Tensions, hints, speculations. All around ALPs.

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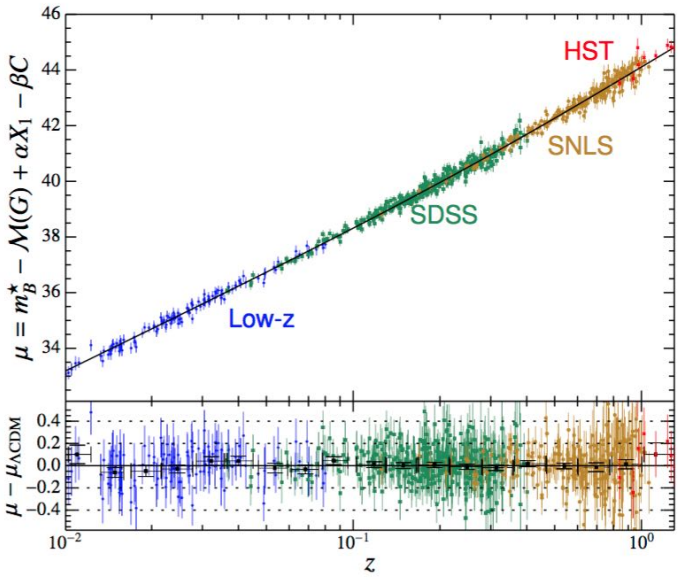
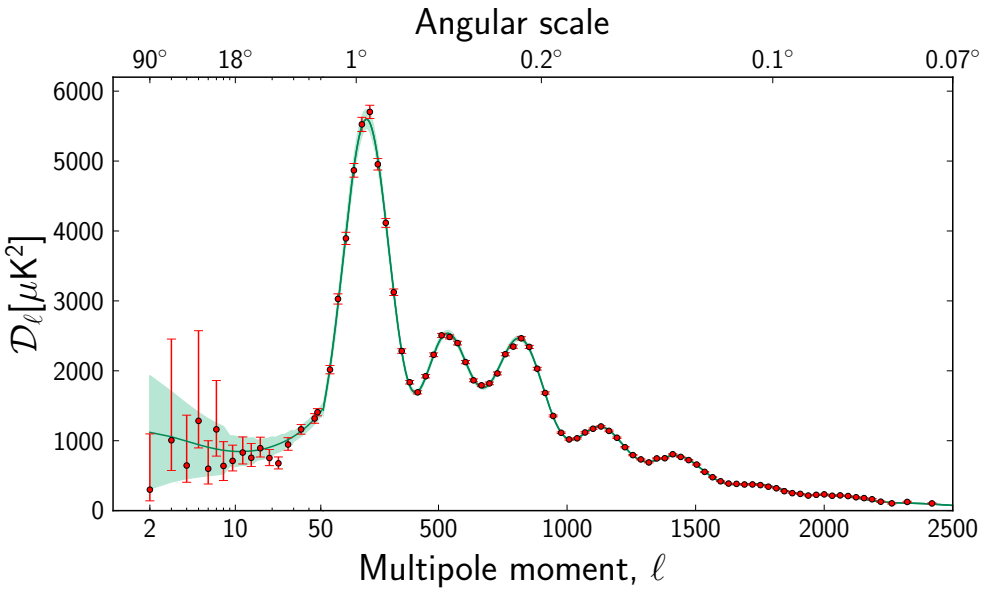
27 February 2017, CERN

Outline

- Tension between low and high z cosmological measurements
  - Hint for Decaying Dark Matter (DDM).
    (Sterile neutrinos, ALPs?)
- Axion (ALP) cosmology and miniclusters
  - Review of minicluser formation
  - Tidal streams and new strategy for direct axion searches
  - Axion Bose stars and FRB
  - Collapse and explosion of Bose stars
- Astrophysical hints for light ALP

Tesion between low and high z measurments





Direct measurements:

$$h = 0.73 \pm 0.0175$$

arXiv: 1604.01424

Planck derived cosmology:

$$h = 0.673 \pm 0.007$$

arXiv:1502.01589

We have $3.2\,\sigma$ discrepancy. Systematics or a hint of new physics?
May be something happened between recombination and today?

Decaying Dark Matter?

- Fix relevant parameters at recombination as ΛCDM best fits.
- Fix angular diameter distance to last scattering.

$\Downarrow$ (Main features of CMBR spectrum will be reproduced)

- DM decays leads to different derived H_0 and σ_8.
- Low and high z measurements can be reconciled.

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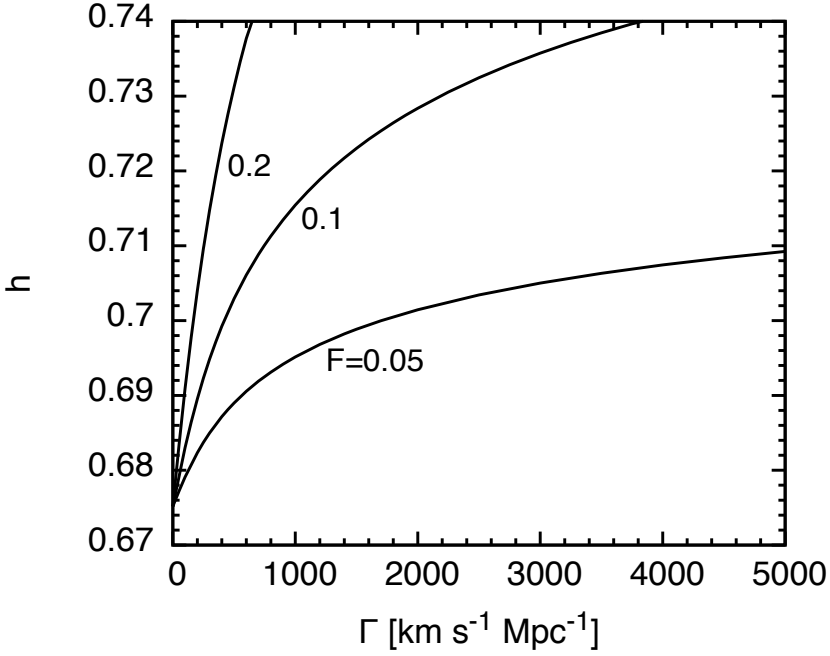
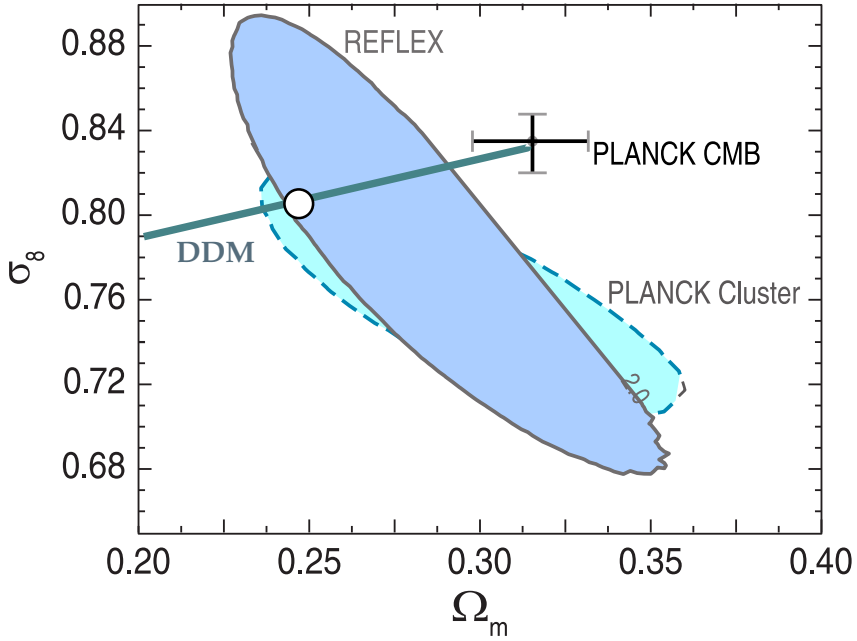
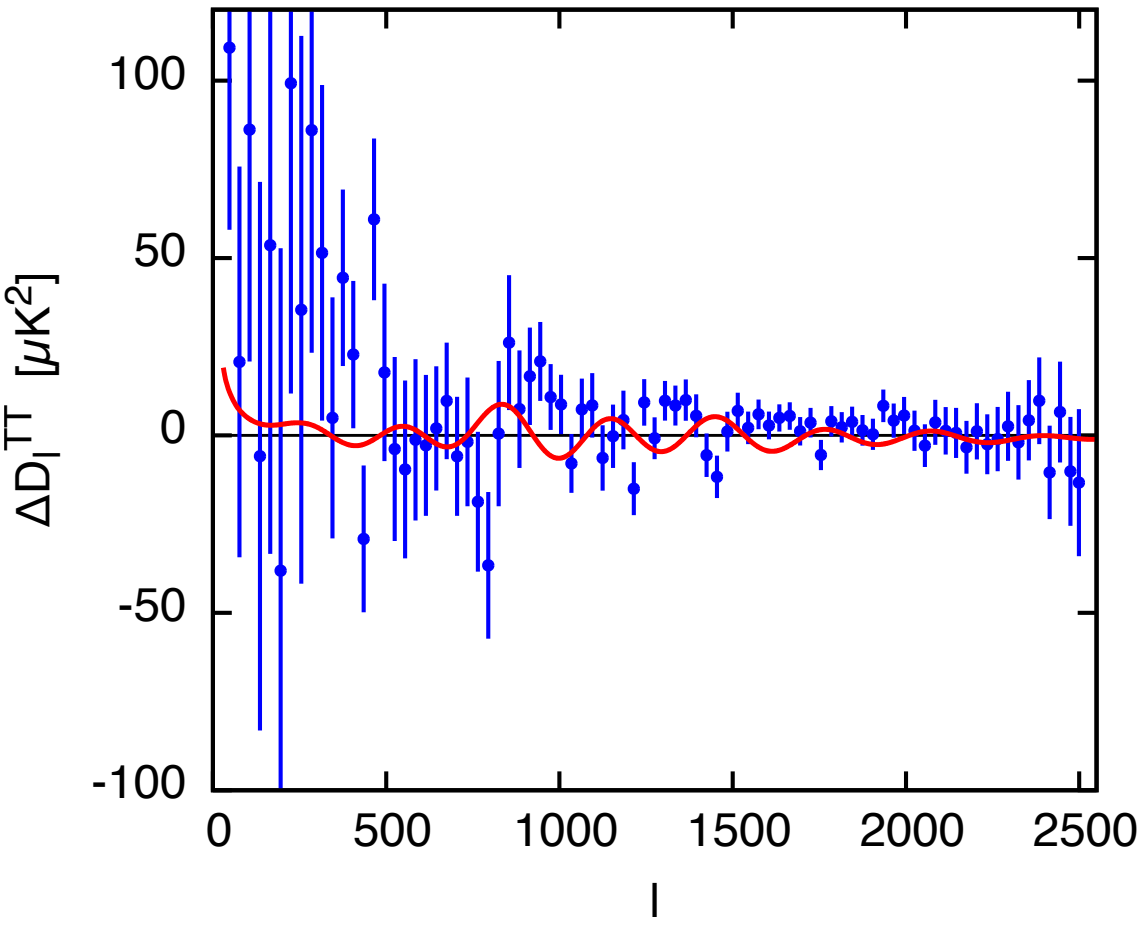


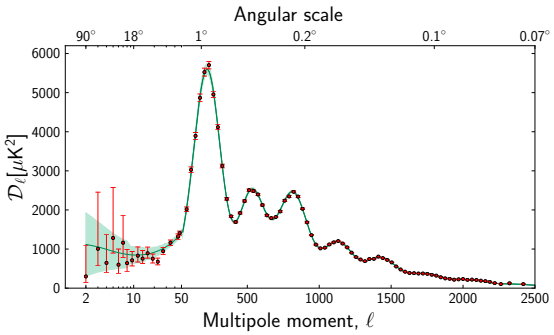


Berezhiani, Dolgov, & I.T., Phys.Rev. D92 (2015) 061303

Decaying Dark Matter?

Caveat to previous: gravitation lensing of CMBR anisotropies.





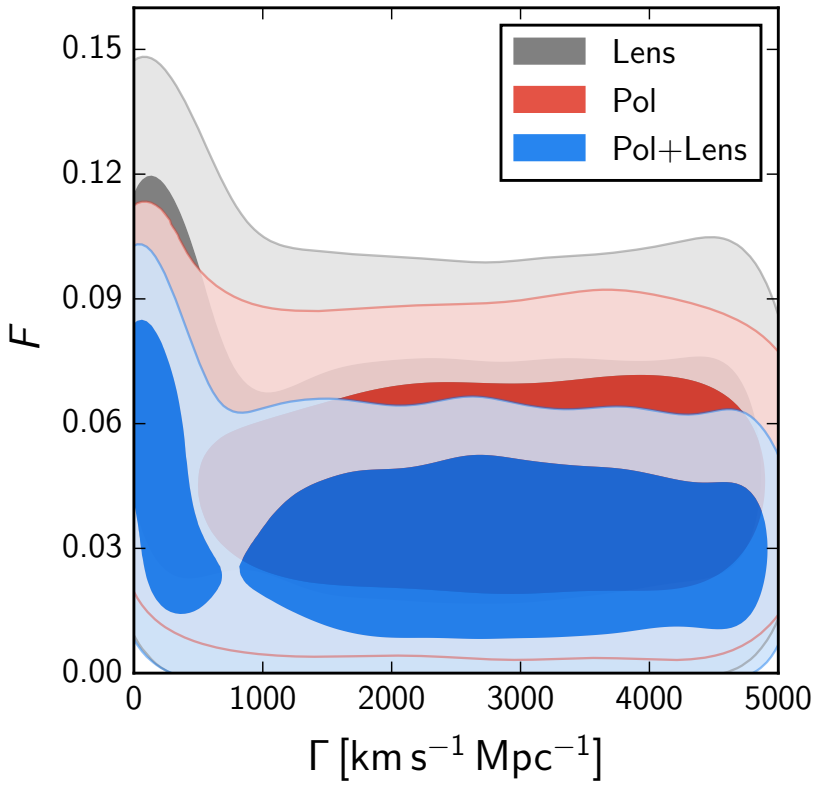
Dots:
difference between data
and best fit ΛCDM

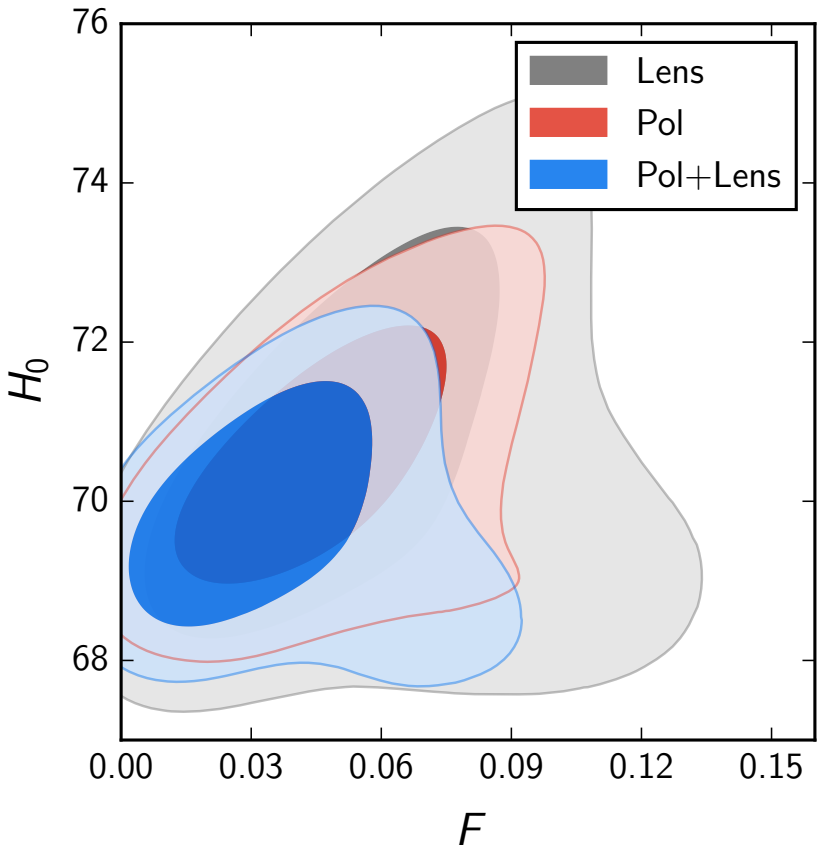
Curve:
difference of DDM
and the same ΛCDM

ΛCDM is not good, but DDM is out of phase with residuals.

A. Chudaykin, D. Gorbunov and I.T., Phys.Rev.D 94 (2016) 023528

Decaying Dark Matter?

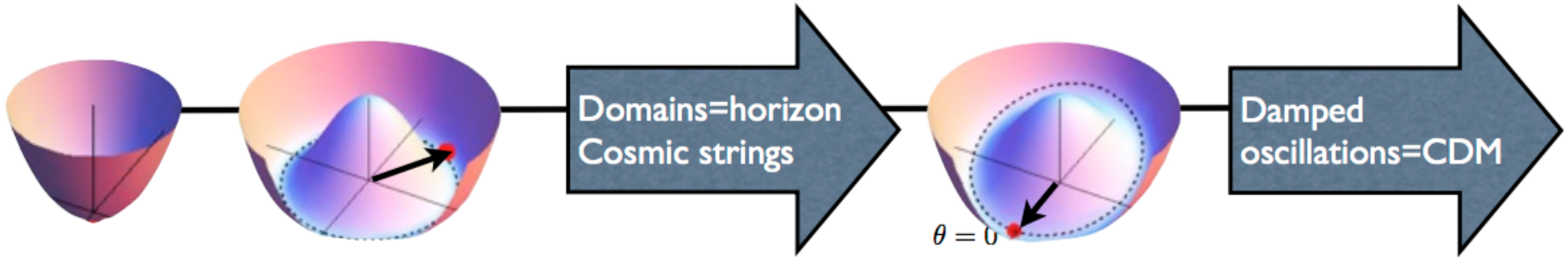




A. Chudaykin, D. Gorbunov and I.T., Phys.Rev.D 94 (2016) 023528

- Low and high z data still may be reconciled
- With current data improvement of **DDM** over **ΛCDM** is $\mathbf{2.5\sigma}$
- There are many candidates for **DDM**. (Sterile neutrinos, ALPs?)

Axion production mechanism



Peccei-Quinn phase transition at $T \sim f_a$

Axion potential switches on at QCD epoch

$$V(a) = f_a m_a(T)\,[1 - \cos(\theta)]$$

where $\theta \equiv a/f_a$

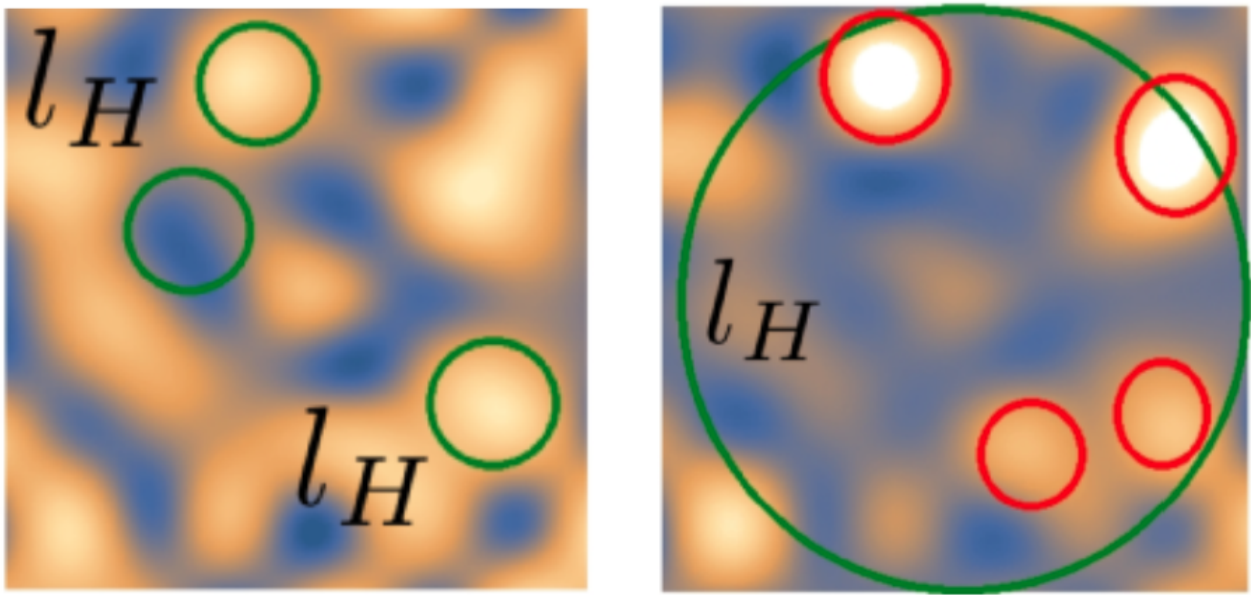
Axion oscillations start when

$$m_a(T) \approx 3H(T)$$

.
This happens at

$$T_{\rm osc} \approx 1\ {\rm GeV}$$

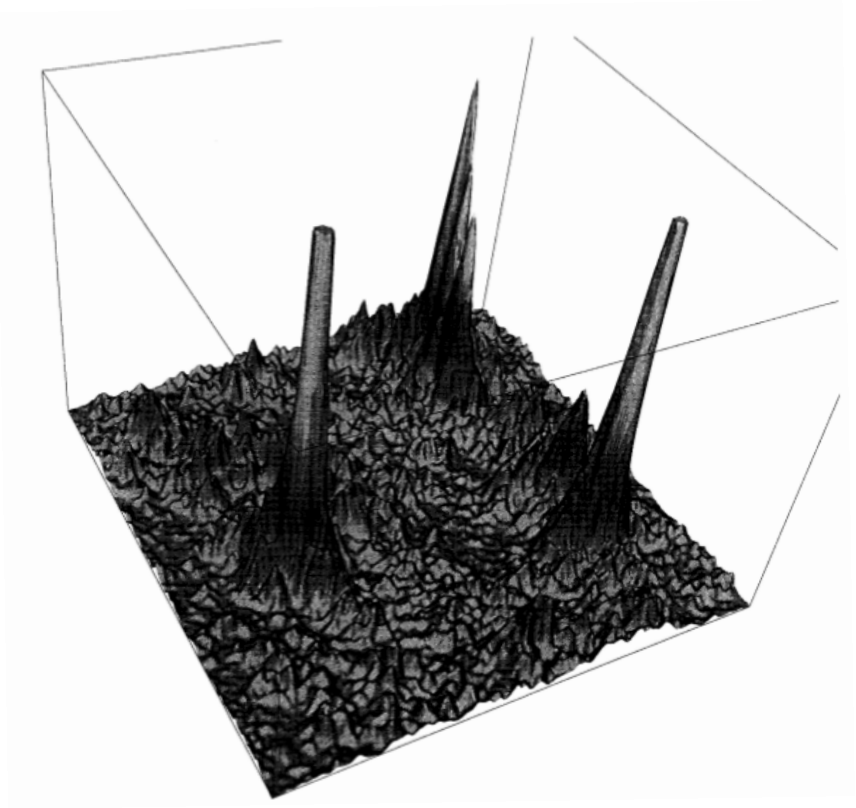
Miniclusters



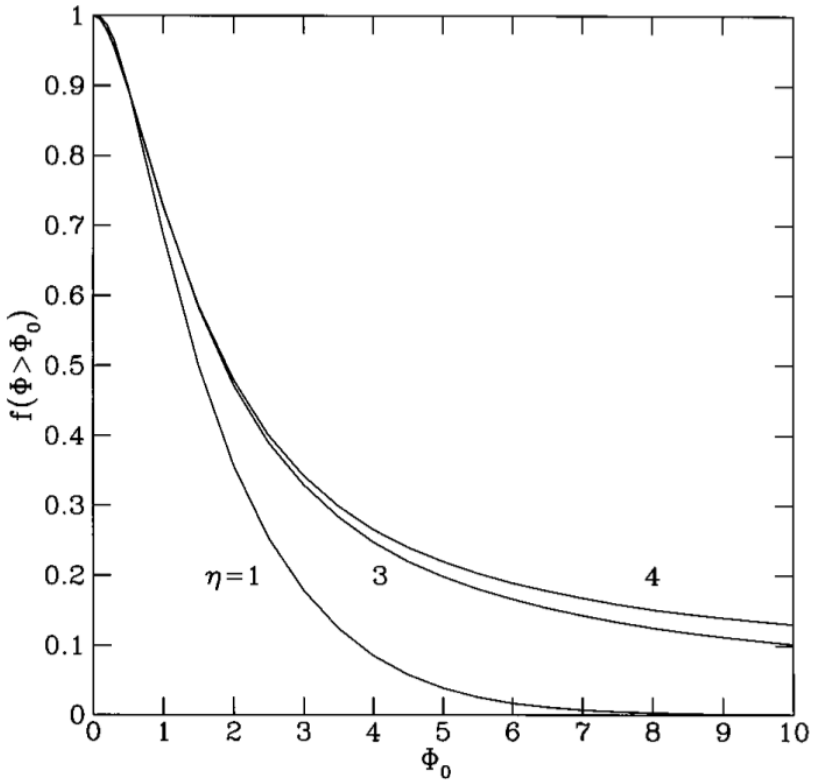
- Before axion mass turns on: $\theta \approx \mathrm{const}$ on a horizon scale l_H.
- After: $0 \lesssim \Delta\theta \lesssim \pi$. This is initial amplitude of oscillations:
  - $M \sim 10^{-12}\, M_\odot$ objects form, which is DM mass within l_H
  - Axion self-coupling is non-negligible
  - Non-linear objects form

Minicluster Formation

$$\delta\rho_a/\rho_a \equiv \Phi$$



Spatial distribution of energy density. The height of the plot $\Phi = 20$.



Mass fraction in miniclusters with $\Phi > \Phi_0$ as a function of Φ_0.

E.Kolb & IT, Phys.Rev. D49 (1994) 5040

Density of a minicluster now

Initially

$$\delta\rho_a/\rho_a \equiv \Phi$$

Clump separates from cosmological expansion at $T \approx \Phi\, T_{\rm eq}$, therefore minicluster density today

$$\rho_{\rm mc} \approx 140\Phi^3(1+\Phi)\bar{\rho}_a(T_{\rm eq})$$

Valid for both miniclusters ($\Phi \gtrsim 1$) and minihalos ($\Phi \ll 1$)

Minicluster abundance

Typical miniclusters with $\Phi \approx 1$:

- 10^{24} in the Galaxy
- $10^{10}\ \mathrm{pc}^{-3}$ in the Solar neighborhood
- Minicluster radius $\sim 10^{7}\ \mathrm{km}$
- Direct encounter with the Earth once in 10^{5} years
- During encounter density increases by a factor 10^{8} for about a day

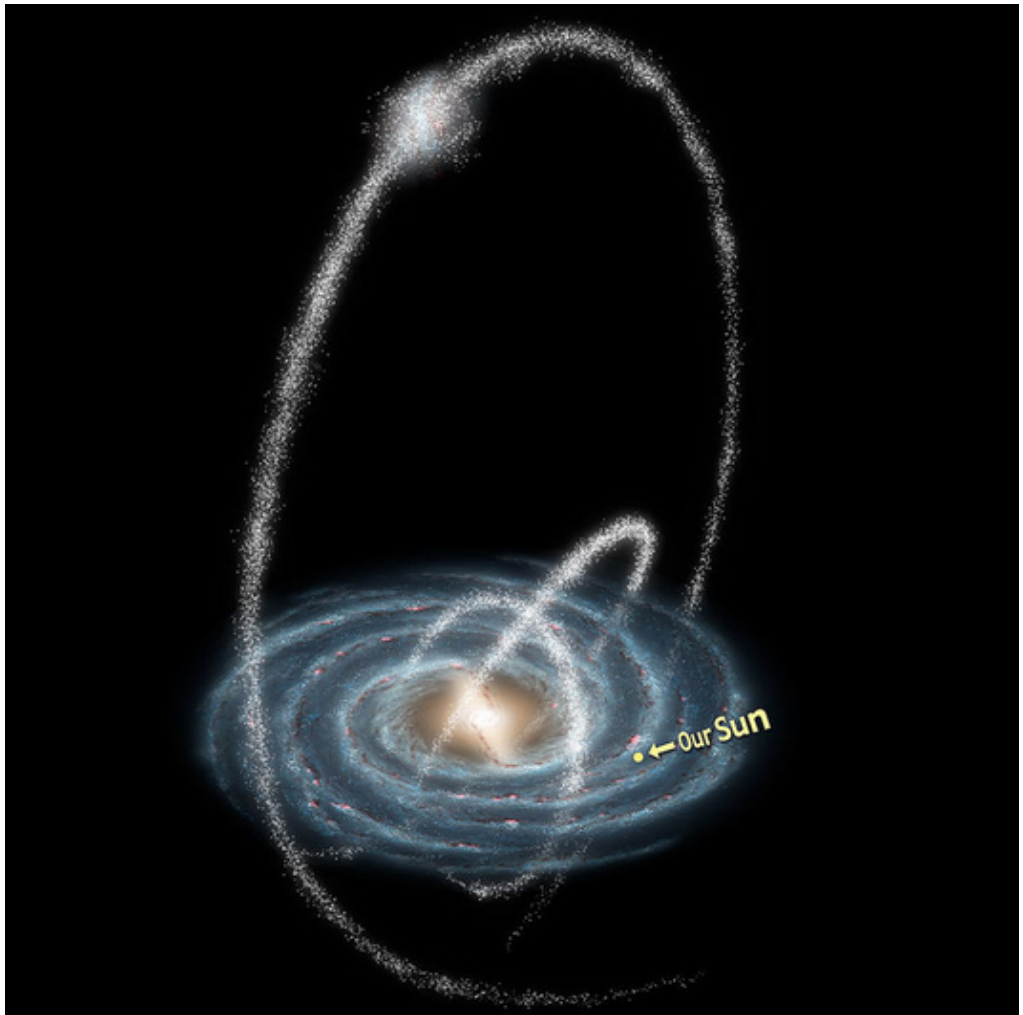
But, some miniclusters are destroyed in encounters with stars. This may change the prospects for DM detection.

Tidal streams from ministers

Probability of a minicluster disruption

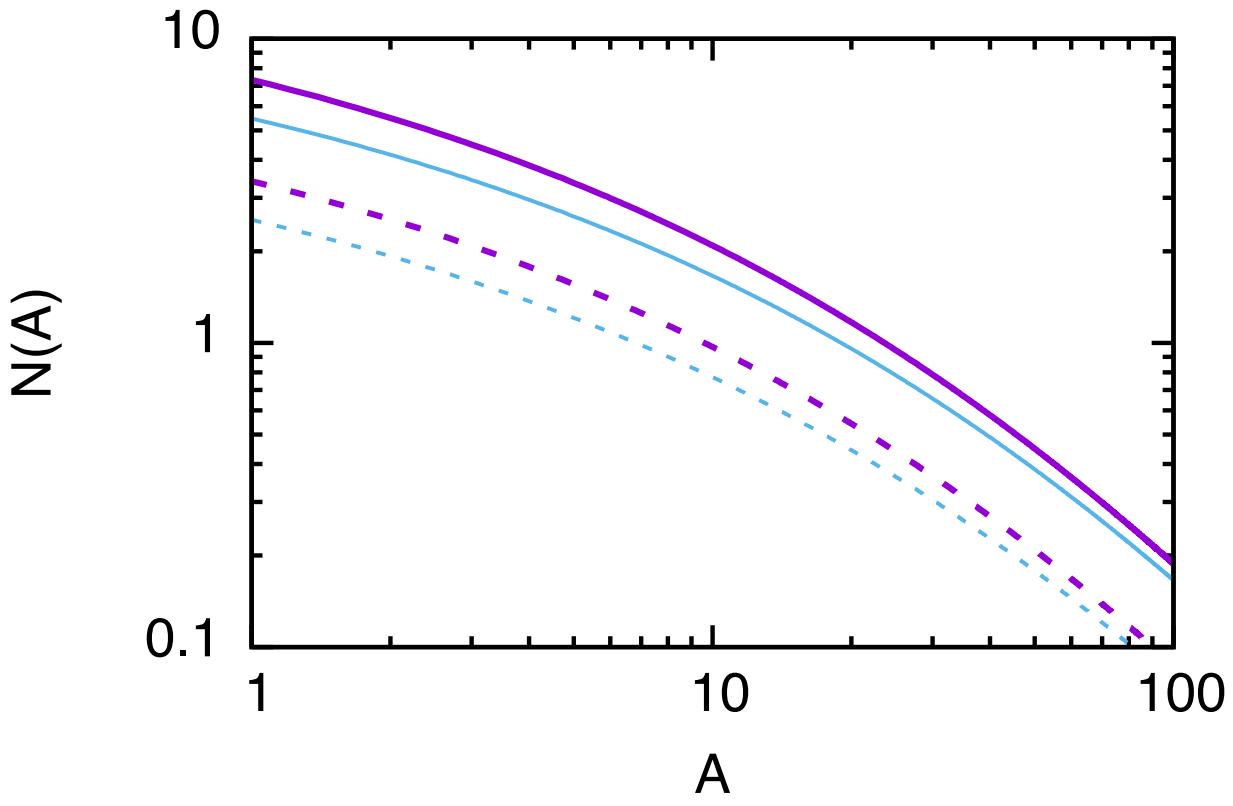
$$P(\Phi) = 0.022 \left(\frac{n}{100}\right) \Phi^{-3/2} (1+\Phi)^{-1/2}$$

P.Tinyakov, IT and K. Zioutas, JCAP 1601 (2016) 035



Crossing tidal streams

Mean number of encounters with axion streams producing amplification factor larger than A, as a function of A. Twenty year observation interval is assumed.



P.Tinyakov, IT and K. Zioutas, JCAP 1601 (2016) 035

Bose-condensation in miniclusters

Relaxation time is enhanced in axionic halo due to large phase space density

$$t_R^{-1} \sim \lambda_a^2 \rho_a^2 v_e^{-2} m_a^{-7}$$

IT, Phys. Lett. B **261** *(1991) 289*

Miniclusters with $\Phi > 30$ Bose condense, forming "Bose-stars"

E.Kolb & IT, PRL **71** *(1993) 3051*

Radius of the star $\sim 300\ \mathrm{km}$, light propagates across of it in $1\ \mathrm{ms}$.

Fast Radio Bursts and axion Bose-stars

FRB - mysterious astrophysical phenomena

- Short radio flash, $\mathbf{1\ ms}$
- Cosmological origin, $z \sim 1$
- Energy release $10^{38} - 10^{40}$ ergs
- Huge brightness temperature $T_B \sim 10^{36}$ K
- Rate: $\sim 10^4$ events/day for the whole sky.

- Radius of axion Bose-star 1 ms
- Minicuster mass $10^{-12} M_\odot = 2 \times 10^{42}$ ergs
- Bose-star can explode in a burst of coherent radiation
- We have 10^{24} miniclusters just in a Galaxy

Can FRBs be explained by axion star explosions into pure radiation?

IT, JETP Letters 101 (2015) 1

A. Iwazaki, PRD 91(2015) 023008

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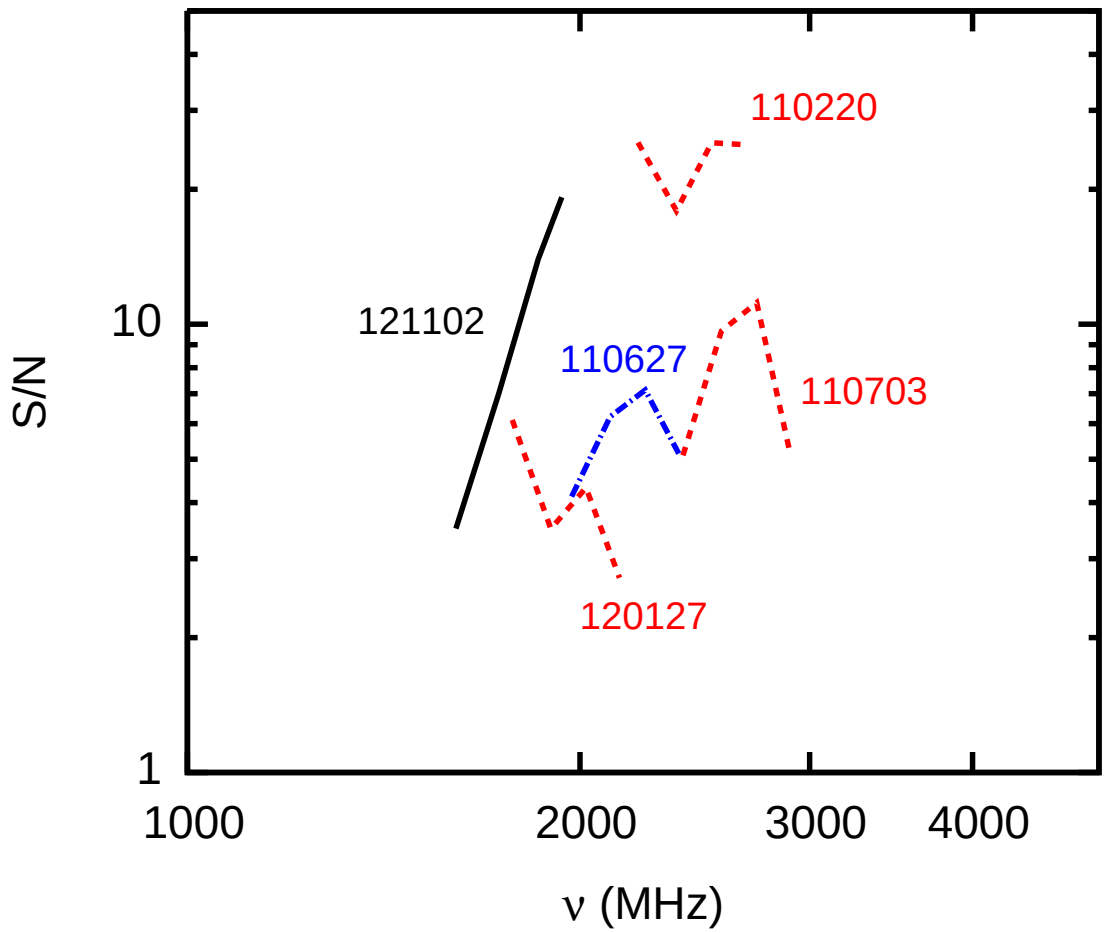
Fast Radio Bursts and axion Bose-stars

FRB spectra shifted to their rest frame

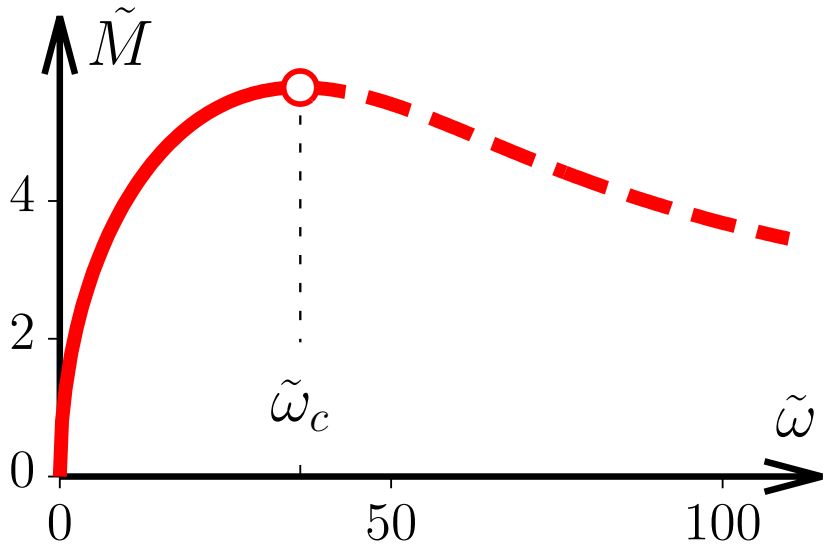


IT, JETP Letters 101 (2015) 1

ALP Bose star instability

$$V(a) = m^2 f_a^2 \left(\frac{1}{2}\theta^2 - \frac{g_4^2}{4!}\theta^4 + \dots \right) , \qquad \theta \equiv a/f_a ,$$

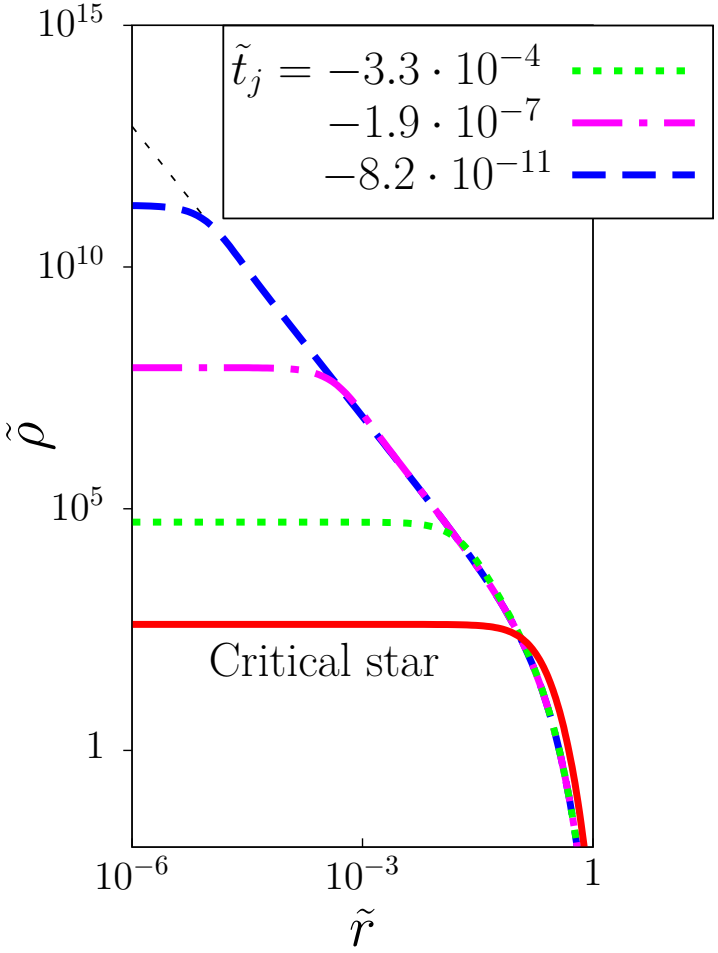
Self-coupling of axions is negative and axion Bose stars are unstable against collapse.



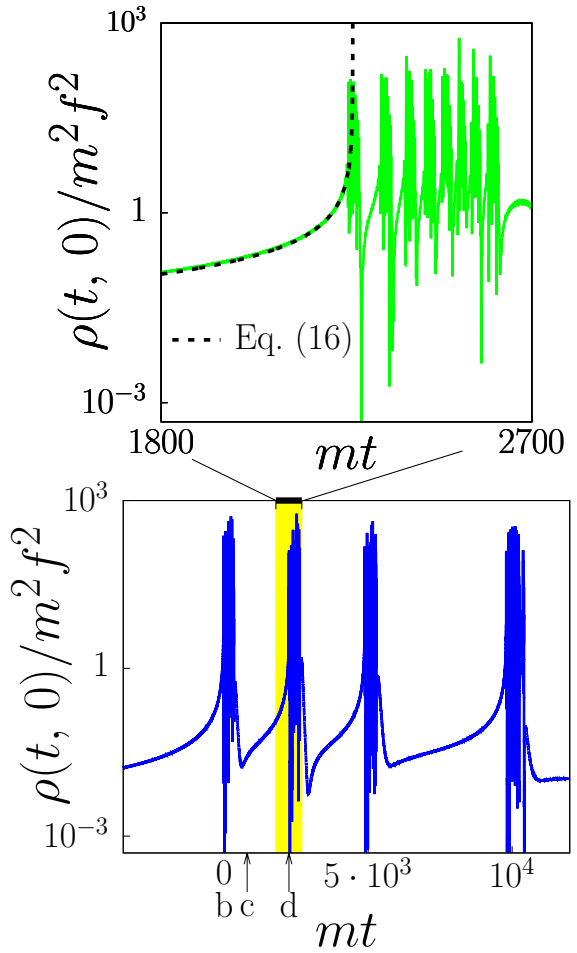
D.Levkov, A.Panin, & IT, PRL 118 (2017) 011301

ALP Bose star collapse

Self-similar wave collapse



Repeated explosions

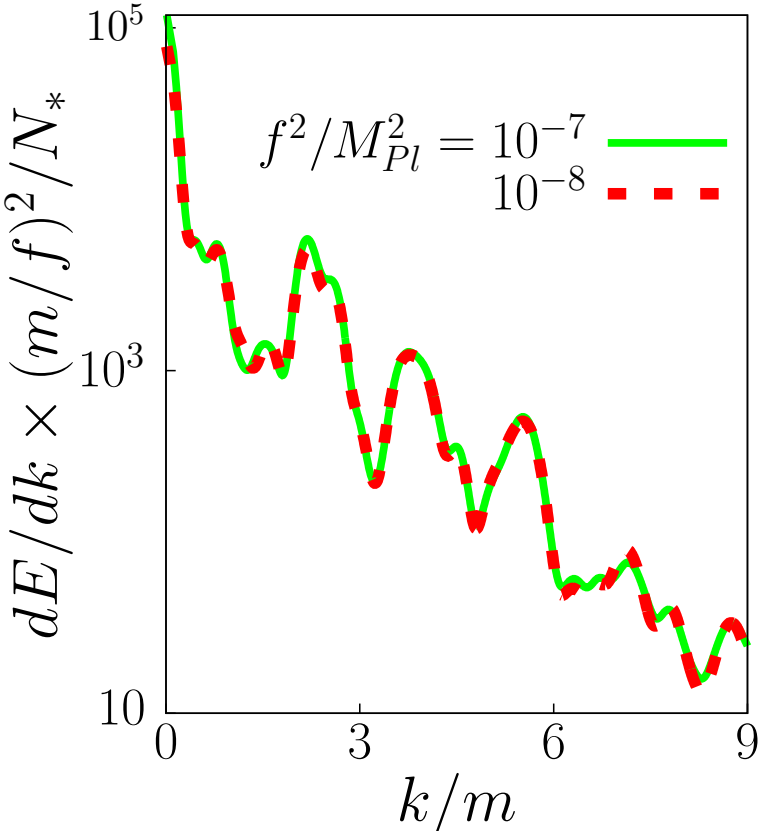


But black hole does not form for $f_a < M_{Pl}$

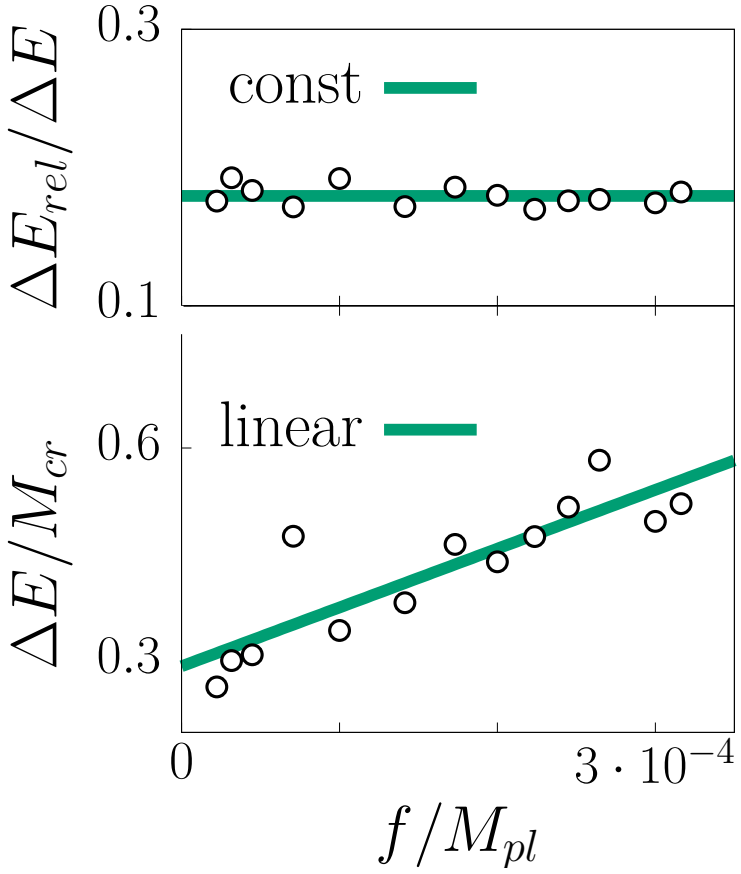
D.Levkov, A.Panin, & IT, PRL 118 (2017) 011301

Decay of Bose star on relativistic axions

Spectra of emitted particles



Total emitted energy fraction

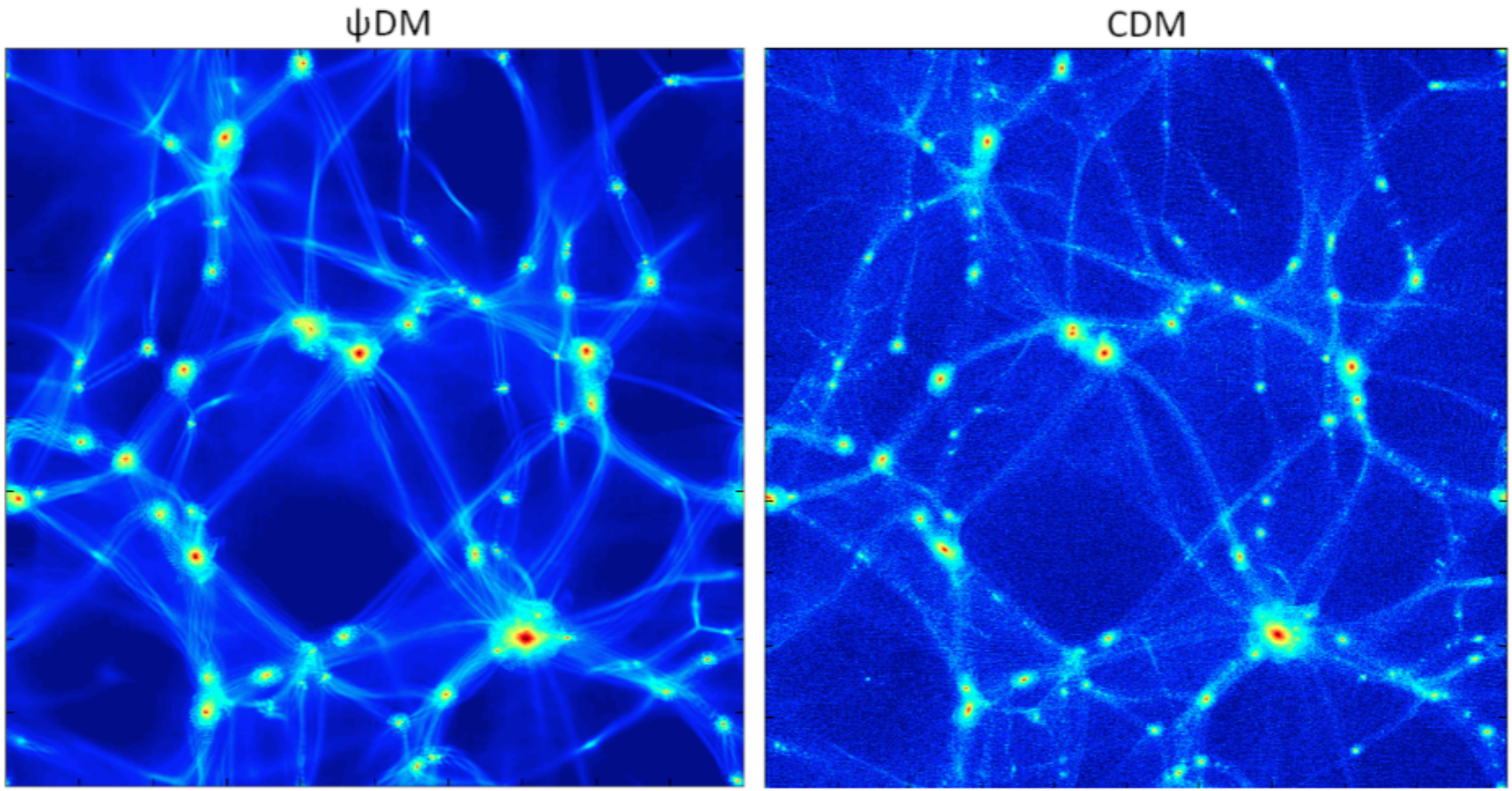


D.Levkov, A.Panin, & IT, PRL 118 (2017) 011301

Why decay on relativistic itself is interesting?

- Recall **DDM**
- Also, important for ultra-light DM

Structure formation with ultra-light ALP:



Hsi-Yu Schive et al, Nature Phys. 10 (2014) 496

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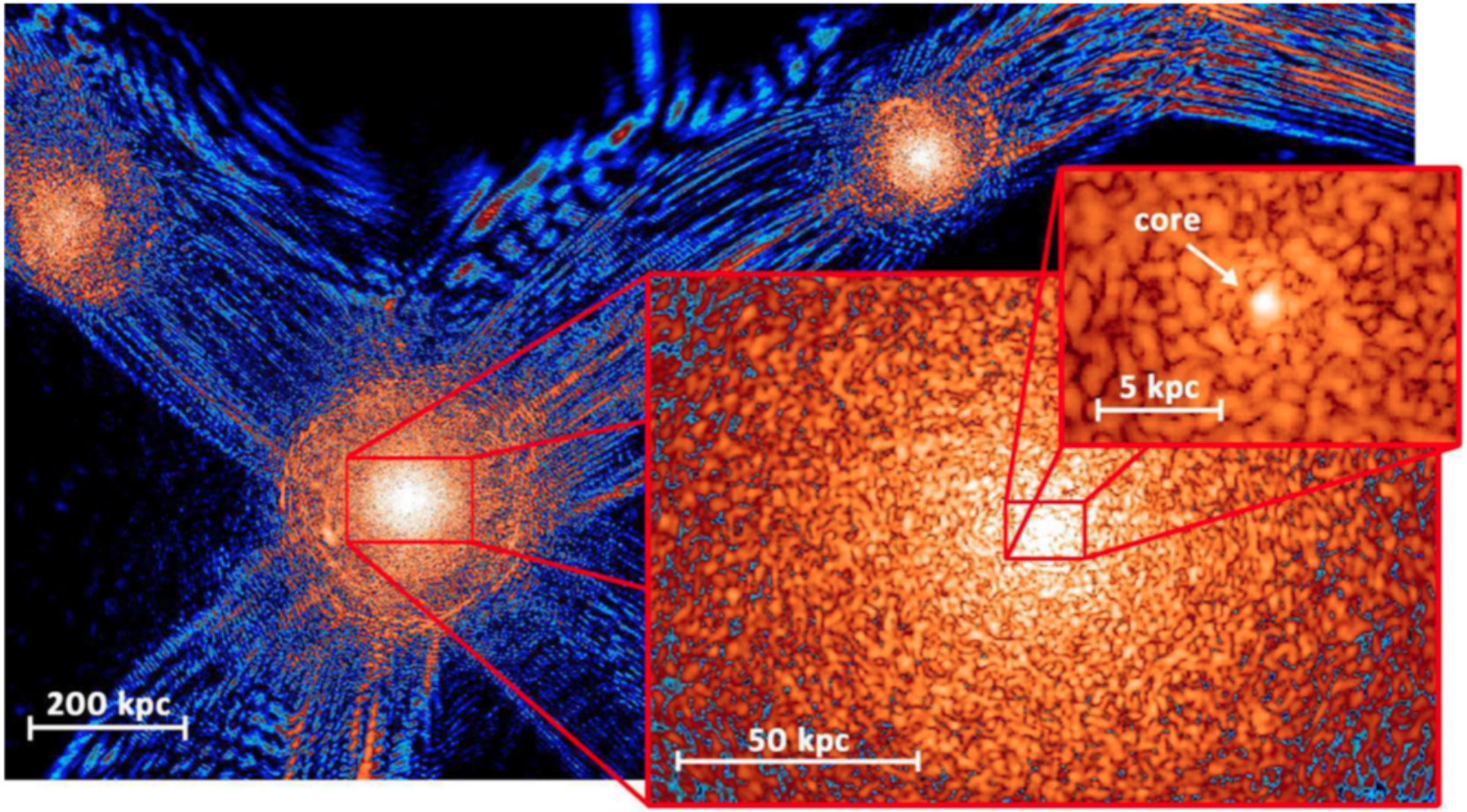


Hsi-Yu Schive et al, Nature Phys. 10 (2014) 496

Cores are heavy Bose-stars. It was speculated they collapse into **black holes** ...

Constraints on axions: definition of parameters

Axion interactions with gauge fields and fermions

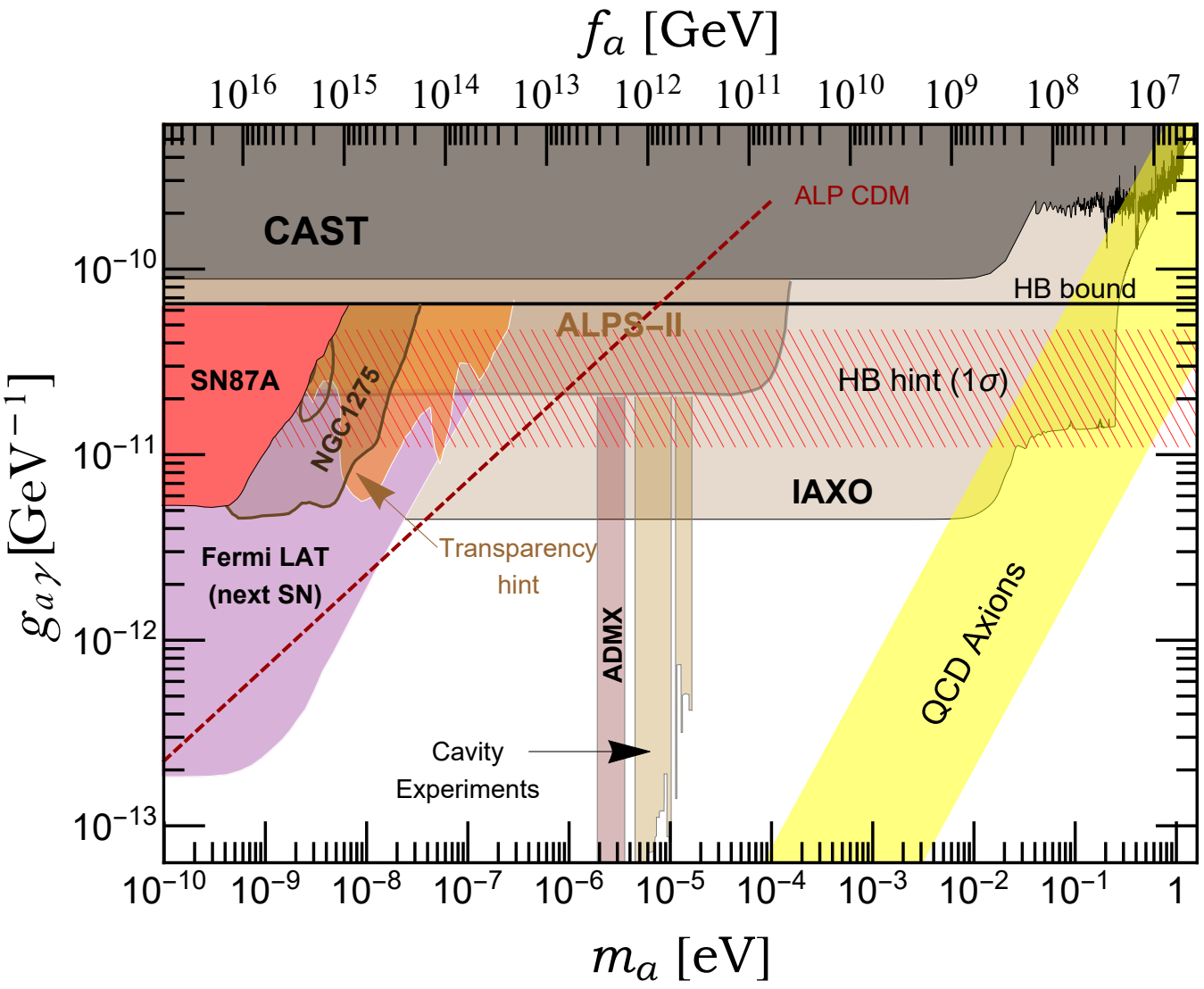
$$L_{\rm int} = -\frac{1}{4} g_{a\gamma}\, a F_{\mu\nu} \tilde{F}^{\mu\nu} - \sum_{\rm fermions} g_{ai}\, a \overline{\psi}_i \gamma_5 \psi_i \,,$$

where

$$g_{a\gamma} \equiv \frac{\alpha}{2\pi} \frac{C_{a\gamma}}{f_a}, \qquad g_{ai} \equiv \frac{m_i}{f_a} C_{ai}$$

with $C_{a\gamma}$ and C_{ai} model dependent parameters.

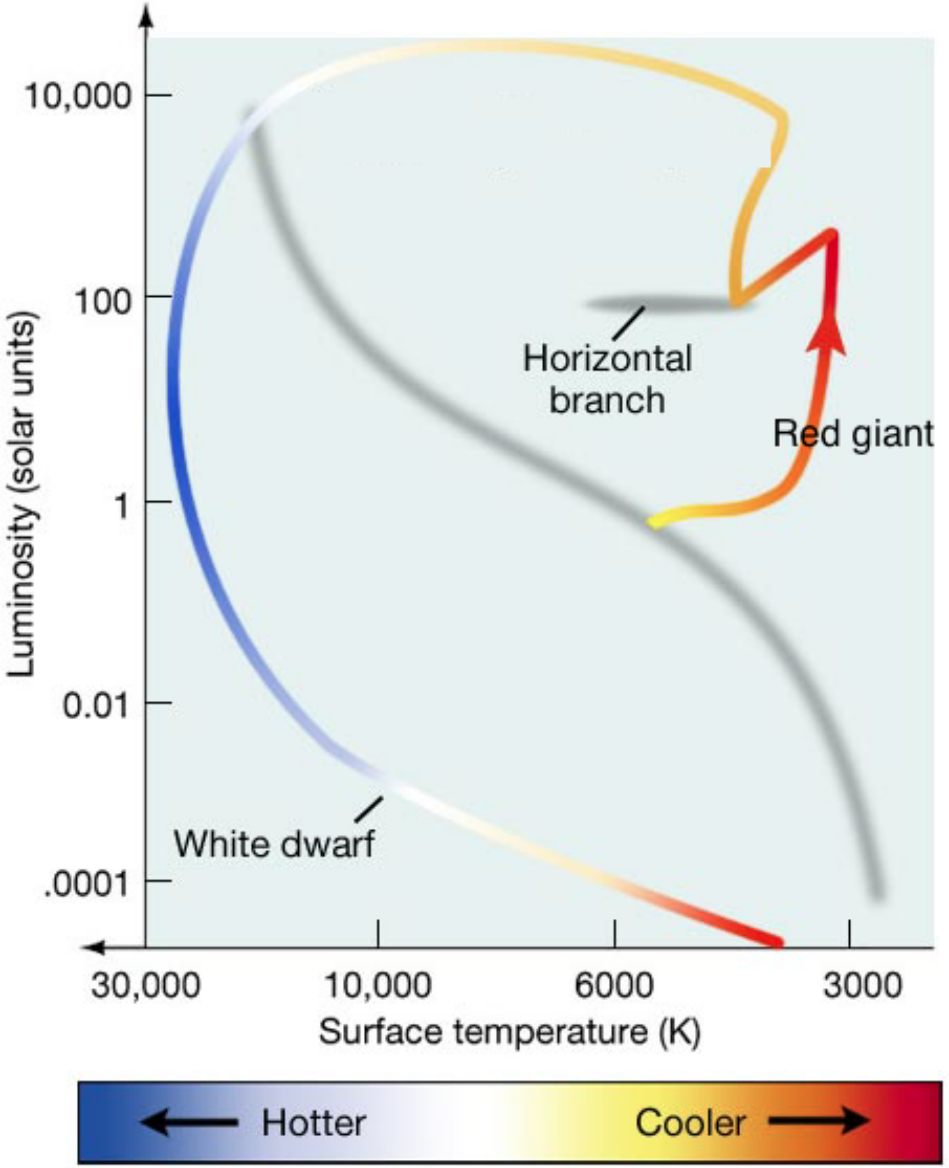
Constraints on and hints for ALP



M. Giannotti, arXiv:1611.04651

Constraints from stars

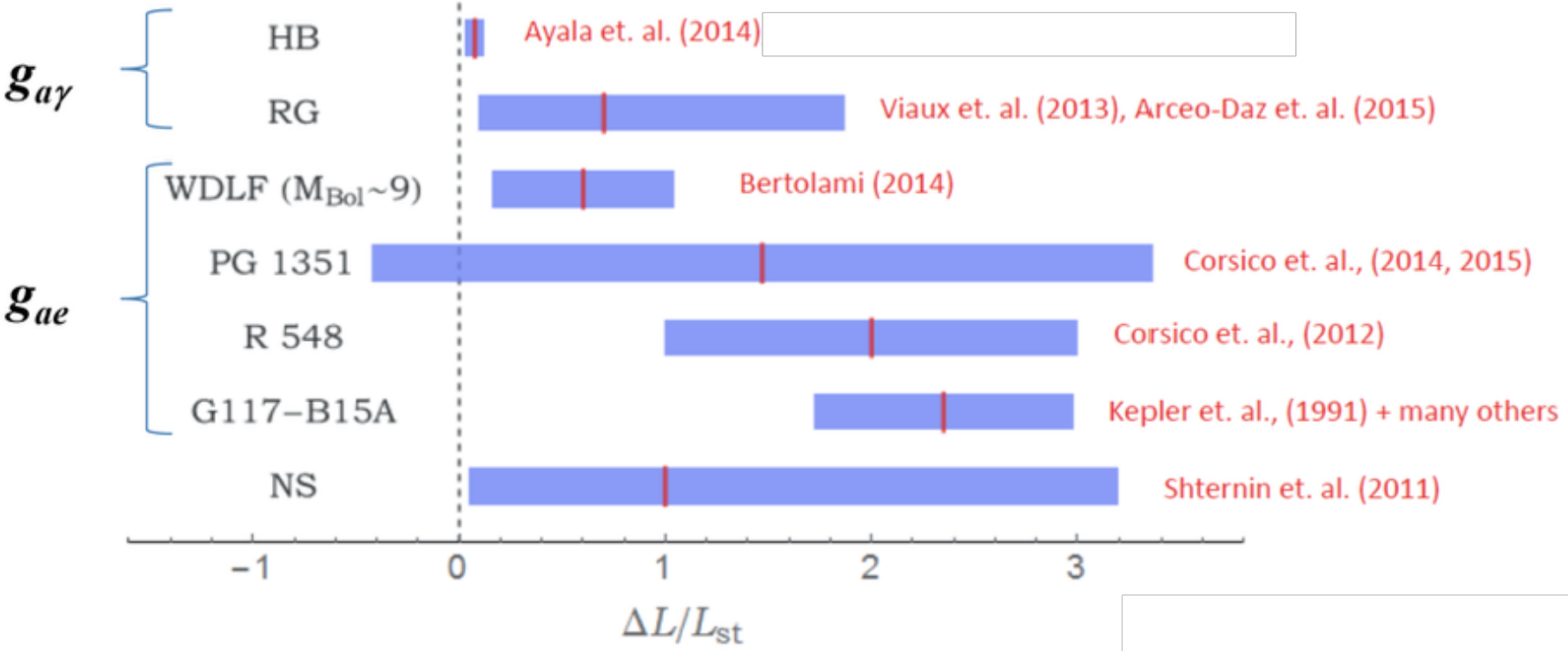
Hertzsprung–Russell diagram



Extra particle emission:

- larger maximum red-giants luminosity
- smaller helium burning lifetime (observed abundance of HB stars)
- increased rate of cooling for WD
- increased rate of cooling for NS

Hints for ALPs from stars

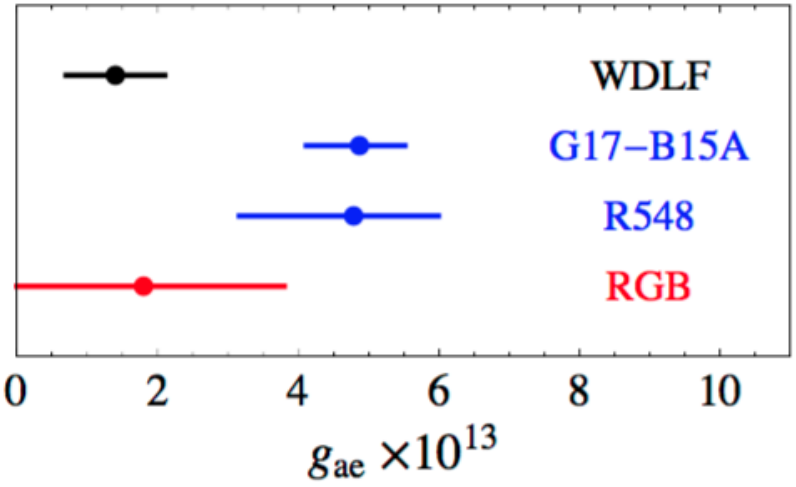


M.Giannotti, et al, JCAP 1605 (2016) 057

Hints for ALPs from stars

Hints of extra energy losses by stars

- $g_{a\gamma}$ from Helium Burning stars: $g_{a\gamma} = 4.5^{+1.2}_{-1.6} \times 10^{-11}\ \mathrm{GeV}^{-1}$
- g_{an} from neuron stars: $g_{an} \approx 4 \times 10^{-10}$
- g_{ae} from White Dwarfs and Red Giants:



All can be combined if e.g. $C_{a\gamma} \sim 1$, $C_{ai} \sim 10^{-2}$
Overall, axion/ALP solution is favored at about 3σ

For reviews see e.g. *A. Ringwald, arXiv:1506.04259*
M. Giannotti, arXiv:1508.07576, arXiv:1611.04651

Coinclusions

- A number of recent cosmological and astrophysical observations are in tension with conventional explanations
- It is tempting to speculate that they give us a hint for a new physics - ALPs