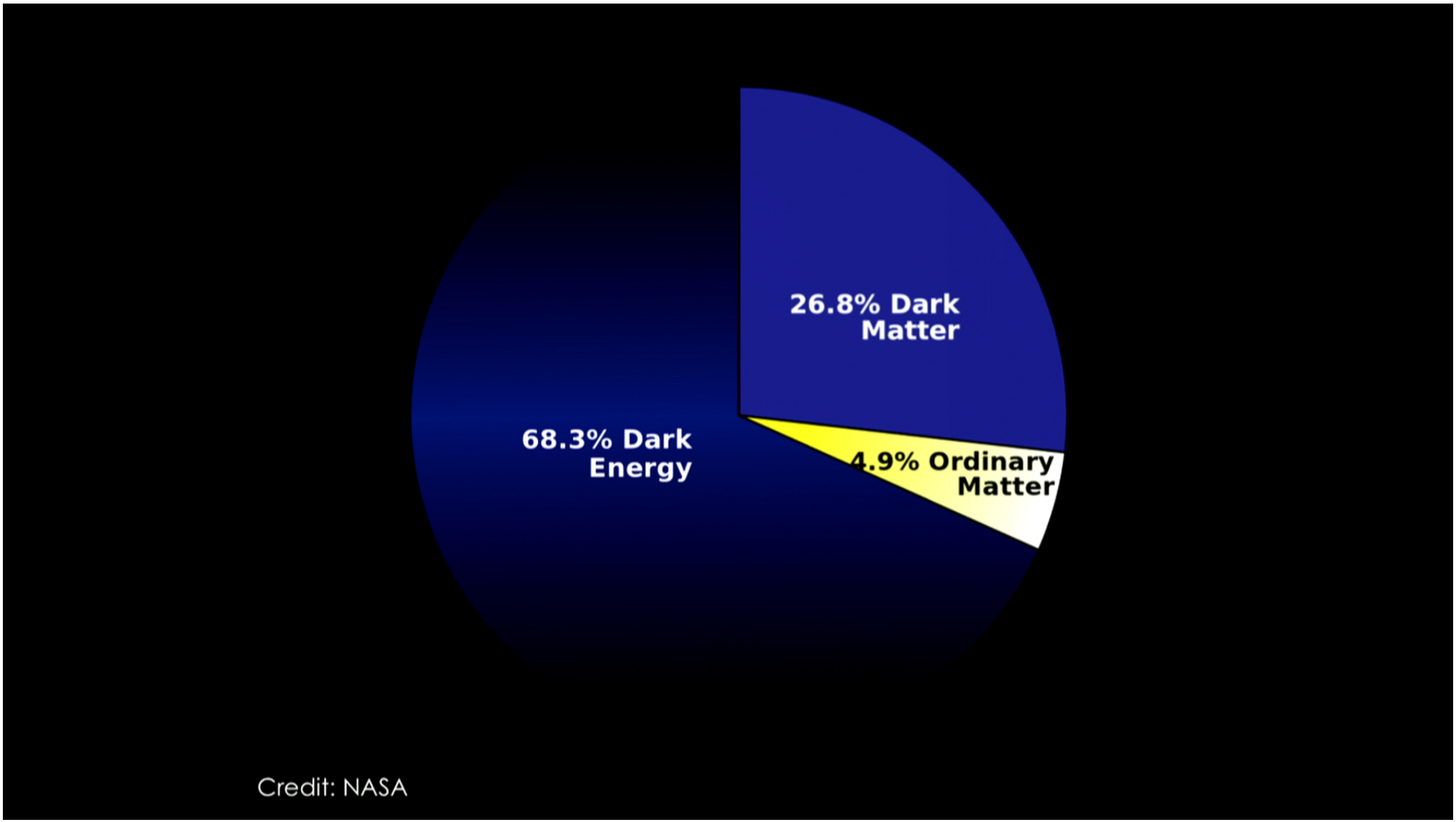
Title: At the Perimeter of Physics: New Probes of Dark Matter and the Early Universe

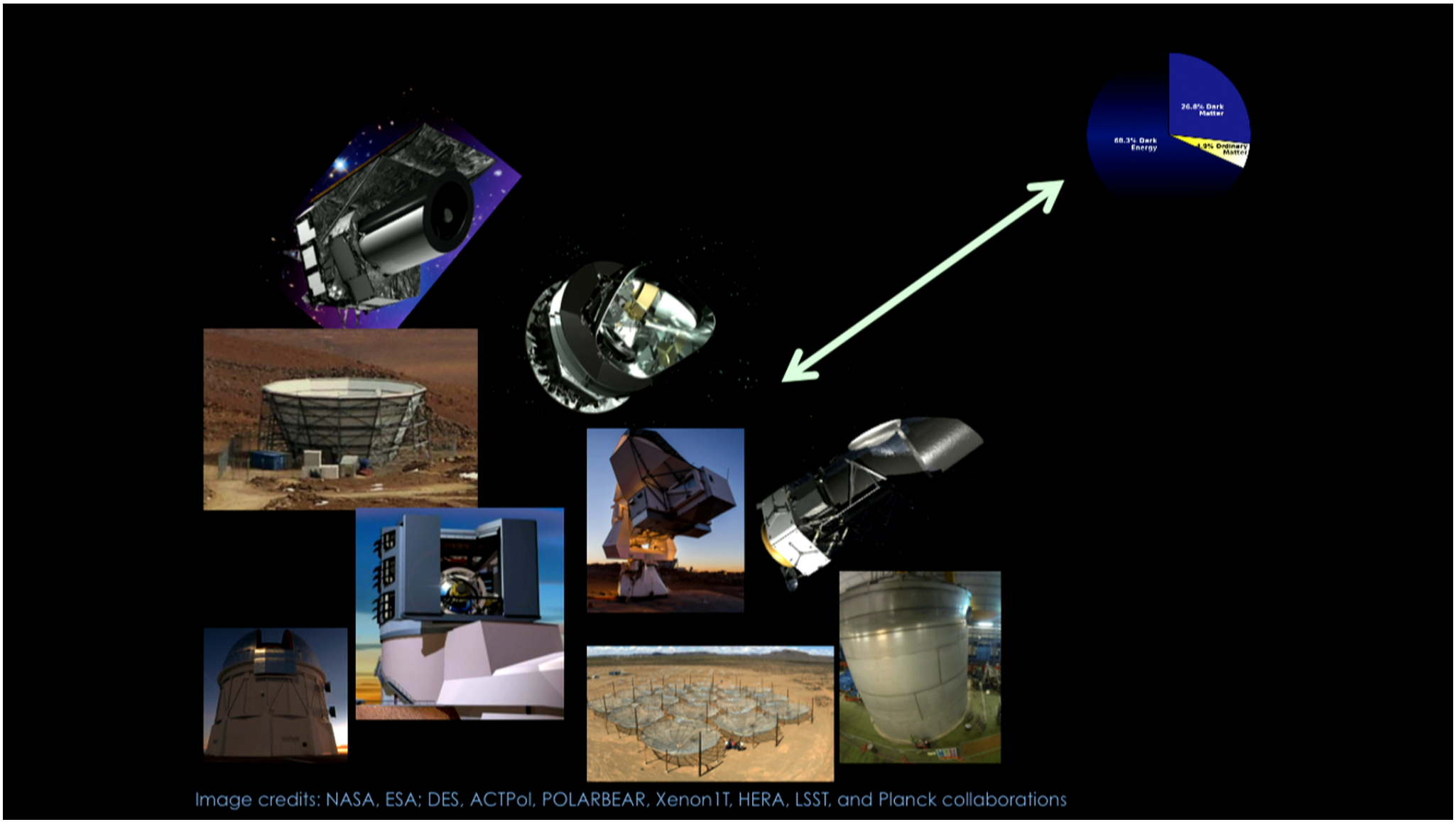
Date: May 04, 2016 10:30 AM

URL: http://pirsa.org/16050027

Abstract:

Credit: Budassi


26.8% Dark Matter
4.9% Ordinary Matter
68.3% Dark Energy
Credit: NASA


26.8% Dark Matter
68.3% Dark Energy
4.9% Ordinary Matter
Image credits: NASA, ESA; DES, ACTPol, POLARBEAR, Xenon1T, HERA, LSST, and Planck collaborations

Outline

I. Dark matter

Insights from underground and from the CMB

II. 21-cm cosmology

A new probe of primordial magnetic fields

~~III. Dark energy~~

~~Looking for swirls in the CMB~~

Dark Matter: what do we know?

There is more gravity than baryons.
(modified gravity? new particles?)

Present throughout cosmic history
(stable, density~1/volume)

It's not a lot of things (~~relativistic~~, ~~strongly interacting~~, …)

It could be a lot of other things (WIMPs, axions, ...)

Direct detection

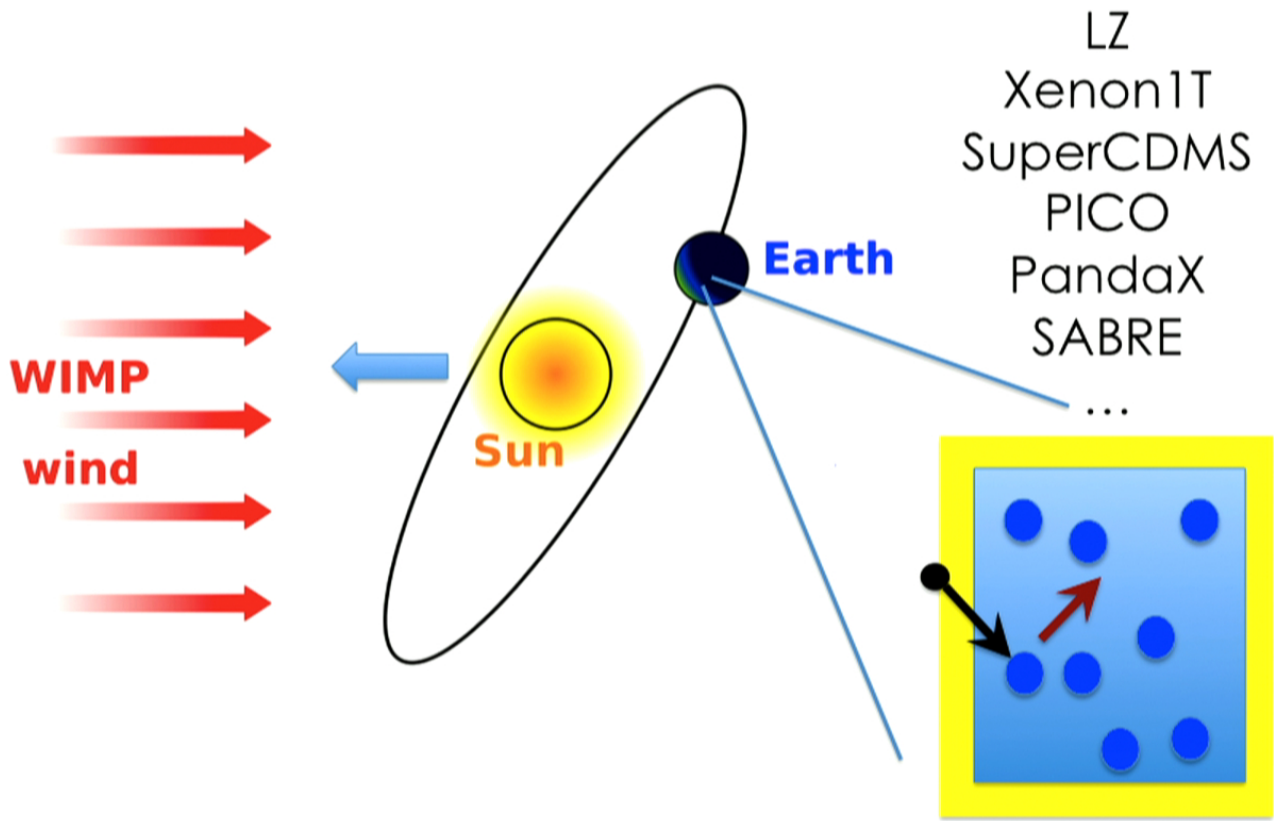


Image credit: Freese et al (2012)

DM-nucleus scattering

Astrophysics

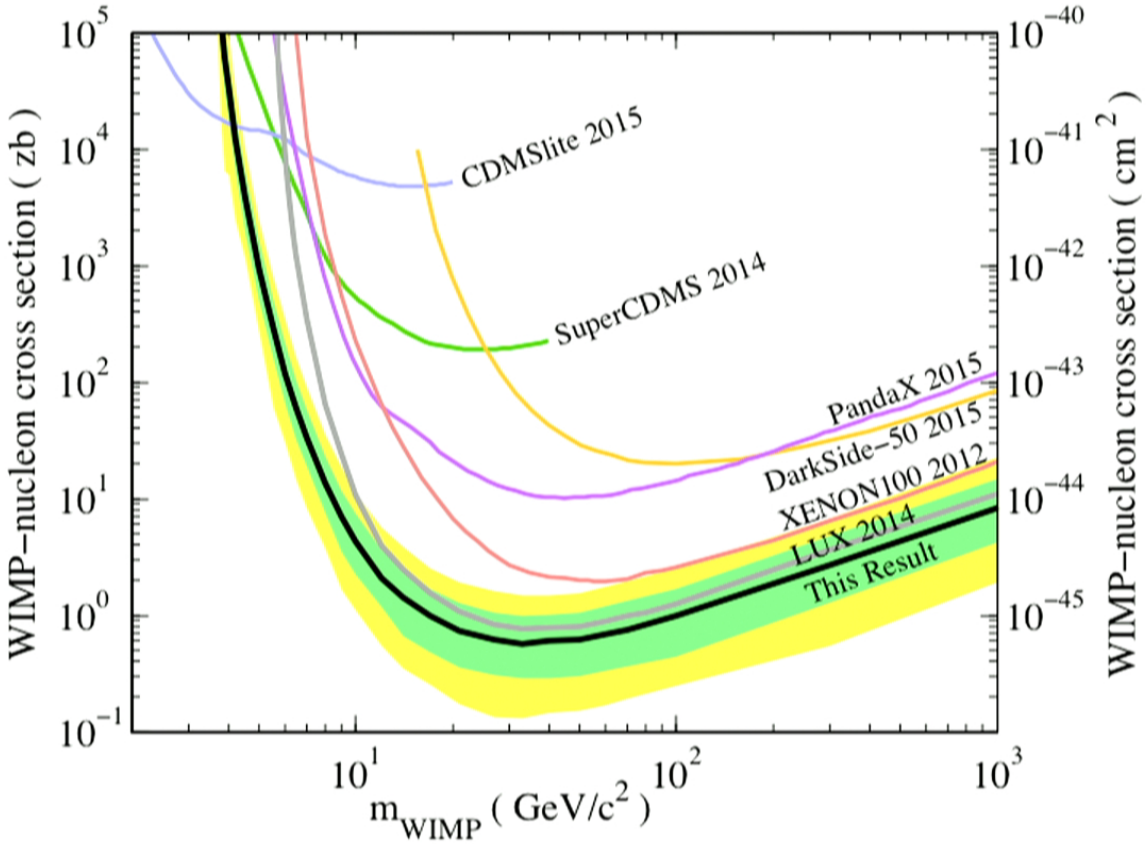
$$\frac{dR}{dE_R}(E_R) = \frac{\rho_\chi}{m_T m_\chi} \int_{v_{\rm min}}^{v_{\rm esc,lab}} v f(\mathbf{v}) \frac{d\sigma_T}{dE_R}(E_R, v) d^3v$$

"Observable"

DM particle + nuclear physics

Nuclear recoil-energy spectrum

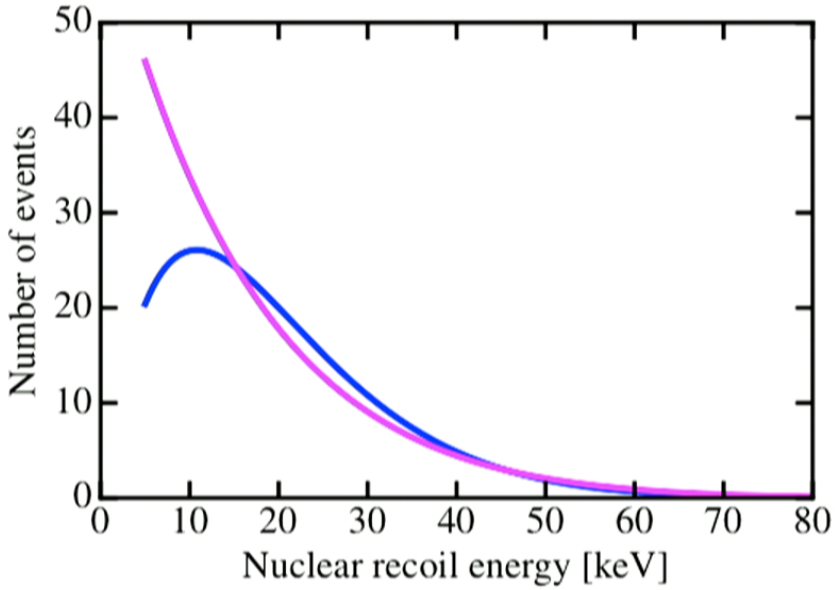
Direct detection



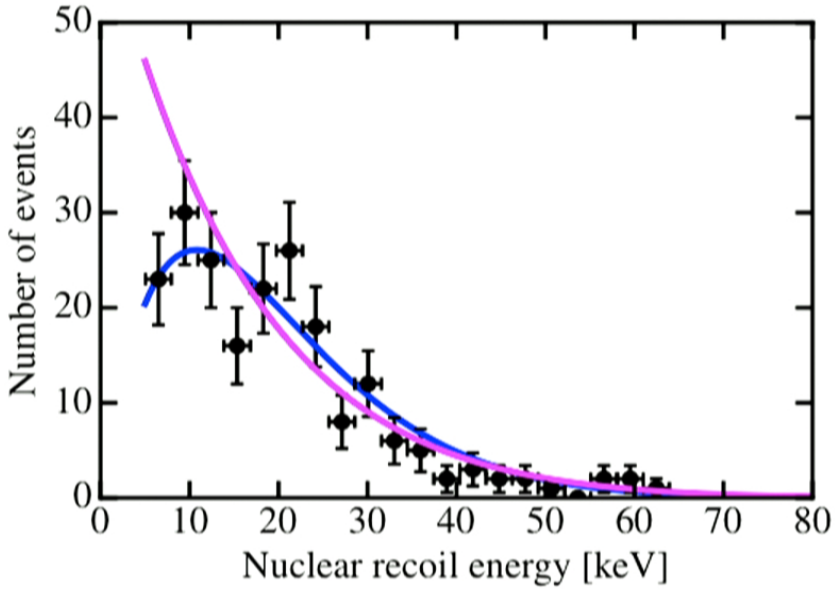
LUX collaboration, 2015

What can we really learn about dark matter ***parameters and theory*** from direct detection?

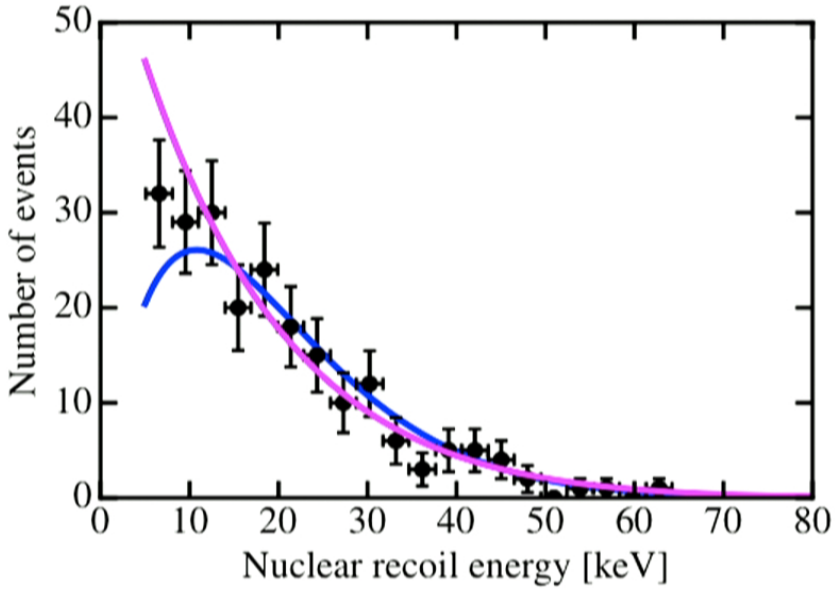
Context: noisy recoil-energy spectra



Context: noisy recoil-energy spectra



Context: noisy recoil-energy spectra



How likely is direct detection to successfully identify the correct DM theory?

How to maximize the science output of these experiments?

VG et al (2015); VG and Peter (2014)

Consider a class of interaction theories:

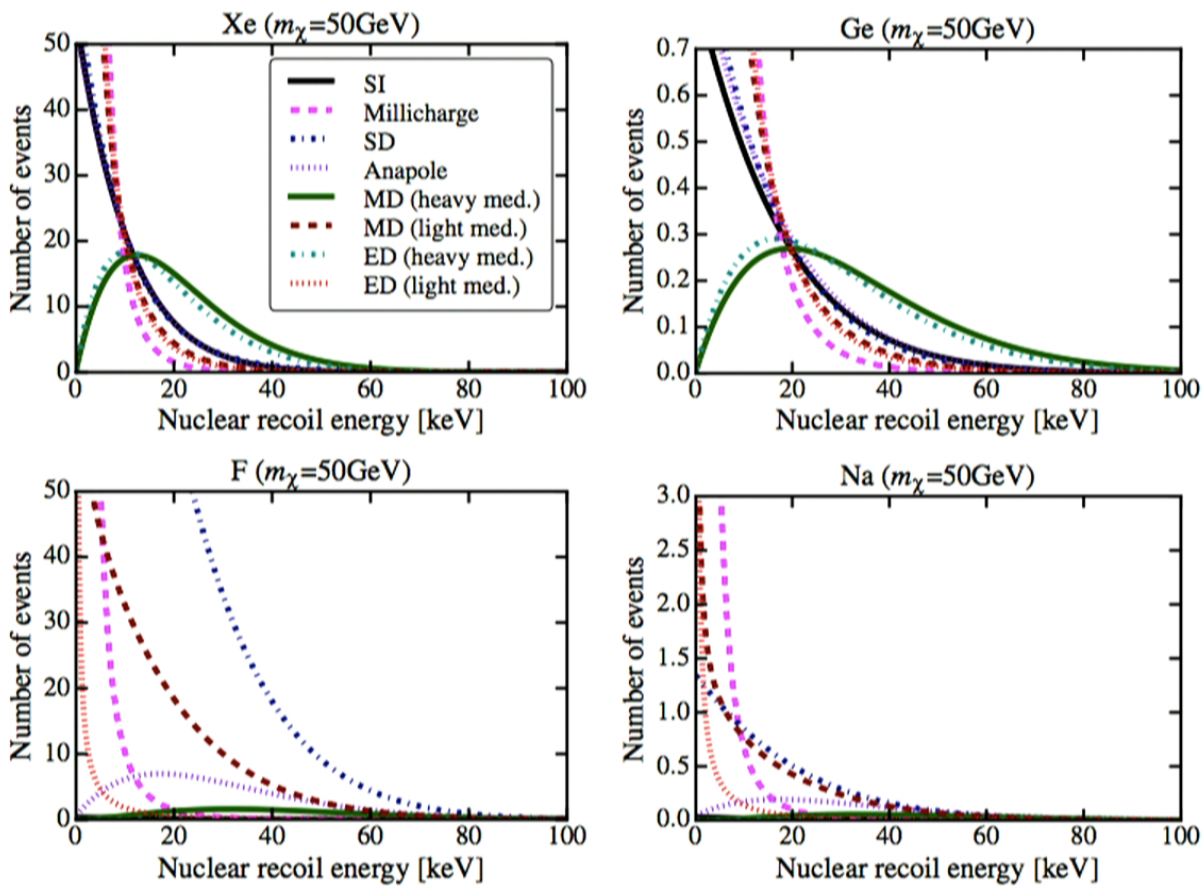
- EFT approach to elastic scattering of spin ½ DM through scalar or vector mediators
- Broad range of (UV complete) theories
- Nuclear responses triggered by non-standard interactions
- Variety of target elements with natural abundances of isotopes

See also: *Fan et al, 2010; Fitzpatrick et al, 2012; Anand et al, 2013; Gresham & Zurek, 2014*

Assemble a long list of specific models:

Model name	Lagrangian	$\vec{q}$, v Dependence	Response	f_n/f_p
SI	$\bar{\chi}\chi\bar{N}N$	1	M	+1
SD	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{N}\gamma_\mu\gamma_5 N$	1	$\Sigma' + \Sigma''$	–1.1
Anapole	$\bar{\chi}\gamma^\mu\gamma_5\chi\partial^\nu F_{\mu\nu}$	$v^{\perp 2}$ $\vec{q}^2/m_N^2$	M $\Delta + \Sigma'$	photon–like
Millicharge	$\bar{\chi}\gamma^\mu\chi A_\mu$	$m_N^2 m_\chi^2/\vec{q}^4$	M	photon–like
MD (light med.)	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	$1 + \frac{v^{\perp 2} m_N^2}{\vec{q}^2}$ 1	M $\Delta + \Sigma'$	photon–like
ED (light med.)	$\bar{\chi}\sigma^{\mu\nu}\gamma_5\chi F_{\mu\nu}$	$m_N^2/\vec{q}^2$	M	photon–like
MD (heavy med.)	$\bar{\chi}\sigma^{\mu\nu}\partial_\mu\chi\partial^\alpha F_{\alpha\nu}$	$\frac{\vec{q}^4}{\Lambda^4} + \frac{v^{\perp 2} m_N^2 \vec{q}^2}{\Lambda^4}$ $\vec{q}^4/\Lambda^4$	M $\Delta + \Sigma'$	photon–like
ED (heavy med.)	$\bar{\chi}\sigma^{\mu\nu}\gamma_5\partial_\mu\chi\partial^\alpha F_{\alpha\nu}$	$\vec{q}^2 m_N^2/\Lambda^4$	M	photon–like
SI_{q^2}	$i\bar{\chi}\gamma_5\chi\bar{N}N$	$\vec{q}^2/m_\chi^2$	M	+1
SD_{q^2} (Higgs-like/flavor–univ.)	$i\bar{\chi}\chi\bar{N}\gamma_5 N$	$\vec{q}^2/m_N^2$	Σ''	$+1/-0.05$
SD_{q^4} (Higgs-like/flavor–univ.)	$\bar{\chi}\gamma_5\chi\bar{N}\gamma_5 N$	$\vec{q}^4/m_\chi^2 m_N^2$	Σ''	$+1/-0.05$
$\vec{L}\cdot\vec{S}$-like	$\bar{\chi}\gamma_\mu\chi\frac{\partial^2\bar{N}\gamma^\mu N}{m_N^2} +$ $+\bar{\chi}\gamma_\mu\chi\frac{\partial_\nu\bar{N}\sigma^{\mu\nu}N}{2m_N}$	$\vec{q}^4/m_N^4$ $\vec{q}^4/m_N^4$ $\frac{\vec{q}^2 v^{\perp 2}}{m_N^2} + \frac{\vec{q}^4}{m_\chi^2 m_N^2}$	M Φ'' Σ'	+1

Figure out corresponding signals:



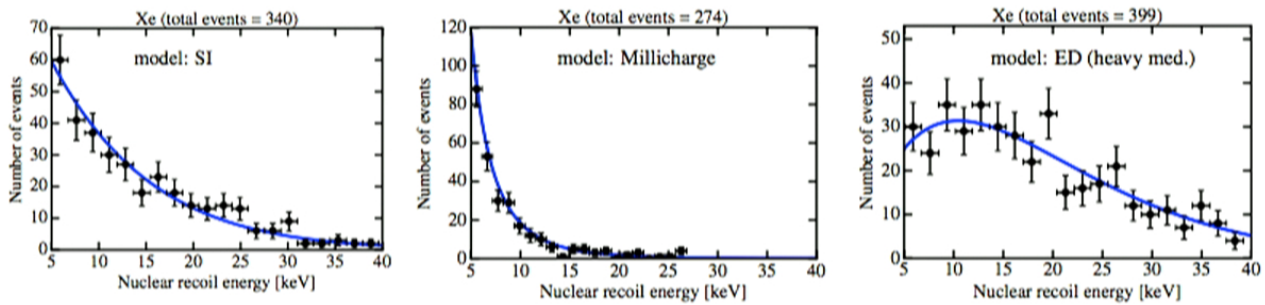
VG et al (2015); VG and Peter (2014)

Consider upcoming experiments (G2+):

	Label	A (Z)	Energy window [keVnr]	Exposure [kg-yr]
Xenon1T ~	Xe	131 (54)	5-40	2000
SuperCDMS ~	Ge	73 (32)	0.3-100	100
	I	127 (53)	22.2-600	212
	F	19 (9)	3-100	606
	Na	23 (11)	6.7-200	38
	Ar	40 (18)	25-200	3000
	He	4 (2)	3-100	300
	Xe(lo)	131 (54)	1-40	2000
	Xe(hi)	131 (54)	5-100	2000
	Xe(wide)	131 (54)	1-100	2000
	I(lo)	127 (53)	1-600	212
	XeG3	131 (54)	5-40	40 000
	I+	127 (53)	1-600	424
	F+	19 (9)	3-100	1200

Analysis

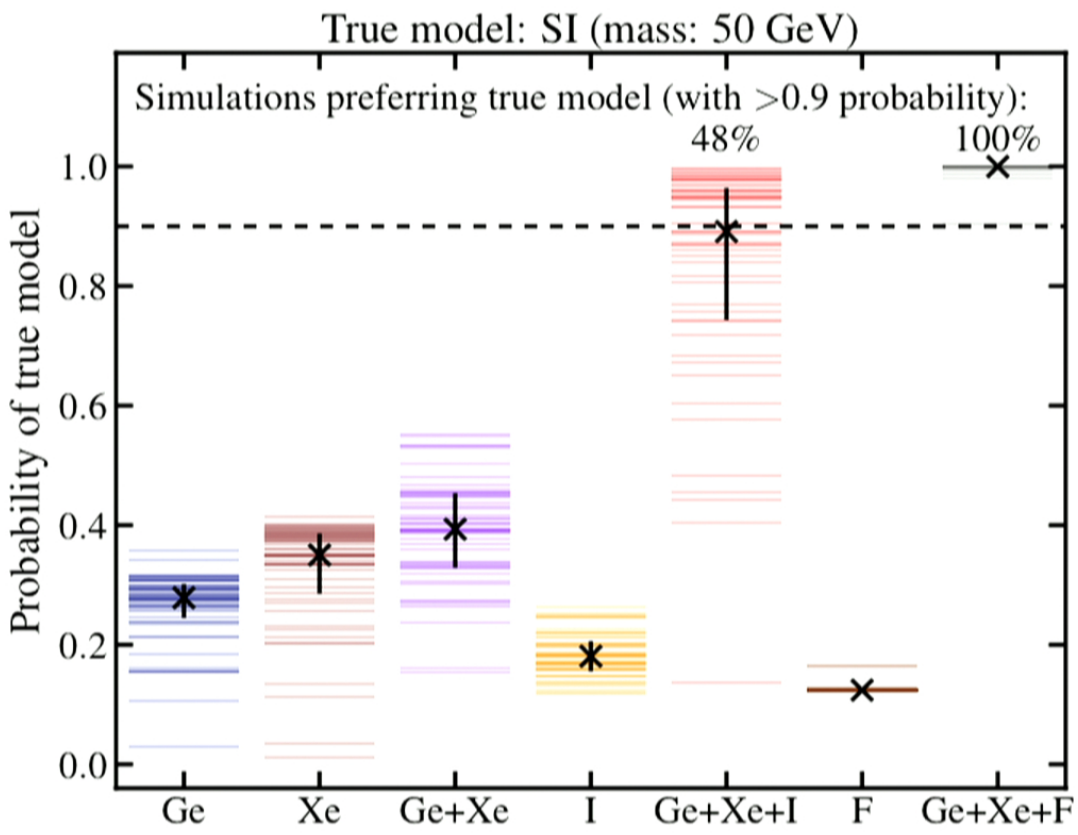
1. Simulate events under different hypotheses, for a signal **just below the current detection threshold**.



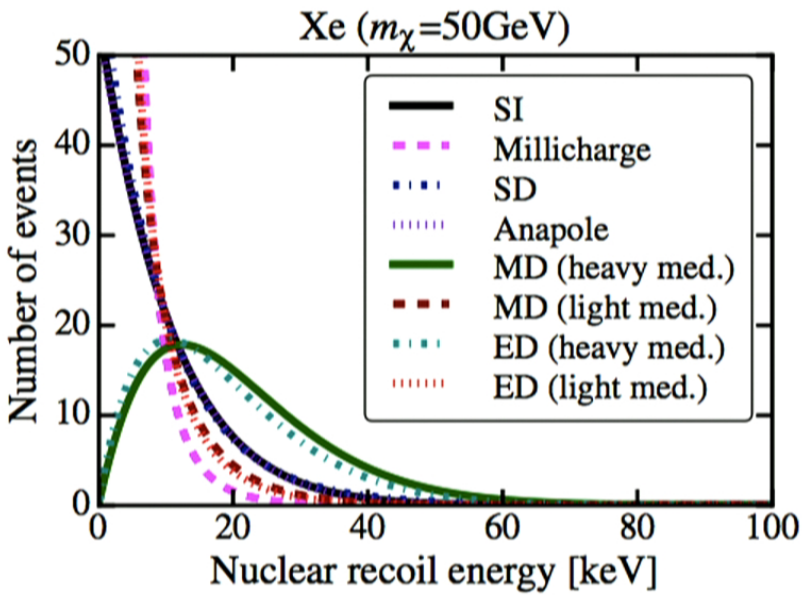
2. Reconstruct posteriors for one or more mock experiments jointly (fit for: **mass** and **cross-section**)

3. Compare models *a posteriori* (Bayesian model selection)

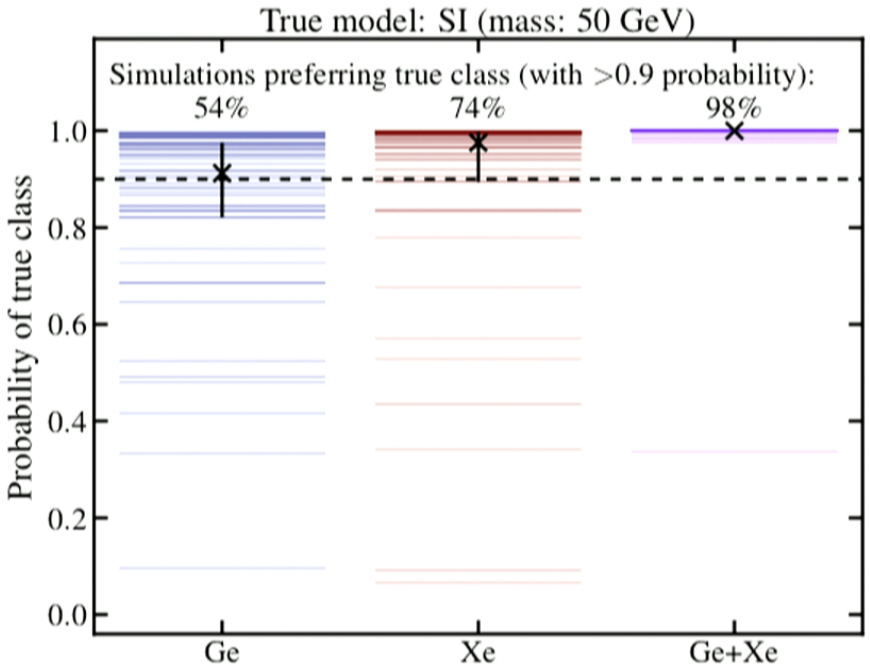
Results



VG et al (2015); VG and Peter (2014)

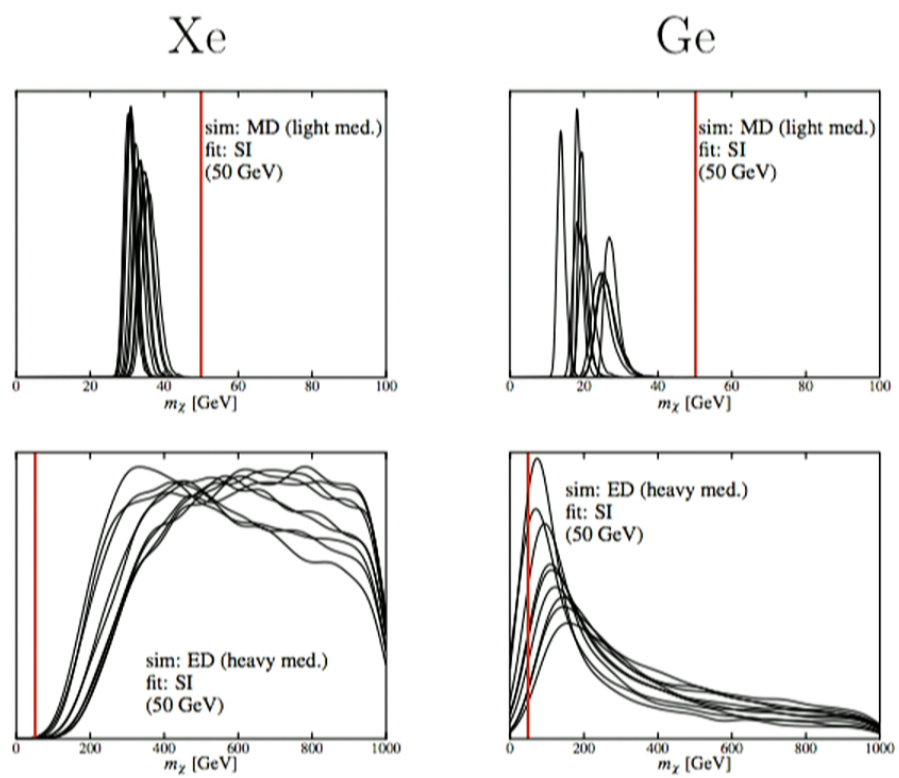

Xe (m_χ=50GeV)
Number of events
Nuclear recoil energy [keV]
0
10
20
30
40
50
0
20
40
60
80
100
SI
Millicharge
SD
Anapole
MD (heavy med.)
MD (light med.)
ED (heavy med.)
ED (light med.)

Momentum dependence is robust



VG et al (2015), VG and Peter (2014)

Wrong model leads to biased mass



VG et al (2015), VG and Peter (2014)

dmdd python tool @ GitHub

>> pip install dmdd

Basic Usage

Here is a quick example of basic usage:

```
from dmdd import UV_Model, Experiment, MultinestRun

model1 = UV_Model('SI_Higgs', ['mass', 'sigma_si'], fixed_params={'fnfp_si': 1})
model2 = UV_Model('SD_fu', ['mass','sigma_sd'], fixed_params={'fnfp_sd': -1.1})

xe = Experiment('Xe', 'xenon', 5, 40, 1000, eff.efficiency_Xe)

run = MultinestRun('sim', [xe,ge], model1,{'mass':50.,'sigma_si':70.},
                model2, prior_ranges={'mass':(1,1000), 'sigma_sd':(0.001,1000)})

run.fit()
run.visualize()
```

VG and McDermott (2015)

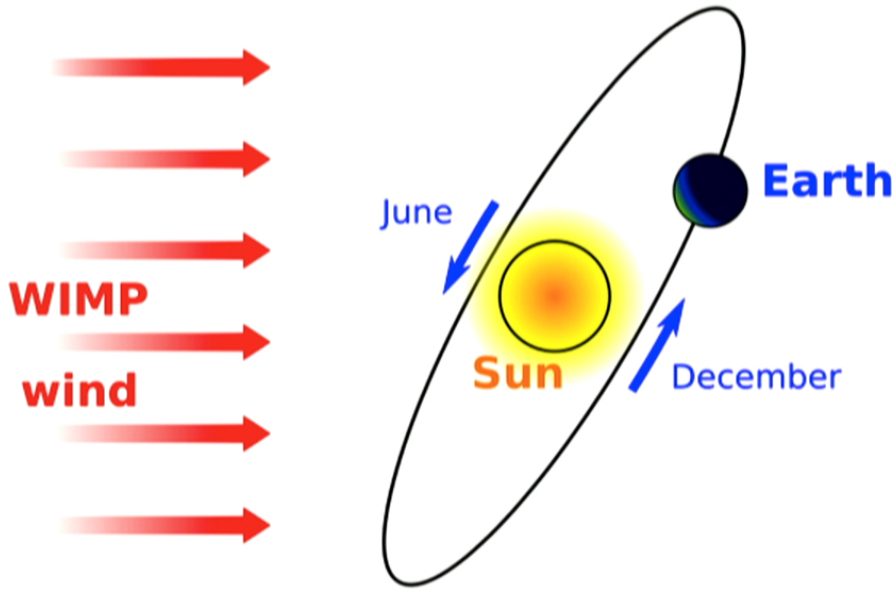
Identifying the right theory is going to be hard!

Anapole and SI are degenerate, same momentum dependence…

…but Anapole~v^2

$$\frac{dR}{dE_R}(E_R) = \frac{\rho_\chi}{m_T m_\chi} \int_{v_{\rm min}}^{v_{\rm esc,lab}} v f(\mathbf{v}) \frac{d\sigma_T}{dE_R}(E_R, v) d^3 v$$

Annual modulation to the rescue?

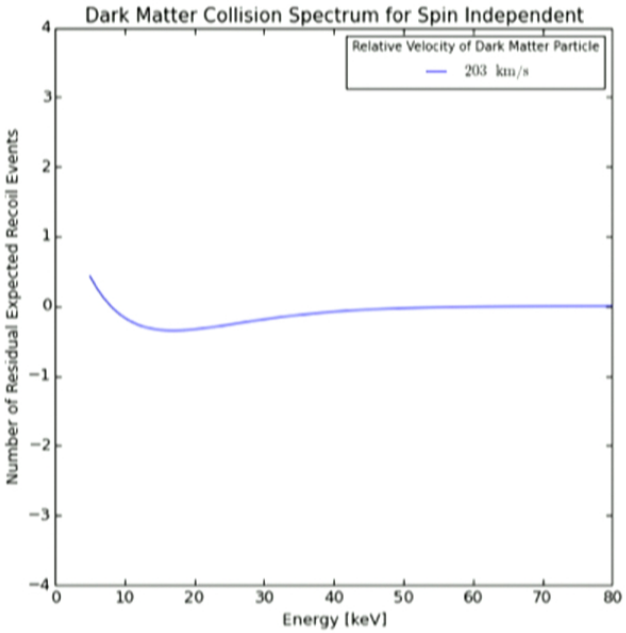


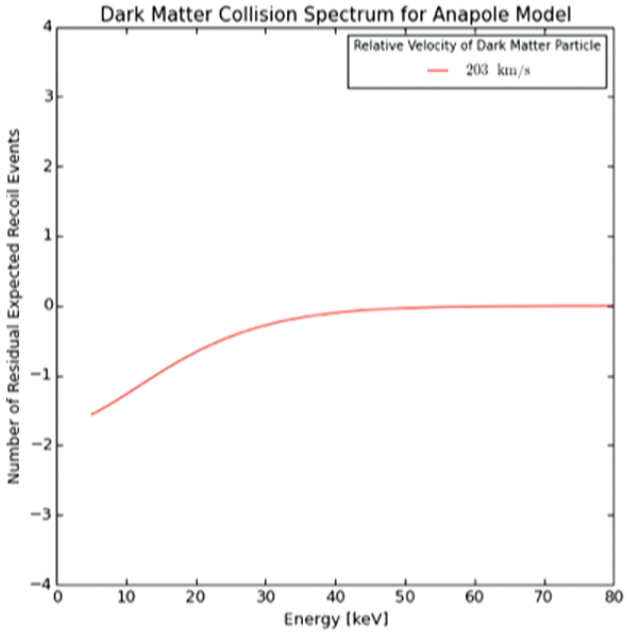
$$\frac{dR}{dE_R}(E_R) = \frac{\rho_\chi}{m_T m_\chi} \int_{v_{\rm min}}^{v_{\rm esc,lab}} v f(\mathbf{v}) \frac{d\sigma_T}{dE_R}(E_R, v) d^3 v$$

Druiker, Freese, and Spergel (1986); Freese et al (2012)

Annual modulation to the rescue?

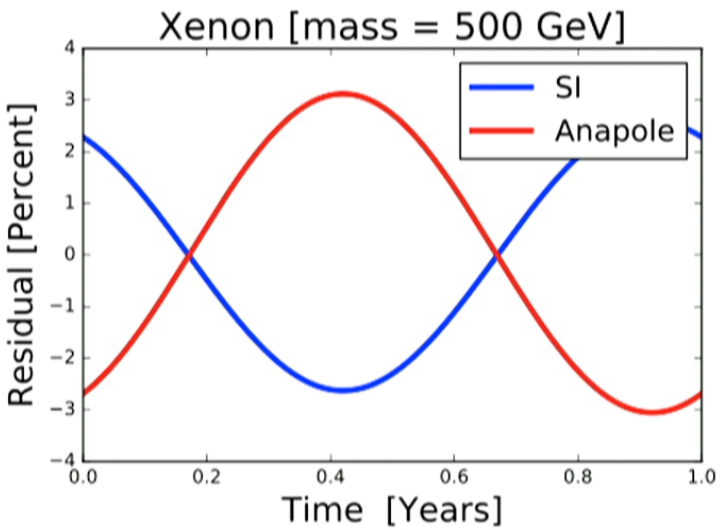
Animations by Katelyn Neese (Princeton):

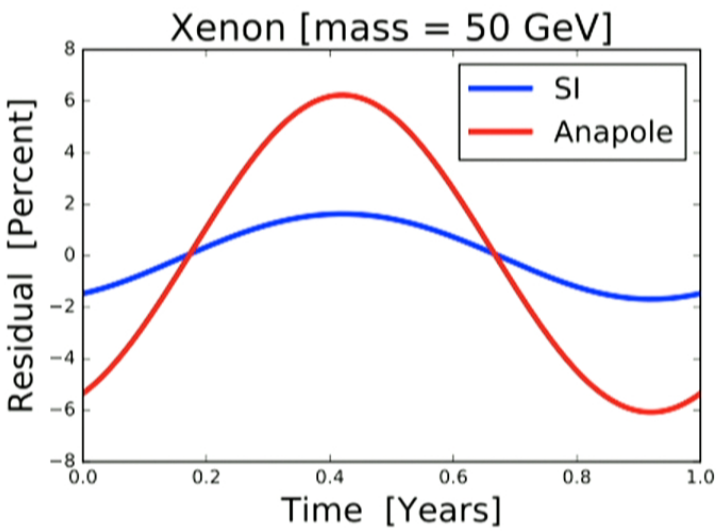




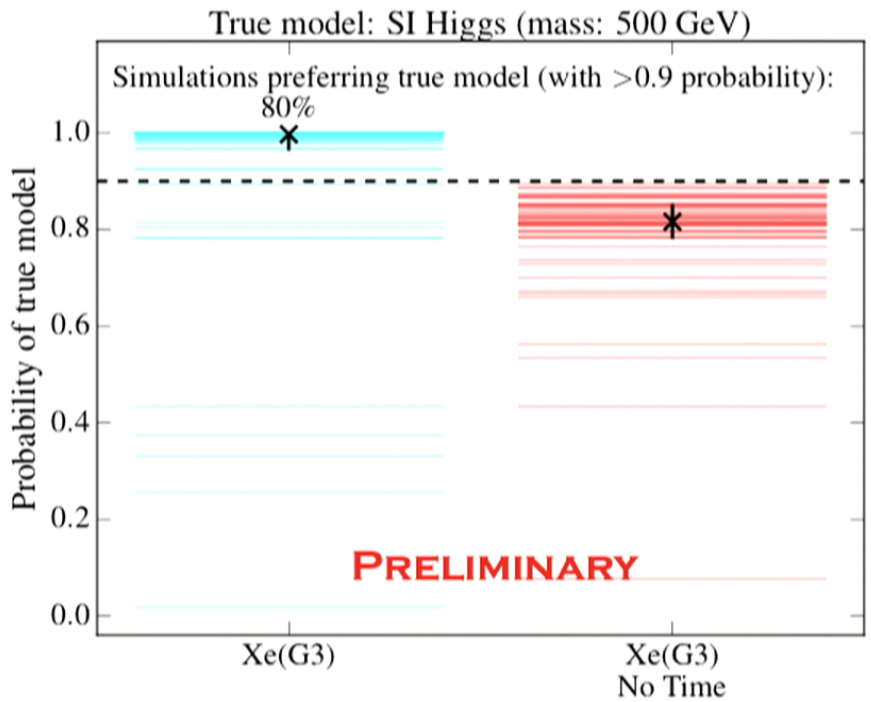
Annual modulation to the rescue?

Plots by Samuel Witte (UCLA):





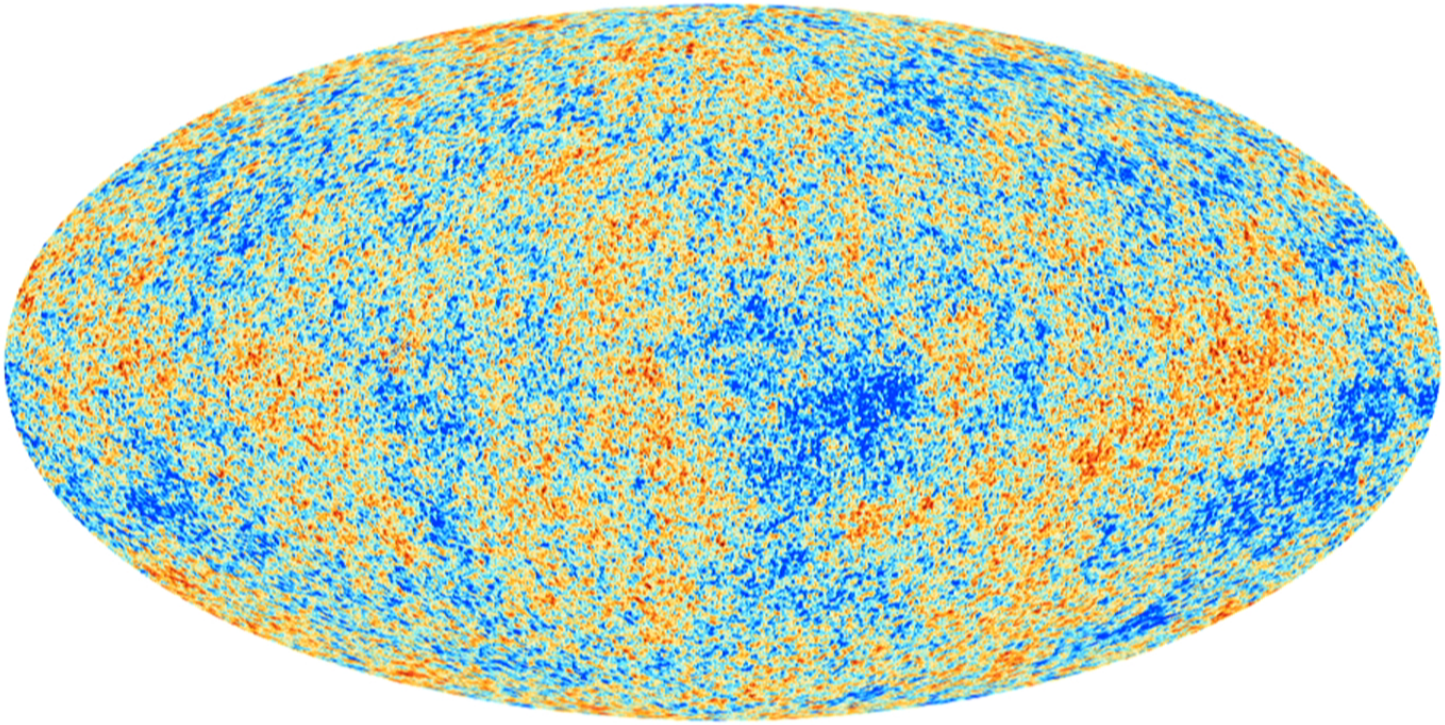
Annual modulation to the rescue?



Plot by Samuel Witte

Witte, VG, and McDermott (in prep.)

Scattering in the early universe

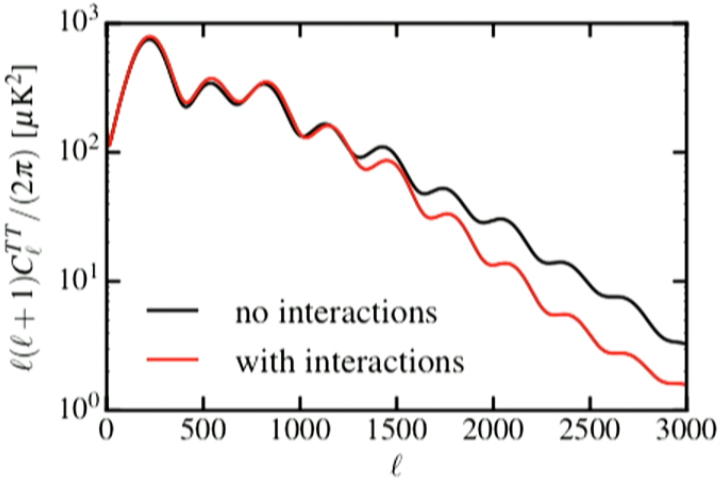


Previous work: Sigurdson et al (2004); Dvorkin et al (2014); etc.

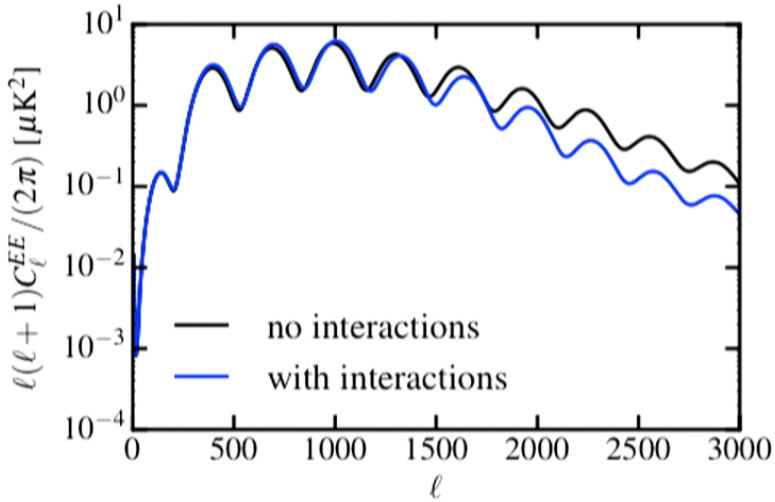
Image credit: ESA and the Planck collaboration

Scattering in the early universe

temperature

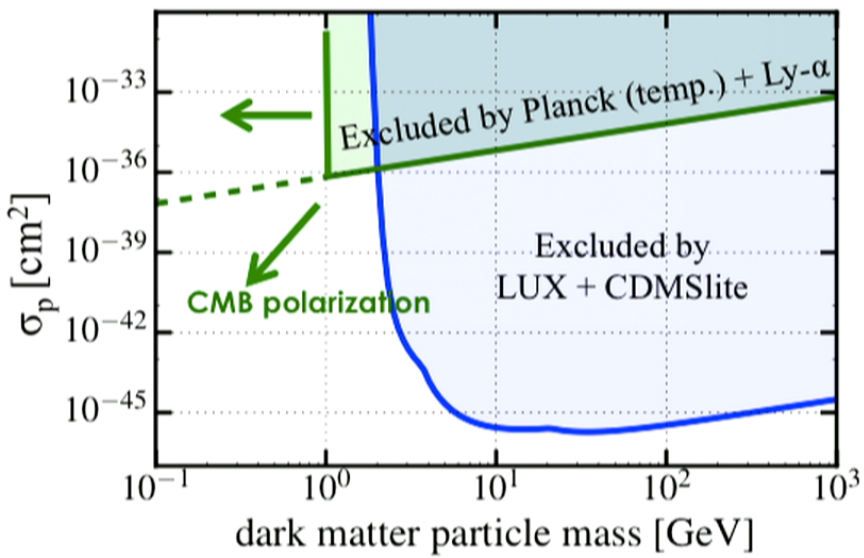


polarization



Work in progress with Kimberly Boddy (UH)

Complimentary probes of DM



Example: constraints on millicharged DM
[from VG et al (2015) and Dvorkin et al (2014)]

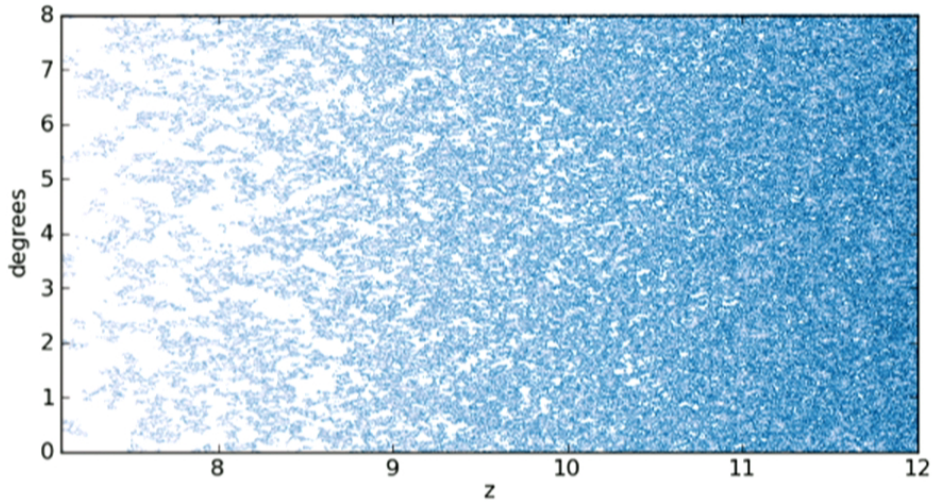
Part I: Conclusions

- ✓ Complementary targets, and a joint analysis of all available direct-detection experiments are essential to learning about DM interactions.
- ✓ Annual modulation could help break degeneracy between interactions with different v-dependence.
- ✓ Cosmological data can probe vast new portions of parameter space.
- ✓ Future: joint analysis is a must!

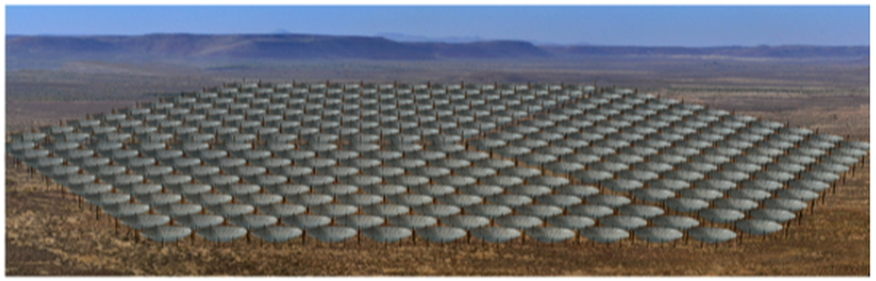
II. 21-cm cosmology

A new probe of primordial magnetic fields

21-cm tomography



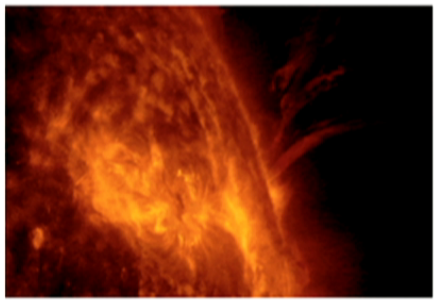
Credit: PAPER collaboration



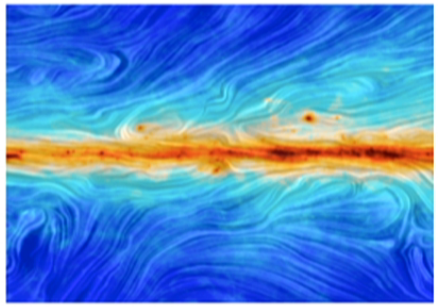
Credit: HERA collaboration

Why PMFs?

- MFs are ubiquitous.
- Origin of seed fields?
- PMFs = new window into physics of the early universe. Predictions: 10^{-30}-10^{-15} G
- Current constraints ~nG (CMB)



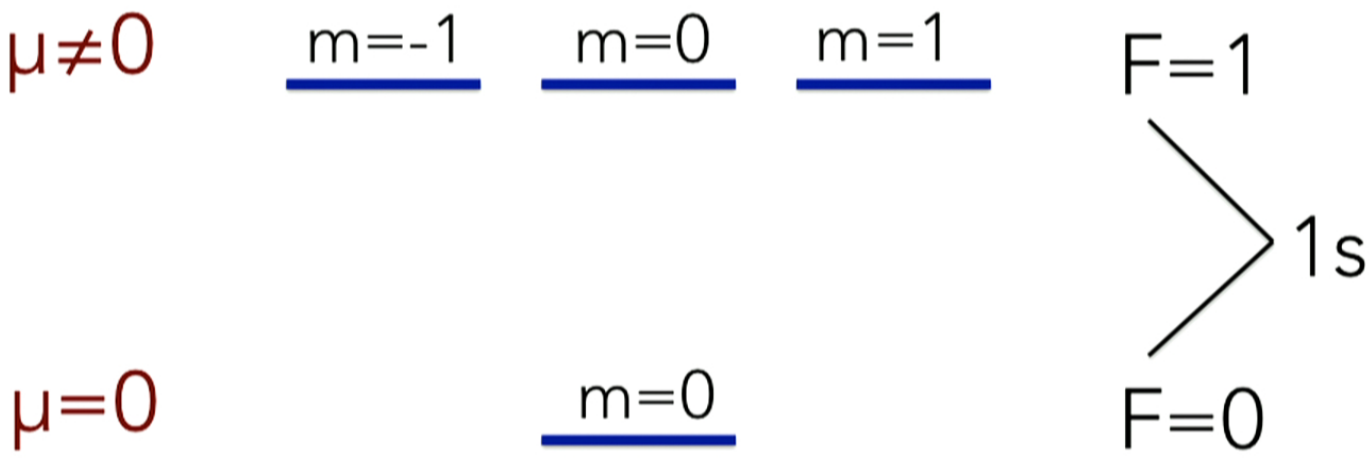
credits: NASA/SDO/Goddard



credits: ESA/Planck Collaboration

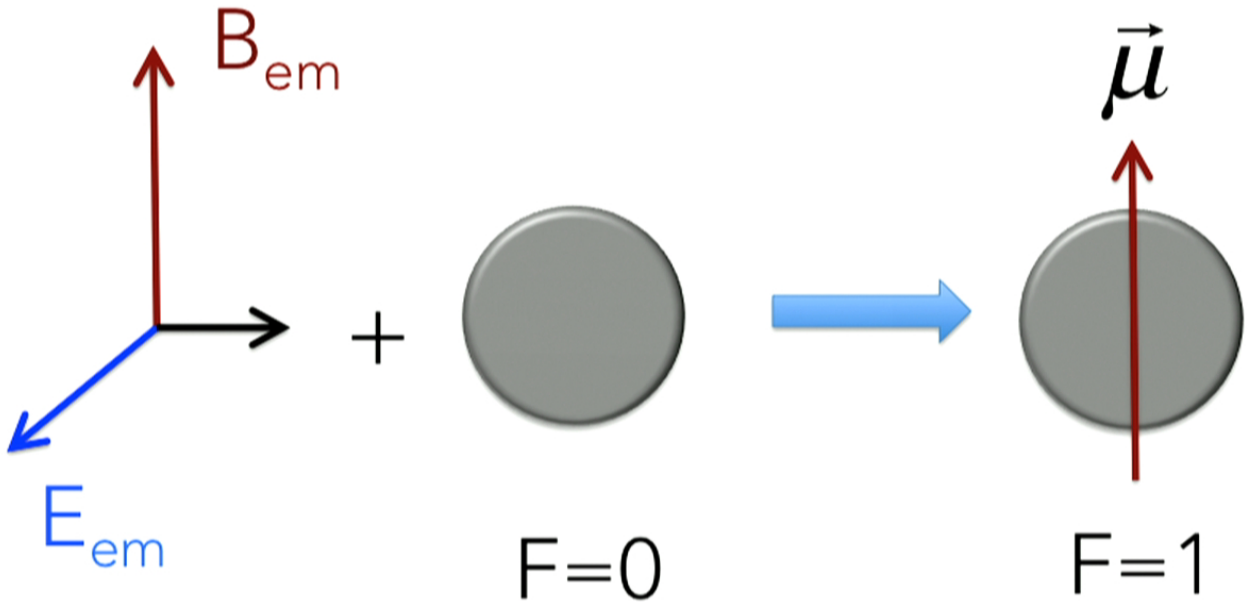
New method that proposes the use of 21-cm tomography to probe miniscule-strength large-scale magnetic fields directly in the high-z IGM.

Hyperfine structure of H atom



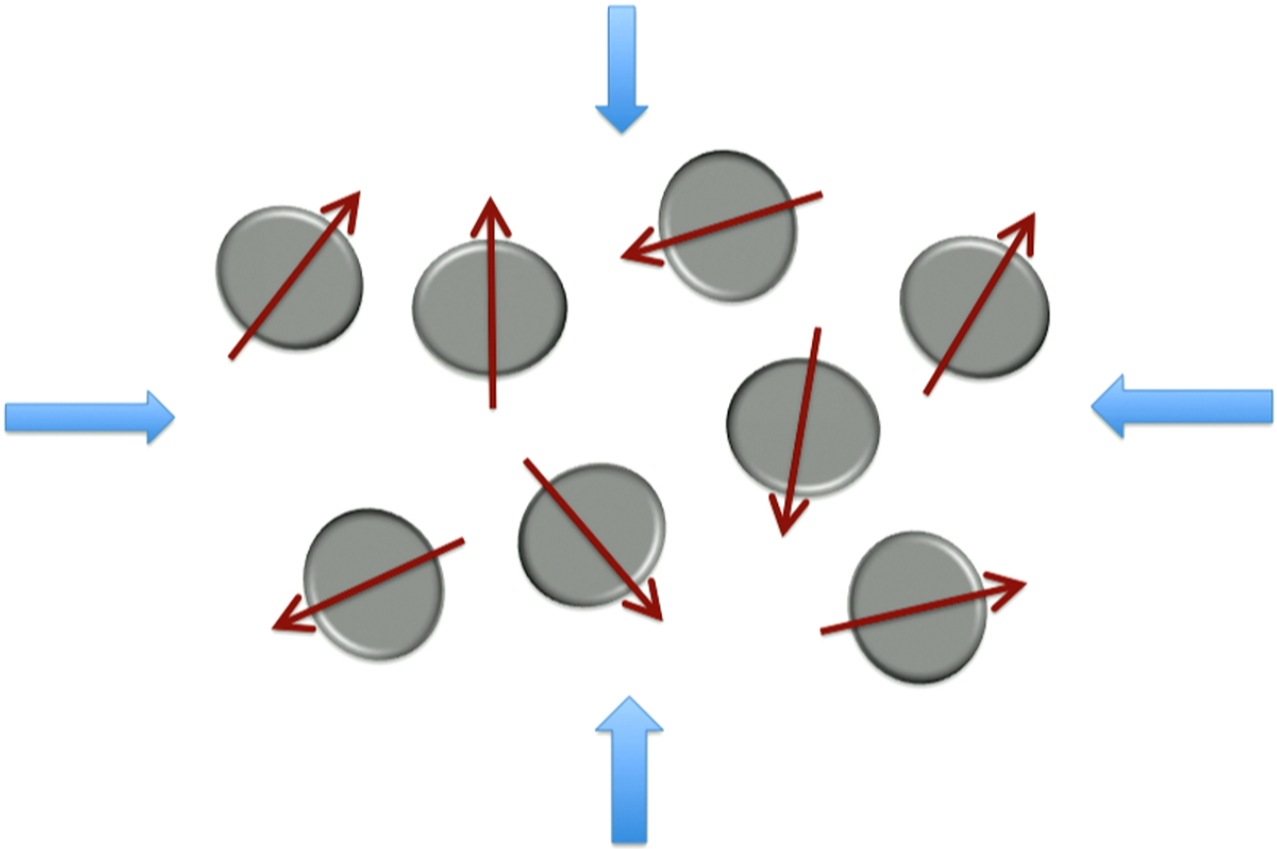
Triplet has a net magnetic moment.

Hyperfine structure of H atom



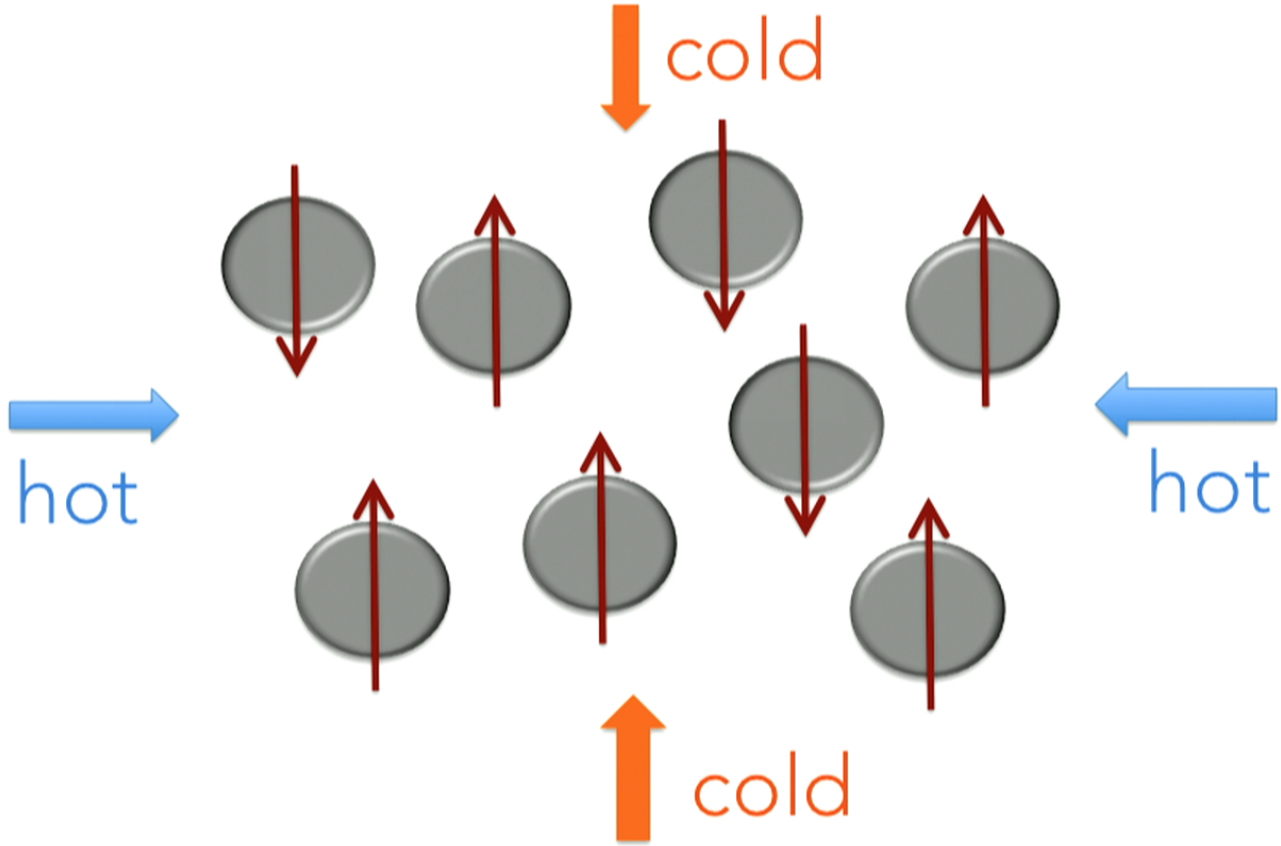
Triplet has a net magnetic moment, and will preferentially emit perpendicular to μ .

Ground state unpolarized



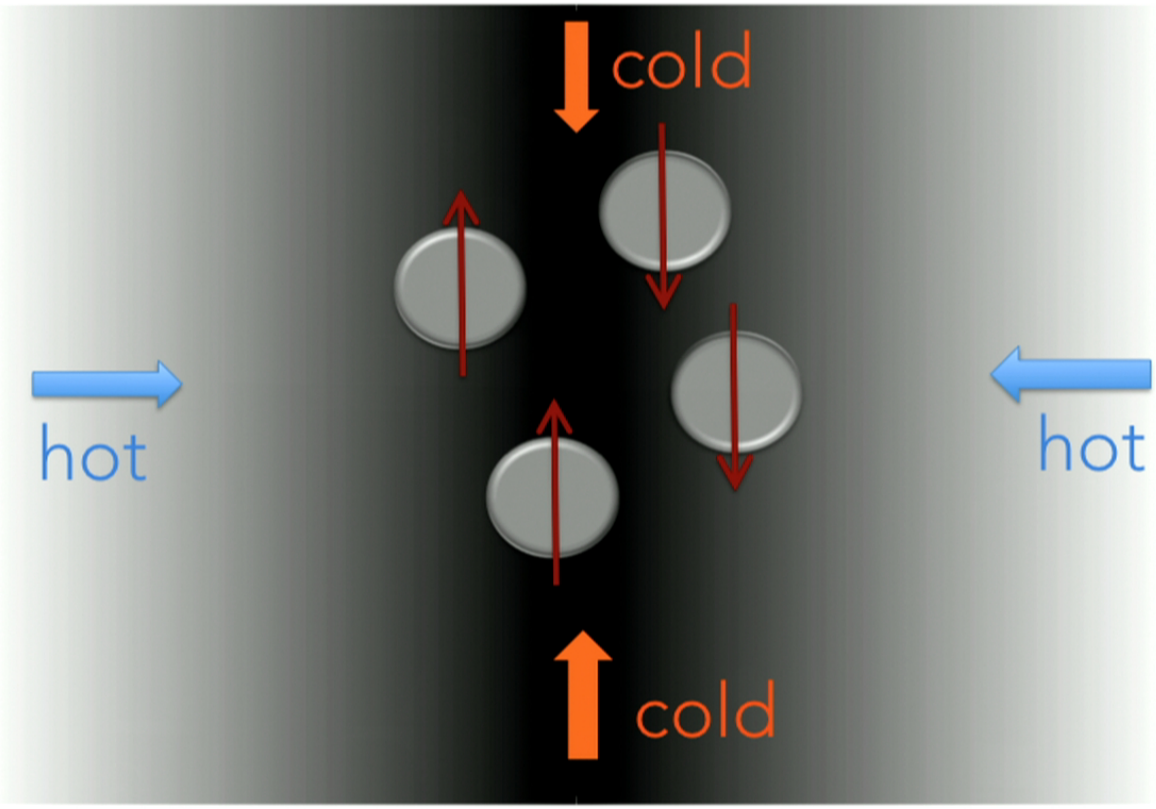
Isotropic bath of 21cm radiation.

Ground state alignment

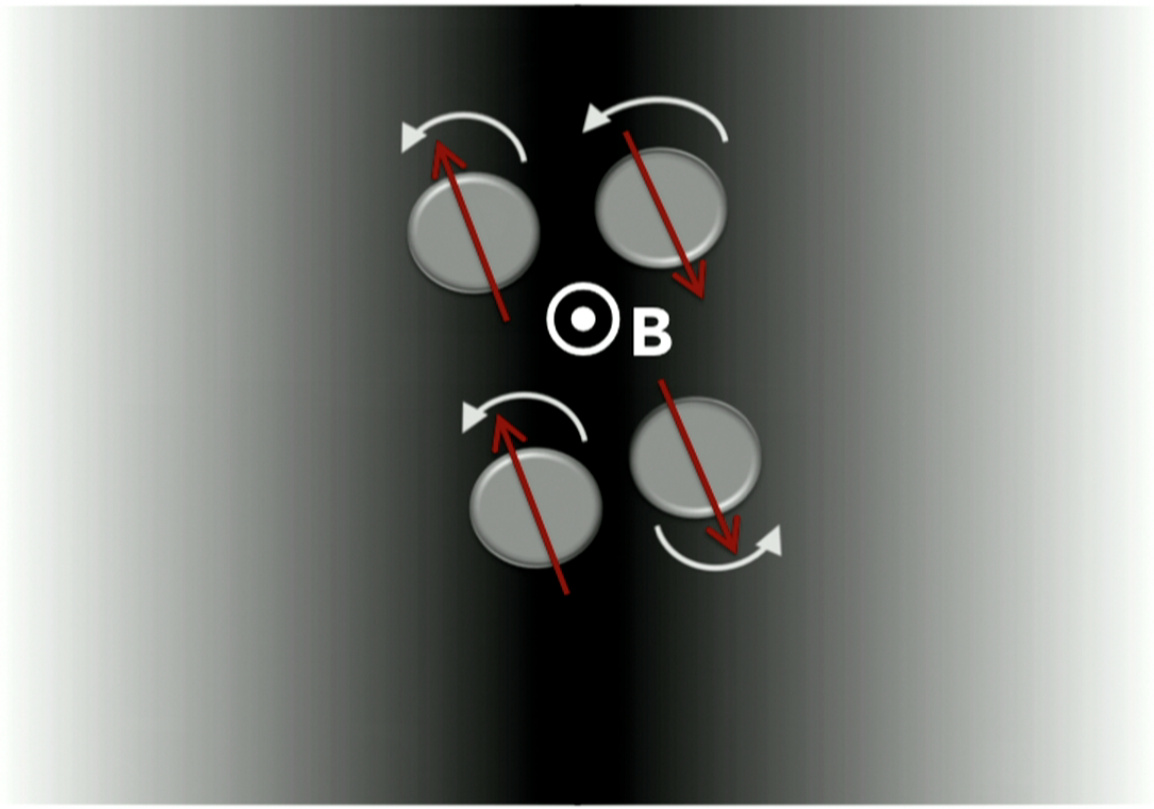


Quadrupolar anisotropy.

Spin alignment in inhomogeneous universe



Precession in an external magnetic field



Paper I:
Microphysics calculation

Include:

- ✓ Radiative transitions
- ✓ Atomic collisions
- ✓ Lyman-α pumping
- ✓ **Magnetic fields**

$$T(\hat{\mathbf{n}},\vec{k}) = \left(1-\frac{T_\gamma}{T_\mathrm{s}}\right) x_{1\mathrm{s}} \left(\frac{1+z}{10}\right)^{1/2}$$
$$\times\left[26.4\ \mathrm{mK}\left\{1+\left(1+(\hat{\mathbf{k}}\cdot\hat{\mathbf{n}})^2\right)\delta(\vec{k})\right\} - 0.128\ \mathrm{mK}\left(\frac{T_\gamma}{T_\mathrm{s}}\right)\right.$$
$$\times x_{1\mathrm{s}}\left(\frac{1+z}{10}\right)^{1/2}\left\{1+2\left(1+(\hat{\mathbf{k}}\cdot\hat{\mathbf{n}})^2\right)\delta(\vec{k})\right.$$
$$\left.\left.-\frac{\delta(\vec{k})}{15}\sum_m \frac{4\pi}{5}\frac{Y_{2m}(\hat{\mathbf{k}})\left[Y_{2m}(\hat{\mathbf{n}})\right]^*}{1+x_{\alpha,(2)}+x_{\mathrm{c},(2)}-imx_\mathrm{B}}\right\}\right]$$

Venumadhav, Oklopcic, VG, et al (2014)

Paper I:
Microphysics calculation

$$T(\hat{\mathbf{n}},\vec{k}) = \left(1-\frac{T_\gamma}{T_\mathrm{s}}\right) x_{1\mathrm{s}} \left(\frac{1+z}{10}\right)^{1/2}$$
$$\times\left[26.4\ \mathrm{mK}\left\{1+\left(1+(\hat{\mathbf{k}}\cdot\hat{\mathbf{n}})^2\right)\delta(\vec{k})\right\} - 0.128\ \mathrm{mK}\left(\frac{T_\gamma}{T_\mathrm{s}}\right)\right.$$
$$\times x_{1\mathrm{s}}\left(\frac{1+z}{10}\right)^{1/2}\left\{1+2\left(1+(\hat{\mathbf{k}}\cdot\hat{\mathbf{n}})^2\right)\delta(\vec{k})\right.$$
$$\left.\left.-\frac{\delta(\vec{k})}{15}\sum_m \frac{4\pi}{5}\frac{Y_{2m}(\hat{\mathbf{k}})\left[Y_{2m}(\hat{\mathbf{n}})\right]^*}{1+x_{\alpha,(2)}+x_{\mathrm{c},(2)}-imx_\mathrm{B}}\right\}\right],$$

Need:

- ✓ Spin temperature
- ✓ IGM kinetic temperature
- ✓ Lyman-α flux evolution

← 21CMFAST

- ✓ Matter flucts. ← CAMB

$$T^S(\vec{k}) = G(\hat{\mathbf{k}})\delta(k)$$

Paper I:
Microphysics calculation

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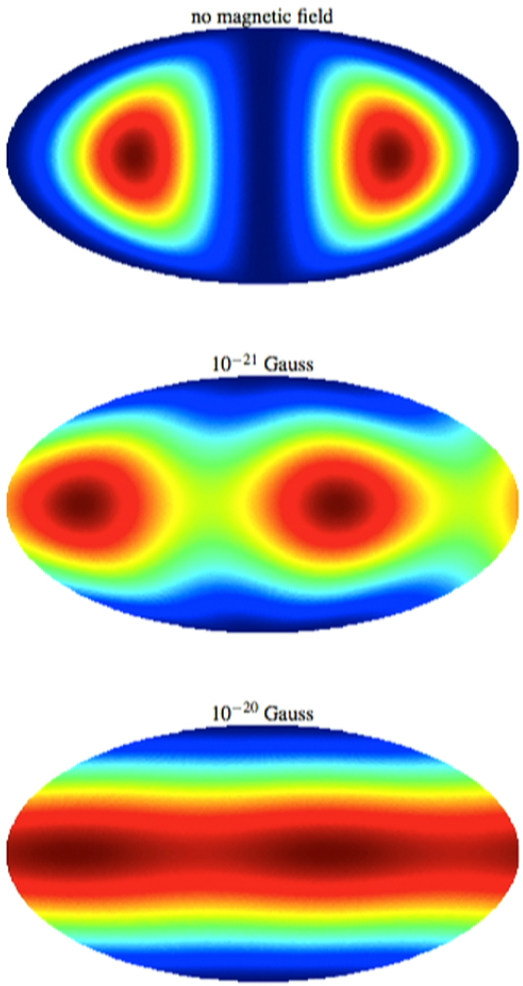
- ✓ **Magnetic fields**

$$T(\hat{\mathbf{n}},\vec{k}) = \left(1-\frac{T_\gamma}{T_\mathrm{s}}\right) x_{1\mathrm{s}} \left(\frac{1+z}{10}\right)^{1/2}$$
$$\times\left[26.4\ \mathrm{mK}\left\{1+\left(1+(\hat{\mathbf{k}}\cdot\hat{\mathbf{n}})^2\right)\delta(\vec{k})\right\} - 0.128\ \mathrm{mK}\left(\frac{T_\gamma}{T_\mathrm{s}}\right)\right.$$
$$\times x_{1\mathrm{s}}\left(\frac{1+z}{10}\right)^{1/2}\left\{1+2\left(1+(\hat{\mathbf{k}}\cdot\hat{\mathbf{n}})^2\right)\delta(\vec{k})\right.$$
$$\left.\left.-\frac{\delta(\vec{k})}{15}\sum_m \frac{4\pi}{5}\frac{Y_{2m}(\hat{\mathbf{k}})\left[Y_{2m}(\hat{\mathbf{n}})\right]^*}{1+x_{\alpha,(2)}+x_{\mathrm{c},(2)}-imx_\mathrm{B}}\right\}\right]$$

Venumadhav, Oklopcic, VG, et al (2014)



Saturation →

VG et al (2016)

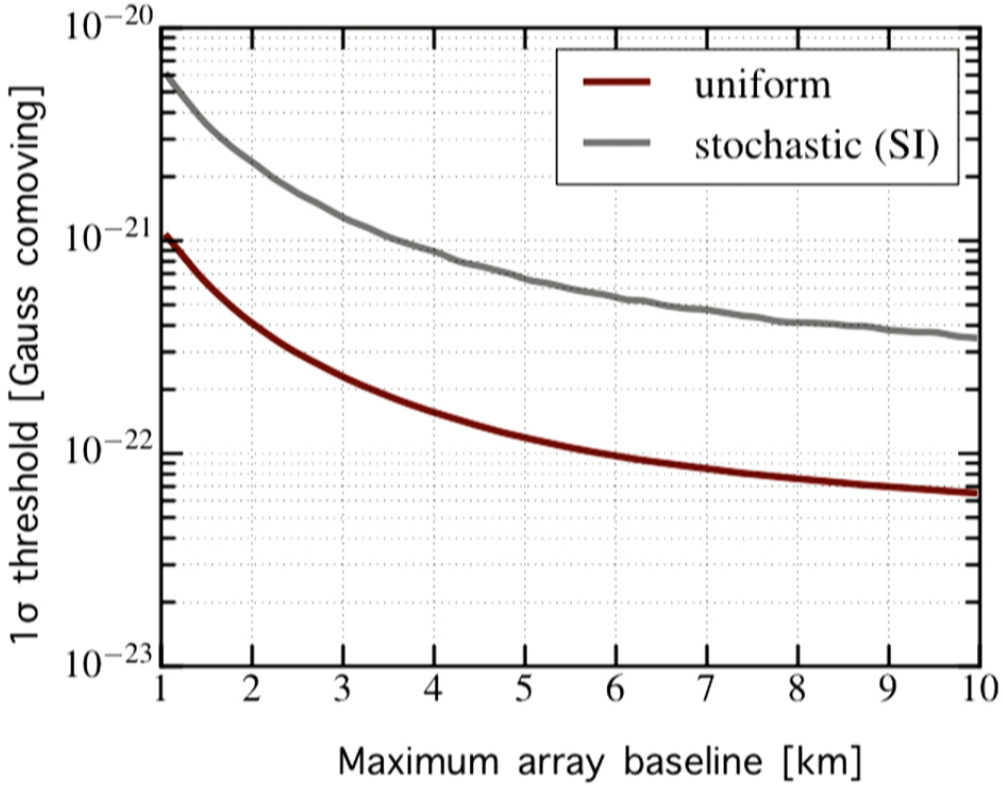
Paper II:
MVQ estimator formalism and forecasts

✧ MF introduces a preferred direction (anisotropy).

✧ Stochastic MF produces correlation between Fourier modes.

VG et al (2016)

Results

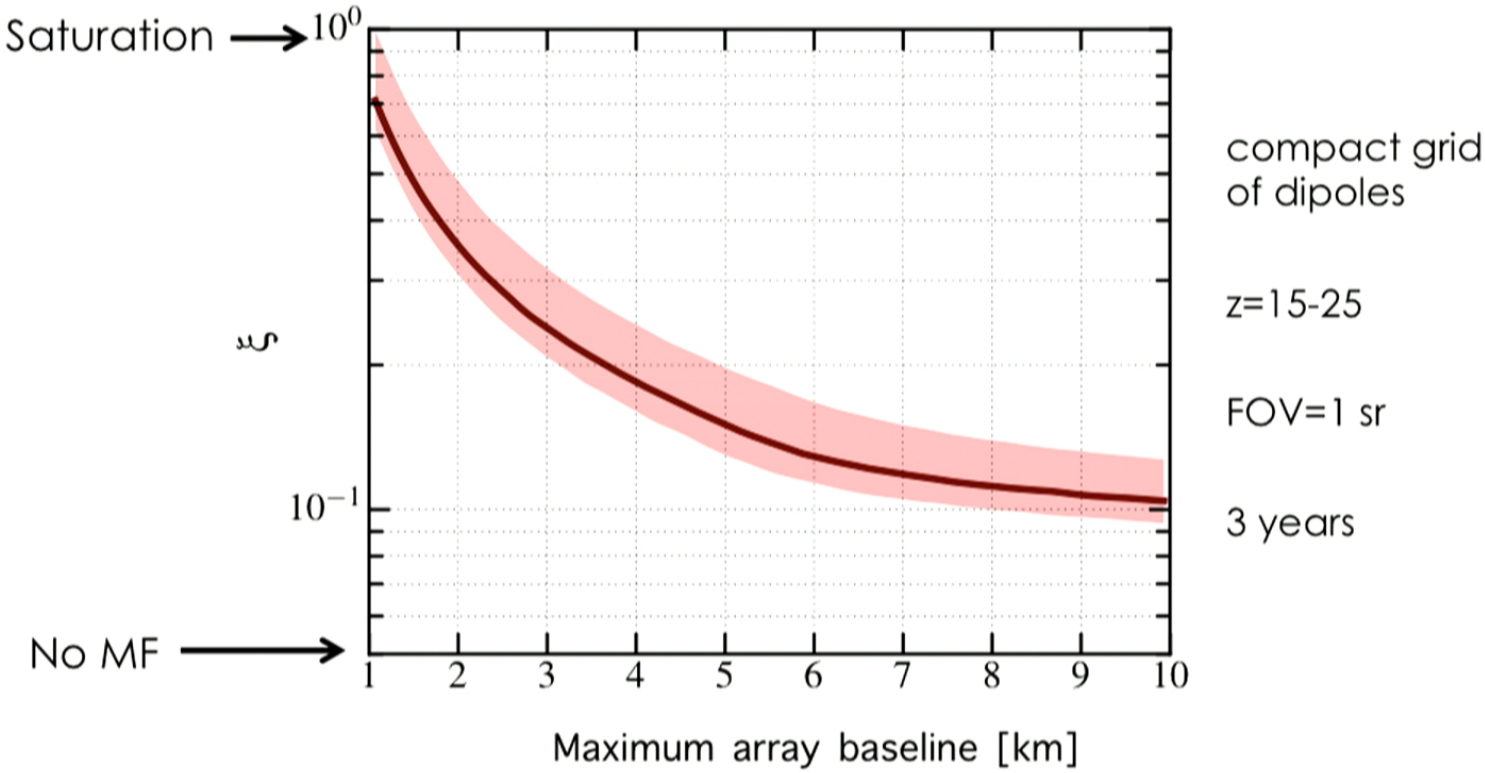


- compact grid of dipoles
- z=15-25
- FOV=1 sr
- 3 years

$$B(z) = B_0(1+z)^2$$

VG et al (2016)

Results



compact grid of dipoles

z=15-25

FOV=1 sr

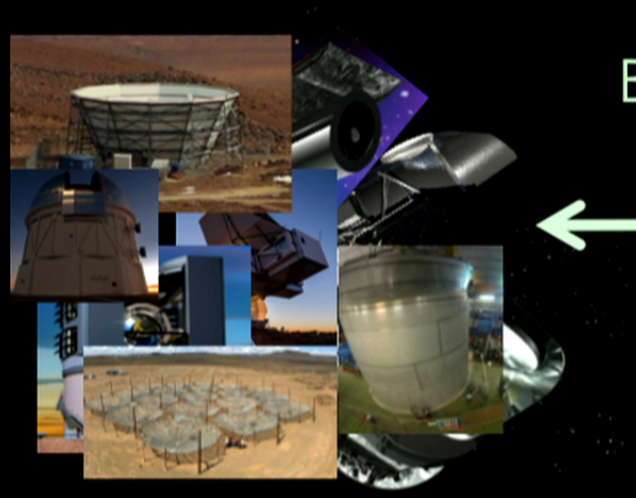
3 years

$$P^S(\vec{k}) = (1-\xi)P^S(\vec{k}, B=0) + \xi P^S(\vec{k}, B \to \infty)$$

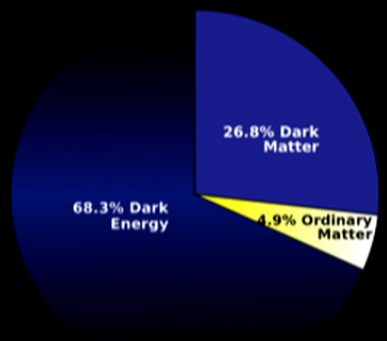
VG et al (2016)

Part II: Conclusions

- ✓ Exquisitely sensitive new probe of large-scale magnetic fields in the pre-reionization IGM.
- ✓ Array of dipoles with ~a square kilometer collecting area can reach 1-sigma sensitivity to 10^{-21} Gauss comoving = 10 oom below CMB constraints!



Bright future ahead!



Precision tools

Vast space for discovery