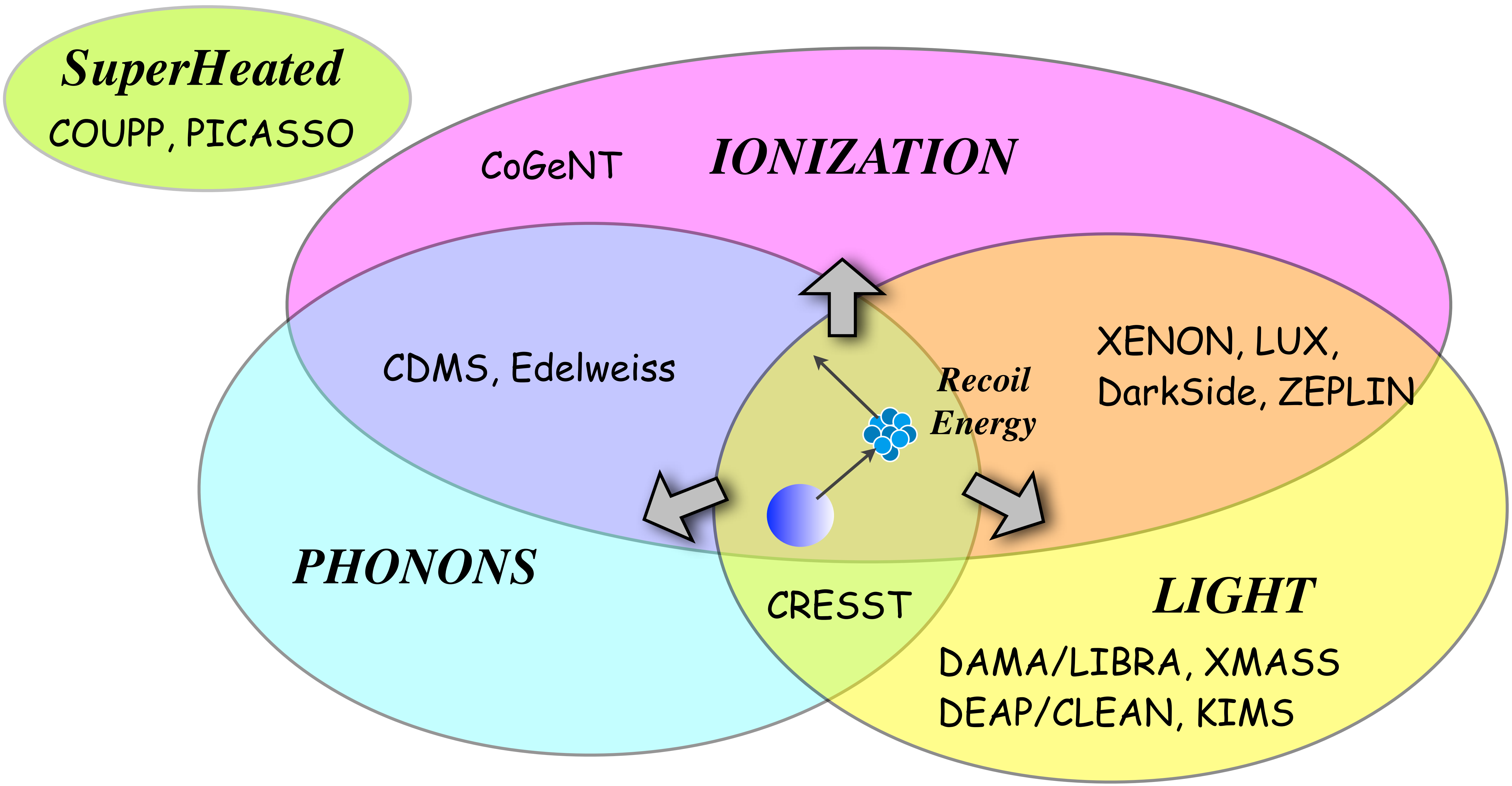
General Detection Principles



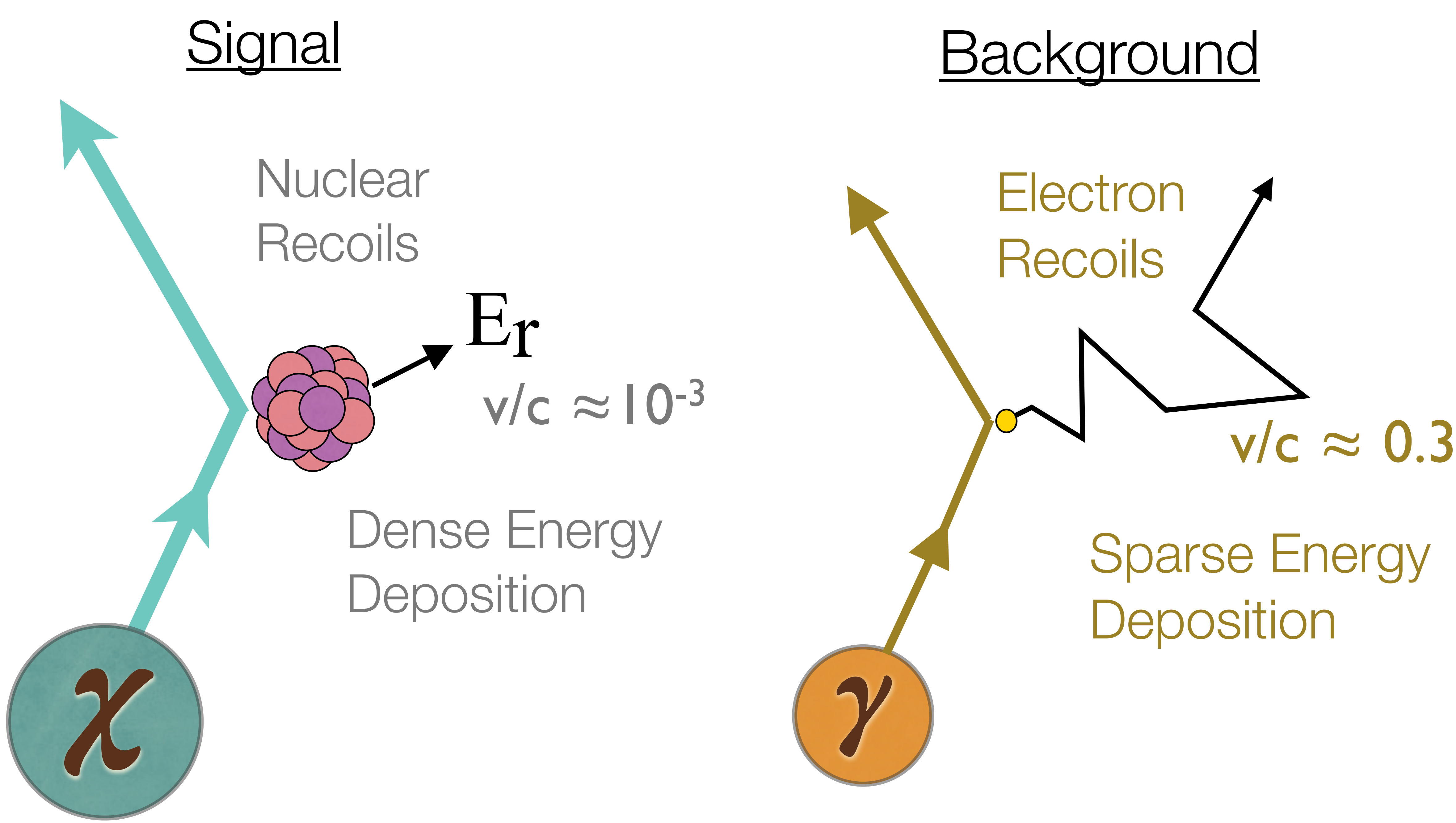
General Detection Principles



Direct Detection Principles



Detection Principles



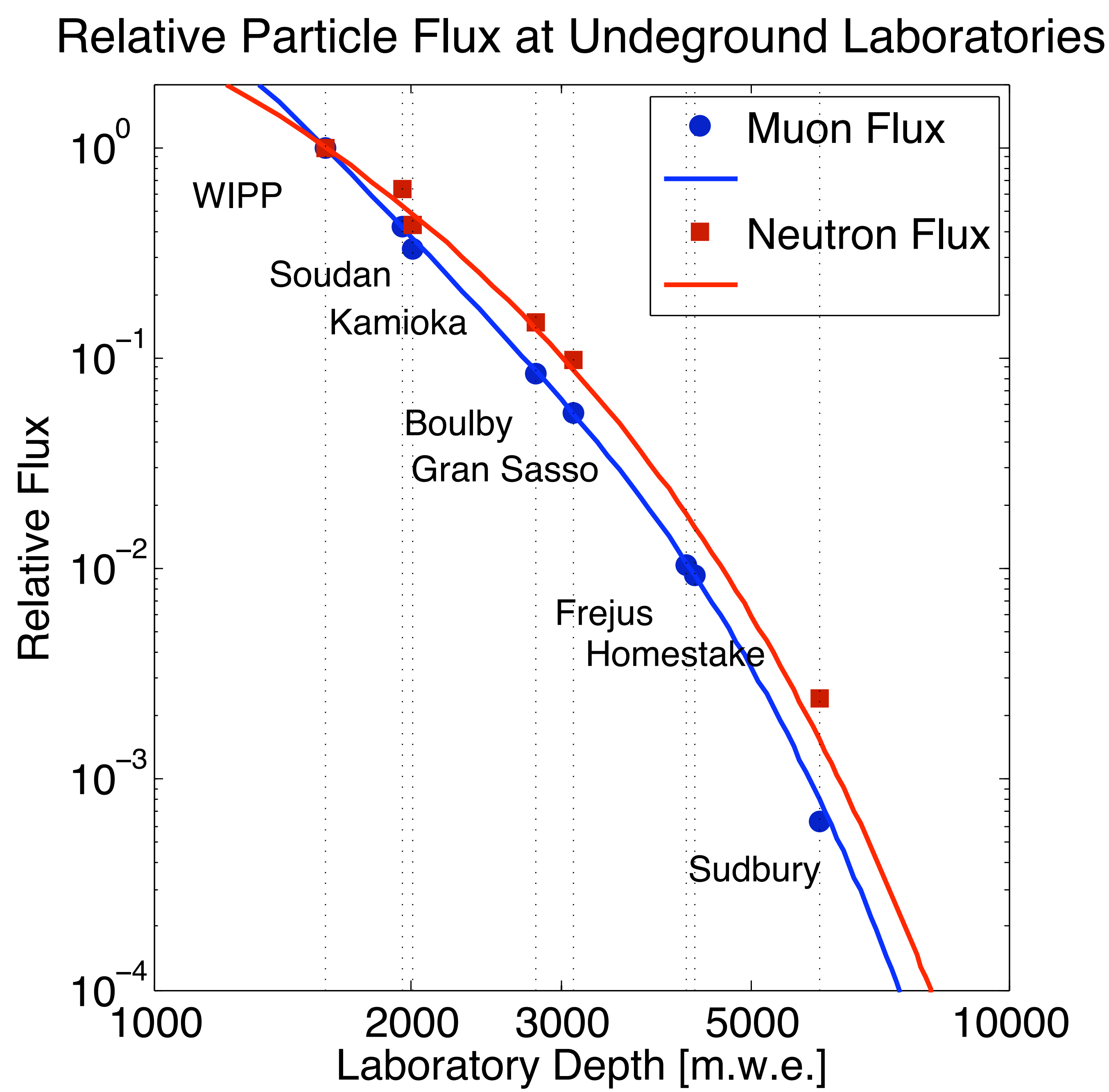
Particle Identification

- Scattering from an atomic nucleus leads to different physical effects than scattering from an electron in most materials.
- Sensitivity to this effect reduces background.
  - Dark Matter is expected to interact with the nucleus and backgrounds interact with electrons*.

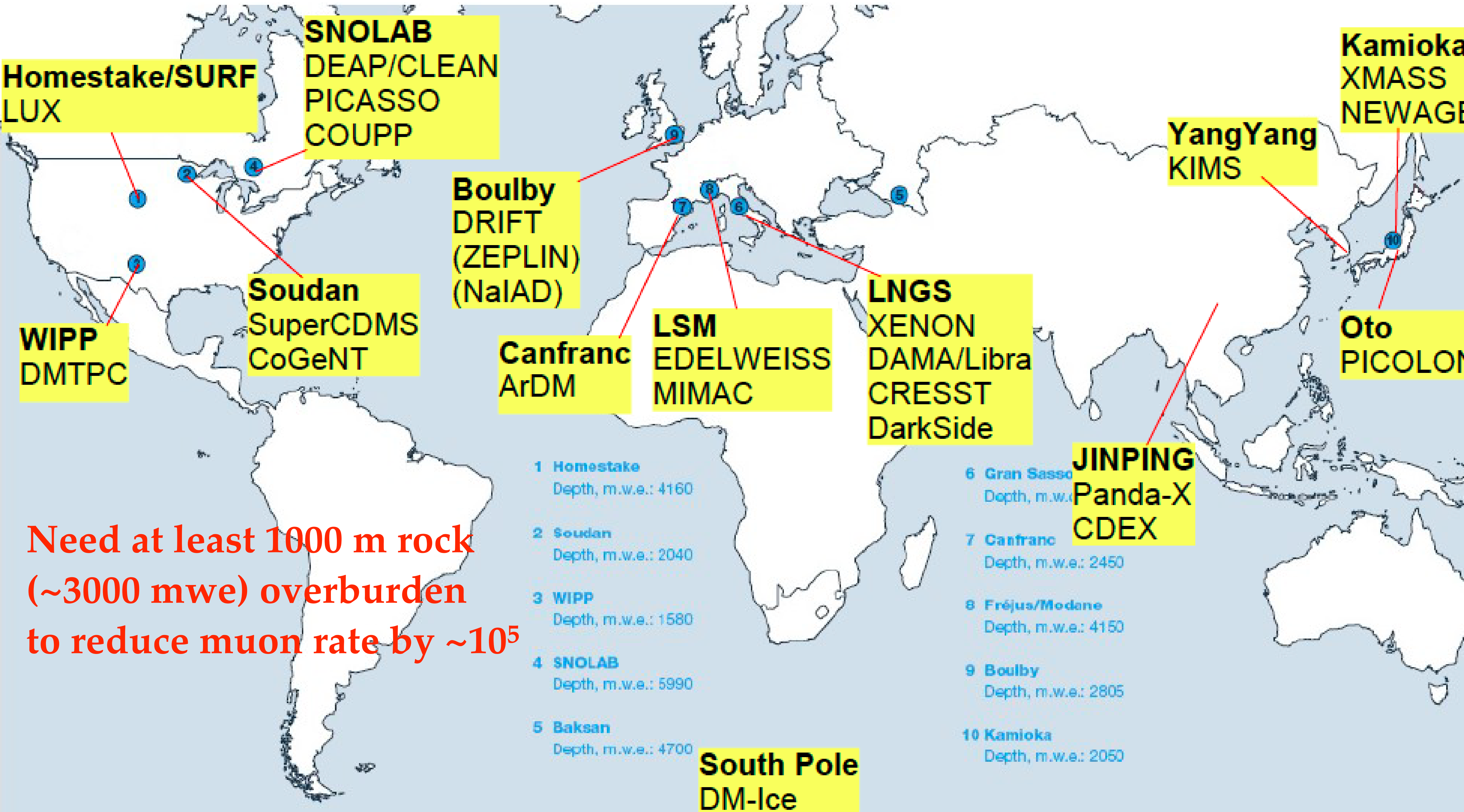
*CAVEAT: Neutrons interact with the nucleus.

Neutrons: Unrejected Background

- Neutrons recoil off atomic nuclei, thus appearing as WIMPs
- Neutrons come from
  - Environmental radioactivity
    - Slow/low energy
    - Can be addressed by shielding
  - Spallation due to cosmic muons
    - Fast/energetic = not shield-able
    - Must go deep underground to avoid



Minimize Backgrounds



Need at least 1000 m rock (~3000 mwe) overburden to reduce muon rate by $\sim 10^5$

Site experiments underground.

Minimize Backgrounds

Active Muon Veto:
rejects events from cosmic rays

- Scintillating panels
- Water Shield

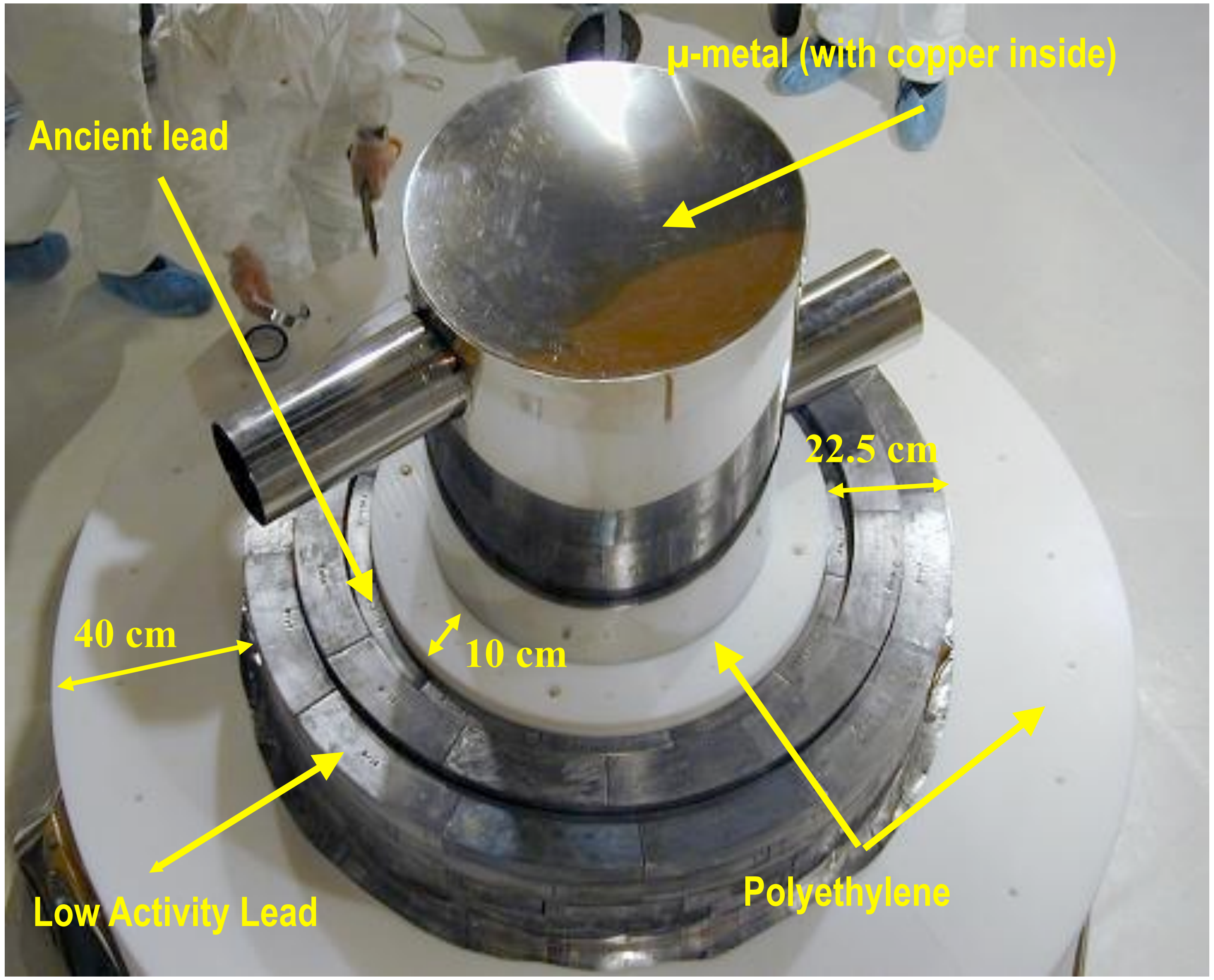
SCDMS active muon veto

LUX water shield

Minimize Backgrounds

Pb: shielding from gammas resulting from radioactivity

Polyethyene: moderate neutrons produced from fission decays and from (α,n) interactions resulting from U/Th decays

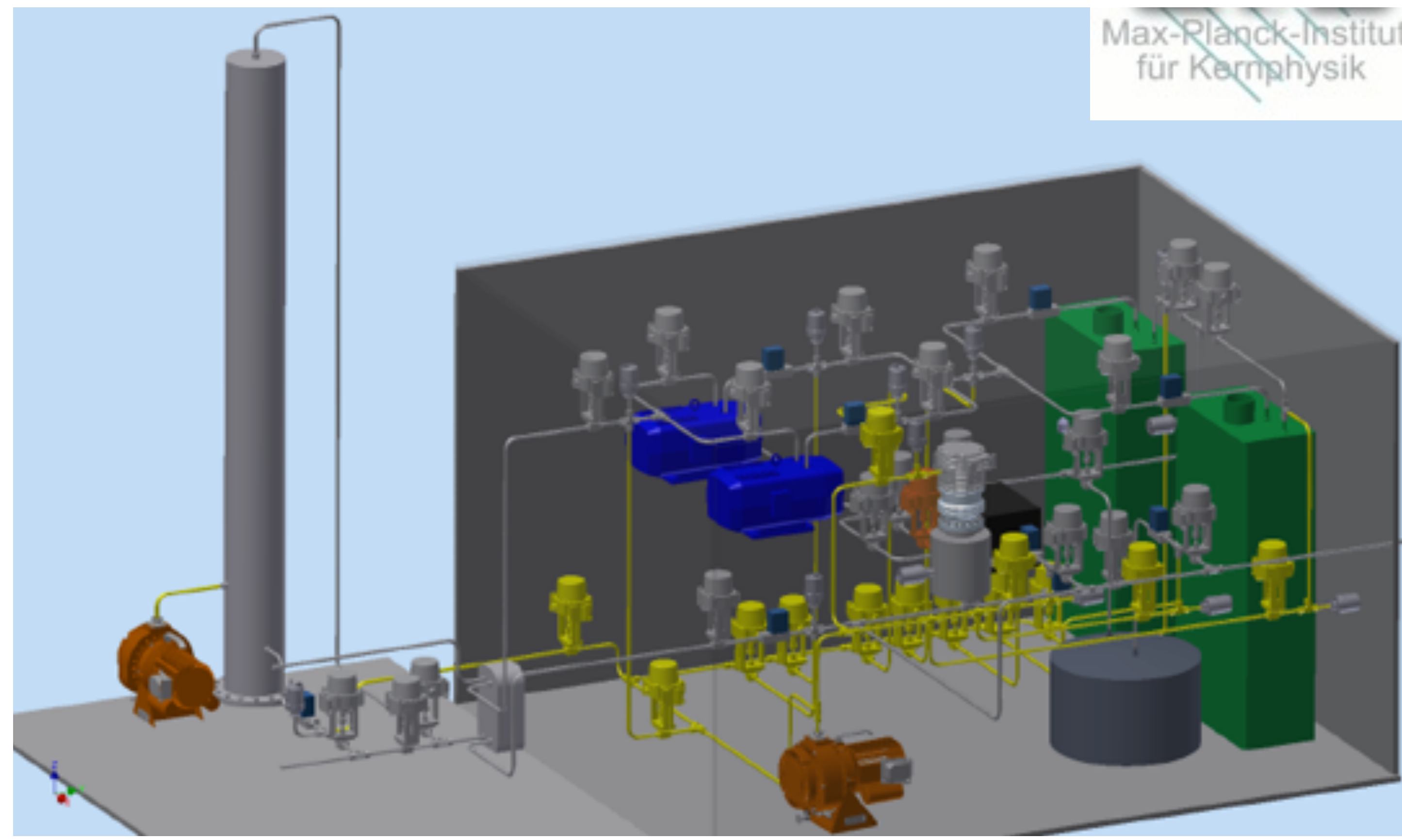


SCDMS - Layers of Polyethylene and Lead

Use Passive Shielding

Minimize Backgrounds

mobile radon extraction unit @ MPIK

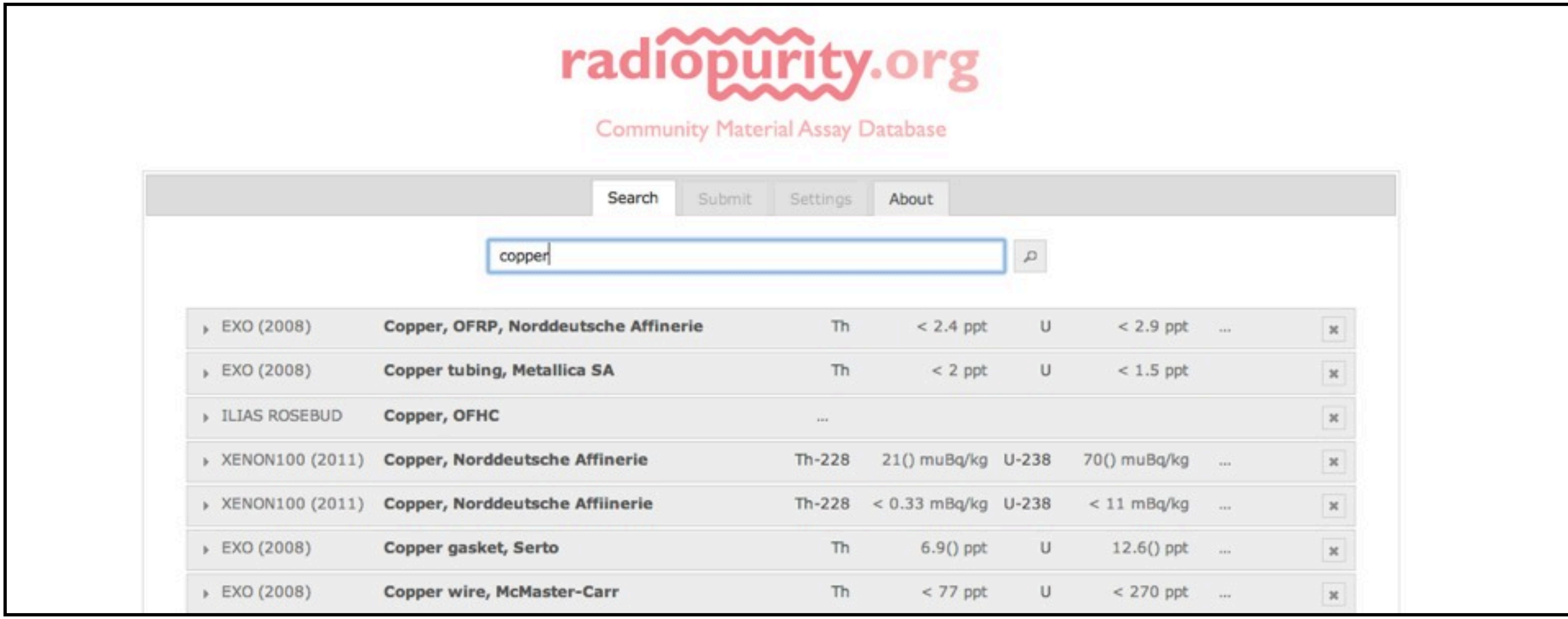


XENON1T purification loop with large charcoal tower.

Krypton and Radon Mitigation

Minimize Backgrounds

http://radiopurity.org



radiopurity.org

Community Material Assay Database

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copper

EXO (2008)	Copper, OFRP, Norddeutsche Affinerie	Th	< 2.4 ppt	U	< 2.9 ppt	...
EXO (2008)	Copper tubing, Metallica SA	Th	< 2 ppt	U	< 1.5 ppt	
ILIAS ROSEBUD	Copper, OFHC	...				
XENON100 (2011)	Copper, Norddeutsche Affinerie	Th-228	21() muBq/kg	U-238	70() muBq/kg	...
XENON100 (2011)	Copper, Norddeutsche Affiinerie	Th-228	< 0.33 mBq/kg	U-238	< 11 mBq/kg	...
EXO (2008)	Copper gasket, Serto	Th	6.9() ppt	U	12.6() ppt	...
EXO (2008)	Copper wire, McMaster-Carr	Th	< 77 ppt	U	< 270 ppt	...

Supported by AARM, LBNL, MAJORANA, SMU, SJTU & others

Use Clean Materials

All Hope is Not Loss

If Our Needle is VERY BIG!

Signals

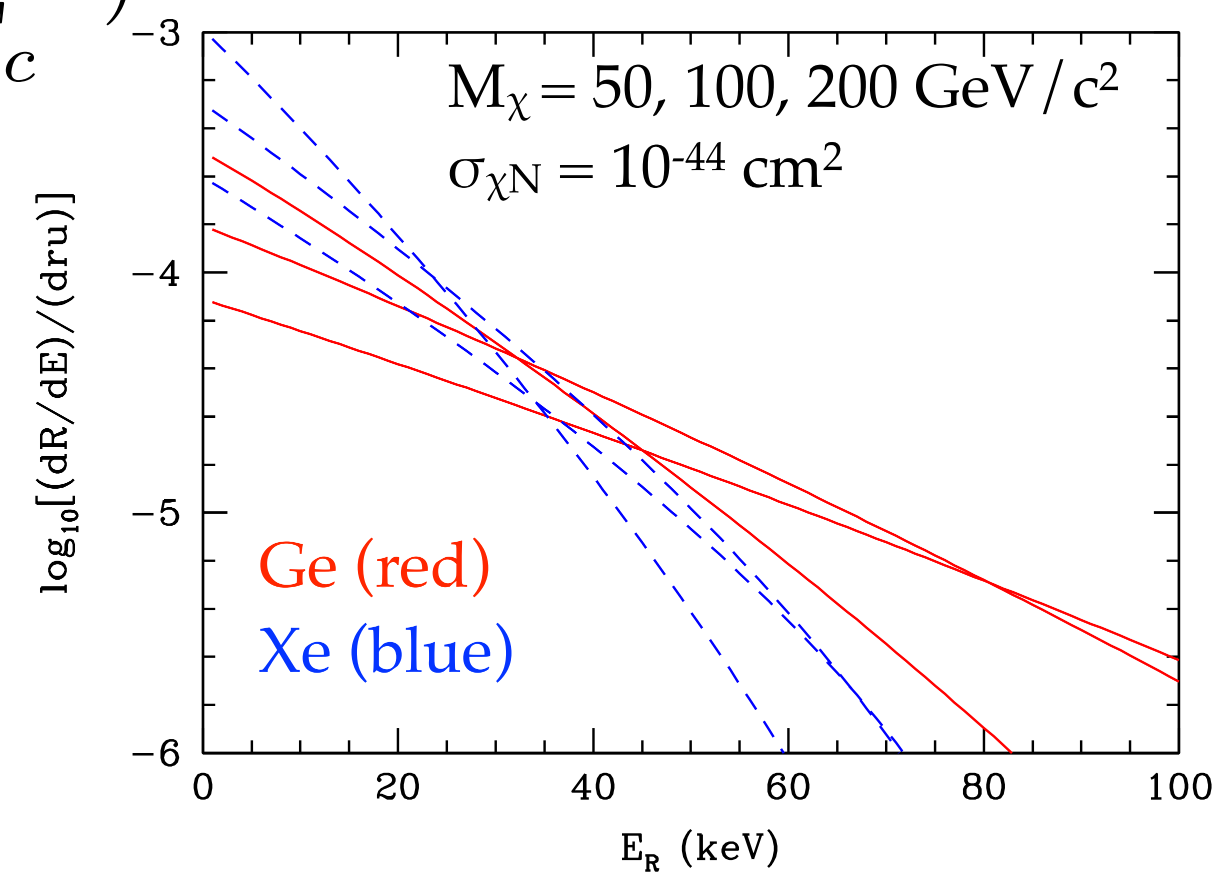
- As we have seen, the recoil rate is energy dependent due to the kinematics of elastic scattering and the WIMP speed distribution.
- In addition, the recoil rate is time- and direction-dependent due to the motion of Earth w.r.t. the galactic rest frame.
- Variations can happen in the
    - Energy spectrum
    - Event rate
    - Recoil direction

Signals: Energy Dependence

For the standard halo model, we can write the differential event rate as:

$$\frac{dR}{dE_R} \approx (\frac{dR}{dE_R})_0 F^2(E_R) exp(\frac{-E_R}{E_c})$$

event rate in limit E --> 0



Characteristic energy scale given by:

parameter that depends on target

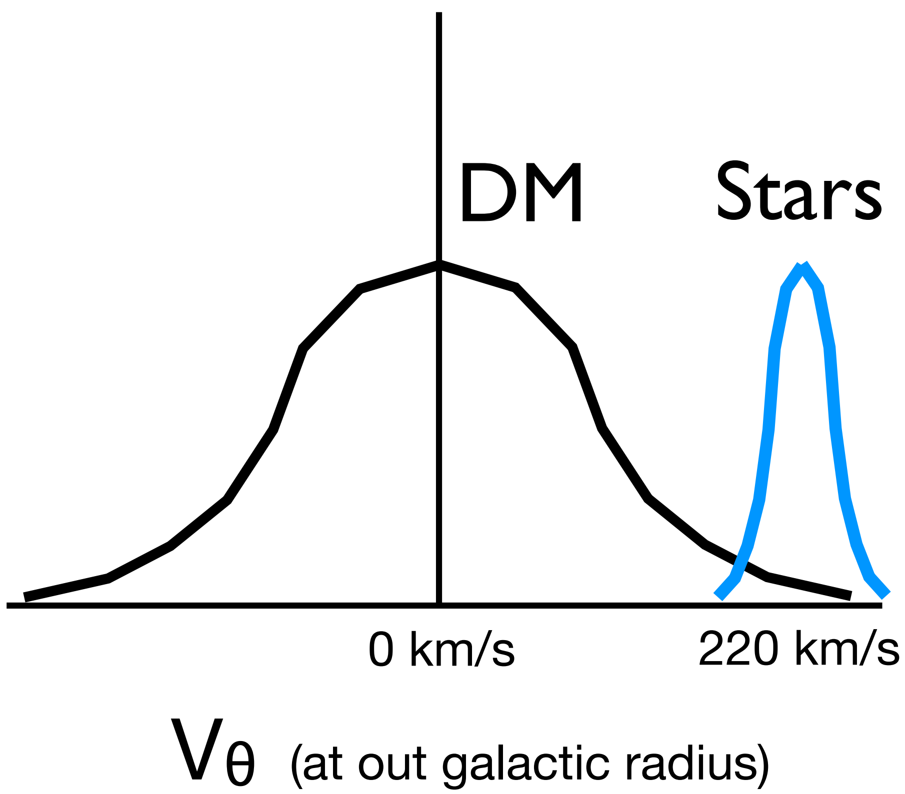
$$E_c = \frac{c_1 2\mu_N^2 v_c^2}{m_N}$$

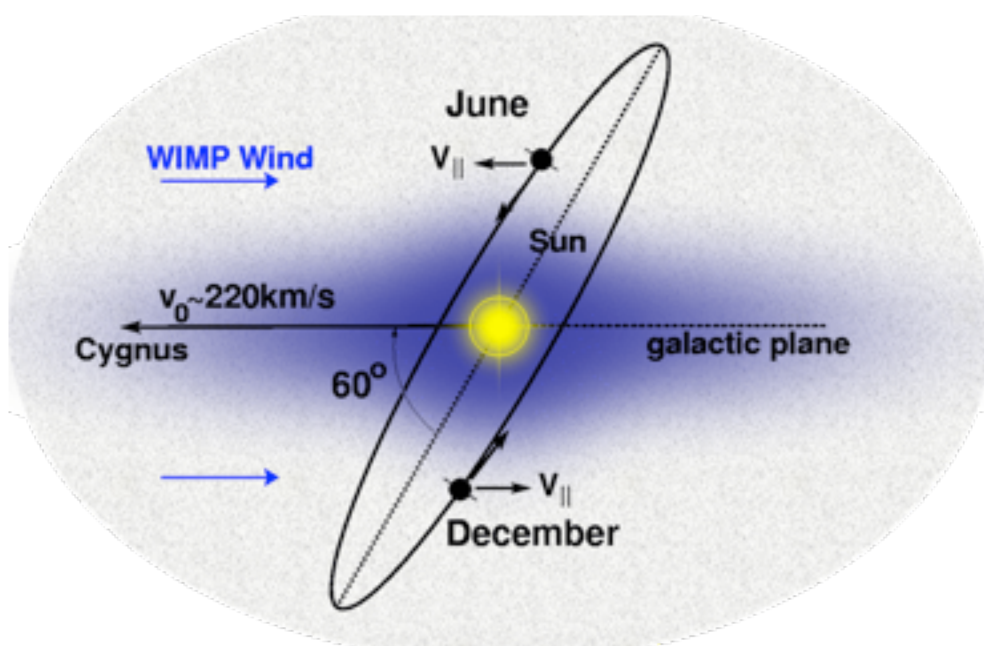
$$m_\chi << m_N \rightarrow E_c \propto \frac{m_\chi^2}{m_N}$$

$$m_\chi >> m_N \rightarrow E_c \propto m_N$$

Total recoil rate is proportional to WIMP number density

Signal Modulation



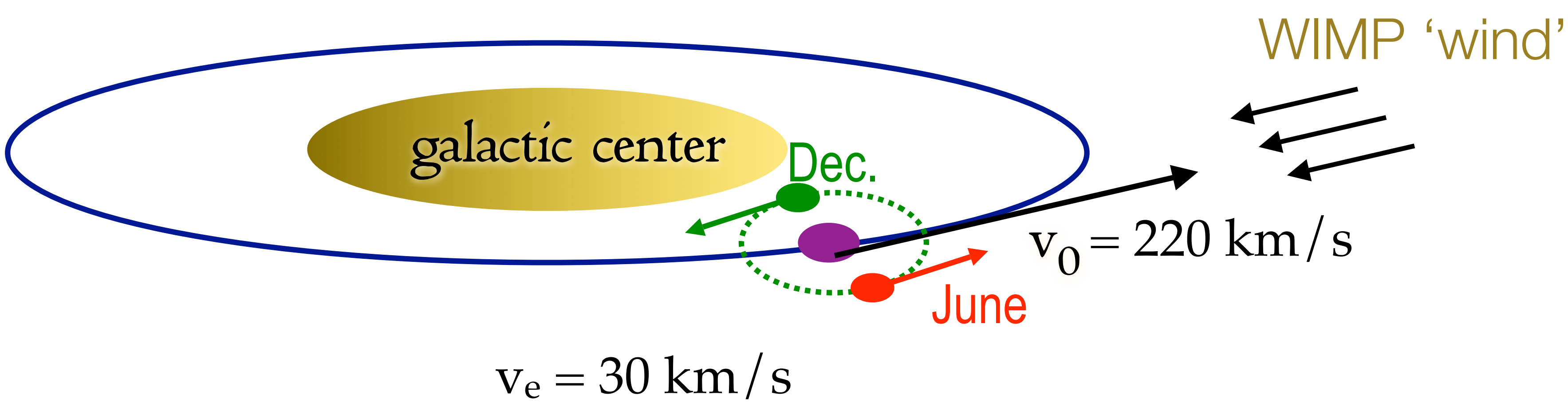


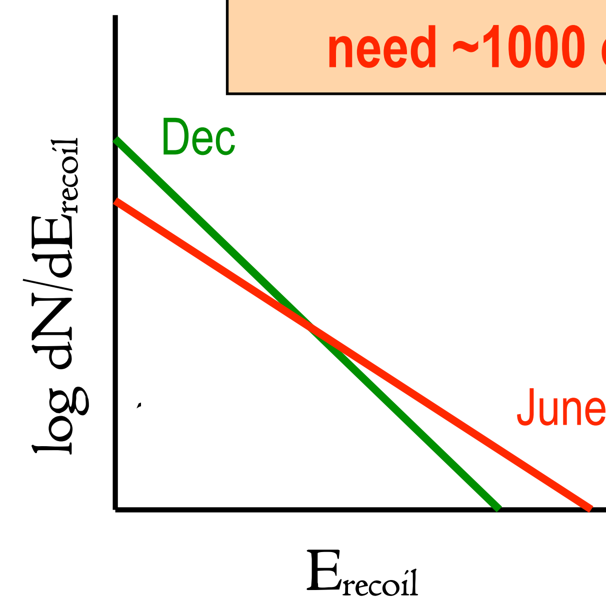
- Baryons travel together in roughly circular orbits with small velocity dispersion
- Dark matter particles travel individually with no circular dependence and large velocity dispersion
- As a result, the flux of WIMPs passing through Earth modulate over the course of a year as Earth rotates around the sun.

Signal Modulation: Rate

Assume WIMP Isothermal Halo:

~2% seasonal effect - need ~1000 events



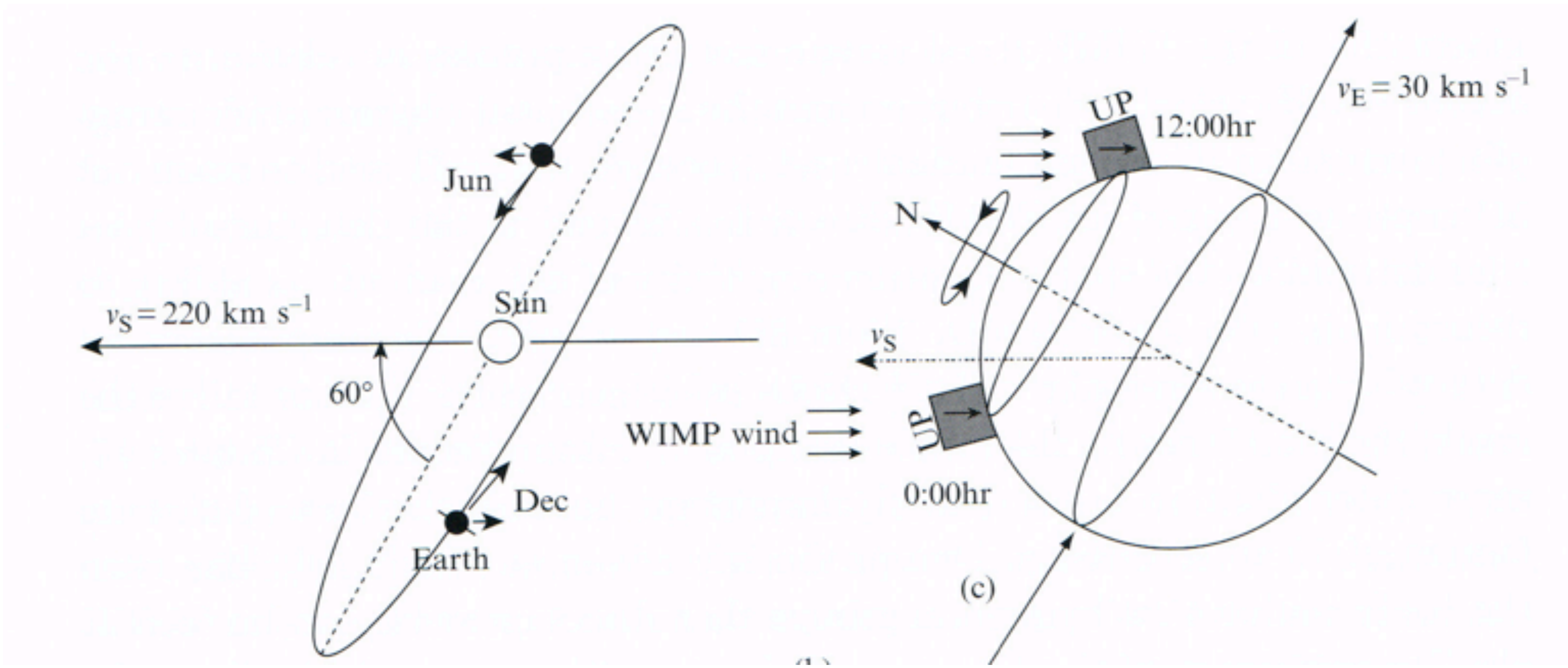


Since Earth's orbital speed around the sun is significantly smaller than the Sun's circular speed, the amplitude of the modulation is small and can be written as a Taylor Series.

$$\frac{dR}{dE_R} \approx \left(\frac{d\bar{R}}{dE_R}\right)[1 + \Delta(E_R)\cos\alpha(t)]$$

where $\alpha(t) = 2\pi(t - t_0)/T$ and T = 1 year, t_0 = 150 days

Signal Modulation: Direction



- A detector at 45 degree latitude will see the dark matter wind oscillate in direction over the course of a day.
- This is a sidereal (tied to stars) effect, not diurnal (tied to sun).

Direct Detection Searches

Many Experiments

Phonon/Charge/Light:

- CDMS/SuperCDMS
- EDELWEISS
- CRESST

Charge Only:

- CoGeNT/C4
- MALBEK
- TEXONO
- CDEX
- CDMSlite

Other:

- DAMIC
- NEXT

Modulation:

- DAMA/LIBRA
- DM-ICE
- KIMS
- ANAIS
- SABRE
- KamLAND-PICO

Bubble Chambers/ Superheated:

- PICASSO
- COUPP
- PICO

Liquid Noble:

- XENON
- LUX
- Darkside
- DEAP
- CLEAN
- XMASS
- PandaX

Directional:

- DRIFT
- DM-TPC

General Detection Principles

- Many direct detection experiments have excellent discrimination between electron recoils (ER) and nuclear recoils (NR) from the simultaneous measurement of two types of energy in an event.
- Most backgrounds will produce electron recoils.
- WIMPs and neutrons produce nuclear recoils.
    - Need to keep neutrons away from the detectors.
- Despite the excellent discrimination capability of these detectors, we still want to keep the backgrounds as small as possible.

Considerations Liquid Nobles

- In response to the passage of radiation we want an excellent scintillator and very good ionizer.
- High atomic number and high density to optimize detector size.
- We want to either have no intrinsic radioactive isotopes or isotopes that are easily removed.
- Boiling and melting point temperatures are considerations for detector handling.
- Abundance

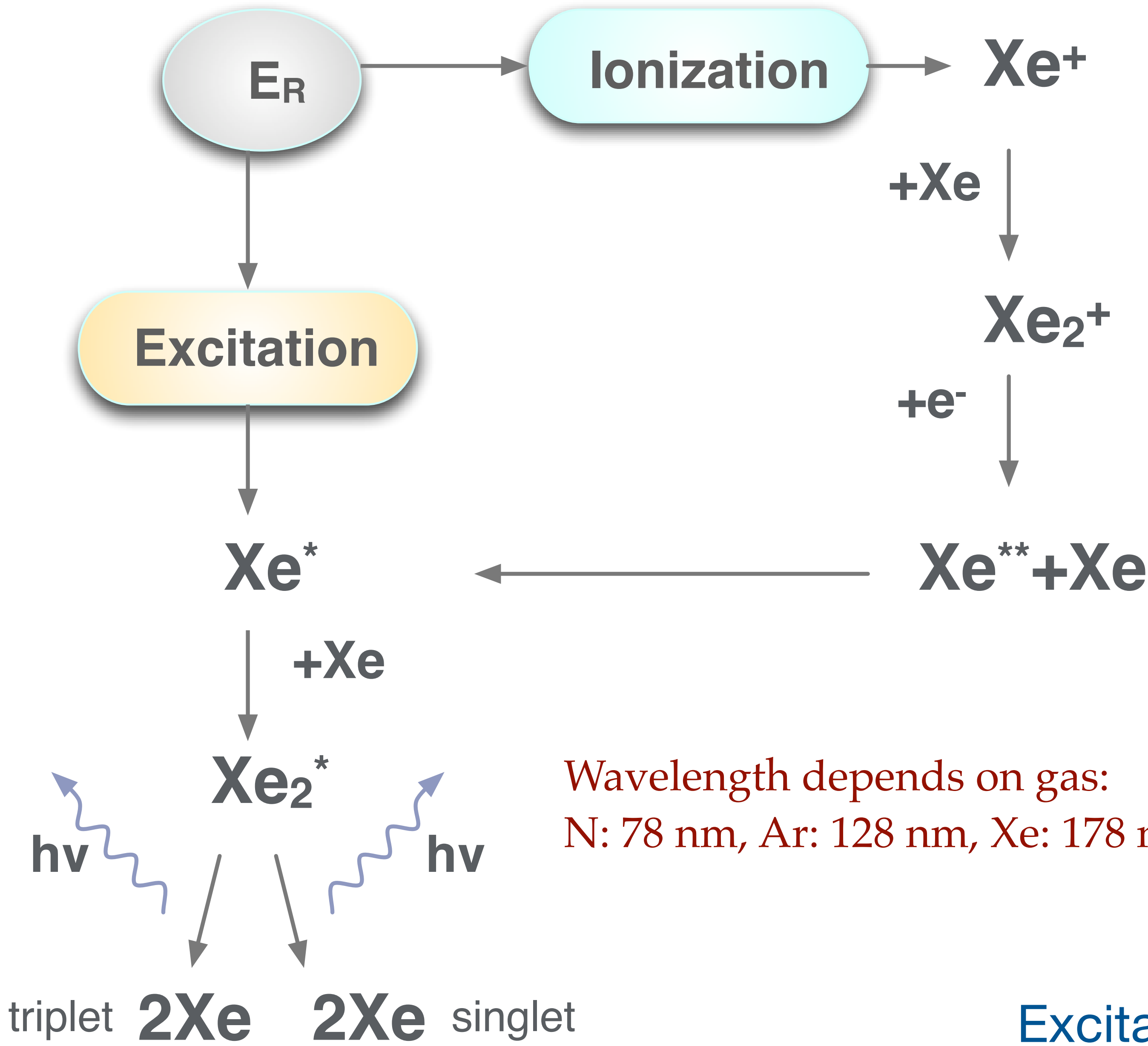
Properties of Xe, Ar and Ne

Table 21.1. *Physical properties of xenon, argon and neon.*

Properties [unit]	Xe	Ar	Ne
Atomic number	54	18	10
Mean relative atomic mass	131.3	40.0	20.2
Boiling point T_b at 1 atm [K]	165.0	87.3	27.1
Melting point T_m at 1 atm [K]	161.4	83.8	24.6
Gas density at 1 atm & 298 K [$g\,l^{-1}$]	5.40	1.63	0.82
Gas density at 1 atm & T_b [$g\,l^{-1}$]	9.99	5.77	9.56
Liquid density at T_b [$g\,cm^{-3}$]	2.94	1.40	1.21
Dielectric constant of liquid	1.95	1.51	1.53
Volume fraction in Earth's atmosphere [ppm]	0.09	9340	18.2

Particle Dark Matter, Cambridge University Press 2010, Bertone (editor)

Liquid Noble Gases: Detection Mechanism



Wavelength depends on gas:
N: 78 nm, Ar: 128 nm, Xe: 178 nm

Time constants depend on gas:
(Ne & Ar few ns/μs, Xe 4/22 ns

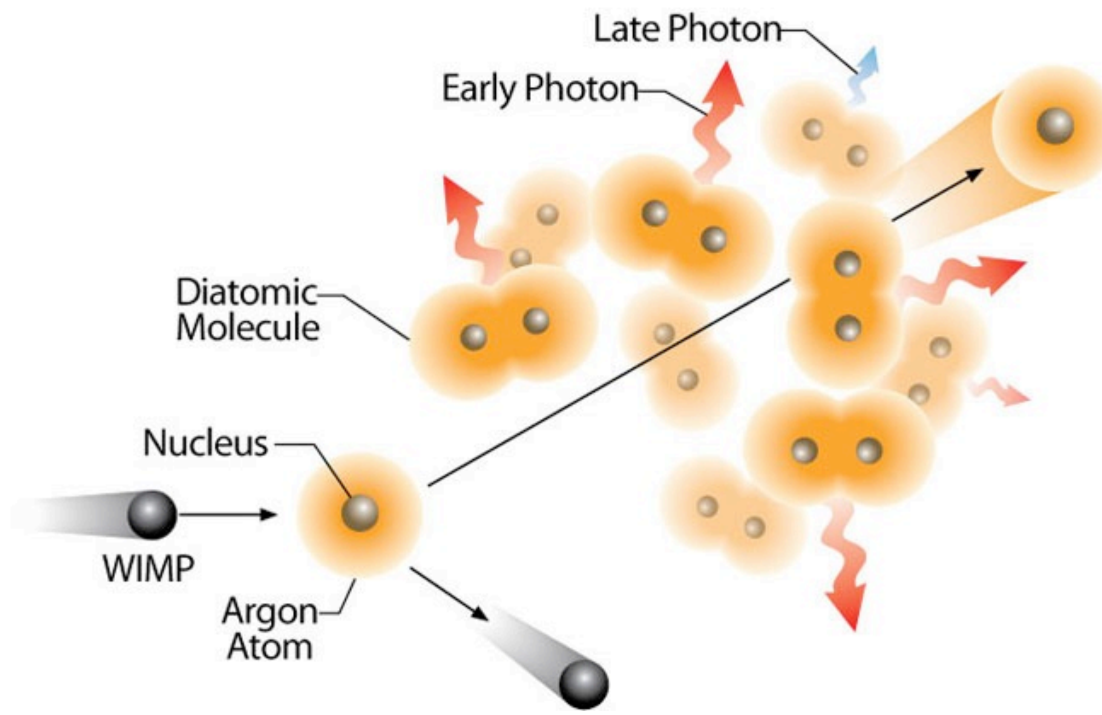
Excited Atoms*:

$$Xe^* + Xe \rightarrow Xe_2^*$$
$$Xe_2^* \rightarrow 2Xe + h\nu$$

Excited Ions+:

$$Xe^+ + Xe \rightarrow Xe_2^+$$
$$Xe_2^+ + e^- \rightarrow Xe^{**} + Xe$$
$$Xe^{**} \rightarrow Xe^* + heat$$
$$Xe^* + Xe \rightarrow Xe_2^*$$
$$Xe_2^* \rightarrow 2Xe + h\nu$$

Excitation/Ionization depends on dE/dx!
⟹ discrimination of signal (WIMPs → NR)
and (most of the) background (gammas → ER)!



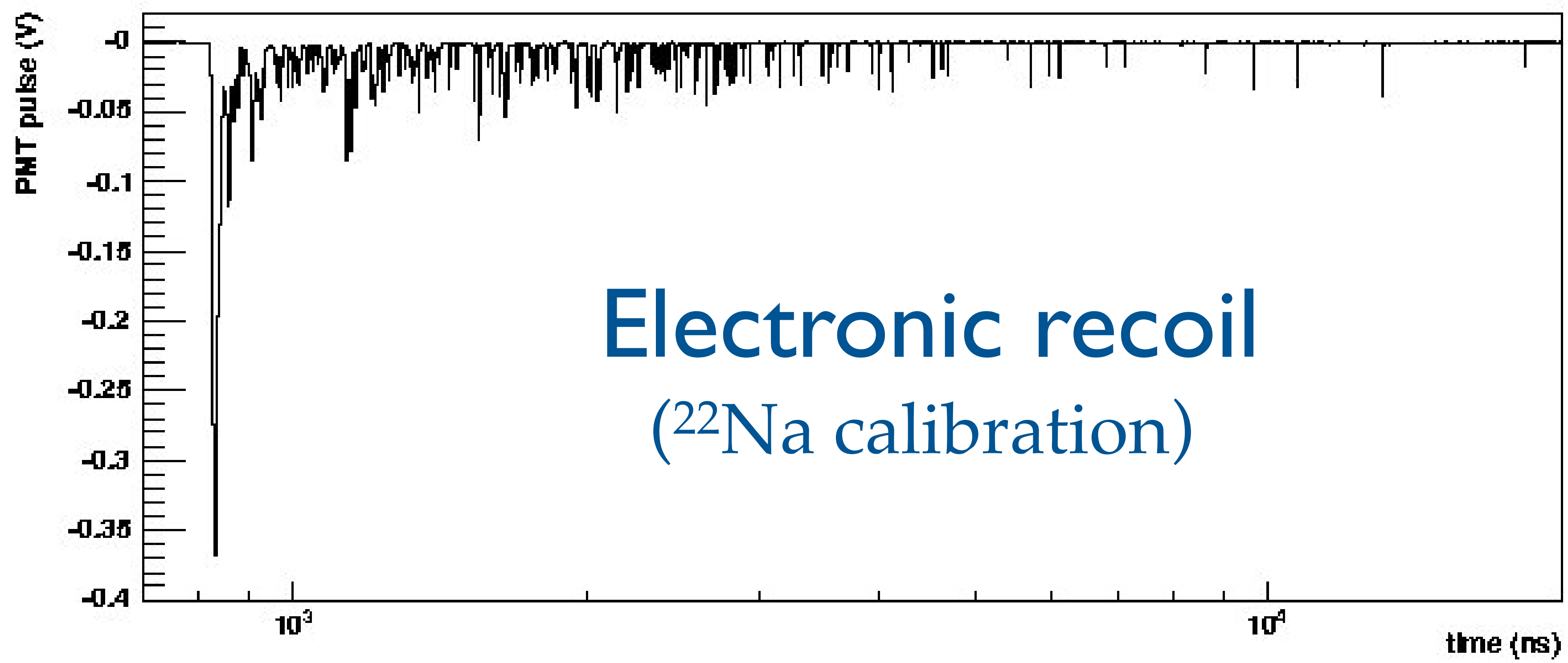
Single Phase Liquid Noble Experiments

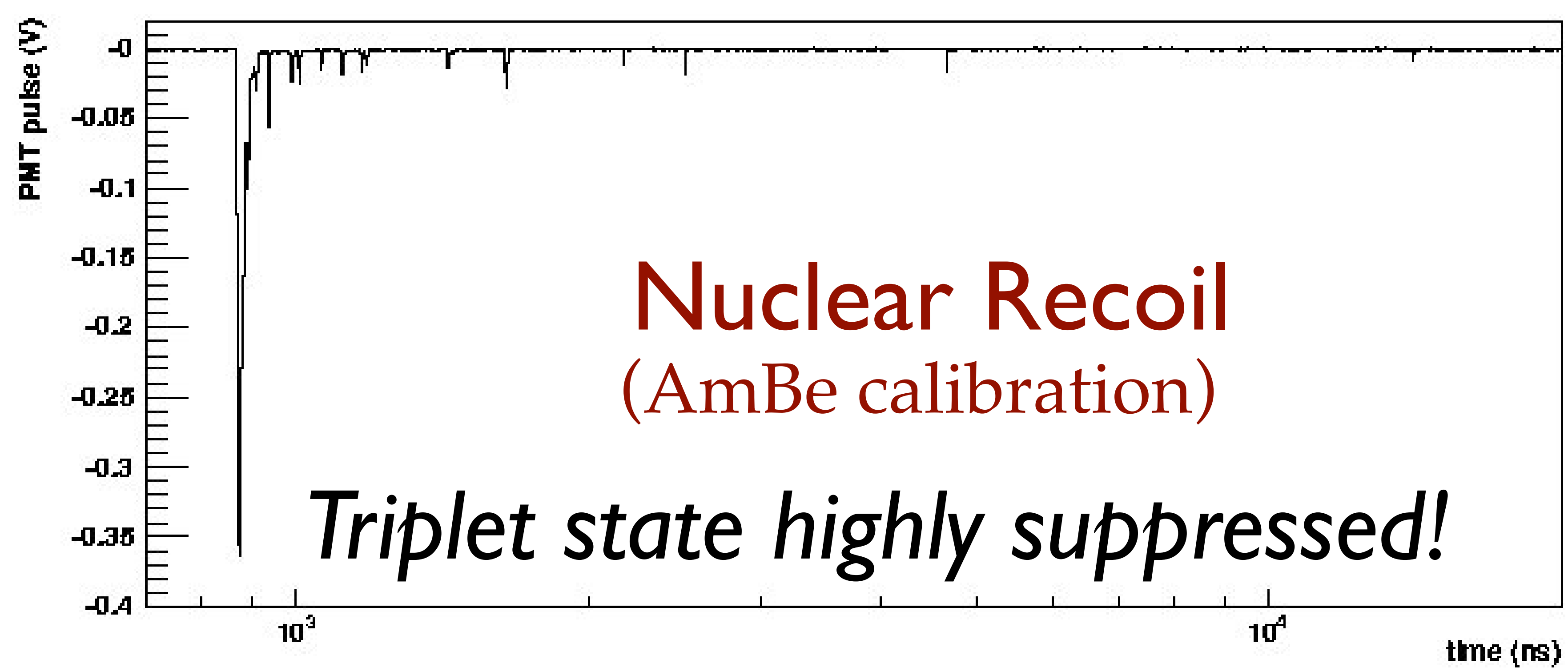
DEAP, MiniCLEAN, (XMASS)

Pulse Shape Analysis

- Early singlet state and delayed triplet state.
- The triplet state is highly suppressed for nuclear recoils.

	Singlet	Triplet
Ne	< 18.2 ns	14.9 μs
Ar	7ns	1.6 μs
Xe	4.3 ns	22 ns

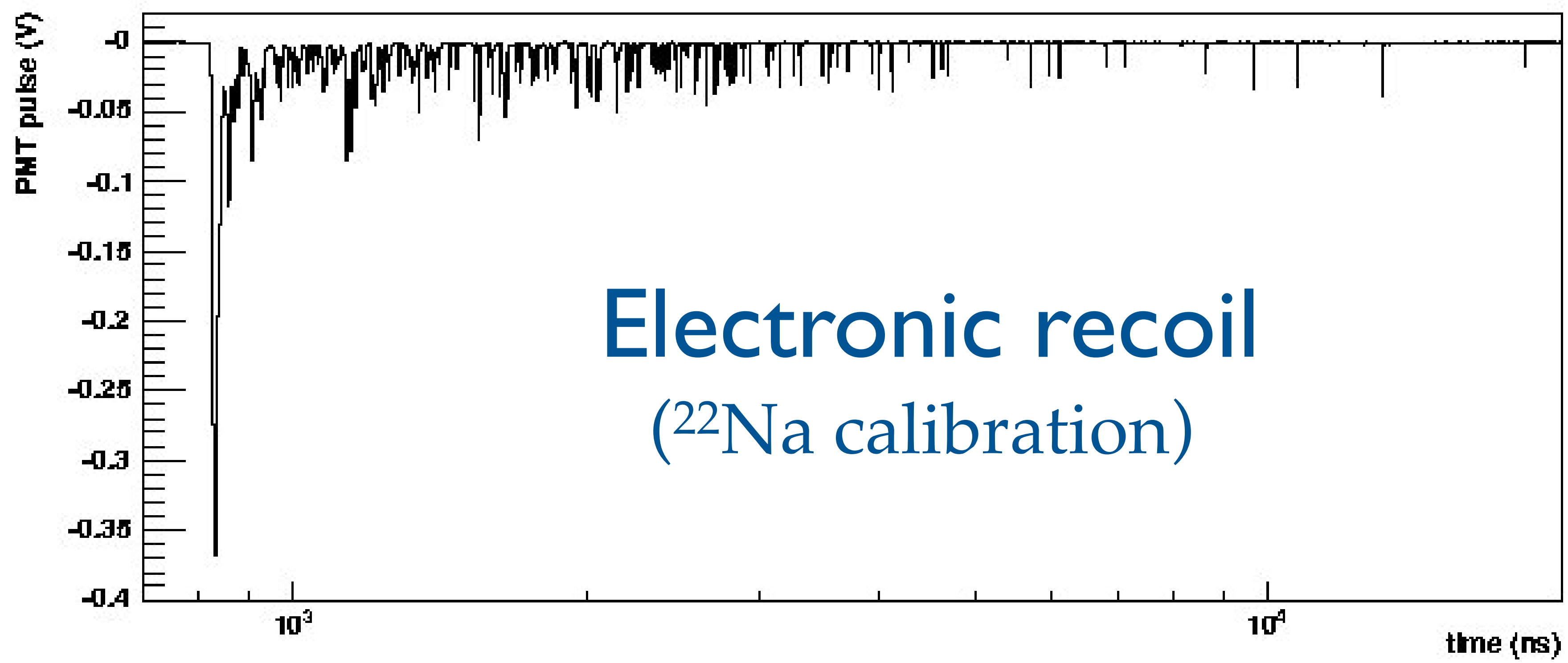


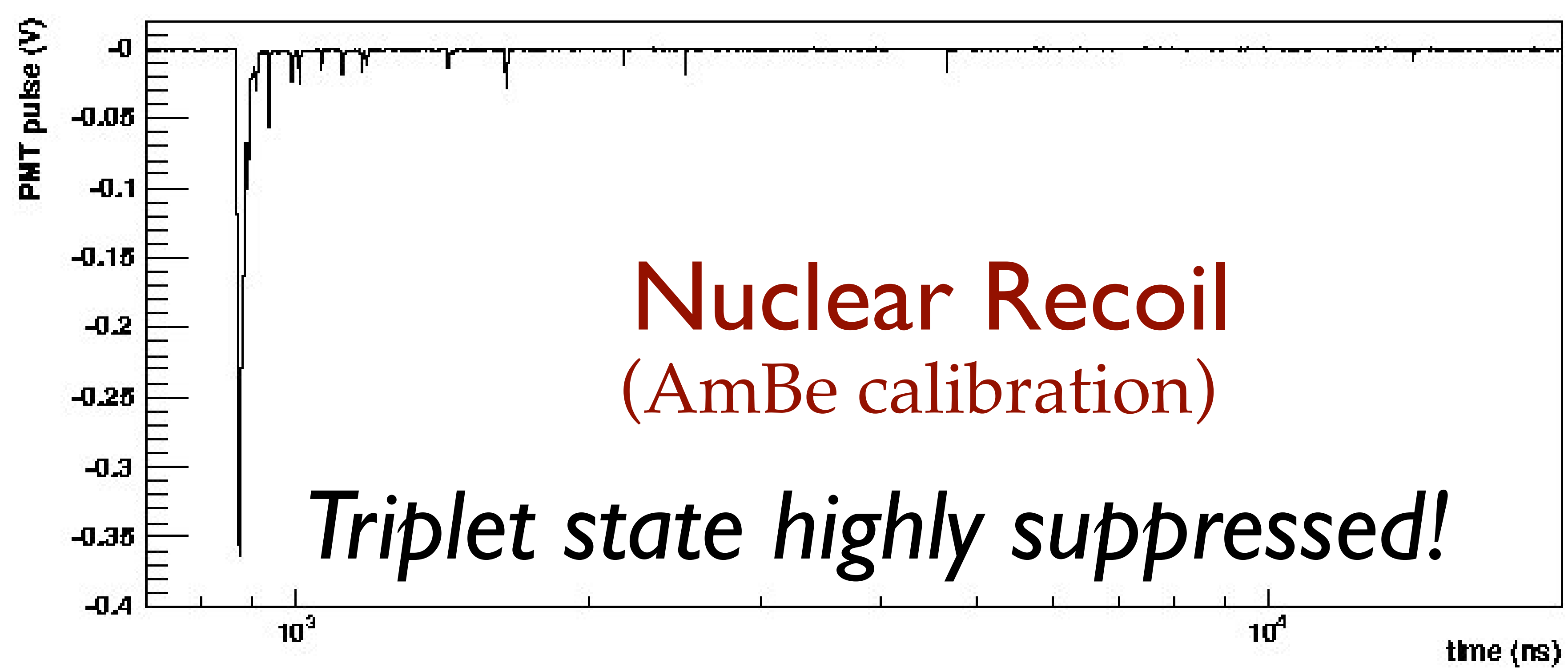


Pulse Shape Analysis

- Early singlet state and delayed triplet state.
- The triplet state is highly suppressed for nuclear recoils.

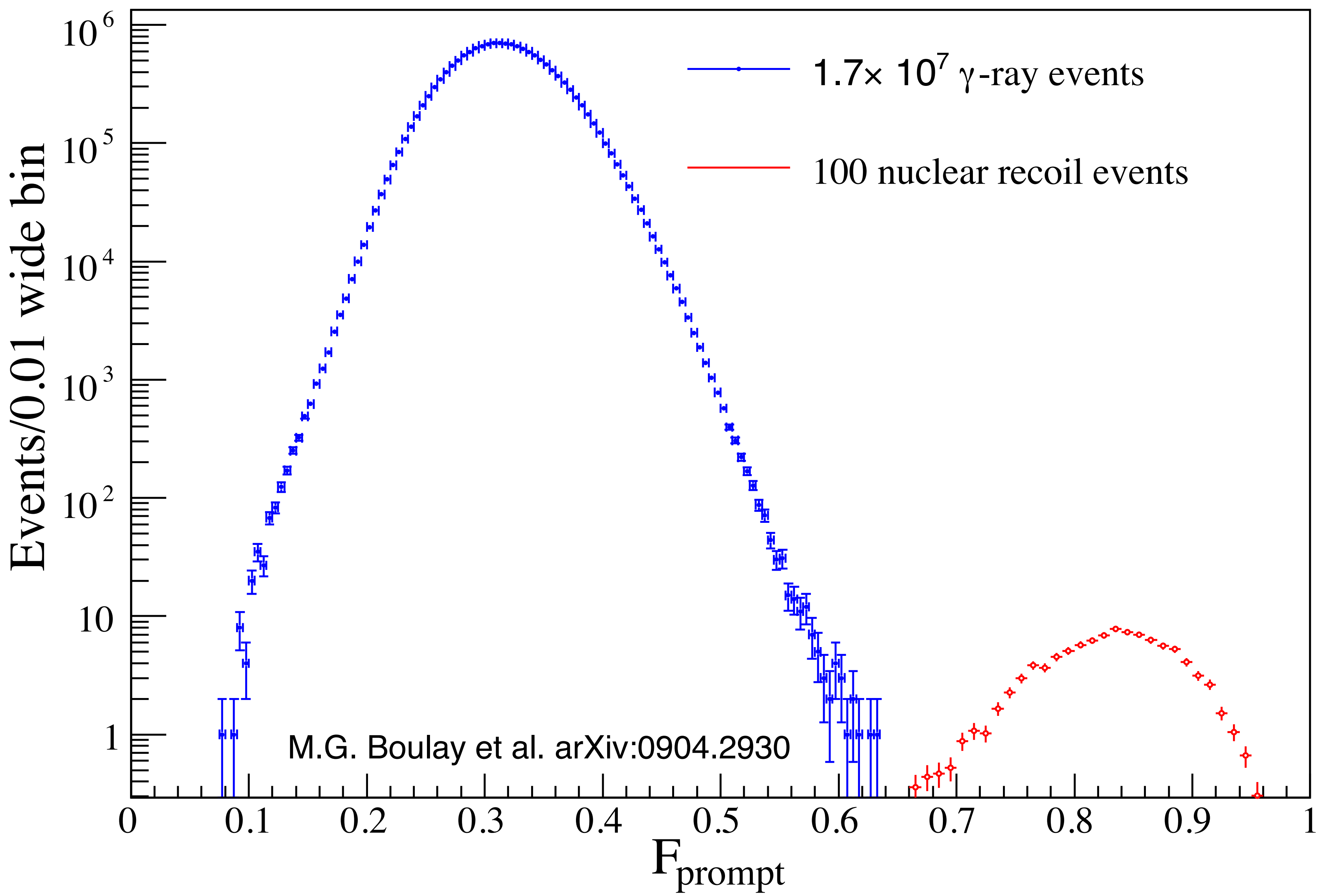
	Singlet	Triplet
Ne	< 18.2 ns	14900 ns
Ar	7ns	1600 ns
Xe	4.3 ns	22 ns





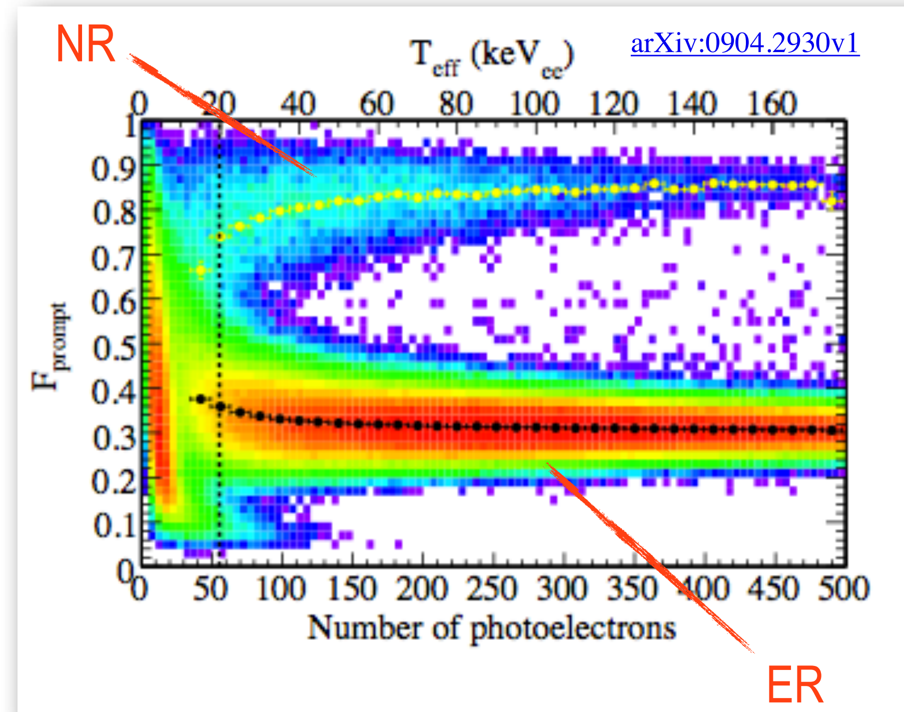
DEAP - Pulse Shape Discrimination

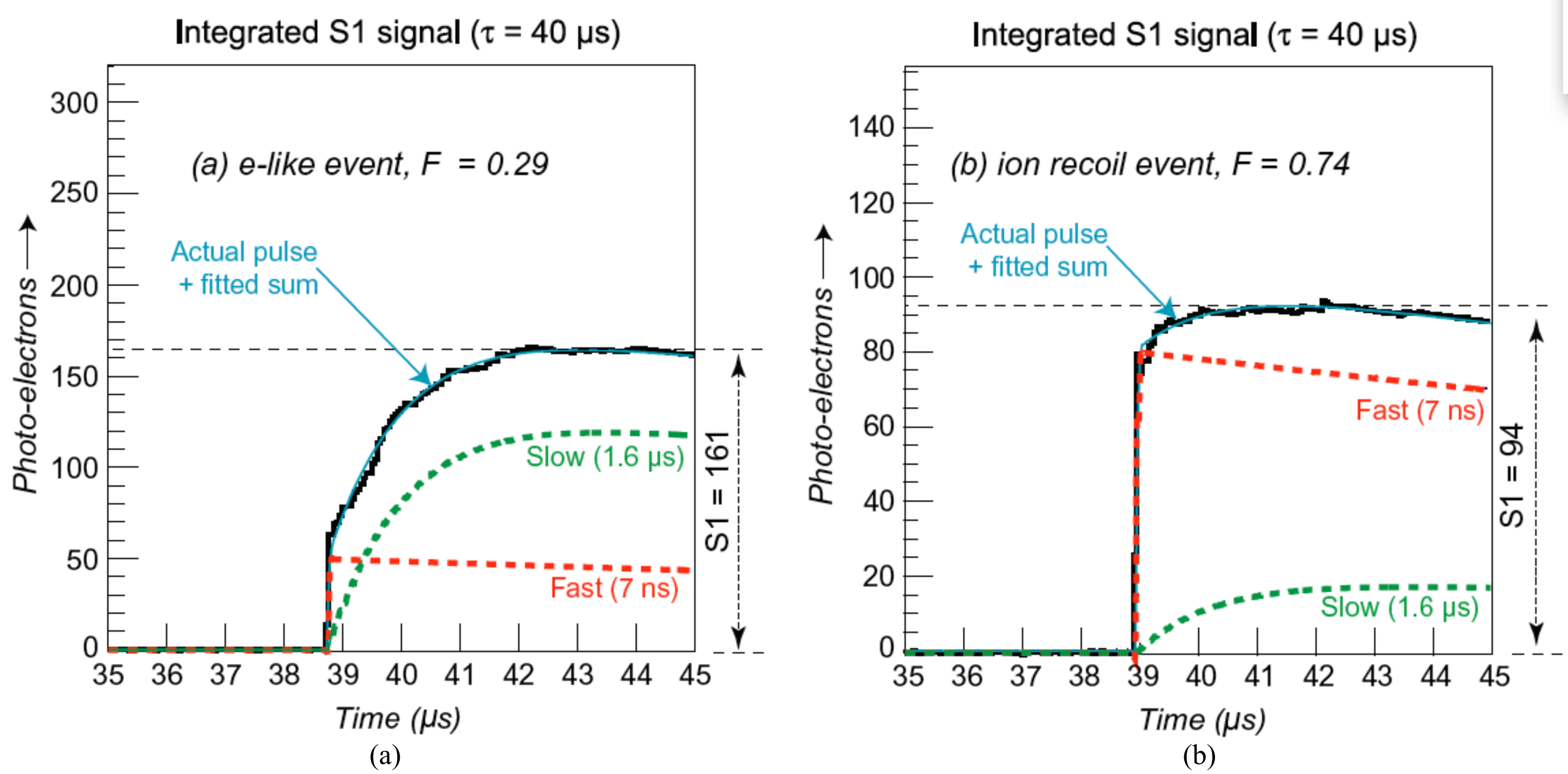
- Discriminate with ratio of prompt light (F_{prompt}) to total light.
- Reject beta and gamma backgrounds with less than 10^{-8} leakage.



DEAP - Pulse Shape Discrimination

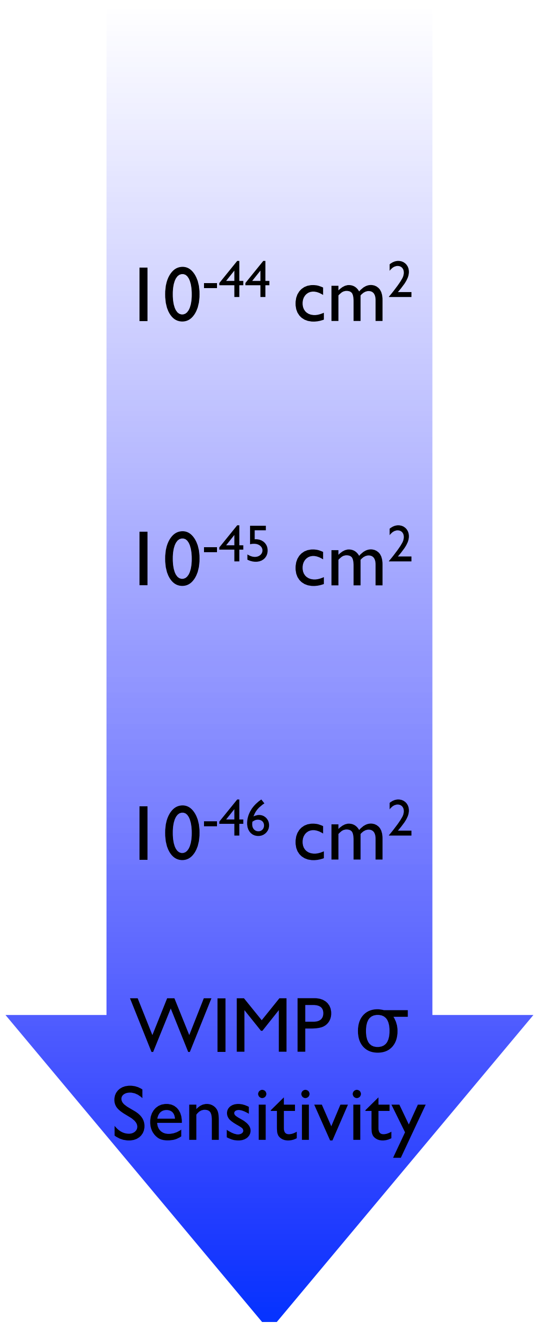
- Discrimination between background and signal comes from pulse shape.
- Excited atoms decay to ground state through formation of single or triplet excimer states which have different decay times.





- 70% of excimer states created by nuclear recoils are singlets
- 30% of excimer states created by electron recoils are triplets

DEAP/CLEAN Program



DEAP-0:
Initial R&D detector

DEAP-1:
7 kg LAr
2 warm PMTs
At SNOLab since 2008

picoCLEAN:
Initial R&D detector

microCLEAN:
4 kg LAr or LNe
2 cold PMTs
surface tests at Yale

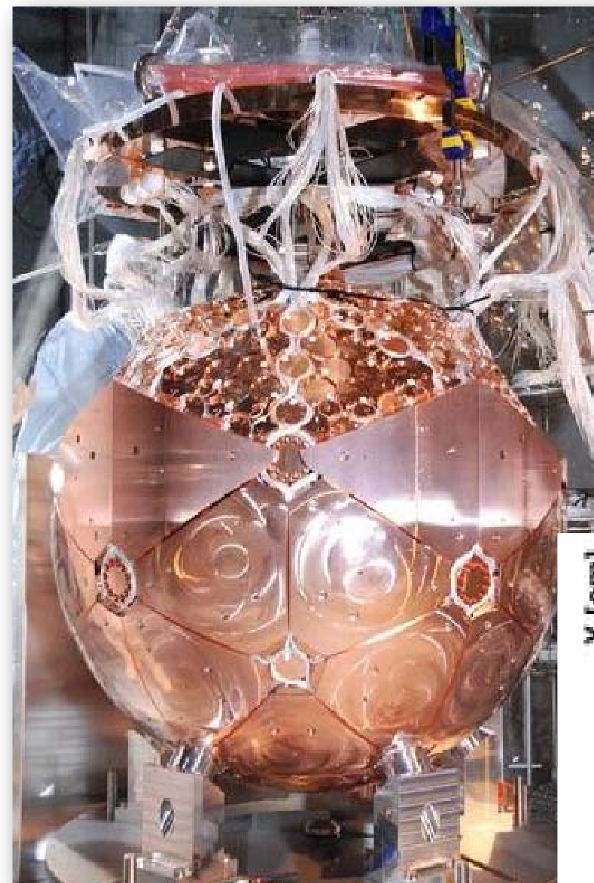
MiniCLEAN:
500 kg LAr or LNe (150 kg fiducial mass)
92 cold PMTs
SNOLAB 2013

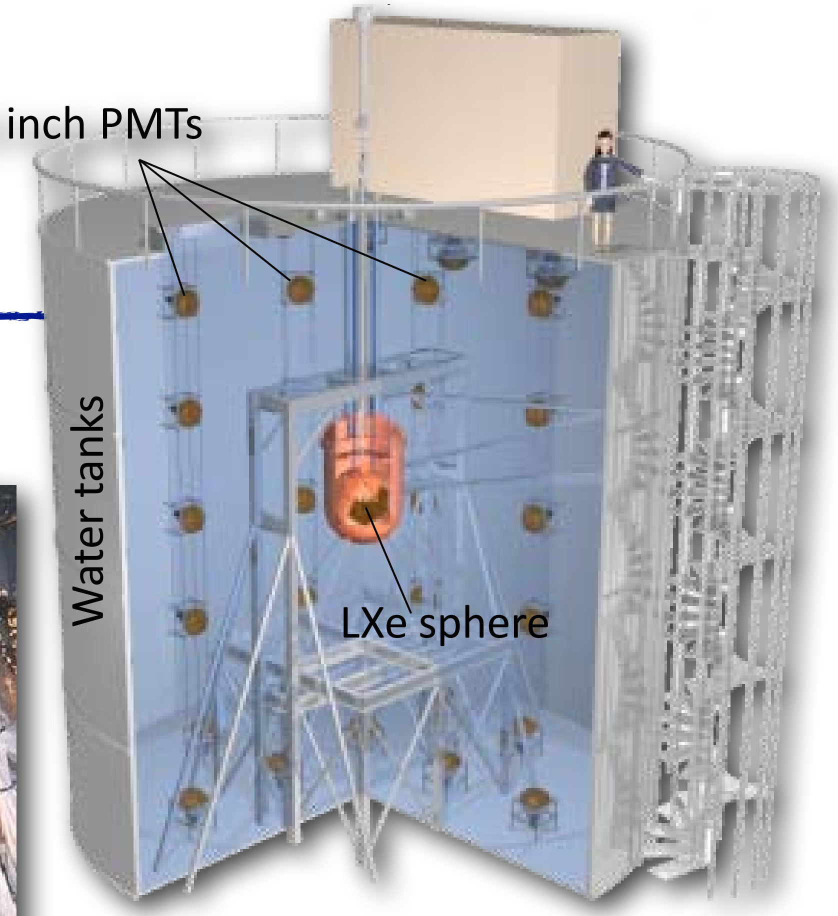
DEAP-3600:
3600 kg LAr (1000 kg fiducial mass)
266 warm PMTs
SNOLAB 2014

40-140 tonne LNe/LAr Detector:
pp-solar ν, supernova ν, dark matter $<10^{-46}$ cm^2
~2018?

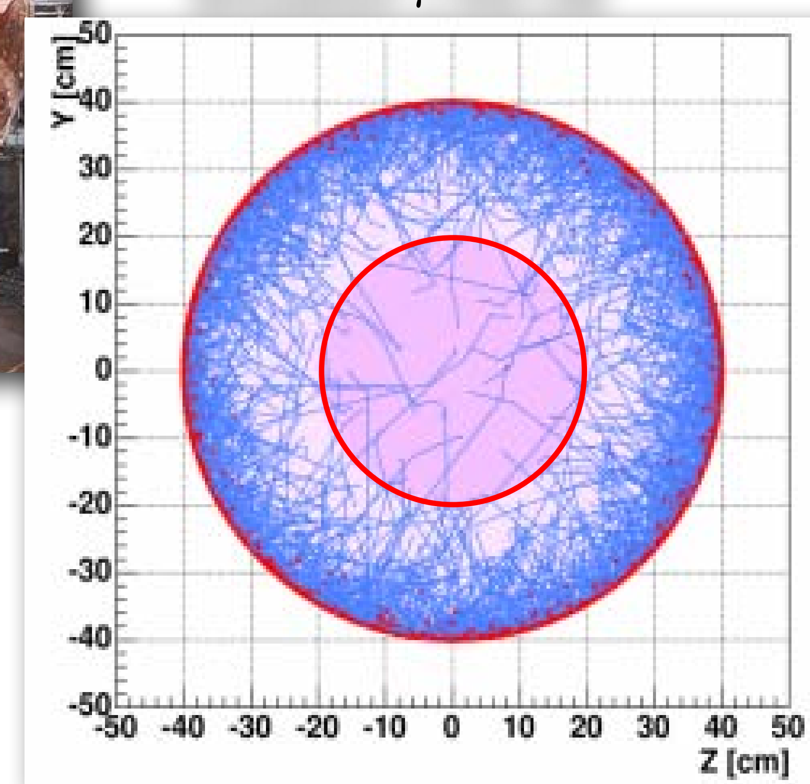
XMASS

- Single phase LXe detector located in the Kamioka Underground Observatory, Japan. Construction finished in late 2010.
- Water tank acts as an active muon veto.
- Key concept to background discrimination is "self-shielding". Gamma particles are absorbed in the outer region of the liquid xenon.
- WIMPs and neutrons are evenly distributed thoughout volume.
- Recent science run revealed unexpected alpha background from materials used to support PMTs.





Simulation: γ into LXe

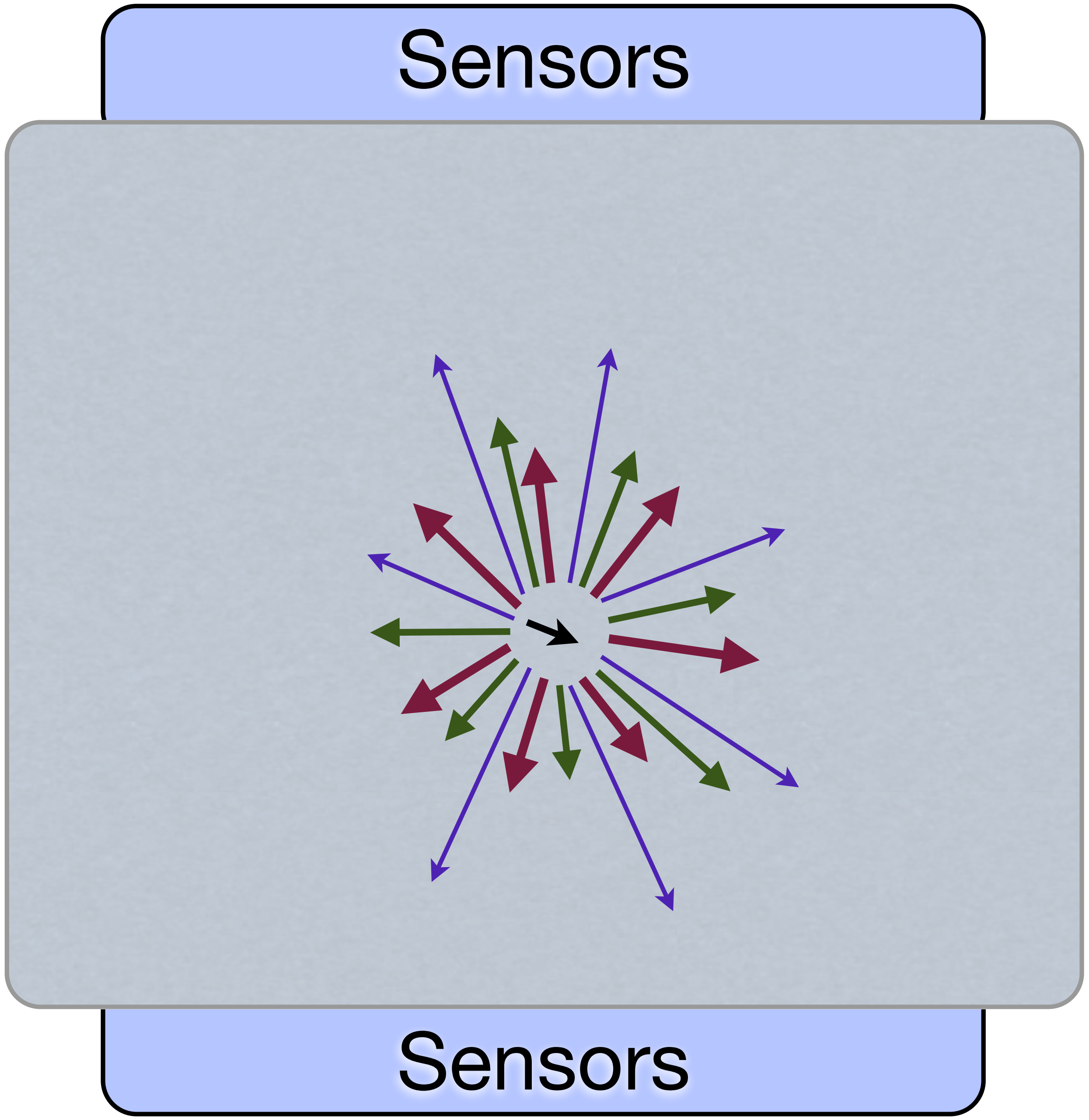


J. Liu TAUP 2011

Two Phase Experiments

CRESST, EDELWEISS, SuperCDMS,
DarkSide, LUX, PandaX, XENON,
and others.

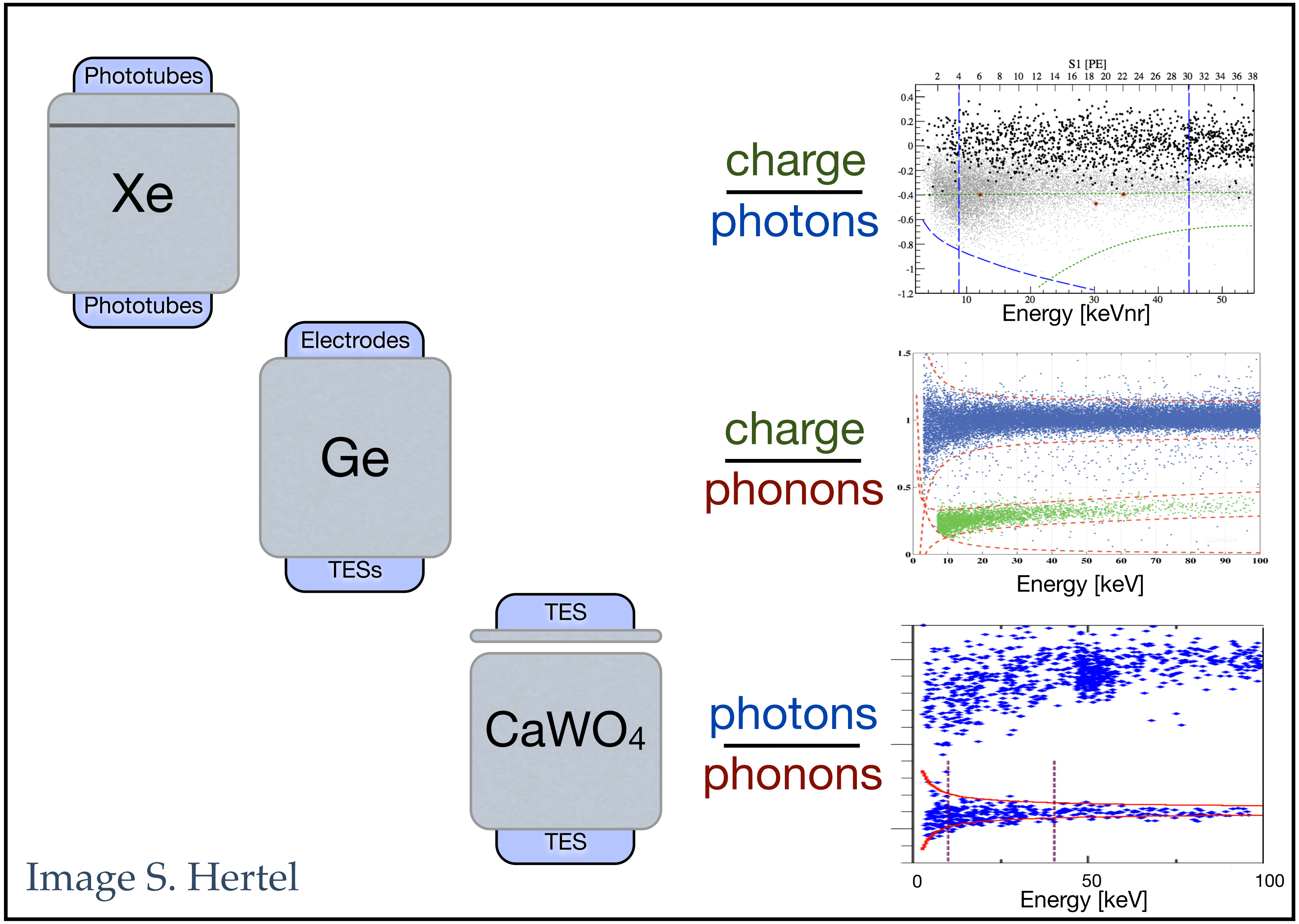
Two Phase Detectors



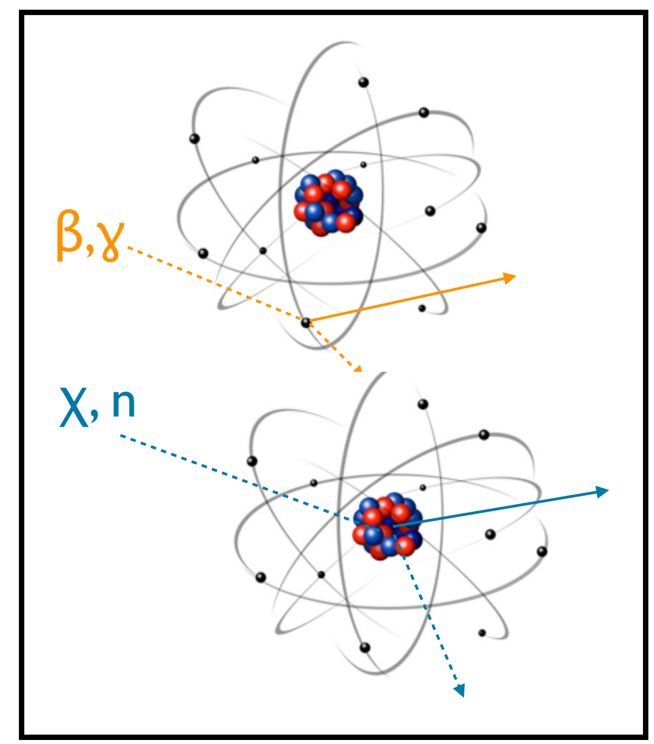
Phonons
Charge Carriers
Photons

Relative fractions depend on dE/dx

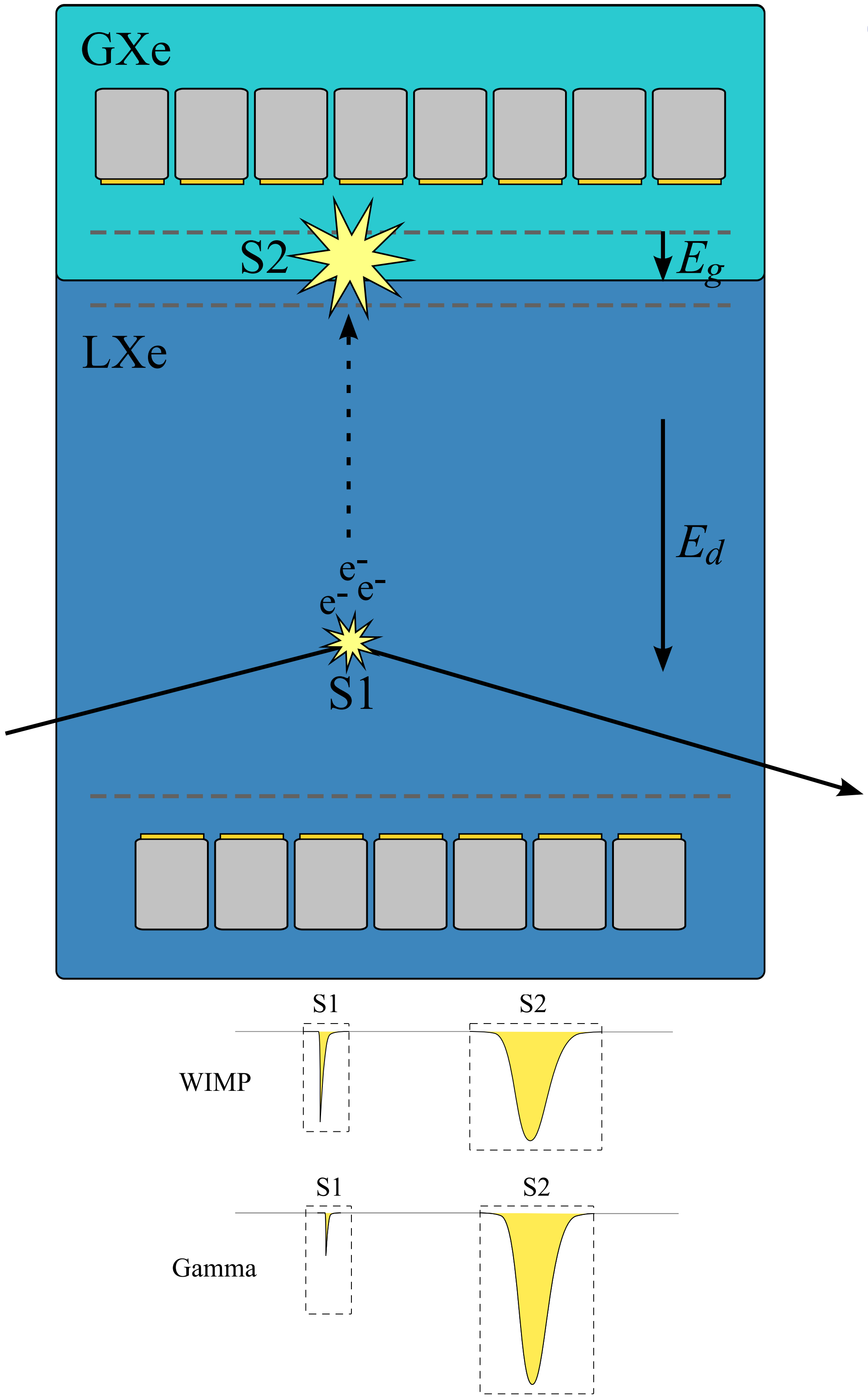
Particle Dependent Response



CRESST, DarkSide, Edelweiss, LUX, SuperCDMS, XENON, etc.



Dual Phase Time Projection Chambers



(XENON, LUX, DarkSide, PandaX and others)

- Interactions in the liquid produce excitation and ionization.
- Excitation leads to scintillation light emission
- Ionization electrons are drifted with an applied electric field into the gas phase (S1).
- In the gas phase, electrons are further accelerated producing proportional scintillation (S2).
- PMTs on the bottom and top of the chamber record scintillation signals.
- Distribution of S2 give xy coordinates, drift time gives z coordinates
- Ratio of S2/S1 discriminates electron and nuclear recoils