Dark Matter - Theoretical and Observational Status
Lecture 3

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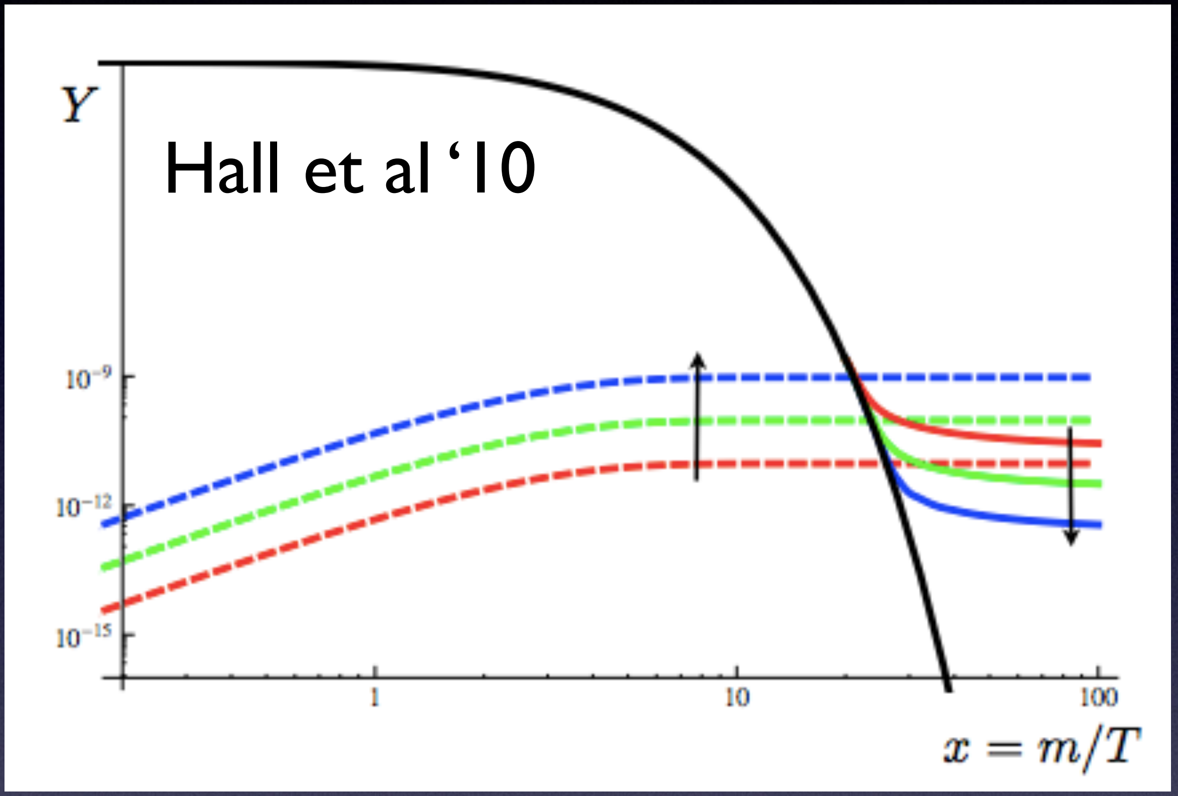
Goals (Lecture 3)

- (from yesterday) Briefly discuss freeze-in benchmark
- Work through signal calculation for classic direct detection
- Discuss approaches to direct detection beyond searches for elastic nuclear recoils
- Outline searches for dark matter and dark sectors at accelerators
  - searches at the LHC
  - searches in lower-energy accelerators
  - searches for dark sector particles

Freeze-in

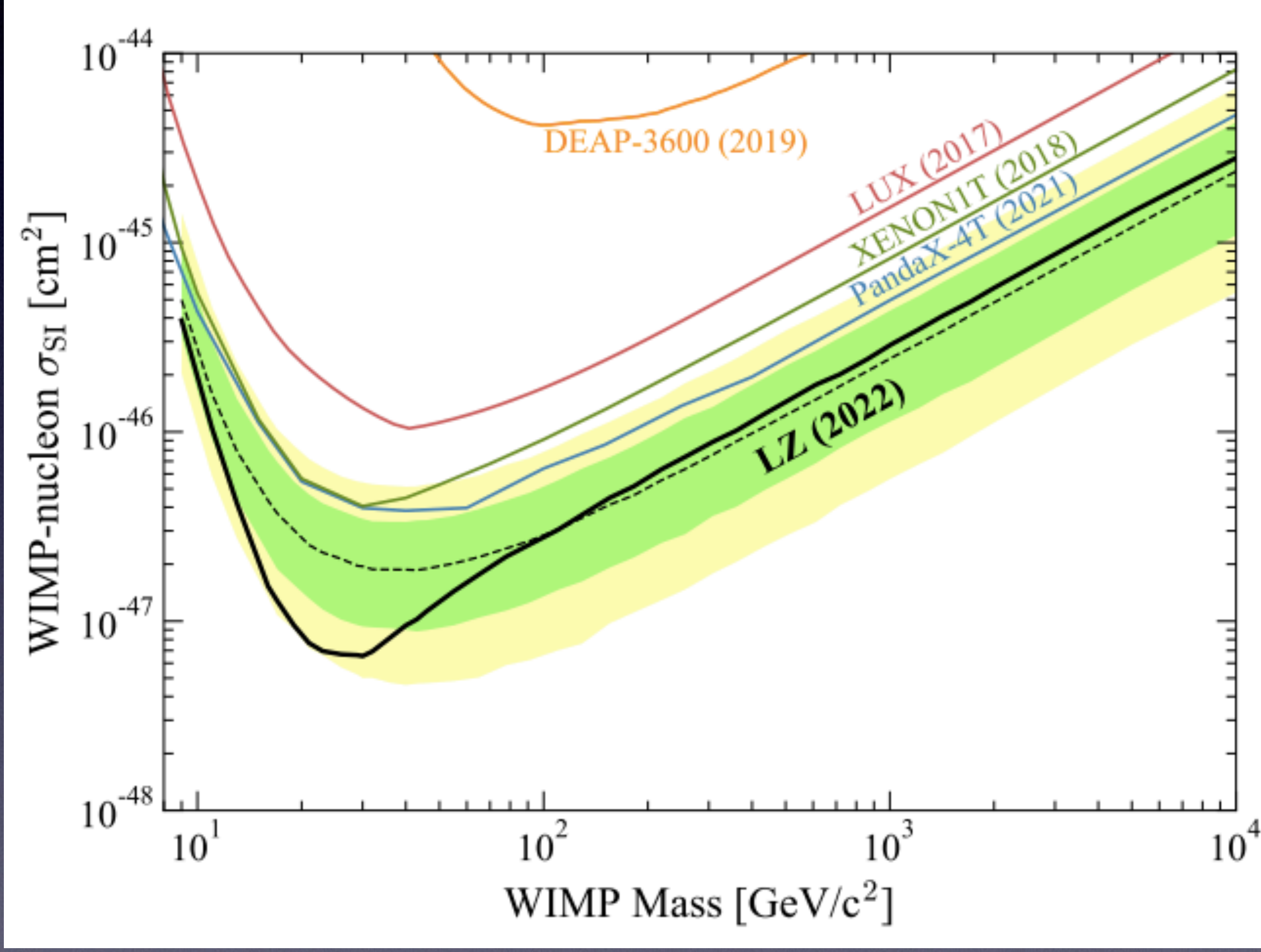
- One other particularly important benchmark is the case of "freeze-in"
- Basic picture [Hall et al '10]:
  - initial abundance of DM is negligible
  - either DM or a DM precursor is produced (with abundance << equilibrium) through rare interactions with the SM bath
  - production cuts off when T < m, due to kinematic suppression
  - if the production rate rises with decreasing T, most DM will be produced by interactions occurring around T~m: abundance will be insensitive to UV physics



- Requires much smaller couplings than freeze-out (avoid equilibration) - can be natural for neutral mediators
- Can still be detectable especially if the mediator is sufficiently light
- Evades BBN bounds (never produced in large enough abundance), but WDM bounds are constraining [e.g. Dvorkin et al '21]

Direct detection in a nutshell

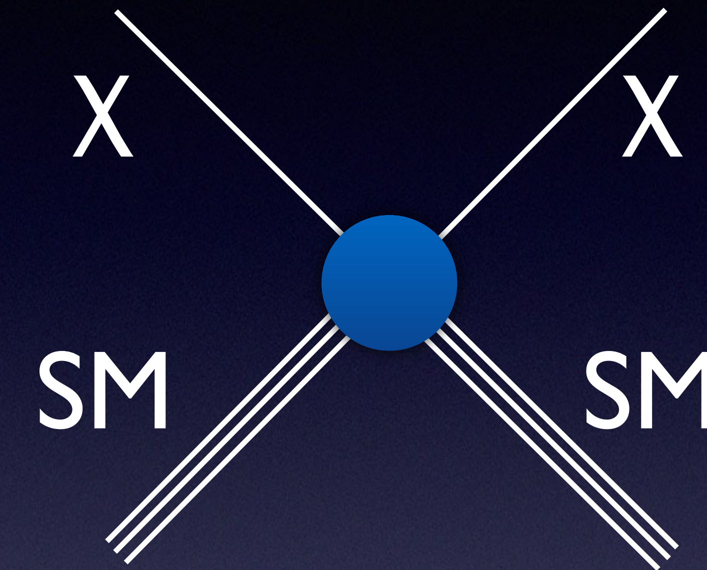
- Put sensitive detectors around large volume
- Bury it underground to reduce backgrounds
- Look for signs of nuclei "jumping"/ recoiling with no apparent cause, or other indications of energy deposition
- If other backgrounds can be shielded out, the cause must be something very weakly interacting - such as neutrinos or DM
- At present neutrino background is too faint to see - signal would be a sign of DM

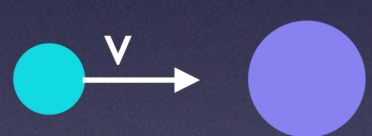


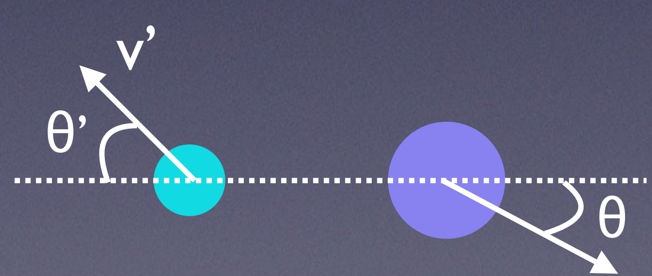
LZ Collaboration '22

DM-nucleus scattering

- Search for nuclei (of mass m_N) recoiling due to scattering of dark matter particle (of mass m_X).
- Observable: dR/dE_R, scattering rate for recoil energy in the range $[E_R, E_R + dE_R]$
- Let's work out the classical kinematics in lab frame (nucleus initially at rest)



Before: 

After: 

conservation of energy and momentum:

$$\frac{1}{2} m_\chi v^2 = \frac{1}{2} m_\chi (v')^2 + E_R$$

$$m_\chi v = m_\chi v' \cos\theta' + \sqrt{2 m_N E_R} \cos\theta$$

$$0 = m_\chi v' \sin\theta' + \sqrt{2 m_N E_R} \sin\theta$$

Some algebra (eliminating v' and θ') gives: $E_R = \dfrac{2\mu^2 v^2 \cos^2\theta}{m_N}$ $\quad \mu = \dfrac{m_N m_\chi}{m_N + m_\chi}$

Note: this result depends only on kinematics of collision - needs to be modified for inelastic collisions, but else quite general

Typical recoil energies

- We thus predict a spectrum of recoils extending from zero recoil energy to:
  $$(E_R)_{\max} = 2\mu^2 v^2 / m_N$$
- Consequently, at a given recoil energy E_R, only DM particles with $v > v_{min} = \sqrt{m_N E_R / 2\mu^2}$ can contribute.
- Let's do some quick estimates: typical $E_R \sim \mu^2 v^2 / m_N$.
- Suppose the target nucleus is O(10-100) GeV (i.e. 10-100 protons+neutrons) and DM is similar mass or heavier, so $\mu \sim m_N$.
- Velocity dispersion of DM locally is $v/c \sim 10^{-3}$ (determined by Galactic gravitational potential).
- Then typical recoil energies should be in the range $\sim 10^{-6}\, m_N \sim$ 10-100 keV.
- If DM is significantly lighter than nucleus, $\mu \sim m_{DM}$, and E_R suppressed by $(m_{DM}/m_N)^2$ relative to O(10-100) keV scale.
  - e.g. for $m_N \sim$ 100 GeV, $E_R \sim$ 100 keV for $m_{DM} > m_N$, but only 0.01 keV for $m_{DM} \sim$ 1 GeV.
  - Detecting light DM this way requires light targets and very low energy thresholds.

Ingredients for the nuclear recoil spectrum

- Amplitude for scattering of DM on individual nucleons (function of v, E_R):
  - Particle physics: how does DM couple to quarks/gluons?
  - Nuclear physics: what is the quark content of the nucleon?
- Amplitude for nucleons → amplitude for scattering on <u>nucleus</u>.
  - Particle physics: is the amplitude spin-dependent or not? More generally, how does it depend on the nucleon properties? Is it the same for protons and neutrons?
  - Nuclear physics: nuclear "form factor" (accounts for finite size of nucleus)
- Scattering amplitude → scattering rate.
  - Astrophysics: number density & velocity distribution for dark matter.

Standard simplifications

- Treat scattering as a contact interaction set by couplings f_n, f_p to neutrons and protons respectively.
    - Standard case: assume f_n, f_p are just constants, independent of e.g. velocity, momentum transfer, scattering angle, etc.
    - Often further assume that $f_n=f_p$.
- Consider the two cases of spin-independent and spin-dependent interactions:
    - Spin-independent interactions: nucleon amplitudes add coherently. Overall rate scales as (atomic mass)^2.
    - Spin-dependent interactions: amplitudes from paired nucleons with opposite spins cancel exactly. Overall rate scales as (net spin)^2 - much weaker limit.
- Form factor: describes momentum dependence of interaction due to finite size of nucleus. Typically use simple parameterization "Helm form factor".
- DM velocity distribution: typically just assume Maxwellian distribution.

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many "non-standard" DM models work by just changing one or more of these assumptions! Can substantially change comparisons between different experiments.

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The standard calculation

- Now let's switch to the center-of-momentum (COM) frame. Let the scattering angle in this frame be labeled θ.
- Why choose this frame? For simple models, rate is independent of scattering angle in COM frame.

- 3-momentum transfer q has magnitude given by:

$$q^2 = |\vec{q}|^2 = |\vec{p} - \vec{k}|^2 = p^2 + k^2 - 2pk\cos\theta = 2\mu^2 v_{\mathrm{rel}}^2 (1 - \cos\theta)$$

- In LAB frame, nucleus gains momentum $q = (2\, m_N\, E_R)_{1/2}$
- So we can express lab-frame recoil energy (which we're interested in) in terms of COM-frame scattering angle:

$$E_R = q^2/(2m_N) = \frac{\mu^2 v_{\mathrm{rel}}^2}{m_N}(1 - \cos\theta)$$

- Thus the rate of events at a given E_R can be written in terms of the rate of events at a given COM scattering angle:

$$\frac{dR}{dE_R} = \frac{m_N}{\mu^2 v_{\mathrm{rel}}^2} \frac{dR}{d\cos\theta}$$

The standard calculation (II)

- Let us assume spin-independent scattering, so contributions from different nuclei add coherently:

form factor

$$\mathcal{M}_{\mathrm{nucleus}} = \mathcal{F}(q)\left[Z f_p + (A-Z) f_n\right]$$

- The cross section in the center-of-momentum frame is related to the matrix element M here by:

$$\frac{d\sigma}{d\Omega} = \frac{\mu^2}{m_\chi^2 m_N^2} \frac{1}{64\pi^2} \left|\mathcal{M}_{\mathrm{nucleus}}\right|^2$$

$$d\Omega = d\phi d(\cos\theta)$$

- To convert from cross section to rate, we have

$$\frac{dR}{d\Omega} = n N_T v_{\mathrm{rel}} \frac{d\sigma}{d\Omega}$$

n = DM # density

N_T = # target nuclei

- Assuming no dependence on the angle φ, so we can trivially integrate over the possible values of φ, we can then finally write:

ρ = DM mass density

$$\frac{dR}{dE_R} = \frac{2\pi m_N}{\mu^2 v_{\mathrm{rel}}^2} \frac{dR}{d\Omega} = \frac{2\pi n N_T m_N}{\mu^2 v_{\mathrm{rel}}} \frac{d\sigma}{d\Omega} = \frac{m_N \rho N_T}{32\pi m_\chi^3 m_N^2 v_{\mathrm{rel}}} \left|\mathcal{F}(q)\right|^2 \left|Z f_p + (A-Z) f_n\right|^2$$

The standard calculation (III)

- Let's define an "effective cross-section" for scattering on a single nucleon:

$$\sigma_{\chi n} = \sigma_{\chi N}|_{q=0} \frac{\mu_{\chi n}^2}{\mu^2} \frac{1}{A^2}$$

- This is the actual quantity that's bounded on those limit plots.
- We can then write our observable spectrum in the form:

$$\frac{dR}{dE_R} = \frac{\sigma_{\chi n}}{\mu_{\chi n}^2} A^2 m_N N_T \frac{\rho}{2 m_\chi v_{\rm rel}} |\mathcal{F}(E_R)|^2$$

- In terms of the f_p, f_n parameters, we have:

$$\sigma_{\chi n} = \frac{1}{16\pi} \frac{\mu_{\chi n}^2}{m_\chi^2 m_N^2} \left| Z f_p + (A - Z) f_n \right|^2 / A^2$$

The velocity distribution

$$\frac{dR}{dE_R} = \frac{\sigma_{\chi n}}{\mu_{\chi n}^2} A^2 m_N N_T \frac{\rho}{2 m_\chi v_{\rm rel}} |\mathcal{F}(E_R)|^2$$

- This result assumes we know the relative velocity of the DM and the nucleus - but in reality, the DM has a distribution of velocities.
- ρ here should be understood to describe the mass density of DM particles with relative velocity $v_{\rm rel}$ - then need to integrate over this parameter.

distribution function normalized to 1

$$\frac{d\rho}{dv_{\rm rel}} = \rho_0 f(v_{\rm rel})$$

overall density

target properties DM properties astrophysics

$$\frac{dR}{dE_R} = \underbrace{\left[A^2 m_N N_T |\mathcal{F}(E_R)|^2\right]}_{\text{target properties}} \underbrace{\left[\frac{\sigma_{\chi n}}{2 m_\chi \mu_{\chi n}^2}\right]}_{\text{DM properties}} \underbrace{\left[\rho_0 \int dv \frac{1}{v} f(v)\right]}_{\text{astrophysics}}$$

The recoil spectrum

- Shape of the spectrum comes from two places:
  - Form factor dependence on E_R - suppresses spectrum at high recoil energies
  - Dependence of velocity integral on E_R

astrophysical piece: $\rho_0 \int \frac{1}{v} f(v) dv = \rho_0 \int_{v_{\min}}^{v_{\max}} \frac{1}{v} f(v) dv$

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

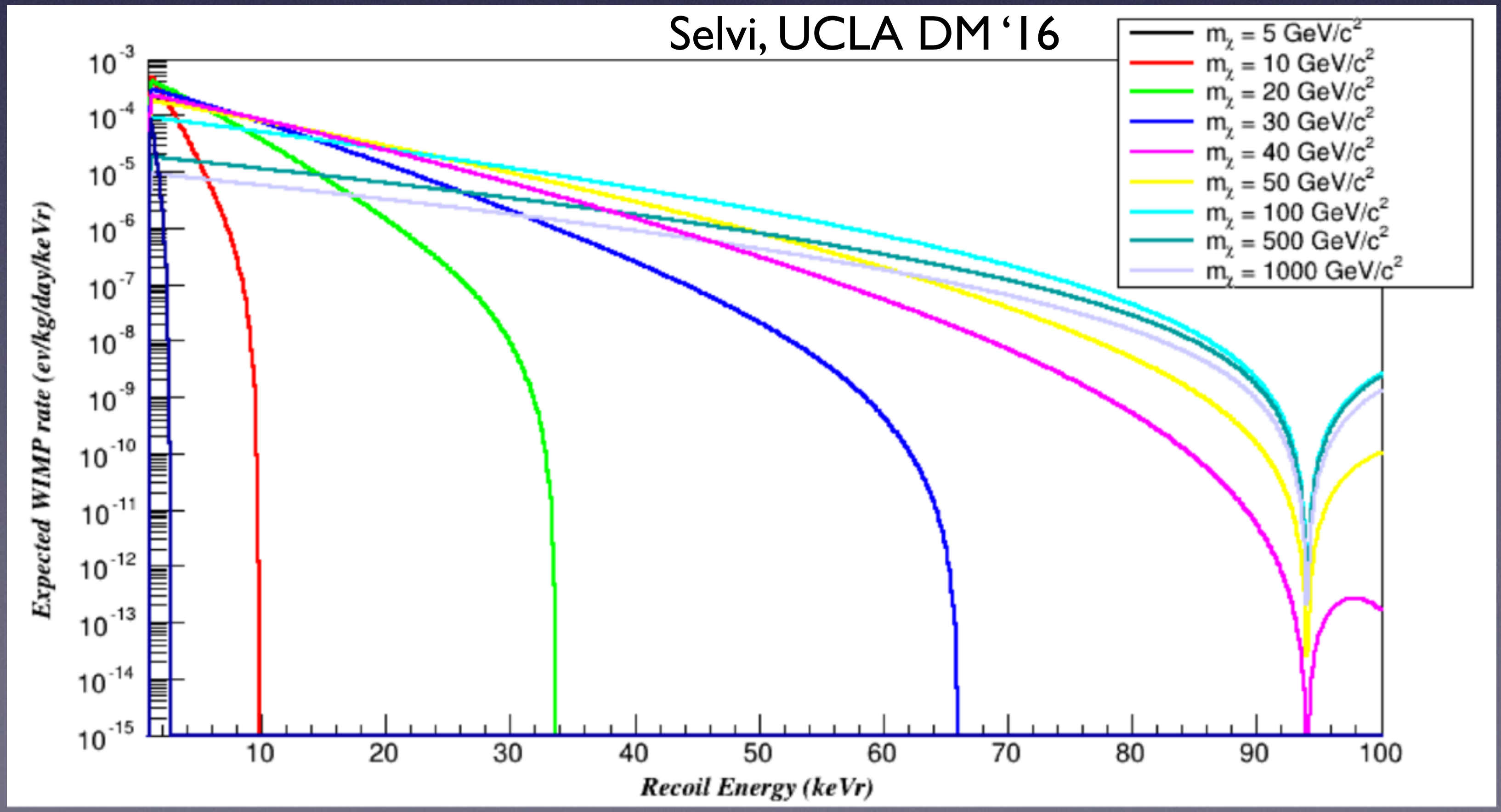
v_{max} set by Galactic escape velocity in frame of Earth
=> v_{max} is (slightly) time-dependent!

A falling spectrum

- For the moment, treat $v_{max} \rightarrow$ infinite, and take f(v) to follow a Maxwellian speed distribution:

$$f(v) = \frac{4}{\sqrt{\pi}} \frac{1}{v_0^3} v^2 e^{-v^2/v_0^2}$$

- Then this integral becomes: $\int_{v_{\min}}^{\infty} \frac{1}{v} f(v) dv = \frac{2}{\sqrt{\pi}} \frac{1}{v_0} e^{-E_R m_N / 2\mu^2 v_0^2}$
- Thus we expect to see a smooth, exponentially falling spectrum, multiplied by the form factor squared.
- Again we see low-energy sensitivity is critical, especially for light WIMPs.
- Note: for a time-dependent treatment, we would approximate f(v) as Maxwellian in the frame of the Galaxy, and include the motion of the Earth with respect to that frame.



Estimating the total rate

- In the limit that the form factor can be ignored, we can integrate over E_R to get the total rate:

$$R = \frac{2}{\sqrt{\pi}} A^2 N_T \frac{\sigma_{\chi n} \mu^2}{m_\chi \mu_{\chi n}^2} \rho_0 v_0$$

- Consider a fiducial volume of 100 kg xenon (atomic mass 132 ~ 100).
- What WIMP-nucleon cross section do you need to see 1 event / year for a 100 GeV WIMP?

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$$N_T \approx N_A \times 1000 \approx 6 \times 10^{26}$$

1 mole xenon ~ 100g

$$\mu \approx 50\mathrm{GeV} \qquad \rho_0 \approx 0.4\mathrm{GeV/cm}^3$$

$$\mu_{\chi n} \approx 1\mathrm{GeV} \qquad v_0 \approx 200\mathrm{km/s} \approx 6 \times 10^{14}\mathrm{cm/yr}$$

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$$R \approx 10^4 \times 6 \times 10^{26} \times 50^2 \times \frac{0.4}{100}/\mathrm{cm^3} \times 6 \times 10^{14}\mathrm{cm/yr} \times \sigma_{\chi n}$$

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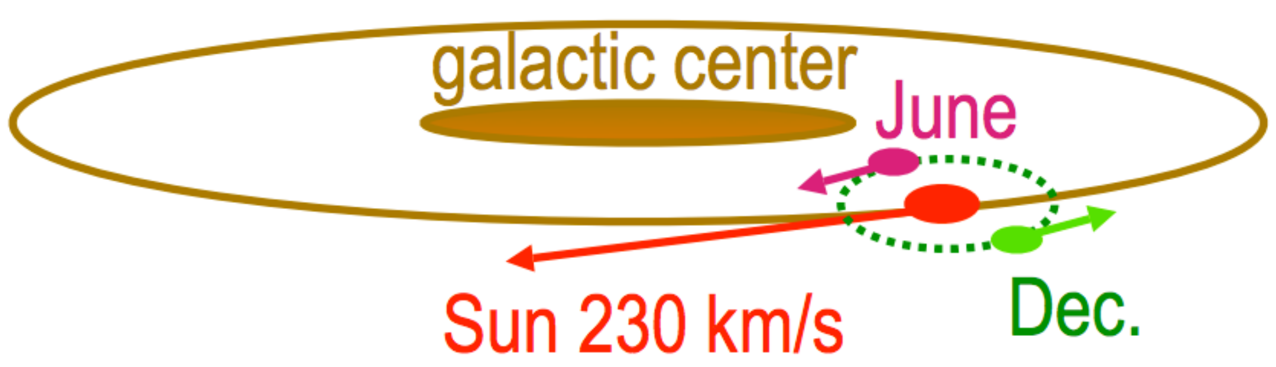
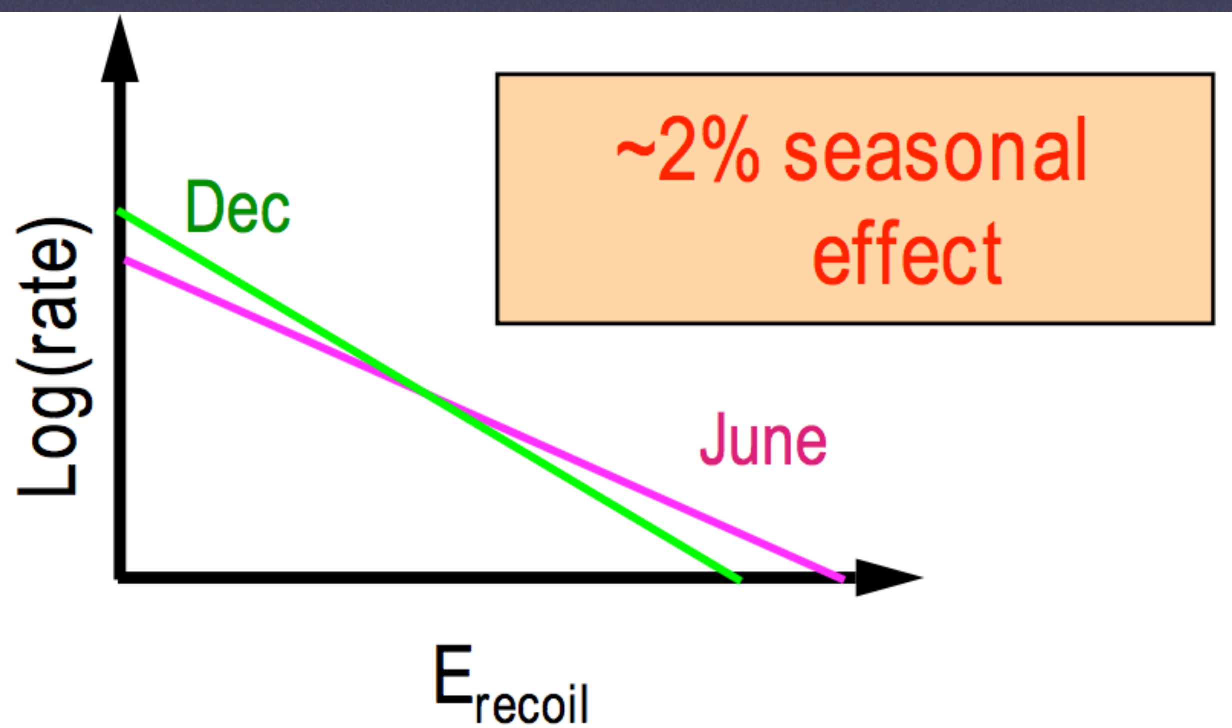
$$\approx \left(10^{46}\sigma_{\chi n}/\mathrm{cm}^2\right)/\mathrm{yr}$$

Modulation

- For more accurate treatment, need to include time dependence and asymmetry of velocity distribution as seen from Earth (even in this approximation, distribution is only isotropic and constant in Galactic frame)
- Finite escape velocity (~500-600 km/s) cuts off exponential distribution at large E_R
- Time dependence induces ~sinusoidal annual modulation
- If observed, could confirm cosmic origin of signal



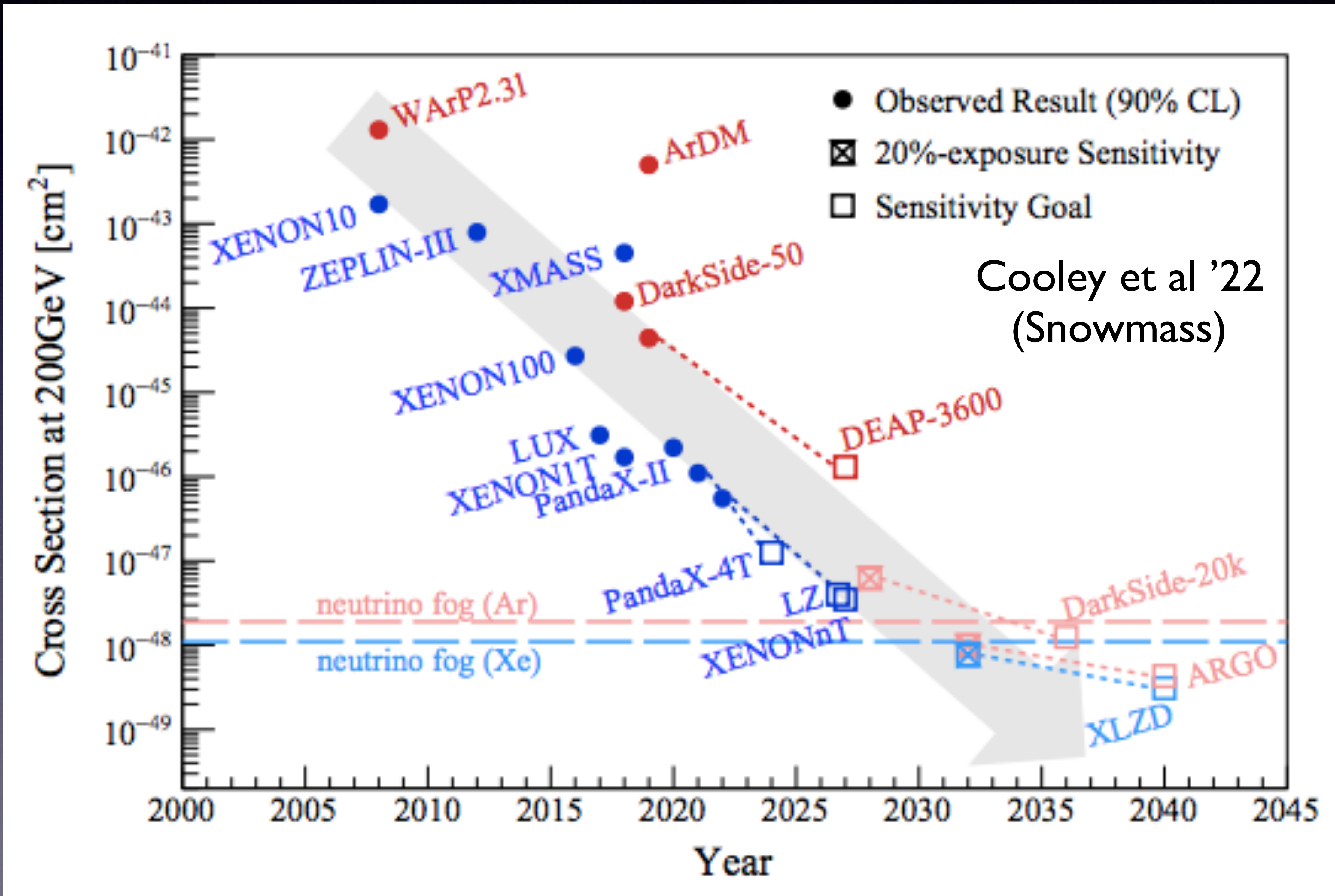


Dan Akerib '07

Experimental strategies

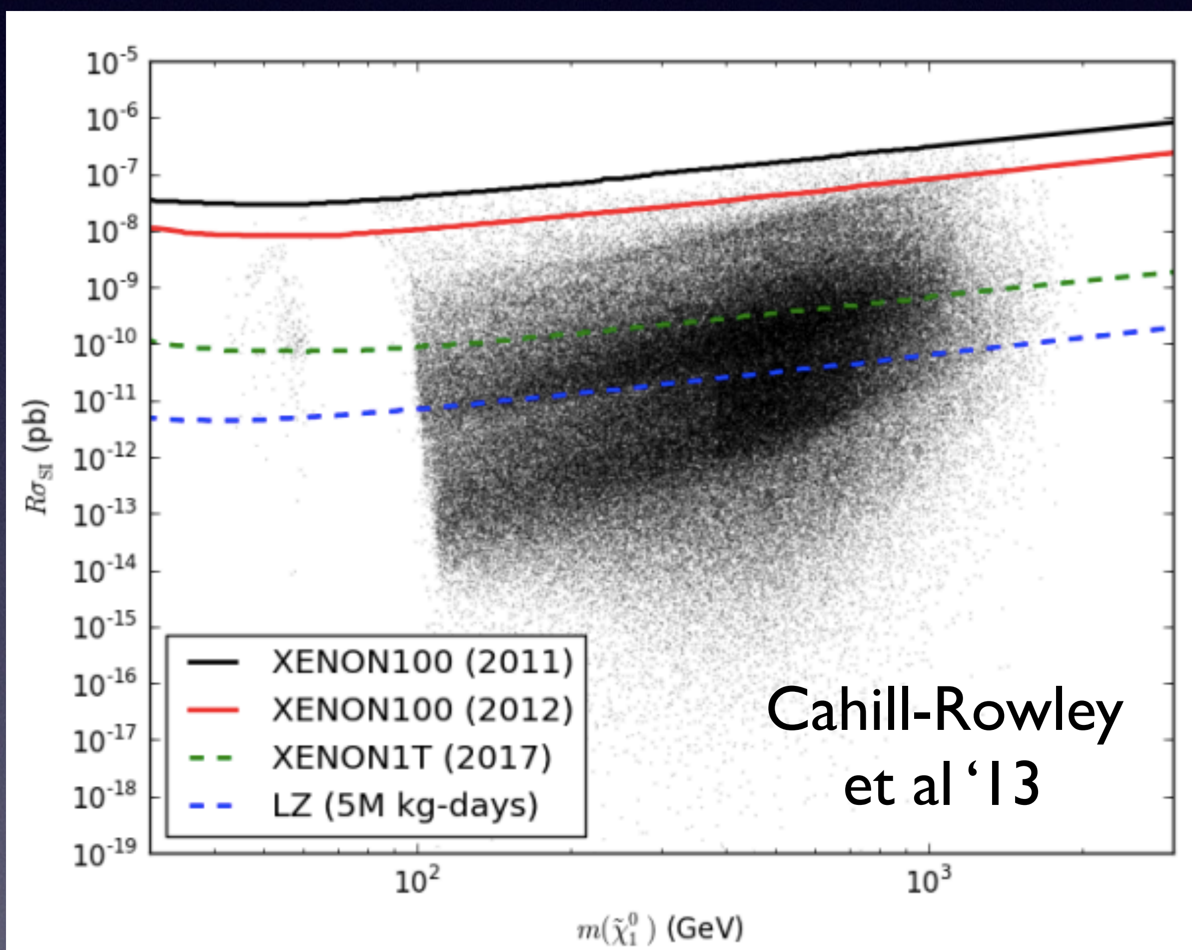
- Want large volumes, high A (except for light DM), low backgrounds
- Backgrounds:
    - Neutron scatters: mimic nuclear recoils, but can be shielded
    - Photon/electron scatters: scatter dominantly off <u>electrons</u> (for kinematic reasons), need to distinguish from nuclear recoils
    - In the future: cosmic neutrino background ("neutrino floor")
- Current flagship experiments focus on reducing background to zero or near-zero, by identifying and rejecting electron scattering events. Key idea is to measure <u>two</u> observables, where behavior of electron/nuclear recoils differs.
    - Liquid noble gas experiments (currently leading experiments are xenon, in the future possibly argon): measure both ionization and scintillation light from recoil. Best limits over most of energy range. (Also ongoing work to develop freon bubble chamber technologies.)
    - SuperCDMS: silicon-germanium semiconductors, measure ionization + photons. In recent years has focused on improved limits for light DM.
- Worth mentioning: DAMA/LIBRA experiment has a long-standing claimed detection, based on annual modulation search - but not background-free. Dfficult to reconcile this result with limits from other experiments, + tension with attempted direct replication by ANAIS-112 (see Leane et al '22 (Snowmass) for a more in-depth discussion).

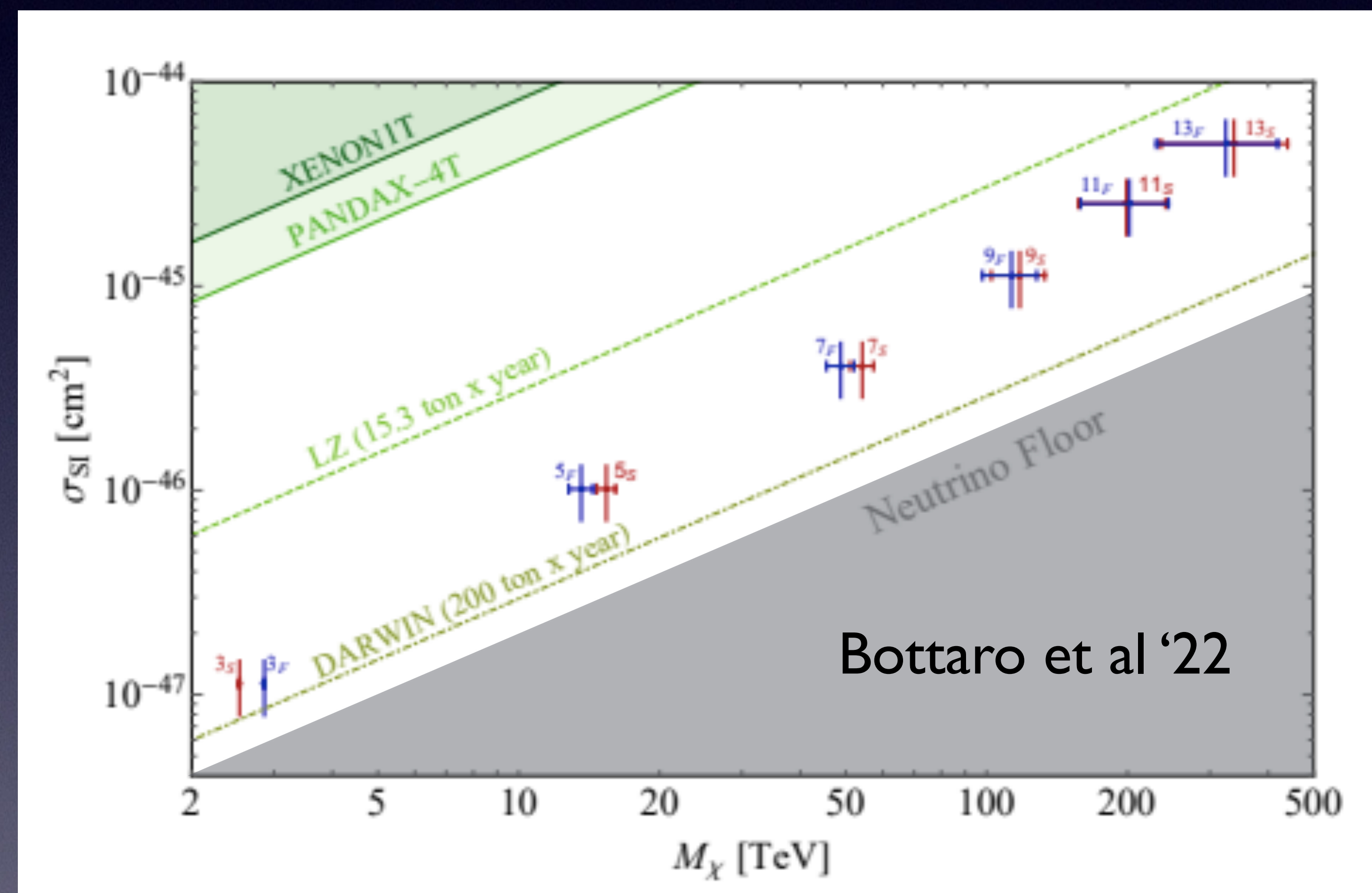
The next 10 years



Cooley et al '22 (Snowmass)

Comparison to some benchmarks



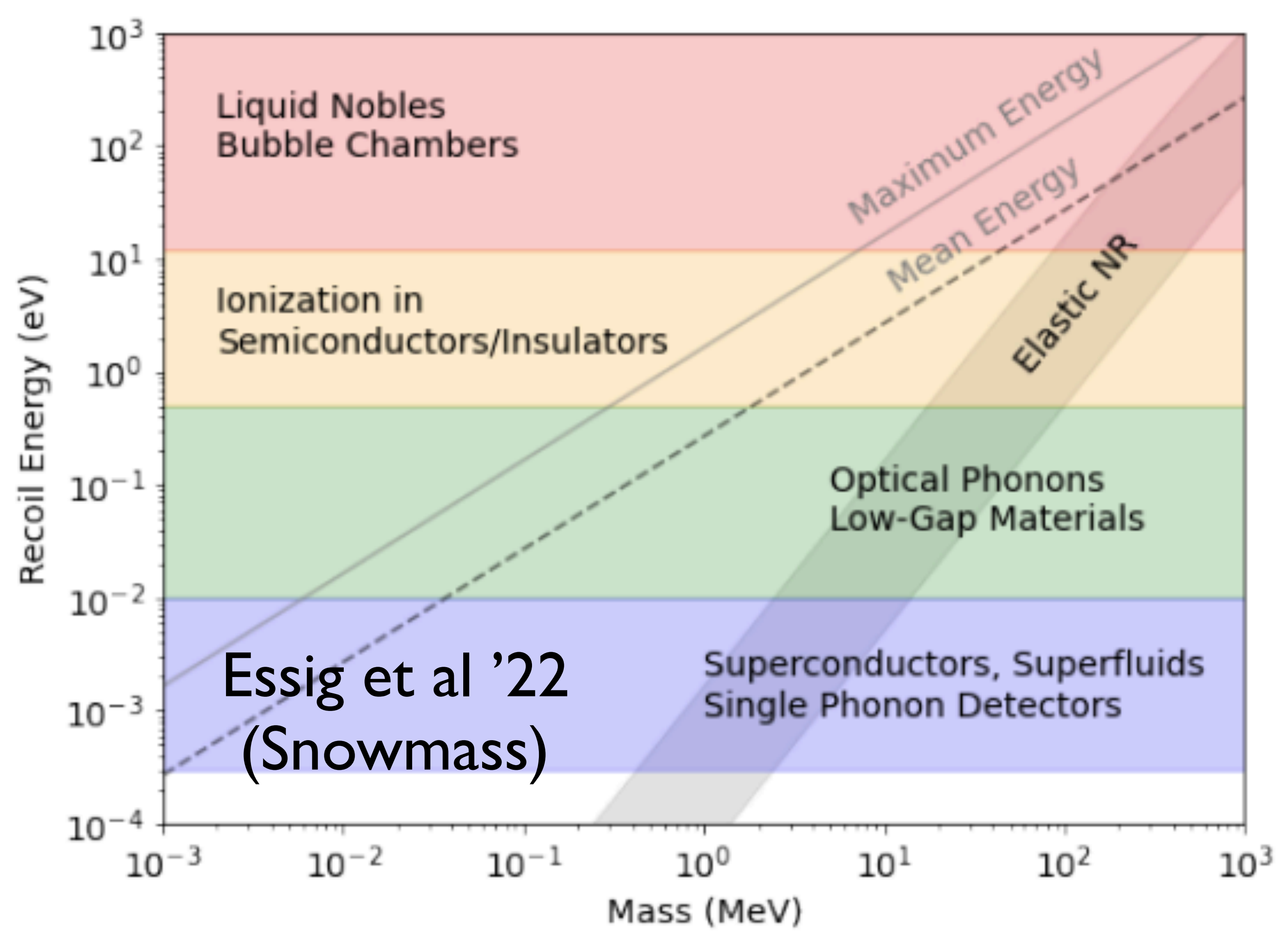


Benchmark points based on a scan over parameters in the phenomenological Minimal Supersymmetric Standard Model (pMSSM). Note: 1 pb = 10^{-36} cm^2

Minimal dark matter scenarios yielding the full correct relic density

Beyond nuclear recoils

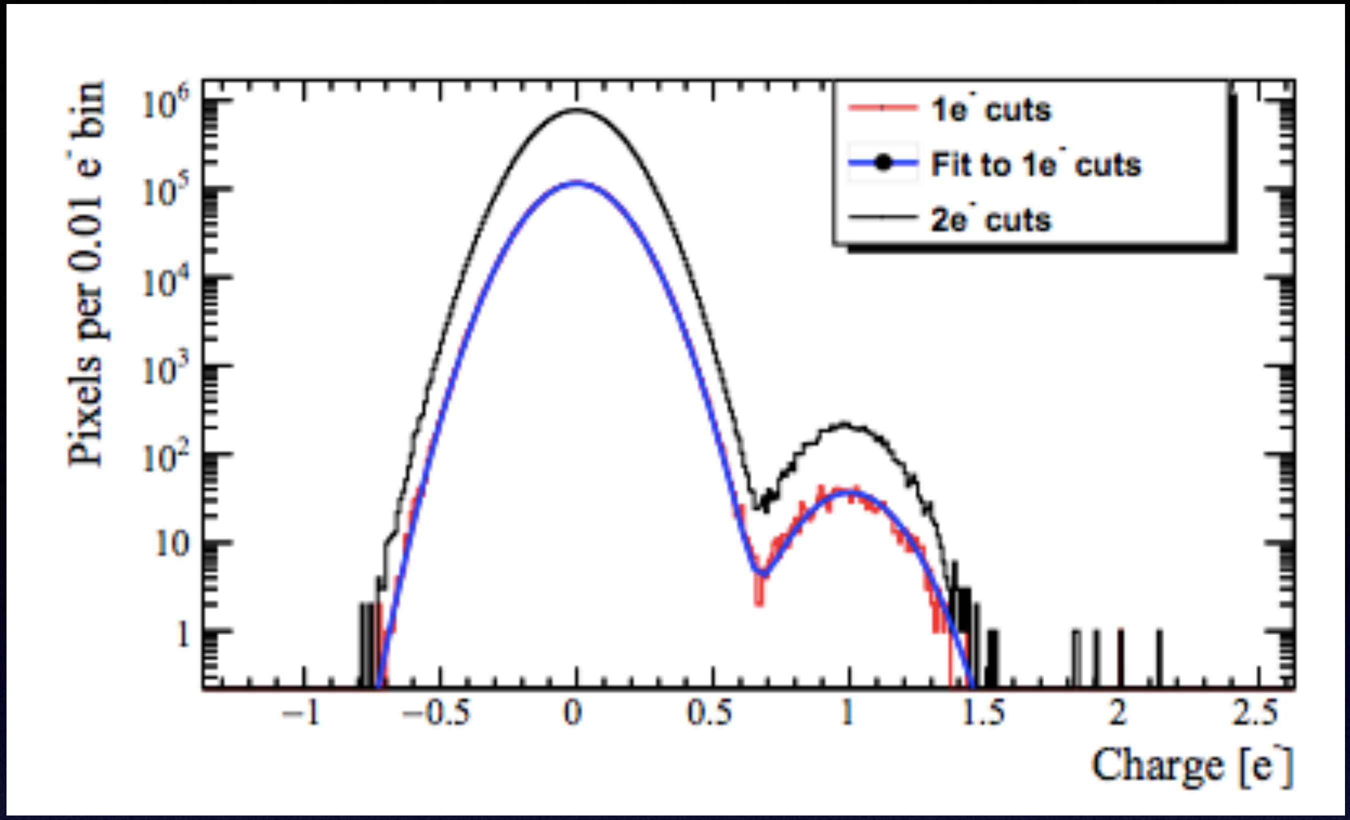
- Searches for elastic nucleus-DM scattering are often inefficient for light DM due to the kinematic mismatch
    - However, secondary photons/electrons produced in conjunction with nucleus-DM scattering, via bremsstrahlung or "Migdal effect", can be detectable [e.g. Kouvaris et al '17, Ibe et al '18]
- Searching for electron recoils provides sensitivity to lighter DM albeit at the cost of higher background
- If DM is absorbed onto SM particles, energy transfer is O(DM mass) rather than O(kinetic energy) or less - absorption searches allow sensitivity to much lighter DM



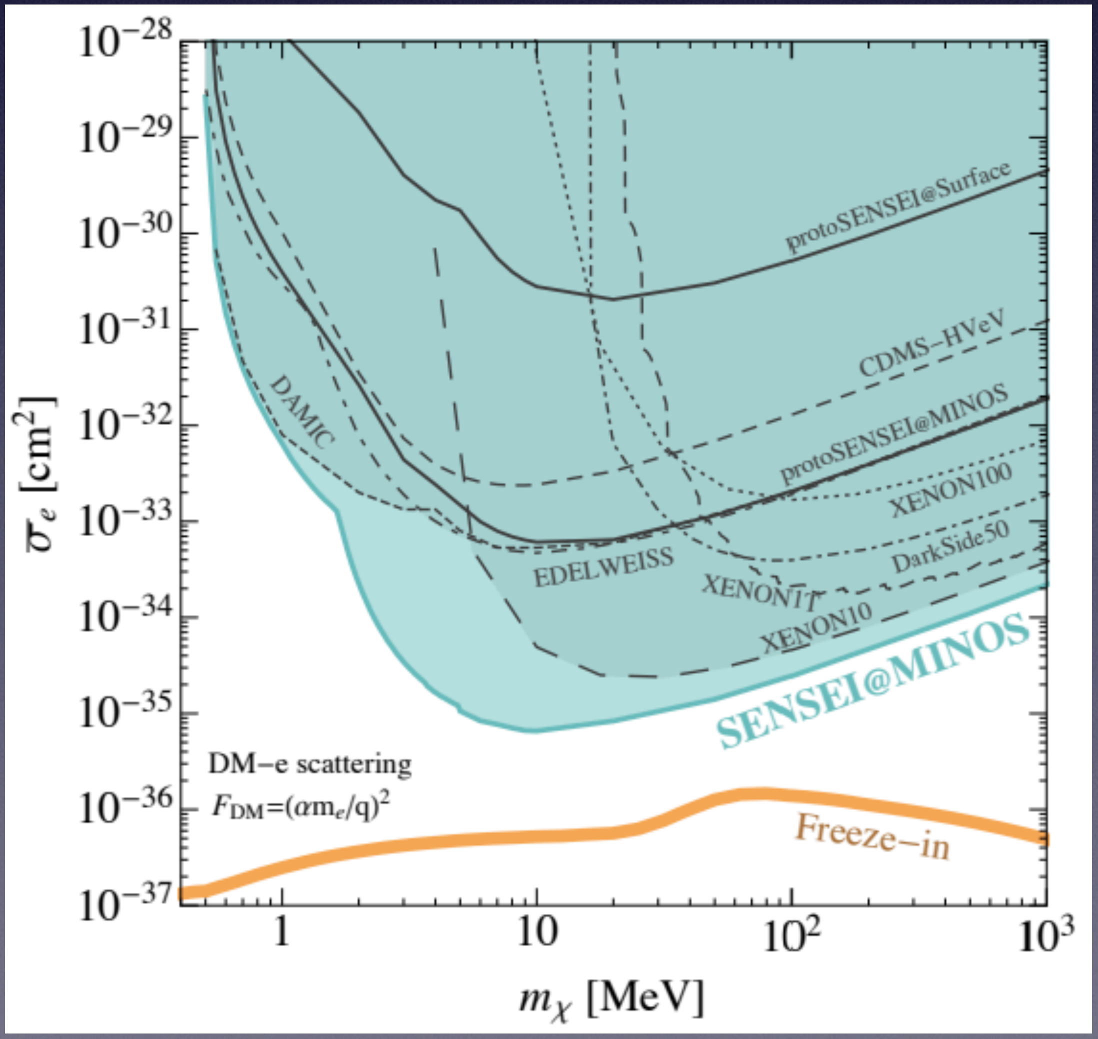
- Very active research program underway to work out possibly observable signatures of tiny energy depositions, often using special features of carefully-chosen target materials, e.g. tiny bandgaps (see Essig et al '22 (Snowmass) for a review)
- Collective/in-medium effects are often critically important

Example: SENSEI

- Employs ultra-low-noise silicon Skipper-Charge-Coupled-Devices (Skipper-CCDs)
- Silicon band gap ~ 1.2 eV
- Recent advances allow measurements of charge in each pixel (over millions of pixels) with sub-electron noise
- Search for single electron excitations across band gap, allowing testing of:
    - DM-electron scattering down to m~500 keV (recoil energy ~ 1 eV)
    - DM-nucleus scattering down to m~1 MeV (via Migdal effect)
    - DM absorption on electrons down to m~1 eV

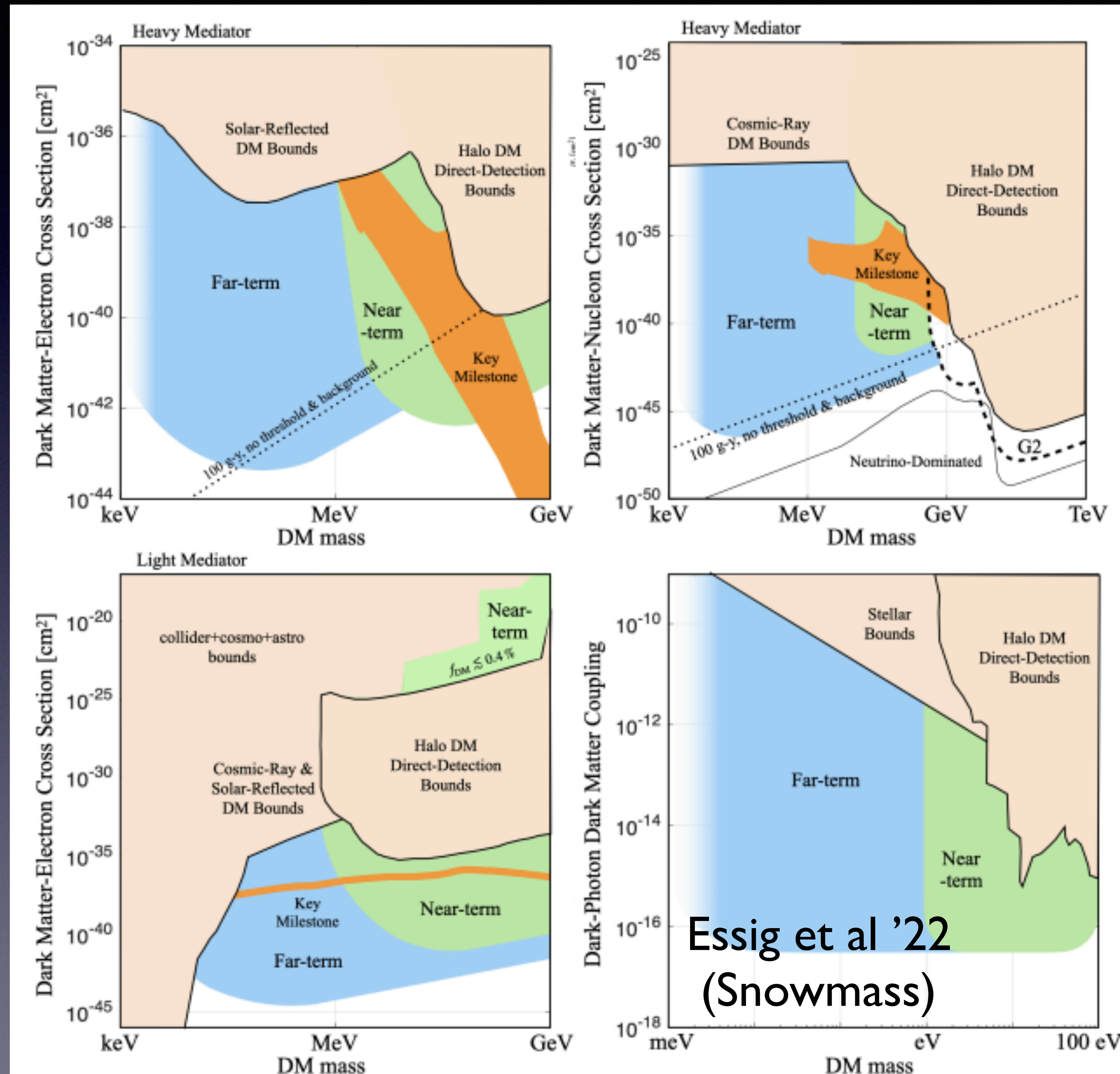


SENSEI Collaboration '20



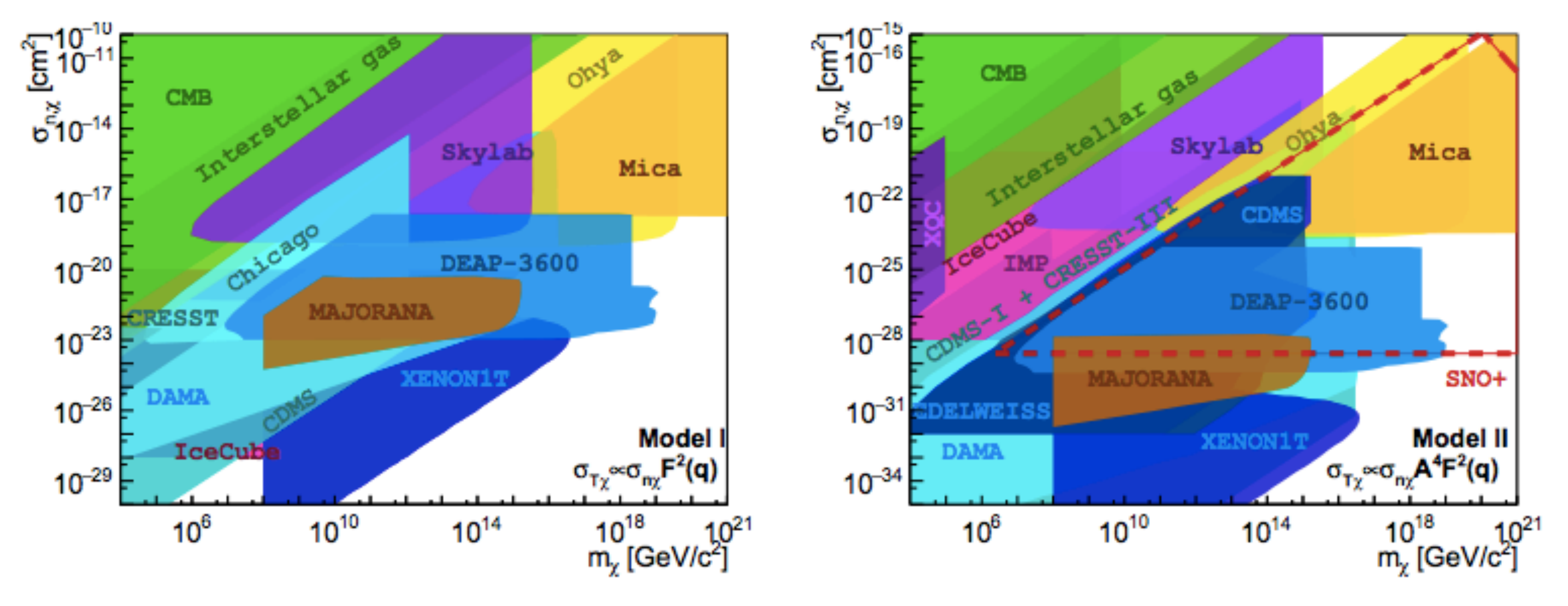
The next 10 years

- Benchmarks:
  - upper panels: freeze-out, asymmetric DM, ELDER (kinetic decoupling sets abundance)
  - lower left: freeze-in through a light kinetically-mixed dark photon (leads to enhancement of scattering at low velocity)
- Near-term: SENSEI and larger experiments using similar technologies (DAMIC-M, Oscura) will extend exposure with sensitivity to eV-scale energy deposition
- Future technologies have the potential to probe down to meV-scale energy deposits
- Astro/cosmo probes of scattering complement direct searches



Ultraheavy DM

- Large liquid noble gas experiments provide stringent constraints up to very high DM masses - signal is ~independent of DM mass (as it is controlled by reduced mass), scales only with the DM number density
- At high cross sections, multiple scatterings can be common - the signal shape for UHDM may vary (depending on mass/model) from one hit to a track of continuous energy loss within the detector volume
- In the presence of long-range forces, DM will act coherently across a many-body target - new quantum-limited mechanical sensors may allow new searches with macroscopic targets [e.g. Carney et al ’20], ultimately perhaps even for gravitational couplings (for sufficiently heavy DM)

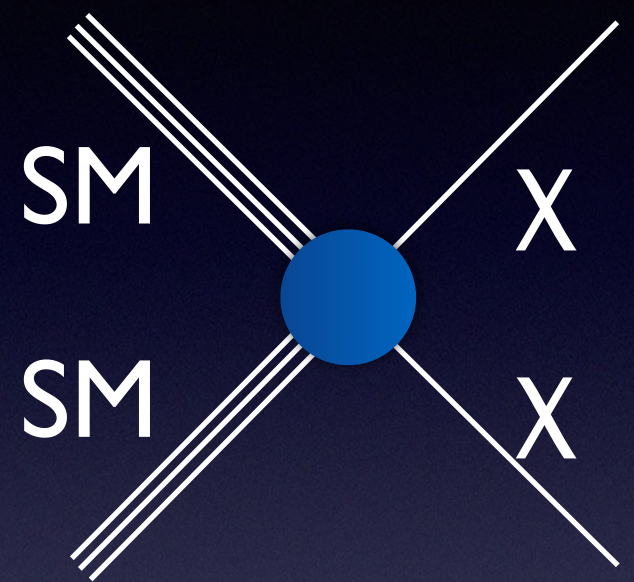


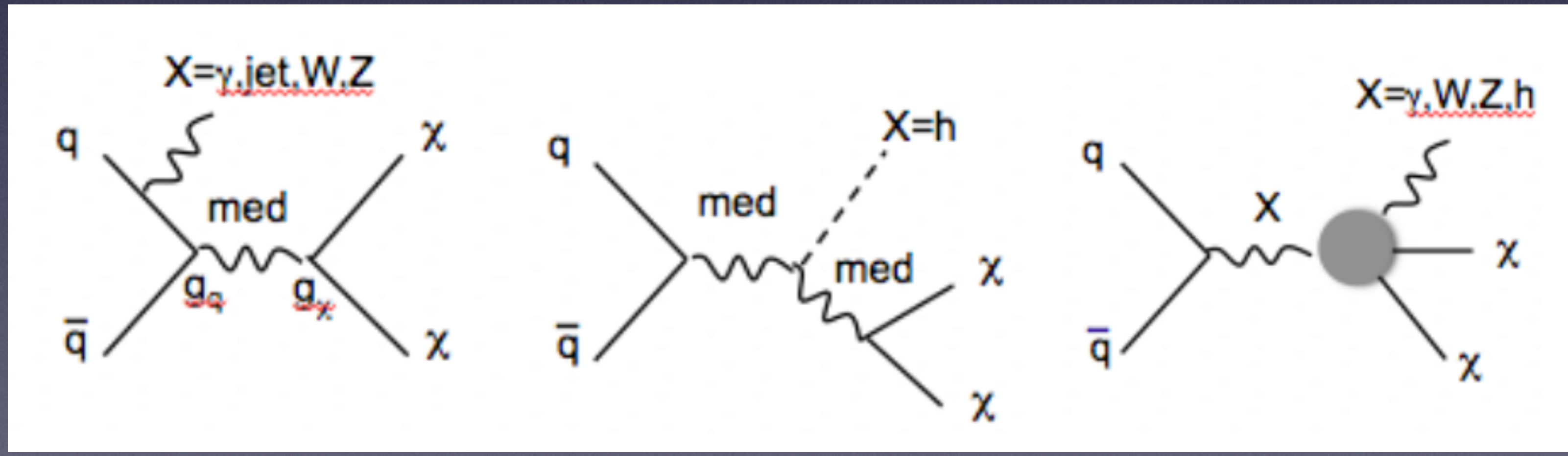
Carney et al ’22 (Snowmass)

Accelerator searches

LHC searches in a nutshell

- If DM is produced at the LHC, it is stable => will escape the detector
- Cannot be detected directly, but will show up as missing energy/momentum
- Most direct DM searches at LHC are "mono-X" searches - look for visible particle recoiling off invisible partner
  - e.g. mono-Higgs
  - mono-jet
  - mono-photon
- Doesn't fundamentally need to be "mono" - could be more than one visible particle/jet in the event





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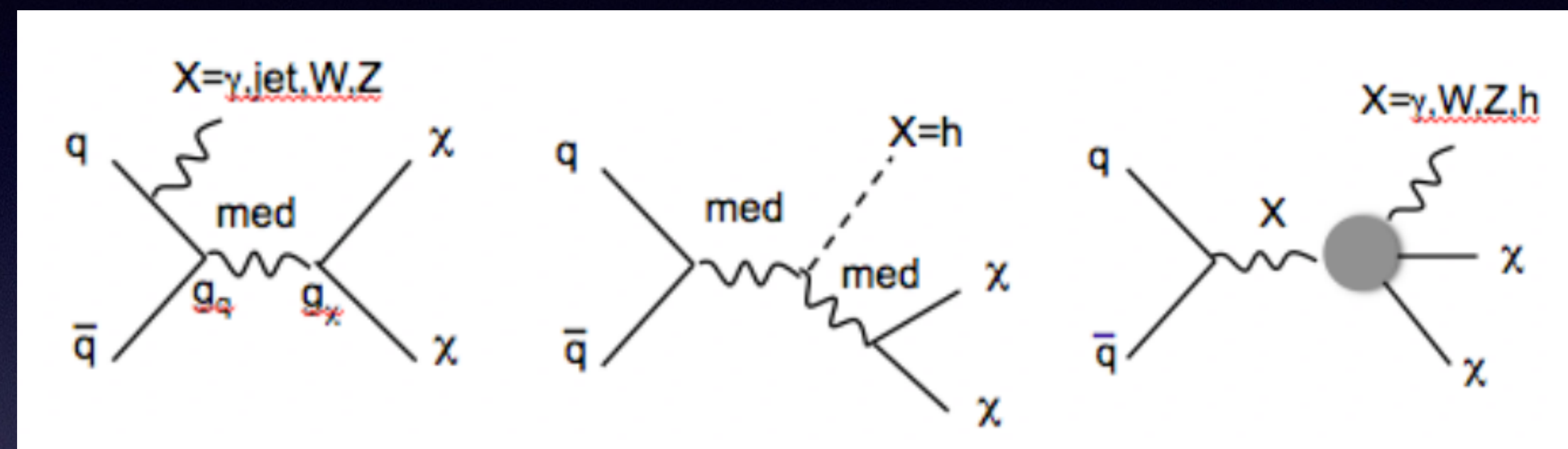
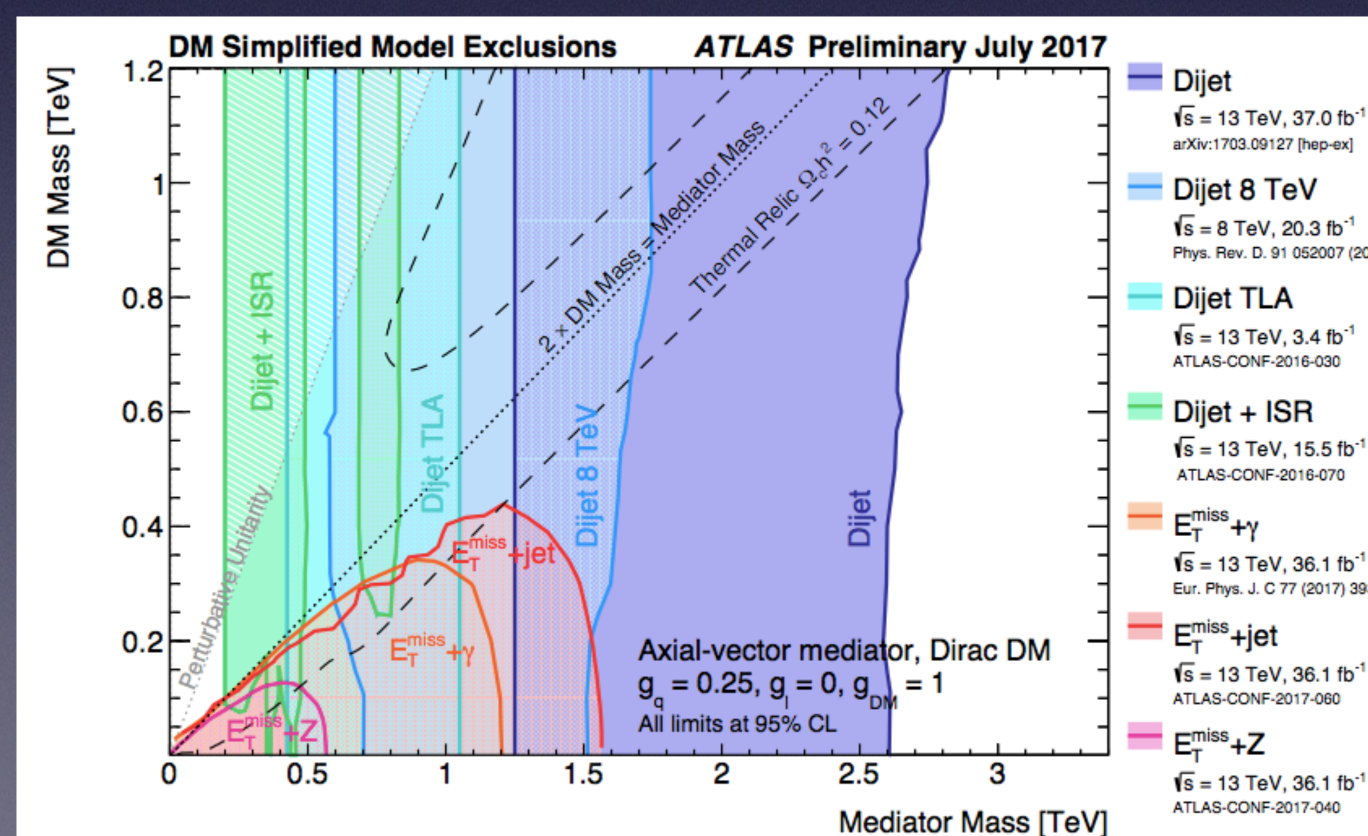
Approaches for dark matter

- Construct <u>detailed</u> model of high-energy physics (e.g. SUSY model), search for resulting signatures
  - Upside: since there are many non-DM particles, can have striking effects. Characteristic signatures can include cascades producing many particles, with large "MET" (missing momentum transverse to the beam direction) - since all SUSY partners decay to the LSP eventually
  - Downside: not easy to translate constraints on one model into bounds on another model. (Not "model-independent".) Makes interpretation more challenging.
- Construct <u>simplified</u> model with only a few ingredients, develop generic searches
  - Upside: easy to translate to many models, reduces the risk of missing a signal due to searching too narrowly
  - Downside: sometimes effects of extra ingredients are important! No guarantee that simplified model can be embedded into reasonable high-energy theory.
- Approaches are complementary.
- Can also use effective field theory approach if heavy degrees of freedom can self-consistently be integrated out (not always the case).

ATLAS simplified model results

- Example of a simplified model approach: suppose DM couples to some heavy mediator, which also couples to quarks
- Exchange of this mediator allows pair production of DM, along with other particles
- Can consider different possibilities for the spin of the mediator - vector, axial vector, scalar, pseudoscalar, etc.

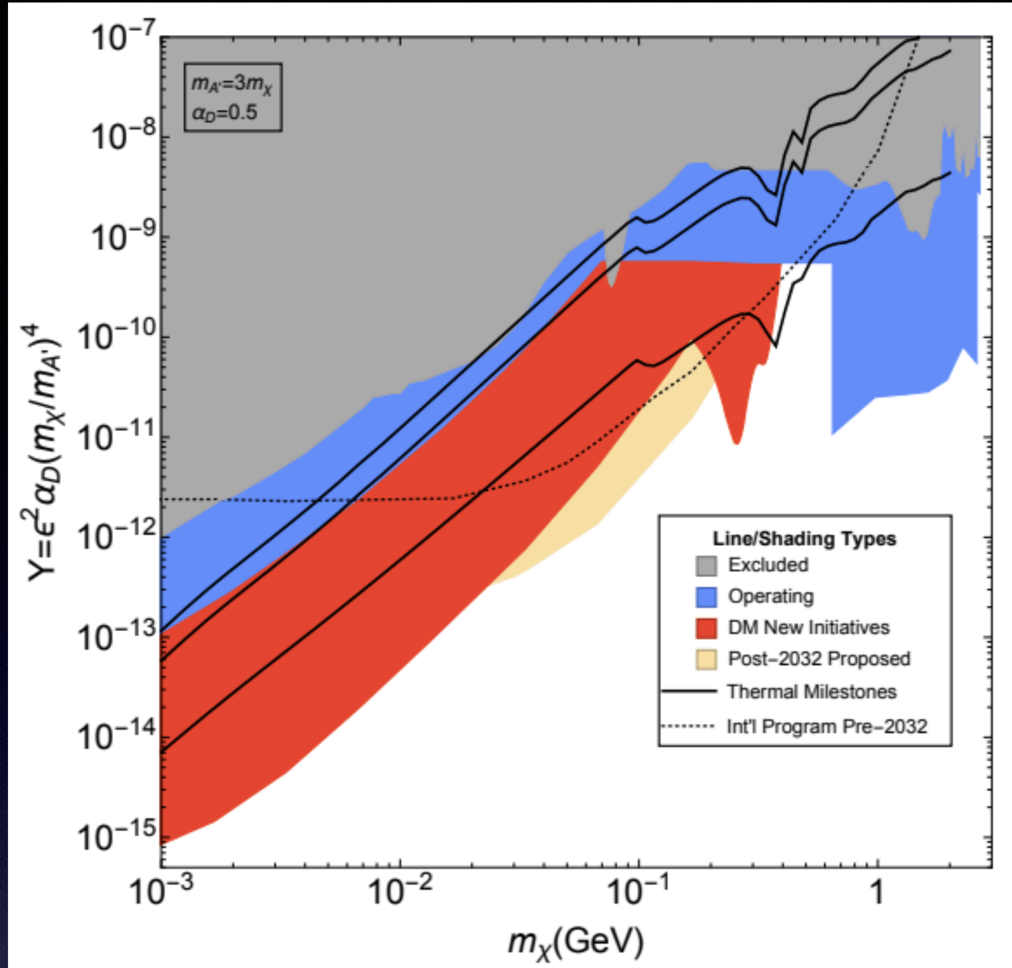


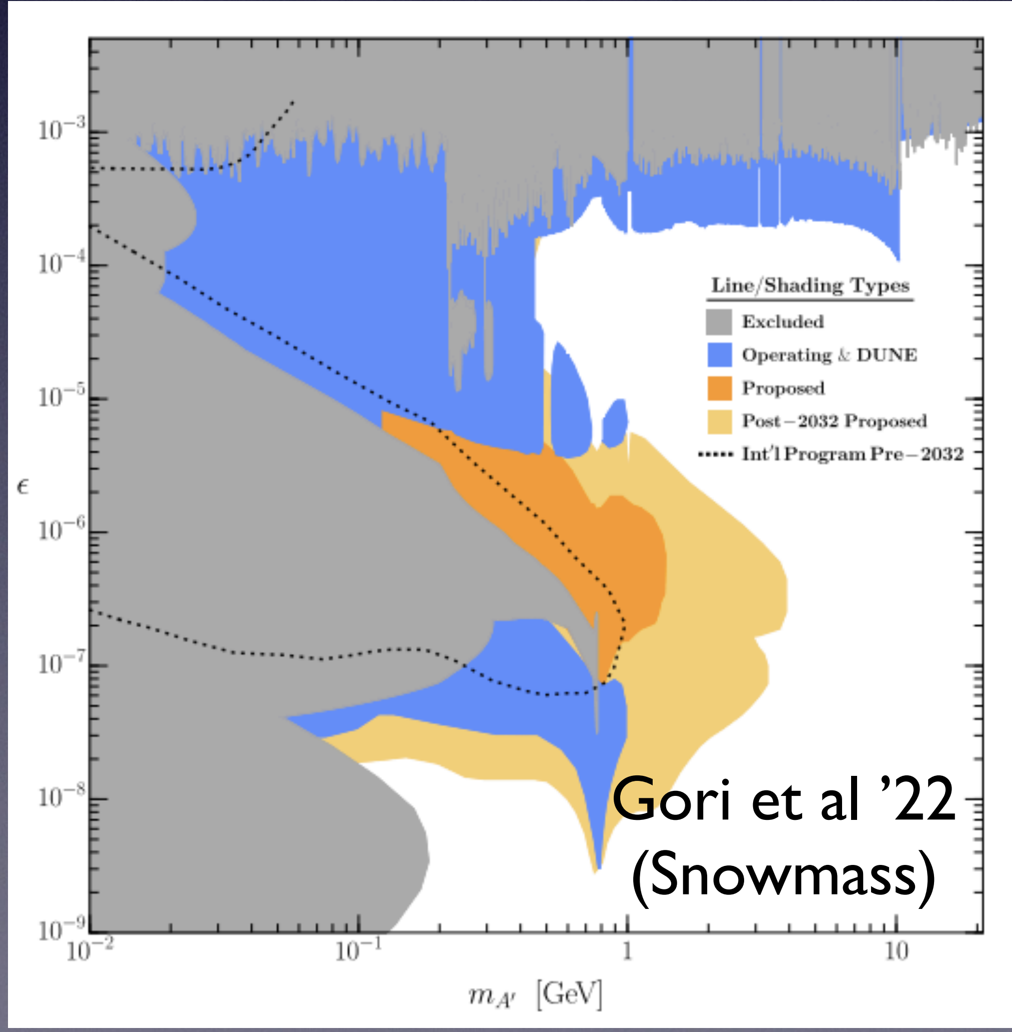


Constraints based on 13 TeV ATLAS data

Other accelerator searches

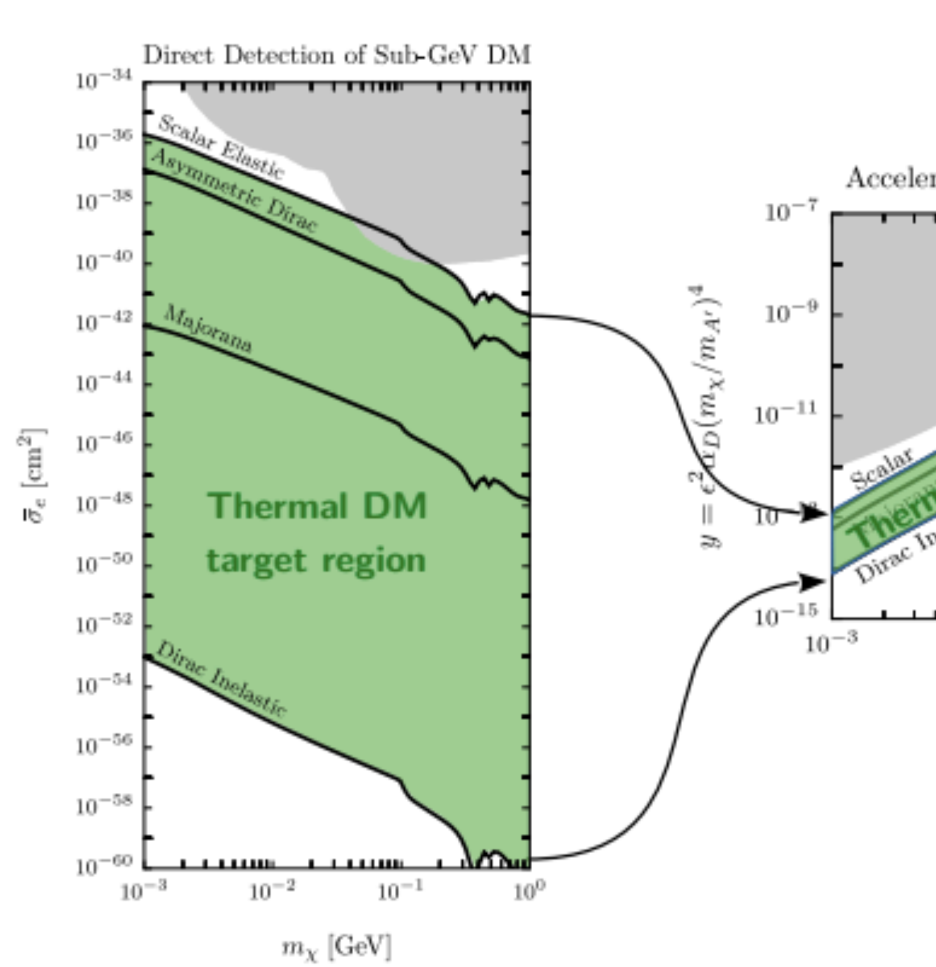
- For light DM or DM that interacts with the SM through new light weakly-coupled particles, high luminosity may be more important than high energy
- Active program of fixed-target and collider experiments to search for both DM annihilating through new mediators + new mediators themselves
- Immediate target: "full exploration of the range of interaction strengths compatible with light DM thermal freeze-out via the simplest mechanism of s-channel annihilation to SM particles mediated by a dark photon"
- Gori et al '22 (Snowmass, RF6 topical report) provides an in-depth discussion



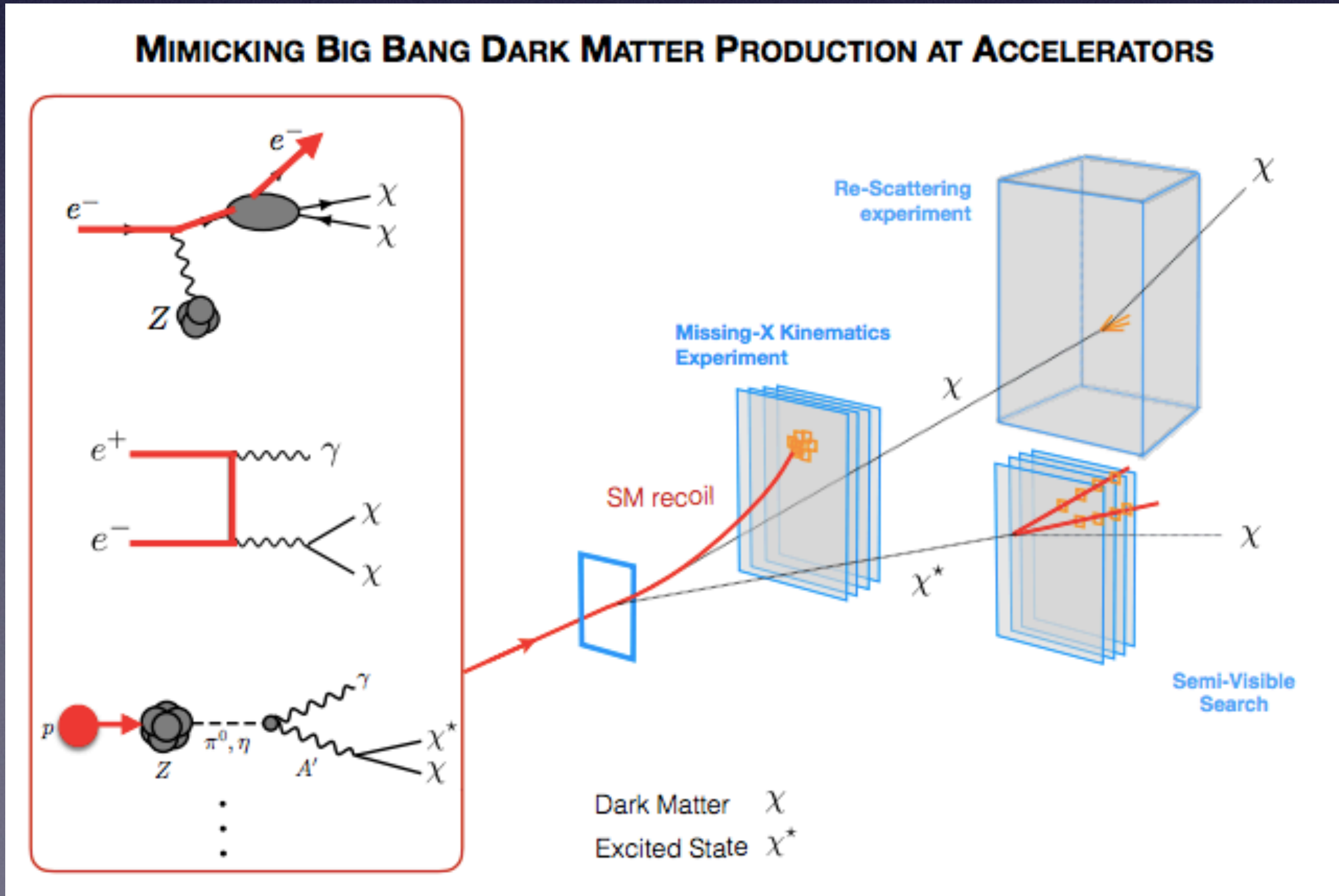


Thermal relic targets

- General argument: direct/ indirect detection largely measure DM interactions in the present-day halo, v ~ 10^{-3}
- Accelerators allow reproduction of conditions in the freezeout epoch (relativistic or near-relativistic DM)
- Leads to relatively narrow range of expected accelerator signals for simple portal models with thermal freezeout
- Multiple channels to probe DM production



Gori et al '22 (Snowmass)



Dark sector searches

- Mediators coupled to the SM through minimal portals could exist whether or not they relate to DM
- In some cases, may be our first clue to the existence of a dark sector
- Mediators can decay to SM particles or invisibly into the dark sector - can search for both
- Can use existing accelerators (including the LHC) as a source of long-lived particles - search for their displaced decays with additional detectors (e.g. FASER, CODEX-b, MATHUSLA)

Example: status of Higgs portal with visible decays