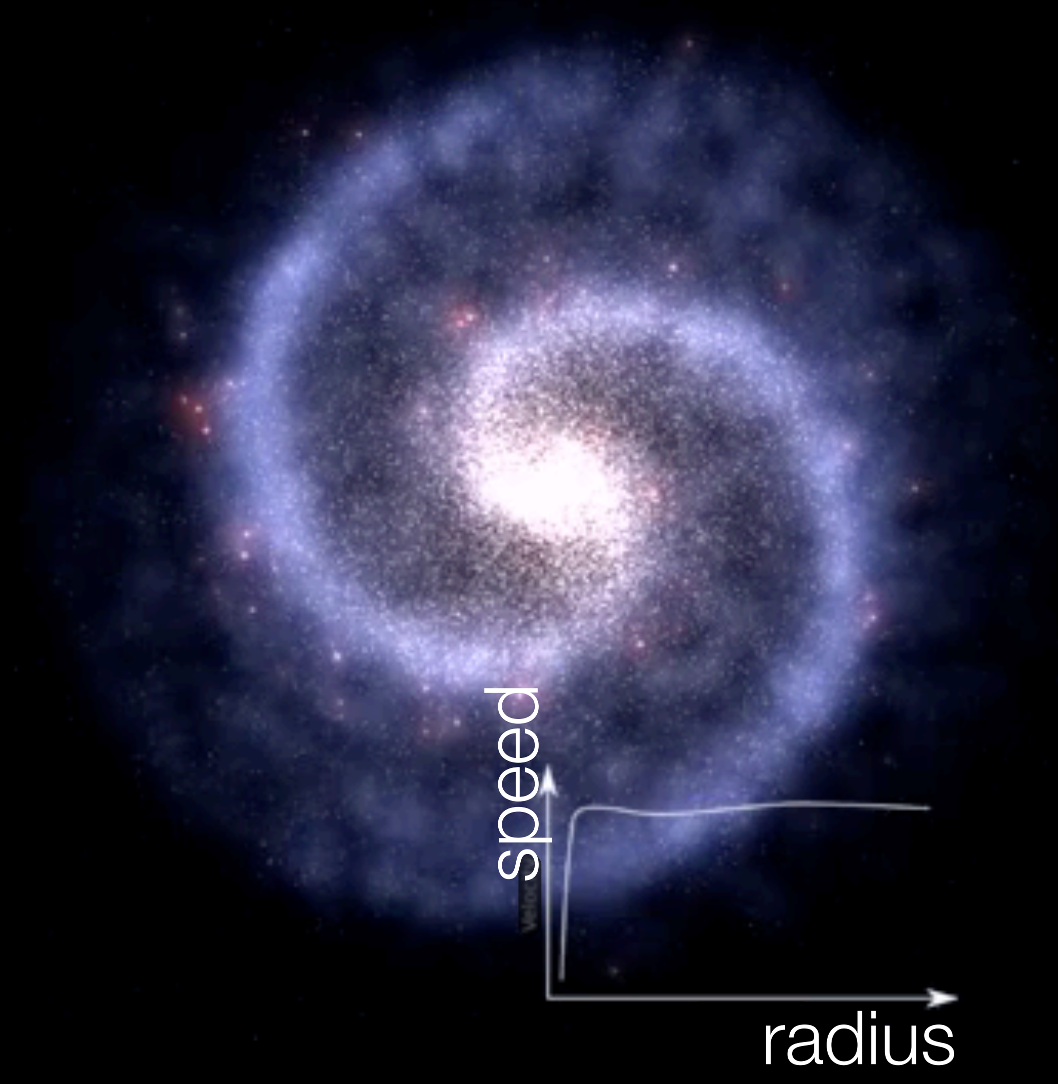
The Nature of Dark Matter

Enectalí Figueroa-Feliciano

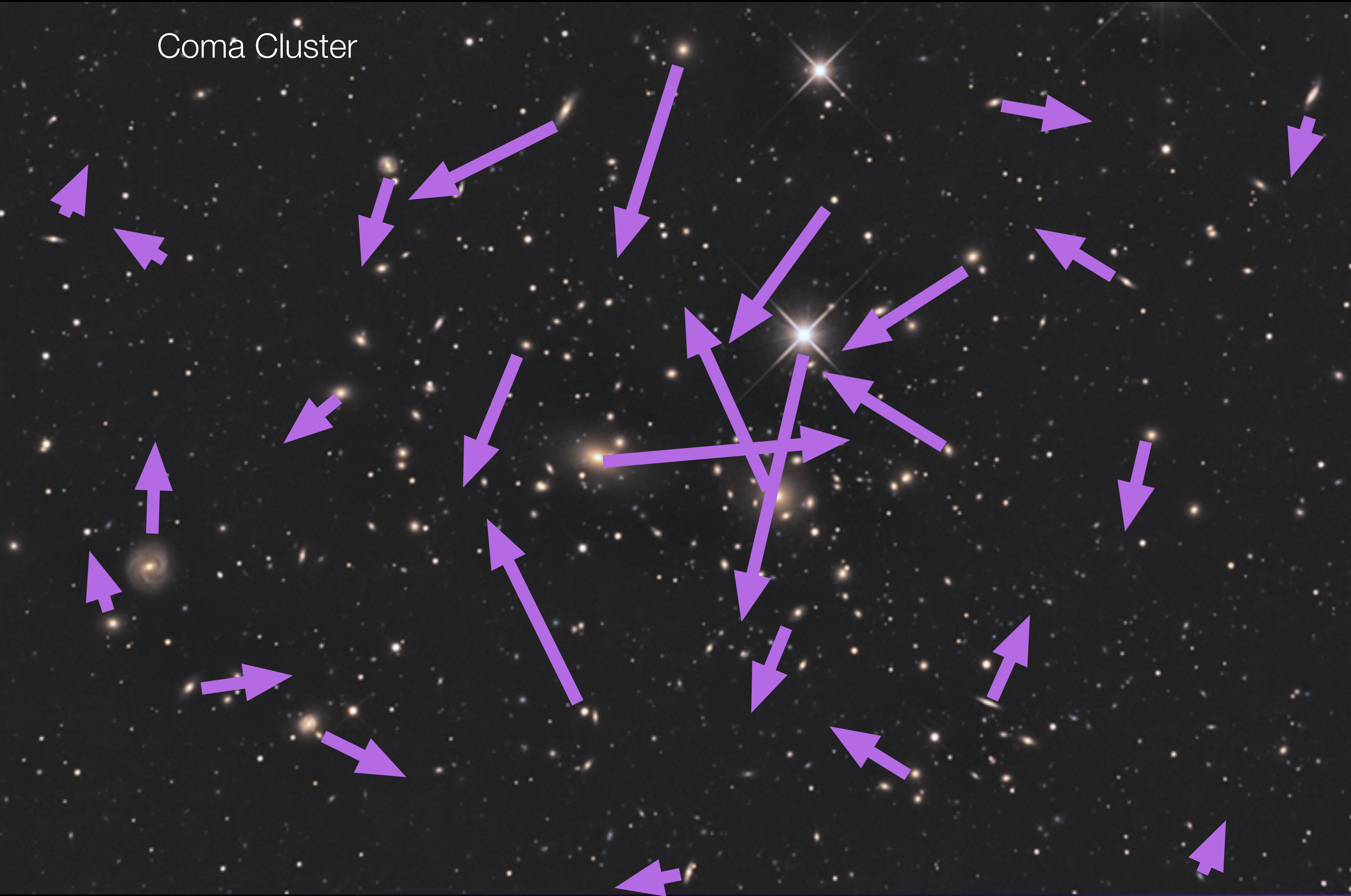
Northwestern

Galaxy Rotation Curves

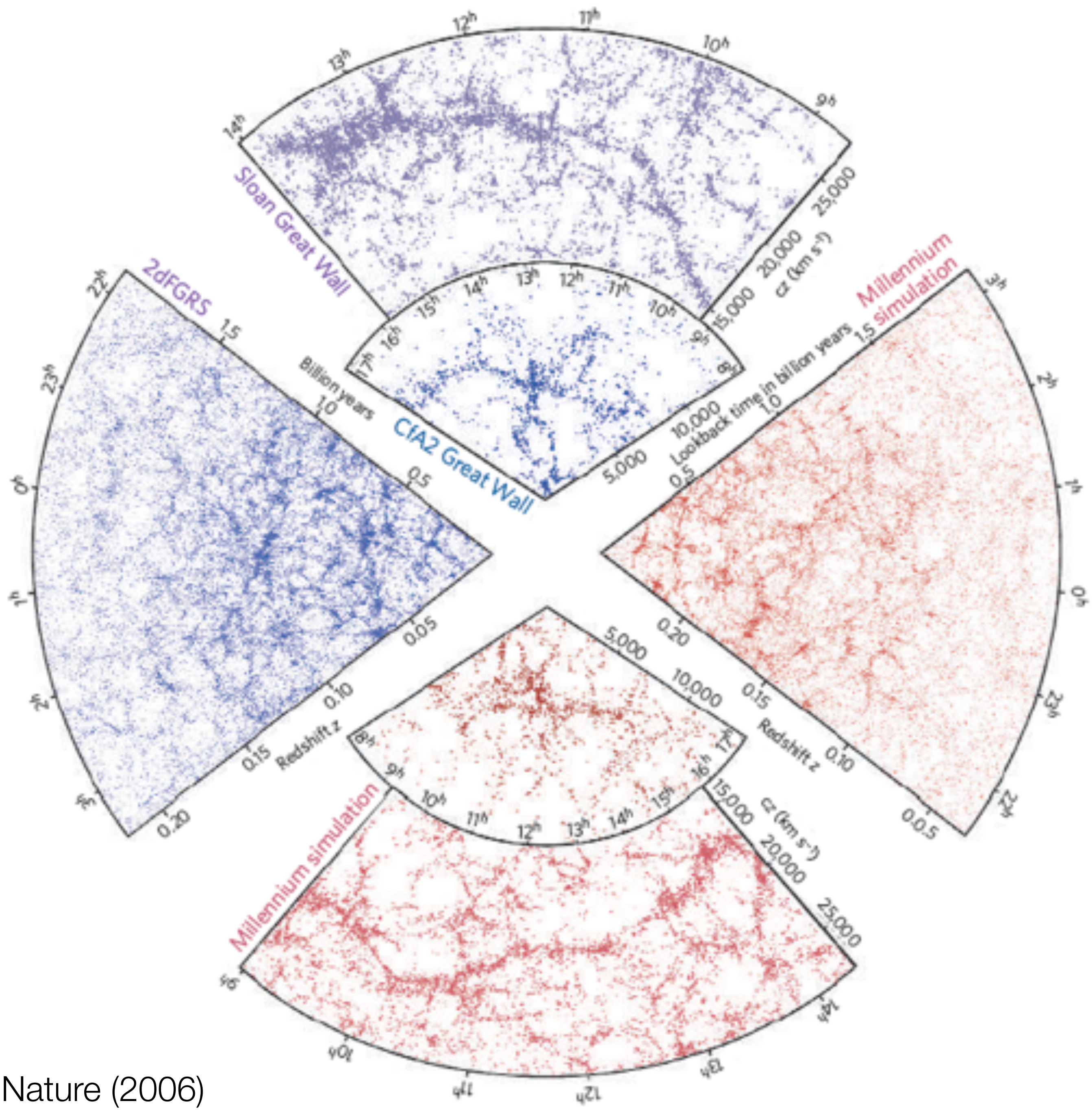
orbits at high radius are
faster than expected

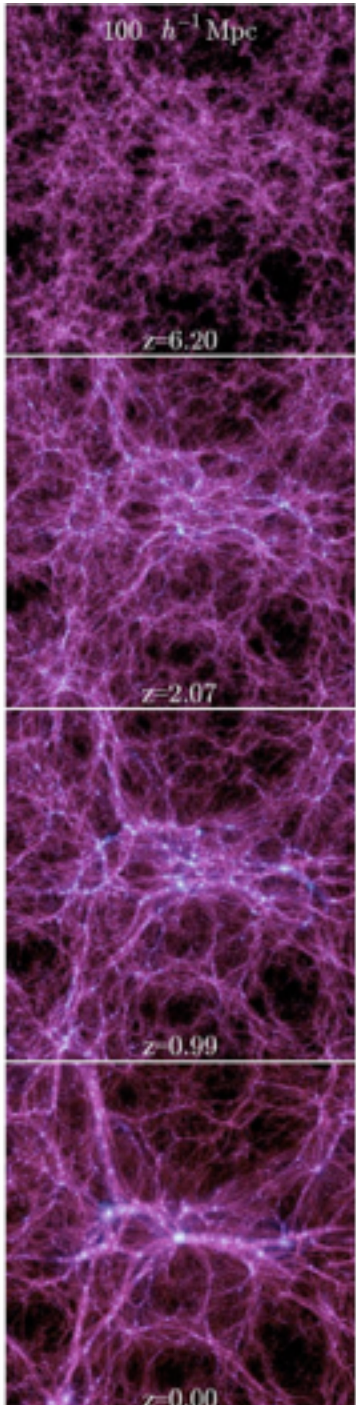


Galaxy Velocities in Clusters



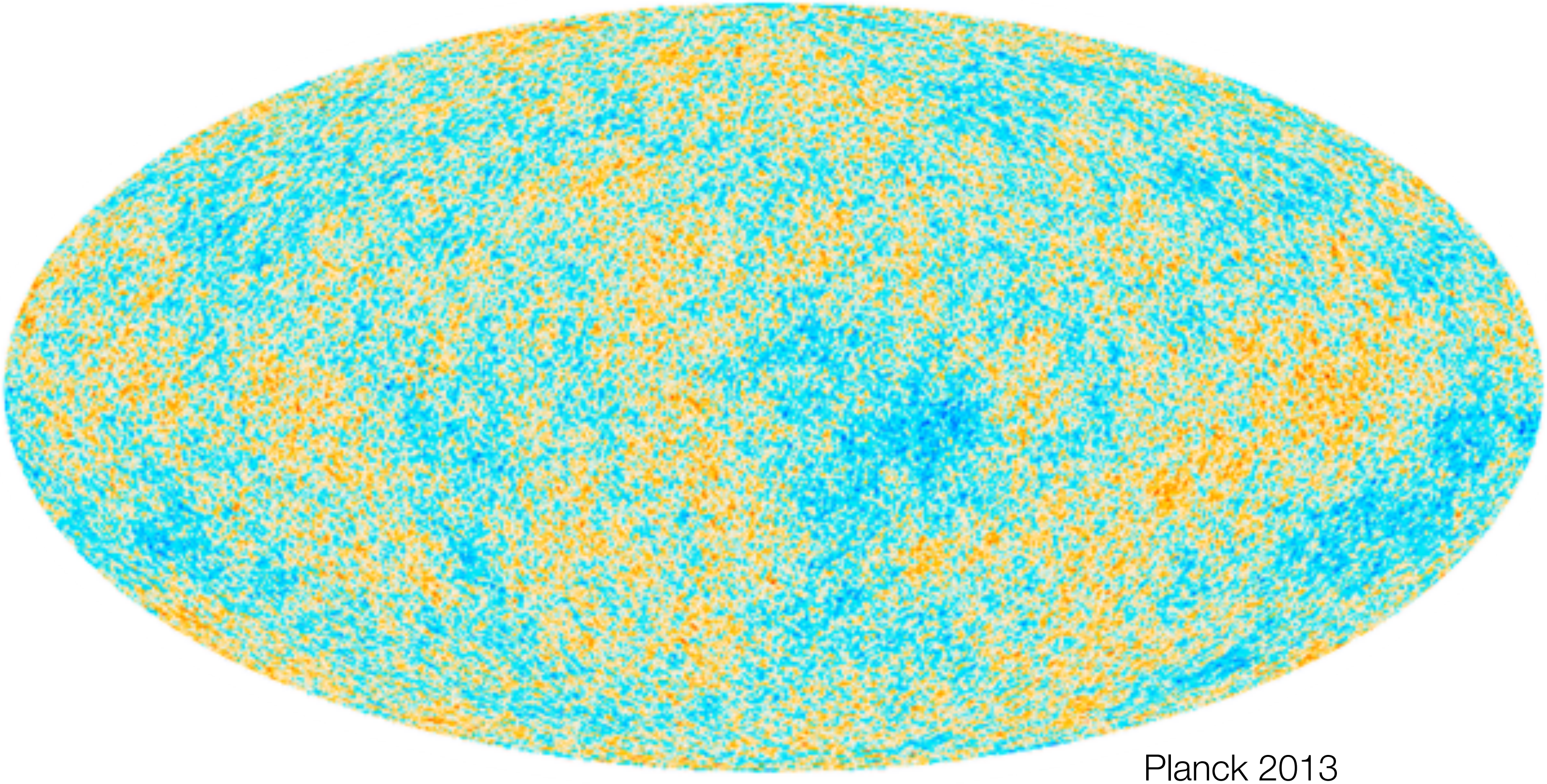
Models of Structure Formation





Springel, Nature (2006)

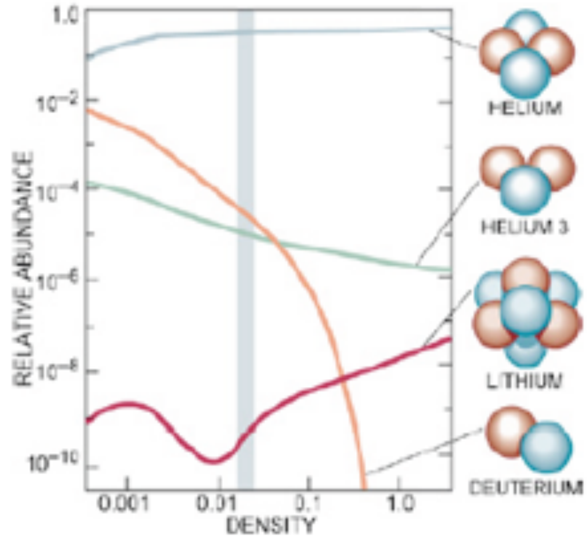
Fits to Cosmic Microwave Background

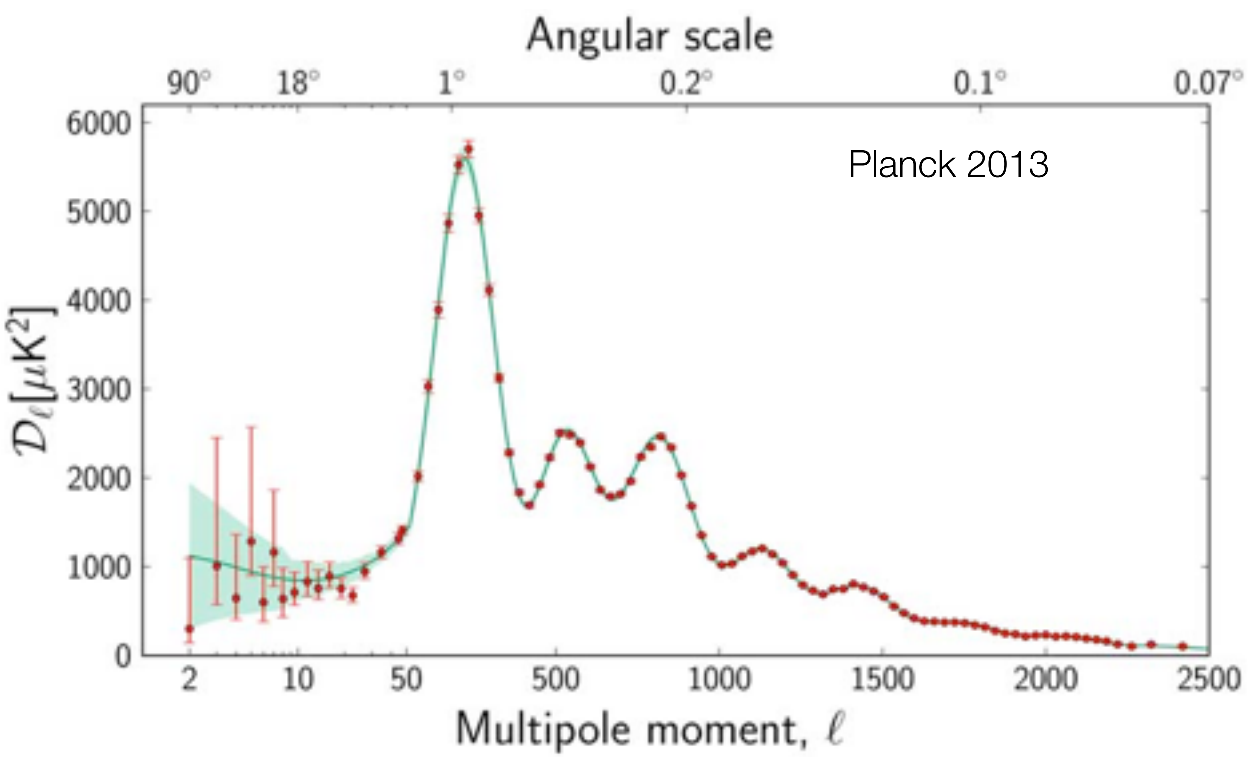


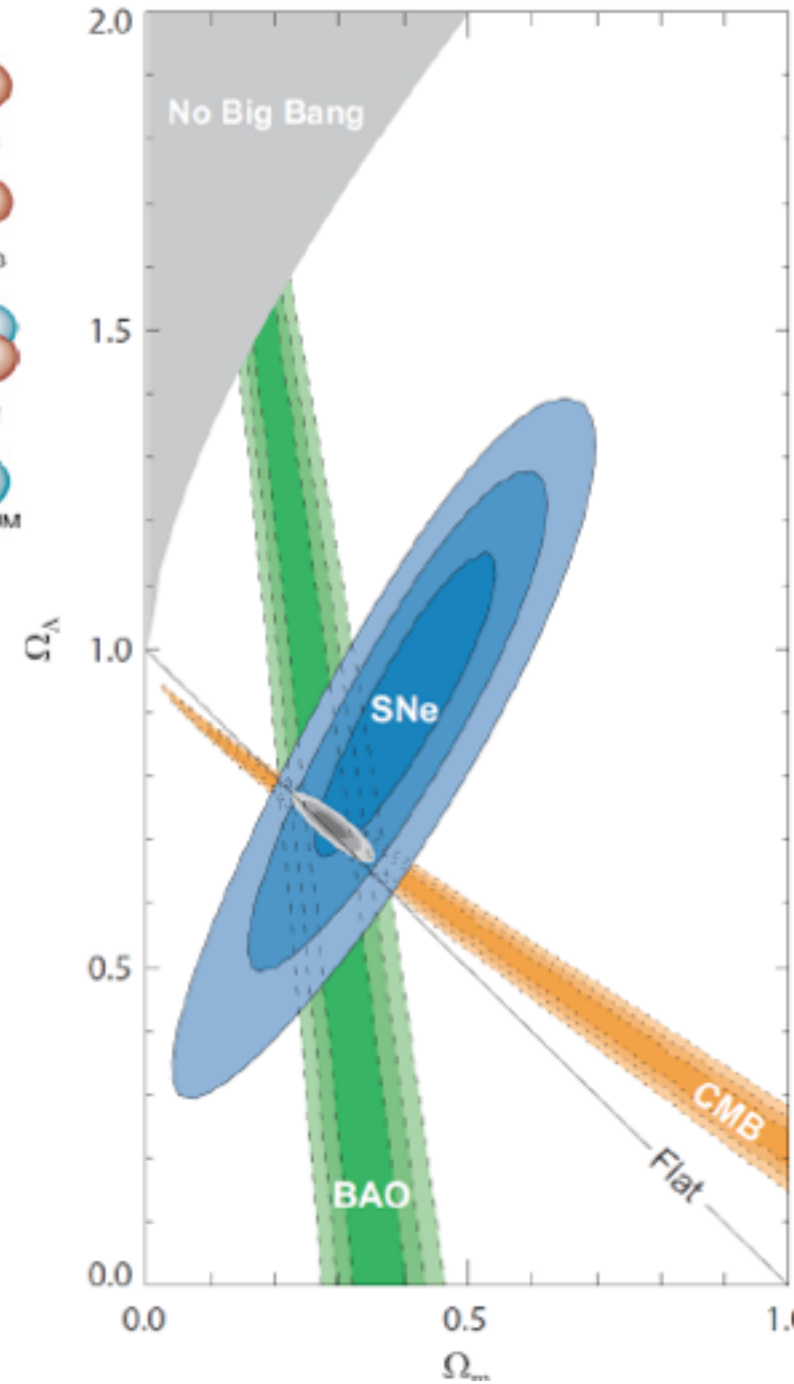
Planck 2013

The ΛCDM Model of Cosmology

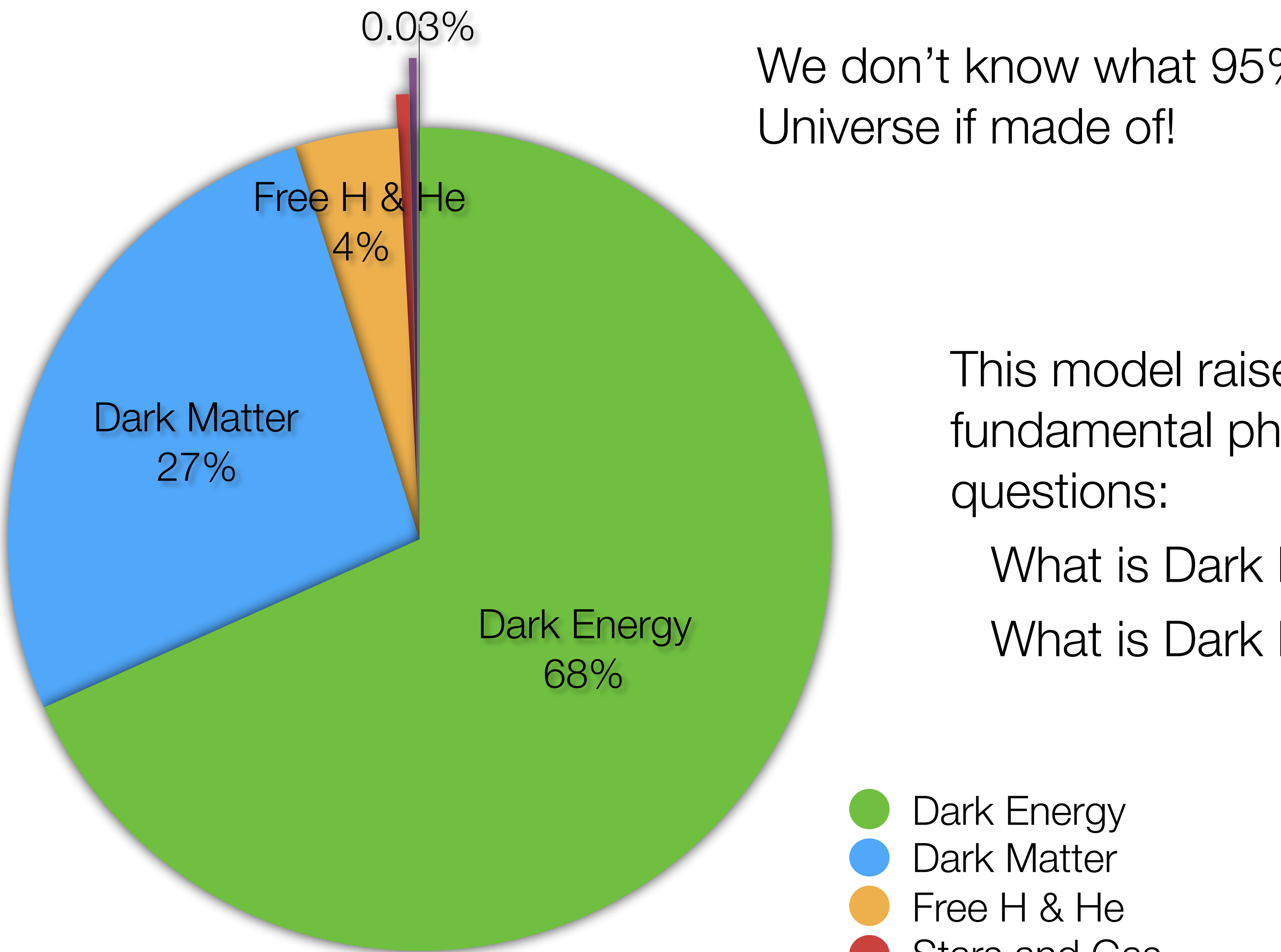
One model has emerged that fits all the observations with only 6 parameters.







The ΛCDM* Model of Cosmology



We don't know what 95% of the Universe if made of!

This model raises some truly fundamental physics questions:

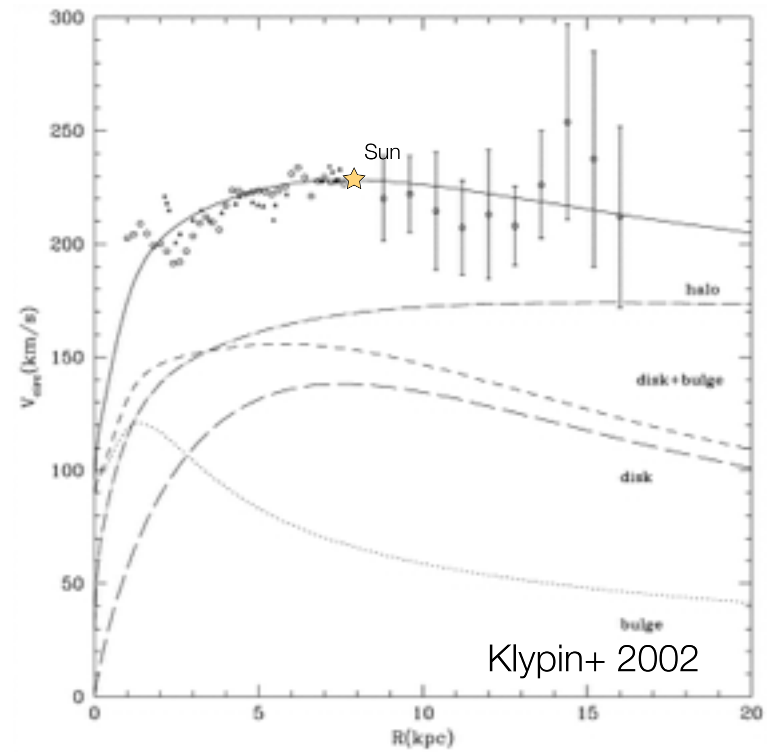
What is Dark Matter?

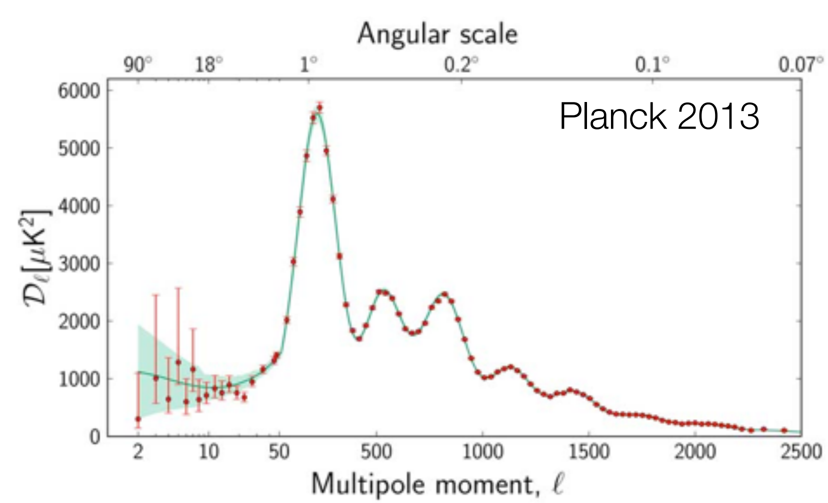
What is Dark Energy?

*Might be ΛWDM…

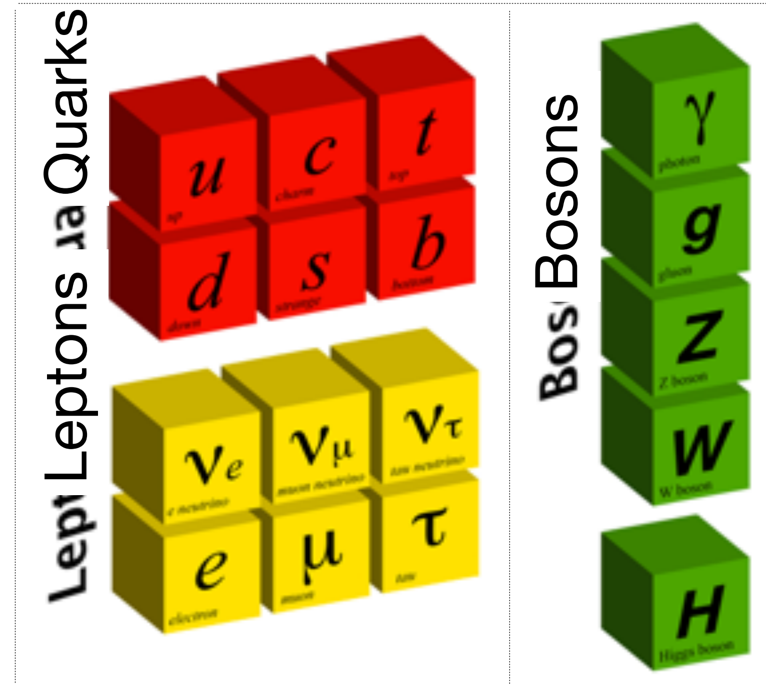
What we Know about Dark Matter

- There is a Missing Mass Problem:
  - Dynamics of stars, galaxies, and clusters
  - Rotation curves, gas density, gravitational lensing
  - Large Scale Structure formation
- There is Wealth of evidence for a particle solution
  - MOND has problems with weak lensing and CMB
  - Microlensing (MACHOs) mostly ruled out
- Dark Matter is Non-baryonic
  - Height of acoustic peaks in the CMB (Ωb, Ωm)
  - Power spectrum of density fluctuations (Ωm)
  - Primordial Nucleosynthesis (Ωb)
- And its STILL HERE!
  - Stable (or extremely long-lived), neutral, non-relativistic
  - Interacts via gravity and (maybe) some sub-weak scale force



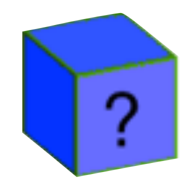


Dark Matter may be a Rosetta Stone!



We know the Standard Model is incomplete.

Where does dark matter fit in?

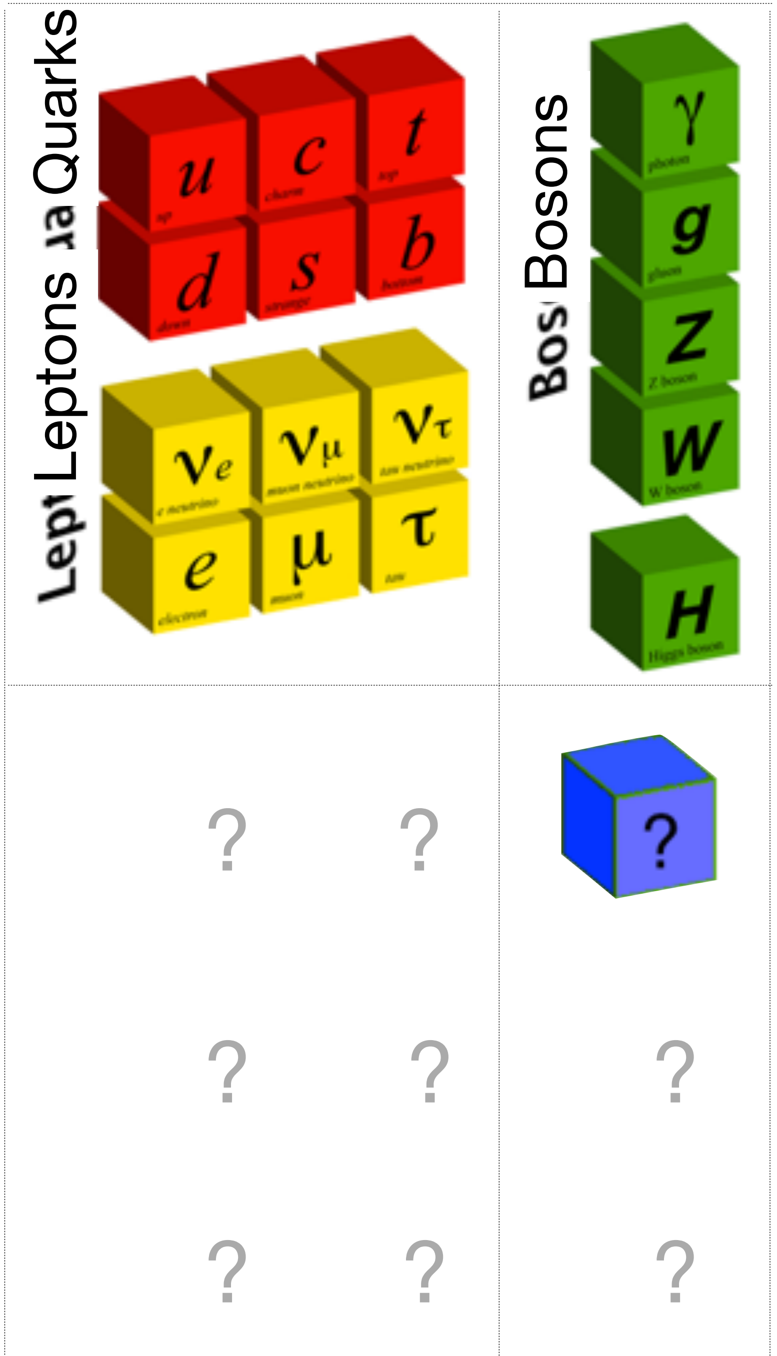


Dark Matter may be a Rosetta Stone!

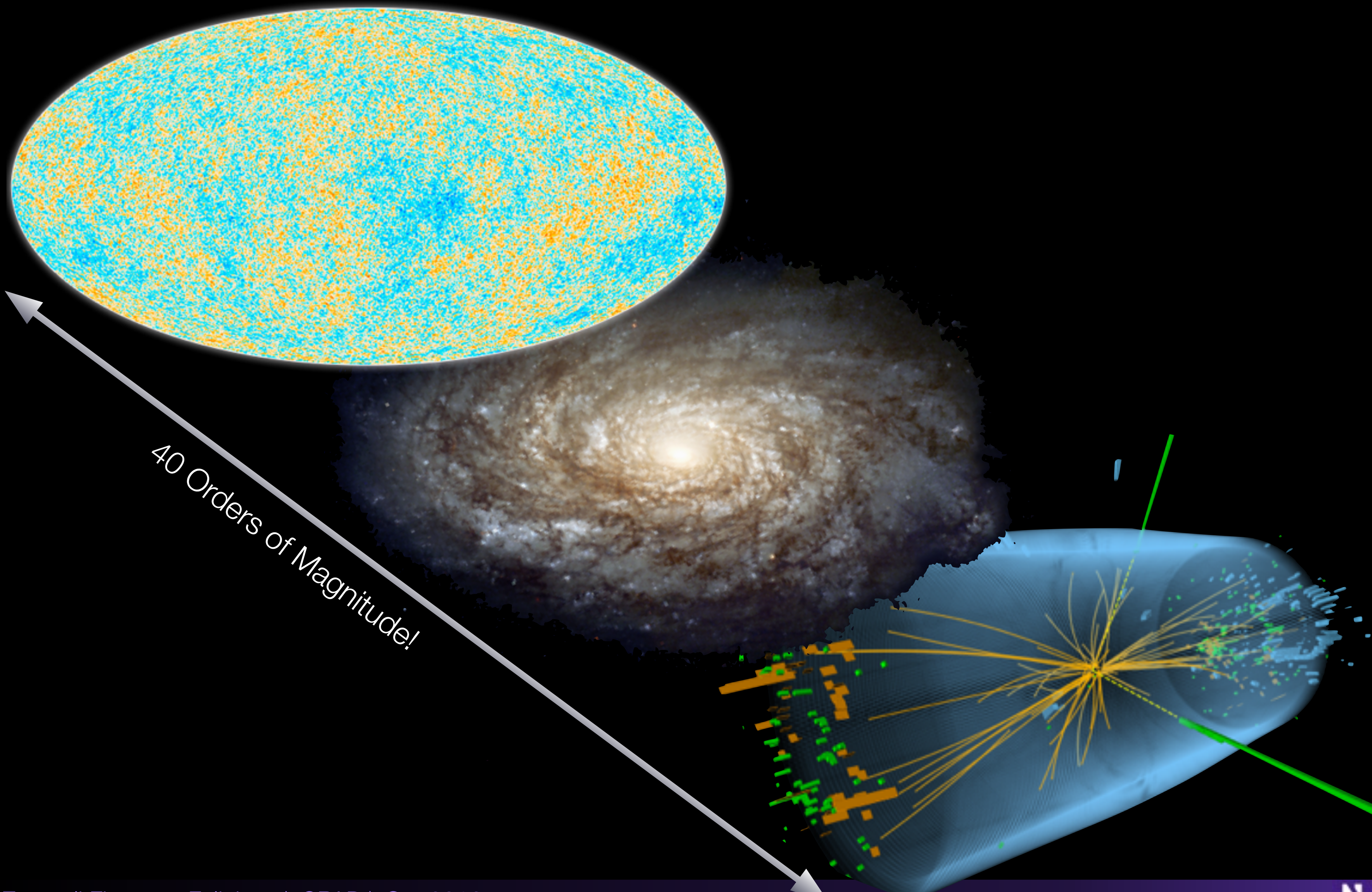
We know the Standard Model is incomplete.

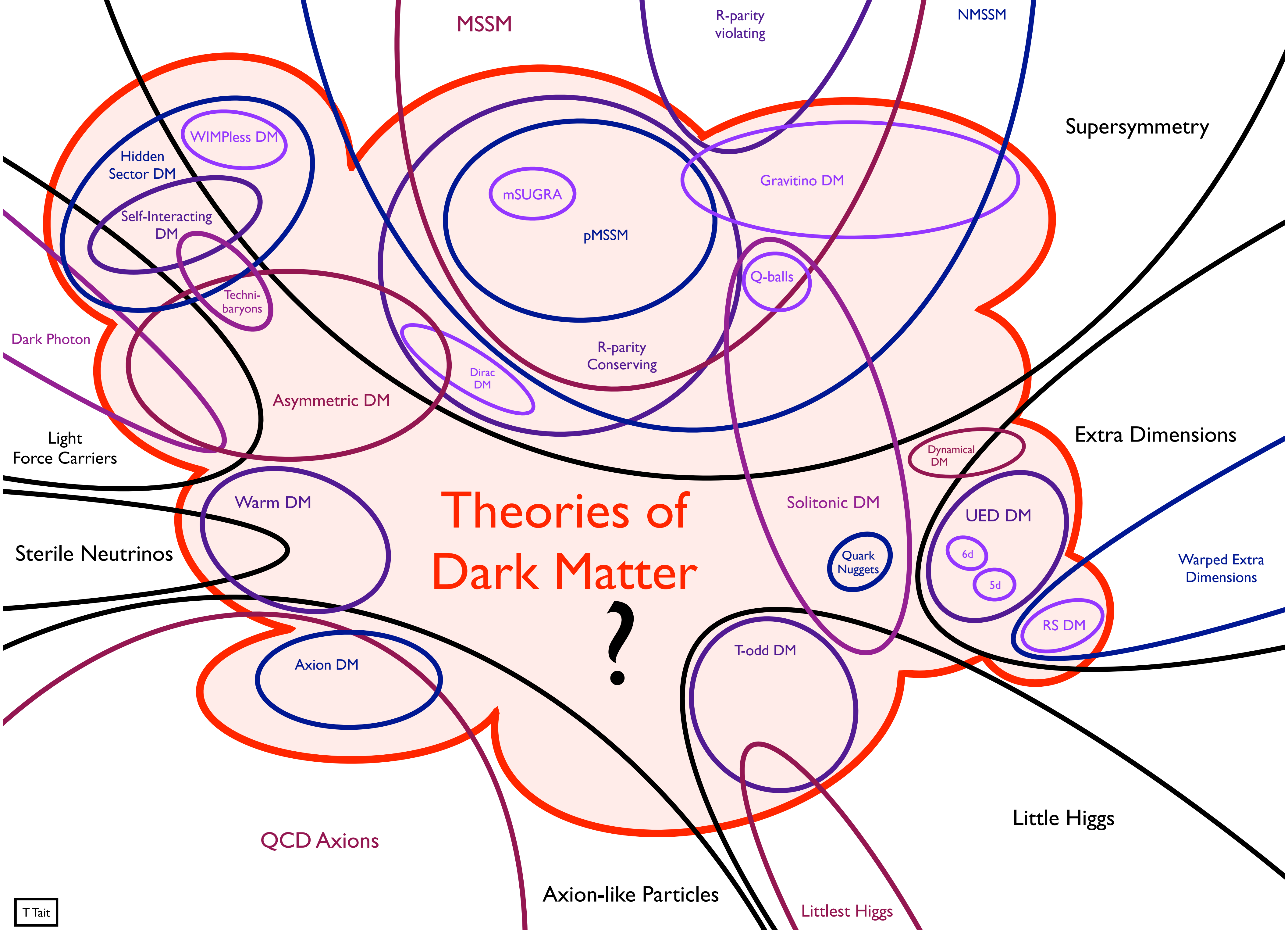
Where does dark matter fit in?

And how does it fit into a more general understanding?



A Beautiful Problem in Physics




MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
Dark Photon
Dirac DM
R-parity Conserving
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

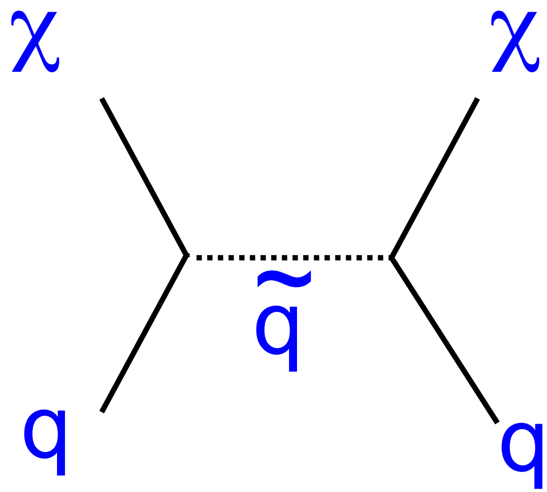
Dark Matter Menu

- Axions
- Axion-like Particles
- Hidden Sector Particles
- Sterile Neutrinos
- WIMPs
- SuperWIMPs
- Solitons
- KK excitations
- Gravitinos
- And many more that can fit the bill…

The Hunt for Dark Matter

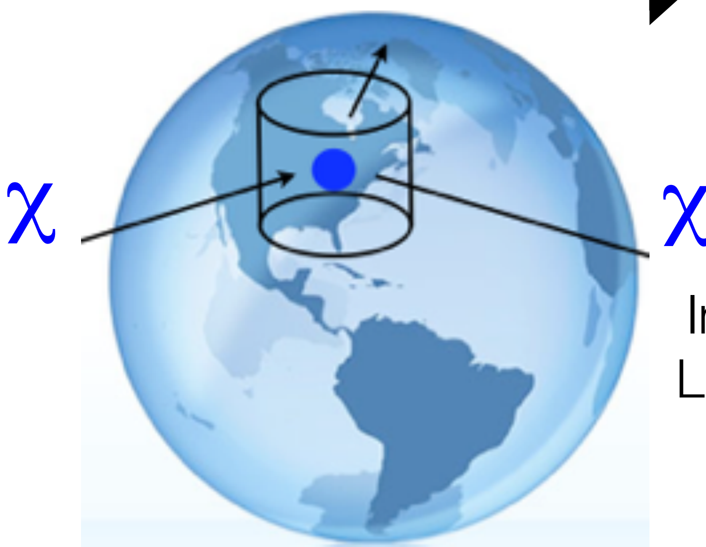
covered by
Simona MURGIA

Relic annihilation or decay in the cosmos
INDIRECT DETECTION



covered by
Antonio BOVEIA

man-made COLLIDER production



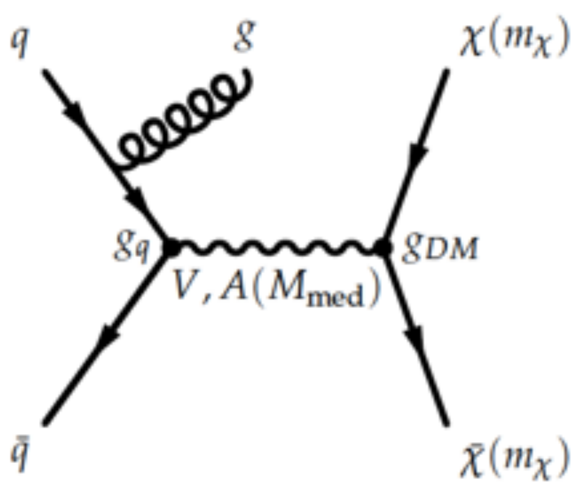
Relic Dark Matter Interacting in a Lab Experiment
DIRECT DETECTION

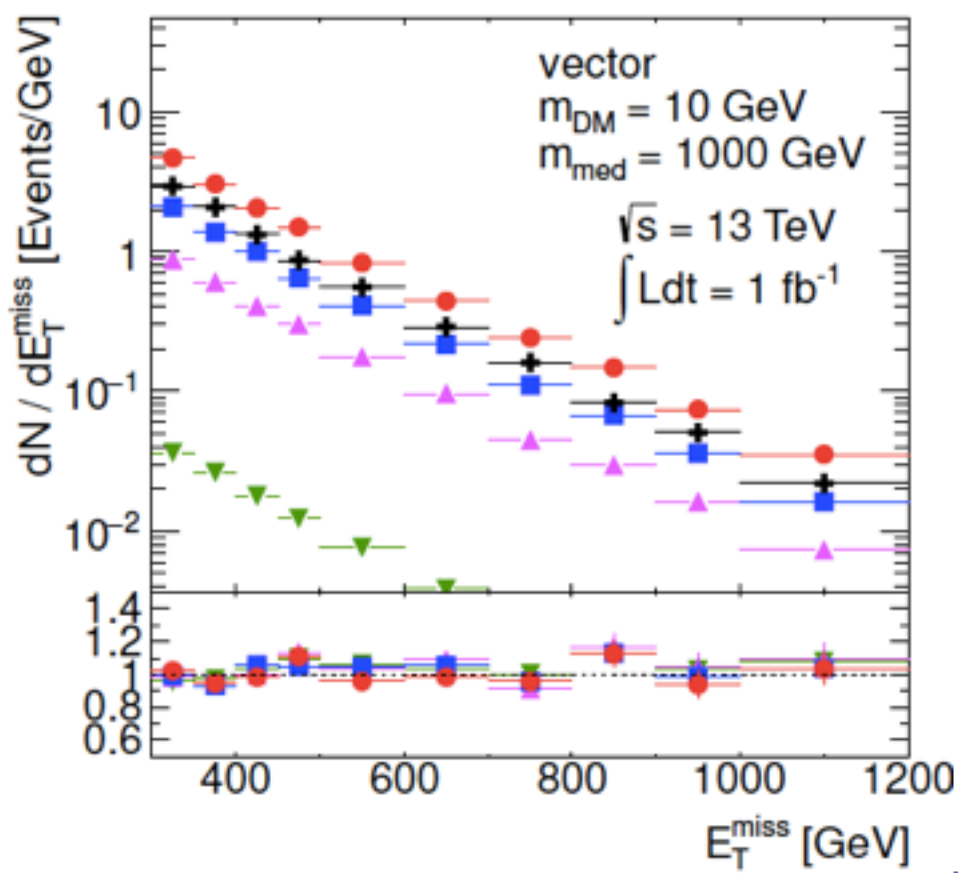
covered by
David TANNER
& Scott HERTEL

LHC: a Dark Matter Factory?

- Dark matter could be produced at the LHC
- If they are produced with visible SM particle(s) X_i, one can search for “mono-X” or $\not{E}_T$ + X reactions
- Can use contact interaction operators in an EFT framework (assuming heavy mediators), or use benchmark simplified models.

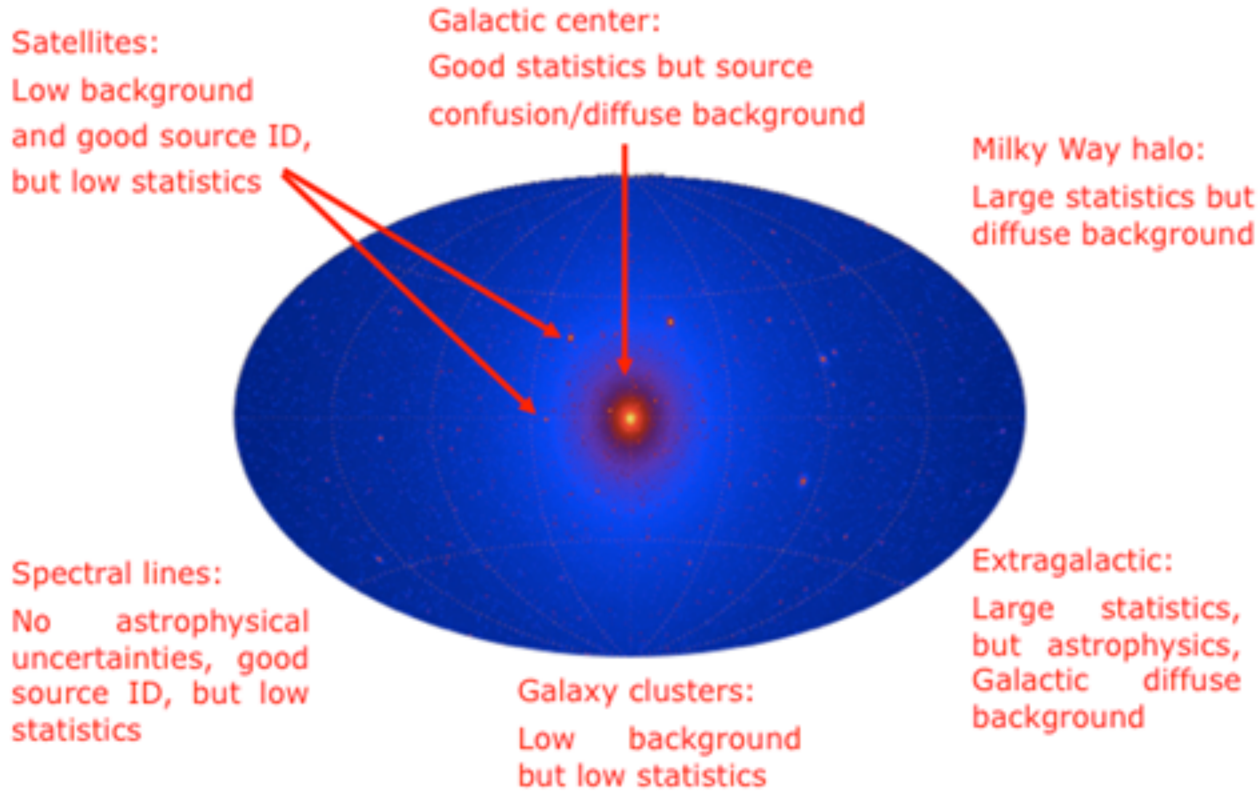
covered by Antonio BOVEIA



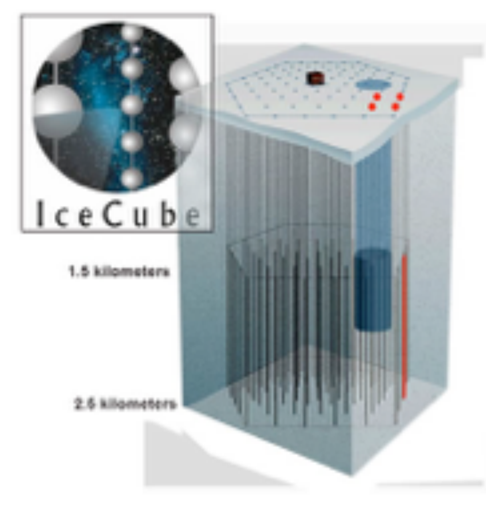


Indirect Detection

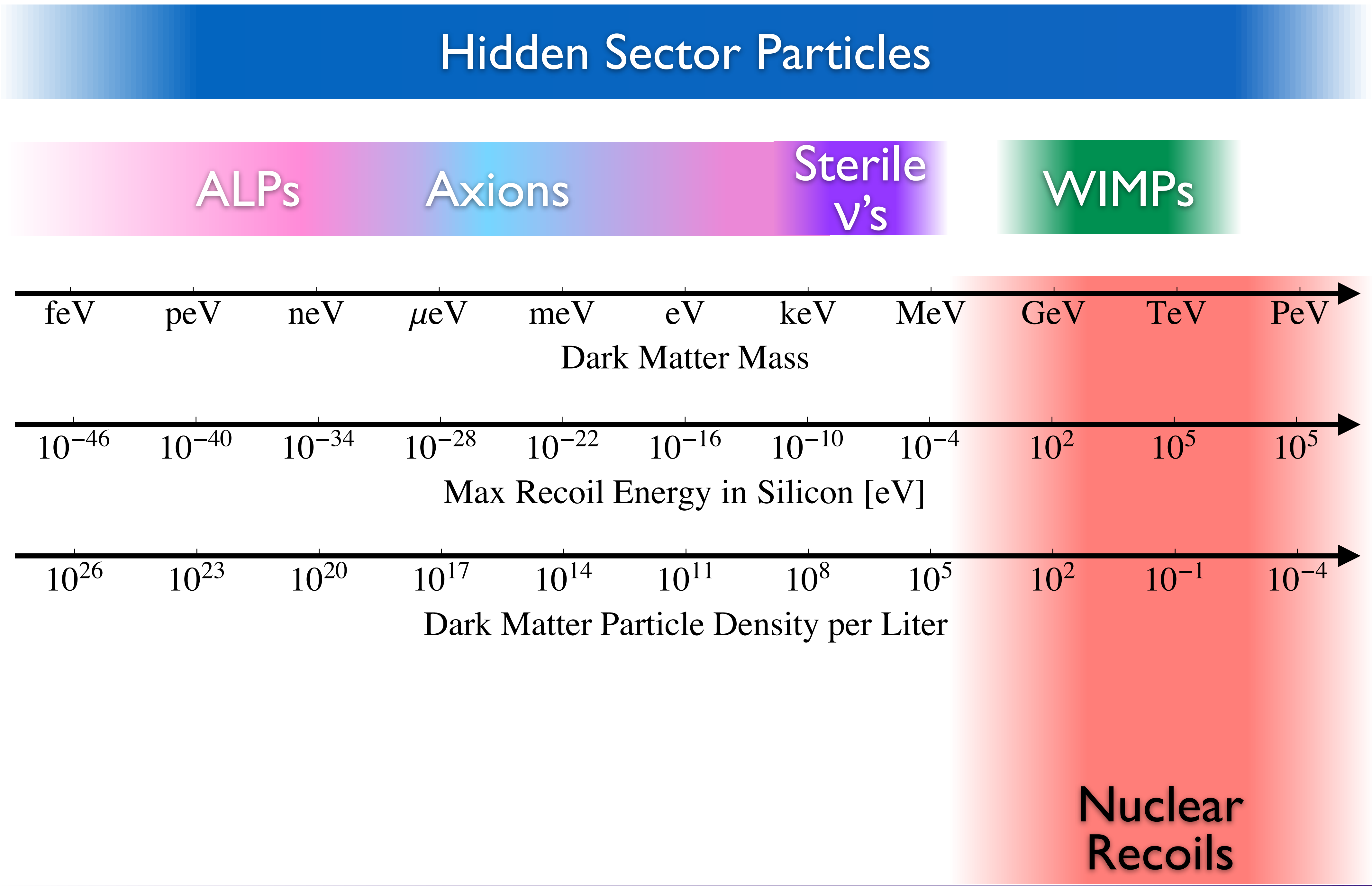
- Dark matter annihilation, decay, or scattering can produce SM particles that can be detected on Earth by ground based and space-based instruments
- Fermi LAT data has been leading the way, but positron excesses and X-ray signals have received much attention too.



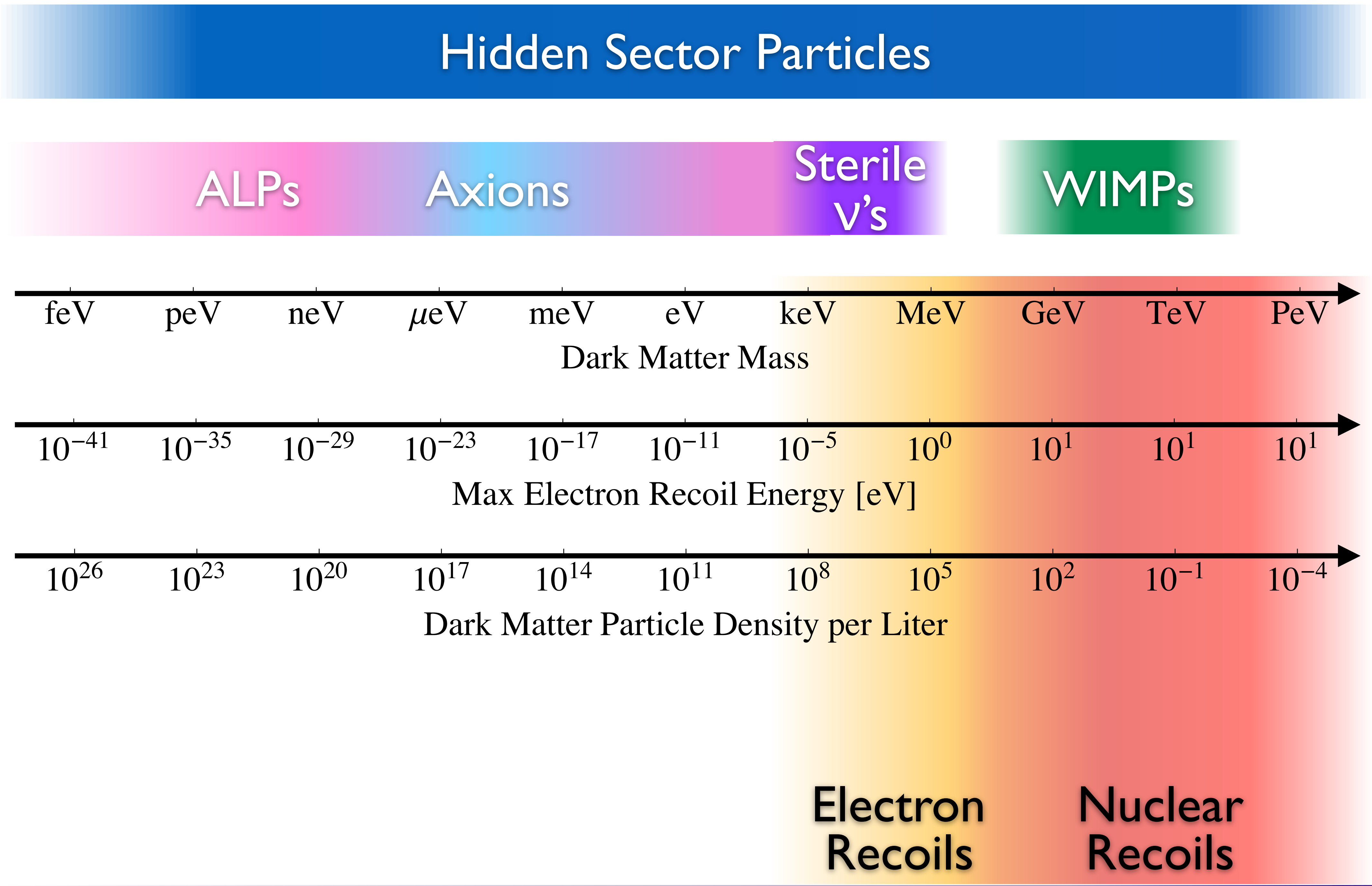
covered by Simona MURGIA



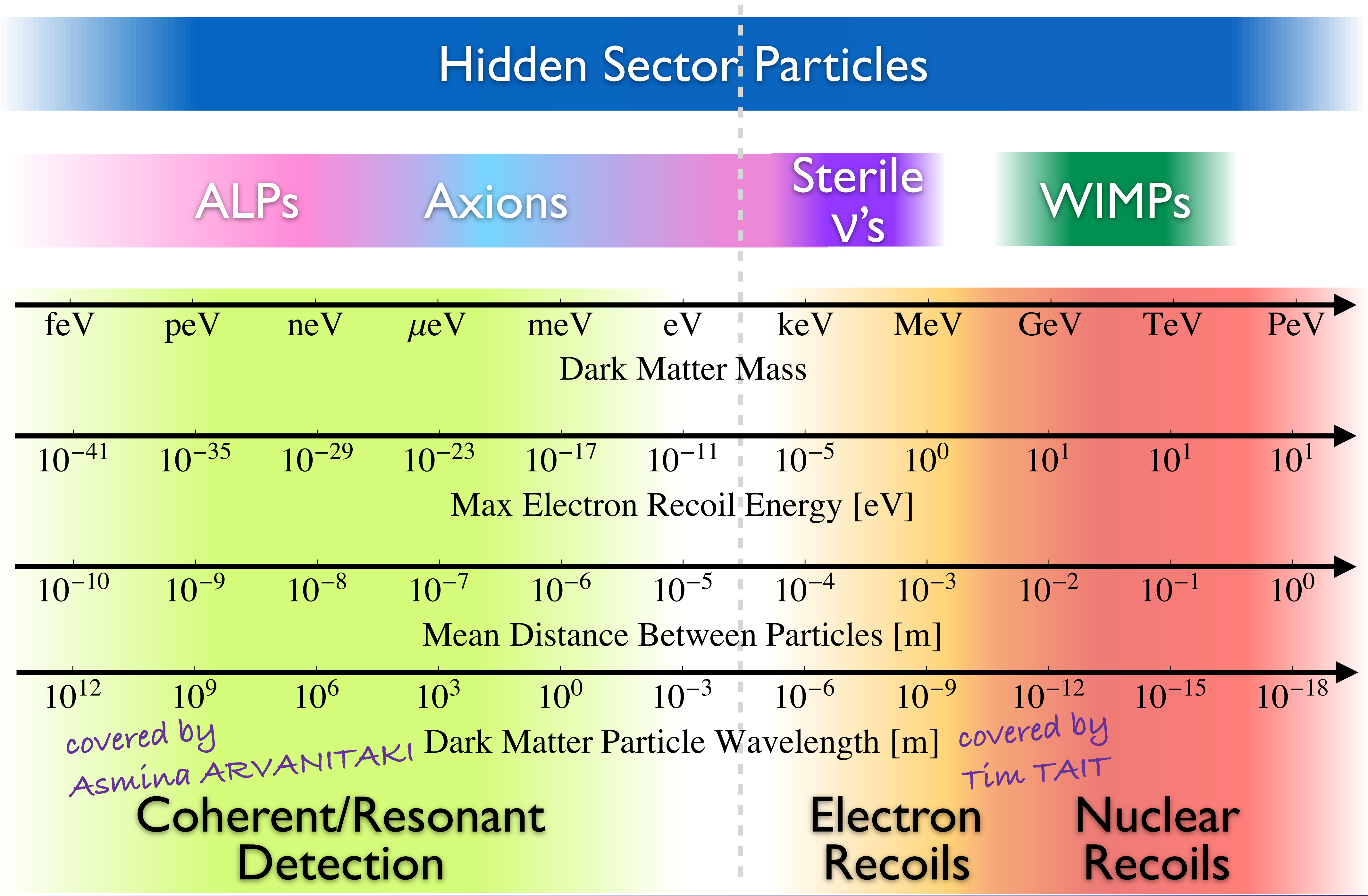
Dark Matter Detection Channels



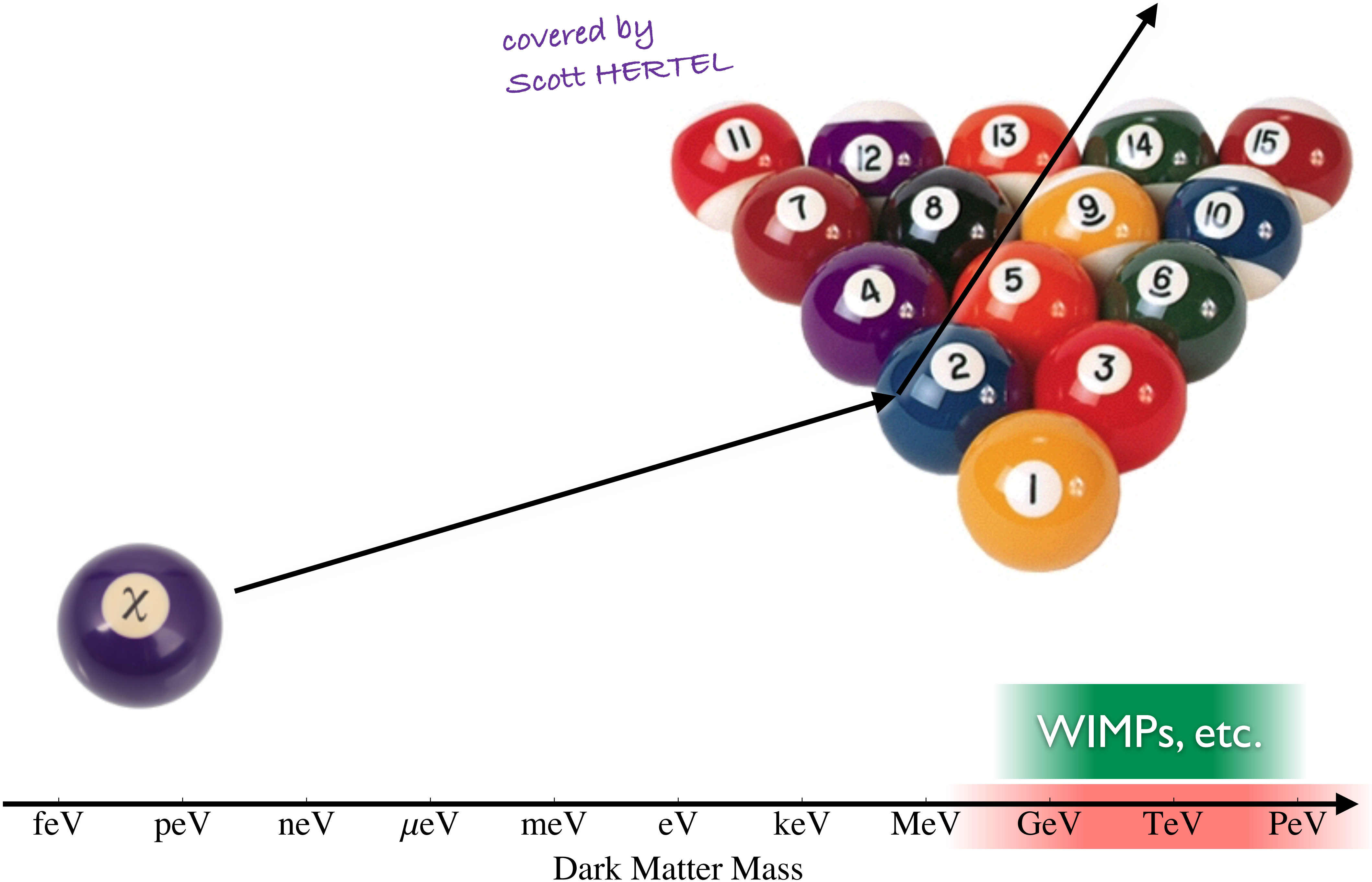
Dark Matter Detection Channels



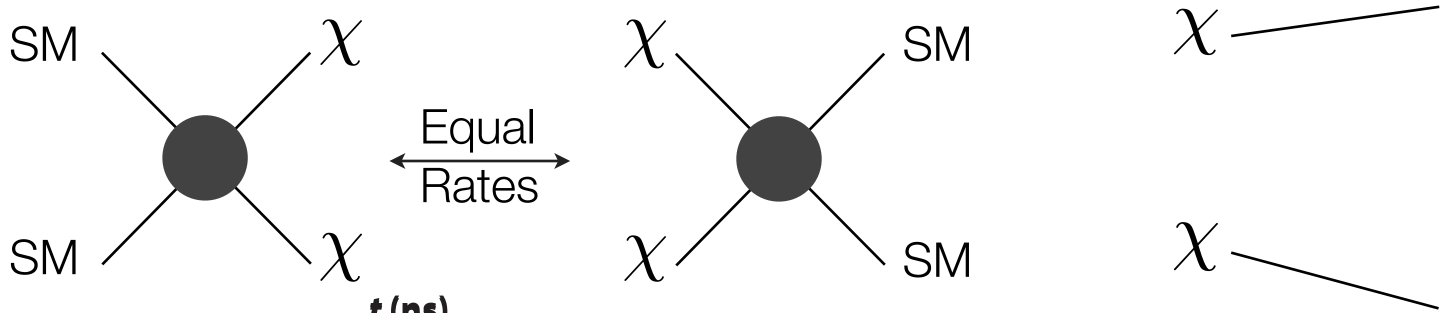
Dark Matter Detection Channels

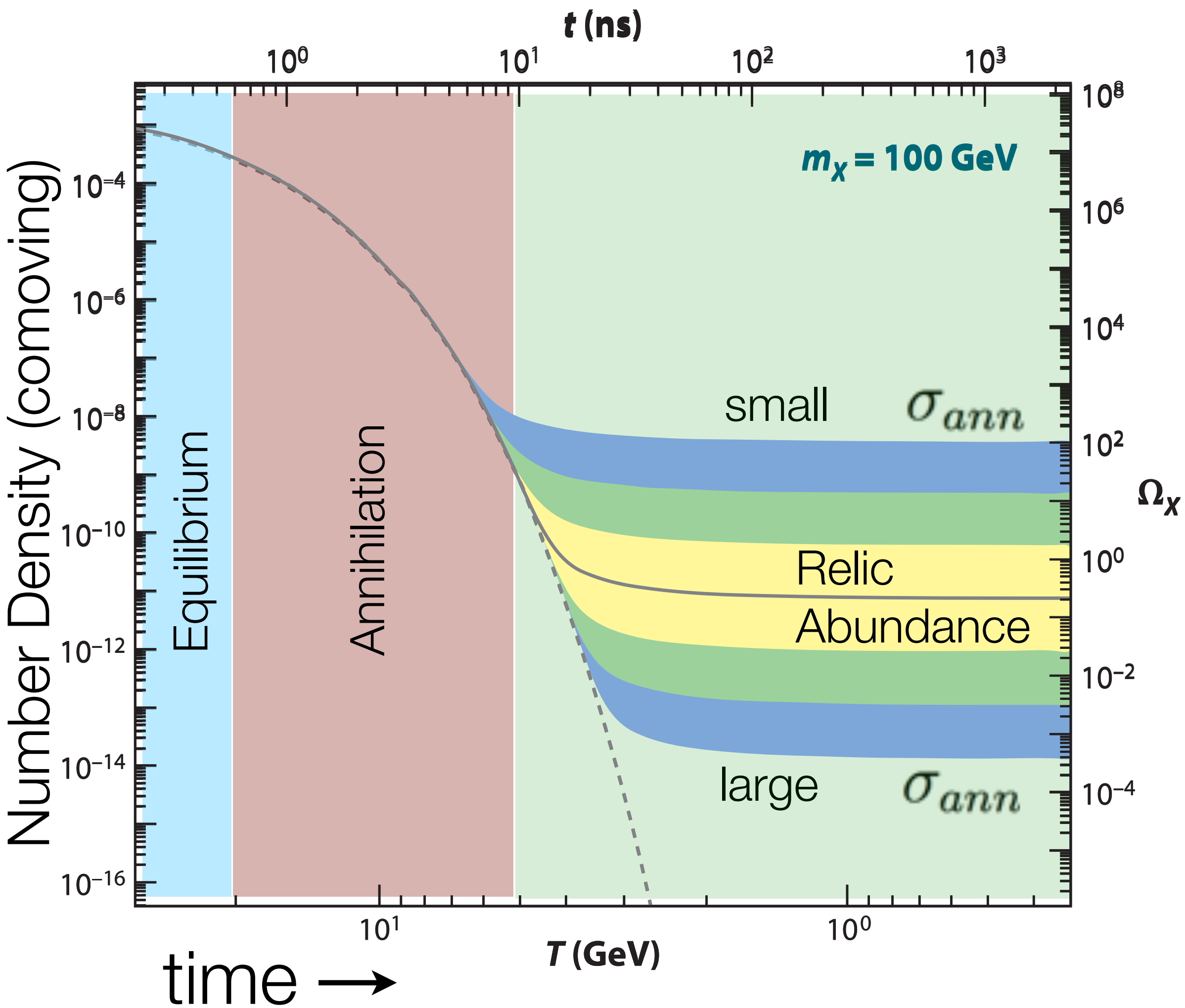


Nuclear Recoils



The WIMP Miracle





$$\Omega_{\mathrm{DM}} \approx \frac{m_{\mathrm{DM}}}{T_f} \frac{T_o^3}{\rho_c \, M_{\mathrm{Pl}} \, \langle \sigma_{ann} v \rangle}$$

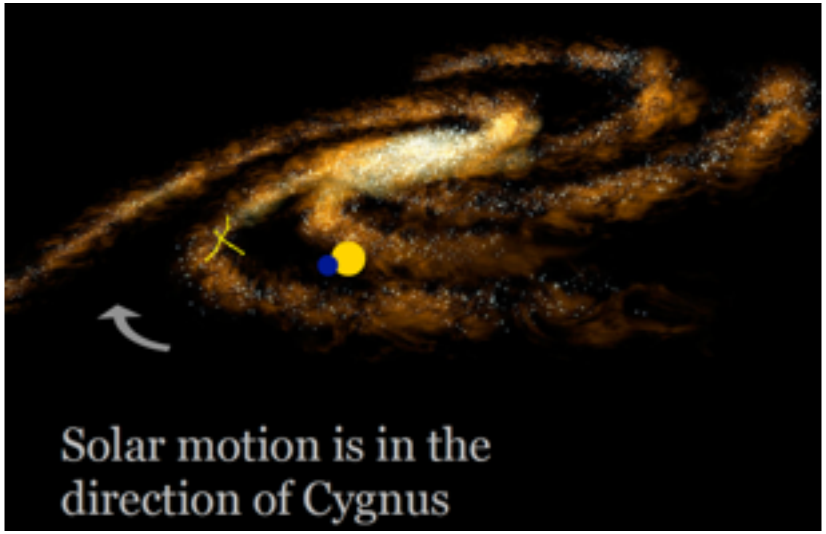
$$m_{\mathrm{DM}} \sim 0.1 - 1\,\mathrm{TeV}$$

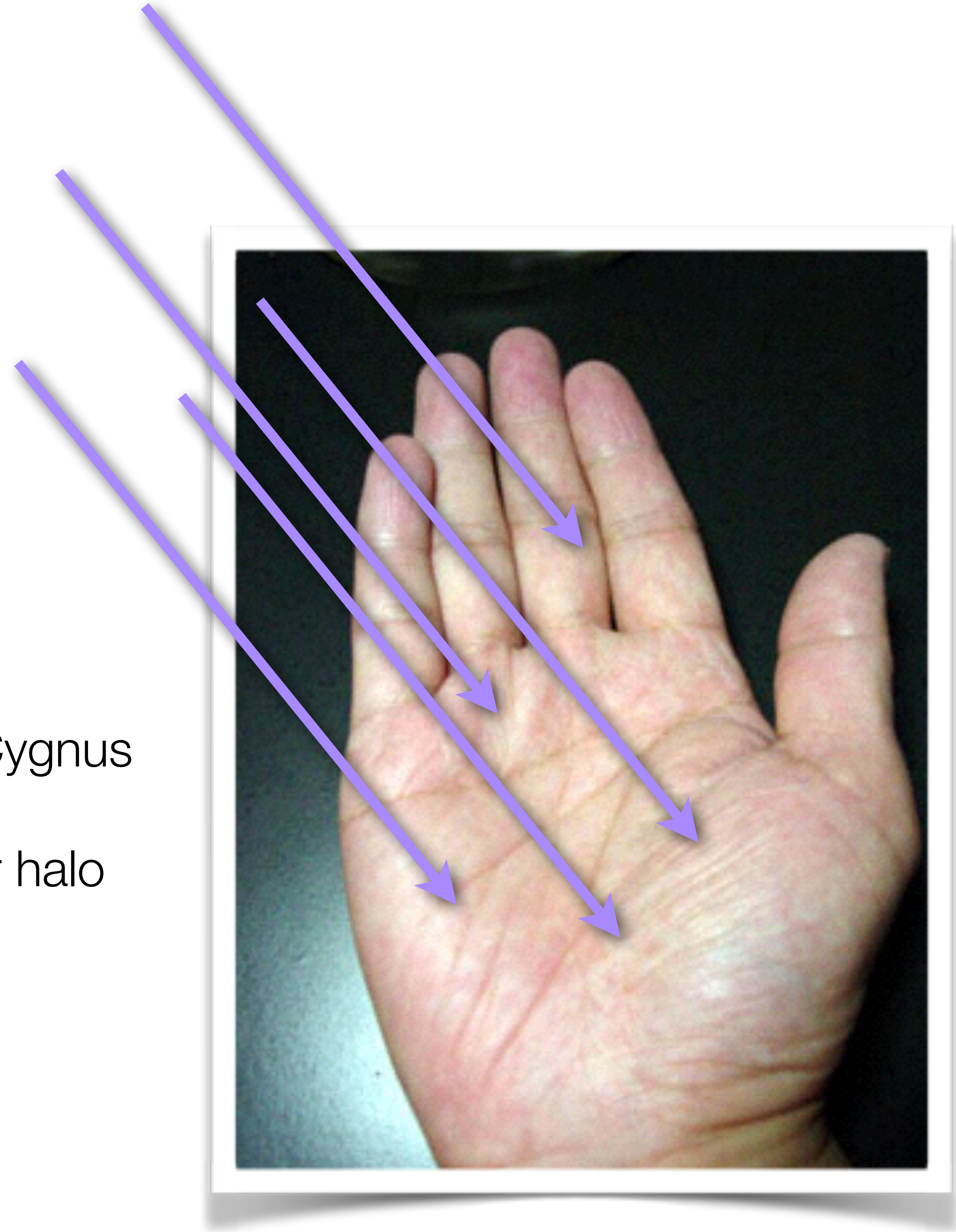
$$\sigma_{ann} = \frac{k\alpha^2}{m_{\mathrm{DM}}^2}$$

$$\sigma_{ann} \sim 1\,\mathrm{pb}$$

Cosmology Predicts the Weak Scale!

The Dark Matter Wind





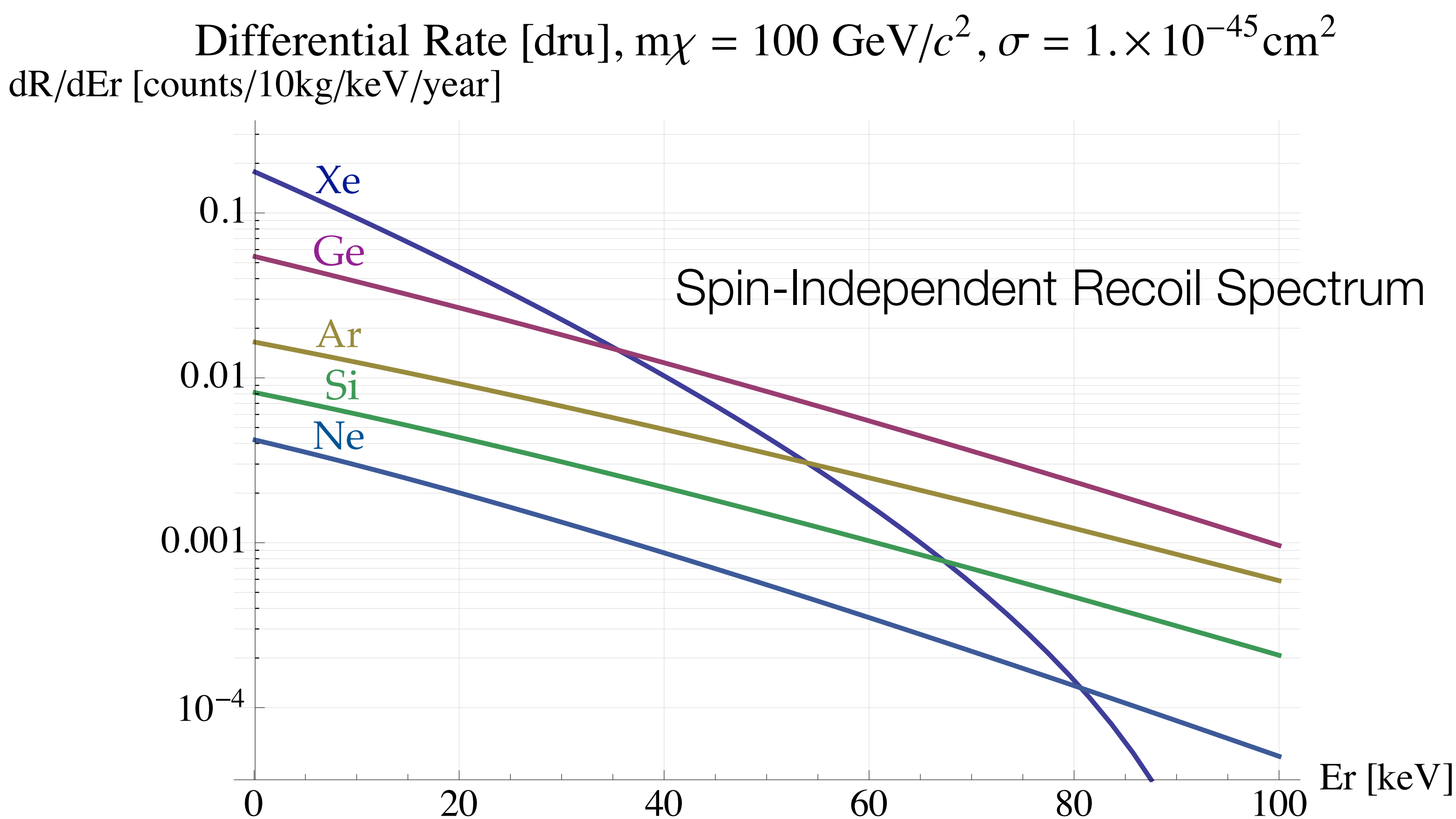
- Dark matter apparently blows from Cygnus
- Our speed relative to the dark matter halo is ~220 km/s
- ~100,000 particles/cm^2/sec
- About 20 million/hand/sec

WIMP Spin-Independent Recoil Spectrum

Interaction Rate [events/keV/kg/day]

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \frac{F^2(E_R)}{m_r^2} \frac{\rho_o\, T(E_R)}{v_o \sqrt{\pi}}$$

particle theory: $\frac{\sigma_o}{m_\chi}$; nuclear structure: $\frac{F^2(E_R)}{m_r^2}$; astrophysics properties: $\frac{\rho_o\, T(E_R)}{v_o \sqrt{\pi}}$



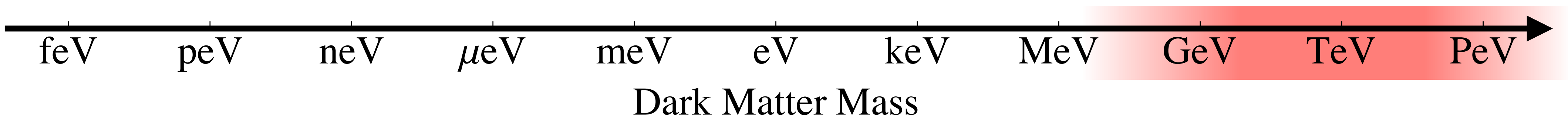
Summary of Nuclear Recoil Direct Detection Requirements

1: Large Exposure (Mass x Time)

2: Low Energy Threshold

3: Low Backgrounds

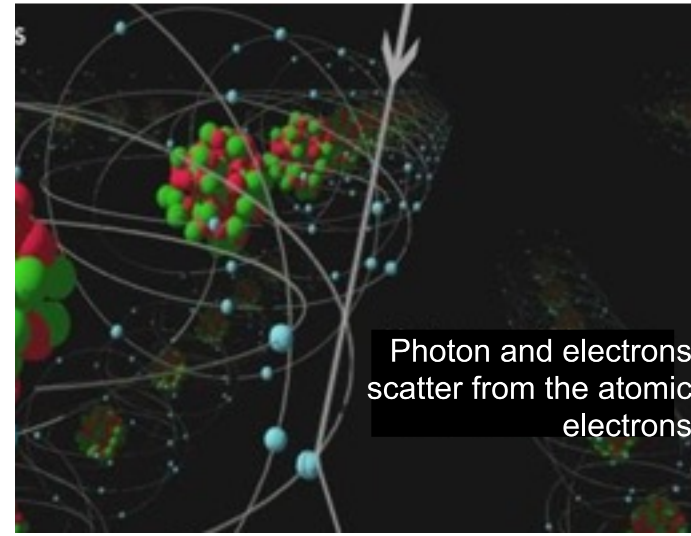
4: Discrimination between Signal and Backgrounds



Typical backgrounds

Most backgrounds are from trace radioactivity (U, Th, K contamination) or induced by cosmic rays (cosmogenic background)

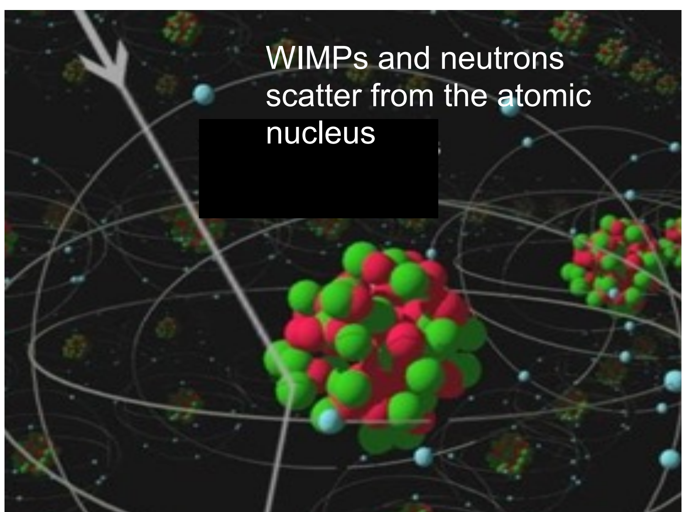
<u>ELECTRON RECOILS (ER)</u>



Gamma: Most prevalent background

Beta: on the surface or in the bulk

<u>NUCLEAR RECOILS (NR)</u>

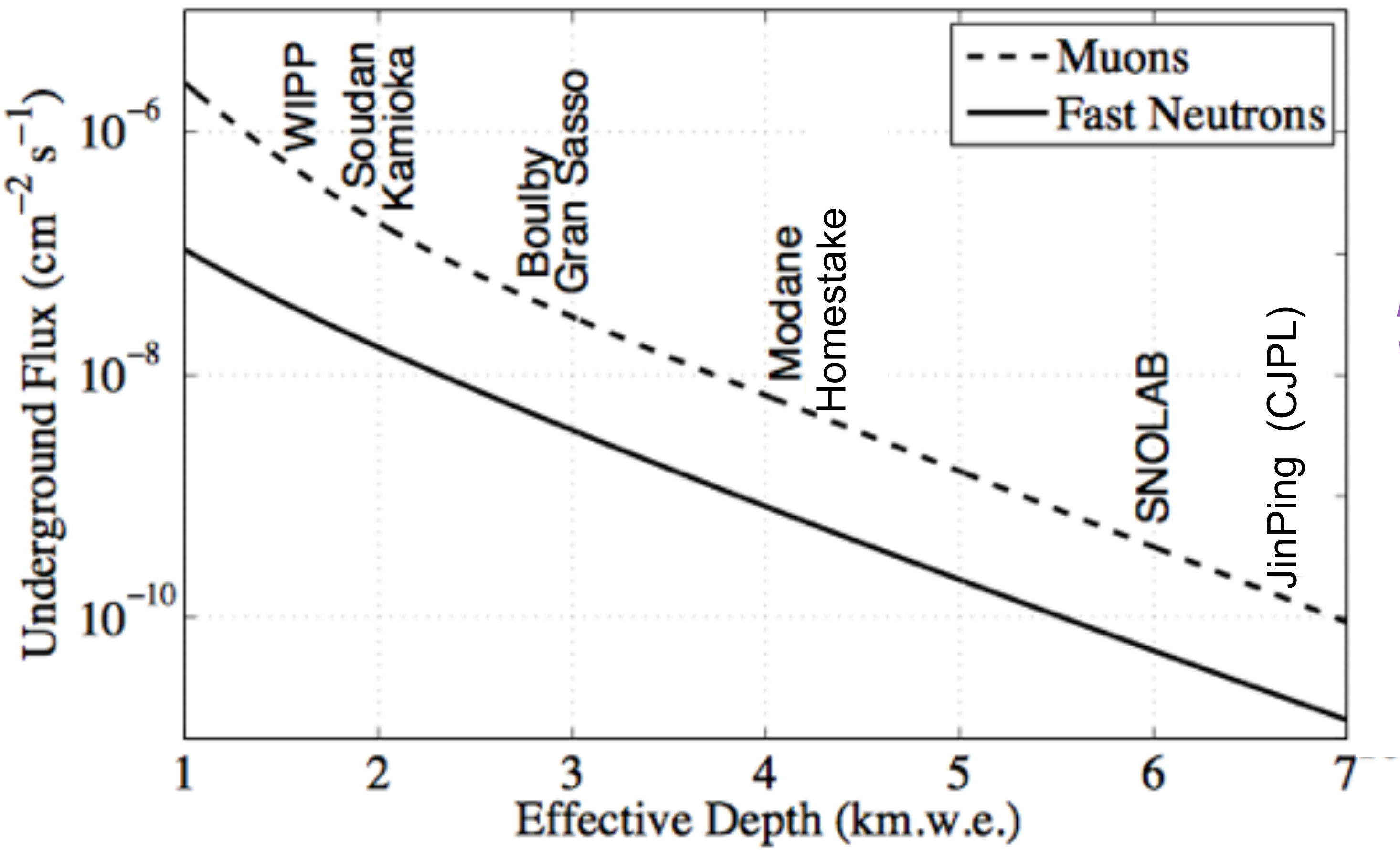


Neutron: NOT distinguishable from WIMP

Alphas: almost always a surface event

Recoiling parent nucleus: yet another surface event

Where to locate your experiment

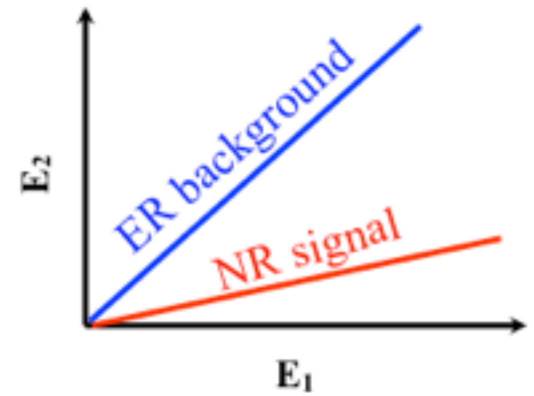


m.w.e. = meters water equivalent

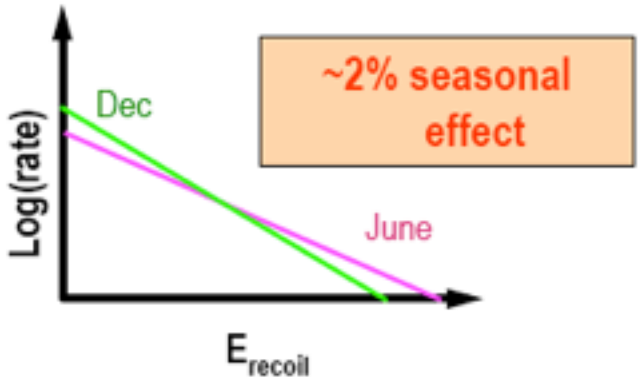
Most experiments use the earth as shielding from muons. The lower the muon rate, the lower the fast neutron rate.

Separating Signal from Background…

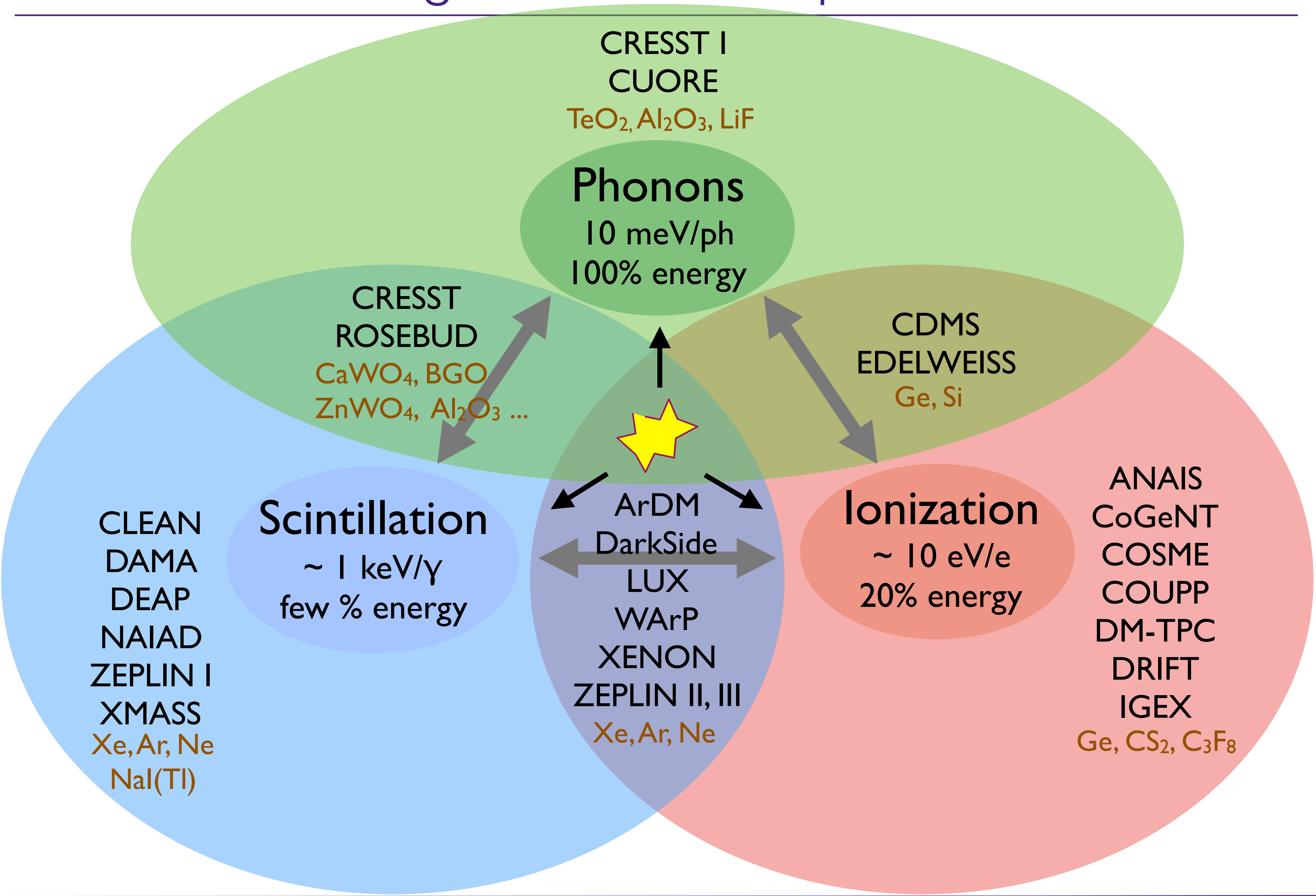
- By Detector Response
  - Obtain particle identification from the physics of the detector response to different types of particle interactions.



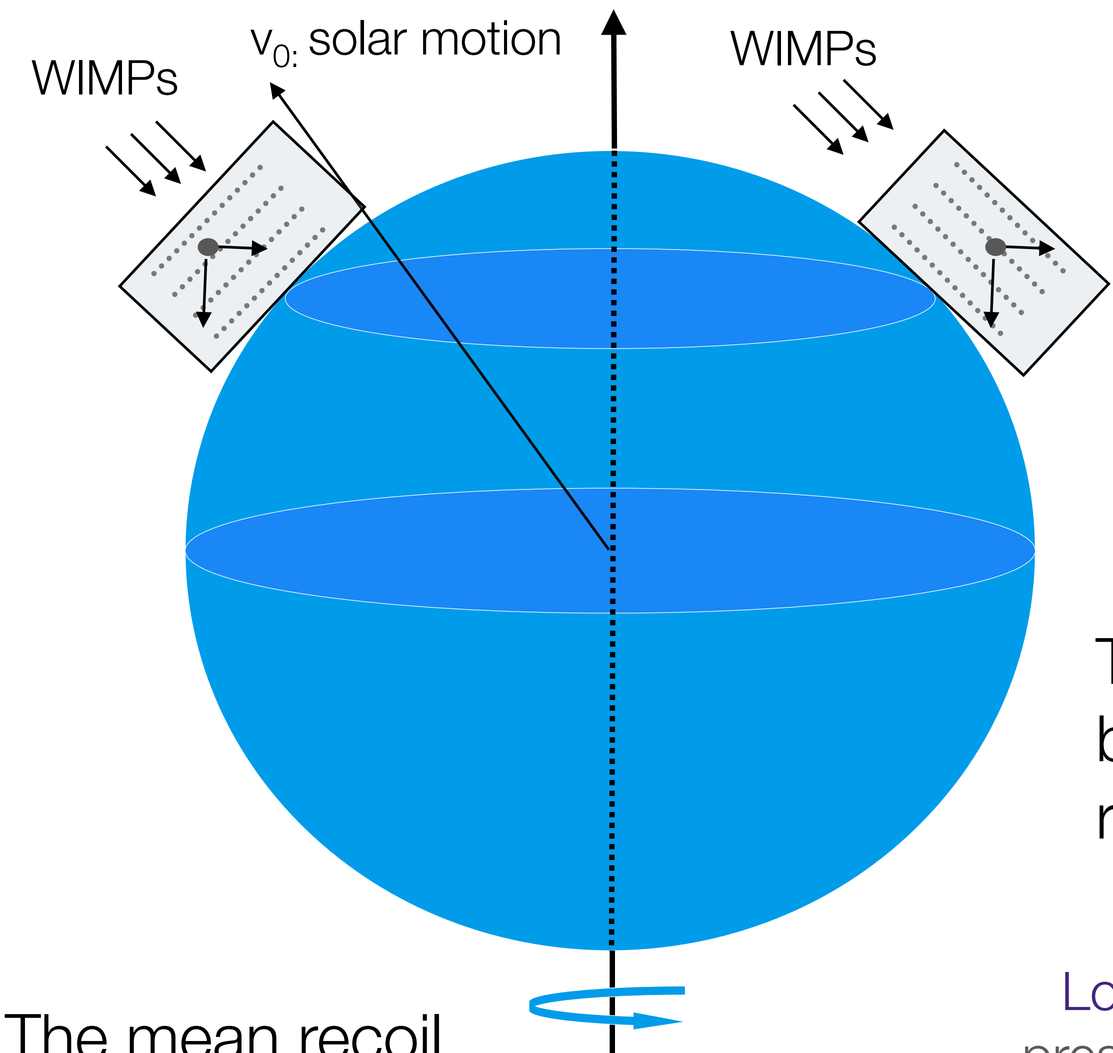
- By Astrophysical Modulation
  - Annual Modulation in the WIMP recoil spectrum. Earth's velocity through the galactic halo is max in June, min in December (DAMA/LIBRA).
  - Daily modulation of the incident WIMP direction. Measure the direction of the short track produced by nuclear recoil. (DM-TPC)
- Can be Event-by-Event or Statistical

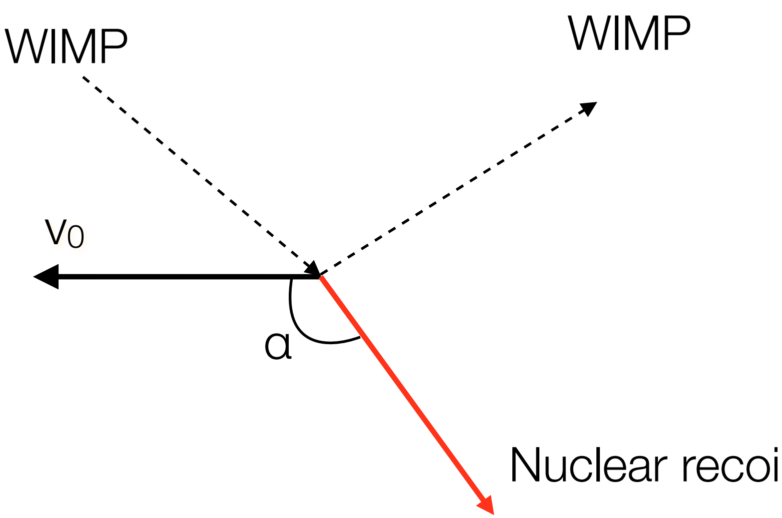


Particle ID Through Detector Response



Diurnal Modulation (a.k.a. Directional Detection)

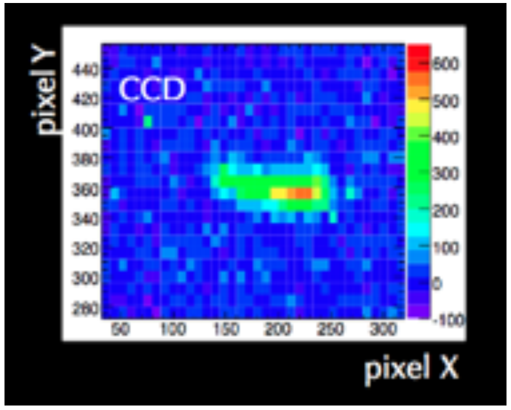




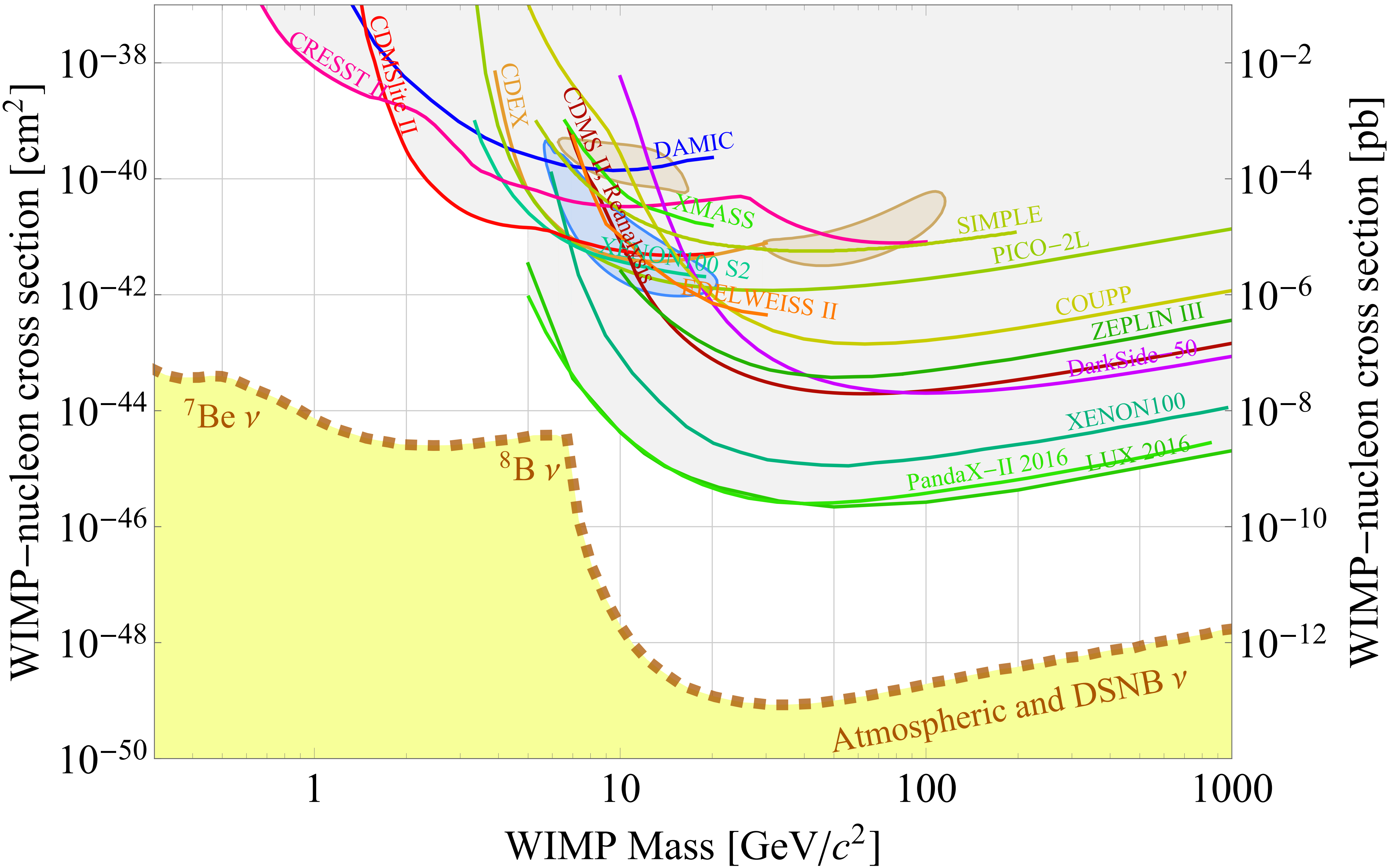
The distribution of the angle α between the solar motion and recoil directions: peaks at α=180°

The mean recoil direction rotates over one sidereal day

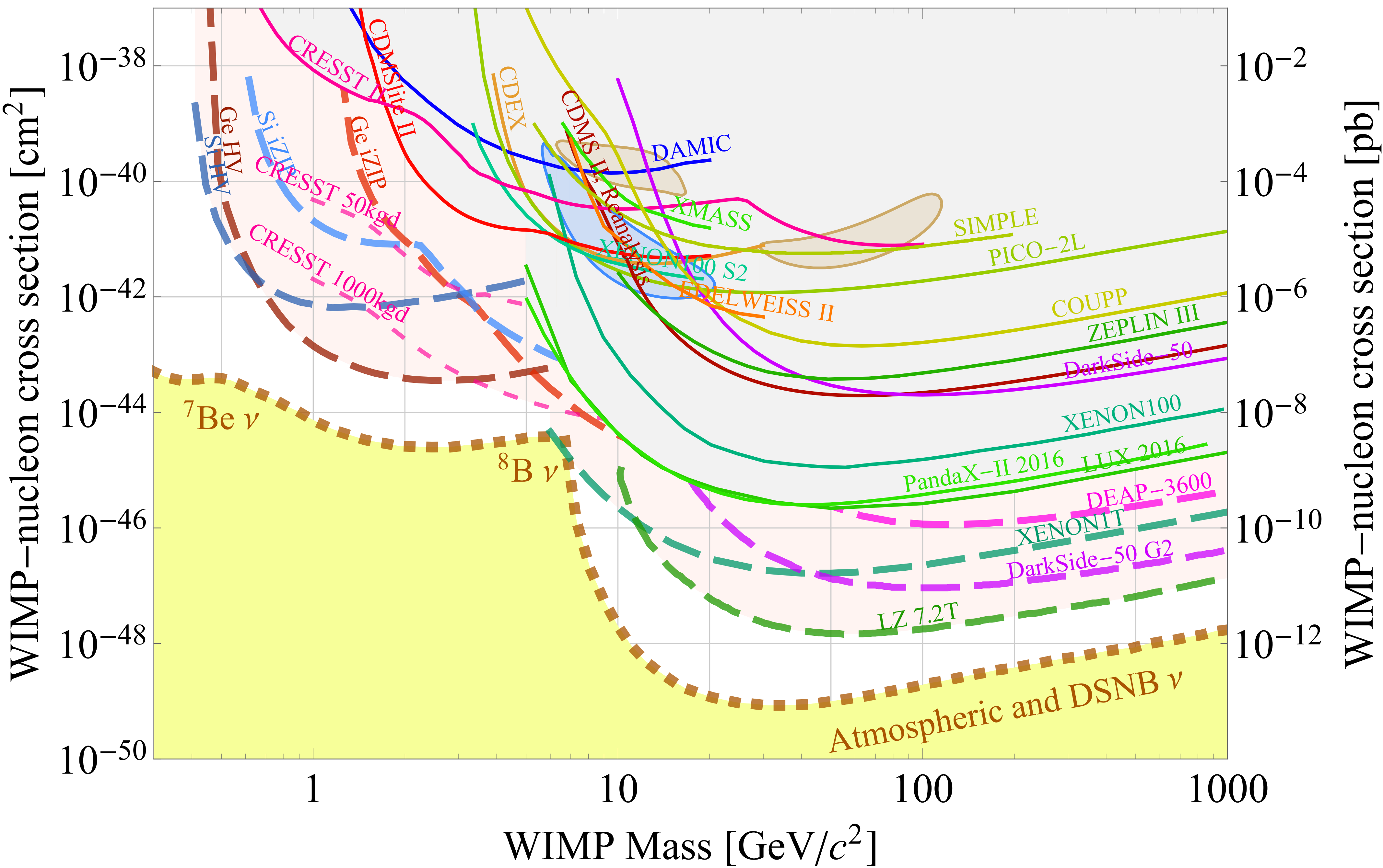
Low pressure TPC's preserve dE/dx profile such that "head to tail" measurement can be made



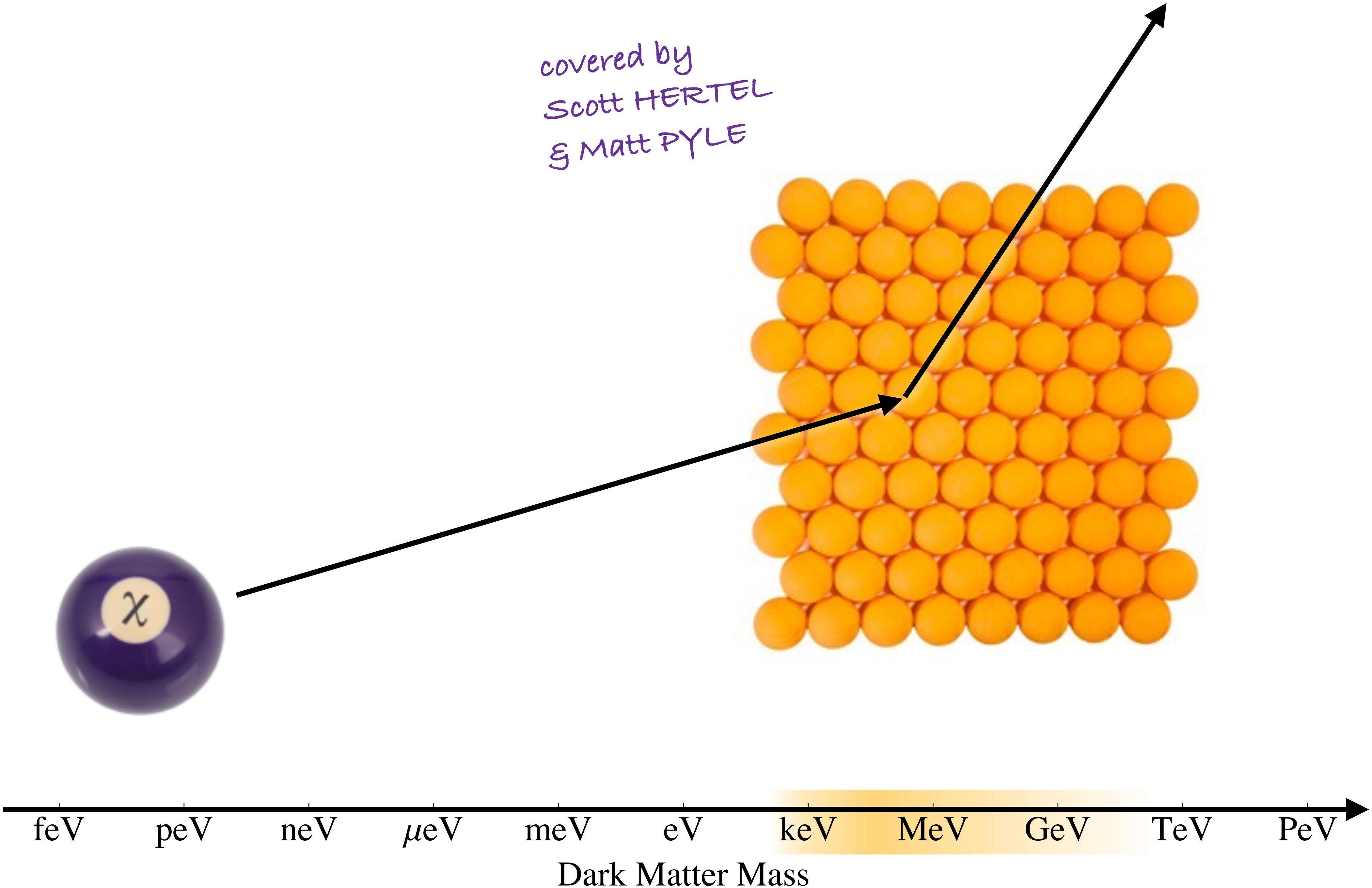
Current Limits



Projections for Second Generation DM Searches (G2)



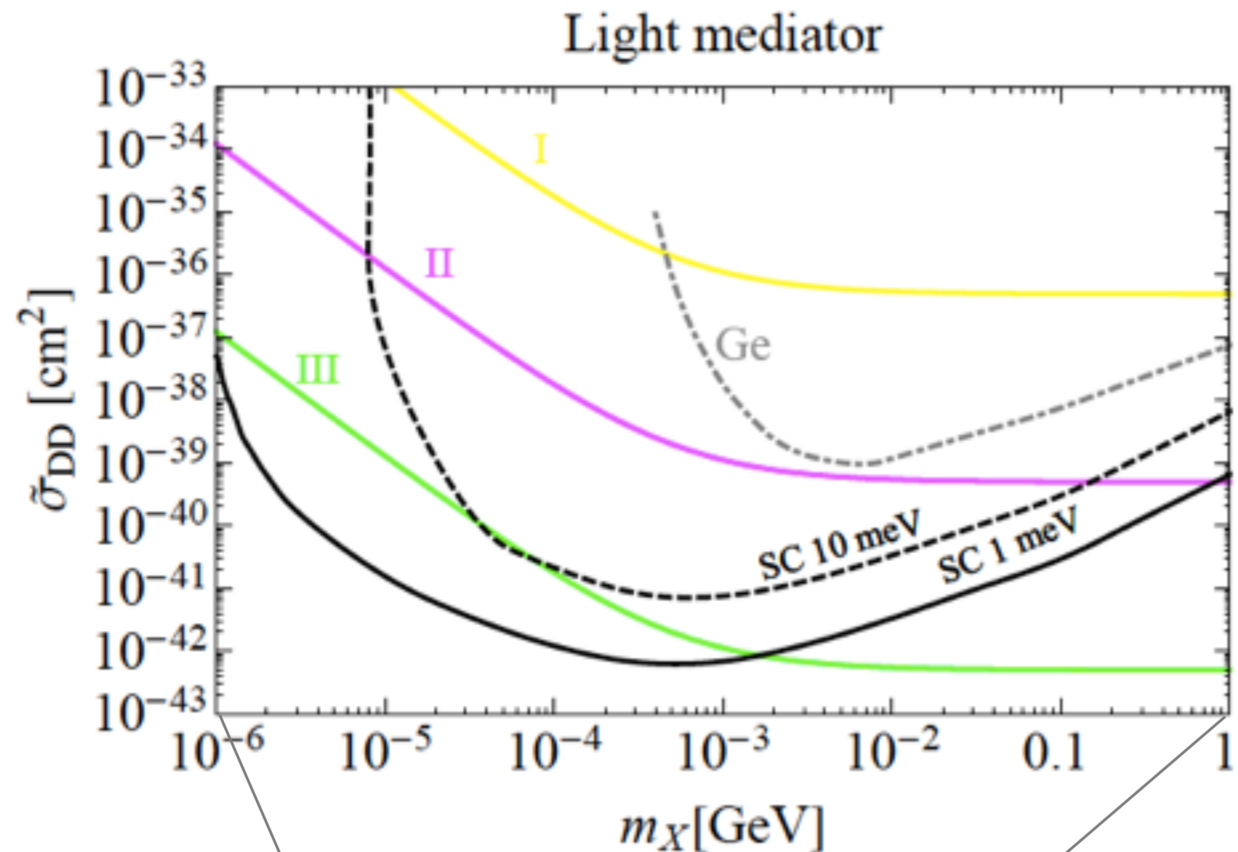
Electron Recoils

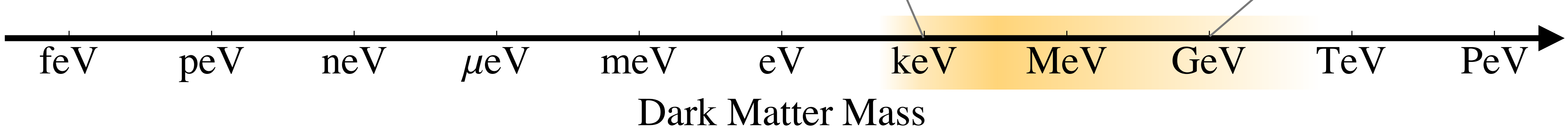


How do we look for DM with electron recoils?

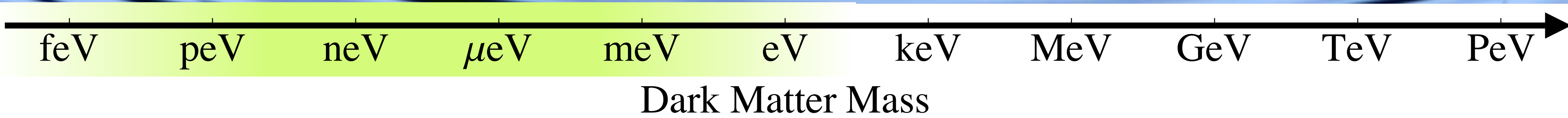
- Pretty much all experiments that look for nuclear recoils also see electron recoils!
- Single electron sensitivity expected in both liquid noble and crystal experiments.
- The main issues are threshold, fiducialization, and lowering backgrounds.
- Using materials with a band gap or even quasiparticles in superconductors can drastically reduce the threshold!

Hochberg et al. 1504.07237
see also Essig et al. 1108.5383

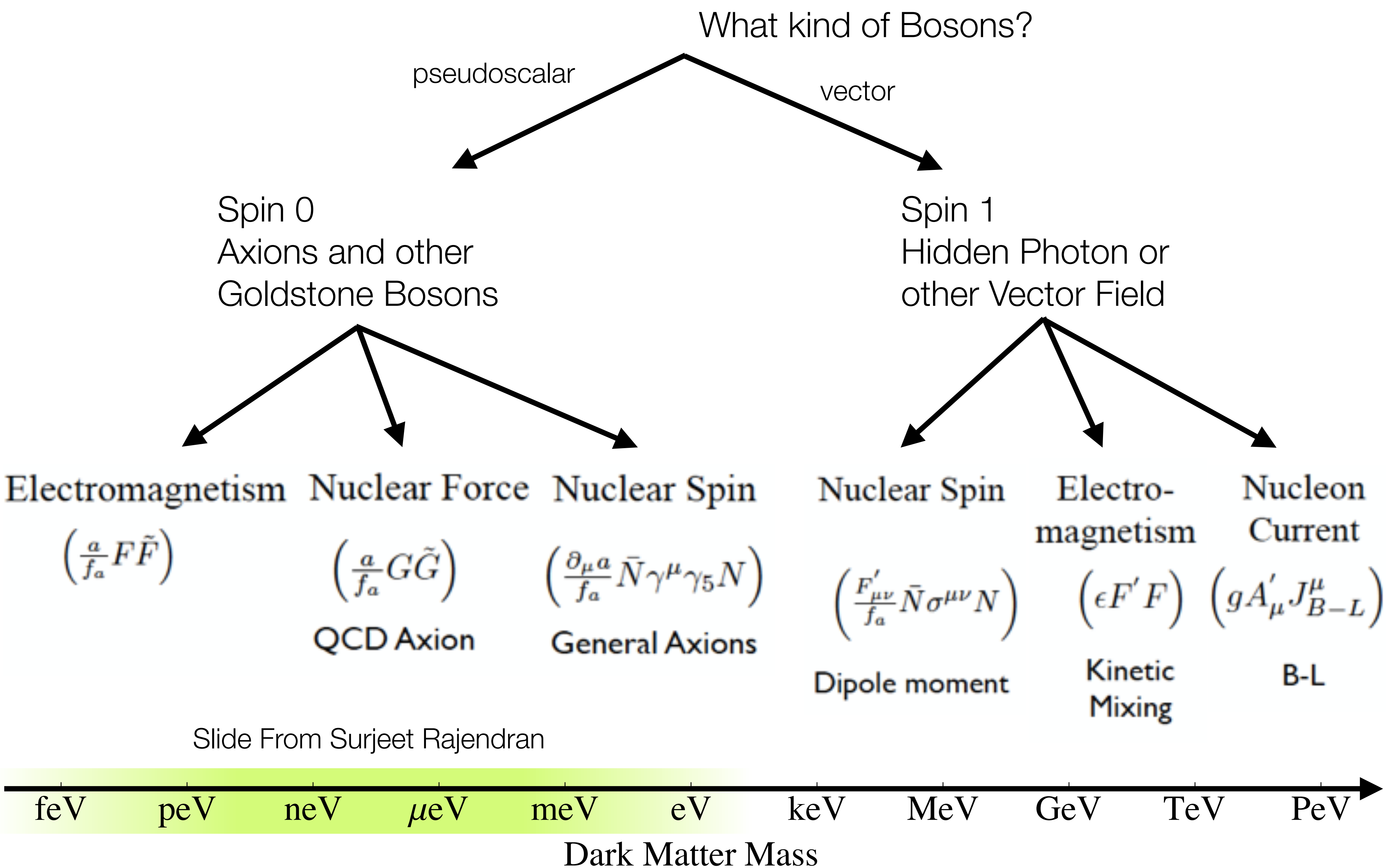




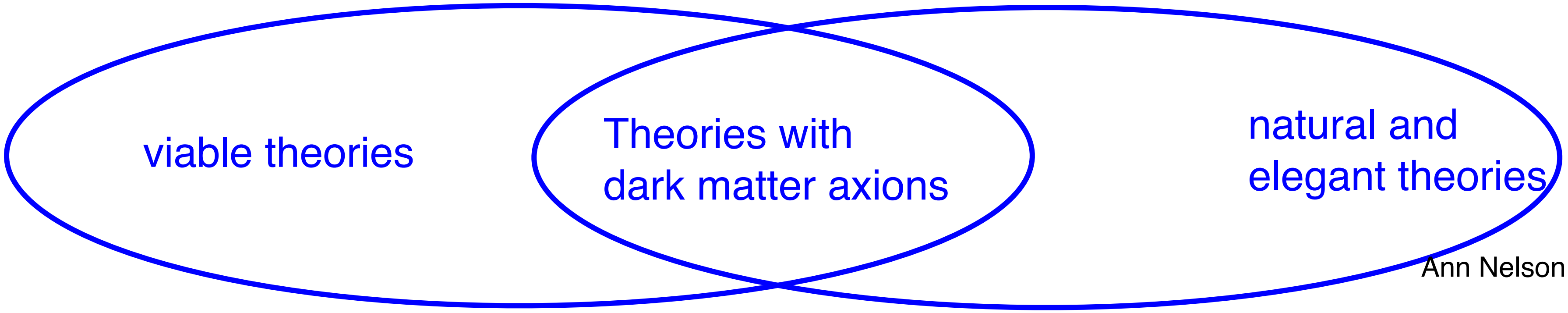
Coherent / Resonant Detection



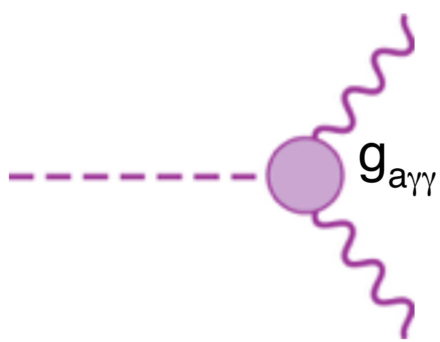
Bosonic Dark Matter



Axions and ALPs



- It's a pseudoscalar (π°-like), extremely light and weakly coupled
- The axion couples extraordinarily weakly to normal particles, including a very feeble 2γ coupling.



$g_{a\gamma\gamma} \propto m_a$

The lighter the axion,
the weaker its couplings.

Axion Mass 'Window'

$10^{-(5\text{ to }6)}\,\mathrm{eV} < m_a < 10^{-(2\text{ to }3)}\,\mathrm{eV}$

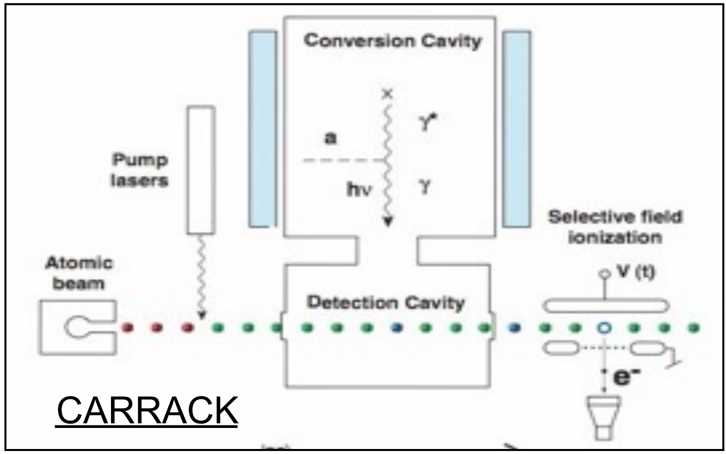
(Overclosure) **(SN1987a)**

With lower end of window preferred if $\Omega_{CDM} \sim 1$

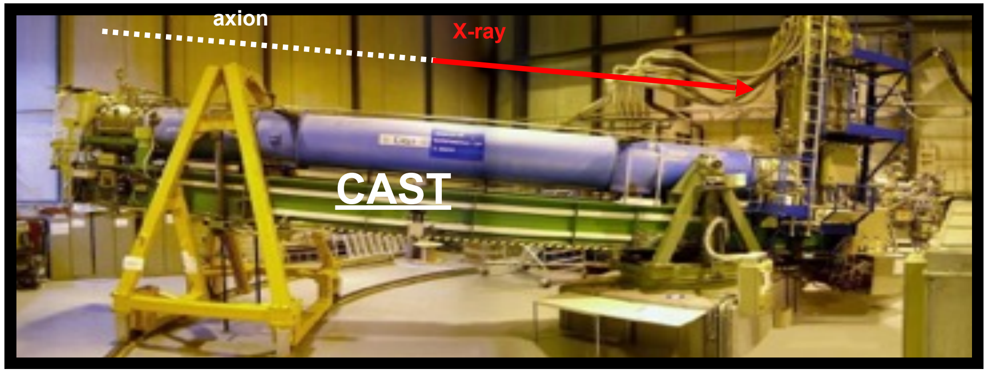
Axions constituting our local galactic halo would have huge number density ~10^{14} cm^{-3}

Variety of Experiments

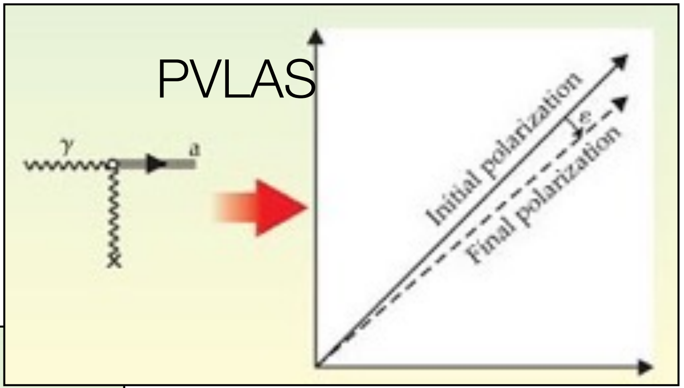
- Microwave Cavities
  - Low noise amplifiers (ADMX) and Rubidium Atoms (CARRACK)
  - Look for dark matter axions (low mass) converting to photons in B-Field

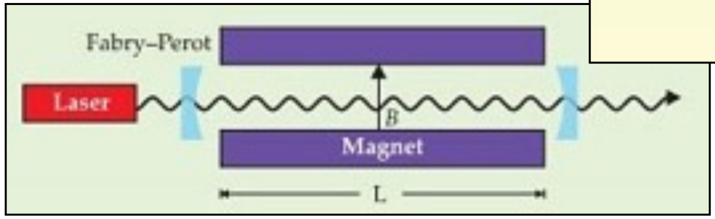


- Solar Observatories
  - X-Ray (CAST) and Germanium detectors
    - Look for axions generated from the sun
    - Higher coupling required than for DM axions.



- Lab experiments
  - Photon regeneration and polarization changes (PVLAS)
    - Look for production of axions from light passing through B-field
    - Higher coupling required.
    - Ultralight axions (nano-eV)
  - (NMR / LC Circuit)

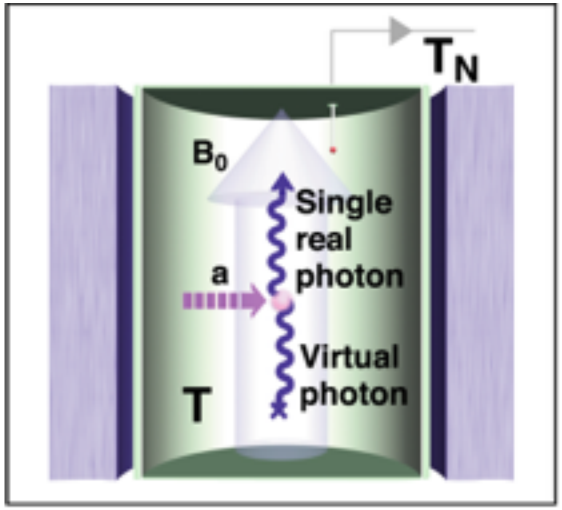




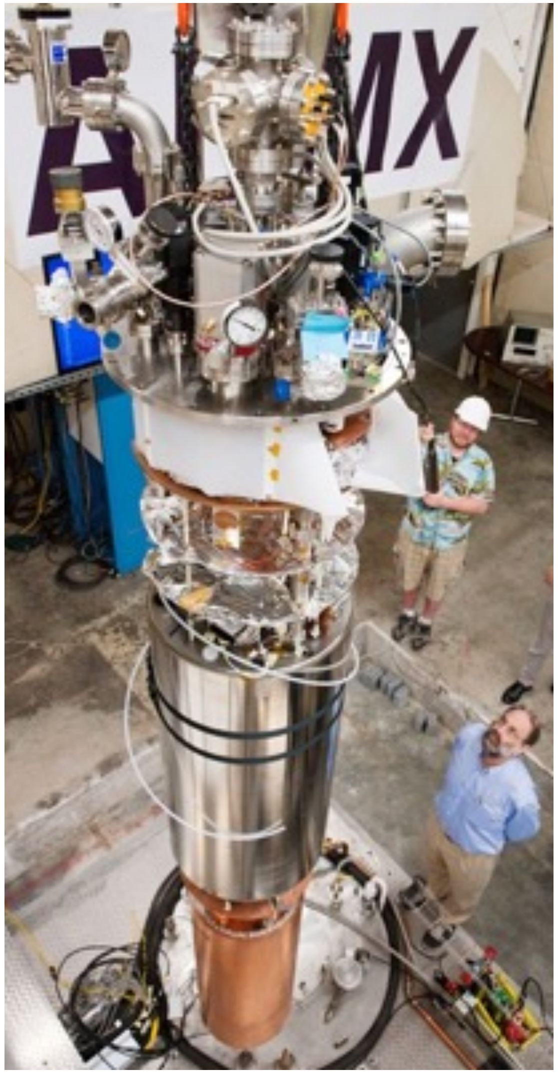
The Axion Dark Matter eXperiment (original concept from P. Sikivie)

G2 Funded Experiment

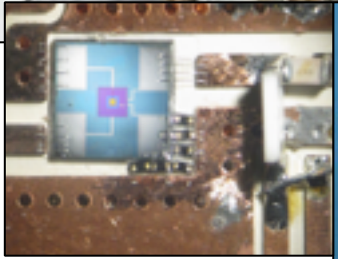
Halo axions convert into microwave photons inside a RF cavity threaded by a strong magnetic field



ADMX is sensitive to sub-yoctowatts of microwave power



New ADMX experiment insert fabricated and being assembled

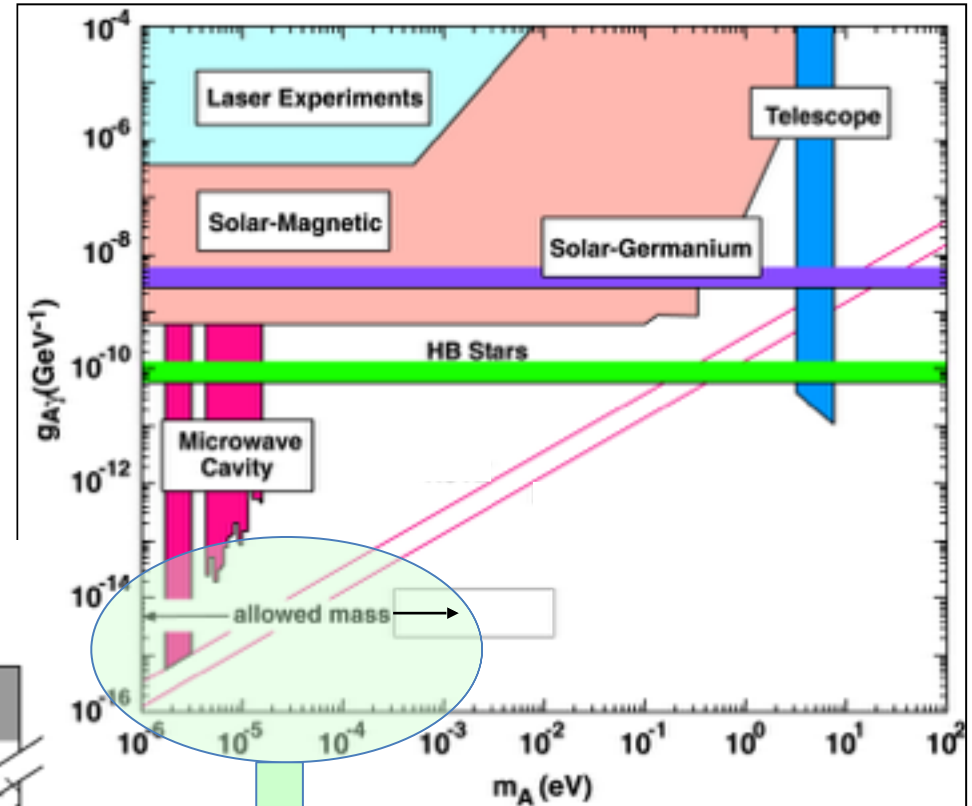


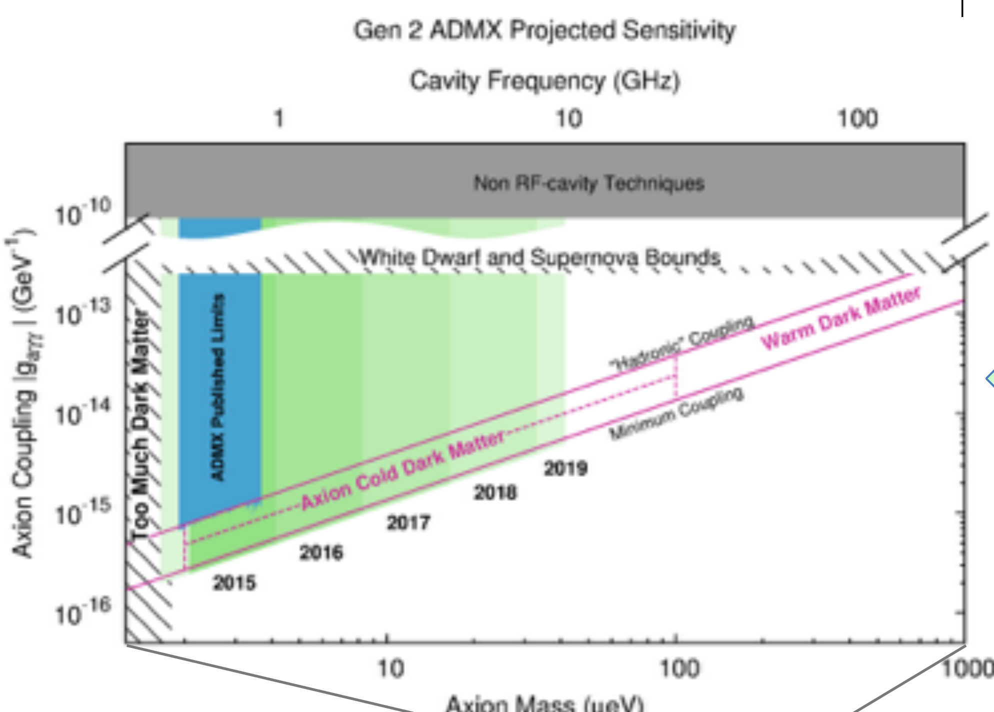
Dilution refrigerator and quantum-limited amplifiers provide sensitivity for the ADMX “Definitive Search”

G2 ADMS Search Capability

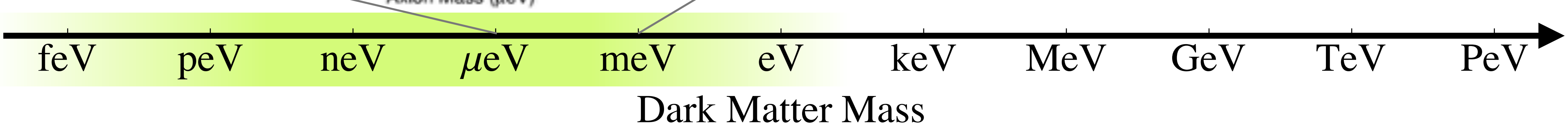
U. Washington, LLNL, U. Florida, U.C. Berkeley, National Radio Astronomy Observatory, Sheffield U., Yale U., U. of Colorado
(+ new collaborators soon)

The dilution refrigerator in ADMX significantly speeds the dark-matter search, so that …



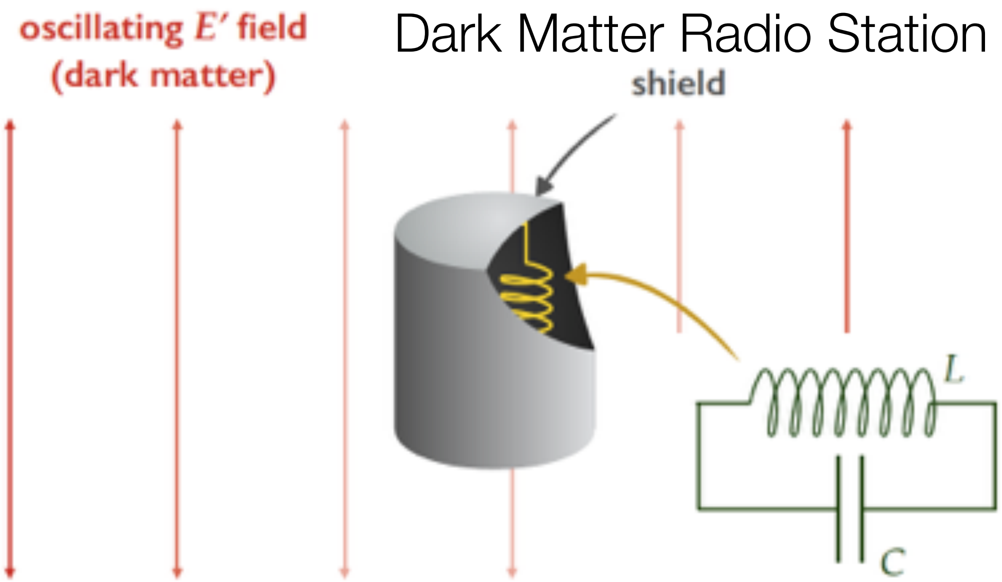


… ADMX has the sensitivity to either detect the dark-matter QCD axion or reject the hypothesis at high confidence. This is called the "Definitive Search".



New Ideas to search for Hidden Photons

Dark Matter Radio Station

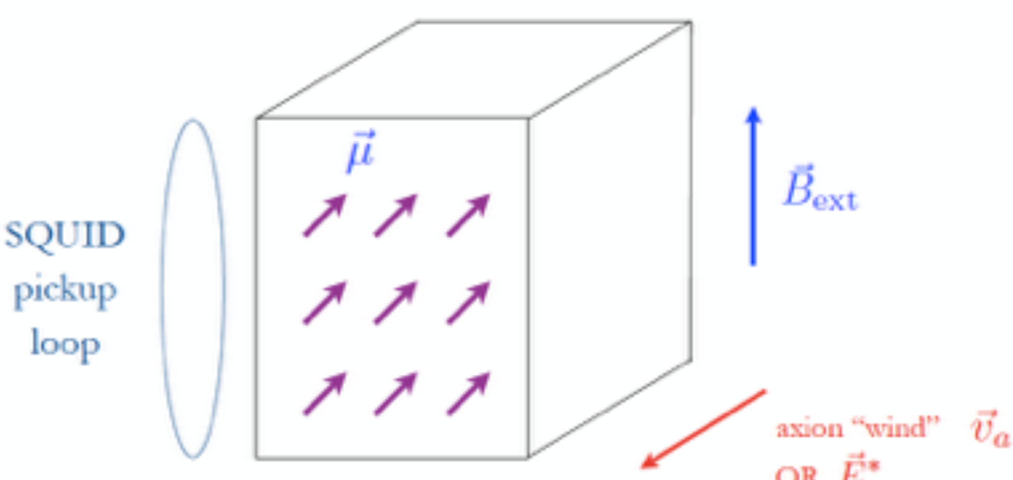


Chaudhuri+ 1411.7382

Tunable resonant LC circuit
(a radio)

CASPEr

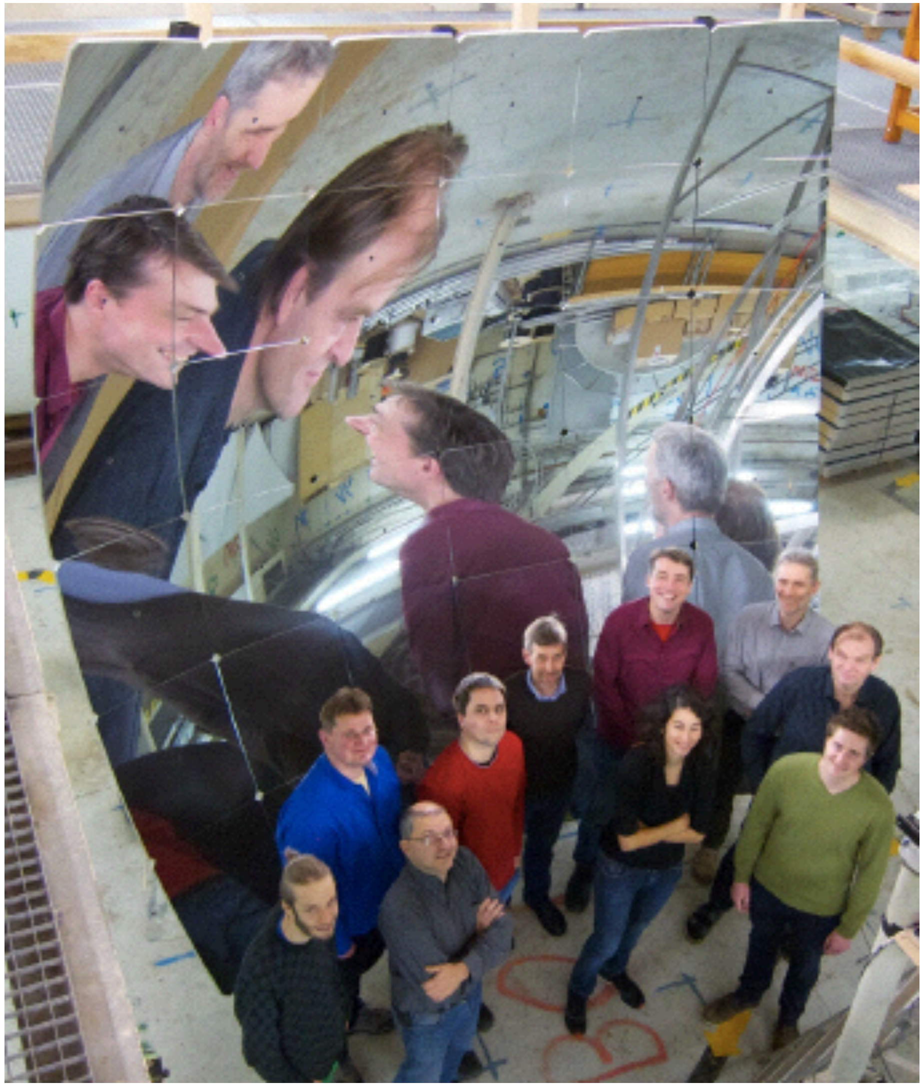
Axion affects physics of nucleus, NMR is sensitive probe



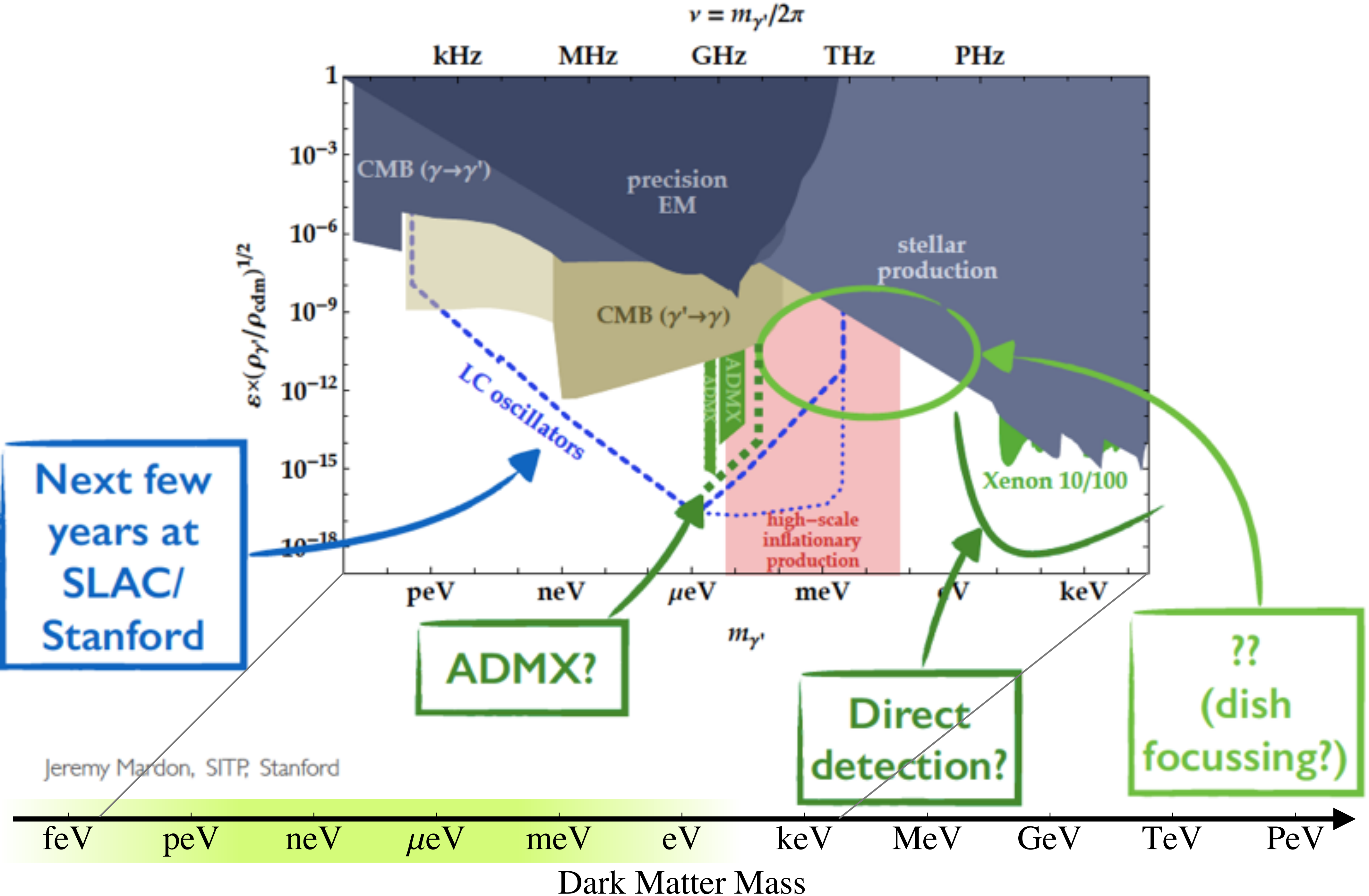
Budker+ 1306.6089

Search for Hidden Photons with a large Spherical Mirror

Döbrich+ 1510.05869



Hidden Photon Searches



Conclusions

- Although WIMPs remain a very interesting dark matter candidate, other scenarios are gaining traction in the theoretical community, while new ideas for direct searches have been proposed and are gaining momentum.
- To make progress in the field, more collaboration between the LHC, indirect detection, and direct detection communities is essential.
- The next ten years will be very exciting for dark matter direct detection. Various G2 Experiments will come online, covering a lot of new parameter space. The new directions for dark matter detection require investments in technology R&D! Exciting opportunities for new parameter space await!