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Journée Matière Sombre France, APC Paris

Dark Matter 'pheno'

Signatures in direct detection experiments

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“How do I know if I have Dark Matter?”

Acute symptoms of DM

acute [*uh-**kyoot***]
adjective

(of disease) brief and severe
(opposed to chronic)

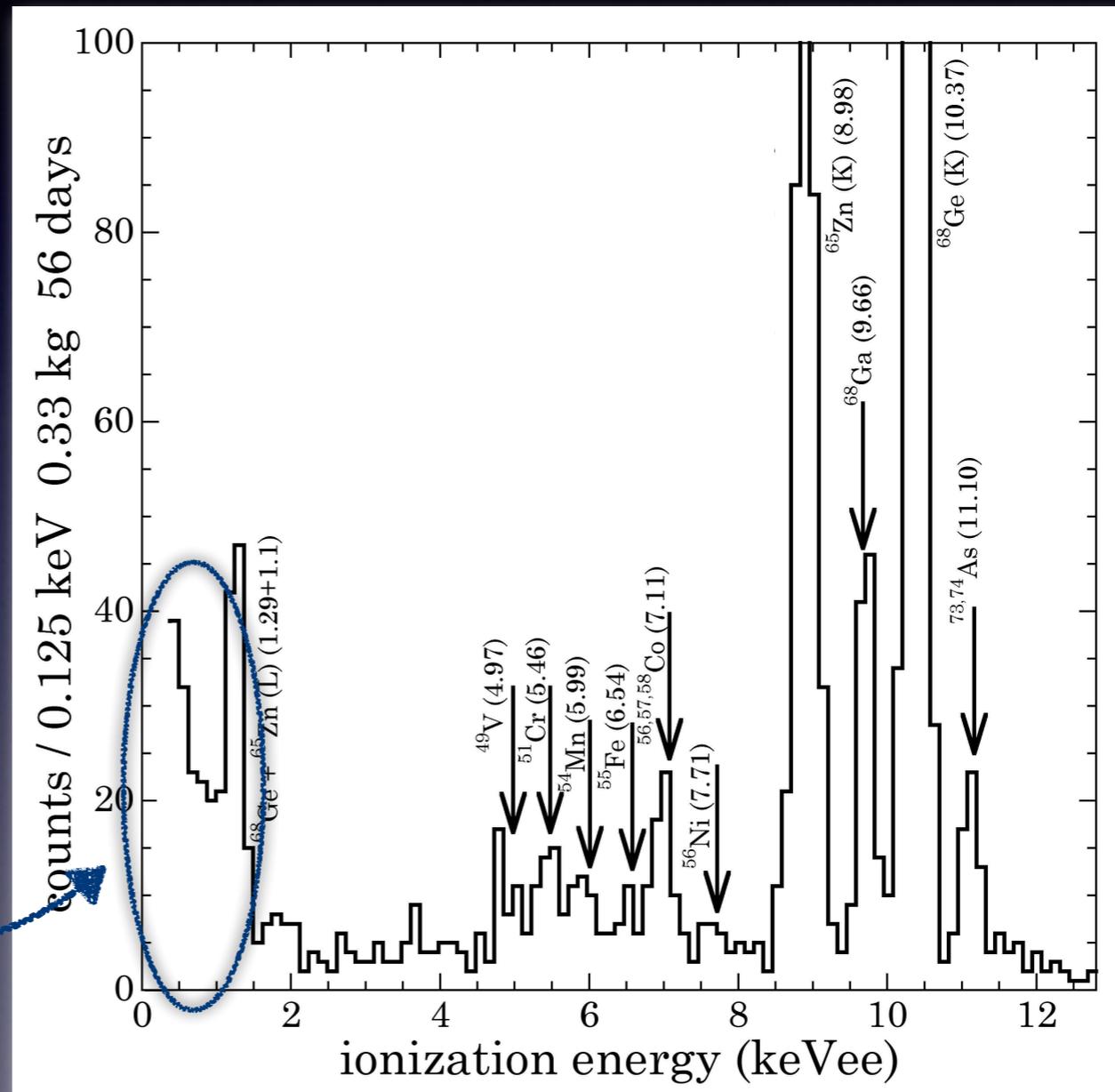
An Excess

Initial symptom: an excess above the expected background...

CoGENT low energy spectrum:

[1002.4703, 1208.5737]

Possible low-energy excess?



How can we definitively diagnose a Dark Matter signal in Direct Detection?

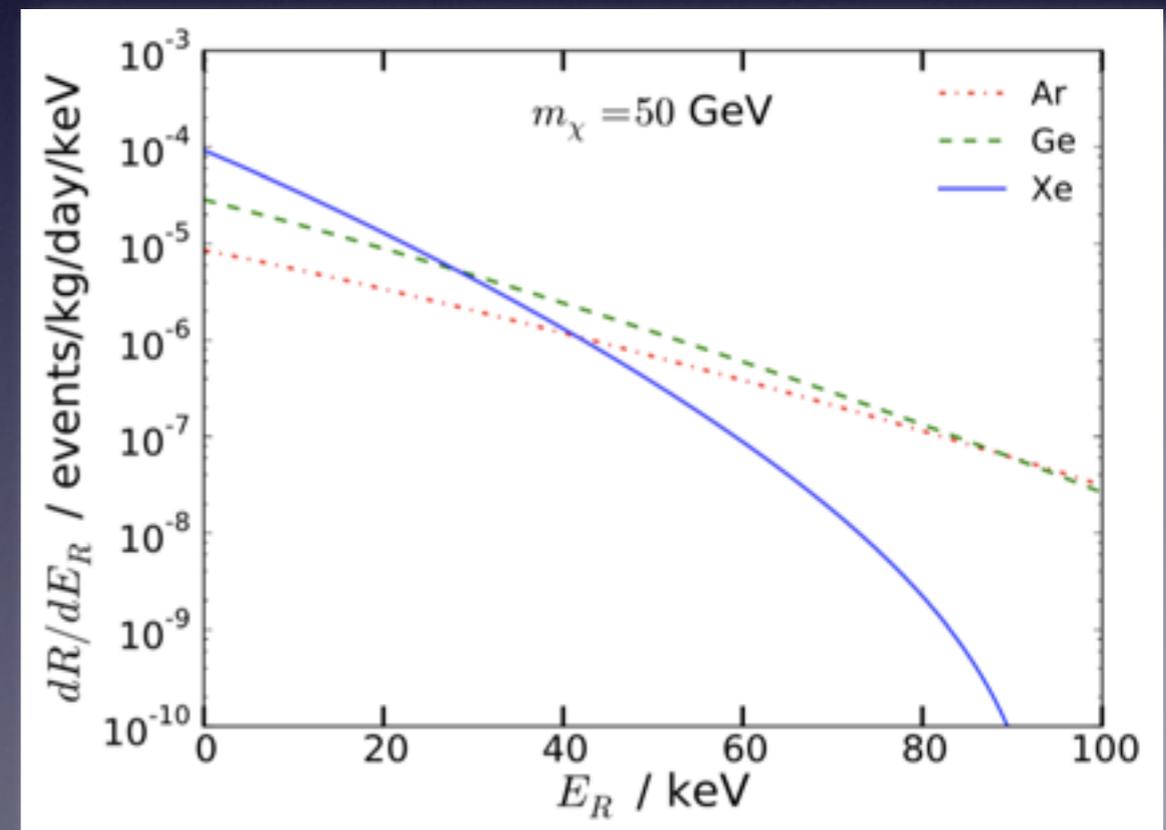
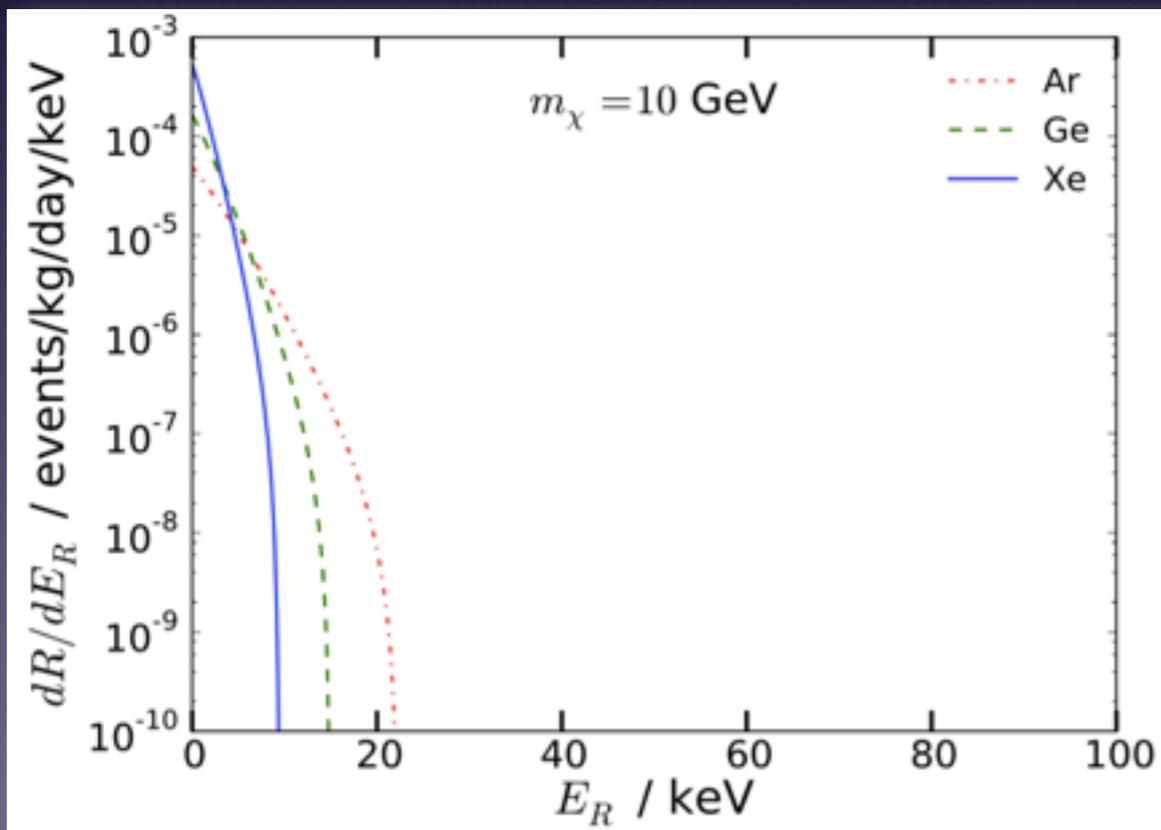
Spectral features (1)

Standard spin-independent (SI) elastic scattering
- roughly exponential spectrum:

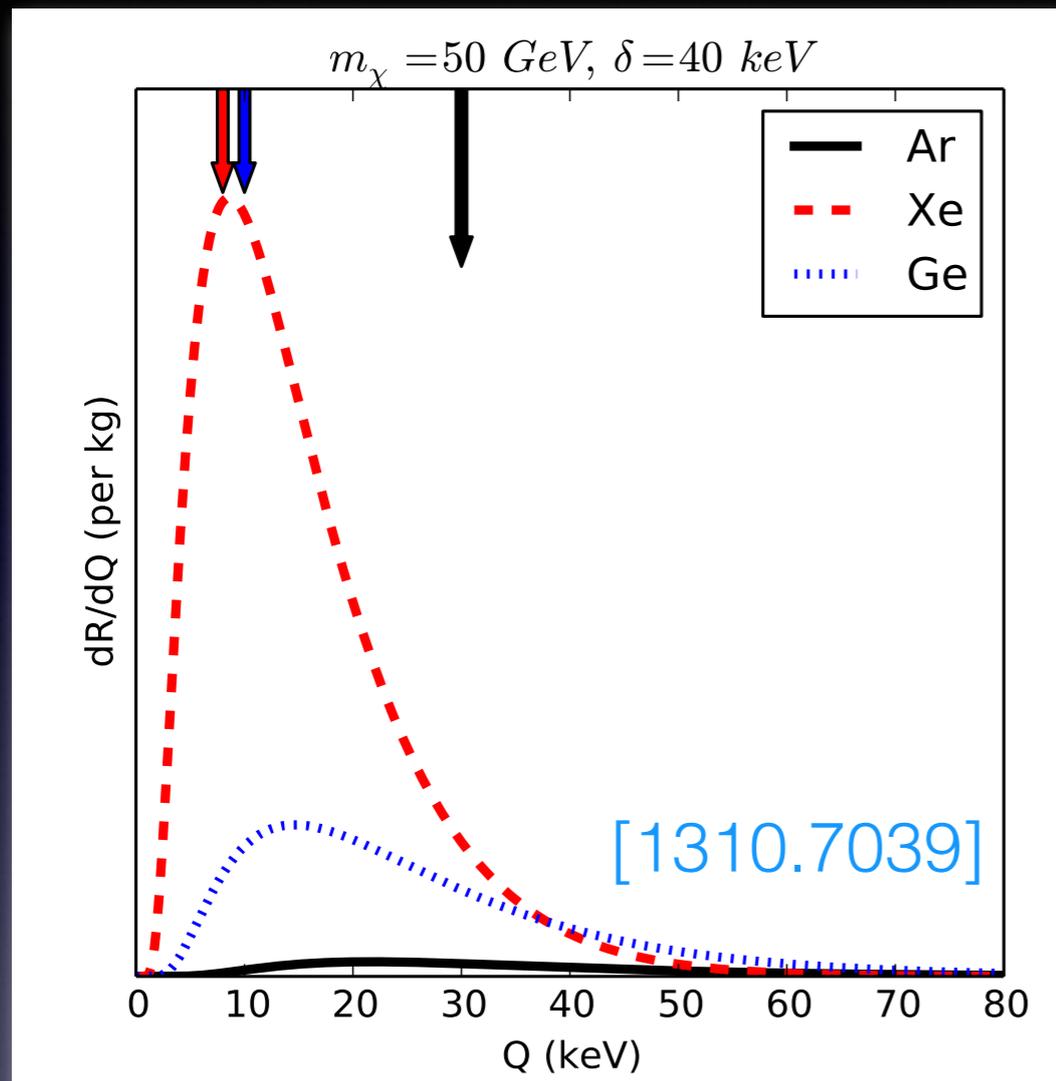
$$\frac{dR}{dE_R} \sim \exp(-E_R/E_0)$$

$$E_0 = 2\mu_{\chi A}^2 v_c^2 / m_A$$

[Lewin & Smith, 1996]



Spectral features (2)

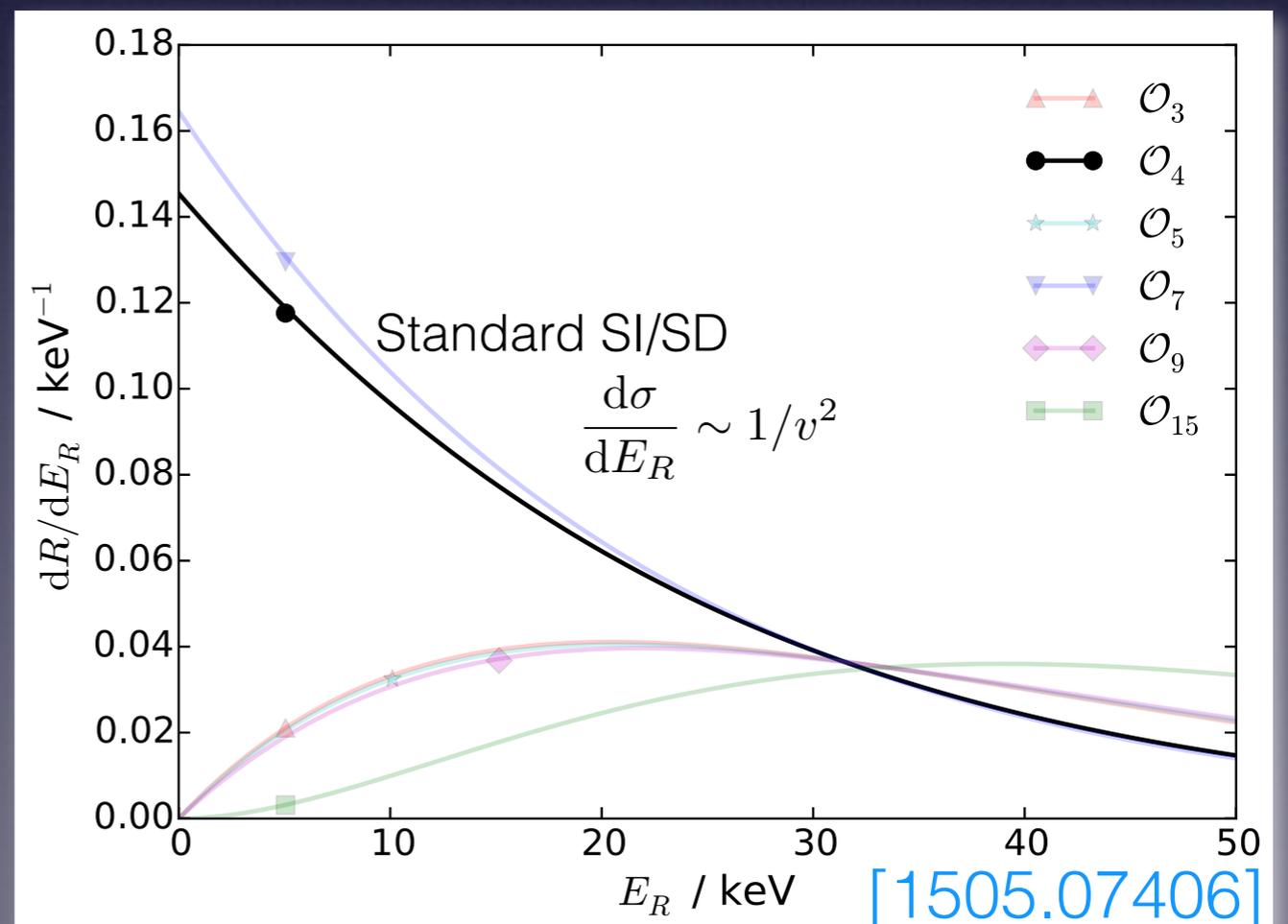


Non-standard kinematics
(inelastic scattering)

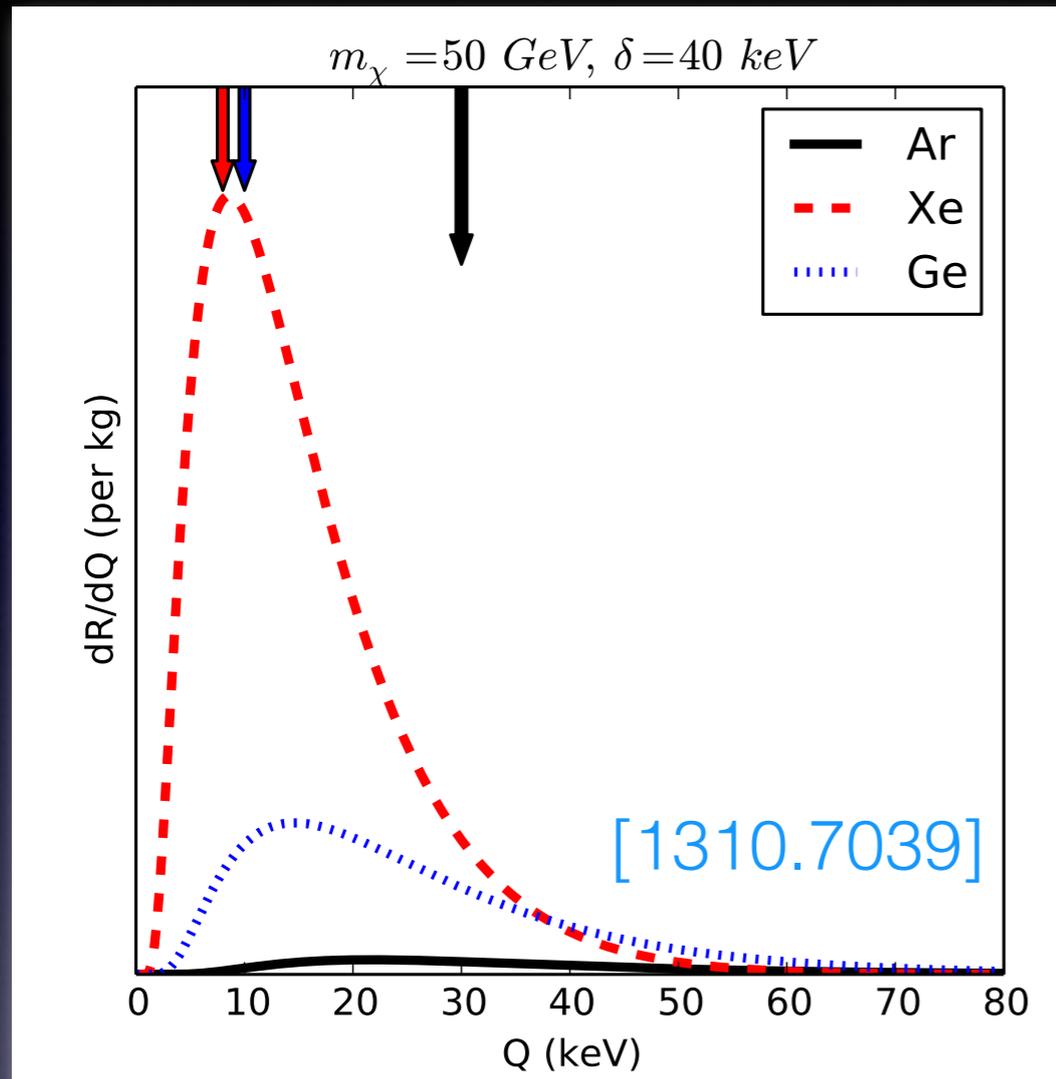
[1309.0825]

Higher-order interactions
(e.g. NREFT)

[1008.1591, 1203.3542]



Spectral features (2)

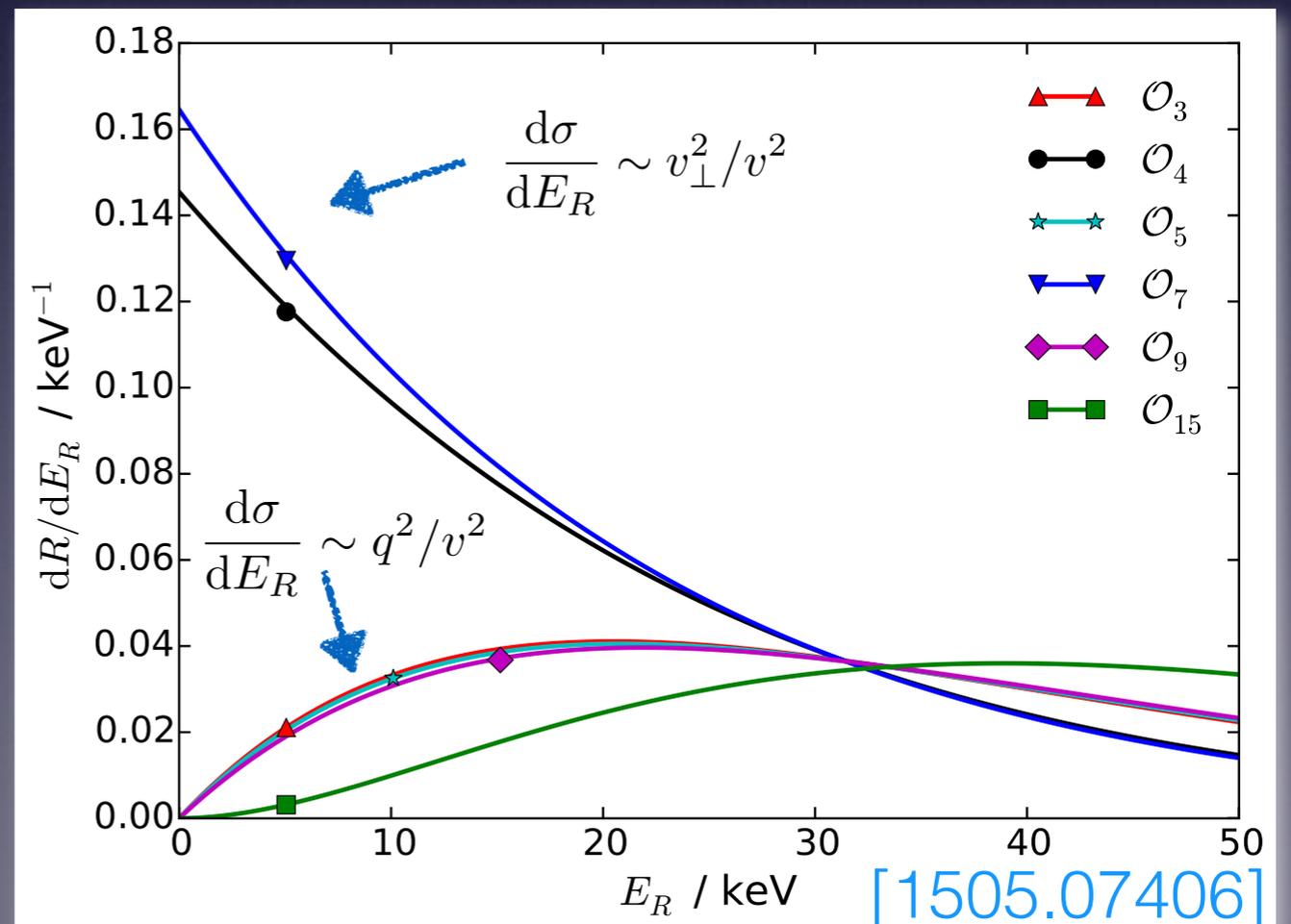


Non-standard kinematics
(inelastic scattering)

[1309.0825]

Higher-order interactions
(e.g. NREFT)

[1008.1591, 1203.3542]



'Materials' Signal

Standard SI scattering rate scales differently for different targets:

$$\frac{dR}{dE_R} \sim \mu_{\chi A}^2 |f_p Z + f_n (A - Z)|^2 \rightarrow \mu_{\chi A}^2 A^2$$

Can use different targets to pin down DM mass (and astrophysical uncertainties)

[1310.7039]

Maximum complementarity when using targets with $Z/(A-Z)$ as different as possible:

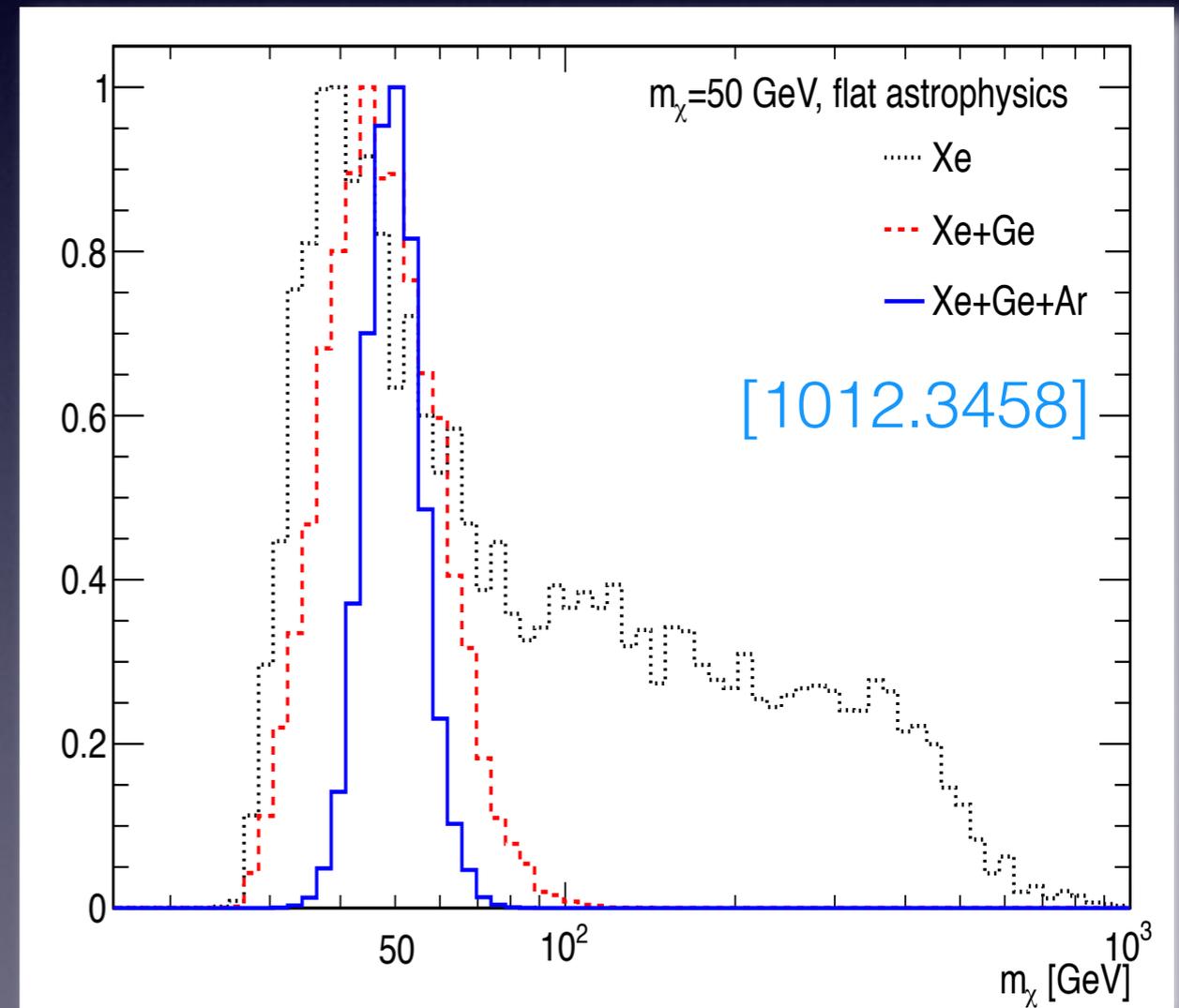
Si: $Z/(A-Z) \sim 1$

vs.

Xe: $Z/(A-Z) \sim 0.68$

[1304.1758, 1610.06581]

$P(m_\chi)$

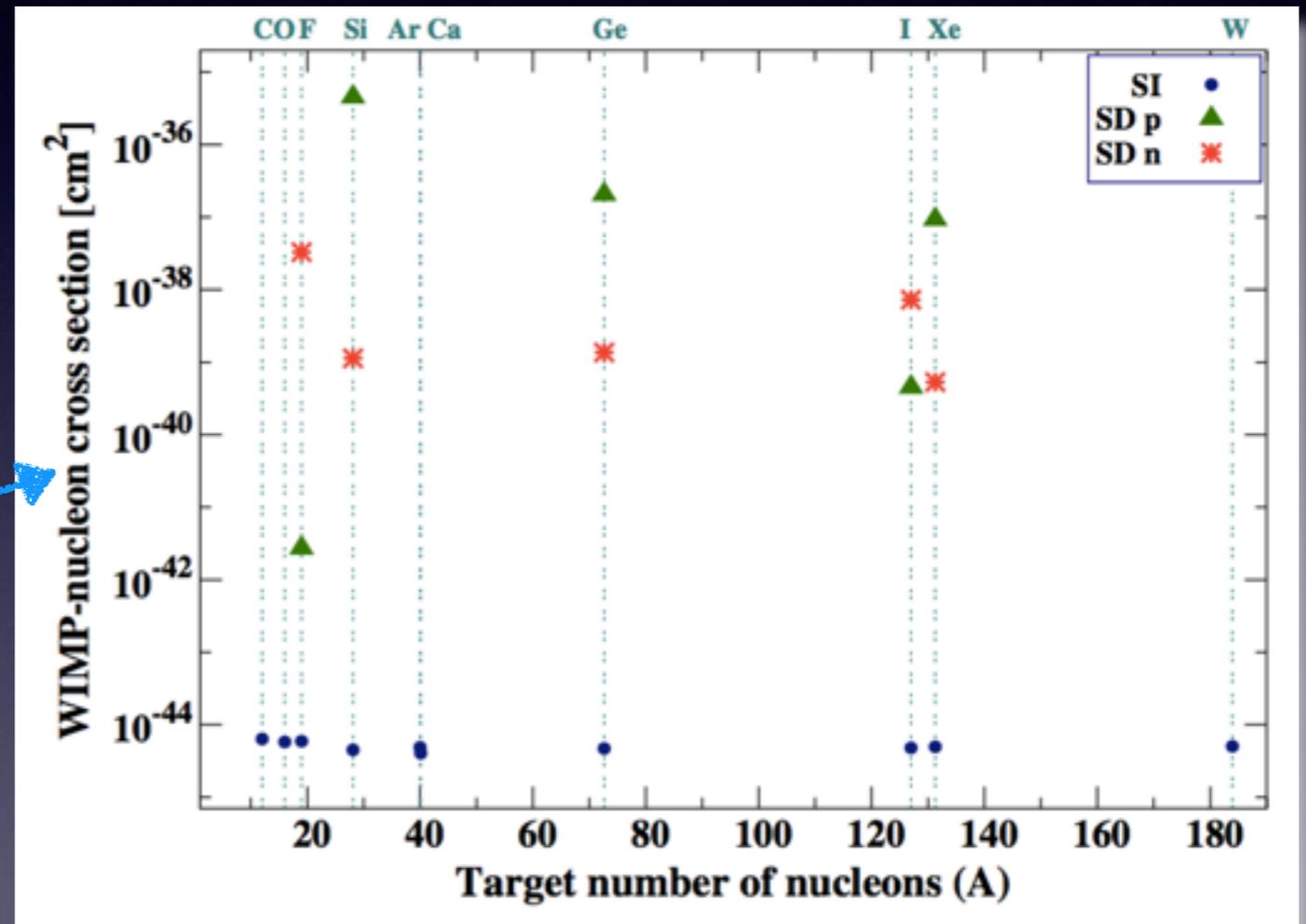


m_χ [GeV]

'Materials' Signal vs Neutrinos

Coherent neutrino scattering: $\frac{dR_\nu}{dE_R} \sim (A - Z)^2$

^8B neutrinos from the Sun
mimic a WIMP with this
cross-section



[1408.3581]

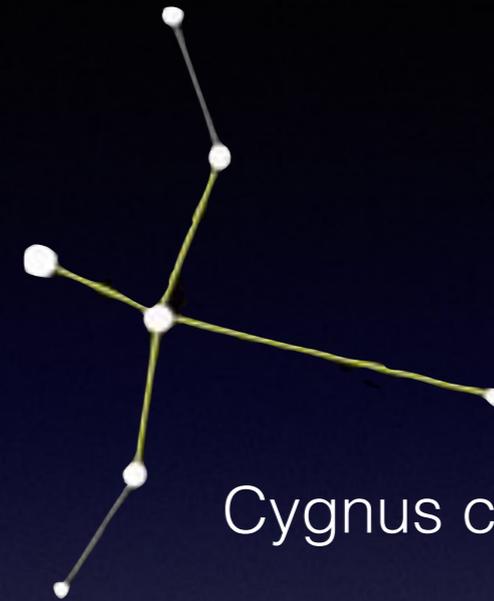
Target complementarity is stronger for spin-dependent interactions than for spin-independent interactions

Directionality (1)

In the DM Halo:

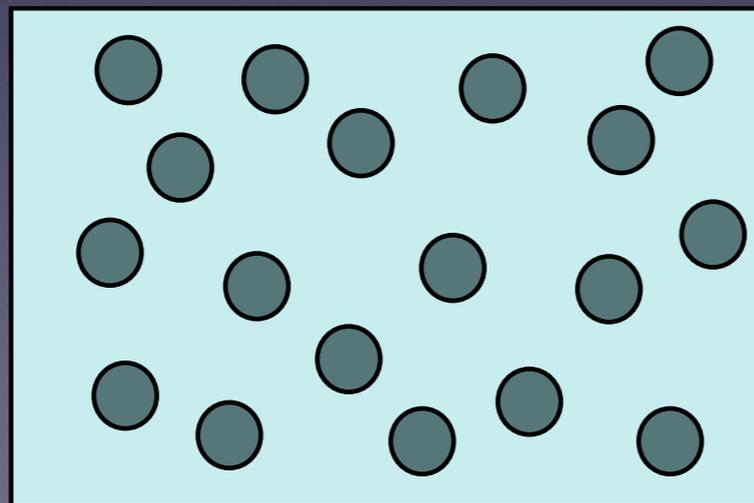


$$v_{\text{sun}} \sim 220 \text{ km s}^{-1}$$

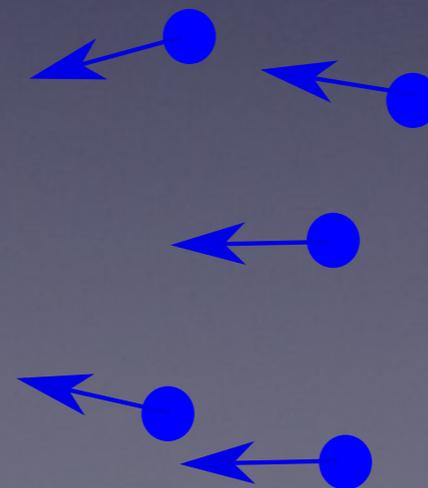


Cygnus constellation

In the lab:



Detector

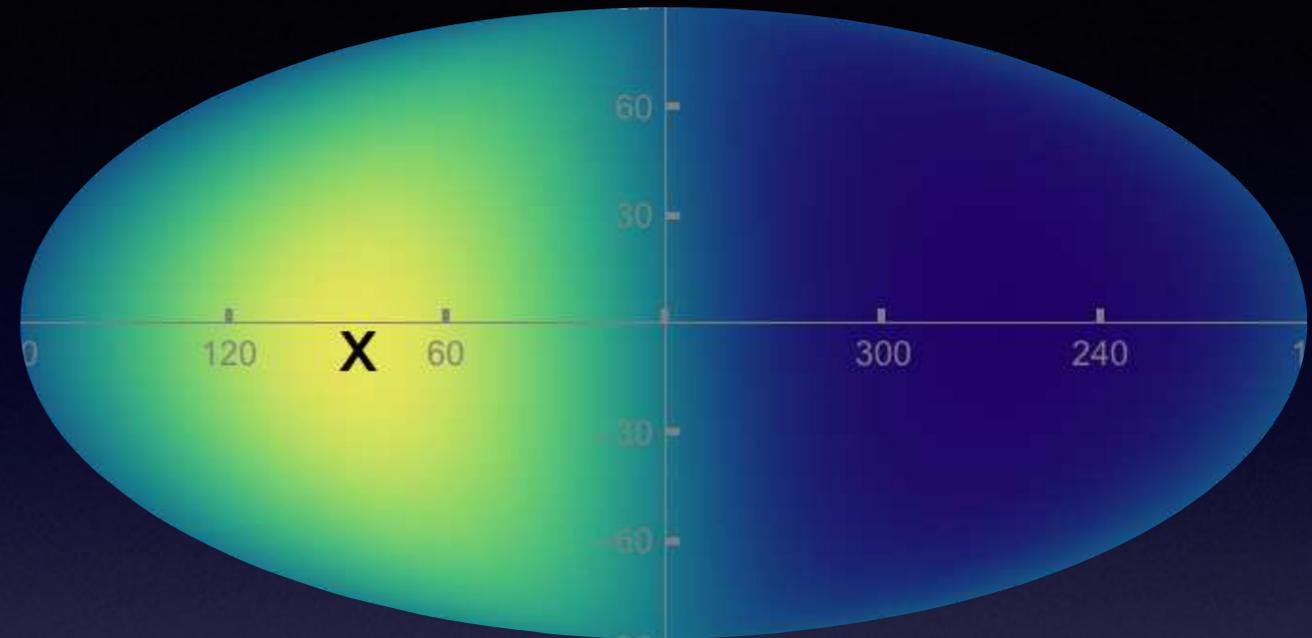


$$\langle v_{\text{DM}} \rangle \sim 220 \text{ km s}^{-1}$$

Directionality (2)

[1602.03781]

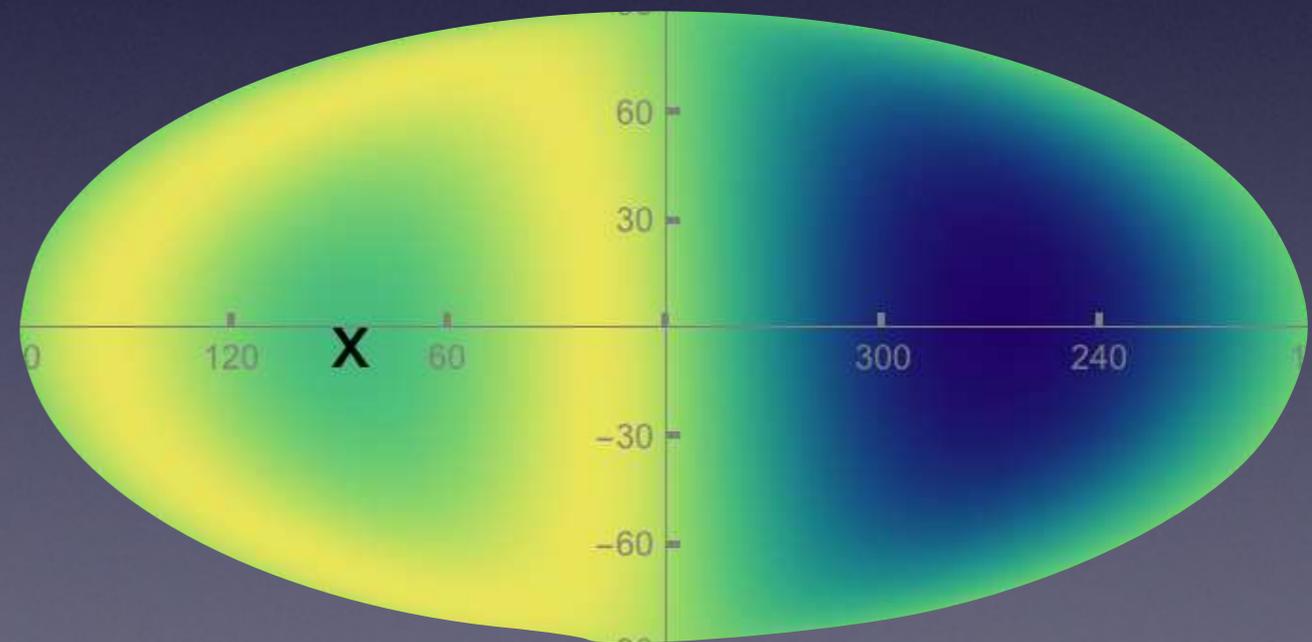
High energy recoils
↓
dipole in recoil directions



Many recoils  Few recoils

Low energy recoils
↓
Ring-like feature

[1111.6361]



'Ring' feature may be enhanced for some non-standard interactions

[1505.07406]

Directionality (3)

Powerful method of confirming DM origin of signal
(and rejecting backgrounds):

Can reject signal isotropy with $O(10)$ signal events

[[hep-ph/9904499](#), [astro-ph/0408047](#)]

Can confirm median recoil direction with $O(30)$ events

[[1002.2717](#), [1012.3960](#)]

Can allow us to distinguish DM and neutrino scattering
and probe into the *neutrino regime*

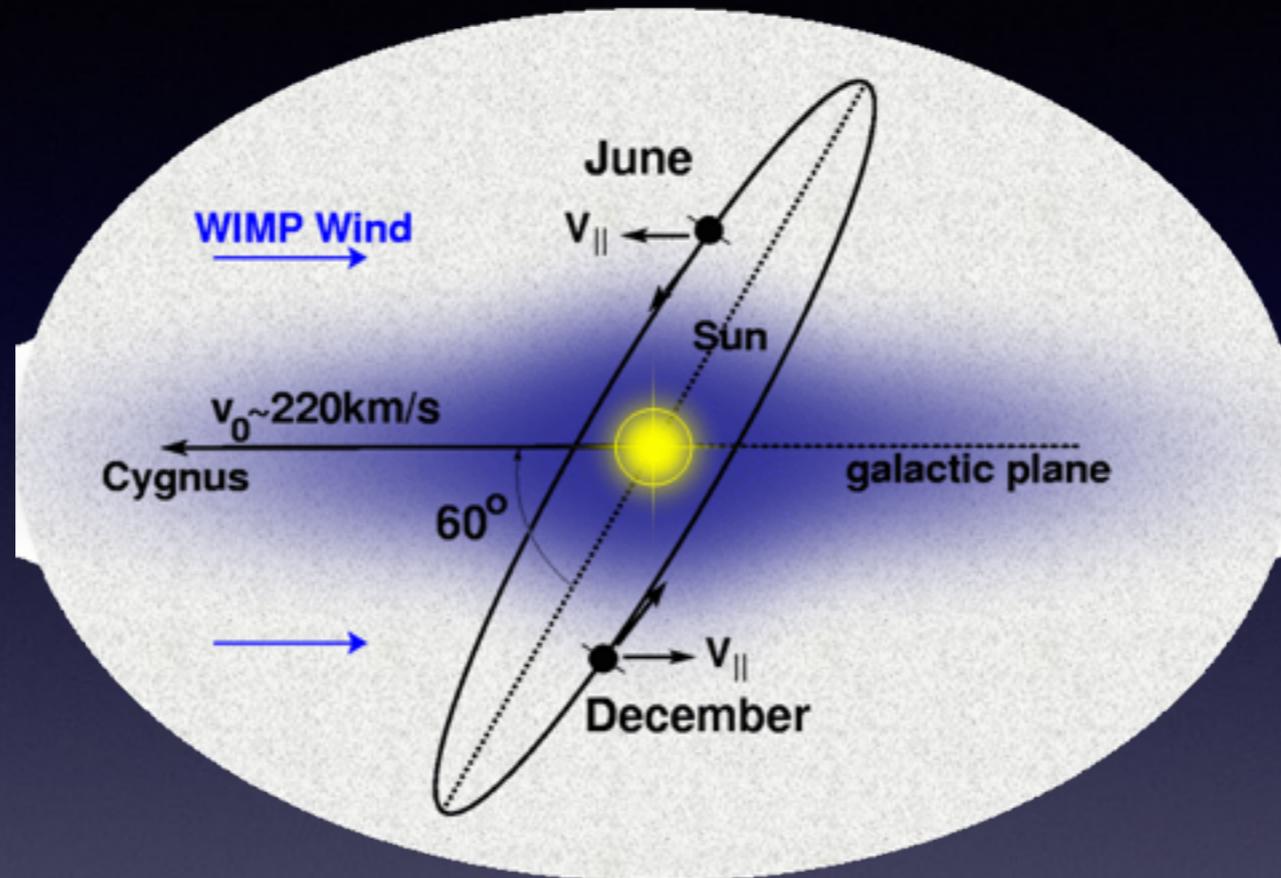
[[1406.5047](#), [1505.08061](#)]

Chronic symptoms of DM

chronic [**kron**-ik]
adjective

(of a disease) having long duration
(opposed to acute)

Annual Modulation (1)

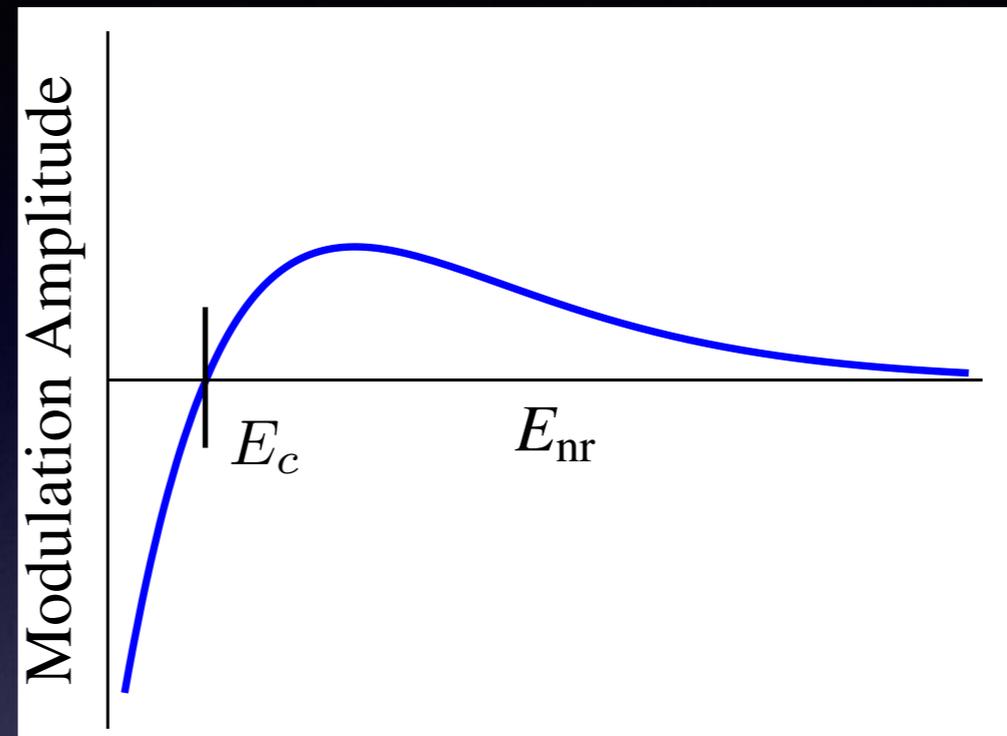
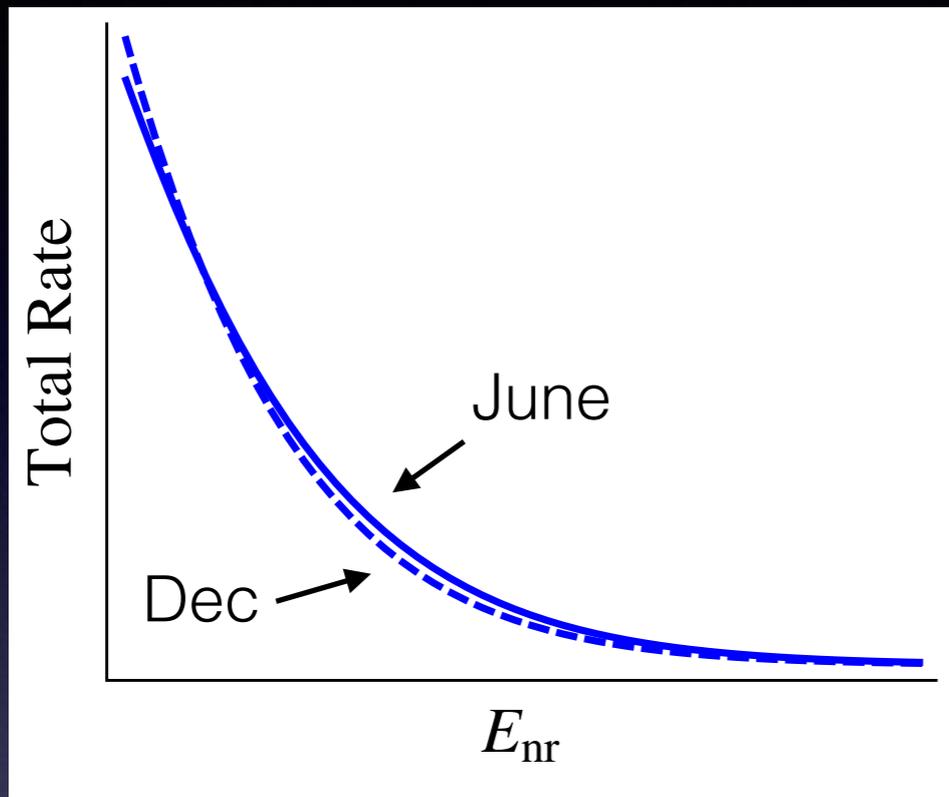


$$v_{\text{Sun}} \approx 230 \text{ km s}^{-1}$$
$$u_{\text{E}} \approx 30 \text{ km s}^{-1}$$

$$\mathbf{v}_{\text{Earth}}(t) = \mathbf{v}_{\text{Sun}} + \mathbf{u}_{\text{E}}(t)$$

O(1-10%) annual modulation of DM flux:
Maximum in June, Minimum in December

Annual Modulation (2)



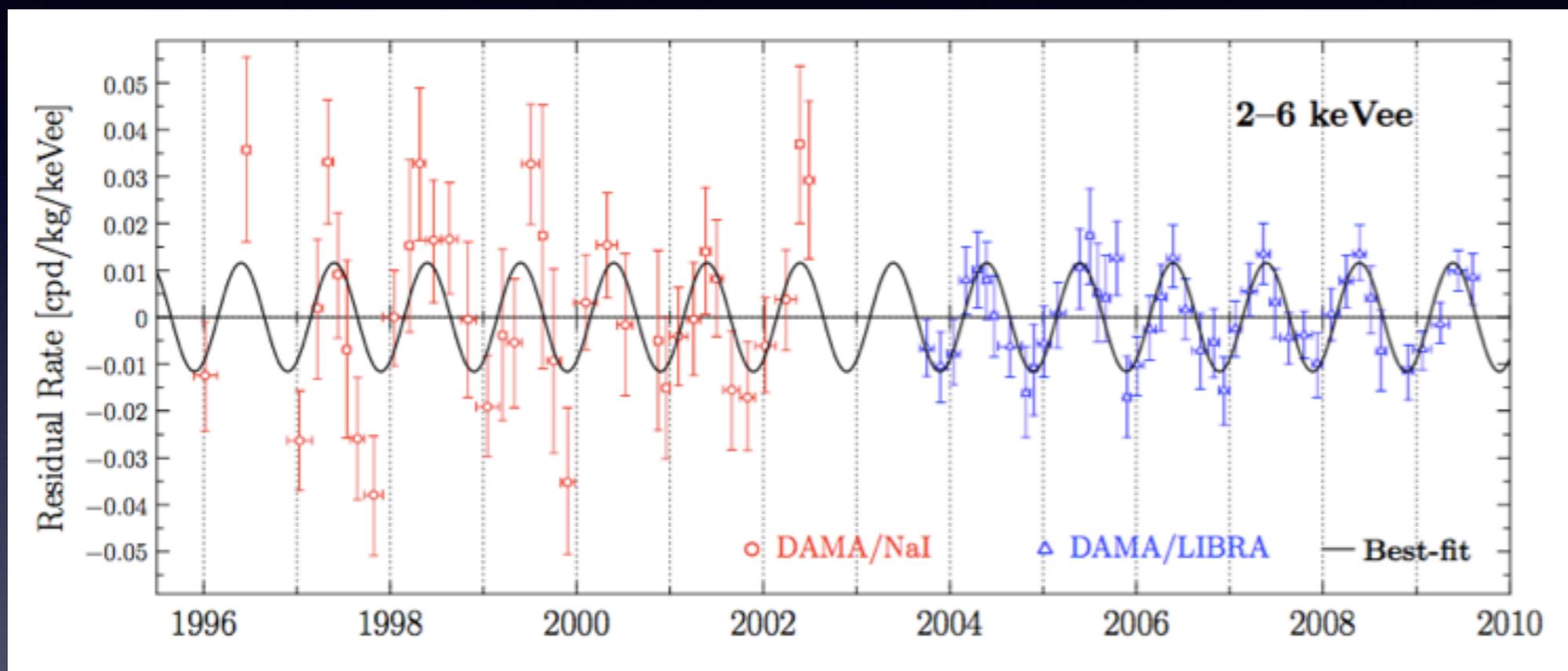
[1209.3339]

Modulation amplitude and phase depends on
DM mass and recoil energy E_{nr}

'Cross-over' energy E_c may help determine the
DM mass [astro-ph/0307190]

Annual Modulation - DAMA

Proposed annual modulation signal due to DM in DAMA experiment...



[1002.1028]

...so far, no 'materials' signal observed...

...even with non-standard astrophysics and/or interactions

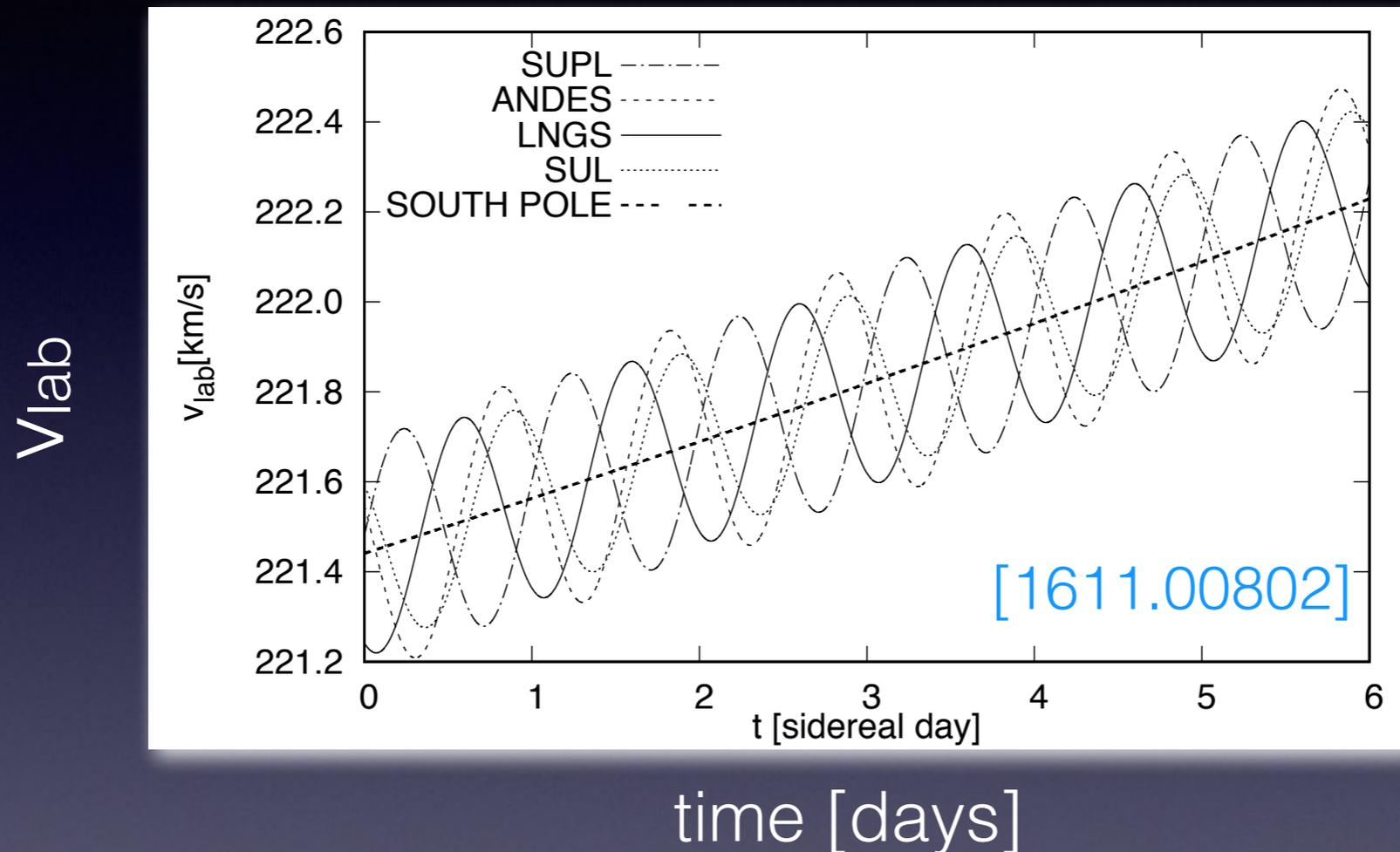
[1205.0134]

[1602.04074]

Daily Modulation (due to Earth's rotation)

$$\mathbf{v}_{\text{Earth}}(t) = \mathbf{v}_{\text{Sun}} + \mathbf{u}_{\text{E}}(t) + \mathbf{v}_{\text{rot}}(t)$$

$$v_{\text{rot}} \approx 0.5 \text{ km s}^{-1}$$



Produces a very small diurnal modulation (amplitude less than 0.1%) - but will be an important consistency check

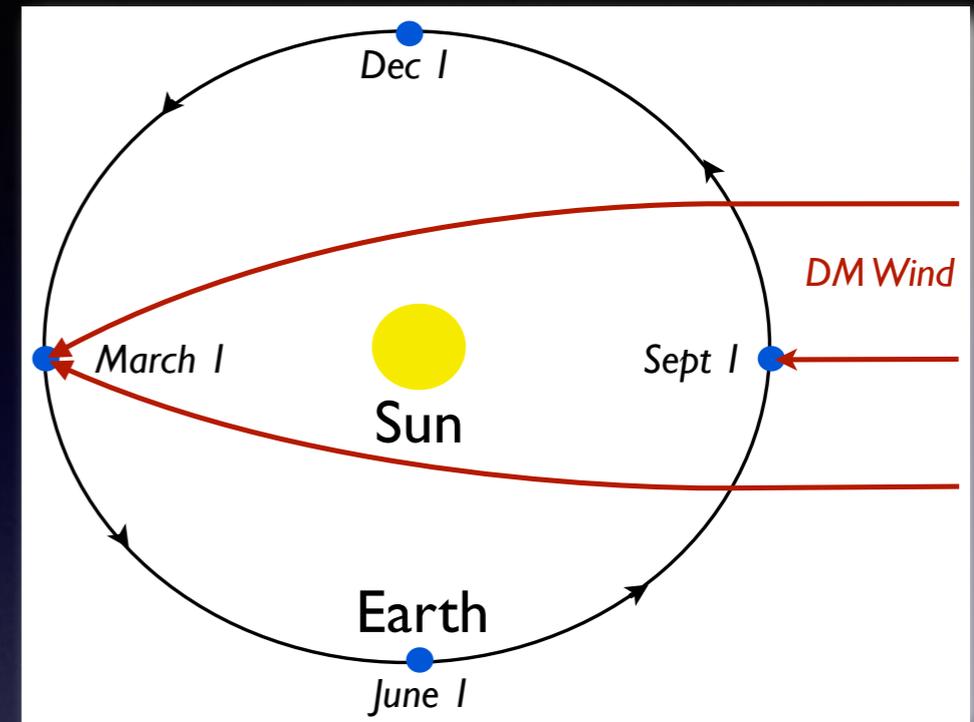
[1505.02615]

Also expect a 10^{-5} monthly modulation due to Moon's influence!

[1409.2858]

Gravitational Focusing

Gravitational focusing (GF) by the Sun produces a percent-level annual modulation of the rate



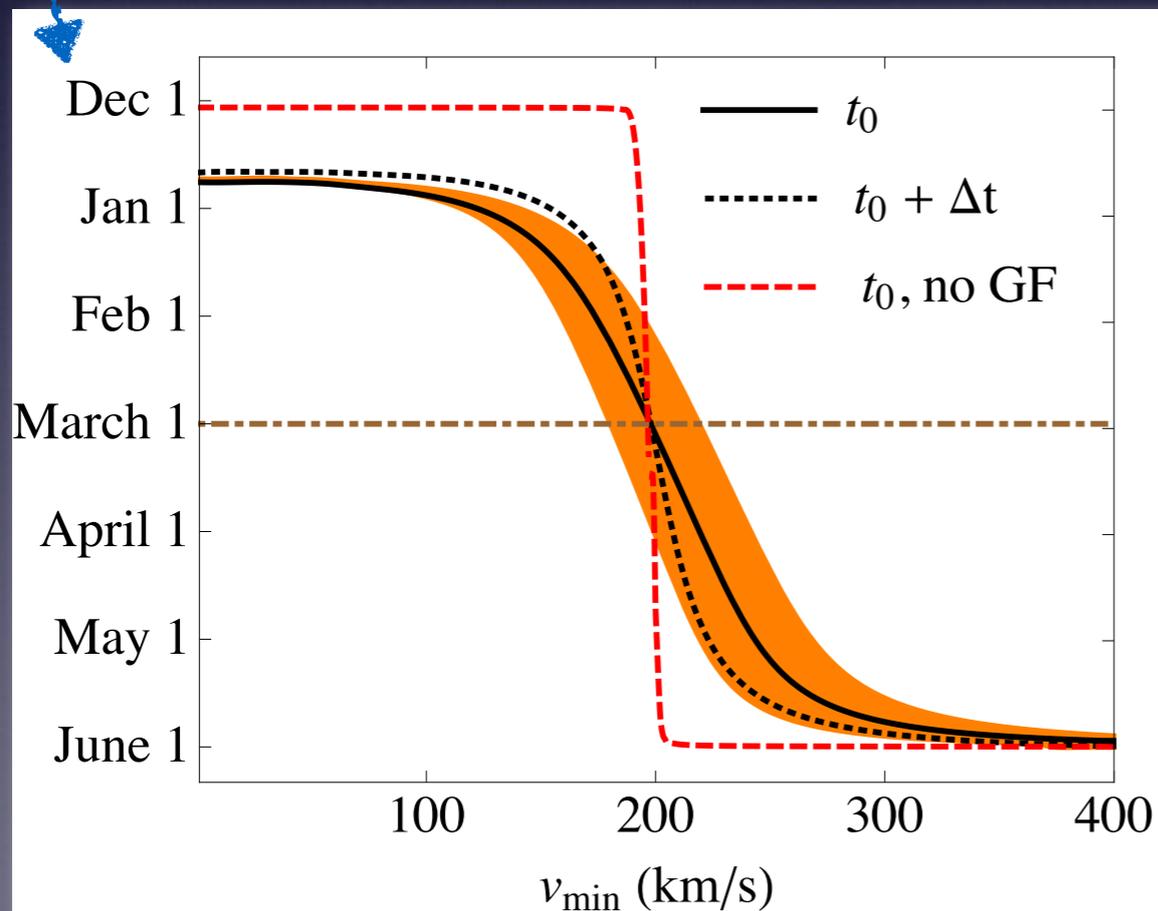
[[astro-ph/0608390](#),
[1308.1953](#), [1405.2340](#)]

GF can shift the phase of the 'standard' annual modulation

Also get small daily modulation due to GF by the Earth

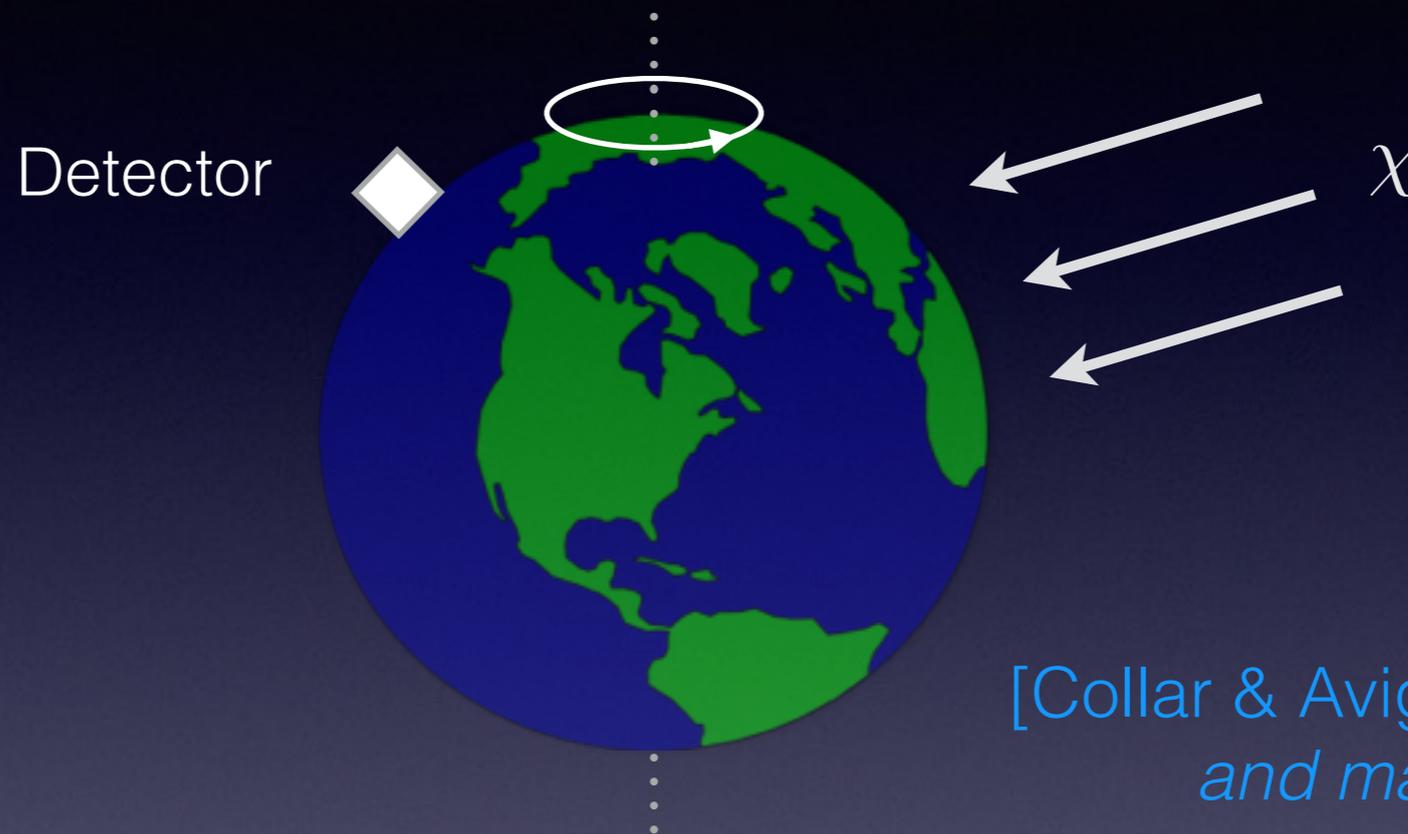
[[1505.02615](#)]

Date when rate is maximal



Earth Scattering (1)

DM particles with 'strong' SI interactions could scatter in the Earth before reaching the detector



Gives rise to a diurnal modulation as the Earth (and detector) rotate

[[astro-ph/9702165](#)]

May also give a directional signature

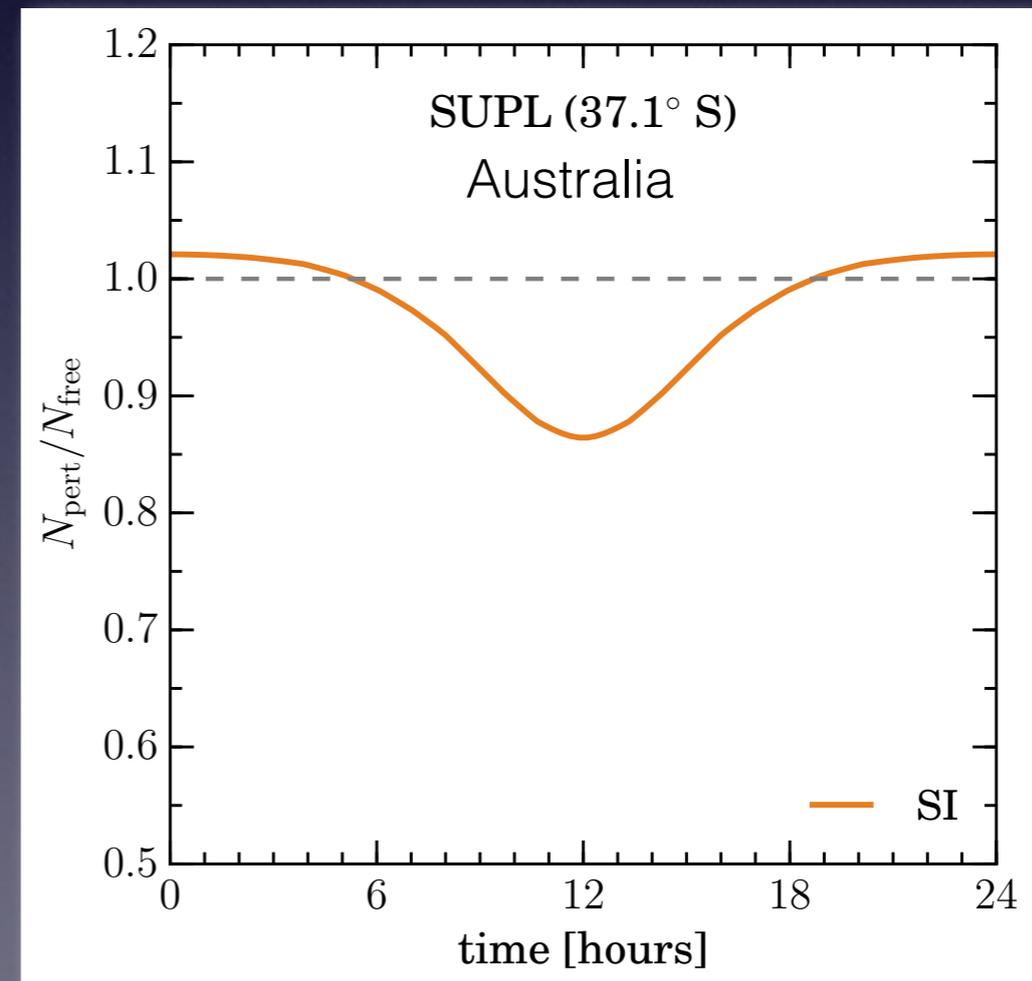
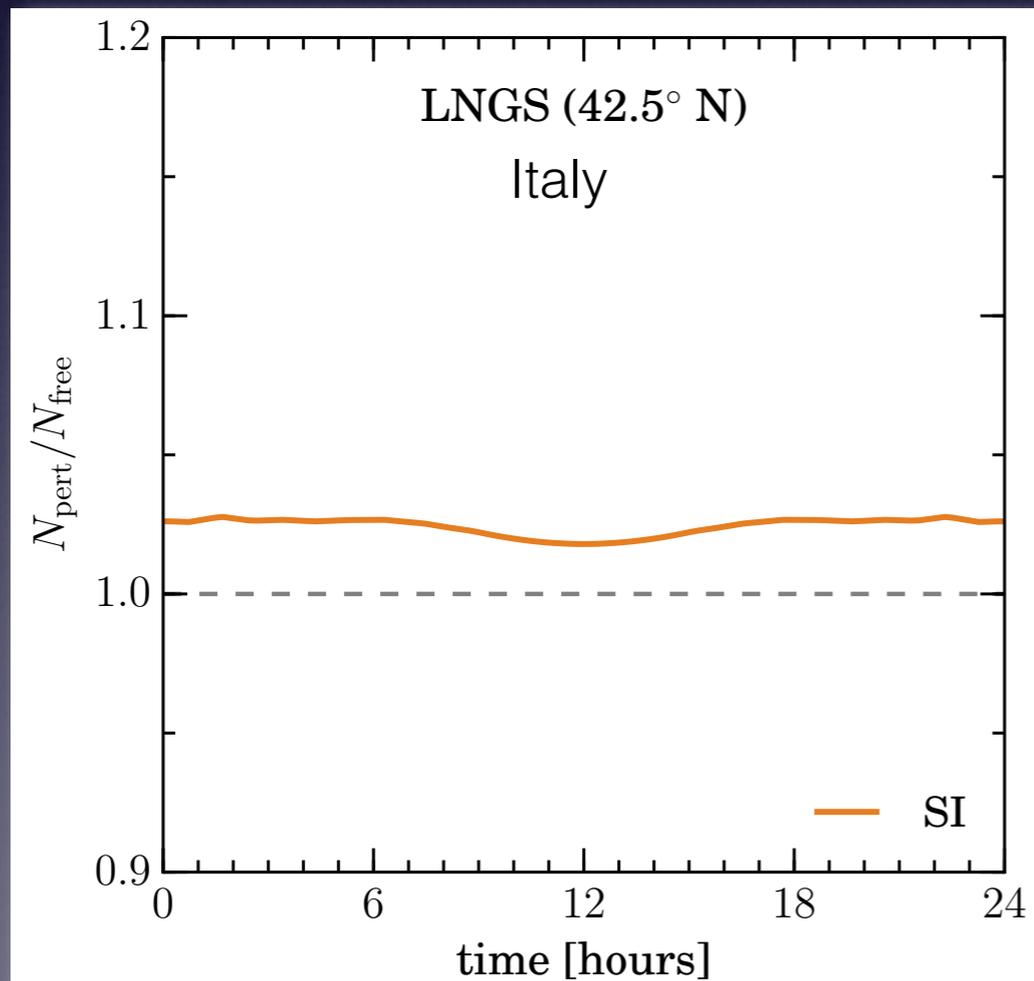
[[1509.08720](#)]

Earth Scattering (2)

Characteristic time variation which depends on location, as well as strength and form of DM interaction

E.g. diurnal modulation due to low mass (0.5 GeV) DM with 10% probability of scattering in the Earth:

Relative rate enhancement
due to Earth-scattering

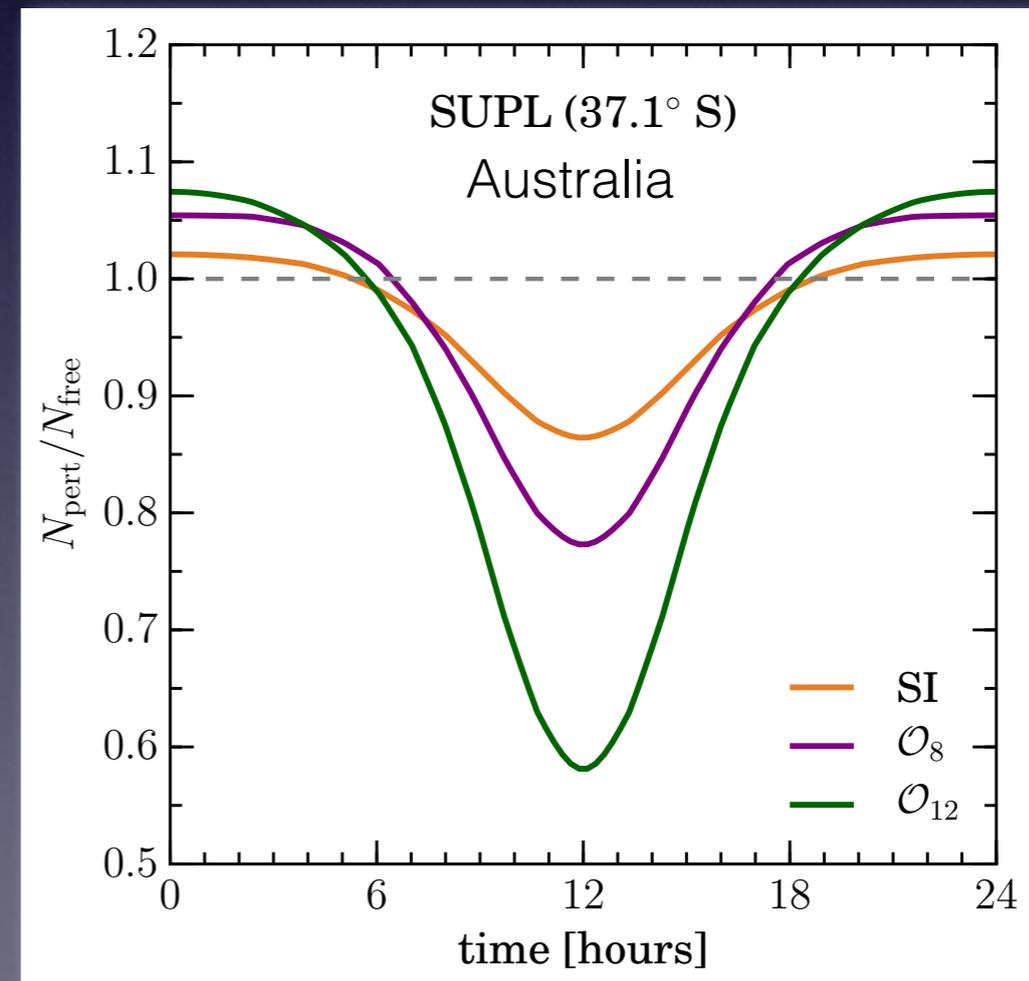
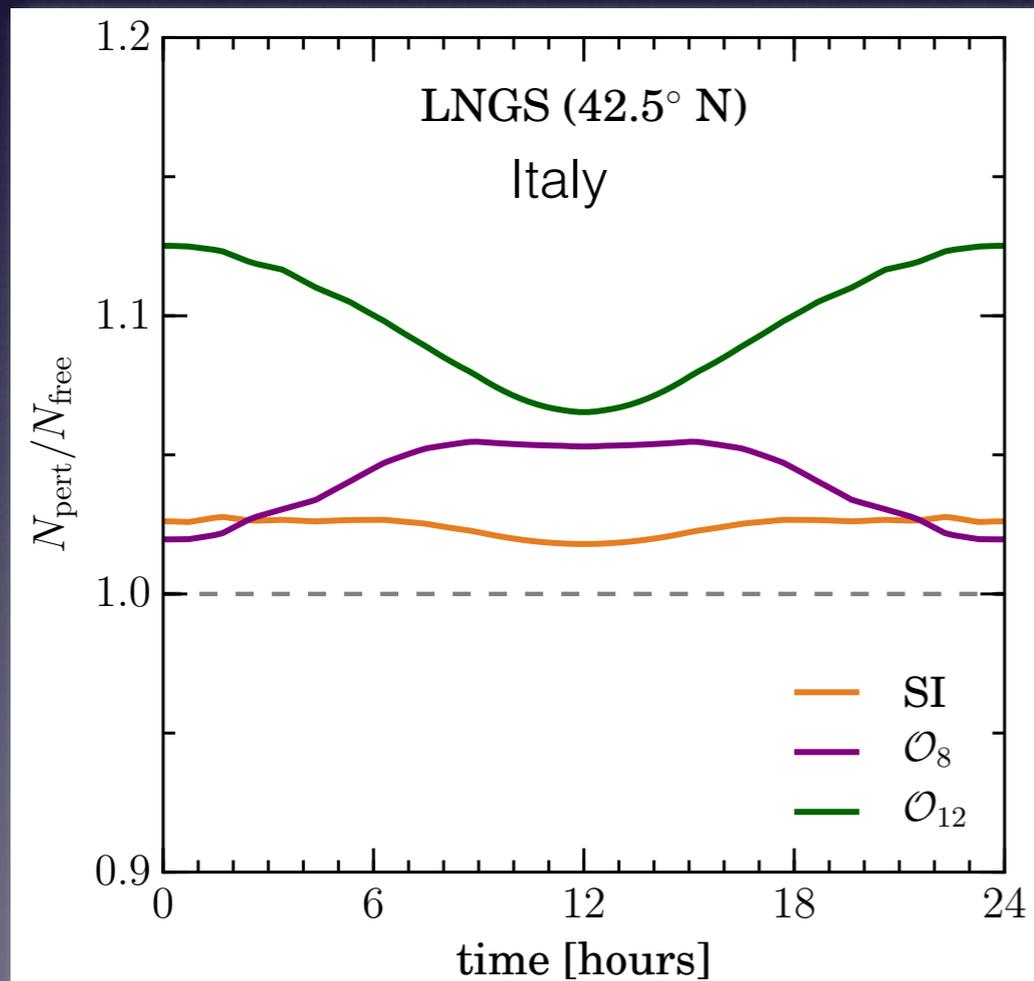


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'Smoking Gun'

Lots of inter-related variables to play with:

Energy, Direction, Timing, Position, Target...

But lots of unknowns:

*Mass, cross section, interactions,
astrophysics, backgrounds...*

'Smoking Gun' would need to be multiple signatures:

Spectrum across multiple detectors

Modulation at different locations

Directionality across a range of energies

Need all the 'symptoms' we can get!

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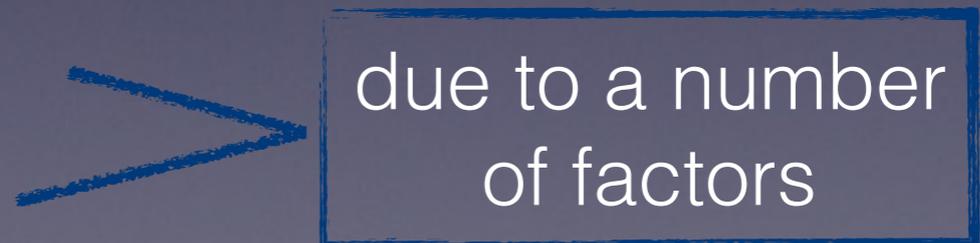
“How do I know if I have Dark Matter in my direct detection experiment?”

Acute Symptoms:

- Excess above background
- Distinctive energy spectrum
- ‘Materials’ signal
- Directionality

Chronic Symptoms:

- Annual Modulation
- Daily Modulation



due to a number of factors

*Not to be confused with coherent neutrino scattering

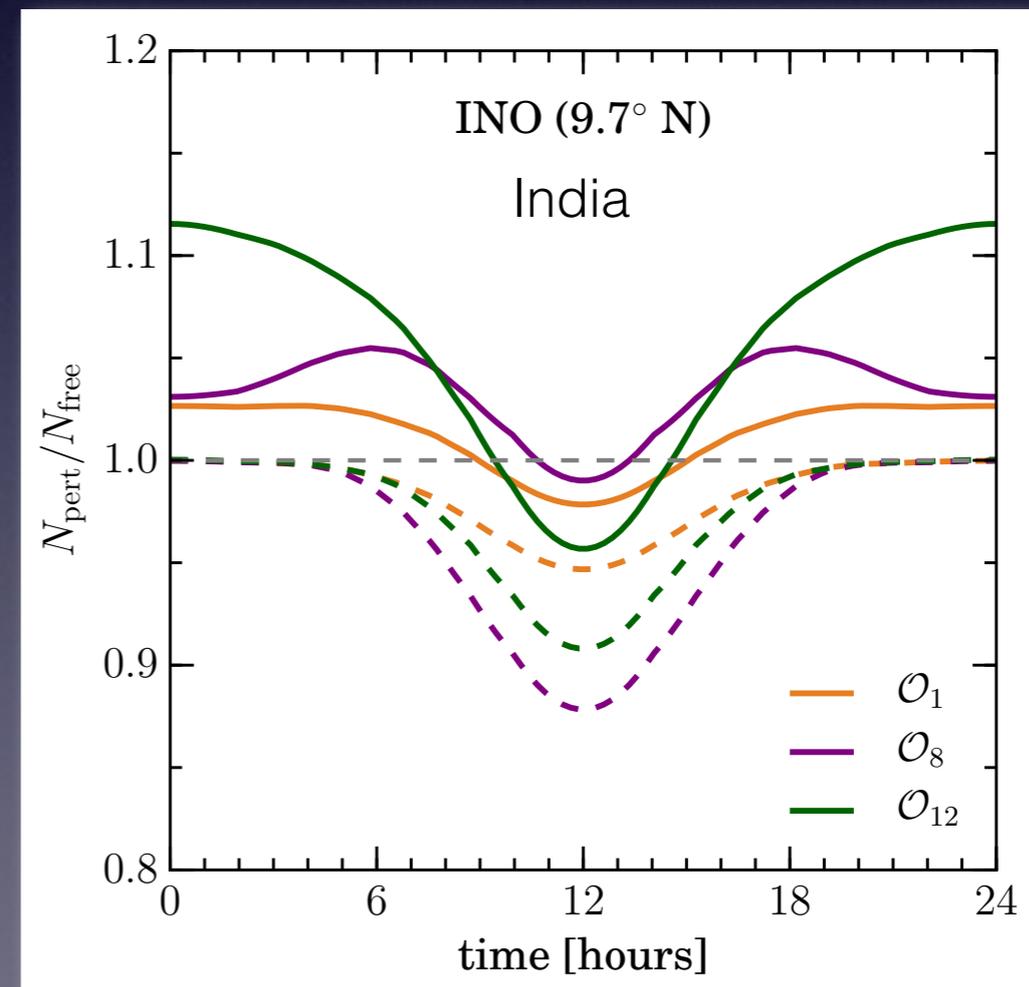
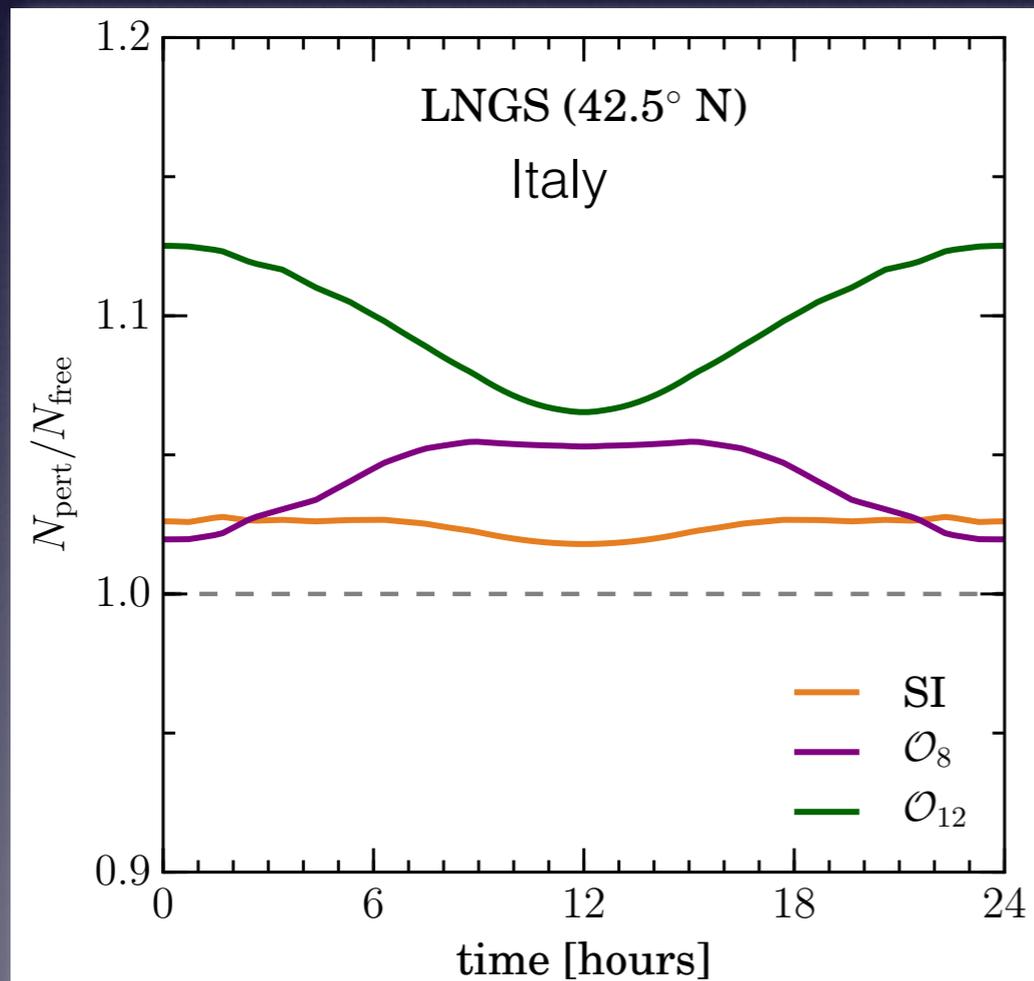
Back-up Slides

Earth Scattering

Characteristic time variation which depends on location, as well as strength and form of DM interaction

E.g. diurnal modulation due to low mass (0.5 GeV) DM with 10% probability of scattering in the Earth:

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Earth Scattering

