Dark Matter direct detection

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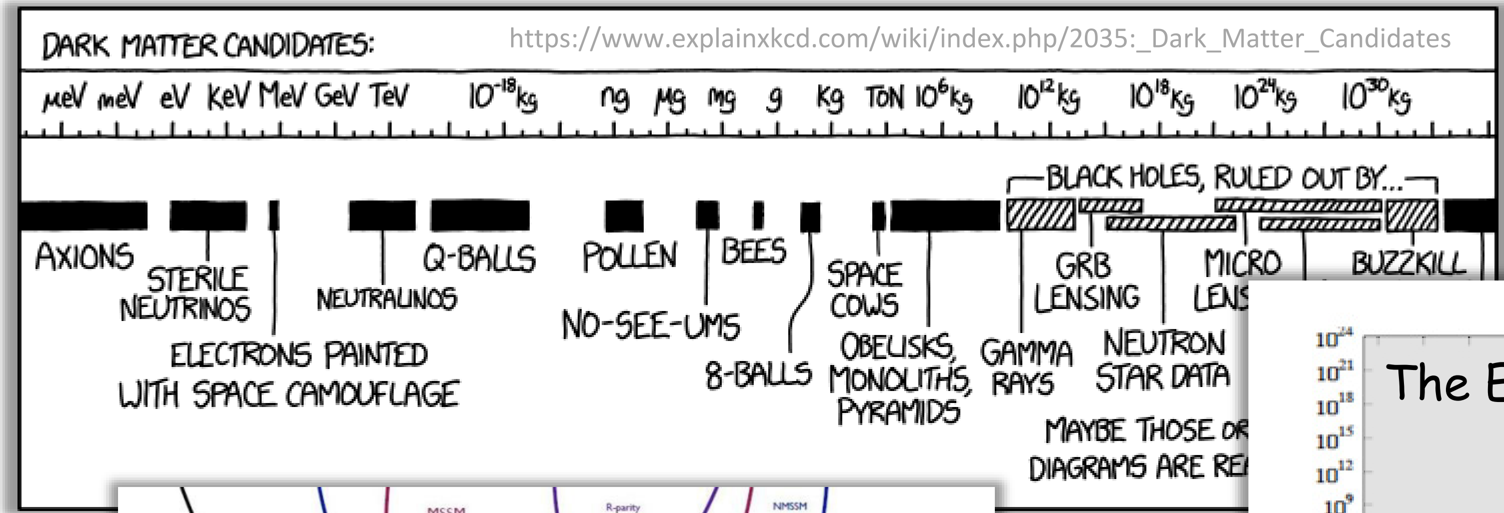
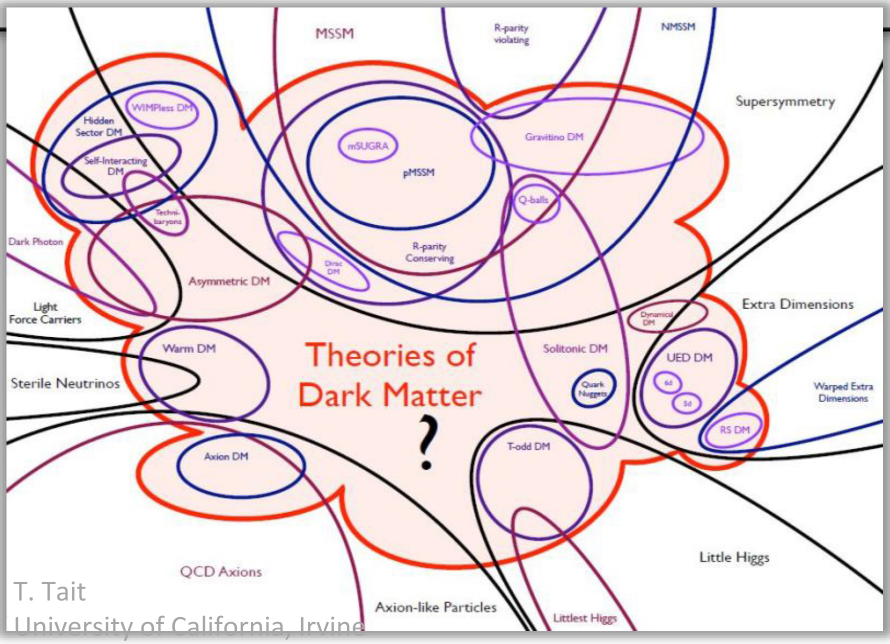
Dark Matter Candidates

The Wannabe Scientist

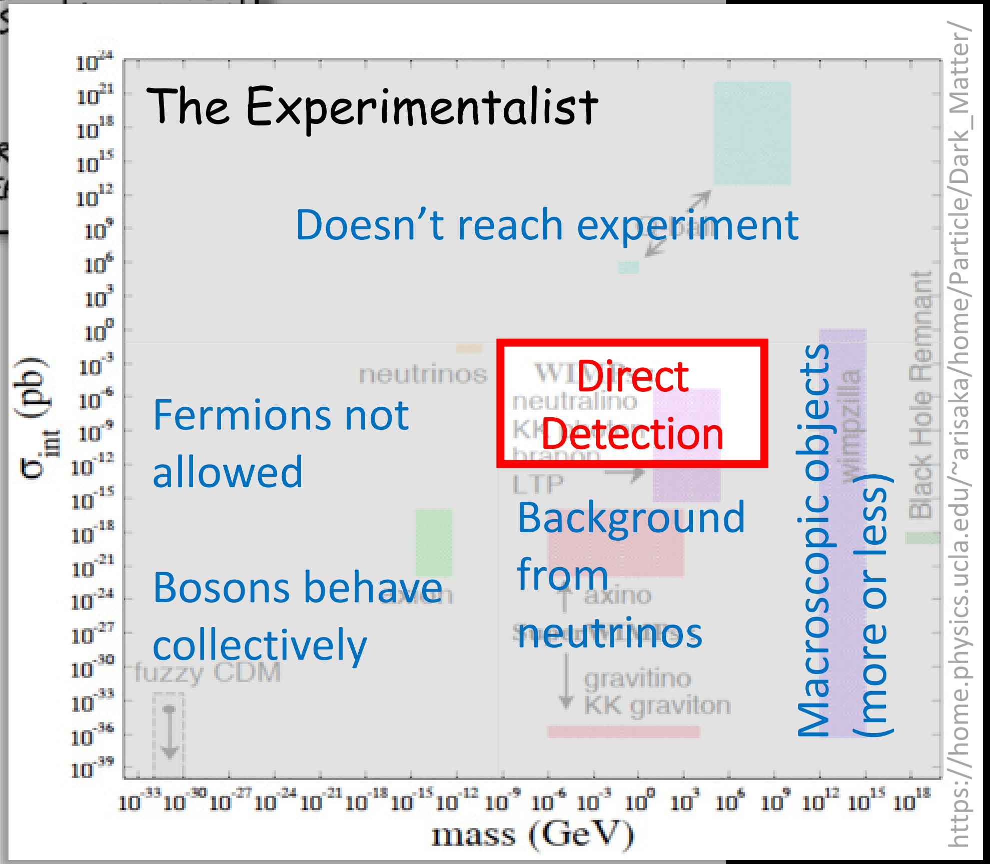
https://www.explainxkcd.com/wiki/index.php/2035:_Dark_Matter_Candidates



The Theorist



T. Tait
University of California, Irvine



https://home.physics.ucla.edu/~arisaka/home/Particle/Dark_Matter/

What will we talk about?

Background and Context

- Dark Matter interactions
  - Kinematics and other considerations
  - Expected DM signal spectra
  - DM signatures
- Background
  - Expected Signal Rates
  - Background sources and mitigation strategies
- Analysis
  - Assumptions
  - Extracting limits or confidence regions
- Detection Mechanisms
  - Electronic excitations and nuclear recoils
  - Special effects at low energy
- Calibration
  - Electron recoil energy scale
  - Nuclear recoil energy scale

Experiments

- The first Kids on the Block
- The Imag(e)inative Descendants
- The really cool ones
- The hot stuff
- The DAMA Drama
- The Xenon Frenzy
- Big, Bigger, Biggest
- The spherical Cow
- What else there is …

Results

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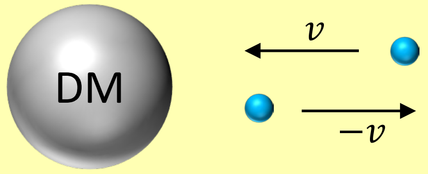
Results

Galactic Dark Matter

- Gravitationally bound
  $\rightarrow v_{DM} \leq v_{esc} \approx 600\ km/s\ =\ 2\ x\ 10^{-3}\ c$
  (typical: $v_{DM} \approx 300\ km/s =\ 10^{-3}\ c$)
  Elastic scattering (basic kinematics)
  $\rightarrow$ Energy transfer to nuclei up to 10s of keV
  $\rightarrow$ Energy transfer to electron up to a few eV
- Typical WIMP mass: 10 – 1000 GeV/c^2
- DM density at location of Earth: 0.3 GeV/c^2/cm^3
- Expected interaction cross section: can be estimated from total amount of DM (production in early universe): 10^{-9} – 10^{-10} pb (for nucleons), but large uncertainty (couple orders of magnitude)
  $\rightarrow$ Very rare interactions (order of evts/(10s of kg to tons)/year)
- Many more interactions from other sources (background): natural radioactivity (U, Th, K, …), cosmic radiation
  $\rightarrow$ Mostly ionizing: electron recoils



Velocity change: $2v$

$E_{kin} = \frac{1}{2} m(2v)^2$

$m = 50\ GeV/c^2\ ;\ E = 100\ keV$

$m = 0.5\ MeV/c^2\ ;\ E = 1\ eV$

Corresponds to 5 WIMPs$^{60\ GeV}$ / litre
Or 150 g/earth
But 150 000/cm^2/s

Interactions

Fermi's Golden Rule:

$$R = \frac{2\pi}{\hbar} \left|\mathcal{M}_{fi}\right|^2 \rho(E)$$

"Probability"
R: Rate
per beam particle
per target

"Particle Physics"
Matrix element
$\mathcal{M}_{fi} = \langle f|\mathcal{H}|i\rangle$
$|i\rangle$: initial state
$\langle f|$: final state
$\mathcal{H}$: interaction Hamiltonian

"Kinematics"
ρ: Density of final states
E: Energy transfer

$\mathcal{H}$ depends on underlying theory; if not known: "Effective Field Theory"
Interaction described by combination of 15 possible operators $\mathcal{O}_i$

$$\mathcal{O}_1 = 1_\chi 1_N$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$
$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$
$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{12} = \vec{S}_\chi \cdot [\vec{S}_N \times \vec{v}^\perp]$$
$$\mathcal{O}_{13} = i[\vec{S}_\chi \cdot \vec{v}^\perp]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right][\vec{S}_N \cdot \vec{v}^\perp]$$
$$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[(\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right]$$

$\mathcal{O}_2$: relativistic, so ignore

Interactions

Simplest case: Spin-independent or spin-dependent DM-nucleus interaction

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int dv\, f(\boldsymbol{v}) v \frac{d\sigma}{dE_R}(v, E_R)$$

$E_R = m_{red}^2 v^2 (1 - \cos(\theta))/m_N$: recoil energy

nuclear mass

scattering angle

$v = |\boldsymbol{v}|$: DM velocity

reduced mass of DM-nucleon system

$\frac{d\sigma}{dE_R} = \frac{\sigma_0}{E_R^{\max}} F^2(q)$: differential DM-nucleon cross-section

$F(q)$: nuclear form factor

$q = \sqrt{2 m_N E_R}$: momentum transfer

σ_0: "point like" total DM-nucleon cross-section

E_R^{max}: maximum recoil energy

DM velocity distribution

ρ_χ: local DM density

m_χ: DM mass

number target nuclei per unit mass

recoil spectrum

Nuclear Physics

Astrophysics

Particle Physics

[for more details: see F. Donato et al, Astroparticle Physics 9 (1998) 247-260]

What is different for other cases?

The integrand may not be so easily factorized for some of the operators.

Interactions

What else to think of?

- Fundamentally: interaction with elementary particles – quarks/gluons, electrons
- Momentum transfer small (wavelength large compared to nucleons):
  mostly coherent interaction with all quarks in a nucleus
  $\rightarrow$ interaction amplitudes for all nucleons add up; probability is $\propto A^2$ (spin-independent)

$\Rightarrow$ Observational: Electron Recoils and Nuclear Recoils

- If energy transfer is in atomic energy range:
  cannot consider electrons/nuclei as free particles

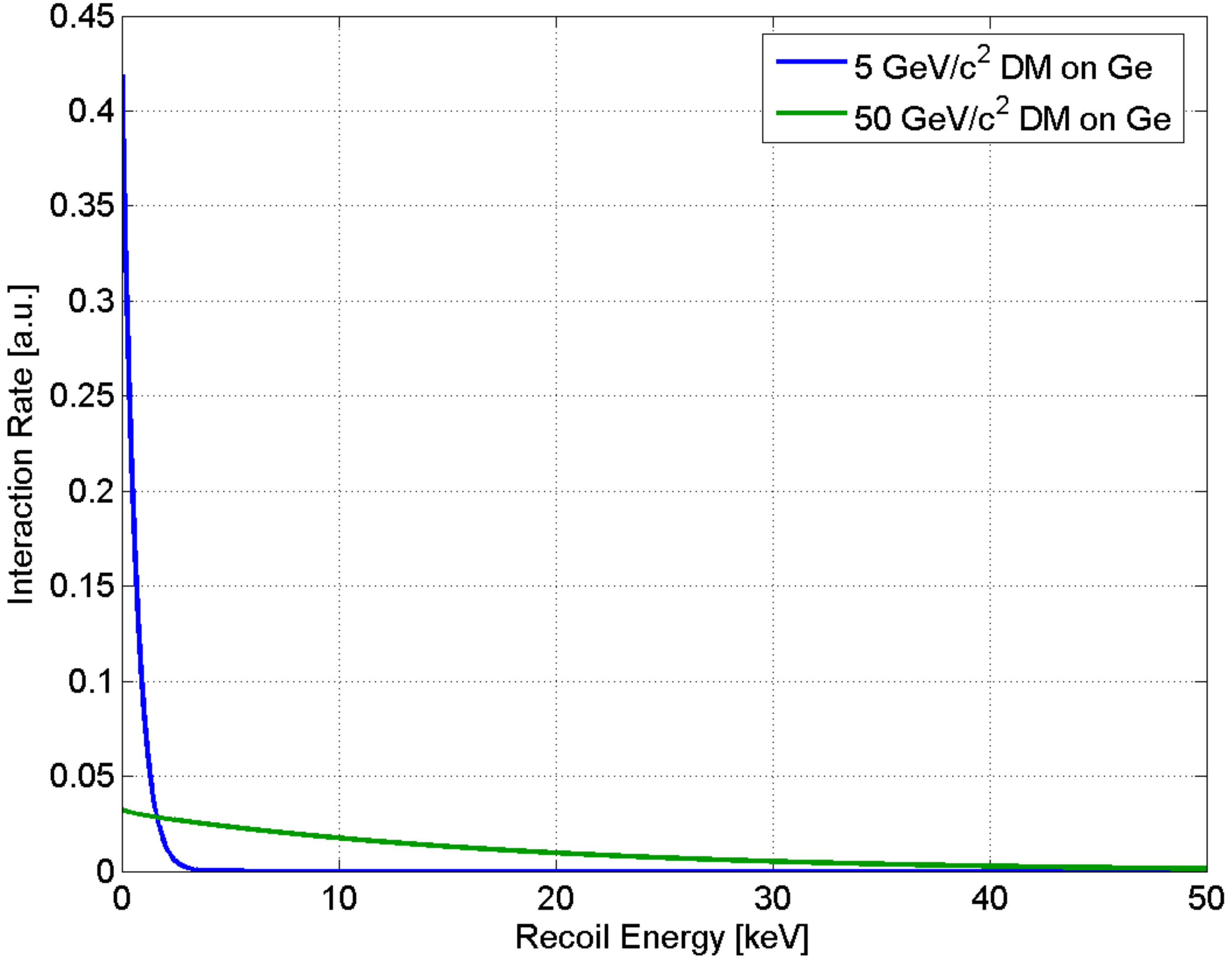
$\Rightarrow$ Need to consider binding energy ('inelastic scattering') and collective effects

- Some bosonic DM particles (Dark Photons, Axion-Like Particles) can be 'absorbed' similar to photoelectric effect; observed energy is $m_{DM}c^2$ (DM is non-relativistic)

- DM particles themselves could be 'excitable' (convertible to a higher-mass state) "Inelastic DM" (changes $E - \vec{p}$ relationship in the interaction and hence recoil spectra)

Interactions – Nuclear Recoil Spectra

Dark Matter
direct detection

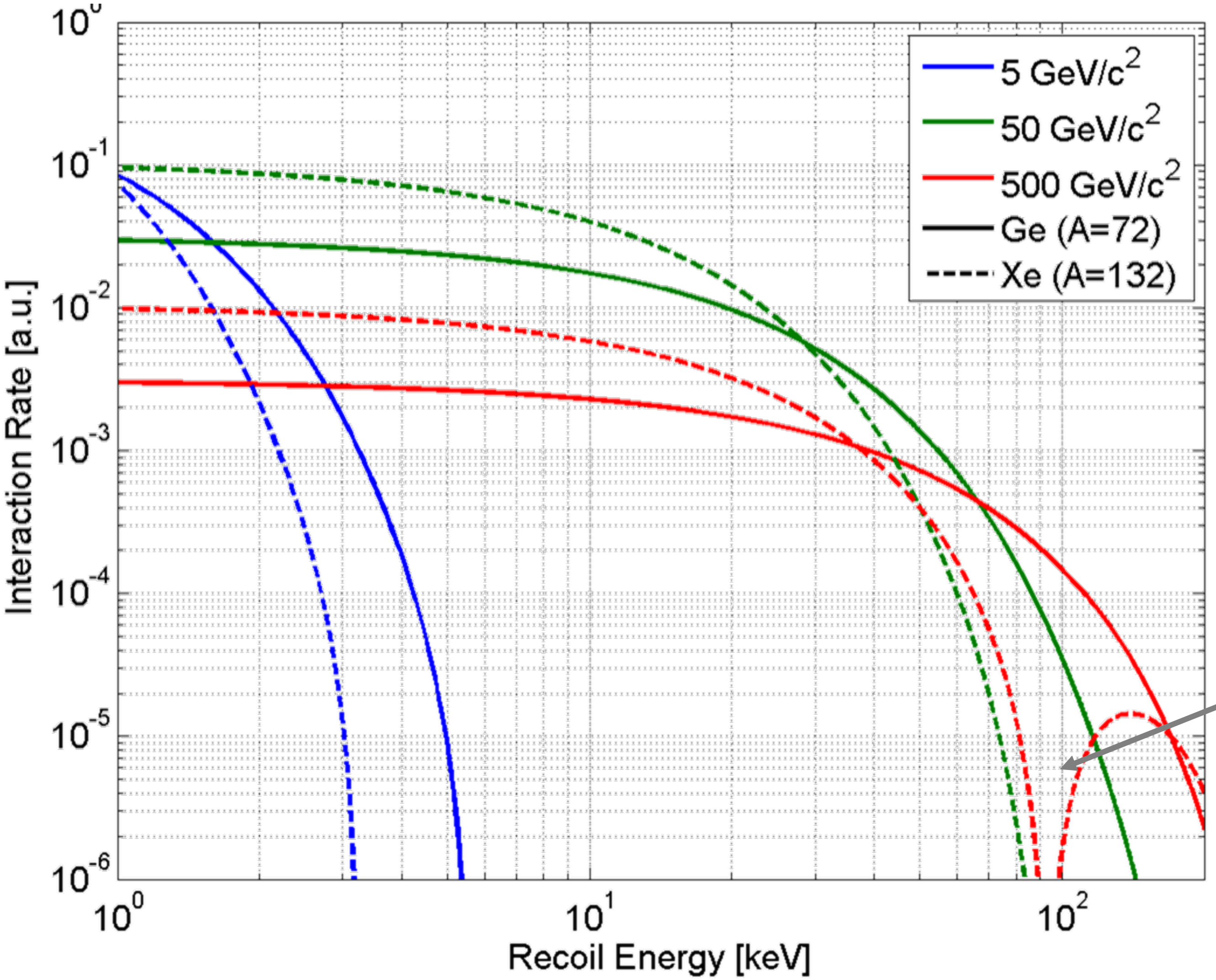


Featureless quasi exponential spectrum

Low-mass DM requires very low thresholds

Interactions – Nuclear Recoil Spectra

Dark Matter direct detection



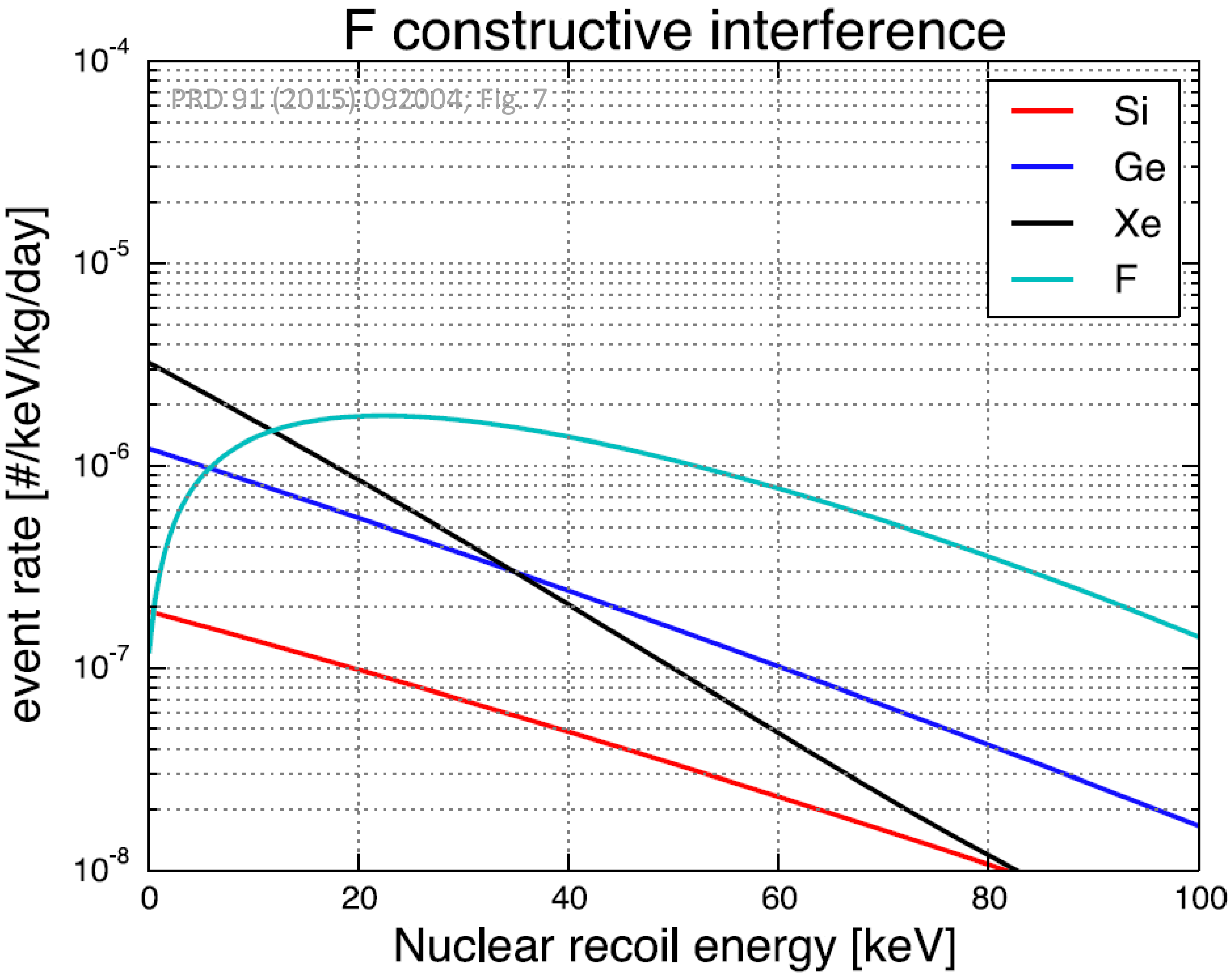
Target/DM mass comparison:
A^2 gain depends strongly on threshold

What is the dip in the Xe spectrum?

"Loss of coherence" (destructive interference between nucleons on opposite sides of the nucleus)

Interactions – Nuclear Recoil Spectra

Dark Matter direct detection

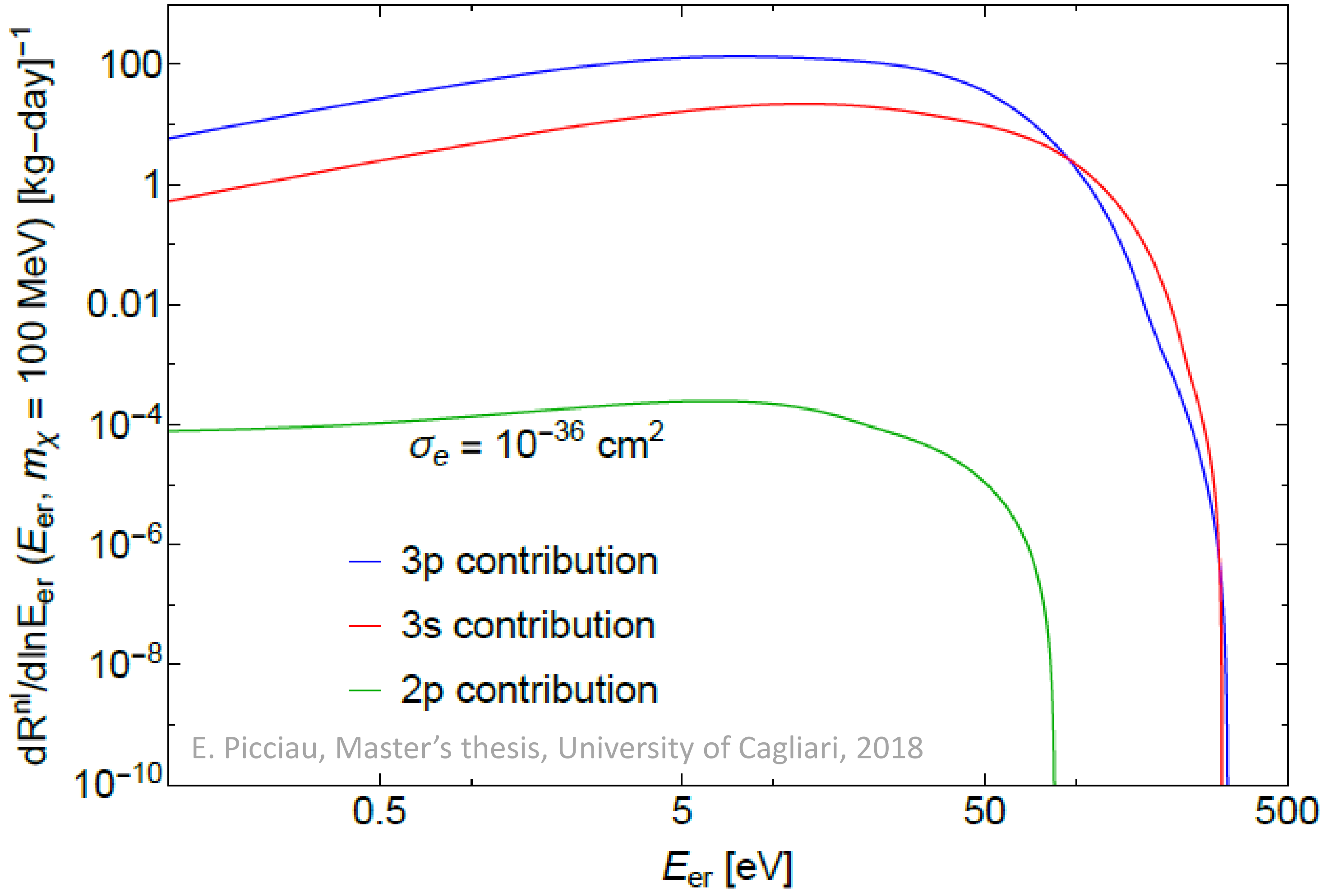


100 GeV DM
$\mathcal{O}_8/\mathcal{O}_9$ ratio chosen to enhance rate on F

Certain operator combinations can enhance rates for particular elements

and change the spectral shape significantly.

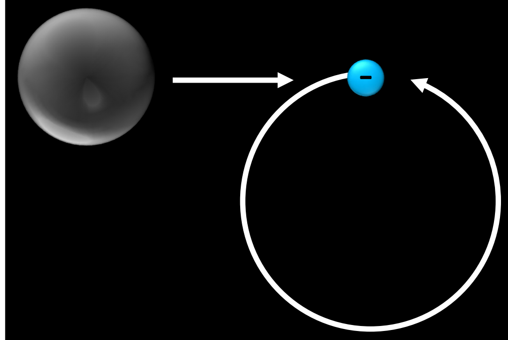
Interactions – Electron Recoil Spectra



100 MeV DM

Electron binding energies modify recoil spectra

Why does the electron have more energy than we had estimated?

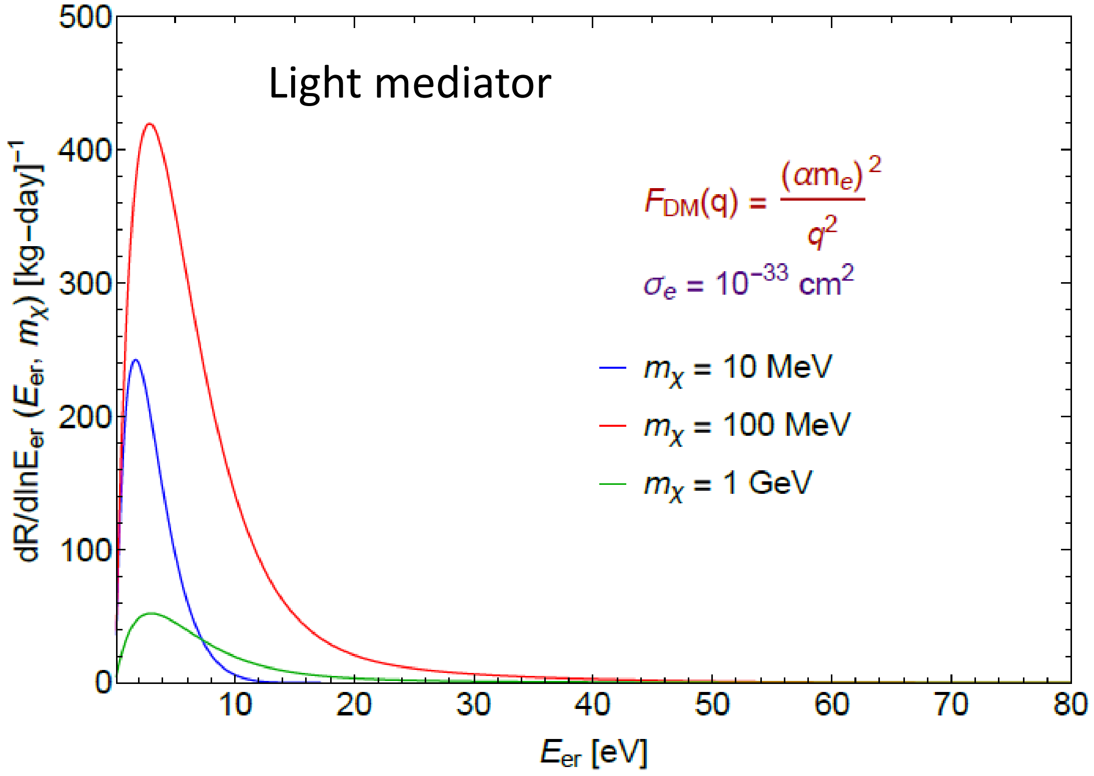


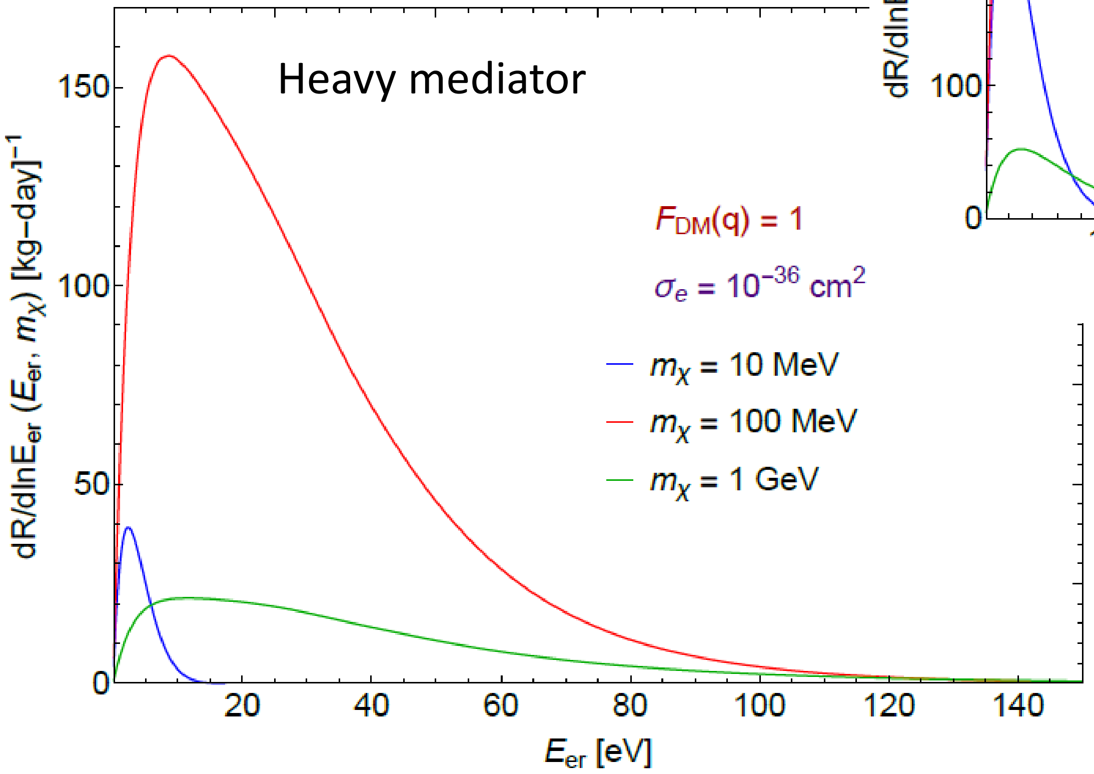
DM-electron relative velocity is much larger than DM velocity

Interactions – Electron Recoil Spectra

Dark Matter direct detection

E. Picciau, Master's thesis, University of Cagliari, 2018





Mediator mass impacts recoil spectrum

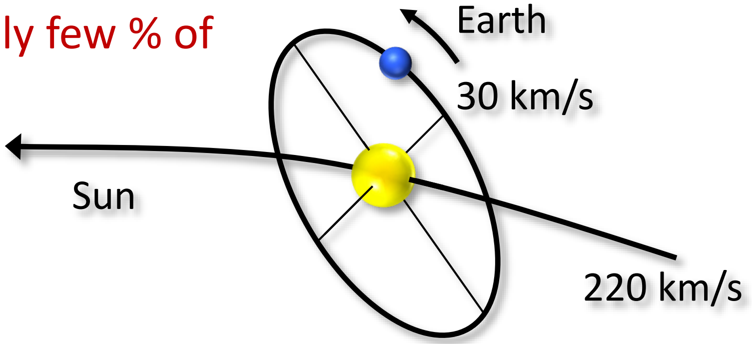
Dark Matter Signatures

Nuclear recoils ("classical" DM searches)
- Eliminate other sources of nuclear recoils (mostly neutrons)
- Discriminate against electron recoils

- Discrimination difficult at low energy
- Does not help for ER

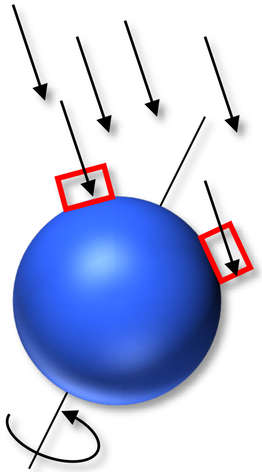
Annual Modulation
- Sun moves about galactic centre Earth moves about sun
- Relative velocity between DM and detector and DM flux change over the year
- Look for (small) periodic variation of the signal

Modulation only few % of the DM signal



Diurnal modulation of direction
- Earth moves through DM cloud
- From earth point of view: 'DM wind'
- Direction relative to detector changes over course of the day
- Look for preferred direction of DM interactions

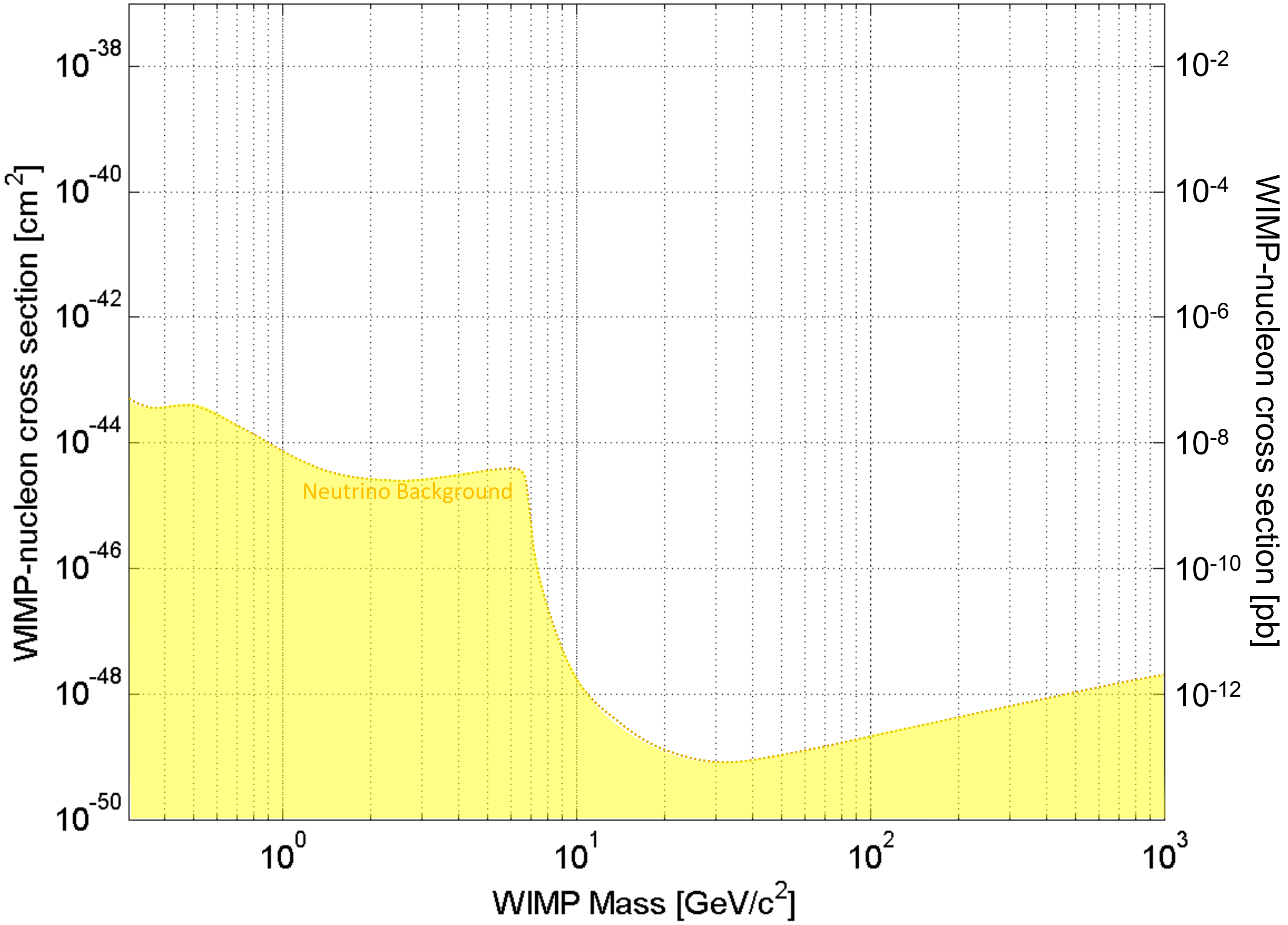
- Recoil not strictly correlated with DM direction
- Need 10s to 100s of events to see a modulation



Anti-signatures
- Erratically varying rate (typically intermittent noise)
- Signal decaying over time (likely radioactivity)
- Non-Poissonian time distribution: correlated events
- Multiple scatters
- Inhomogeneous spatial distribution

Rates and Backgrounds

Dark Matter
direct detection



NOTE
"Neutrino Background" is a rough guide. There is no hard limit and where exactly it appears depends on the target material.