Direct Detection of Dark Matter

Sunil Golwala

Ay127

2017/01/19

The Particle Dark Matter Zoo

Neutrinos

only massive (sterile) neutrinos can be cold or warm. Low-mass neutrinos make hot dark matter.

Axions

Form as Bose condensate in early universe: cold in spite of low mass

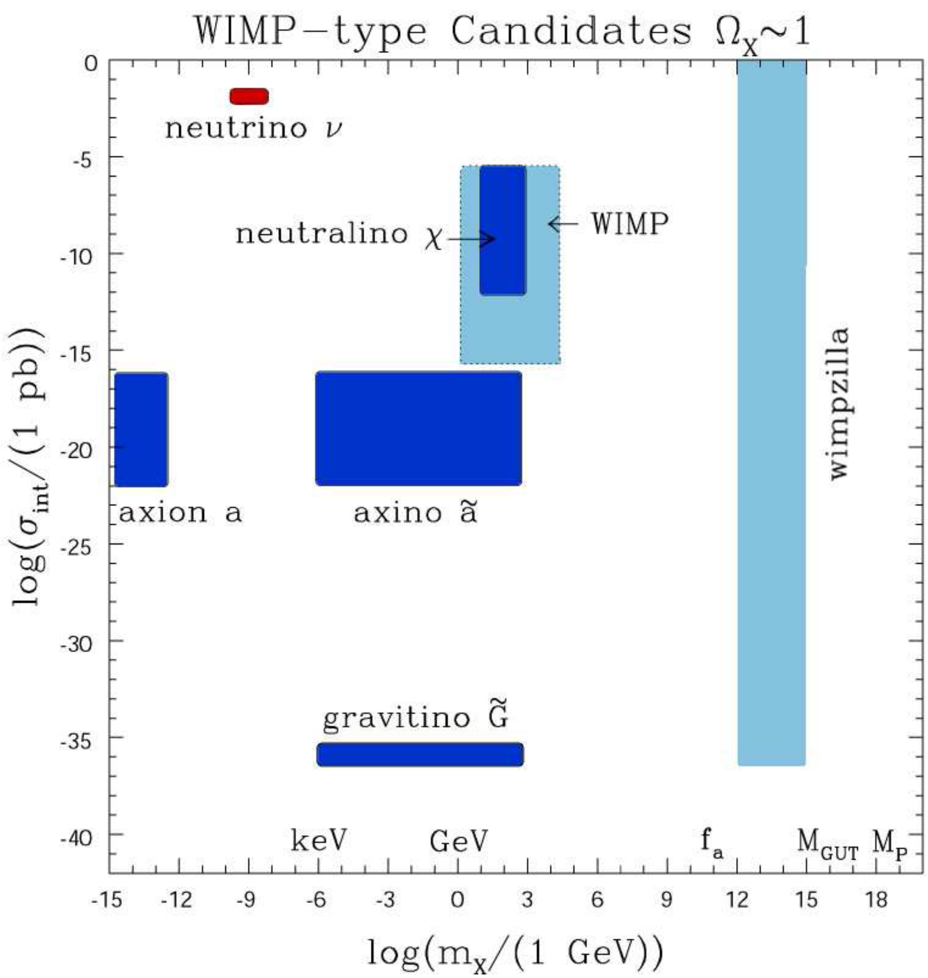
Weakly Interacting Massive Particles (WIMPs)

new massive (~100 GeV) particle with electroweak scale interactions with normal matter

SUSY neutralino

Lightest Kaluza-Klein particle in universal extra dimensions

L. Roszkowski



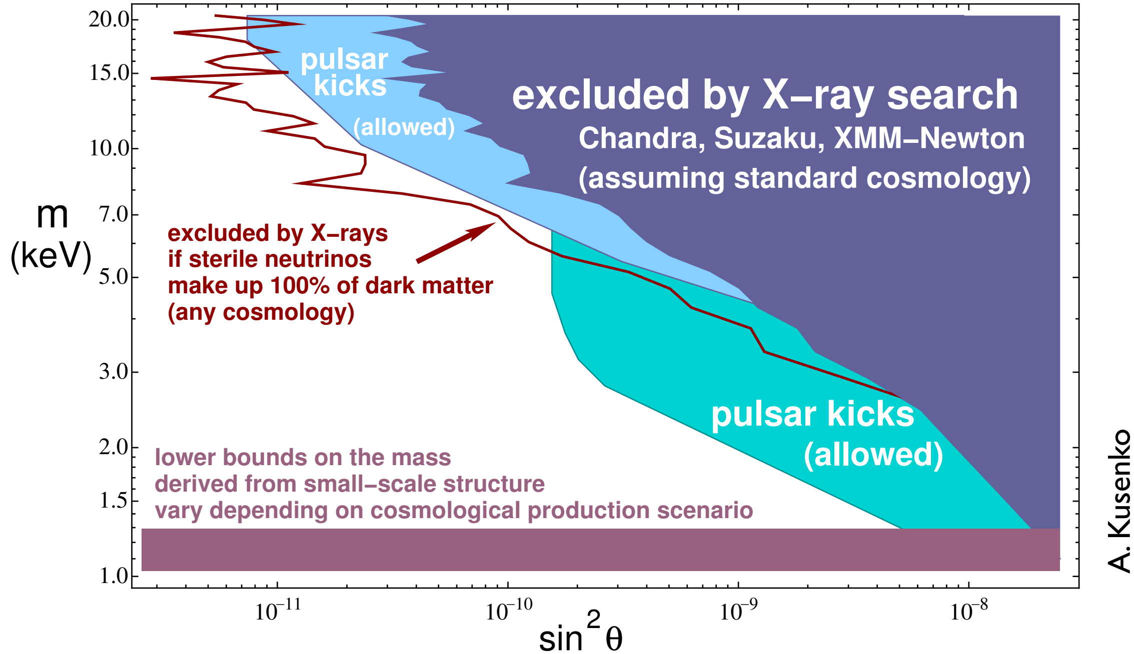
Less compelling candidates:

SUSY gravitinos (SuperWIMPs) and axinos WIMPzillas, SIMPzillas, primordial black holes, Q-balls, strange quark nuggets, mirror particles, CHArged Massive Particles (CHAMPs), self interacting dark matter, D-matter, cryptons, brane world dark matter...

Massive Sterile Neutrinos

keV sterile neutrino

- acts as warm dark matter:
  - cold enough to form structure correctly, hot enough to fix some cosmological quandaries
- Produced in early universe by oscillations of active neutrinos (Dodelson-Widrow (DW) mechanism)
- Decays to (M/2) photons via SM penguin diagrams



(mixing angle with active neutrinos)

Limits

- overclosure
- x-ray emission from decays
  - sensitivity will improve with future X-ray satellites (Astro-H and Athena): limited by energy resolution
- Lyman-α forest: too light a neutrino is too hot, washing out small-scale structure
  - Bounds may improve with better understanding of systematics in measurements and simulations
- pulsar kicks: asymmetry in scattering of neutrinos off magnetic-field-polarized e and N yields asymmetric neutrino emission; improved modeling may reduced allowed regions

Axions

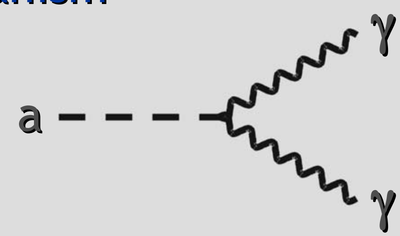
G. Raffelt

Particle-Physics Motivation

CP conservation in QCD by Peccei-Quinn mechanism

→ Axions $a \sim \pi^0$

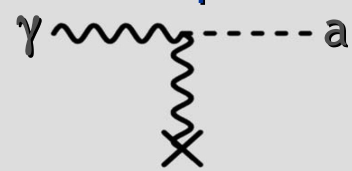
$m_\pi f_\pi \cong m_a f_a$



For $f_a \gg f_\pi$ axions are "invisible" and very light

Solar and Stellar Axions

Axions thermally produced in stars, e.g. by Primakoff production

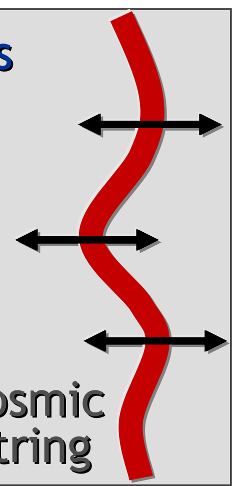


- Limits from avoiding excessive energy drain
- Search for solar axions (CAST)

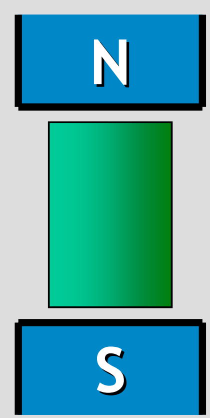
Cosmology

In spite of small mass, axions are born non-relativistically ("non-thermal relics")

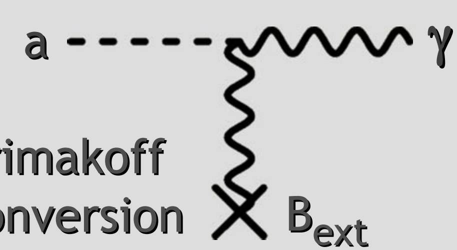
→ Cold dark matter candidate
$m_a \sim 1\text{-}1000\ \mu\text{eV}$



Search for Axion Dark Matter



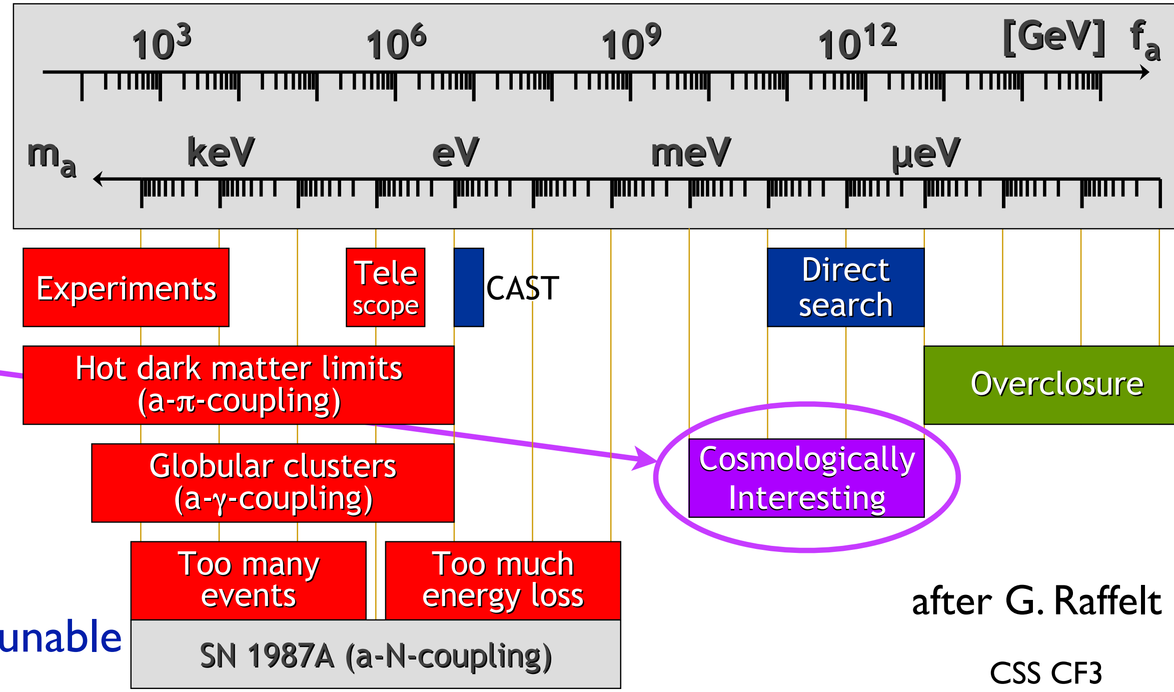
Microwave resonator (1 GHz = 4 μeV)



Primakoff conversion

Axion Direct Search Techniques

Cosmologically interesting: provides appropriate Ω_{DM}, m_a = 1 μeV to 1 meV

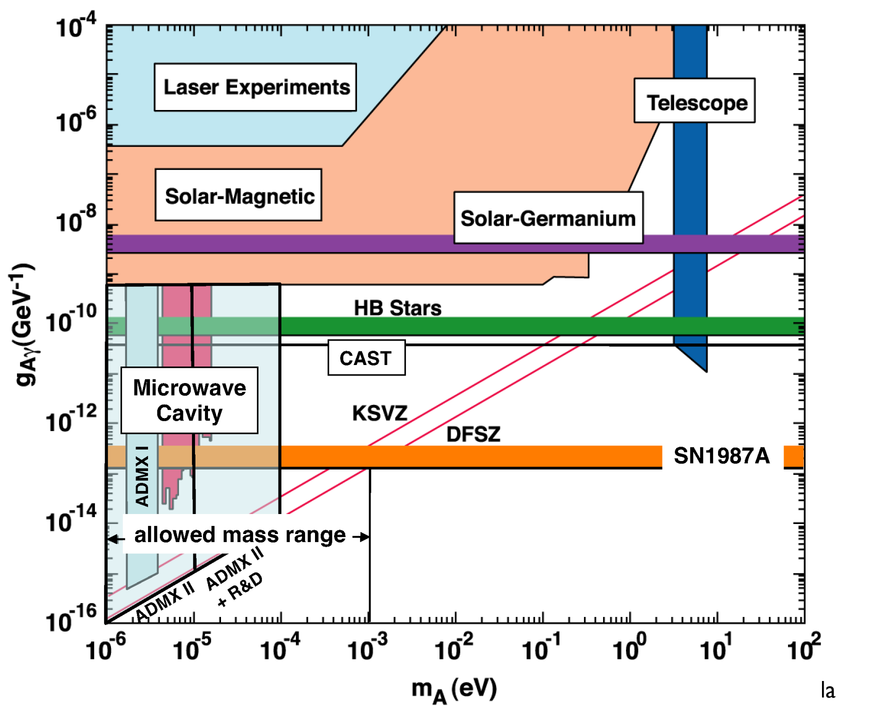


after G. Raffelt

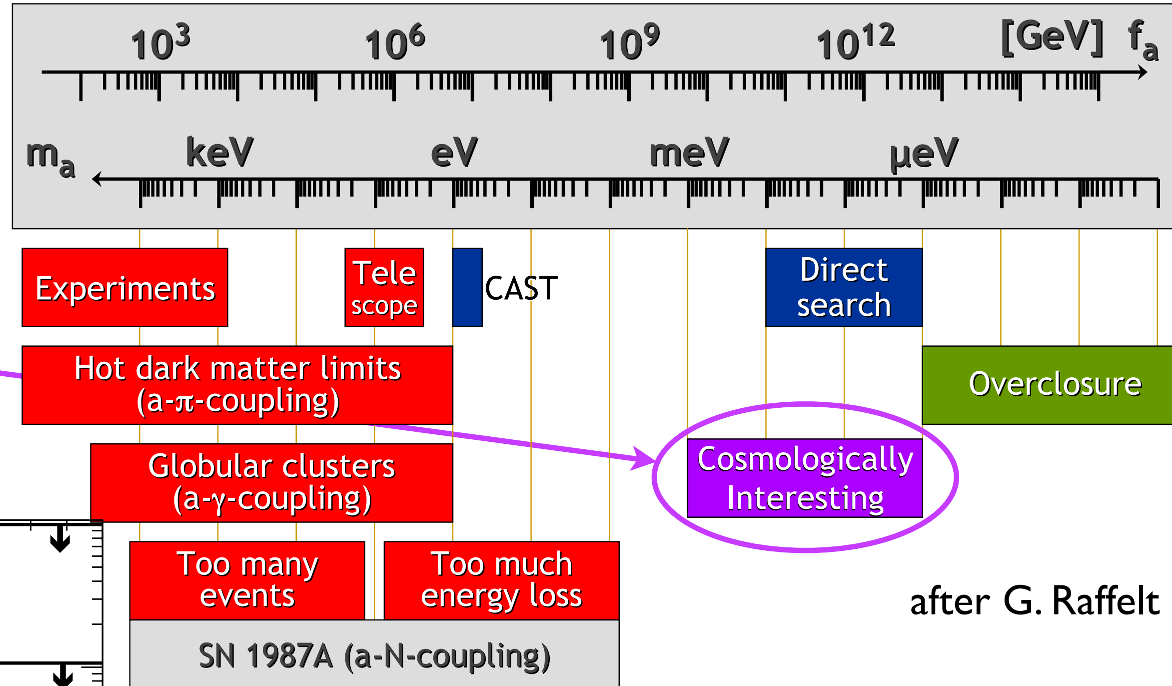
CSS CF3

Microwave cavity conversion

- 1 GHz = 4 μeV: use high-Q tunable cavity in high B field; when $f_0 = m_a$, excess power
- Detection: RF amplifier + Fourier transform power spectrum, excited Rydberg atom photodetection
- Can cover ~1 μeV to 100 μeV; cavities become too small > 100 μeV
- With μwave SQUID amplifier and colder cavity, ADMX II will definitively test full KSVZ to DFSZ for part of cosmologically interesting m_a range

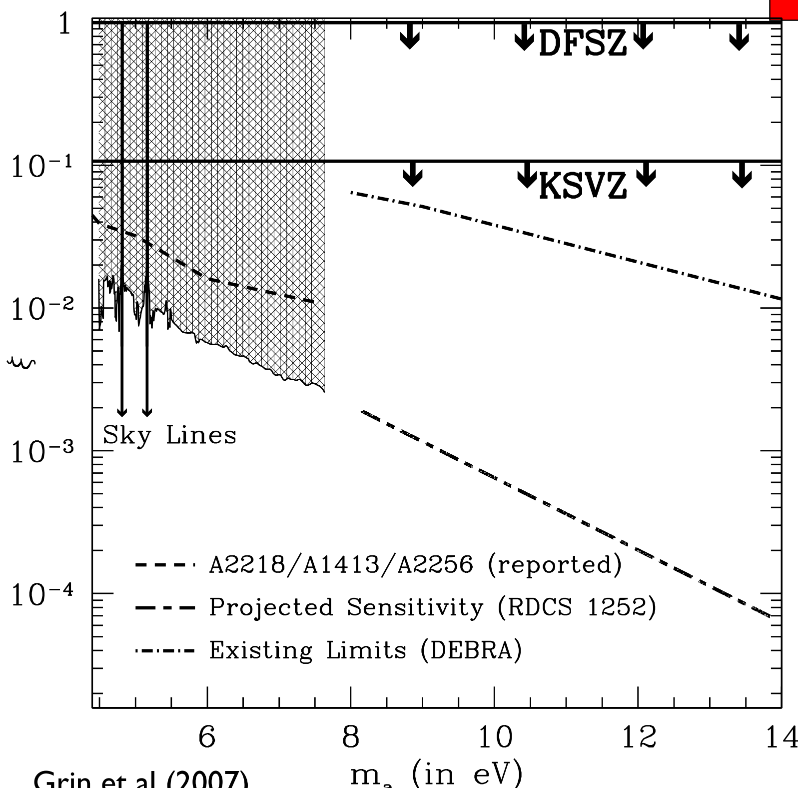


Axion Direct Search Techniques



Cosmologically interesting: provides appropriate Ω_{DM}, m_a = 1 μeV to 1 meV

after G. Raffelt



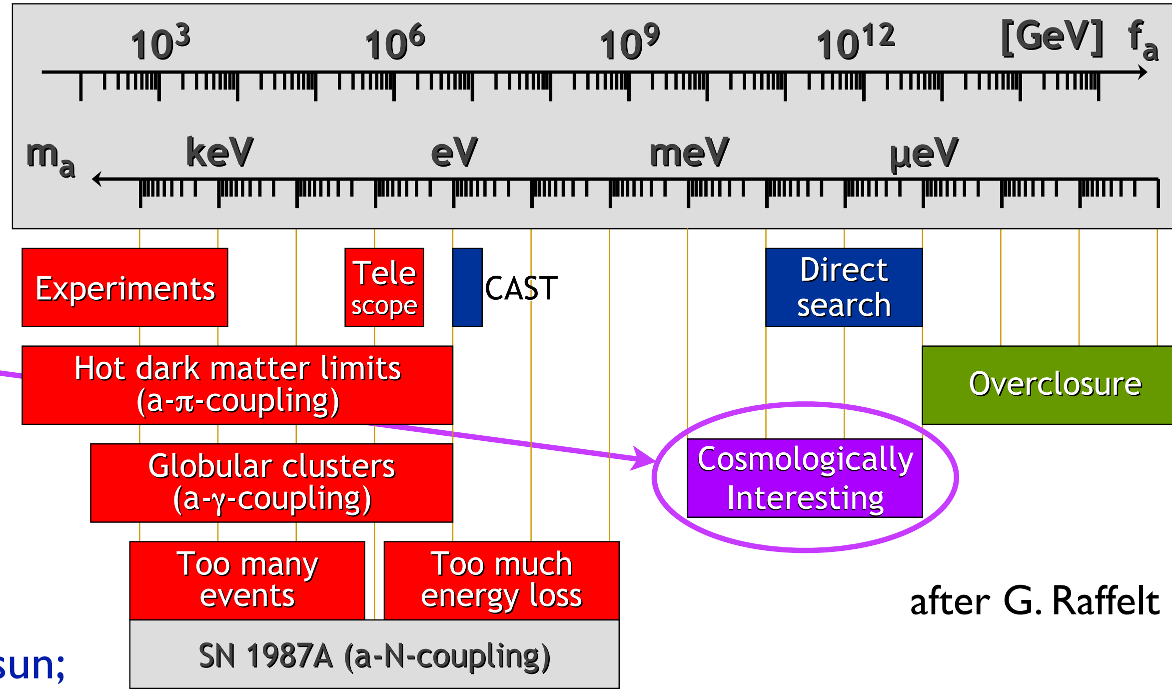
Grin et al (2007)

Decays

- $a \to 2\gamma$, $E_\gamma = m_a/2$ spectral line
- Old and more recent searches done at optical wavelengths, excluded DFSZ and KSVZ axion models
- Improvements in radio receivers may enable searches in mm/cm-wave regime where cavity expts are more difficult (100 μeV - 1 meV), but not easy w/o enhancement by B!

Axion Direct Search Techniques

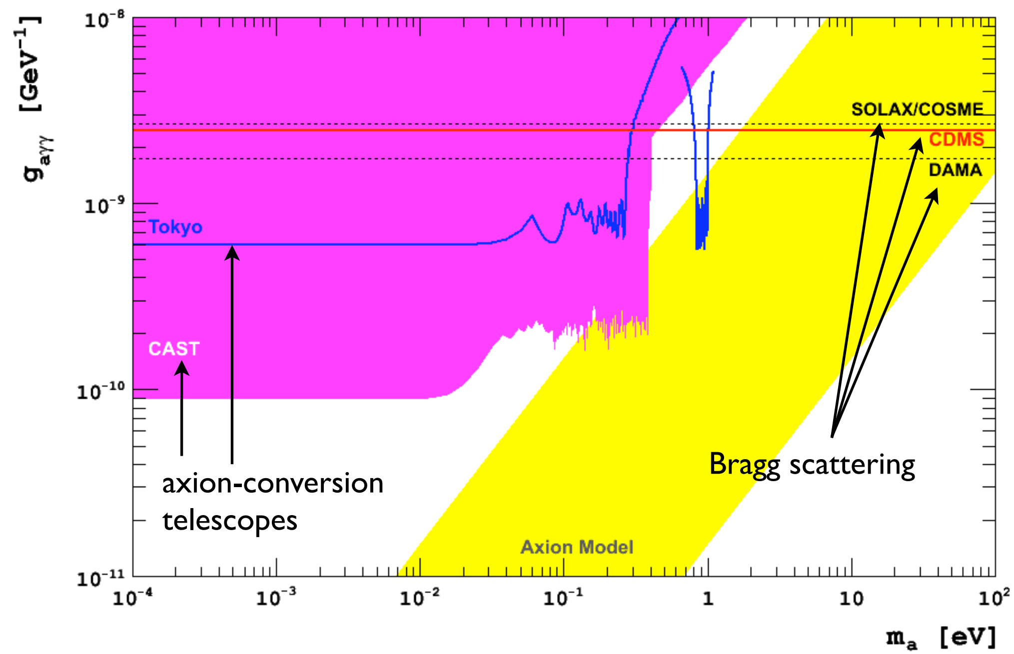
Cosmologically interesting: provides appropriate Ω_{DM}, m_a = 1 μeV to 1 meV



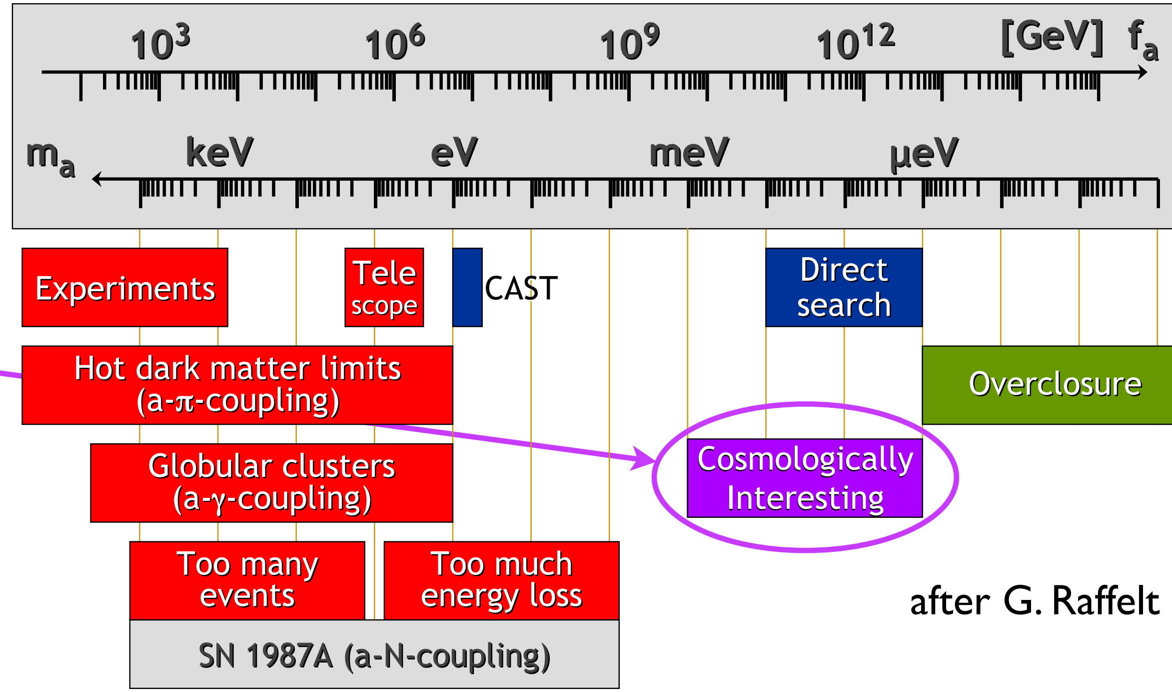
after G. Raffelt

Solar axions

- Photons convert to axions via Primakoff process in sun; ~keV thermal kinetic energy
- Axion-conversion telescopes sensitive to ~1 eV axions; too massive to be CDM, could be HDM (though ≪ Ω_{DM})
- Higher masses probed by Bragg scattering searches
- Beginning to probe DFSZ and KSVZ models



Axion Direct Search Techniques



Cosmologically interesting: provides appropriate Ω_{DM}, m_a = 1 μeV to 1 meV

after G. Raffelt

Other laboratory searches

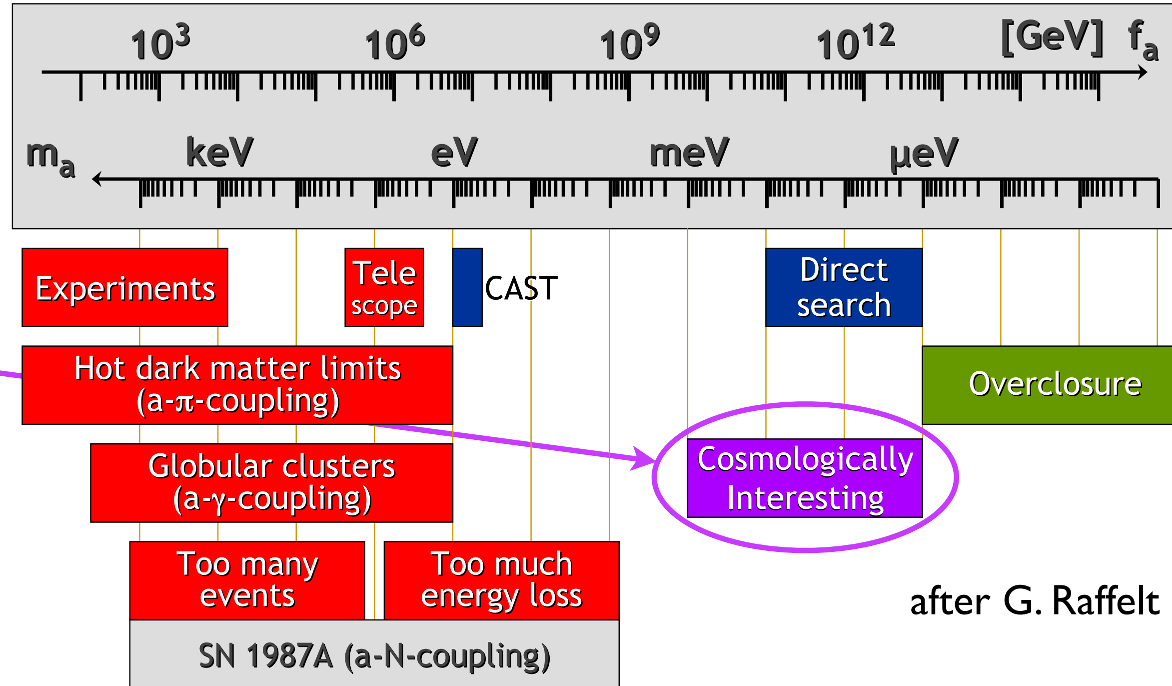
- γ → a → γ in B field; relatively poor sensitivity bec. two vertices; very far away from plausible models
  - Shining light thru walls. Will be more sensitive w/high Q optical cavities in future.
  - B-induced polarization rotation
  - B-induced birefringence
- Torsion pendulum (Eot-Wash group)
  - Axions mediate a P and T violating force between electrons and nucleons
  - Look for violations of $1/r^2$

Axions: Definitively Testable

Cosmologically interesting: provides appropriate Ω_{DM}, m_a = 1 μeV to 1 meV

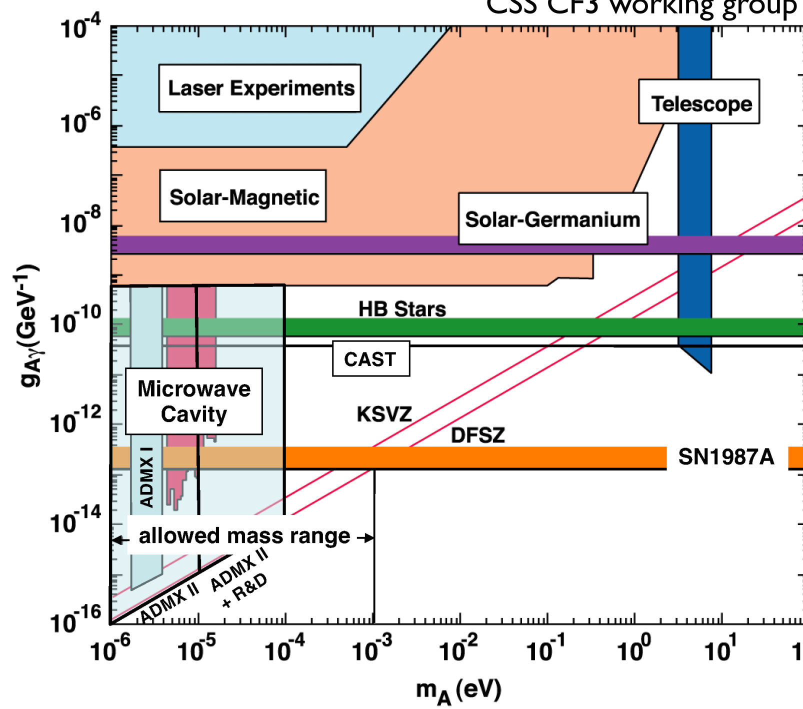
Microwave cavity conversion

- 1 GHz = 4 μeV: use high-Q tunable cavity in high B field; when $f_0 = m_a$, excess power
- Detection: RF amplifier + Fourier transform power spectrum, excited Rydberg atom photodetection
- Can cover ~1 μeV to 100 μeV; cavities become too small > 100 μeV
- With μwave SQUID amplifier and colder cavity, ADMX II will definitively test full KSVZ to DFSZ for part of cosmologically interesting m_a range



after G. Raffelt

CSS CF3 working group



The Classic WIMP Scenario

A WIMP χ is like a massive neutrino: produced when T >> m_χ via pair annihilation/ creation. Reaction maintains thermal equilibrium.

If interaction rates high enough, comoving density drops as $\exp(-m_\chi / T)$ as T drops below m_δ : annihilation continues, production becomes suppressed.

But, weakly interacting → will "freeze out" before total annihilation if

$$H > \Gamma_{ann} \sim \frac{n_\chi}{\langle \sigma_{ann}\, v \rangle}$$

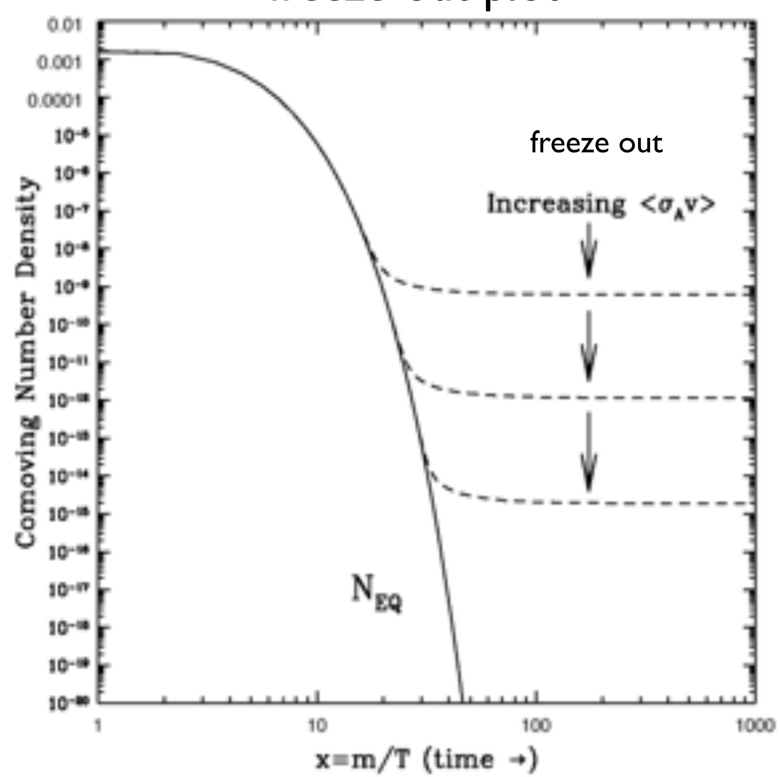
i.e., if annihilation too slow to keep up with Hubble expansion

Leaves a relic abundance:

$$\Omega_\chi \left(\frac{H_0}{100\ \mathrm{km/s/Mpc}} \right) \approx \frac{10^{-27}}{\langle \sigma_{ann}\, v \rangle_{fr}}\ \mathrm{cm^3\, s^{-1}}$$

for m_χ = O(100 GeV)
→ if m_χ and σ_{ann} determined by new weak-scale physics, then Ω_χ is O(1)

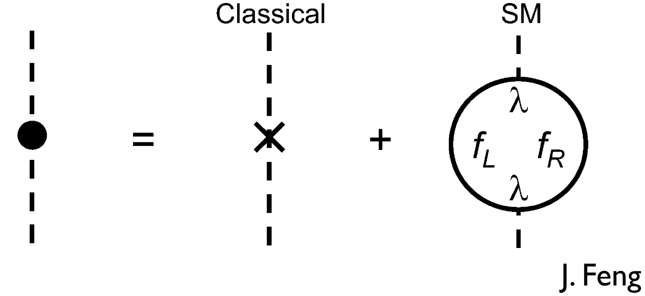
canonical Kolb and Turner freeze-out plot



Supersymmetry and WIMPs

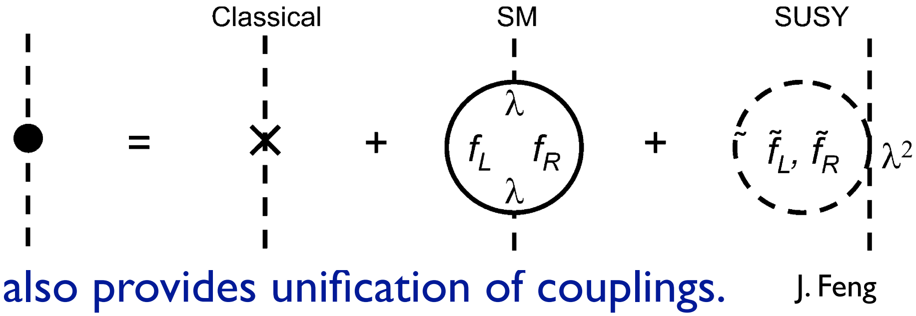
The Gauge Hierarchy problem: Why is $M_{Pl} >> M_{EW}$?

- Alternatively: why are Standard Model particle masses so small compared to M_{Pl}? Radiative corrections destabilize Higgs boson mass: $\Delta m_H^2 = O(\alpha/\pi)\ \Lambda^2 \quad \Lambda \sim M_{Pl}$



Supersymmetry provides a solution

- Standard Model particles in supermultiplets combining particles of different spin
- stabilizes radiative corrections: every bosonic loop has a corresponding fermionic loop carrying opposite sign
- SUSY-breaking splits masses so superpartners not yet visible
- Λ given by SUSY-breaking scale: loop cancellation works above Λ. Need $\Lambda \sim 1$ TeV to keep Higgs light; also provides unification of couplings.



Lightest superpartner is a good WIMP candidate

- stable, m = O(100 GeV), undetected bec. neutral & interacts only via heavy mediators (EW gauge bosons, Higgs, superpartners of quarks)

SUSY Particle Content and Parameters

Every SM fermion (spin-1/2) gets spin-0 "scalar fermion (sfermion)" partner

Every SM gauge boson (spin-1) gets spin-1/2 "gaugino" partner

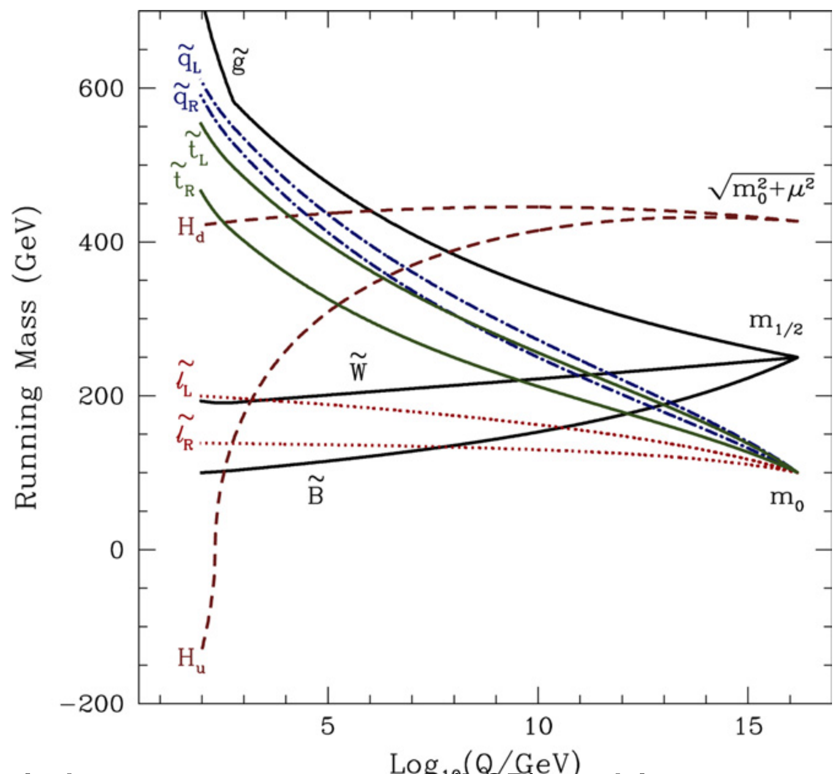
Higgs (spin-0) acquires spin-1/2 "higgsino" partner

Need a second Higgs to preserve SUSY

Graviton (spin-2) gets spin-3/2 "gravitino"

Parameters

- In unbroken SUSY, all params fixed by SM
- SUSY breaking results in O(100) params
- mSUGRA assumption: Masses assumed to be universal at GUT scale: m_0 scalar mass, $m_{1/2}$ "ino" mass
- tan β = ratio of two Higgs vacuum expectation values
- μ = Higgs mass parameter
- Trilinear couplings A_0 (analogue of Yukawa couplings in SM)



R-parity prevents proton decay and makes lightest superpartner (LSP) stable

LHC Tests of Constrained Minimal Supersymmetry

Assume CMSSM:
  Constrained Minimal Supersymmetric Standard Model

Very narrow blue strips:
  LSP relic density matches DM density

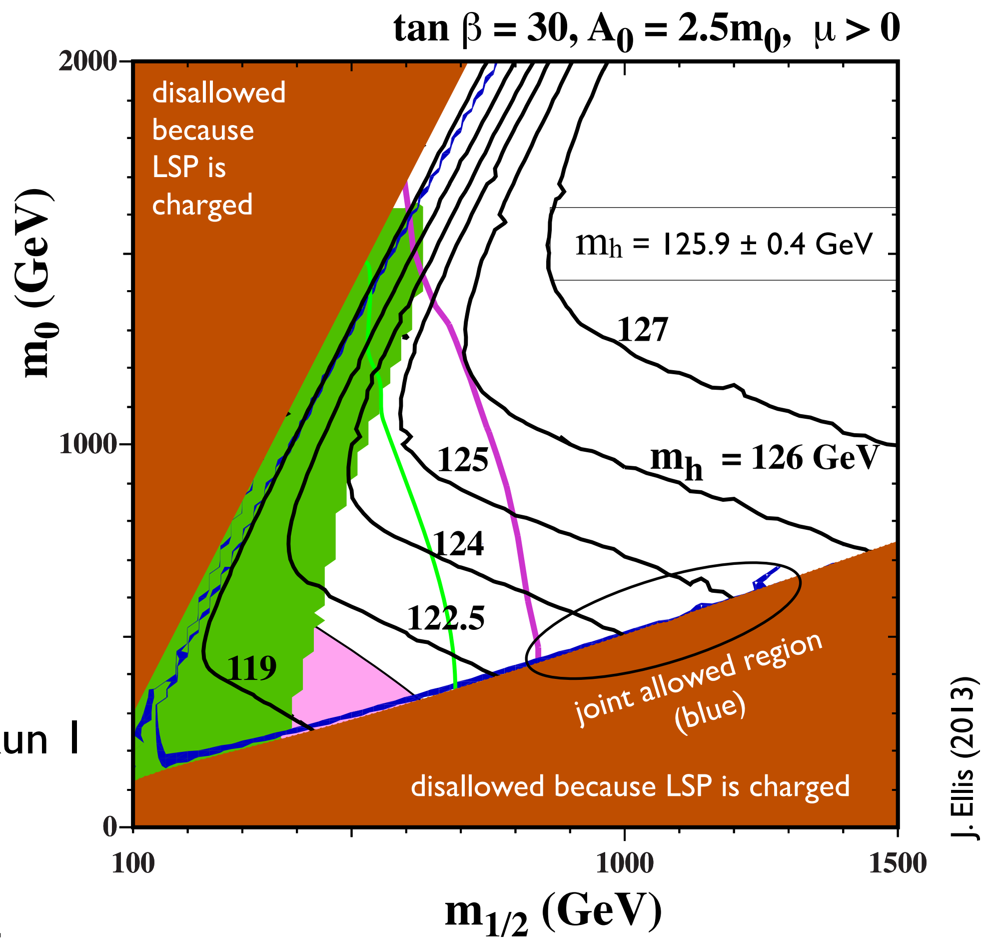
Green: BR($b \to s\,\gamma$) too large

Pink: $g_\mu - 2$ deviation from SM explained by SUSY

Purple line: lower limit on parameter space due to absence of missing transverse energy events at LHC Run 1

Green line: BR($B_s \to \mu^+\mu^-$) provides lower limit on parameters space

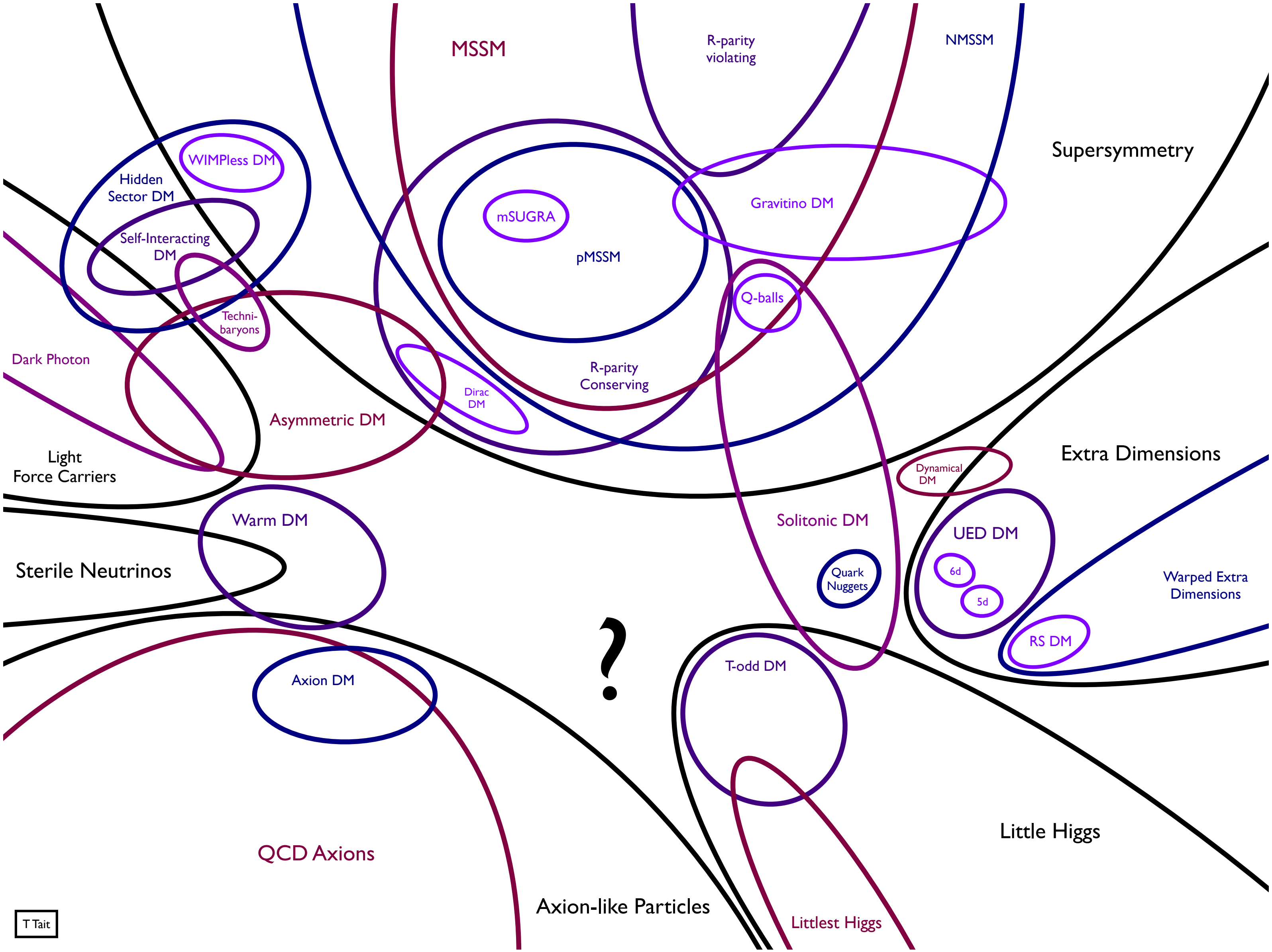
Black lines: Various Higgs mass values



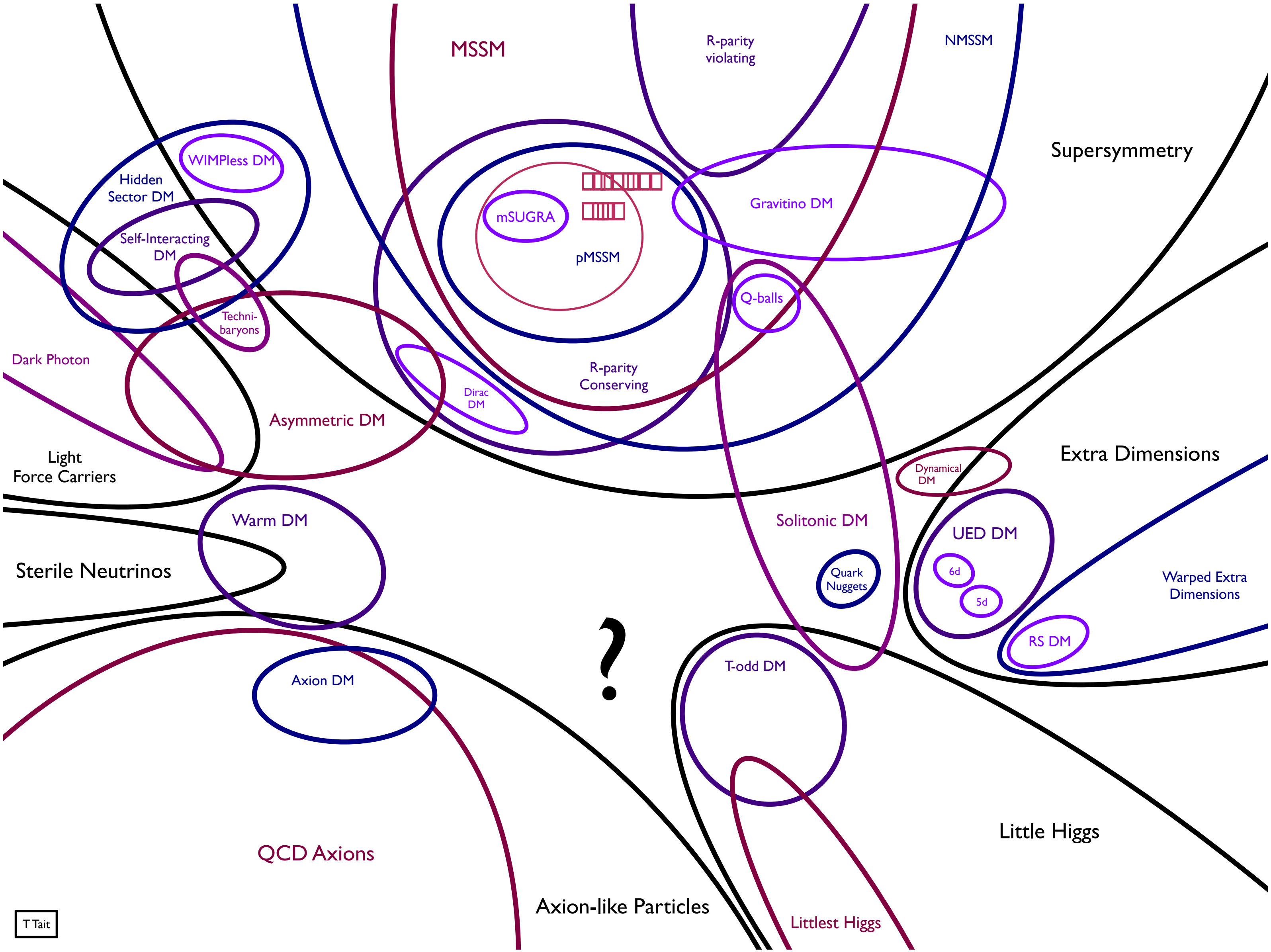
Changes in tan β and A_0 affect $m_h \Rightarrow$ reduced compatibility with relic density

Very limited parameter space where LSP relic density can match DM density, complies with excluded regions, and provides acceptable Higgs mass. Cannot explain $g_\mu - 2$. Can release assumptions about SUSY (e.g. non-universal Higgs mass) at cost in elegance.

Beyond Supersymmetric Dark Matter



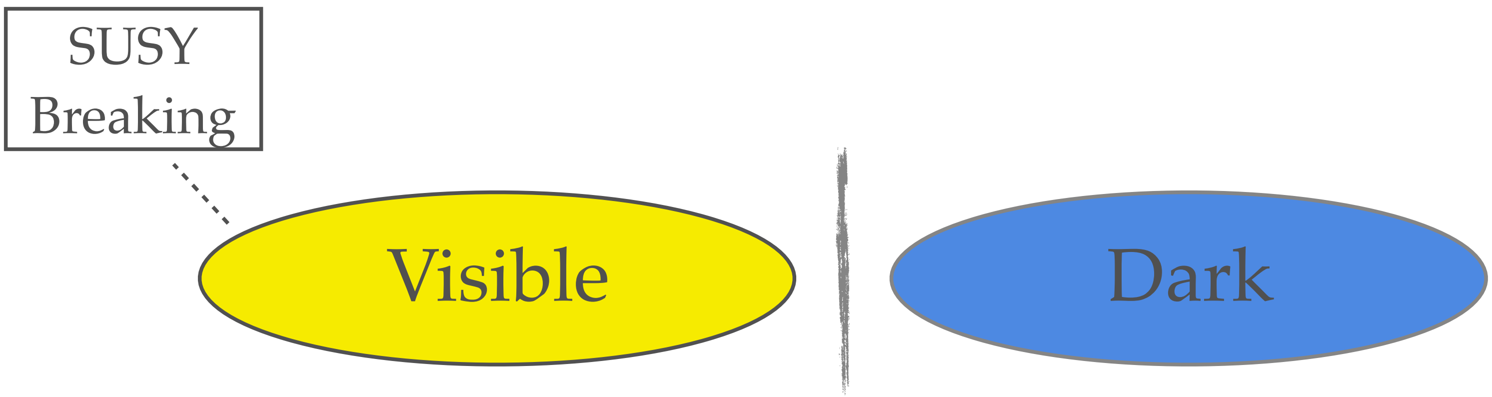
Beyond Supersymmetric Dark Matter



Hidden Sectors

Low-mass WIMPs (<< EW scale = 100 GeV) historically disfavored theoretically because of mismatch with scale of new physics (SUSY)

Can adjust DM mass scale via weak coupling between dark and visible sectors, with SUSY preserved in visible sector



Amount of SUSY breaking transmitted sets DM mass scale
Small coupling between sectors = small mass

100 GeV ⟶ 1 GeV

Hooper, Zurek

Asymmetric Dark Matter

Asymmetric Dark Matter

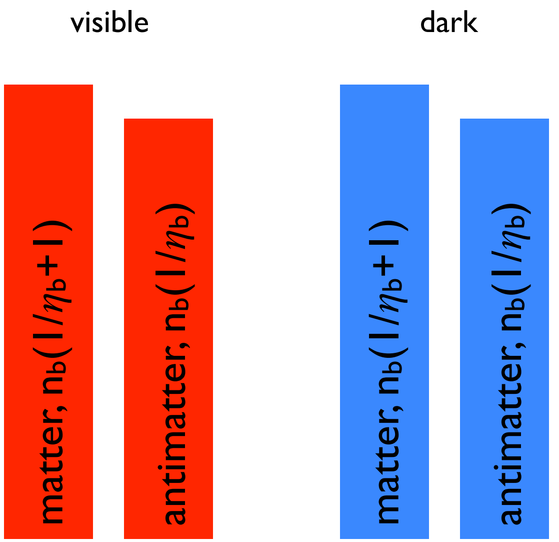
Why is $\Omega_{DM} = 5\ \Omega_b$?

Asymmetric Dark Matter

Why is $\Omega_{DM} = 5\ \Omega_b$?

Proposal:

- n_{DM} and n_b generated by same physics, $n_{DM} \approx n_b$
  - observed asymmetry $\eta_b \approx n_b/n_\gamma \approx 6 \times 10^{-10}$ can be generated in the b, DM or both
  - need a mechanism that
    - couples asymmetries in the two sectors to each other so $\eta_b \approx \eta_{DM}$
    - becomes weak as universe cools so asymmetries are preserved ("hidden")

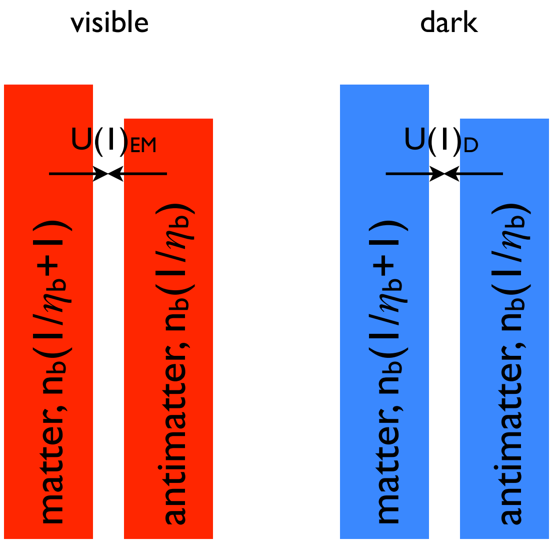


Asymmetric Dark Matter

Why is $\Omega_{DM} = 5\ \Omega_b$?

Proposal:

- n_{DM} and n_b generated by same physics, $n_{DM} \approx n_b$
  - observed asymmetry $\eta_b \approx n_b/n_\gamma \approx 6 \times 10^{-10}$
    can be generated in the b, DM or both
  - need a mechanism that
    - couples asymmetries in the two sectors to each other so $\eta_b \approx \eta_{DM}$
    - becomes weak as universe cools so asymmetries are preserved ("hidden")
  - need to make n_{DM}/η_{DM} annihilate to leave n_{DM} (as baryons do): a new $U(1)_D$, "dark photon"



Asymmetric Dark Matter

Why is $\Omega_{DM} = 5\ \Omega_b$?

Proposal:

- n_{DM} and n_b generated by same physics, $n_{DM} \approx n_b$
  - observed asymmetry $\eta_b \approx n_b/n_\gamma \approx 6 \times 10^{-10}$ can be generated in the b, DM or both
  - need a mechanism that
    - couples asymmetries in the two sectors to each other so $\eta_b \approx \eta_{DM}$
    - becomes weak as universe cools so asymmetries are preserved (“hidden”)
  - need to make n_{DM}/η_{DM} annihilate to leave n_{DM} (as baryons do): a new $U(1)_D$, “dark photon”

Asymmetric Dark Matter

Why is $\Omega_{DM} = 5\ \Omega_b$?

Proposal:

- n_{DM} and n_b generated by same physics, $n_{DM} \approx n_b$
  - observed asymmetry $\eta_b \approx n_b/n_\gamma \approx 6 \times 10^{-10}$ can be generated in the b, DM or both
  - need a mechanism that
    - couples asymmetries in the two sectors to each other so $\eta_b \approx \eta_{DM}$
    - becomes weak as universe cools so asymmetries are preserved (“hidden”)
  - need to make n_{DM}/η_{DM} annihilate to leave n_{DM} (as baryons do): a new $U(1)_D$, “dark photon”
- Simple prediction for DM particle mass:

$$\frac{m_{DM}}{m_b} = \frac{\Omega_{DM}}{\Omega_b}\,\frac{\eta_b}{\eta_{DM}/q_{DM}}\,\frac{1-\eta_{DM}}{1+\eta_{DM}}$$

Asymmetric Dark Matter

Why is $\Omega_{DM} = 5\ \Omega_b$?

Proposal:

- n_{DM} and n_b generated by same physics, $n_{DM} \approx n_b$
  - observed asymmetry $\eta_b \approx n_b/n_\gamma \approx 6 \times 10^{-10}$ can be generated in the b, DM or both
  - need a mechanism that
    - couples asymmetries in the two sectors to each other so $\eta_b \approx \eta_{DM}$
    - becomes weak as universe cools so asymmetries are preserved ("hidden")
  - need to make n_{DM}/η_{DM} annihilate to leave n_{DM} (as baryons do): a new $U(1)_D$, "dark photon"

- Simple prediction for DM particle mass:

$$\frac{m_{DM}}{m_b} = \frac{\Omega_{DM}}{\Omega_b} \frac{\eta_b}{\eta_{DM}/q_{DM}} \frac{1-\eta_{DM}}{1+\eta_{DM}}$$

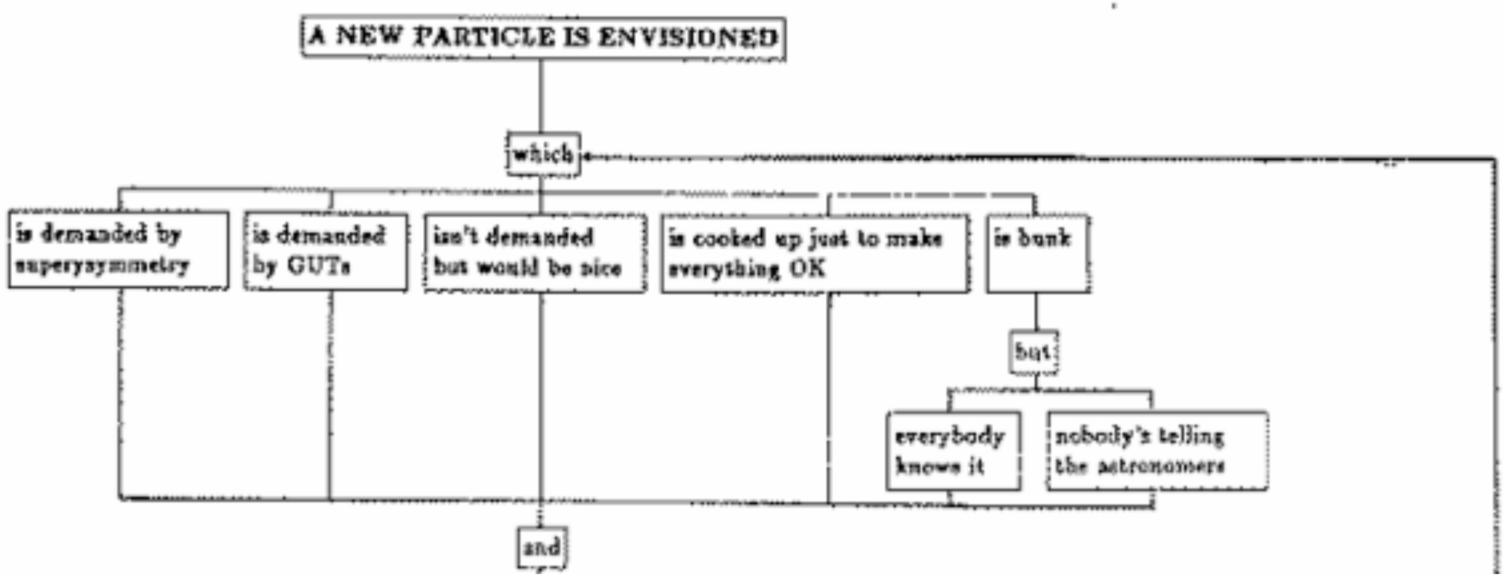
A new look at DM:

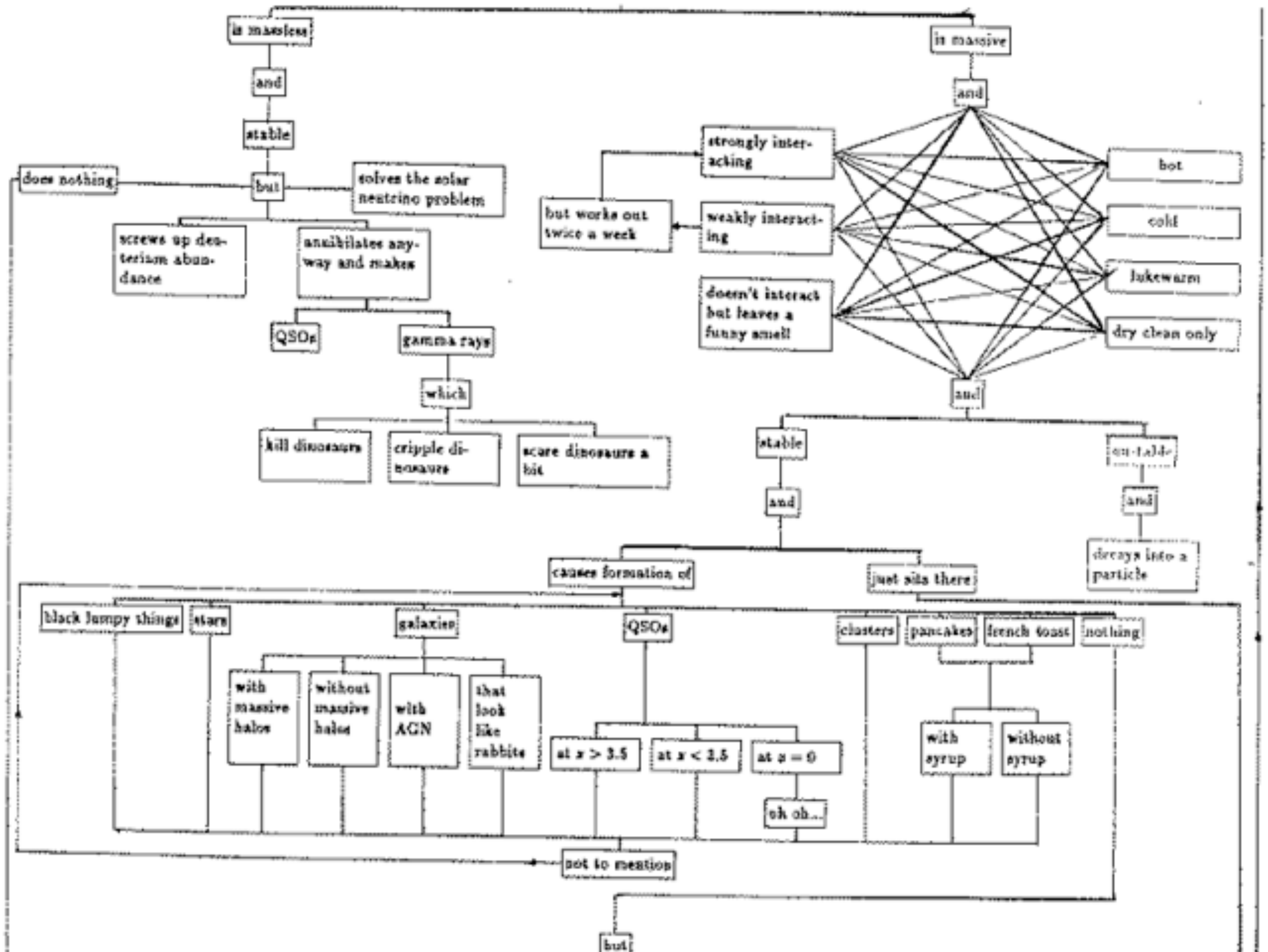
- Totally plausible non-SUSY theory; not subject to SUSY minimum mass bounds
- New "dark force" opens up possibilities: heavy photons, velocity-dependent self-interaction, scattering via light mediators, dark atoms, etc.
- Momentum-transfer-dependent cross section can reconcile results of different direct detection experiments that use different targets or cover different energy ranges

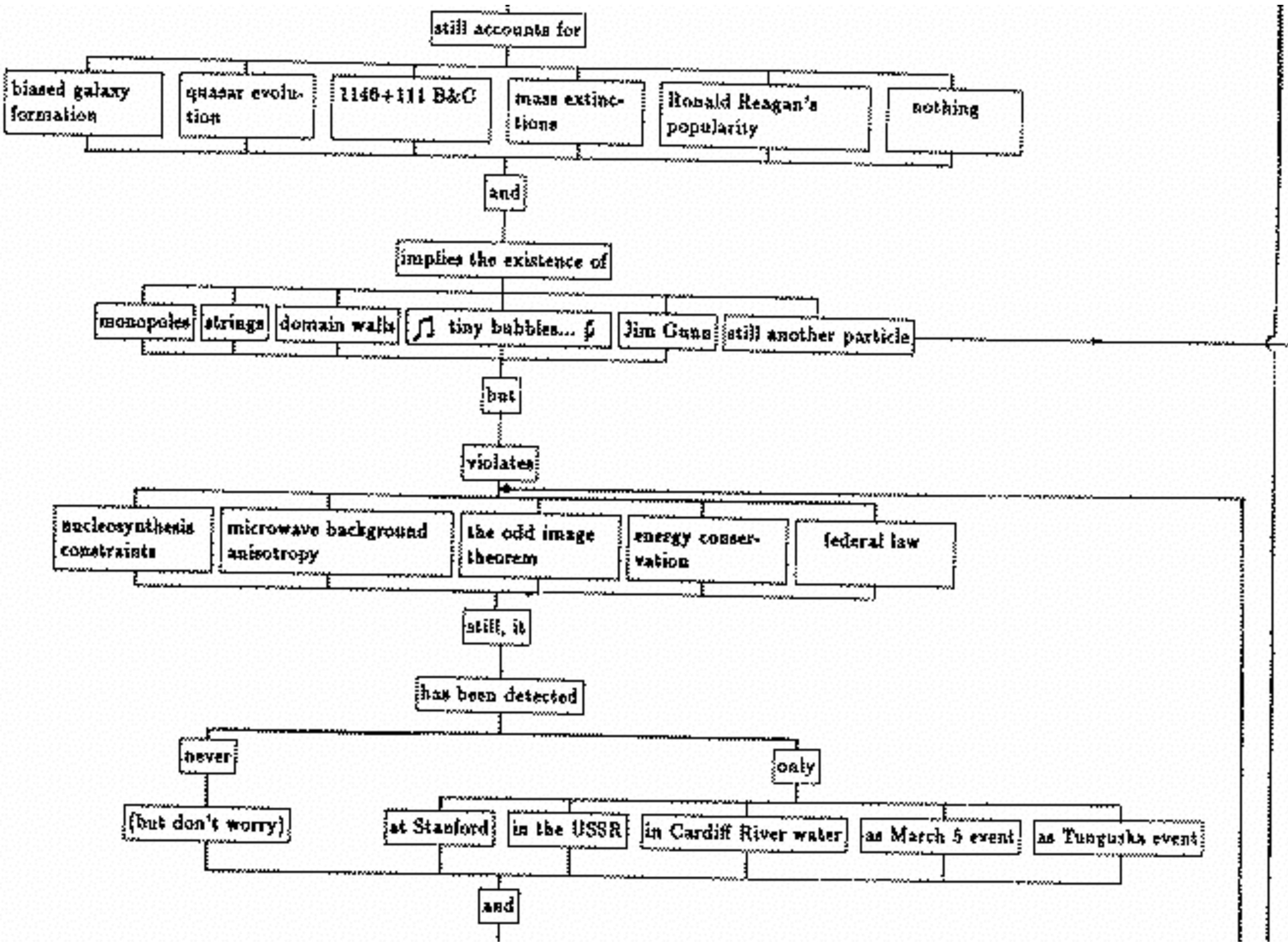
A NEW AND DEFINITIVE META-COSMOLOGY THEORY

T. R. Lauer
T. S. Statler
B. S. Ryden
D. H. Weinberg

Department of Astrophysical Sciences, Princeton University

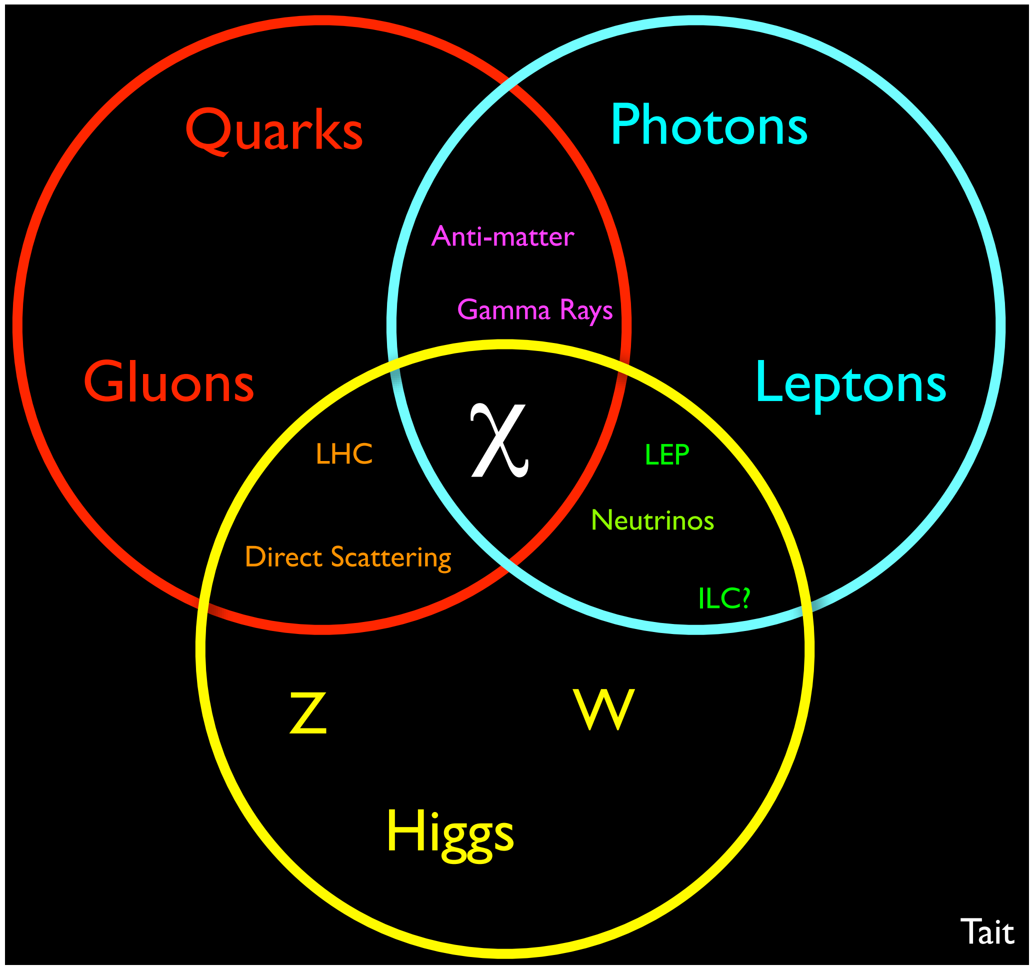



is massless
and
stable
but
does nothing
solves the solar neutrino problem
screws up deuterium abundance
annihilates anyway and makes
QSOs
gamma rays
which
kill dinosaurs
cripple dinosaurs
scare dinosaurs a bit
is massive
and
strongly interacting
weakly interacting
doesn't interact but leaves a funny smell
but works out twice a week
hot
cold
lukewarm
dry clean only
and
stable
unstable
and
and
decays into a particle
causes formation of
just sits there
black lumpy things
stars
galaxies
with massive halos
without massive halos
with AGN
that look like rabbits
QSOs
at z > 3.5
at z < 3.5
at z = 0
oh oh...
clusters
pancakes
french toast
nothing
with syrup
without syrup
not to mention
but


still accounts for
biased galaxy formation
quasar evolution
1146+111 B&C
mass extinctions
Ronald Reagan's popularity
nothing
and
implies the existence of
monopoles
strings
domain walls
tiny bubbles...
Jim Gunn
still another particle
but
violates
nucleosynthesis constraints
microwave background anisotropy
the odd image theorem
energy conservation
federal law
still, it
has been detected
never
only
(but don't worry)
at Stanford
in the USSR
in Cardiff River water
as March 5 event
as Tunguska event
and

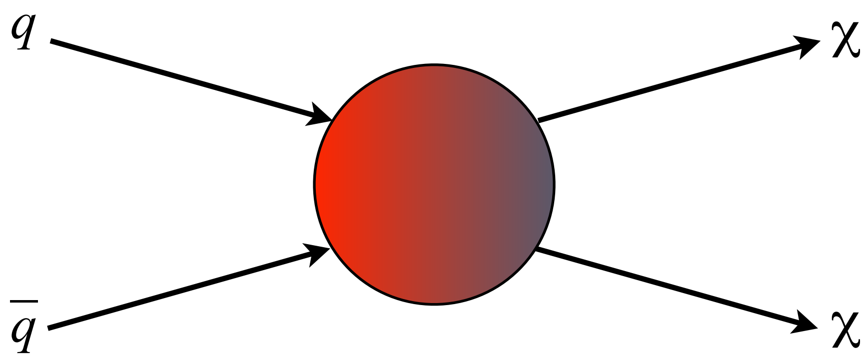
Purely Phenomenological Approach?

Since we don't know the theory that explains the DM,
all possible interactions with χ need to be mapped out experimentally
using all the tools we have available...



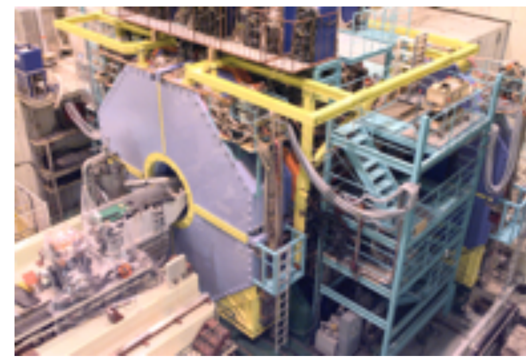
Detecting and Studying Dark Matter

Accelerator Production: make DM in lab w/quark-antiquark (p-anti-p) collisions

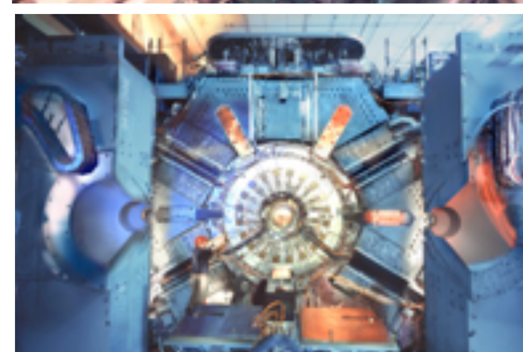


CMS, ATLAS, and LHCb at LHC

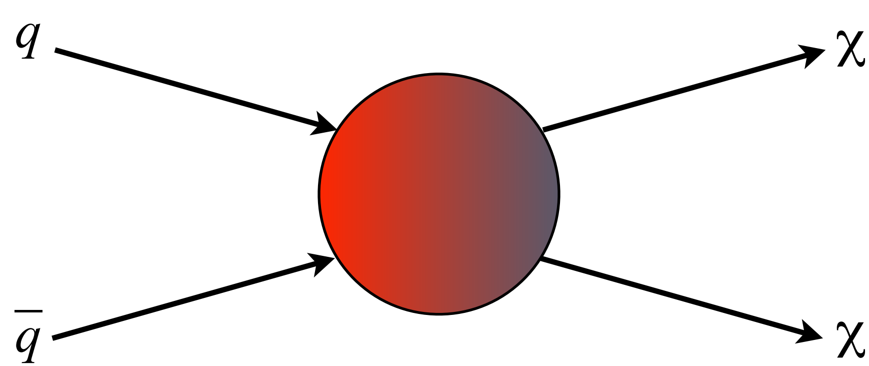
Belle, Belle II

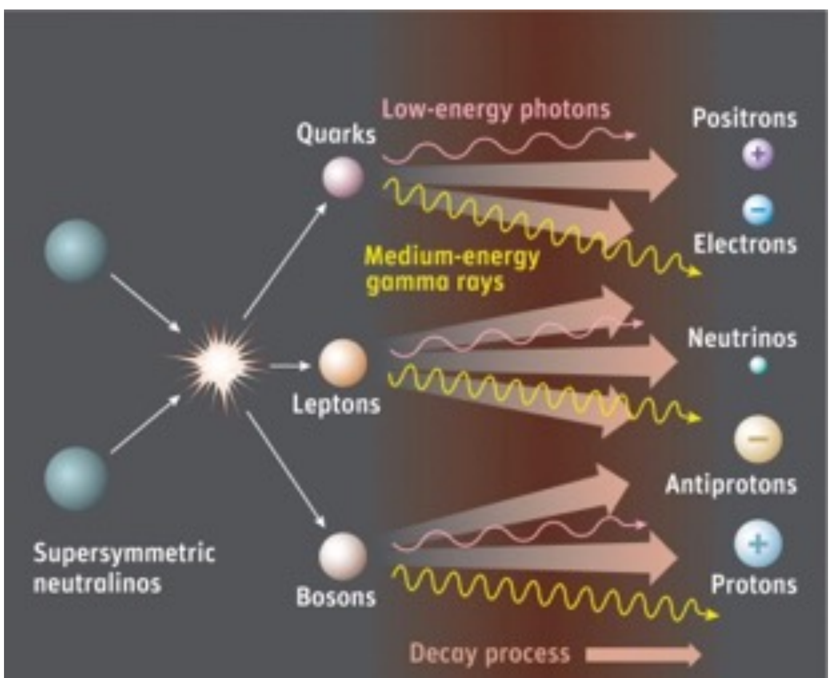


BaBar



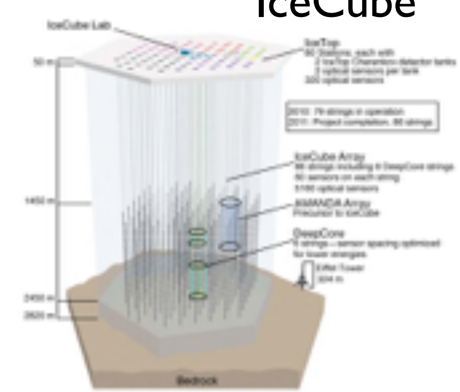
Detecting and Studying Dark Matter





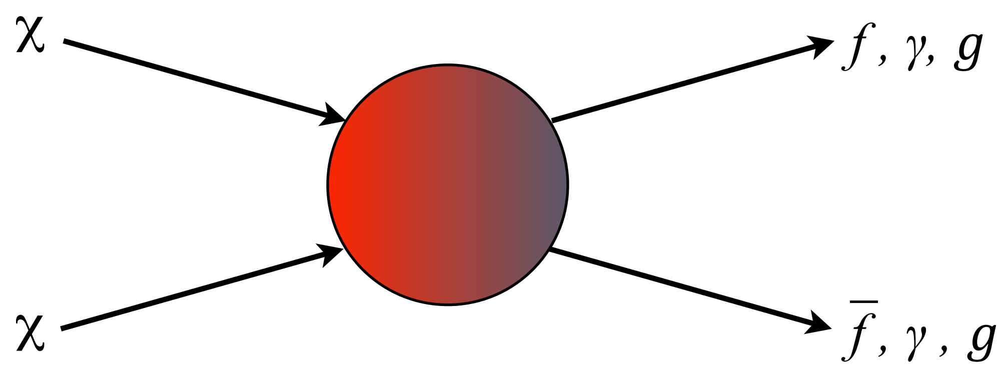
AMS

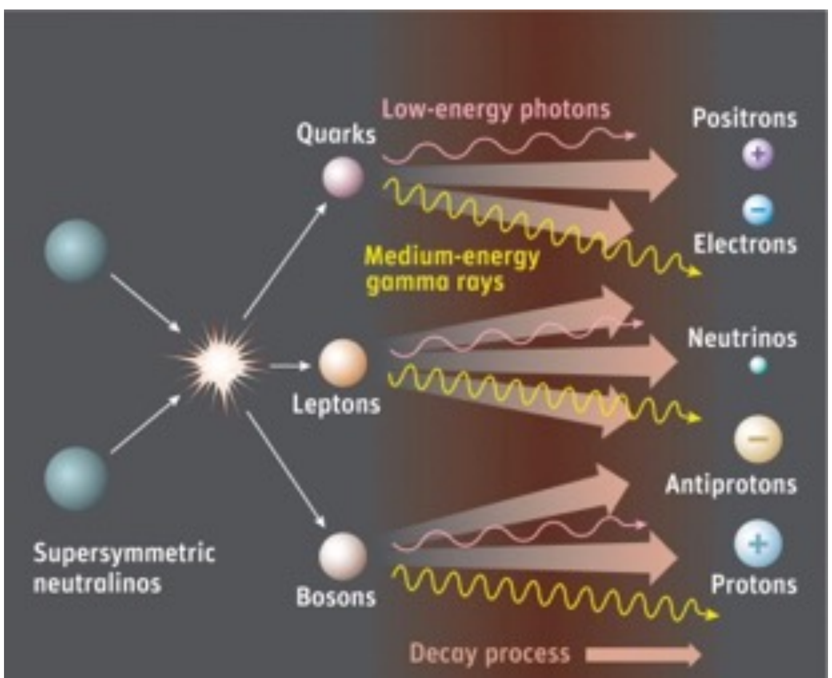
IceCube



Detecting and Studying Dark Matter

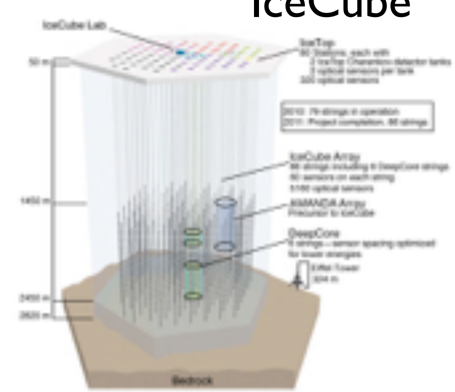
Indirect Detection: DM self-annihilates to other particles



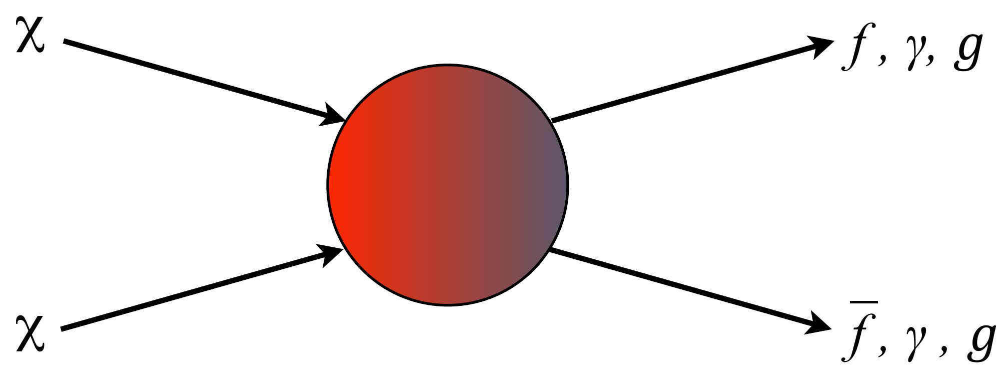


AMS

IceCube

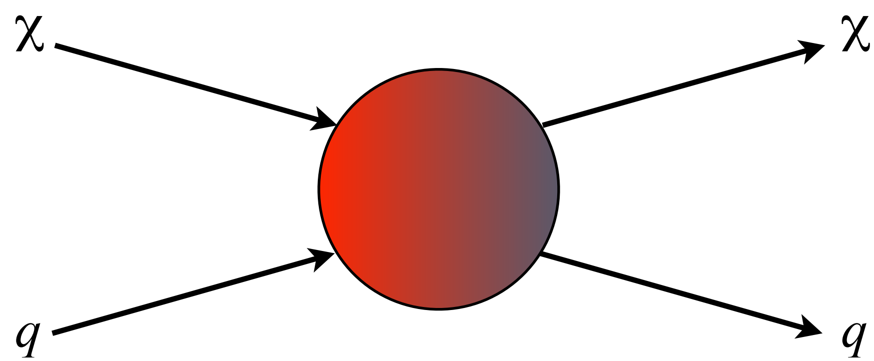


Detecting and Studying Dark Matter



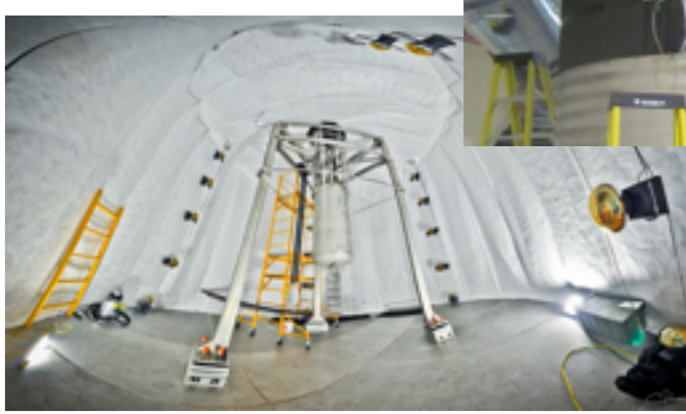
Detecting and Studying Dark Matter

Direct Detection: DM scatters with normal matter



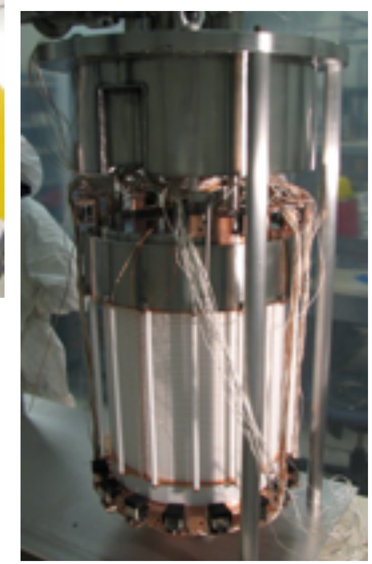
SuperCDMS

LUX



COUPP

XENON100



Direct Detection of WIMPs

WIMPs expect to dominate halo of our galaxy with following characteristics:

- mass ~ 100 proton masses
- speed ~ 300 km/s ~ 0.001c

With these characteristics, they scatter off of nuclei like billiard balls.

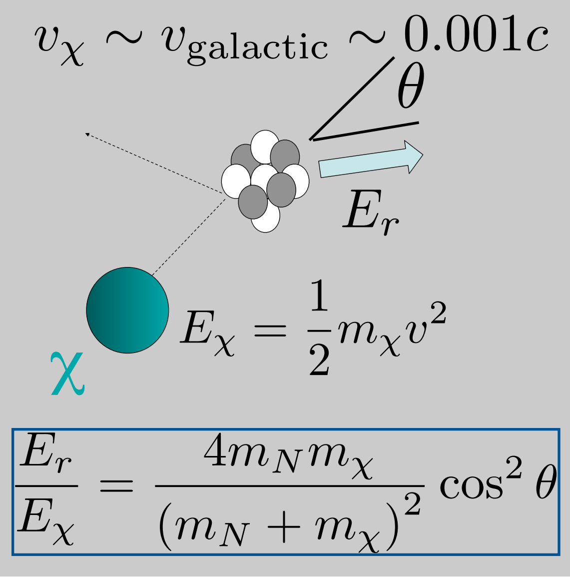
- typical energy deposited:
  - tens of keV (like a medical X-ray; not very energetic!)
- typical rate: < 0.01/kg/day

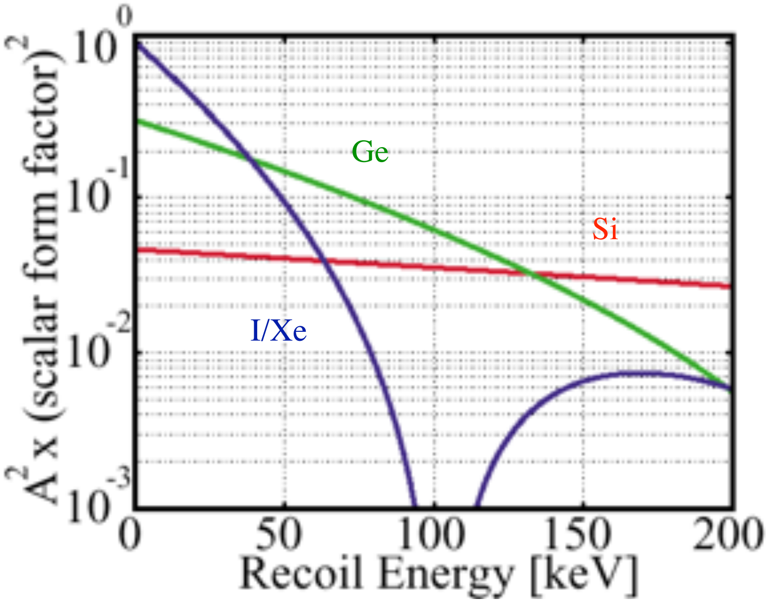
Electron scatters not energetic enough

- Like a tennis ball against a wall
- So only look for nuclear recoils
- Though searches for sub-eV ERs growing

Expected nucleus and energy dependence:

- A^2 scaling at zero momentum transfer
- Form factor for breakdown of coherence

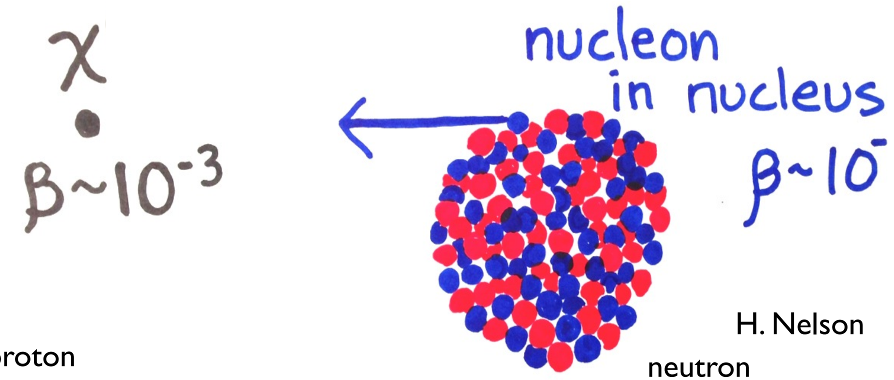




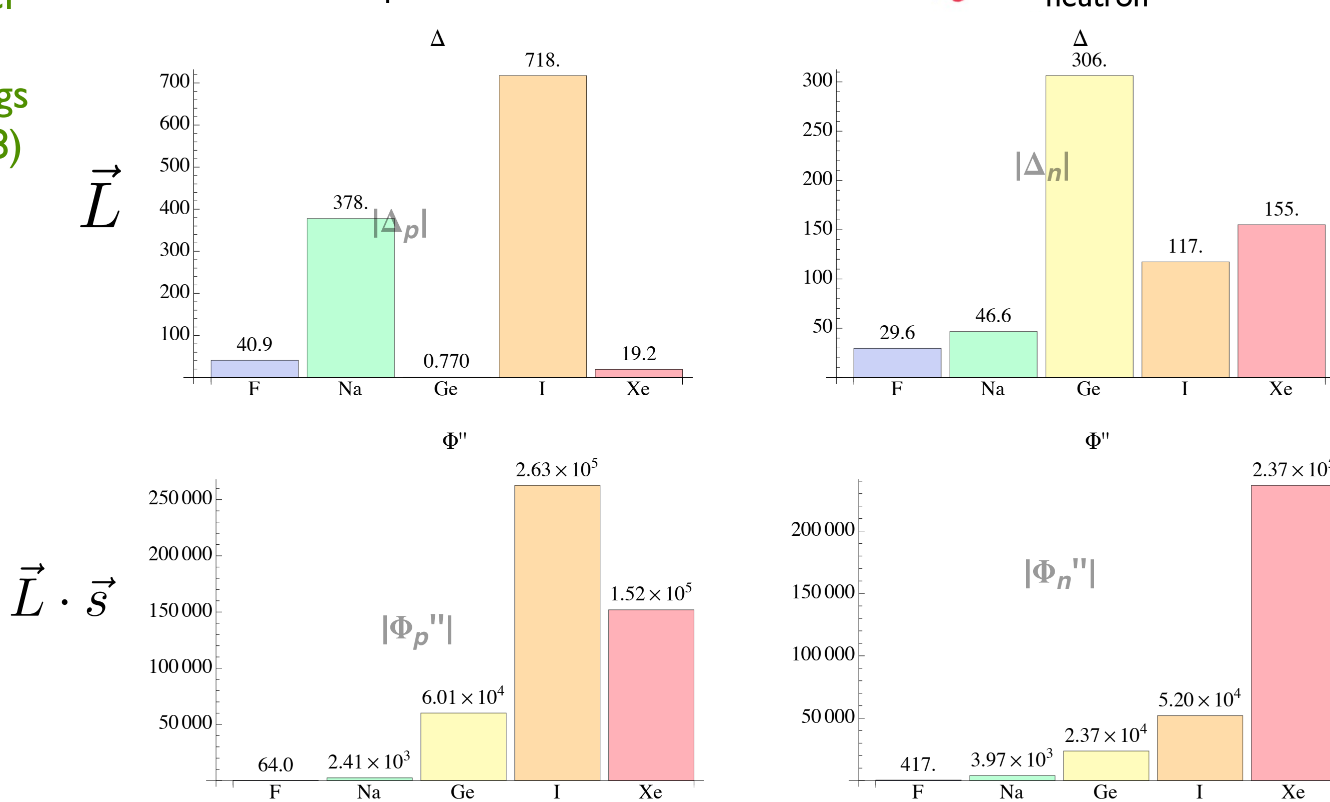
Interaction of Dark Matter with Normal Matter

Beyond simple A^2 scaling:

- NR limit valid for WIMP but not for nucleons!
- Fitzpatrick, Haxton, Katz, Lubbers, Xu 2013:
  - Need to consider much larger set of couplings to nucleons (8)
  - Orbital angular momentum of nucleons can play important role
  - Changes nature of coherence
  - Surprising patterns
- Why not violate isospin?



H. Nelson



Why is this difficult?

Very low rates

- For comparison, there are natural radioactive decays in your body of comparable energy happening much more frequently (10 million/day):
  - potassium-40: about 4000 decays/second with energies around 500 keV
  - carbon-14: similar rate, energy around 100 keV
- Earth itself is radioactive due to uranium, thorium, radon
- Particles from outer space hit the top of the atmosphere and create showers of particles that reach us all the time (cosmic rays)
- Need lots of target mass!

Low energy depositions

- Because of low rate, need big detectors (> 10-100 kg these days)
- But also need to detect very small amounts of energy!

Need to separate nuclear recoils due to WIMPs from electron recoils due to radioactive backgrounds

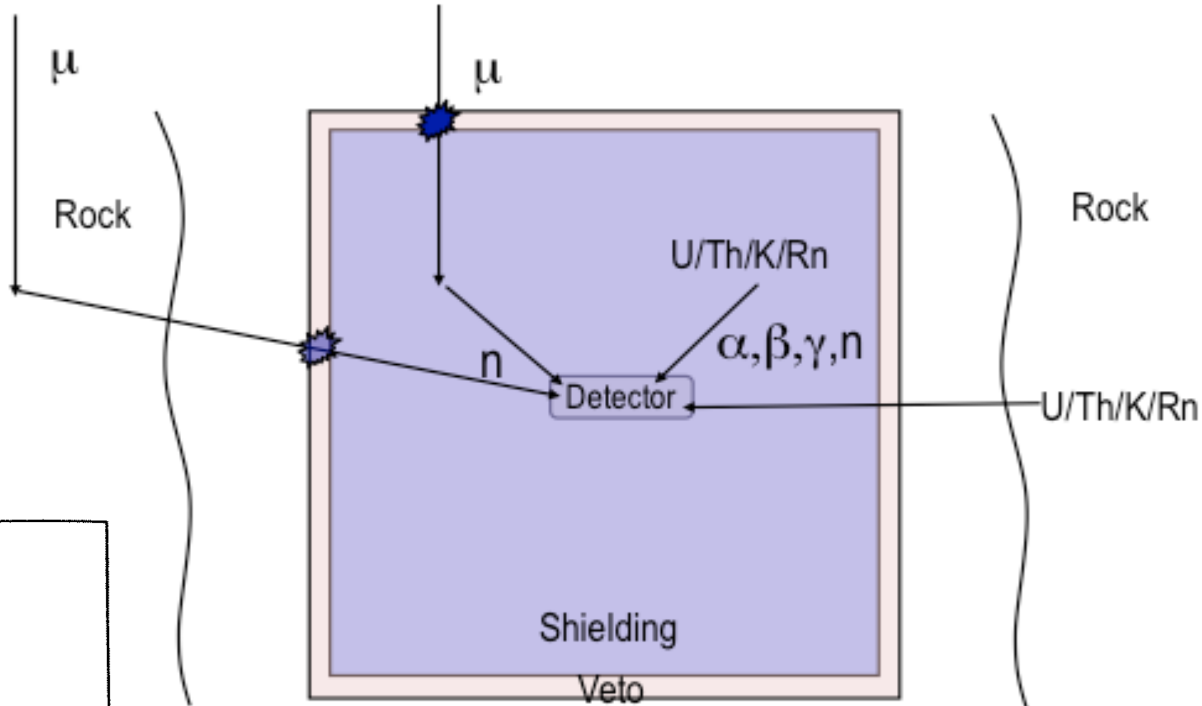
Backgrounds

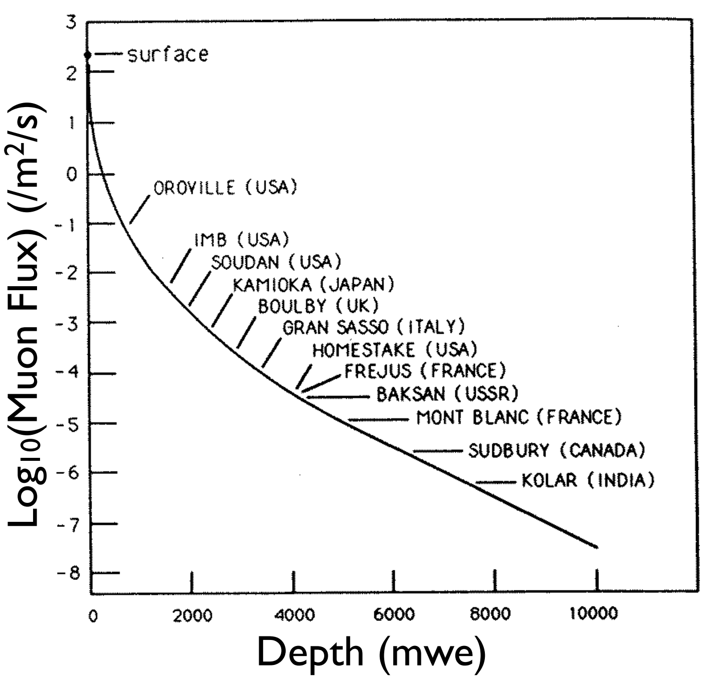
Particle types:

- α, β, γ, n

Source:

- radiogenic
- cosmogenic





Parent location:

- in the target
- on the surface
- on nearby surfaces
- in surrounding materials

Backgrounds

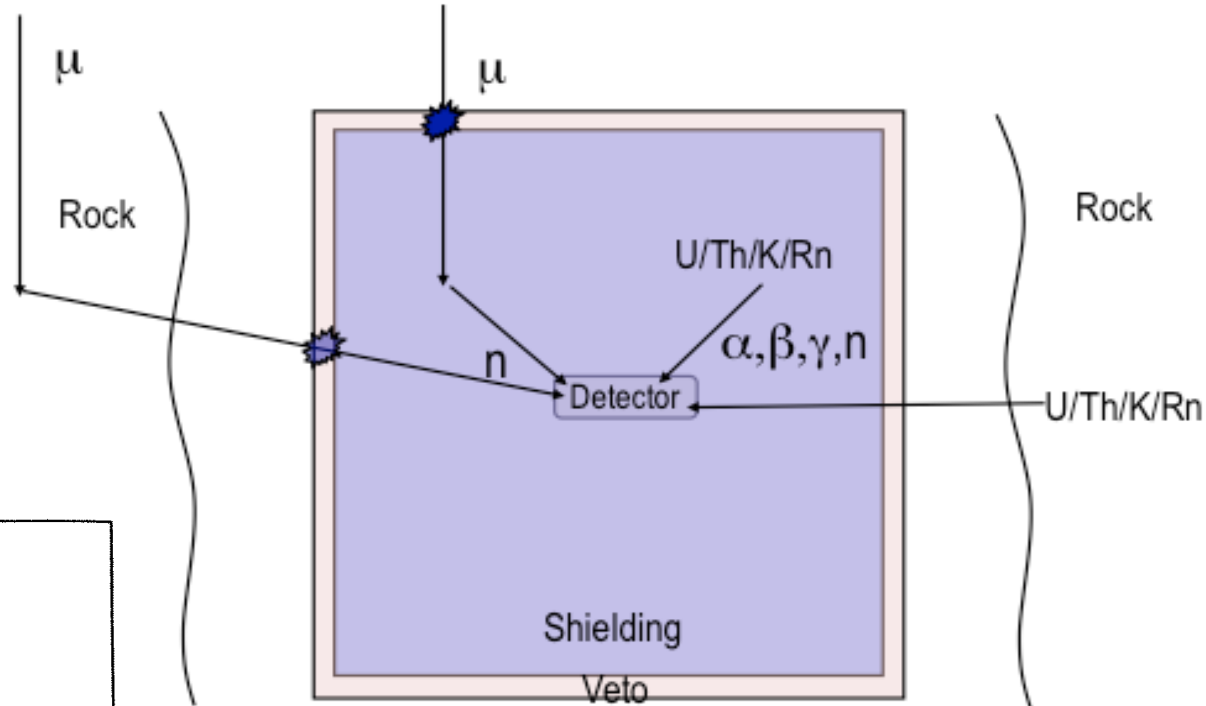
Particle types:

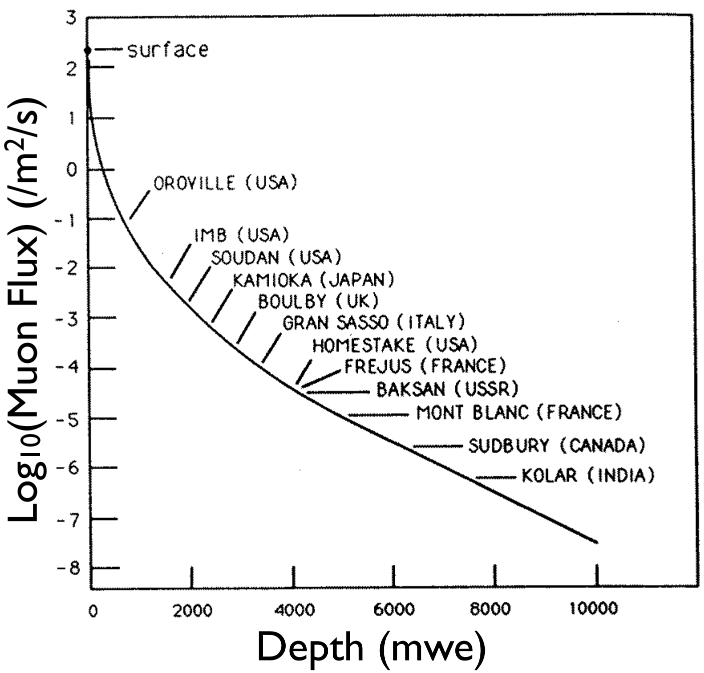
α, β, γ, n

Source:

radiogenic

cosmogenic





Parent location:

in the target

on the surface

on nearby surfaces

in surrounding materials

+ eventually, the ultimate background: coherent nuclear scattering of solar, atmospheric, and diffuse supernova bgnd neutrinos. Irreducible!

What are good materials to use?

Semiconductors (silicon, germanium)

Liquified noble gases (neon, argon, xenon)

Copper

- OFHC is pure, electroformed even purer

Lead

- Except 210Pb (22 year half-life)

Plastics

Water

Strategies and Signatures

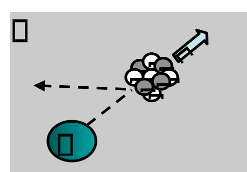
Challenges

Very **low energy** thresholds (~10 keV)

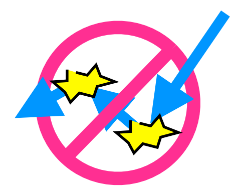
Large **exposures** (large active mass, long-term stability)

Stringent **background control** (cosmogenic, radioactive)
Cleanliness
Shielding (passive, active, deep site)

Discrimination power



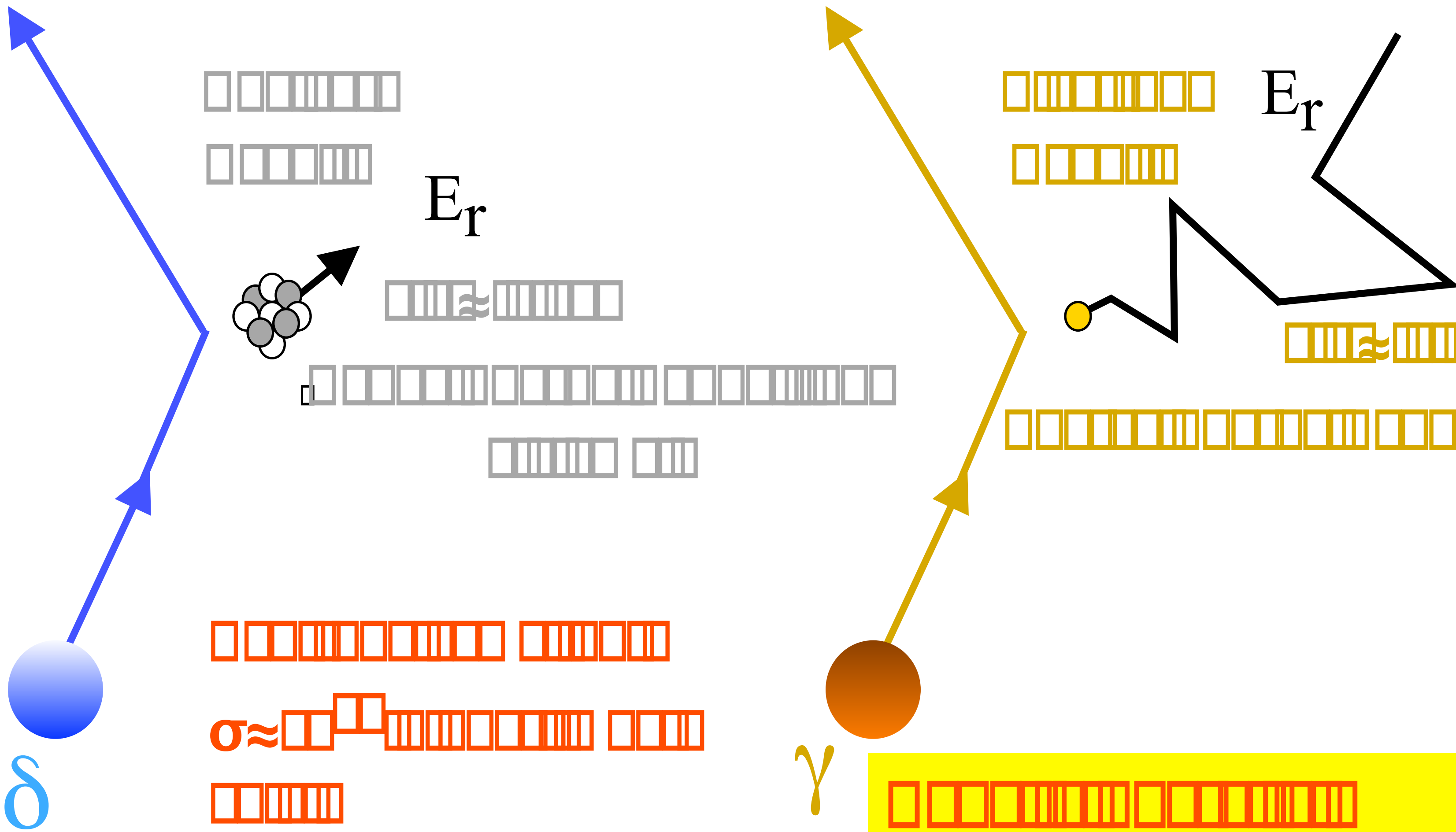
Nuclear recoils



No multiplicity

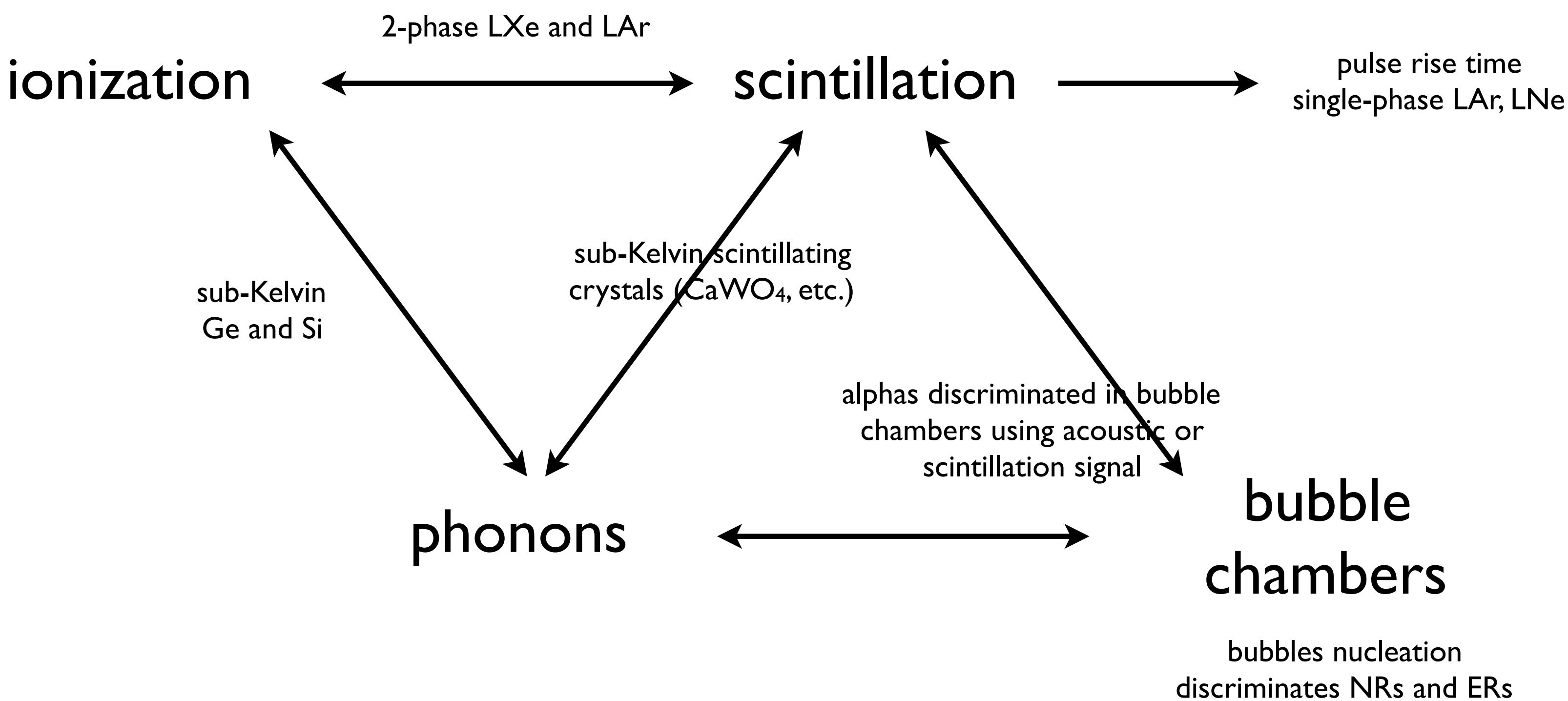
→ Enormous range of techniques!

Nuclear Recoil Discrimination



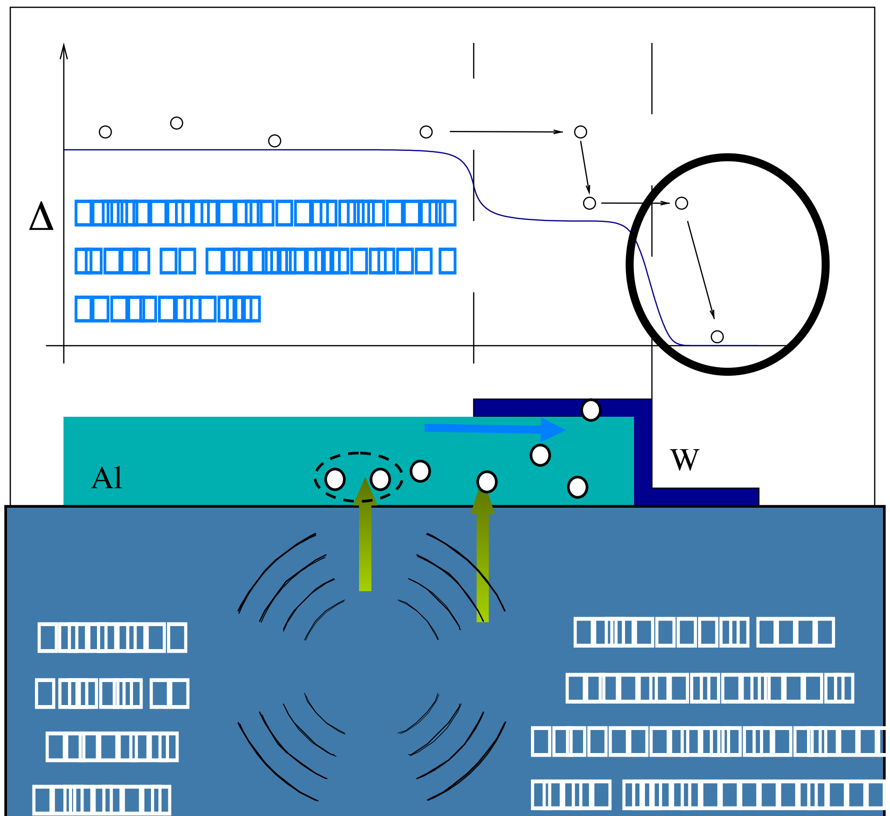
Discrimination Techniques

Need sensitivity to energy deposition characteristics (density, energy) to discriminate nuclear recoils (NRs), electron recoils (ERs), and alphas: Enormous innovation in discrimination techniques in the last 20 years.

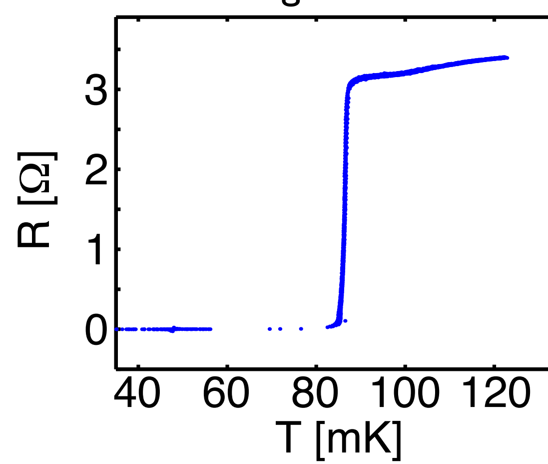


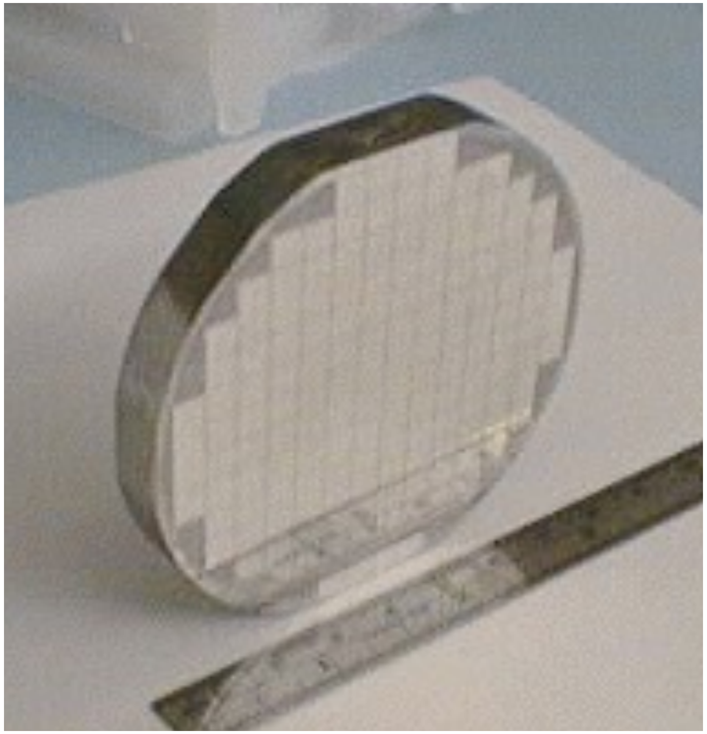
Using Sound to Detect Dark Matter

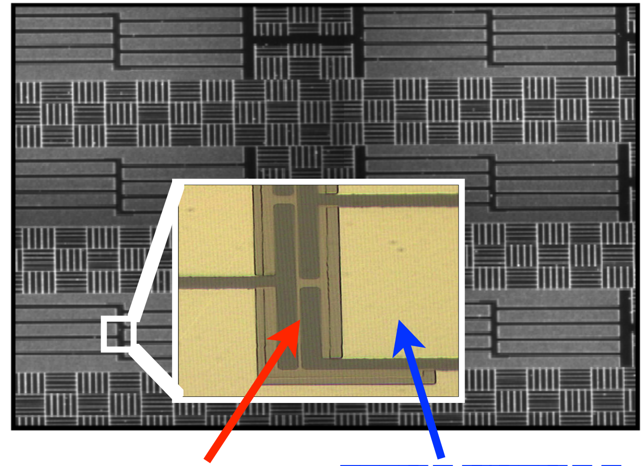
Interactions of any particle in a target cause acoustic vibrations: sound!
In fact, most of the energy goes into sound. If we can detect this sound,
we can measure very small energy depositions, and we can measure total energy
irrespective of the type of particle.



TES = transition edge sensor



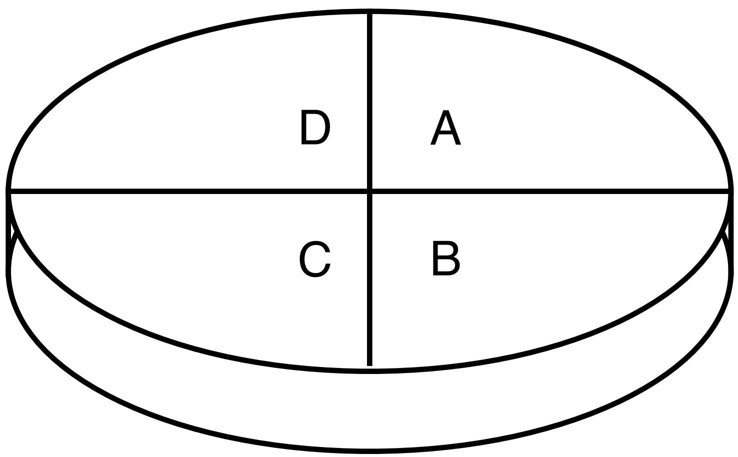




closeup on acoustic sensor

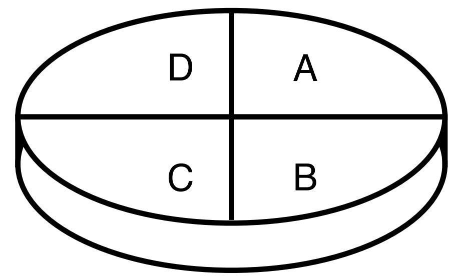
7.5 cm x 1 cm germanium or silicon crystal w/sensor patterned on surface

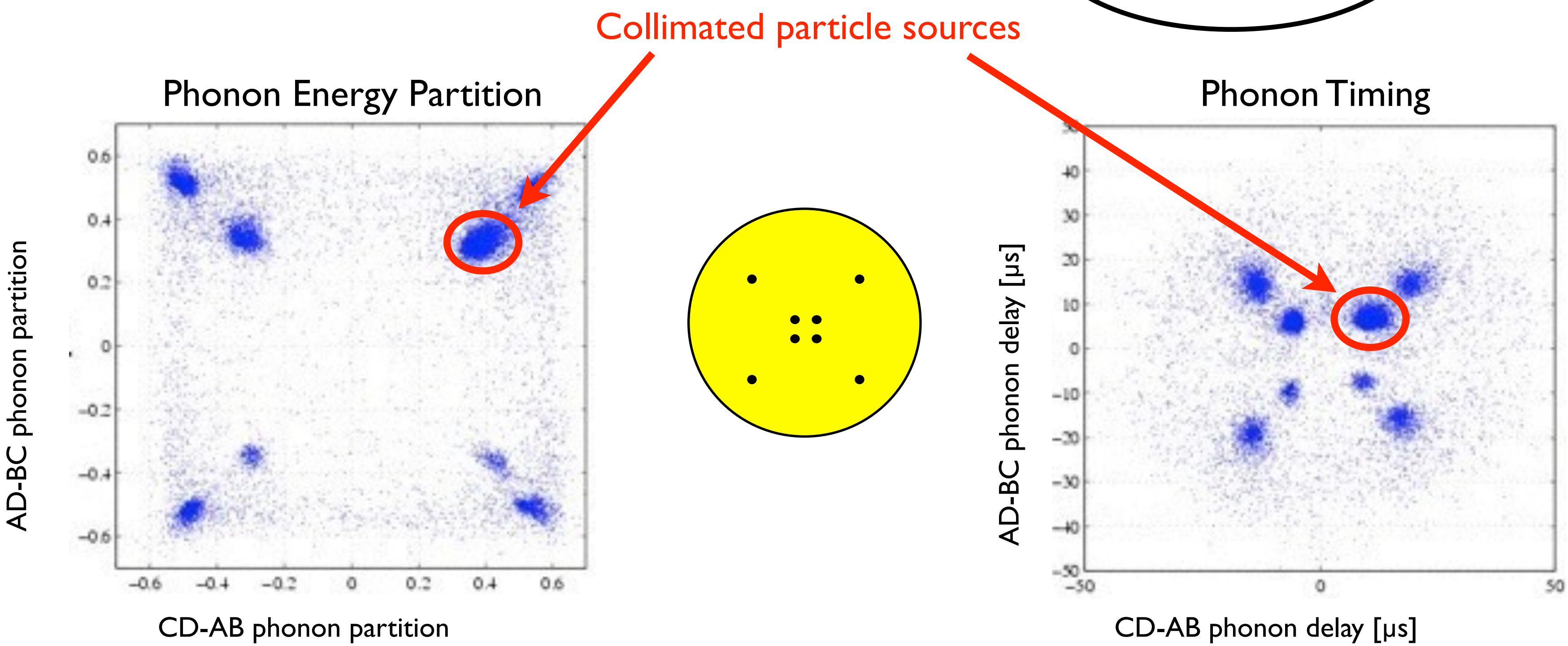
sensor segmented into four quadrants to reconstruct position



Position Reconstruction

Sound speed ~ 1 cm/0.000001s
Sensors measure position and energy.





Innovation in Techniques: SuperCDMS

SuperCDMS:

1990s:

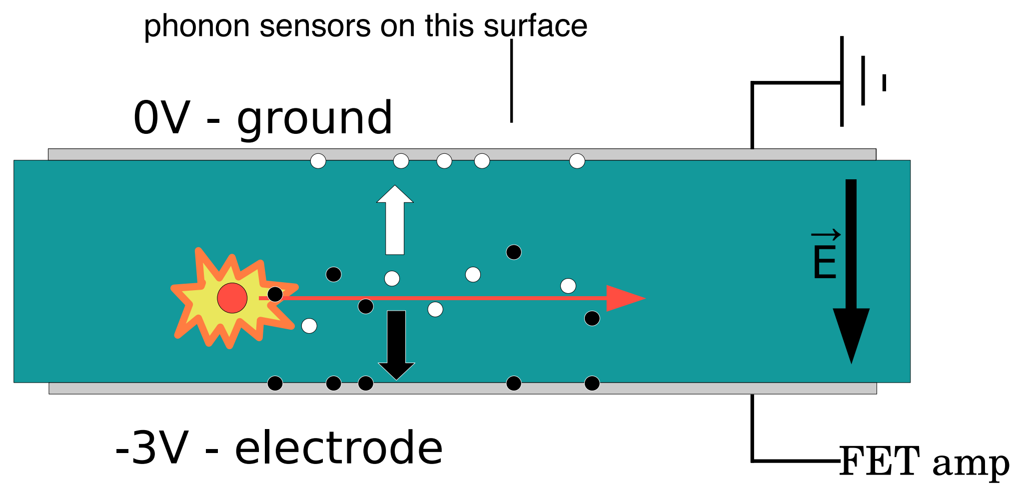
- phonons + ionization
  - discriminate NRs from ERs at low bias (few V)

2000s:

- phonon rise time
  - discriminates surface events from bulk events

2010s:

- sophisticated electrode
  - structure discriminates surface events from bulk events (EDELWEISS also)
- double-sided phonon sensor
  - promises phonon asymmetry discrimination
- measure ionization only using
  - phonons with high field: new sensitivity to low mass



Innovation in Techniques: SuperCDMS

SuperCDMS:

1990s:

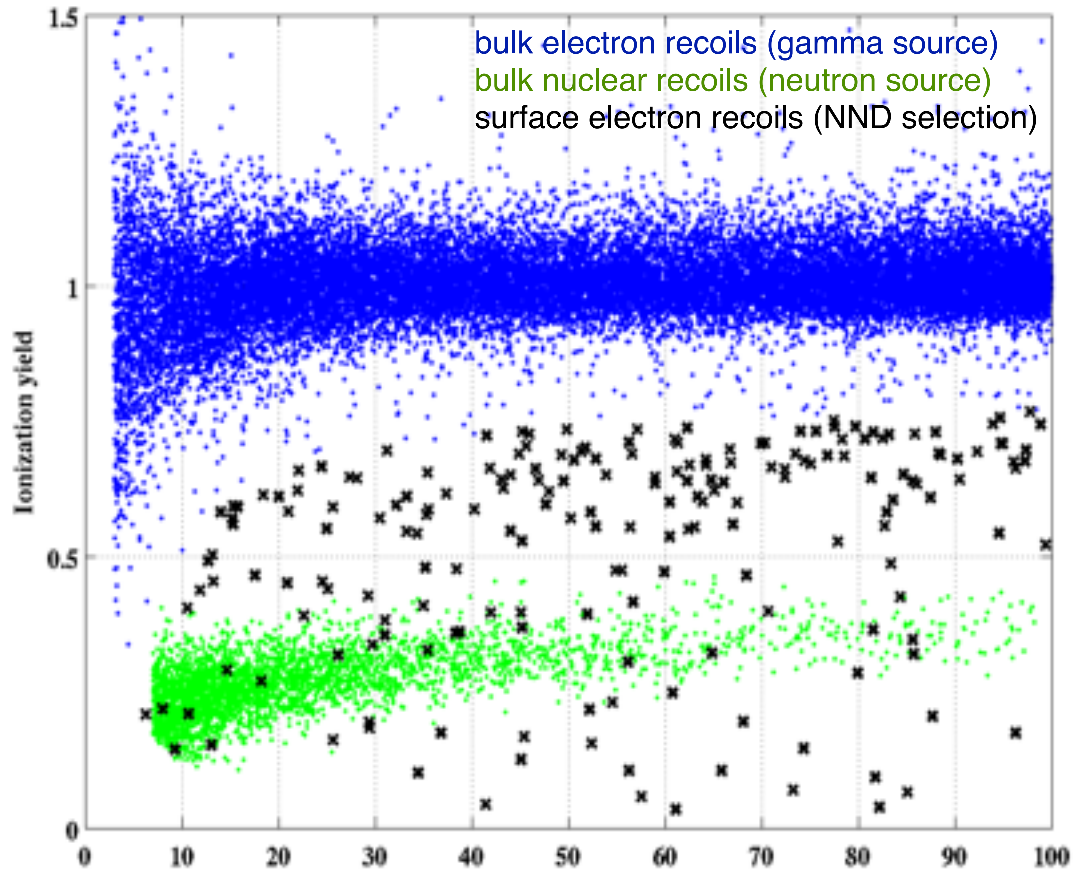
- phonons + ionization
  - discriminate NRs from ERs at low bias (few V)

2000s:

- phonon rise time
  - discriminates surface events from bulk events

2010s:

- sophisticated electrode
  - structure discriminates surface events from bulk events (EDELWEISS also)
- double-sided phonon sensor
  - promises phonon asymmetry discrimination
- measure ionization only using
  - phonons with high field: new sensitivity to low mass



Innovation in Techniques: SuperCDMS

SuperCDMS:

1990s:

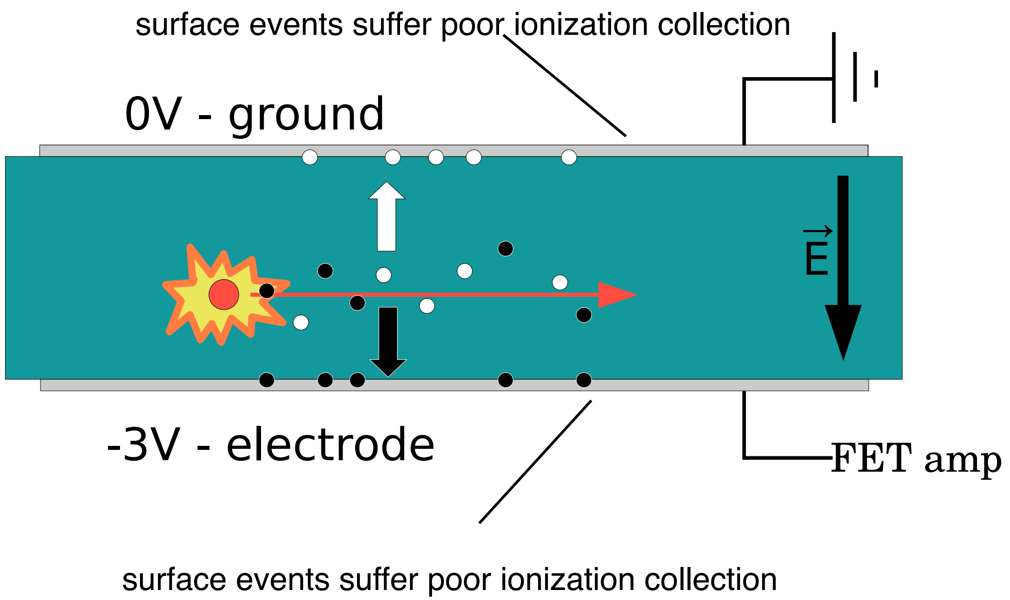
- phonons + ionization
  - discriminate NRs from ERs at low bias (few V)

2000s:

- phonon rise time
  - discriminates surface events from bulk events

2010s:

- sophisticated electrode
  - structure discriminates surface events from bulk events (EDELWEISS also)
- double-sided phonon sensor
  - promises phonon asymmetry discrimination
- measure ionization only using
  - phonons with high field: new sensitivity to low mass



Innovation in Techniques: SuperCDMS

SuperCDMS:

1990s:

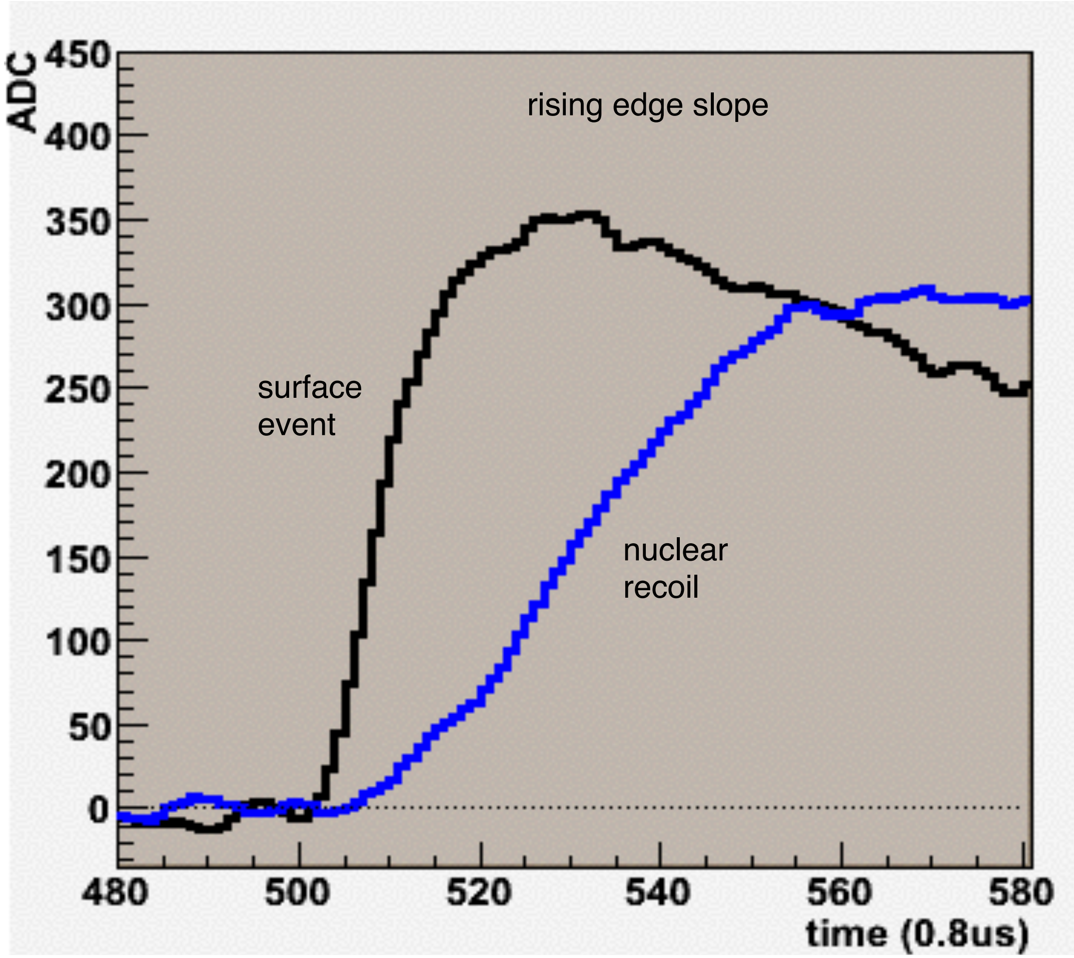
- phonons + ionization
  - discriminate NRs from ERs at low bias (few V)

2000s:

- phonon rise time
  - discriminates surface events from bulk events

2010s:

- sophisticated electrode
  - structure discriminates surface events from bulk events (EDELWEISS also)
- double-sided phonon sensor
  - promises phonon asymmetry discrimination
- measure ionization only using
  - phonons with high field: new sensitivity to low mass



Innovation in Techniques: SuperCDMS

SuperCDMS:

1990s:

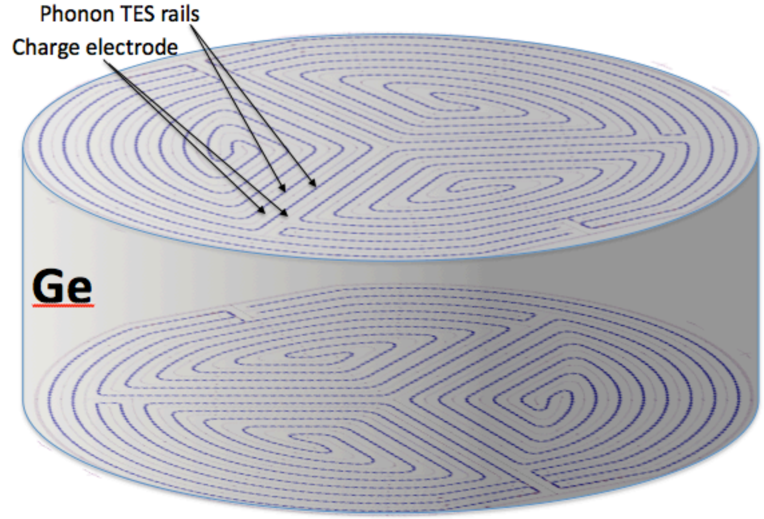
- phonons + ionization
  - discriminate NRs from ERs at low bias (few V)

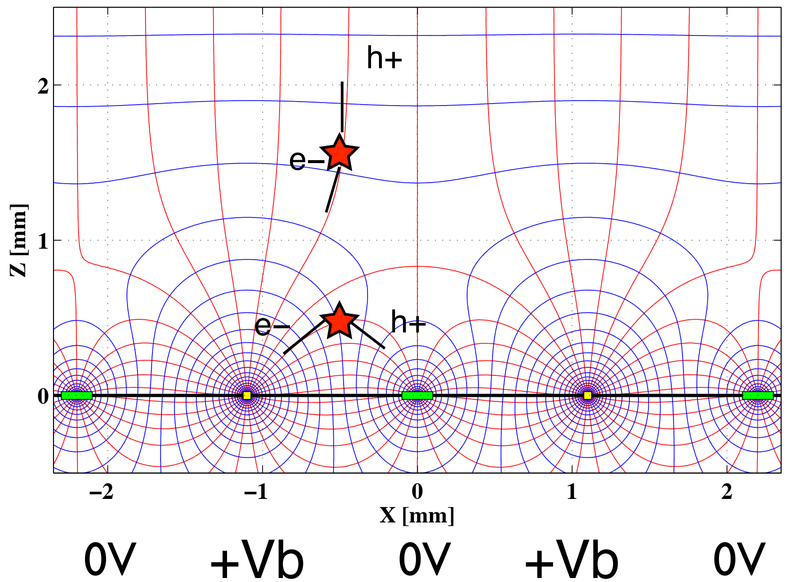
2000s:

- phonon rise time
  - discriminates surface events from bulk events

2010s:

- sophisticated electrode
  - structure discriminates surface events from bulk events (EDELWEISS also)
- double-sided phonon sensor
  - promises phonon asymmetry discrimination
- measure ionization only using
  - phonons with high field: new sensitivity to low mass





Innovation in Techniques: SuperCDMS

SuperCDMS:

1990s:

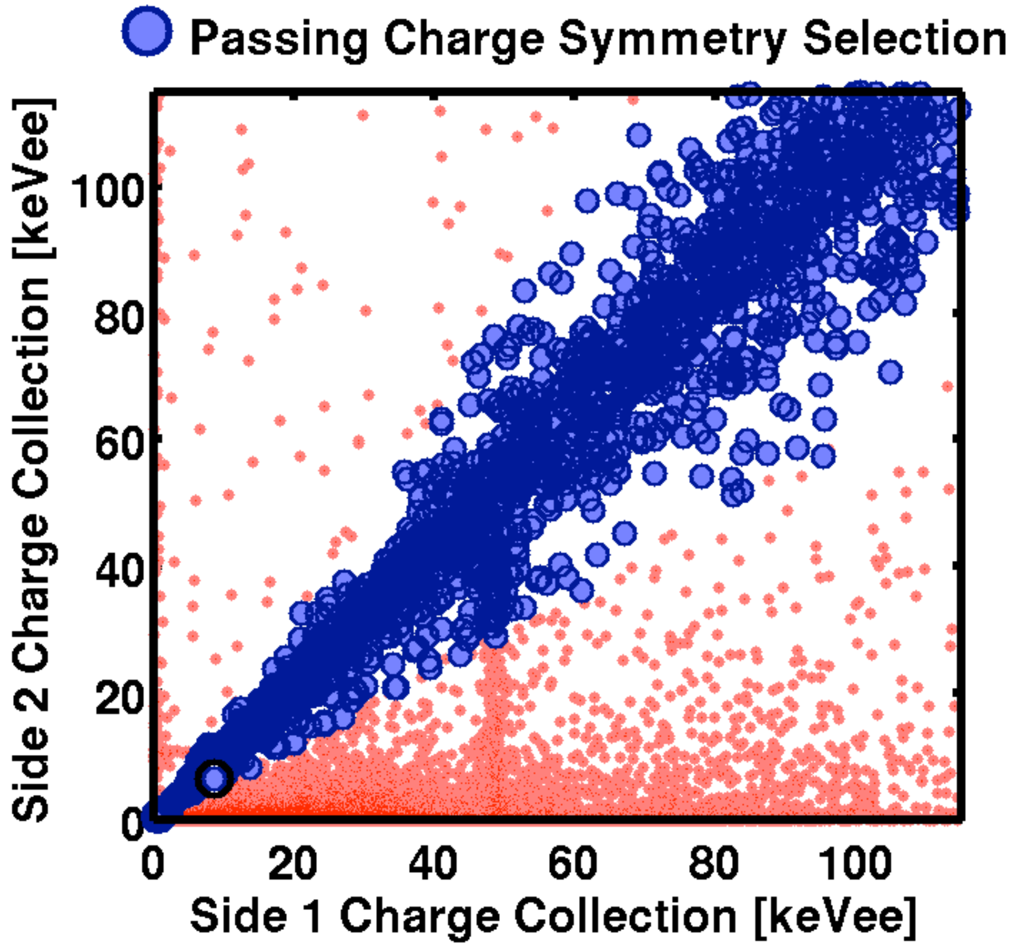
- phonons + ionization
  - discriminate NRs from ERs at low bias (few V)

2000s:

- phonon rise time
  - discriminates surface events from bulk events

2010s:

- sophisticated electrode
  - structure discriminates surface events from bulk events (EDELWEISS also)
- double-sided phonon sensor
  - promises phonon asymmetry discrimination
- measure ionization only using
  - phonons with high field: new sensitivity to low mass



Innovation in Techniques: SuperCDMS

SuperCDMS:

1990s:

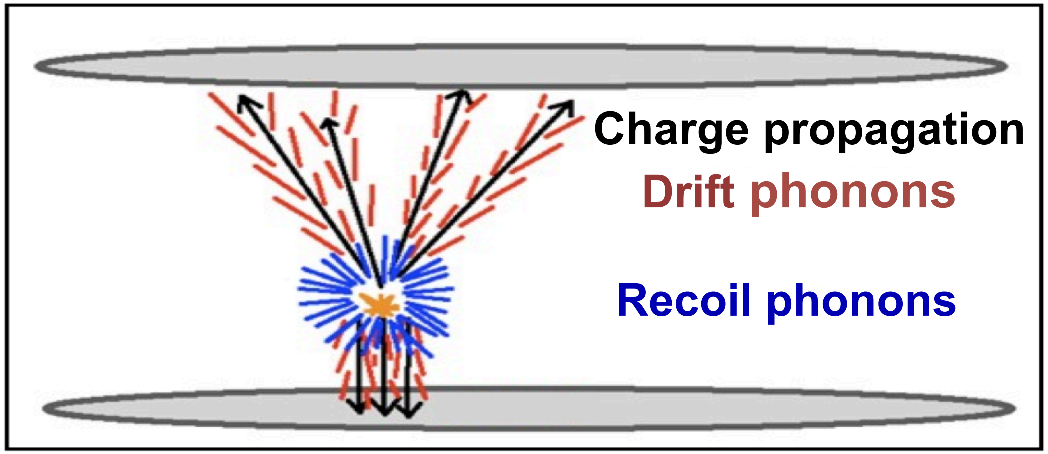
- phonons + ionization
  - discriminate NRs from ERs at low bias (few V)

2000s:

- phonon rise time
  - discriminates surface events from bulk events

2010s:

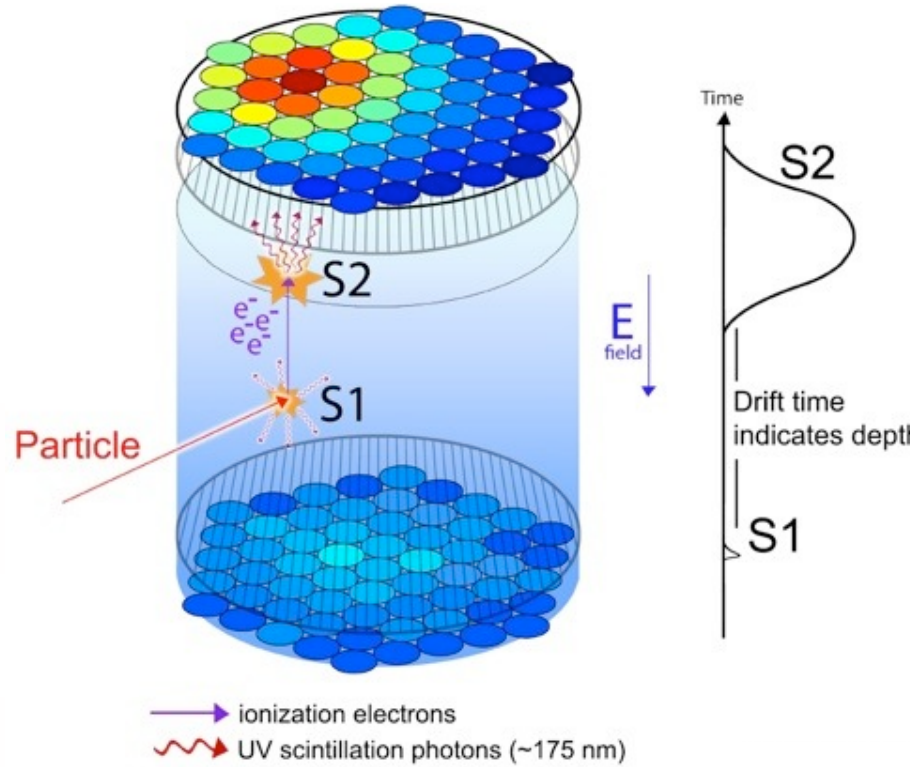
- sophisticated electrode
  - structure discriminates surface events from bulk events (EDELWEISS also)
- double-sided phonon sensor
  - promises phonon asymmetry discrimination
- measure ionization only using
  - phonons with high field: new sensitivity to low mass



Innovation in Techniques: 2-Phase Liquid Nobles

2-Phase Liquid Nobles

- Multiple realizations ~ 2000
  - scintillation/ionization (S1/S2) discriminates NRs from ERs in LXe, LAr
  - scintillation (S1) rise time discriminates NRs from ERs in LAr (and LNe)
  - LXe has no worrisome isotopes and is highly purifiable
    - primarily Kr, Rn, and e-attaching impurities to be worried about
- Around 2005
  - Self-shielding could make up for limited ER rejection (99%-99.9%) of LXe
  - Light collection key to LXe low-mass sensitivity
  - Underground Ar could provide LAr low in 39Ar beta decay



Very successful program thanks to these innovations:

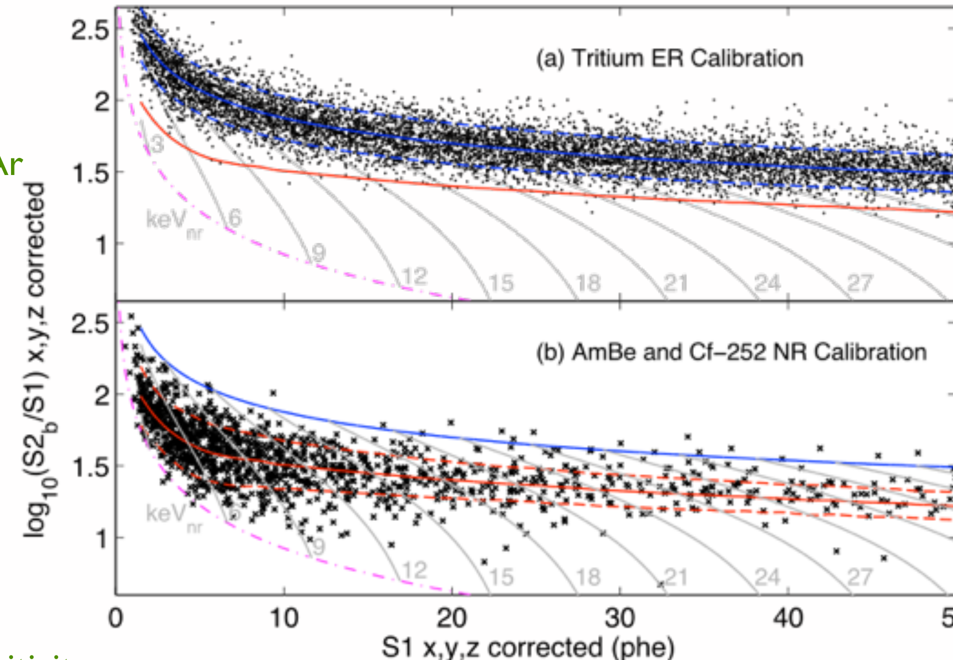
- LXe: XENON100, LUX have best limits at high mass; XENON1T to commission this year
- LAr: DArkSide 50 recently completed first science run
- Multi-ton experiments proposed
- Single-phase (S1 only) LAr close to starting to take data (MiniCLEAN, DEAP-3600)

Innovation in Techniques: 2-Phase Liquid Nobles

2-Phase Liquid Nobles

Multiple realizations ~ 2000

- scintillation/ionization (S1/S2) discriminates NRs from ERs in LXe, LAr
- scintillation (S1) rise time discriminates NRs from ERs in LAr (and LNe)
- LXe has no worrisome isotopes and is highly purifiable
  - primarily Kr, Rn, and e-attaching impurities to be worried about



Around 2005

- Self-shielding could make up for limited ER rejection (99%-99.9%) of LXe
- Light collection key to LXe low-mass sensitivity
- Underground Ar could provide LAr low in 39Ar beta decay

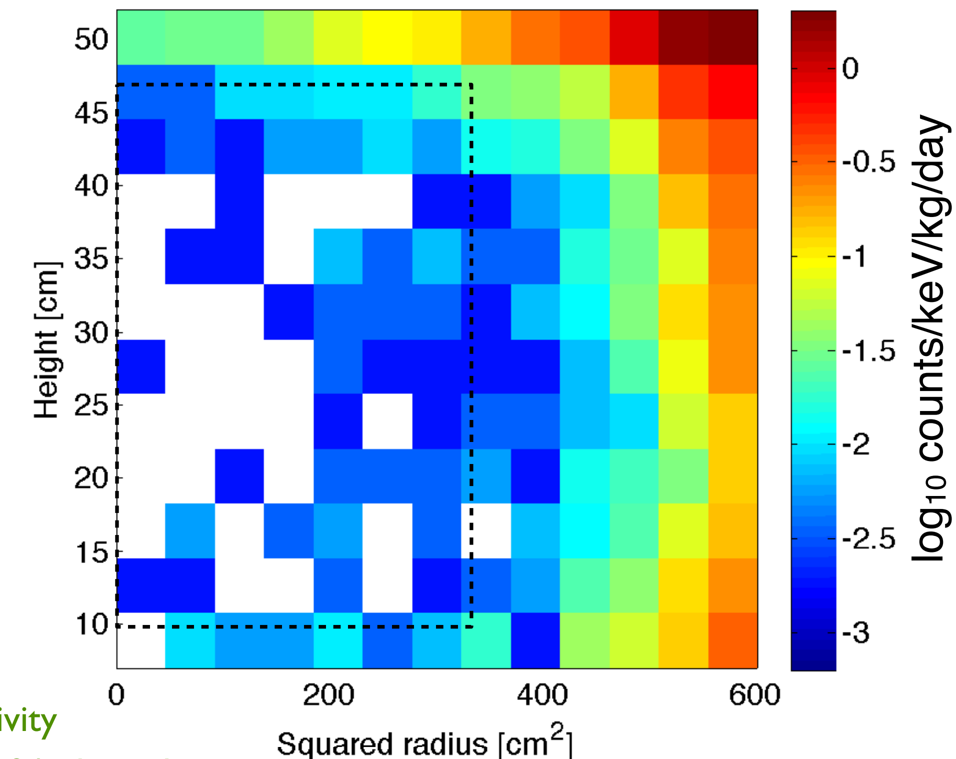
Very successful program thanks to these innovations:

- LXe: XENON100, LUX have best limits at high mass; XENON1T to commission this year
- LAr: DArkSide 50 recently completed first science run
- Multi-ton experiments proposed
- Single-phase (S1 only) LAr close to starting to take data (MiniCLEAN, DEAP-3600)

Innovation in Techniques: 2-Phase Liquid Nobles

2-Phase Liquid Nobles

- Multiple realizations ~ 2000
  - scintillation/ionization (S1/S2) discriminates NRs from ERs in LXe, LAr
  - scintillation (S1) rise time discriminates NRs from ERs in LAr (and LNe)
  - LXe has no worrisome isotopes and is highly purifiable
    - primarily Kr, Rn, and e-attaching impurities to be worried about
- Around 2005
  - Self-shielding could make up for limited ER rejection (99%-99.9%) of LXe
  - Light collection key to LXe low-mass sensitivity
  - Underground Ar could provide LAr low in 39Ar beta decay



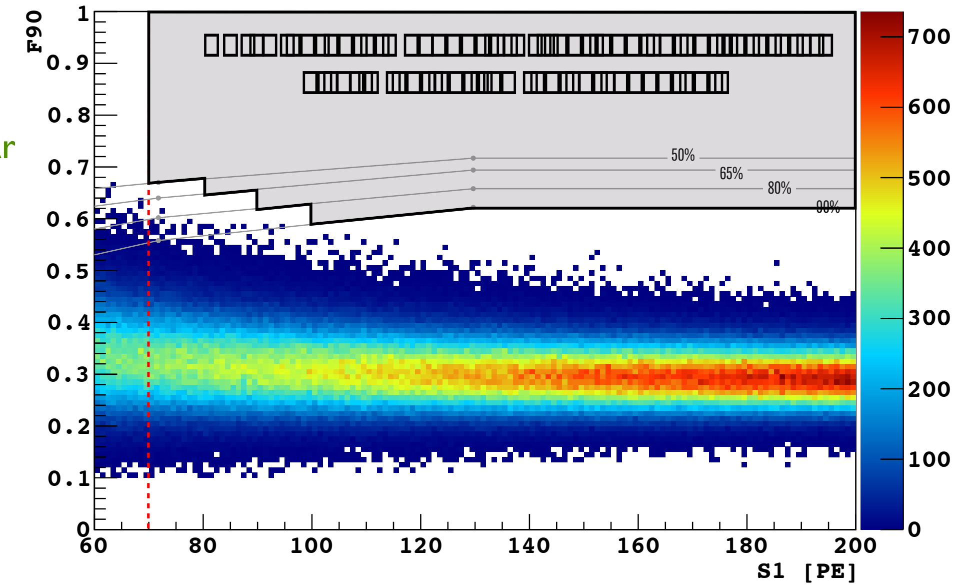
Very successful program thanks to these innovations:

- LXe: XENON100, LUX have best limits at high mass; XENON1T to commission this year
- LAr: DArkSide 50 recently completed first science run
- Multi-ton experiments proposed
- Single-phase (S1 only) LAr close to starting to take data (MiniCLEAN, DEAP-3600)

Innovation in Techniques: 2-Phase Liquid Nobles

2-Phase Liquid Nobles

- Multiple realizations ~ 2000
  - scintillation/ionization (S1/S2) discriminates NRs from ERs in LXe, LAr
  - scintillation (S1) rise time discriminates NRs from ERs in LAr (and LNe)
  - LXe has no worrisome isotopes and is highly purifiable
    - primarily Kr, Rn, and e-attaching impurities to be worried about
- Around 2005
  - Self-shielding could make up for limited ER rejection (99%-99.9%) of LXe
  - Light collection key to LXe low-mass sensitivity
  - Underground Ar could provide LAr low in 39Ar beta decay

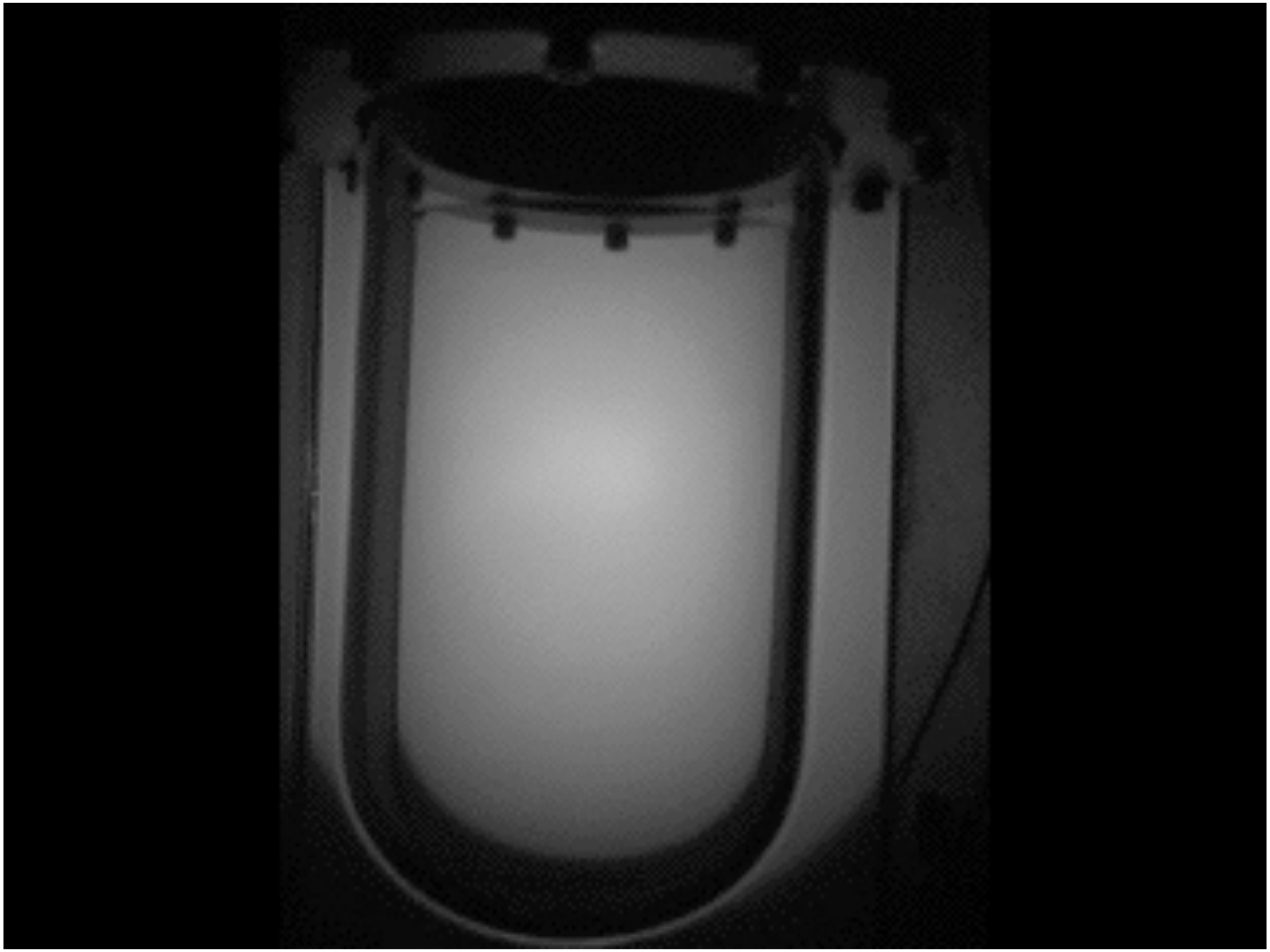


Very successful program thanks to these innovations:

- LXe: XENON100, LUX have best limits at high mass; XENON1T to commission this year
- LAr: DArkSide 50 recently completed first science run
- Multi-ton experiments proposed
- Single-phase (S1 only) LAr close to starting to take data (MiniCLEAN, DEAP-3600)

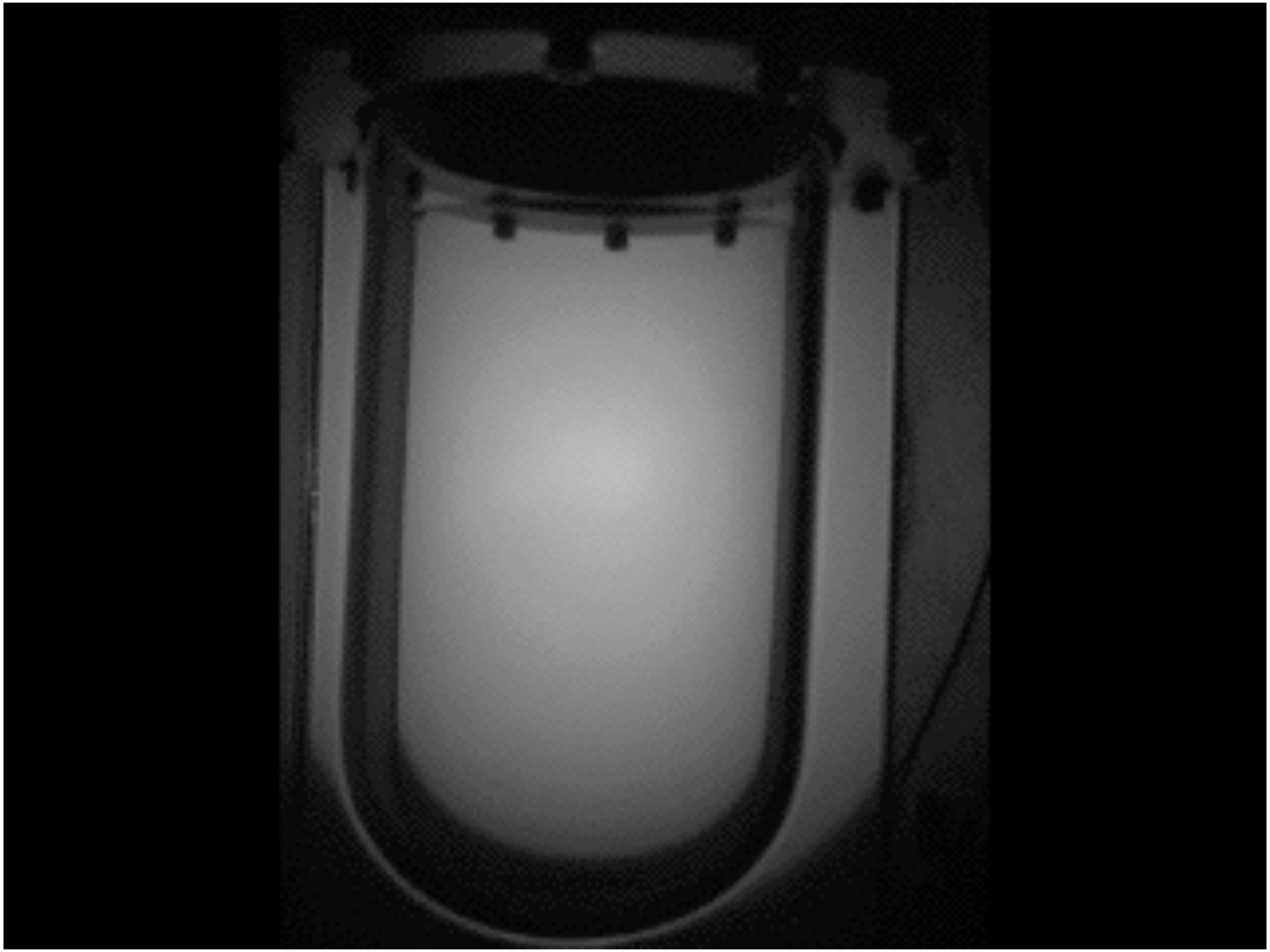
Innovation in Techniques: Bubble Chambers

In action: triple neutron scatter



Innovation in Techniques: Bubble Chambers

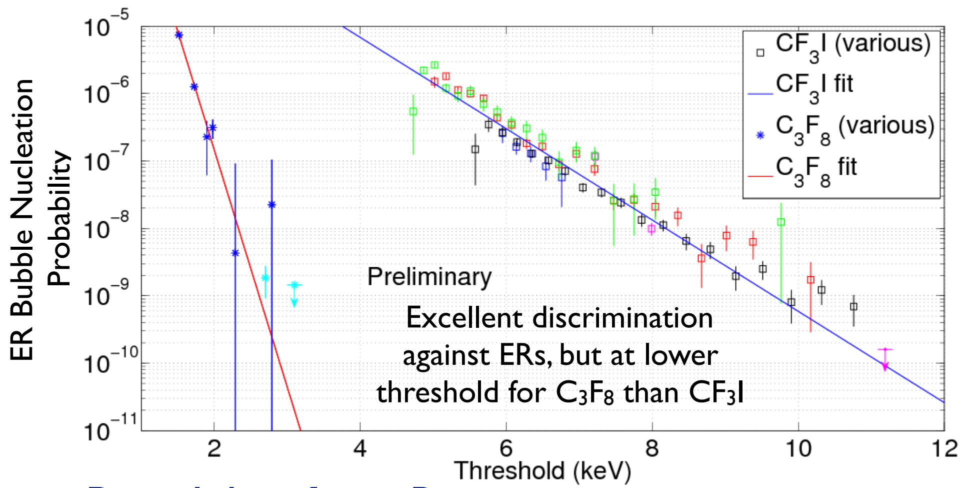
In action: triple neutron scatter



Innovation in Techniques: Bubble Chambers

Bubble Chambers

Classic Seitz bubble theory gave incredible discrimination against ERs



But: alphas from Rn contamination

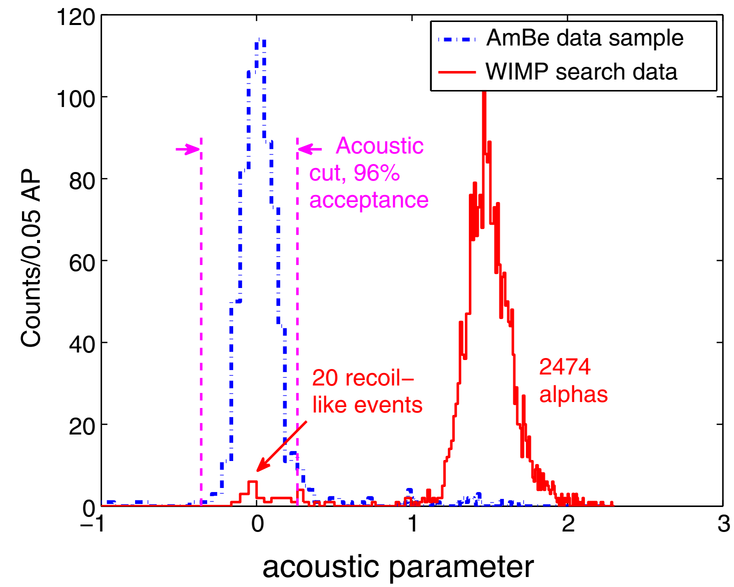
→ acoustic measurements discriminate alphas

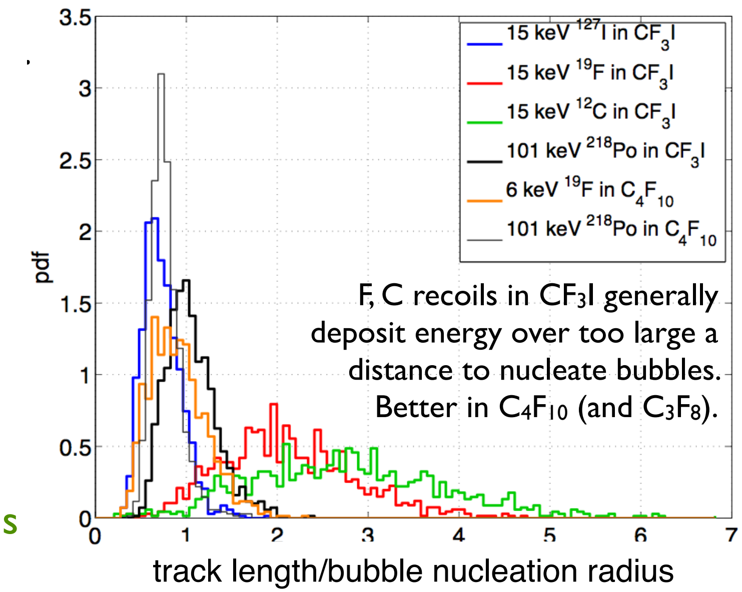
Higher threshold, poorer F (and C) recoil efficiency than desired in CF3I

→ develop C_3F_8

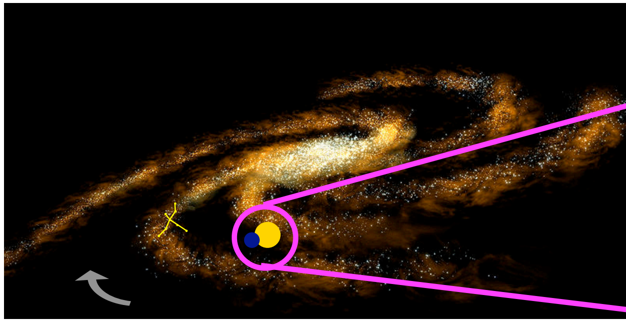
No energy information

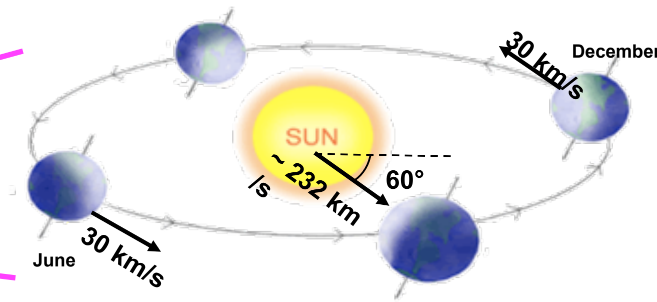
Develop bubble chambers with scintillating materials

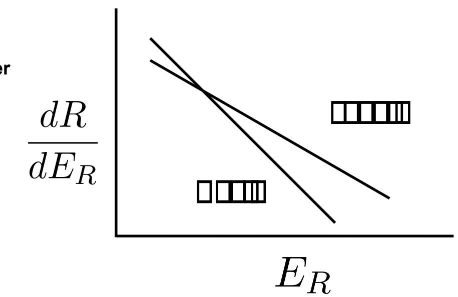


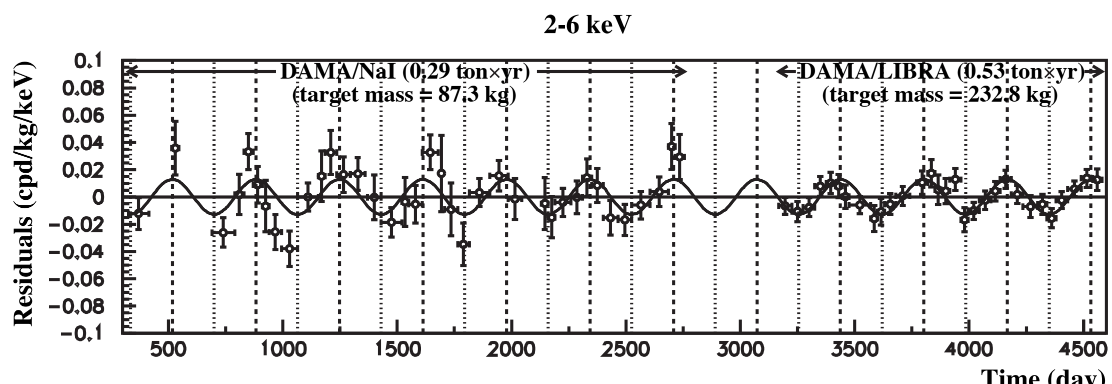


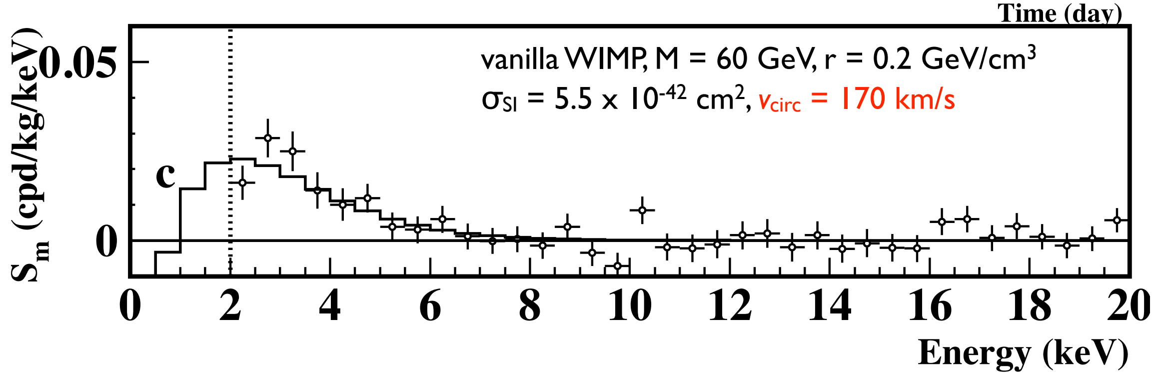
Annual Modulation







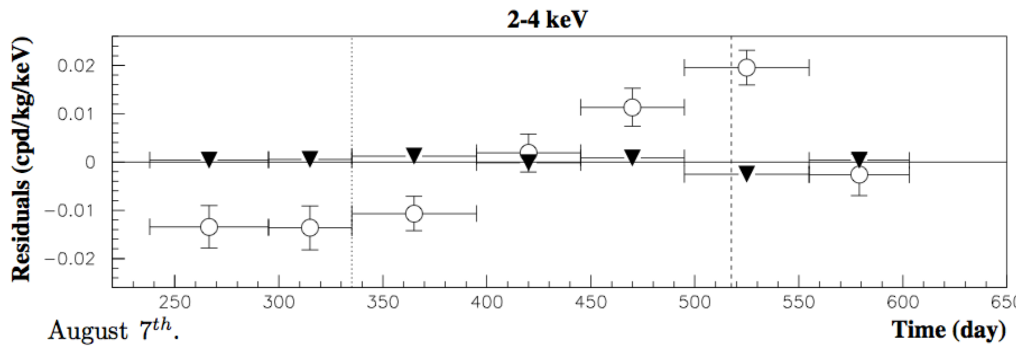




Innovation in Techniques: Addressing DAMA

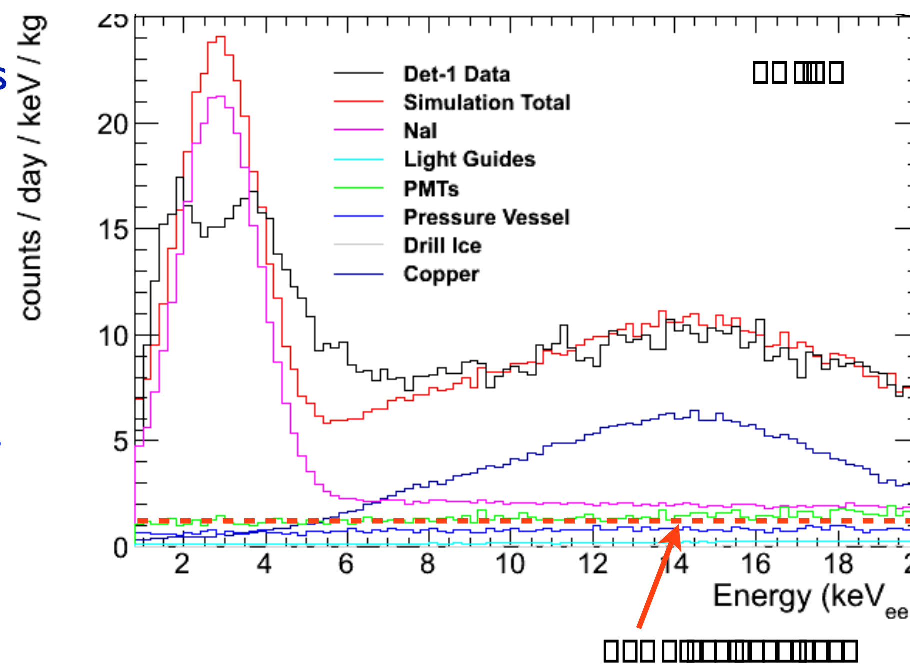
DAMA annual modulation a sore point for community

- Huge statistical significance
- No other existing expt uses Na and I



New efforts to test underway!

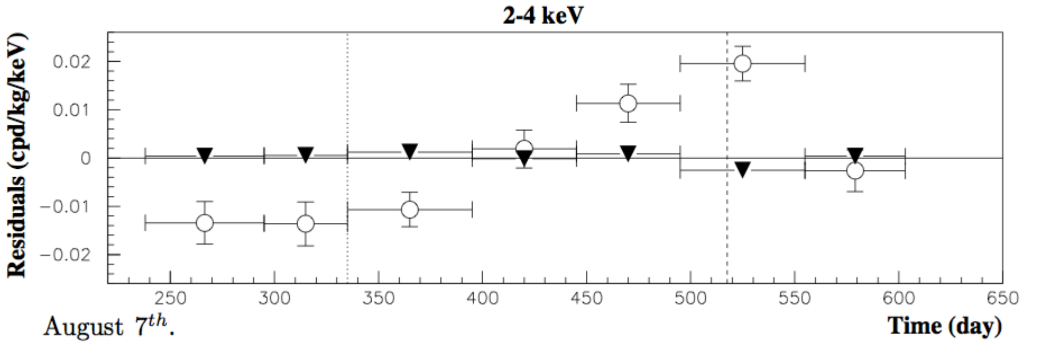
- DM-ICE: NaI with different systematics
  - southern hemisphere, situated inside IceCube
  - also a movable copy: run in N and S
  - operation in ice demo'd, ice v. clean
  - working on reducing contaminations
- SABRE: NaI with reduced backgrounds
  - Better source powder for NaI
  - Lower radioactivity photomultipliers
  - Better light collection
  - Lower radioactivity housings
  - Surrounded in liquid scintillator to reject backgrounds (esp. 3 keV 40K escape peak)



Innovation in Techniques: Addressing DAMA

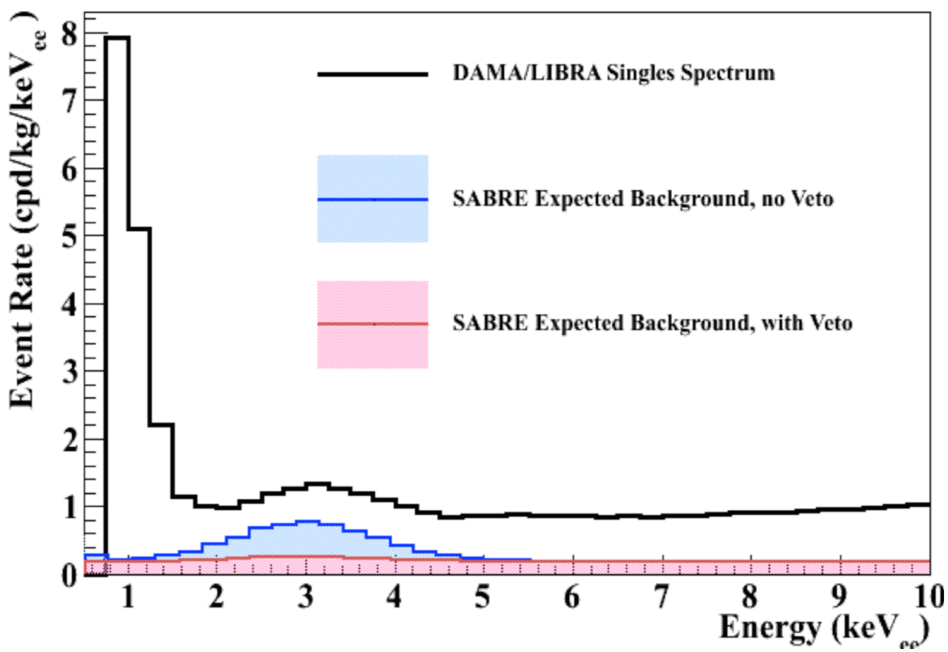
DAMA annual modulation a sore point for community

- Huge statistical significance
- No other existing expt uses Na and I



New efforts to test underway!

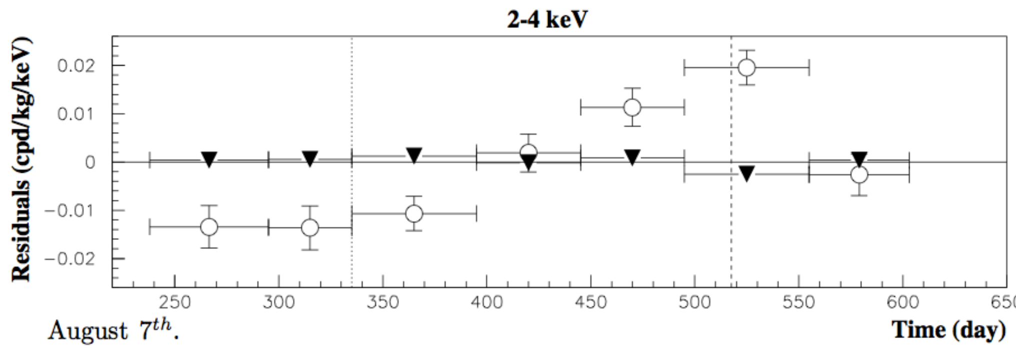
- DM-ICE: NaI with different systematics
  - southern hemisphere, situated inside IceCube
  - also a movable copy: run in N and S
  - operation in ice demo'd, ice v. clean
  - working on reducing contaminations



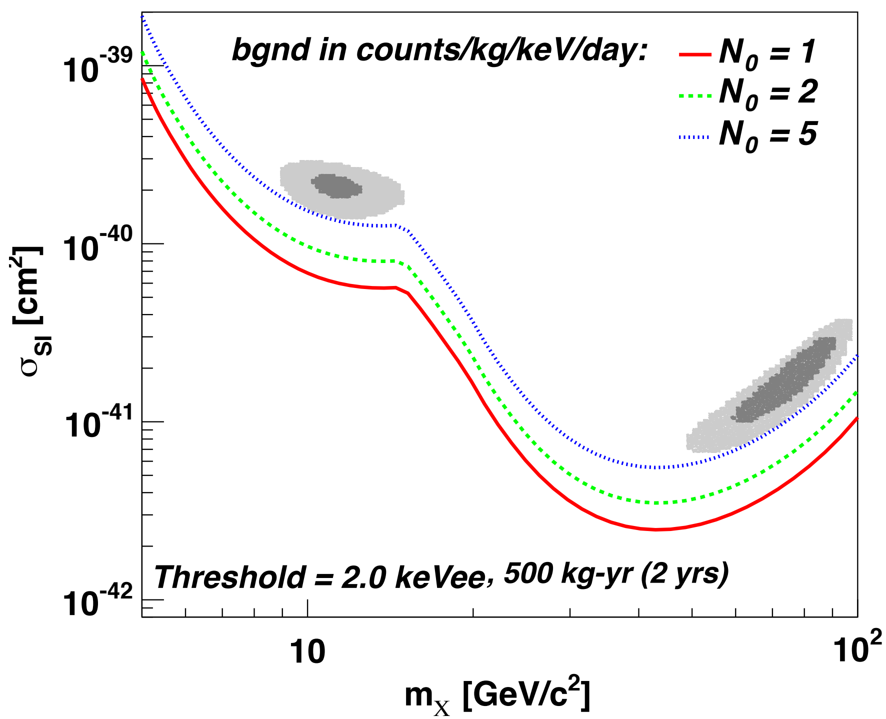
- SABRE: NaI with reduced backgrounds
  - Better source powder for NaI
  - Lower radioactivity photomultipliers
  - Better light collection
  - Lower radioactivity housings
  - Surrounded in liquid scintillator to reject backgrounds (esp. 3 keV 40K escape peak)

Innovation in Techniques: Addressing DAMA

DAMA annual modulation a sore point for community
- Huge statistical significance
- No other existing expt uses Na and I

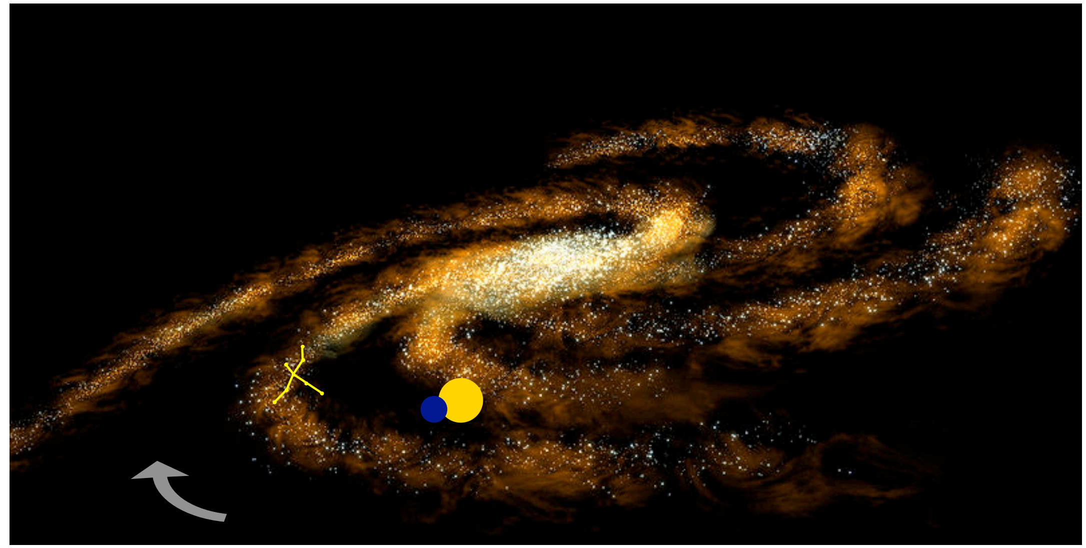


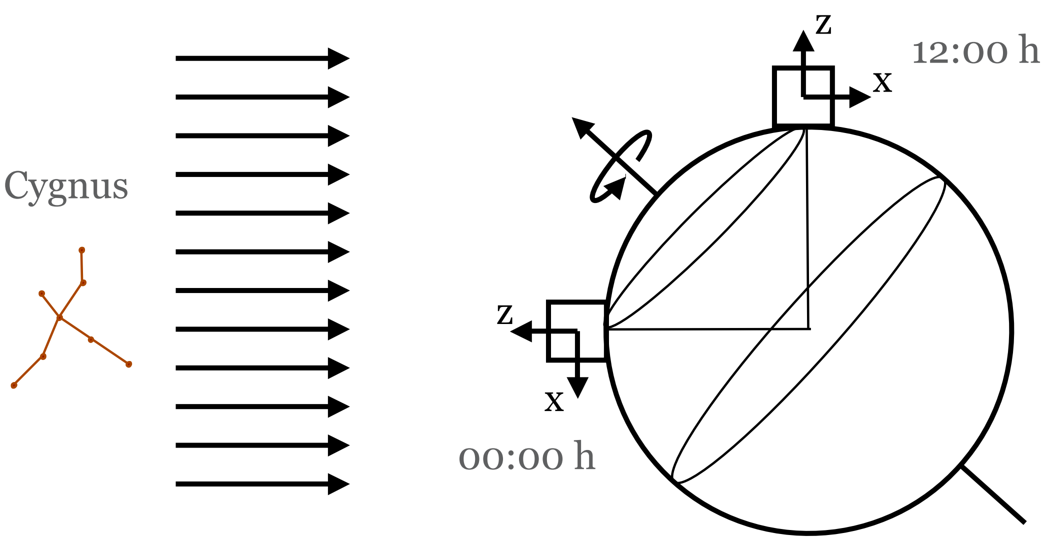
New efforts to test underway!
- DM-ICE: NaI with different systematics
  - southern hemisphere, situated inside IceCube
  - also a movable copy: run in N and S
  - operation in ice demo'd, ice v. clean
  - working on reducing contaminations
- SABRE: NaI with reduced backgrounds
  - Better source powder for NaI
  - Lower radioactivity photomultipliers
  - Better light collection
  - Lower radioactivity housings
  - Surrounded in liquid scintillator to reject backgrounds (esp. 3 keV 40K escape peak)

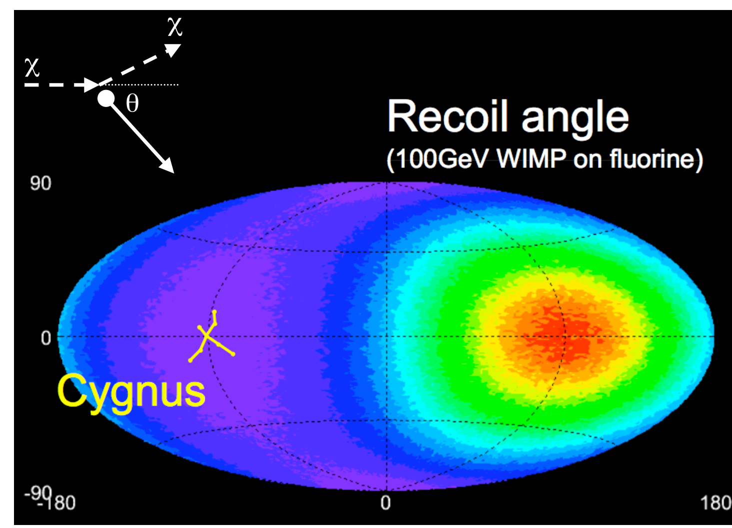


Diurnal Modulation

- WIMPs directional in terrestrial frame
- Direction of WIMP wind varies diurnally due to Earth's rotation
- Recoiling nucleus will preserve some directionality
- Large modulation (~ DC signal) possible in theory
- Backgrounds will be unmodulated







Figures courtesy of J. Battat

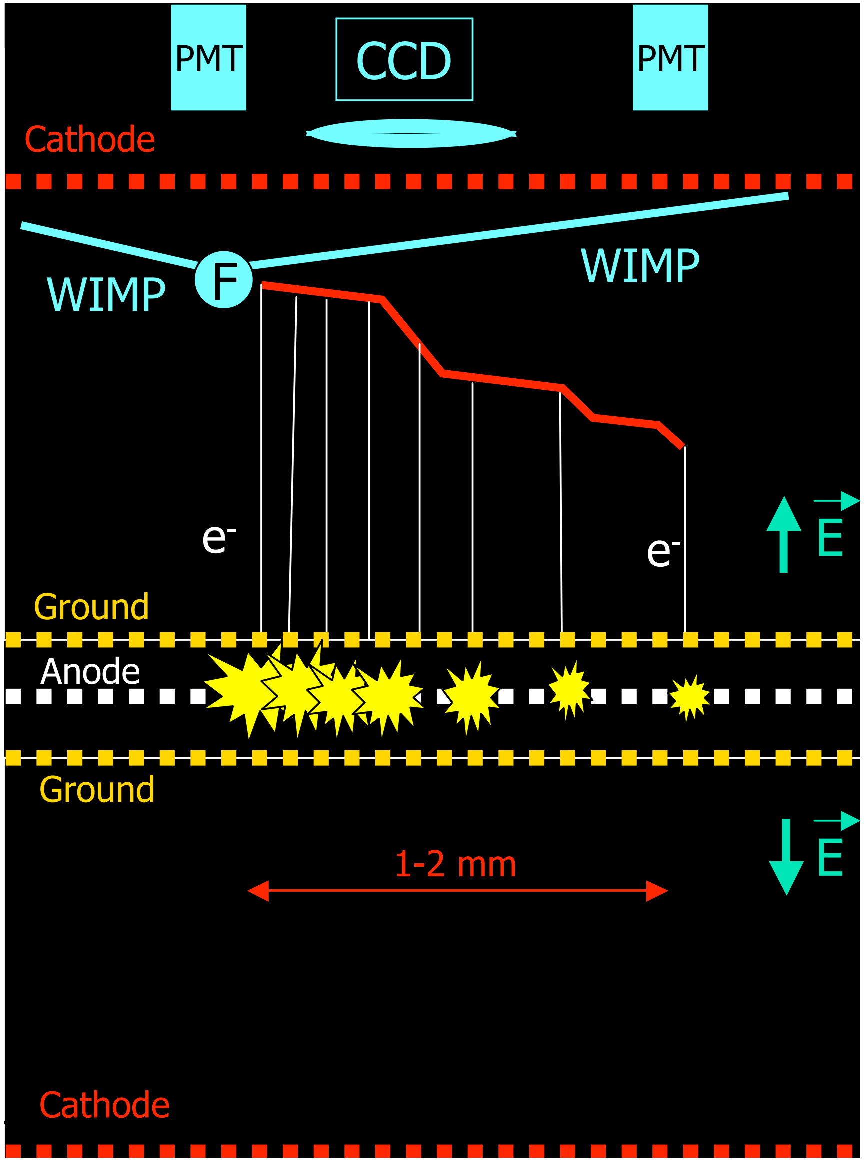
Time Projection Chambers

Goal: reconstruct the direction of the recoiling particle to obtain information about direction of incoming WIMP and thereby make use of diurnal modulation

Time Projection Chamber method:

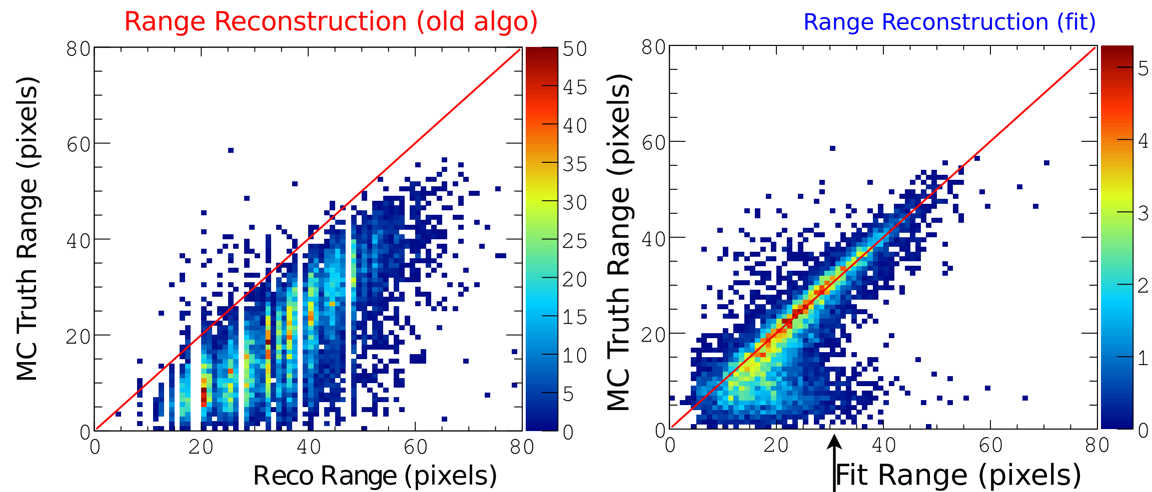
- recoiling particle creates ionization track in gas
- apply E field to drift track to amplification region
- take picture of scintillation light created as track creates avalanche
- reconstruct x, y, z image of track
- energy and dE/dx from scintillation light intensity

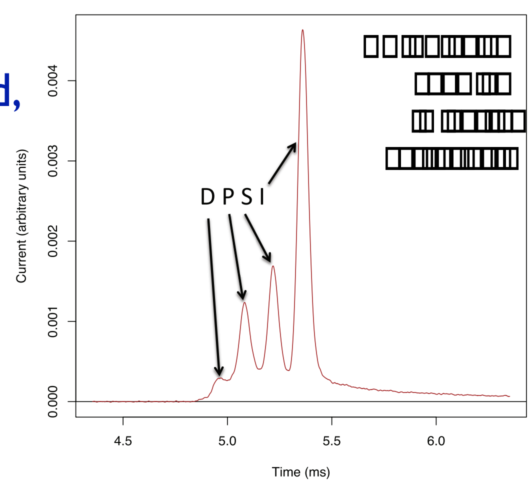
Very promising, but difficult to get lots of target mass (~100s of grams per m3 chamber)

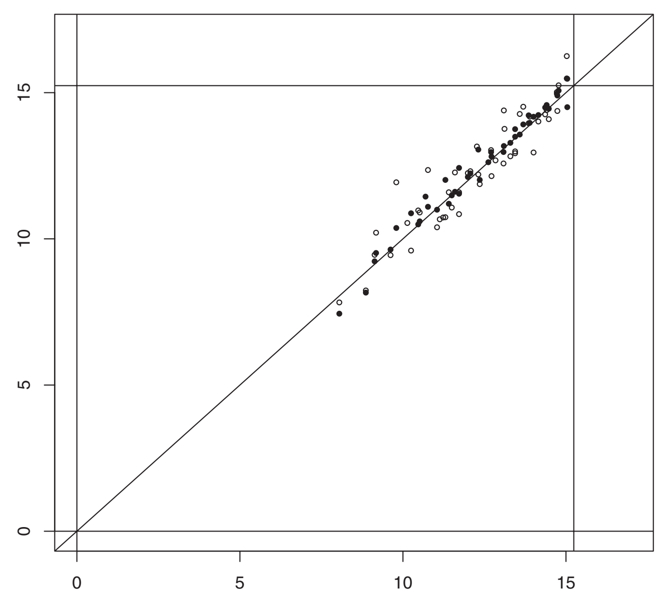


Innovation in Techniques: Directional Detection

- Demonstrators continue to make good progress
- DMTPC:
  - Improved range reconstruction provides better head-tail sensitivity, critical for directional signal
  - Scaling up to 1 m3, running 1L prototype at WIPP
- DRIFT
  - "Minority carriers" have different speed, provides t0 and rejection of surface backgrounds
  - Deploying DRIFT IIe toward DRIFT III





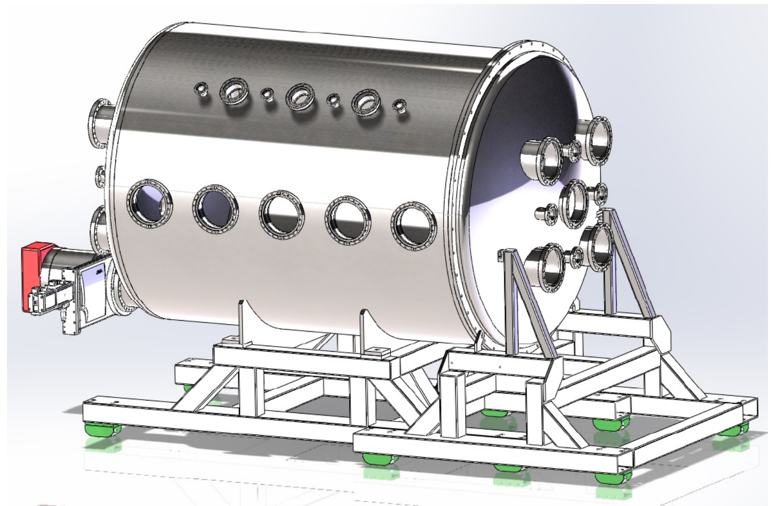


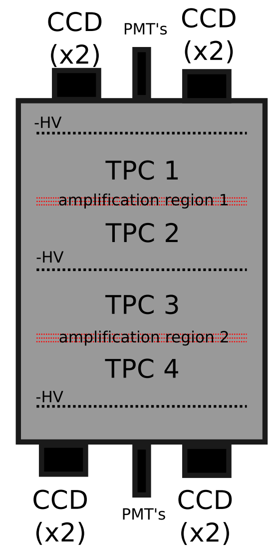
Innovation in Techniques: Directional Detection

Demonstrators continue to make good progress

DMTPC:

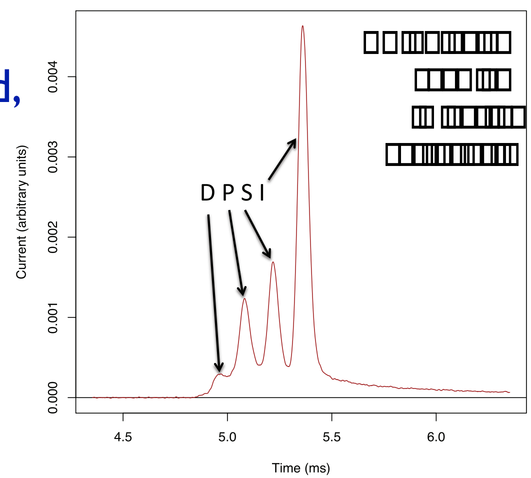
- Improved range reconstruction provides better head-tail sensitivity, critical for directional signal
- Scaling up to 1 m3, running 1L prototype at WIPP

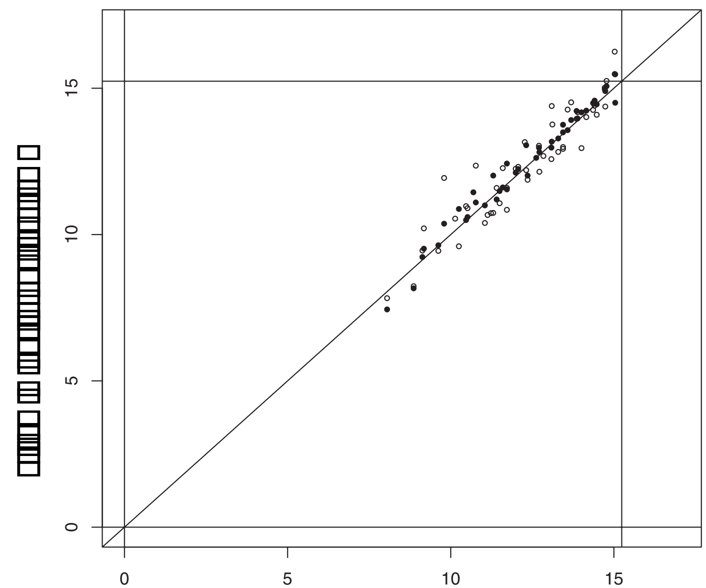




DRIFT

- "Minority carriers" have different speed, provides t0 and rejection of surface backgrounds
- Deploying DRIFT IIe toward DRIFT III



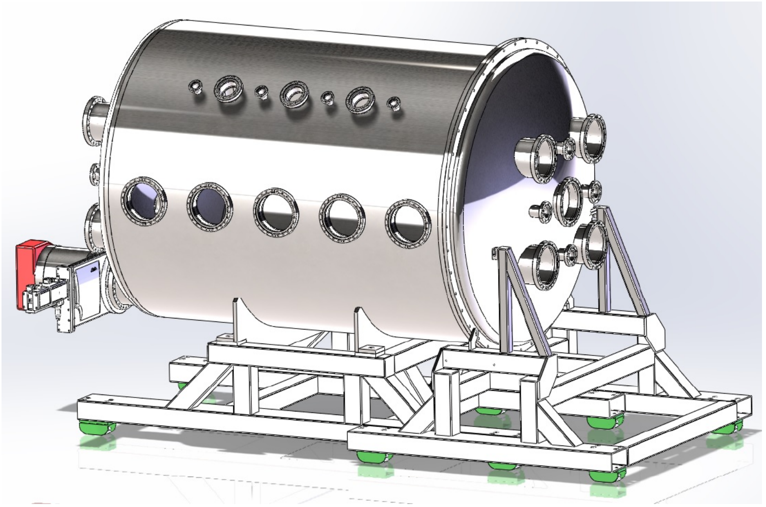


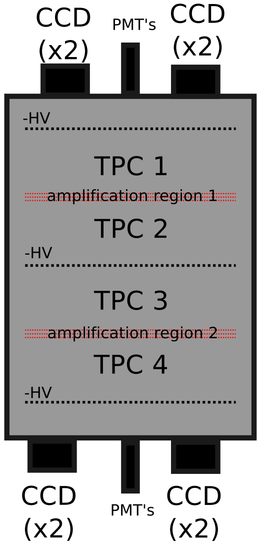
Innovation in Techniques: Directional Detection

Demonstrators continue to make good progress

DMTPC:

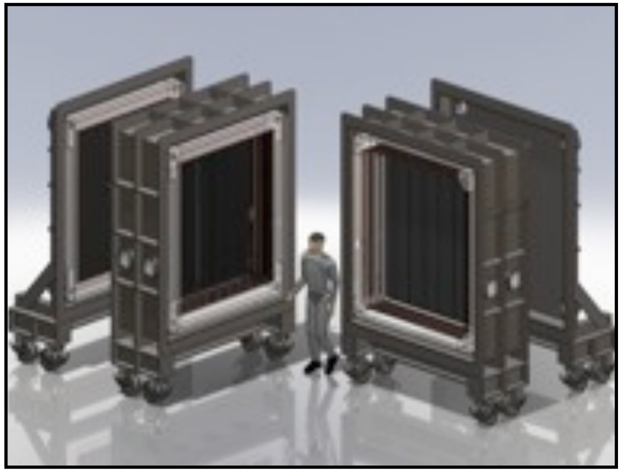
- Improved range reconstruction provides better head-tail sensitivity, critical for directional signal
- Scaling up to 1 m3, running 1L prototype at WIPP

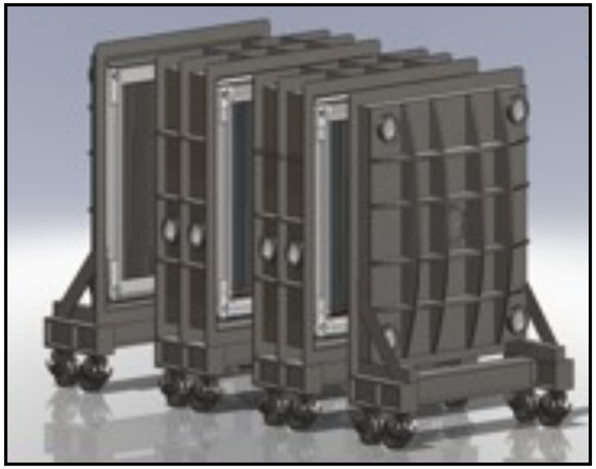




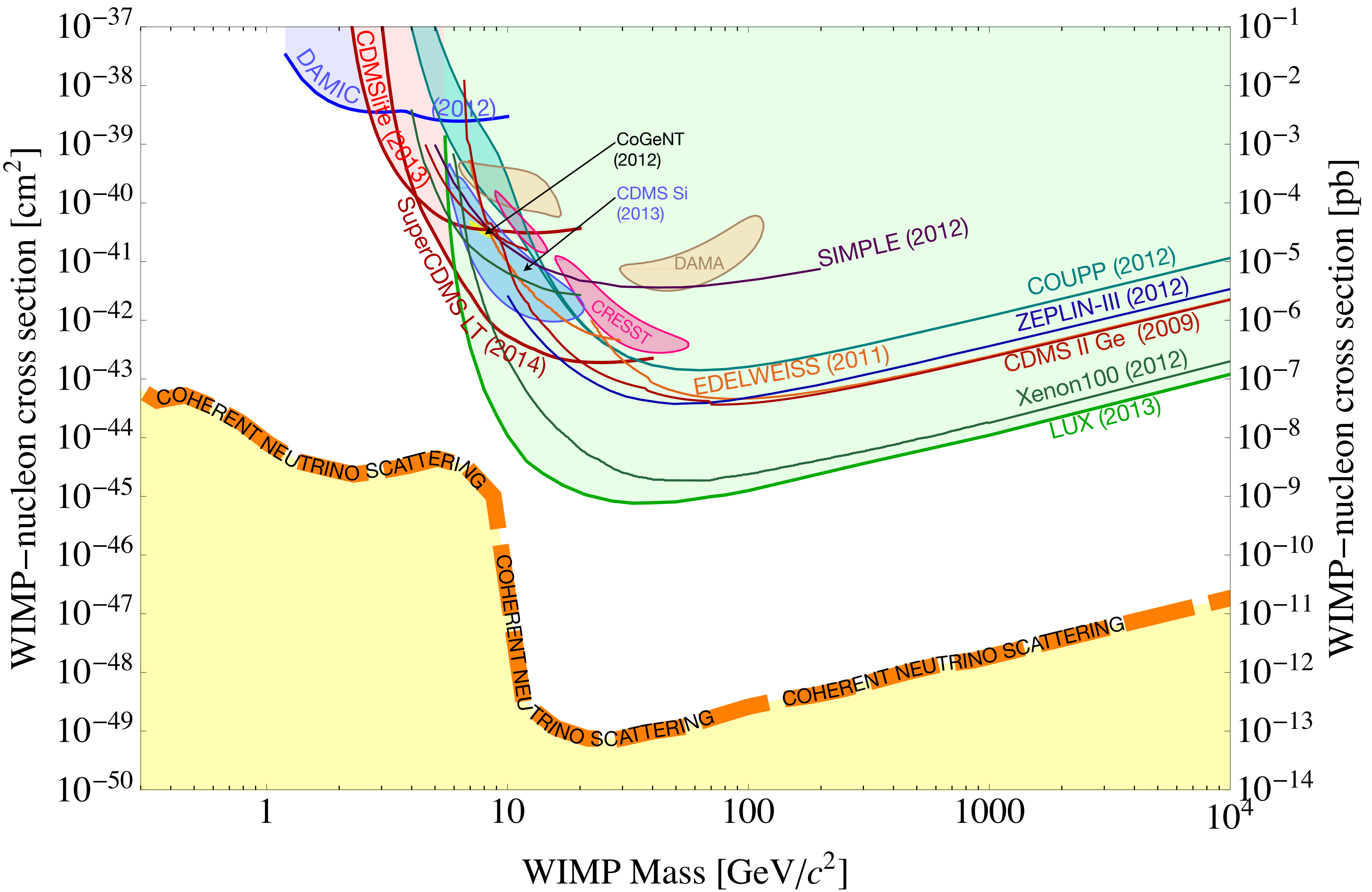
DRIFT

- "Minority carriers" have different speed, provides t0 and rejection of surface backgrounds
- Deploying DRIFT IIe toward DRIFT III

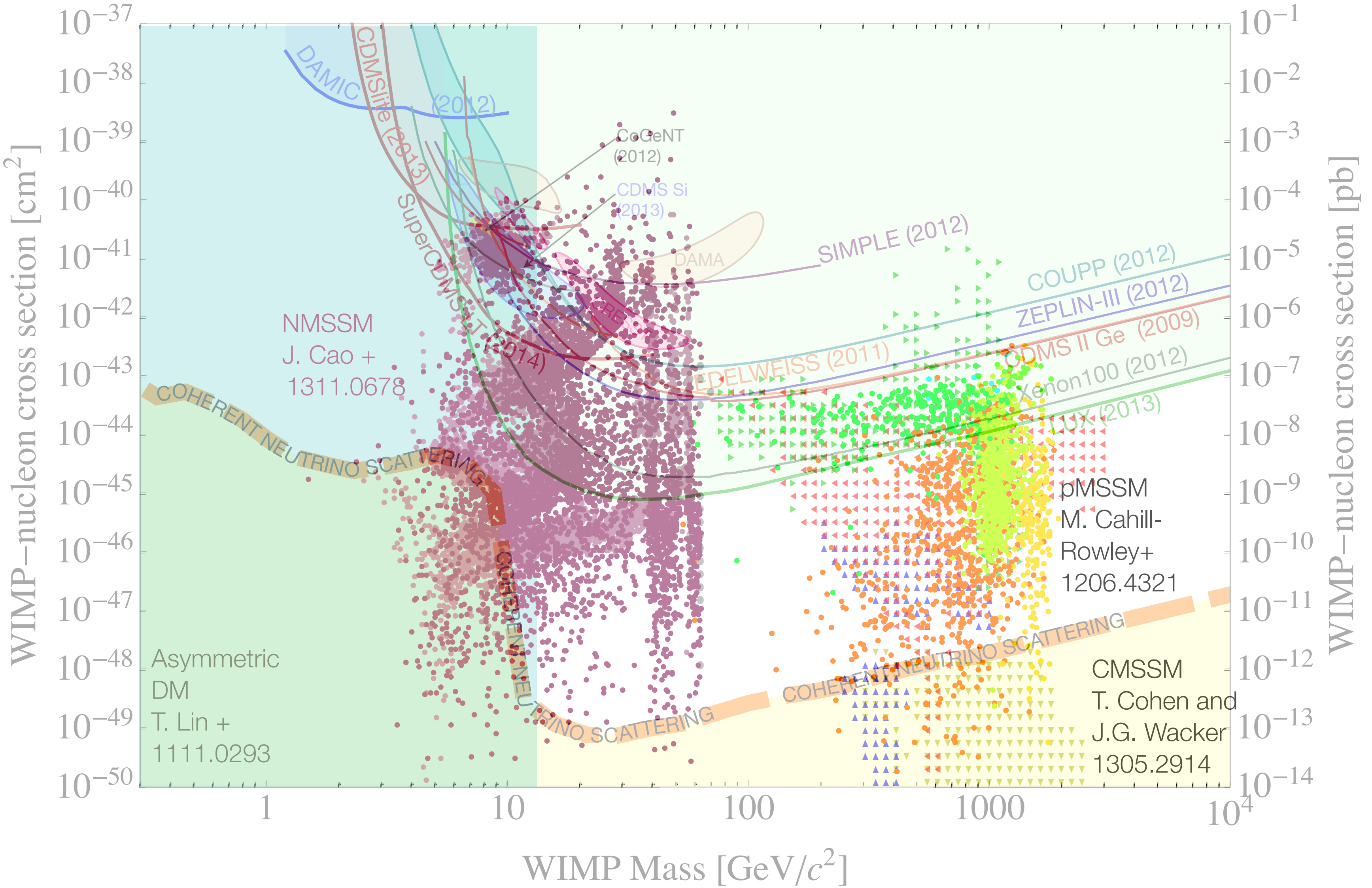




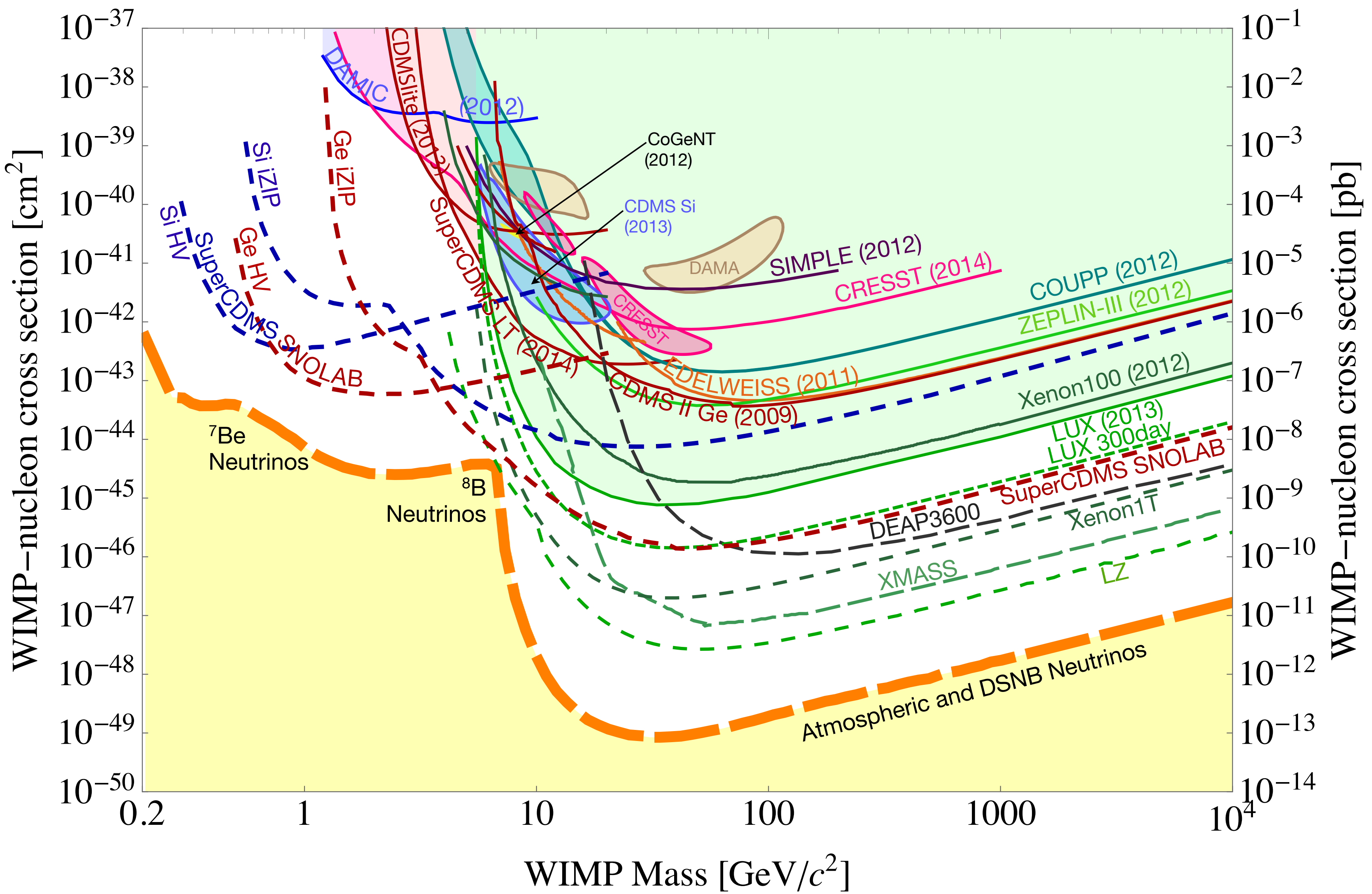
Current State of the Field



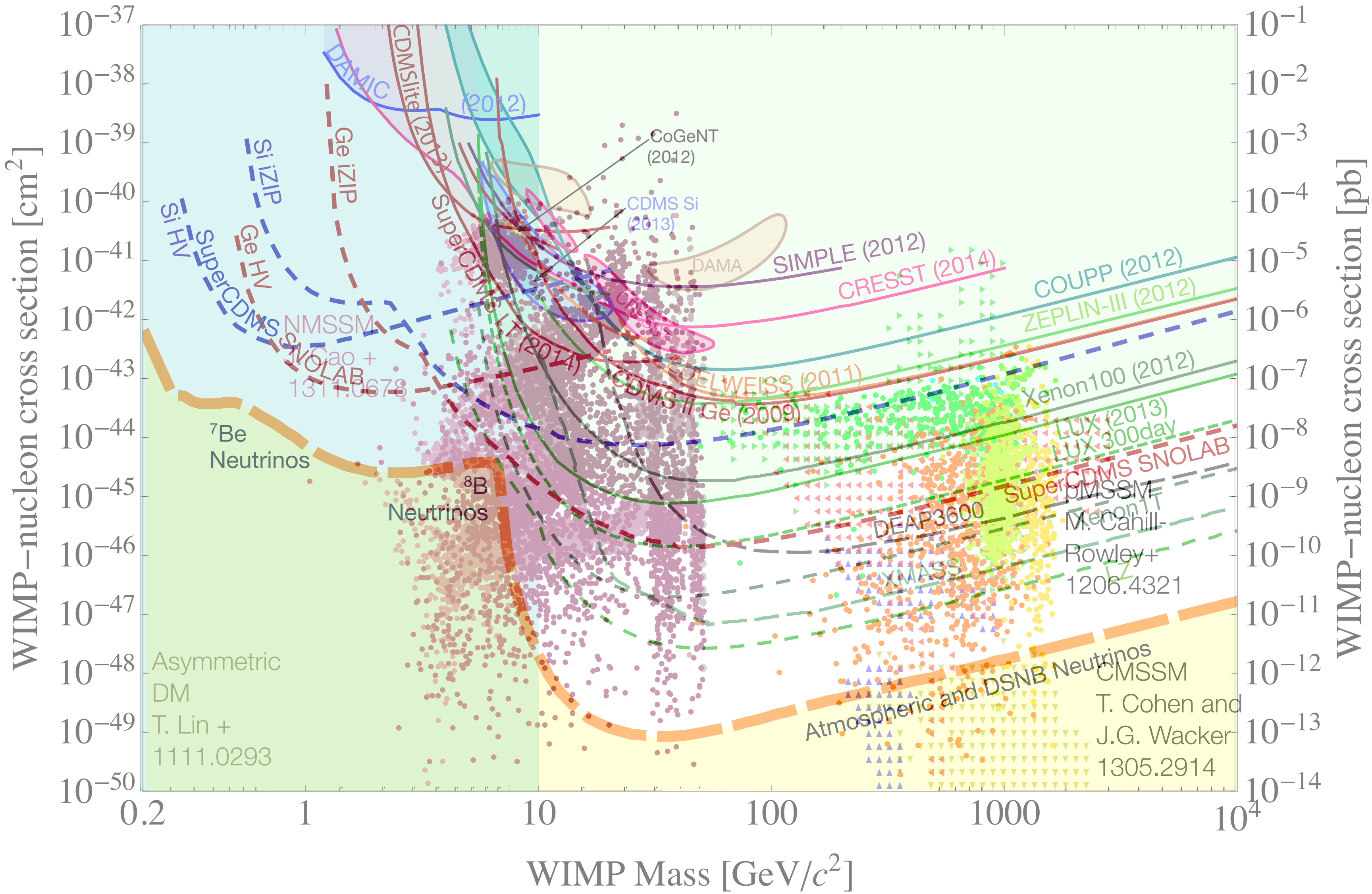
Current State of the Field



Future of the Field



Current State of the Field



A View to the Future

We would like to see:

- Accelerator production via multiple consistent channels
- Indirect detection in multiple channels with consistent parameters
- Direct detection in multiple targets
- Eventually, direct detection with recoiling particle directionality

These will tell us:

- The couplings of dark matter to a variety of normal matter particles
- The local density and velocity structure of the dark matter halo
- The dark matter abundance globally in the halo of our galaxy and in nearby galaxies
- Is what we detect enough?

A lot of work to do!