Direct detection of self-interacting dark matter

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Based on arXiv:1512.06471 and [to appear]

[online slides for animations]

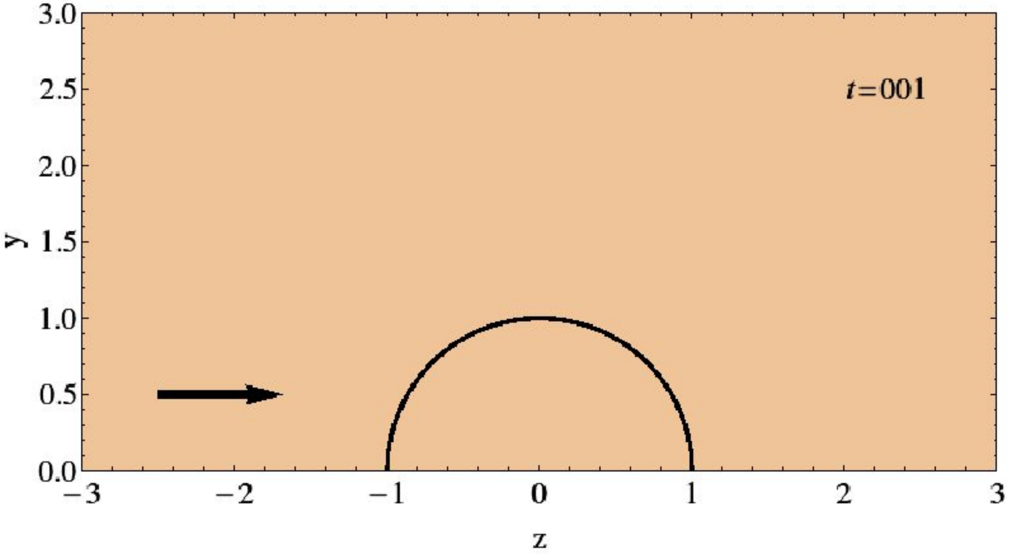
CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Earth frame: the WIMP picture

- DM wind varies with phase $t_0 \simeq 153$ days [June 2nd]

$$v_\infty = 232 + 15\cos\left(\frac{2\pi(t-t_0)}{\text{year}}\right) \ \text{km/s}$$

- Signal rate independent of position of detector

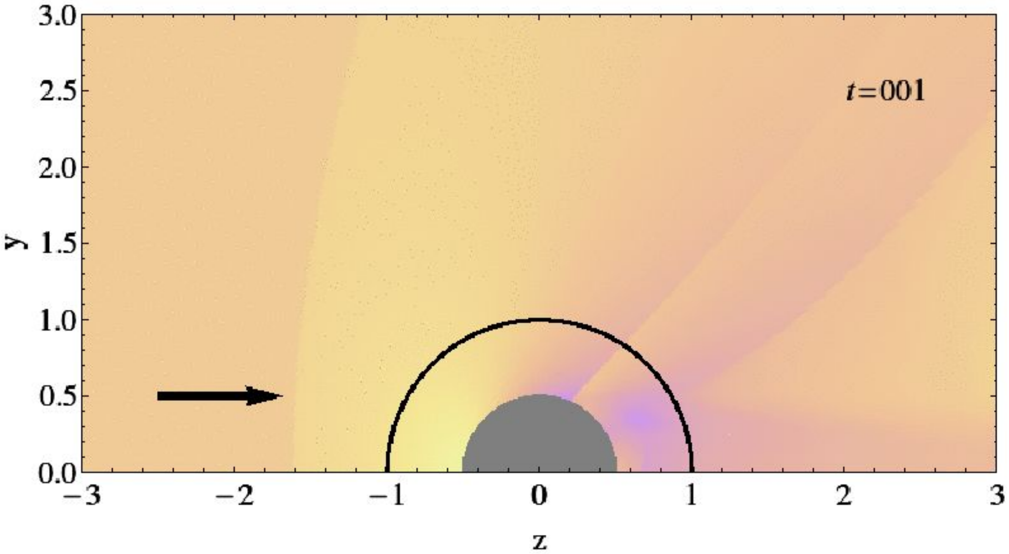


Part I

Self-interacting dark matter: general picture

Earth frame: the SIDM picture

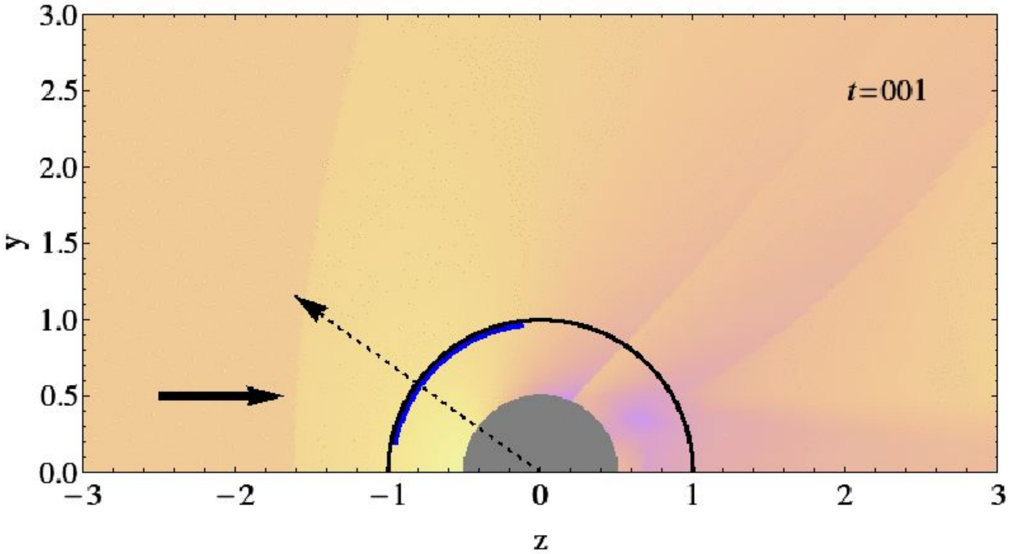
- Consider self-interacting dark matter (SIDM)
  - any captured DM now an obstacle to the DM wind
  - ⇒ spatially dependent DM direct detection scattering rate
- Now we care about where our detector is...



spatial dependence here just illustrative

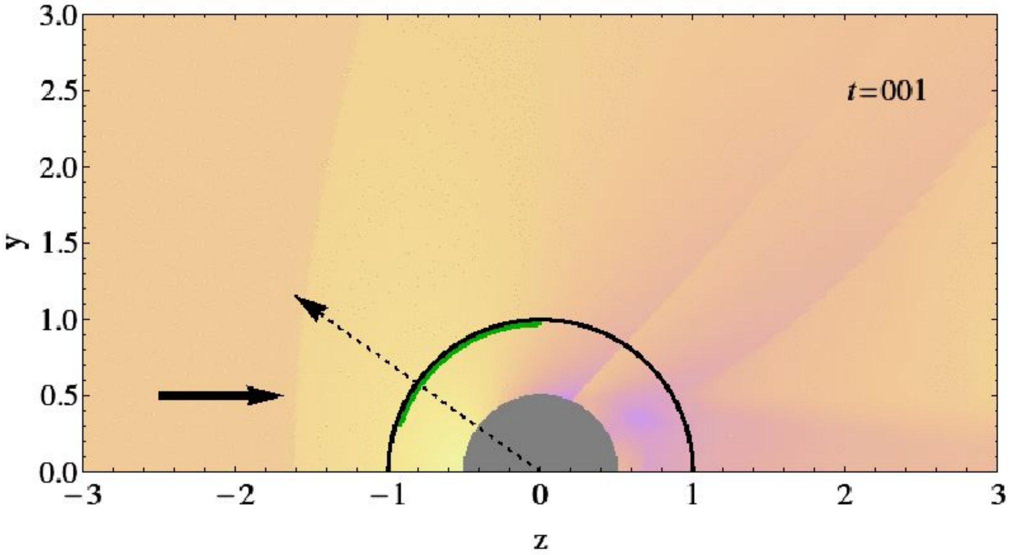
Earth frame: the SIDM picture

- E.g. Gran Sasso (43°)



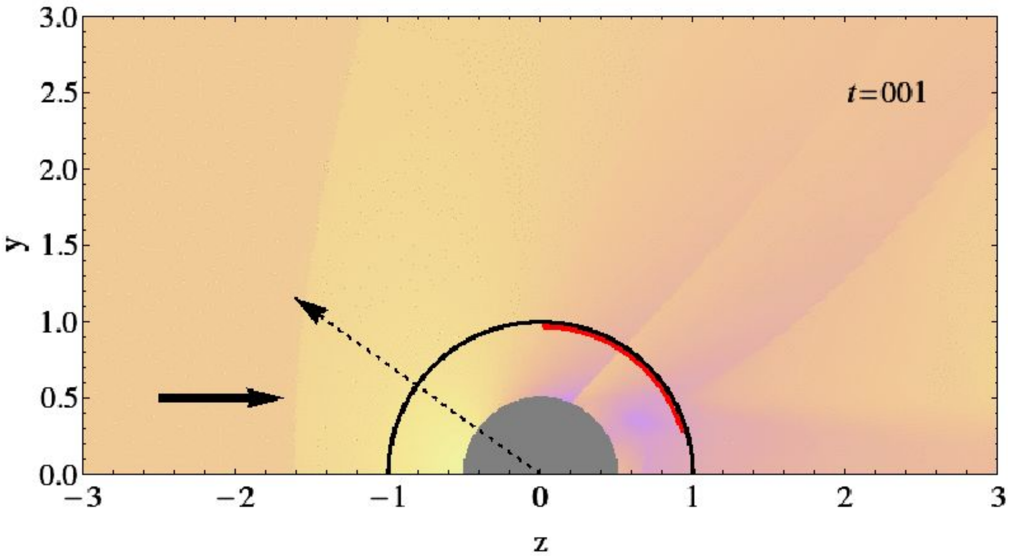
Earth frame: the SIDM picture

- E.g. Gran Sasso (43°), Kamioka (36°)



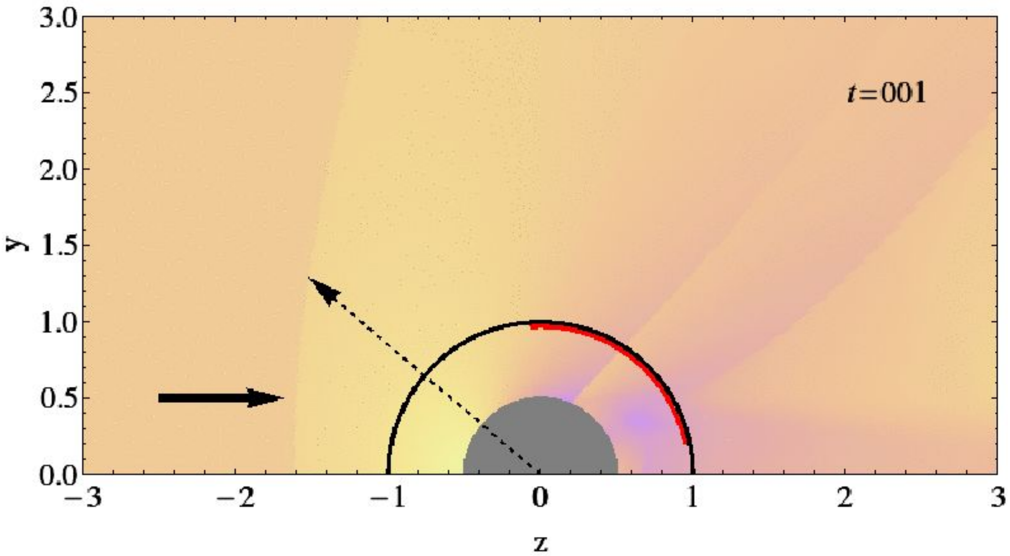
Earth frame: the SIDM picture

- E.g. Gran Sasso (43°), Kamioka (36°), and Stawell (-37°)



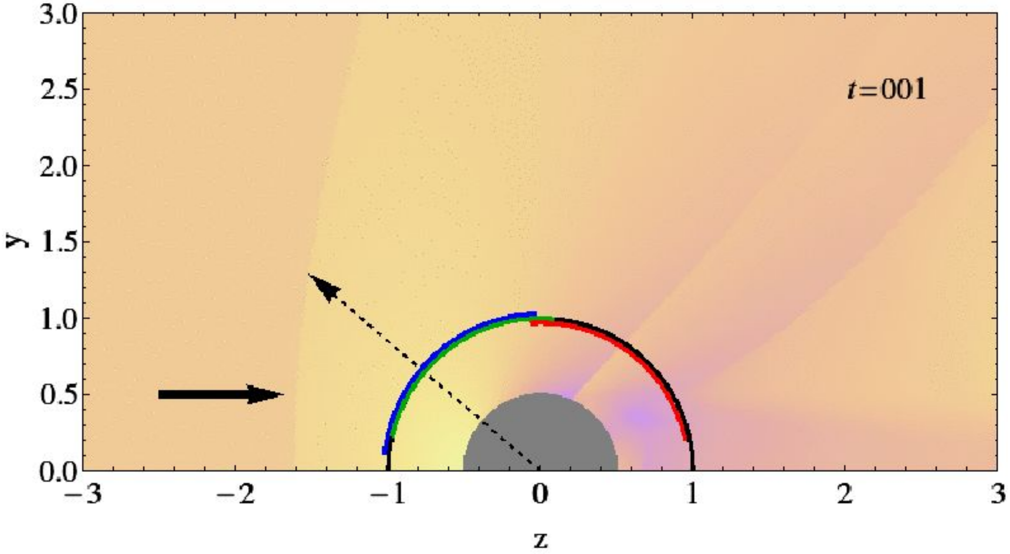
Earth frame: the SIDM picture

- E.g. Gran Sasso (43°), Kamioka (36°), and Stawell (-37°)
- Also: Earth rotation axis annually oscillates with t_o = 115 days [April 25th]



SIDM: Implications

- Important take-home implications:
  - Latitudinally dependent signal [southern hemisphere particularly interesting]
  - New source of annual modulation [t_o=115 days]
  - **Sidereal modulation** [T_{sid}≃24hrs-4mins]



Part II

Plasma dark matter:
a case study

Plasma dark matter

- Hidden sector dark matter comprising:
  - Dark electron
  - Dark proton
  - Massless dark photon

$$\mathcal{L} = \mathcal{L}_{SM}(e, \mu, u, d, A^{\mu}, \ldots) \; + \; \mathcal{L}_{\rm dark}(e_d, p_d, A_d^{\mu}) \; + \; \frac{\epsilon'}{2} \, F^{\mu\nu} F'_{\mu\nu}$$

- Free parameters:

$$m_{e_d}, m_{p_d}, Z', \alpha_d, \epsilon$$

[for this talk consider $m_{ed} \ll m_{pd}$]

Plasma dark matter

- Important are the dark atomic ionisation energy, and halo temperature:

$$I = \tfrac{1}{2}\ Z'^2 \alpha_d^2 m_{e_d} \qquad T \sim \frac{1}{2}\ \bar{m} v_{\rm rot}^2$$

- If I/T ≪ 1 then DM will be in ionised "plasma" state in Milky Way

$$\frac{I}{T} \sim 0.2\ Z'^2(Z'+1)\left(\frac{\alpha_d}{10^{-2}}\right)^2\left(\frac{m_{e_d}}{\rm MeV}\right)\left(\frac{\rm GeV}{m_{p_d}}\right)\left(\frac{220\ \rm km/s}{v_{rot}}\right)^2 \ll 1$$

Implication #1

Energy equipartition implies e_d have velocity dispersion $\gg$220km/s

$$v_0(e_d) \sim \left(\frac{\bar{m}}{m_{e_d}}\frac{\text{MeV}}{\text{GeV}}\right)^{\frac{1}{2}}\left(\frac{v_{rot}}{220\ \text{km/s}}\right) 7000\ \text{km/s}$$

Dark electromagnetism keeps them from escaping the galaxy

Implication #2

Large-scale plasma dynamics described by magnetohydrodynamics:
fluid-like behaviour emerges from collective effects of long-range scattering

Sound speed

$$c_s = \sqrt{\frac{\gamma T}{\bar{m}}} \sim \sqrt{\frac{5}{6}} v_{rot}$$

Implies Mach numbers $M = v_{wind}/c_s \sim 1$

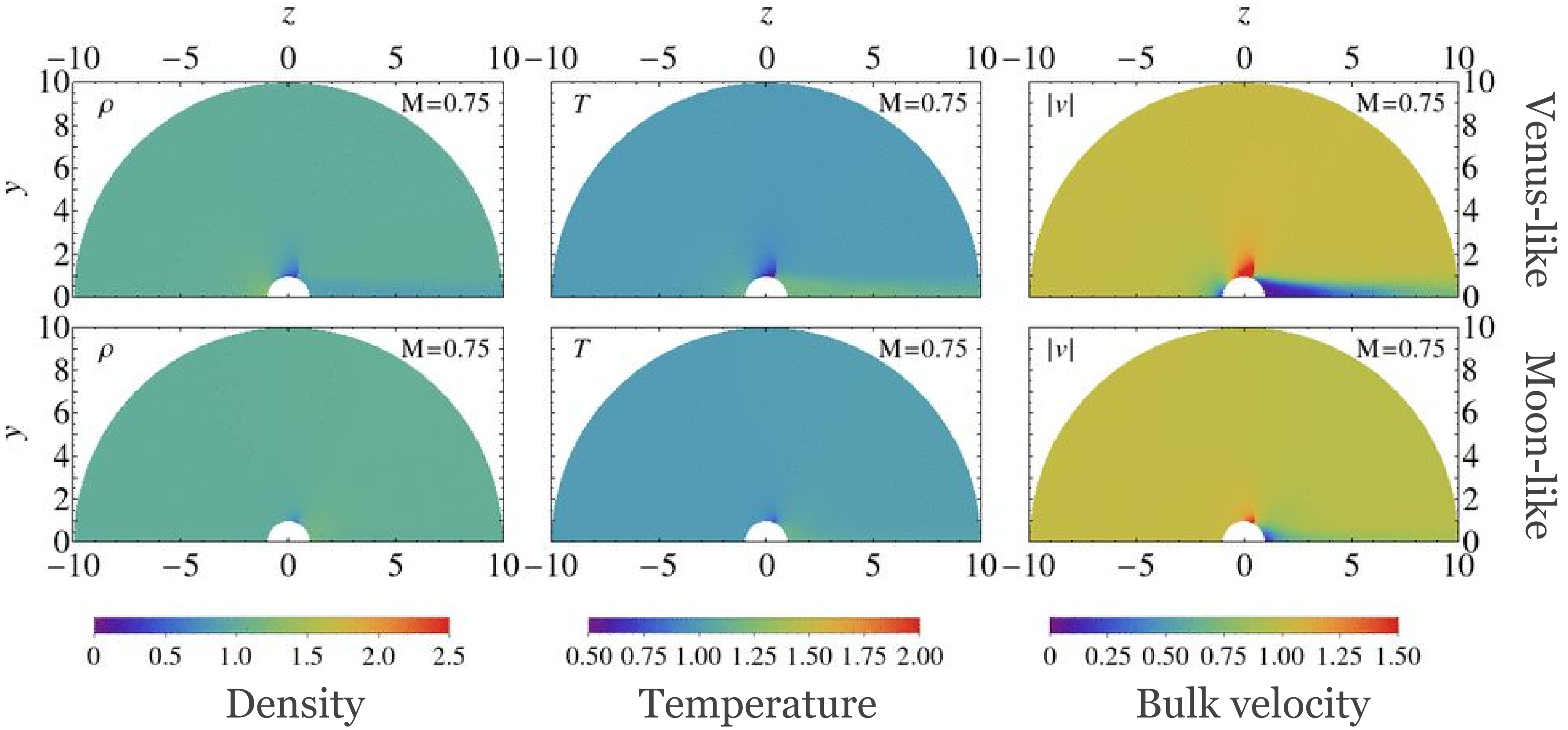
Implication #3

Captured DM comes into thermal equilibrium with T_{Earth}~5000K...

If $I \gg T_{Earth}$ then largely neutral : absorbing "**Moon-like**" scenario

If $I \ll T_{Earth}$ then largely ionised : reflecting "**Venus-like**" scenario

Simulations



Direct detection

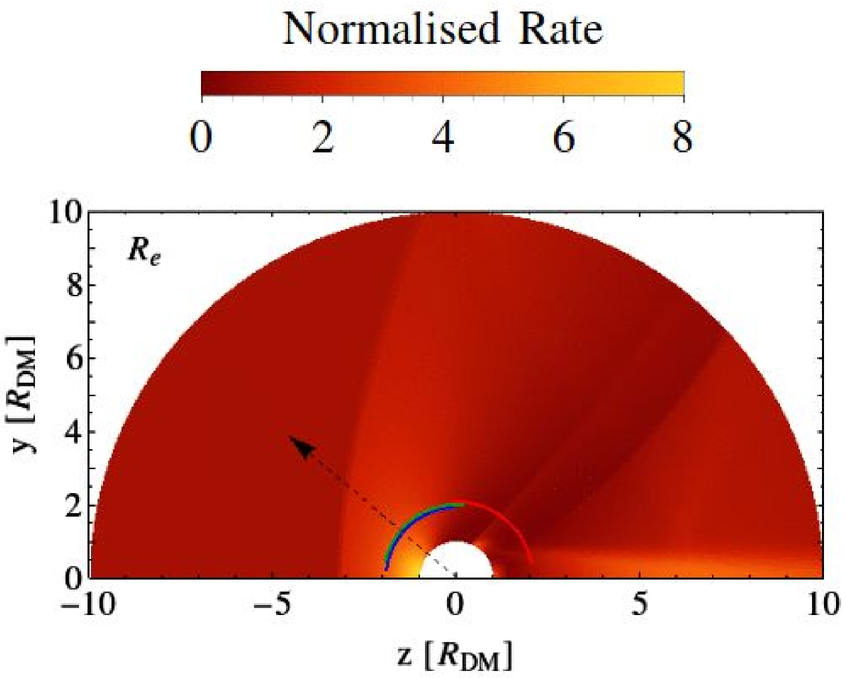
- Consider example: electron recoils in mirror dark matter...
  - Assume f(**v**) everywhere locally a boosted Maxwellian [a bad assumption but all we can do]
  - v_o~11,200km/s*(cs/200km/s)
  - v_{min}~26,500km/s for $E_{threshold}$~2keV
  - In limit $|v_B|^2 \ll v_o^2$ get rate:

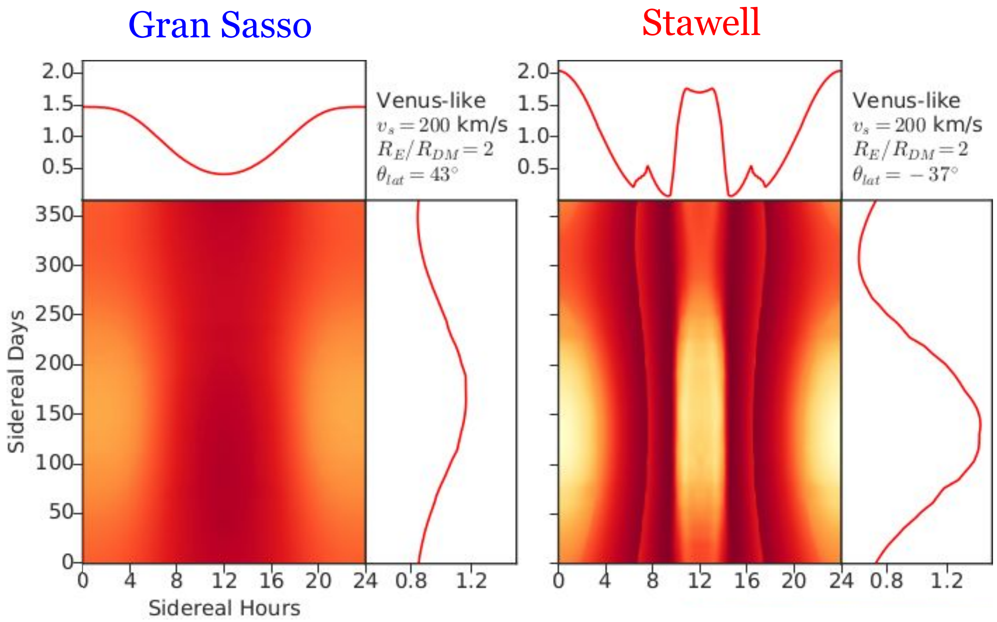
$$R_e = N_T g_T n_{e_d} \lambda \left(\frac{2m_{e_d}}{\pi T}\right)^{\frac{1}{2}} \left(\frac{e^{-\frac{E_t}{T}}}{E_t} - \frac{\Gamma\left[0, \frac{E_t}{T}\right]}{T}\right)$$

- Both T and n_{ed} temporal/spatial variation come from simulation

Examples

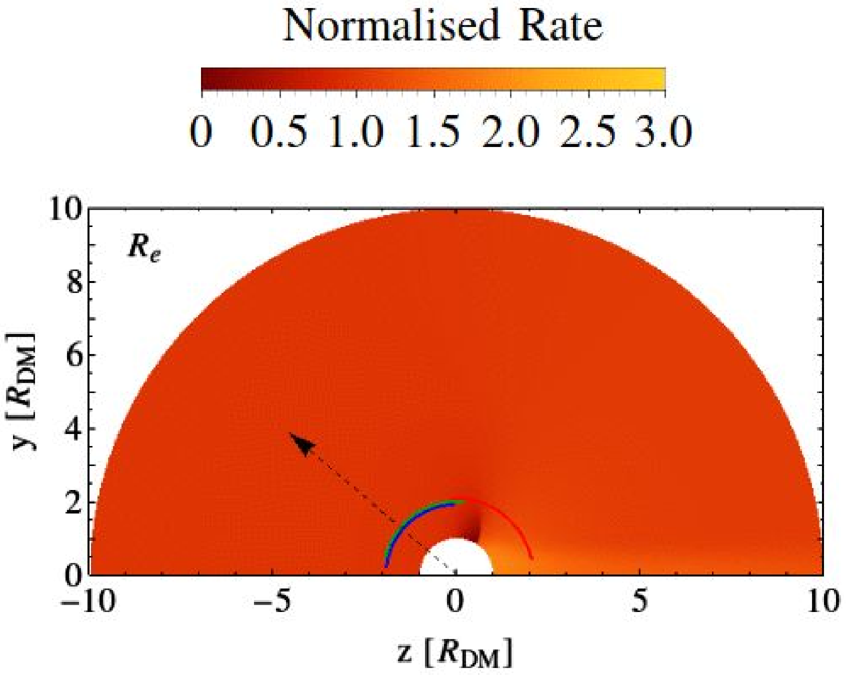
- Venus-like; c_s=200 km/s; R_E/R_{DM}=2



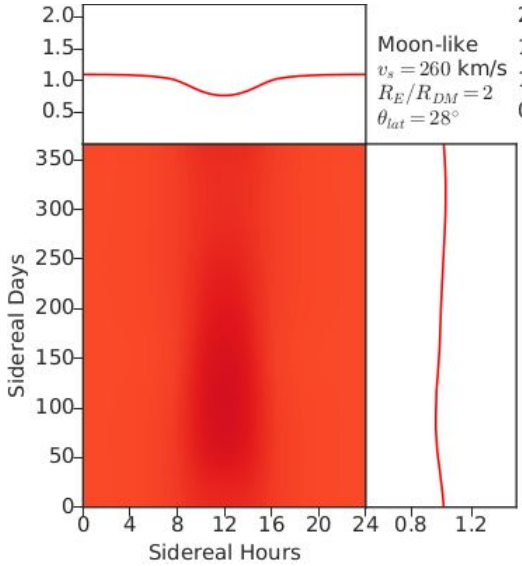


Examples

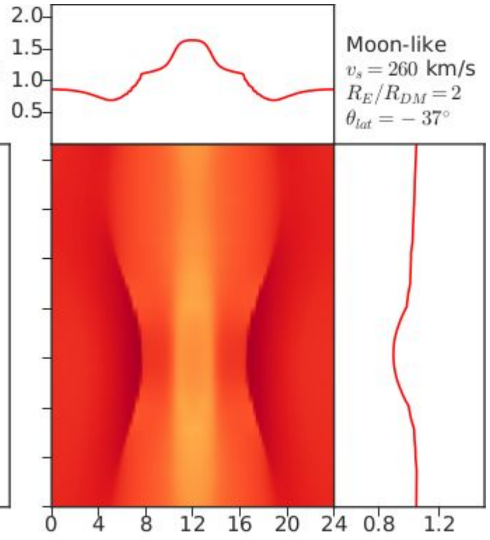
- Moon-like; c_s=260 km/s; R_E/R_{DM}=2



China JinPing



Stawell



Part III

Sidereal modulation: model-independent search strategies

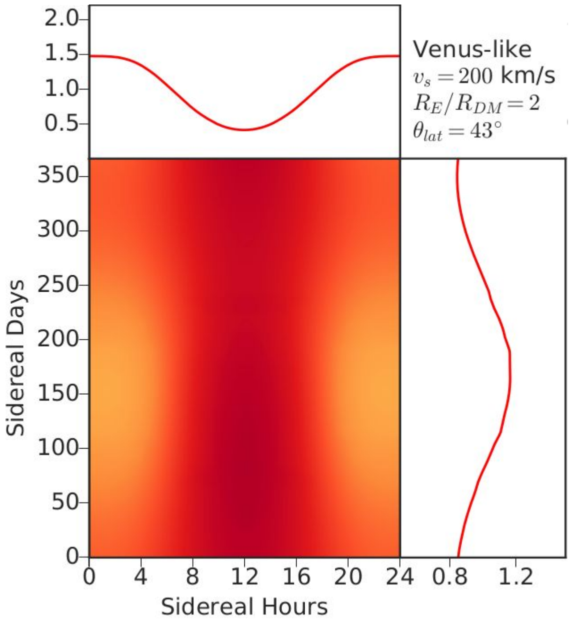
Sidereal modulation

If this general picture is *even remotely plausible*, we should be searching for sidereal modulation!

If we see it, we know immediately it is of cosmological origin

Sidereal modulation

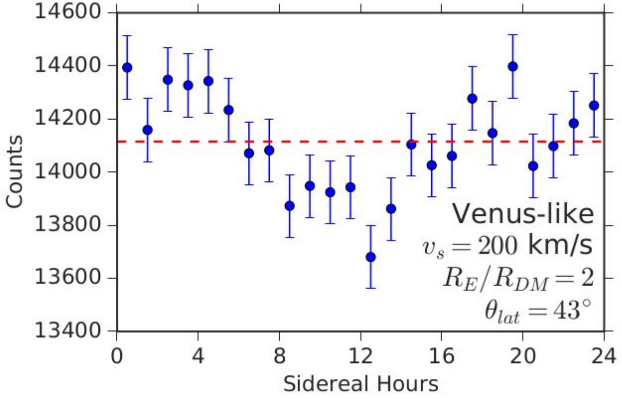
- Consider a nice example: Venus-like at Gran Sasso...

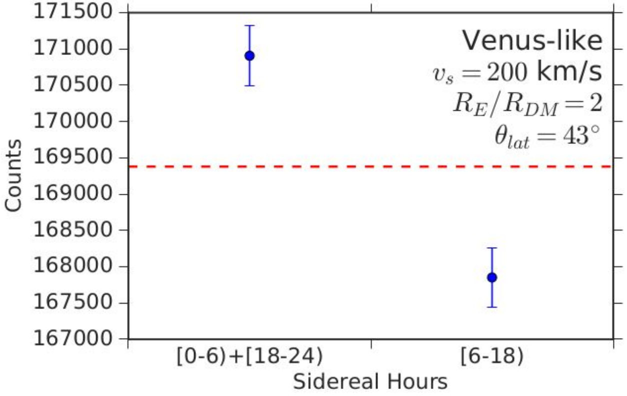


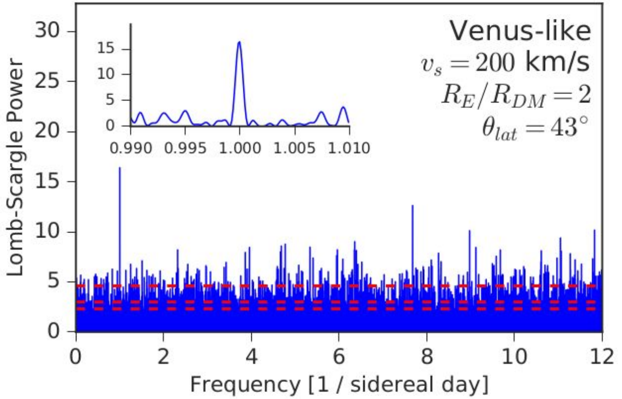
- Suggest: simple binned χ^2, far/near ratio, or Lomb-Scargle spectral analysis

Sidereal modulation

E.g. binned χ^2 near/far χ^2 Lomb-Scargle power





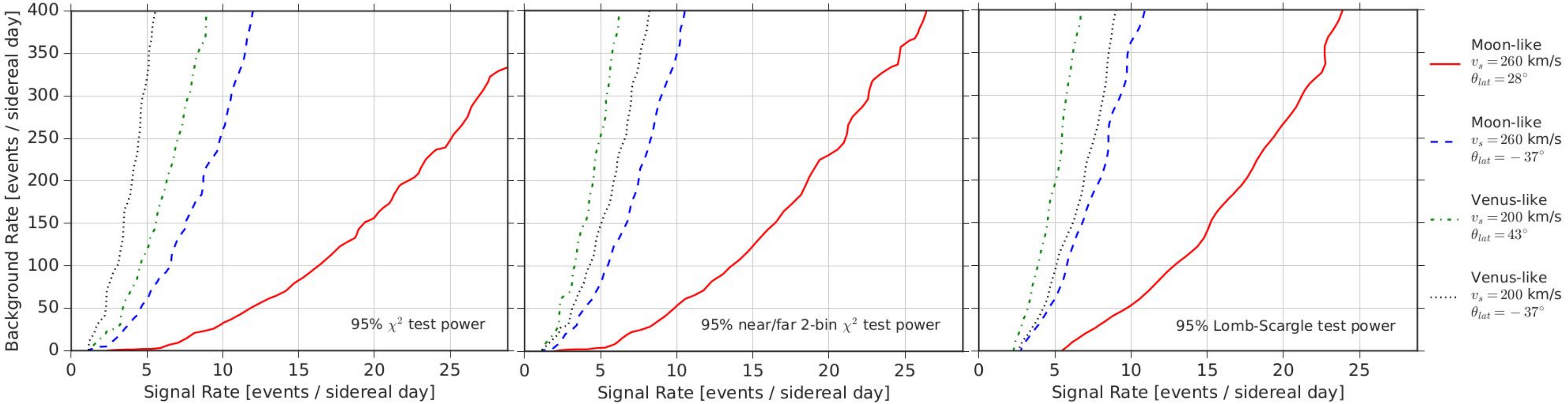


Sidenote: DAMA see a ≈2.3σ discrepancy in this ratio

[Generated taking: $S_0 \approx 8$ cpd, flat background $B_0 = 300$ cpd, 3 years data taking]

Sidereal modulation

E.g. binned χ² near/far χ² Lomb-Scargle power



Conclusion

Interaction of DM wind with captured DM implies a non-trivial, **spatially varying** near-Earth DM distribution

An interesting implication is a potentially strong **sidereal modulation** signal for direct detection (particularly perhaps for Southern Hemisphere detectors)

We should be looking for it!