Title: Precision Physics of the QCD axion and other new light particles

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Abstract: <p>I will discuss the properties, and constraints on, new light</p>

<p>particles, which appear in many extensions of the Standard Model. An</p>

<p>especially well motivated example is the QCD axion, and I will show how</p>

<p>its mass and couplings can be extracted at high precision. I will also</p>

<p>discuss its properties at finite temperature, and possible distinguishing</p>

<p>features if it makes up dark matter. More generally, strong constraints on</p>

<p>the couplings of new light particles to the Standard Model come from their</p>

<p>production in the hot cores of stars, and the effect on stellar cooling.</p>

<p>The large electron density in stellar cores gives large thermal effects,</p>

<p>and I will show how these can parametrically change the production rates</p>

<p>compared to a 'tree level' calculation.</p>

Why new light particles?

Motivated from UV and IR physics

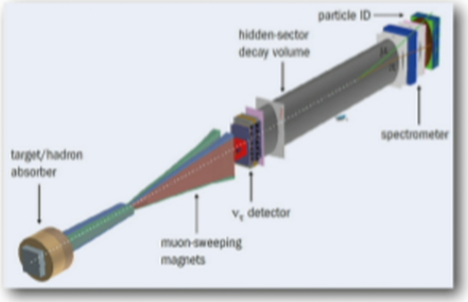
- Solve problems with the SM (QCD axion)
- Dark Matter candidates (interesting self interaction possibilities) or portals to dark sectors
- Well motivated by typical string compactifications
- Various borderline interesting experimental anomalies

Less explored than other possibilities, experimental progress likely

No sharp prediction for where to look, but plausible ranges

Why precision theory?

Many interesting experiments



Highlight especially well motivated parts of parameter space

Determine existing limits from complicated, e.g. astrophysical systems

Understand physics implications of new searches

In case of an anomaly or discovery interpret what has been seen

This talk

- QCD Axion
  - Couplings, dark matter, cosmology
- Axion-like-particle
  - Astrophysics, possibility of dark matter in large gravitationally bound objects
- Hidden photons
  - Understanding limits from Supernova

QCD Axion

$$\mathcal{L} \supset \frac{\alpha_s}{8\pi}\theta_0 G\tilde{G}$$

Experiment: $\theta = \theta_0 + \arg\,\det M_q \lesssim \mathcal{O}(10^{-10})$

Other phases in Yukawa matrices order 1

Non-decoupling contributions from new CP violating physics at arbitrarily high scales

Effects on large distance physics irrelevant for $\theta \lesssim 10^{-1} \div 10^{-2}$

Begs for a dynamical explanation!

Standard Model + extra pseudo-goldstone boson with coupling

$$\mathcal{L} \supset \frac{\alpha_s}{8\pi}\left(\theta + \frac{a}{f_a}\right) G\tilde{G}$$

Strong coupling $\longrightarrow$ Axion potential & axion VEV that removes θ

$\longrightarrow$ Axion mass $\mathcal{O}(m_\pi f_\pi / f_a)$

In a large part of parameter space can be dark matter

"Generic" feature of string compactifications (but expected decay constants?)

Small couplings mean discovery hard, but several ideas

Resonance effects: possible to measure its mass with relative accuracy

$$\delta m/m \sim 10^{-6}$$

Depending on experiment other couplings as well

Could we exploit such a high precision experiment?

Possible to infer the UV completion of the axion and its cosmology?

Lagrangian

UV Lagrangian:

$$\mathcal{L}_a = \frac{1}{2}(\partial a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{1}{4}\,a\,g^0_{a\gamma\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu} + j^{\mu}_{a,0}\frac{\partial_\mu a}{2f_a}$$

where $g^0_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a}\frac{E}{N}$ Anomalous EM coupling

$j^{\mu}_{a,0} = c^0_q \bar{q}\gamma^{\mu}\gamma_5 q$ Model dependent axial current

Chiral Perturbation Theory

Axion: external source, non−derivative couplings via dressed mass matrix, derivative coupling an external axial vector current

Low energy correlators from chiral perturbation theory
[Georgi, Kaplan, Randall]

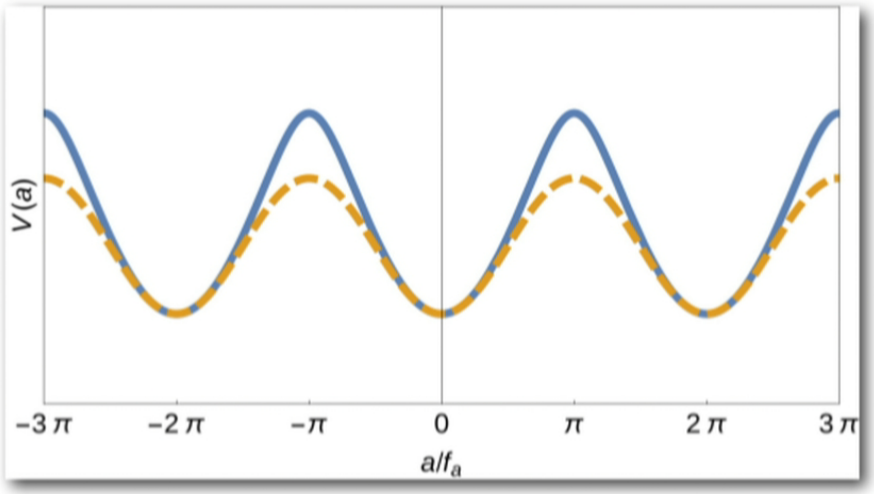
$$\mathcal{L}_{p^2} \supset 2B_0 \frac{f_\pi^2}{4} \langle U M_a^\dagger + M_a U^\dagger \rangle$$

where $U = e^{i\Pi/f_\pi}\,, \quad \Pi = \begin{pmatrix} \pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & -\pi^0 \end{pmatrix}$

Free to shift axion into the first two generations only

Potential

$$V(a,\pi^0) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{a}{2f_a}\right)}$$



Not a cosine

$$m_a^2 = \frac{m_u m_d}{(m_u+m_d)^2}\frac{m_\pi^2 f_\pi^2}{f_a^2}$$

Mass at NLO

From CPT, loops and higher terms, e.g.

$$\mathcal{L}_{p^4} \supset \frac{l_7}{8} \left\langle \left(D^\mu U + D^\mu U^\dagger \right) 2B_0 \left(M_a + M_a^\dagger \right) \right\rangle$$

$$m_a^2 = \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2} \left[1 + 2\frac{m_\pi^2}{f_\pi^2} \left(h_1^r - h_3^r - l_4^r + \frac{m_u^2 - 6 m_u m_d + m_d^2}{(m_u + m_d)^2} l_7^r \right) \right]$$

Turns out no logs at this order

Determining low energy constants

$$l_7^r = \frac{m_u + m_d}{m_s}\frac{f_\pi^2}{8m_\pi^2} - 36L_7 - 12L_8^r + \frac{\log(m_\eta^2/\mu^2)+1}{64\pi^2} + \frac{3\log(m_K^2/\mu^2)}{128\pi^2} = 7(4)\cdot 10^{-3},$$

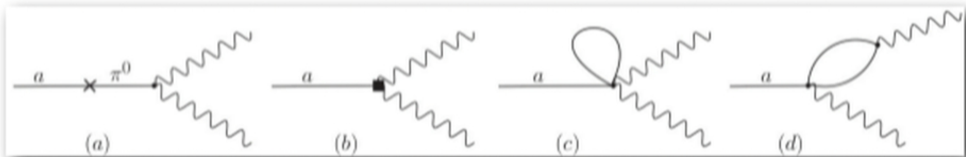
$$h_1^r - h_3^r - l_4^r = -8L_8^r + \frac{\log(m_\eta^2/\mu^2)}{96\pi^2} + \frac{\log(m_K^2/\mu^2)+1}{64\pi^2} = (4.8 \pm 1.4)\times 10^{-3}$$

$$z \equiv \frac{m_u^{\overline{\mathrm{MS}}}(2\ \mathrm{GeV})}{m_d^{\overline{\mathrm{MS}}}(2\ \mathrm{GeV})} = 0.48(3)$$

$$\boxed{m_a = 5.70(6)(4)\ \mu\mathrm{eV}\left(\frac{10^{12}\mathrm{GeV}}{f_a}\right) = 5.70(7)\ \mu\mathrm{eV}\left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)}$$

First error from z, second from low energy constants

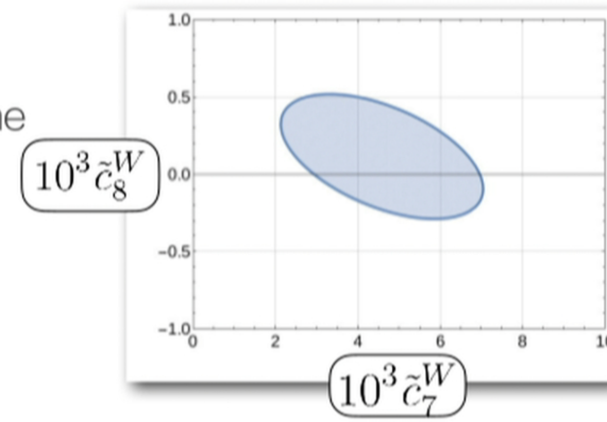
Coupling to Photons

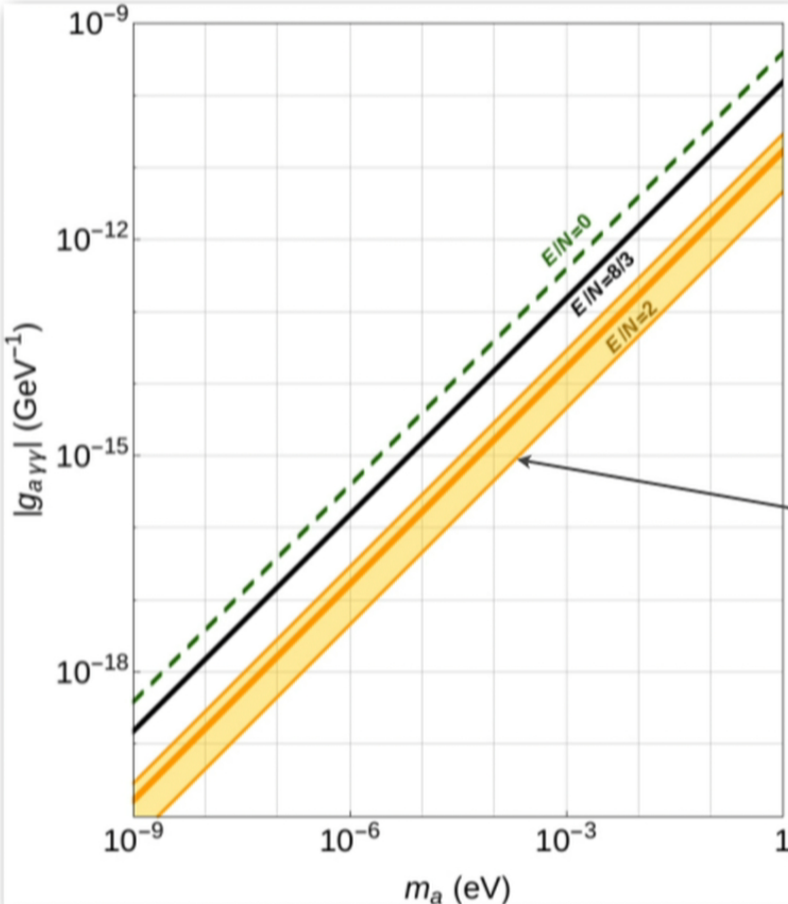


$$g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a}\left\{\frac{E}{N} - \frac{2}{3}\frac{4m_d+m_u}{m_d+m_u} + \frac{m_\pi^2}{f_\pi^2}\frac{8m_u m_d}{(m_u+m_d)^2}\left[\frac{8}{9}\left(5\tilde{c}_3^W + \tilde{c}_7^W + 2\tilde{c}_8^W\right) - \frac{m_d-m_u}{m_d+m_u}l_7^r\right]\right\}$$

New low energy constants to determine

Harder to get these precisely





$$g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a}\left[\frac{E}{N} - 1.92(4)\right]$$

Maximum possible cancellation

Couplings to Matter

Safest thing to do is use an effective theory well below QCD mass gap,

Non-relativistic nucleons $\dfrac{\partial_\mu a}{2f_a} c_N \bar{N}\gamma^\mu\gamma_5 N$

Need matrix elements $s^\mu \Delta q \equiv \langle p|\bar{q}\gamma^\mu\gamma_5 q|p\rangle_Q$: use neutron decay and lattice

$$c_p^{\rm KSVZ} = -0.48(3)\,,$$
$$c_n^{\rm KSVZ} = 0.03(3)\,,$$

$$c_p^{\rm DFSZ} = -0.622 + 0.434\sin^2\beta \pm 0.024\,,$$
$$c_n^{\rm DFSZ} = 0.249 - 0.415\sin^2\beta \pm 0.024\,.$$

Low Temperature

Compute temperature dependence with CPT

But one loop correction is only from local NLO couplings, so

$$\frac{m_a^2(T)}{m_a^2} = \frac{\chi_{top}(T)}{\chi_{top}} \overset{\text{NLO}}{=} \frac{m_\pi^2(T) f_\pi^2(T)}{m_\pi^2 f_\pi^2} = \frac{\langle \bar{q}q \rangle_T}{\langle \bar{q}q \rangle}$$

$$= 1 - \frac{3}{2}\frac{T^2}{f_\pi^2} J_1\left[\frac{m_\pi^2}{T^2}\right] , \qquad J_1[\xi] = \frac{1}{\pi^2}\frac{\partial}{\partial \xi}\int_0^\infty dq\, q^2 \log\left(1 - e^{-\sqrt{q^2+\xi}}\right) .$$

Effects of heavy states suppressed by $e^{m/T}$

Ratio m/T_c not huge, and many new states appear, so breaks down at crossover

High Temperatures

At high enough temperatures, instanton calculation (Gross, Pisarski, Yaffe)

$$f_a^2 m_a^2(T) \simeq 2 \int d\rho\, n(\rho, 0) e^{-\frac{2\pi^2}{g_s^2} m_{D1}^2 \rho^2 + \ldots}$$

Where $n(\rho, 0) \propto m_u m_d e^{-8\pi^2/g_s^2}$ is zero temperature instanton density

Integral is over instanton size ρ

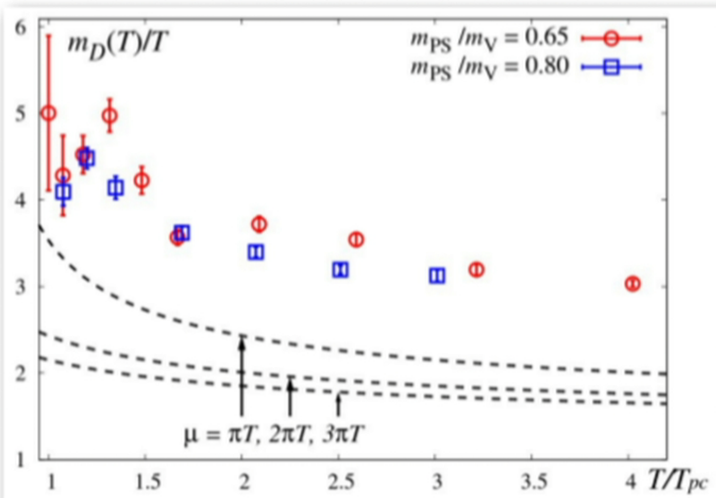
Cut off by screening from leading order Debye mass

$$m_{D1}^2 = g_s^2 T^2 (1 + n_f/6)$$

Finite T QCD convergence...

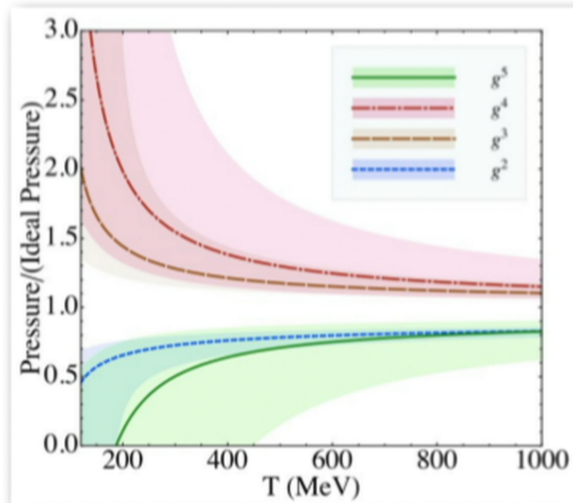
E.g. $m_D = m_{D0} + \frac{N}{4\pi} g^2 T \log \frac{m_{D0}}{g^2 T} + c_N g^2 T + \mathcal{O}\left(g^3 T\right)$

~gT



WHOT-QCD Collaboration

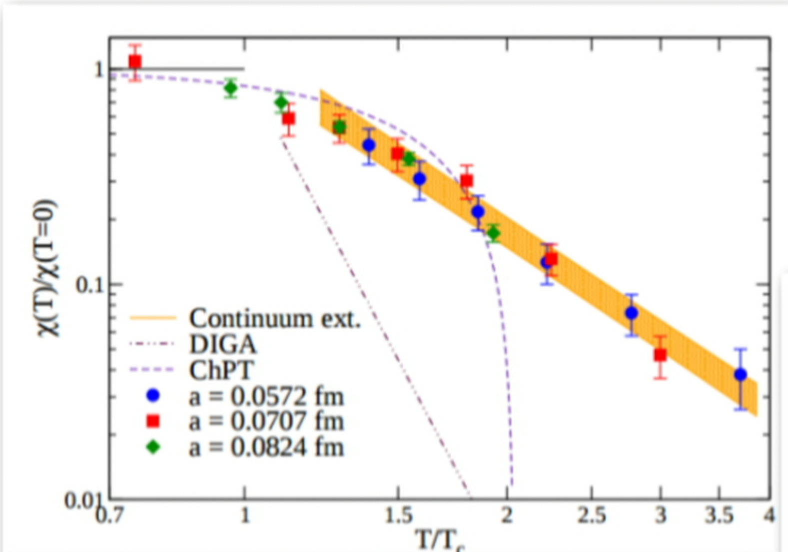
Debye mass



Andersen et al 1103.2528

Pressure

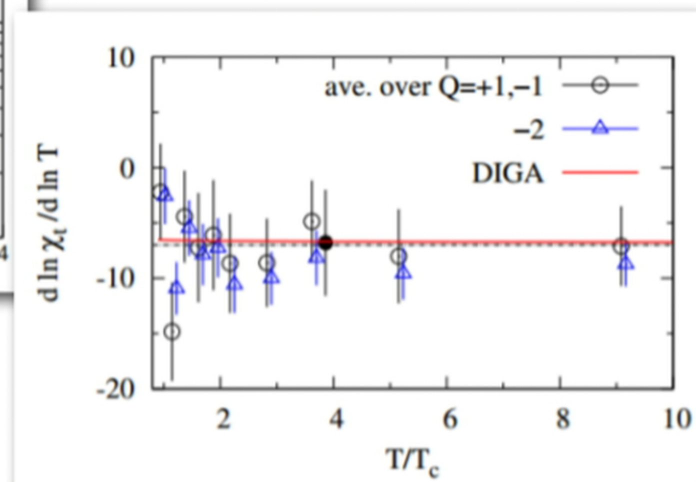
Lattice data



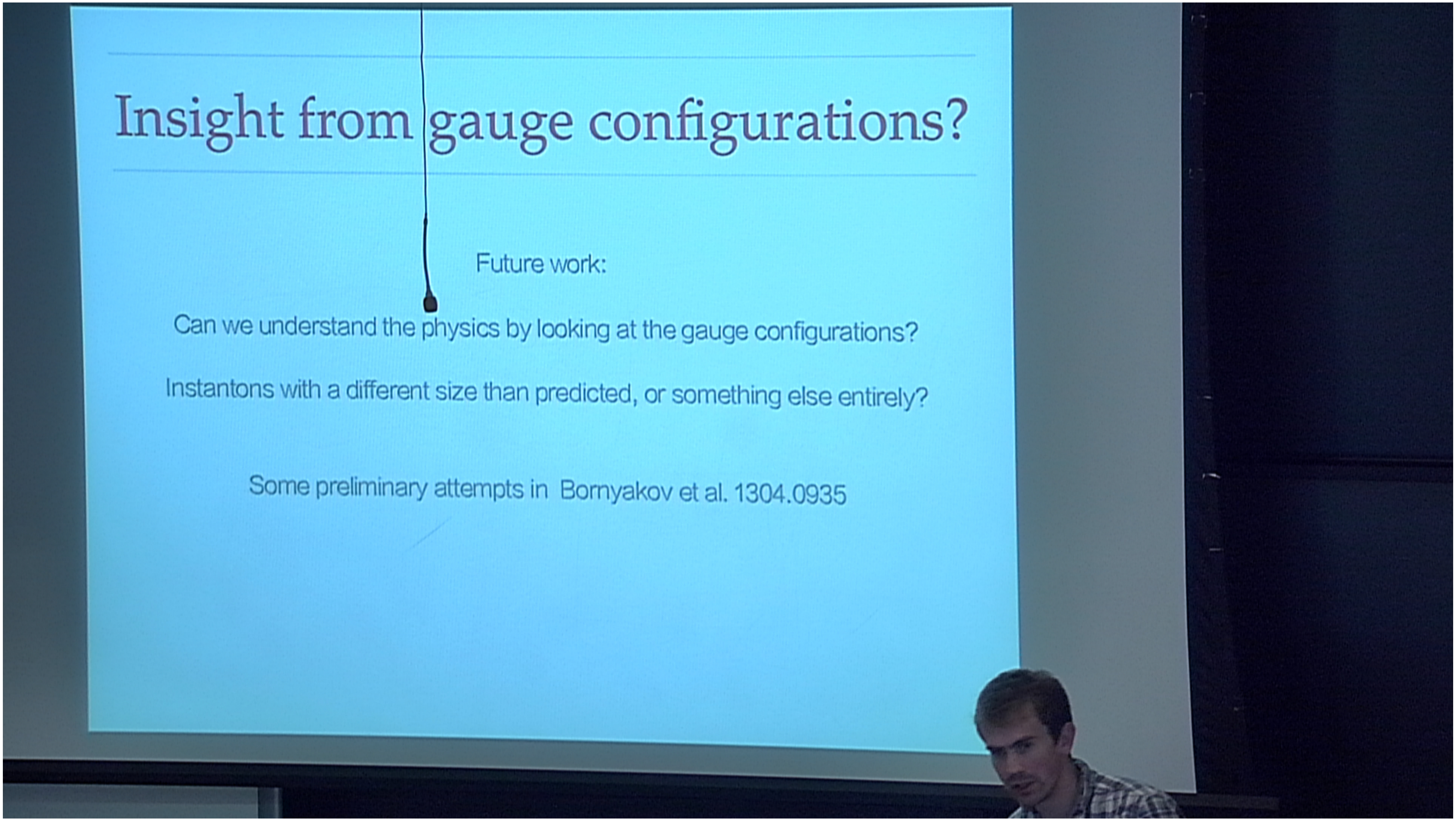
Bonati et al. '15

Situation unclear

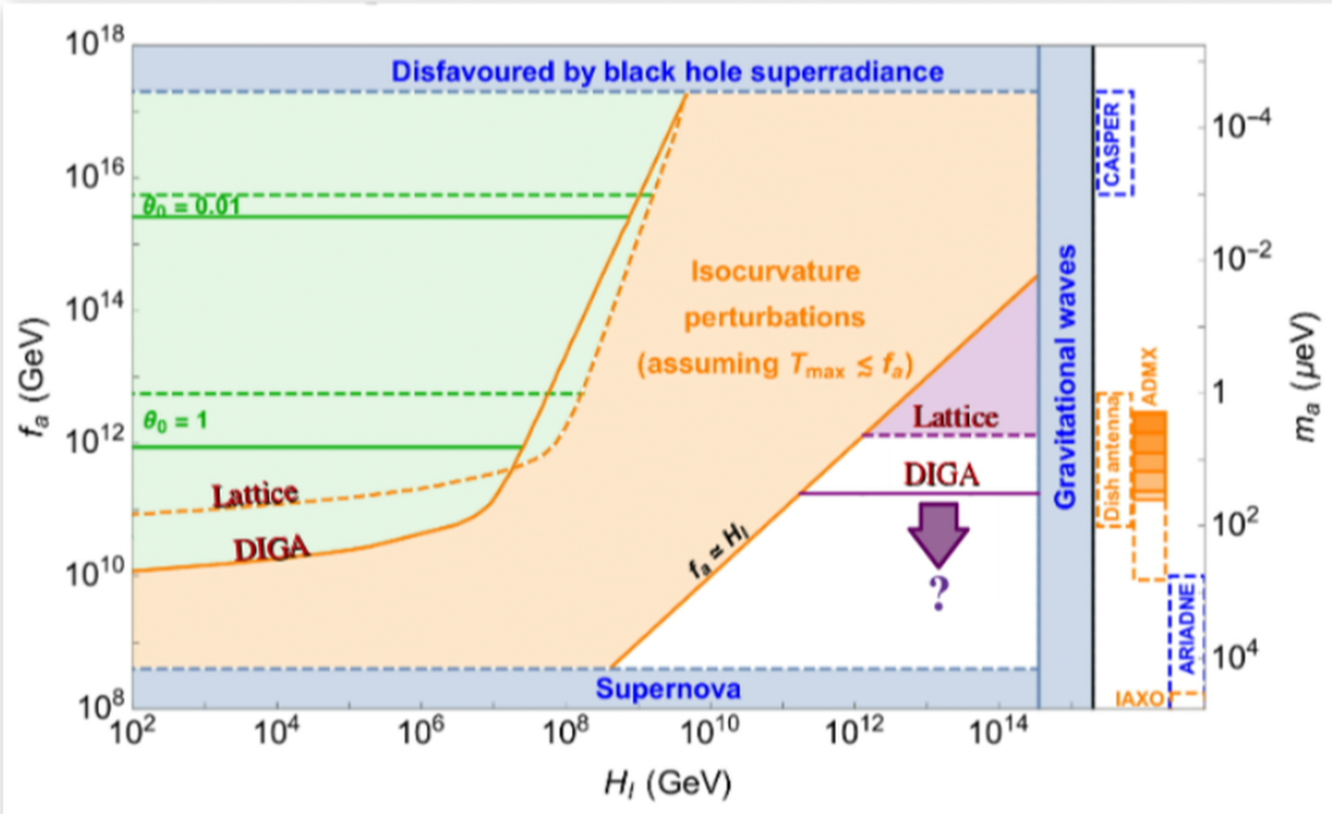
Future work will help, up to temperatures ~ GeV



Frison et al '16


Insight from gauge configurations?
Future work:
Can we understand the physics by looking at the gauge configurations?
Instantons with a different size than predicted, or something else entirely?
Some preliminary attempts in Bornyakov et al. 1304.0935

Cosmological Parameter Space




Hidden Sector Photons

Axion-like-particles

Similar to the QCD axion

Shift symmetry, but get mass either from hidden sector with strong coupling, or some non-perturbative effects at a high scale

Dark matter: PQ breaking before inflation can tune the initial misalignment angle

PQ breaking after inflation, random over the observable universe

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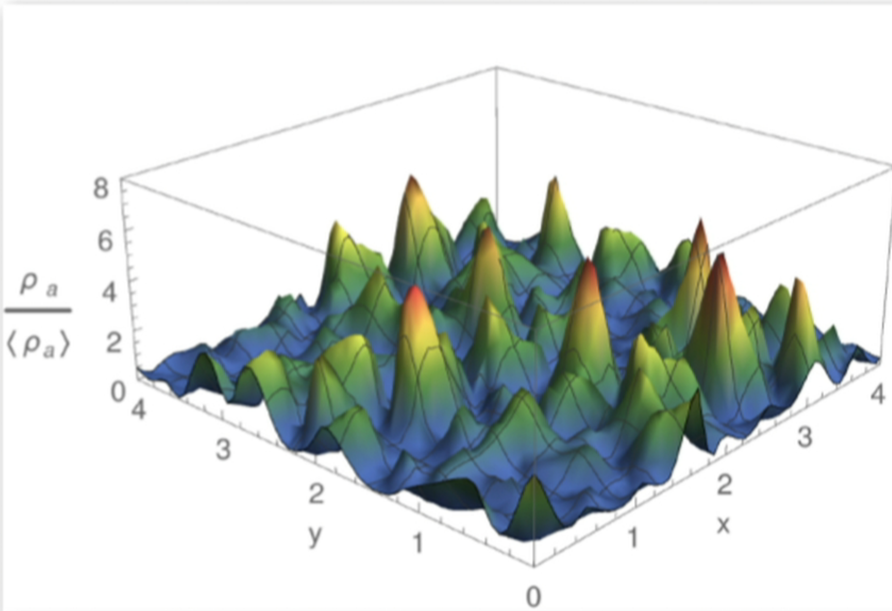
Miniclusters

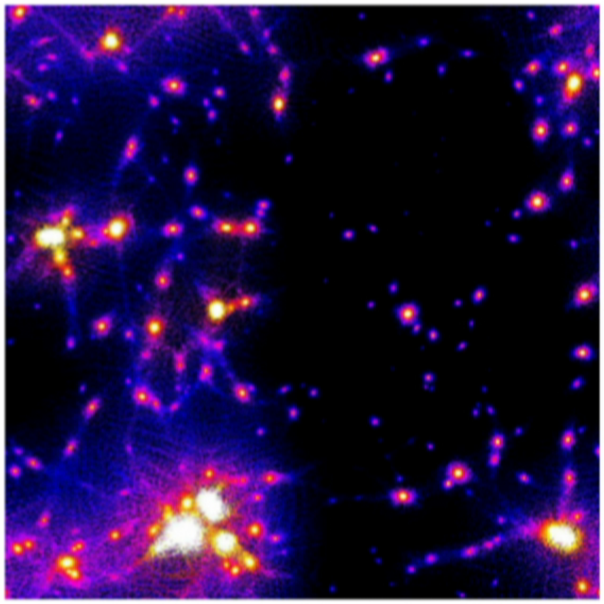


Start with a random field, evolve forward numerically

Smoothing on scales corresponding to the Hubble parameter when axion mass turns on

Overdensities compared to average: factor about 6

Late time evolution



Zurek et al
astro-ph/0607341

At matter radiation equality overdensities collapse

$$\rho \simeq 140\Phi^3\,(\Phi+1)\,\rho_c$$

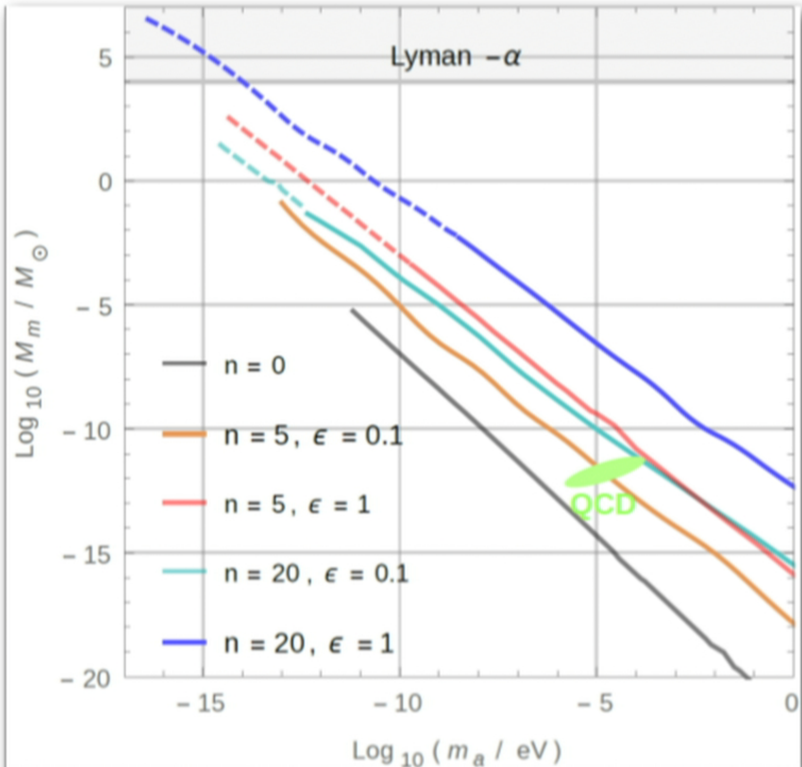
$$\Phi = \delta\rho/\rho \simeq 6$$

$$M_m \simeq 3\times 10^{-11} M_\odot \left(\frac{\mathrm{GeV}}{T_0}\right)^3$$

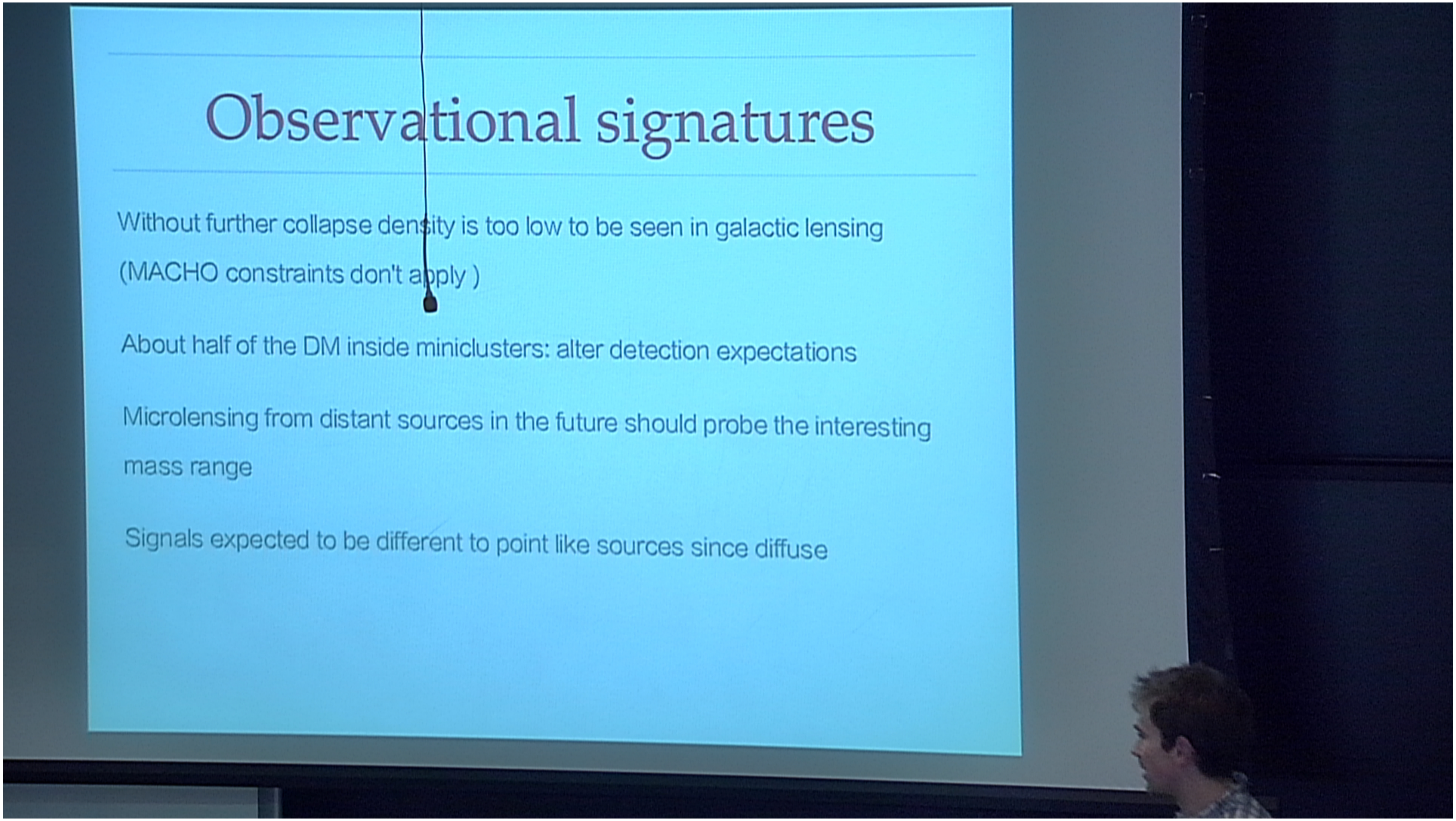
$$R_m \simeq \frac{10^{11}\,\mathrm{m}}{\Phi\,(1+\Phi)^{1/3}} \left(\frac{\mathrm{GeV}}{T_0}\right)$$

can further contraction to bose stars occur?

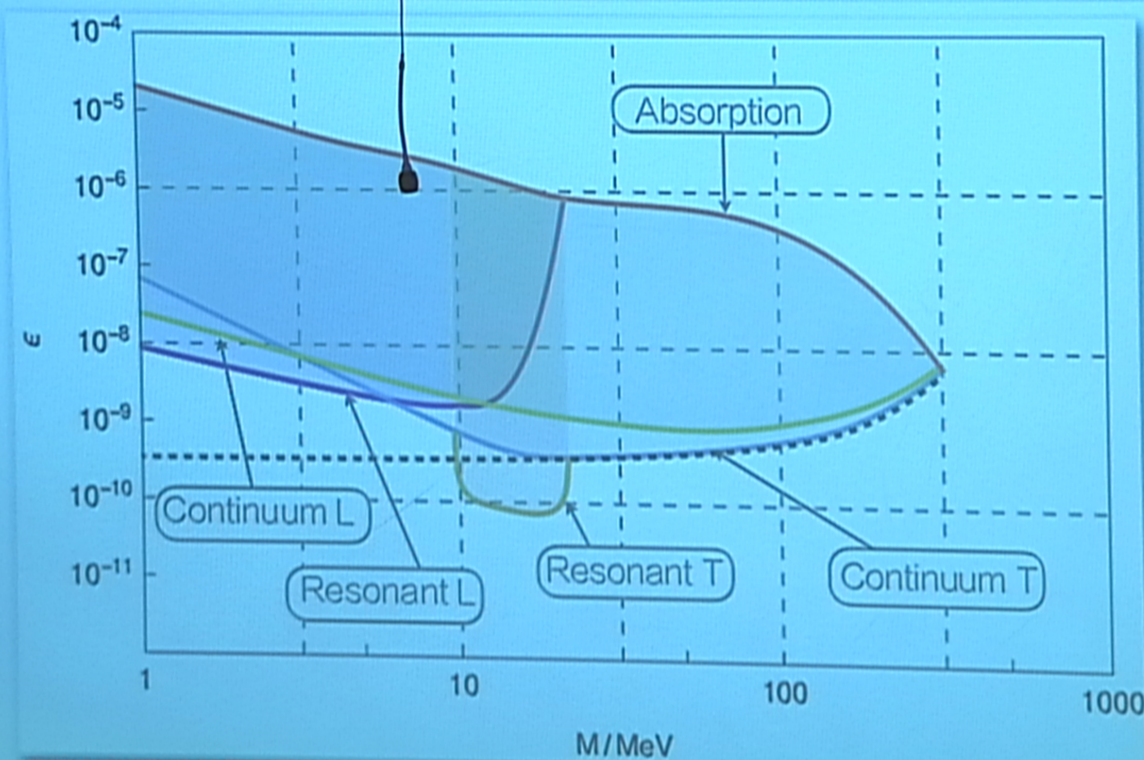
Minicluster Masses



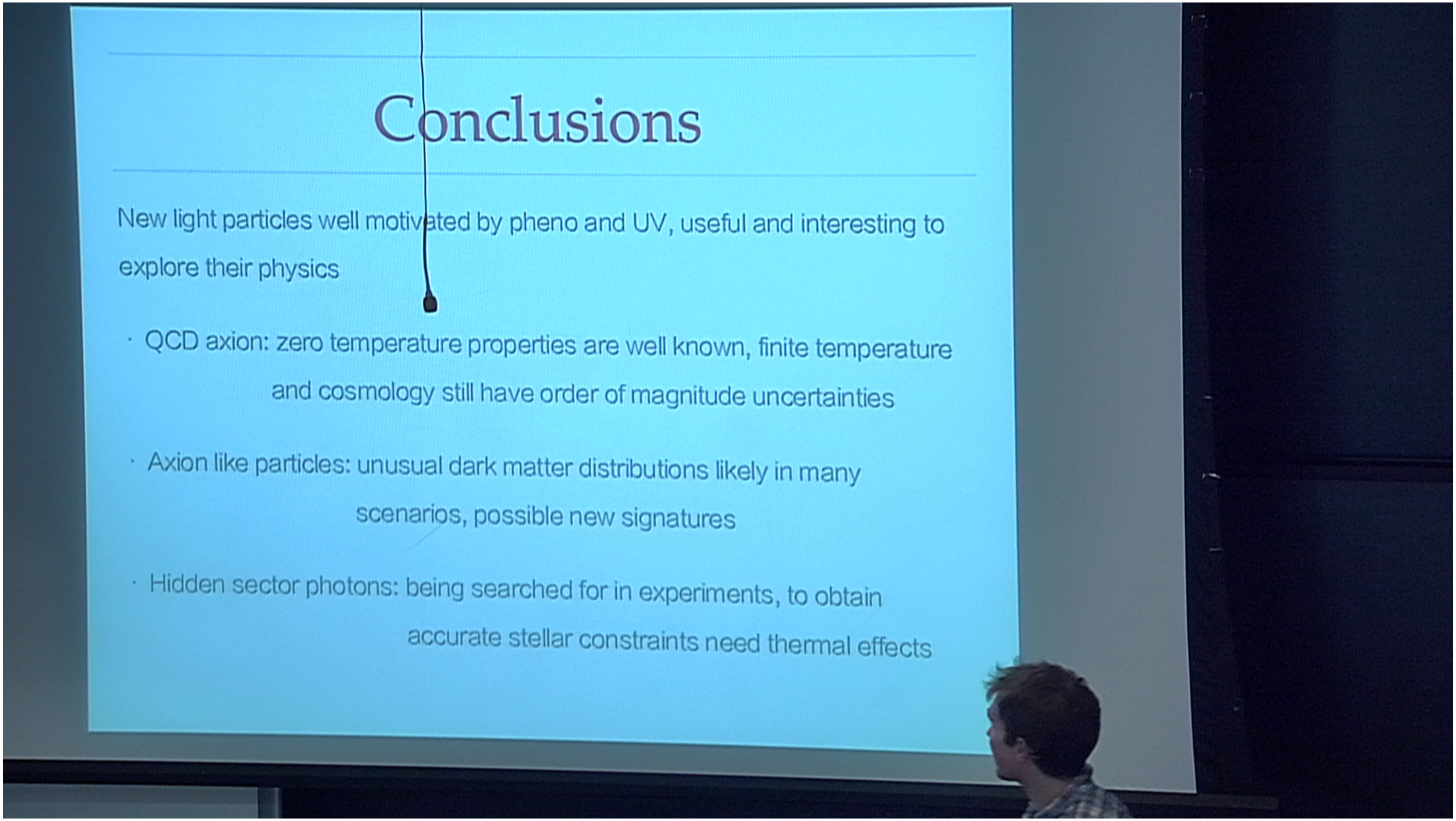
$$R_m \simeq 10^9 \mathrm{m} \left(\frac{M_m}{10^{-12} M_\odot} \right)^{1/3}$$

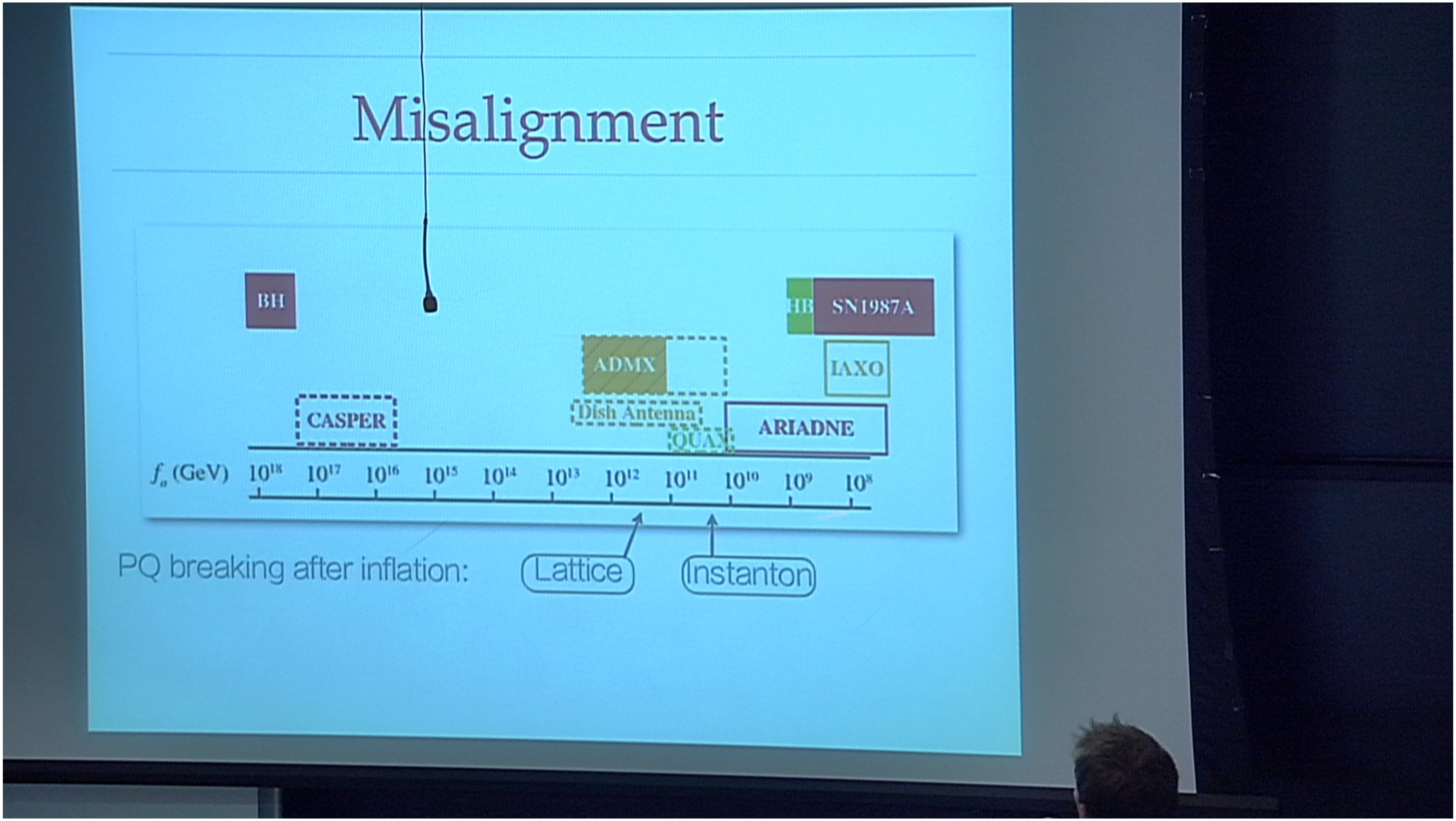

Observational signatures
Without further collapse density is too low to be seen in galactic lensing
(MACHO constraints don't apply)
About half of the DM inside miniclusters: alter detection expectations
Microlensing from distant sources in the future should probe the interesting
mass range
Signals expected to be different to point like sources since diffuse

Results



Absorption
Continuum L
Resonant L
Resonant T
Continuum T
ε
M / MeV


Conclusions
New light particles well motivated by pheno and UV, useful and interesting to explore their physics
· QCD axion: zero temperature properties are well known, finite temperature and cosmology still have order of magnitude uncertainties
· Axion like particles: unusual dark matter distributions likely in many scenarios, possible new signatures
· Hidden sector photons: being searched for in experiments, to obtain accurate stellar constraints need thermal effects


Misalignment
BH
HB
SN1987A
ADMX
IAXO
CASPER
Dish Antenna
ARIADNE
QUAX
f_a (GeV) 10^{18} 10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8}
PQ breaking after inflation:
Lattice
Instanton