Axionic waves as dark matter: potential detection with physical experiments and astronomical observations.

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Observations of the galaxy dynamics and distribution in the Universe, and of the Cosmic Microwave Background fluctuation power spectrum, have shown that DARK MATTER is 84% of all matter in the Universe, behaves as Cold Dark Matter to account for the large-scale structure, and is non-baryonic.

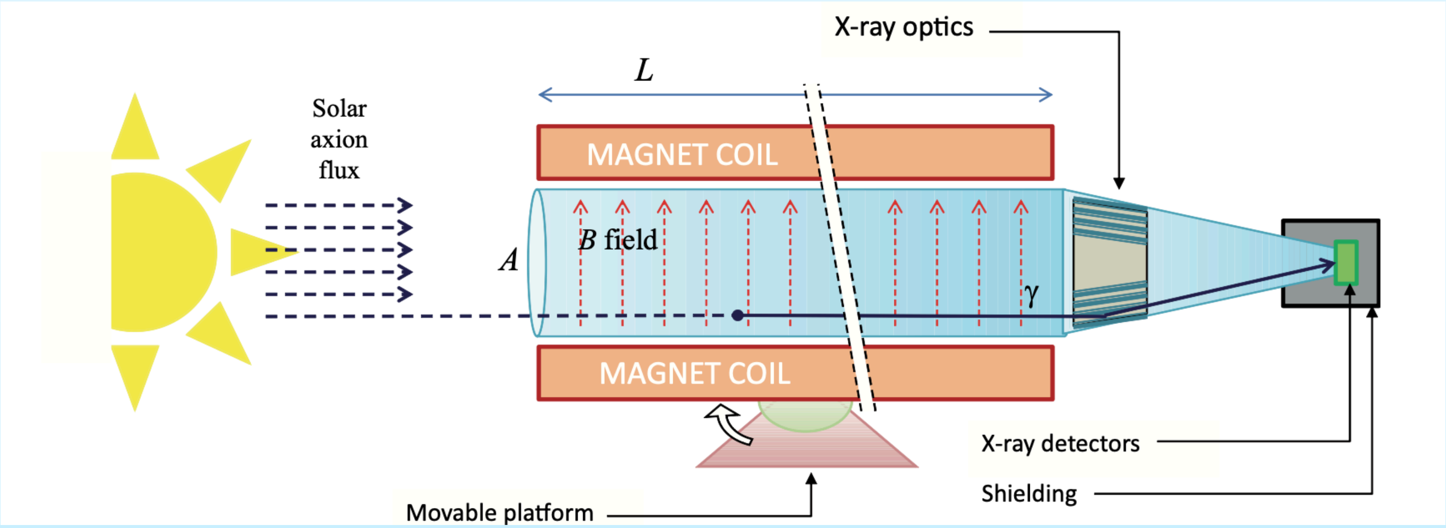
Three types of Cold Dark Matter candidates:

- Thermalized particle: it must be massive (Weakly Interacting Massive Particle), to make the velocity dispersion today low. Problem: What motivates yet another massive, neutral, weakly interacting, non-decaying particle?
- Primordial black holes: made from radiation in the early Universe. Problem: What motivates the large primordial fluctuations needed to form them at a specific mass scale, compared to the low amplitude on the observed galaxy scale? Black holes of very low mass (10^{16} g) are already ruled out by the absence of any gamma-ray Hawking radiation from them.
- Light particle, created in a non-thermalized, cold state of the field during the early Universe, a classical wave with very high quantum occupation number.

Why are axions the best dark matter candidate?

- Axions were a prediction of an elegant model to solve a particle physics problem: the strong QCD problem. This prediction was unrelated to dark matter! Depending on the unknown axion mass, the observed dark matter density can reasonably be produced.
- Axion dark matter would be a pseudoscalar classical wave. The classical world has only one fundamental wave, the electromagnetic field. Axions would be a new fundamental classical wave, not yet detected because of its very weak interactions, except as the dark matter of the Universe.
- Axions at rest: $\phi(t) = \phi_0 \exp(i\omega t), \qquad \omega = \frac{m_a c^2}{\hbar}$
- Apart from their gravitational interaction, axion waves would have a very weak interaction with electromagnetic fields, modifying Maxwell's equations.

Inverse Primakoff effect



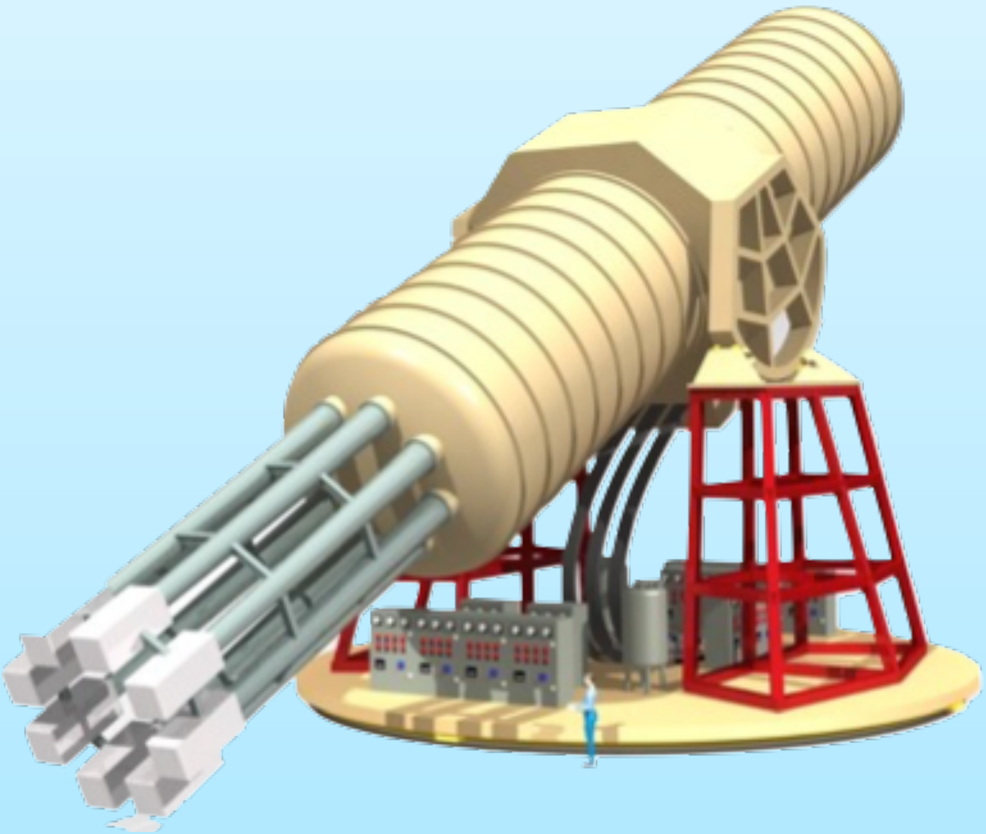
Armengaud et al. 2019

» Conversion of axions to photons in a strong magnetic field.

» Axions are produced in the Sun when a photon is converted into an axion in the strong electric field of a nucleus or electron. On Earth, they convert to X-rays inside a magnet.

» If axions are the dark matter, they can also convert to radio photons inside the same magnets.

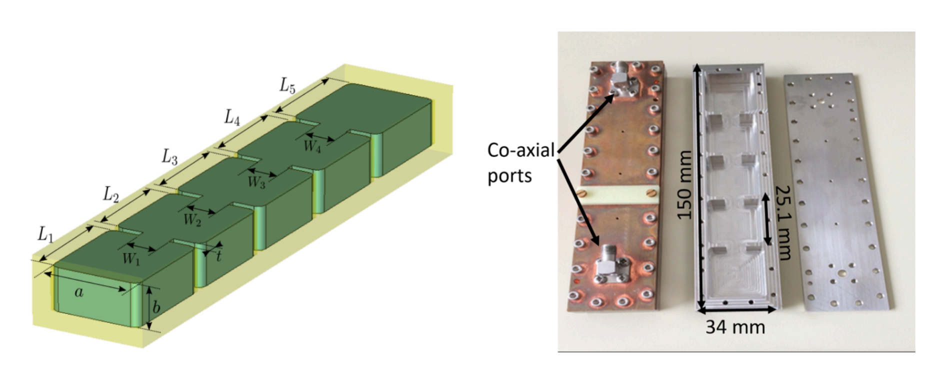
International Axion Observatory (IAXO)

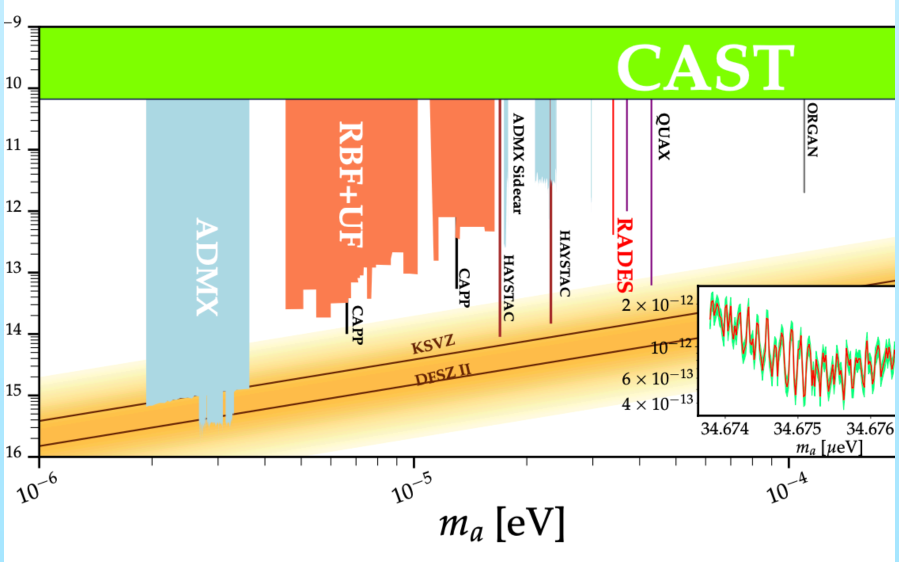


- IAXO will search for axions coming from the Sun, improving limits on axion-photon coupling.
- The ICCUB is contributing to the data reading instrument for the initial BabyIAXO stage, with high purity requirements for ultra-low X-ray background (Eduardo Picatoste).
- An opportunity for data analysis at ICCUB.

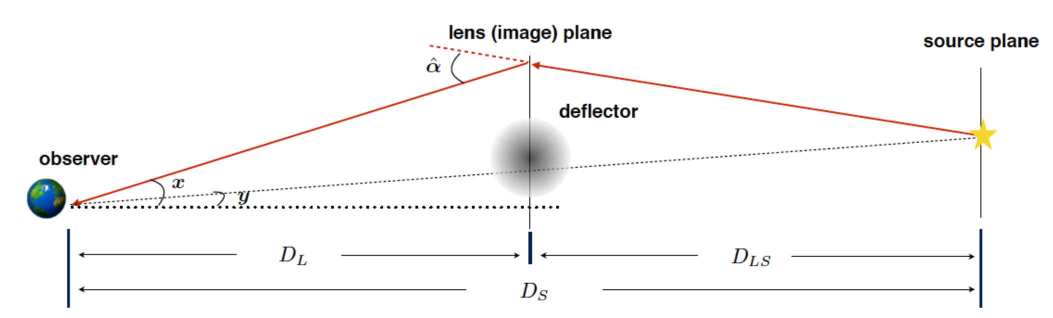
RADES experiment: searching for axion dark matter (Sergio Arguedas)

- Connected cavities in a magnetic field cause a resonance of the electromagnetic field under the forcing by an axion wave, which greatly increases the axion-photon conversion when the axion frequency is matched.
- Work on data acquisition and analysis is going on for exisiting RADES data and future experiments with RADES on various magnets.





Axion detection in astronomy: gravitational lensing.



» In most cases, the axion field has small-scale fluctuations that collapse to small minihalos of asteroid-like masses, $\sim 10^{-12}\, M_\odot$ of size ~ 0.1 AU, soon after the matter-radiation equalization epoch.

» Today, much of the dark matter in galactic halos would still be in these minihalos, and a hierarchy of larger objects formed through a merger sequence. Dark matter would be clumpy!

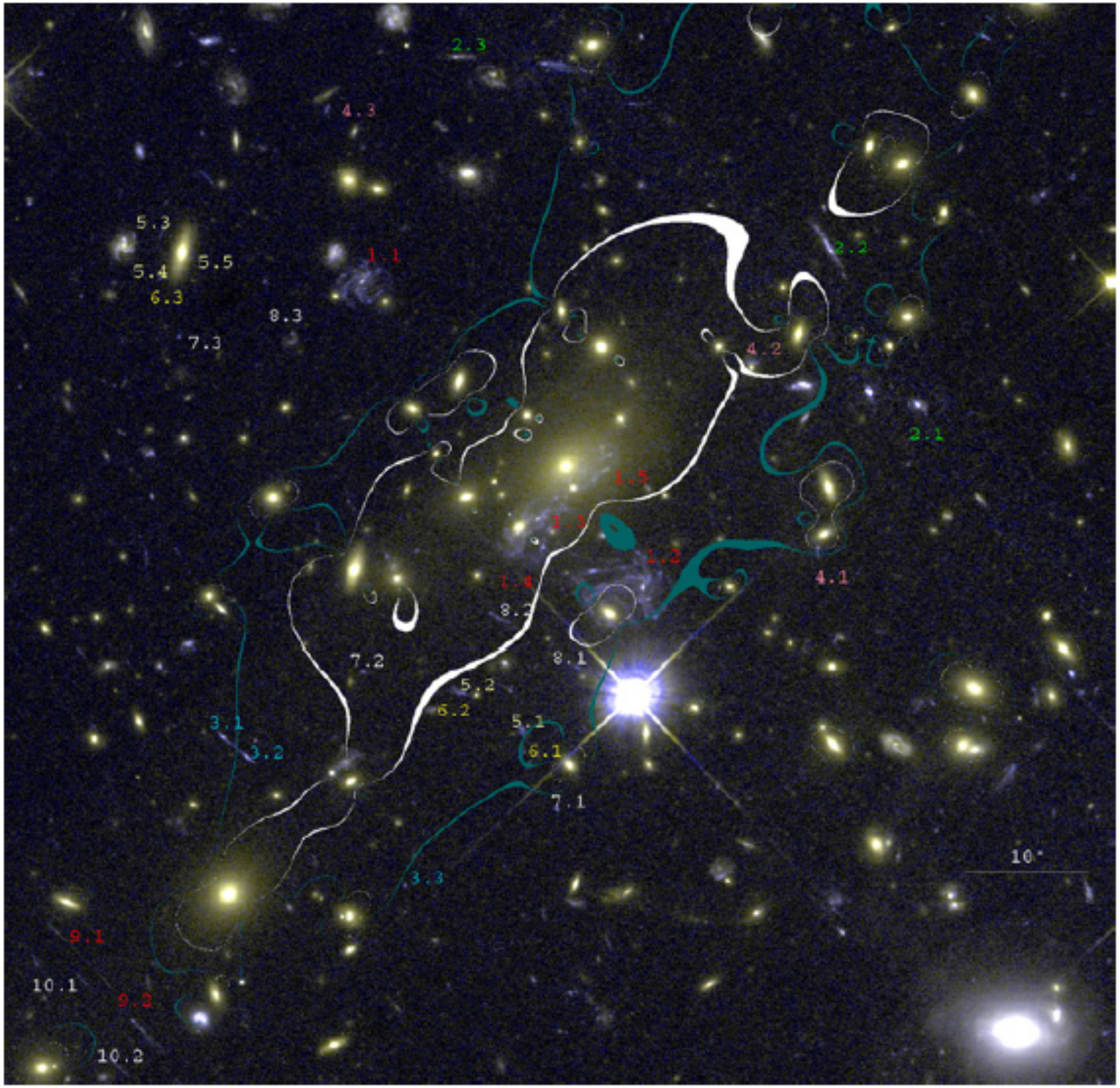
» Minihalos could be detected through gravitational lensing. The difficulty is that the minihalo surface density is $\Sigma \sim 10^{-4}\Sigma_{\rm crit}$ even at cosmological distances!

» $$\Sigma_{\rm crit} = \frac{c^2}{4\pi G}\frac{D_S}{D_L D_{LS}}$$

» These highly sub-critical lenses may only be detectable when seen near lensing caustics of larger-scale lenses.

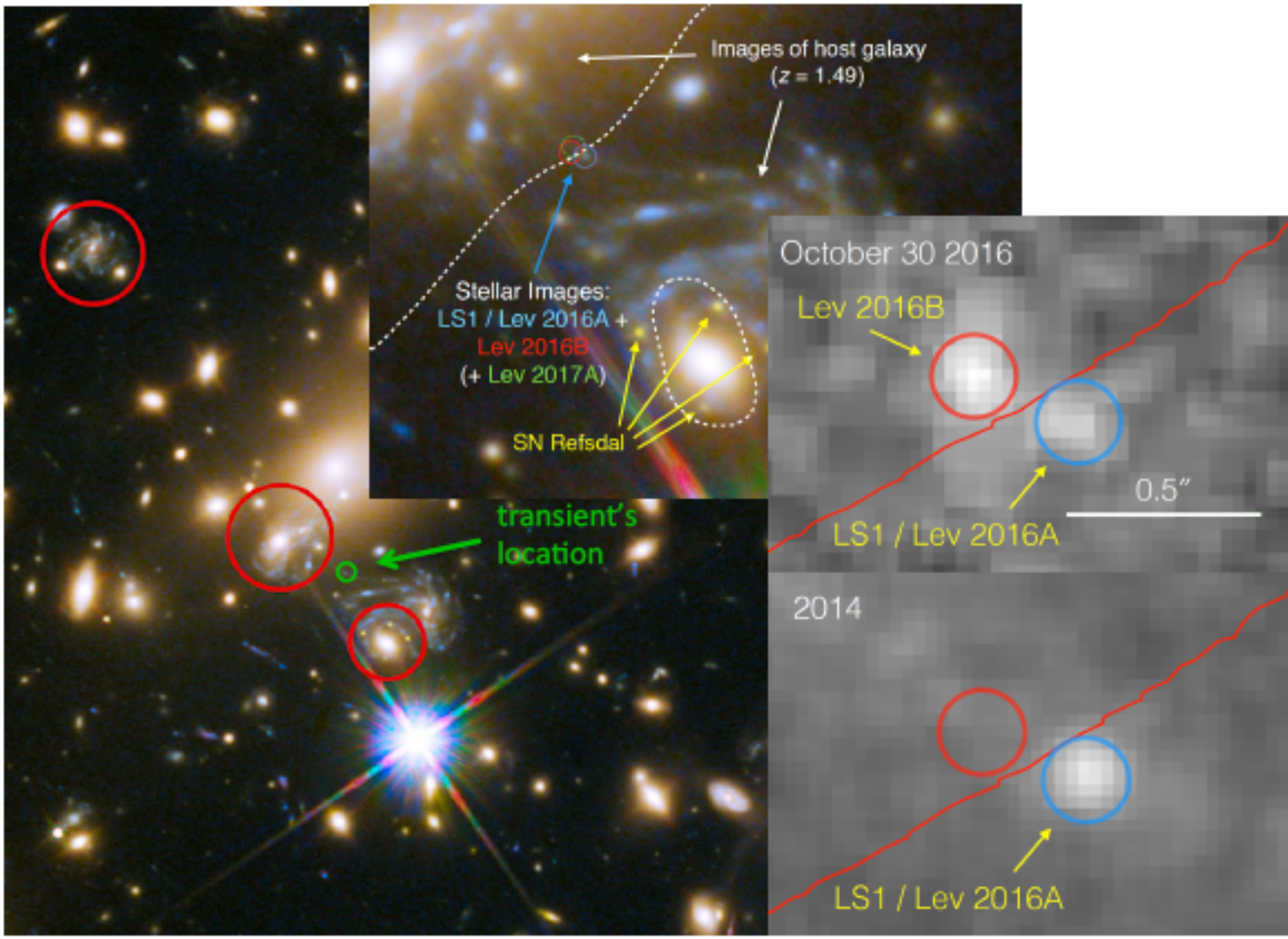
The lensing cluster MACSJ1149

(Zitrin & Broadhurst 2009)

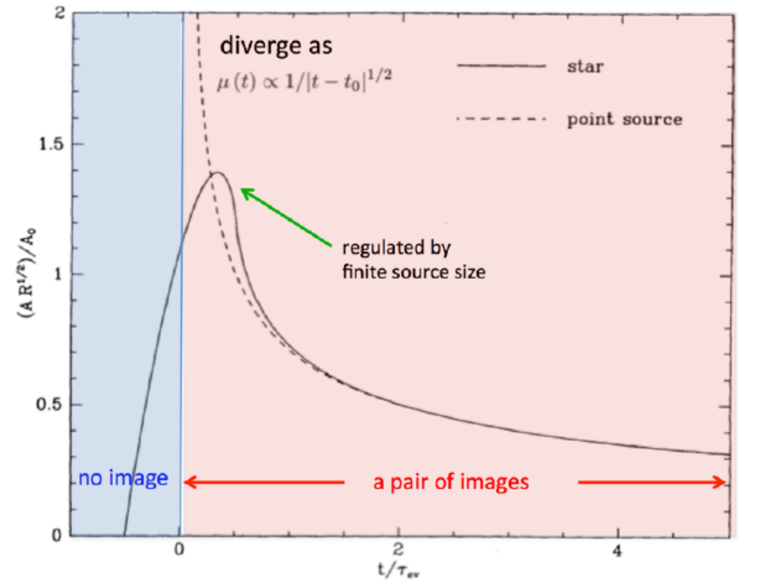


A spiral galaxy at z=1.49 is highly magnified, around the critical line shown as white band.

A caustic-crossing star was detected with Hubble Space Telescope by Kelly et al. (2018) in MACS J1149

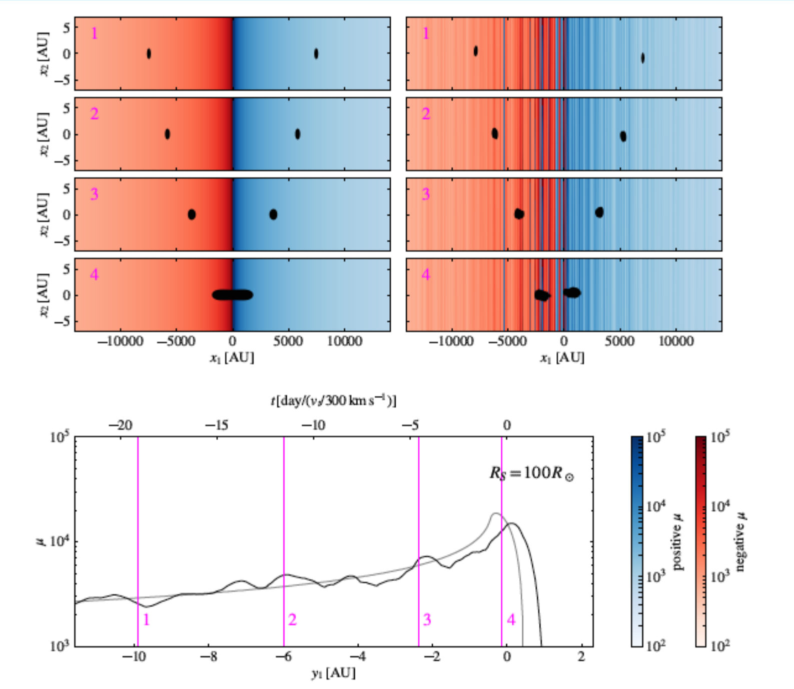


Lightcurve of a star crossing a caustic



» A star crossing a caustic is highly magnified and becomes visible, following a predicted lightcurve.

» Axion minihalos perturb this lightcurve, introducing observable fluctuations.

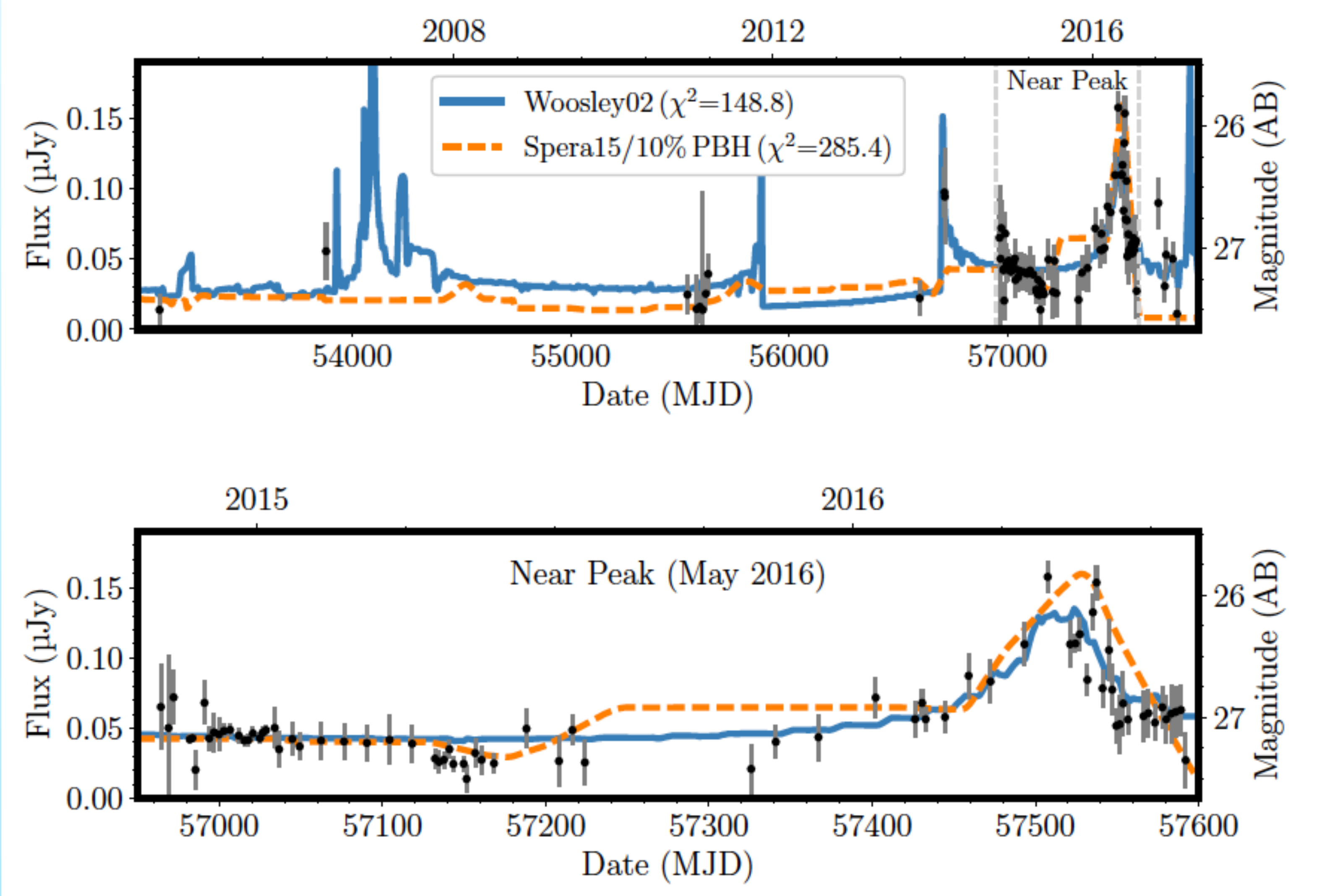


M-E 1991 Dai & M-E 2020

Conclusions

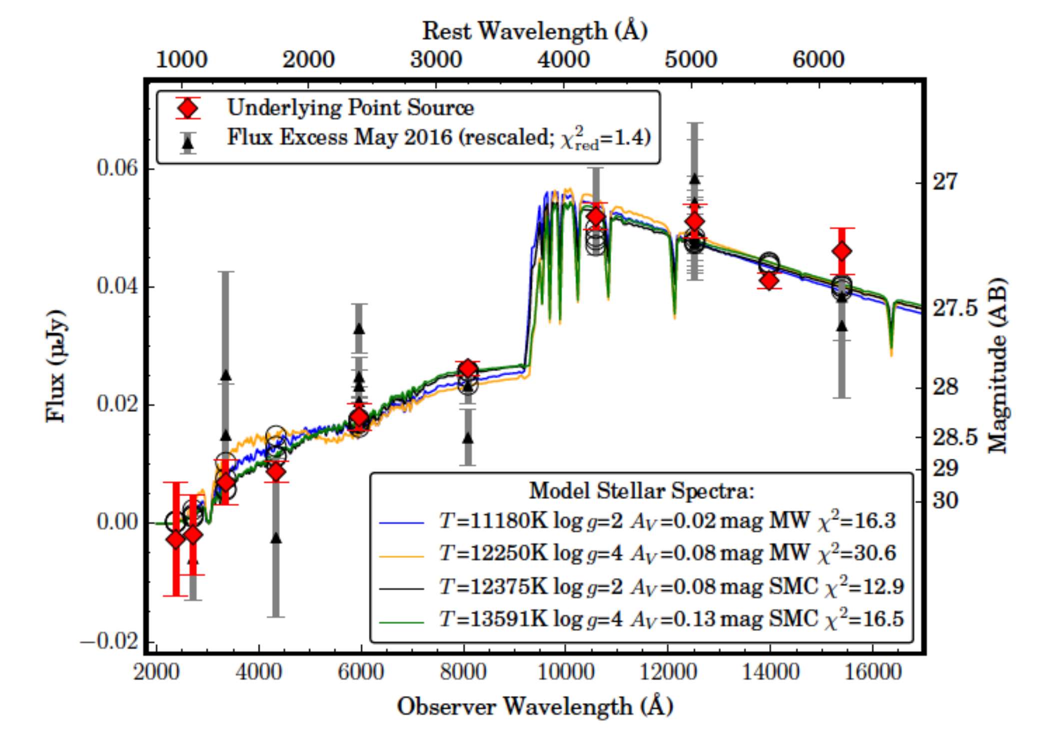
- IMHO, axions are the best dark matter candidate! If true, they would be waves sloshing around galactic halos.
- We can detect axions through their interaction with electromagnetic fields. The best technique is to use a magnet with the largest possible magnetic field and volume, and try to detect solar axions converting to X-rays, or dark matter axions converting to radio waves in resonant cavities. The IAXO and RADES collaborations are working on this, with ICCUB participation.
- Axions may also be detectable in astronomical observations: for example, if axions form minihalos they are detectable through gravitational lensing on small scales, with the difficulty that minihalos are highly below the critical threshold to form multiple images. But they can still be detected in magnification events of caustic crossings.

Lightcurve of magnified star



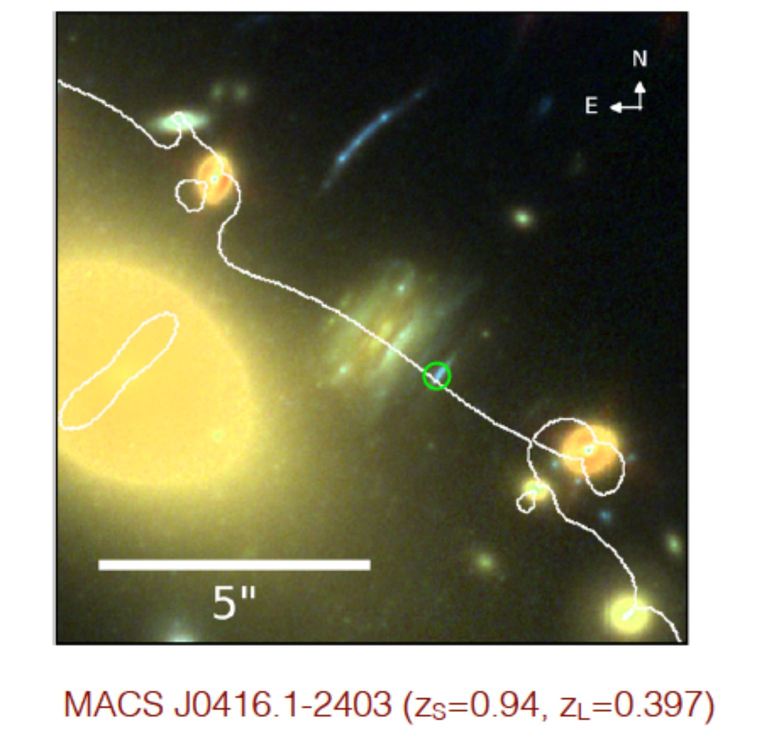
Kelly et al. 2017: points are observations, curves are random realizations with microlensing (they should not match observations exactly, only statistically).

Spectrum of the magnified star



Kelly et al. 2017: spectrum of the star in 2011-2015 and the excess flux in 2016 is consistent with a star at T ~ 12000 K.

More discoveries



Evidence of more highly magnified stars is being discovered in HST archive, and future discoveries with JWST and large ground-based telescope can be expected

(Kaurov etal 2019, Chen etal 2019.

Oguri et al. 2018: limits on abundance of primordial black holes.

- They use an observed caustic crossing duration and star temperature to derive star radius and luminosity, and maximum magnification.
- However, the proximity of the observed event to the model critical line, and the expected stellar luminosity functions, are also important constraints.