Theory Working Group Report.

Axions and Axion-Like Particles in Theory, Astrophysics and Cosmology

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Vistas in Axion Physics,
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Theory Working Group

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Towards a Roadmap for Theoretical and Experimental Axion Physics through 2025

- Experiments need guidance from theory, astrophysics, and cosmology
- What are the best motivated regions in the landscape of axion and axion-like particle (ALP) parameters?
  - THEORY:

    What are the theoretically favored parameter ranges for the axion decay constant f_a and its couplings to standard model particles?

    Are there good reasons to expect also ALPs? What are their decay constants and couplings?
  - ASTROPHYSICS:

    Constraints from current and future observations in astrophysics which point to the existence of axions and ALPs? What are the accessible parameter ranges?
  - COSMOLOGY:

    Are there favored regions in parameter space for axions and ALPs such that they may constitute CDM?
- There are some hot spots in this landscape: overlaps between theory, astrophysics and cosmology

THEORY

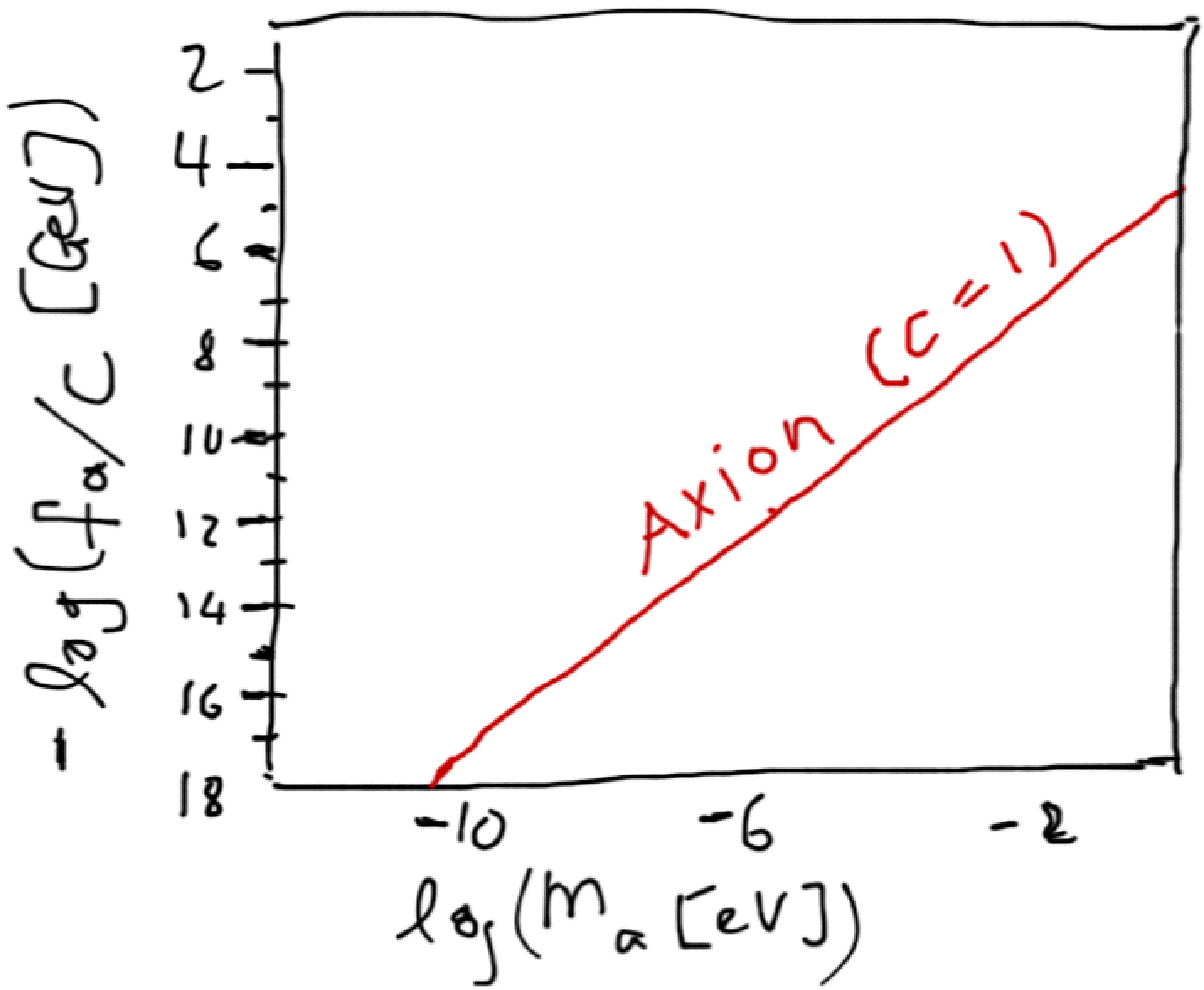
- What are the theoretically favored parameter ranges for the axion decay constant f_a and its couplings to standard model particles?
- Most general effective lagrangian for the axion at the weak scale in the standard model, cf. Georgi, Kaplan, Randall `86

$$
\begin{aligned}
\mathcal{L}^{a} = {} & \tfrac{1}{2}(\partial^{\mu}a)(\partial_{\mu}a) \\
& + (\partial^{\mu}a/f)\left(x_{\varphi}\varphi^{\dagger}\, i\overleftrightarrow{D}_{\mu}\varphi + \sum_{\psi} \bar{\psi_{L}}\gamma_{\mu}X_{\psi}\psi_{L}\right) \\
& - (a/f)[(g_3^2/32\pi^2)G\tilde{G} + C_{aWW}(g_2^2/32\pi^2)W\tilde{W} \\
& + C_{aYY}(g_1^2/32\pi^2)Y\tilde{Y}]\ .
\end{aligned}
$$

- Scale effective field theory down below chiral symmetry breaking scale: model independent predictions, such as mass and coupling to photons and nucleons

$$
m_a^2 = \frac{m_\pi^2}{(m_u + m_d)\,\mathrm{tr}(M^{-1})}\,\frac{f_\pi^2}{f^2}
$$

THEORY



THEORY

- To be more predictive, need specific ultra-violet completion
  - KSVZ and DFSZ are particular examples with free parameter f_a
- More predictive: completions which also solve other problems and link f_a to other scales such as the see-saw scale 10^10 GeV, the GUT-scale 10^16 GeV or the string scale (which can be both)
- String compactifications generically contain pseudo-scalar fields with axionic coupling to gauge fields and anomalous global shift symmetry, cf. Witten `84

$$a_i F\tilde{F} \qquad\qquad a_i \longrightarrow a_i + \epsilon$$

- These axion and axion-like particle (ALP) candidates arise in string compactifications as KK zero modes of antisymmetric tensor fields:

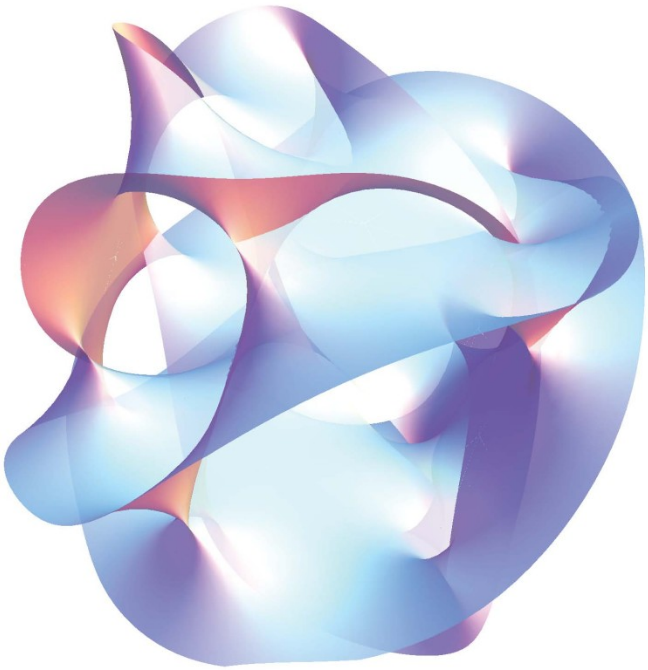
$$\text{heterotic string}: \quad B_2$$

$$\text{IIB string}: C_2, C_4$$

THEORY

- KK reduction (expansion in harmonic forms):

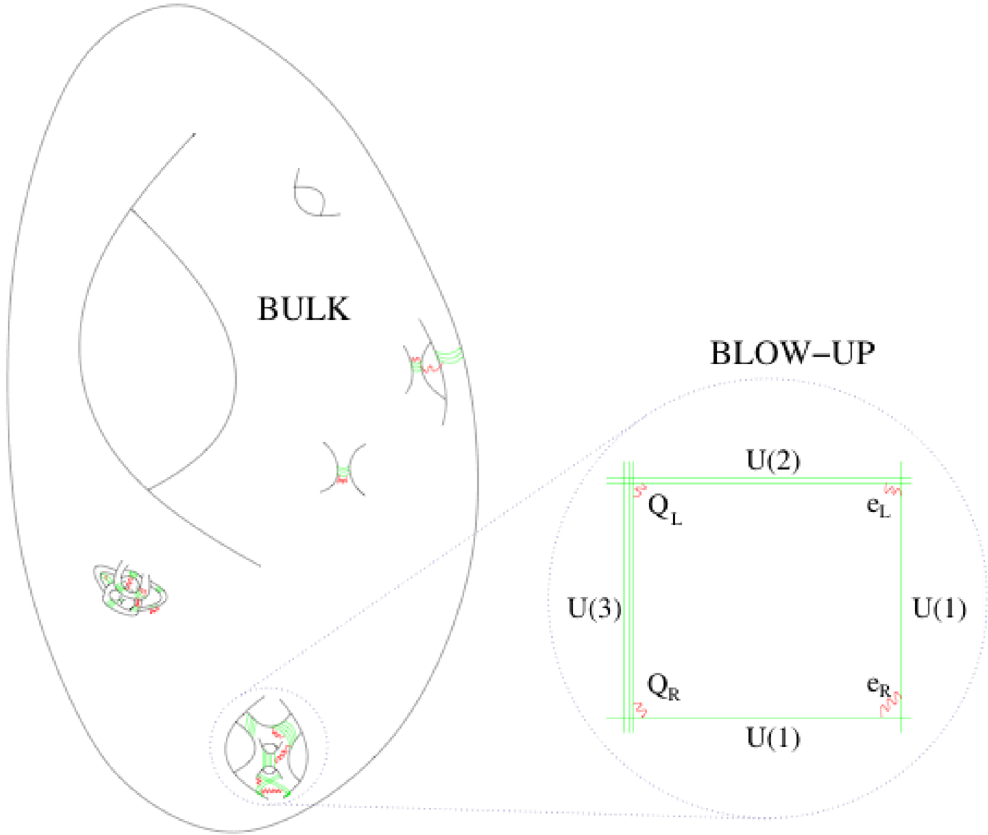
$$C_2 = c^a(x)\omega_a, \quad a = 1, ..., h^{1,1}_-$$
$$C_4 = c_\alpha(x)\tilde{\omega}^\alpha + \ldots, \quad \alpha = 1, ..., h^{1,1}_+$$



- Number of axionic fields, h^(1,1), determined by topology of the 6D compactification manifold: number of topologically non-equivalent 2D or 4D submanifolds called cycles
- This number can be large

THEORY

- Cycles can be wrapped by space-time filling branes
- Each of these branes gives rise to a gauge theory at low energy
- Axion and ALP decay constants as well as couplings to gauge bosons, e.g. photons, can be extracted after integrating out heavy KK fields



THEORY

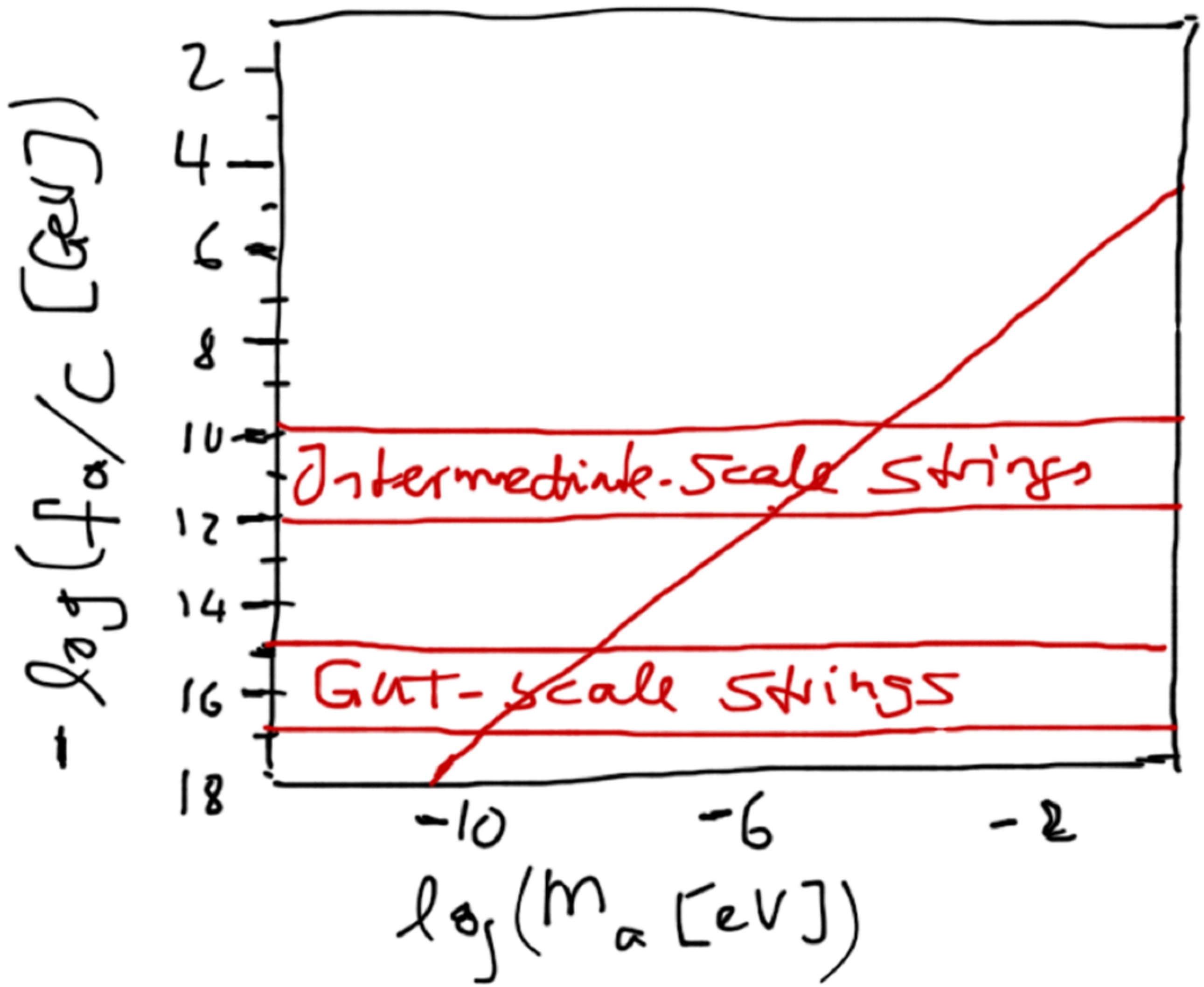
- QCD axion plus many ALPs – an axiverse – guaranteed from string theory? cf. Arvanitaki et al. `09
- Acharya, Bobkov, Kumar `11: examples in M-theory with f~10^16 GeV
- Cicoli, Goodsell, AR, DESY 12-058, 1205.nnnn: explicit globally consistent chiral model examples in IIB-theory (CYs with h_11=4,5,few, plus brane setups and fluxes), cf. Cicoli,Mayrhofer,Valandro `11:
  - GUT-like model with 5 magnetised D7 branes: QCD axion with f~10^16 GeV
  - MSSM-like model: QCD axion plus one light ALP, both have f ~ 10^16 GeV
  - Chiral model with QCD axion plus one light ALP, both have f ~ M_s ~ 10^11 GeV
- In string compactifications with a QCD axion one expects that typically there are in addition further ALPs which have approximately the same decay constant and coupling to photons as the QCD axion

THEORY

- Low energy effective lagrangian:

$$
\begin{aligned}
\mathcal{L} \supset\ & \frac{1}{2}\,\partial_\mu a_i\,\partial^\mu a_i - \frac{g_3^2}{32\pi^2}\left(\theta_0 + C_{i33}\,\frac{a_i}{f_{a_i}}\right) F^b_{3,\mu\nu}\tilde{F}_3^{b,\mu\nu} \\
& - \frac{g_2^2}{32\pi^2}\,C_{iWW}\,\frac{a_i}{f_{a_i}}\,F^b_{W,\mu\nu}\tilde{F}_W^{b,\mu\nu} - \frac{g_Y^2}{32\pi^2}\,C_{iYY}\,\frac{a_i}{f_{a_i}}\,F_{Y,\mu\nu}\tilde{F}_Y^{\mu\nu} \\
& - \sum_{\psi_L,\psi_R}\left(\psi_R M \psi_L + \overline{\psi}_L M^\dagger \overline{\psi}_R\right) + \sum_{\psi_L}\frac{X^i_{\psi_L}}{f_{a_i}}\psi_L\sigma^\mu\overline{\psi}_L\partial_\mu a_i + \sum_{\psi_R}\frac{X^i_{\psi_R}}{f_{a_i}}\psi_R\sigma^\mu\overline{\psi}_R\partial_\mu a_i \\
& - \sum_{\psi_L,\psi_R}\left(i\psi_R g^i \psi_L \frac{a_i}{f_{a_i}} + h.c.\right) - V(a_i),
\end{aligned}
\qquad (\mathrm{A.1})
$$

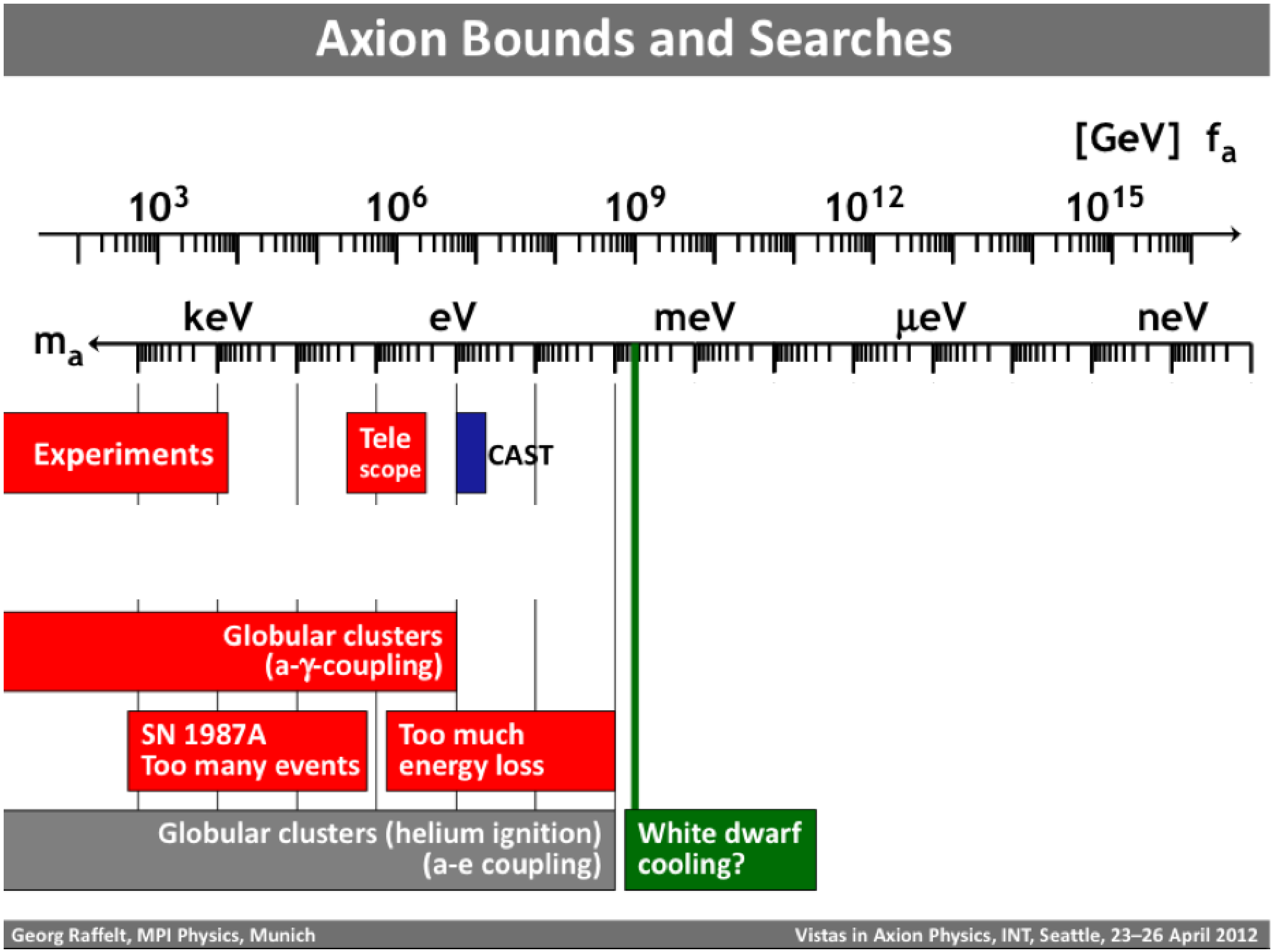
THEORY



$-\log(f_a/C\ [\mathrm{GeV}])$
2
4
6
8
10
12
14
16
18
Intermediate-Scale strings
GUT-scale strings
-10
-6
-2
$\log(m_a\ [\mathrm{eV}])$

ASTROPHYSICS

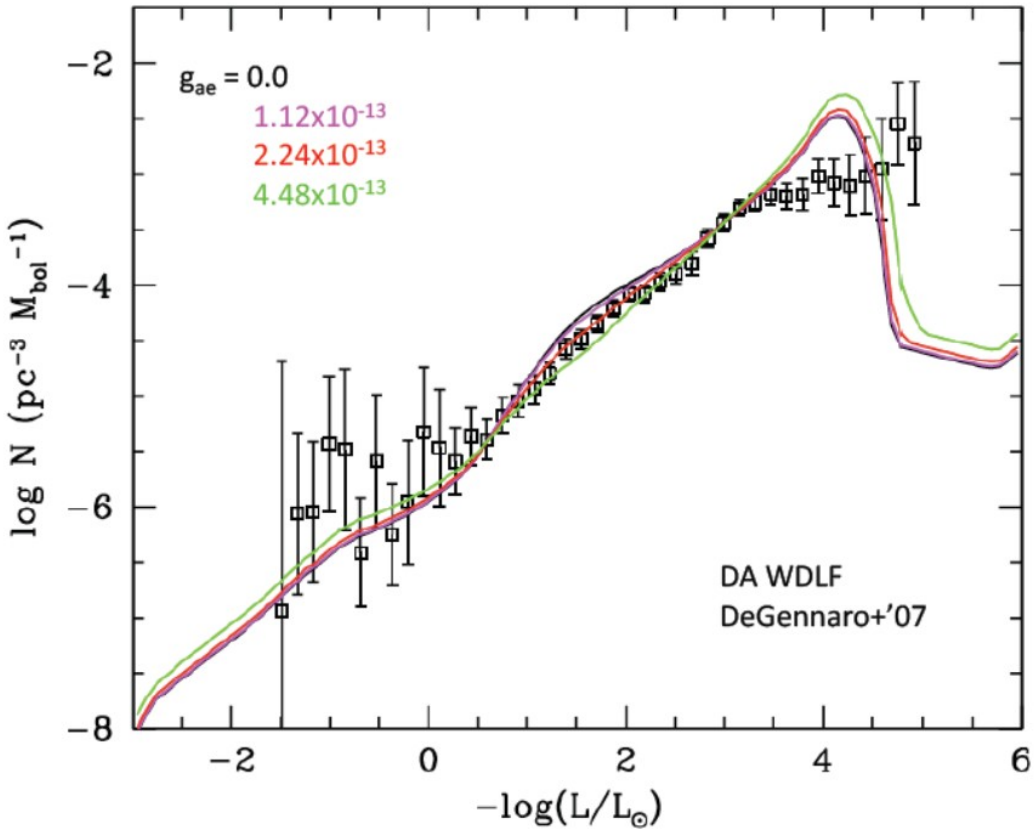
- Astrophysics constrains f/C > 10^9 GeV for C_gamma and C_e, but at the border there are some intriguing observations



ASTROPHYSICS

- Standard model does not fit to white dwarf luminosity function
- Extra energy loss compatible with axion or ALP bremsstrahlung

Isern et al. `08



ASTROPHYSICS

- Required parameters:

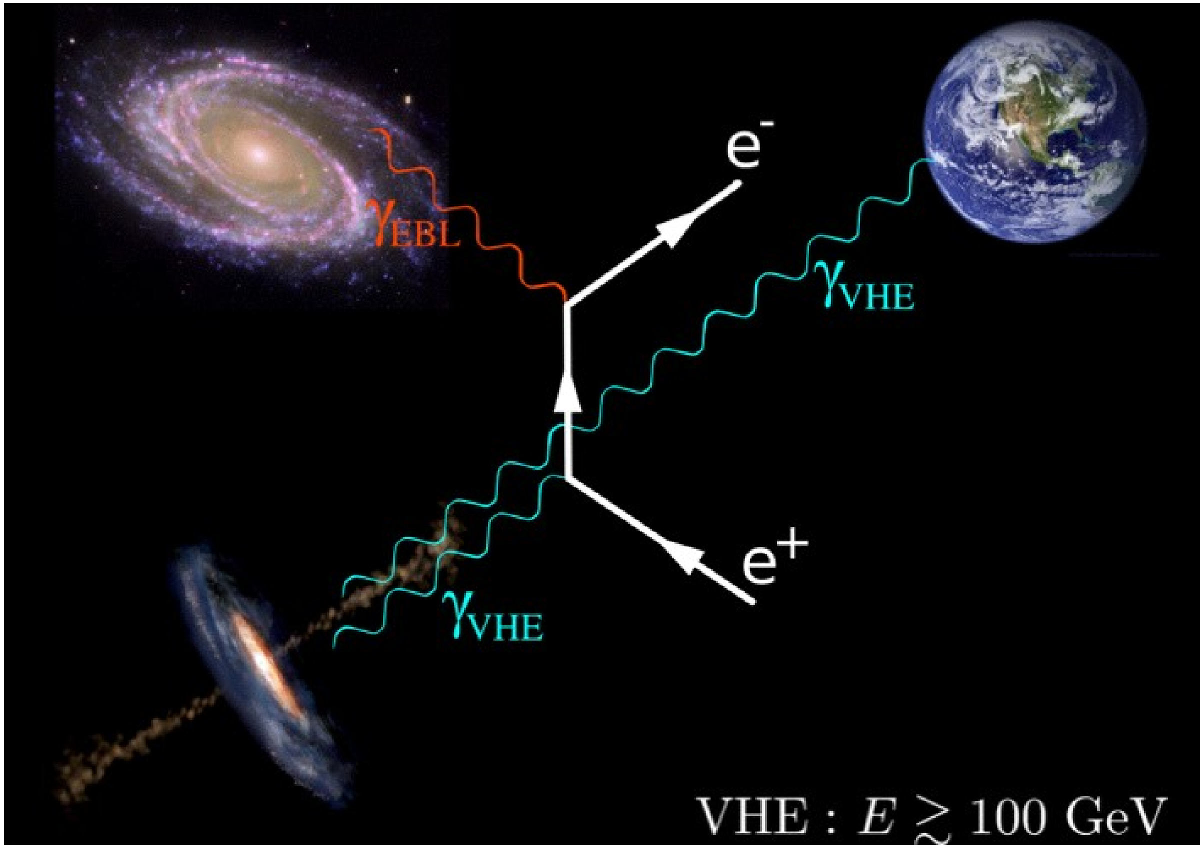
$$m_{a_i} \lesssim \mathrm{keV}, \;\; g_{ie} \equiv \frac{C_{ie} m_e}{f_{a_i}} = (0.6 \div 1.7) \times 10^{-13}$$

$$\Rightarrow f_{a_i} \sim 10^{10} \; C_{ie} \; \mathrm{GeV}$$

- Can be axion or ALP

ASTROPHYSICS

- TeV photon spectra of distant AGNs should show absorption feature due to electron-positron pair production on extra-galactic background light

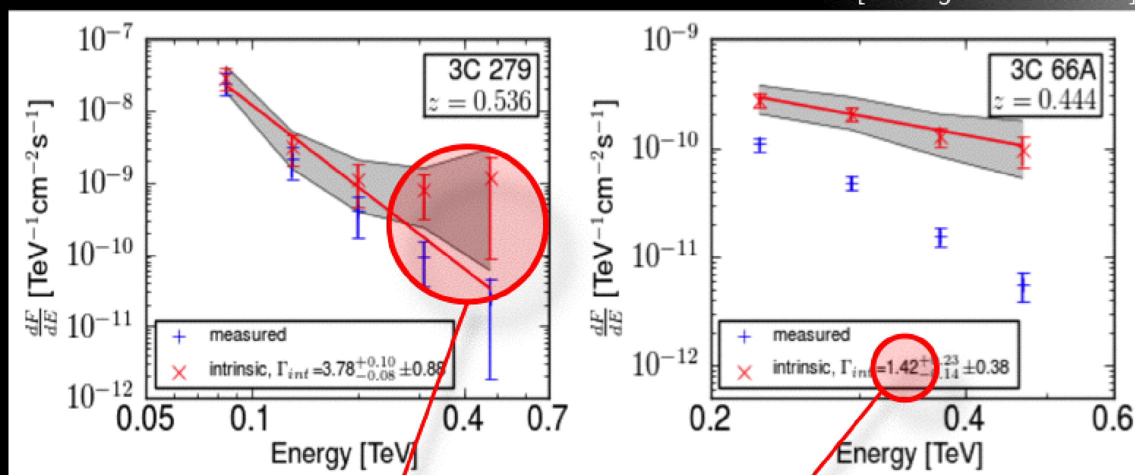


ASTROPHYSICS

Hints for new physics?

- Some recent gamma-ray observations pose substantial challenges to the conventional models.
  - Intrinsic spectrum deviates from a power-law: pile-up problem (Dominguez+12).
  - Very hard intrinsic spectrum of FSRQs (e.g. Albert+08, Alecsik+11, Wagner+10)
  - Extremely rapid and intense flares (Tavecchio+12).
  - GeV spectral breaks!

[Domínguez et al. 2011]



See also Horns+12 !

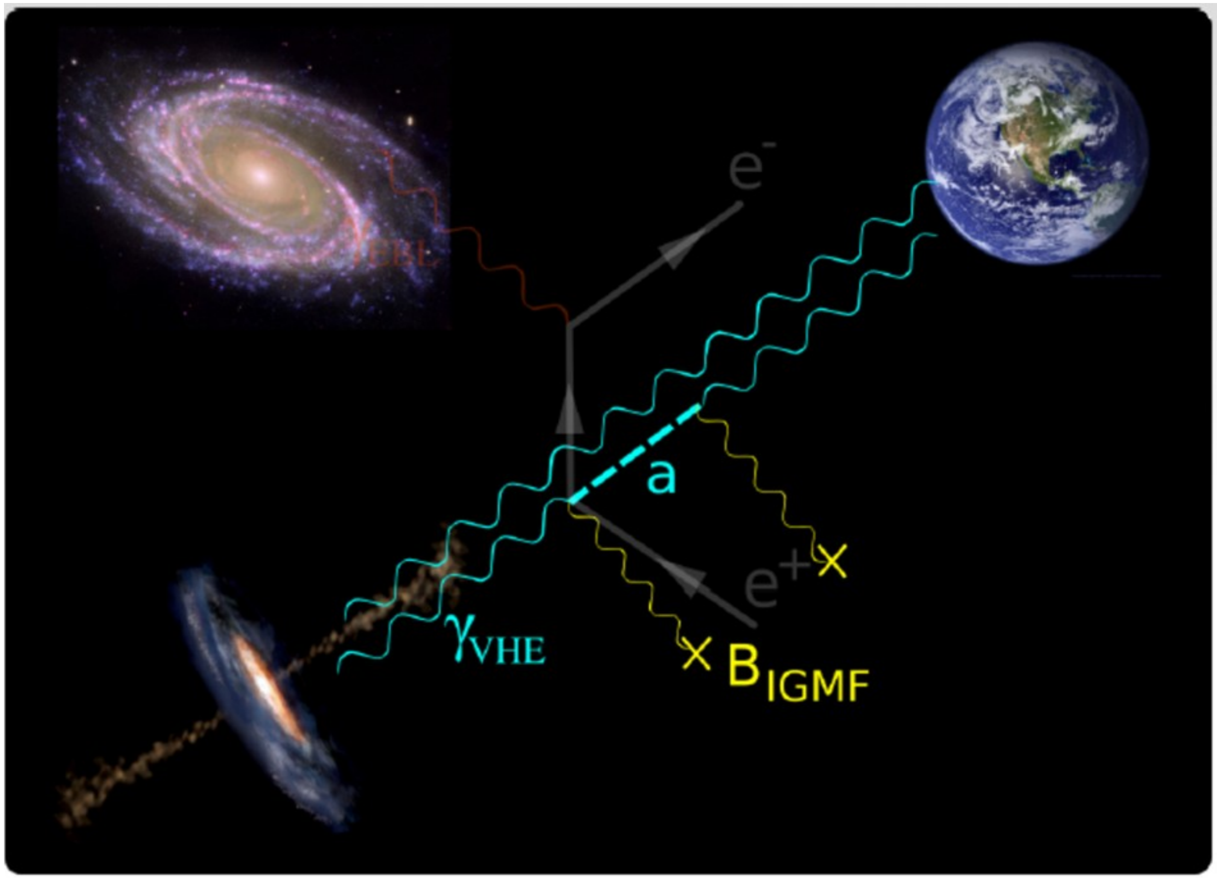
PILE-UP!

Modeling of AGN emission mechanisms typically assume **spectral index >1.5**

cf. Sanchez-Conde

ASTROPHYSICS

- Possible explanation: photon <-> ALP oscillations in astrophysical magnetic fields



ASTROPHYSICS

- Required parameters: cf.

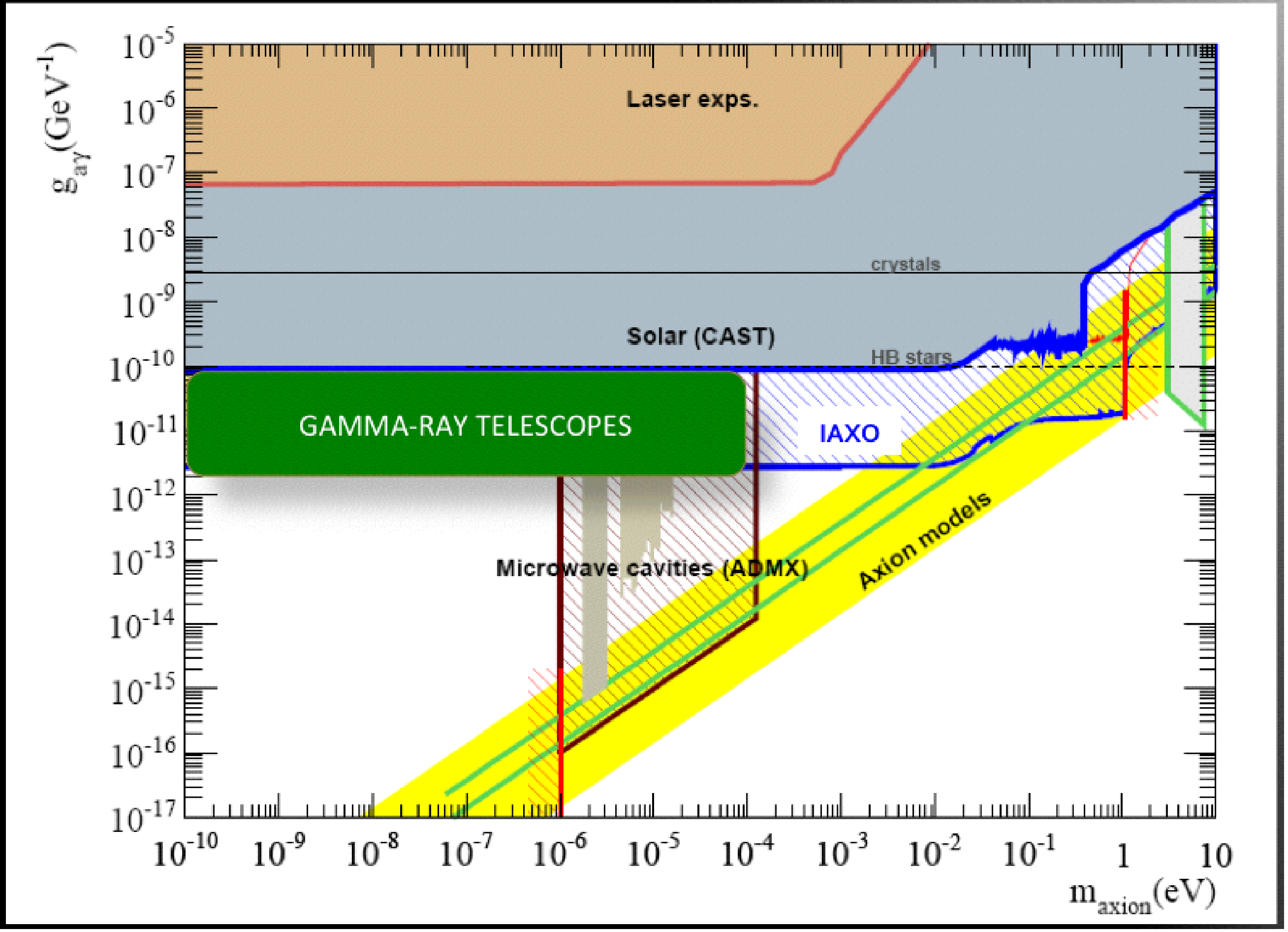
$$m_{a_i} \lesssim \text{neV}, \quad g_{i\gamma} \equiv \frac{\alpha}{2\pi} \frac{C_{i\gamma}}{f_{a_i}} \sim 10^{-12} \div 10^{-11} \ \text{GeV}^{-1}$$

$$\Rightarrow f_{a_i} \sim 10^8 \div 10^9 \ C_{i\gamma} \ \text{GeV}$$

- Must be an ALP, too light for an axion with such a decay constant

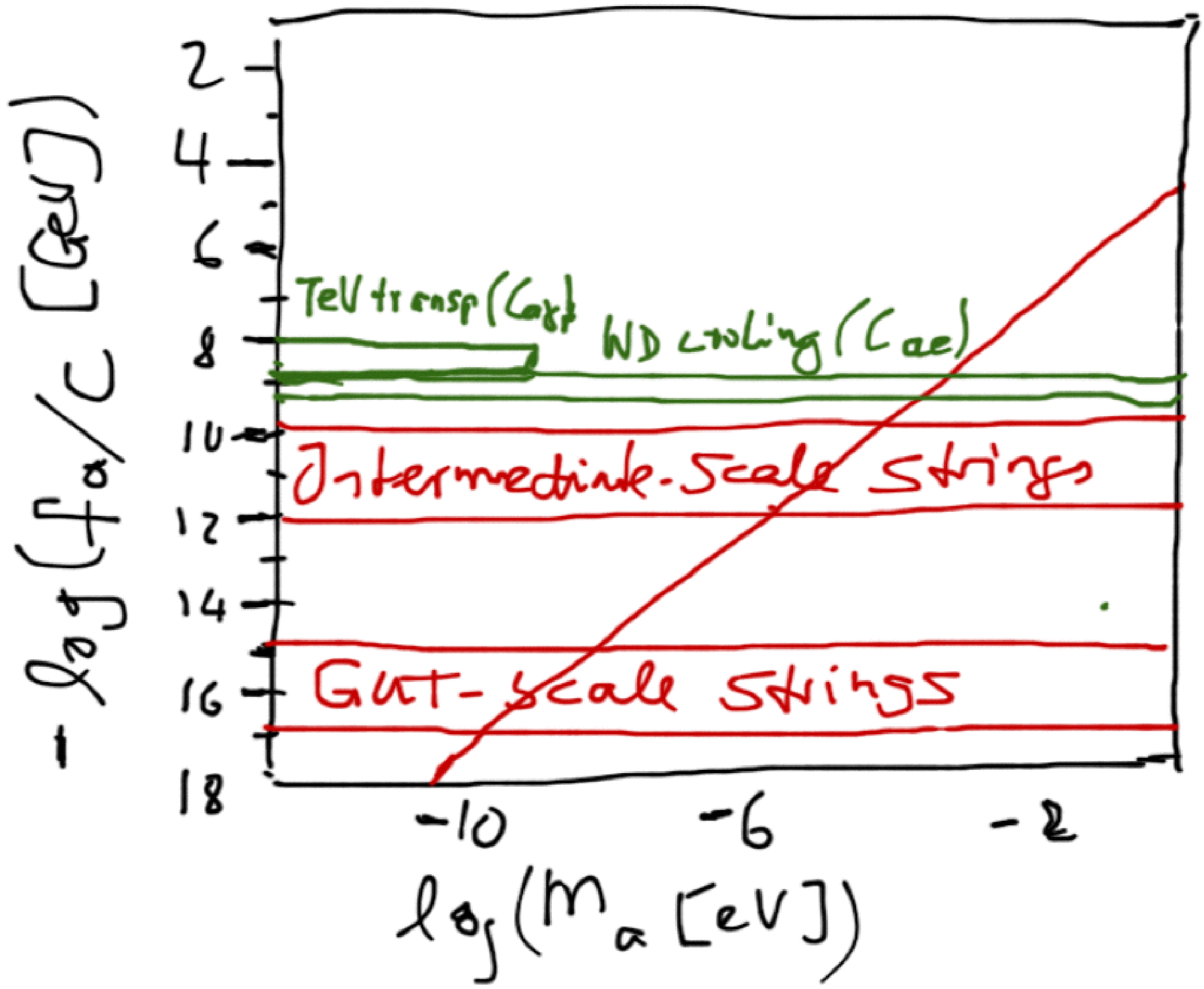
ASTROPHYSICS

Fermi + IACTs can explore a region of the ALP parameter space that is difficult to explore otherwise!



> cf. Sanchez-Conde

ASTROPHYSICS



COSMOLOGY

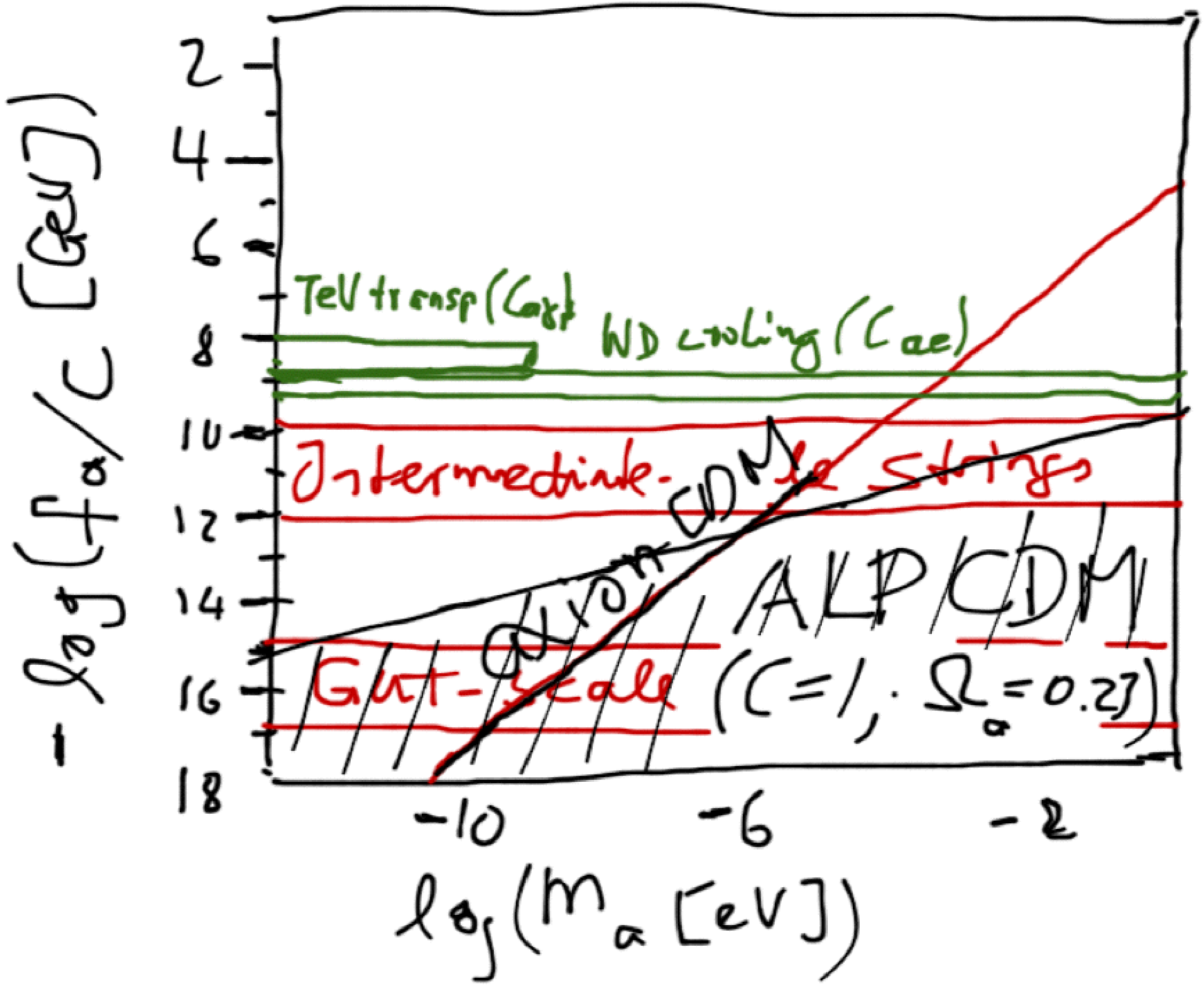
- Are there favored regions in axion or ALP parameter space such that they constitute CDM?
- Axion produced via misalignment mechanism,

$$\Omega_a h^2 \approx 0.7 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}} \right)^{7/6} \left(\frac{\theta_i}{\pi} \right)^2$$

- Generic ALP also produced via misalignment mechanism. Constitutes all CDM for (cf. Redondo)

$$\Omega_{a_i} h^2 \approx 10^{-2} \times \left(\frac{m_{a_i}}{\mu\mathrm{eV}} \right)^{1/2} \left(\frac{f_{a_i}}{10^{12}\ \mathrm{GeV}} \right)^2 \left(\frac{\theta_{a_i}}{\pi} \right)^2$$

COSMOLOGY



TeV transp (Caγ)
WD cooling (Cae)
Intermediate-scale strings
axion CDM
ALP CDM
GUT-scale
(C=1, Ωa=0.23)
2
4
6
8
10
12
14
16
18
-10
-6
-2
-log(fa/C [GeV])
log(ma [eV])

COSMOLOGY

> Wide mass range where axion or ALP could be dark matter:

Conclusions

For axions to be 100% of cold dark matter.....

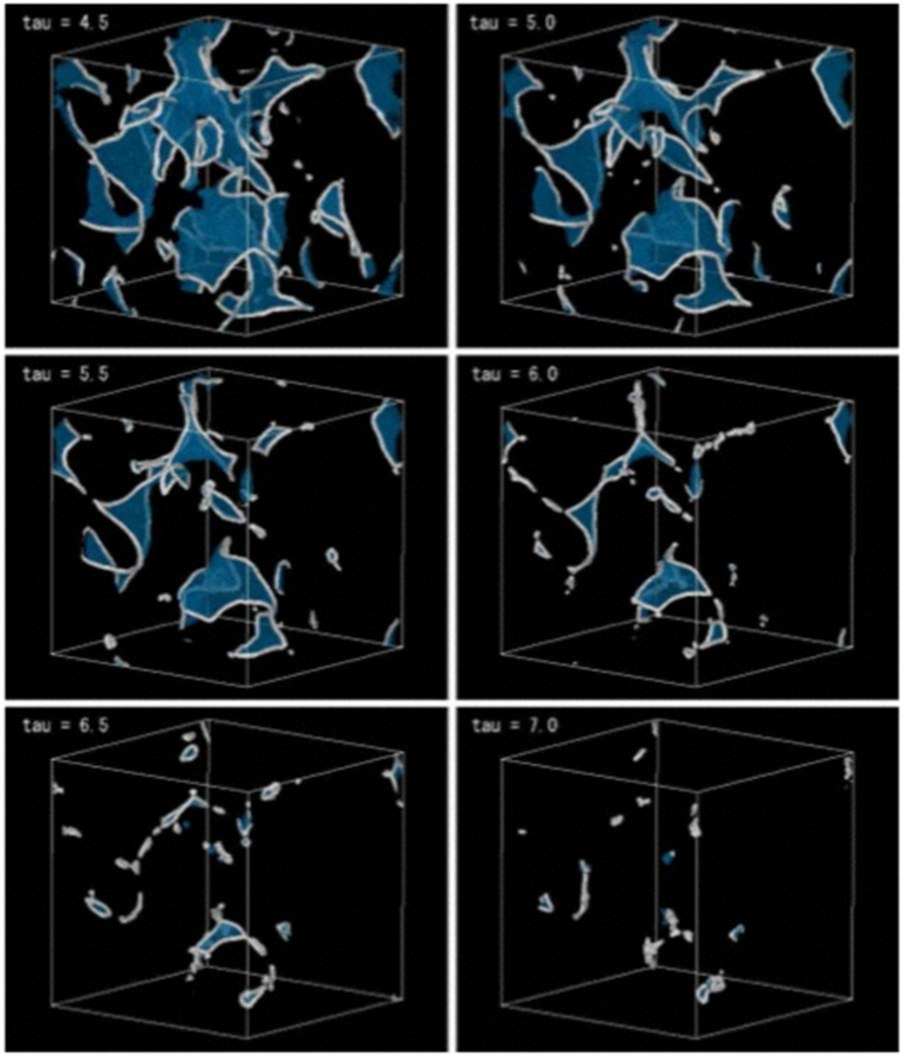
- If the Peccei-Quinn symmetry breaks after inflation ends, the axion mass must be $\boxed{m_a = 83\ \mu\mathrm{eV}}$ in standard cosmology
  - much smaller m_a in LTR cosmology
  - much larger m_a in kination cosmology

  $\boxed{0.1\ \mu\mathrm{eV} < m_a < 15\ \mathrm{meV}}$

- If the Peccei-Quinn symmetry breaks before inflation ends, an initial misalignment angle θ_i can be chosen for any $\boxed{m_a < 15\ \mathrm{meV}}$
  - larger allowed region and larger θ_i in LTR cosmology
  - smaller allowed region and smaller θ_i in kination cosmology

> cf. Gondolo

Axion Production by Domain Wall and String Decay



Recent numerical studies of collapse of string-domain wall system

$$\Omega_a h^2 = (16 \pm 6) \left(\frac{f_a}{10^{12}\mathrm{GeV}} \right)^{1.19} \times \left(\frac{g_{*,1}}{70} \right)^{-0.41} \left(\frac{\Lambda}{400\ \mathrm{MeV}} \right)$$

Implies a CDM axion mass of

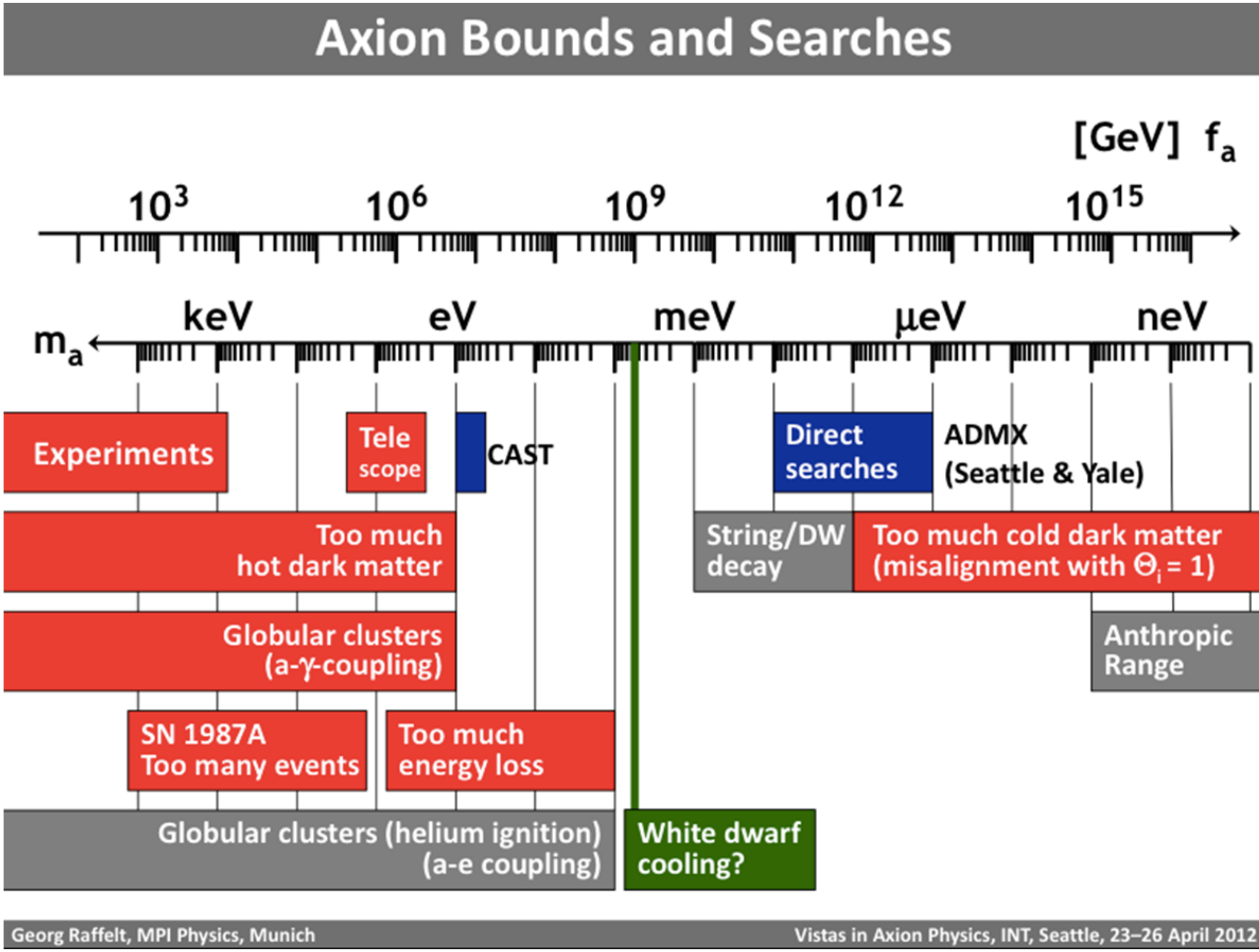
$$m_a \sim 1\ \mathrm{meV}$$

Hiramatsu, Kawasaki, Saikawa, Sekiguchi, arXiv:1202.5851 (2012)

Remains to be confirmed, interpretation of numerical studies not entirely straightforward

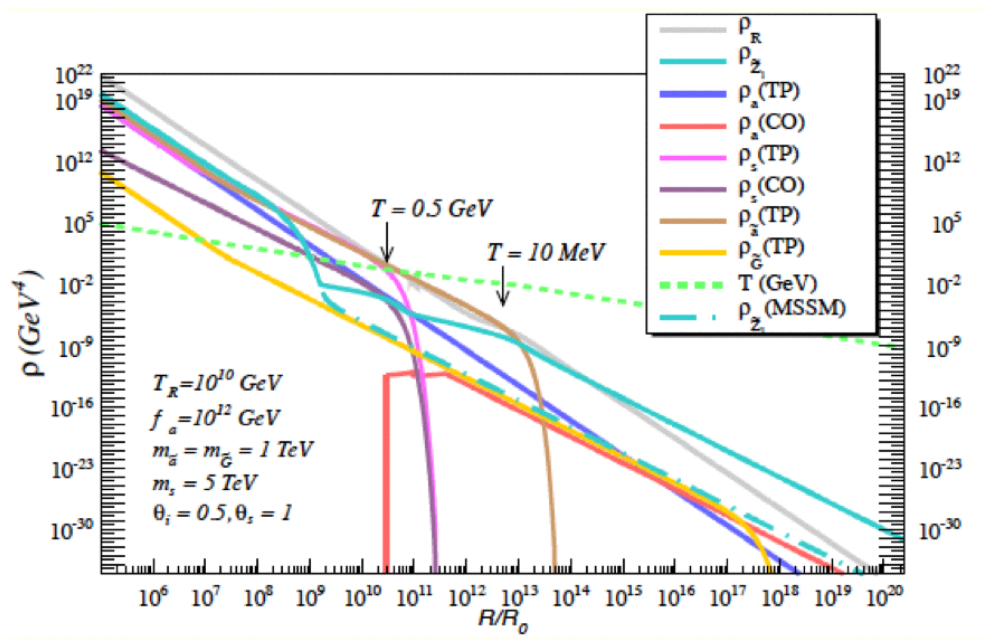
COSMOLOGY

> Wide mass range where axion or ALP could be dark matter:



COSMOLOGY

- The SUSY solution to gauge hierarchy problem and axion solution to strong CP problem are complementary: one needs both.
- Since lack of p-decay suggests R-parity conservation, then in this case one would get mixed axion-LSP dark matter.
- In this case, one must calculate the dark matter abundance including effects of SUSY LSP, axion, axino, saxion and gravitino. LSP might be neutralino, axino or gravitino, cf. Baer

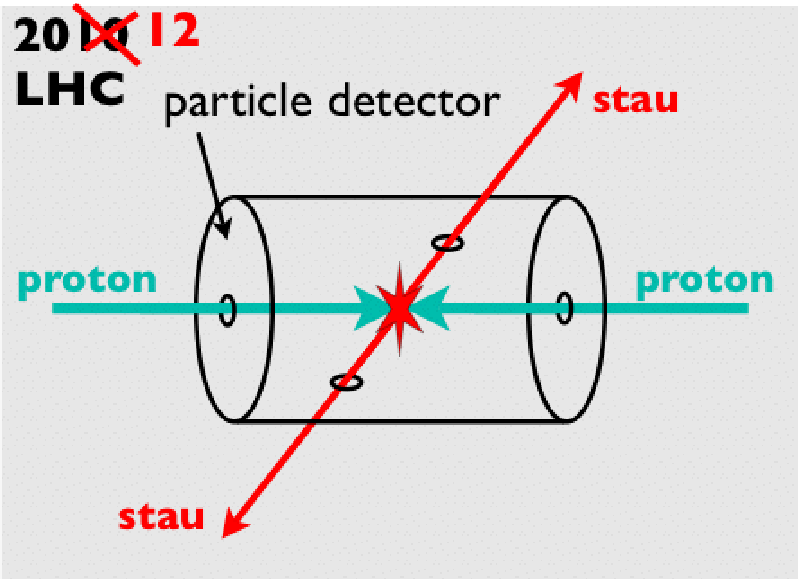


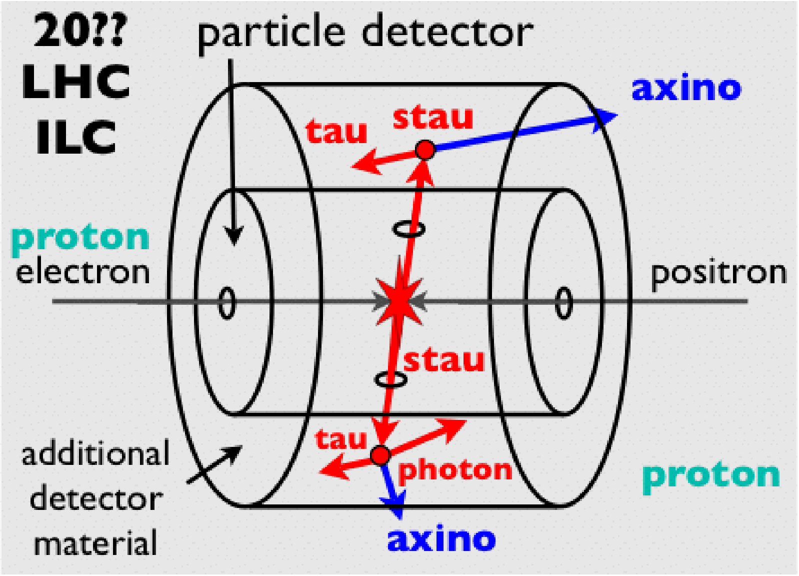
COSMOLOGY

- Much wider range of f_a is now allowed due to possibility of entropy dilution at temperature T_fr>T>T_BBN , and also variable theta_i . f_a can lie between 10^{9}-10^{16} GeV, cf. Baer
- Interesting link to collider physics:
  - Depending on what LHC (and later ILC) might see, we may be able to distinguish nature of LMSSMP, whether it is bino-like, higgsino-like, stau, or other.
  - SUSY models with bino-like LMSSMP usually give standard overabundance which can be diminished by decay to light MeV scale axino.
  - SUSY models with higgsino or wino-like LMSSMP and hence standard underabundance of neutralinos favor a weak scale axino mass since thermal axino production in early universe followed by decay to neutralino builds up the neutralino abundance.

> Probing the axion decay constant at the LHC, cf. Steffen

Stopping of long-lived staus

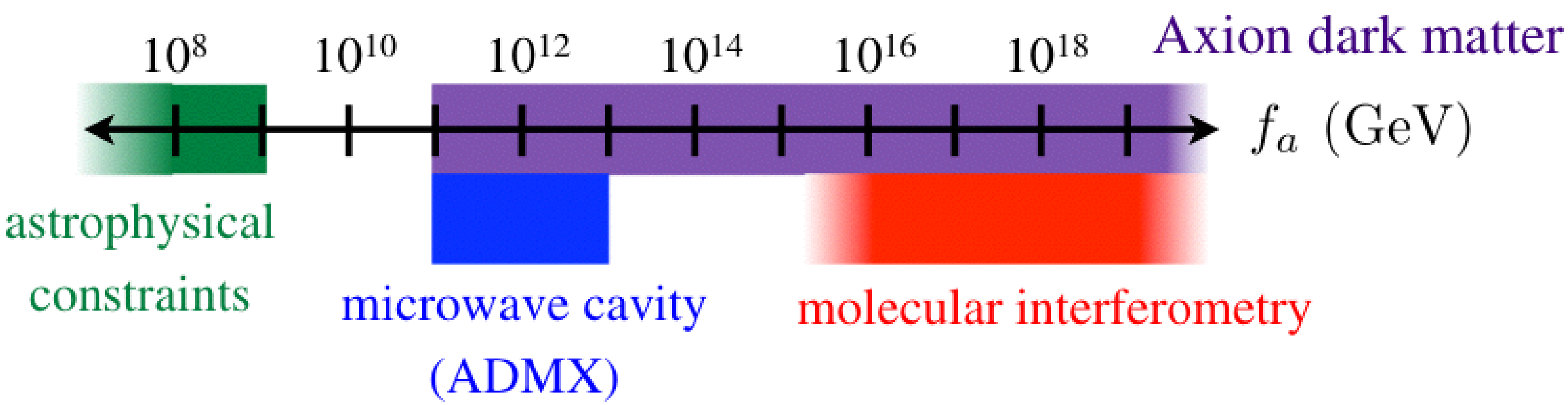




Probing f_a @ Colliders

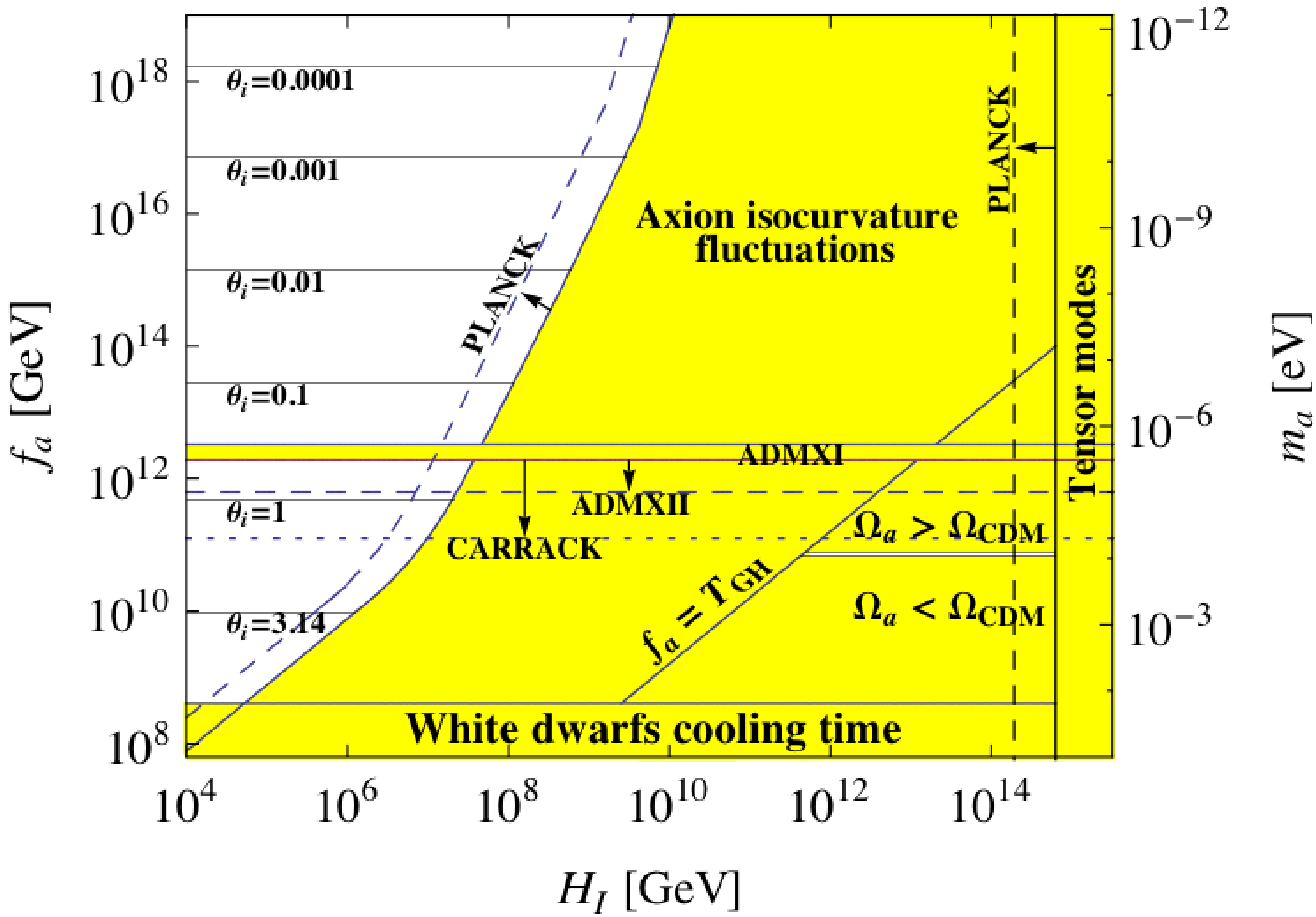
COSMOLOGY

- Direct axion and ALP CDM searches should be extended towards smaller and larger masses
- f_a ~ 10^12 GeV, m_a ~ micro-eV axion or ALP CDM doable
- f_a ~ 10^16 GeV, m_a ~ 10^-10 eV axion CDM possibility big challenge
  - Direct detection of time varying shifts of atomic energy levels due to the coupling between internal atomic fields and time varying CP-odd nuclear moments? cf. Graham, Rajendran `11



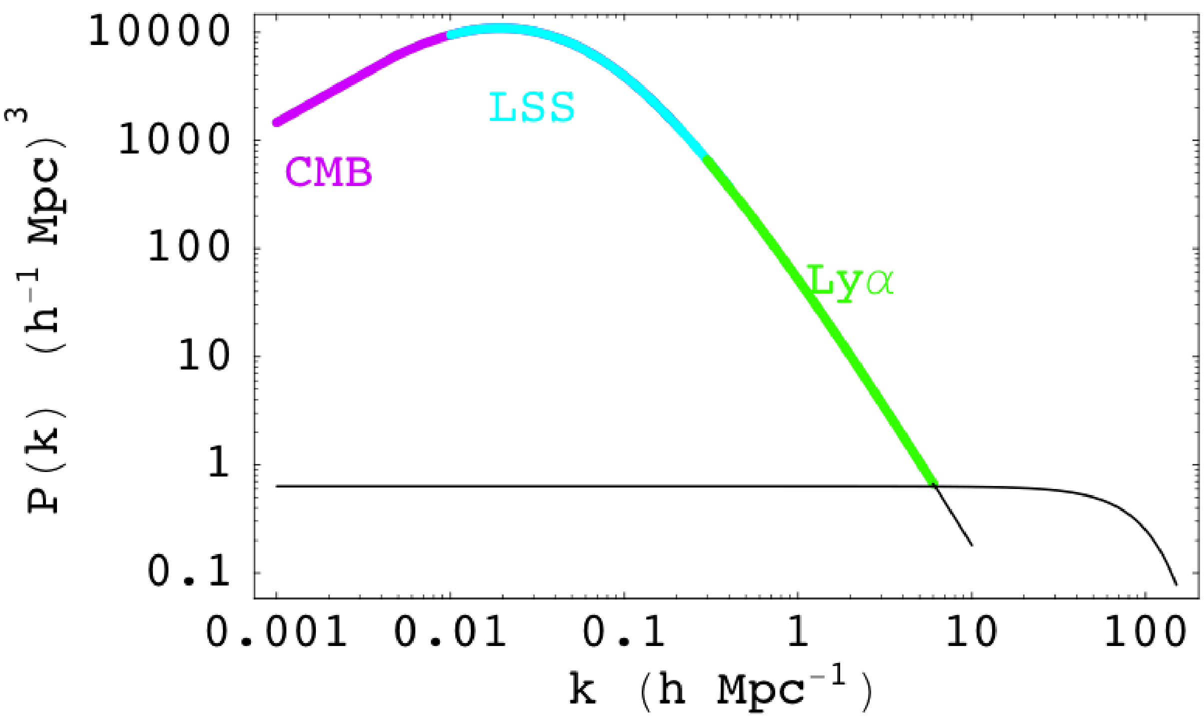
COSMOLOGY

- CMB probes:
  - Isocurvature fluctuations as a probe of large f_a: require low H_I, cf. Gondolo



COSMOLOGY

- CMB probes:
  - Isocurvature fluctuations as a probe of large f_a
- Large scale and CDM structure probes:
  - Miniclusters: enhancements in power spectrum, cf. Zurek, Hogan, Quinn `07



COSMOLOGY

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- Large scale and CDM structure probes:
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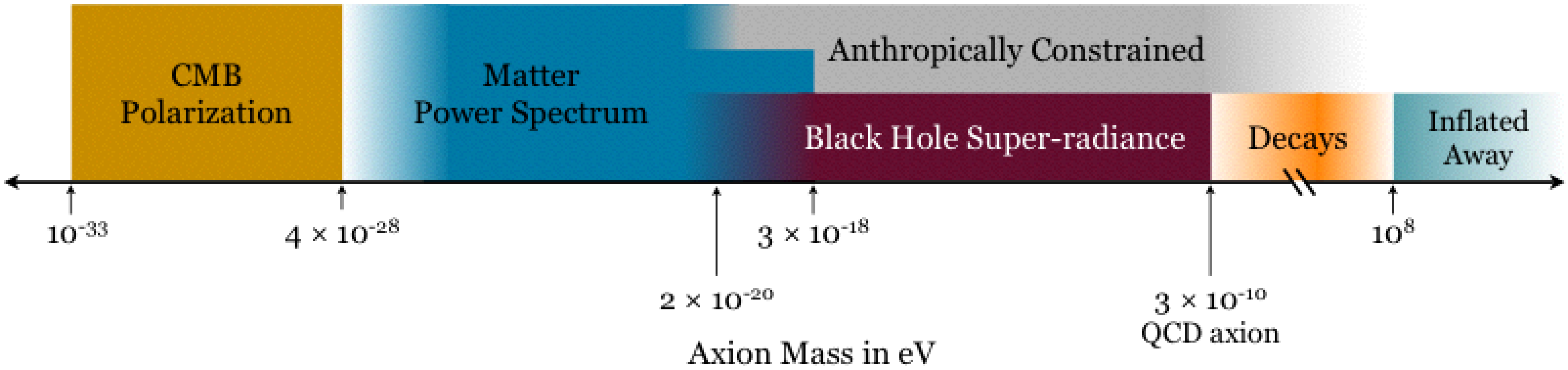
  - If axions or ALPs are Bose Einstein Condensate: possible solutions to CDM structure problems, cf. Salucci, Sikivie, Quinn
  - Ultra-light ALPs: effects on large scale structure and CMB, cf. Marsh, Macaulay, Trebitsch, Ferreira `11



cf. Arvanitaki et al. `10

COSMOLOGY

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- Large scale and CDM structure probes:
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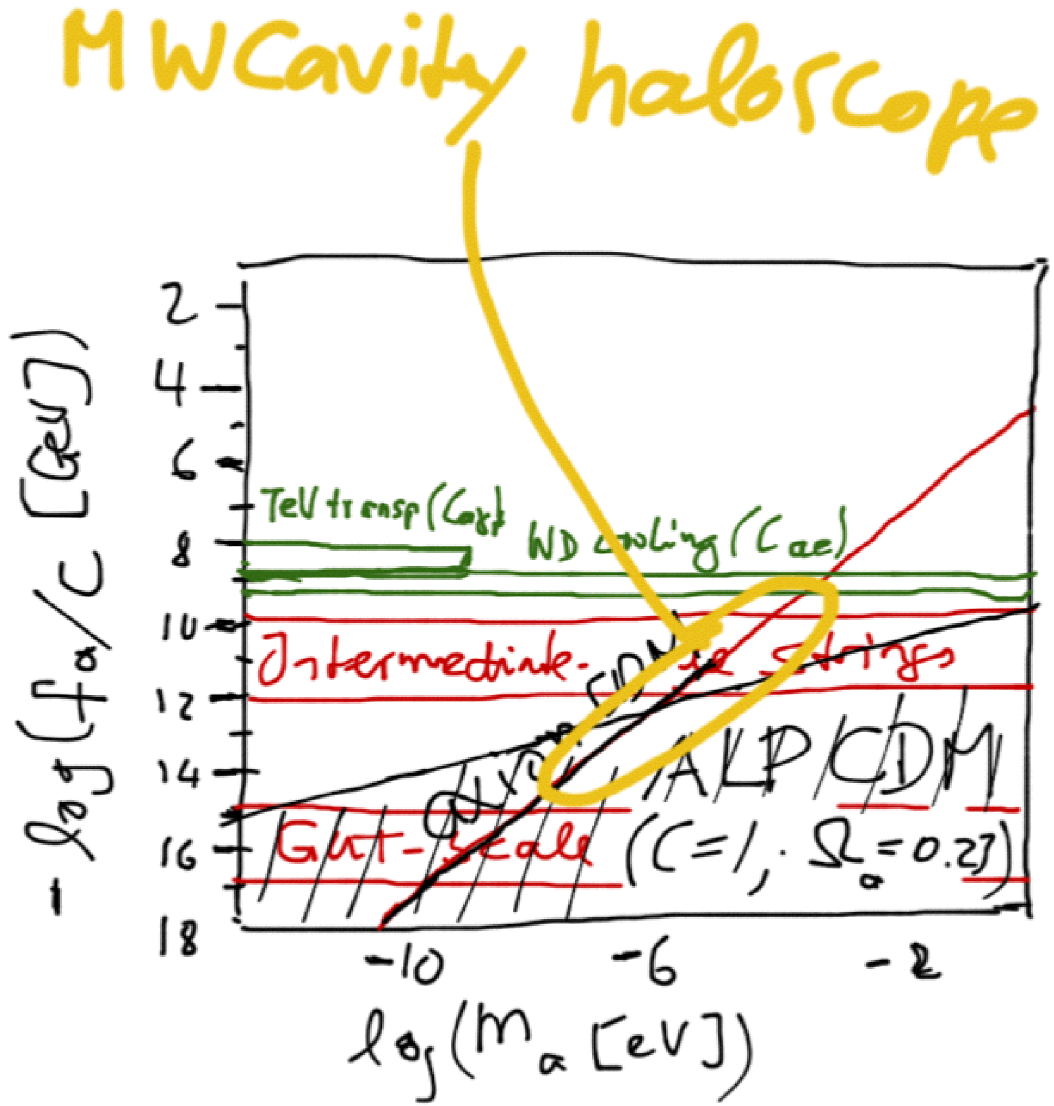
  - If axions or ALPs are Bose Einstein Condensate: possible solutions to CDM structure problems, cf. Salucci, Sikivie, Quinn
  - Ultra-light ALPs: effects on large scale structure and CMB, cf. Marsh, Macaulay, Trebitsch, Ferreira `11
- Combination of both:
  - Tilted universe (cf. Turner) where the photon rest frame differs from the matter rest frame, may be a probe for axions with GUT scale f_a, cf. Kaplan

CONCLUSIONS

- Hot spots in the landscape of axions and ALPs:



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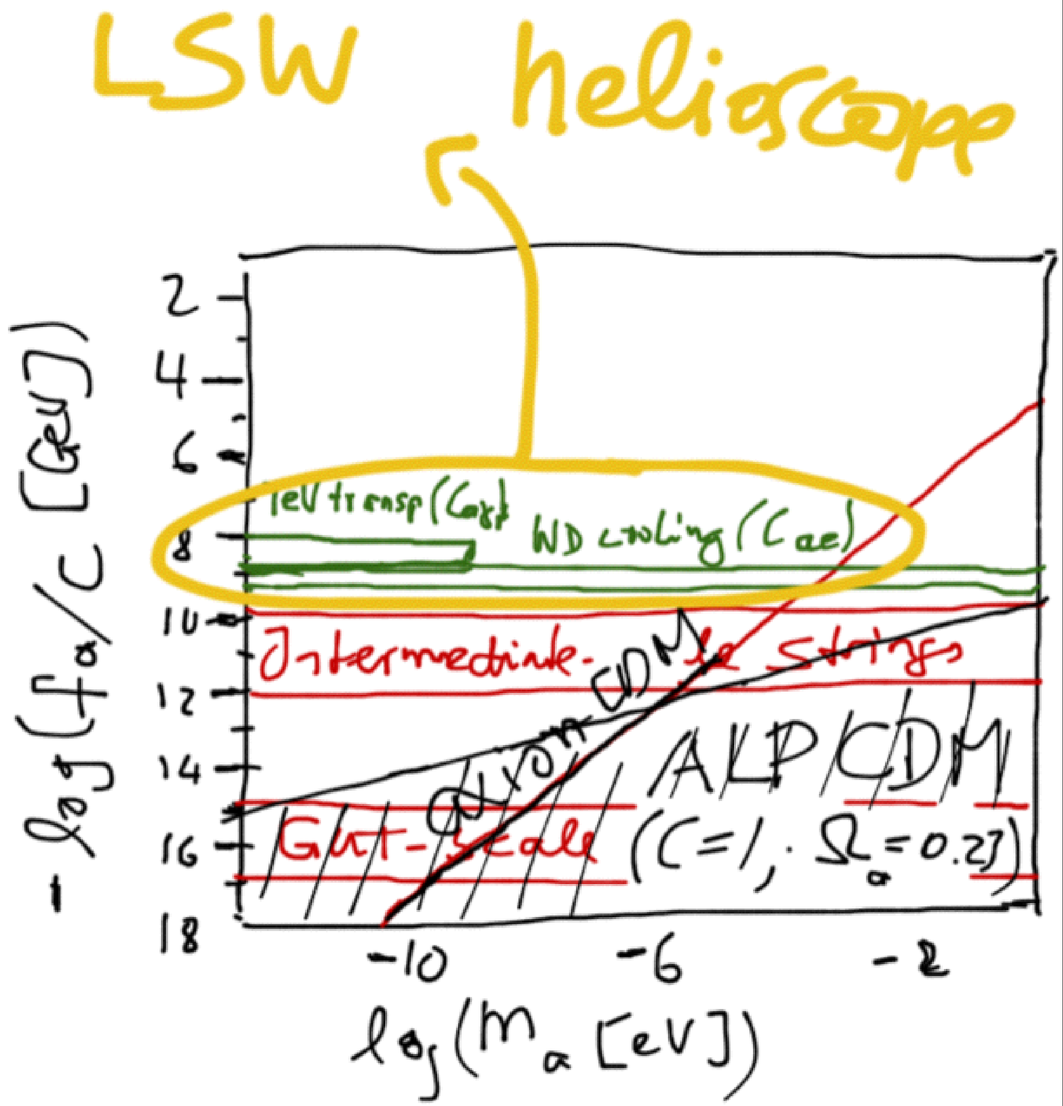

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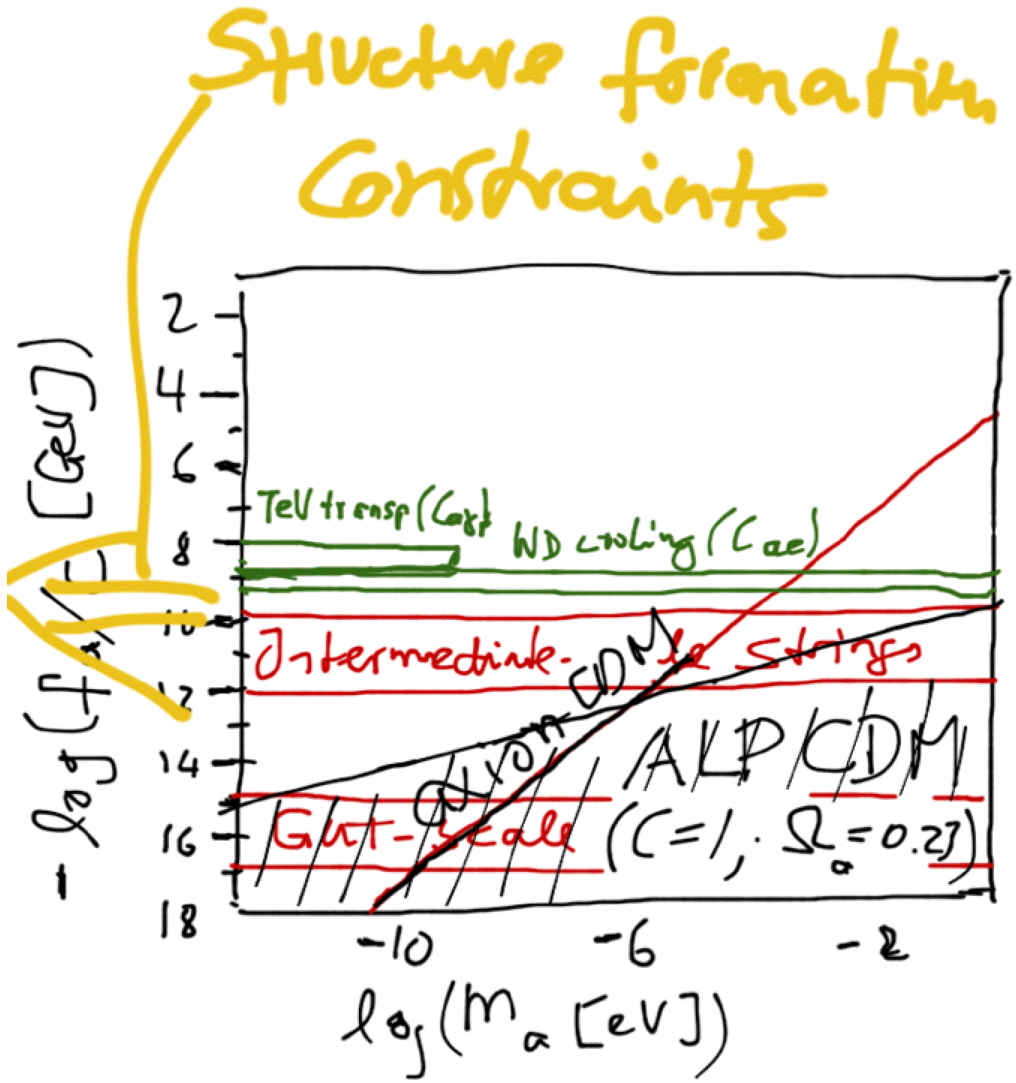

CONCLUSIONS

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