Old and New Topics in Dark Matter

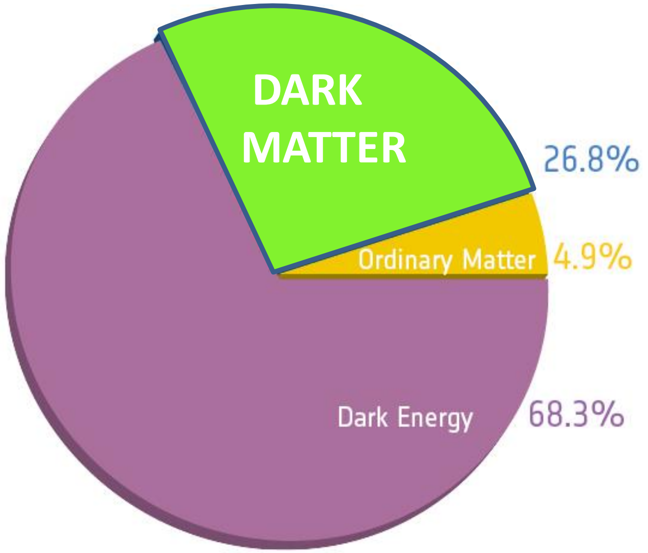
Malcolm Fairbairn

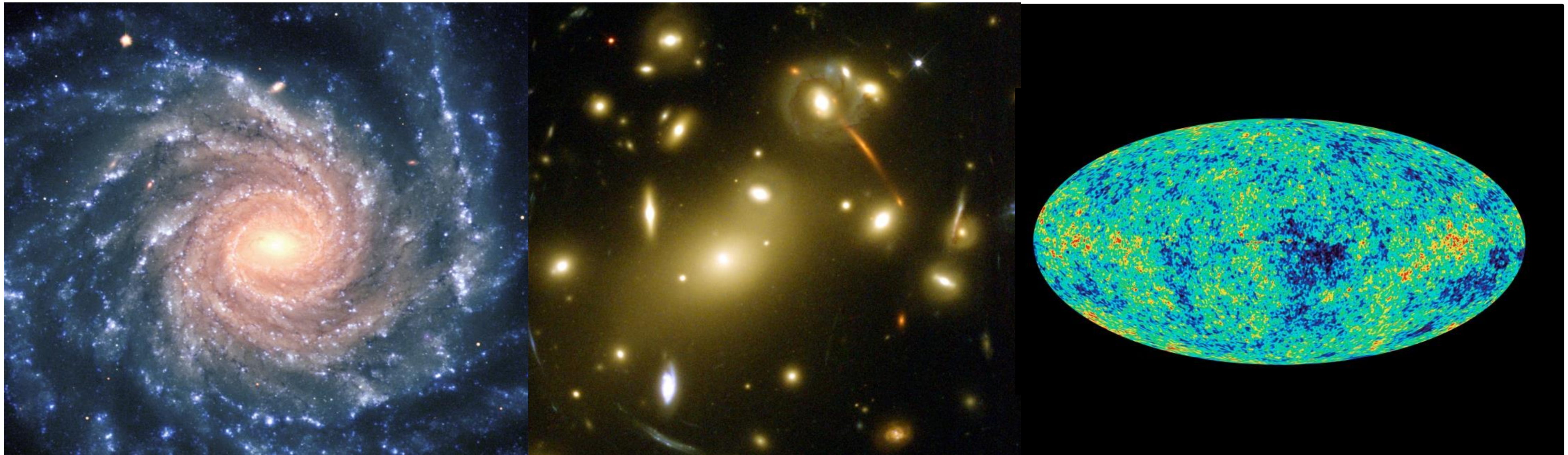
Chichely Hall – May 3rd 2017

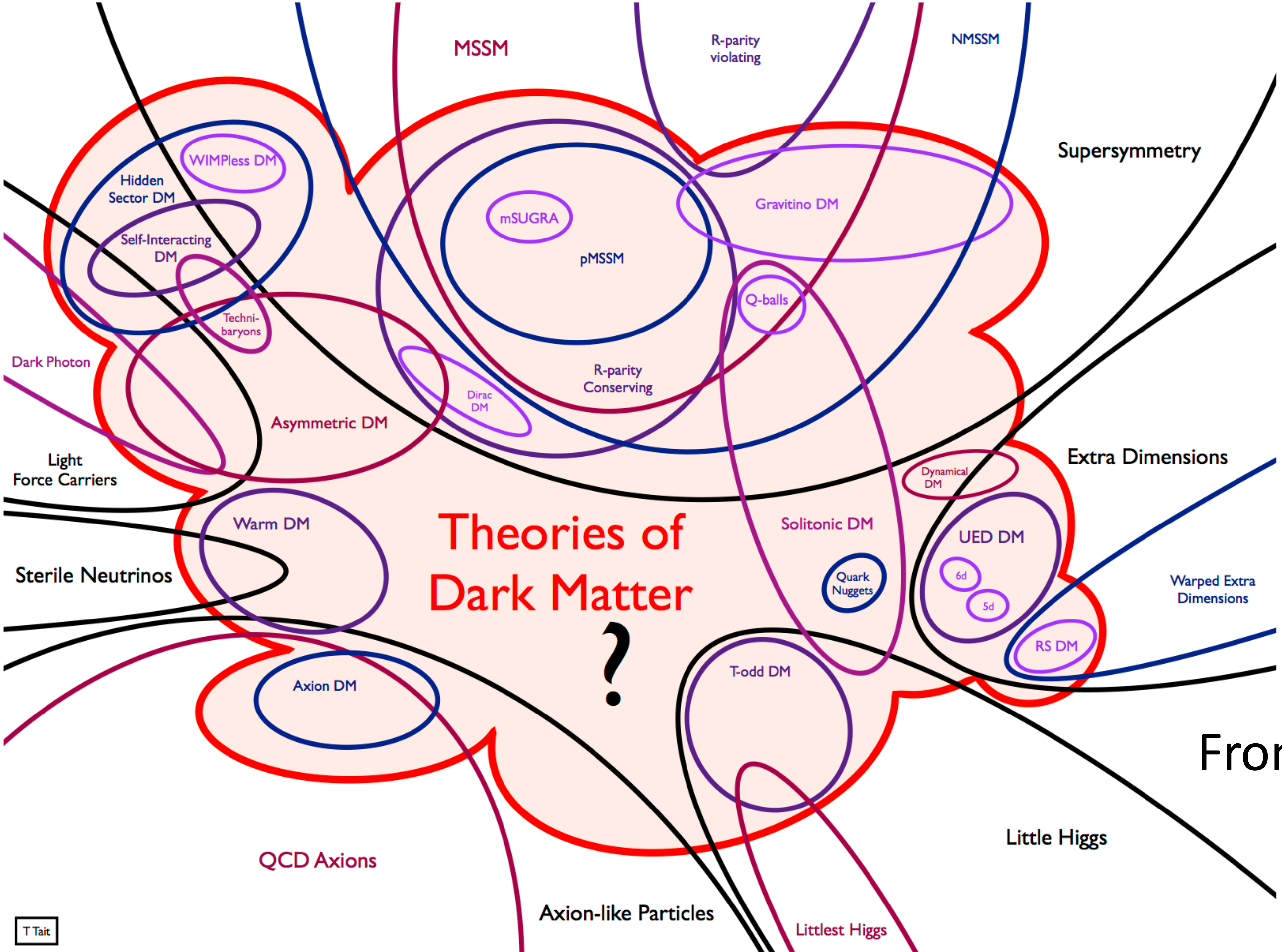
Dark Matter:

Much better at explaining missing matter in the Universe than modified gravity.

Still need dark energy but modified gravity doesn't solve that problem..

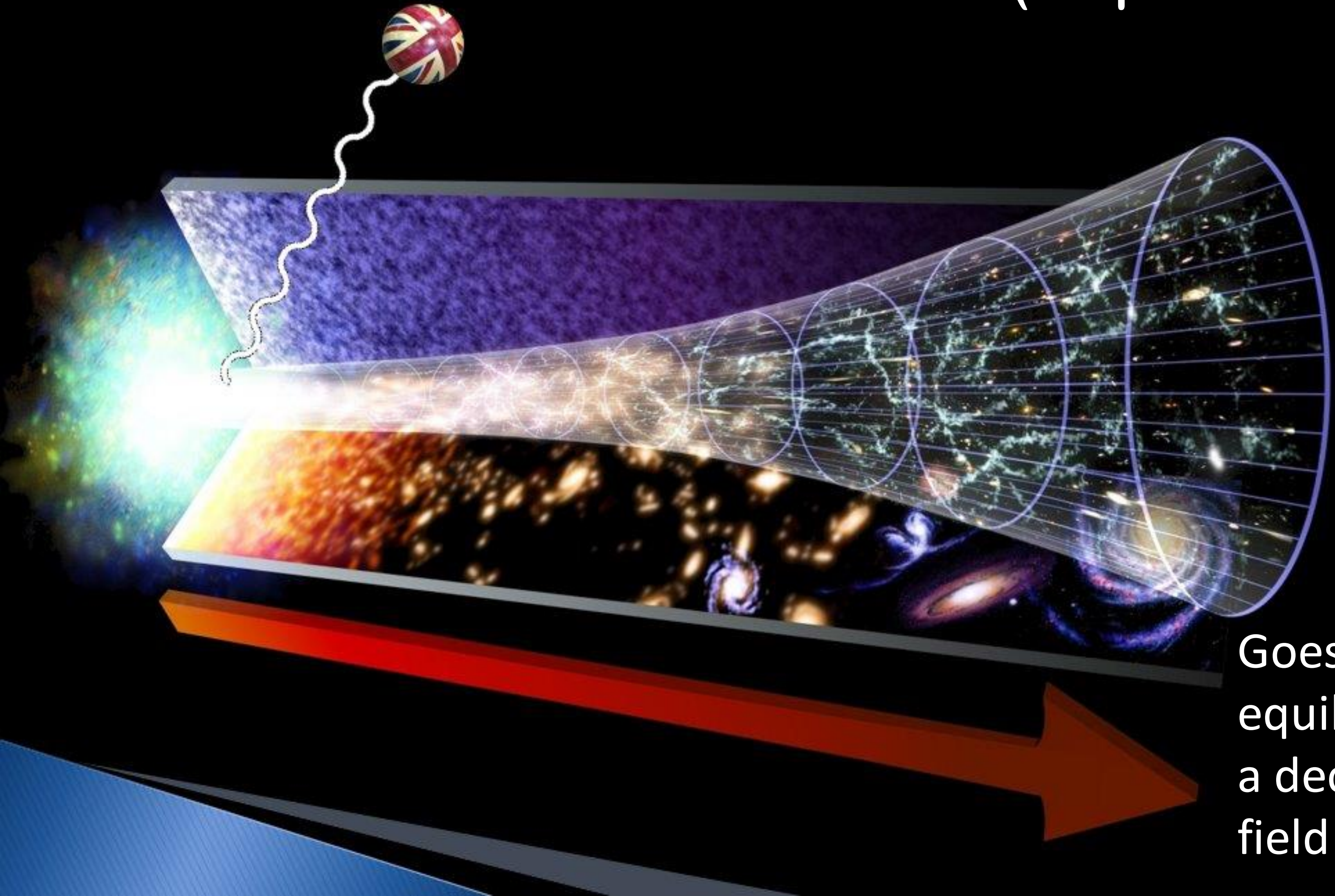






From Tim Tait

The Brexiton (Enqvist 2017, Rajantie 2017)



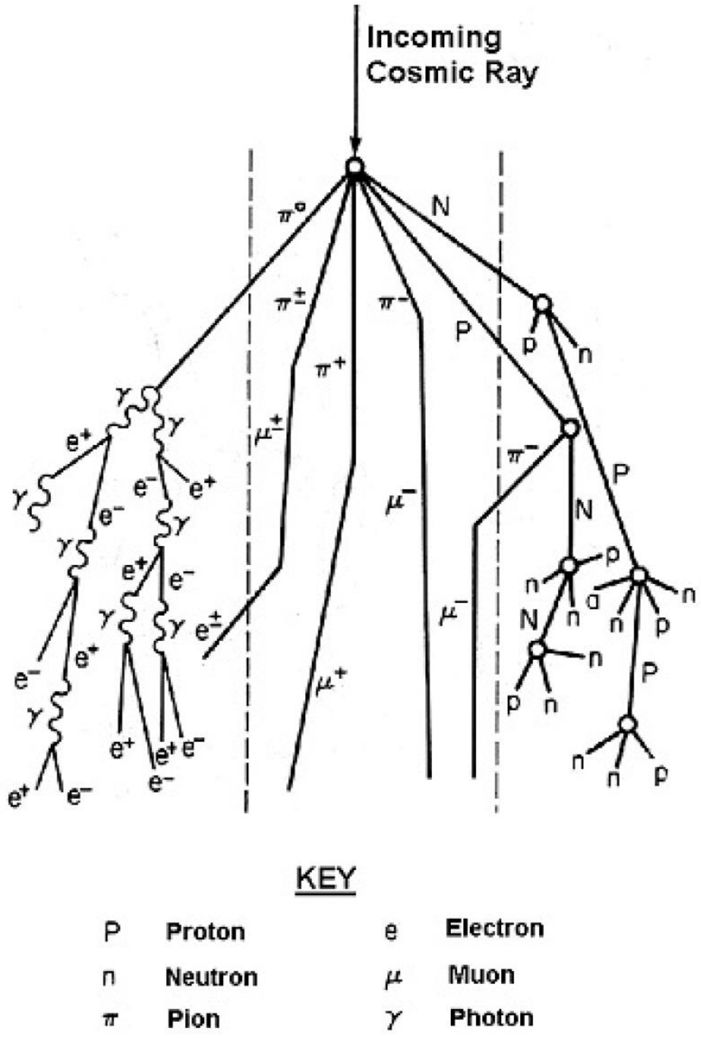
Goes out of thermal equilibrium then acts as a decoupled spectator field while it decays

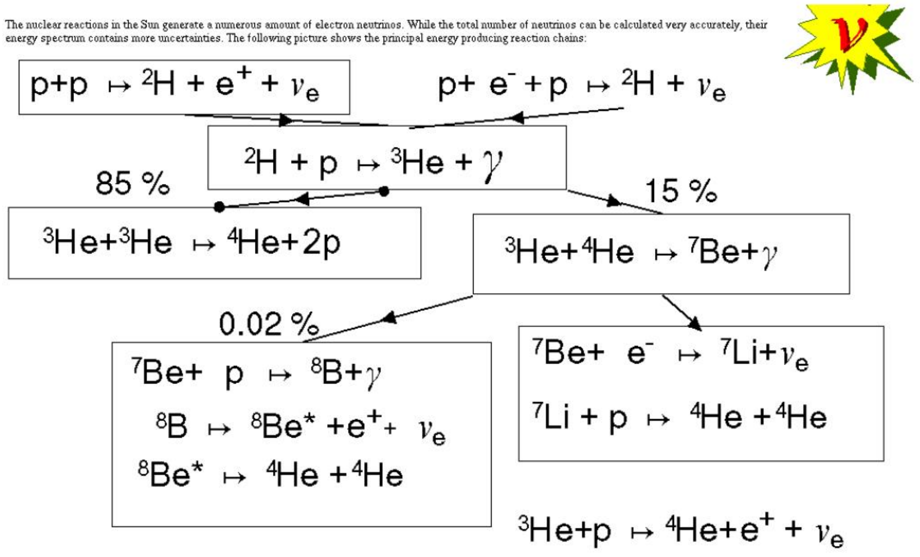
Part I

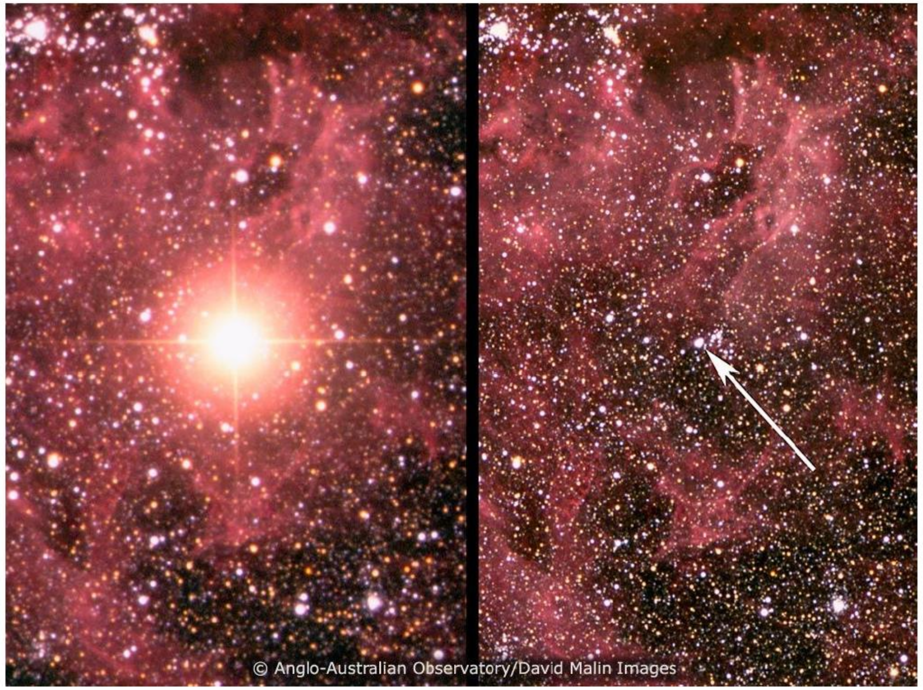
Thermal relic Dark Matter
and the
Neutrino Background

Science & Technology Facilities Council

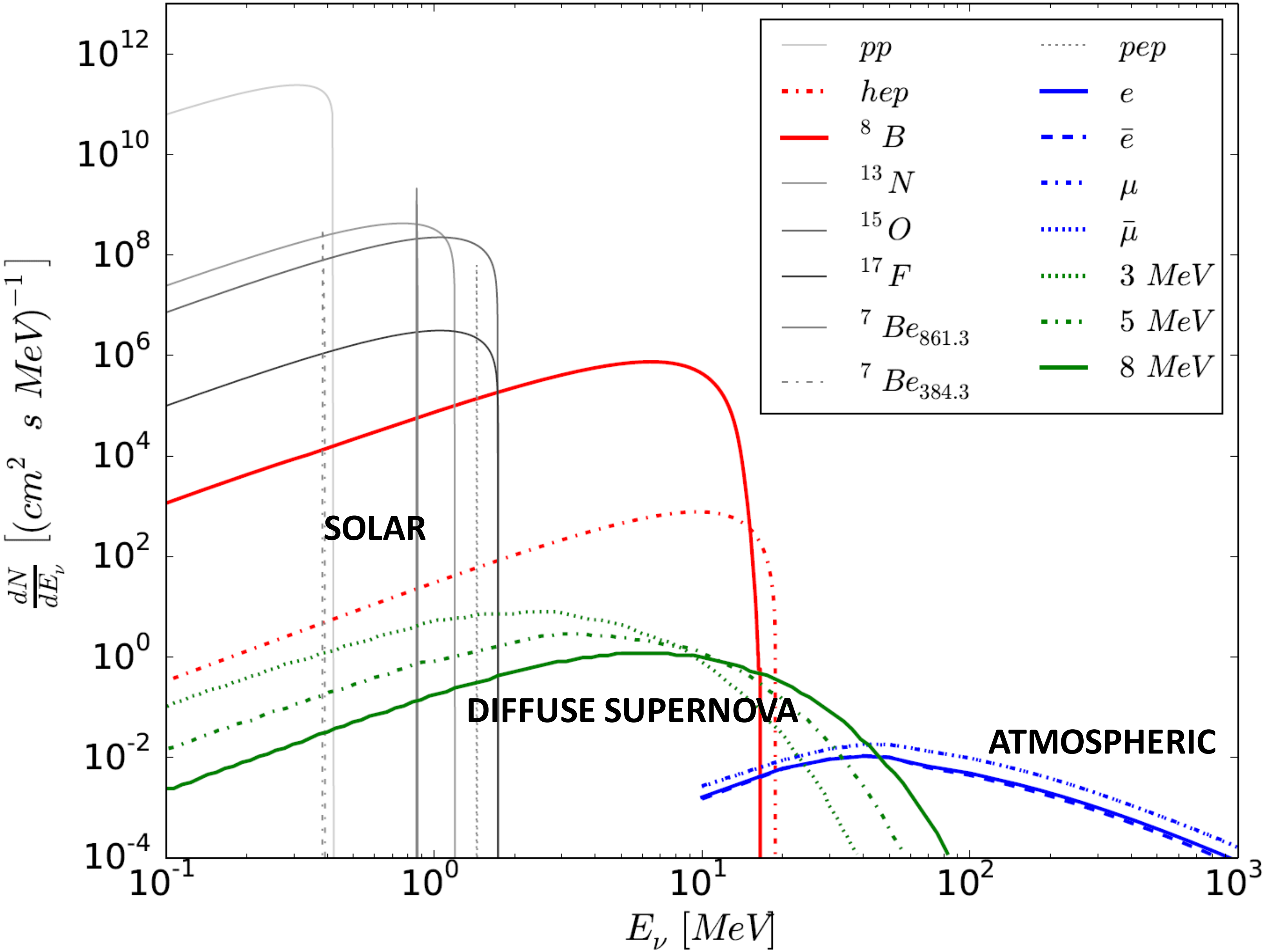
Astrophysical Neutrino Sources







Neutrino Background



Coherent Neutrino-Nucleon Interactions

$$\frac{d\sigma}{d(\cos\theta)} = \frac{G_F^2}{8\pi} Q_W^2 \, E_\nu^2 \, (1+\cos\theta) \, F(Q^2)^2$$

- Enhanced by factor N^2:

$$Q_W = N - (1 - 4\sin^2\theta_W)Z \simeq N - 0.08 \times Z \simeq N$$

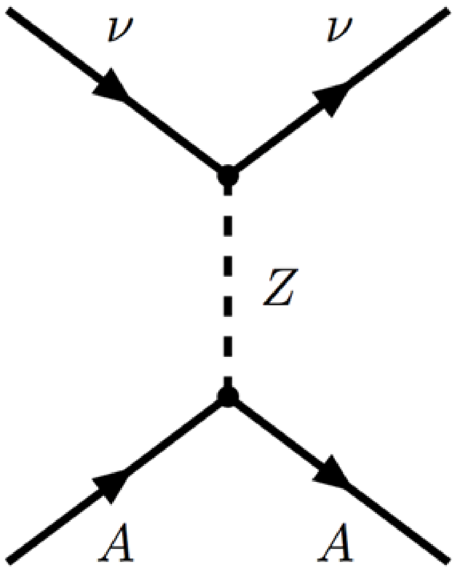
STILL NOT OBSERVED IN STANDARD MODEL

- $\cos\theta$: angle between in- … $\ll 1$
- $2m_T E_r = q^2 = 2E_\nu^2(1 -$ …

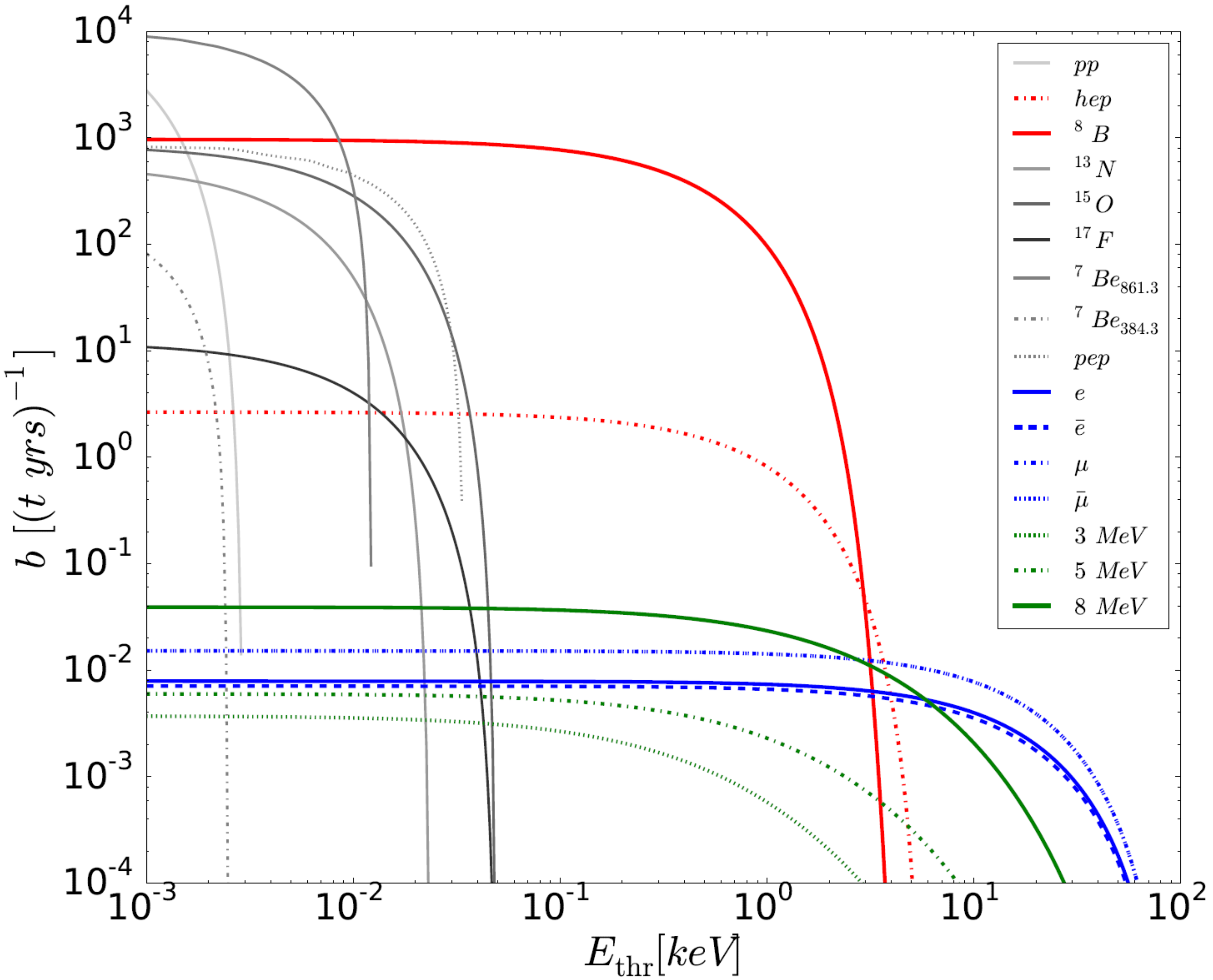
$$\Rightarrow \frac{d\sigma}{dE_r} = \frac{G_F^2}{4\pi} Q_W^2 \, m_T \, (1 - \frac{m_T E_r}{2E_\nu^2}) \, F(Q^2)^2.$$

$$\frac{dR_\nu}{dE_r} = n_T \int_{t_0}^{t_1} \int_{E_\nu^{\rm min}}^{\infty} \frac{dN(t)}{dE_\nu} \frac{d\sigma(E_\nu, E_r)}{dE_r} \, dE_\nu \, dt$$

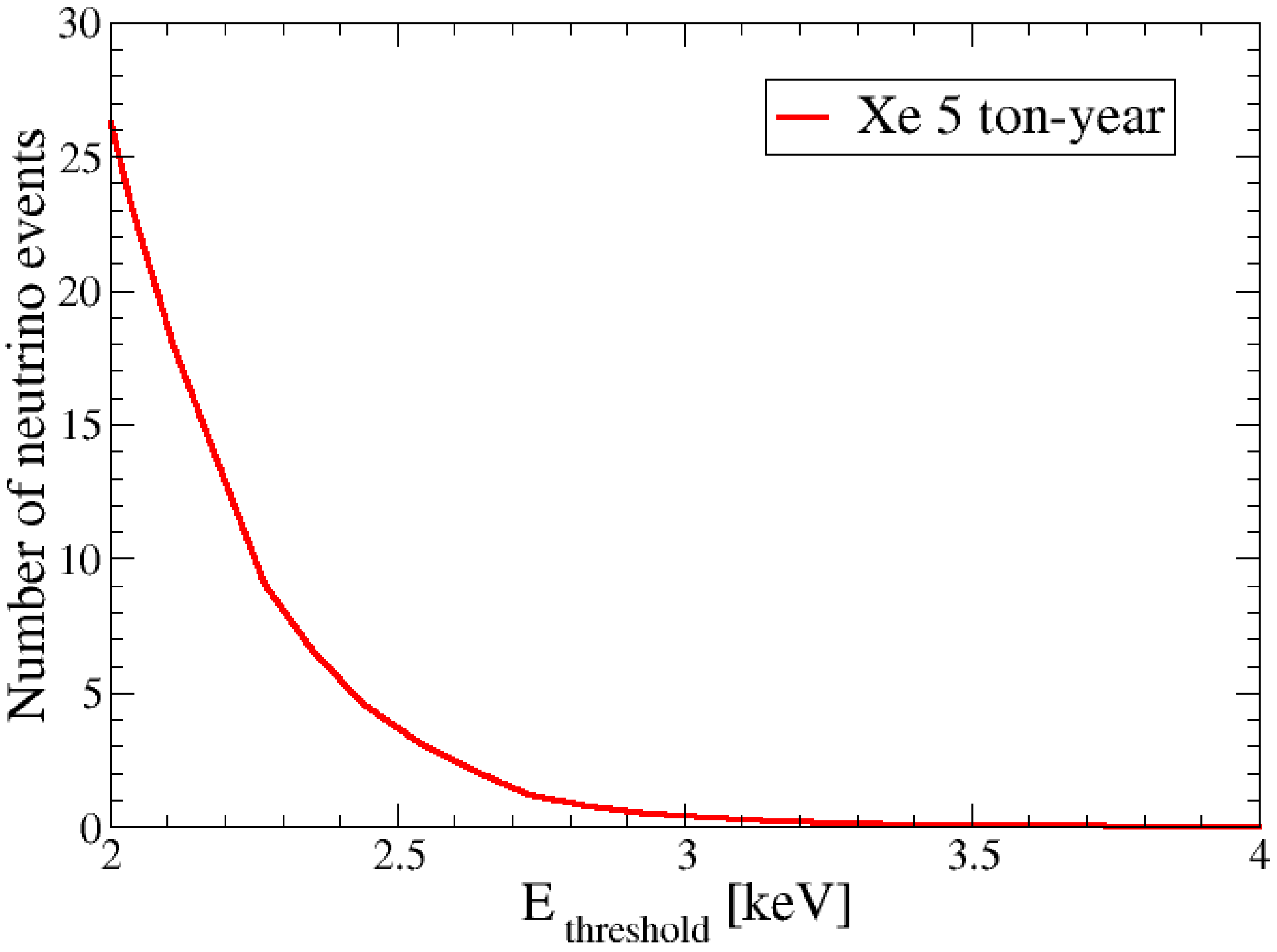
$$R_\nu = \int_{E_{\rm thr}}^{E_{\rm up}} \frac{dR_\nu}{dE_r} dE_r$$



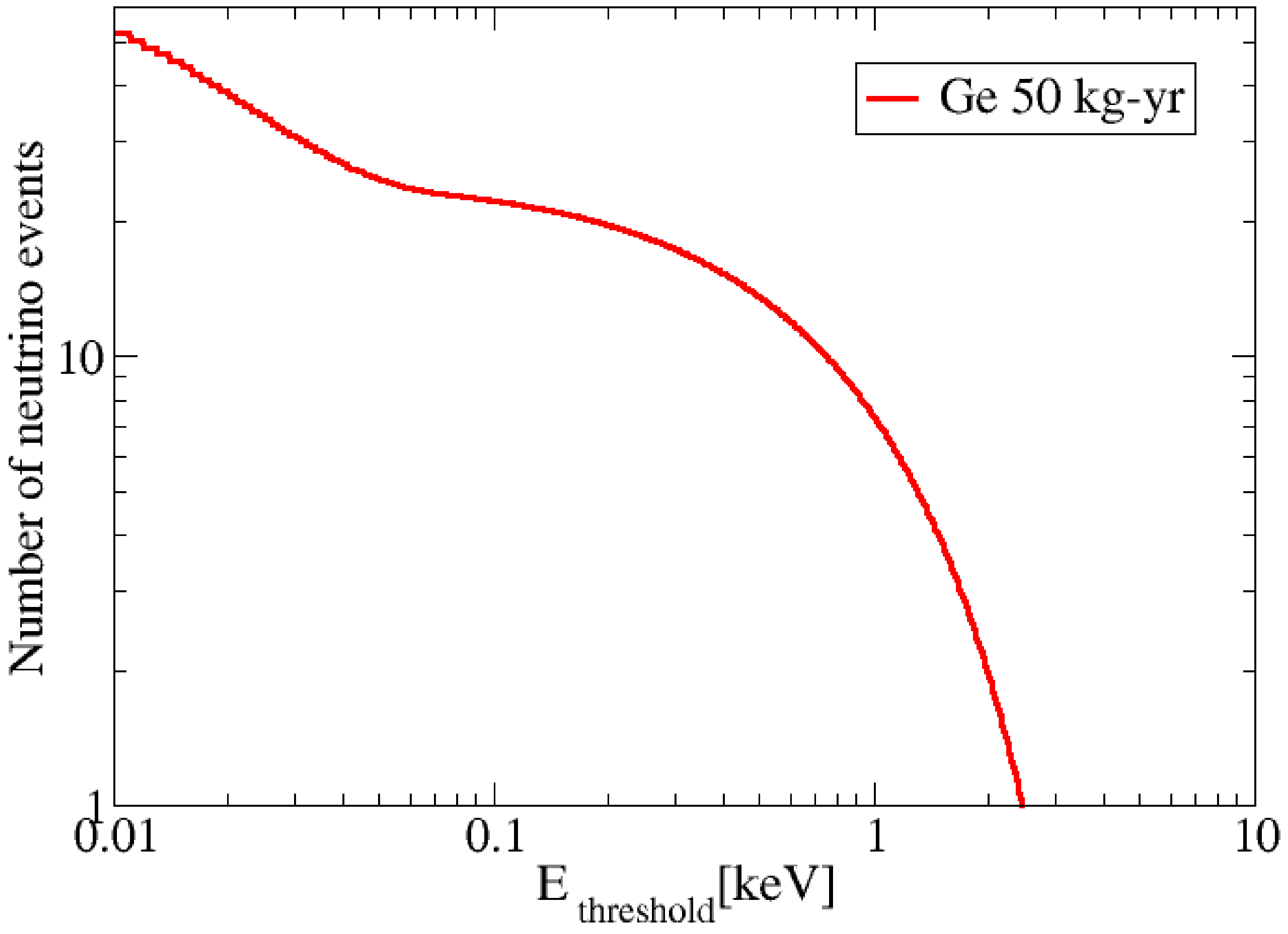
Integrated Event Rate in CF_4 detector above different Thresholds



Integrated Event Rate in Xe detector above different Thresholds



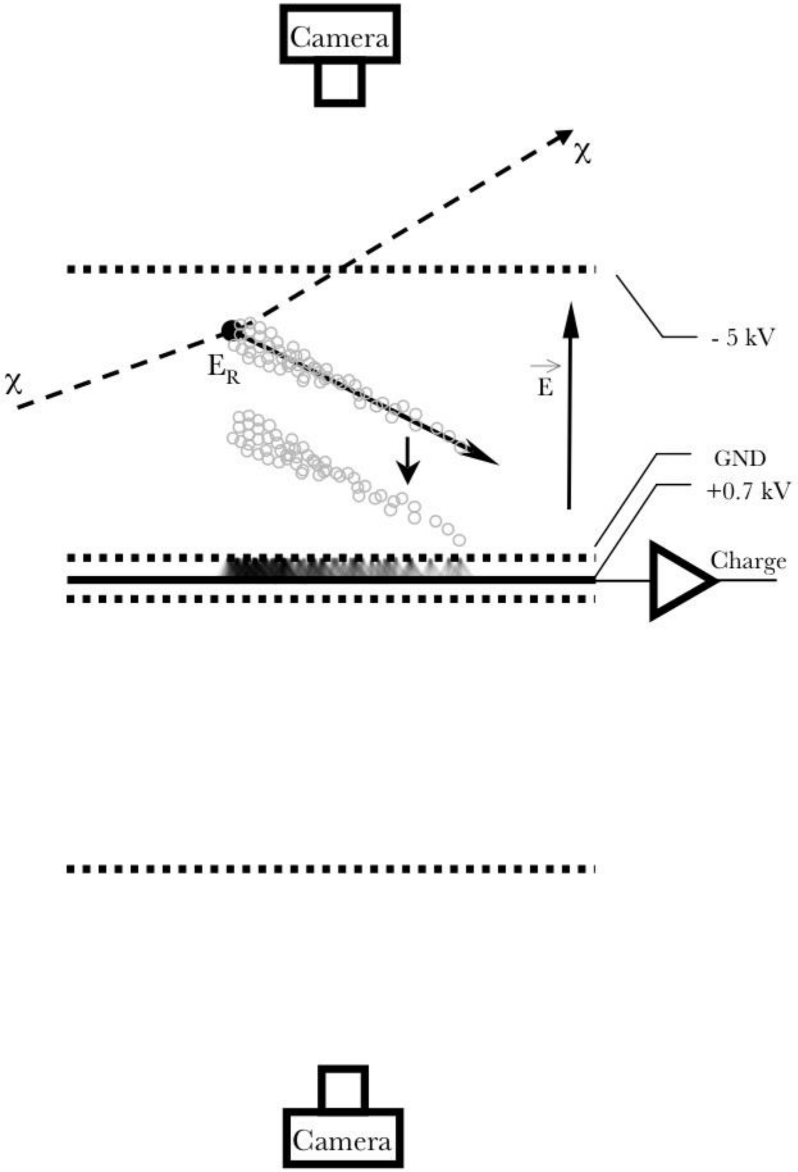
Integrated Event Rate in Ge detector above different Thresholds (B8, hep, N13, O15, F17 and Be7 lines)



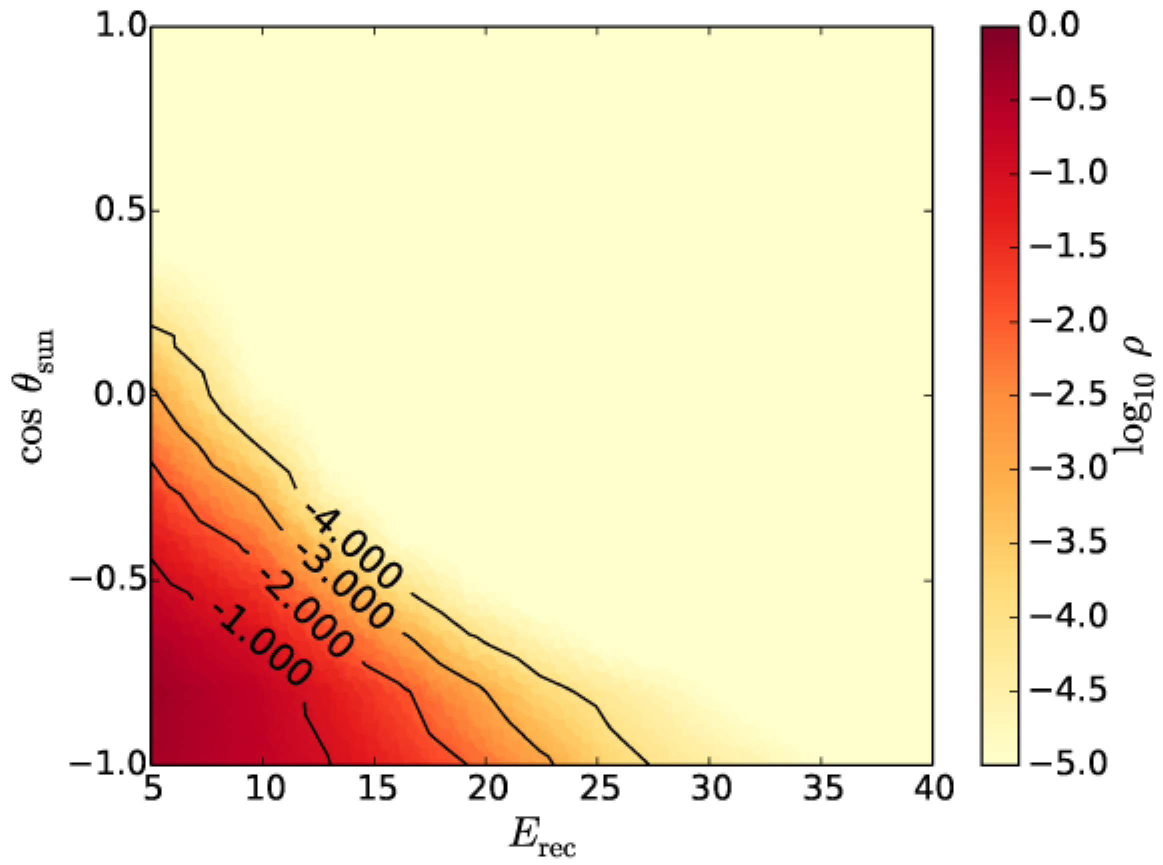
What if we can Tell which direction the dark matter is coming from?

DIRECTIONAL DARK MATTER DETECTION

e.g. DMTPC



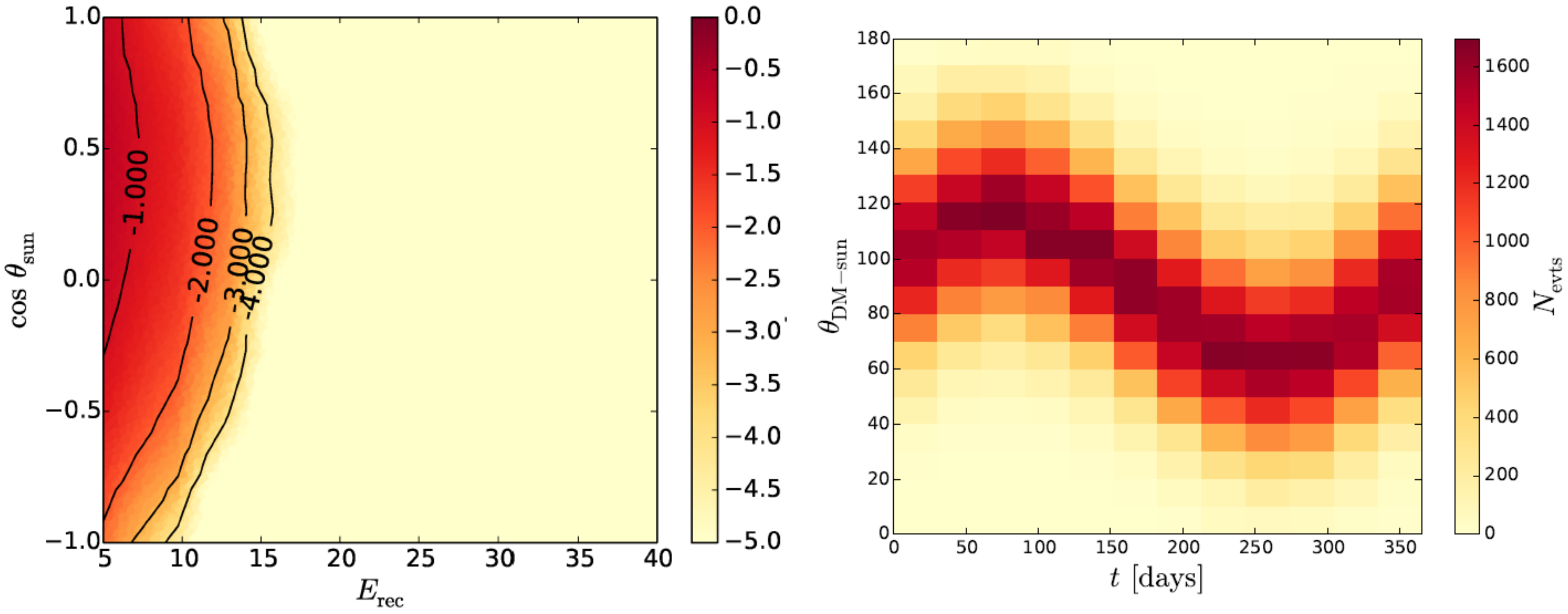
angle between recoil from Solar neutrino and sun



$$\cos\theta' = \frac{E_\nu + m_T}{E_\nu}\sqrt{\frac{E_{\rm r}}{2m_T}}$$

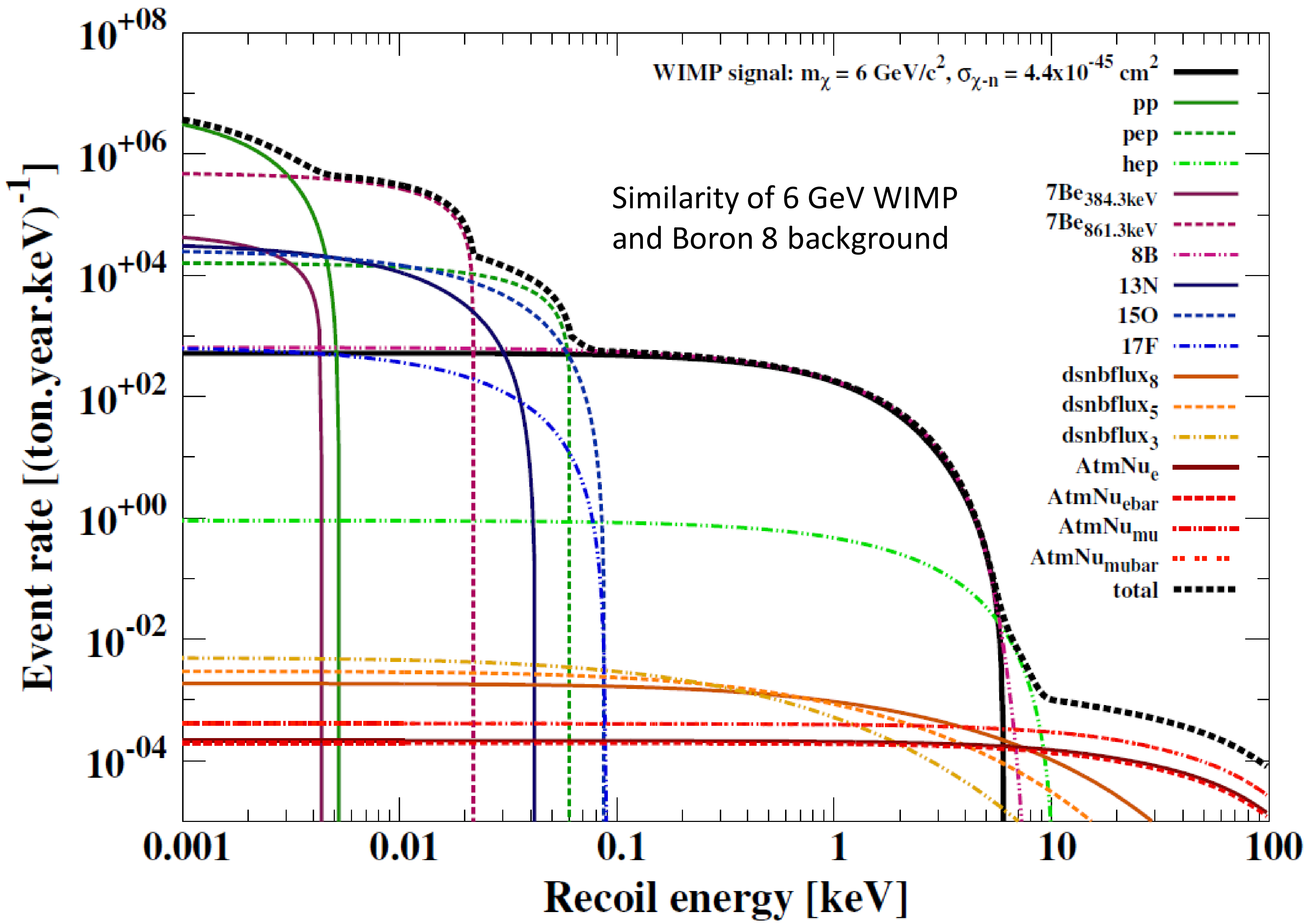
arXiv:1406.5047

angle between recoil from Dark Matter and sun

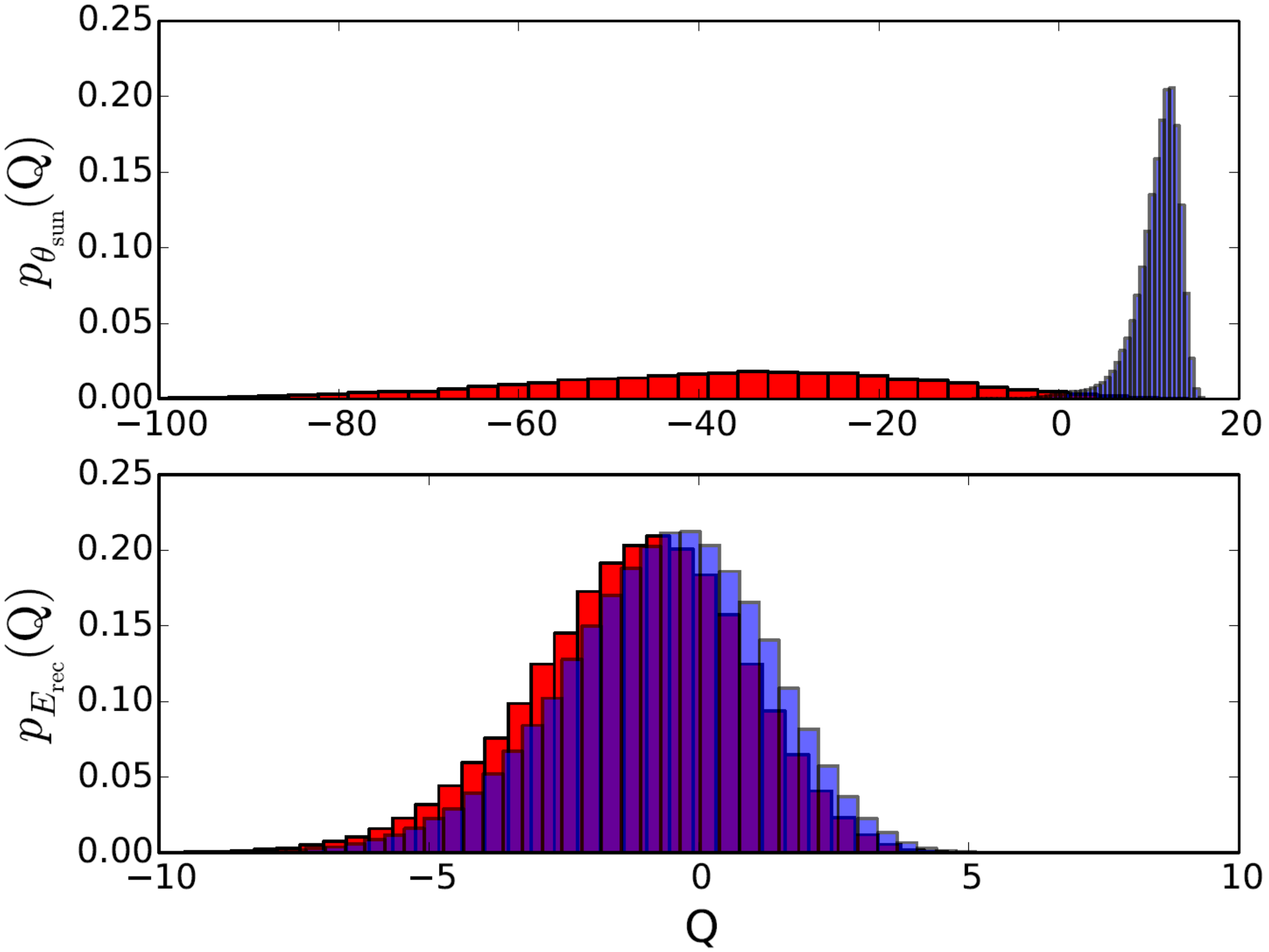


- Preferred arrival direction roughly from Cygnus A
- This changes during the year
- Lighter (heavier) dark matter more (less) directional above a given threshold

arXiv:1406.5047



Ruppin et al 1408.3581



The normalised background only distribution $p_B(Q_B)$ (blue) and signal plus background distribution $p_{SB}(Q_{SB})$ (red) including angular information (top) and excluding angular information (bottom) for s=10 and b=500 for a 6 GeV dark matter particle in a CF_4 detector.

arXiv:1406.5047

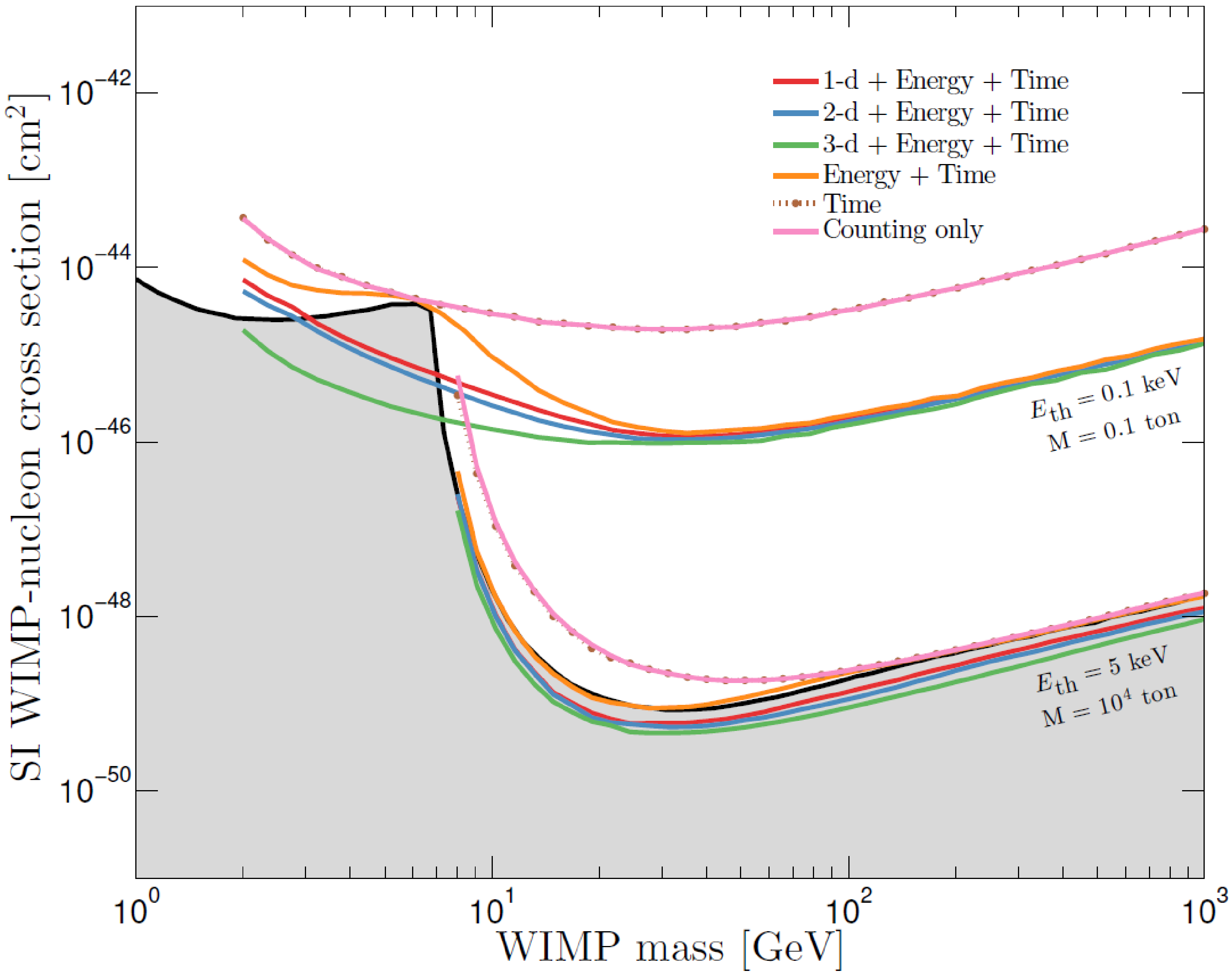
Various Effects, some of which compete with each other:-

- For Low mass DM, only fastest moving particles will give a signal, so that points right back to Cygnus, easy to discriminate from the Sun

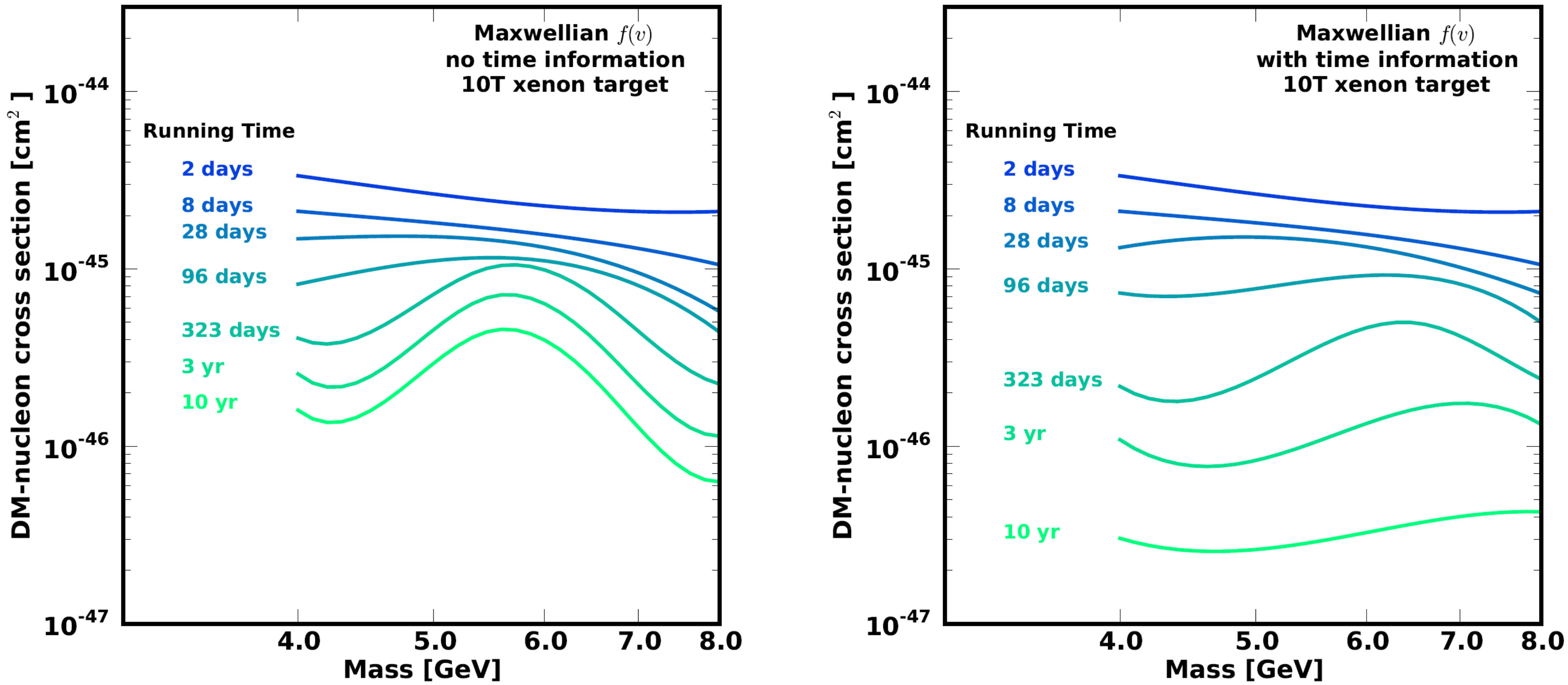
- High mass DM can give a signal for DM coming from all directions so directionality less important, but it has an energy spectrum quite different from solar neutrinos

- Higher energy recoil tracks have a much better directional angle reconstruction

results from O'Hare et al
arXiv:1505.08061



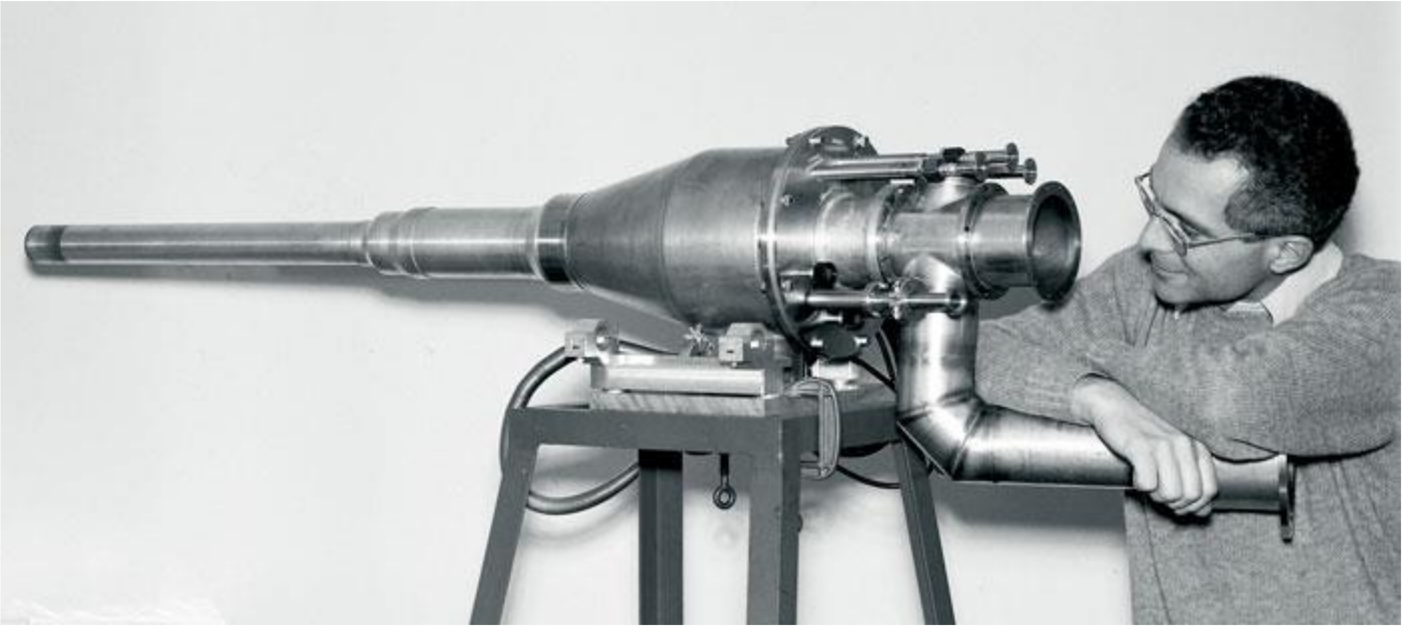
What about NO DIRECTIONALITY, only TIME information?



Davis arXiv:1412.1475

In principle, direction, energy and time information can discriminate neutrinos from dark matter.

Interesting Possibility – Polarised targets



Michel Borghini with a polarized target at CERN in 1976.

see also

"Dark Matter Detection with Polarized Detectors"

Chiang, Kamionkowski & Krnjaic, arXiv:1202.1807

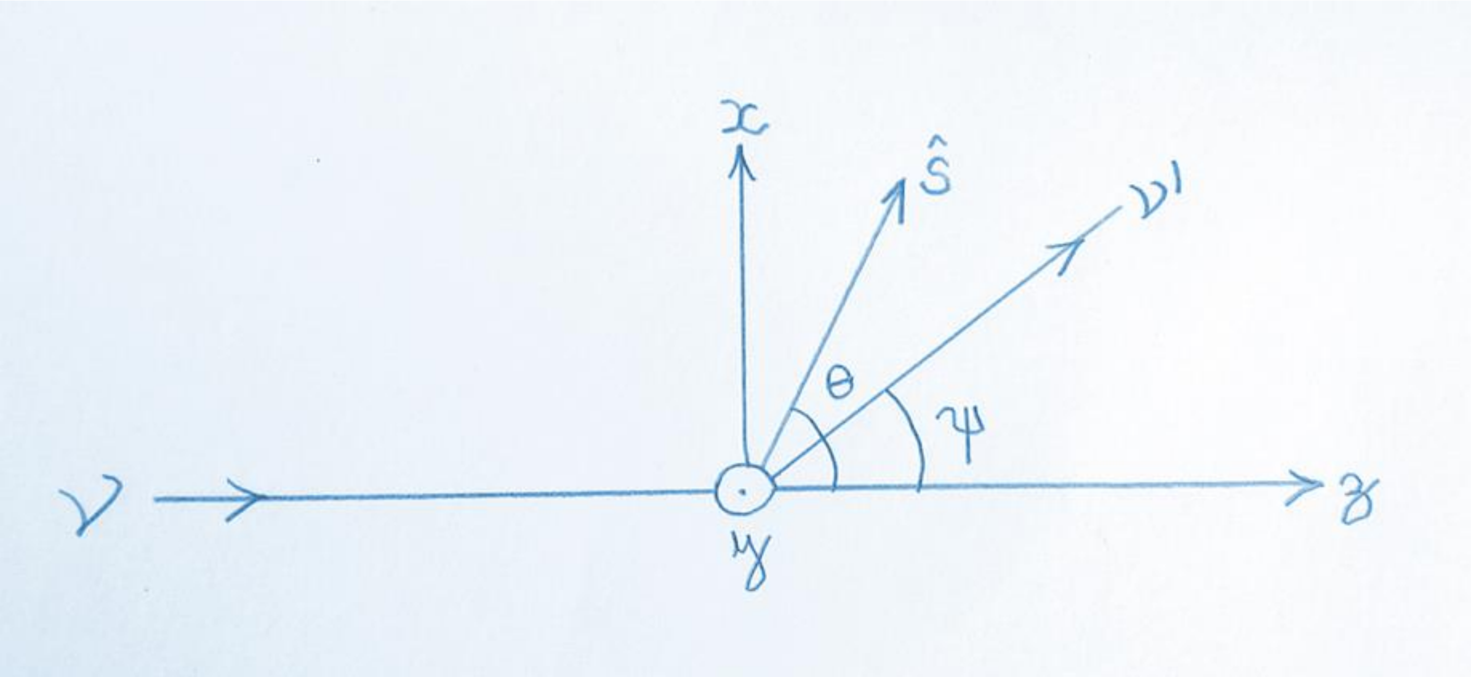
Interesting Possibility – Polarised targets

- Polarised targets not very directional for dark matter
  (effect is supressed when no preferred helicity)

- Polarised targets with unpaired neutrons ARE directional to axial coupling of neutrinos

- Effect usually dwarfed by vector coupling due to coherent enhancement

- Notable exception is Helium-3



if N=1 and c_A due to unpaired neutron

cancellation between V and A for particular orientations of the spin and the arrival direction of the neutrino

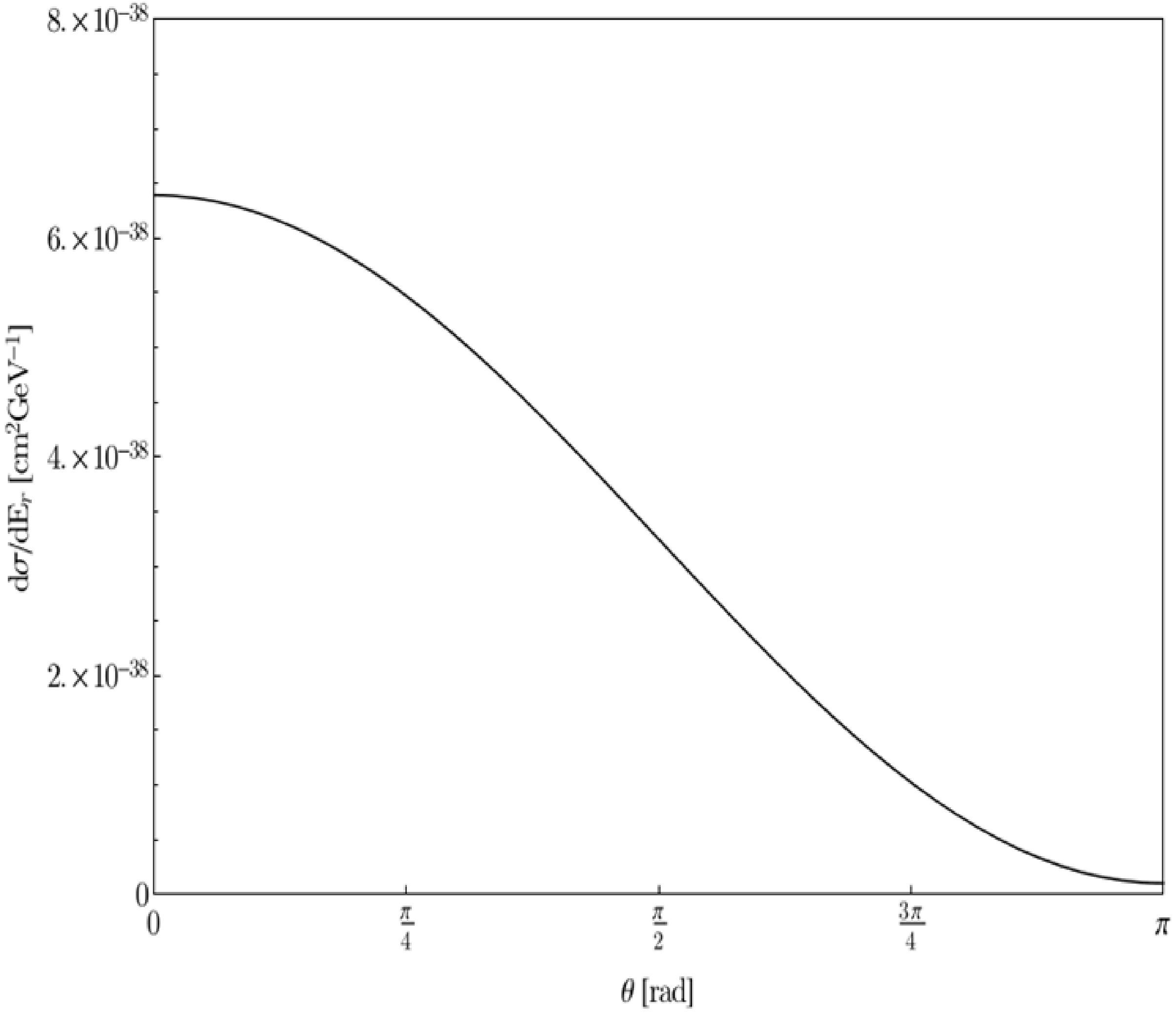
$$\frac{d\sigma}{d\Omega} = \frac{G_F^2 E_\nu^2}{16\pi^2}\{\underbrace{c_V^2 - 3c_A^2 + (c_V^2 - c_A^2)\cos\psi}_{\textbf{SI}} + \underbrace{2c_A[(c_V - c_A)\hat{v}.\hat{s} + (c_V + c_A)\hat{v}'.\hat{s}]}_{\textbf{SD}}\}$$

$$c_V^{\text{nucleus}} = Zc_V^p + Nc_V^n$$
$$c_A^{\text{nucleus}} = c_A^{\text{unpaired nucleon}}$$

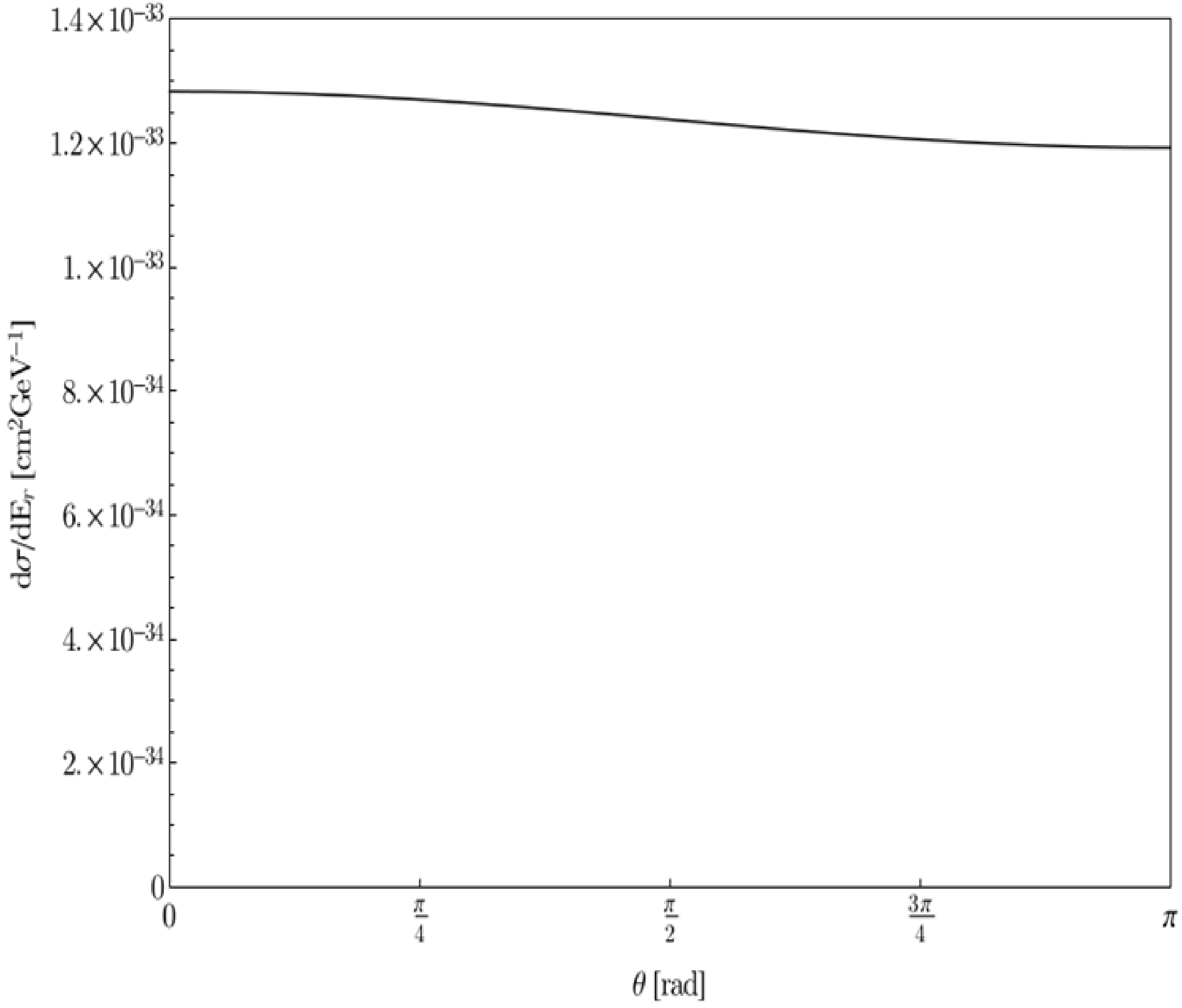
	c_V	c_A
Proton	$1 - 4\sin^2\theta_W$	1.26
Neutron	-1	-1.26

6.4 MeV Neutrino-nucleon cross section as function of angle

For Xenon there is a small effect while for Helium-3 there is almost a complete cancellation.



^{3}He



^{129}Xe

Some obvious problems with Helium-3

- Tritium contamination would be a major background

- Simplest Polarisation scheme for He-3 for NMR uses potassium and/or rubidium, both of which are potential contaminants

- Helium-3 makes Xenon look as cheap as water

$$\alpha = \frac{1}{2}\left|\frac{\frac{d\sigma}{dE_r}(0) - \frac{d\sigma}{dE_r}(\pi)}{\frac{d\sigma}{dE_r}(\pi/2)}\right|$$

	α
^{3}He	0.97
^{13}C	0.41
^{15}N	0.36
^{19}F	0.22
^{129}Xe	0.04

We expect to detect Neutrinos. What could we do with this information?

Experiment	ϵ (ton-year)	$E_{th,n}$ (keV)	$E_{th,o}$ (keV)	E_{max} (keV)	$R(pp)$	$R(^8\text{B})$
G2-Ge	0.25	0.35	0.05	50	–	[62 – 85]
G2-Si	0.025	0.35	0.05	50	–	[3 – 3]
G2-Xe	25	3.0	2.0	30	[2104 – 2167]	[0 – 64]
Future-Xe	200	2.0	1.0	30	[17339 – 17846]	[520 – 10094]
Future-Ar	150	2.0	1.0	30	[14232 – 14649]	[6638 – 12354]
Future-Ne	10	0.15	0.1	30	[1141 – 1143]	[898 – 910]

arXiv:1604.01025

We expect to detect Neutrinos. What could we do with this information?

Can measure the Weinberg angle at very low energies

Exp.	$\phi_\nu^{^8\mathrm{B}}$	ϕ_ν^{pp}	$\sin^2\theta_W$
Measured	2.0% [a]	10.6 %[b]	
G2	1.9% (1.9%)	2.5 % (2.5%)	4.6% (4.5%)
Future-Xe	1.8% (0.9%)	0.7% (0.7%)	1.7% (1.7%)
Future-Ar	1.0% (0.6%)	0.6% (0.5%)	1.5% (1.4%)
HyperK[c]	1.43%	–	–

Measure Boron-8 flux using nuclear recoils and pp flux using electron recoils

arXiv:1604.01025

We expect to detect Neutrinos. What could we do with this information?

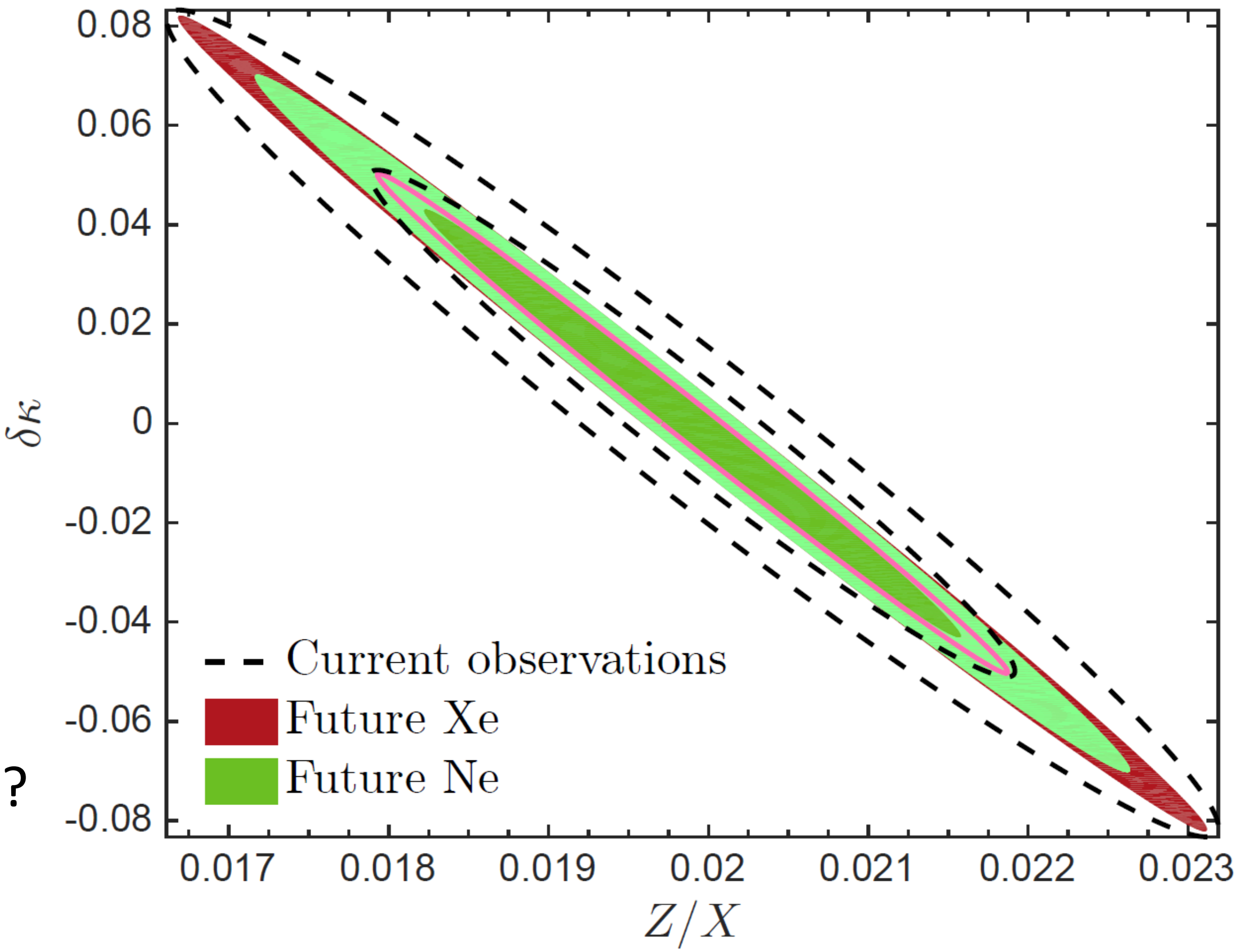
Limits average opacity vs. metallicity

Narrows line but still huge degeneracy

Needs to be broken by observation of CNO neutrinos –

SNO+ ???

Future direct detection experiments ???



arXiv:1604.01025

Tests of BSM Physics

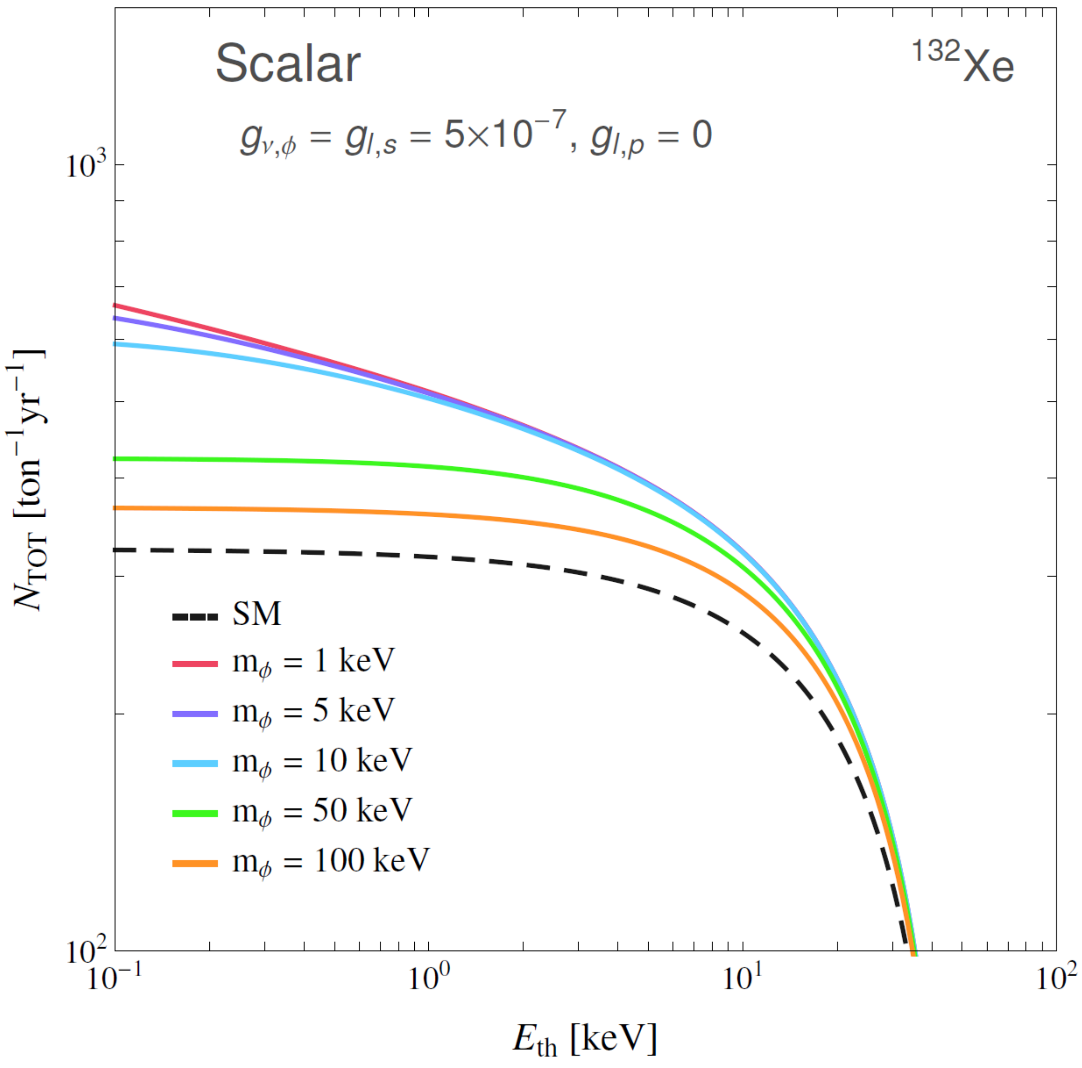
Momentum exchanged for pp-neutrino electron events is around 10 keV

Momentum exchanged for neutrino-nucleon events is about MeV scale

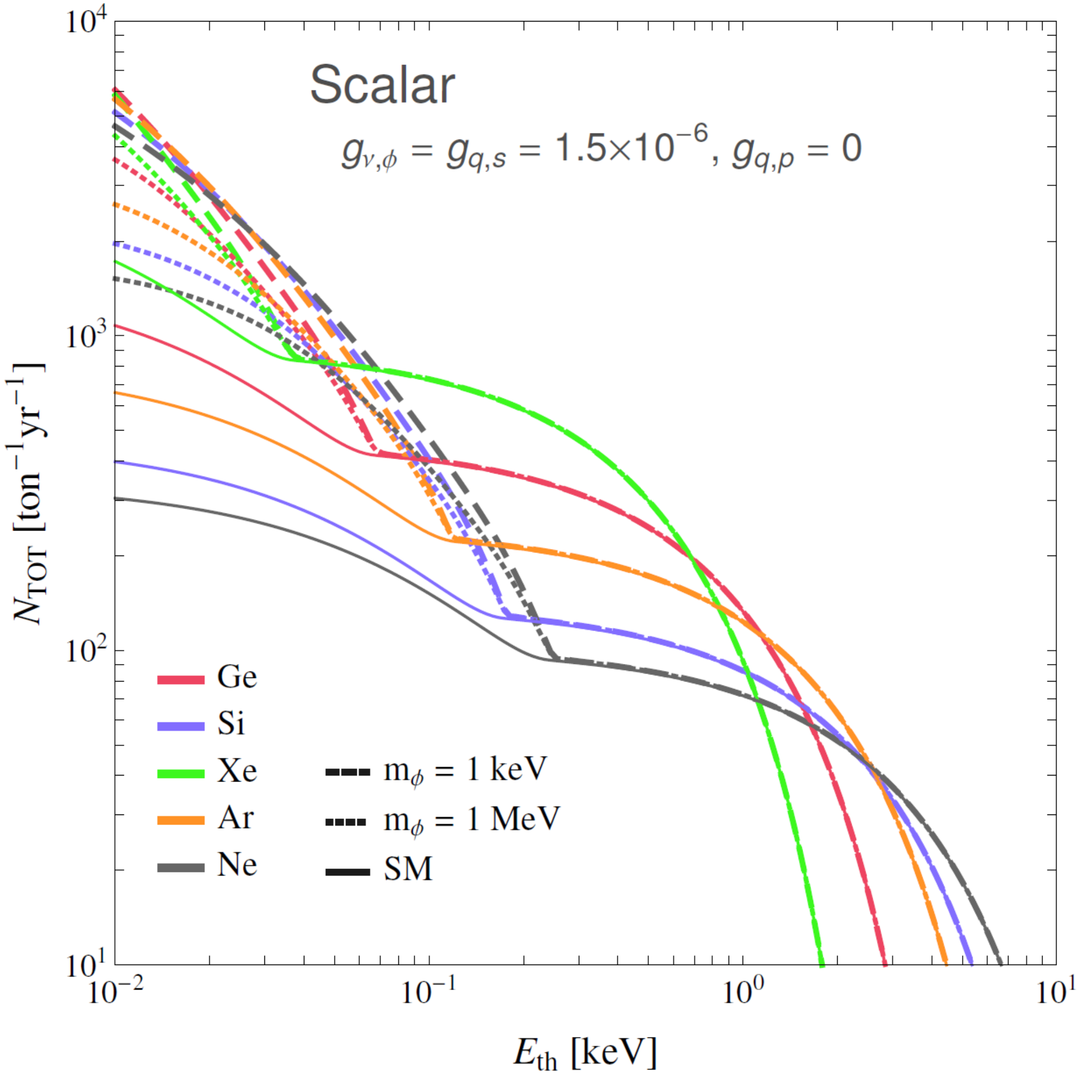
Both Q^2 unstudied in those settings, can probe new interactions.

Tests of BSM Physics

$$(g_{\nu,\phi}\,\phi\bar{\nu}_R\nu_L + h.c.) + \phi\bar{\ell}g_{\ell,s}\ell + \phi\bar{q}g_{q,s}q$$



electron recoils



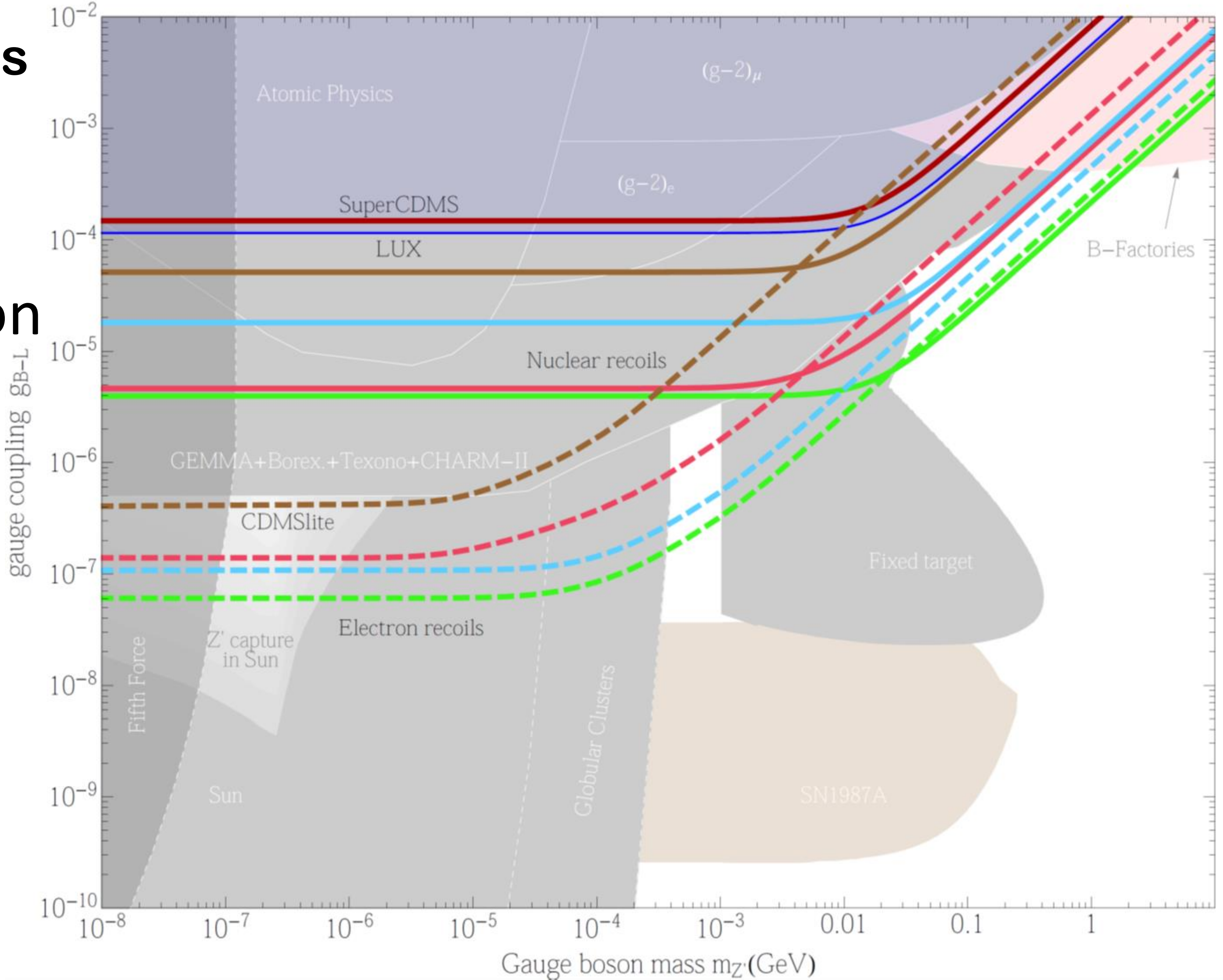
nuclear recoils

Tests of BSM Physics

U(1)$_{B-L}$ gauge boson couples to B-L charge of SM particles

Dashed electron, solid nucleon.

Green future xenon
Blue G2 xenon
Red G2 germanium



Part II

Detecting Axion Mini-clusters through Microlensing

Science & Technology Facilities Council

erc

Axions as Dark Matter

What is this?

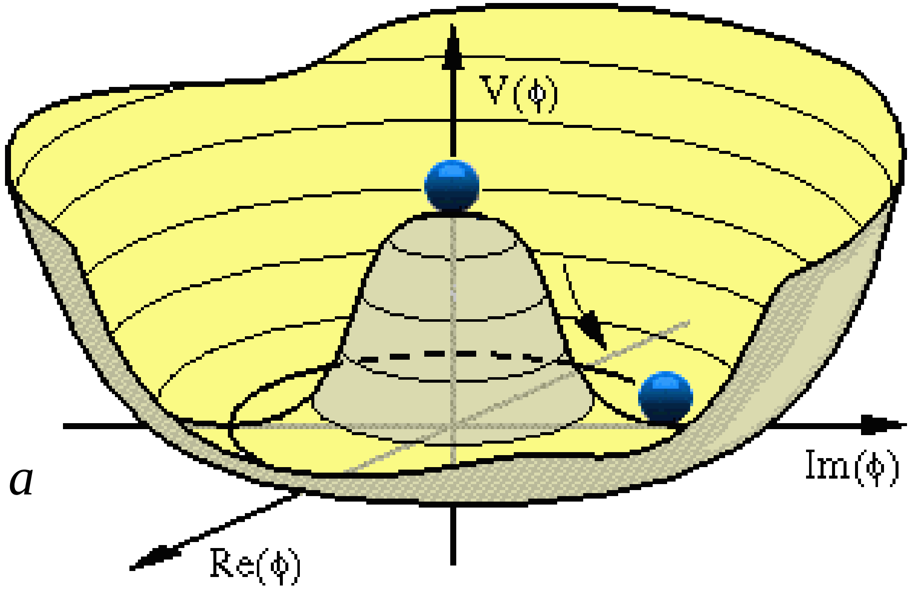
$$S = \int d^4x \left[-\frac{1}{4g^2} G^{a,\mu\nu} G^a_{\mu\nu} + \frac{\theta}{32\pi^2} G^{a,\mu\nu} \tilde{G}^a_{\mu\nu} + i\bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} M \psi \right]$$

Gluon kinetic energy

quark kinetic energy

quark mass

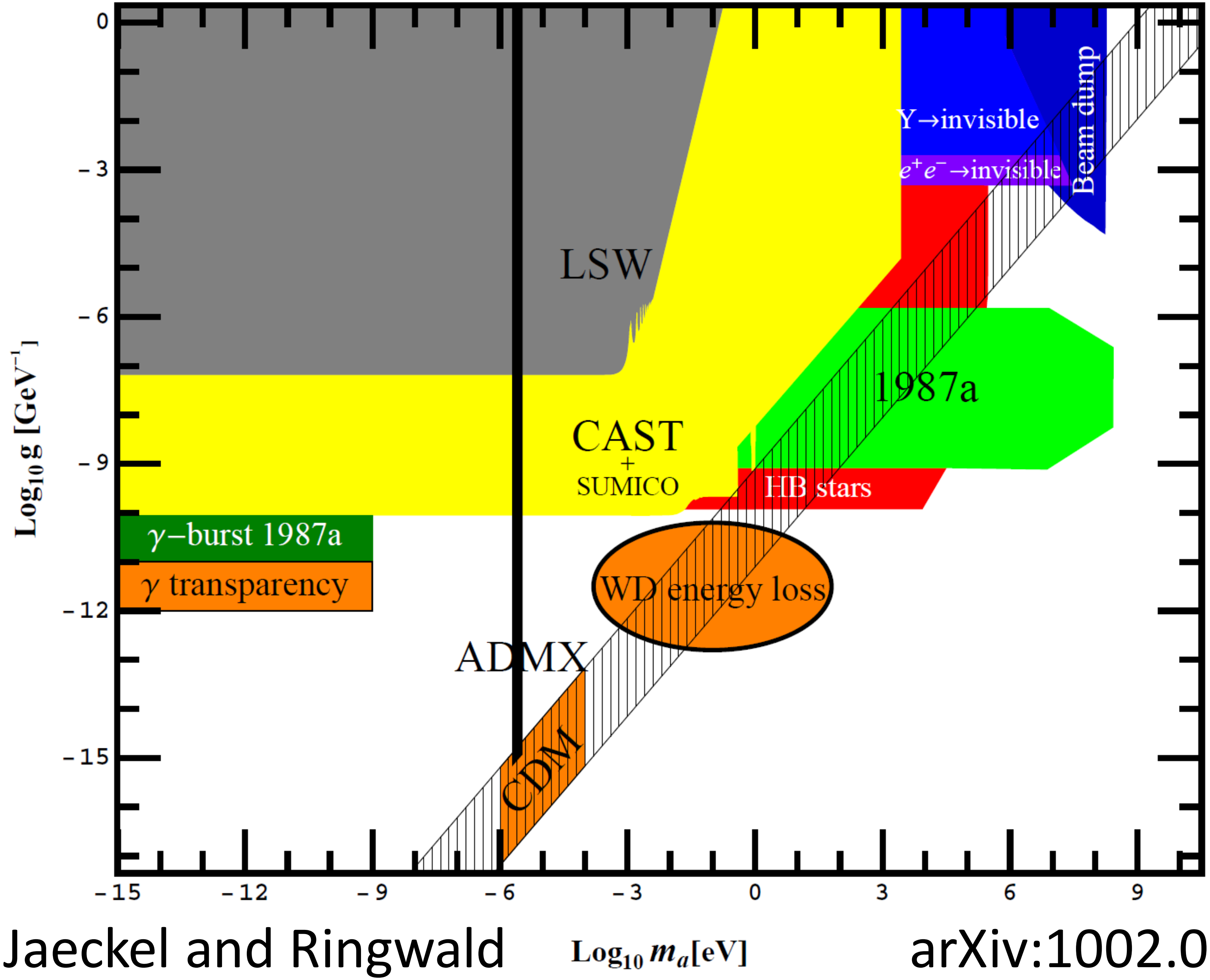
$$\theta \longrightarrow \theta - a/f_a$$



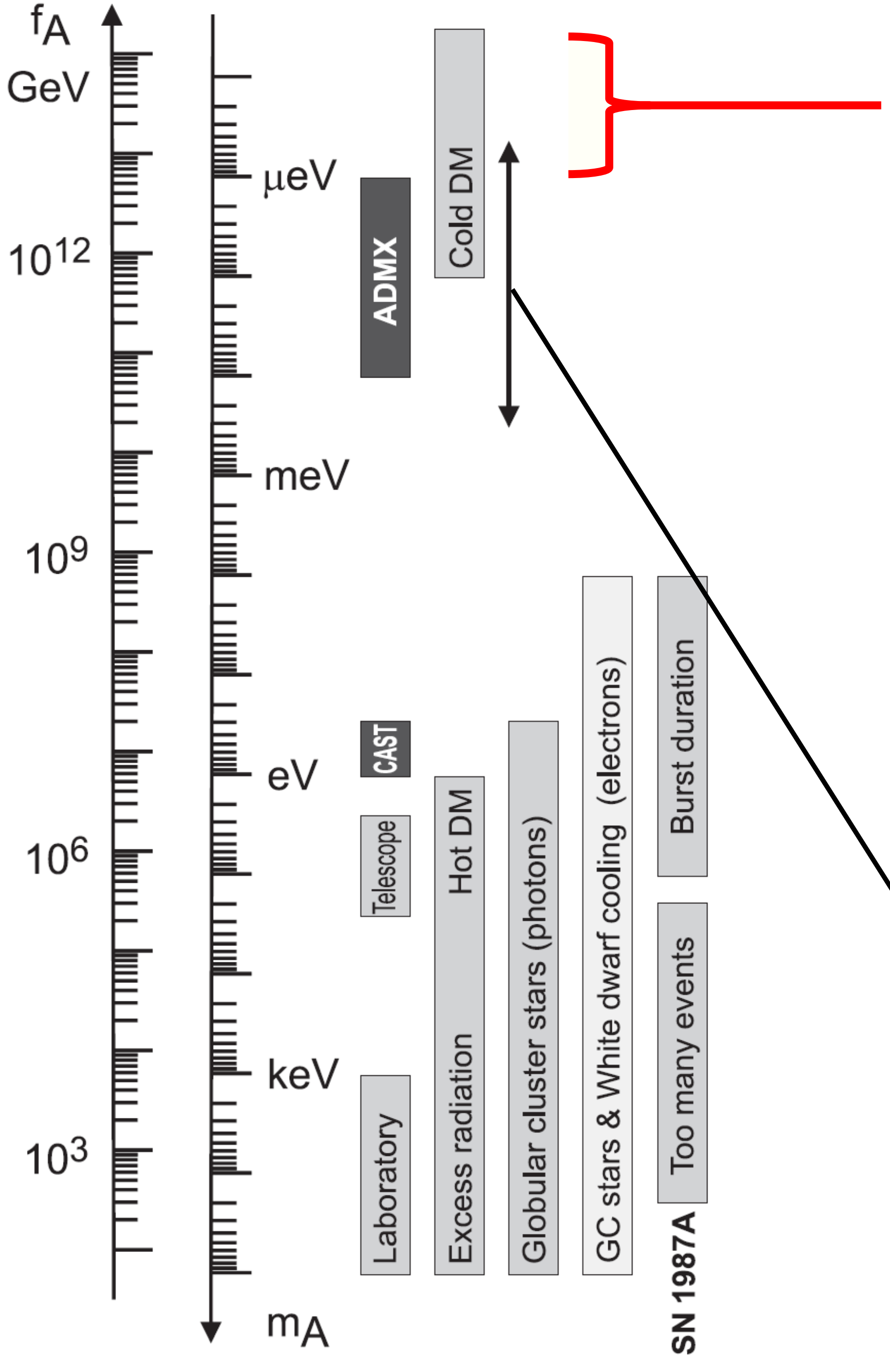
Promote θ to field a

$$m_a^2 \sim \frac{f_\pi^2 m_\pi^2}{f_a^2}$$

Also induces coupling to photons



Jaeckel and Ringwald arXiv:1002.0329



Here you can get good dark matter, but generically you get too many isocurvature perturbations if PQ symmetry was broken before inflation (although see Hogan, Fairbairn and Marsh and Ballesteros et al for ways around this.)

Tuning required to fix this worse than strong CP problem in first place (Mack 2009)

Can also get good relic abundance if PQ symmetry broken after inflation.

U(1) PQ symmetry broken by axion mass after inflation

Relic abundance then set by different value of the axion field in different regions of the Universe

Generic answer (from particle data group) is given by

$$\Omega_A^{\rm real} h^2 \approx 0.11 \left(\frac{41 \ \mu{\rm eV}}{m_A} \right)^{1.19}$$

On its own suggests that the axion mass is about 40 micro-eV but there is a range over perhaps a couple of orders of magnitude because the contribution from the decay of topological defects is uncertain.

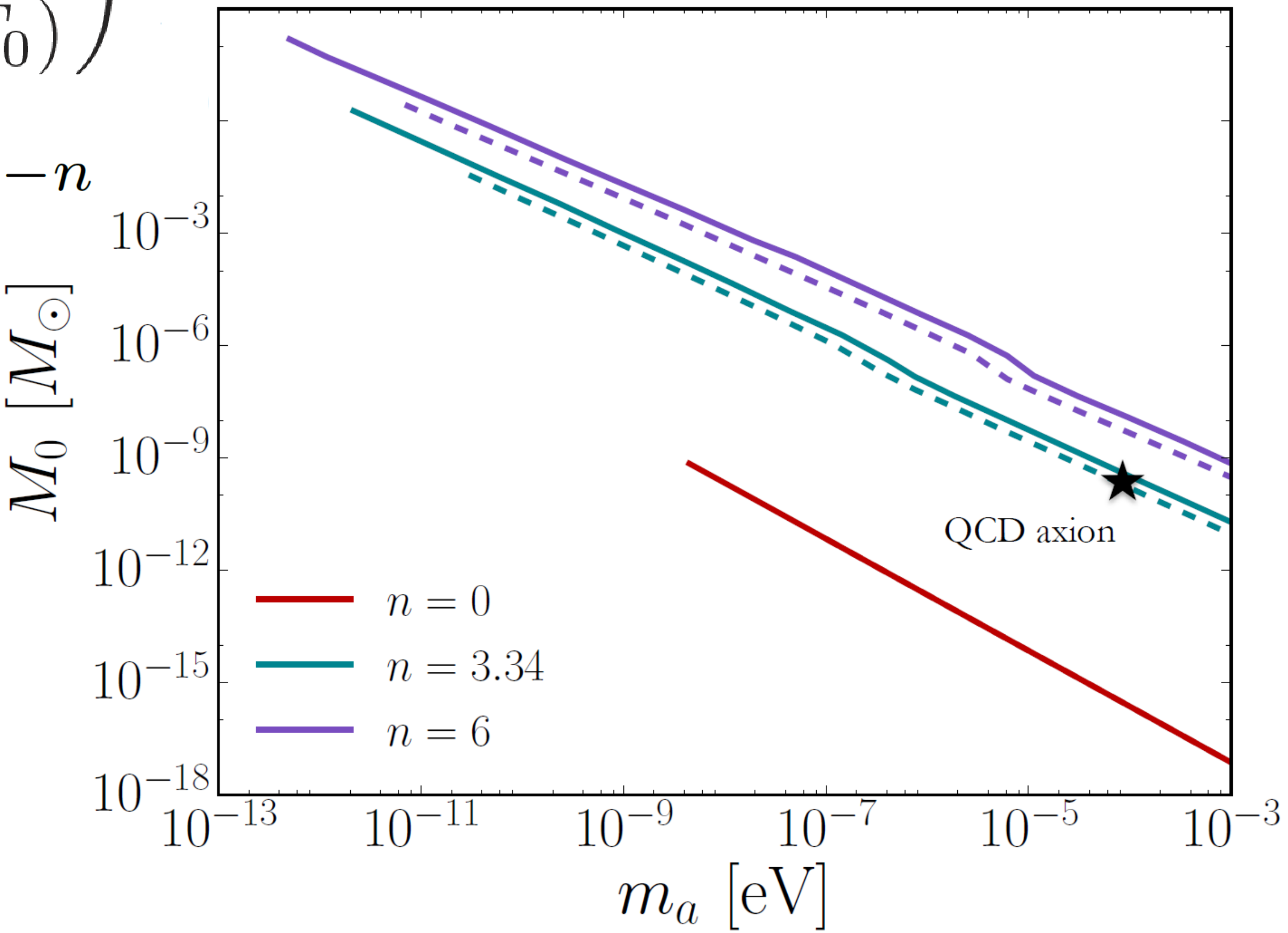
Correlations in this field are on length scale of horizon at phase transition – very small- much smaller than cosmological Planck/galaxy scales etc.

U(1) PQ symmetry broken by axion mass after inflation

$$M_0 = \bar{\rho}_a \frac{4}{3}\pi \left(\frac{\pi}{a(T_0)H(T_0)} \right)^3$$

$$m_a(T) = m_{a,0}(T/T_c)^{-n}$$

Mass inside horizon = M_0



For QCD instantons, Theory and lattice simulations suggest that n=3.34. Wantz and Shellard, 0910.1066. Borsanyi et al., 1508.06917, 1606.07494.

T_0 depends upon n

Formation of dense miniclusters

when miniclusters form, large distribution of values of δ produced.

distribution is non-Gaussian due to anharmonicity of axion potential

minihalos subsequently collapse, rapidly, when their local region of Universe becomes matter dominated.

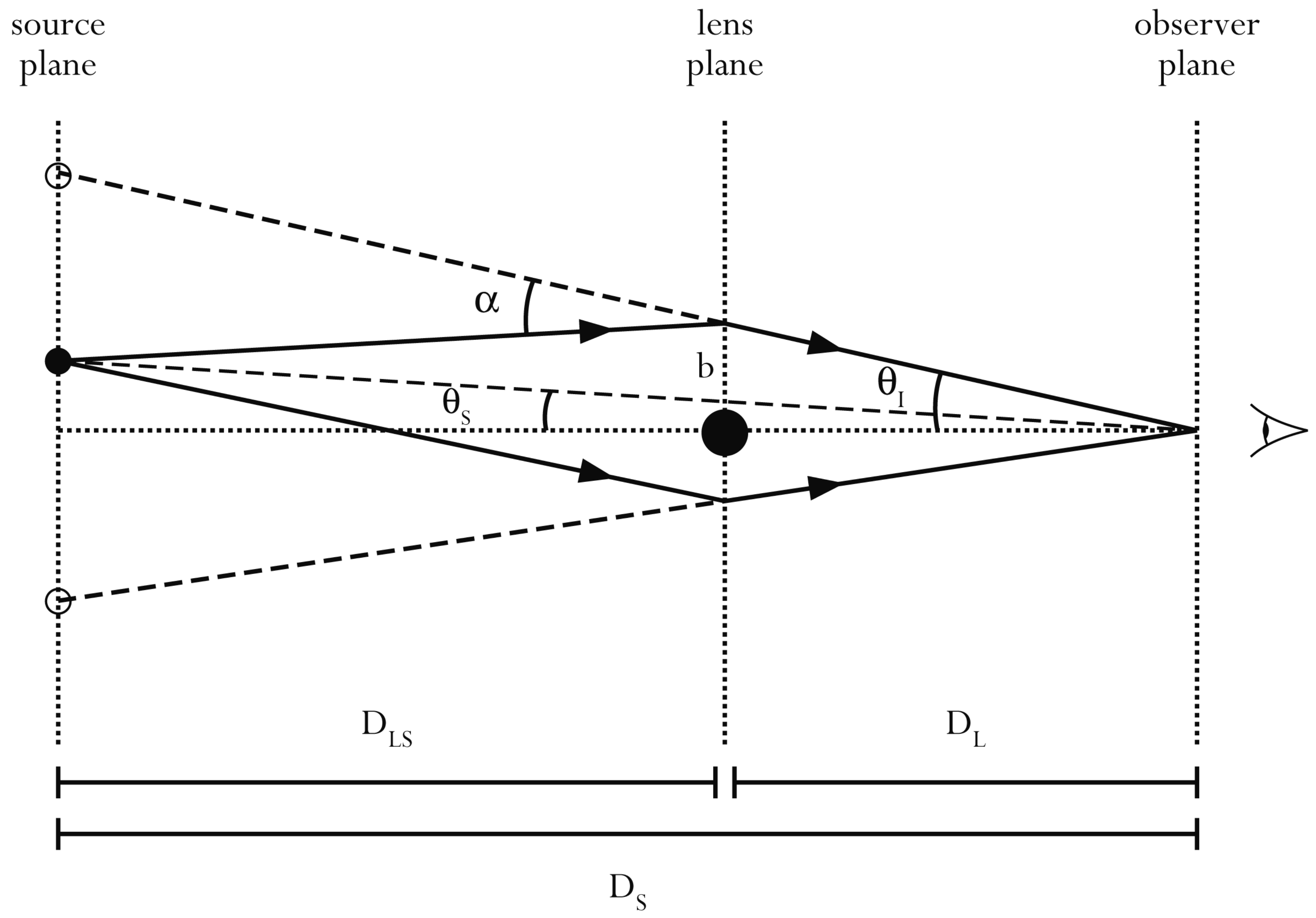
Characteristic density is even larger than expected due to large overdensities changing local era of matter domination.

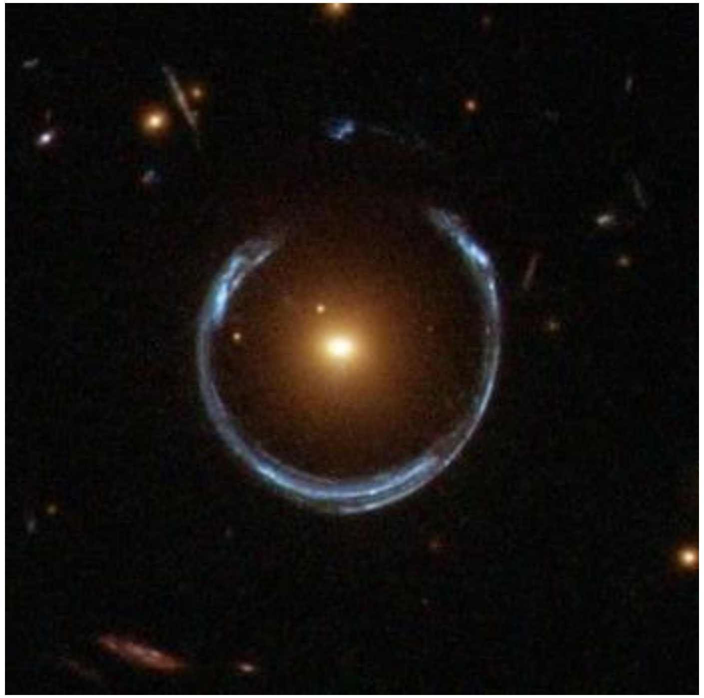
$$\rho_c = 140\delta^3(1+\delta)\rho_a(1+z_{\rm eq})^3$$

Non-Gaussian distribution of halo overdensities is obtained from Numerical simulations. We then take haloes to have NFW shape.

See e.g. Kolb and Tkachev 1990s various

Gravitational Lensing





$$R_{\mathrm{E}}(x, M) = 2\left[GMx(1-x)d_s\right]^{1/2}$$

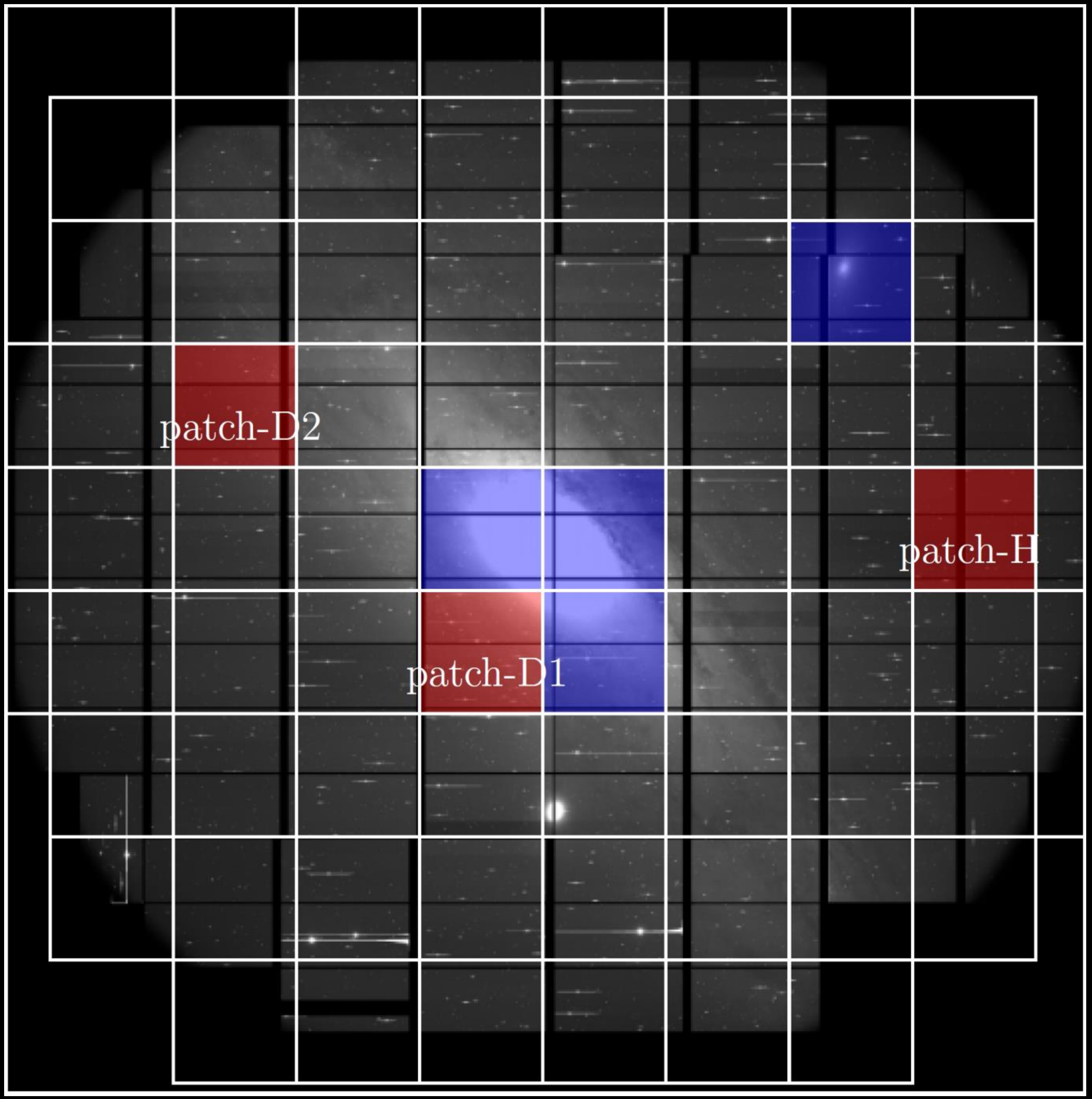
Subaru Hyper Suprime Cam (HSC)

1.5 degree coverage on sky, can cover whole of Andromeda Galaxy (M31)

Blue patches excluded due to too many objects

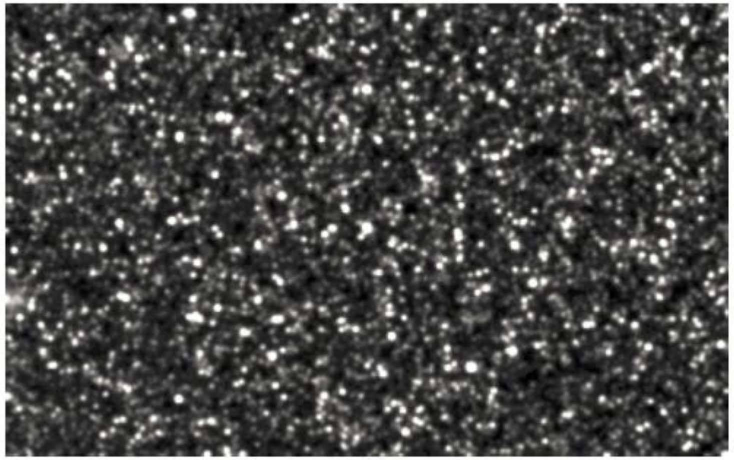
D1 representative of inner disk
D2 outer disk
H halo

Niikura et al, 1701.02151

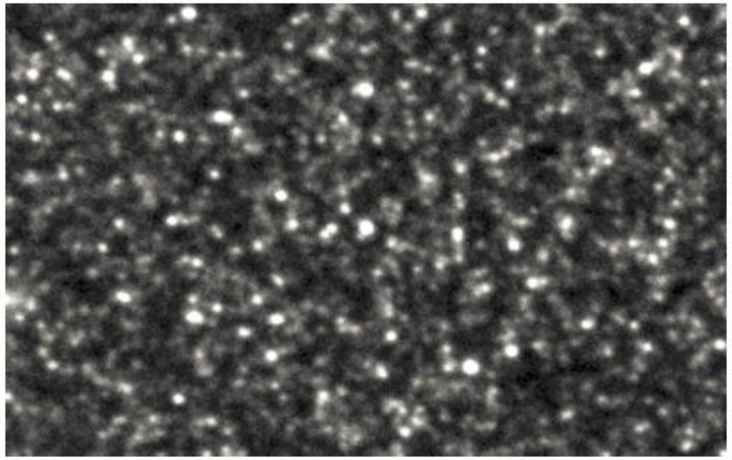


Subaru Hyper Suprime Cam (HSC)

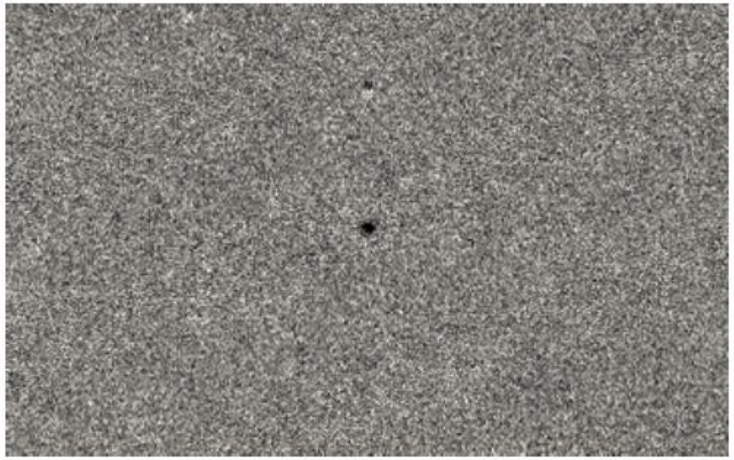
Has only collected 7 hours of data – already has very strong constraints on lensing events



Good stacked image



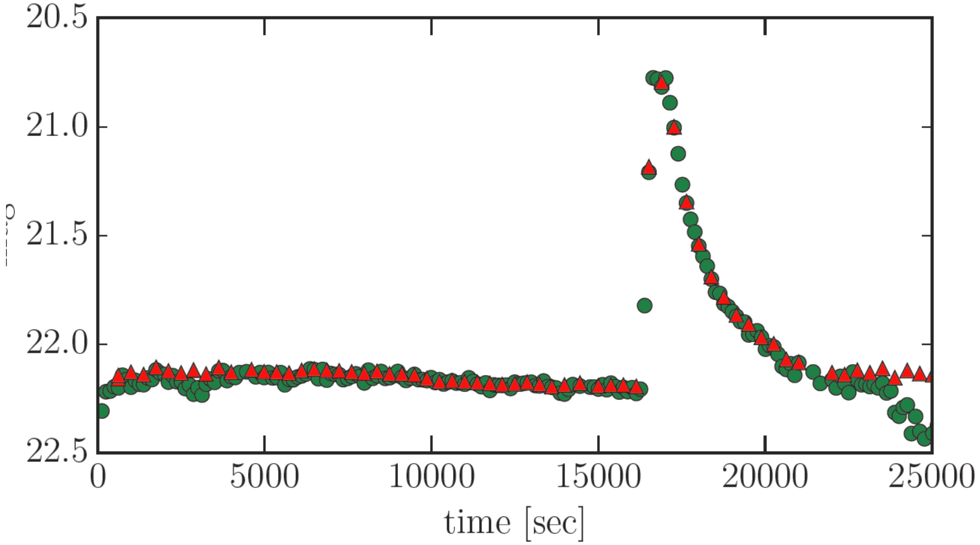
representative target image



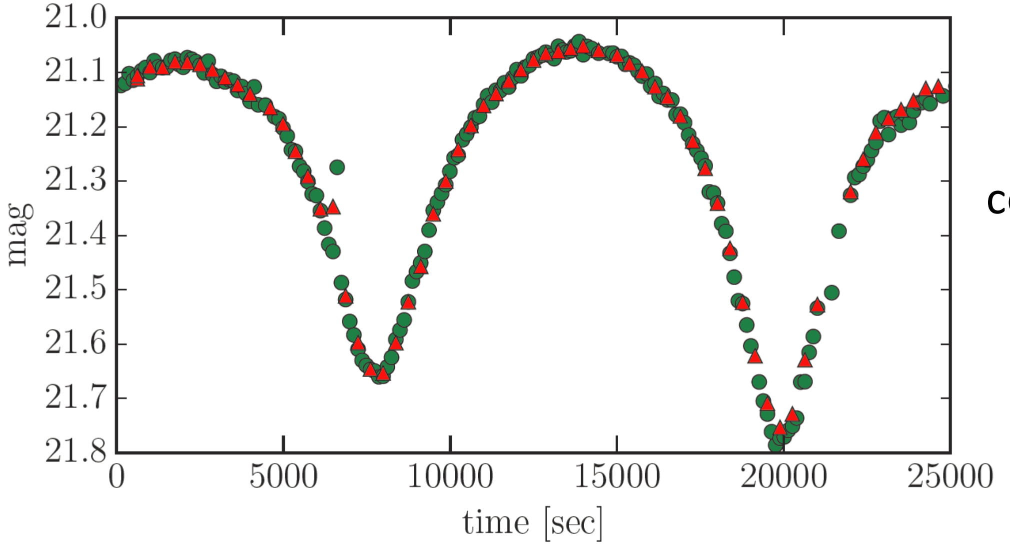
difference – change in one star’s flux

Subaru Hyper Suprime Cam (HSC) Niikura et al, 1701.02151

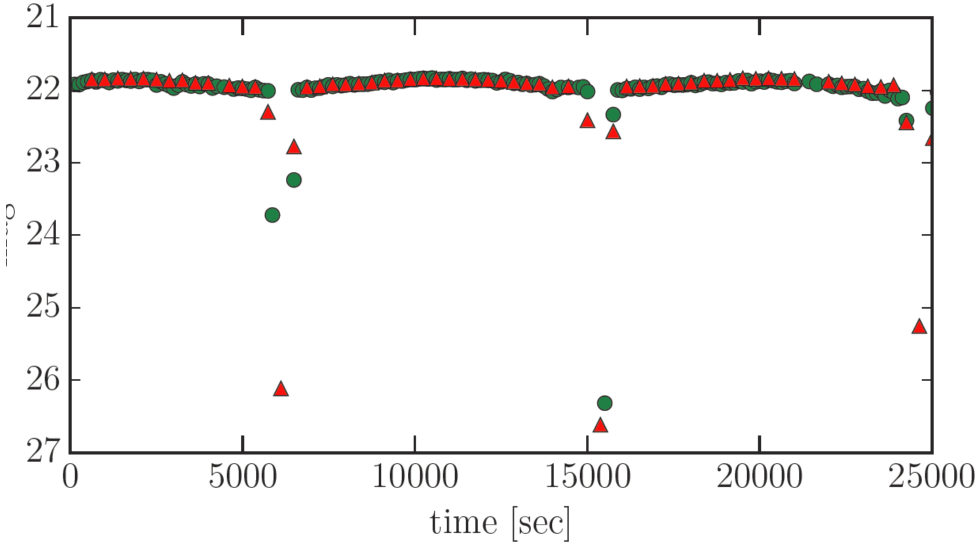
Stellar flare?



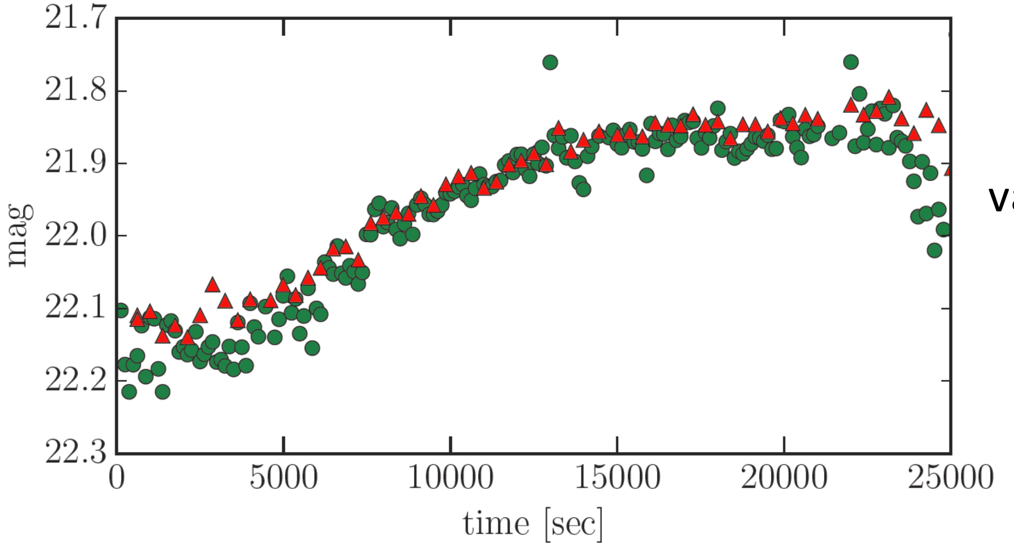
contact binary?



Eclipsing Binary?

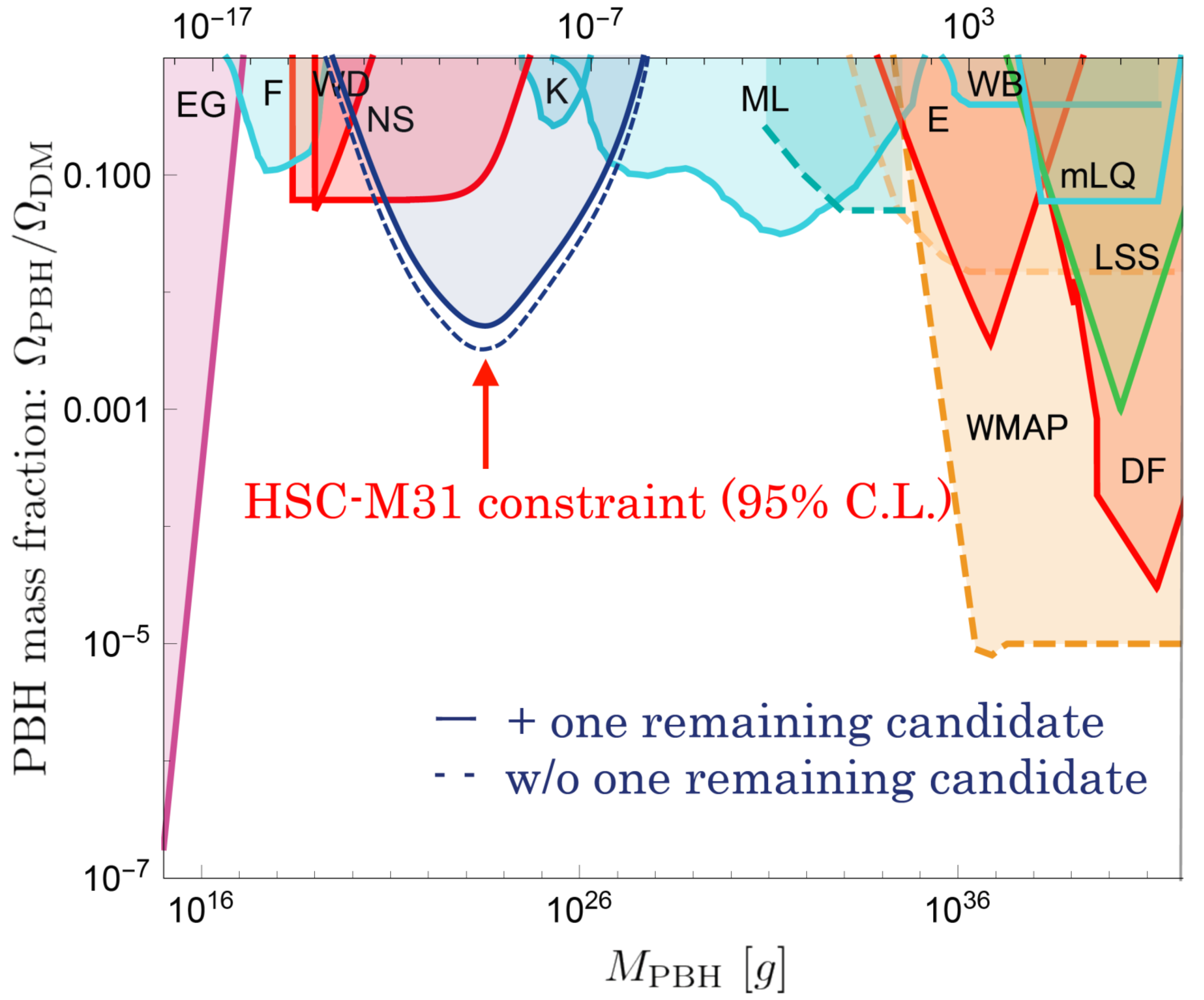


variable star?



HSC constraint on Primordial Black Holes

Niikura et al, 1701.02151



Magnification in the point mass vs. the extended mass case

Most haloes are very diffuse and therefore cause no lensing

Magnification for a distributed source

$$\mu = \left[(1 - B)\,(1 + B - C) \right]^{-1}$$

$$C = \frac{1}{\Sigma_c \pi r} \frac{dM(r)}{dr} \;;\; B = \frac{M(r)}{\Sigma_c \pi r^2} \;;\; \Sigma_c = \frac{c^2 D_S}{4\pi G D_L D_{LS}}$$

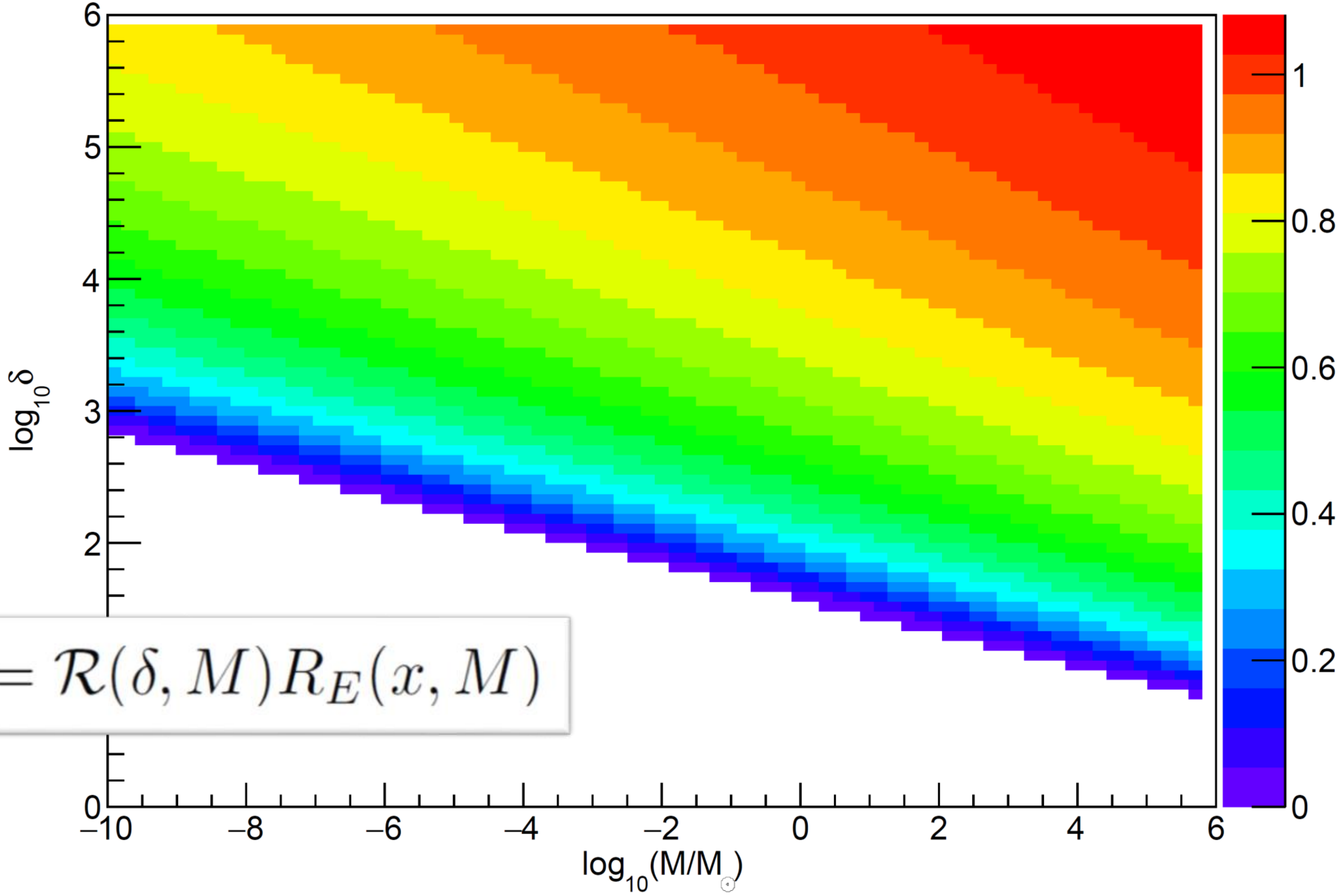
We have distributed density which, while dense, is not a point mass.

For each halo we need to integrate inwards to find value of r where μ=1.34.

In practise the corresponds to outer image having magnification of 1.17.

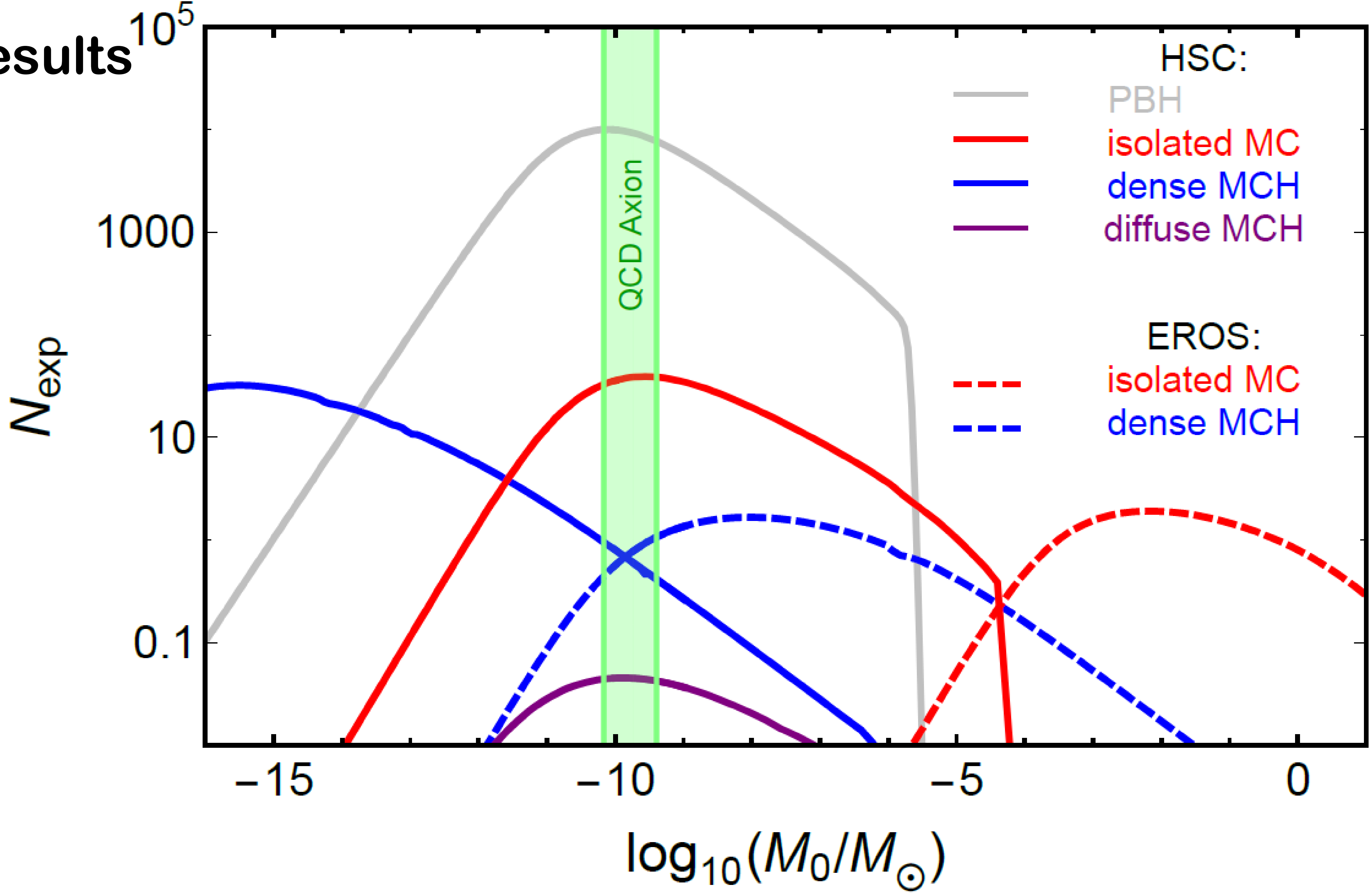
Effective diameter / Einstein diameter

Most haloes are very diffuse and therefore do not cause enough lensing



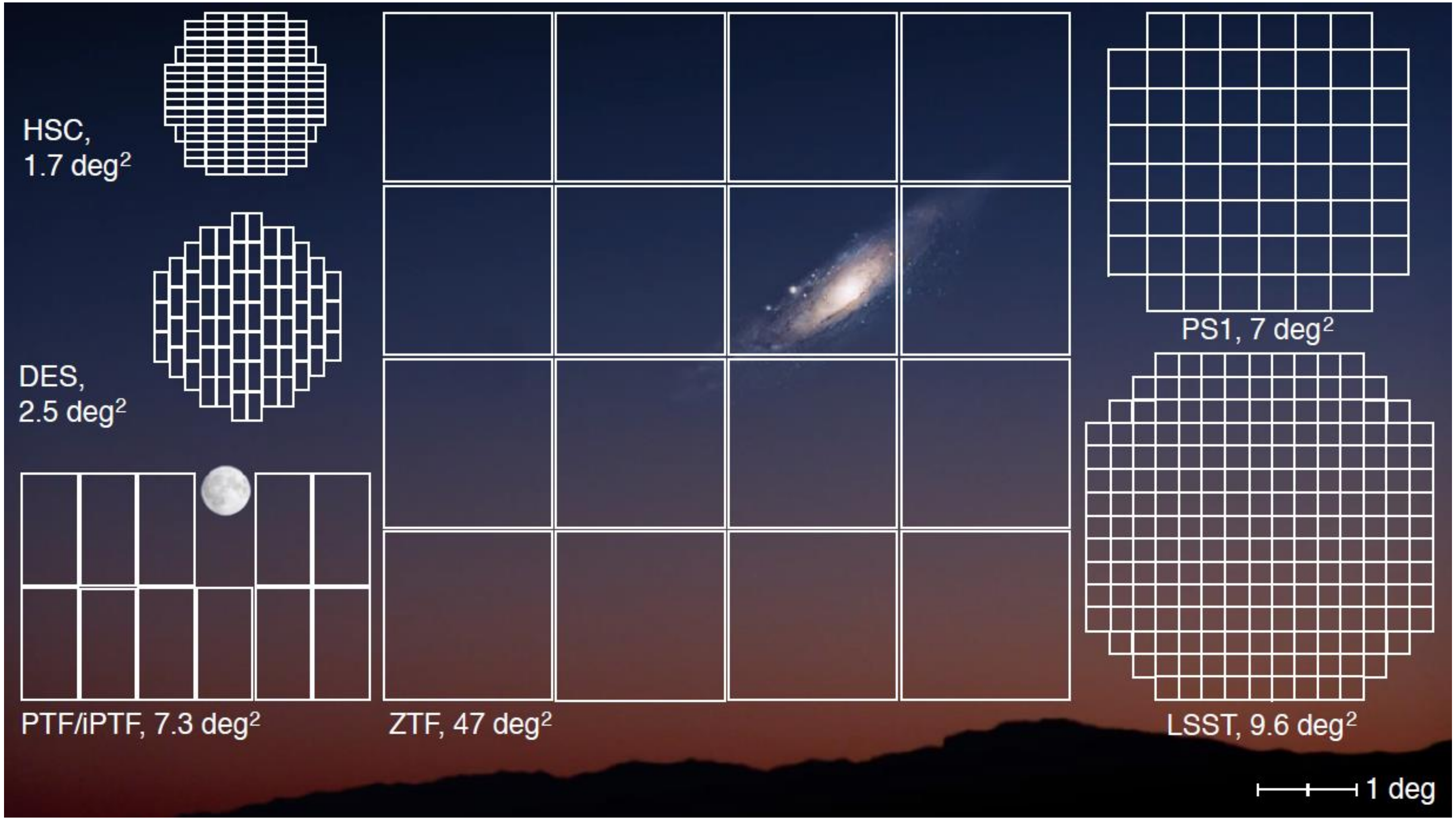
$$R_{\mathrm{MC}}(x, M, \delta) = \mathcal{R}(\delta, M) R_E(x, M)$$

Our Results



10^5
1000
10
0.1
N_{exp}
QCD Axion
HSC:
PBH
isolated MC
dense MCH
diffuse MCH
EROS:
isolated MC
dense MCH
−15
−10
−5
0
$\log_{10}(M_0/M_\odot)$

Upcoming Surveys - many of which are much better than HSC



Dark Matter Searches are no place for Dogma.

Could be WIMPs, sterile neutrinos, axions, hidden sector glueballs, KK particles, whatever….

Whenever we come up with an idea to test one of these we should do so. There will be lots of new ways to test these scenarios in the coming Years…

Science & Technology Facilities Council
erc

Part III

Hidden Sector Glueball Dark Matter

Science & Technology Facilities Council

An example of Self interacting DM:- Hidden Sector Glueballs

Boddy et al arXiv:1402.3629

Assume hidden sector non-Abelian gauge group
If b positive - confining

$$\Lambda = \mu_0 \, e^{-8\pi^2/bg_0^2}$$

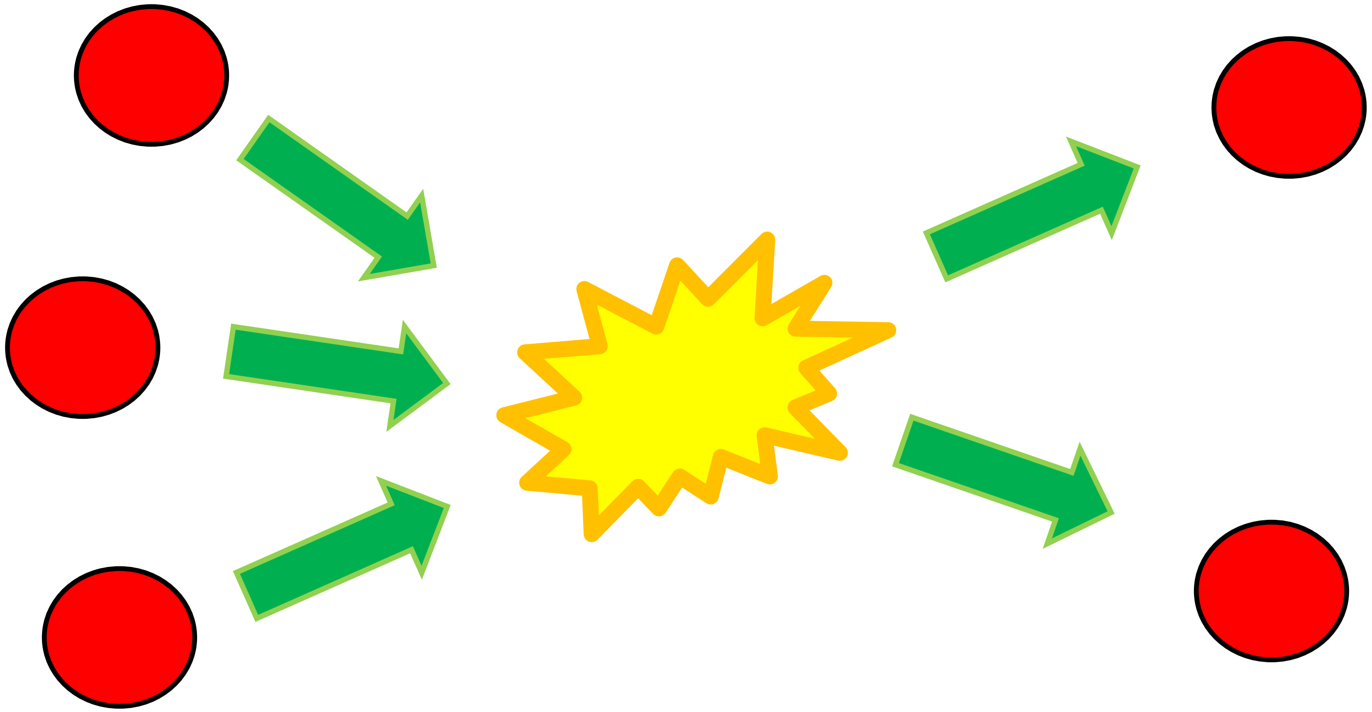
quantity Λ tells you where coupling blows up sets mass scale for hadrons. If no light quarks, lowest lying states are glueballs

Good candidates for short range SIDM,
although vanilla scenario ruled out

$$Y_\infty = \frac{3}{4}\frac{N_C^2 - 1}{g_{*S}(T = \Lambda)} \qquad \Lambda = \frac{\Omega_{DM}\rho_{c0}}{Y_\infty s_0} \sim 1eV$$

$$\sim 10^{23} \text{ cm}^2\text{g}^{-1} \qquad \sigma/m \propto \Lambda^{-3}$$

3 to 2 processes reduce abundance



$$\langle \sigma v^2 \rangle_{3\to 2} = \frac{16\pi}{3\Lambda^5}$$

Missed from original analysis (authors acknowledge this)

3 to 2 processes reduce abundance

$$\frac{dn}{dt} + 3Hn = s\frac{dY}{dt} = -\langle \sigma v^2 \rangle_{3\to 2} n^3$$

Leads to simplified form with $\kappa \sim M_{Pl} / \Lambda$ which admits an analytic solution

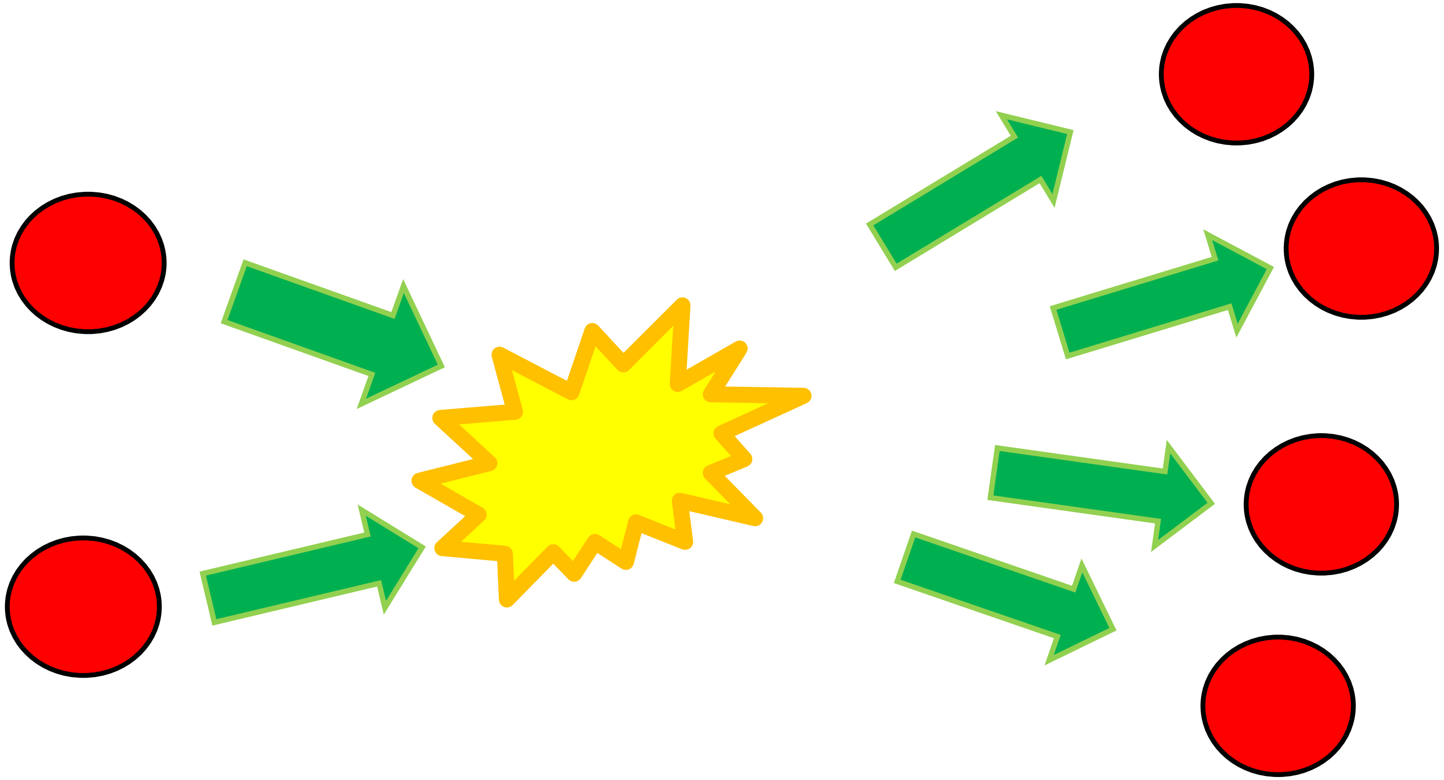
$$\frac{dY}{dx} = -\kappa \frac{Y^3}{x^5} \qquad Y_\infty = 4.326 \times 10^{-10} \frac{\text{GeV}}{\Lambda} \simeq \sqrt{2/\kappa}$$

$$\Lambda = 0.132 \frac{g_{*S}^{2/3}}{g_*^{1/6}} c^{1/3} \text{GeV} \sim \text{cm}^2 \text{g}^{-1} \text{ !!!}$$

3 to 2 processes reduce abundance to right level for good Self interacting phenomenology

HOWEVER

3 to 2 processes lead to 2 to n processes



3 to 2 processes reduce abundance but increase K.E. very rapidly

Becomes energetically possible to produce multiple glueballs

3 to 2 processes lead to 2 to n processes

Typical energy of hadrons in jets at LHC

$$E_{typ} = 3\Lambda \ln\left[0.4675\frac{E_{com}}{\Lambda}\right]$$

use this to estimate the value of n as we evolve abundance (need to also evolve E)

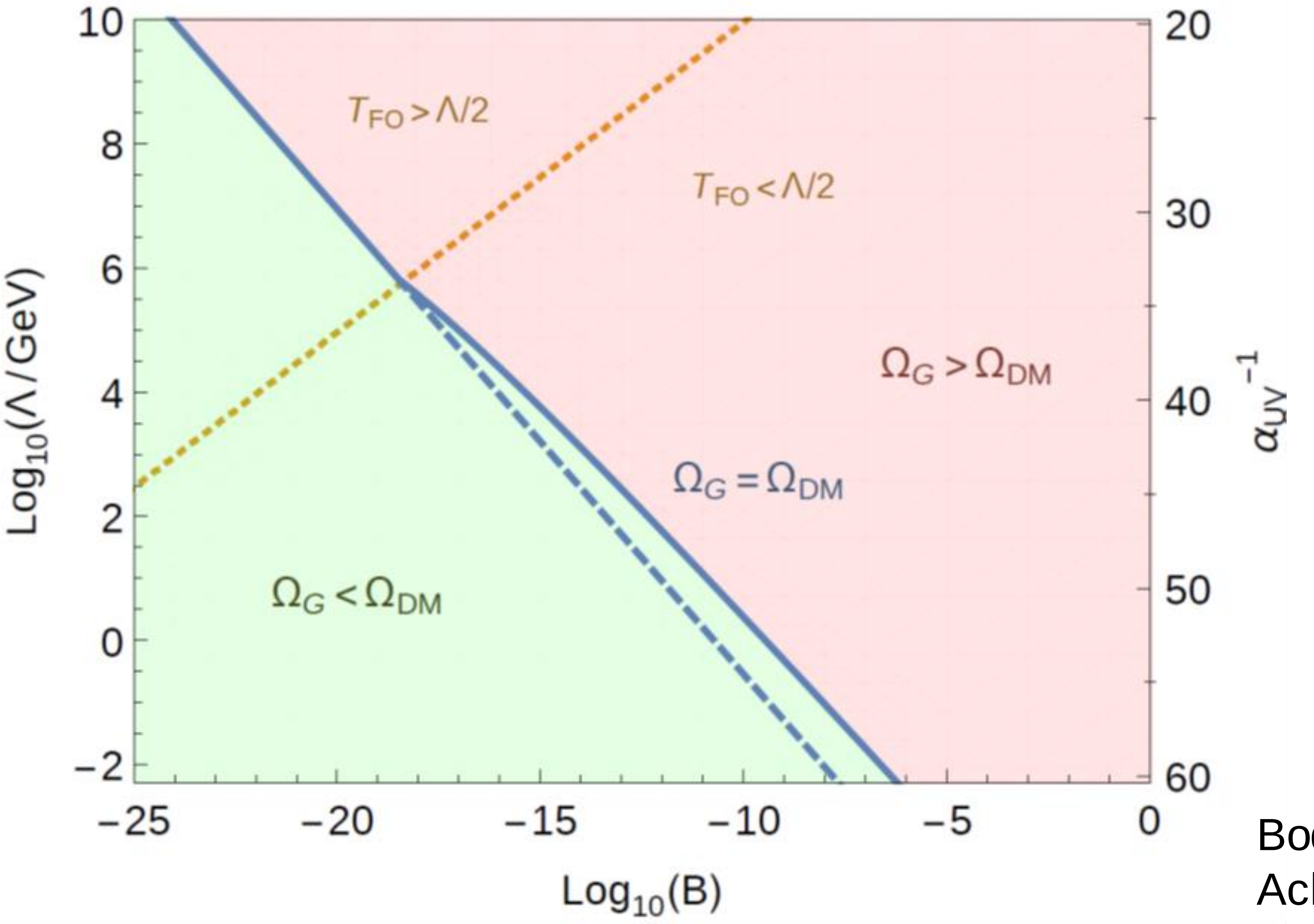
$$\frac{dY}{dx} = -c_1\kappa\frac{Y^3}{x^5} + c_2\kappa\frac{Y^2}{x^2}f(E)$$

3 to 2 2 to n multiplicity

cannot be solved for interesting numbers
because κ very large, around M_{Pl} / Λ

Hidden Sector Glueballs

For early reheating this 3->2 stuff doesn't change much (dashed vs. non dashed line below)
STILL PROBLEM
Simplest fix – change inflaton decay rate B into hidden Sector



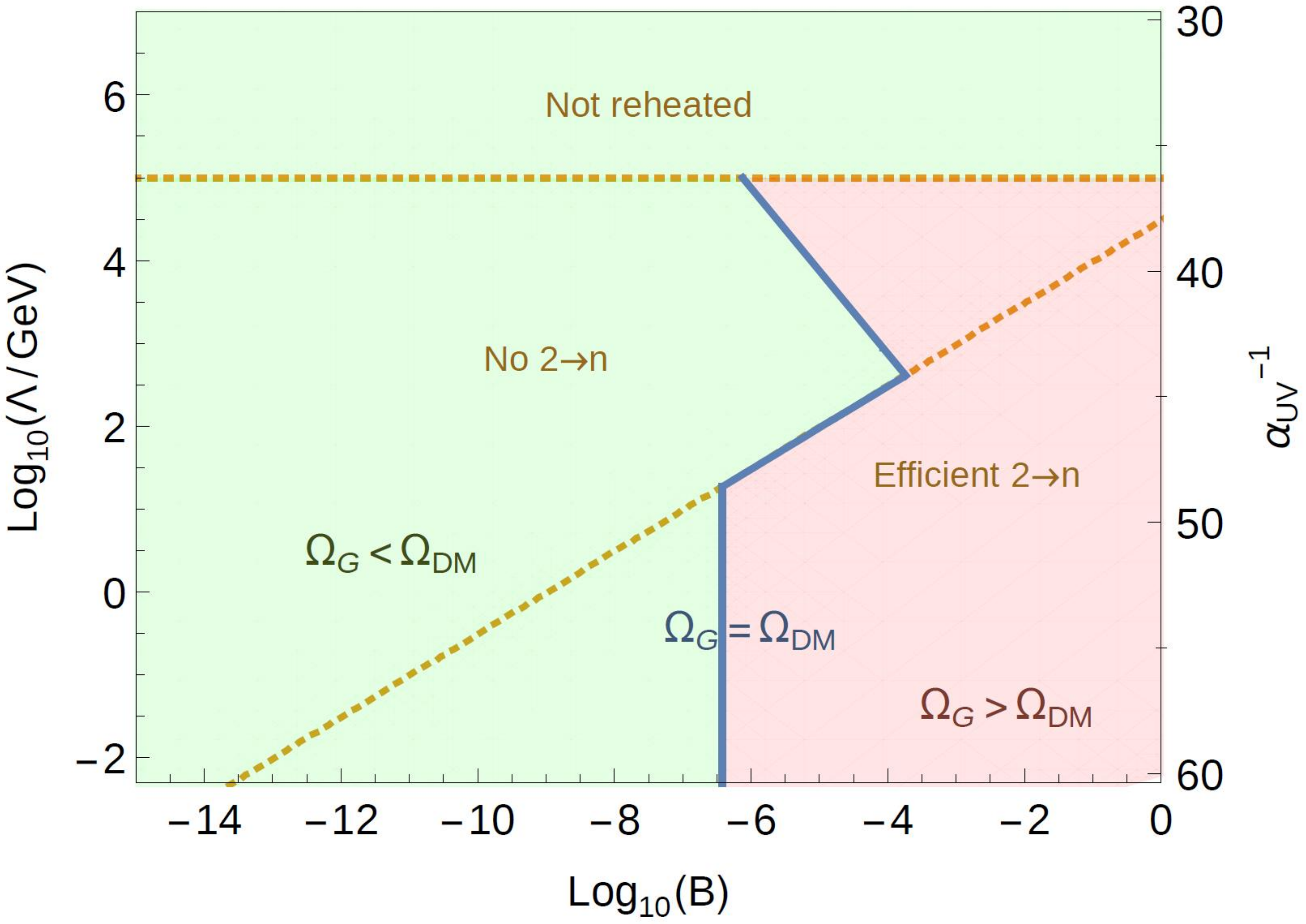
Boddy et al arXiv:1402.3629
Acharya et al arXiv:1704.01804

Hidden Sector Glueballs

Low reheat scenario – Gravitinos decay before nucleosynthesis

After a period of matter domination in the Early Universe.

If Λ is less than a GeV there may be self interaction effects.



Part IV

Nuclear Dark Matter

Simulations of Nuclear Dark Matter

If we assume that Dark Matter is made up of nucleons with *A* nuclei

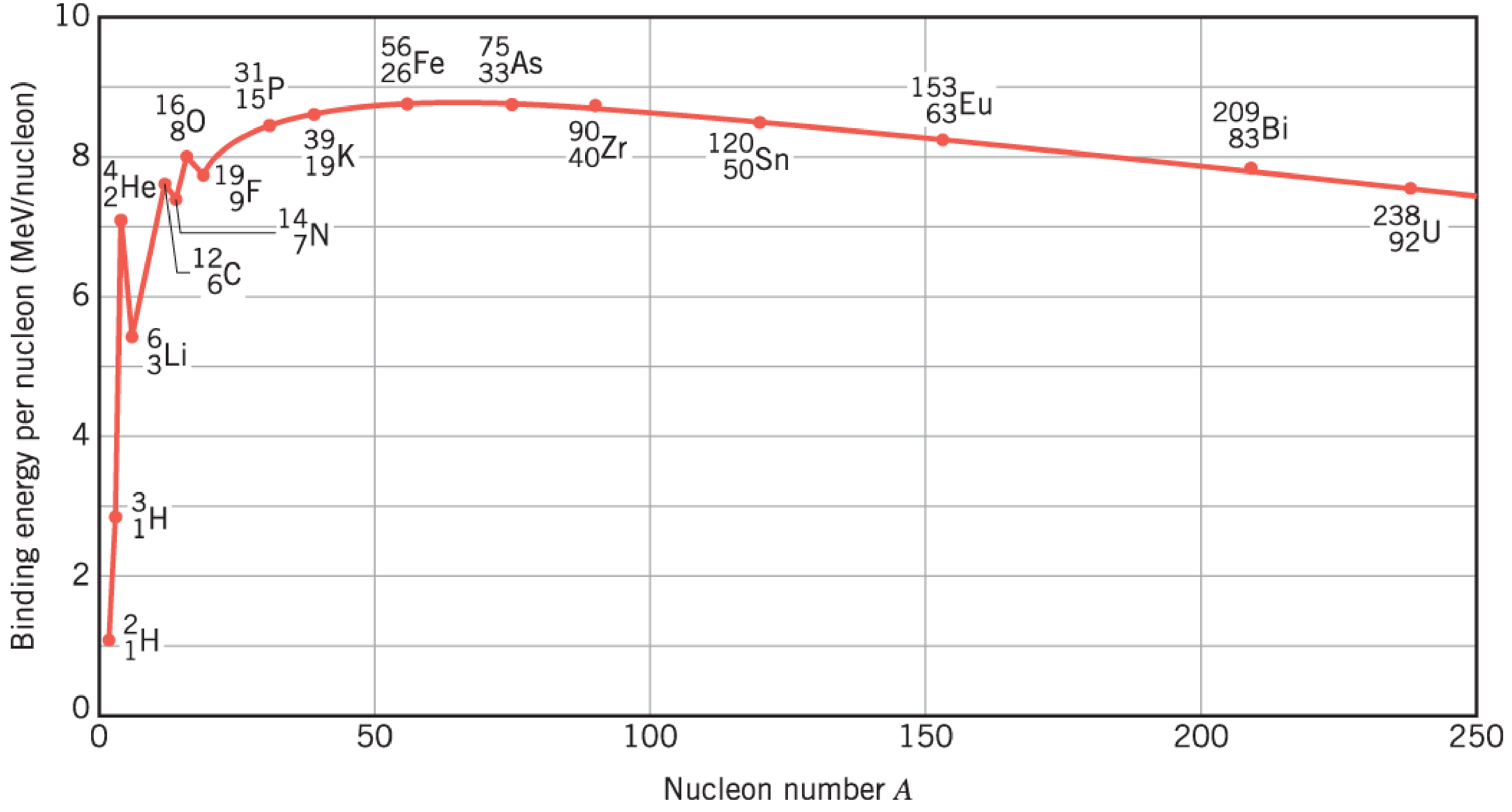
$$M_A = a_V A - a_S A^{2/3}$$

Such that the cross section goes like

$$\sigma = \sigma_0 A^{2/3}$$

Then you can have fusion

And for more complicated situations fission



Simulations of Nuclear Dark Matter

Self interacting dark matter leads to more cored profiles.

Warm Dark matter erases smaller profiles.

Fusion leads to ***cuspier*** cores…