Experimental Searches for Dark Matter

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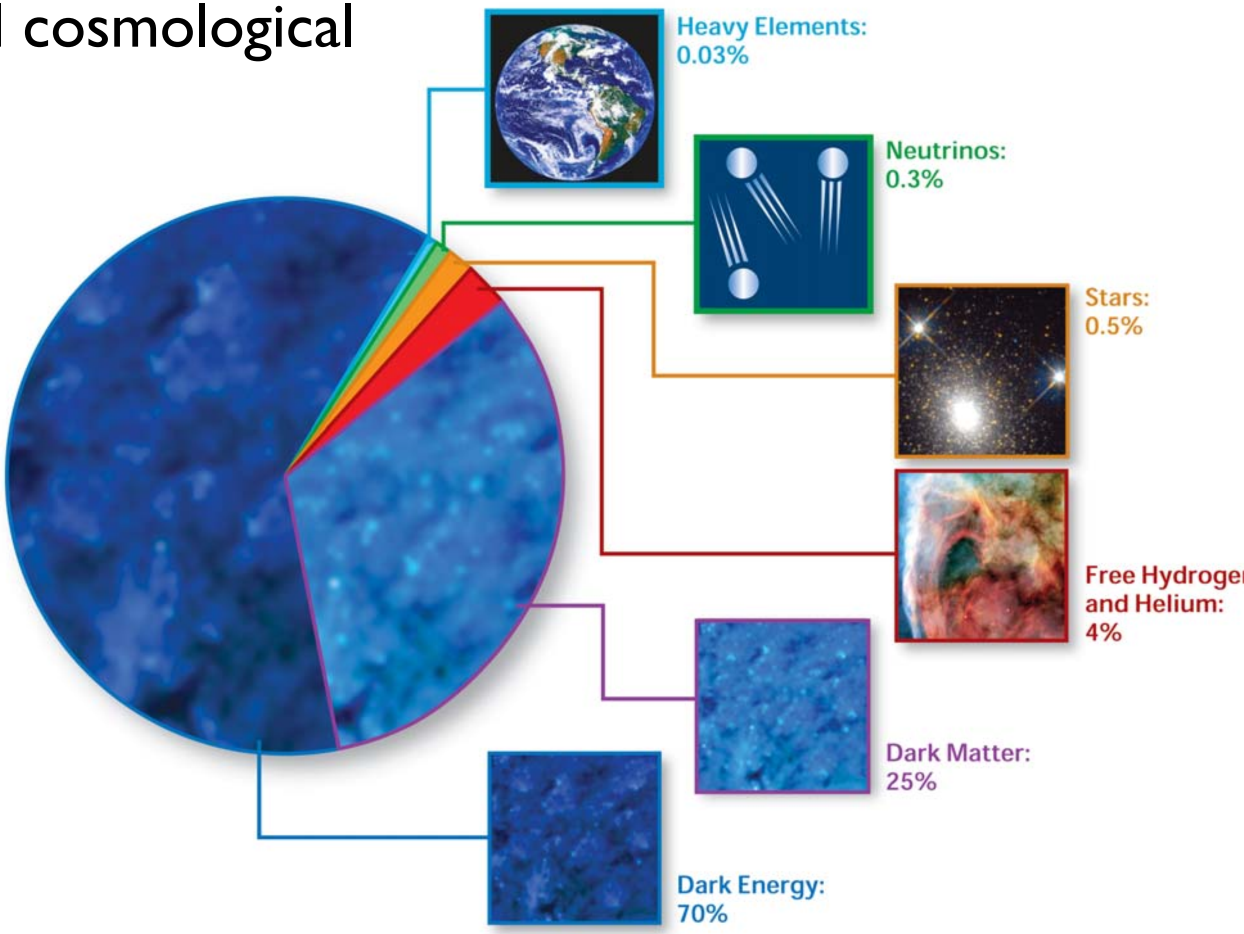
Overview

- Why Dark Matter?
- The Particle Dark Matter Zoo
- Specific candidates and search techniques, with editorial selection
  - Sterile Neutrinos
  - Axions
  - WIMPs

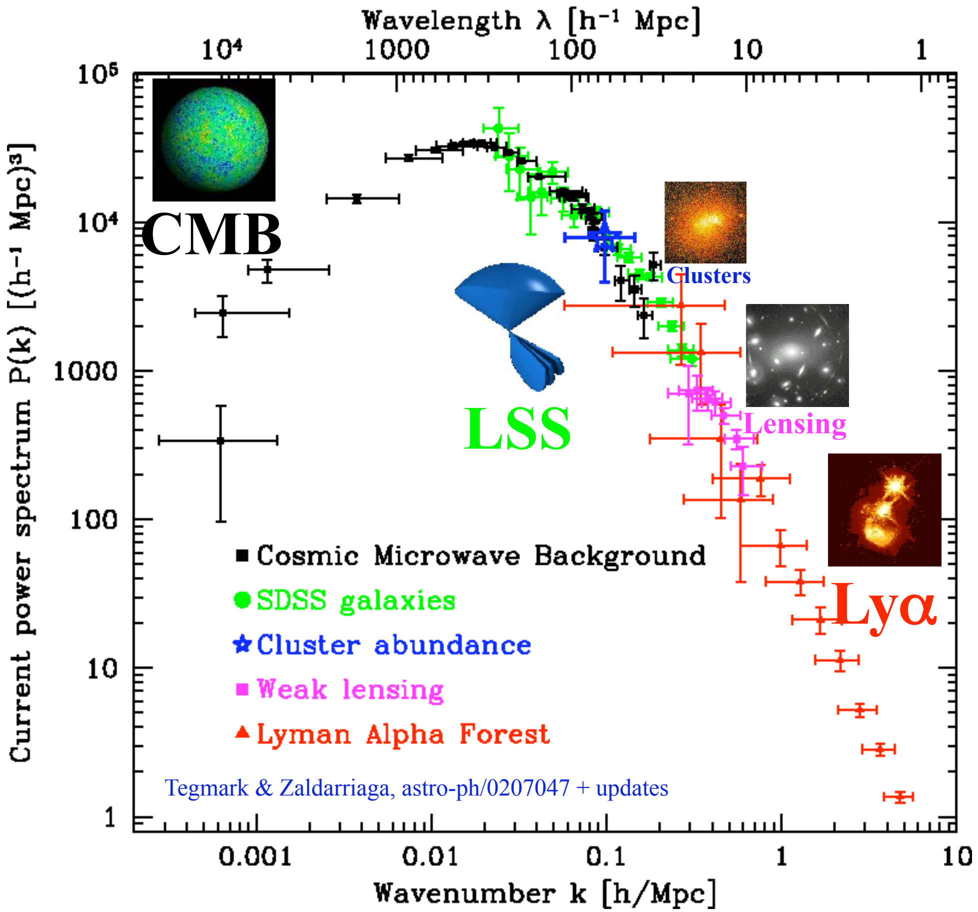
Why Dark Matter?

- A host of astronomical and cosmological observations indicate:
  - Total energy density = critical density ρ_{crit} needed for spatially flat universe (within errors)
  - The bulk is in the form of *dark energy*, a fluid that has negative pressure (causes the universe's expansion to accelerate) and does not clump gravitationally, $\Omega_{DE} = \rho_{DE}/\rho_{crit} = 0.73 \pm 0.03$
  - Most of the matter is in the form of *dark matter*, matter that interacts gravitationally but not electromagnetically, $\Omega_{DM} = \rho_{DM}/\rho_{crit} = 0.20 \pm 0.03$
  - The remainder is in the form of baryons, $\Omega_B = \rho_B/\rho_{crit} = 0.042 \pm 0.004$ (though much of this has not yet been directly observed!)



Required Dark Matter Characteristics

- Dark matter must be:
  - Cold/warm (not hot):
    - nonrelativistic at matter-radiation equality ($z \sim 3500$) to seed LSS. M < keV (e.g., ν) too hot.
  - Nonbaryonic
    - Light element abundances + Big Bang Nucleosynthesis measure baryon density: too low.
    - Baryonic matter could not collapse until recombination ($z \sim 1100$): too late to seed LSS

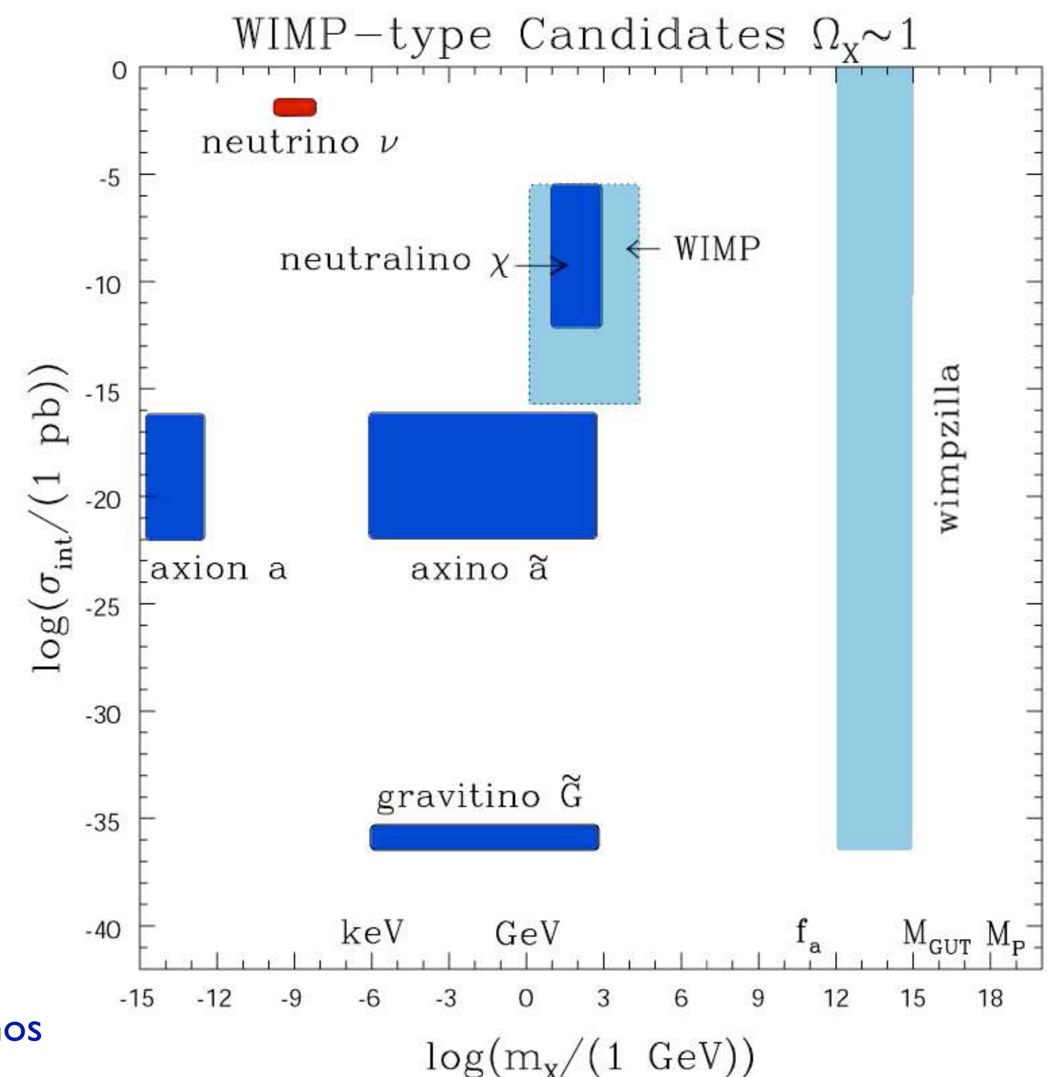


- Locally, we know
  - density ~ 0.1-0.7 GeV/cm^3: ~1 proton/3 cm^3, ~1 WIMP/coffee cup
  - velocity: simplest assumption is Maxwell-Boltzmann distribution with $\sigma_v \approx 270$ km/s (recently increased based on VLBA maser measurements!)

The Particle Dark Matter Zoo

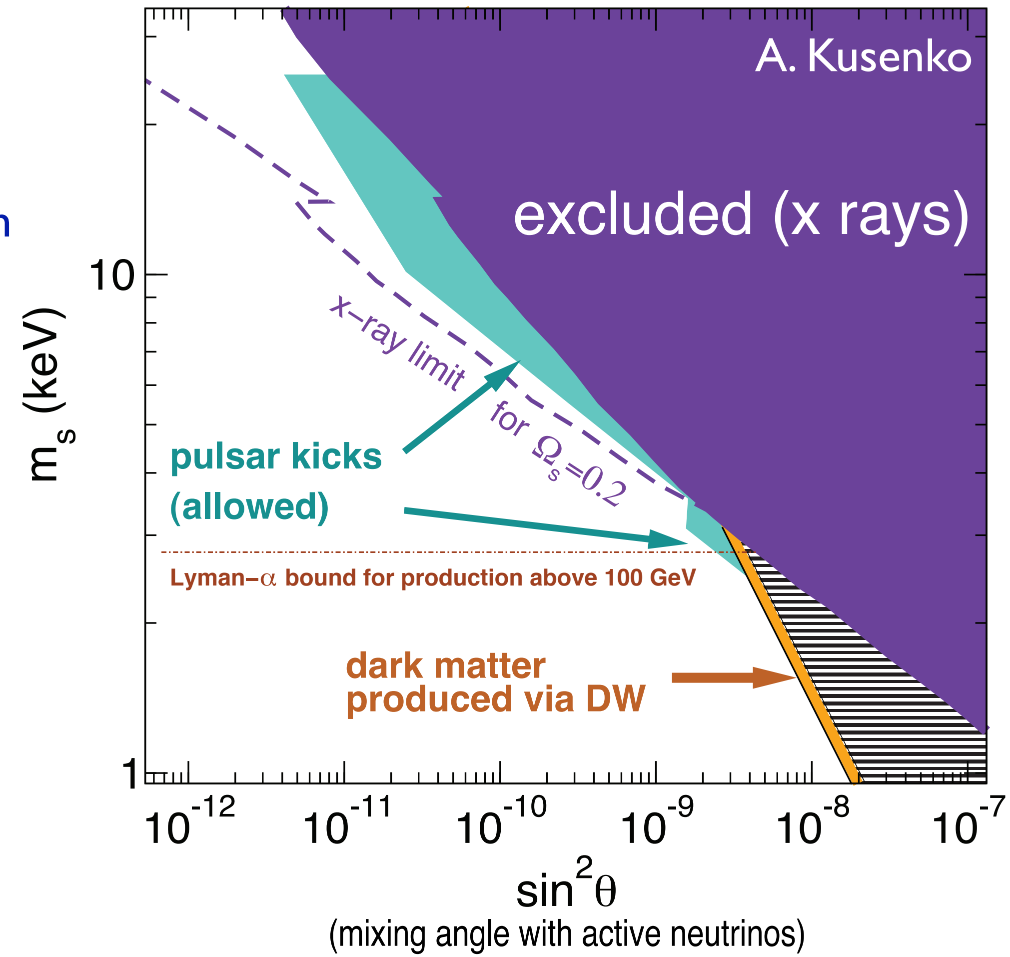
- Neutrinos
  - only massive (sterile) neutrinos can be cold or warm. Low-mass neutrinos make hot dark matter.
- Axions
  - Form as Bose condensate in early universe: cold in spite of low mass
- Weakly Interacting Massive Particles (WIMPs)
  - new massive (~100 GeV) particle with electroweak scale interactions with normal matter
  - SUSY neutralino
  - Lightest Kaluza-Klein particle in universal extra dimensions
- 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...

L. Roszkowski



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
- Limits
  - overclosure
  - x-ray emission from decays
    - bounds will improve with future X-ray satellites (Astro-H and IXO): sensitivity 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 electrons and nucleons results in asymmetric neutrino emission
    - improvements perhaps with better modeling of supernovae

Axions

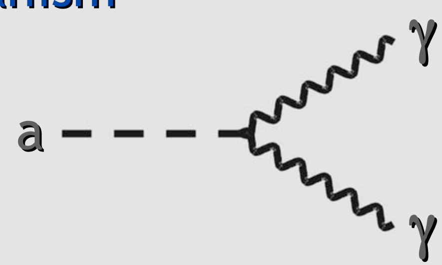
G. Raffelt

Particle-Physics Motivation

CP conservation in QCD by Peccei-Quinn mechanism

→ Axions $a \sim \pi^0$

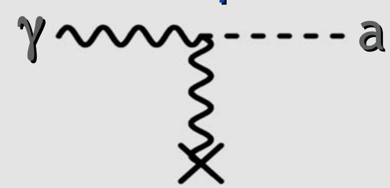
$m_\pi f_\pi \cong m_a f_a$



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

Solar and Stellar Axions

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

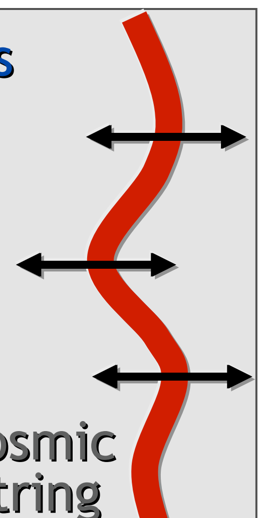


- Limits from avoiding excessive energy drain
- Search for solar axions (CAST)

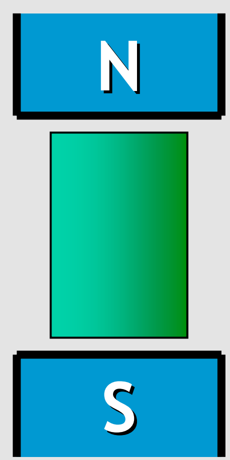
Cosmology

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

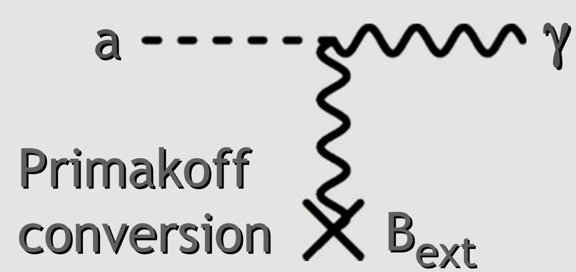
→ Cold dark matter candidate
m_a ~ 1-1000 μeV



Search for Axion Dark Matter



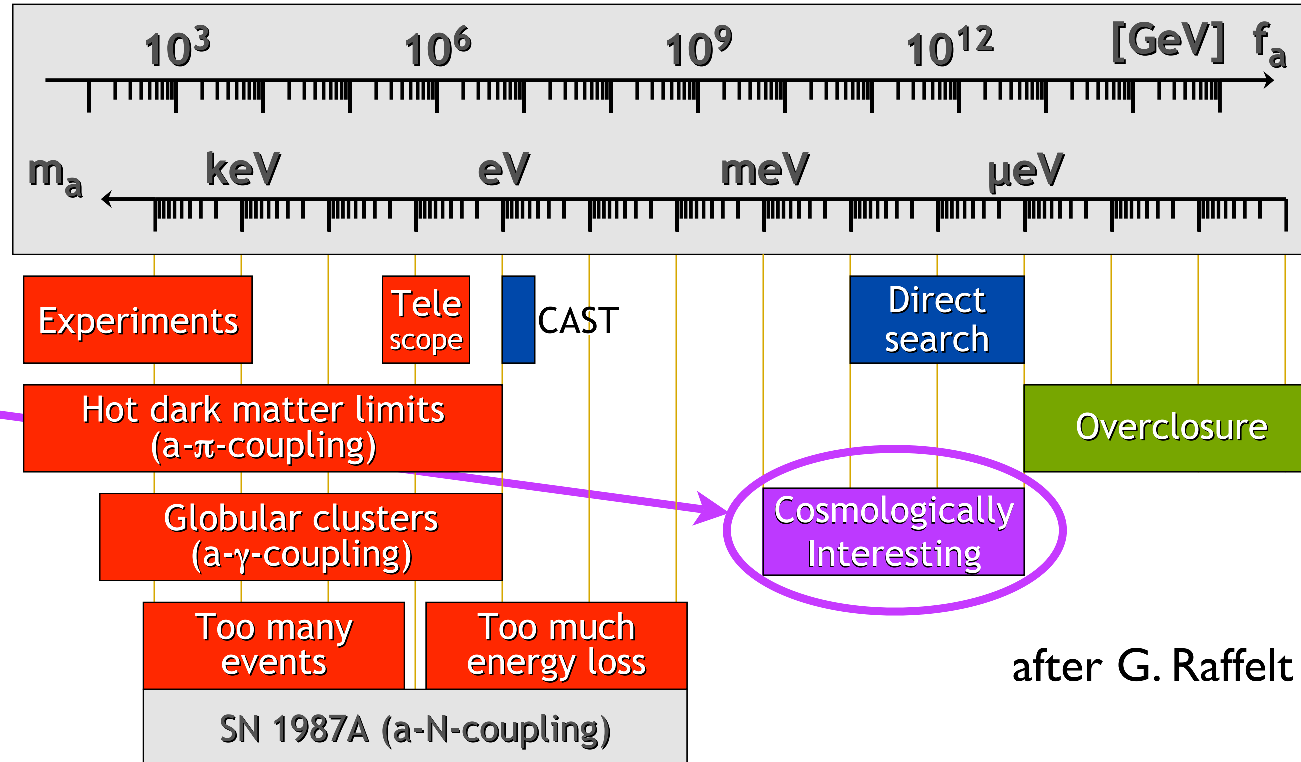
Microwave resonator (1 GHz = 4 μeV)



Axion Direct Search Techniques

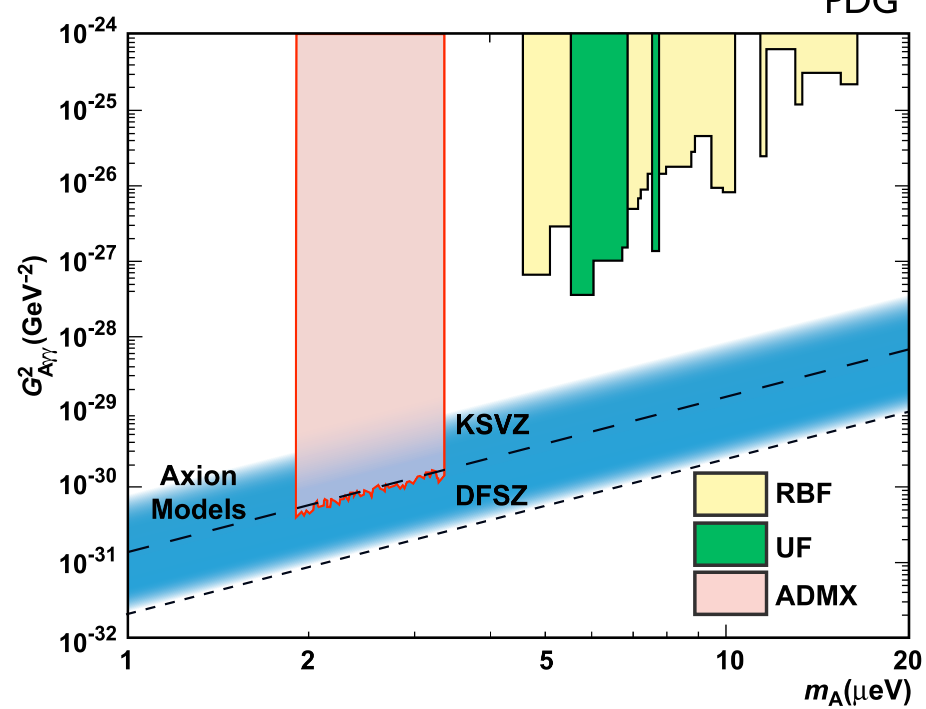
Cosmologically interesting: provides appropriate Ω_{DM}, m_a = 1 μeV to 1 meV

- 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, will test full KSVZ-DFSZ range



after G. Raffelt

PDG



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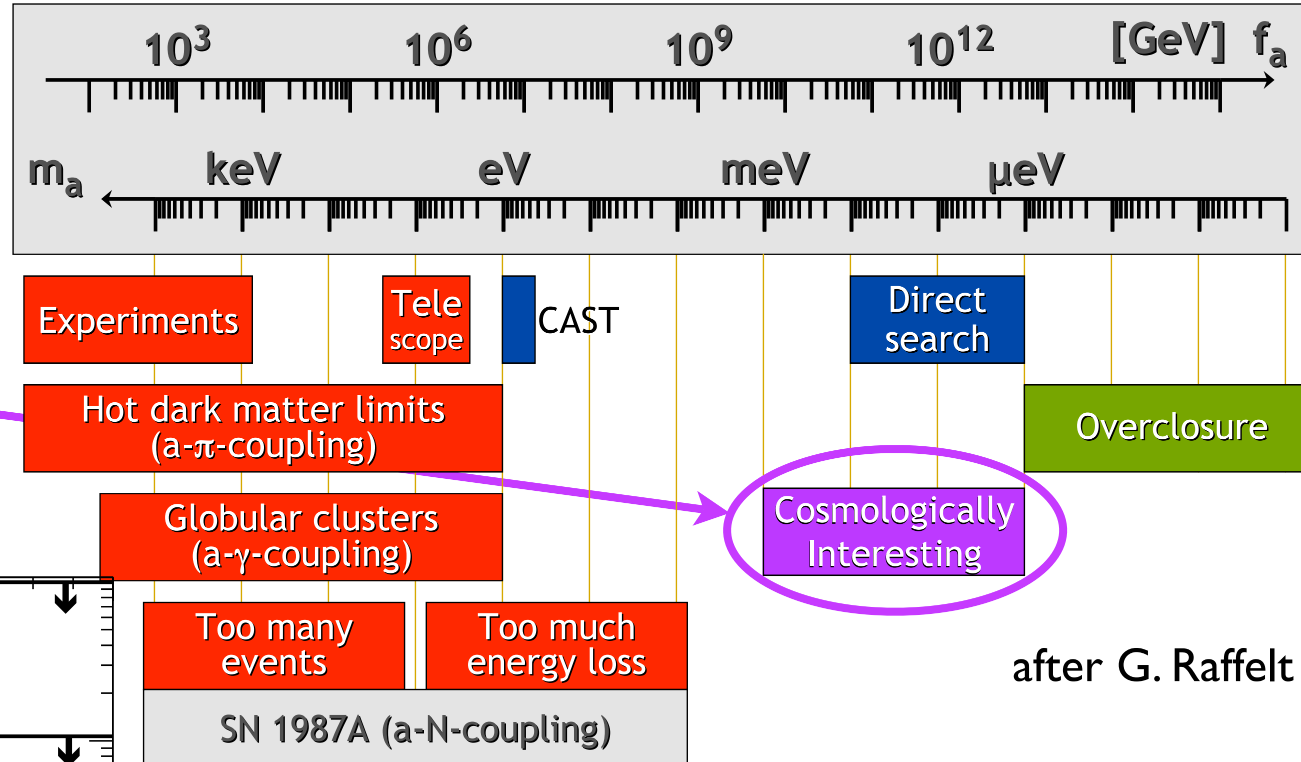

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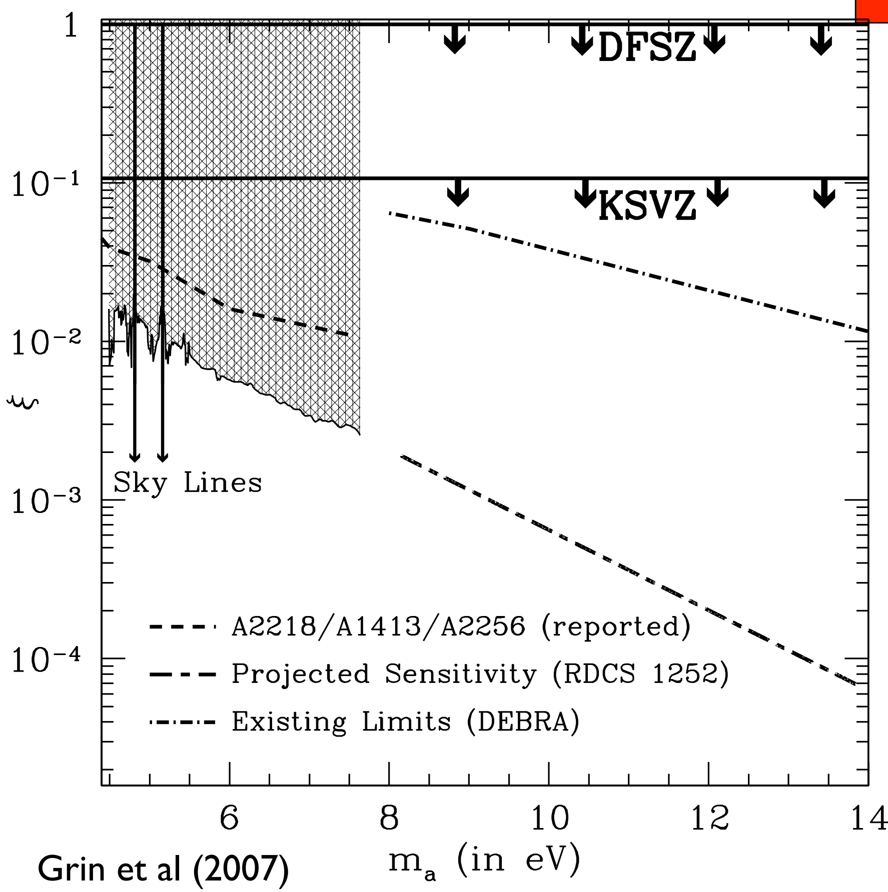
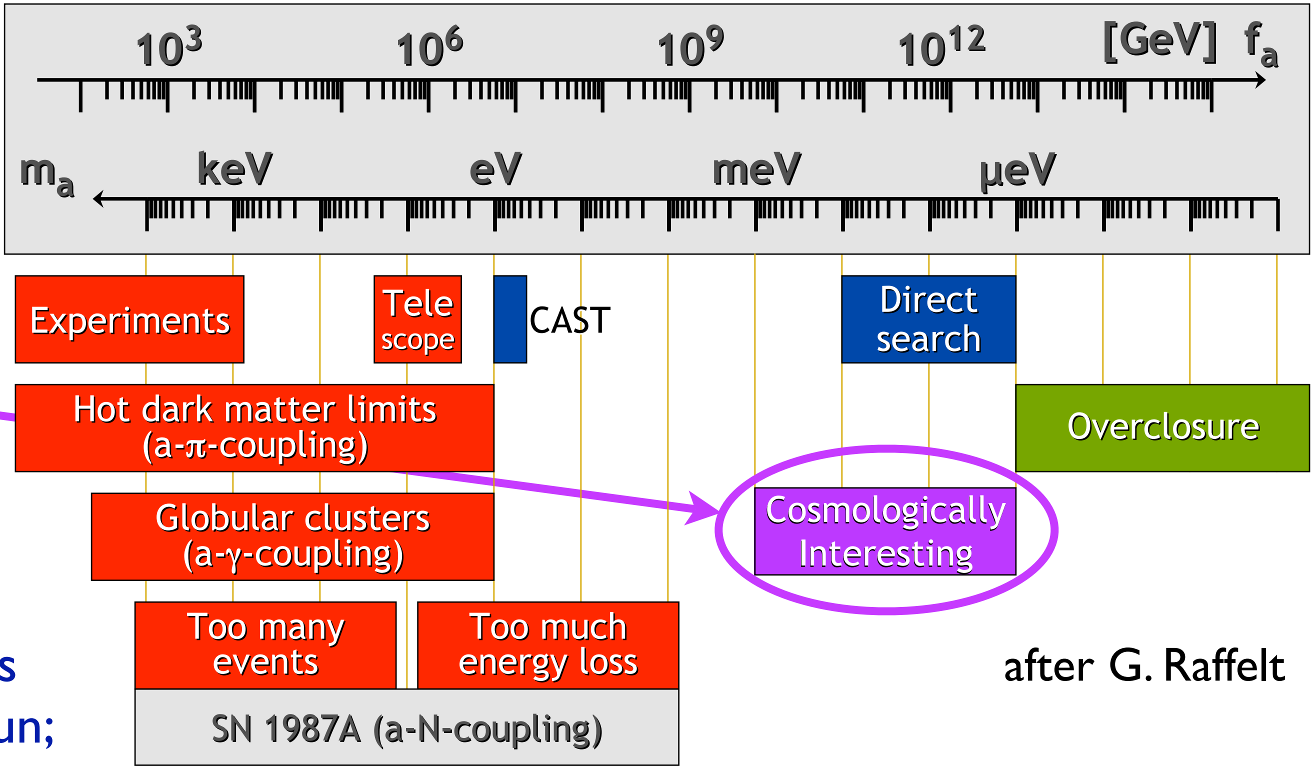


Grin et al (2007)

- Decays
  - $a \rightarrow 2\gamma$, $E_\gamma = m_a/2$ 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!

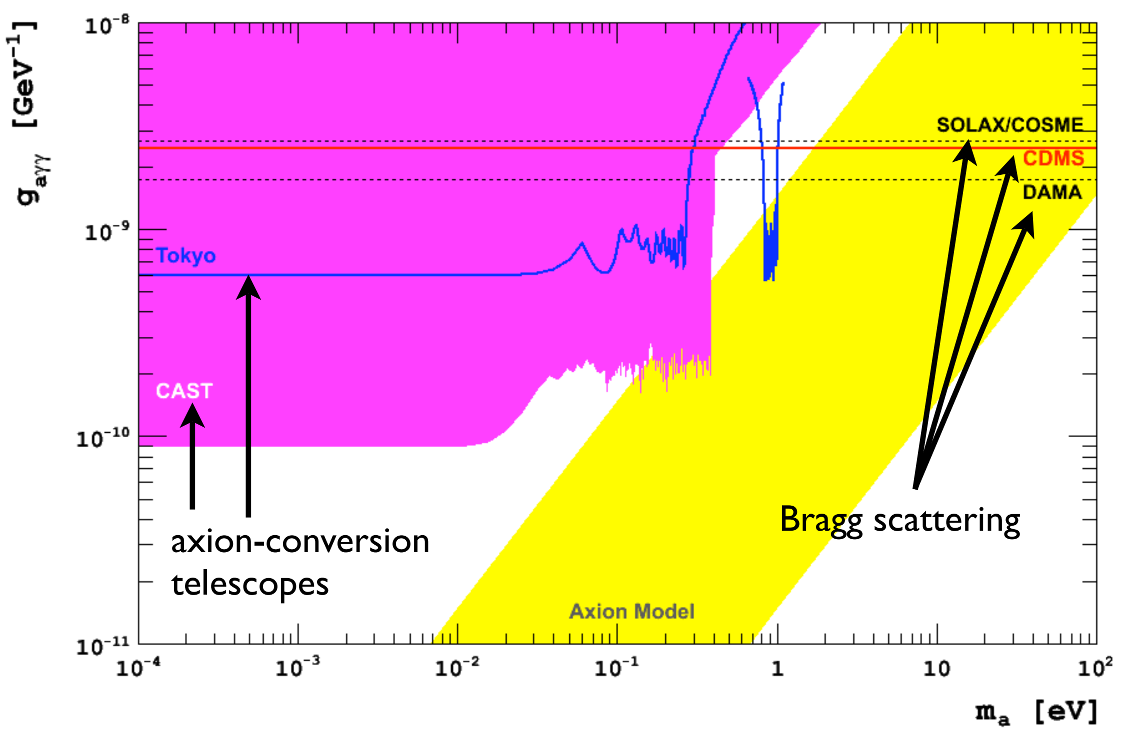
Axion Direct Search Techniques



after G. Raffelt

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

- 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



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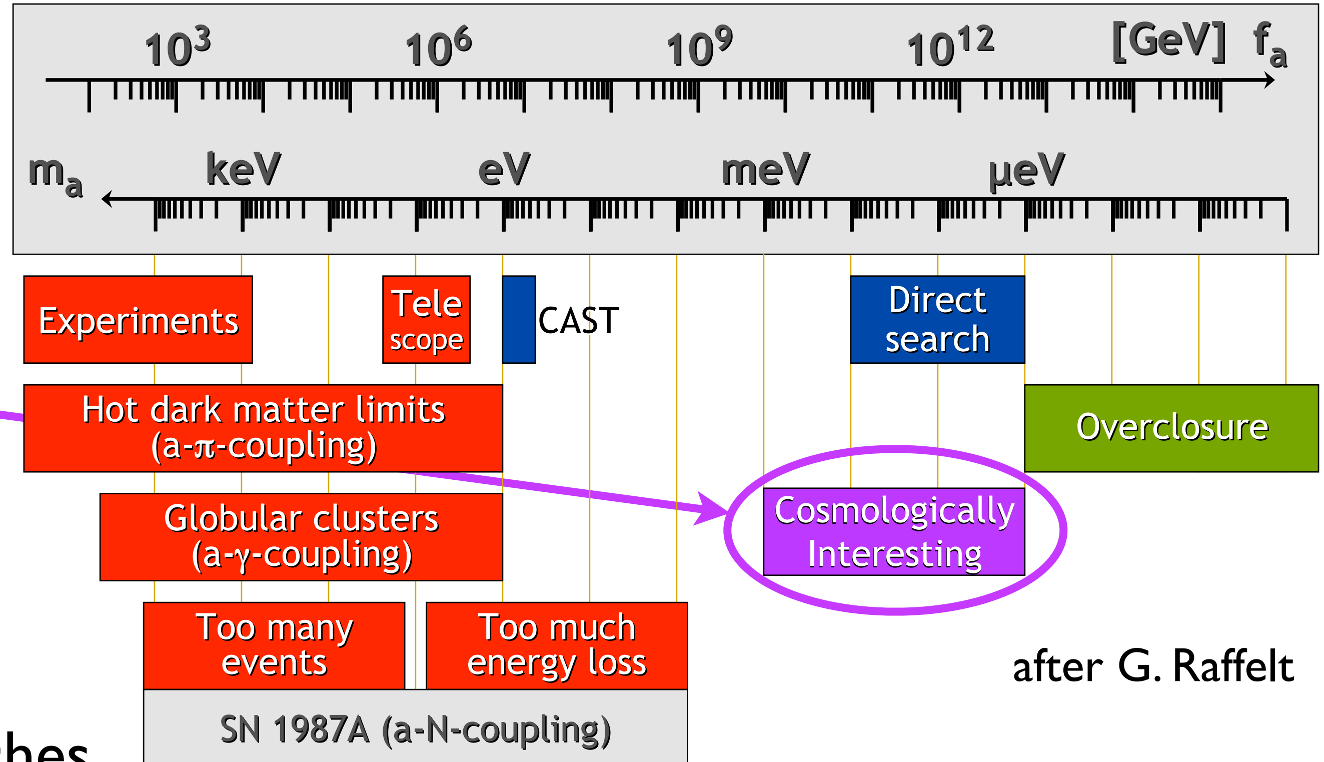


after G. Raffelt

- Other laboratory searches
  - $\gamma \rightarrow a \rightarrow \gamma$ 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;
      PVLAS polarization rotation signal has disappeared in second measurement
    - B-induced birefringence
  - Torsion pendulum (Eot-Wash group)
    - Axions mediate a P and T violating force between electrons and nucleons
    - Look for violations of $1/r^2$

WIMPs

- A WIMP δ is like a massive neutrino: produced when T >> m_δ via pair annihilation/creation. Reaction maintains thermal equilibrium.
- If interaction rates high enough, comoving density drops as $\exp(-m_\delta / T)$ as T drops below m_δ : annihilation continues, production becomes suppressed.
- But, weakly interacting → will "freeze out" before total annihilation if

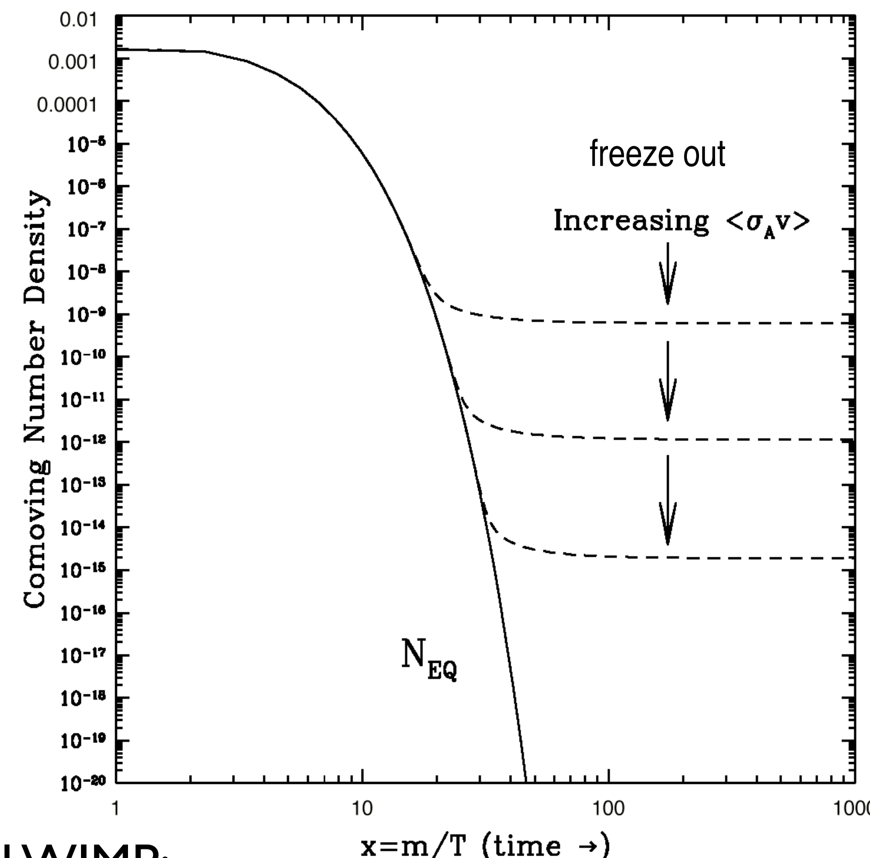
$$H > \Gamma_{ann} \sim \frac{n_\delta}{\langle \sigma_{ann}\, v \rangle}$$

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

- Leaves a relic abundance:

$$\Omega_\delta\, h^2 \approx \frac{10^{-27}}{\langle \sigma_{ann}\, v \rangle_{fr}}\ \mathrm{cm}^3\, \mathrm{s}^{-1}$$

  → if m_δ and σ_{ann} determined by new weak-scale physics, then Ω_δ is O(1)

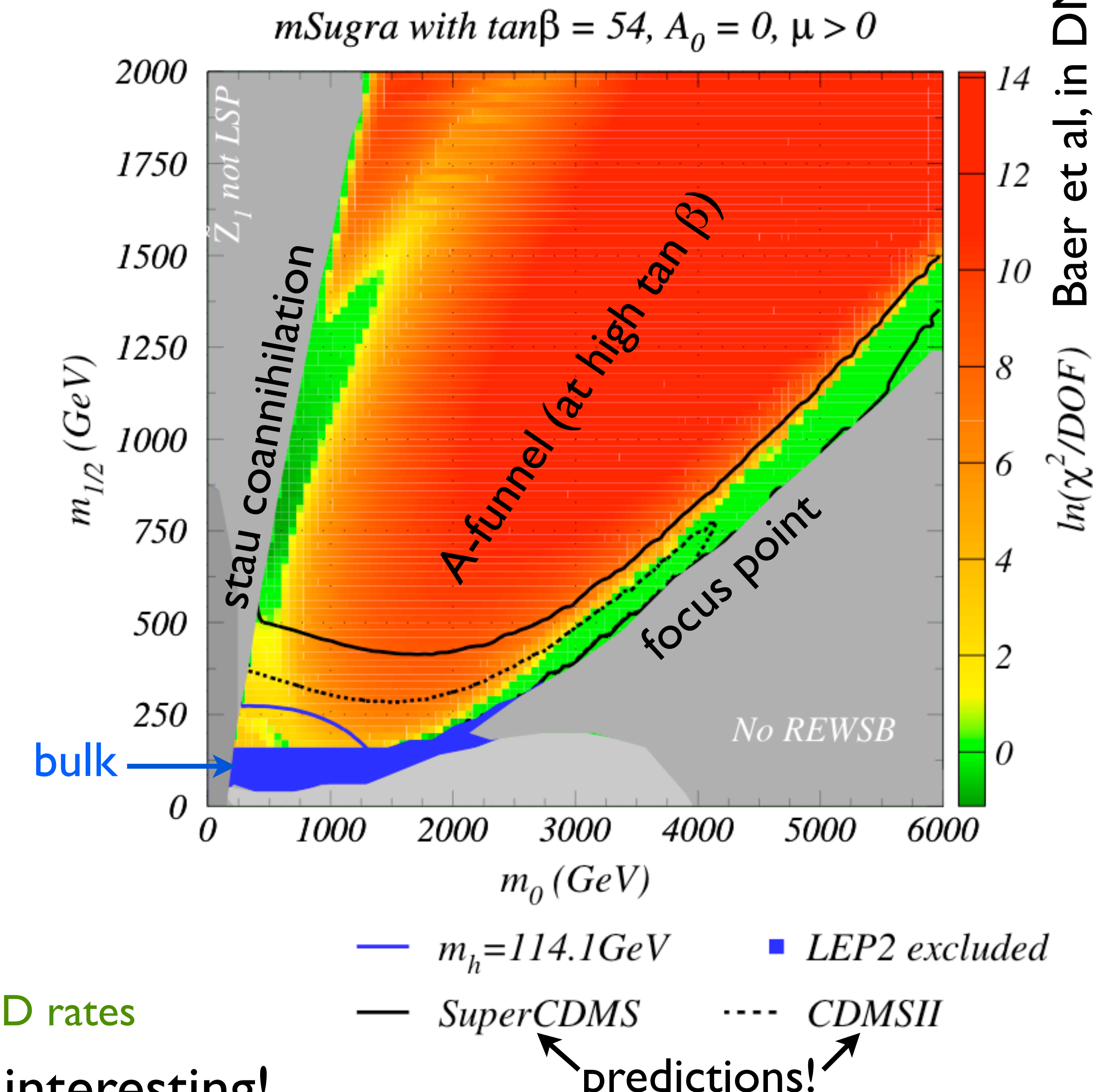


- LSP in R-parity conserving SUSY is an ideal WIMP: weak-scale cross-section, neutral, stable. But WIMPs are not SUSY-specific!

Supersymmetric WIMPs

- SUSY lightest superpartner w/ R-parity cons. is WIMP(-like)
- Neutralino LSP δ
  - mixture of bino, wino, higgsinos; spin 1/2 Majorana particle
  - Allowed regions
    - bulk: δ annih. via t-channel slepton exchange, light h, high BR(b→sγ) and $(g-2)_\mu$; good DD rates
    - stau coann: δ and stau nearly degenerate, enhances annihilation, low DD rates
    - focus point: less fine-tuning of REWSB, δ acquires higgsino component, increases annihilation to W, Z, good DD rates
    - A-funnel: at high tan β, resonant s-channel annihilation via A, low DD rates
- Gravitino LSP: nondetection interesting!

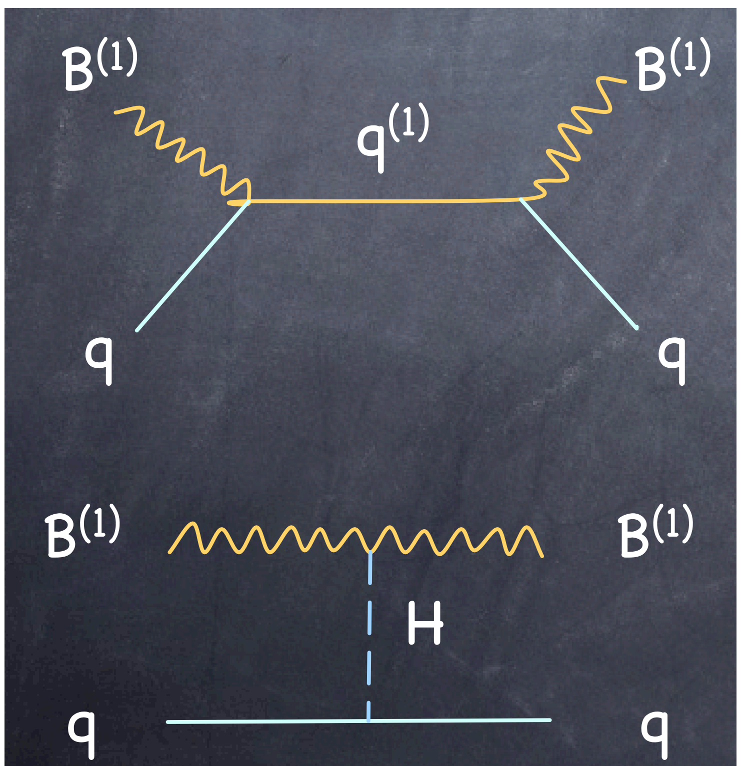
χ^2 of fit to BR(b→sγ), muon g-2, and relic density (dominated by relic density: avoid overclosure)



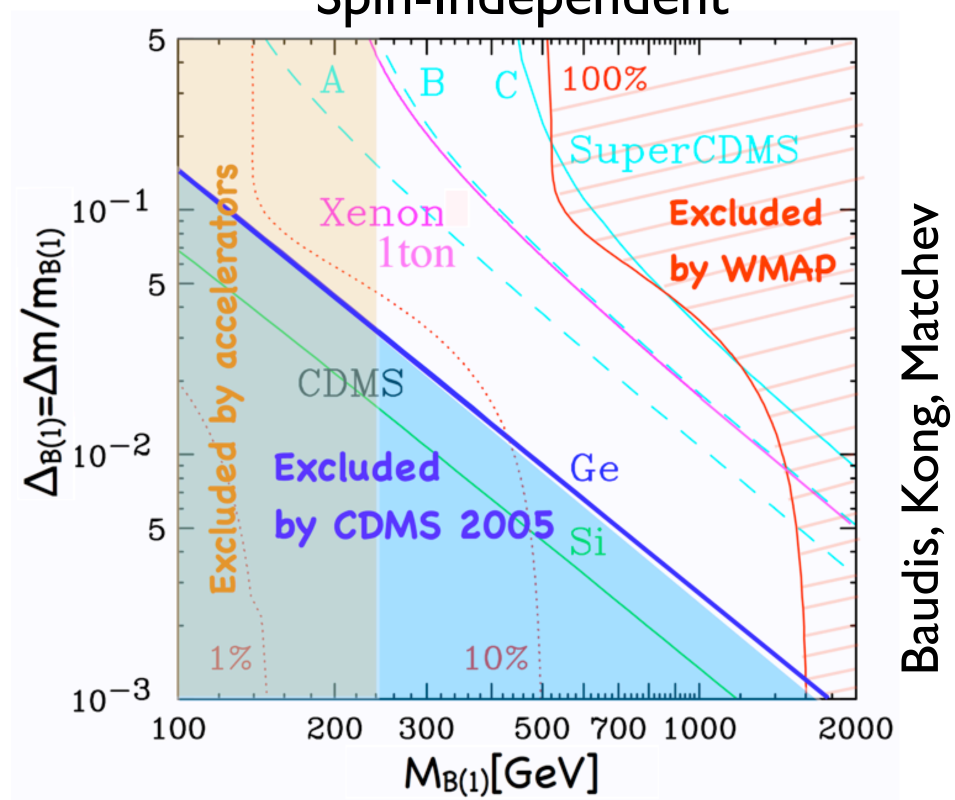
Baer et al, in DMSAG report

Universal Extra Dimensions WIMPs

- Kaluza-Klein tower of partners due to curled-up extra dimension of radius R
  - n = quantum number for extra dimension, $m_n^2 \sim n^2/R^2$
  - momentum cons. in extra dim. → exact cons. of KK particles (KK parity)
  - KK parity $P_{KK} = (-1)^n$ implies lightest KK partner (n = 1) is stable
- $B^{(1)}$, n = 1 partner of B gauge boson, is lightest KK partner in simple cases
- Cross-section on quarks depends on fractional mass difference between $B^{(1)}$ and 1st KK partner of quarks, $q^{(1)}$

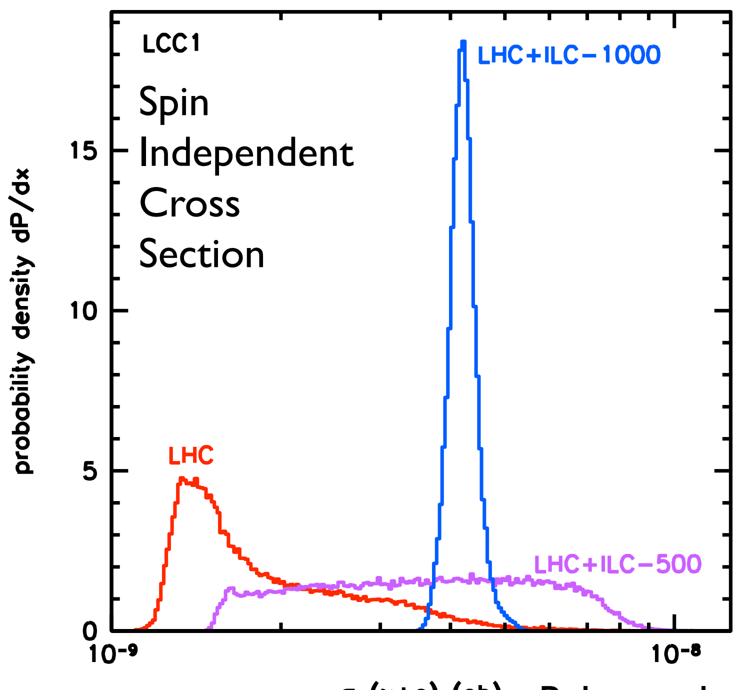


Spin-Independent

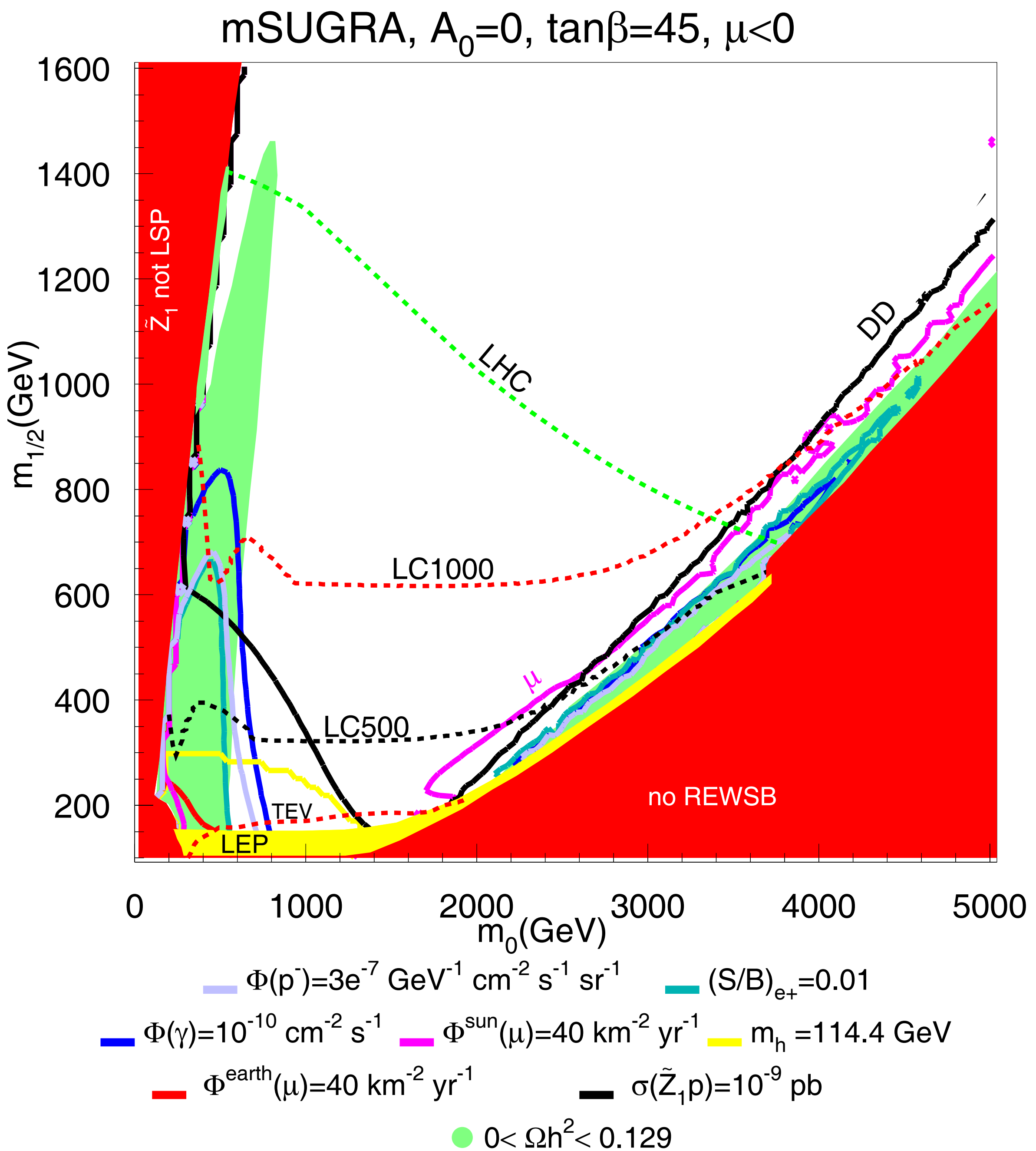


Astrophysical Detection and Colliders

- Astro searches will limit σ_{scatt} and σ_{annih} as colliders push up in mass
- Astro searches test whether collider DM candidate is stable and measures σ_{scatt} and σ_{annih}
- Hopefully we will narrow down the parameter space together.



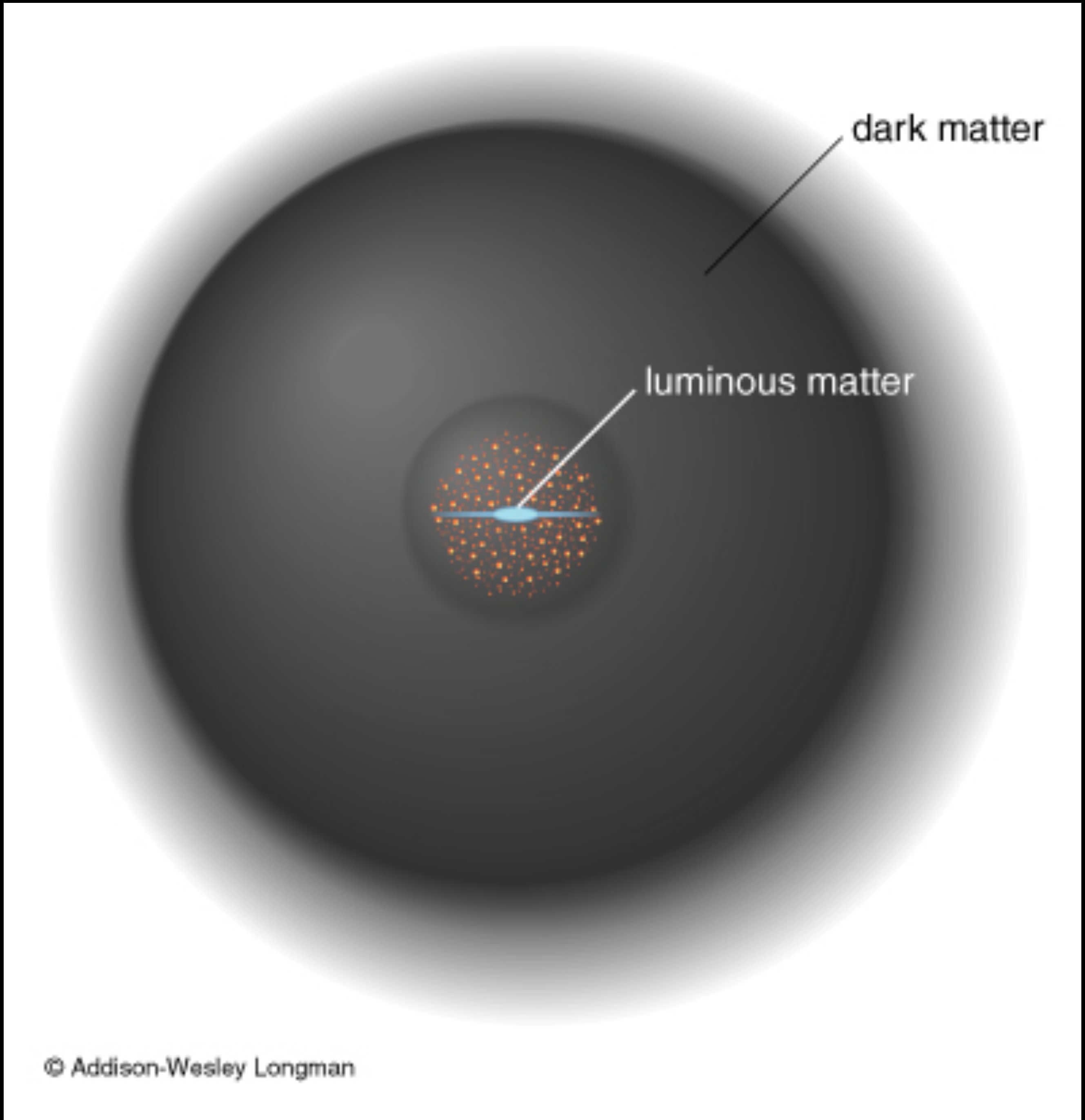
Baltz et al



Indirect Searches

- In many places, the WIMP density becomes large enough for annihilation to occur in spite of low cross sections: galactic haloes/ cores, Sun, Earth
- Annihilation products:
  - fermion pairs (via Z, A, sfermion exchange), though note helicity suppression for SUSY neutralino WIMPs, which are Majorana
  - gluons, which hadronize
  - Z, W, Higgs, which decay to fermions
  - neutrinos (direct production at exactly $m_\delta/2$, continuum from decays of other products)
  - photons (via 2nd-order diagrams only, at $m_\delta/2$, continuum from decays of other products)
  - stable hadrons and antihadrons (from hadronization of antiquarks)
  - synchrotron emission (resulting from electron products near the galactic center spiraling in the mG magnetic field)
- Caveats
  - Very dependent on modeling of dark matter density, esp. its clumpiness

WIMPs pair-annihilate to stable, SM particles



S. Profumo

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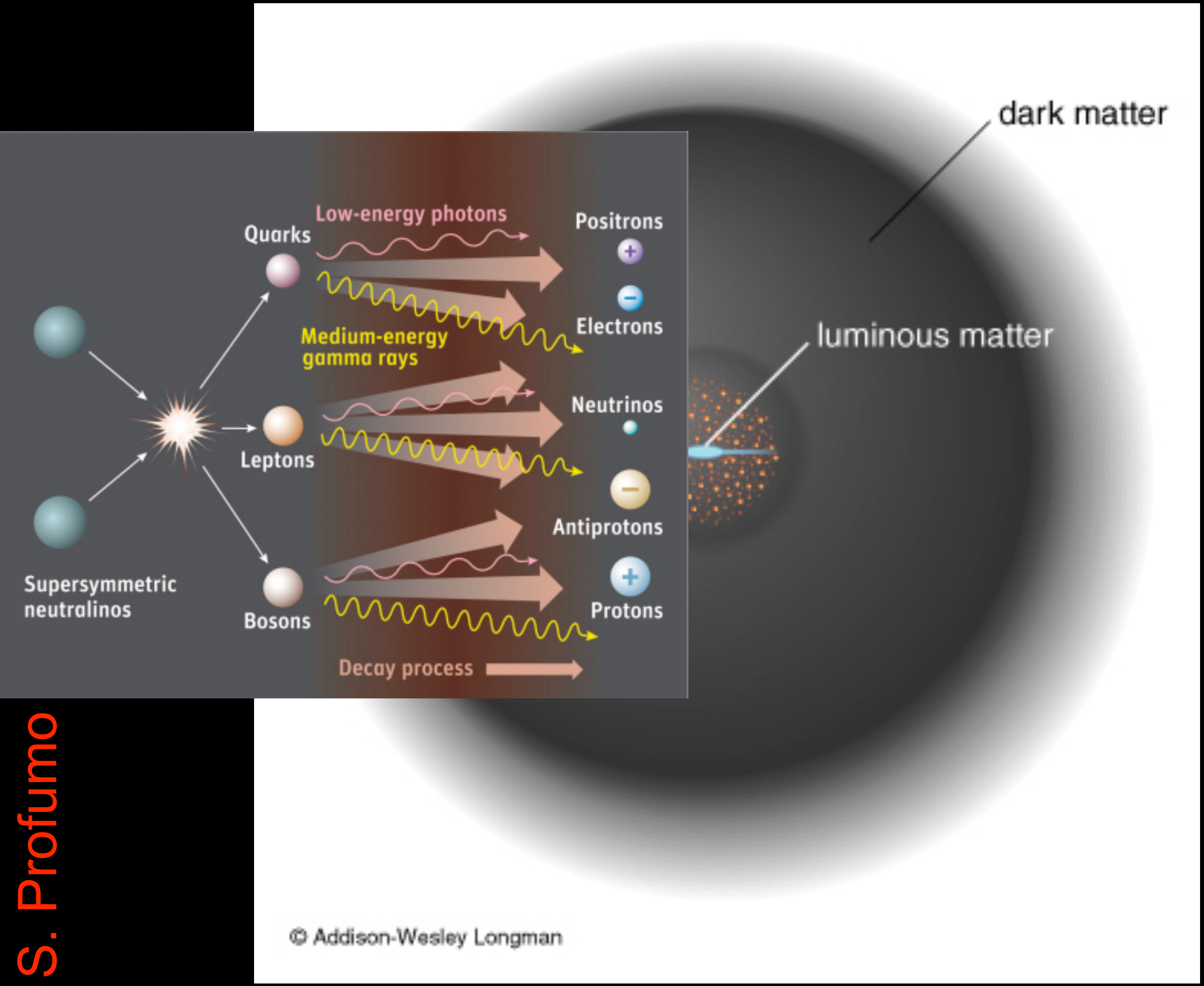

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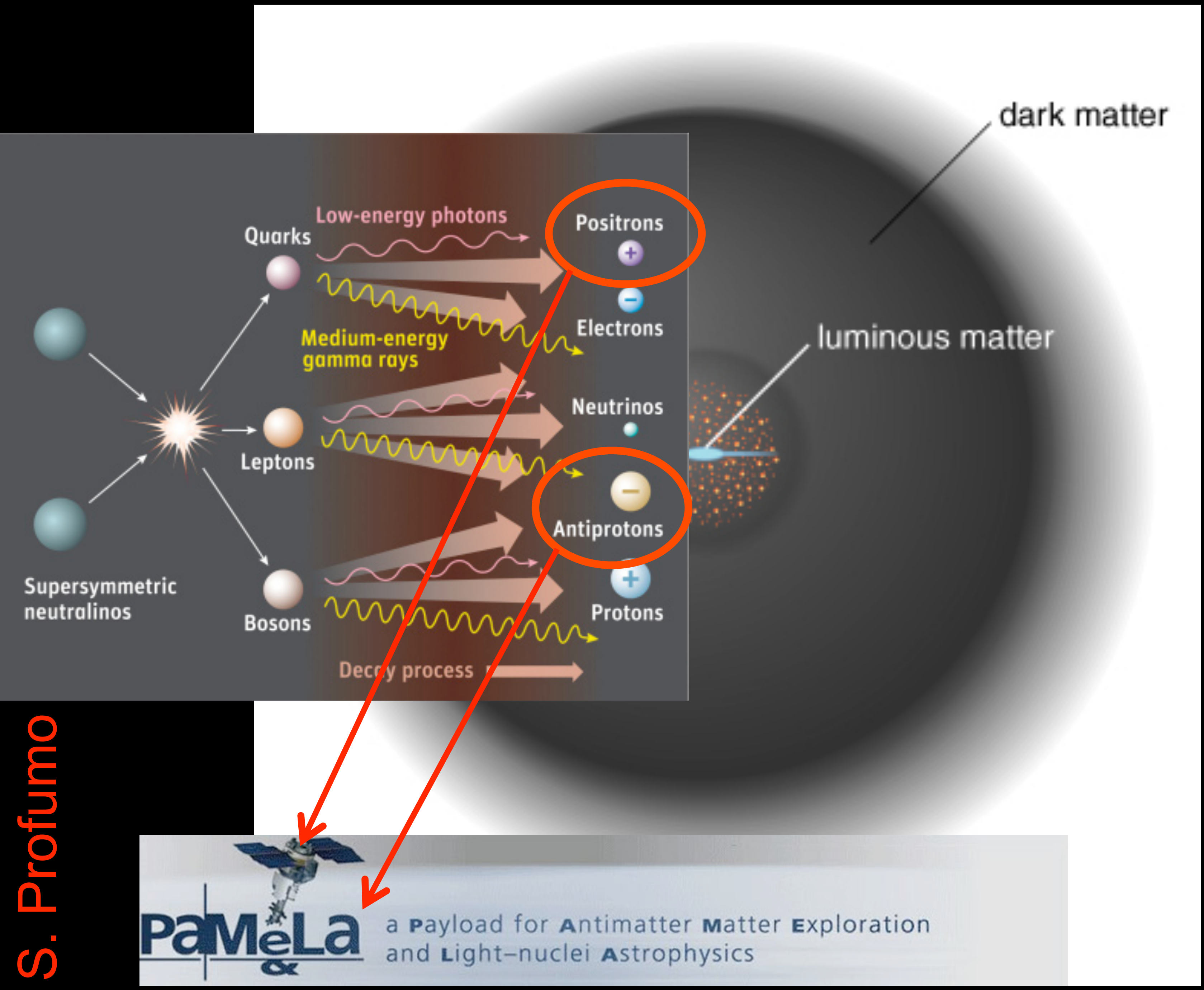

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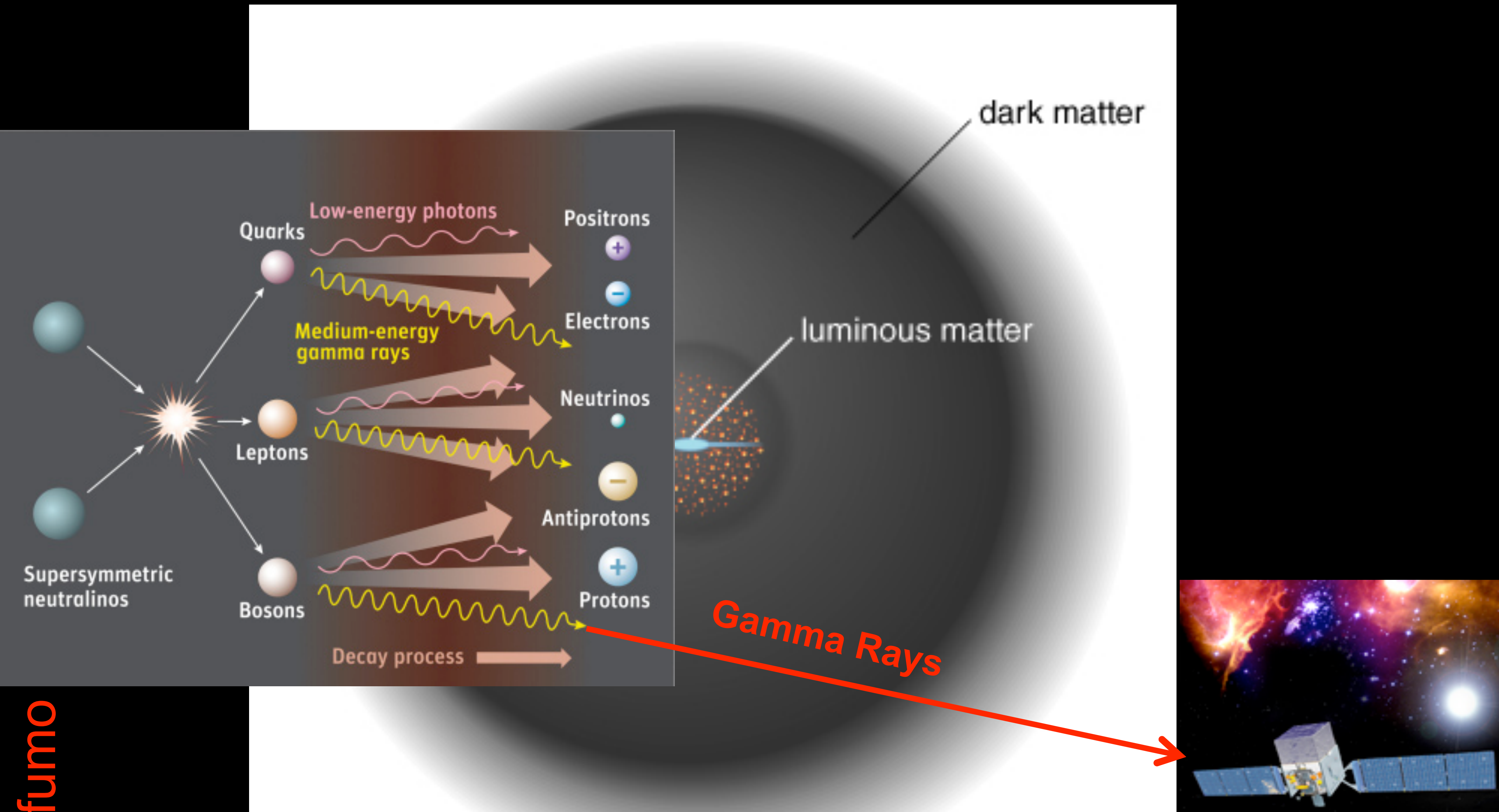

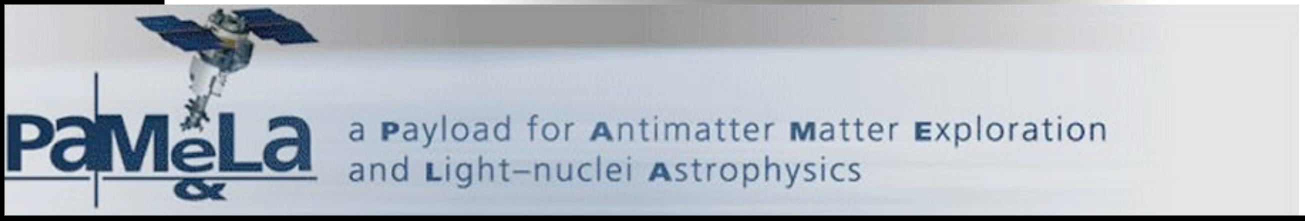

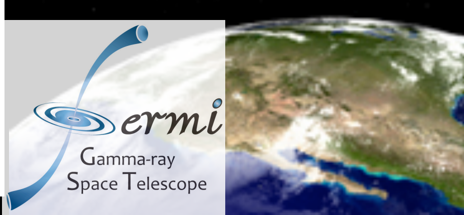

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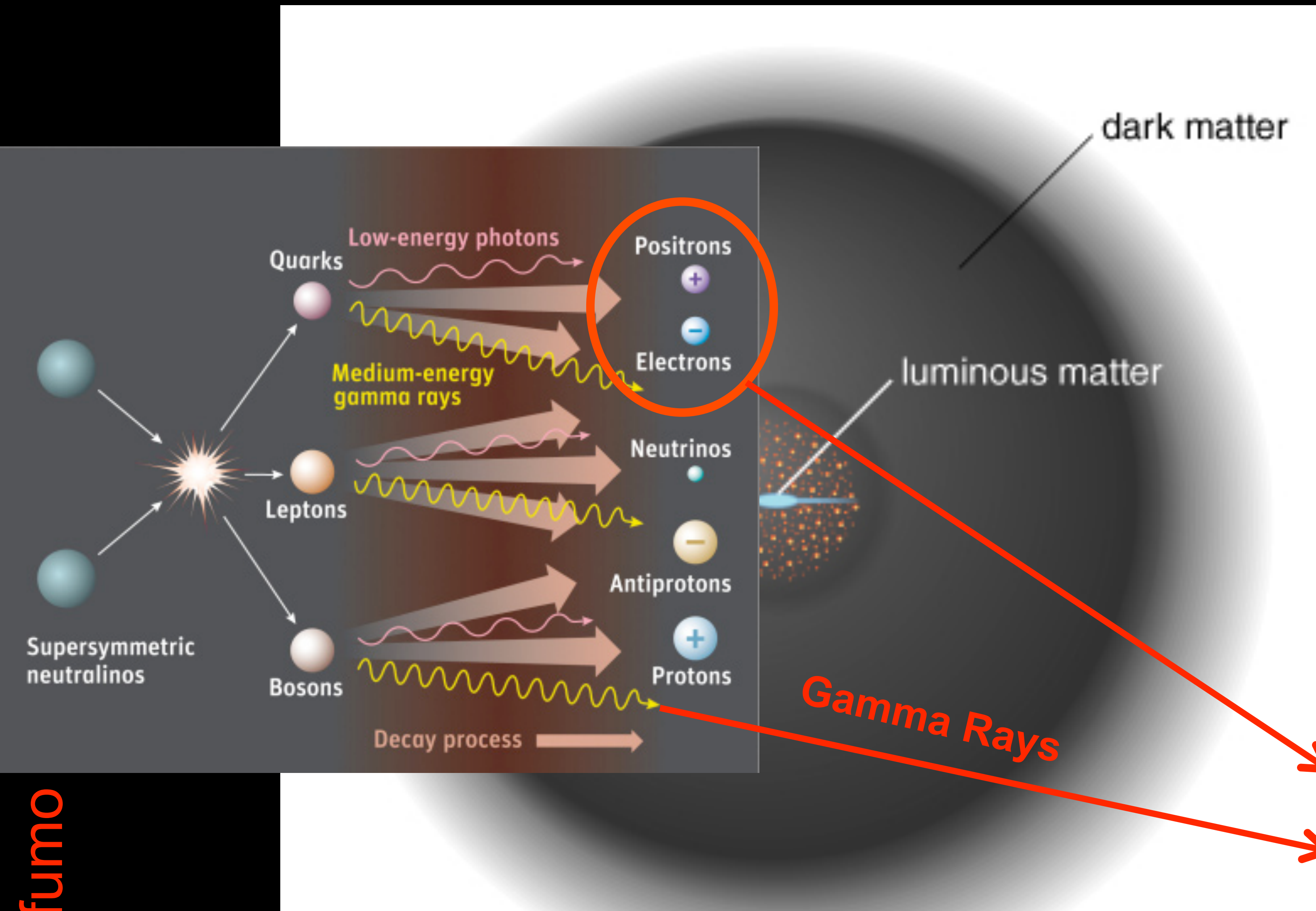

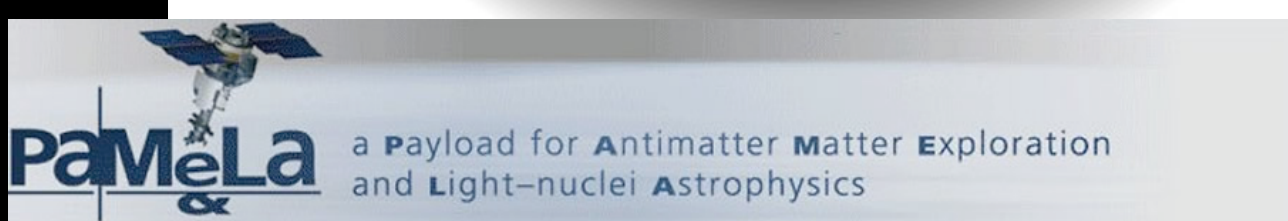

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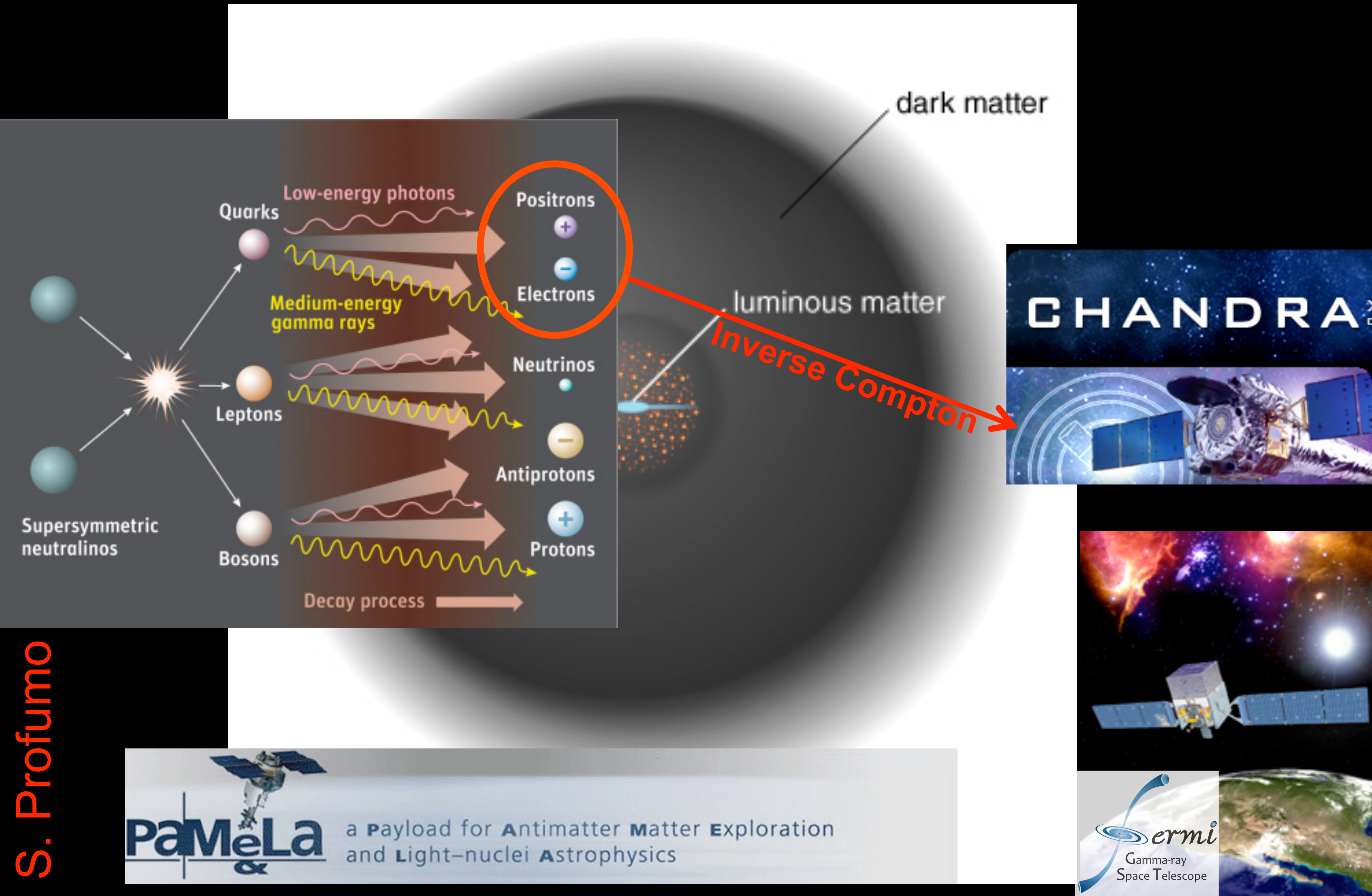

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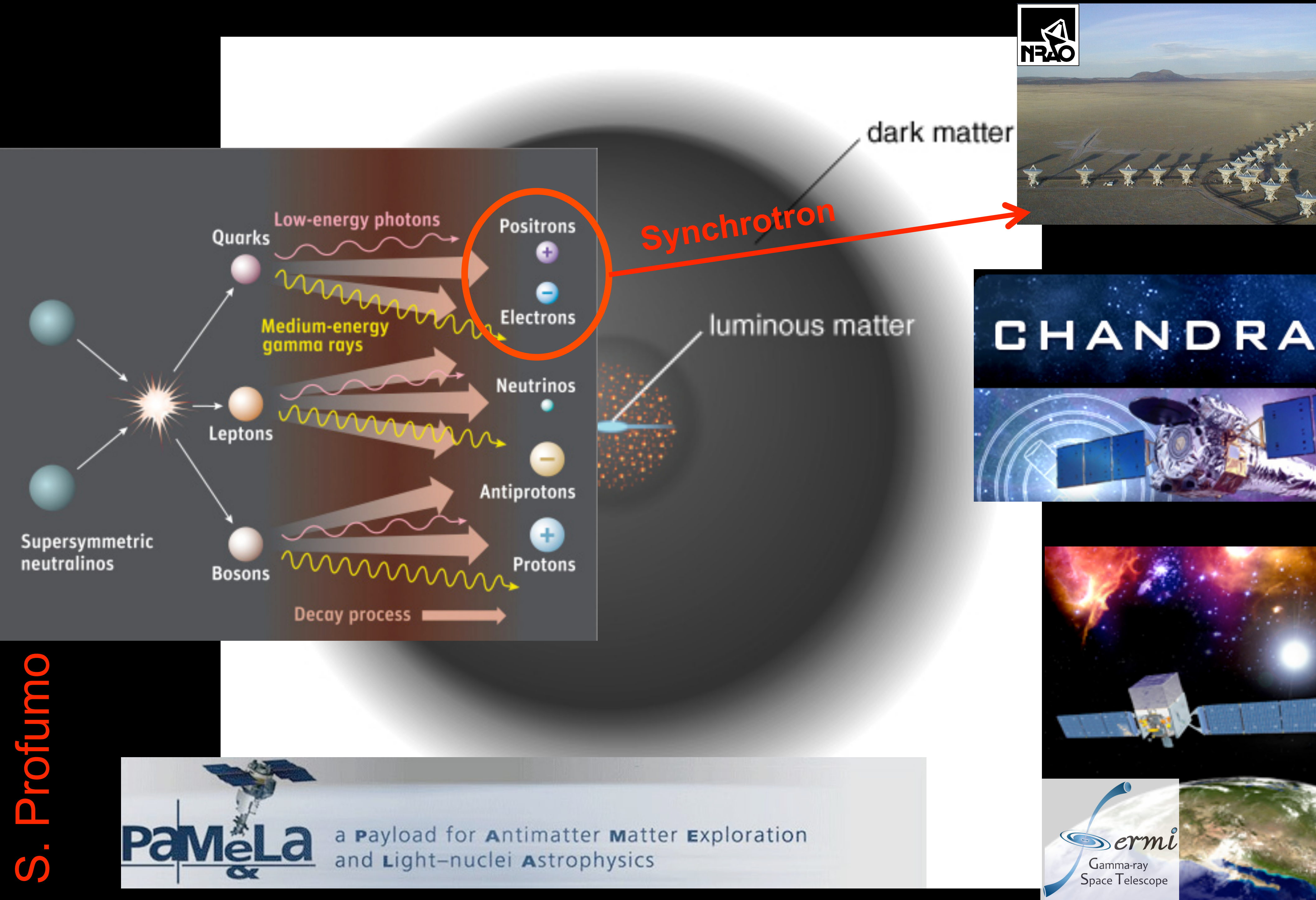

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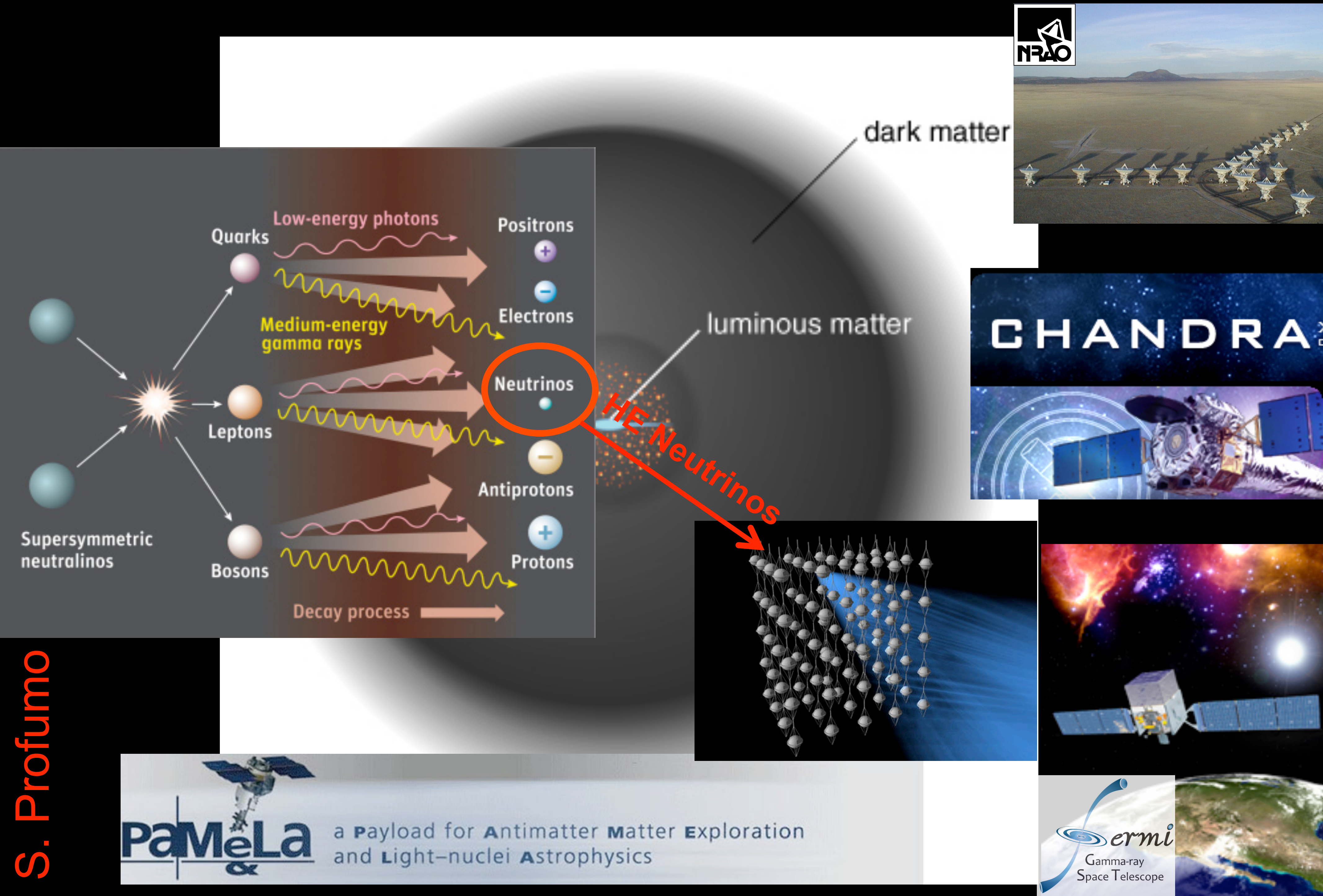

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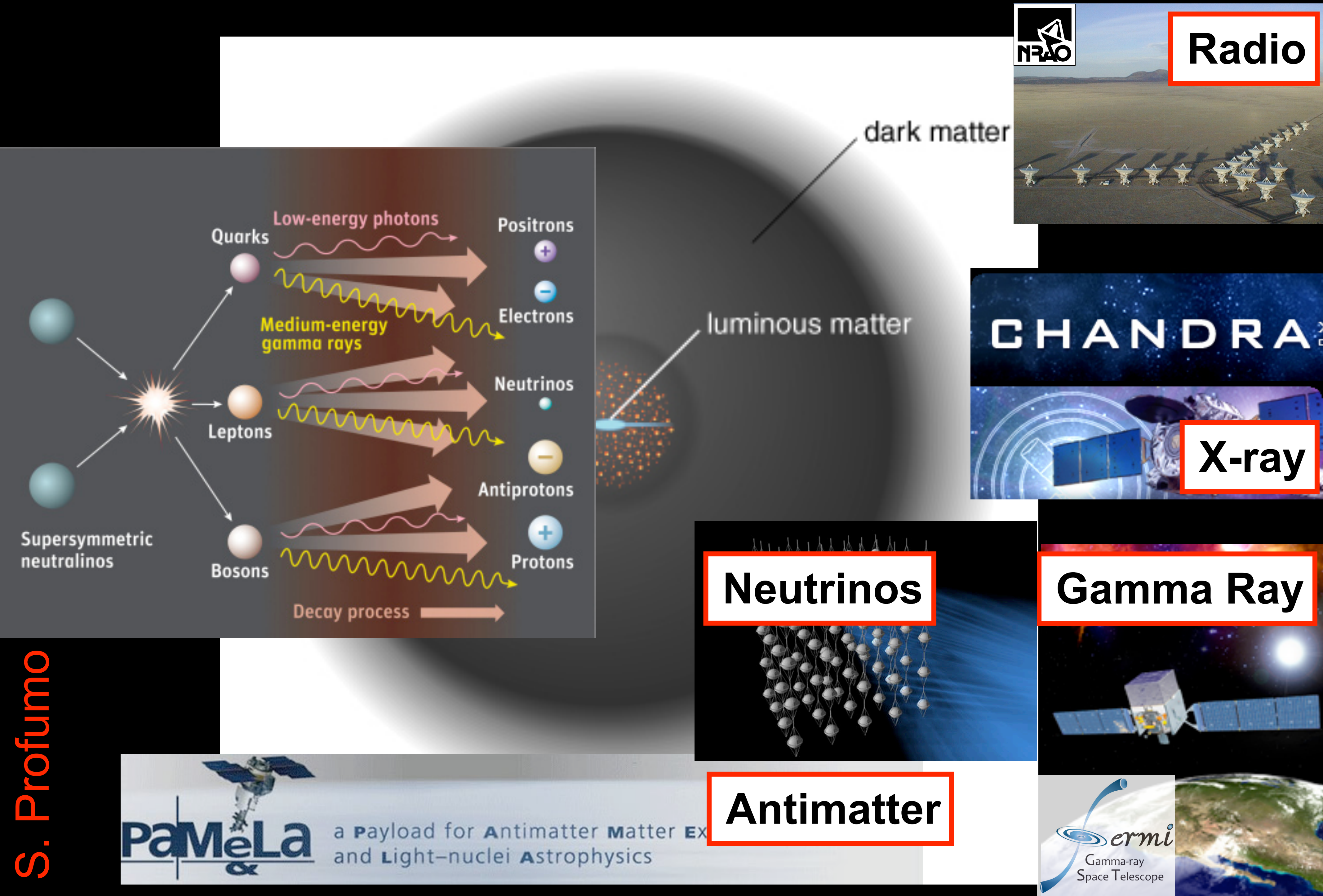

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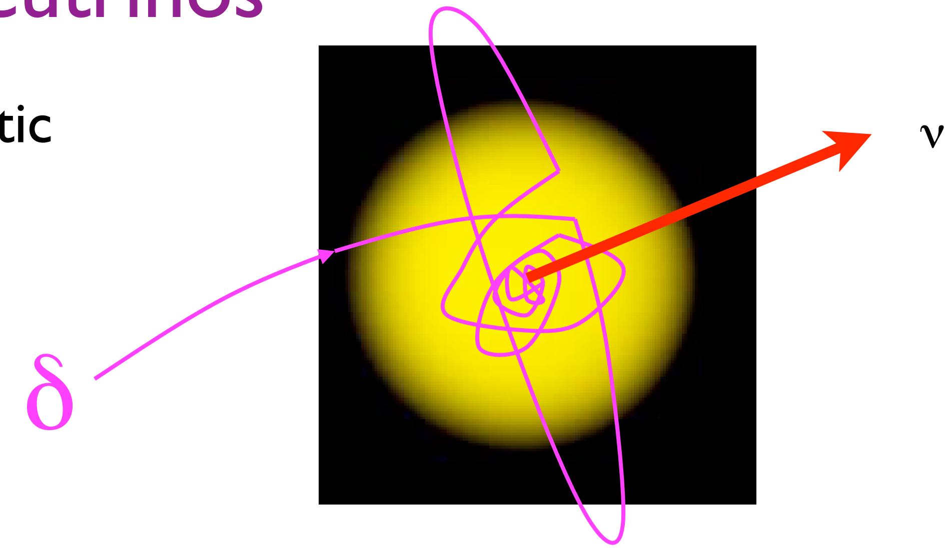
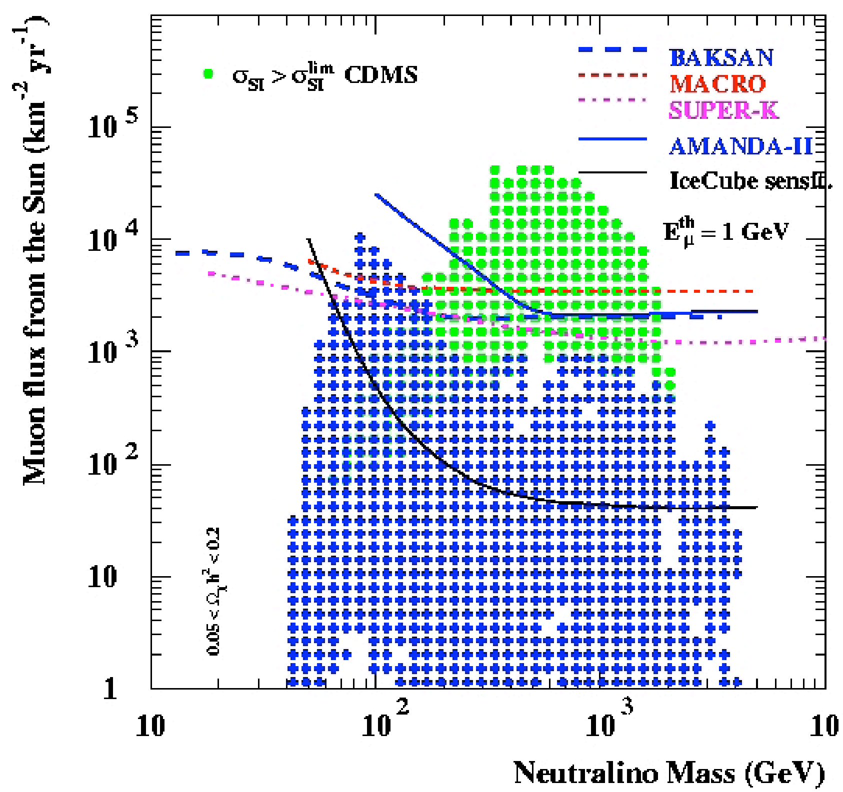
Neutrinos

- WIMPs suffer energy loss via elastic scattering with p and n in Sun
  - density at galactic center, elsewhere in halo not large enough
  - density predictions pretty solid
- WIMPs annihilate to neutrinos, yielding continuum signal:
  - Directly produced neutrinos lose energy as they leave sun
  - Much bigger phase space for neutrinos from decay of other annihilation products
- Search for ν_μ via upward-going μ in ν telescopes such as IceCube, Antares
  - Sensitive to SUSY-relevant mass range, $\gtrsim$100 GeV
  - To first order, sensitivity of neutrino searches and direct detection are proportional because both scale with nucleon-scattering cross-section

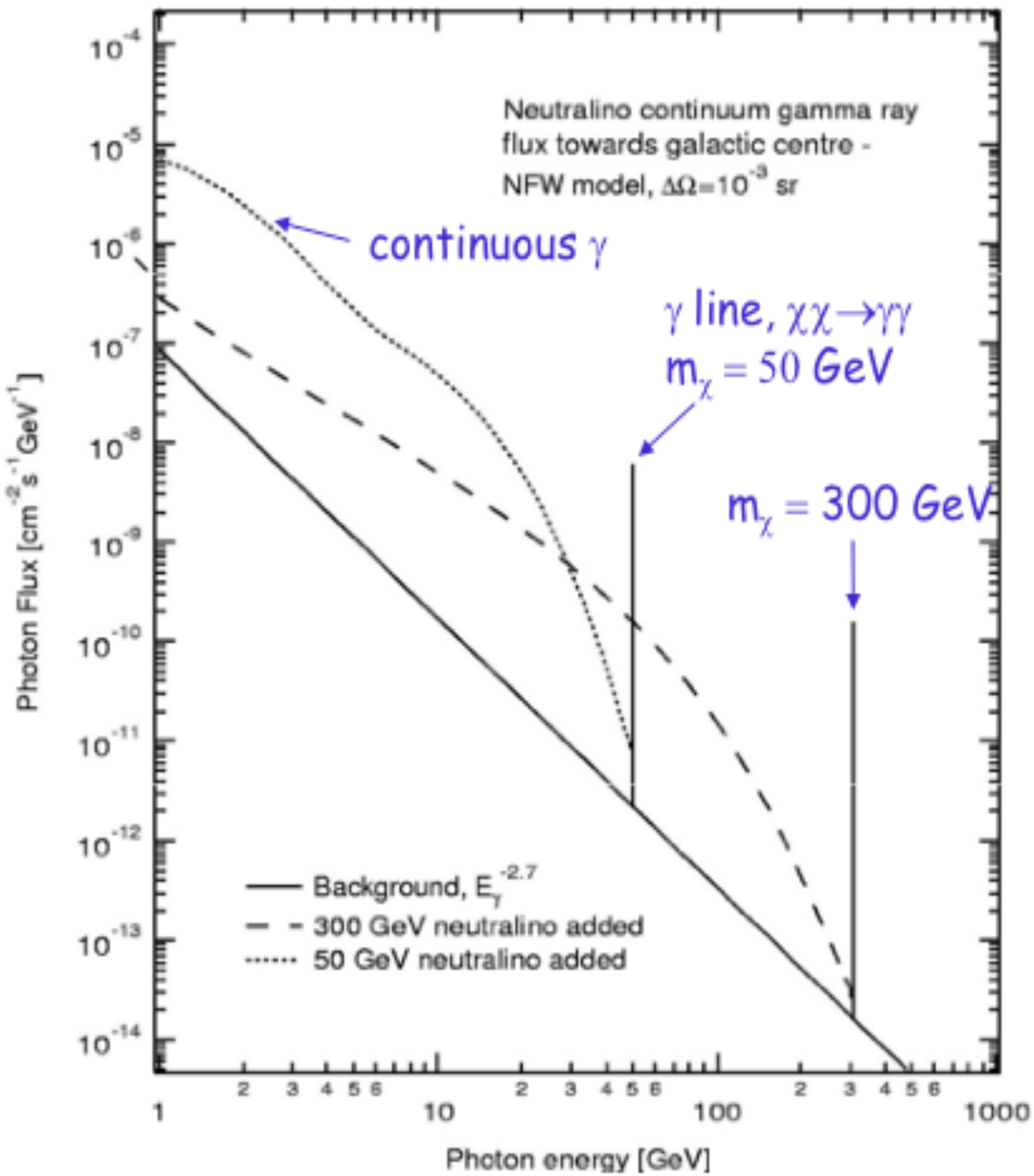


Green excluded by direct detection, blue allowed



Gamma Rays

- Two types of instruments
  - GLAST: satellite mission with large silicon strip tracker + CsI calorimeter, sensitive up to few x 100 GeV
  - Air Cerenkov Telescopes (ACTs): ground-based telescope collecting Cerenkov light from gamma-ray air showers; E > tens of GeV → few GeV (future km^2 array)
  - (Ground-based air-shower arrays, E > 1 TeV)
- Requires large clumping factors
  - $J \sim \langle \rho^2 \rangle / \langle \rho \rangle^2 \sim 1000$ possible in galaxies depending on density profile
  - Astro bgnds problematic
- Current limits
  - HESS GC limit not useful yet
  - HESS Sagittarius dwarf, Whipple M15, Ursa Minor, Draco limits begin to be interesting, but requires modeling to calculate J



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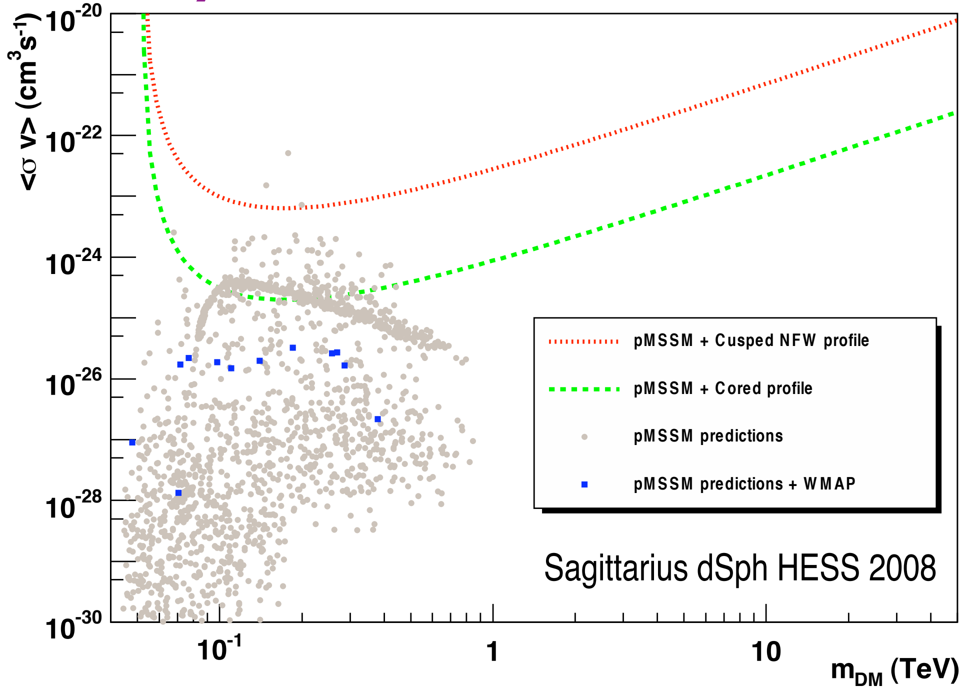

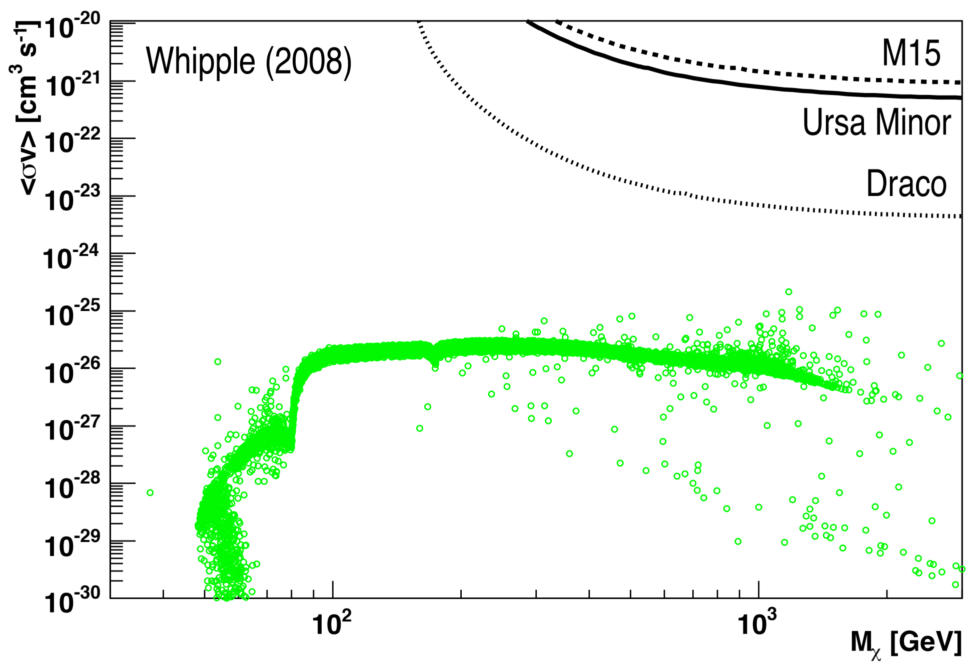

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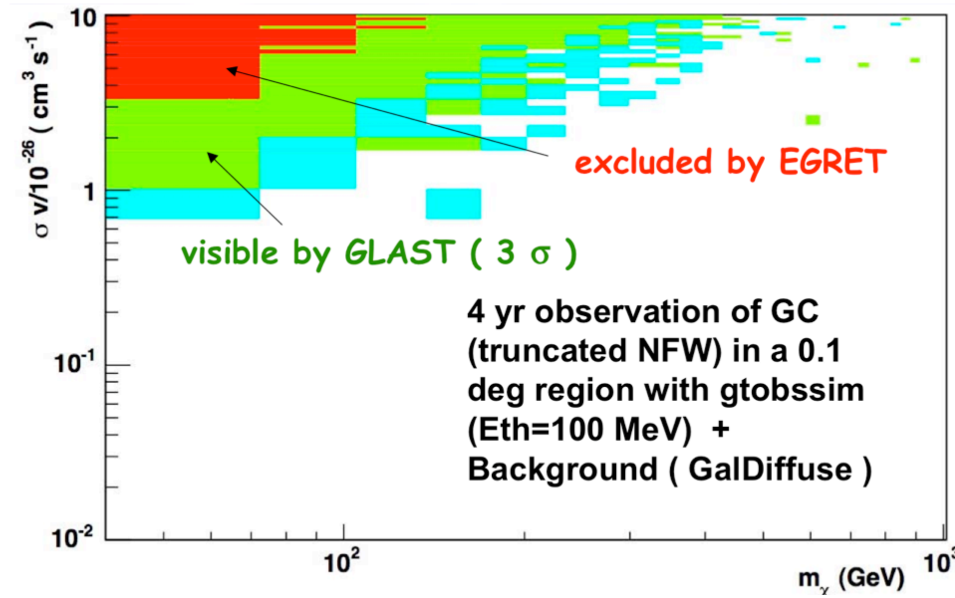
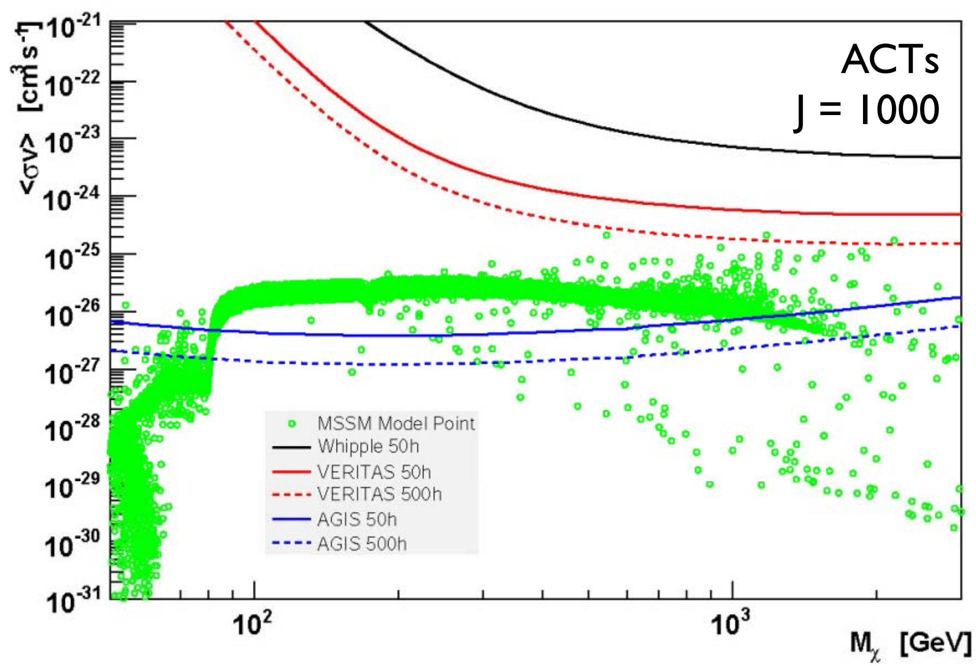


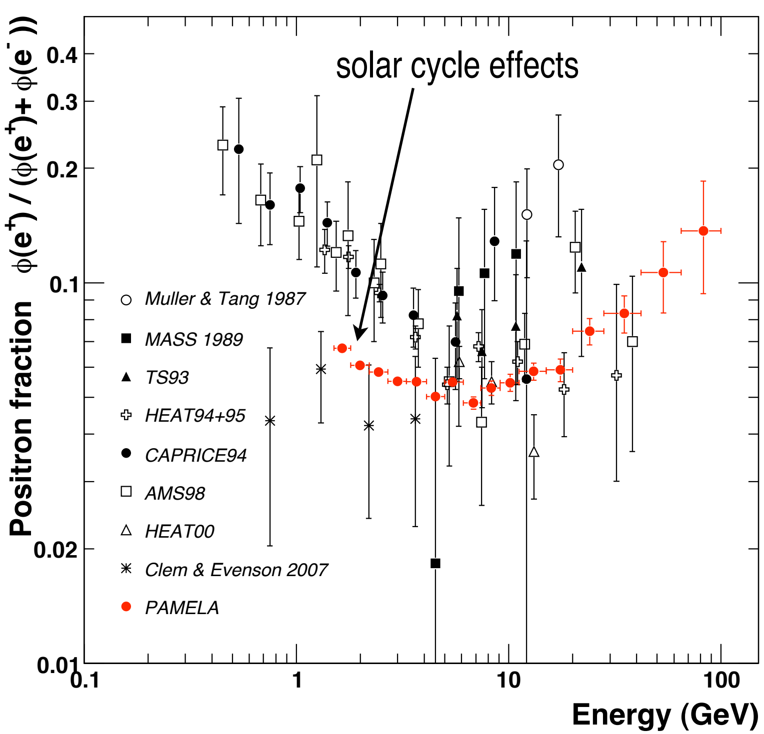
Morselli

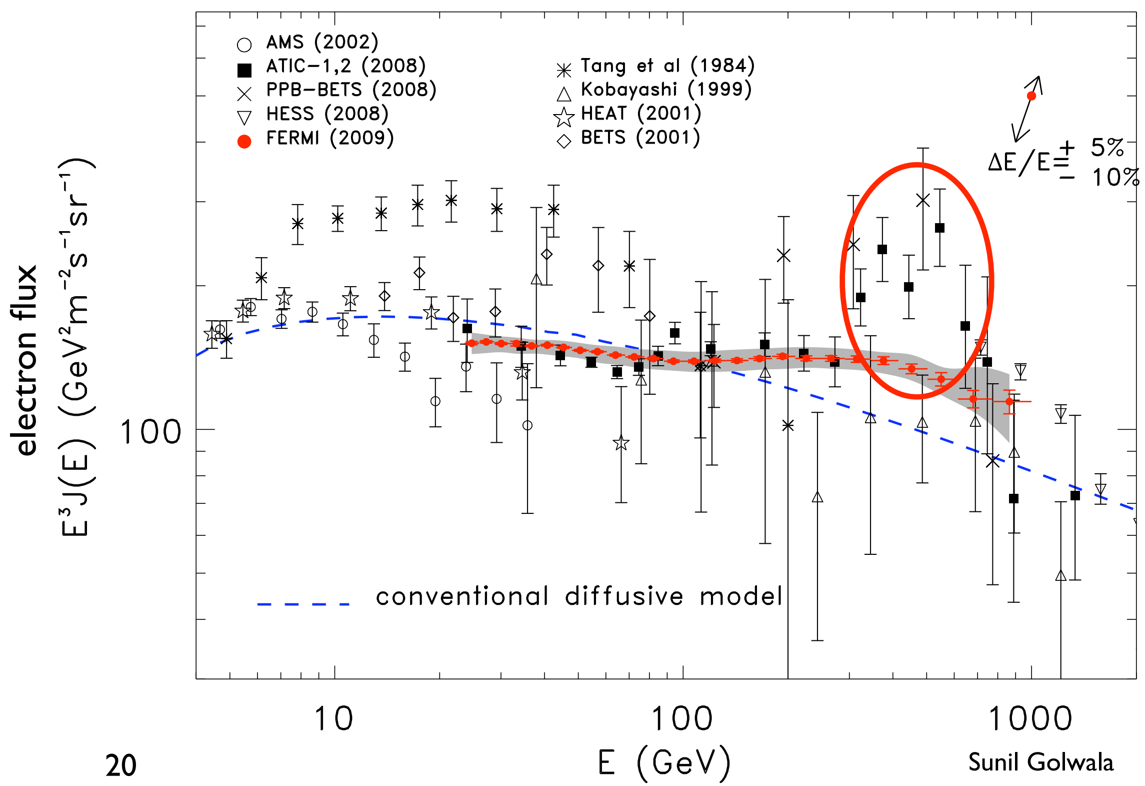


Vassiliev

Antimatter

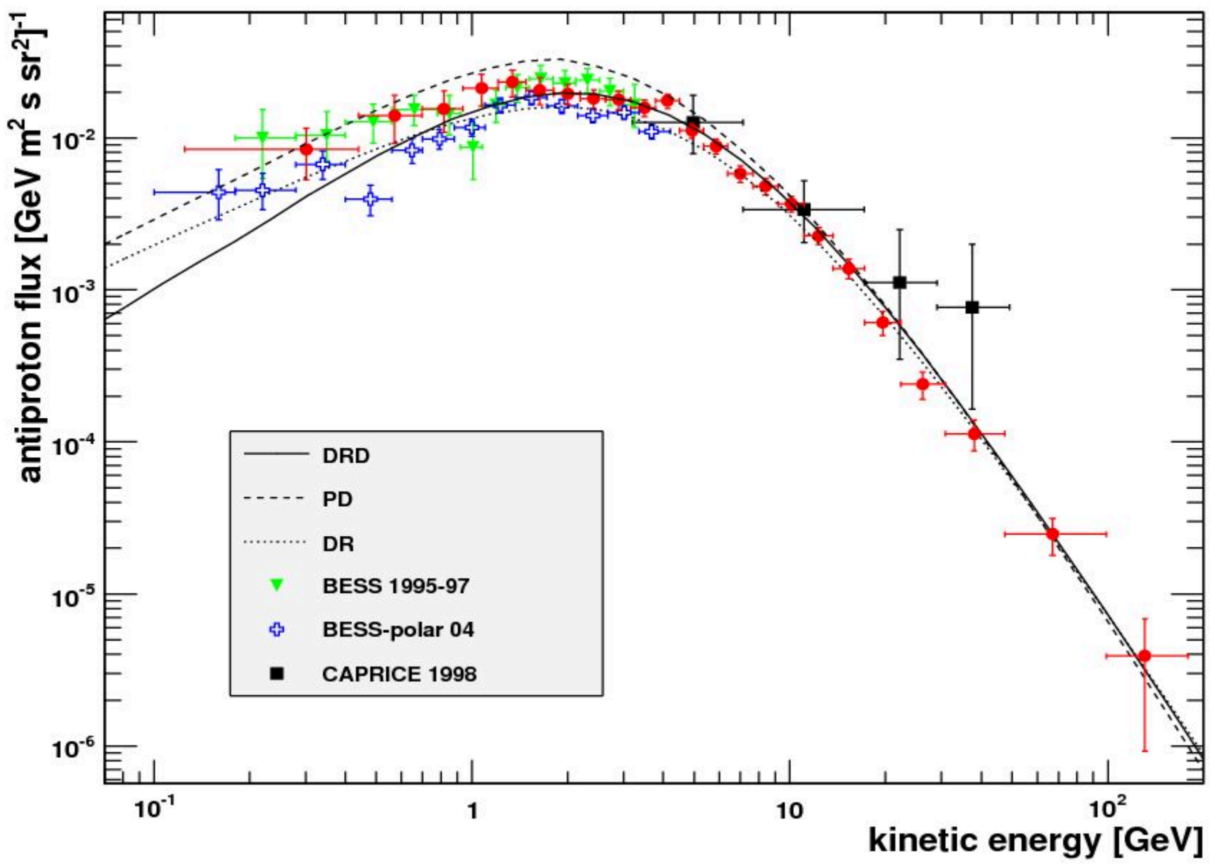
- Positrons:
  - Measure dE/dx and rigidity, ID those too light to be CR and w/wrong sign to be electrons
    - key experimental issue: misidentification of p as e^+. Need 10^3-10^4 rejection.
  - HEAT balloon payload (mid-1990s) saw a bump in e^+/e^- consistent with WIMP annihilation
  - PAMELA satellite (launched 2006) has confirmed rise in positron fraction
  - ATIC, PPB-BETS balloons saw bump in total electron flux, not seen by Fermi
  - PEBS balloon will measure fraction to much better precision up to 200 GeV
  - See Aaron Pierce's talk for scientific interpretation



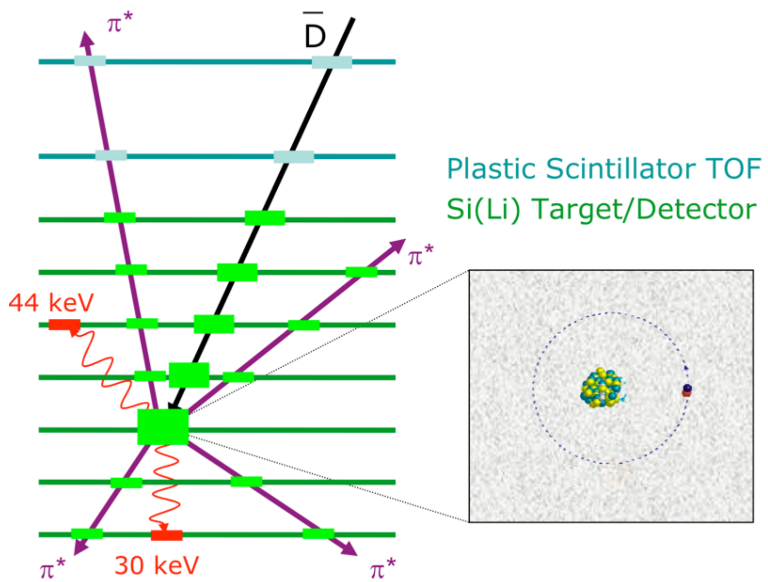


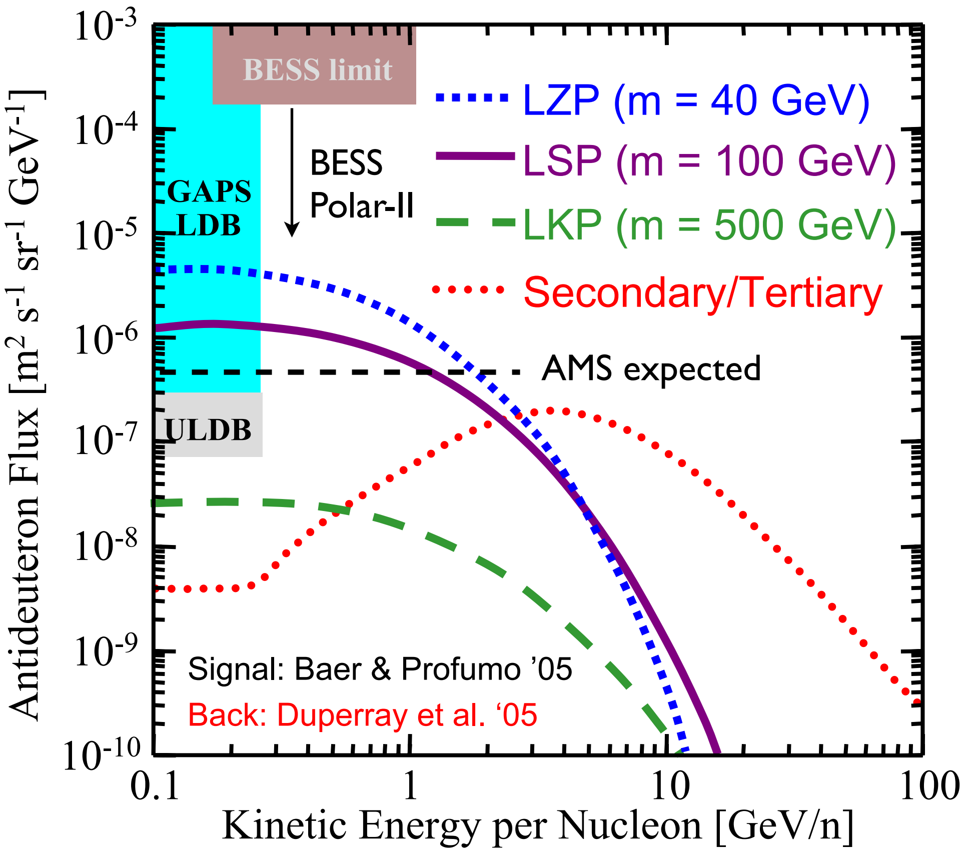
Antimatter

- Antiprotons
  - Previous experiments measurements have been fully consistent with expected spectrum
  - PAMELA has improved precision greatly
  - No sign of signal from vanilla WIMP consistent with positron excess
  - See A. Pierce's talk



Antimatter





- Antideuterons
  - Antideuteron production possible during hadronization of annihilation products
  - Expected flux at earth far exceeds backgrounds from cosmic ray spallation; a very different regime than positron and antiproton searches (Donato, Baer and Profumo)
- GAPS
  - Detects antideuterons by capture: Antideuteron slows to stop in detector, forms atom; antideuteron atom deexcites via X-rays and Auger electrons; annihilation into pions
  - Challenging! 200 kg of Si(Li) wafers target (~5000 4" wafers), coincidence demo'd in beam test; test flight 2009, Antarctic long-duration balloon 2013, perhaps 100-day ULDB

Direct Detection: Signature

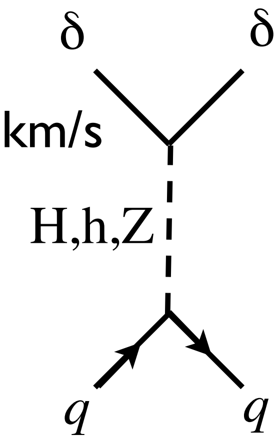
- WIMPs collected in spherical isothermal halo: ideal gas with gravity, $kT = \langle mv^2/2 \rangle$, $\sqrt{\langle v^2 \rangle} \approx 220$ km/s
- WIMPs elastically scatter off quarks in target nuclei, producing nuclear recoils, with $\sigma_{q\delta}$ related to σ_{ann} (same diagrams: via Z, h, H, and squarks)
- Energy spectrum of recoils is exponential, $\langle E_R \rangle \sim 50$ keV, depends on WIMP and target masses: Boltzmann distribution (spherical isothermal halo) + NR s-wave scattering

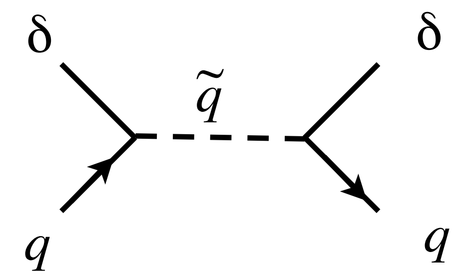
$$E_0 = \frac{2\, m_\delta^2\, m_N}{(m_\delta + m_N)^2}\, v_0^2 \approx \frac{m_N}{10^6} \sim 50\ \mathrm{keV}$$

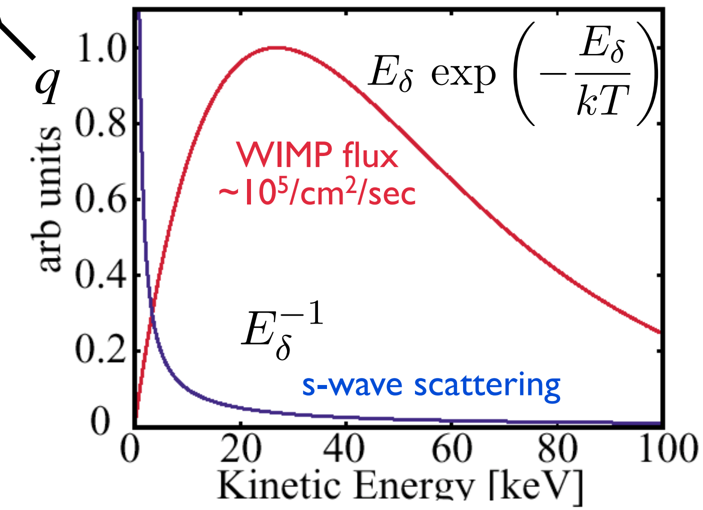
- Amplitude of recoil energy spectrum, i.e. event rate, normalized by $\sigma_{n\delta}$, local WIMP number density, and nucleus-dependent $A^2F^2(E_R)$:

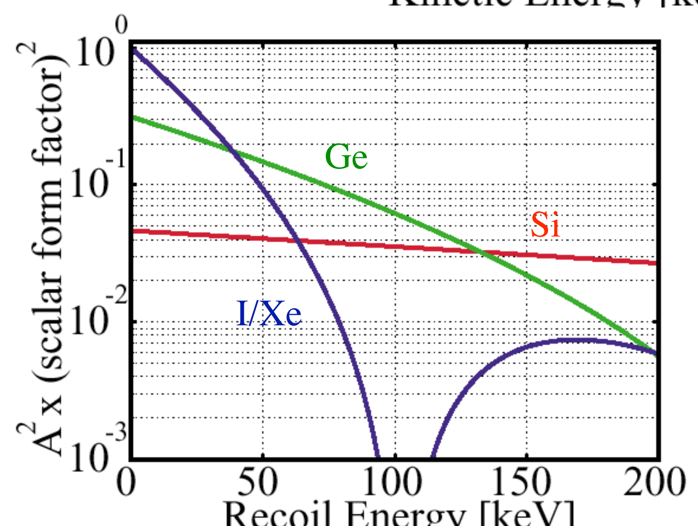
$$\frac{dR}{dE_R} \propto \frac{n_\delta\, \sigma_{n\delta}}{E_0} \exp\left(-\frac{E_R}{E_0}\right) A^2\, F^2(E_R)$$

- At low E_R, scattering is coherent and $\propto A^2$. Coherence lost at larger E_R via form factor $F^2(E_R)$









Scattering Cross Sections

- In general, a Lorentz-invariant Lagrangian L has *S, P, V, A* interactions
- WIMP can be fermion, boson, or scalar
- In non-relativisitic limit, reduces to two cases
  - Scalar interaction, scales as A^2 because deBroglie wavelength is large

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

f_p and f_n are effective couplings to p and n, equal in most theories under consideration

  - Spin-spin interaction couples to net nuclear spin J_N

$$\sigma_{SD} = \frac{32}{\pi} G_F^2 \frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2} \frac{J_N + 1}{J_N}\left(a_p \langle S_p \rangle + a_n \langle S_n \rangle\right)^2$$

$\langle S_p \rangle$, $\langle S_n \rangle$ are total proton and neutron spin contributions

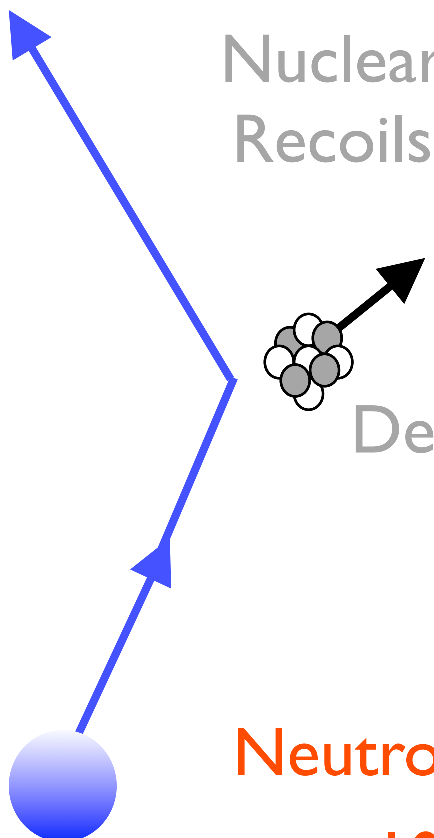
a_p and a_n are couplings to p and n

WIMP Direct Searches

- Fundamental goal: See a very small WIMP signal in presence of many other particles interacting in detectors (photons, electrons, alpha particles, neutrons)
- Many different techniques:
  - Reduce backgrounds
    - (HDMS, IGEX), CoGeNT: Ge γ spectrometers
    - XMASS: single-phase LXe
  - Reduce backgrounds + annual modulation
    - DAMA: NaI scintillator; KIMS: CsI scintillator
  - Statistical nuclear recoil discrimination
    - DAMA, UKDMC: pulse-shape analysis in NaI, LXe
  - Event-by-event nuclear recoil discrimination
    - phonons + ionization/scintillation: CDMS, EDELWEISS, CRESST, ROSEBUD
    - Liquid Nobles: direct electronic excitation + ionization: XENON, ZEPLIN, LUX, WArP, ArDM, DEAP/CLEAN, etc.
    - Superheated droplets: bgnd-insensitive threshold detectors; SIMPLE, PICASSO
    - DRIFT, DMTPC: TPCs engineered for low diffusion
  - Diurnal modulation
    - DRIFT, DMTPC

Nuclear Recoil Discrimination

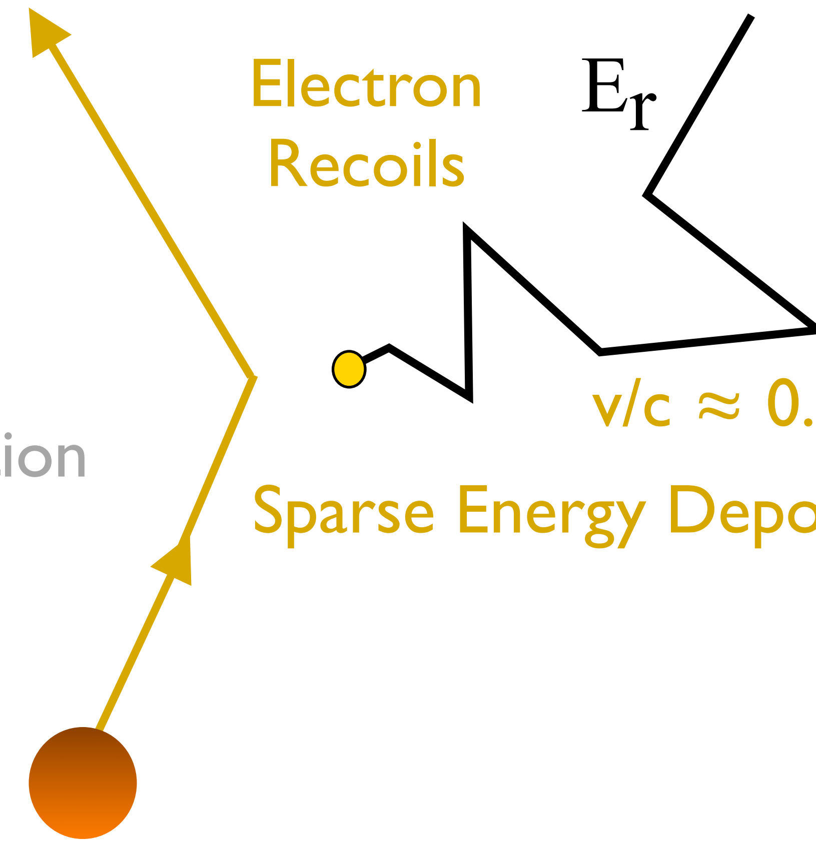
Signal



Neutrons same, but $\sigma \approx 10^{20}$ higher; must shield

δ

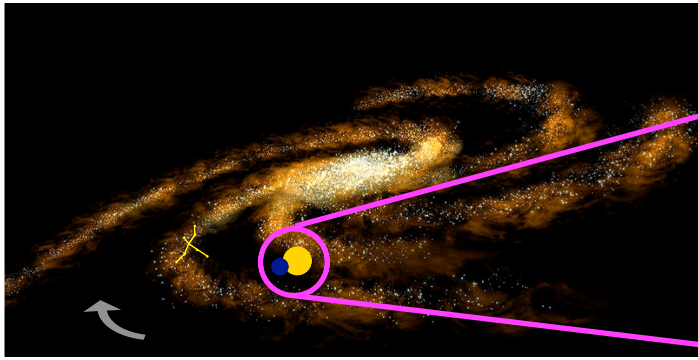
Background

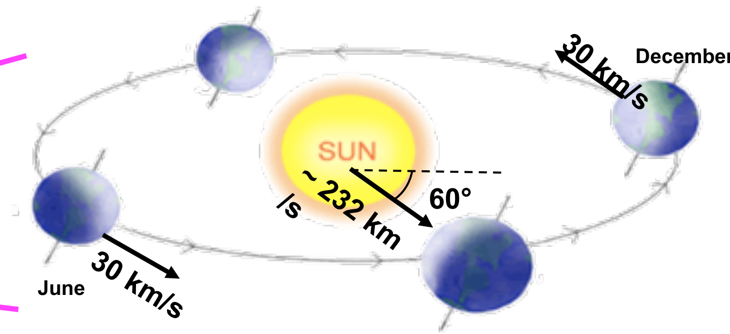


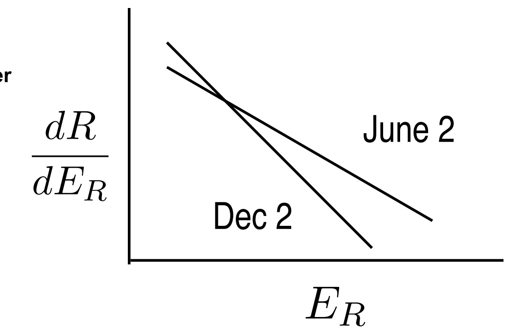
γ

Density/Sparsity: Basis of Discrimination

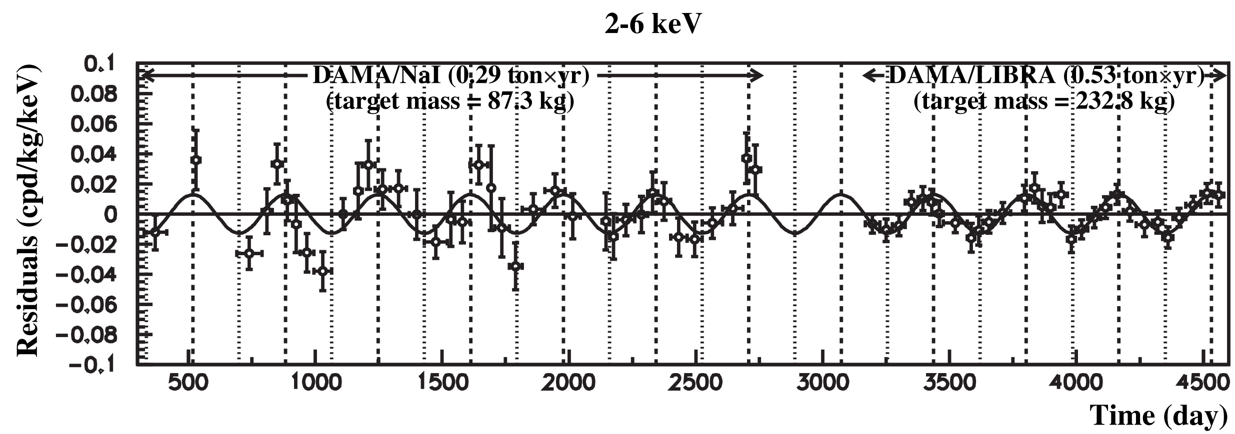
Annual Modulation

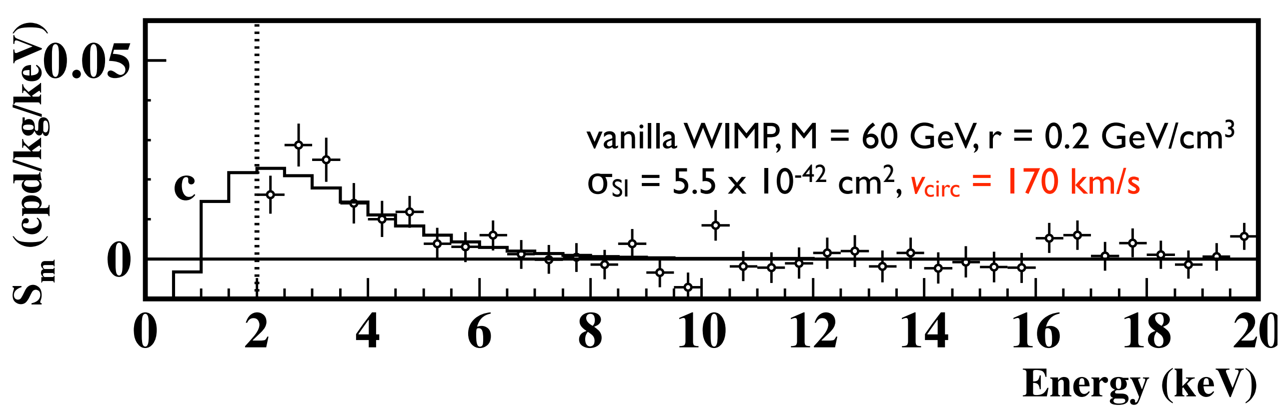






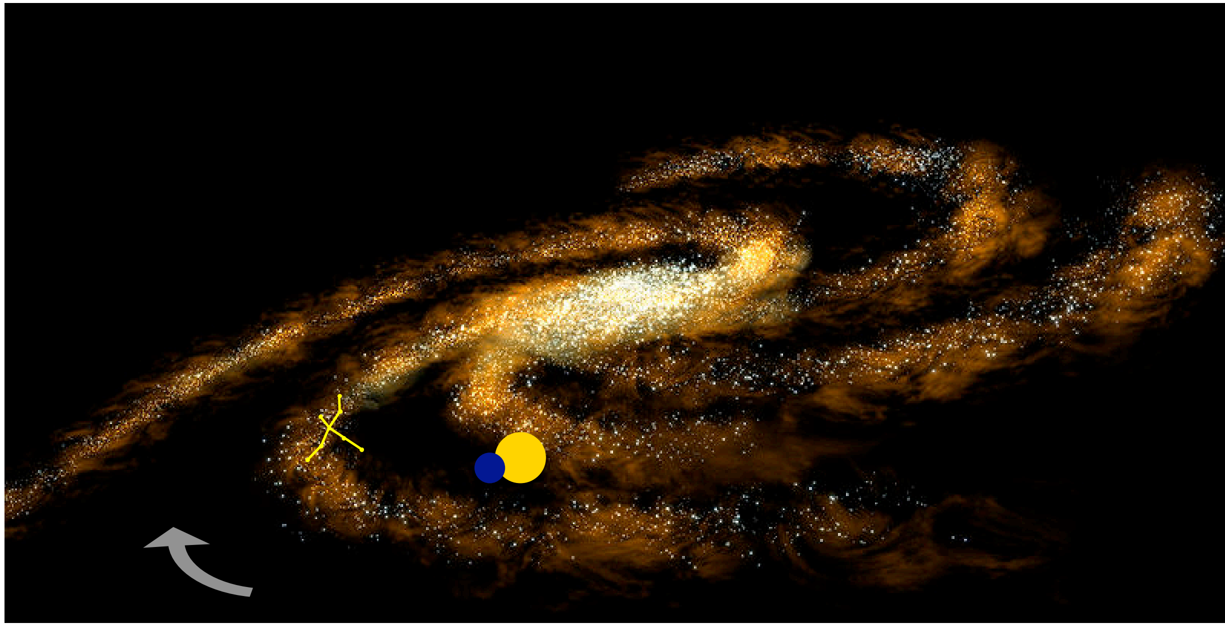
- WIMP wind ~ isotropic in halo frame, v_{rms} ~ 270 km/s
- Sun travels through this cloud at 270 km/s
- Earth adds or subtracts 15 km/s (= 30 km/s X cos 60^0) to solar velocity
- Expect ± 1-few % modulation in rate, energy deposition, depending on target and threshold
- DAMA/LIBRA: clear modulation; is it a WIMP?
- KIMS Korean CsI scintillator experiment aiming to test

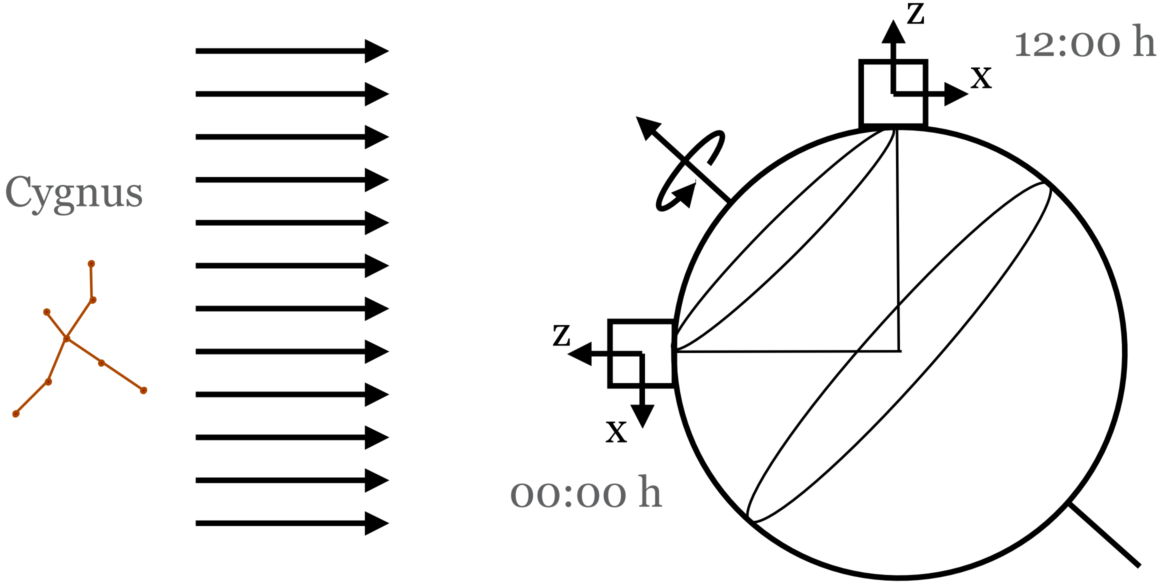


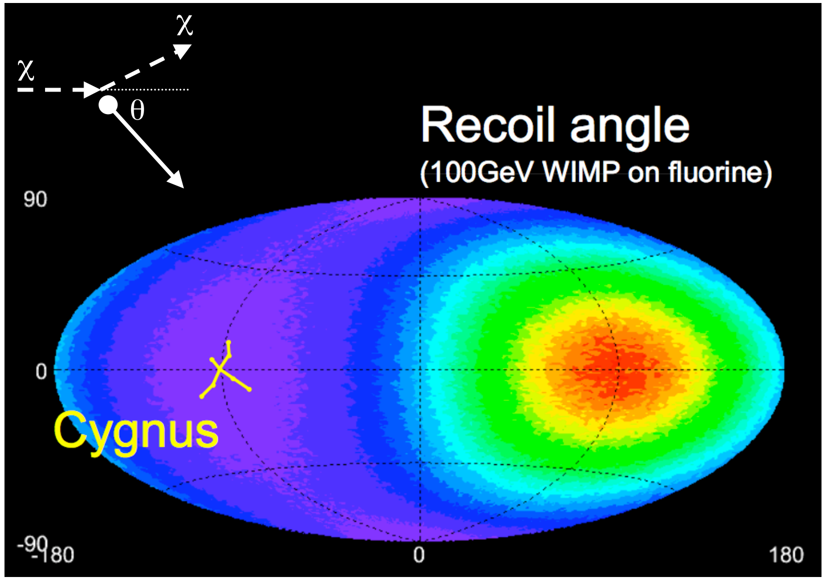


Diurnal Modulation

- 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



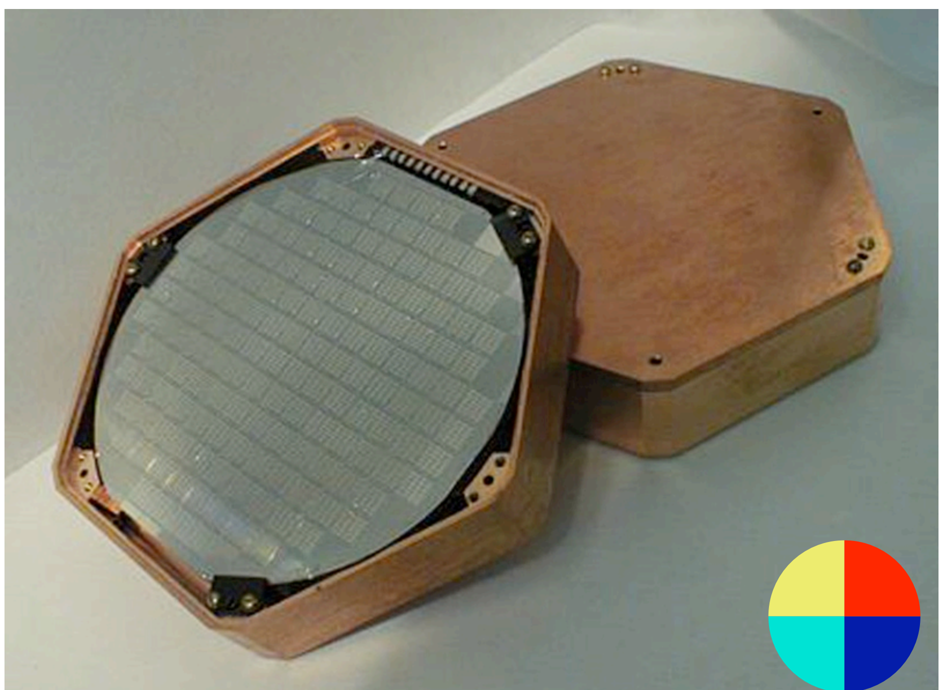


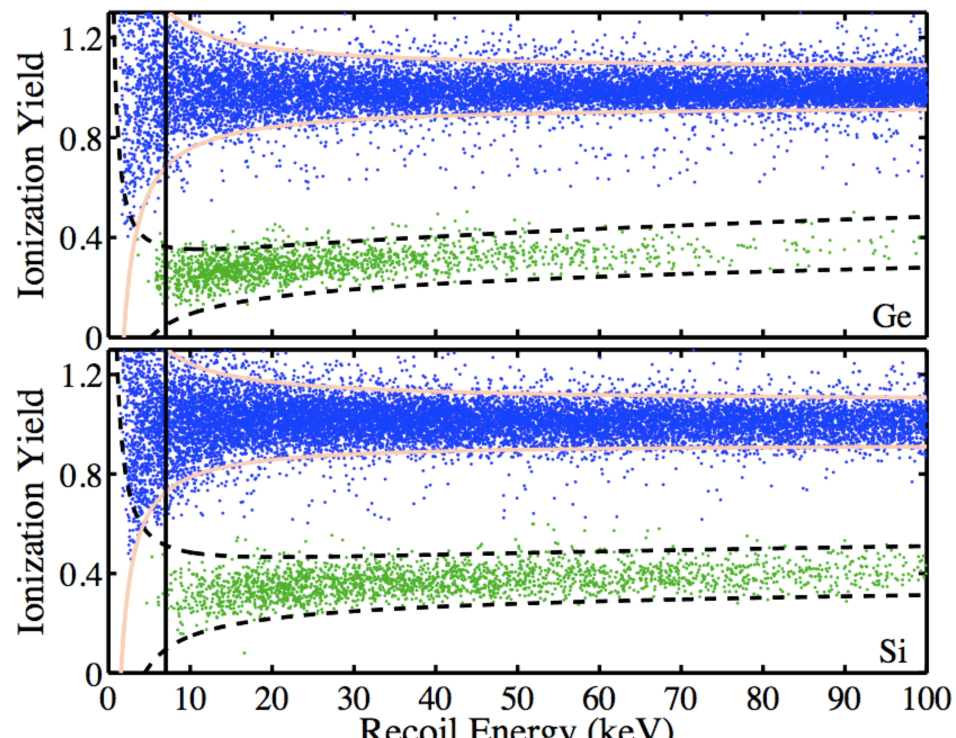


Figures courtesy of J. Battat

Cryogenic Dark Matter Search (CDMS)

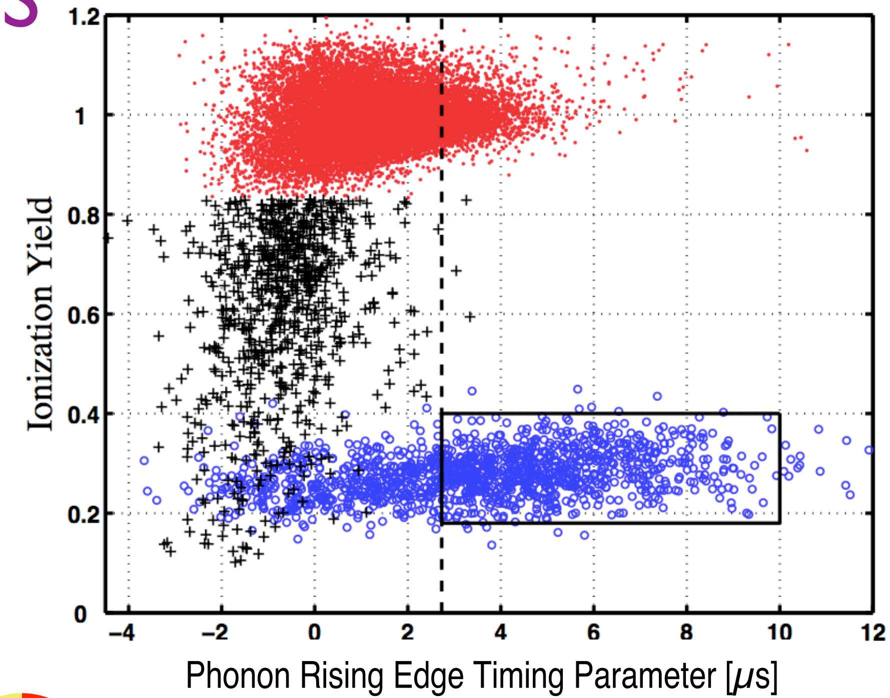
- NR discrimination via total recoil energy + ionization + phonon timing/position:
  - phonon signal provides total recoil energy (athermal phonon sensor using tungsten transition-edge sensors attached to aluminum phonon absorbers)
  - ionization signal depends on density of deposition, ionization yield ~ 1/3 for NRs in Ge
    - Collected using H-a-Si electrodes to minimize dead-layer effects
  - detectors close-packed with no intervening material: detectors see other clean detectors, not outside radiation sources
  - radial segmentation of electrode enables rejection of events at outer edge of detector
  - Also: CRESST, EDELWEISS, ROSEBUD (no time to discuss here)

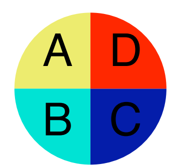


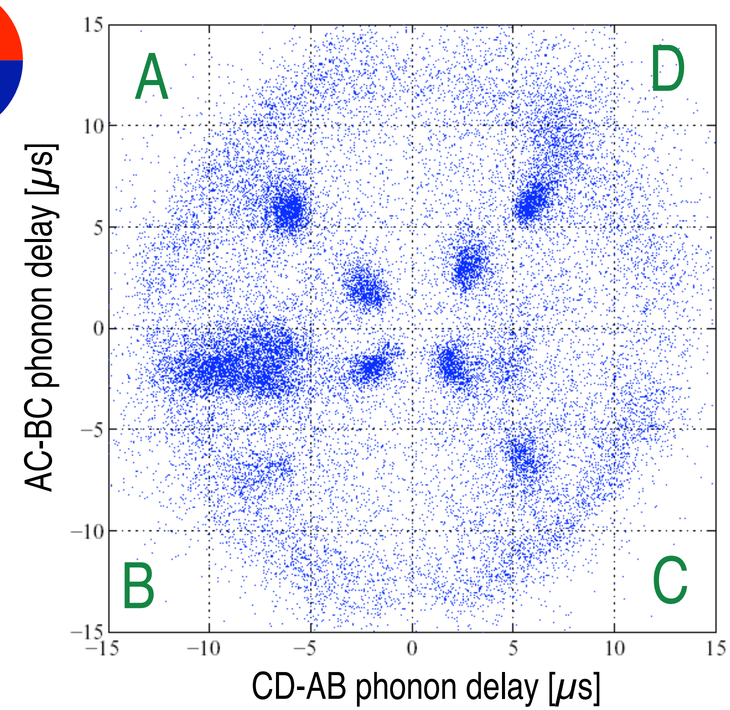


CDMS

- Dead layer and athermal phonons
  - tens of μm deep "dead layer" due to loss of hot charges into "wrong" electrode before drift field takes over
  - athermal phonon sensor provides rejection: phonon signal rising edge provides 2-d imaging and sensitivity to z position; latter provides rejection of ionization dead-layer events
- Background rejection (15-45 keV, 50-70% acceptance)
  - in CDMS II:
    2×10^{-6} misid of gamma events
    2×10^{-3} misid of surface electron events
  - SuperCDMS:
    1×10^{-7} for gammas,
    2.5×10^{-4} for surface electrons
- Final CDMS II results expected late summer/early fall; see Oleg Kamaev talk for status update in PAC II, Tuesday 2pm

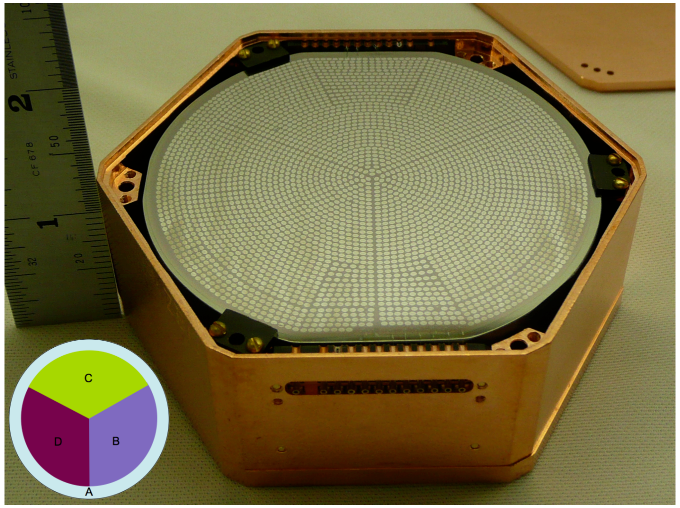




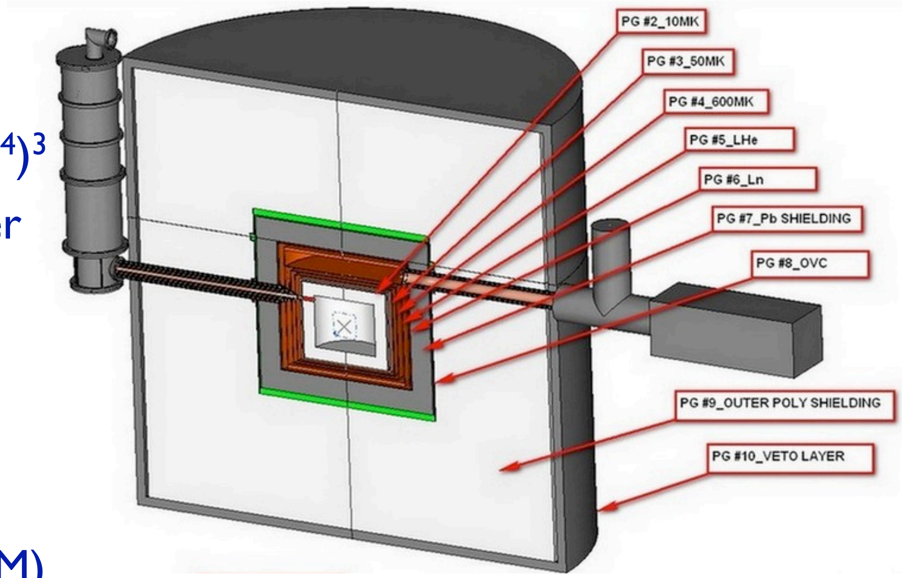


SuperCDMS

- SuperCDMS Soudan:
  - 1 cm → 2.5 cm thickness (0.25 kg → 0.65 kg)
  - New phonon sensor design reduces surface event misid
  - New understanding that cosmogenic neutron bgnd much lower than previously expected (2000 mwe)
  - 16 kg total: 5 x 10^{-45} cm^2 reach at end of 2011, likely limited by apparatus background
  - Production of first 8 kg funded, proposal for second 8 kg and running submitted Oct 2008



- Breaking news (LTD13)
  - new electrode design ID's surface events with < 3 x 10^{-4} misid in three independent ways; Need underground demo to demonstrate $(3 \times 10^{-4})^3$
  - EDELWEISS has similar results (one method, better limit on misid bec of underground demo)
- Enables:
  - SuperCDMS SNOLAB
    - 100 kg mass; reach of 3 x 10^{-46} cm^2
  - DUSEL Germanium Observatory for DM (GEODM)
    - 1.5 T mass, reach of 2 x 10^{-47} cm^2



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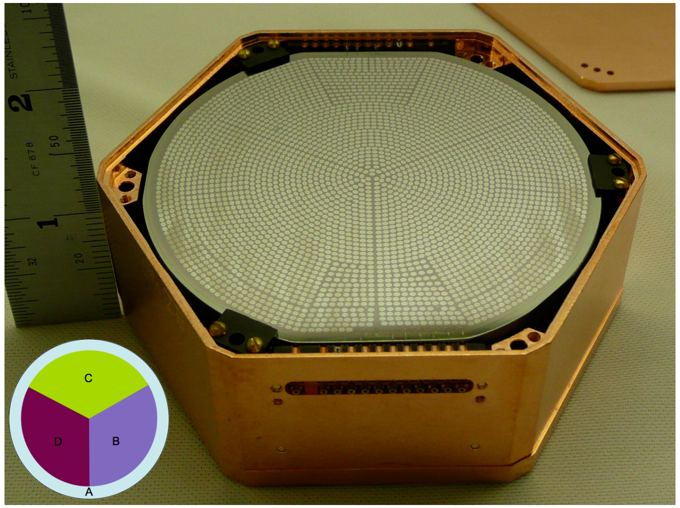

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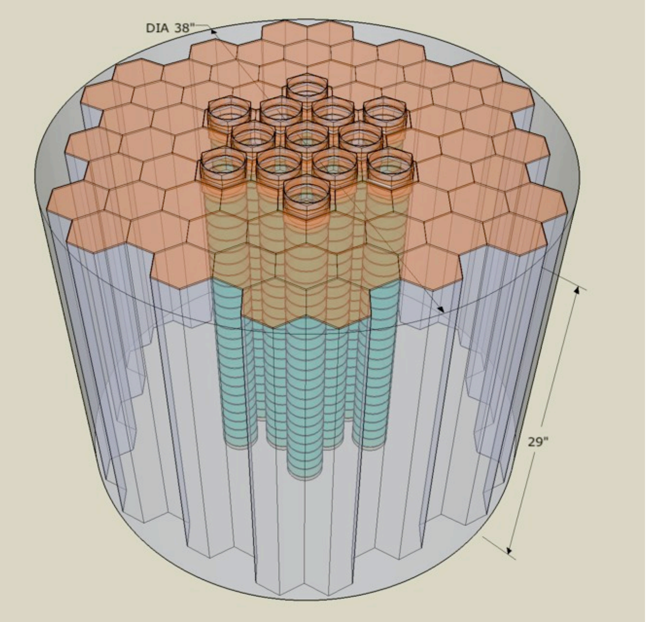

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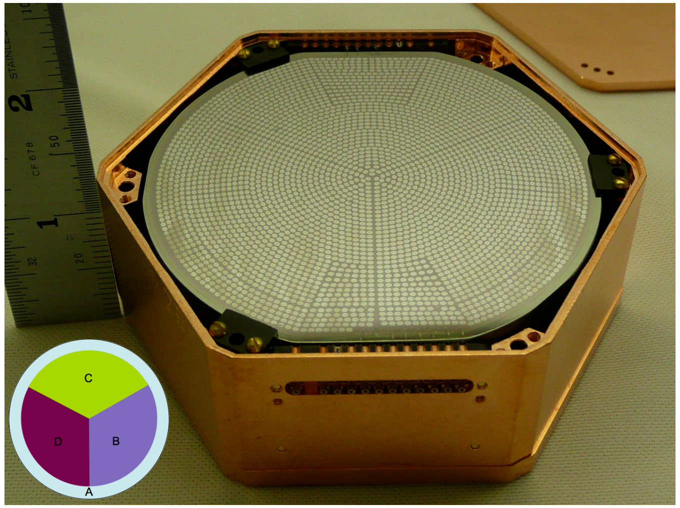

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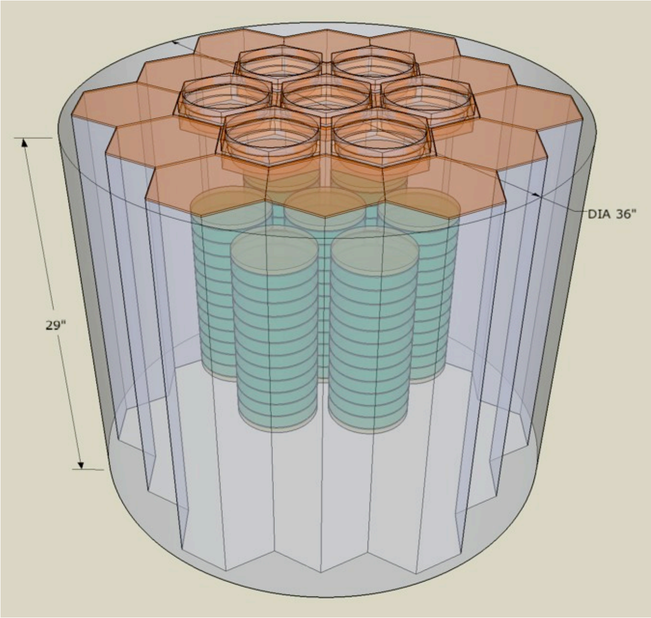
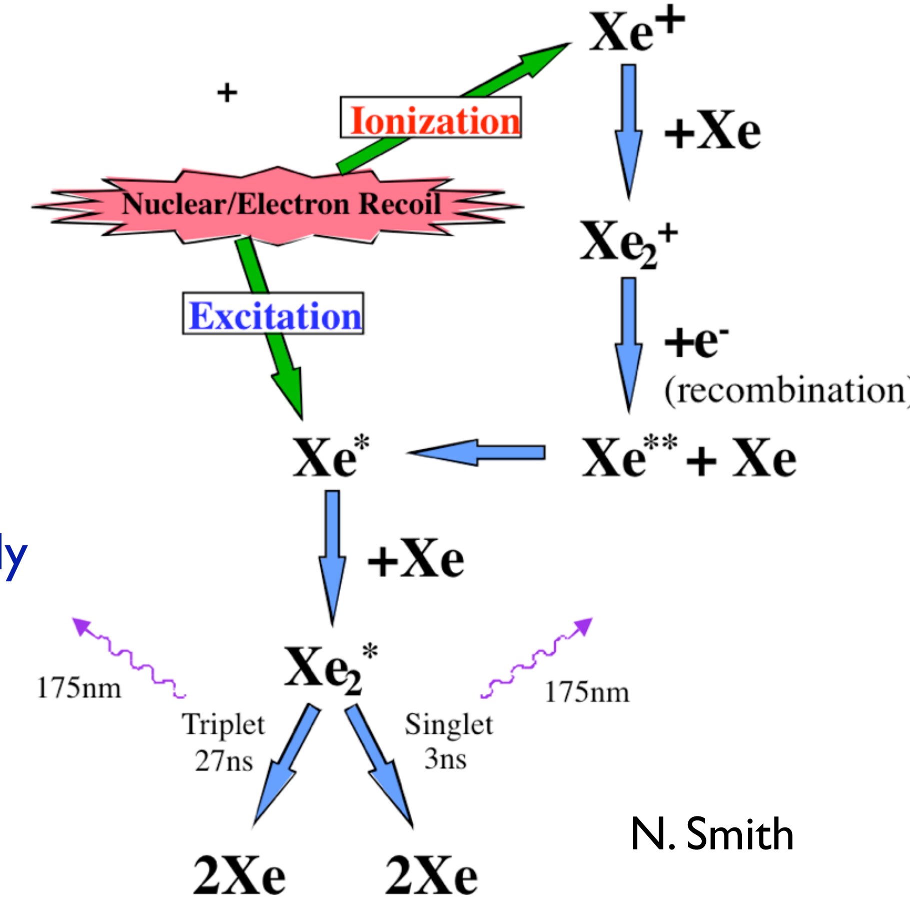


Noble Liquids/Gases

- Method:
  - ionization and direct excitation paths have different populations for nuclear and electron recoils
  - *independently*, different paths populate fast singlet and slow triplet states differently
- Implementations:
  - LXe: observe scintillation and drift e-
  - LNe: observe slow and fast scintillation
  - LAr, GXe: both



N. Smith

	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125	40,000	^{39}Ar, ^{42}Ar	1.6
LKr	2.4	120	1200	150	25,000	^{81}Kr, ^{85}Kr	0.09
LXe	3.0	165	2200	175	42,000	^{136}Xe	0.03

D. McKinsey

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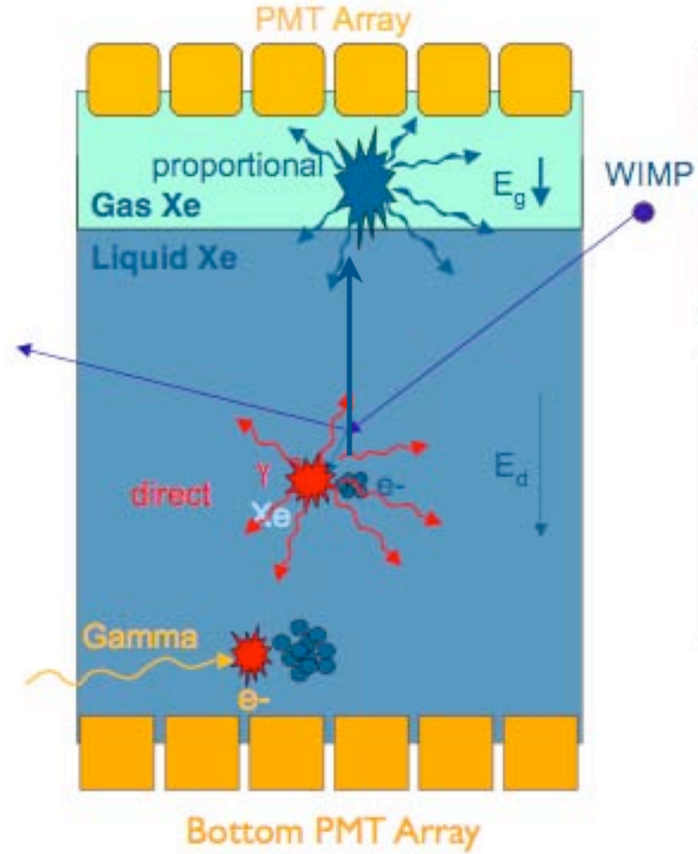

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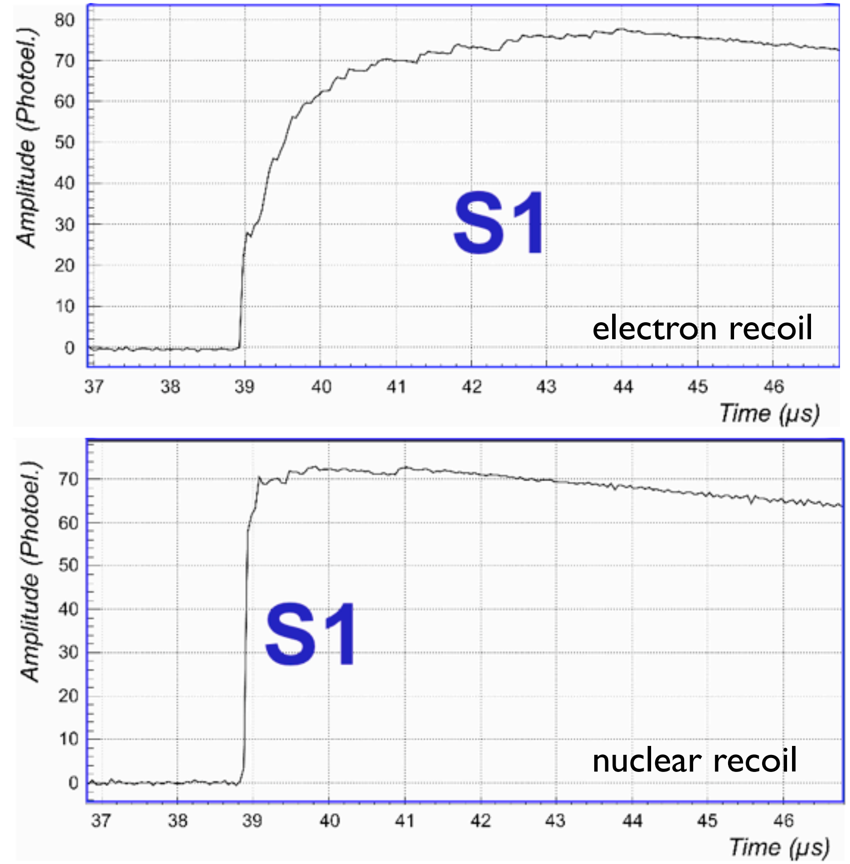

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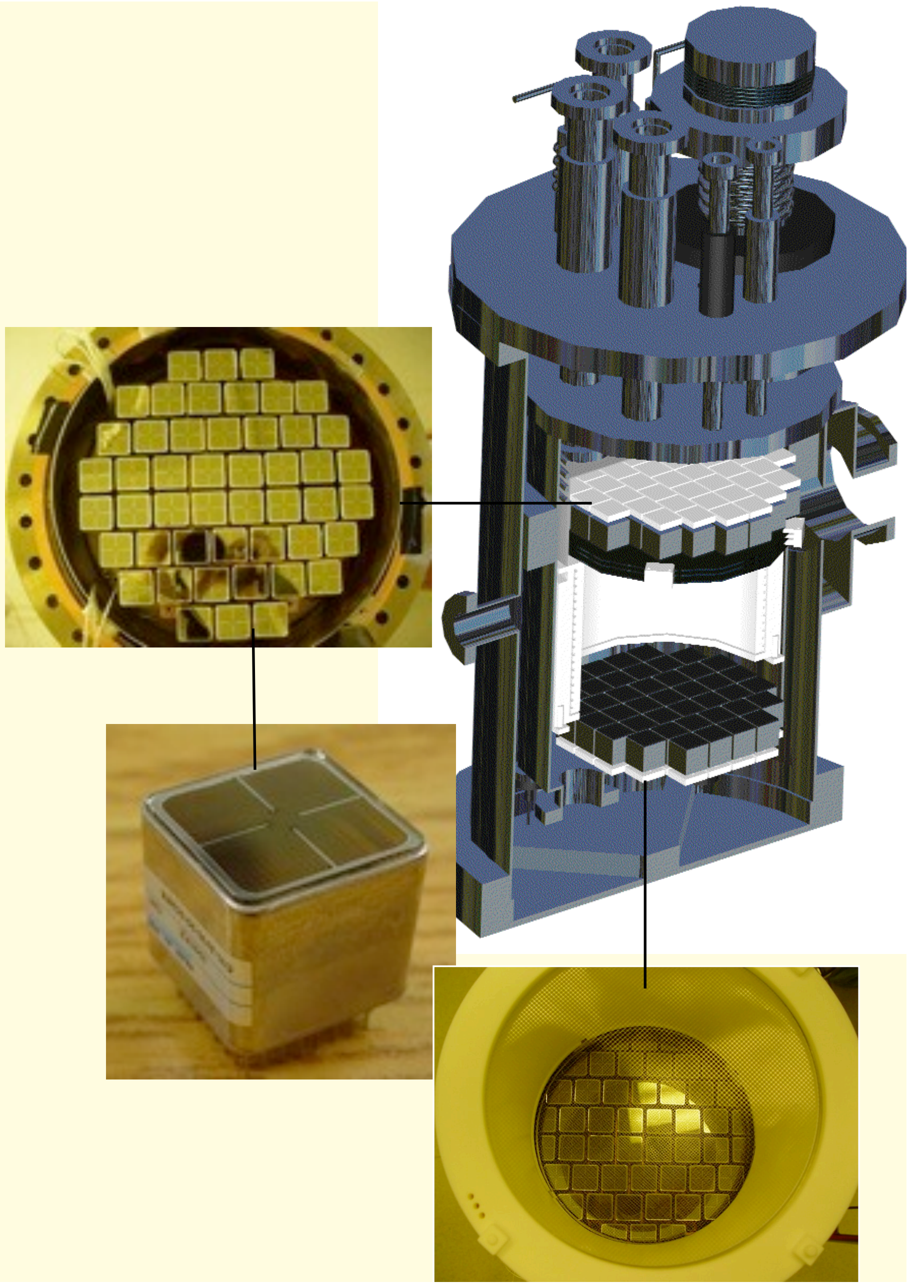
D. McKinsey

Liquid Xenon

- XENON10 (Gran Sasso)
  - First competitive LXe expt
    - 5.4 kg fiducial
    - good light collection (5 pe/keV)
    - good bgnds in in prototype
  - 2007 results limited by bgnd consistent with tail of EM into WIMP acceptance region
  - cutting harder will reduce NR acceptance from 50%
  - Scale-up needed to reduce bgnd by self-shielding, need to maintain ionization and light collection efficiency
- ZEPLIN III (Boulby)
  - similar idea, higher bgnds, less self-shielding
  - low-bgnd PMTs in process



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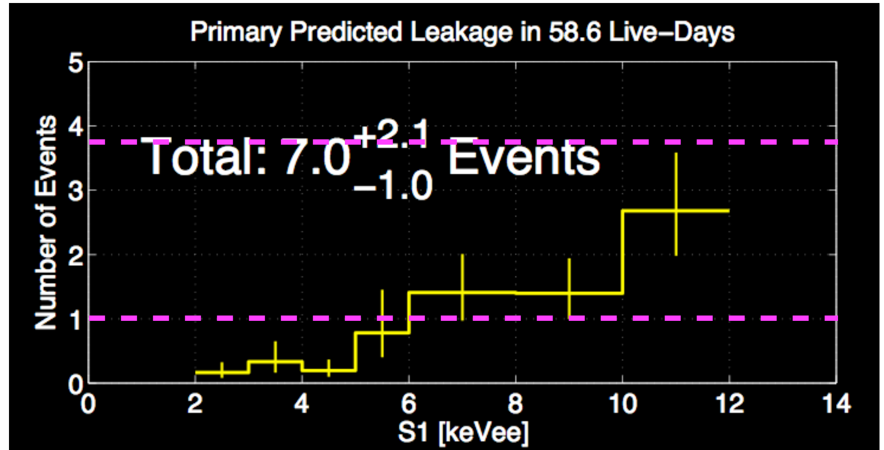
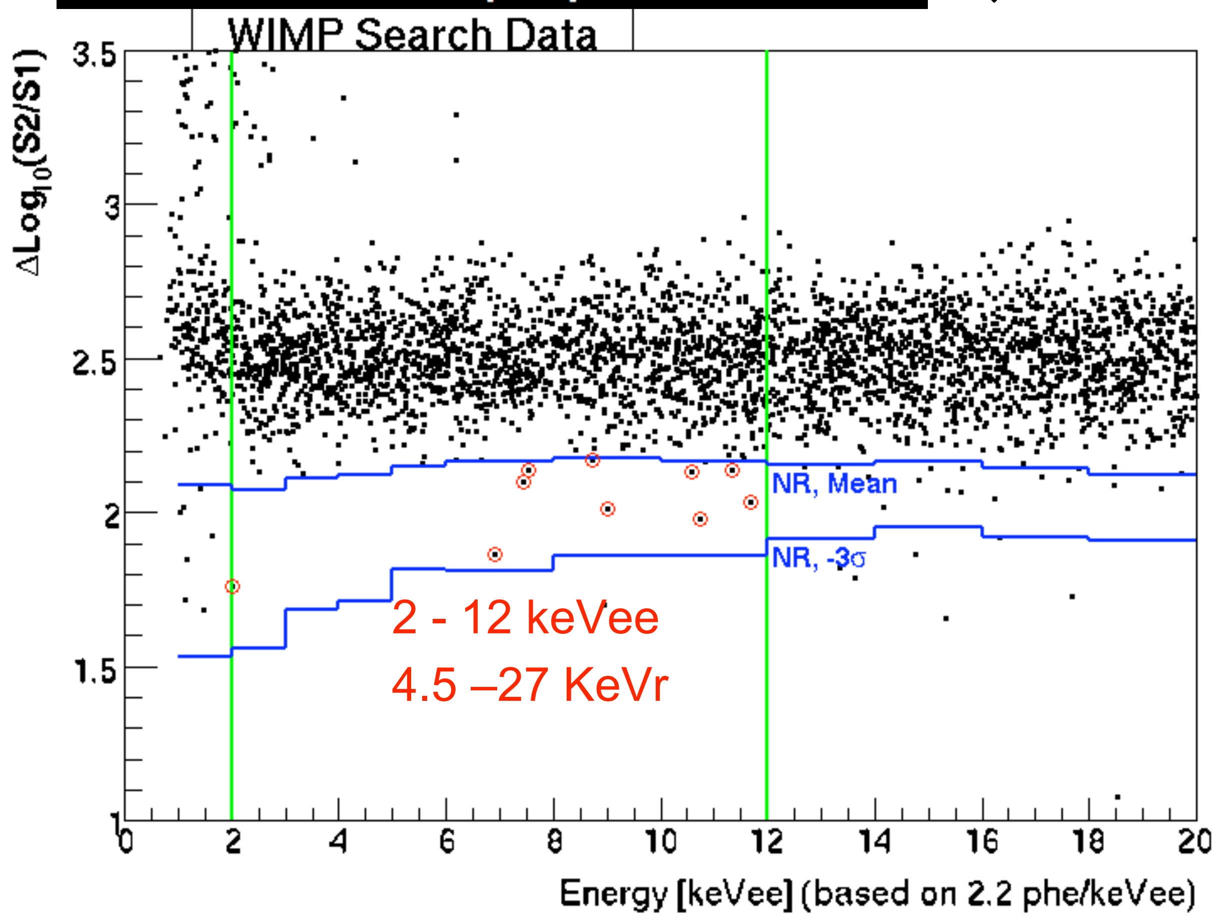


99.0% rejection

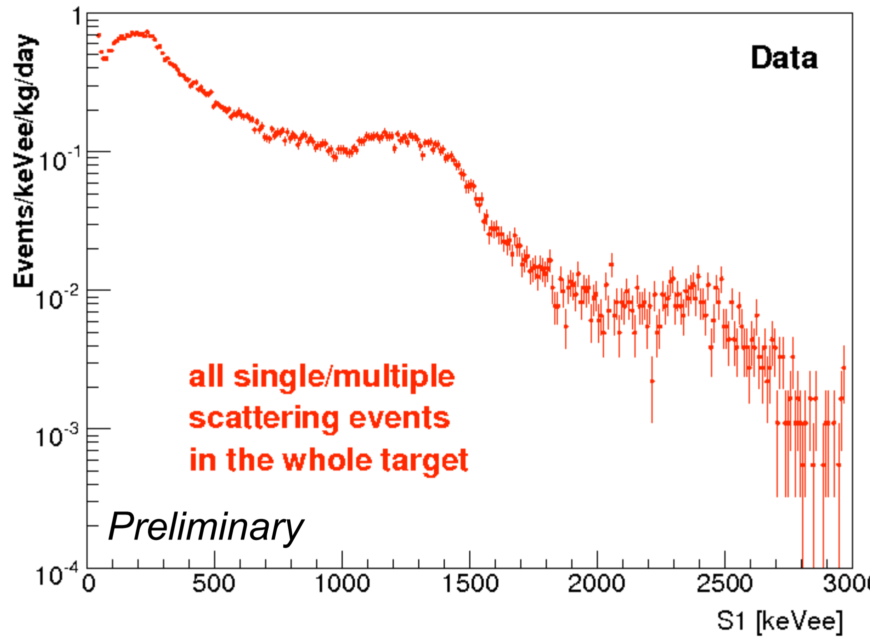
99.9% rejection



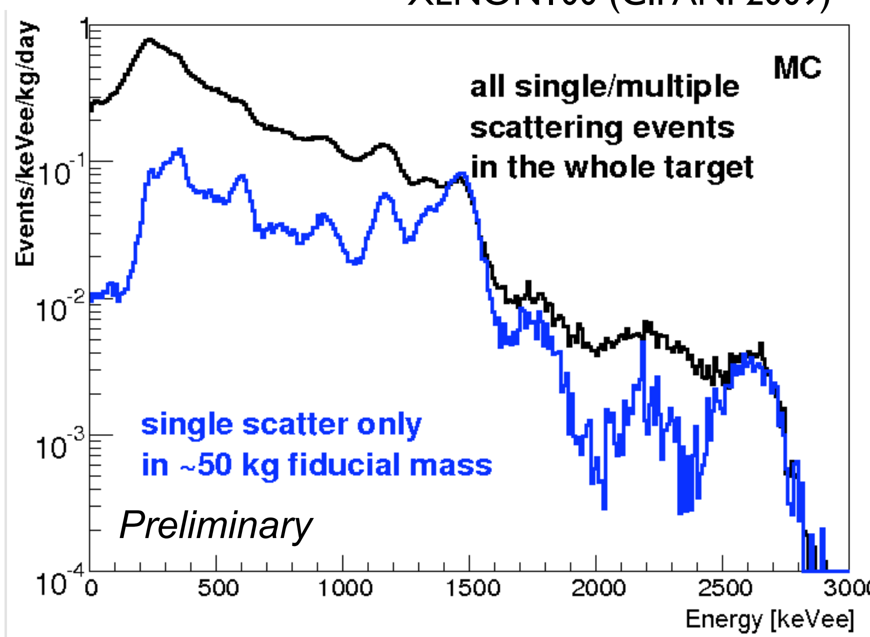
Liquid Xenon

- XENON100 (Gran Sasso)
  - upgrade of XENON10,
    50 kg fiducial, 170 kg total
  - cold and operating since mid-2008, working on light yield and bgnd issues, physics running to begin by end 2009
  - XENON 100+: 100-kg fiducial w/QUPIDs
- LUX (Sanford/Homestake)
  - high-bgnd test cryostat for 60 kg LXe operational w/0.5 kg LXe at Case
  - Ti cryostat in fab
  - constructing surface lab
  - 4850 ft level dewatered, deploy to surface lab in Fall, 2009, underground in 2010?
- XMASS
  - single-phase: self-shielding only, shielding built, detector in process, commissioning ~start 2010

XENON100 (CIPANP2009)

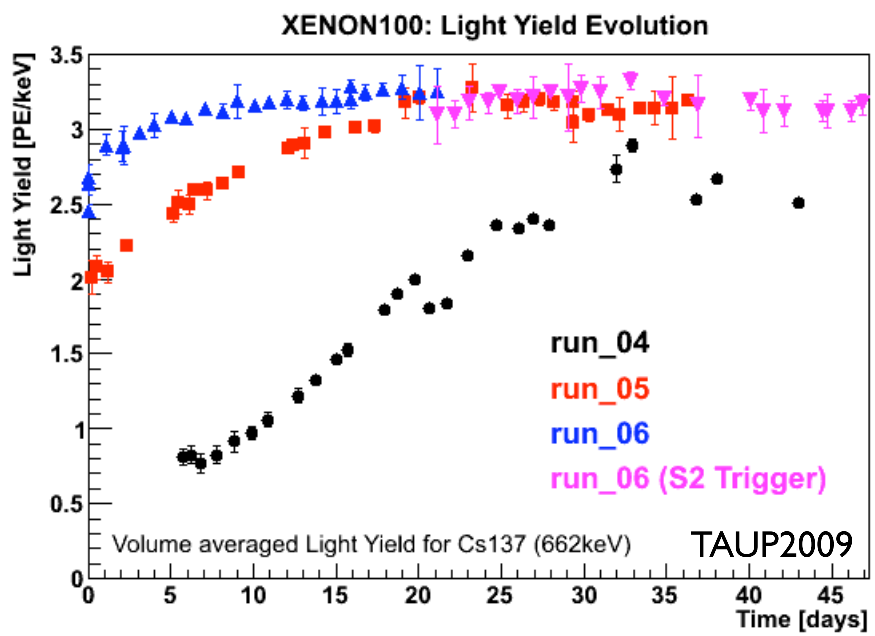


XENON100 (CIPANP2009)



Liquid Xenon

- XENON100 (Gran Sasso)
  - upgrade of XENON10, 50 kg fiducial, 170 kg total
  - cold and operating since mid-2008, working on light yield and bgnd issues, physics running to begin by end 2009
  - XENON 100+: 100-kg fiducial w/QUPIDs
- LUX (Sanford/Homestake)
  - high-bgnd test cryostat for 60 kg LXe operational w/0.5 kg LXe at Case
  - Ti cryostat in fab
  - constructing surface lab
  - 4850 ft level dewatered, deploy to surface lab in Fall, 2009, underground in 2010?
- XMASS
  - single-phase: self-shielding only, shielding built, detector in process, commissioning ~start 2010



3 pe/keV at 662 keV = 5 pe/keV at low energy

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LUX 0.1

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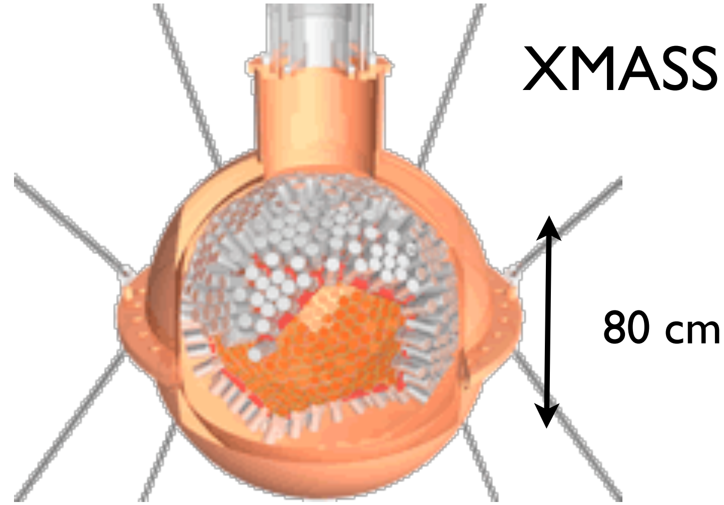
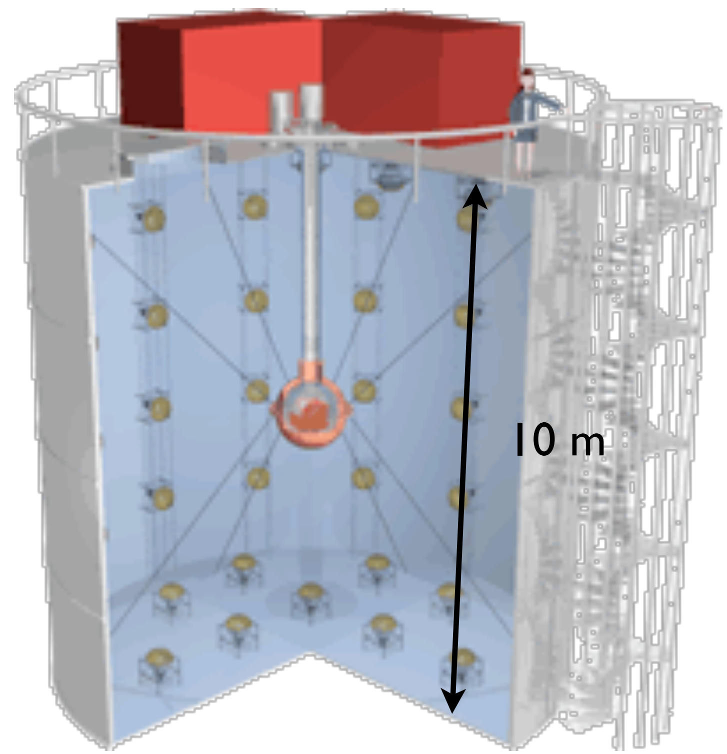


100 kg fiducial, 800 kg total



Liquid Argon

- WArP (Gran Sasso)
  - 140-kg detector being commissioned inside passive water shield, active LAr shield
- ArDM
  - still in R&D phase, but 1-ton R&D detector constructed and filled, uses fewer larger PMTs, uses LEMs for ionization gain
- DEAP/CLEAN (SNOLAB)
  - single-phase Ar/Ne
  - miniCLEAN:
    150 kg fiducial, 500 kg total
  - hall at SNOLAB under construction
  - detector under construction

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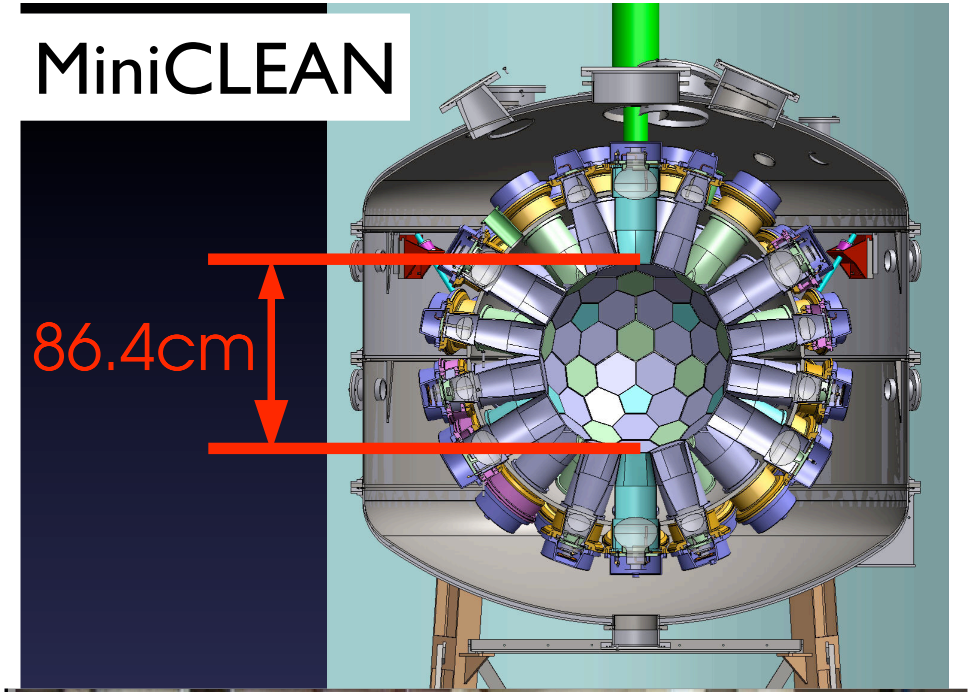
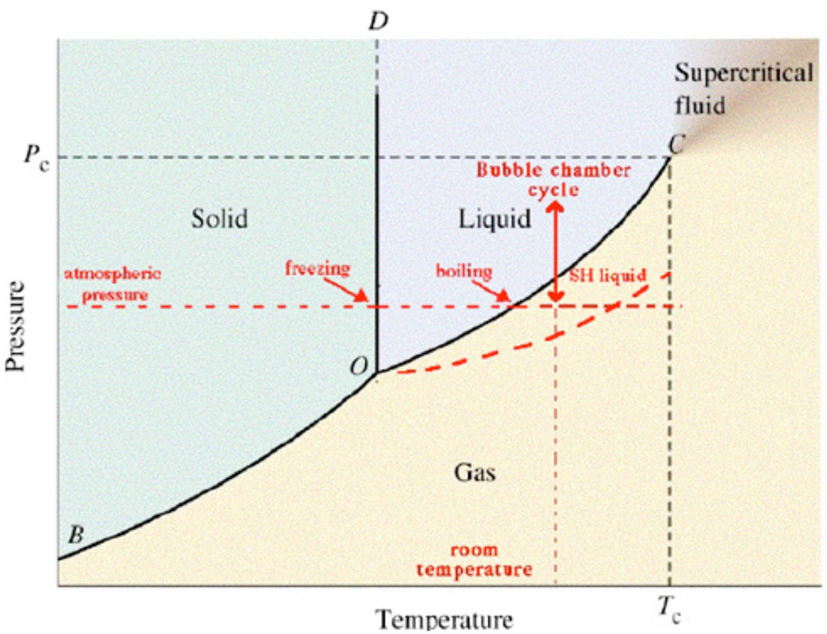
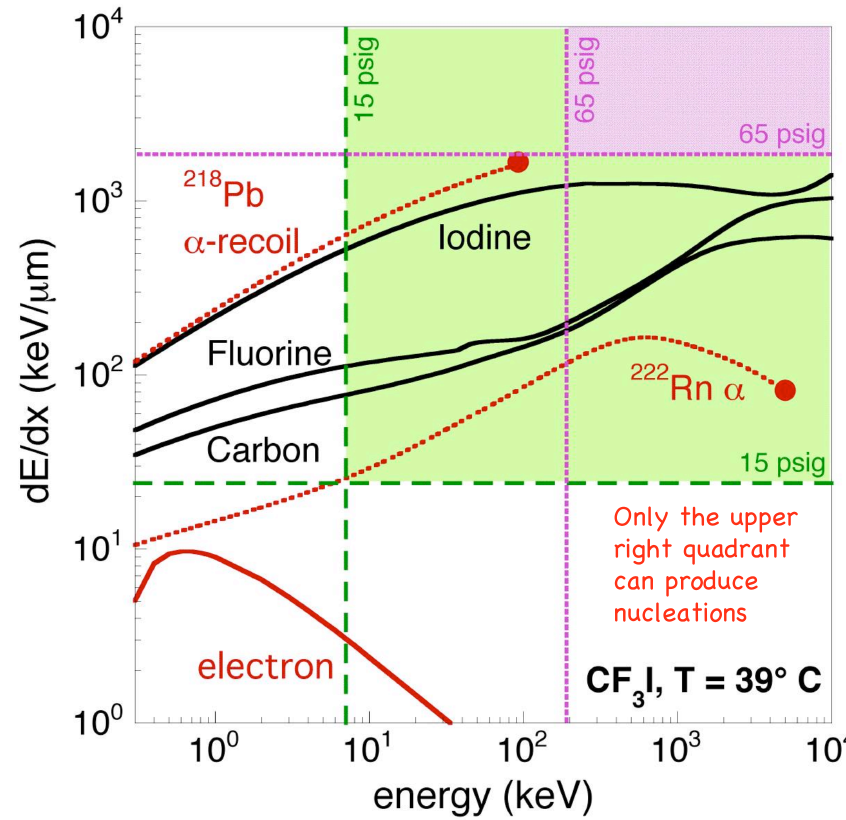


Metastable Bubble Chamber Detectors

- Bubble chamber
  - Superheated liquid or gel + energy density effect: ER deposition density too small to nucleate bubbles
  - Excellent rejection of ERs: >10^{13} @ 10 keVr threshold (COUPP)

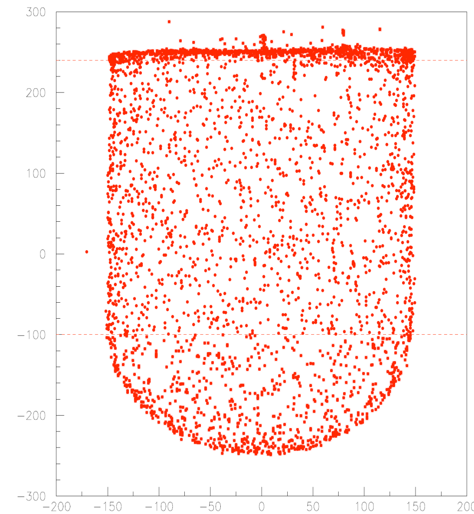




  - Threshold detector, controlled by temperature & pressure.
  - Video and acoustic readout
- Assorted nuclei, spin-indep (I and Br) and spin-dep (F)
- In principle, inexpensive

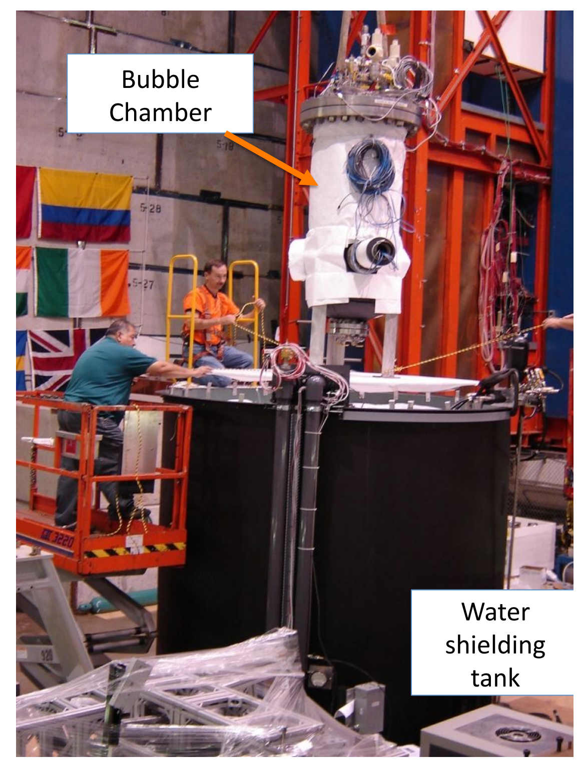
Metastable Bubble Chamber Detectors

- COUPP
  - video readout
  - prior run of 2-kg at 300 mwe limited by α bgnd from vessel (edge events) and α events from radon emanation into bulk
  - 60 kg tested at surface, running underground at 300 mwe with water shield; want to demonstrated alpha bgnd at Borexino levels
- PICASSO (SNOLAB)
  - acoustic (piezo) readout
  - 14 kg-d from 0.12 kg provides new spin-dep constraints
  - 1.9 kg running since start 2009
  - demonstrated NR/α discrim. via acoustic pulse height



COUPP
2-kg detector

COUPP
60-kg detector
surface test



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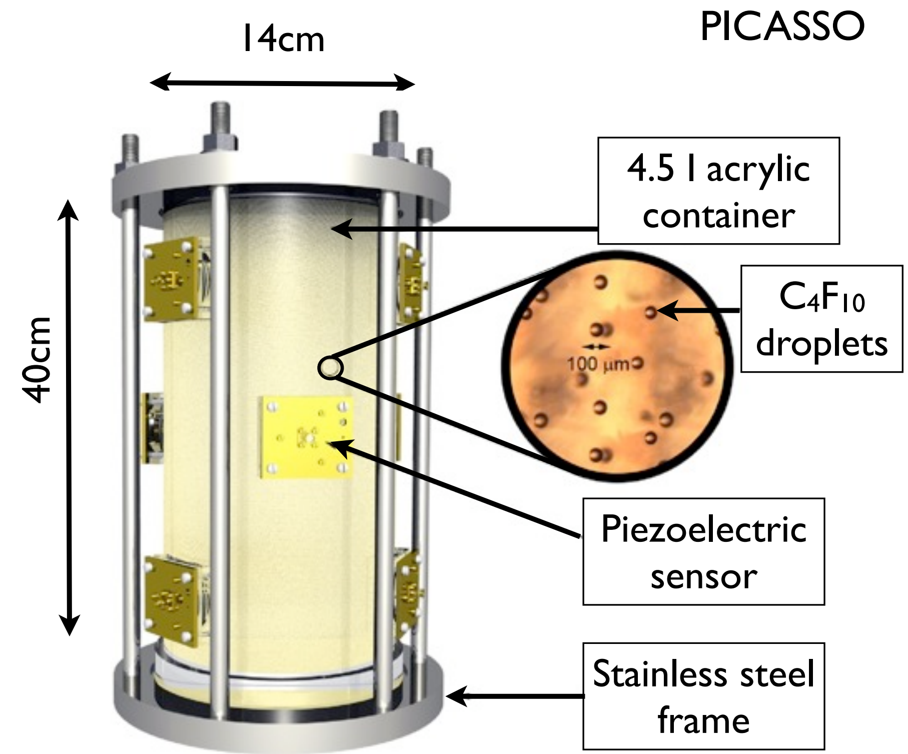
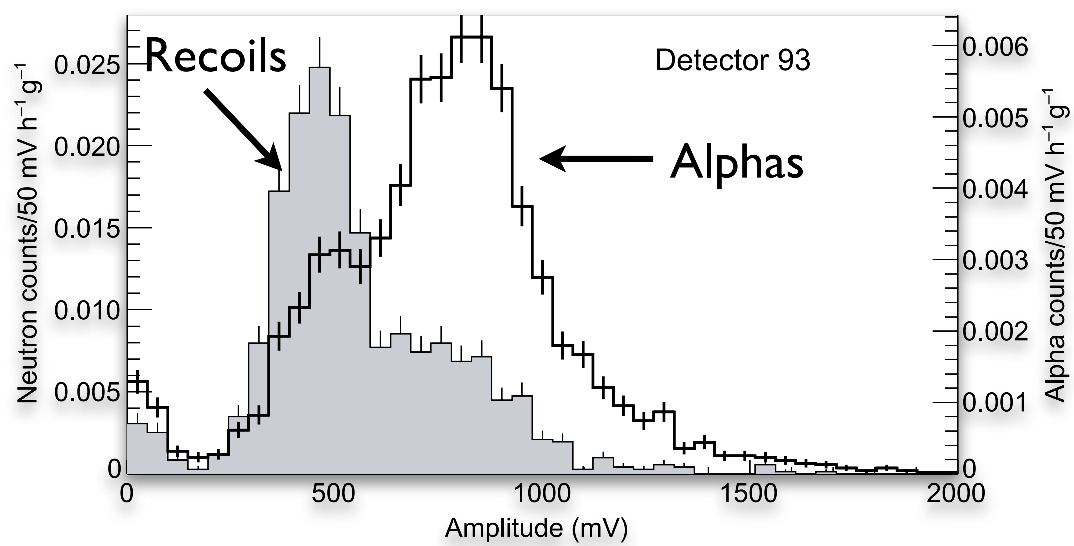
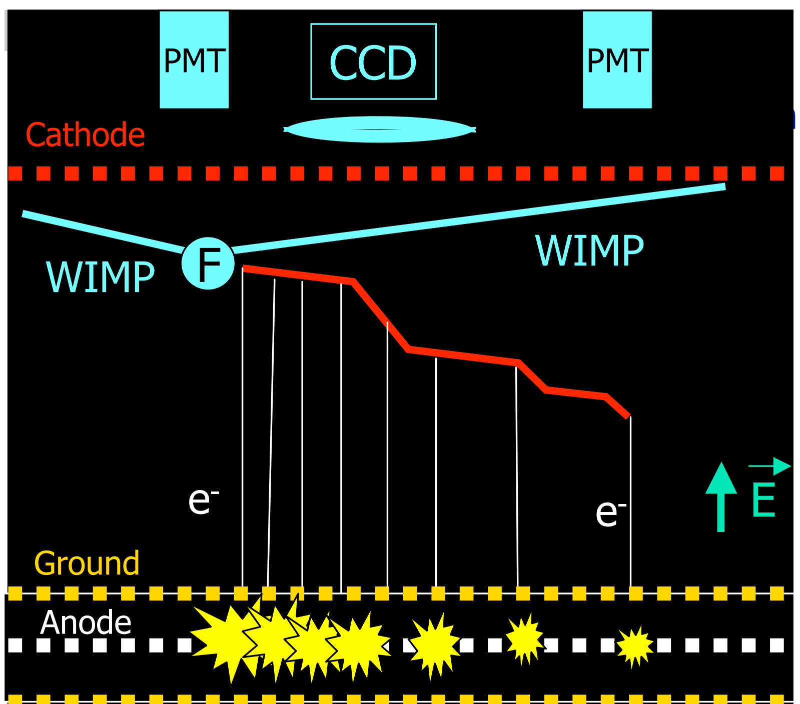




Time Projection Chambers

- DMTPC
  - CF_4 gas: low diffusion, scintillates well
  - PMTs for trigger, z information
  - CCD images avalanche region to obtain energy, xy track orientation (good posn resolution with CCD, ~100 μm)
  - Excellent gamma/beta rejection based on track size
  - head/tail based on dE/dx: directionality!



- DRIFT
  - negative ion TPC, e- + $CS_2 \rightarrow CS_2^-$: drifting of heavy ion suppresses diffusion
  - 2 mm pitch anode + crossed MWPC grid give xyz imaging and energy
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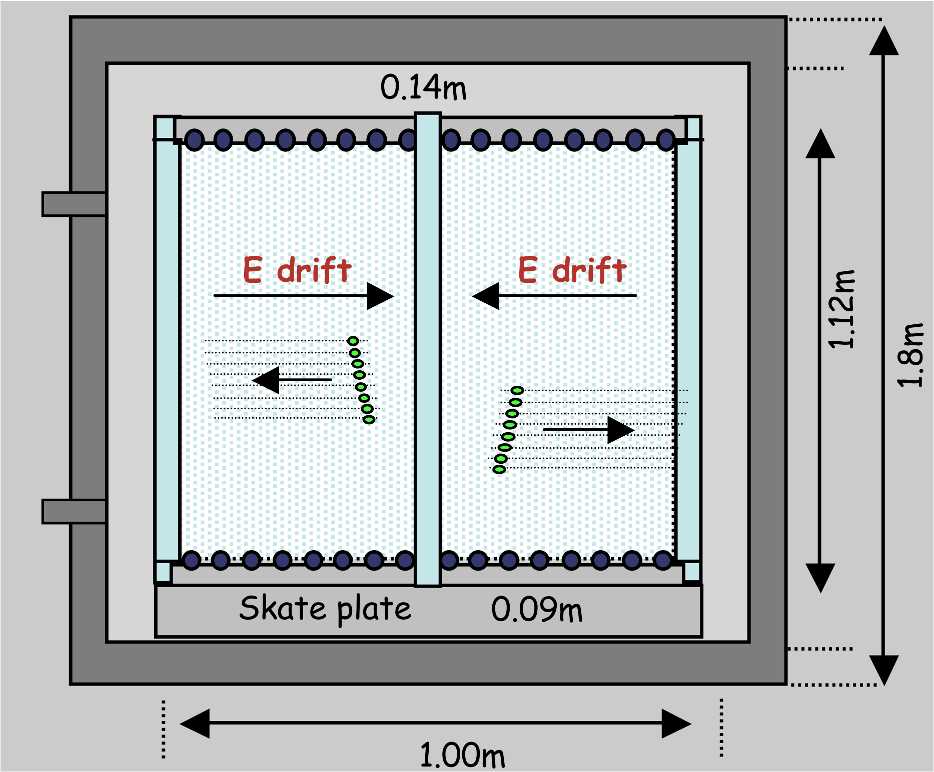

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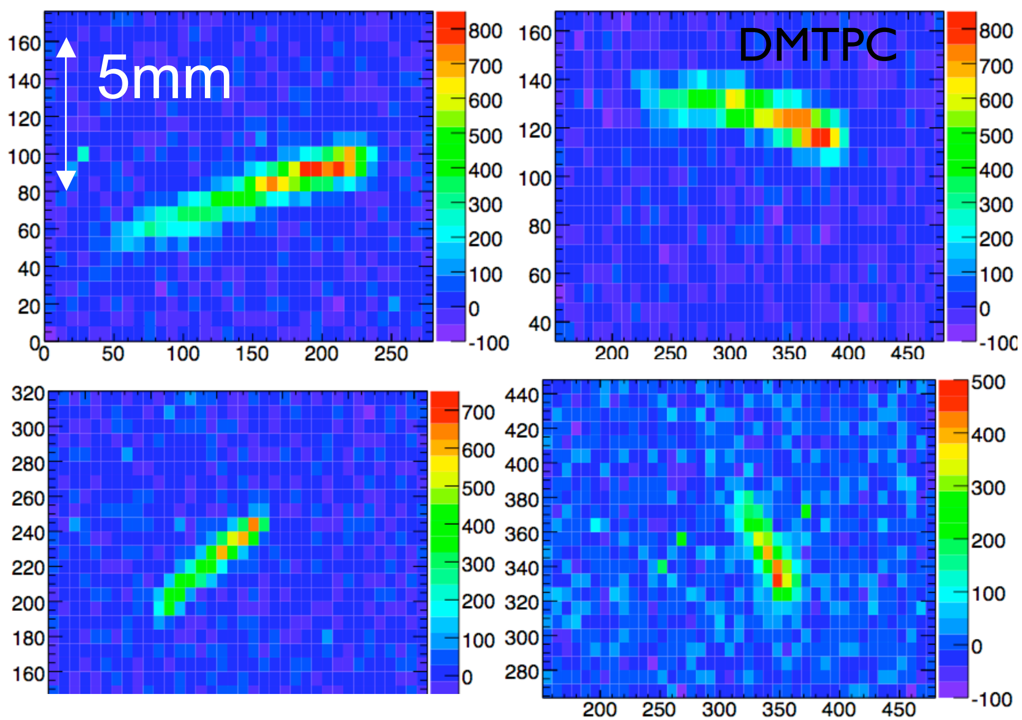

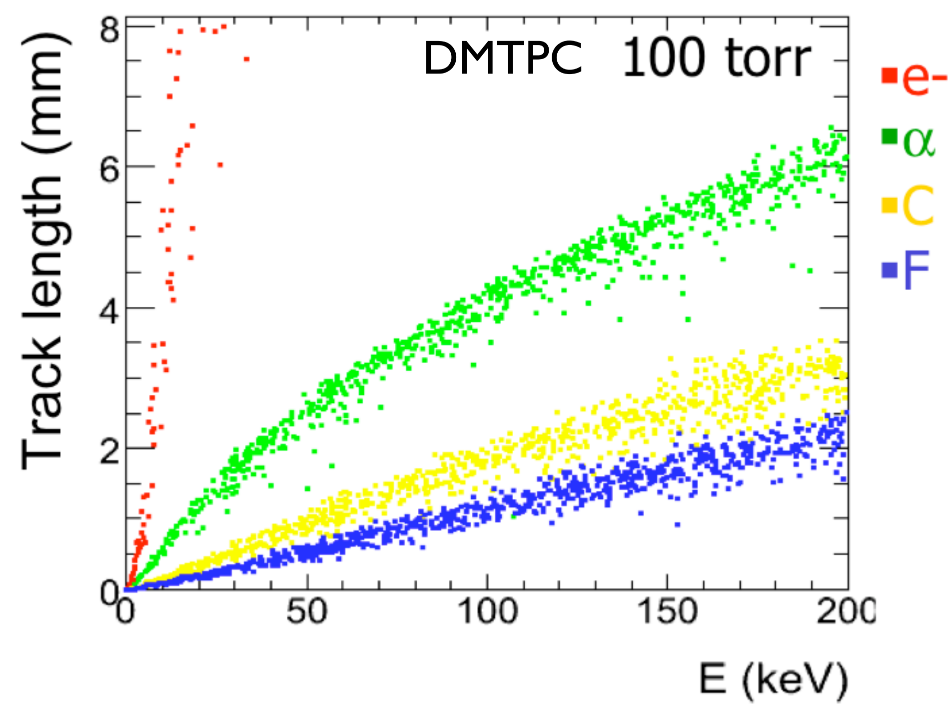

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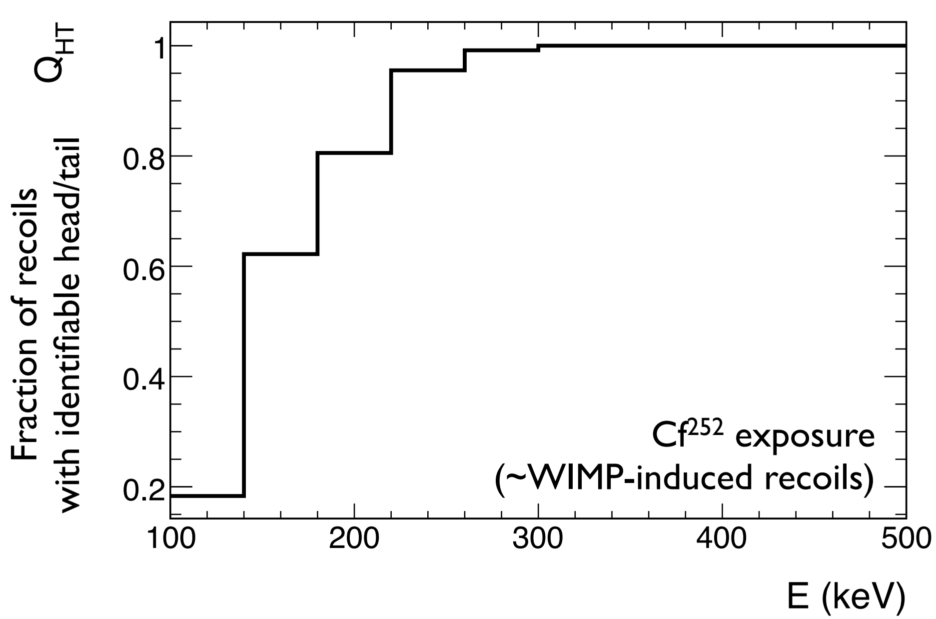

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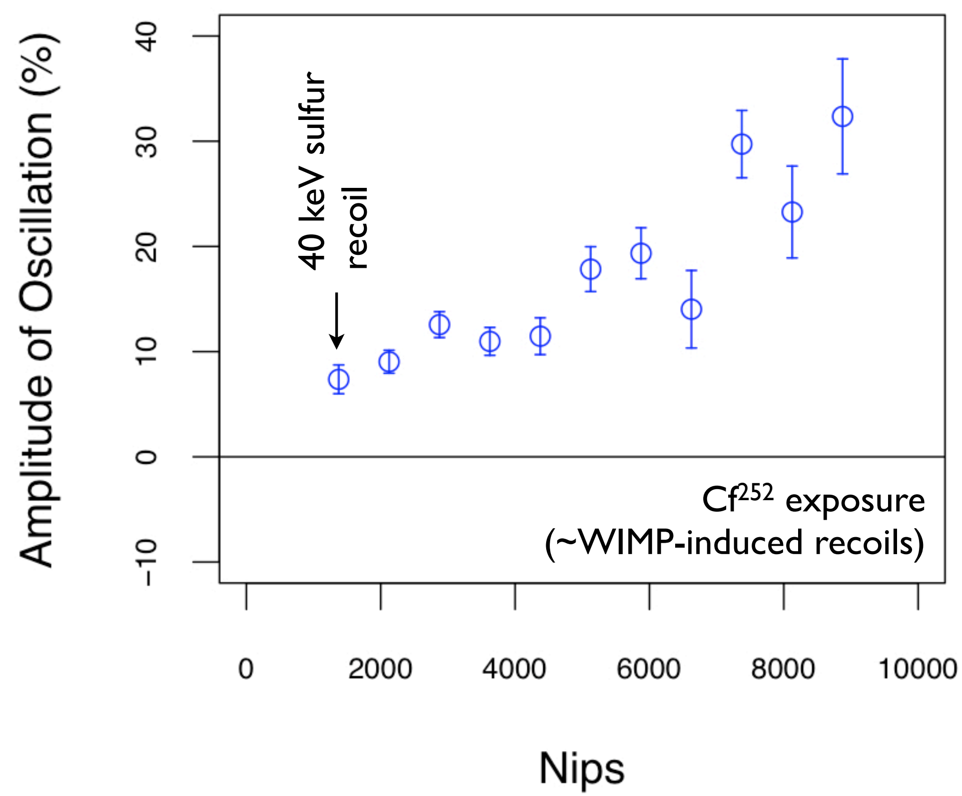
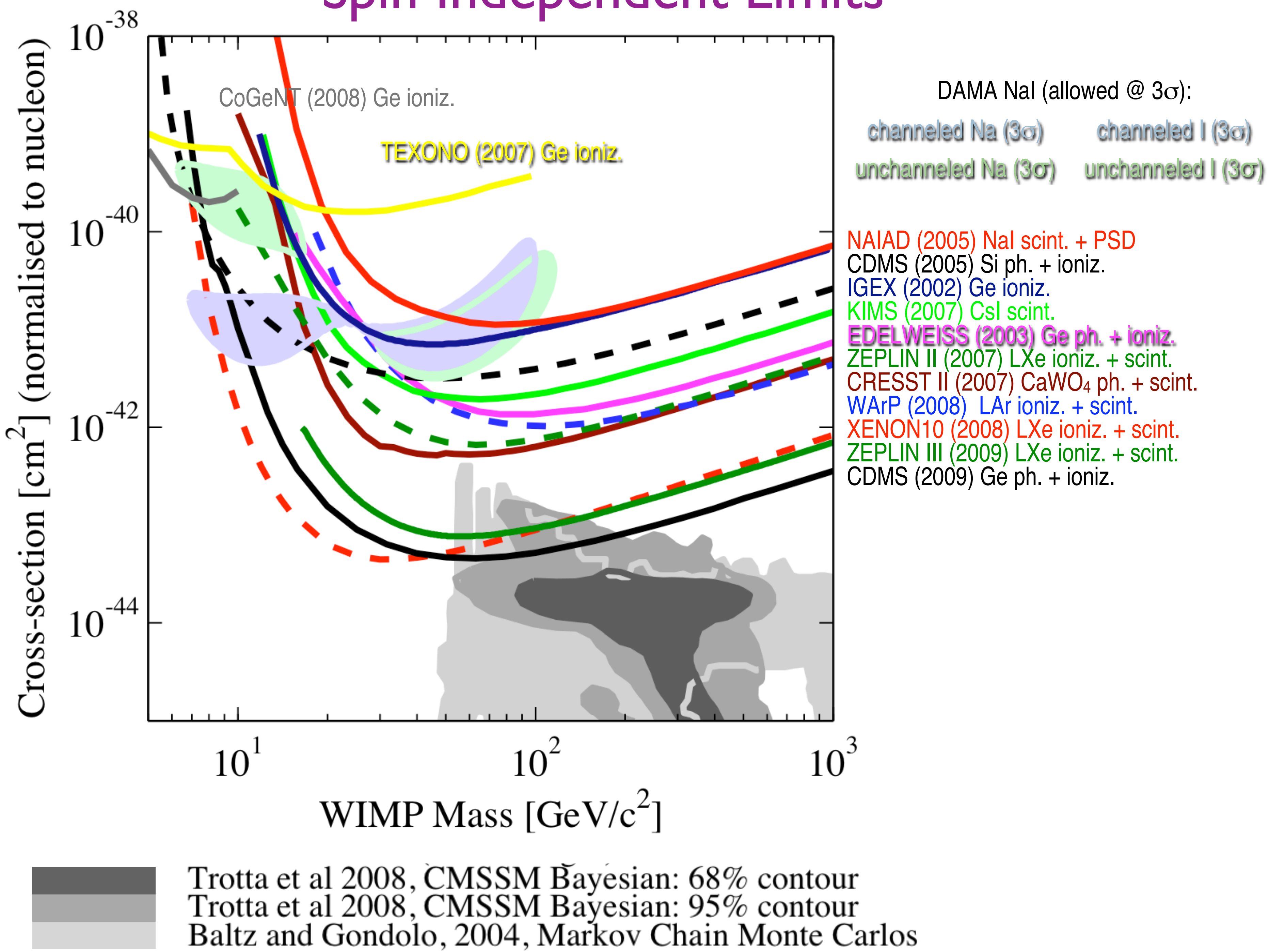


Time Projection Chambers

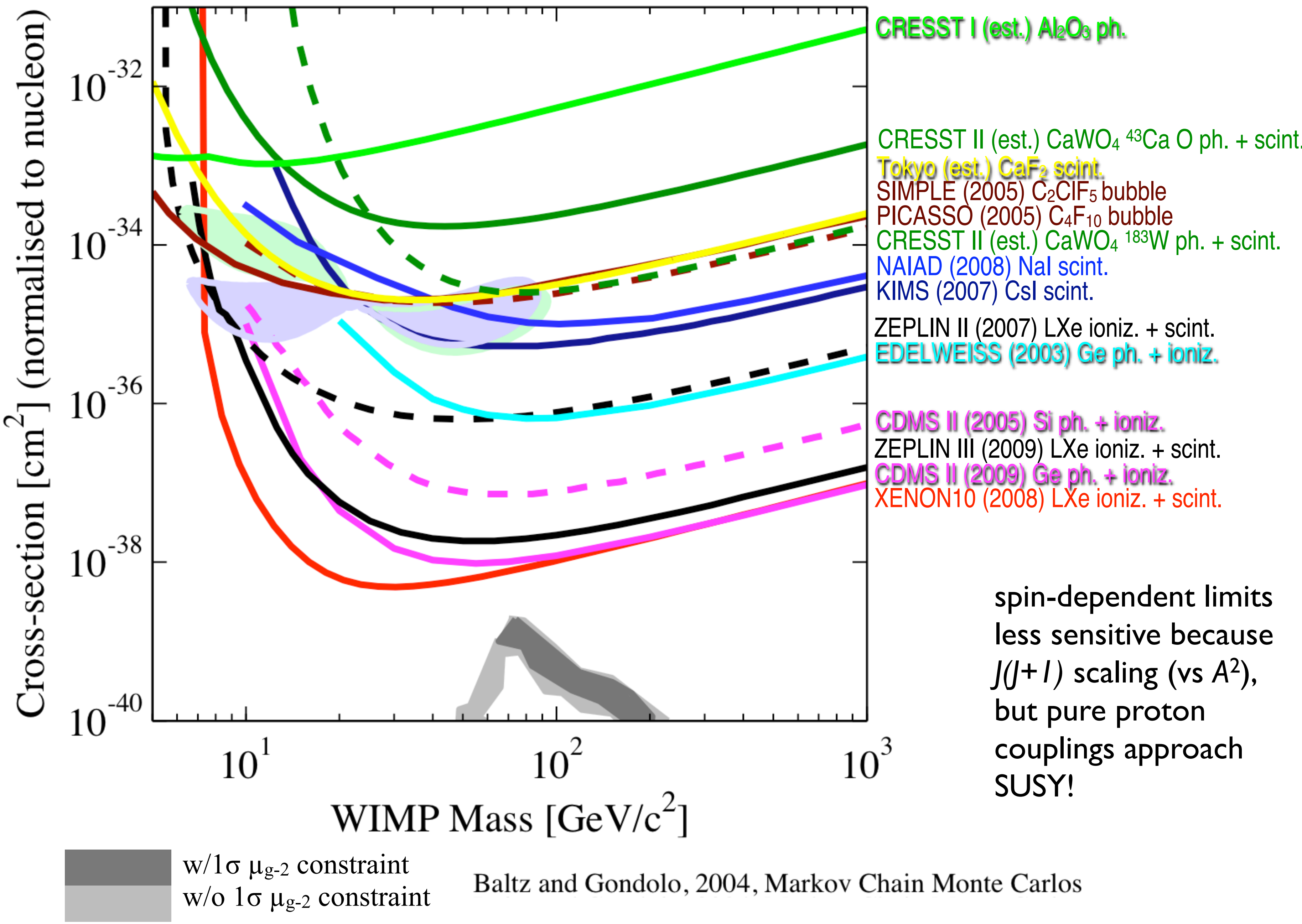
- DMTPC
  - CF_4 gas: low diffusion, scintillates well
  - PMTs for trigger, z information
  - CCD images avalanche region to obtain energy, xy track orientation (good posn resolution with CCD, ~100 μm)
  - Excellent gamma/beta rejection based on track size
  - head/tail based on dE/dx: directionality!
  - 1 m^3 detector in fabrication, will be run underground (WIPP)
- DRIFT
  - negative ion TPC, e- + $CS_2 \rightarrow CS_2^-$: drifting of heavy ion suppresses diffusion
  - 2 mm pitch anode + crossed MWPC grid give xyz imaging and energy
  - Excellent gamma/beta rejection based on track size
  - head/tail based on dE/dx: directionality!
  - Multiple underground runs of 1 m^3 at Boulby mine (UK), still dealing with radon emanation and daughter issues
  - Demonstrated CS_2-CF_2 mixtures for spin-dependent sensitivity

Spin Independent Limits



plot compiled by P. Cushman using Gaitskell, Mandic, and Filippini http://dmtools.brown.edu

Spin Dependent Limits: Pure Neutron Coupling



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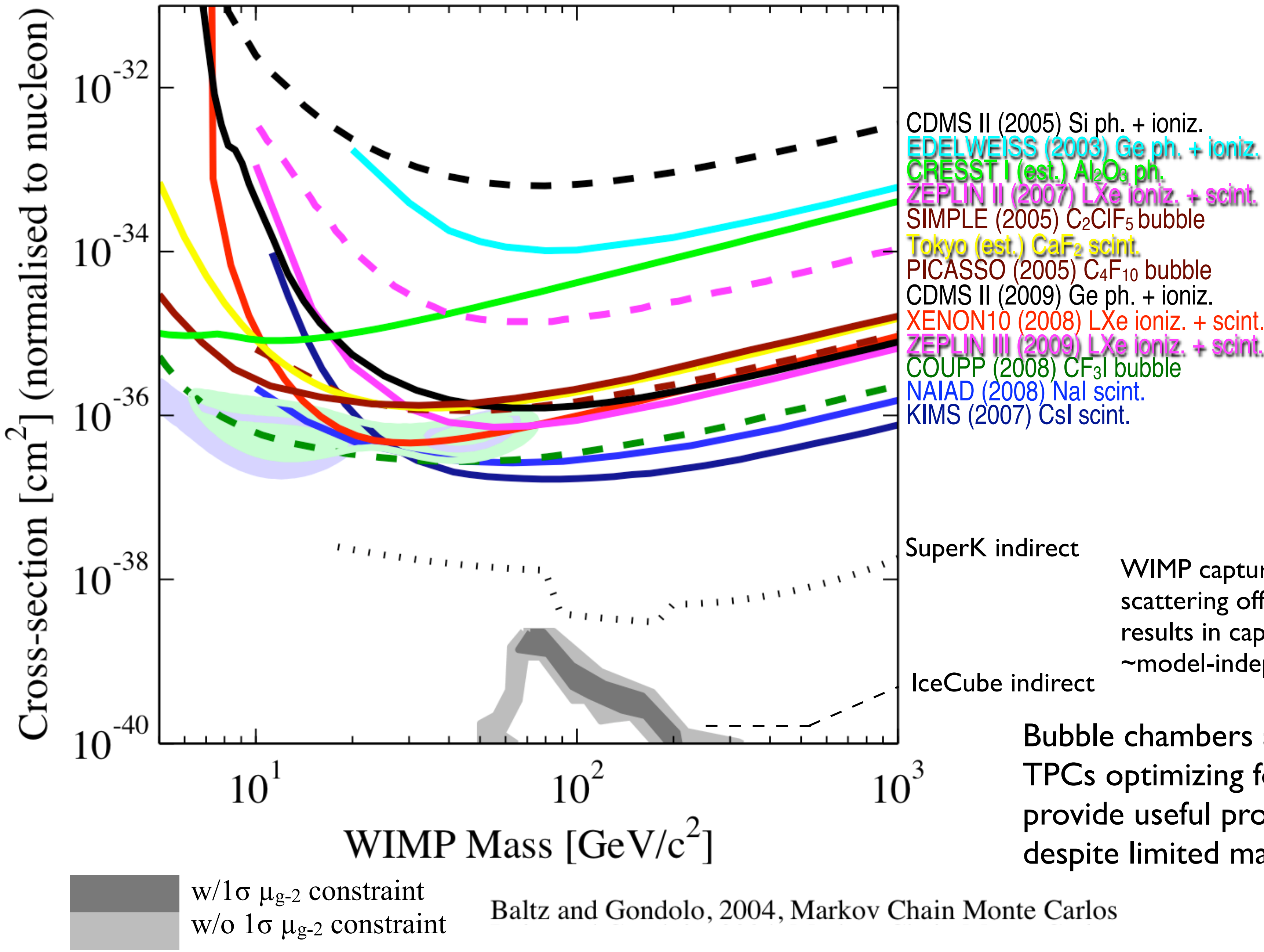
spin-dependent limits less sensitive because $J(J+1)$ scaling (vs A^2), but pure proton couplings approach SUSY!

Spin Dependent Limits: Pure Proton Coupling



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WIMP capture in Sun: scattering off p results in capture, ~model-independent

Bubble chambers and TPCs optimizing for SD to provide useful progress despite limited mass.

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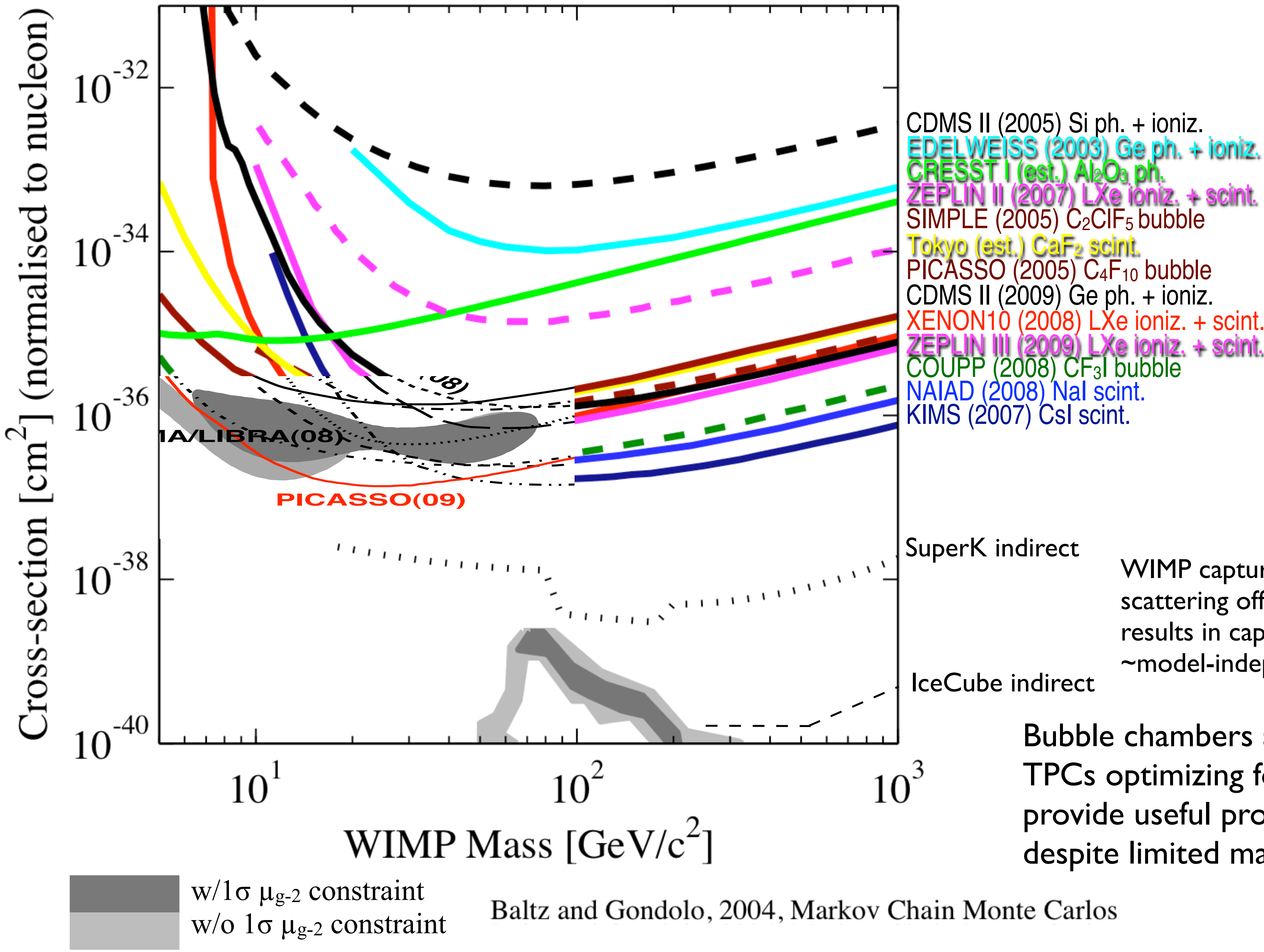

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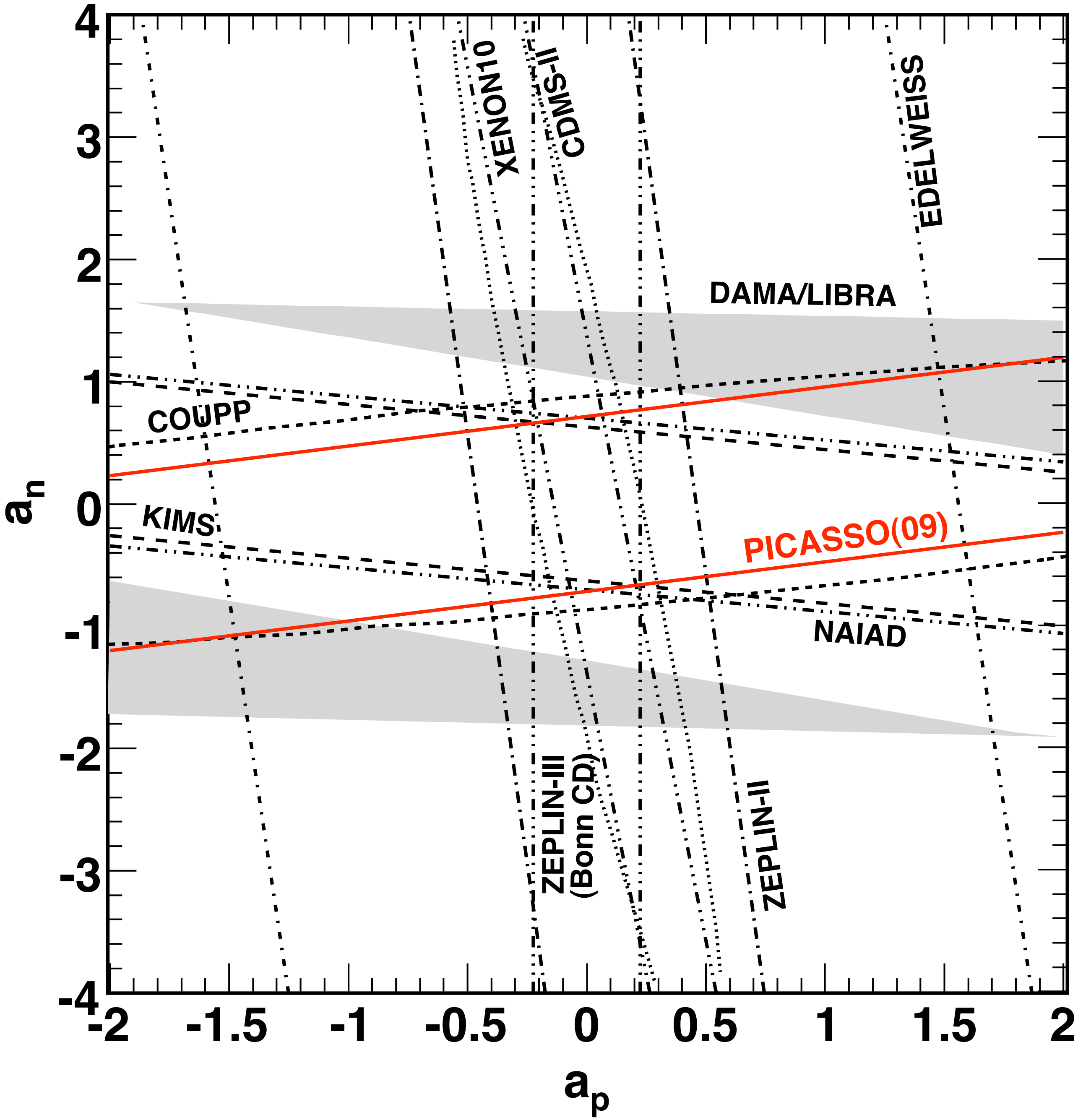
Spin-Dependent Limits

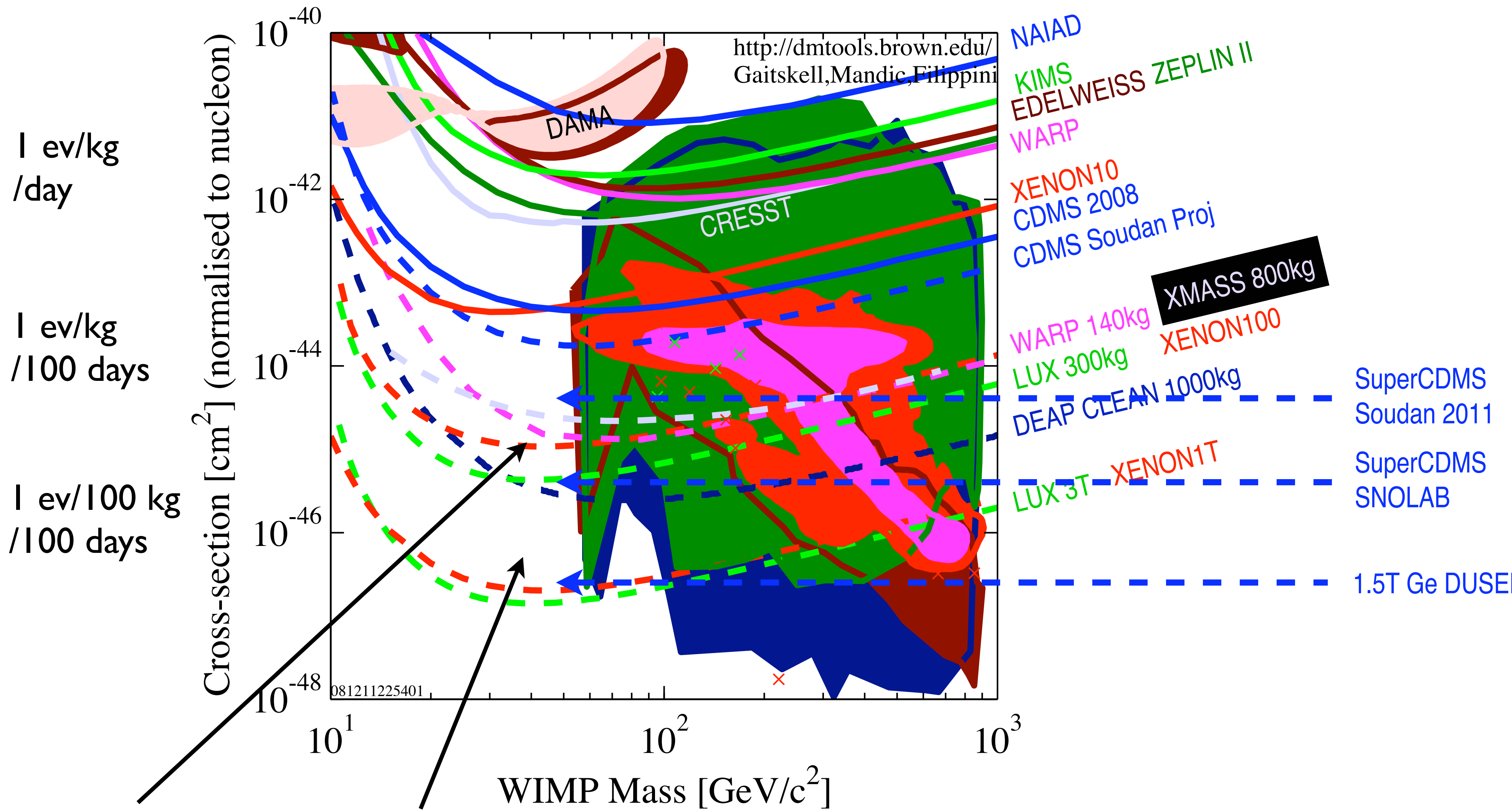


from PICASSO (2009) using Gaitskell, Mandic, and Filippini http://dmtools.brown.edu

M = 50 GeV regions inside contours allowed at 90% CL

spin-dependent limits more model-dependent, $\langle S_p \rangle$, $\langle S_n \rangle$ calculated from nuclear model

The Future of Direct Searches



where the coming generation is aiming, 10^{-9}-10^{-8} pb

Many technologies under development promise 10^{-10} pb, but the devil is in the details!
DUSEL is coming: S4 engineering funding announcements soon,
S5 proposals early 2010, DUSEL PDR late 2010, construction start 2013?