Imprints of the Early Universe on Dark Matter Substructure

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Based on 1905.06952 and 1911.07853 with Nikita Blinov, Jonathan Kozaczuk and Patrick Draper.

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Axion-Like Particles

- Axions/ALPs: (spin 0) Pseudo-Nambu-Goldstone bosons, or zero-modes of higher dimensional gauge fields.
- Naturally light, (very) weakly coupled. Well-known dark matter candidate.
- Will not discuss QCD axion (solution of Strong CP problem)

$$\boxed{\begin{gathered}\mathcal{L} \supset -\frac{1}{2} m_a^2 a^2 + \frac{1}{4} g_{a\gamma\gamma} F\tilde{F} \\ g_{a\gamma\gamma} \sim \frac{\alpha}{2\pi f_a}\end{gathered}}$$

- QCD axion has $m_a \sim m_\pi f_\pi / f_a$
- ALP has m_a and f_a independent.
- Also other possible couplings.

Many people since the early 1980s. Also many people since the 2010s.

ALP Dark Matter: Misalignment

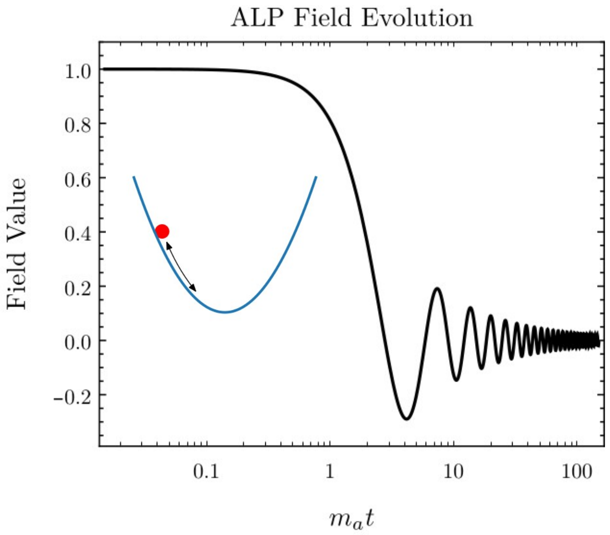
- The axion/ALP is not a thermal relic (i.e. not a WIMP)
- Field displaced from origin in early universe
- Starts to oscillate around origin when

$$m_a \sim H(T_{\rm osc})$$

- The ALP field evolves as

$$a \sim a_i \left(\frac{R_0}{R(t)}\right)^{3/2} \cos m_a t$$

- R(t) is the scale factor of the FRW cosmology.



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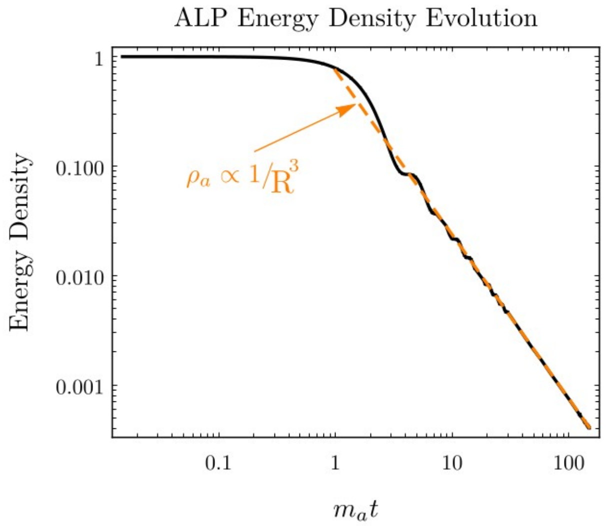
ALP Dark Matter: Misalignment

- Average over oscillation periods, find $\rho_a \sim 1/R^3$
- ALPs behave as CDM (mostly).
- Assuming standard cosmology with radiation domination in early universe:

$$\Omega_a = \frac{1}{2}\frac{m_a^2 f_a^2 \theta_0^2}{\rho_c}\left(\frac{R_{\rm osc}}{R_0}\right)^3$$

ALP abundance depends on initial misalignment

ALP abundance depends on expansion since oscillations began.



$$\boxed{\Omega_a h^2 \simeq 0.12\left(\frac{f_a\theta_0}{1.9\times10^{13}\ {\rm GeV}}\right)^2\left(\frac{m_a}{1\ \mu{\rm eV}}\right)^{1/2}}$$

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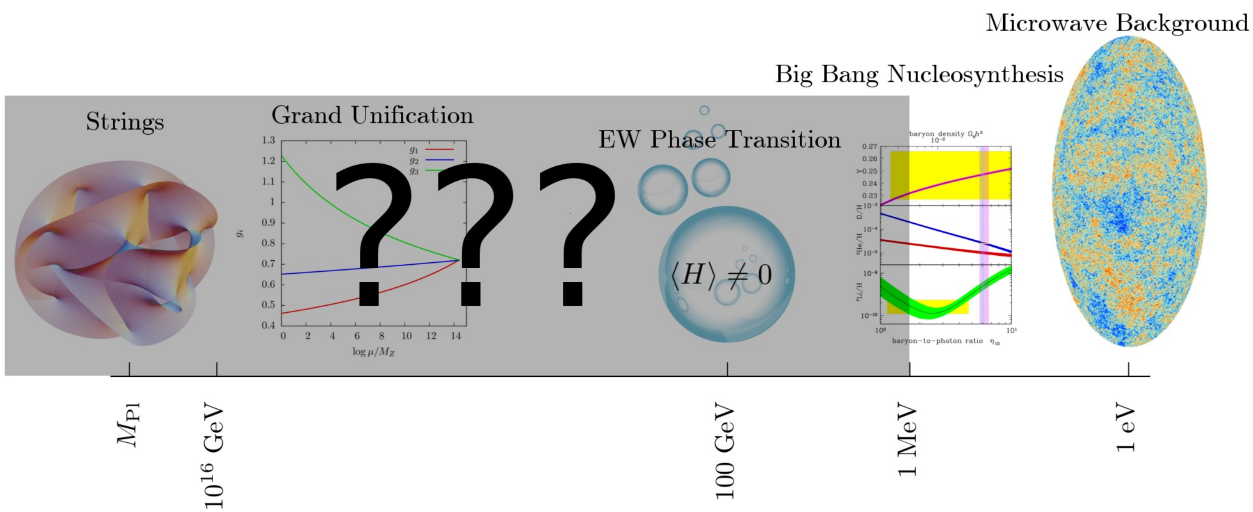
ALP Dark Matter: Misalignment

- Don't know the evolution of the universe before BBN.

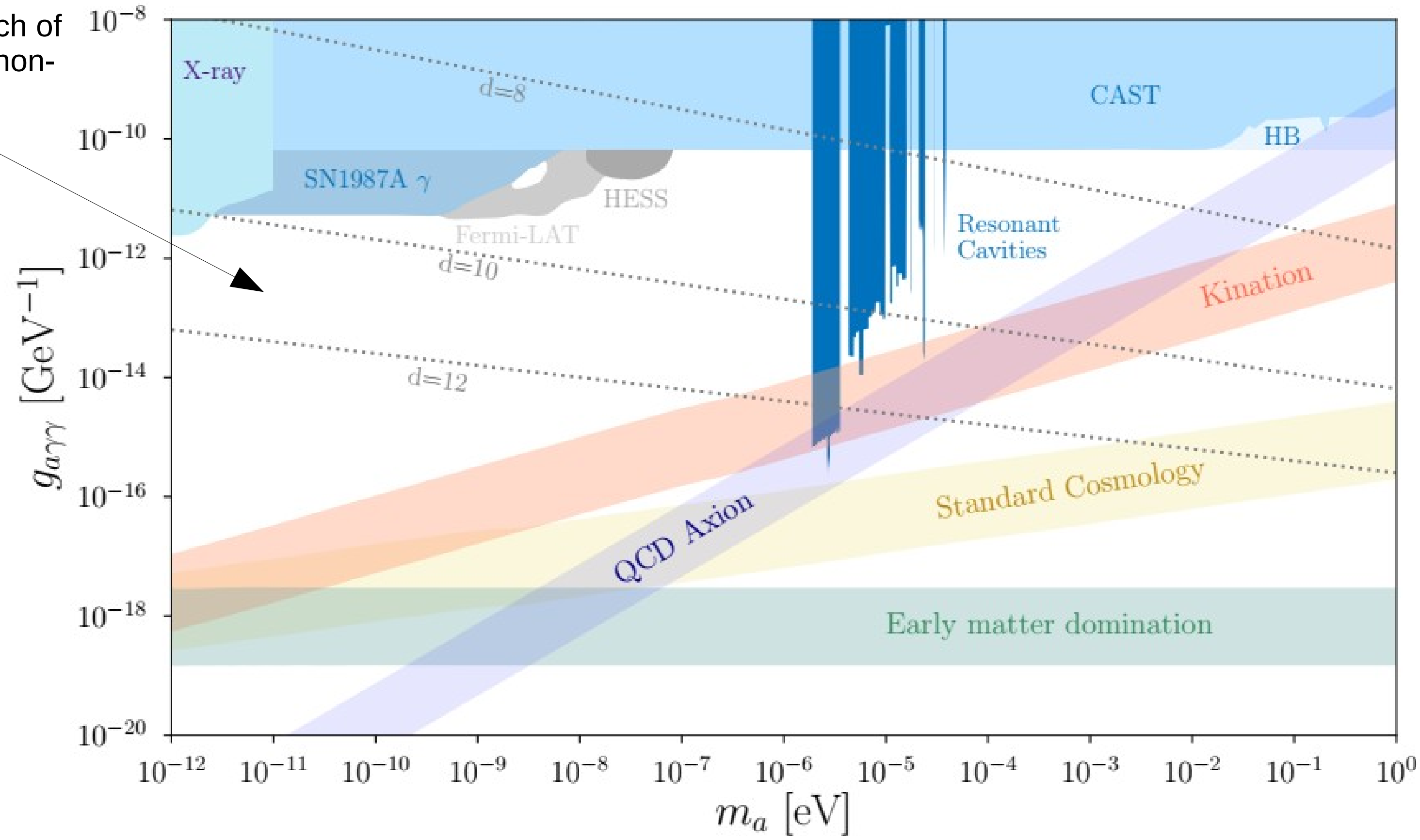


- ALP UV completions often involve an epoch of Early Matter Domination (EMD).
- Transition from EMD to radiation domination (reheating – RH) happens at T_{RH}
- BBN constraint: $T_{RH} > 5 \text{ MeV}$

$$\boxed{\Omega_a h^2 \simeq 0.12 \left(\frac{f_a \theta_0}{9 \times 10^{14} \text{ GeV}} \right)^2 \left(\frac{T_{RH}}{10 \text{ MeV}} \right)}$$

Current Constraints

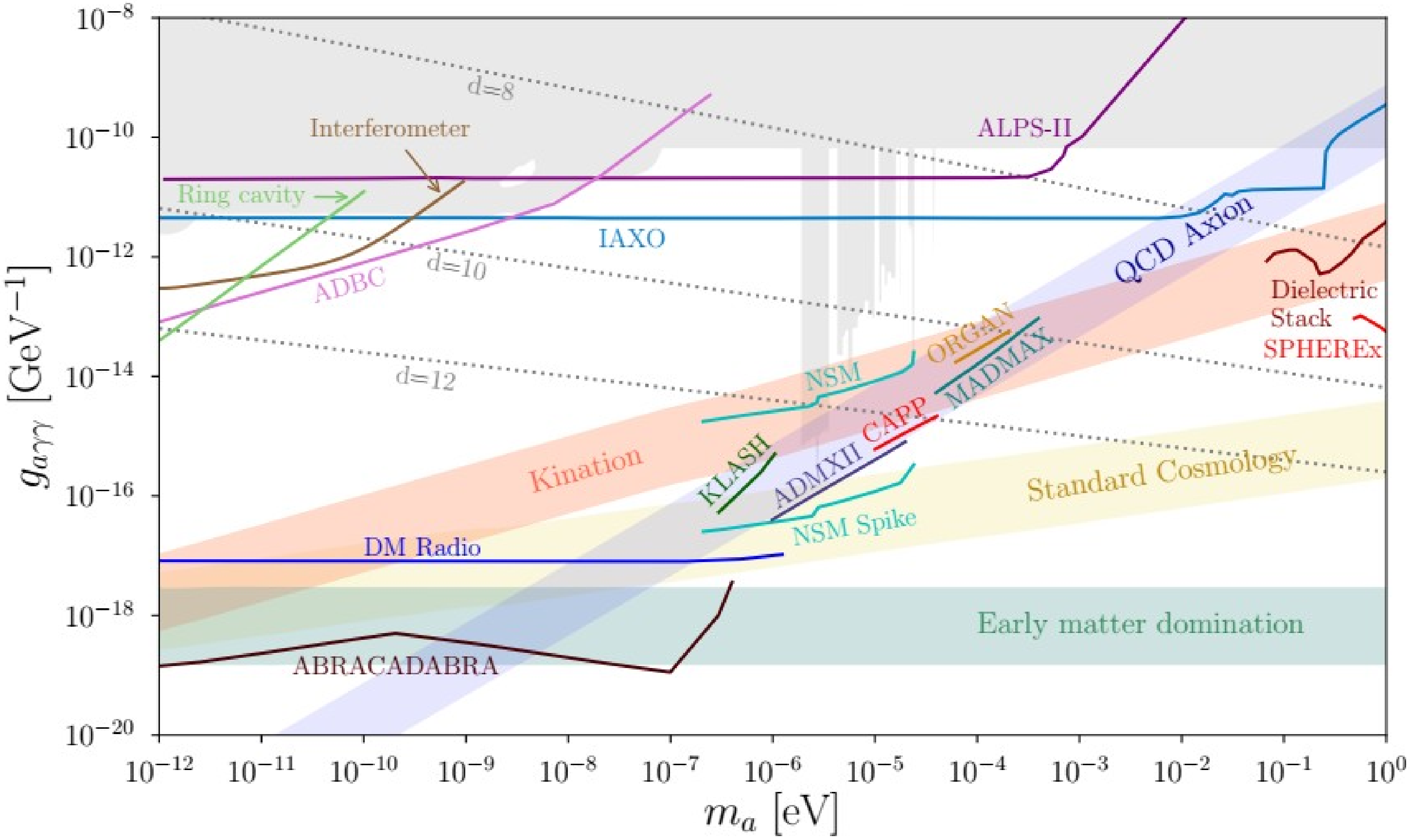
Can also fill this much of this region out with non-cosmological modifications



Non-DM out here: collider, astrophysical, flavour constraints.
MJD, Kahlhoefer, McCabe, Schmidt-Hoberg 2014;
MJD, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg 2017
MJD, Hiskens, Volkas, to appear

Blinov, MJD, Draper, Kozaczuk 1905.06952

Current Constraints



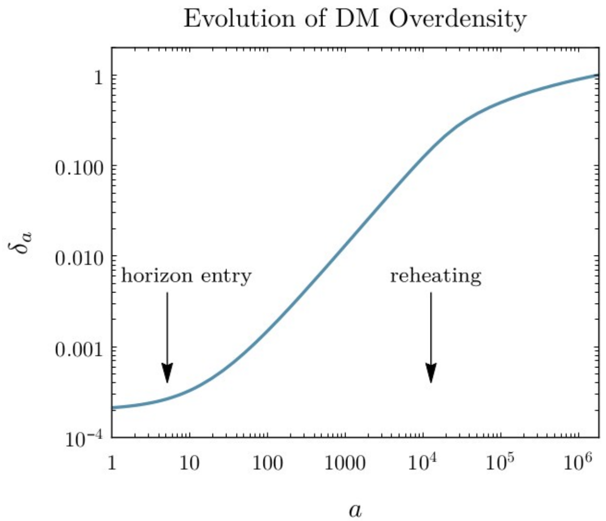
Blinov, MJD, Draper, Kozaczuk 1905.06952

Impact on Small Scale Structure: Clumps

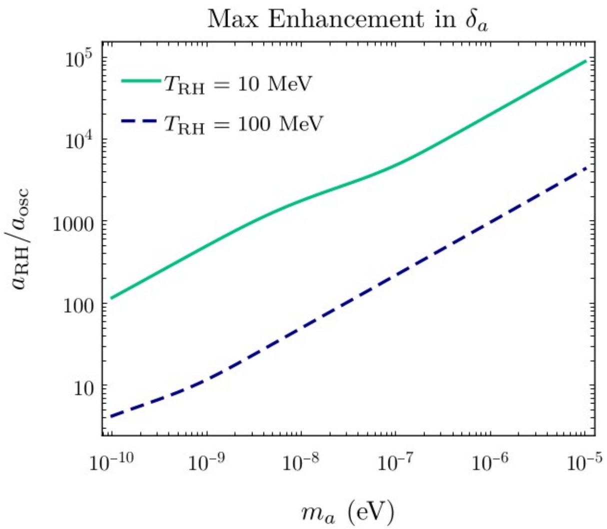
- Changing cosmology changes growth of density perturbations in early universe.
- Consider a CDM density perturbation $\delta = (\rho(x) - \bar{\rho})/\bar{\rho}$
- Evolves as $\ddot{\delta} + \mathcal{H}\dot{\delta} \approx -k^2\Psi$ where k = comoving inverse size of perturbation

$$\delta \propto \begin{cases} a & \text{MD} \\ \ln a & \text{RD} \end{cases}$$

- EMD enhances growth by $\sim (a_{\rm RH}/a_{\rm hor}) \sim (k/k_{\rm RH})^2$



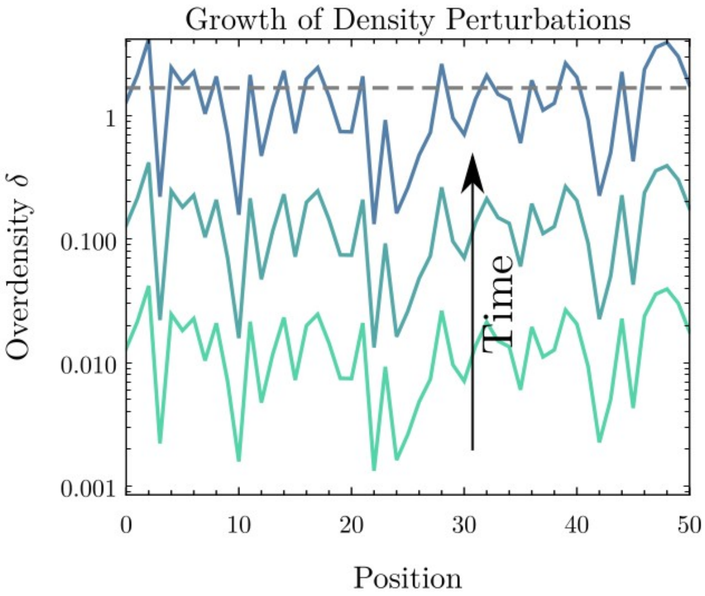
$$\frac{a_{\rm RM}}{a_{\rm osc}} \sim 10^6 \left(\frac{m_a}{10^{-5}\ \text{eV}}\right)^{2/3} \left(\frac{5\ \text{MeV}}{T_{\rm RH}}\right)^{4/3}$$



Erickcek, Sigurdson 2011
Gondolo, Visinelli 2009++; Nelson Xiao 2018; Blinov, MJD, Draper 1911.07853

Typical Clumps

- The early universe is a realisation of the primordial density distribution



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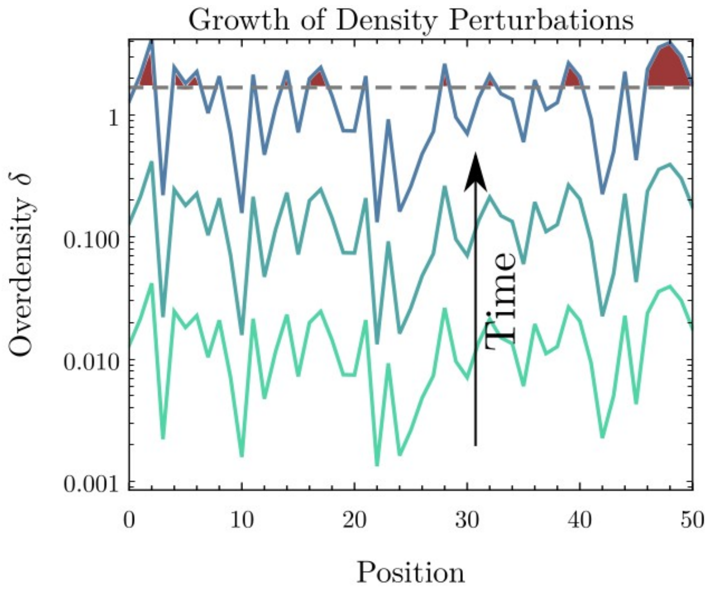
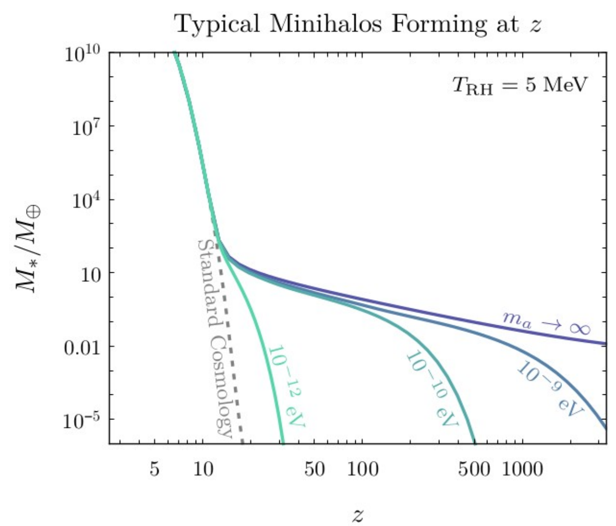
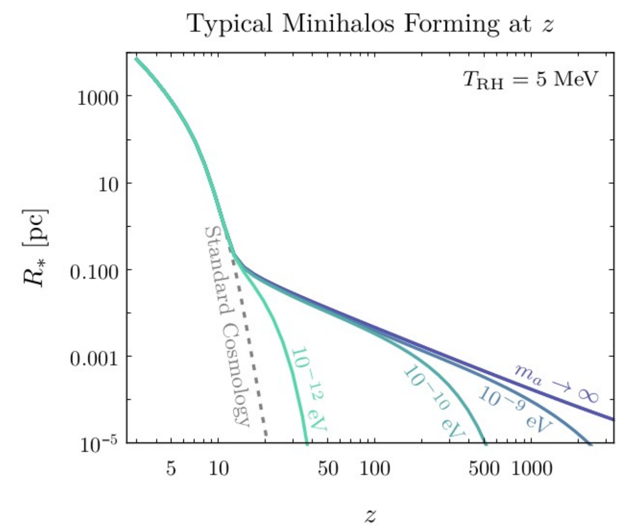


- If a clump grows dense enough, decouples from Hubble flow and collapses at redshift z_c and forms a virialised minihalo.
- Study statistics of collapsed density perturbations using Press-Schechter theory.

Press, Schechter 1974 + many others

Typical Clumps





- If a clump grows dense enough, decouples from Hubble flow and collapses at redshift z_c and forms a virialised minihalo.
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$$\rho(z_c) \approx 230\ \mathrm{GeV/cm}^3 \left(\frac{1+z_c}{100}\right)^3$$

$$M_*(z_c) \approx 250 M_\oplus \left(\frac{5\ \mathrm{MeV}}{T_{\rm RH}}\right)^3 \left(\frac{2.6}{1+z_c}\right)^{6/(n_s+3)}$$

$$R_*(z_c) \approx 4\times 10^{-3}\ \mathrm{pc} \left(\frac{5\ \mathrm{MeV}}{T_{\rm RH}}\right) \left(\frac{100}{1+z_c}\right)^{\frac{5+n_s}{3+n_s}}$$

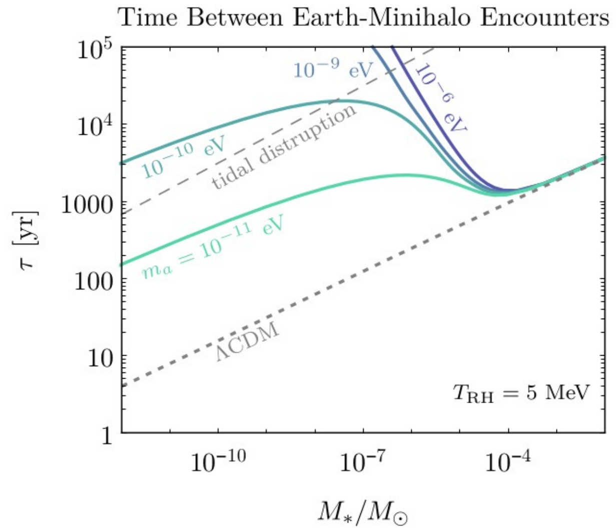
Direct Detection Implications

- Clumps can be disrupted by mergers, clump-clump encounters, encounters with the galactic disk, stars, etc.
- Structures collapsing before z=250 probably survive.

- Small couplings already difficult: $\propto 1/f_a$
- Time between earth-clump encounters can be larger than experimental lifetimes

$$\tau = \frac{1}{n\sigma v}, \quad \text{where } n \sim \rho_0/M_* \,, \quad \sigma = \pi R_*^2$$

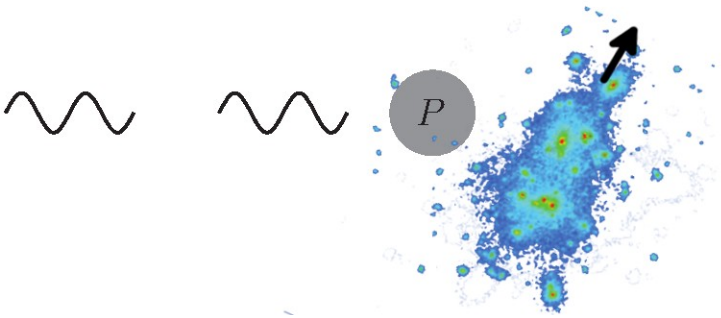
- Can create DM streams from clump disruption
- All fertile ground for N-body simulations.



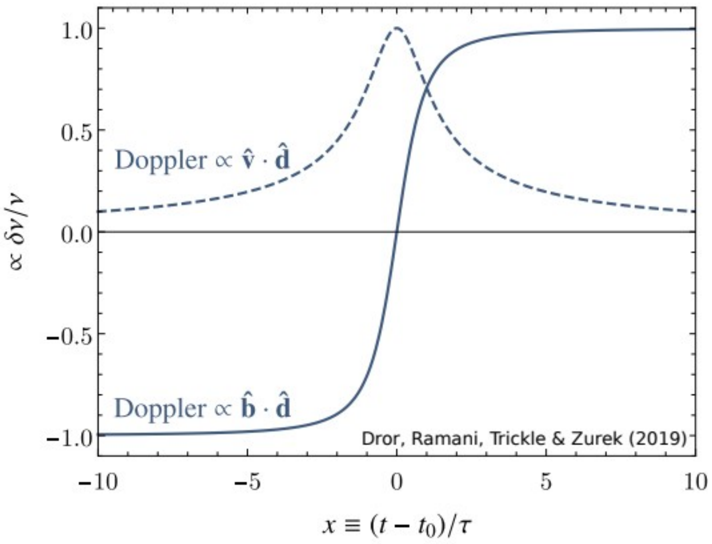
Van den Bosch et al 2017, Dokuchaev, Tkachev et al 2014+; Erickcek, Sten Delos et al 2017+

Astrophysical Probes: Pulsar Timing Arrays

- Clump passes near line of sight to a pulsar.
- Gravitational interactions alters pulse arrival time



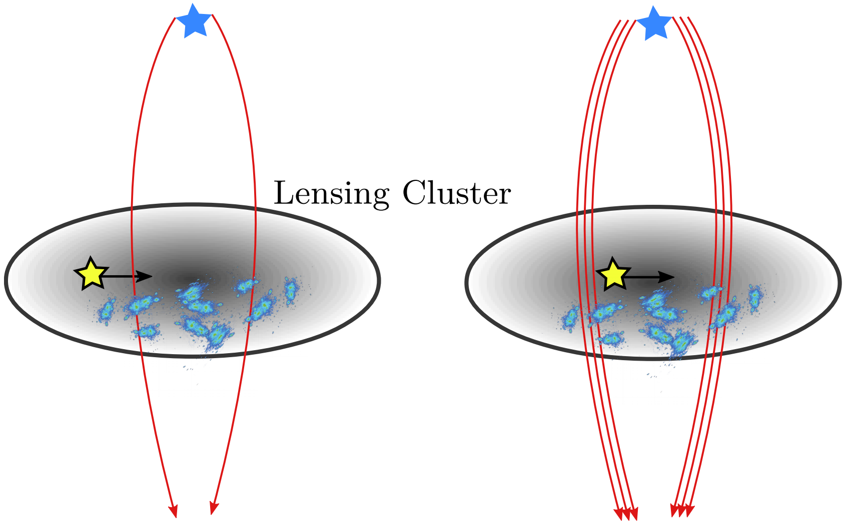
$$\frac{\delta \nu}{\nu} \sim \frac{GM}{v r_{min}}$$

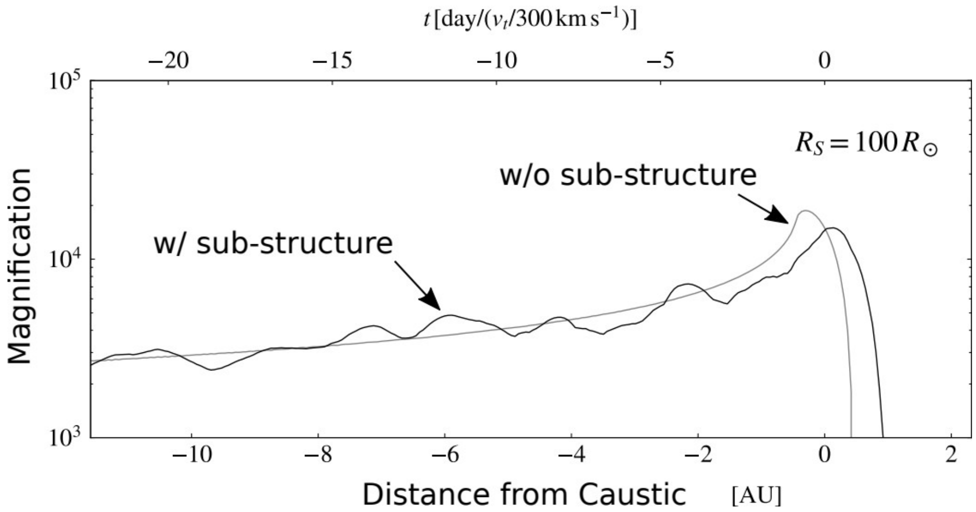


Dror, Ramani, Trickle, Zurek 2019, 2020

Astrophysical Probes: Caustic Microlensing

- Extragalactic star is lensed by a cluster, and then microlensed by an intra-lens star
- First known example in 2017 using Hubble (by accident).
- Tiny density fluctuations due to clumps amplified.
- Signature is ‘noise’ on the microlensing lightcurve.

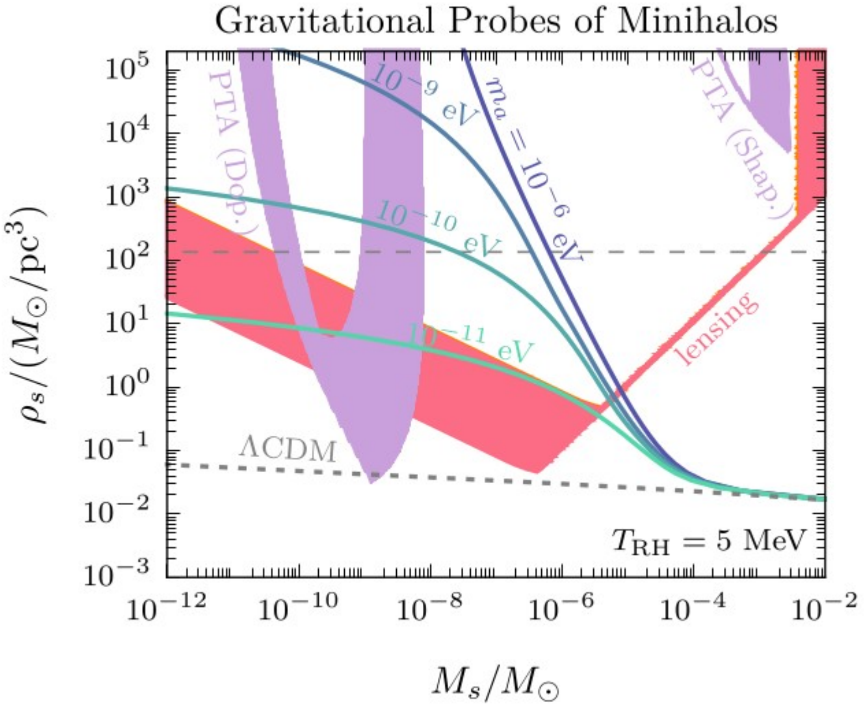




Dai, Miralda-Escudé 2019

Astrophysical Probes: Caustic Microlensing

- Assumes PTA of 200 pulsars observed for 20 years with SKA (but ignores important sources of noise!)
- Bands vary fraction of DM in clumps from 0.3 to 1.
- PTAs and Lensing may be sensitive to EMD-motivated very small-scale substructure.



Blinov, MJD, Draper 2019

Conclusions

- Non-thermal DM production sensitive to early universe cosmology.
- Well-motivated targets can be easier/harder for direct detection than standard scenario.
- A number of other possibilities lead to enhanced substructure from early universe dynamics.
- Substructure is a window into the pre-BBN universe.