CoEPP

ARC Centre of Excellence for Particle Physics at the Terascale

Sidereal modulation searches for the direct detection of dark matter

Jackson D. Clarke
with Noel Dawe and Robert Foot

Based on arXiv:1512.06471 and [to appear]

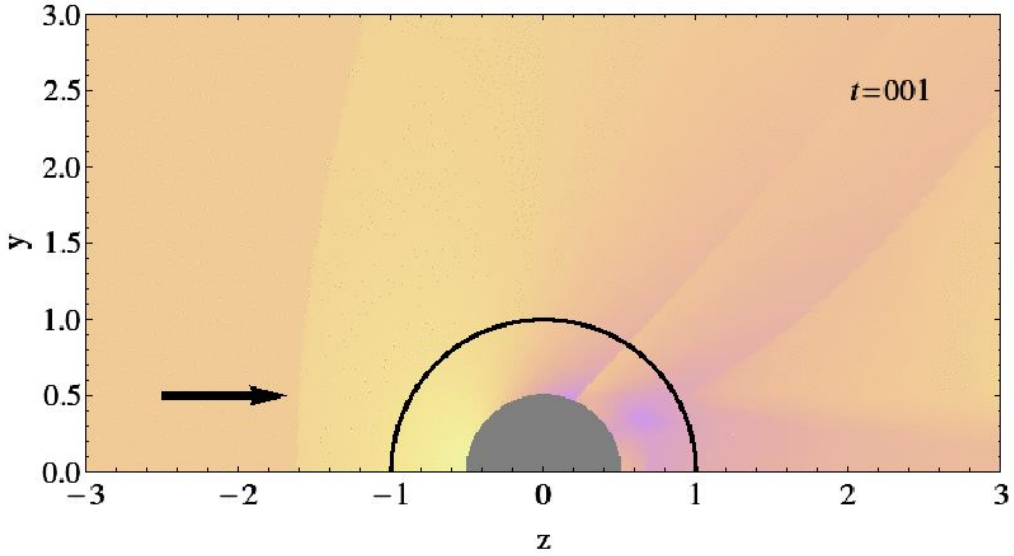
[online slides for animations]

Part I

Self-interacting dark matter direct detection: general picture

Earth frame: the SIDM picture

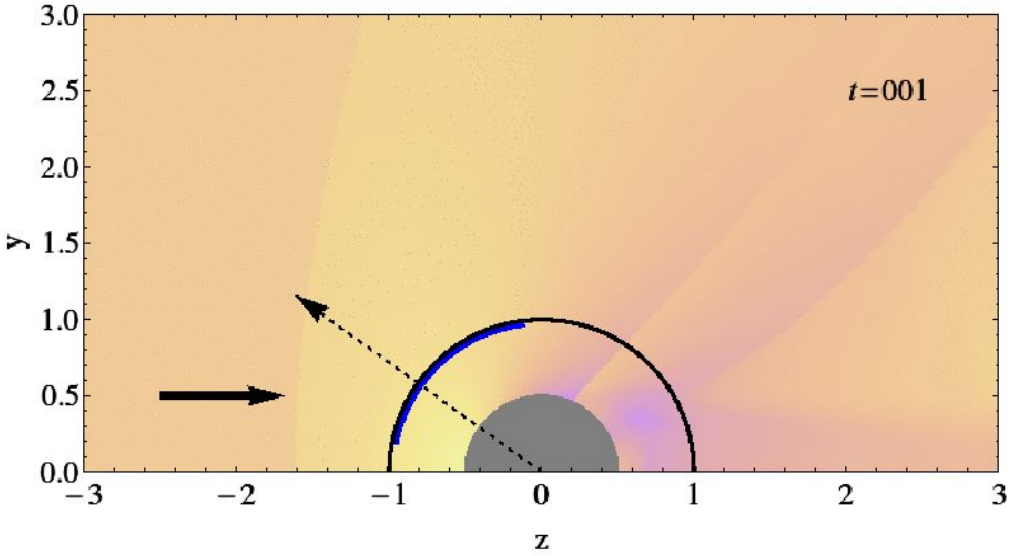
- Consider self-interacting dark matter (SIDM)
  - any captured DM is an obstacle to the DM wind
  - ⇒ spatially dependent DM direct detection scattering rate
- Now we care about where our detector is…



spatial dependence here just illustrative

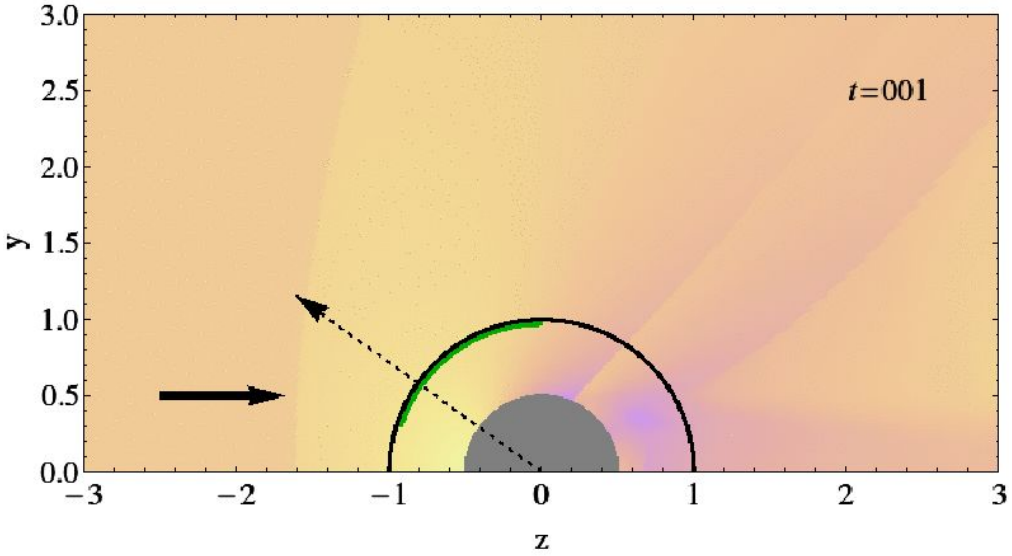
Earth frame: the SIDM picture

- E.g. Gran Sasso (43°)



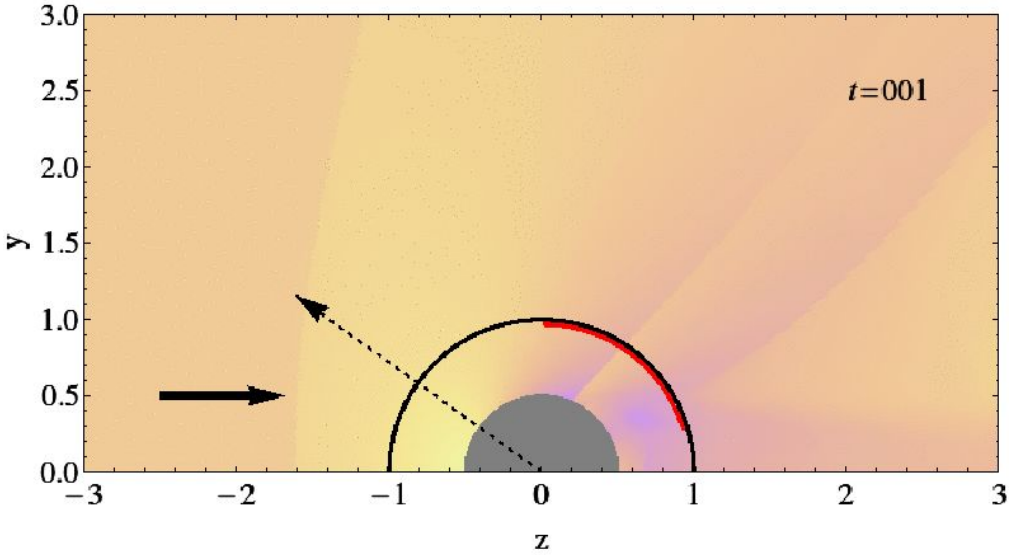
Earth frame: the SIDM picture

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



Earth frame: the SIDM picture

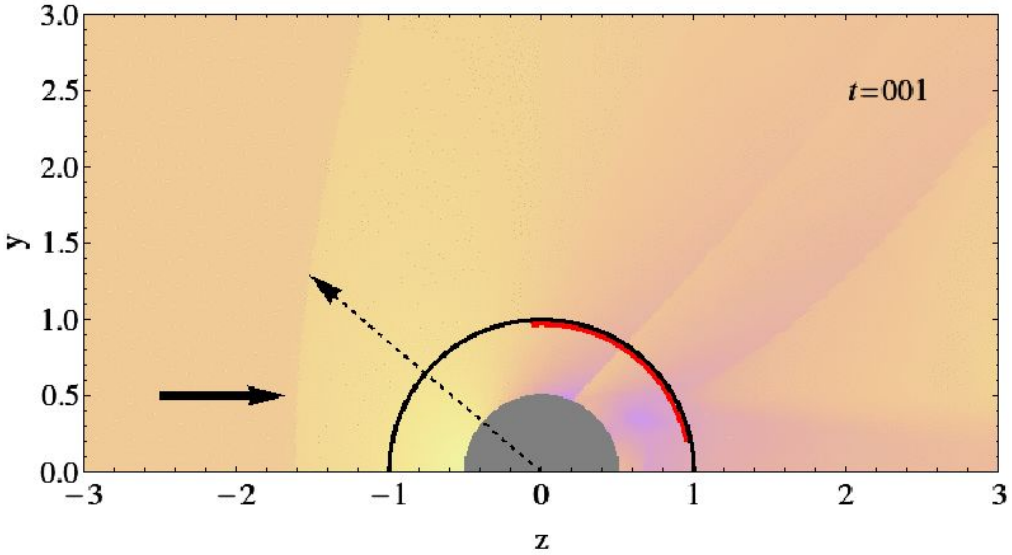
- E.g. Gran Sasso (43°), Kamioka (36°), and Stawell (-37°)



Earth frame: the SIDM picture

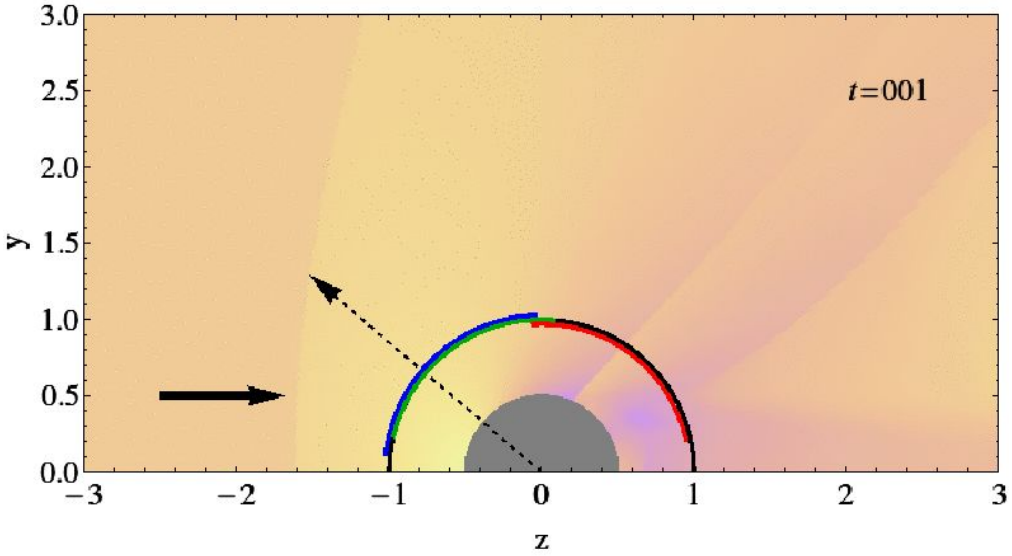
- E.g. Gran Sasso (43°), Kamioka (36°), and Stawell (-37°)

- 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 direct detection: a case study

Plasma dark matter

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

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

- 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$\ll$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

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

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

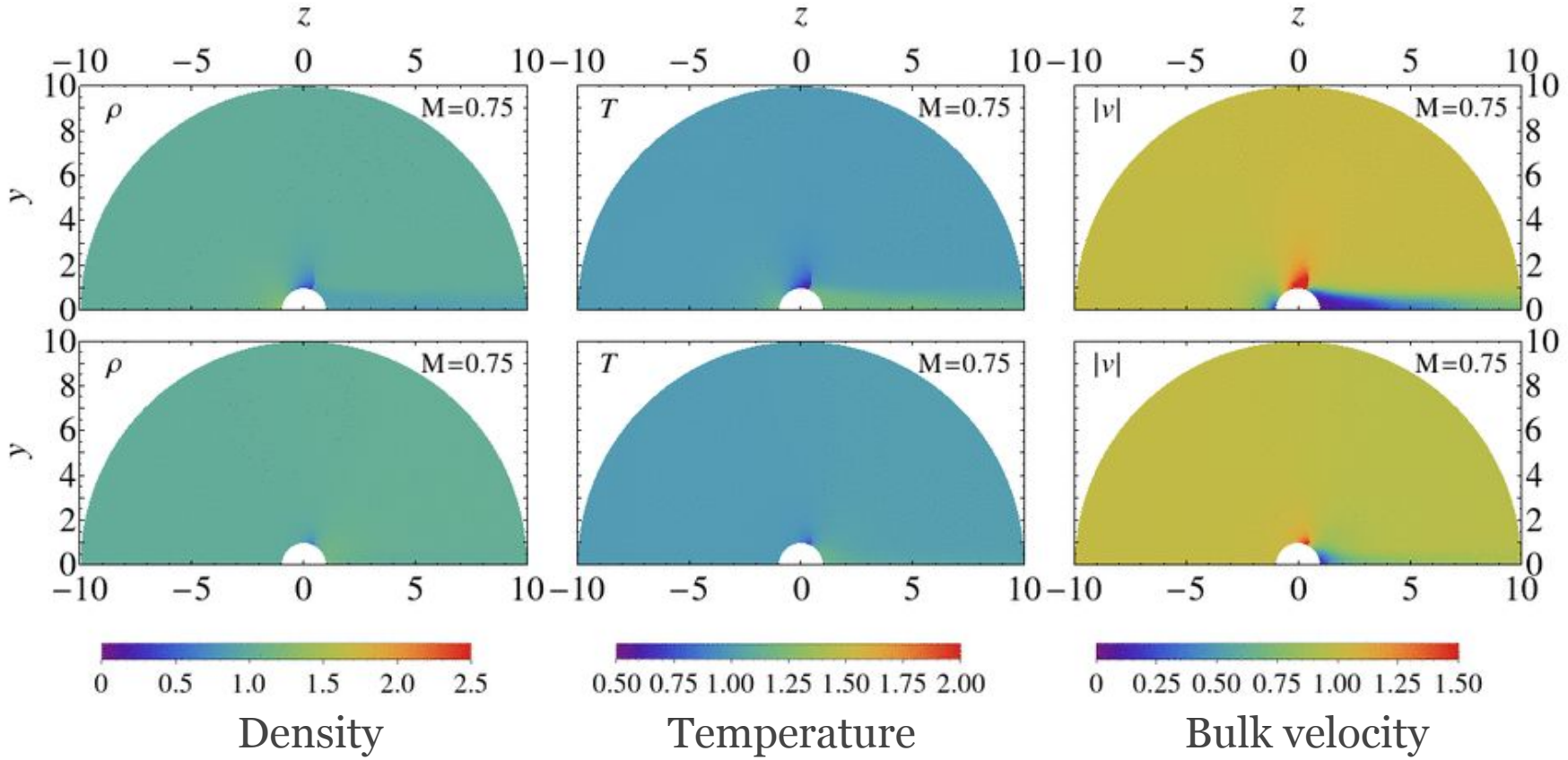
Implication #3

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

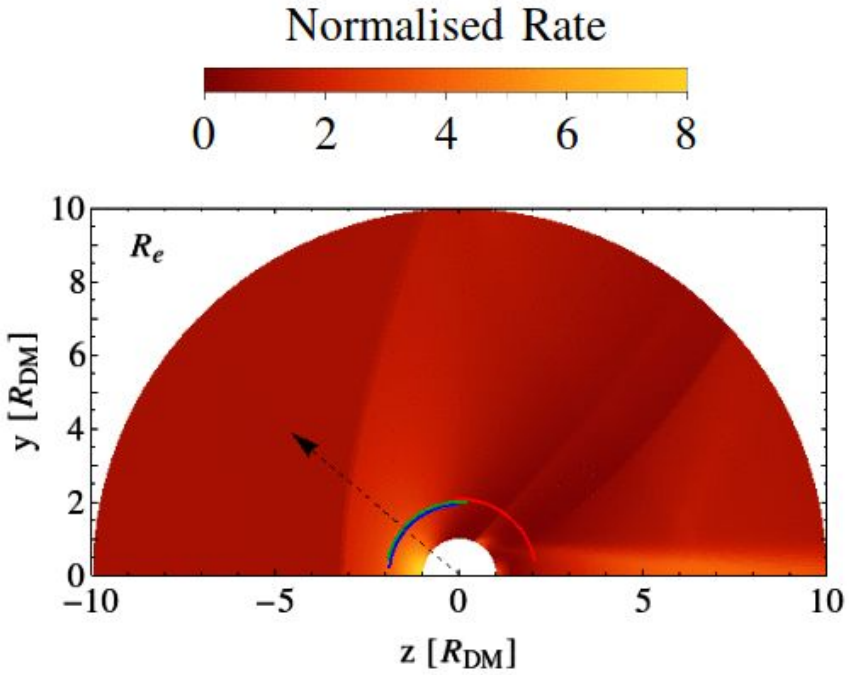
- Consider example: electron recoils in mirror dark matter…
  - Assume f(**v**) everywhere locally a boosted Maxwellian [a bad assumption but all we can do]
  - v_o~11,200km/s*(cs/200km/s)
  - v_{min}~26,500km/s for $E_{threshold}$~2keV
  - In limit $|v_B|^2 \ll v_o^2$ get rate:

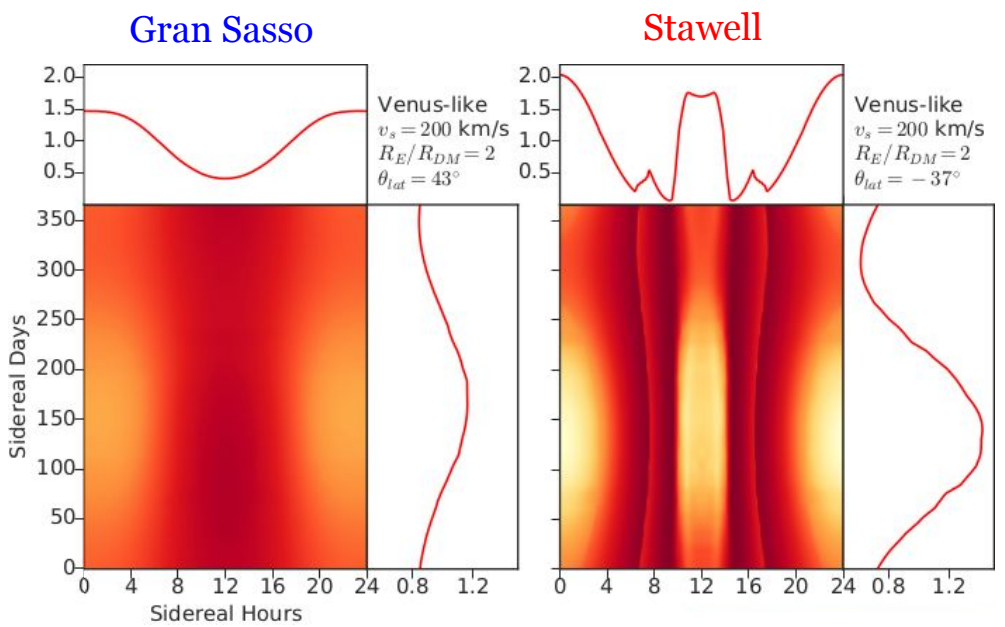
$$R_e = N_T g_T n_{e_d} \lambda \left(\frac{2m_{e_d}}{\pi T}\right)^{\frac{1}{2}} \left(\frac{e^{-\frac{E_t}{T}}}{E_t} - \frac{\Gamma\left[0, \frac{E_t}{T}\right]}{T}\right)$$

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

Examples

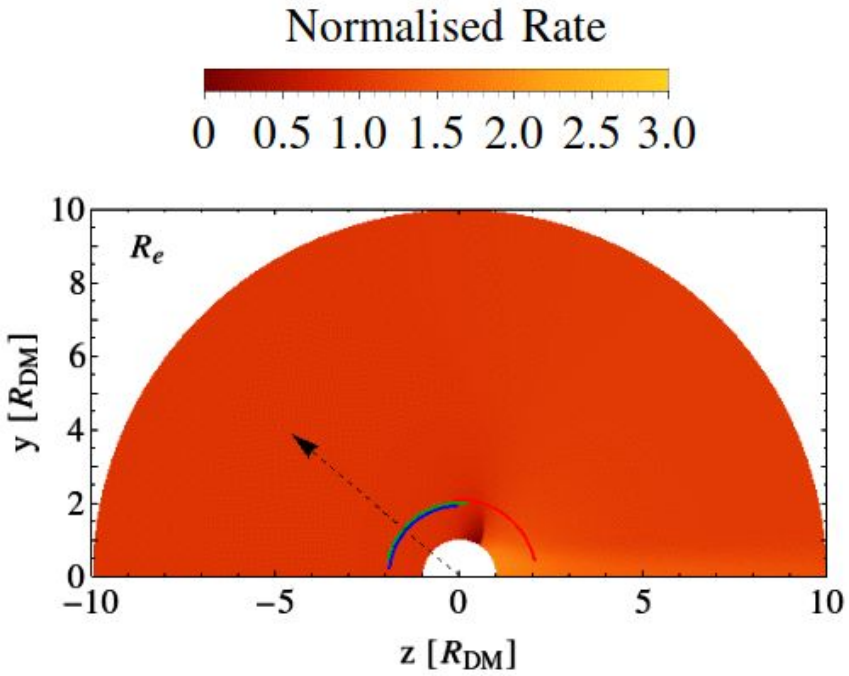
- Venus-like; c_s=200 km/s; R_E/R_{DM}=2



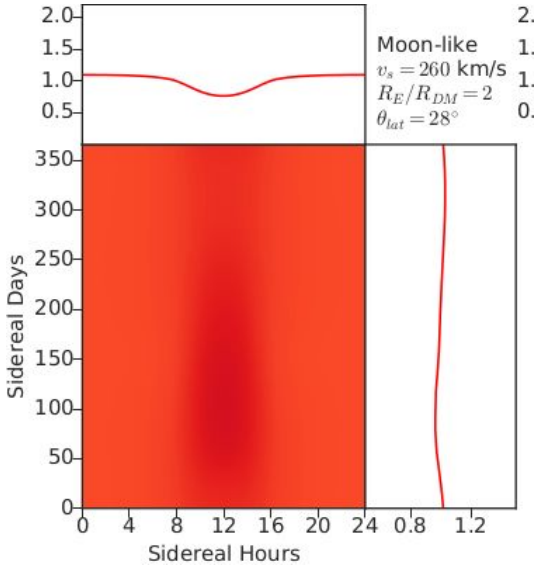


Examples

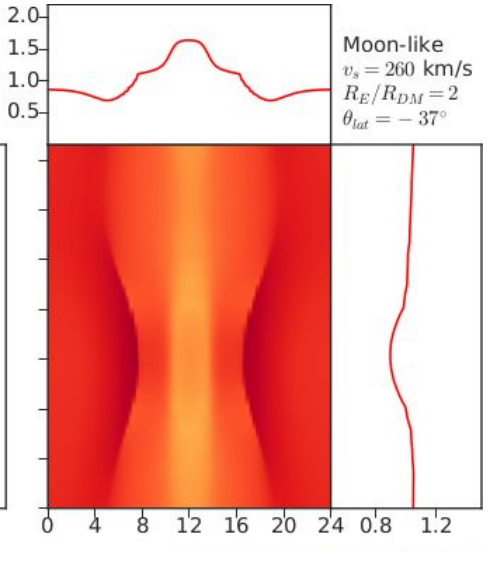
- Moon-like; c_s=260 km/s; R_E/R_{DM}=2



China JinPing



Stawell



Part III

Sidereal modulation: model-independent search strategies

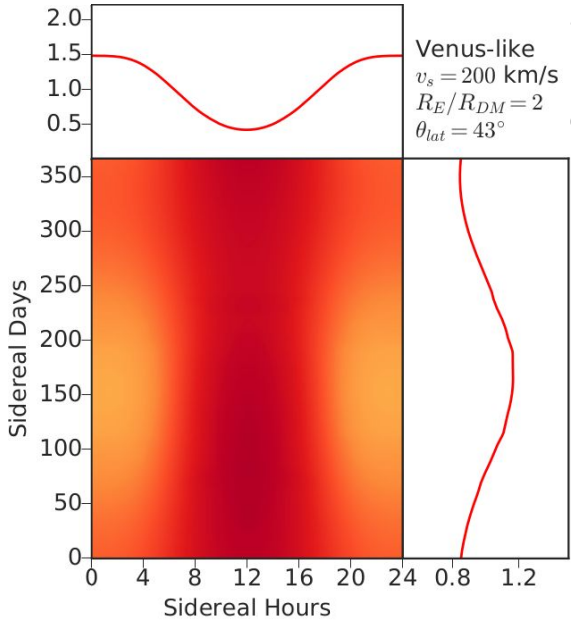
Sidereal modulation

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

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

Sidereal modulation

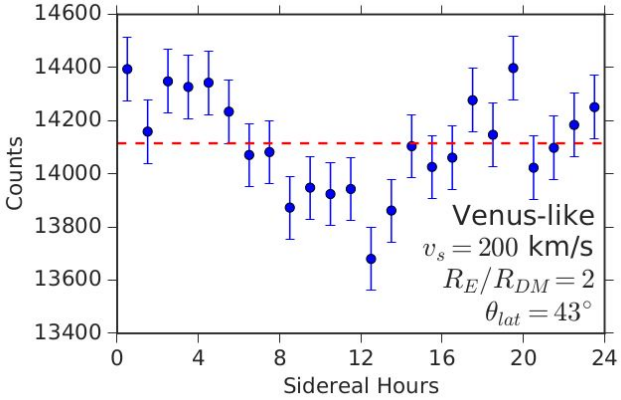
- Consider a nice example: Venus-like at Gran Sasso...

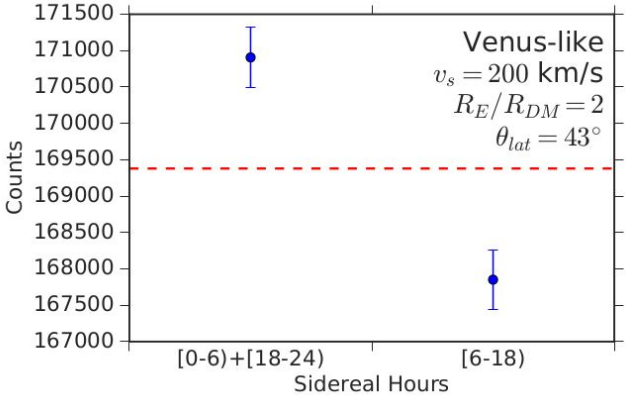


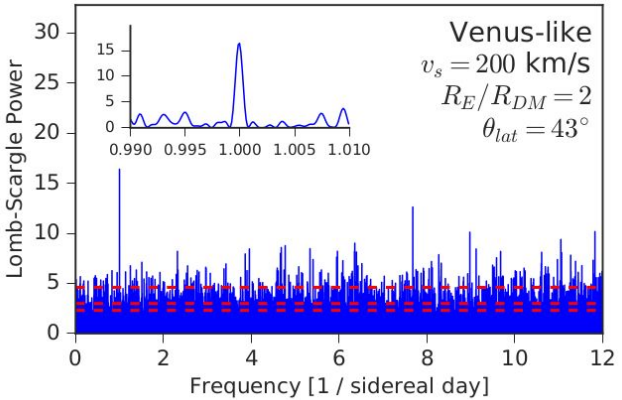
- Suggest: simple binned χ^2, far/near ratio, or Lomb-Scargle spectral analysis

Sidereal modulation

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





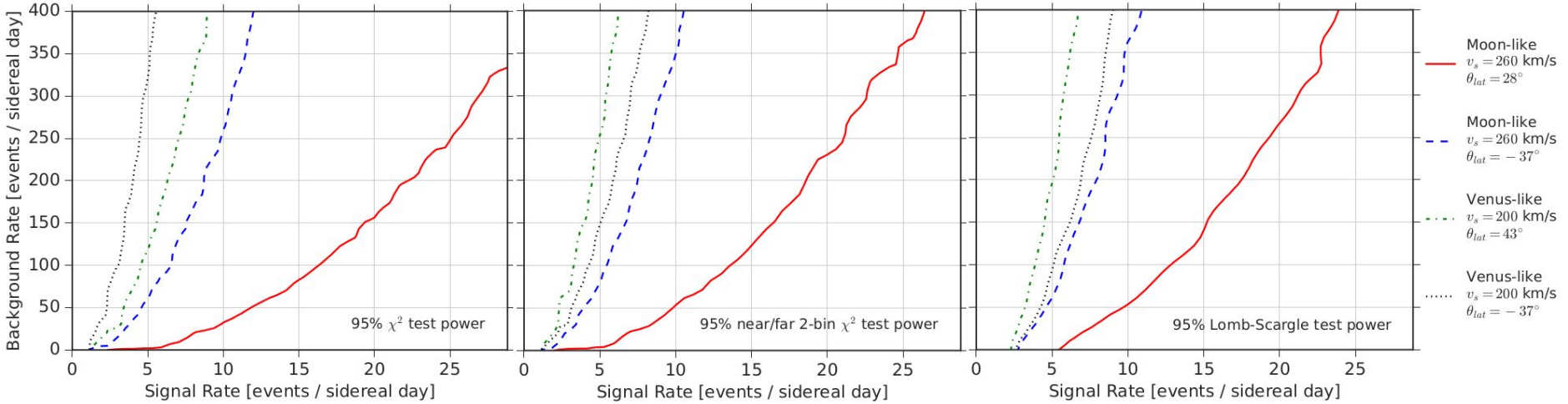


Sidenote: DAMA see a ≈2.3σ discrepancy in this ratio

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

Sidereal modulation

E.g. binned χ^2 near/far χ^2 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!

[would love to talk to experimentalists on practicalities]