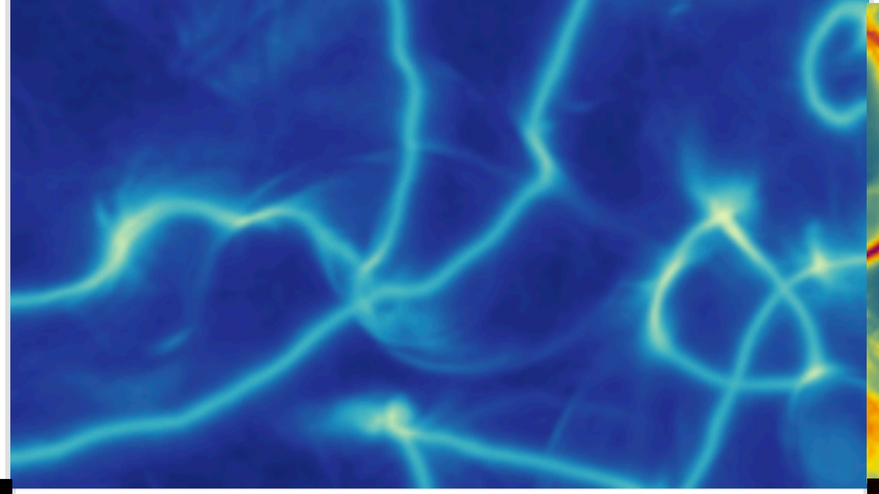
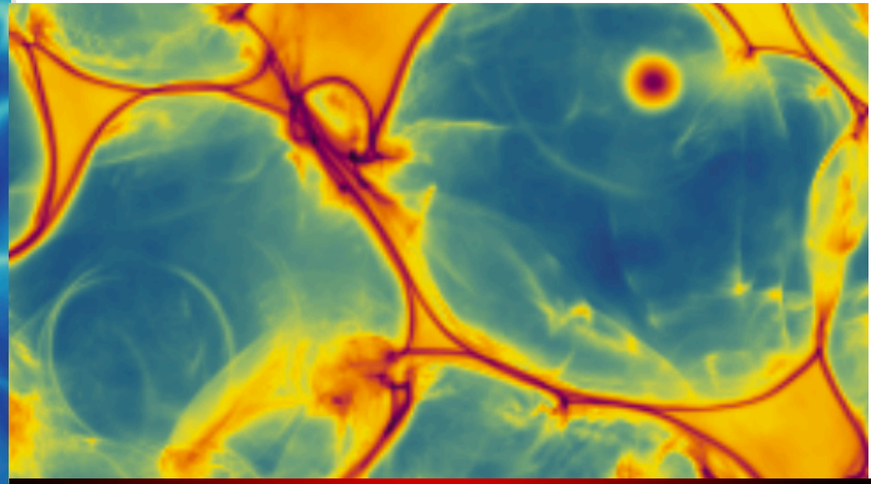
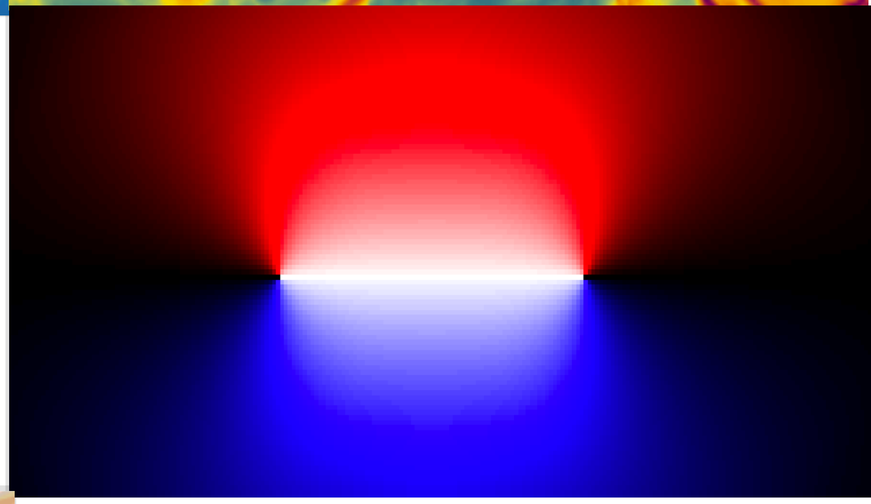
Axion stringS





Javier Redondo
23 September 2025,
20thPatras Workshop
La Laguna Tenerife

&



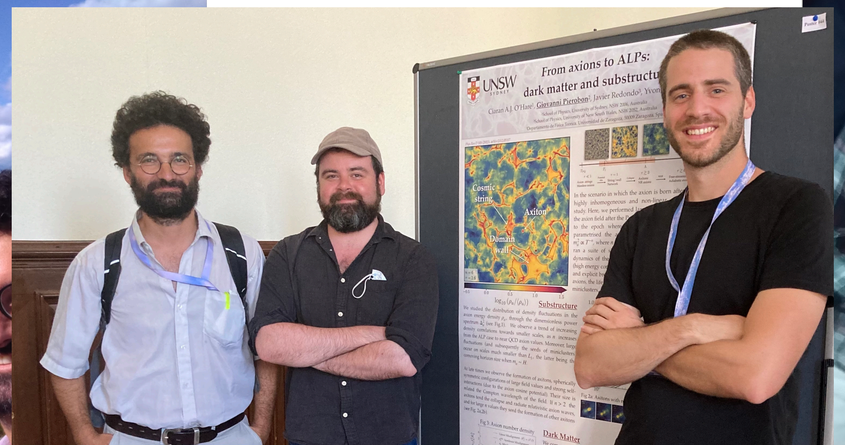
Mini clusterS

based on :

Many in preparations ...
2401.17253 [hep-ph] Spectrum of global string networks and the axion dark matter mass
2311.17367 [hep-ph] Axion Minicluster Streams in the Solar Neighborhood
2307.09941 [hep-ph] Miniclusters from axion string simulations
2212.00560 [hep-ph] Axion minivoids and implications for direct detection
2204.13187 [hep-ph] Structure of axion miniclusters
2112.05117 [hep-ph] Simulations of axionlike particles in the postinflationary scenario
1911.09417 [astro-ph.CO] First Simulations of Axion Minicluster Halos
1809.09241 [astro-ph.CO] Early Seeds of Axion Miniclusters

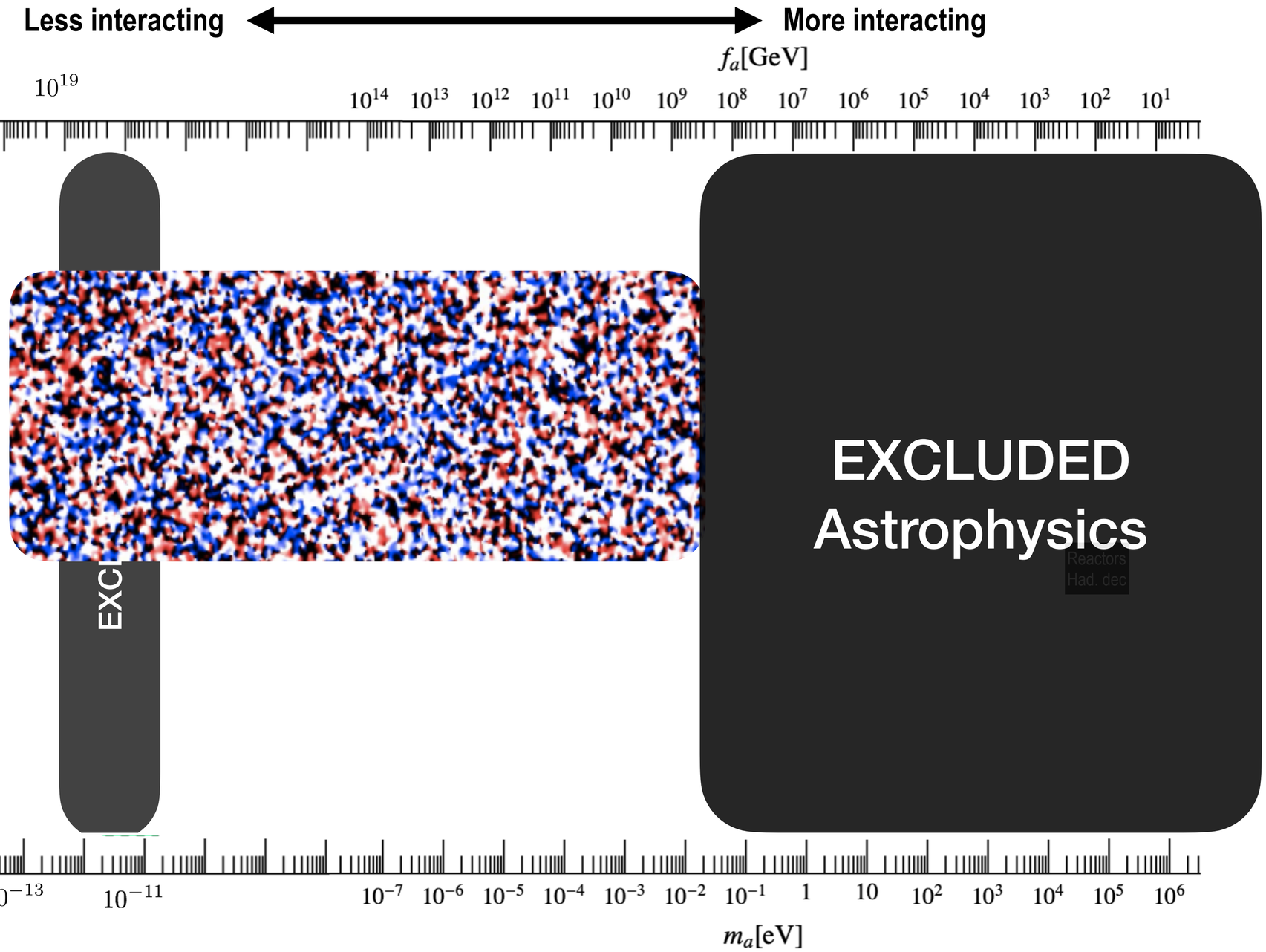
in collaboration with :

Alejandro Vaquero, Mathieu Kaltschmidt, Ivan Rybak (Zaragoza U), Kenichi Saikawa (Kanazawa U.)
Giovanni Pierobon, YYY Wong (South Wales U) Ciaran O'Hare (Sidney U)
Kierthika Chathirathas, Thomas Schwetz (IAP, Karlsruhe),
Guy Moore (Darmstadt U.), Benedikt Eggemeier, Bodo Schwabe, David Ellis, Jens Niemeyer (Göttingen U) Klaus Dolag (Mun
David Marsh (KCLondon)



The axion DM mass: two predictions

POST-Inflation Scenario
- Axion Initial conditions @ phase transition
- All values of theta -> mass prediction -> Inmediate discovery!
- Inflation BEFORE or NO inflation
- Cosmic strings, walls carry huge energy
- String radiation is uncertain!
- Miniclusters



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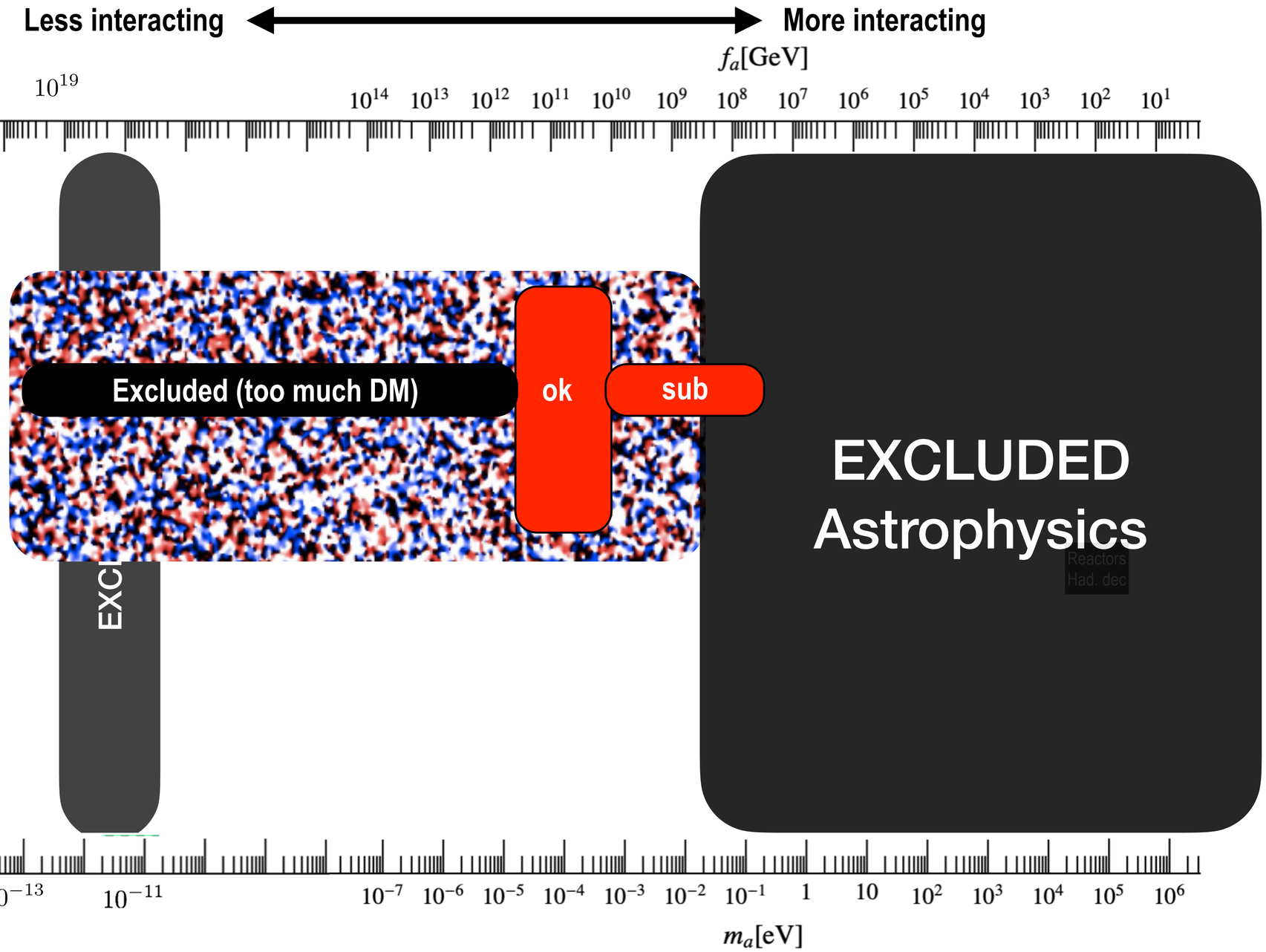

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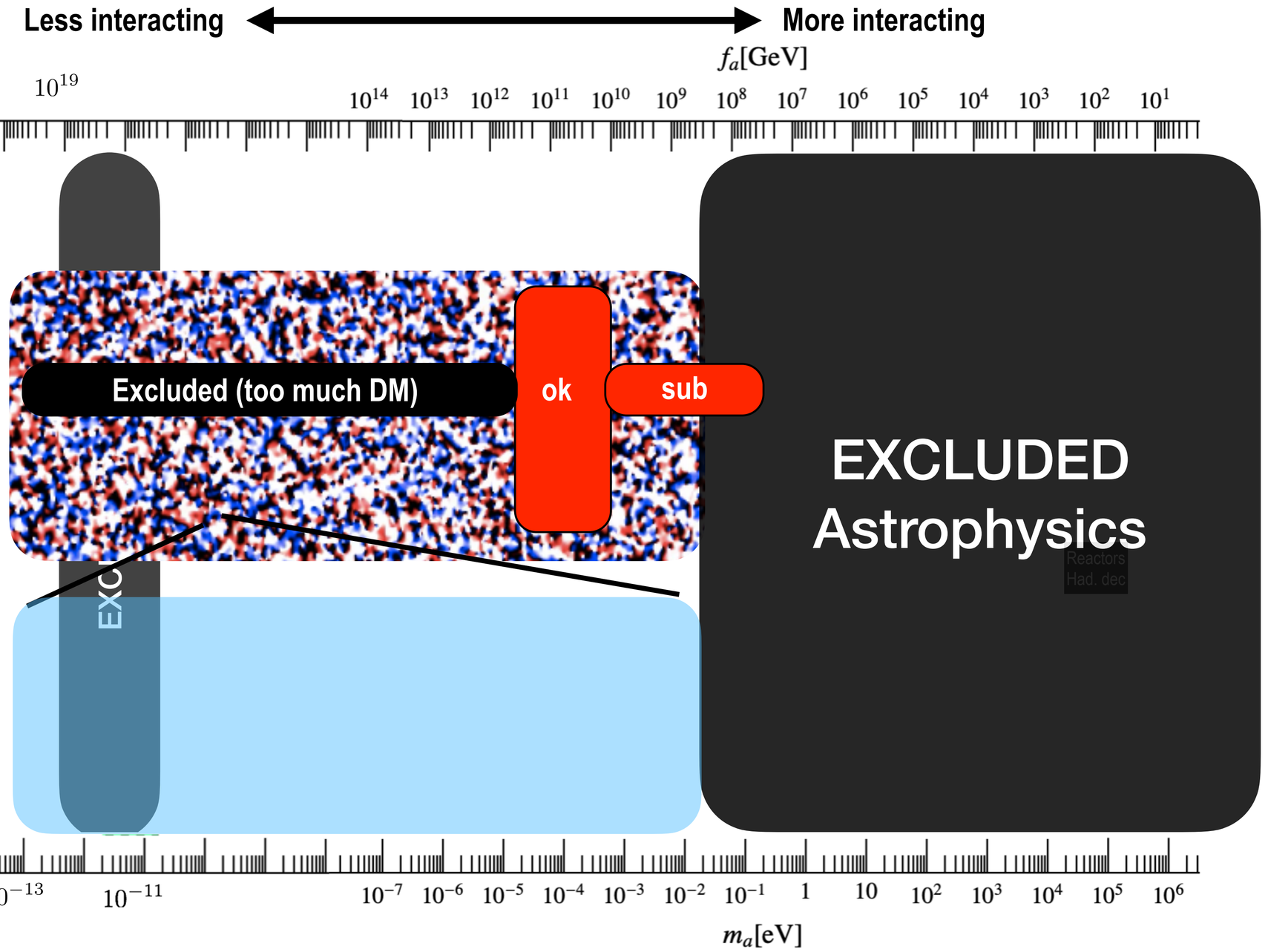

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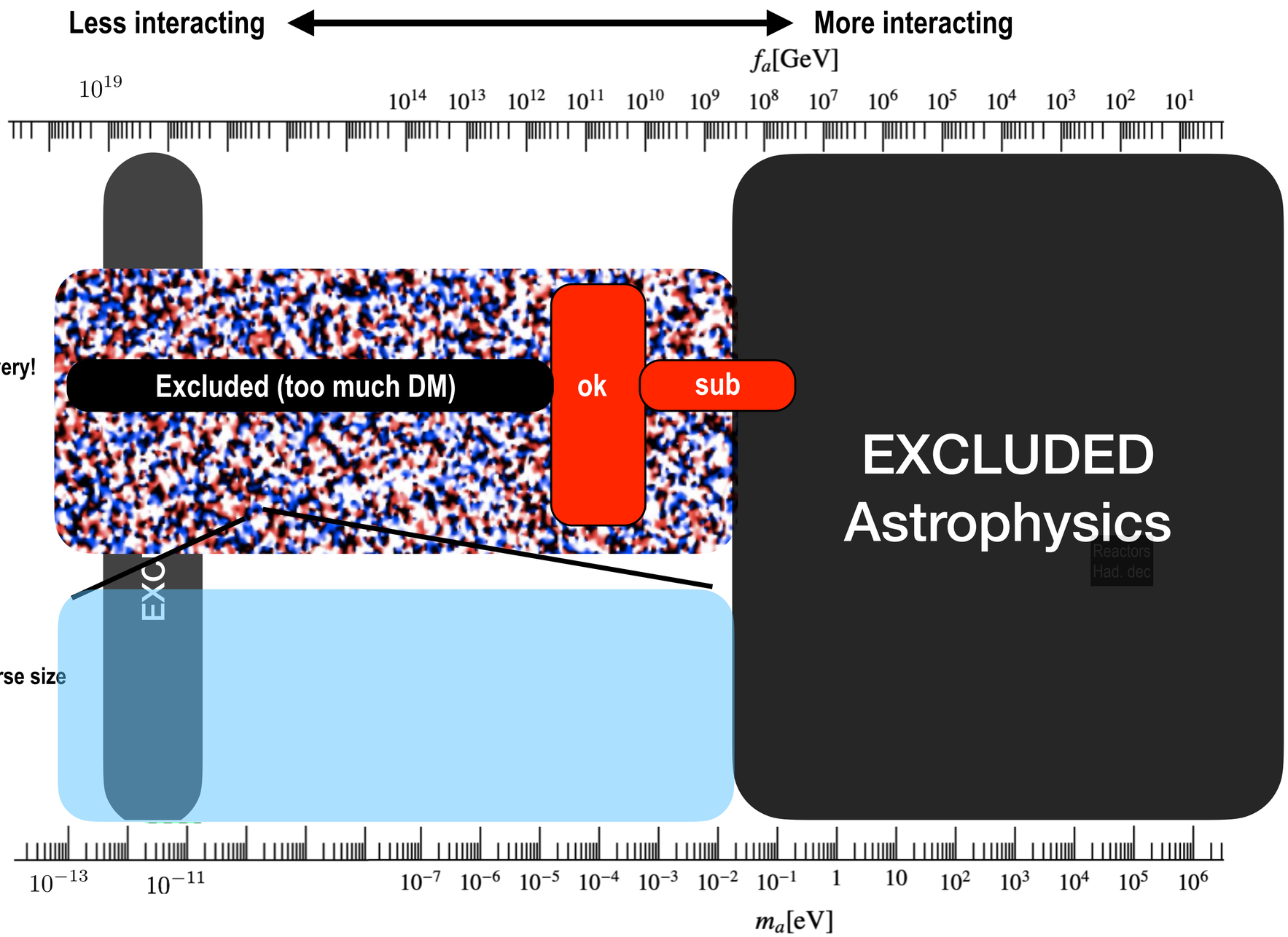

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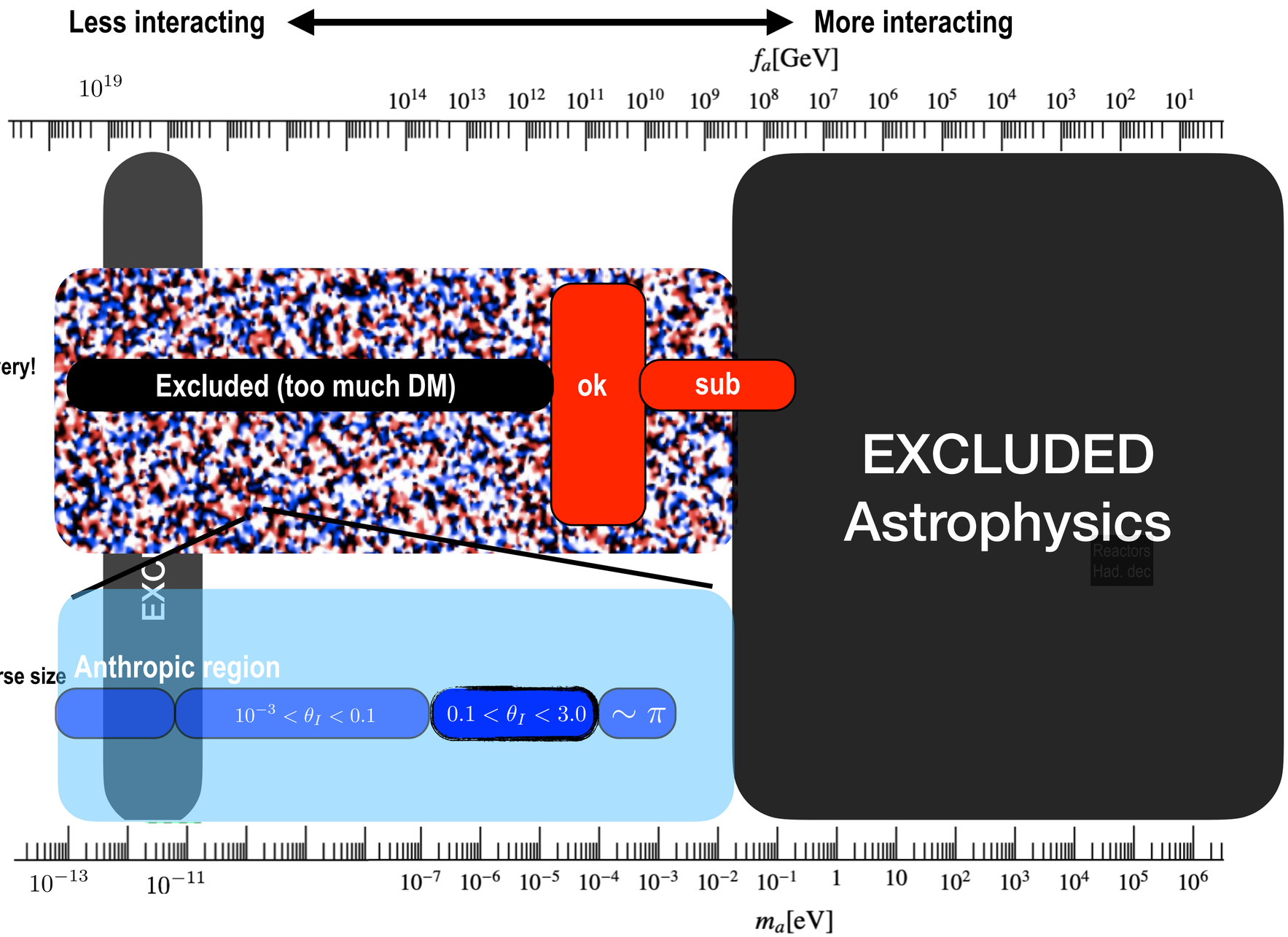

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- String network energy, axion radiation rate,

$$\rho_{network} \sim \xi f_A^2 H^2 \log \frac{d_H}{d_s}$$

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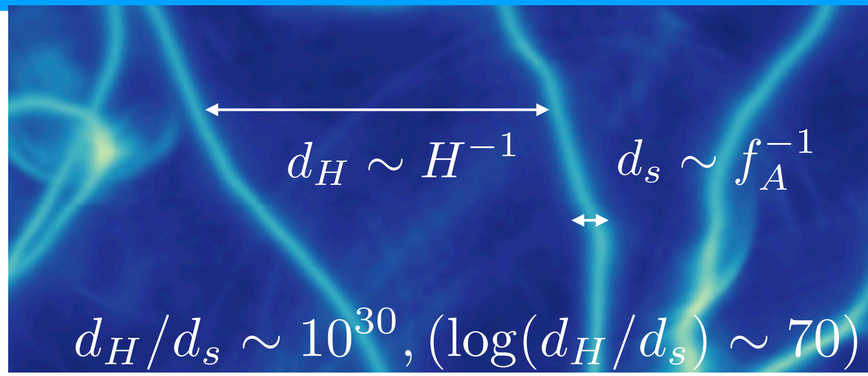

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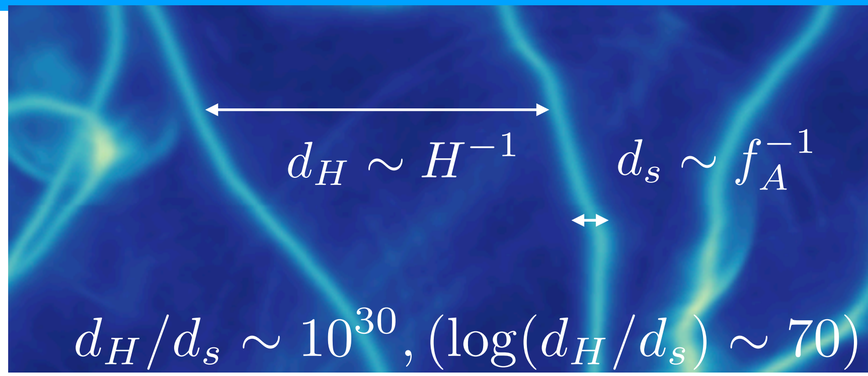

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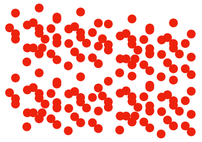

300 axions of E~H

3 axions of E~fA
same total E

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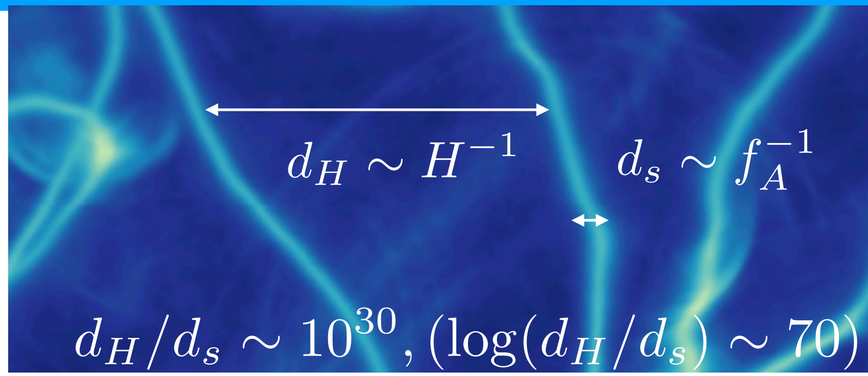

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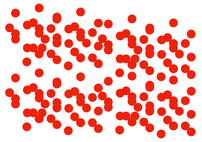

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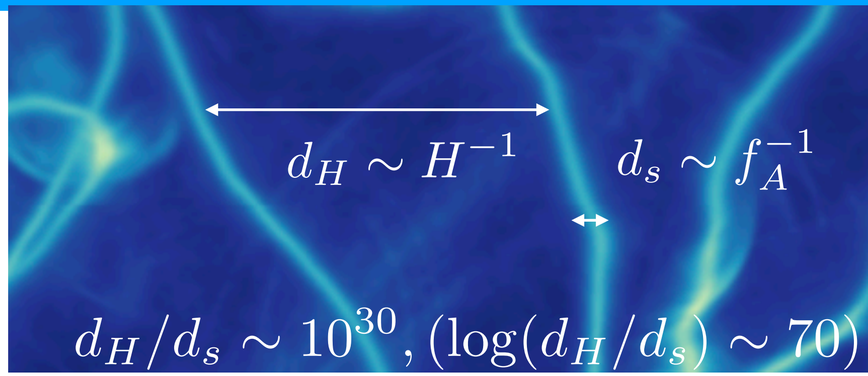

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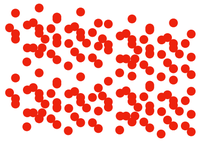

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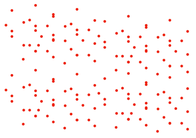

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100 times less DM

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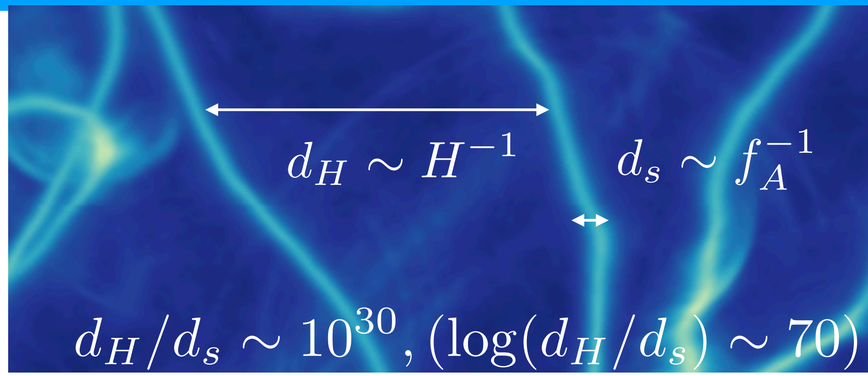

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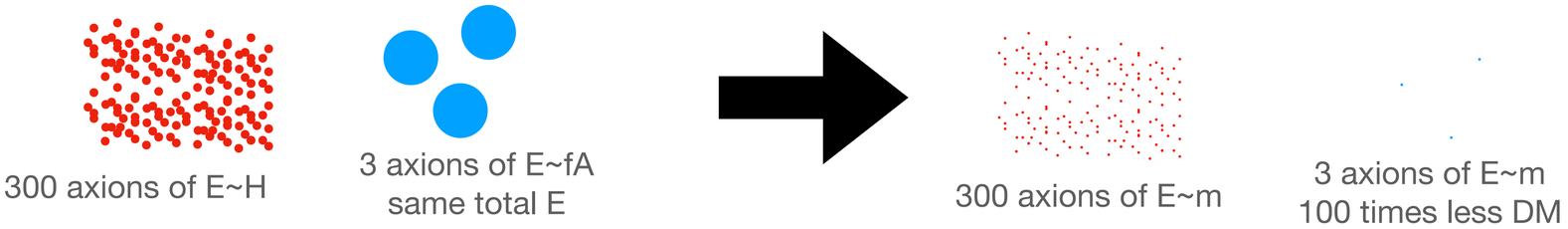

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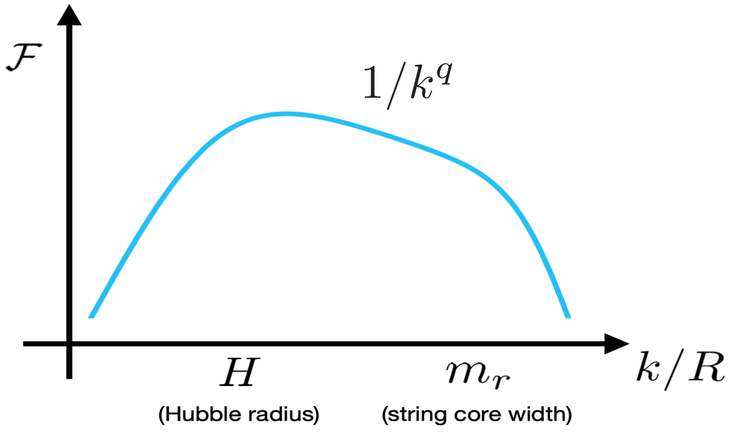
- Energy dependence of production rate:

$$\mathcal{F} = \frac{1}{(f_a H)^2} \frac{\partial}{\partial(k/R)} \frac{d\rho_A}{dt}$$

$$\mathcal{F} = \begin{cases} \mathcal{F}_0 k^{-q} & H \lesssim k/R \lesssim f_a \\ 0 & \text{otherwise} \end{cases}$$



Effective theory

- Nambu-Goto string

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Kalb-Rammond field

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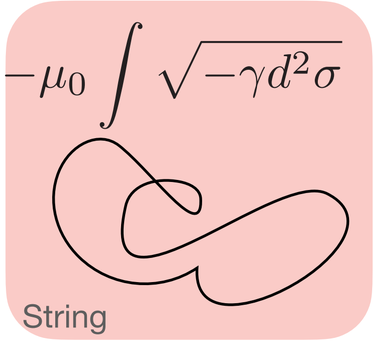

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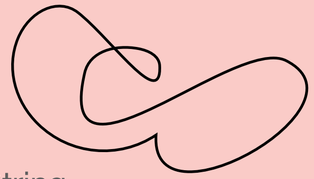

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$$+\frac{1}{6}\int H^2\sqrt{-g}d^4x$$

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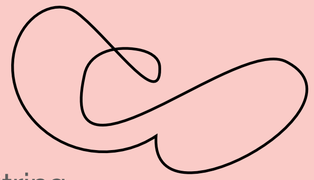

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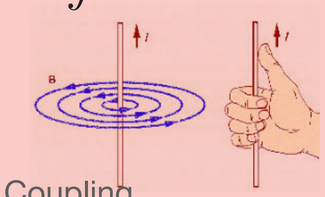

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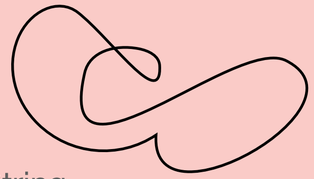

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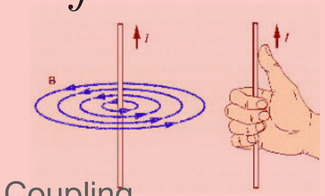

Coupling

- KR field renormalises NG string tension

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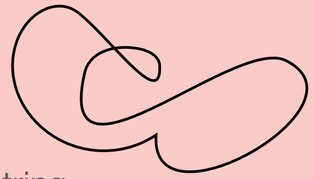

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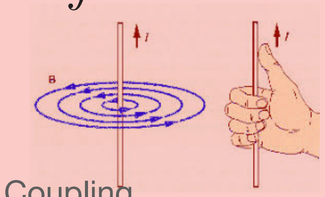

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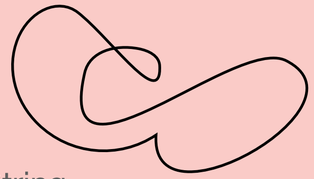

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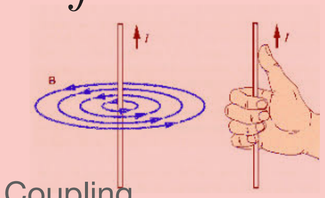

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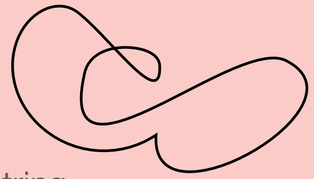

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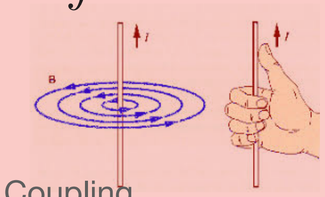

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large logs suppress effect of KR field in the RHS

renormalised KR field (no UV) has no log

Effective theory vs numerical simulations

- Compare KR EFT with 3D and 2D sims

  Similar accelerations
  Correct trend towards NG
  but some unaccounted diffs...

Effective theory

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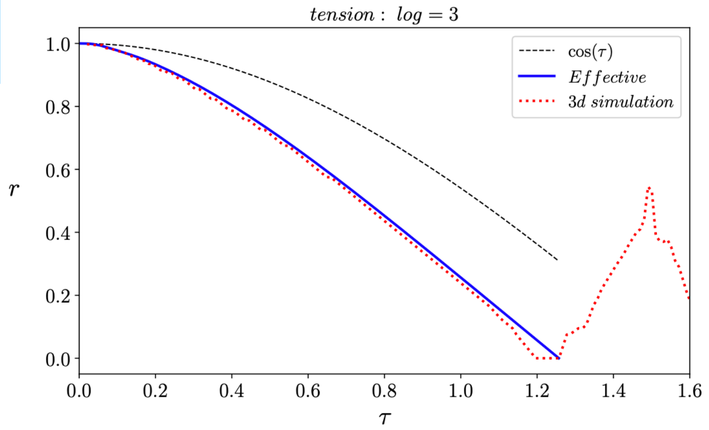

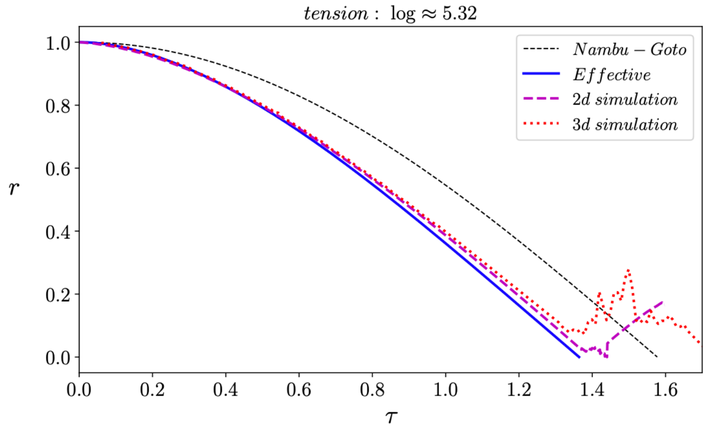

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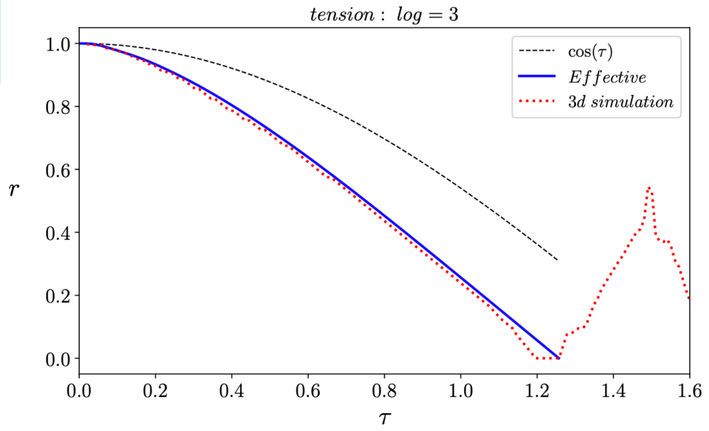

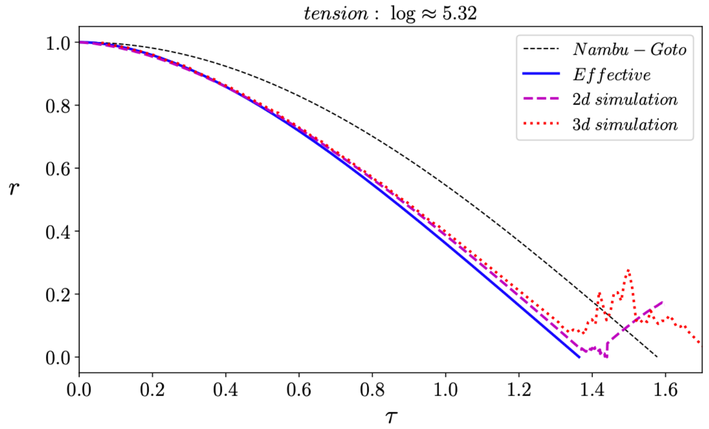

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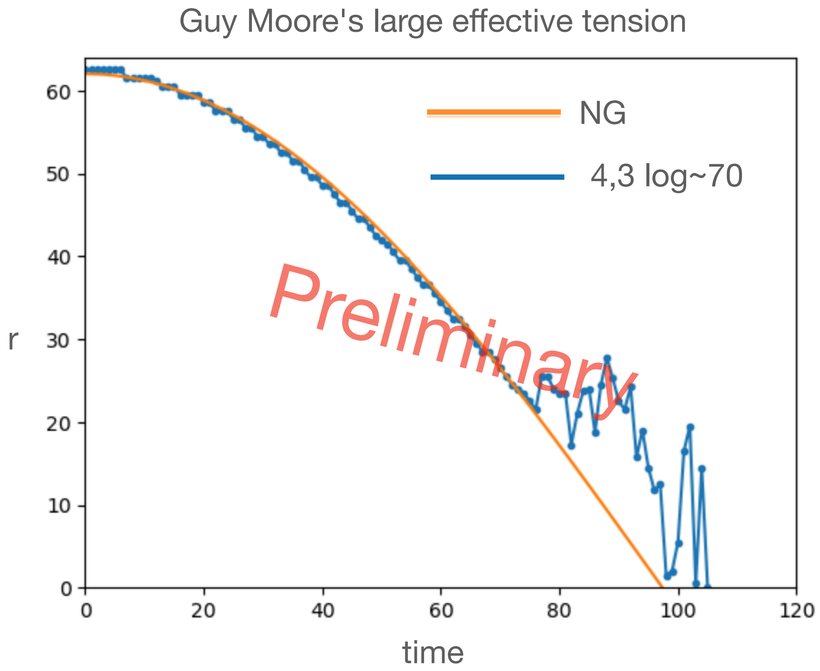

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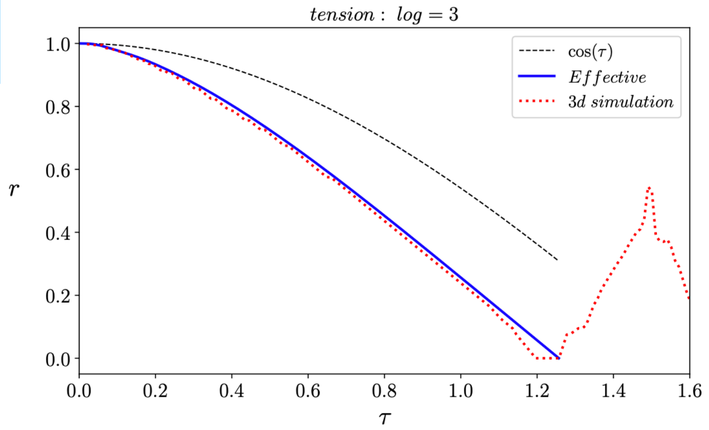

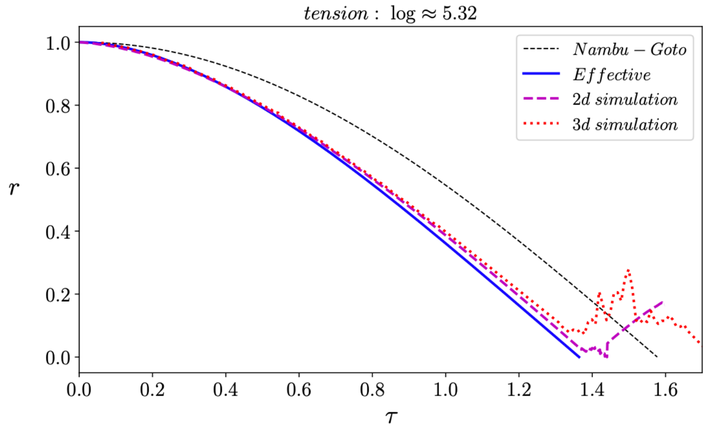

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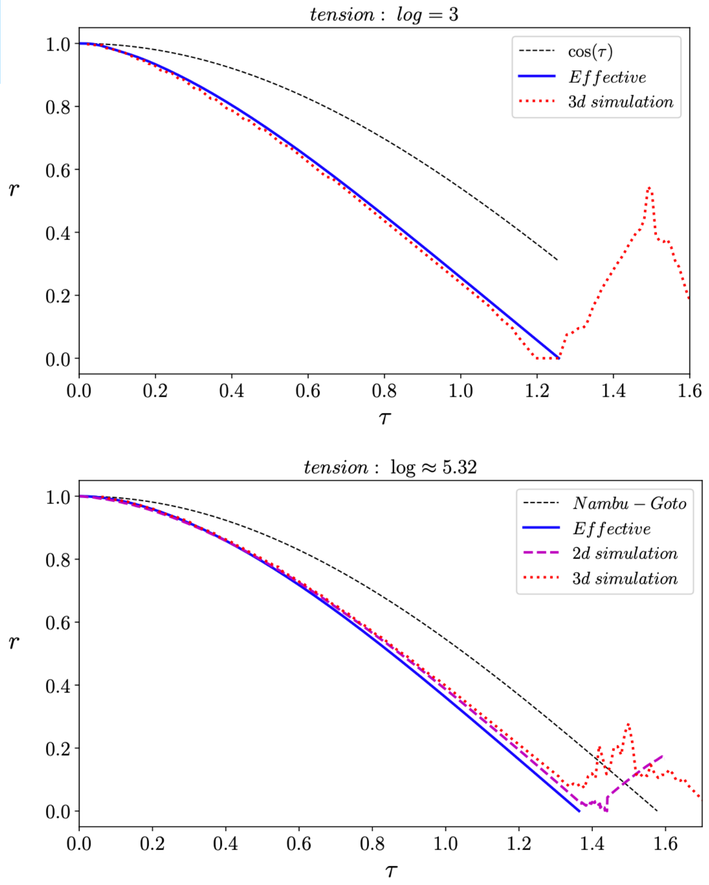

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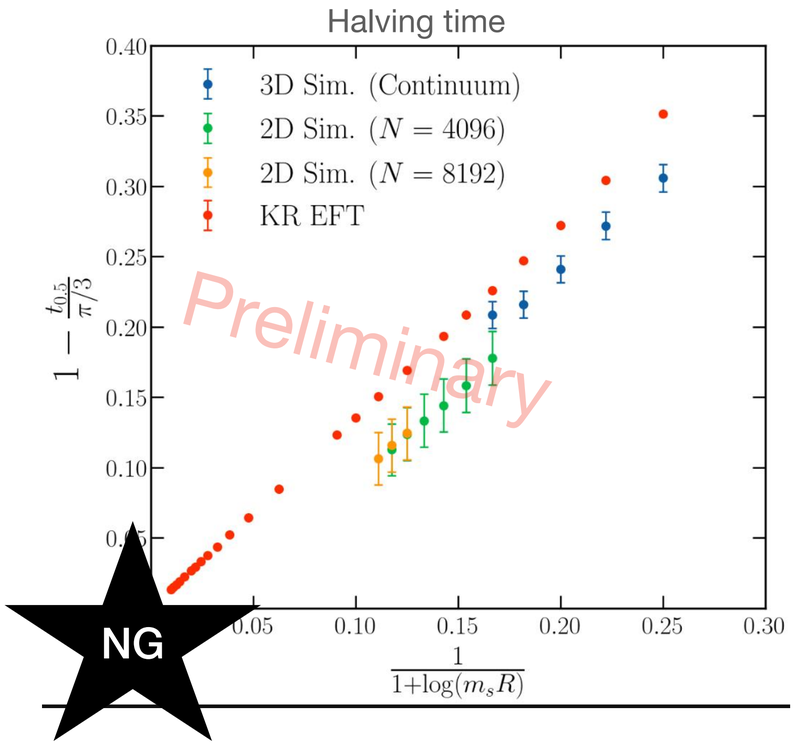

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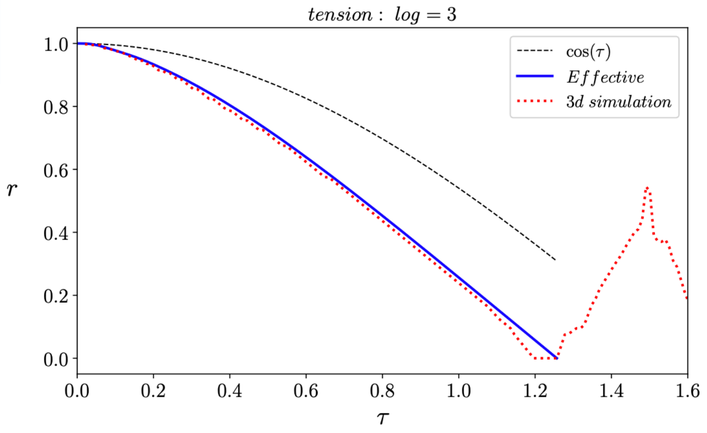

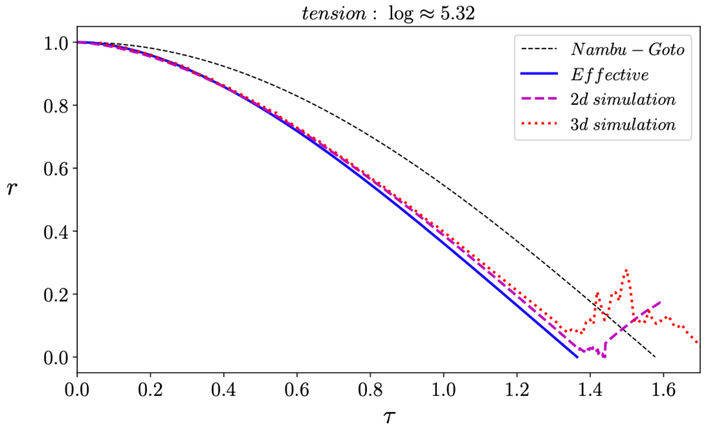

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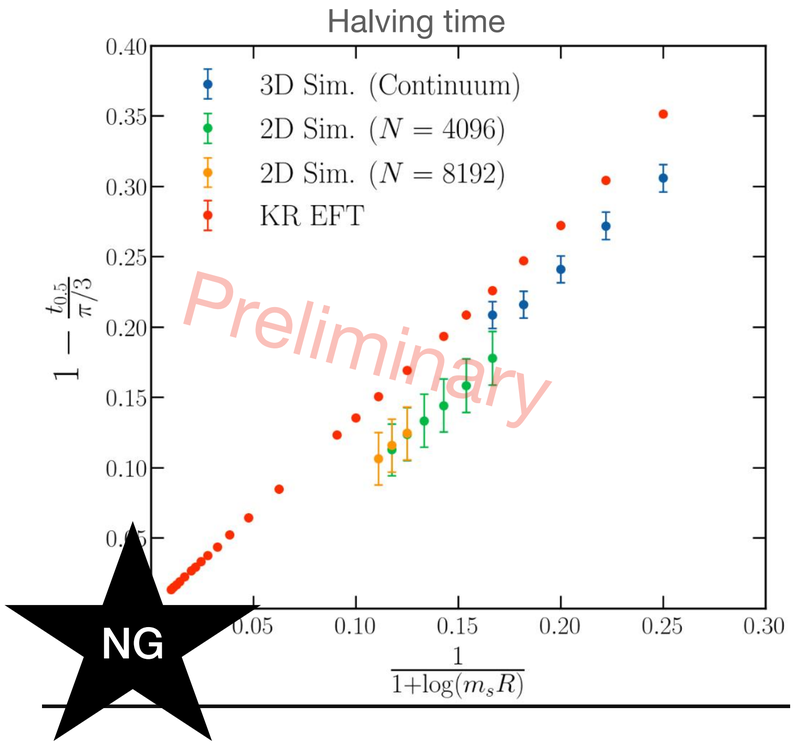

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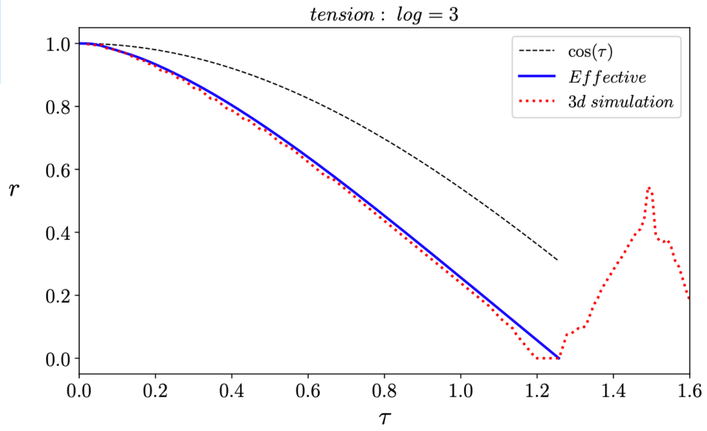

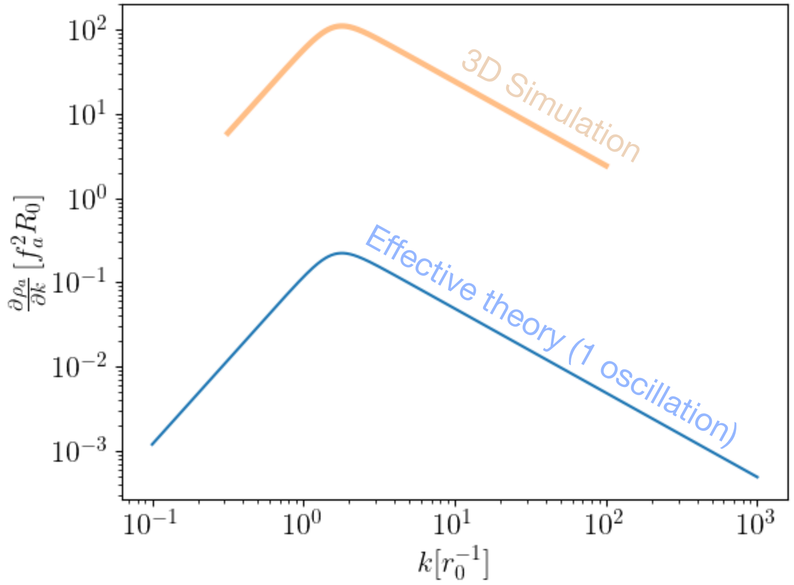

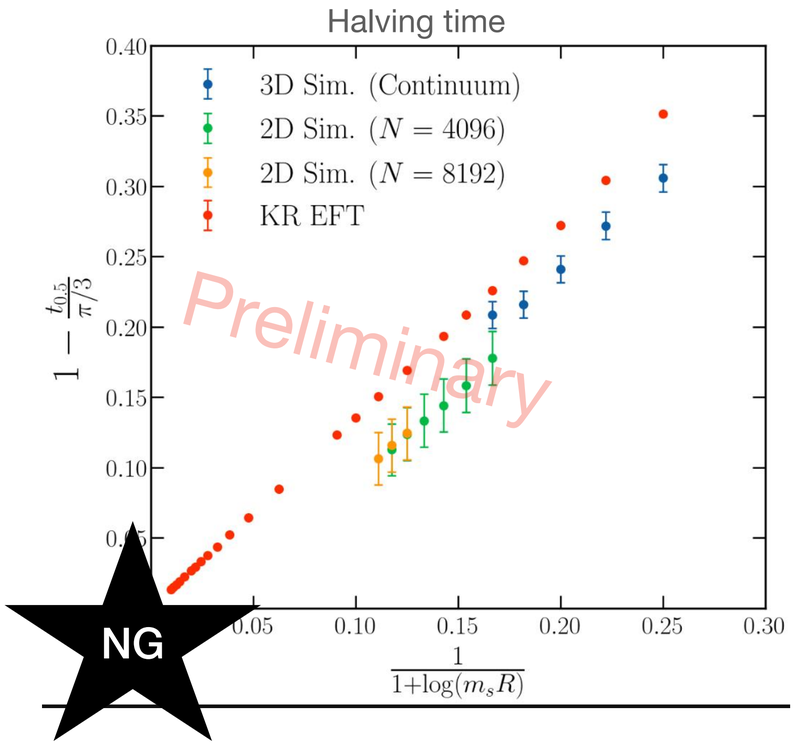

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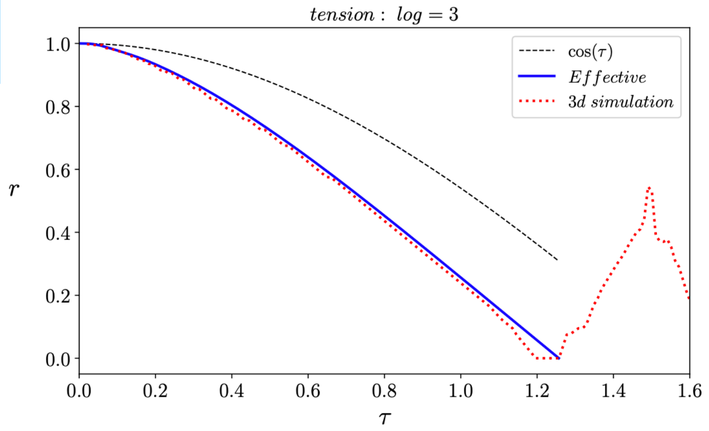

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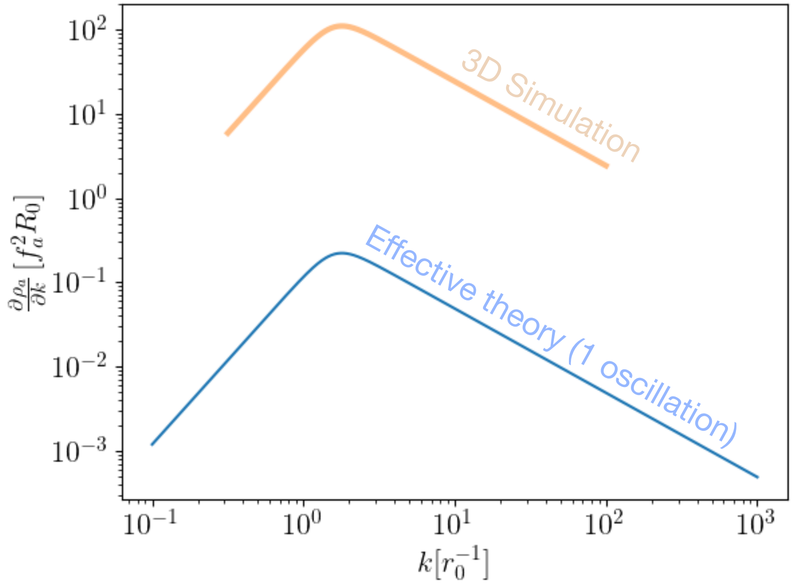

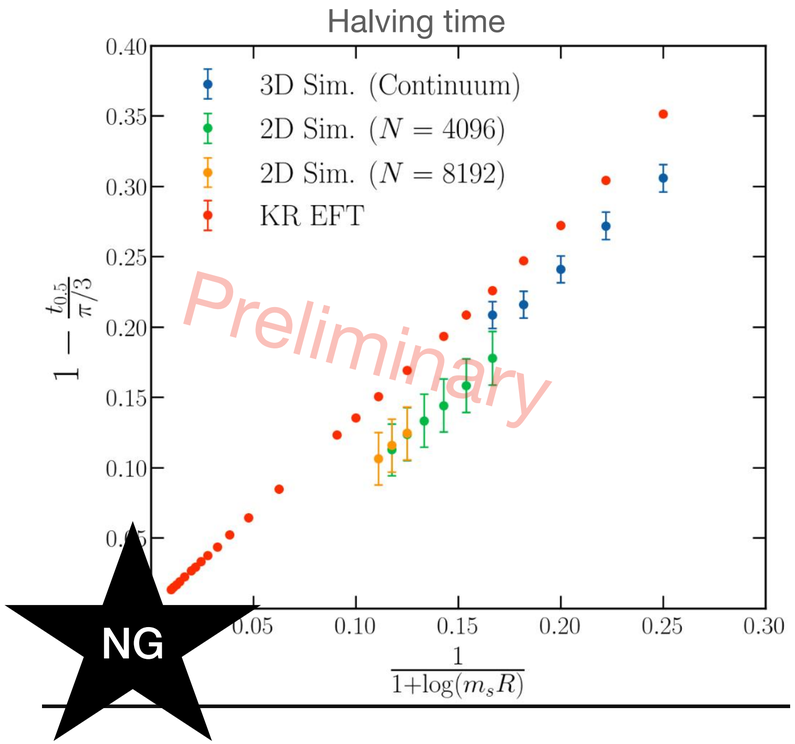

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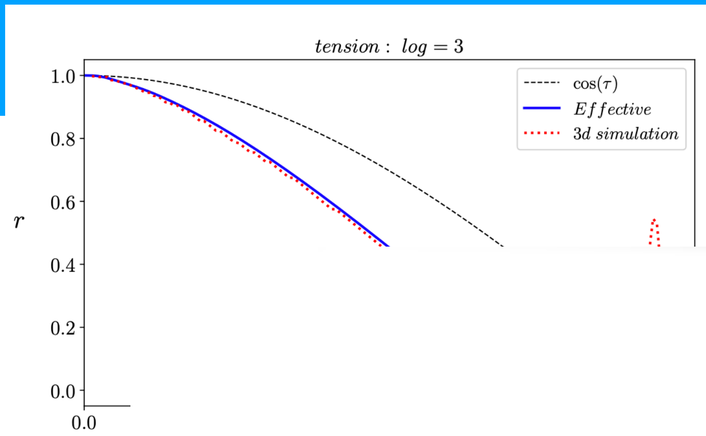

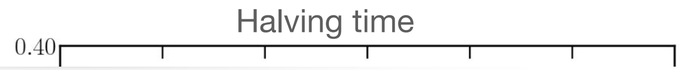

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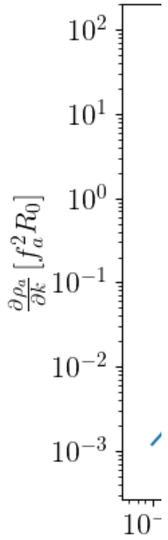

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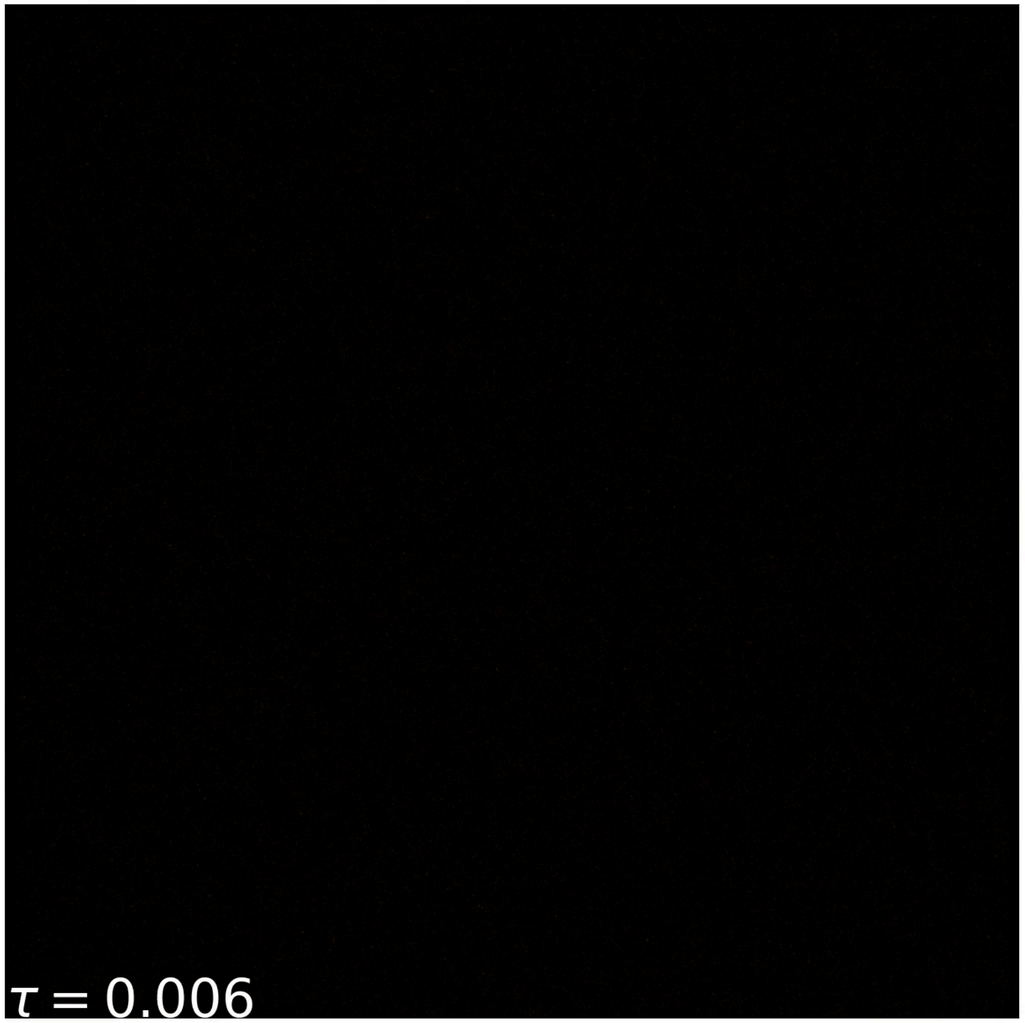
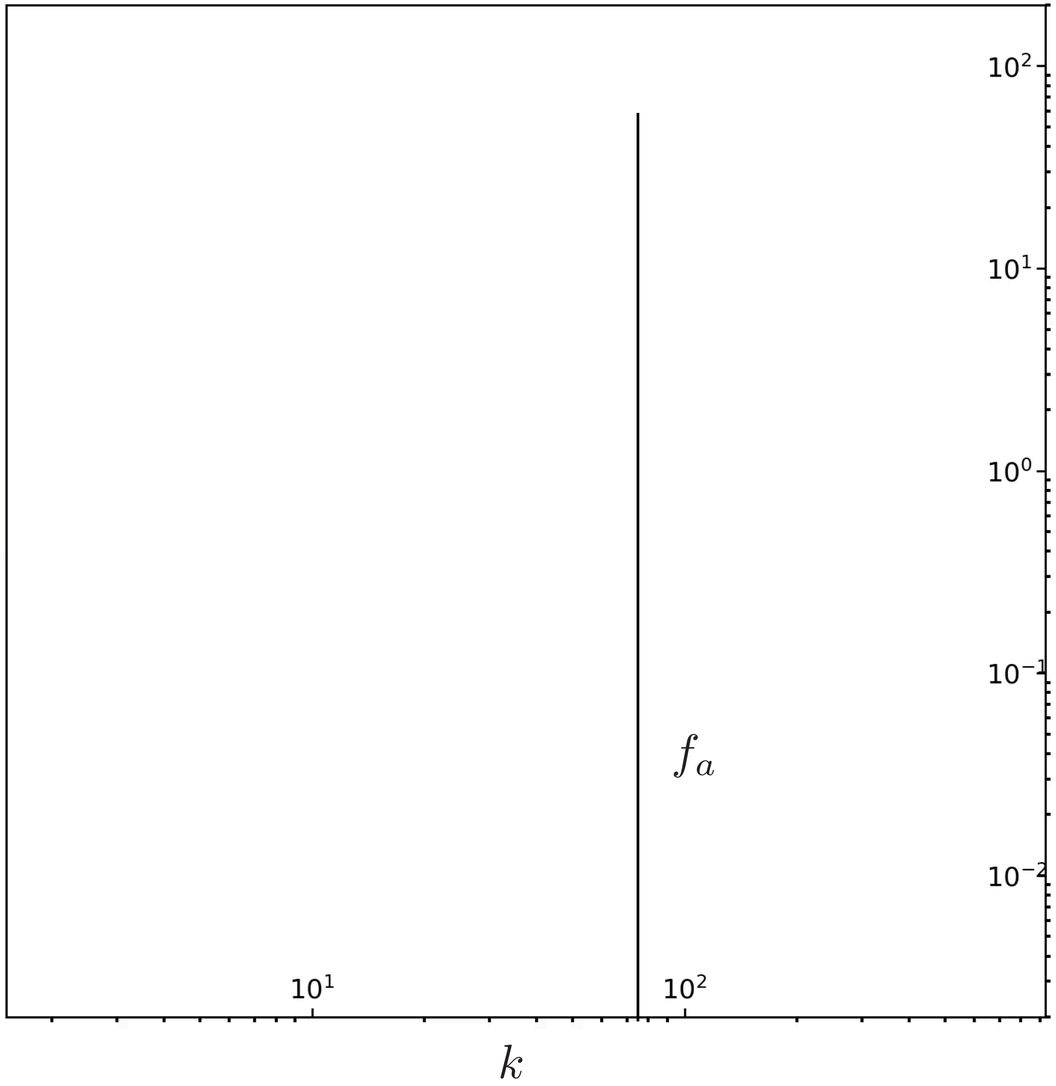
- Causality driven tracking solution identified, q estudied for the whole network by taking derivatives of spectra masking cores

Proyection plot of axion energy density (3D->2D)



$\sim \partial\rho_a/\partial k$



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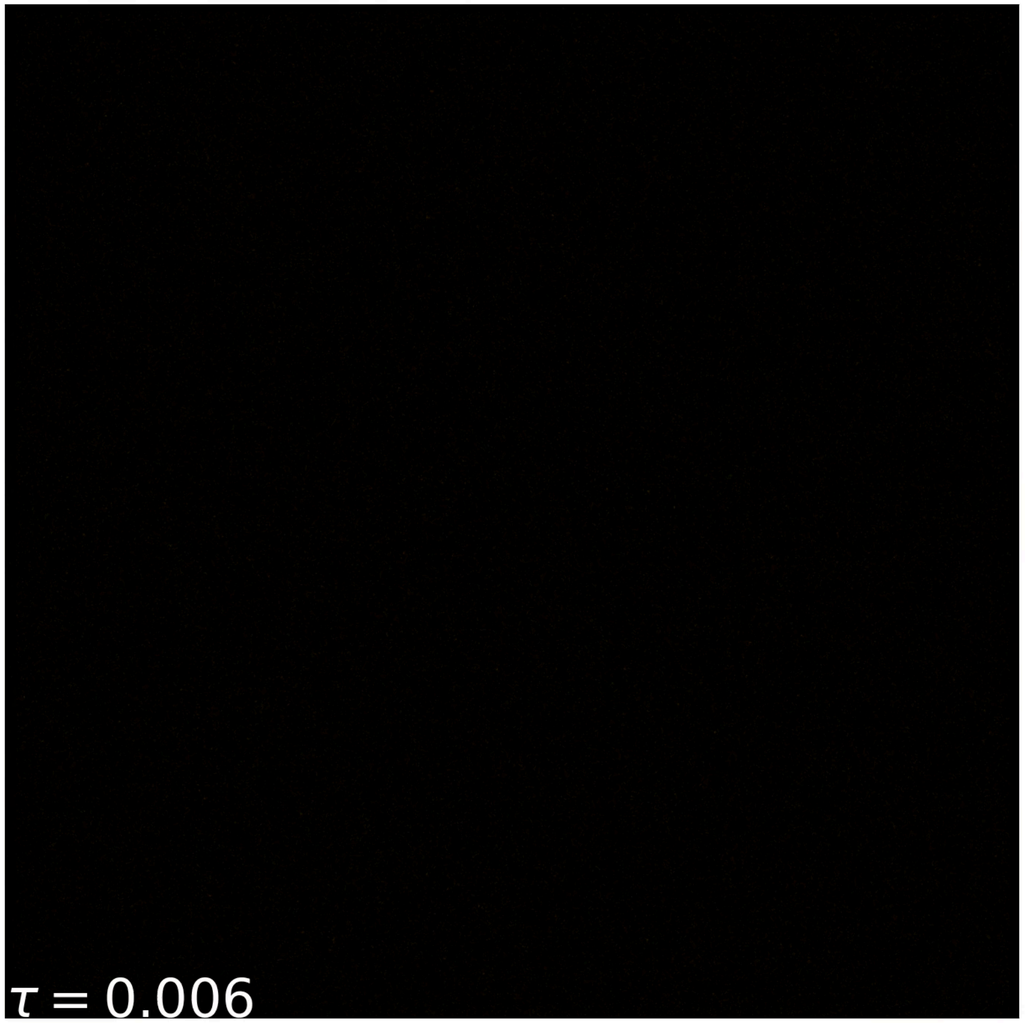

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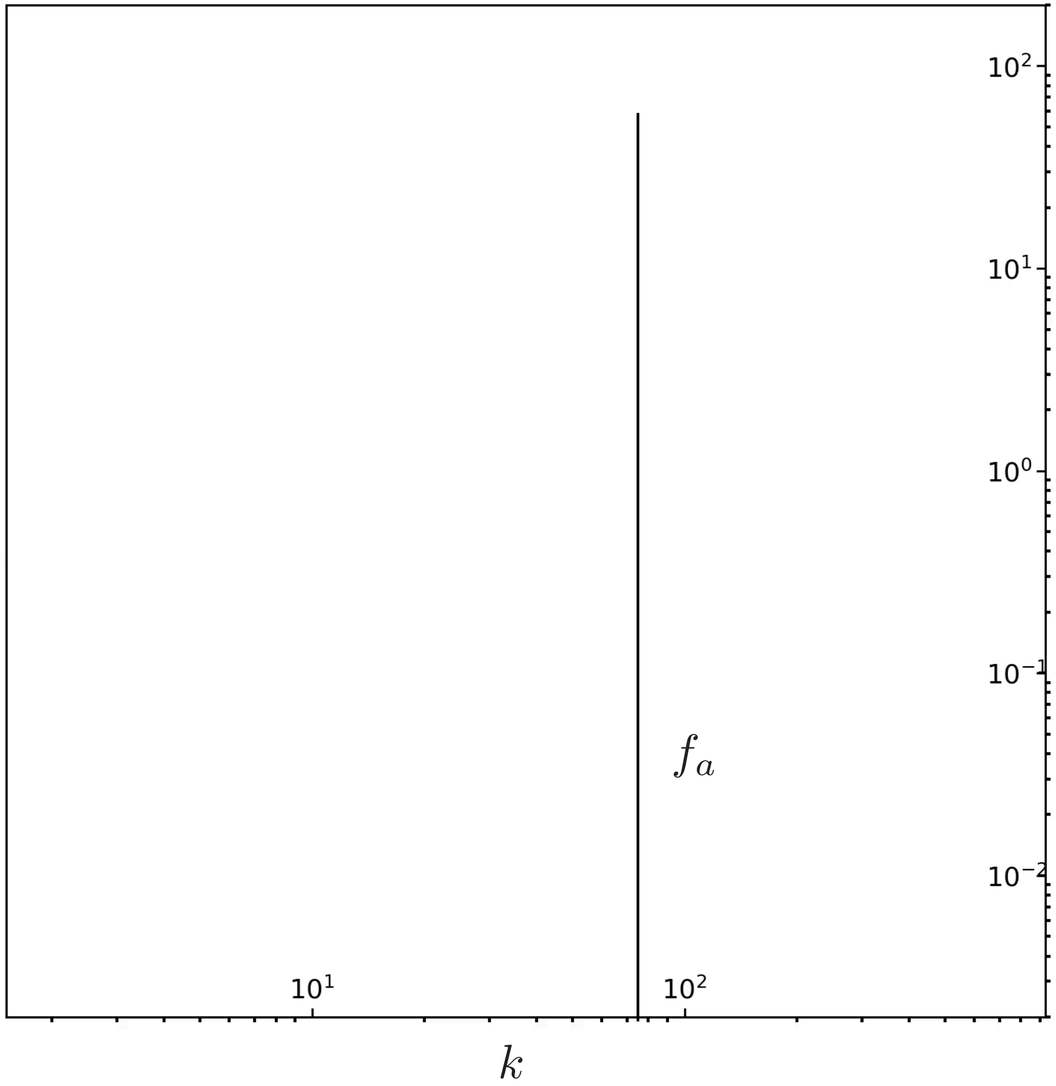
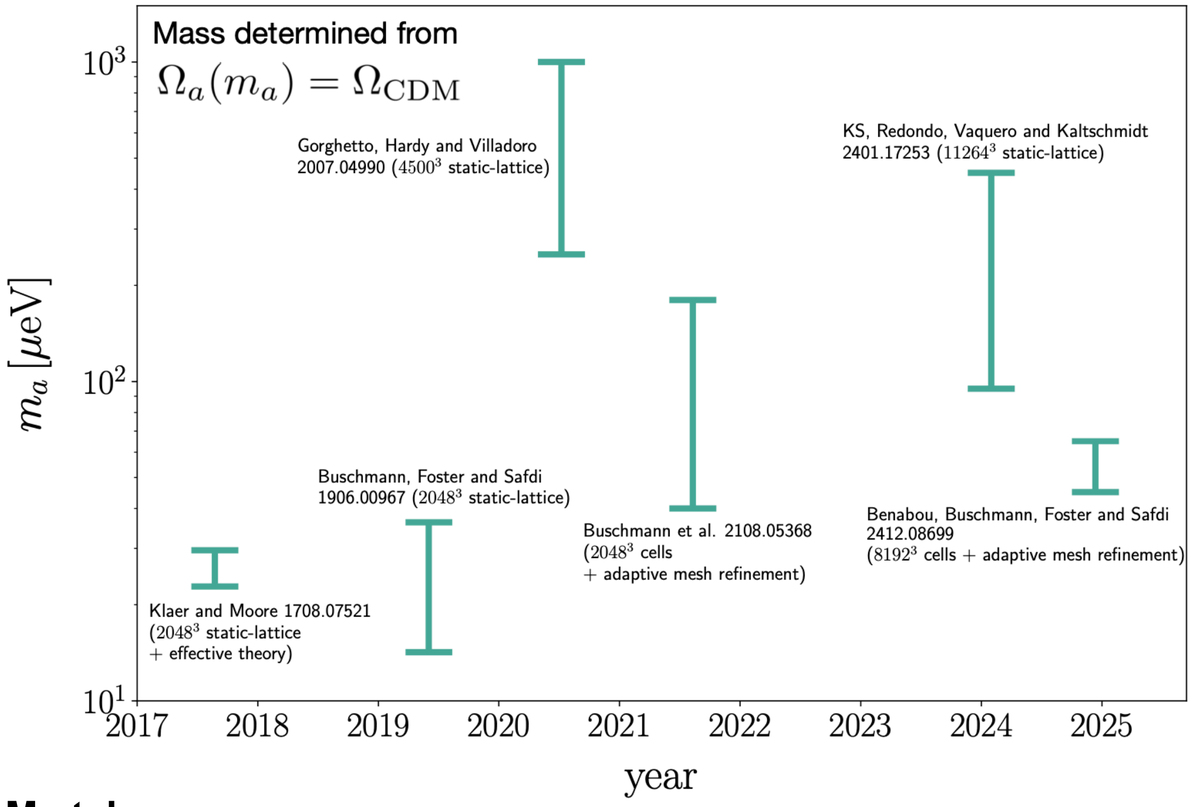


Results

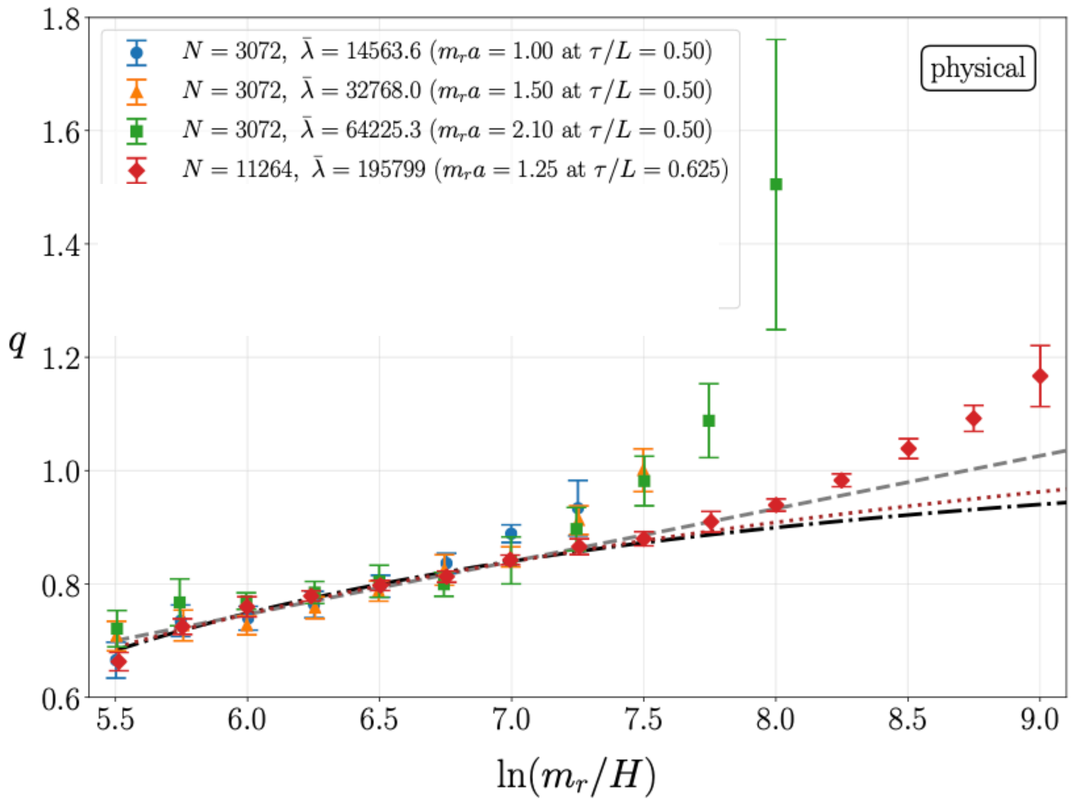
- **Summary of results from various groups**

Saikawa 25



We found Equally good fits to linearly growing q or q->1
(once discretisation effects are accounted)

[KS, Redondo, Vaquero, Kaltschmidt, 2401.17253]



- **My take:**
- **Self-fields have q~1**
- **Abandoned when loops break lead to q~1 axions + UV burst (effective q<1)**
- **1 vs growing ... ICs, statistics,**

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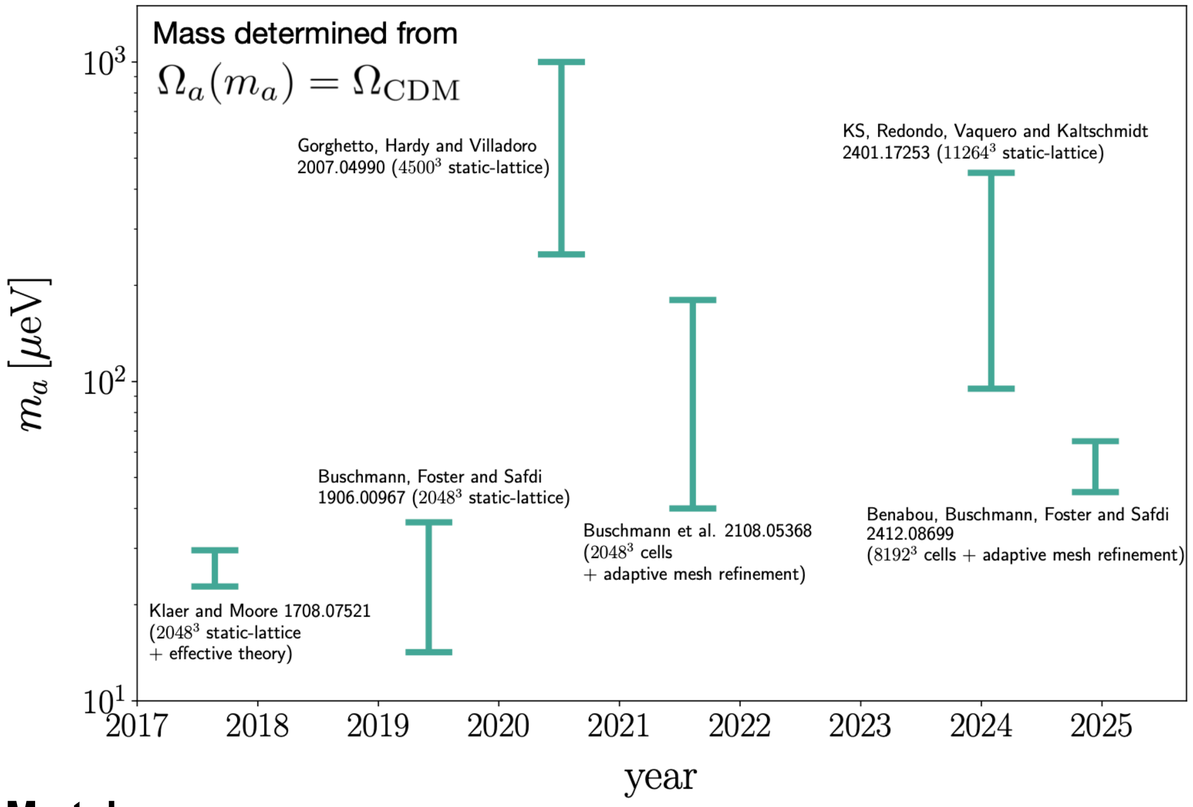

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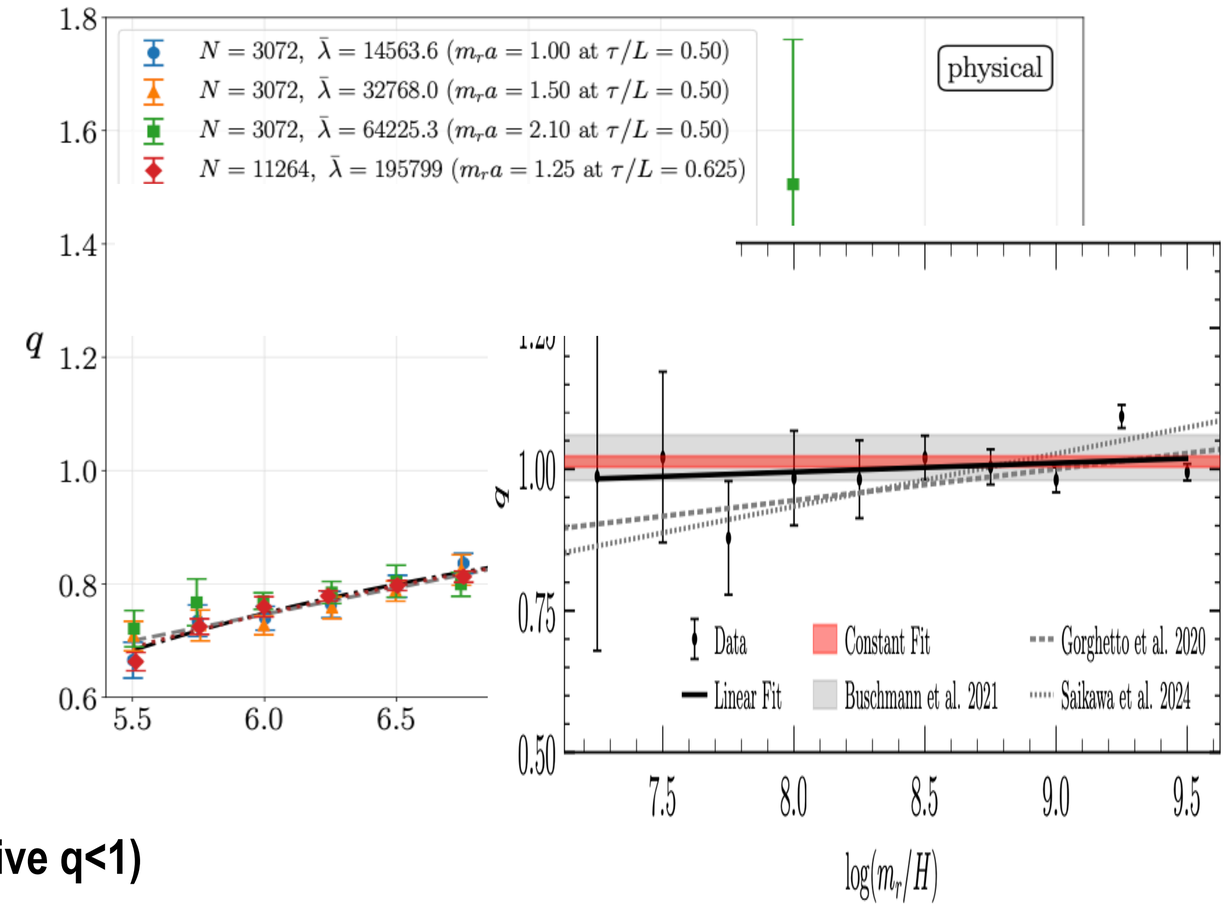

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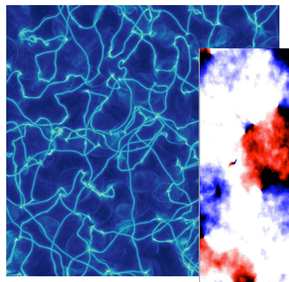
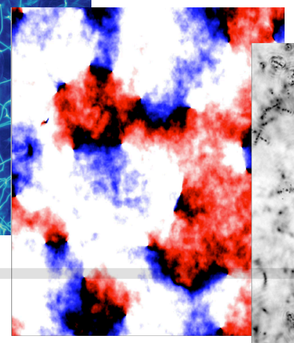
Miniclusters

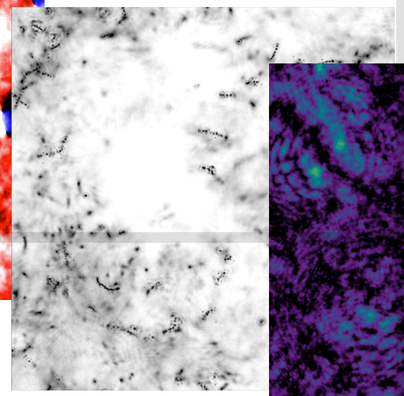
Scaling



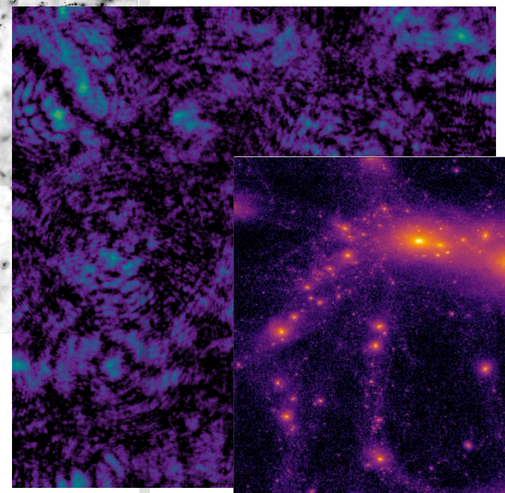
Misalignment



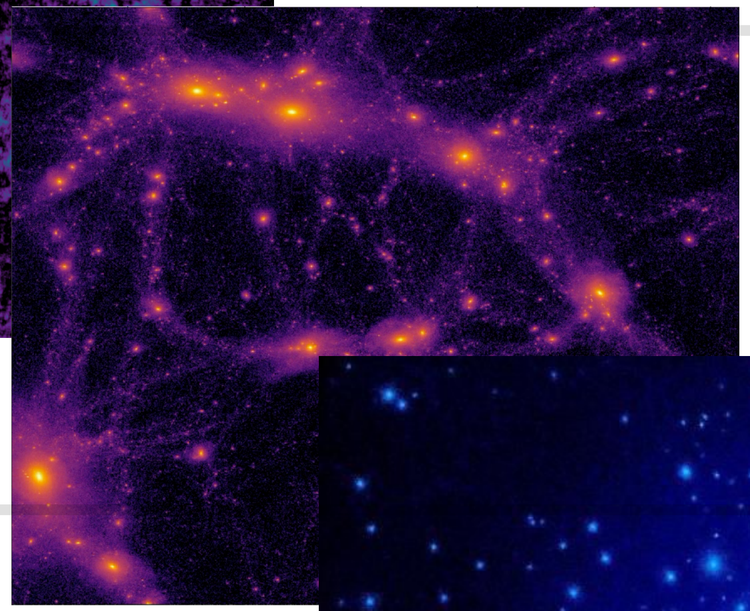
Axitons



Free-stream (RD)



Miniclusters form



hierarchical growth

Galaxy forms with MC halo

Previous work

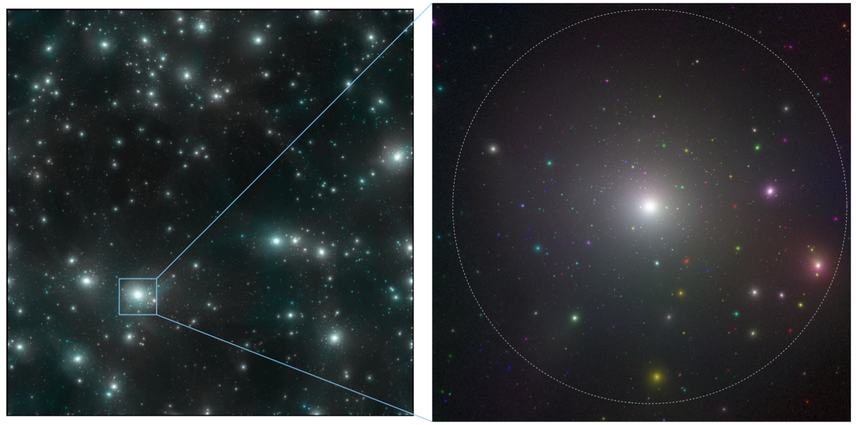
- low - tension simulations, free-streamed to z~6 -> resampled with particles. GADGET to study gravitational evolution

- Early collapse M~10^{-13} M_{sun} M~10^{-11} at equality, then hierarchical merging

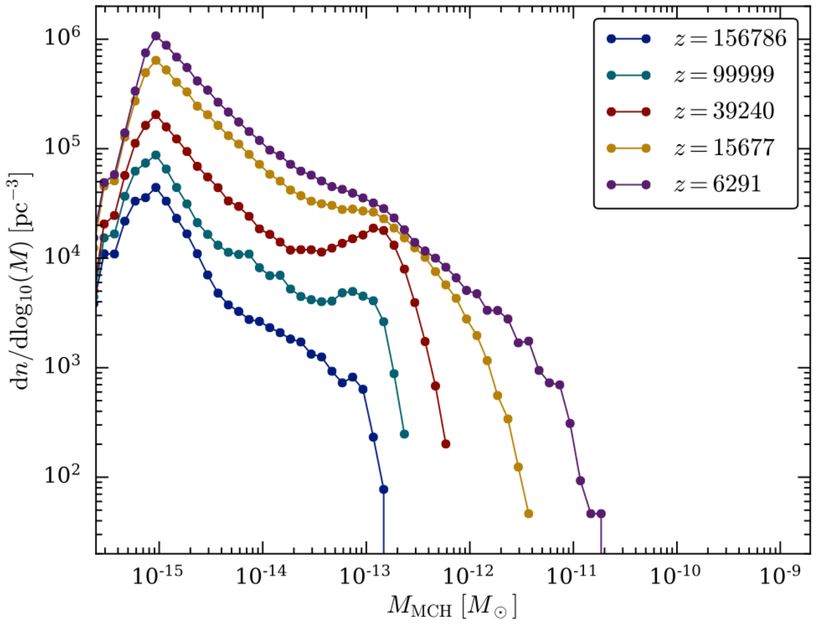
- Bound fraction ~ 80%!!!

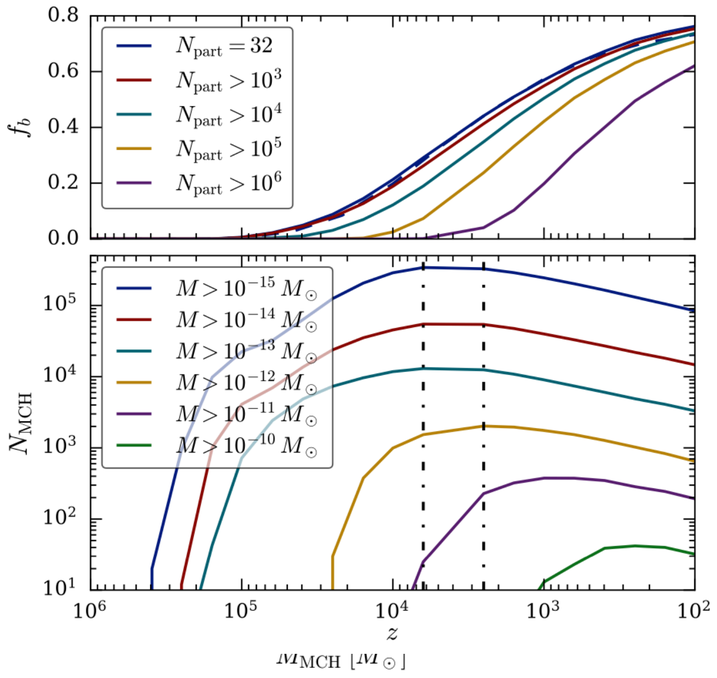
- Microlensing very hard

First simulations of axion minicluster halos

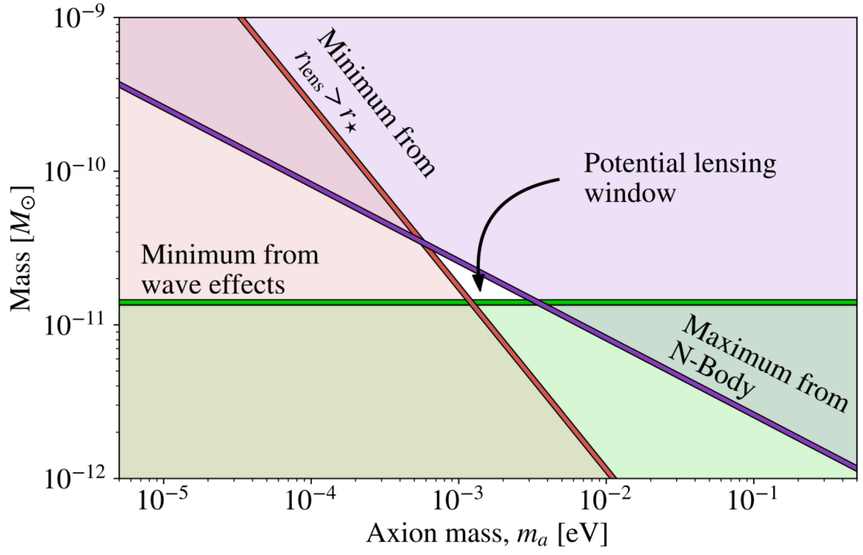


First sims...





Microlensing

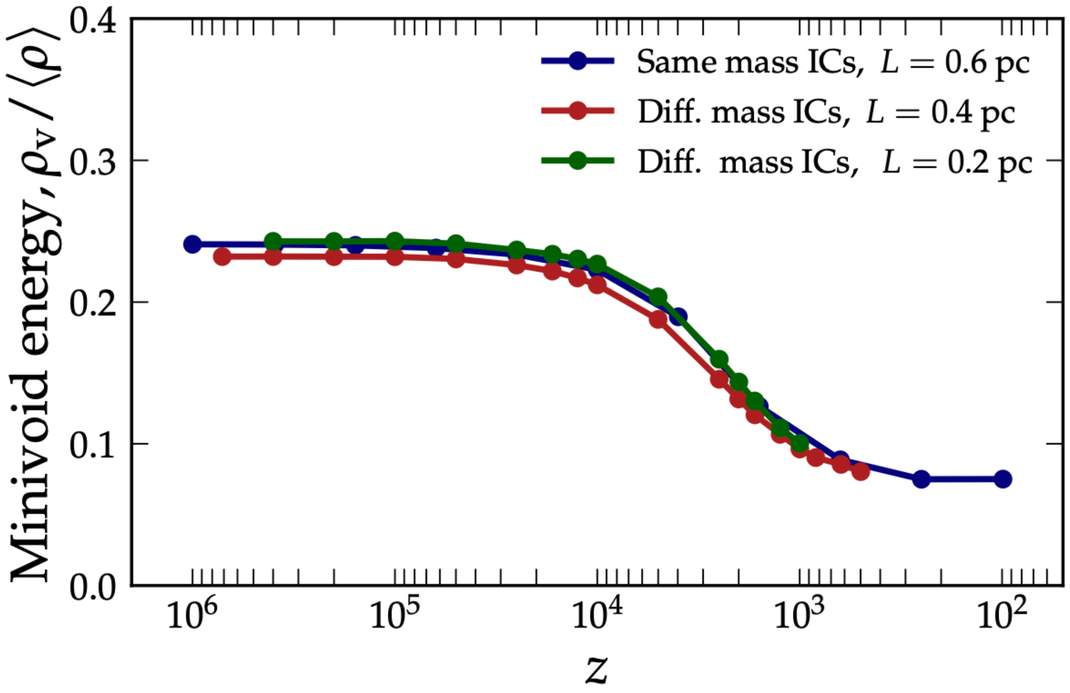


minivoids

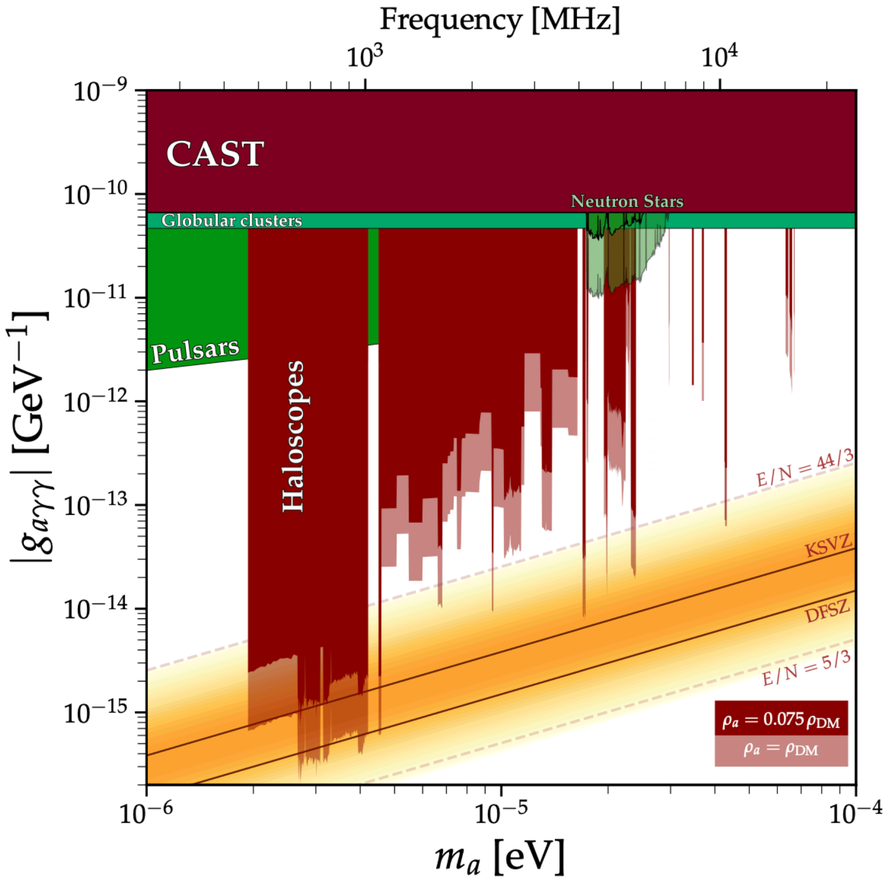
- 80% of the axions in small MCs is very bad news ... what is the void density relevant to experiments??

- voids defined to be delta<-0.7, average density converges to ~8%, 80% of the volume

- Experiments in Post-inflation scenario are less sensitive?



rescaling sensitivites of haloscopes



@ galaxy formation

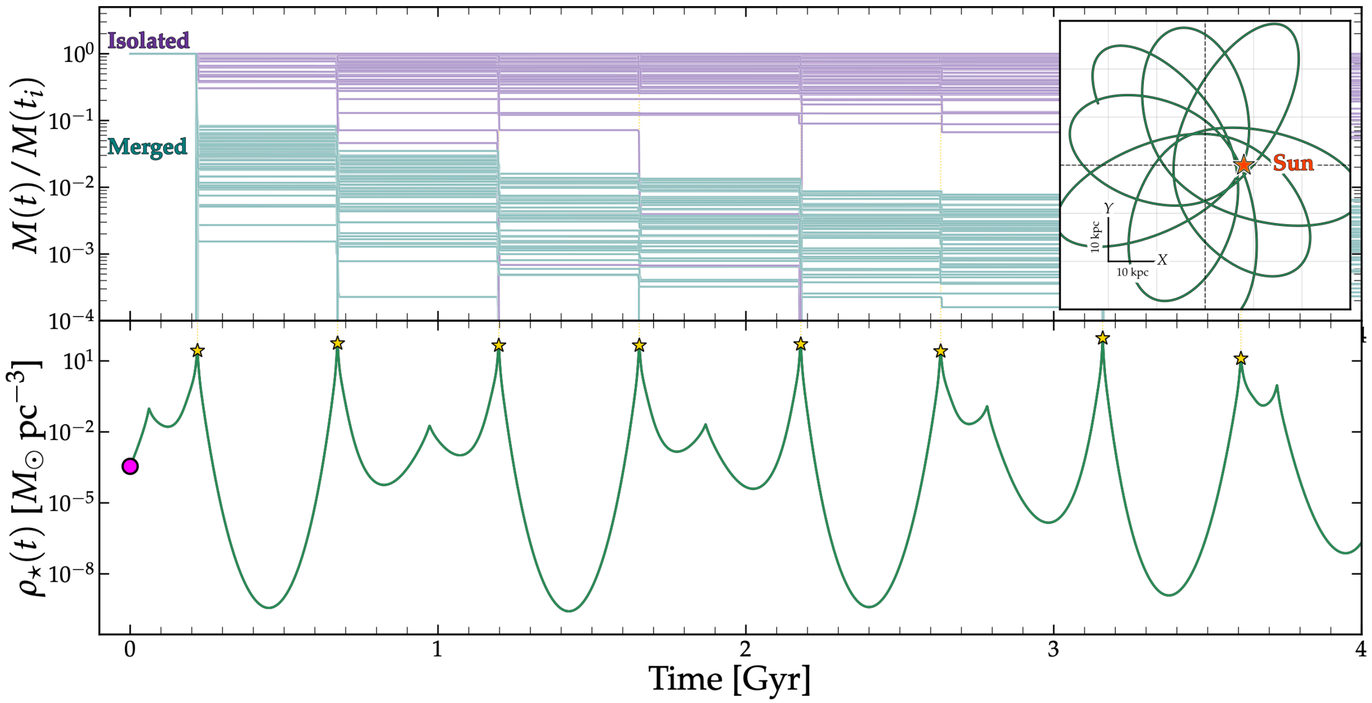
- what is the expected distribution of axion DM today?

- MCs extremely difficult to encounter ...

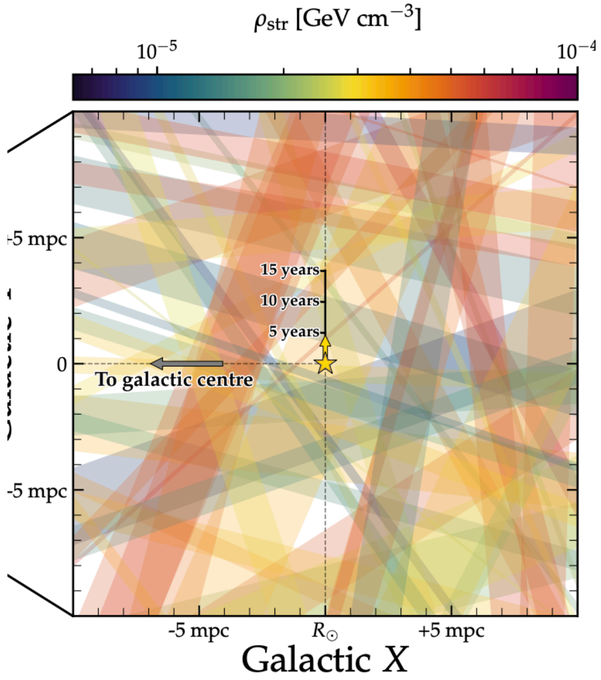
- MCs can get disrupted in stelar encounters forming DM streams

- Montecarlo evolution of streams with initial distributions from simulation

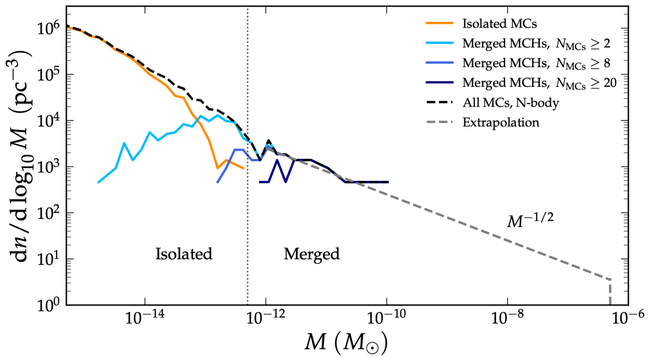
isolated MCs tend to survive, more massive (bigger, less dense) merged halos get disrupted



the local neighbourhood is expected to have ~1000 faint streams
and the average density is 70-90% from the homogeneous expectatio



MCs have two populations, MCs and MChalos



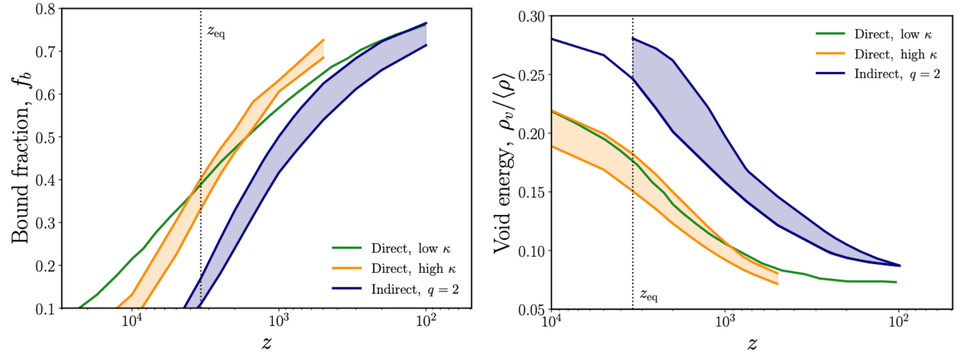
Uncertainties in axion spectrum translate into minicluster uncertainties

- 3 types of early Universe simulations: low tension (log~7) high tension (Moore) and extrapolated axion configuration using q=2

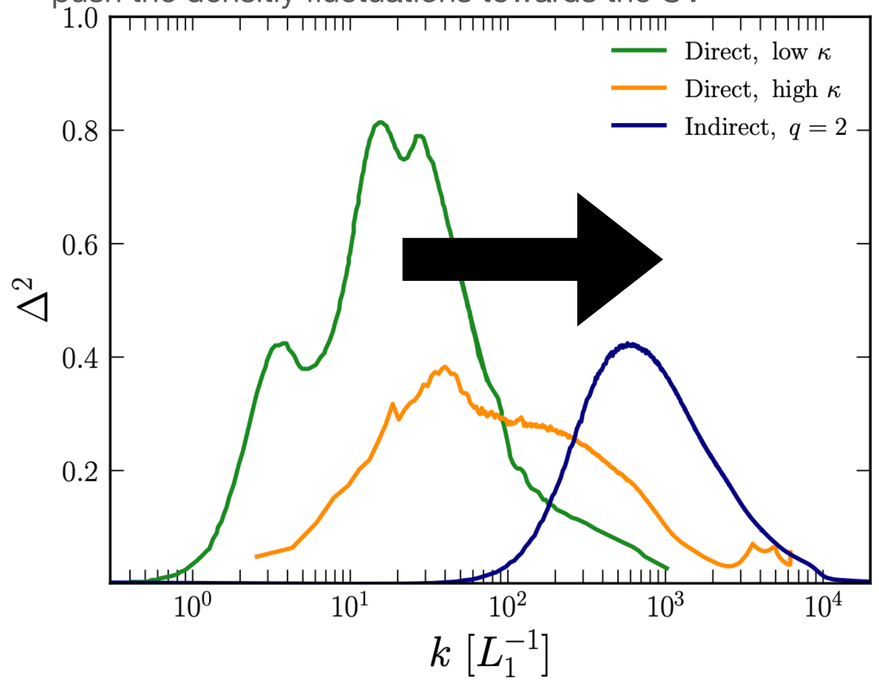
- Bound fraction, void density does not change

- q>1, xi>>13 push fluctuations towards UV (up to 2 ord. of mag!)

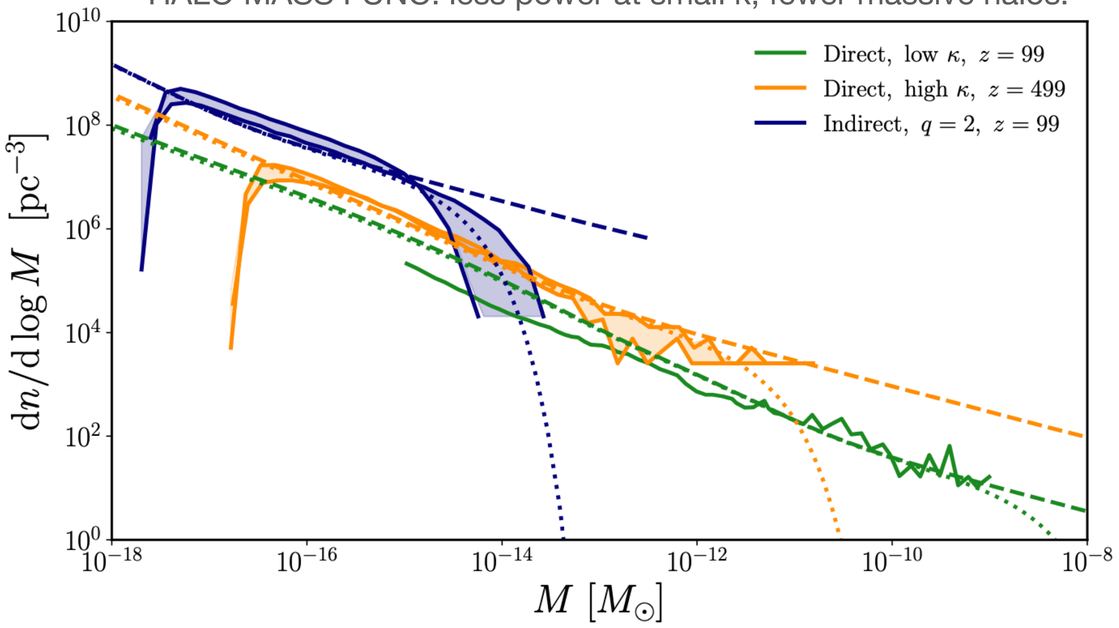
- halos have lower masses, less microlensing likely!



High density networks and non-linearities if q>1 push the densitiy fluctuations towards the UV



HALO MASS FUNC: less power at small k, fewer massive halos!



Miniclusters in the pre-inflation scenario

- In both, large misalignment and kinetic misalignment scenarios, small density fluctuations can grow exponentially

Arvanitaki, Co, Eroncel,etc...

- Adiabatic fluctuations in KM prop. to initial velocity

- Amplification at "trapping" depends on initial angle too!

- small fA requires large velocity -> large amplification > miniclusters

- density fluctuations O(1) (fragmentation of the condensate)

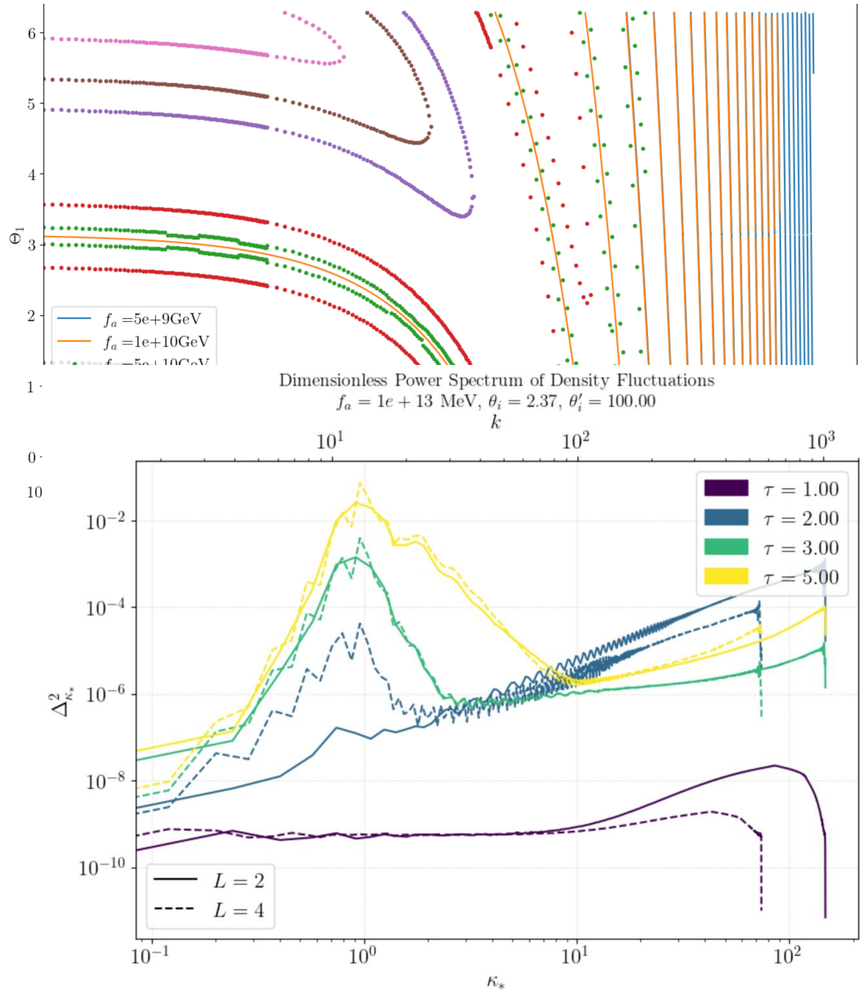
- @ smaller scales than typical misalignment, similar to q>1 scenario!

- microlensing not easier...

- might be difficult to disentangle both scenarios from MCs

- axitons and domain walls can form too

The correct relic density can be obtained for several values of initial misalignment angle and velocity



Conclusions

- Axions (and similar ALPs) are well motivated DM candidates

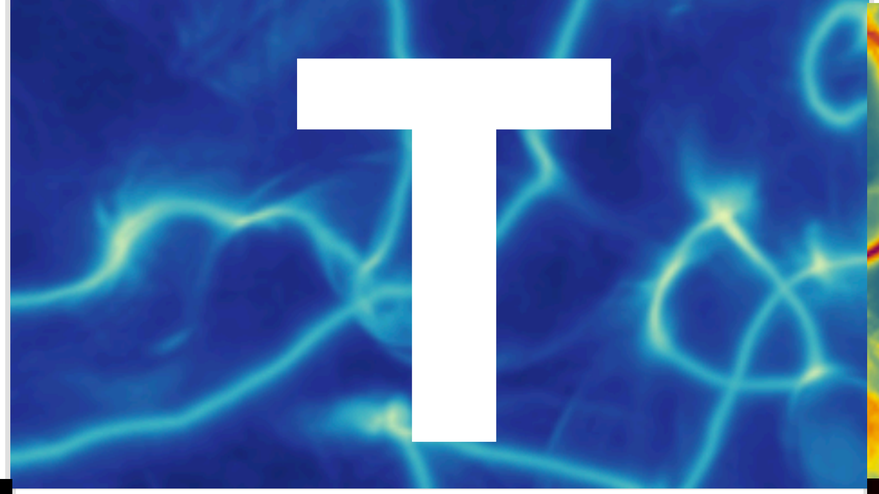
- We can predict the axion DM mass in the pre-inflationary scenario if we solve the axion string radiation problem

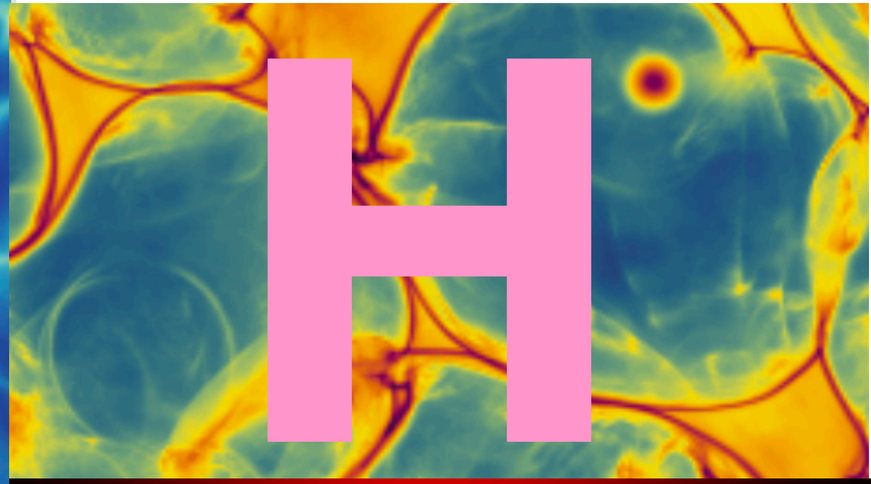
- Latest simulations point to O(10) uncertainty

- Minicluster sizes have O(100) uncertainty in mass, but other very rubust properties

- Miniclusters in the pre-inflationary scenario can have similar phenomenology, but always at relatively large masses.

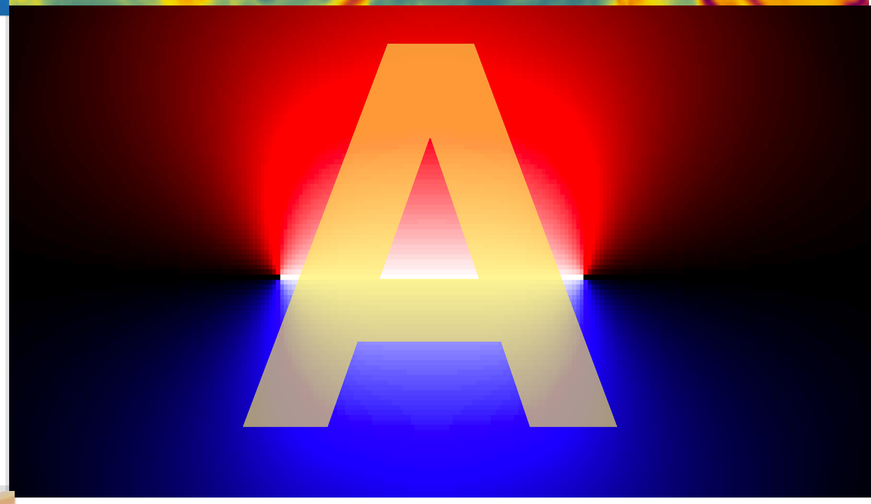
Axion stringS





Javier Redondo
23 September 2025,
20thPatras Workshop
La Laguna Tenerife

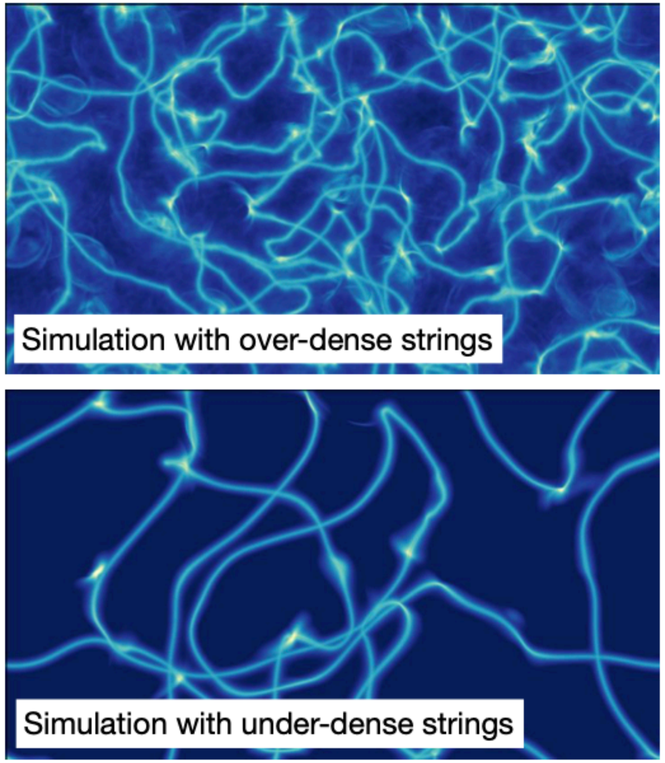
&

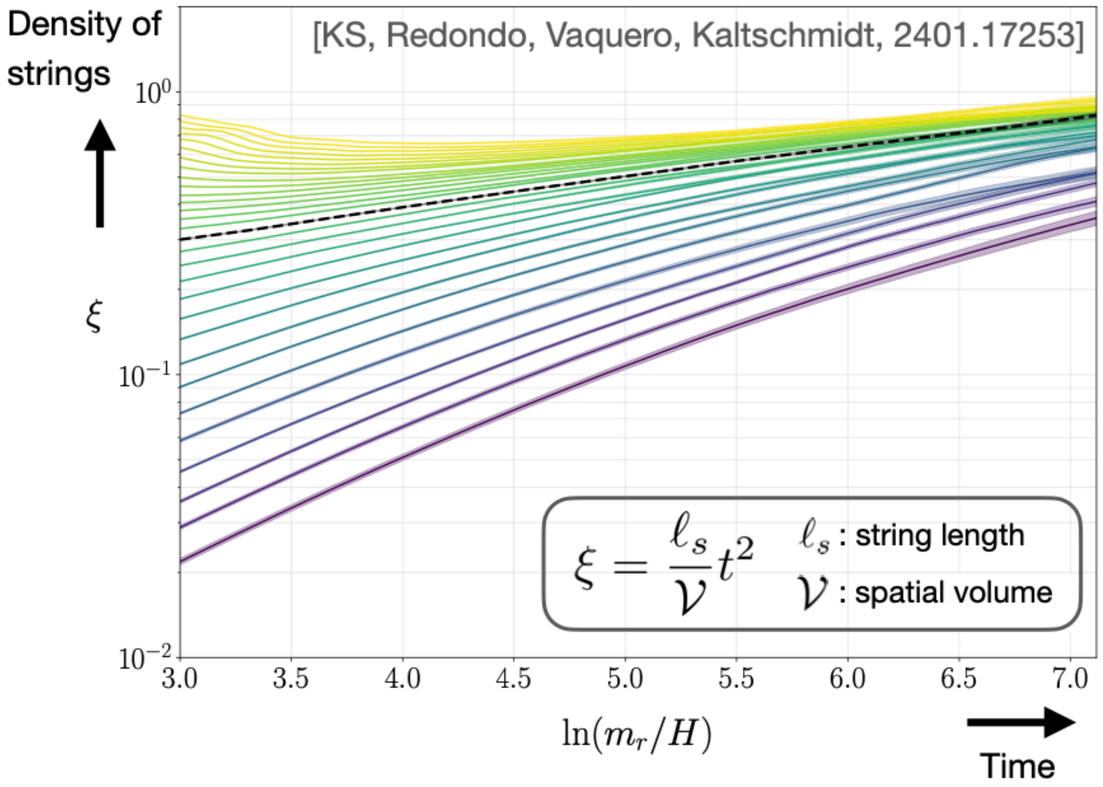


Mini clusterS

Vacap

Atractor

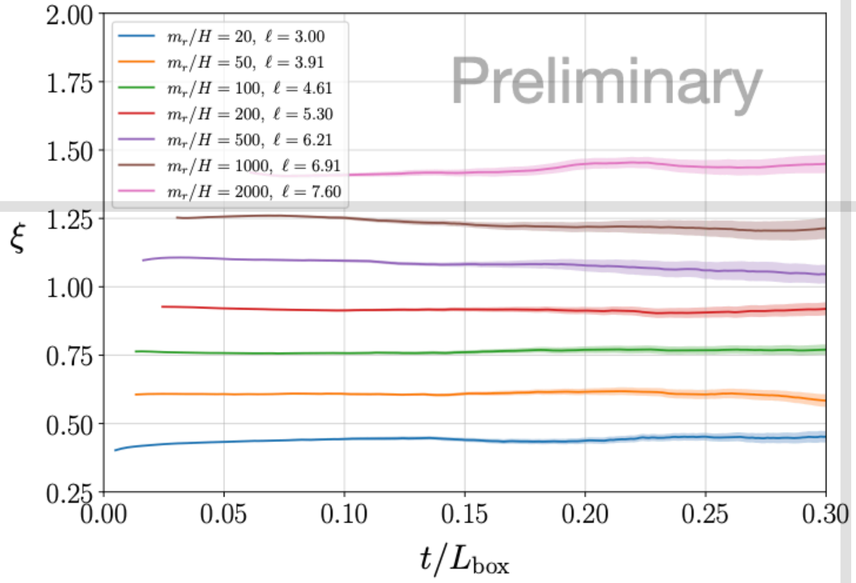

Simulation with over-dense strings
Simulation with under-dense strings

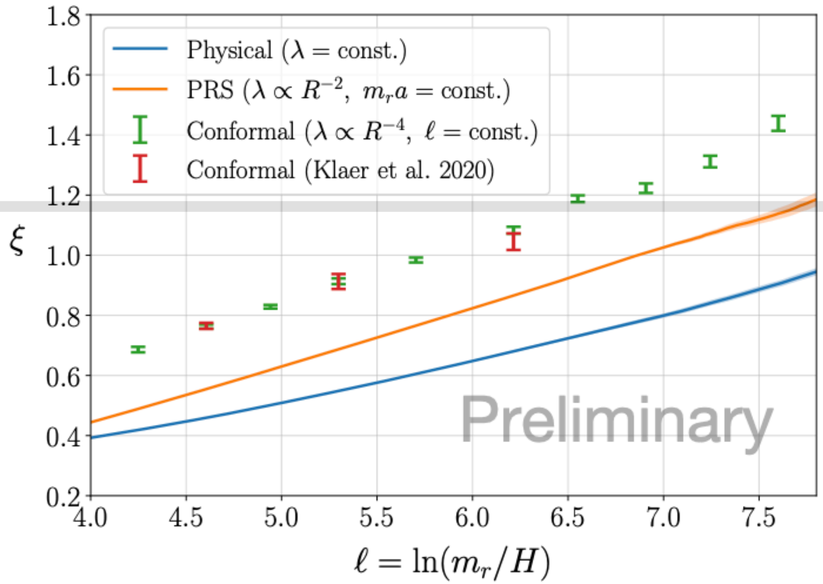

Density of strings
[KS, Redondo, Vaquero, Kaltschmidt, 2401.17253]
10^0
ξ
10^{-1}
10^{-2}
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
$\ln(m_r/H)$
Time
$\xi = \frac{\ell_s}{\mathcal{V}} t^2$
ℓ_s : string length
$\mathcal{V}$: spatial volume

Conformal networks

- **Make log constant by** $m_s \propto 1/t$
- **log dependent scaling!**

[Klaer, Moore, 1912.08058; KS, Redondo, work in progress]





- **model predicts Phys. and PRS atractors**

[KS, Redondo, Vaquero, Kaltschmidt, 2401.17253]

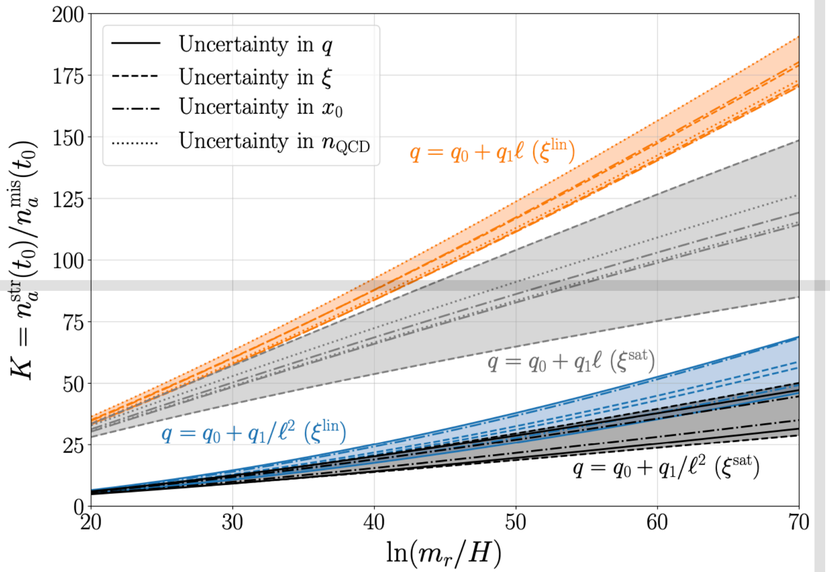
$$\frac{d\xi}{dt} = \frac{C}{t}\left(\xi_c(\ell(t)) - \xi(t)\right)$$

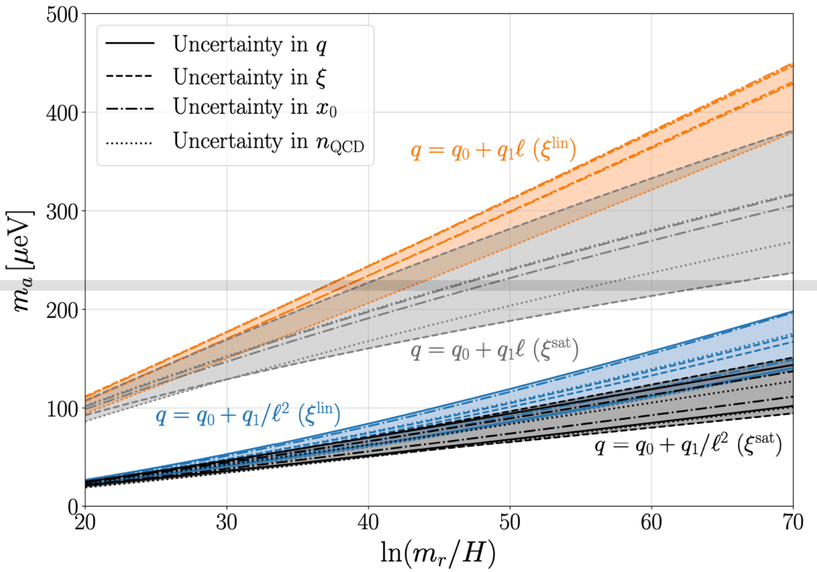
$$\Rightarrow \quad \xi \simeq \xi_c(\ell) - \frac{f}{C}\frac{d\xi_c}{d\ell} \qquad f = \begin{cases} 1 & \text{(physical)} \\ 1/2 & \text{(PRS)} \end{cases}$$

tracking solution

DM mass prediction

- different assumptions
  different extrapolations





[KS, Redondo, Vaquero, Kaltschmidt, 2401.17253]