WGII

WISPs Dark Matter and Cosmology

State of the art

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COST21106 kick off meeting

LNF 23-24/02/2023

CA21106

Dep. Theoretical Physics
Universidad de Zaragoza

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Our Working group 2

WG 2: WISPs Dark Matter and Cosmology.

... WISPs as dark matter candidates ...

... Production mechanisms ...

... Axion Thermal mass (lattice, ChiPT) ...

... Cosmic string decays ...

... Effects on Large and small-scale structure ...

... hot DM (lattice, ChiPT) ...

WISPs = Weakly-interacting slim/sub-eV Particles*

**not weak like electro-weak*

WISPs as dark matter candidates

- WISPS are **natural candidates for CDM**

  low mass, need to be feebly interacting, thermal populations subleading*, **bosons***..
  axions (QCD&ALP), pseudo Nambu-Goldstones, U(1) bosons, ... moduli, MCPs, sterile nu's..

- They need **non-thermal production mechanisms**

  WISPs are/can be **sensitive to initial conditions** and **very early cosmology** (good and bad
  (thermalisation erases effects of initial conditions in cases like WIMP DM)
  vacuum realignment, topological defects decay, vacuum fluctuations ...

- WISPy DM might have disctintive **effects at small cosmological scales**

  wave-effects, **miniclusters**

- They are often **decaying DM**

  low mass, feebly interacting nature makes **loooong lifetimes**
  some **opportunities for LM detection**

Production mechanisms

- Vacuum realignment

1 - Initial conditions are not on the vacuum state

2 - WISPy potential drives the field to oscilate around it from times t~ 1/mass

3 - oscillations are coherent state of particles with EOS <w>~0

(if ICs are sufficiently homogeneous ... typically k~H)

1 - ICs vary with cosmology model ...

pre-inflation (~homogenous field)
stochastic axion (large vacuum fluctuations) [Graham 2016]
kinetic misalignment (~large field velocity)
hill-top ICs

2 - well understood

... in the linear regime (when fluctuations are small and linear)
not so in non-linear regimes (need some more numerical sims, resolution issues, axitons)

3 - well understood

*except perhaps the issue of Sikivie's Bose-Einstein condensation and its effects on galactic scales**

Production mechanisms

- **Decay from topological defects**

  - *topological defects have dynamics on O(1/H) scales that produce k~H axions*
  - *they require numerical simulations for precision*
  - *theoretical models can be sometimes conflicting*

- **global cosmic strings**
- **domain walls**
- **other similar structures?**

  - *Monopoles*
  - *Bubbles from phase transitions*
  - *??*

- **Mostly studied in the case of the QCD axion**

  - *ALP generalisation is easy (some works already)*
  - *Some other scalars like relaxions*
  - *what about other WISPs? hidden photons, MCPs … ? not much*

  - *generalisation to non-standard cosmologies*

Production mechanisms

- Thermal production

- can be naturally subleading
- can still produce hot-warm dark matter effects (suppression PS at high-k, etc...)
- Computationally easy in perturvative regimes

- Uncertainty from early Universe

- model dependency (more particles, d.o.f)
- entropy production?
- treat on a model basis
- CMB4 detection of Neff, window to new d.o.f.

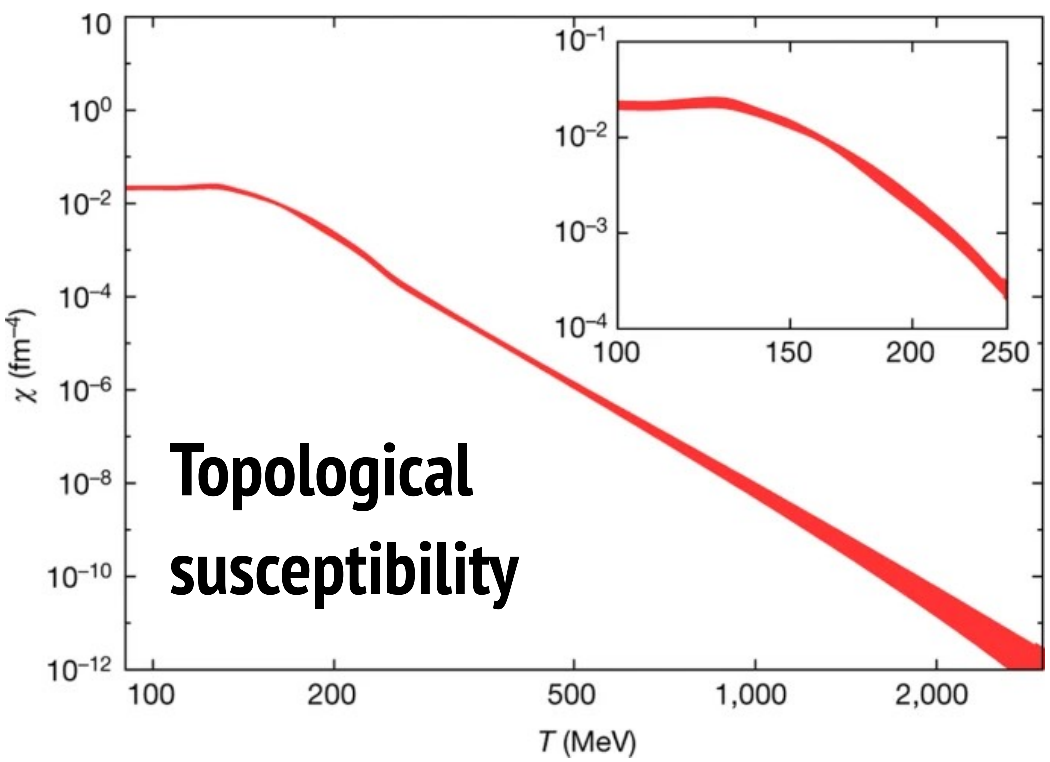
- Uncertainty from non-perturbative QCD

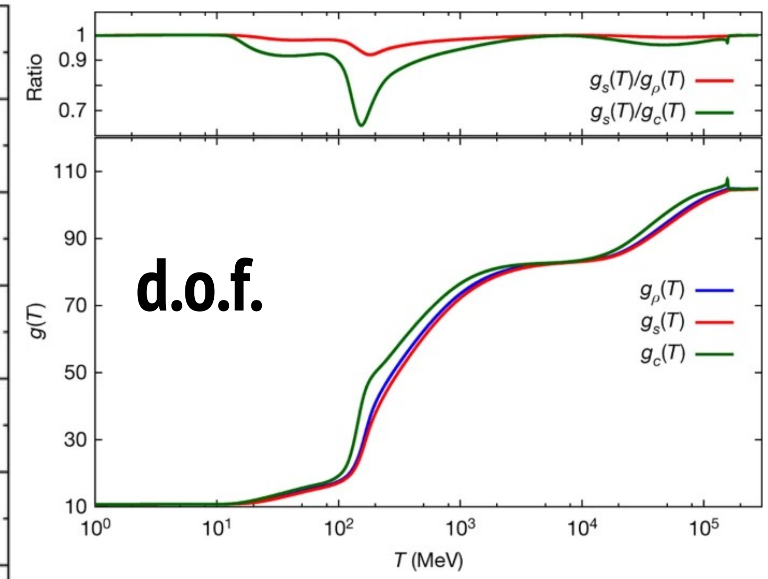
- QCD axions in the ~ eV mass regime decouple during the QCD cross-over T~ 150MeV where perturvative calculations are not reliable
- lattice QCD input could be useful
- region is borderline-excluded

Axion thermal mass

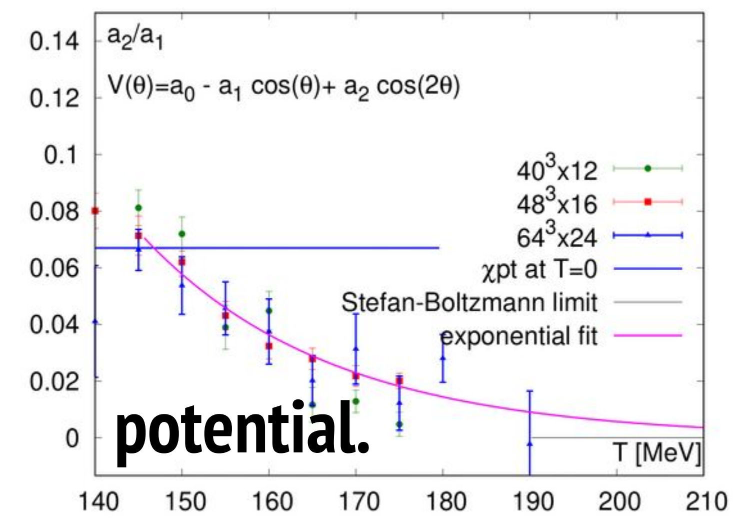
- Lattice input for QCD axion cosmology

Borsanyi 16

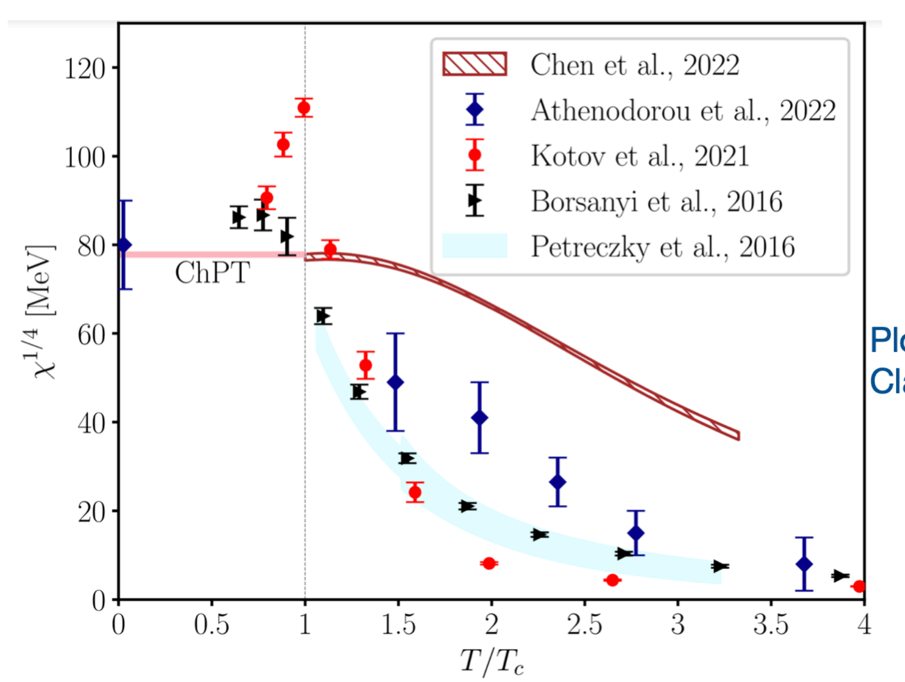




Borsanyi 22



- Different groups do not converge (topology at high T is extremely resource consuming)



Plot by
Claudio Bonanno

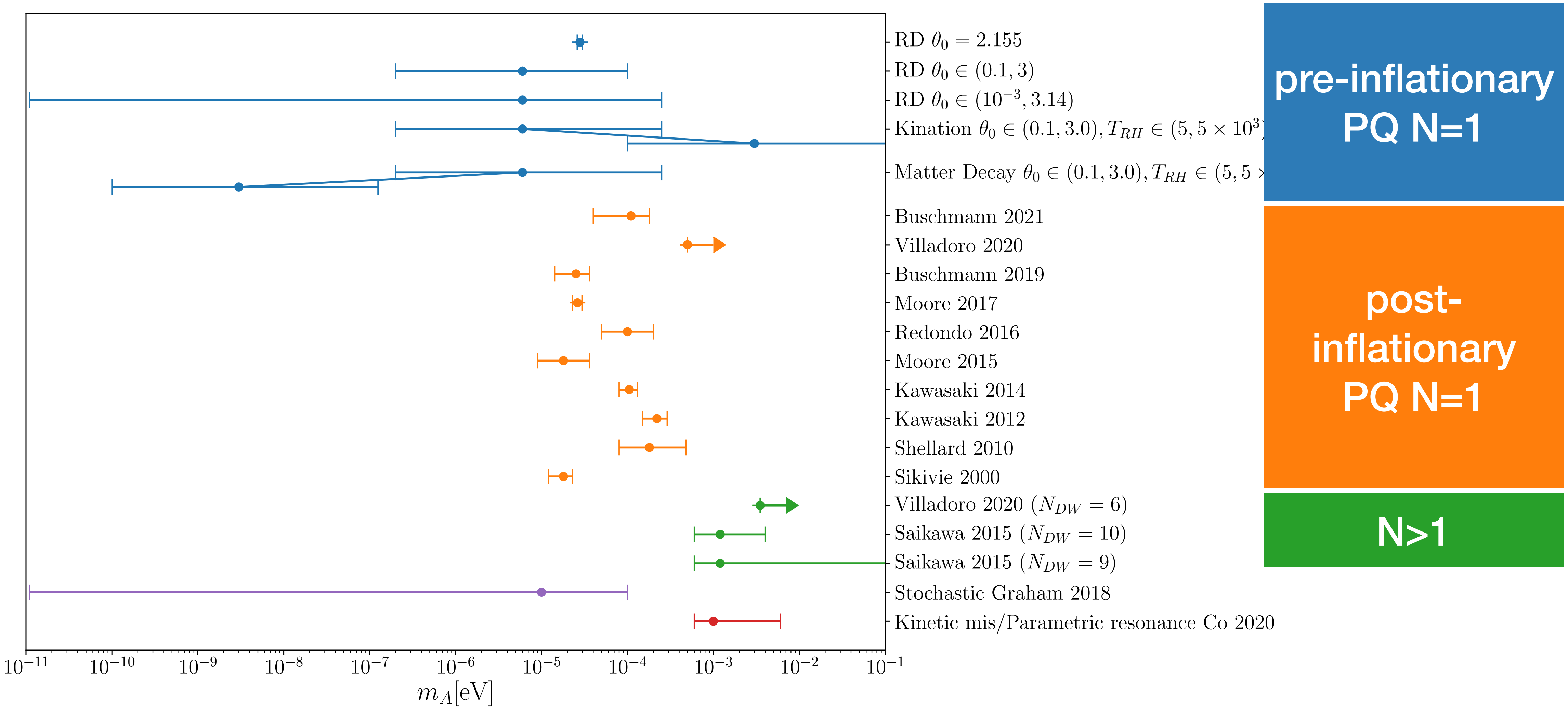
...Lattice issues: Results not entirely settled; extrapolation to high temperature regime may be subtle and needs further studies...

Lombardo 23

Cosmic string decays (axion DM mass)

- Axion DM mass from theory could/should (not) guide the experiment

Different Cosmo scenarios

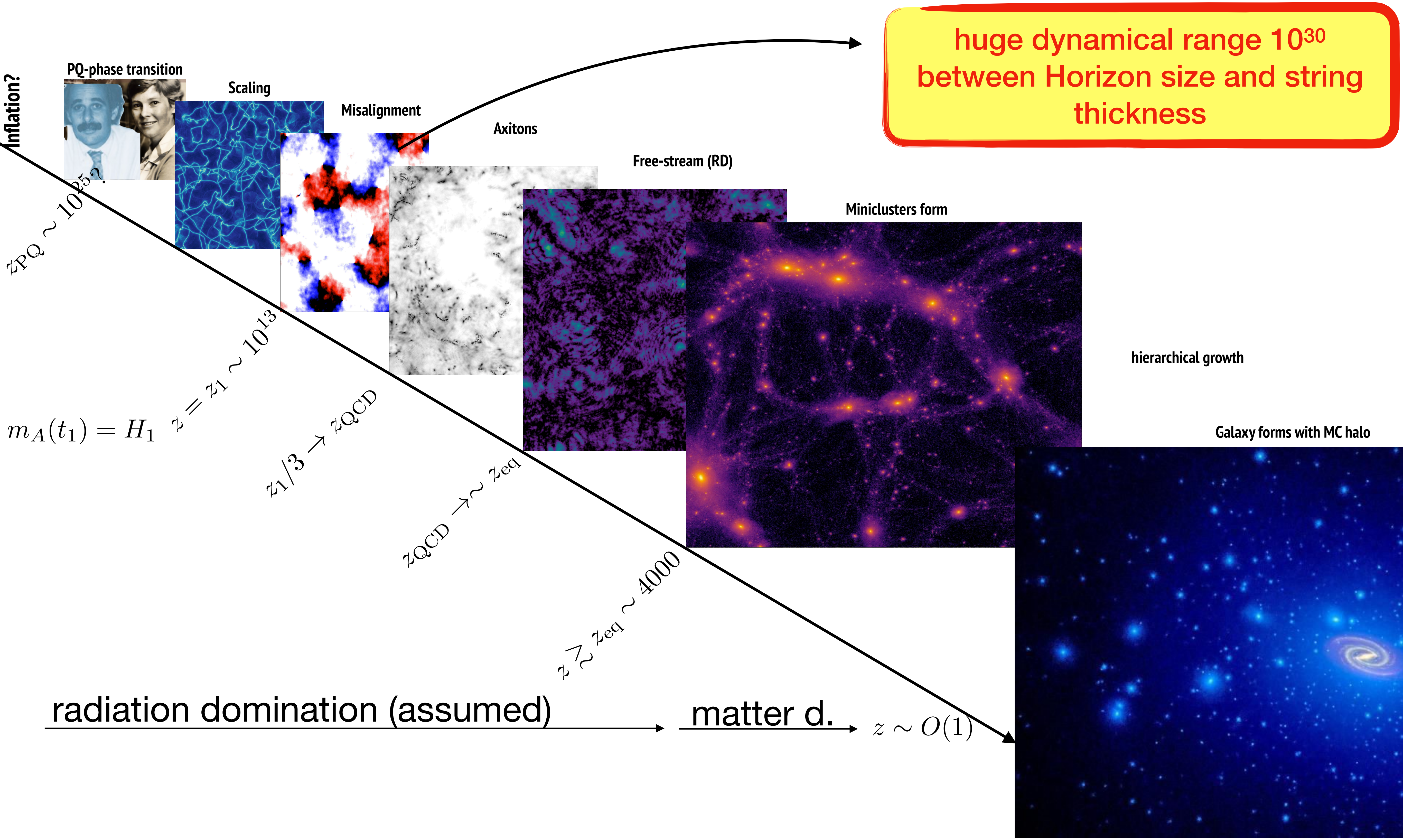


- post-inflationary PQ N=1 has no IC uncertainty (some model, and cosmology uncertainty)

the estimates of the axion DM mass disagree due to the different interpretation of numerical simulations

post-inflationary scenario

- ordered by time, scale factor, redshift, temperature

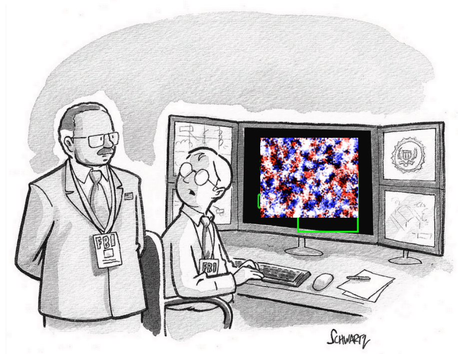


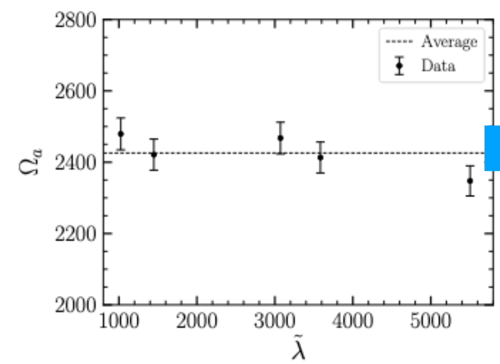
how to tackle the large-dynamical range problem

Two approaches:

Direct simulation : 1) Simulate and 2) count the axions, extrapolate

Moore, Redondo, Buschmann





Usual U(1) global string

$$\mu = 2\pi \int r dr \left(\partial_r|\varphi|^2 + V(|\varphi|) + \frac{|\varphi|^2}{r^2}\right) \sim v^2 + \pi v^2 \log(v r_{\rm cut})$$

Moore, Redondo, Buschmann

1 extra degree of freedom
unphysical DW destruction
PRS trick (enhanced tension at early times)

Moore tension string

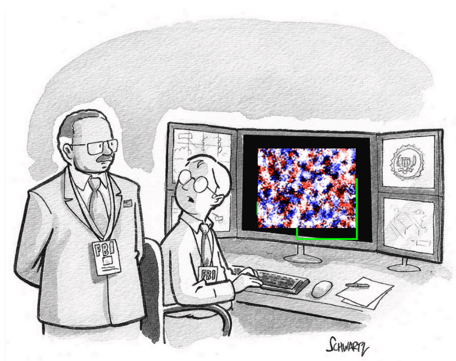
$$\mu =\sim 2v^2 + \pi \frac{v^2}{q_1^2 + q_2^2} \log(v r_{\rm cut})$$

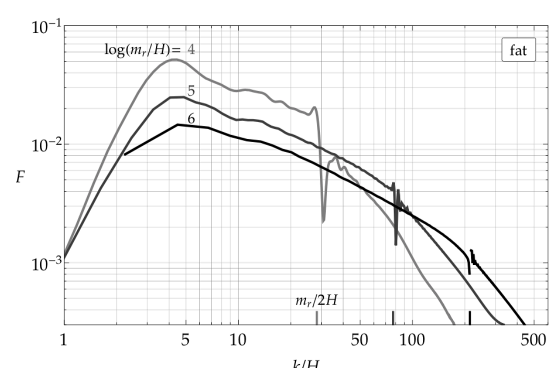
Moore

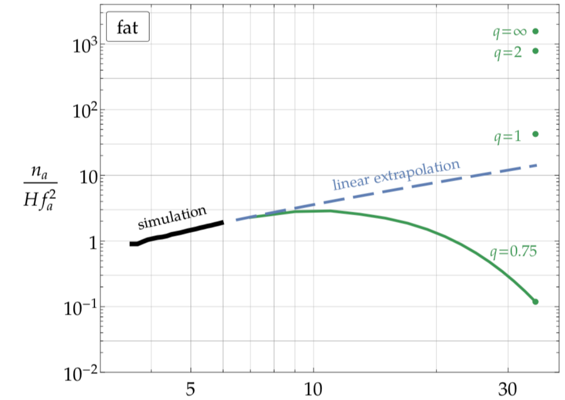
2+3 extra degrees of freedom (two higgs, 1 vector field)
no unphysical DW destruction
PRS trick (enhanced tension at early times)

In-Direct simulation : 1) Simulate to model axion emission from strings, 2) extrapolate the spectrum, 3) count the axions

Kawasaki, Gorghetto, Buschmann



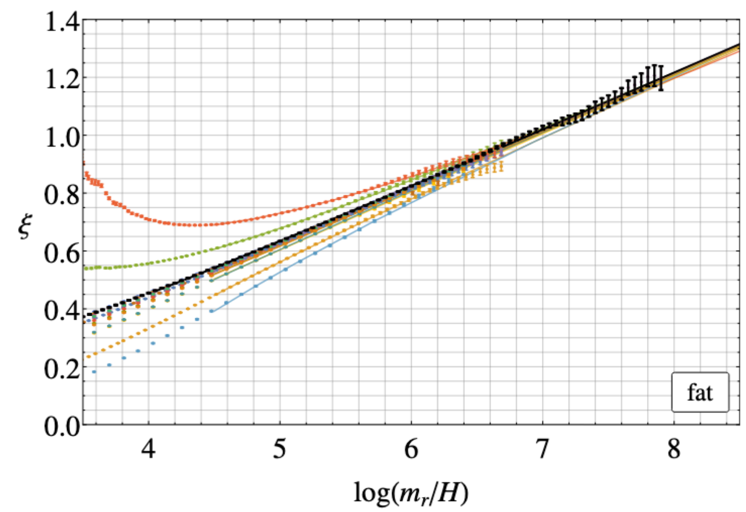




Indirect method

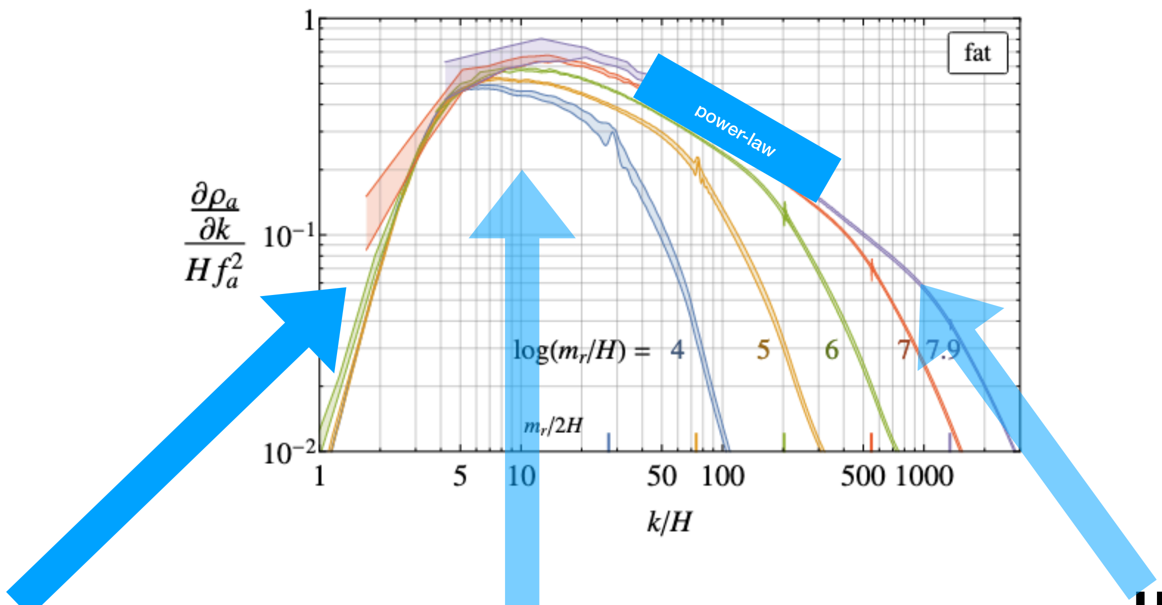
- **scaling solution (with log corrections!)**

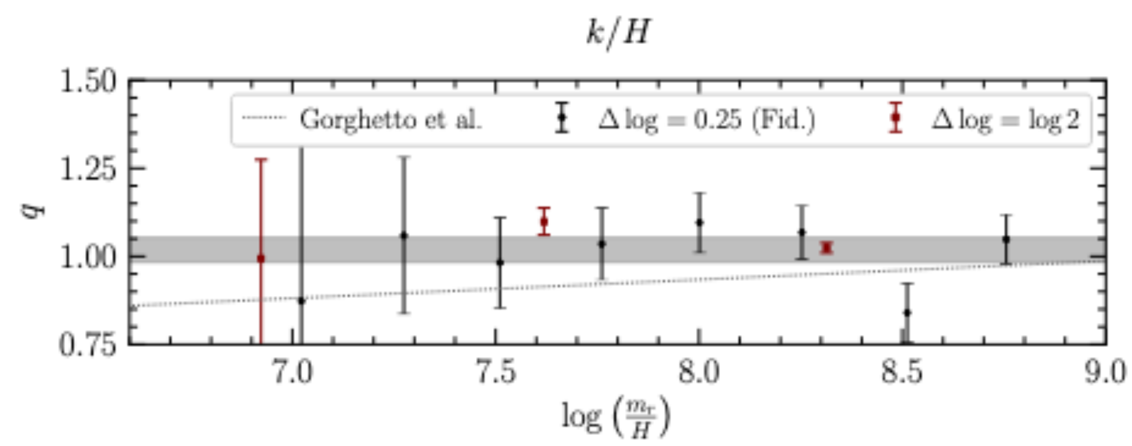
  (log corrections challenged)



Gorghetto, Redondo, Buschmann

- **axion spectrum .. power-law with UV and IR cut-offs (with log corrections*)** *Gorghetto*, Redondo*, Buschmann*





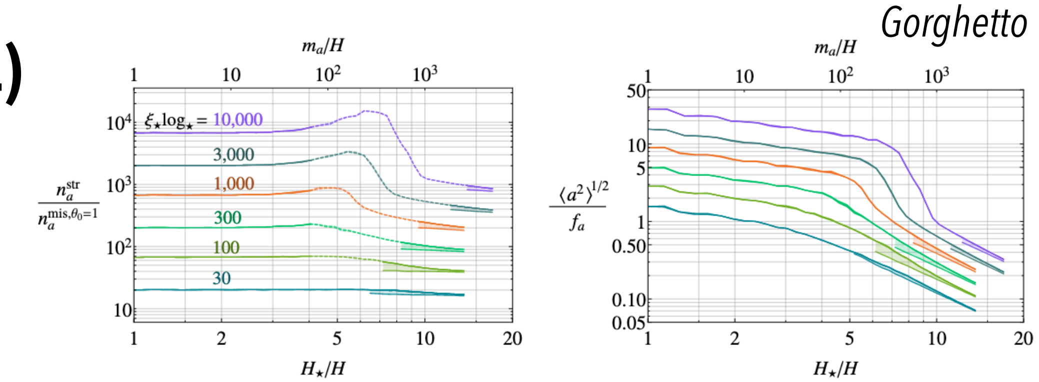
low-k cut-off

most of axions k~horizon

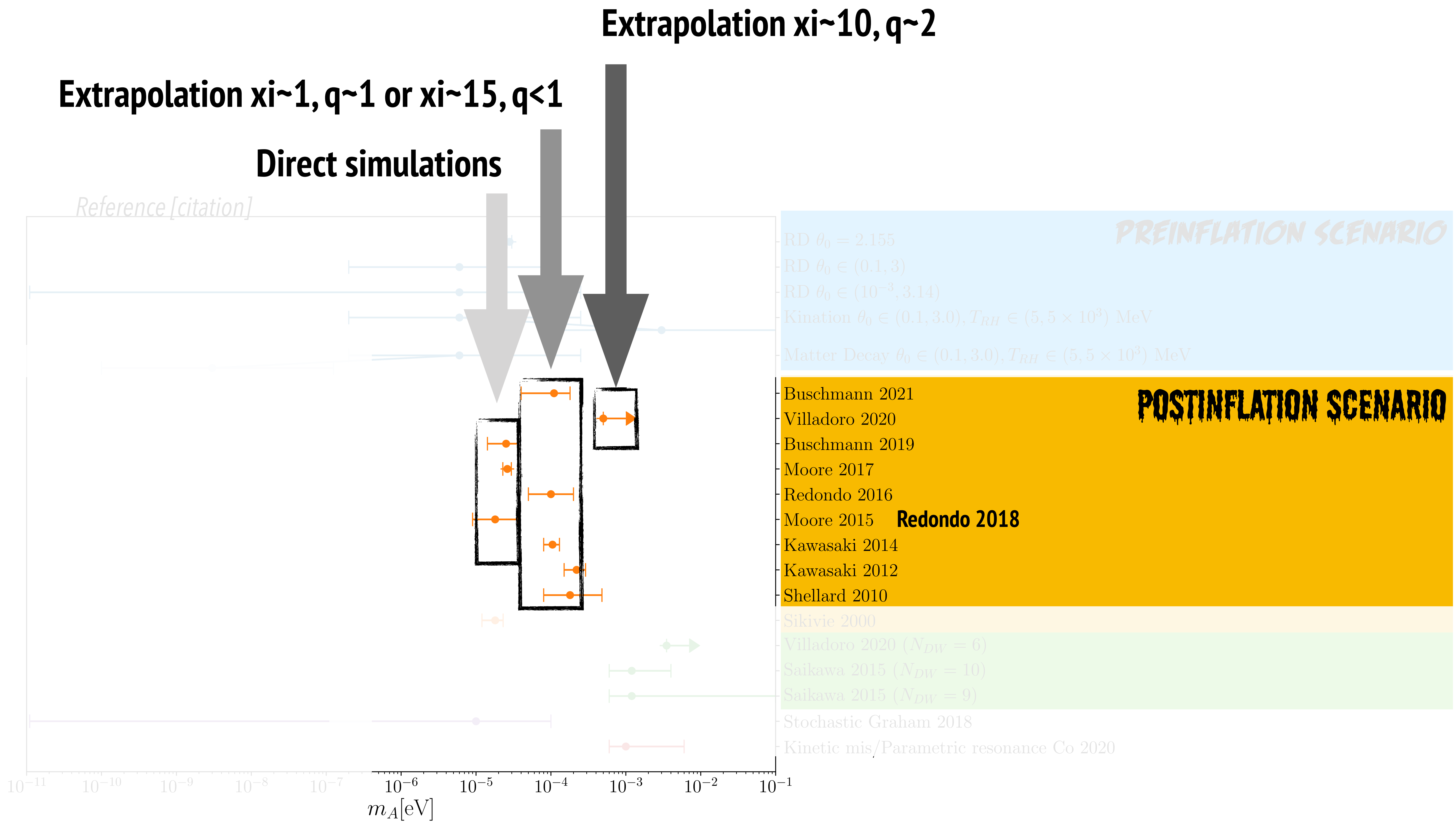
UV cut-off at radial mass

- **Possible non-linear effects for large axion density (q>>1)**

Gorghetto



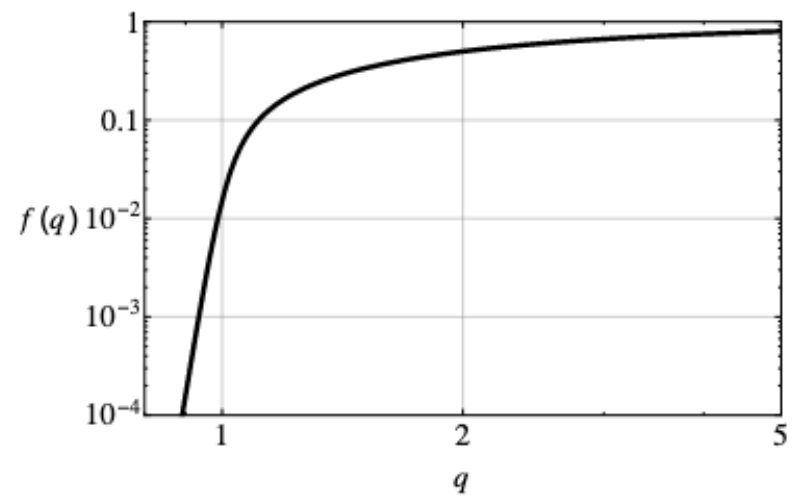
Results and controversies



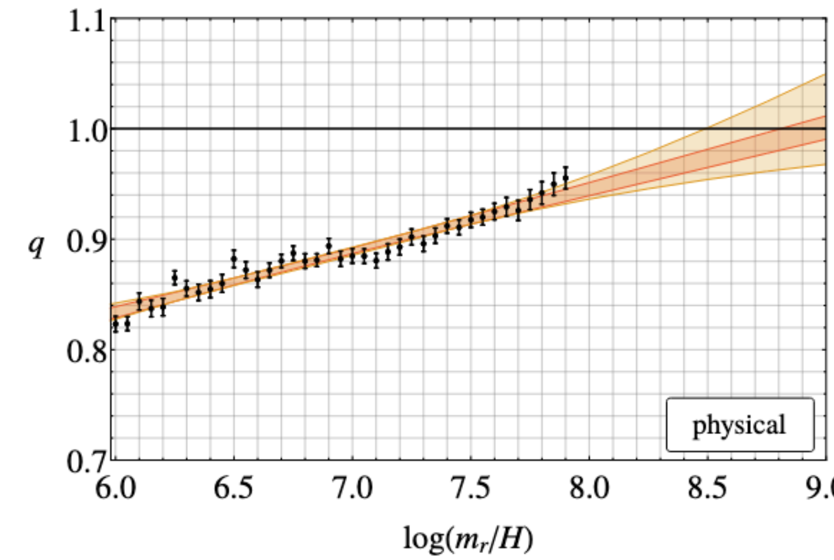
Current plans ...

- Numerical simulations (4000^3, 1100^3) reach almost the critical value

$$n_a(t) \approx \frac{8H\xi(t)\mu_{\rm eff}(t)}{x_0} \times \begin{cases} 1 - 1/q & q > \\ \frac{1}{\log\left(\frac{m_r}{Hx_0}\right)} & q = \\ \frac{1-q}{q(2q-1)}\left[\frac{Hx_0}{m_r}\right]^{1-q} & \frac{1}{2} < q < \end{cases}$$

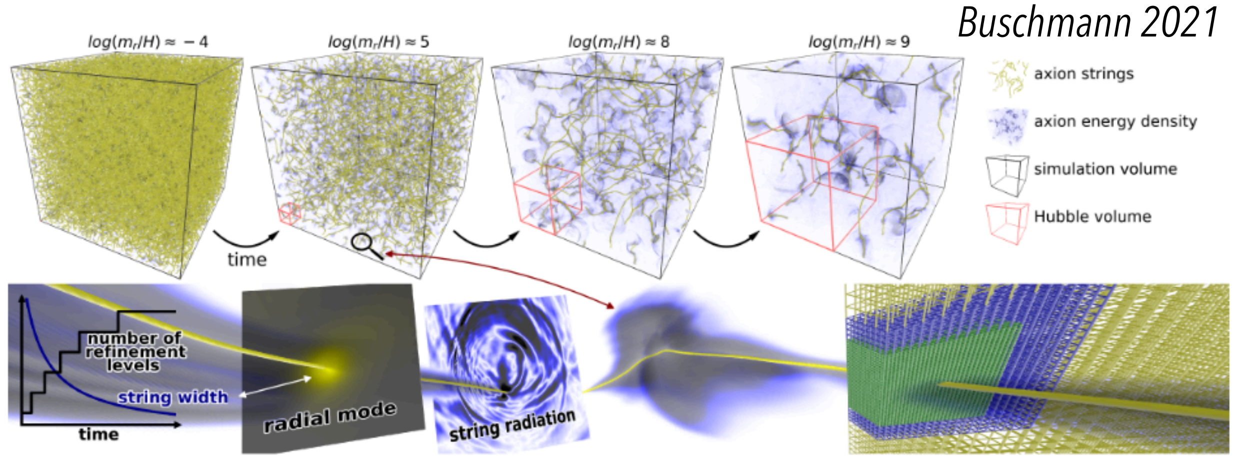


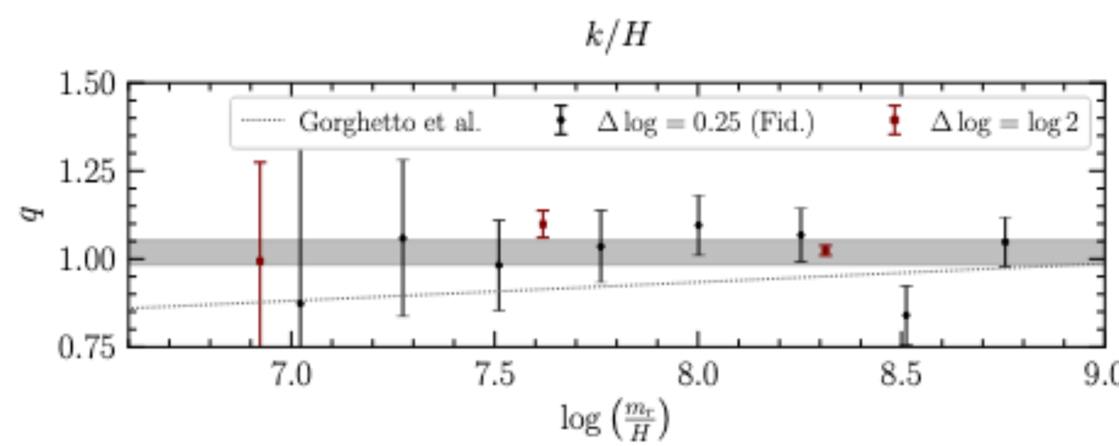
Gorguetto



- AMR can give us a few extra factors of 2 to reach 9~10 (theoretically up to 12)

Buschmann 2021



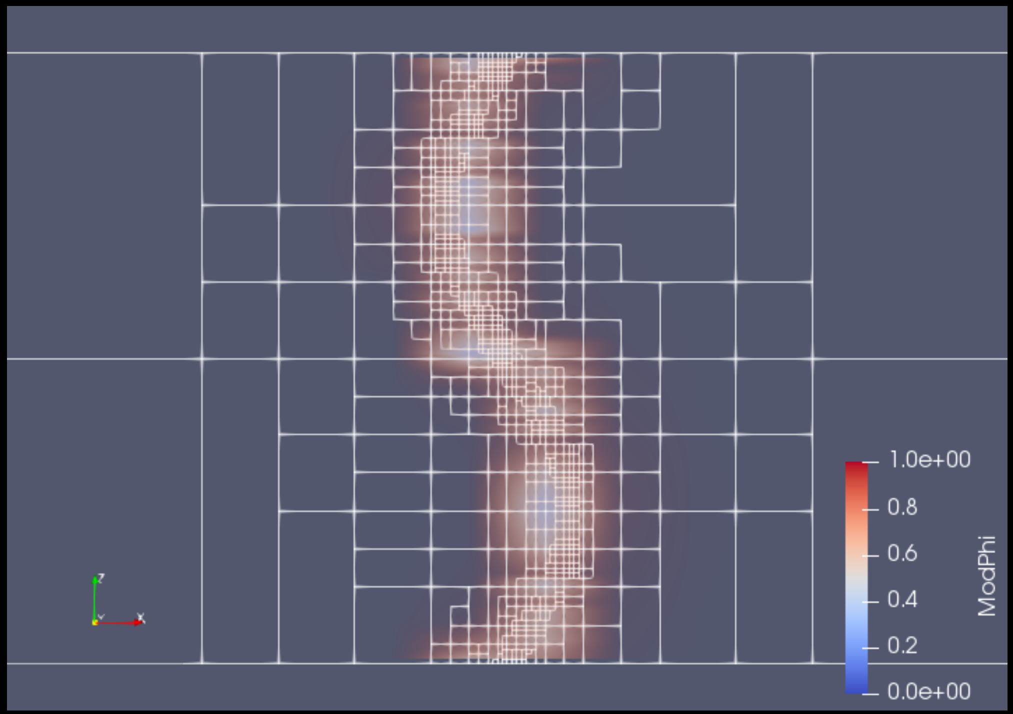


Adaptive Mesh Refinement

For strings…

Fixed Grid

- Δx fixed throughout the simulation
- For $\delta \sim 1$ strings, must use at least $\Delta x \sim 0.5$
- Computational resources typically limit to $\sim 4096^3$ grid points, $\ln(R/\delta) \sim 8$



AMR

- Enables increase $\ln(R/\delta)$ with fixed (limited) resources
- E.g. equivalent $\ln(R/\delta) \sim 8$ simulation ran on **32x fewer processors AND multiple 10x faster using AMR**

$$\mathcal{O}(\text{days}) \rightarrow \mathcal{O}(\text{hours})$$

- Should comfortably achieve $\ln(R/\delta) \sim 10$ or higher with same resources
- Equivalent fixed grid would need fixed grid of *at least* $> 65000^3$ for same box size

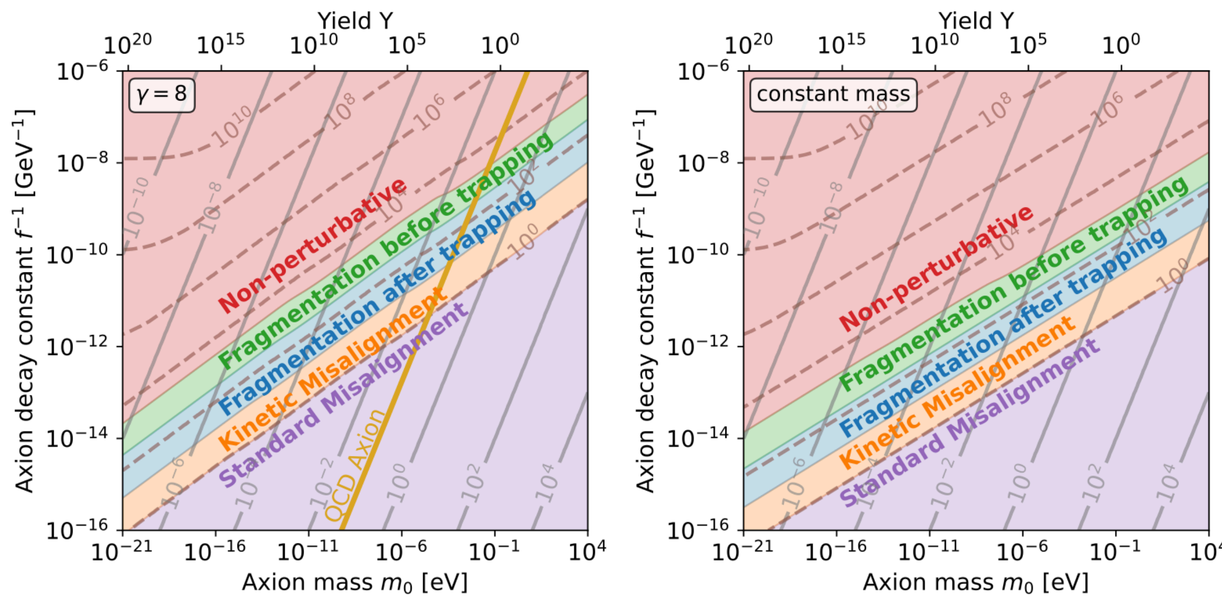
Bonus: potential for even further speedups with GPU support

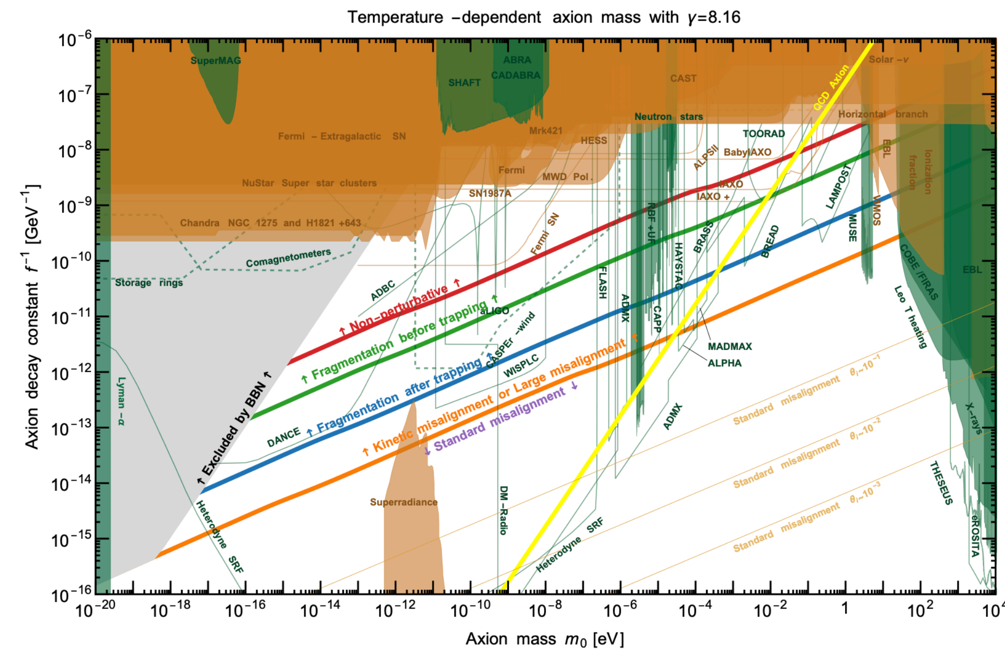
Simulations for ``pre-inflation" non-linear scenarios

Use our very powerful codes for these rare non-linear scenarios

kinetic misalignment

Eröncel 22

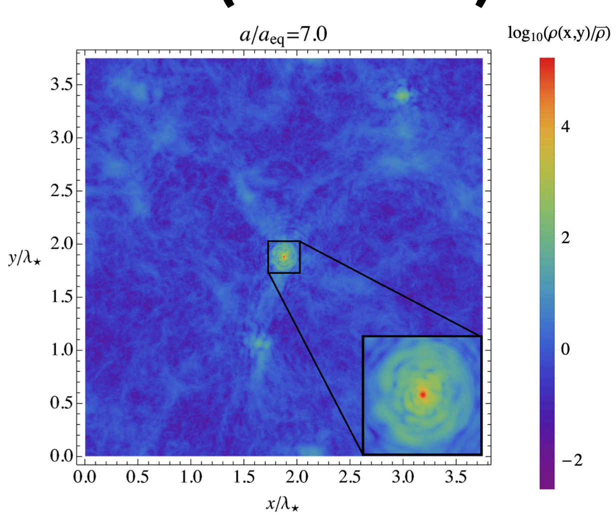


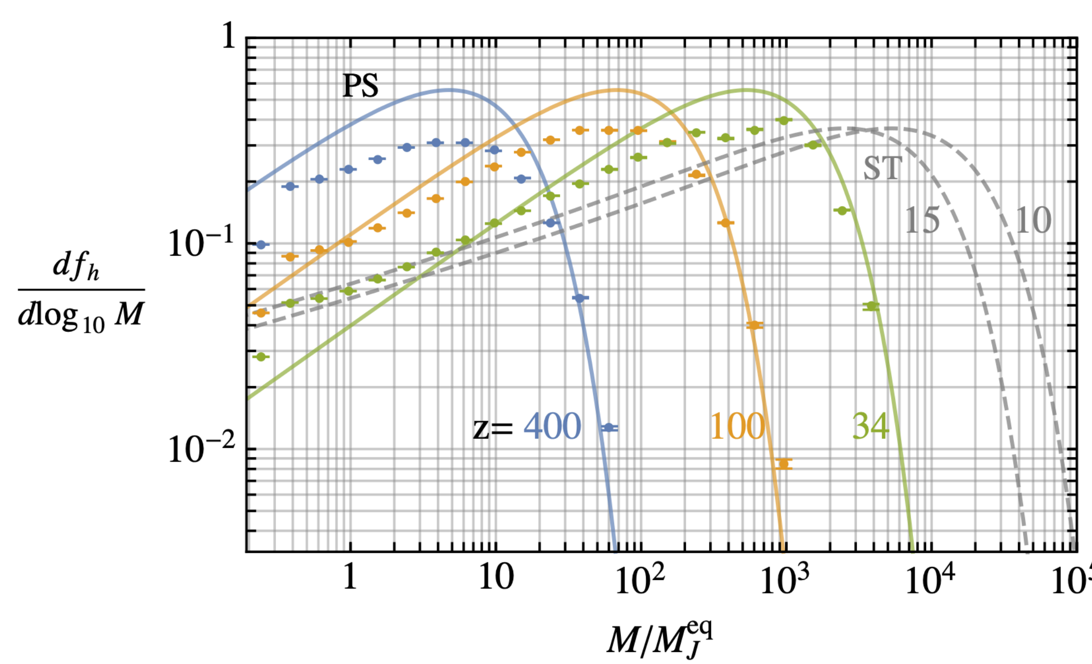


theta~pi

?

dark photons (and stars) *Gorghetto 22*





NDW>1

Saikawa 15, Gorghetto 21, 22

Small structure

Axion minihalos and axion stars (same for dark photons)

Seeds in early Universe:

Gravitational collapse around z_eq

Hyerarchical growth

Survival in the galaxy

DM field in the galaxy (voids?) see talk of Giovanni Pierobon

Microlensing

Collisions with compacts, radio signals

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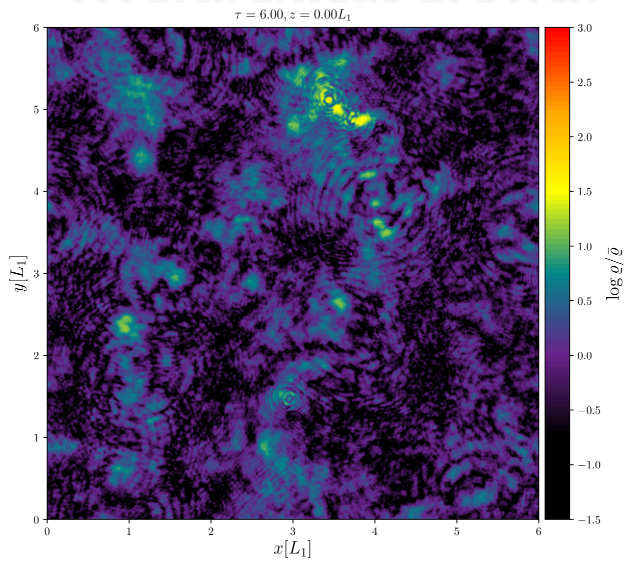
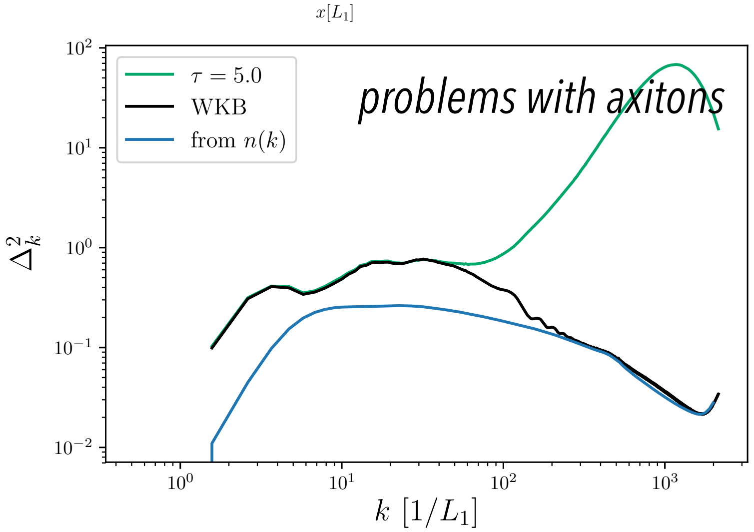
Simulations with Strings, other needed, problems with extrapolation

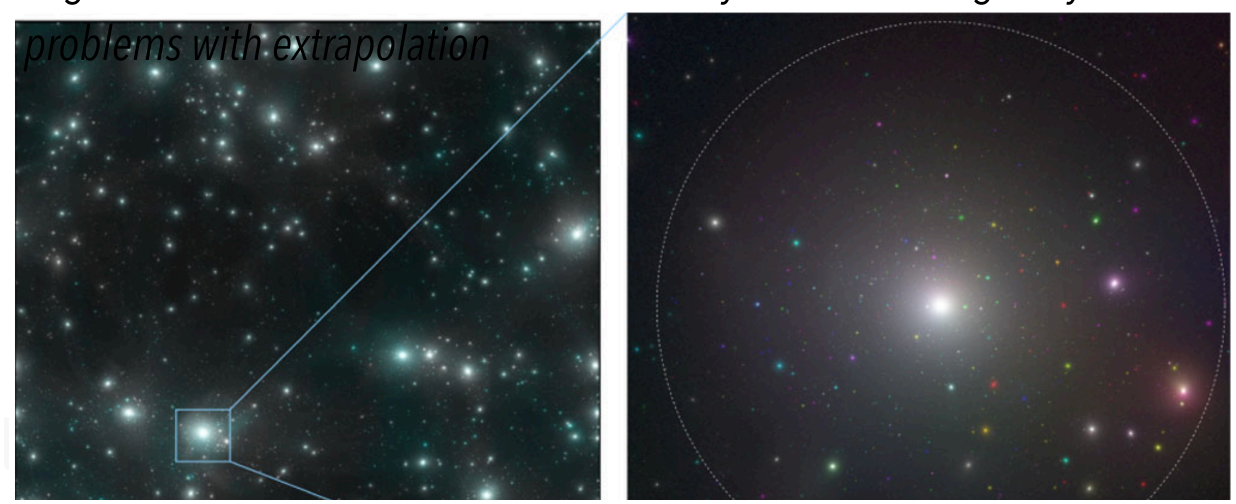




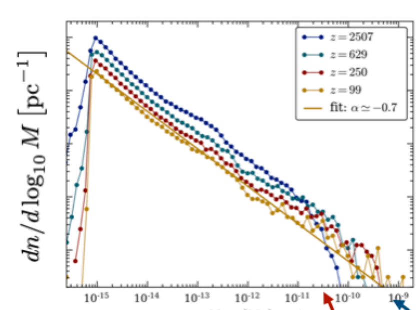
problems with axitons

large scales are trustable, convert to N-body and simulate gravity *Eggemeier 20*

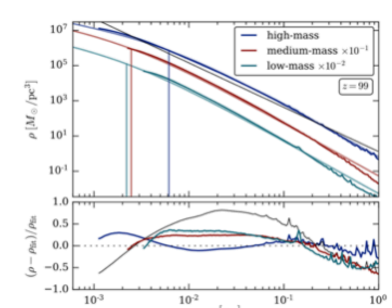
problems with extrapolation



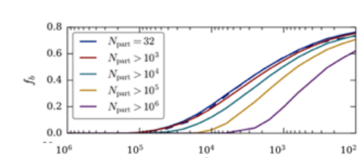
- Large simulation ($N=1024^3$ particles) in a Large box ($L= 24\ L_1$) simulated with jaxions in a 8192^3 grid
- Periodic boundaries, volume effects when smallest scale becomes non-linear



- Loads of low-M MCs
- Spherical collapse with $\Phi = \langle\delta\rangle \sim 1$ at $z \sim z_{eq}\Phi$
- Typical MC $\Phi \sim 1 \to M_0 \sim 10^{-11} M_\odot$
- Clusters of miniclusters $\Phi < 1$



- NFW reasonable fit
- better than $r^{-9/4}$ (acretion)
- concentration ~ M
  not well resolved for small M



- Nearly 80% of axions bound in MCs!!
- Tidal disruption with galaxy stars can lower the number
- Most axions in Massive MCs
- Mean MC has low mass

Small structure

Axion minihalos and axion stars (same for dark photons)

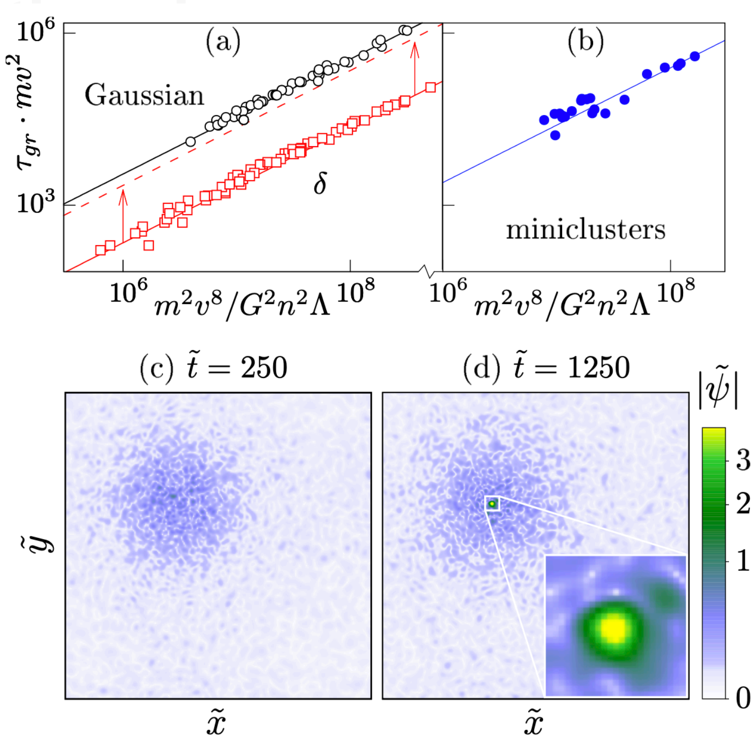
Seeds in early Universe:

Redondo 18, Buschmann 19, Gorghetto 22

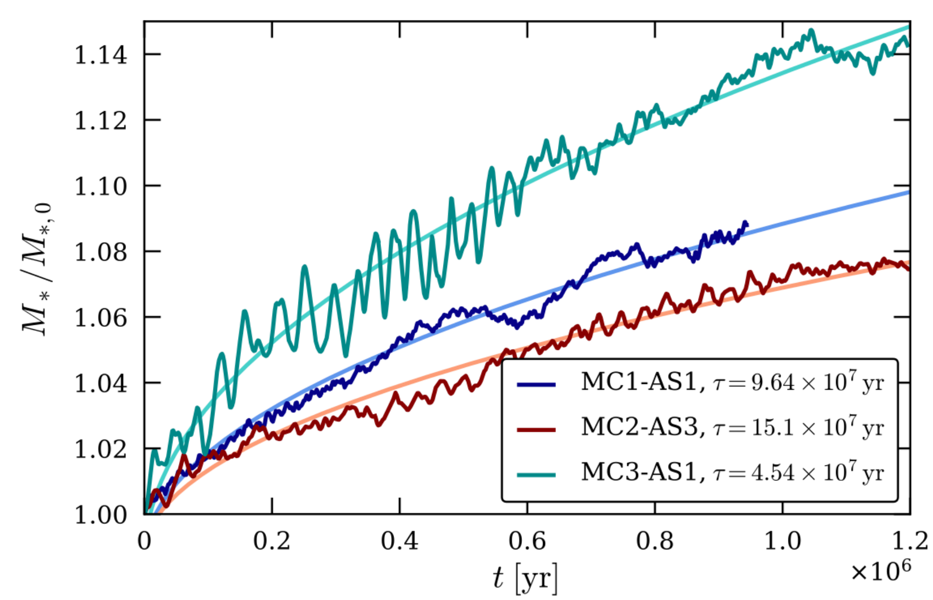
Gravitational collapse around z_eq

Formation and Growth of axion stars in MCs

Levkov 18



Eggemeier 19



Small structure

Axion minihalos and axion stars (same for dark photons)

Seeds in early Universe:

Gravitational collapse around z_eq

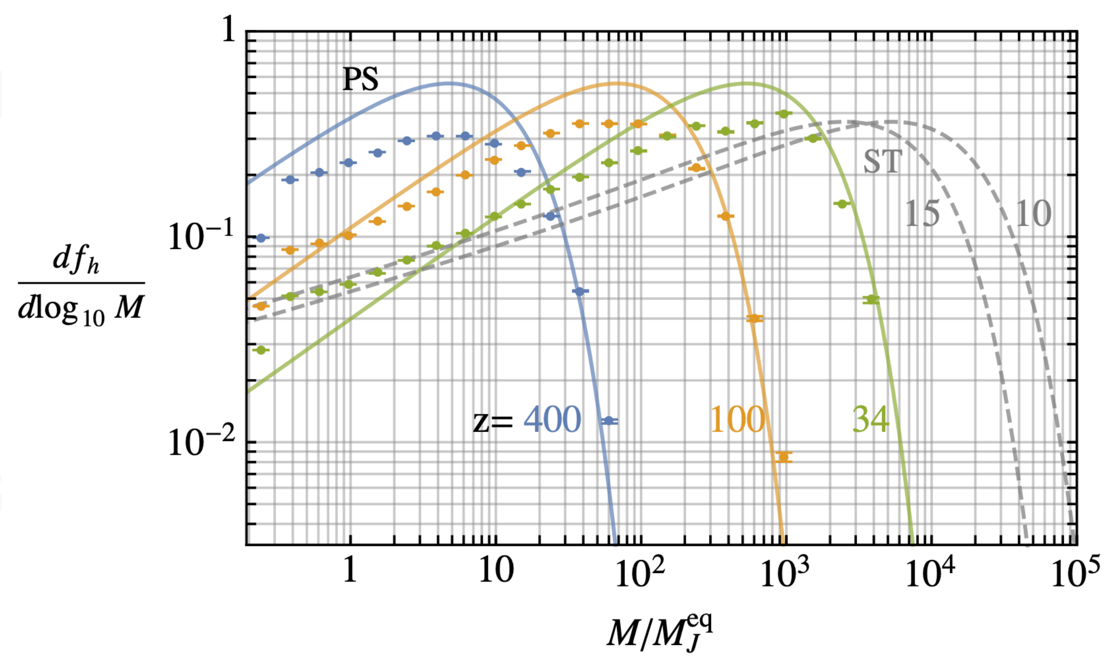
Hyerarchical growth *partially addressed, not so complicated* *Eggemeier 20, Gorghetto 22*

Survival in the galaxy

DM field in the galaxy (voids?) see t

Microlensing

Collisions with compacts, radio sign



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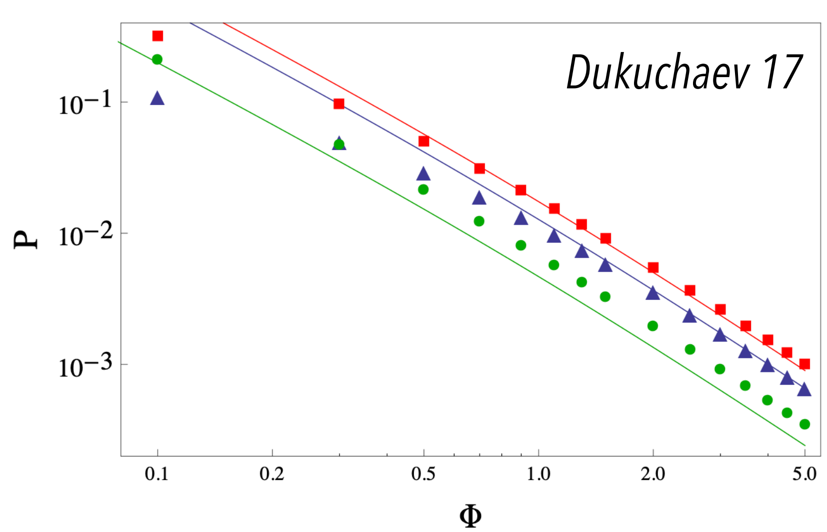
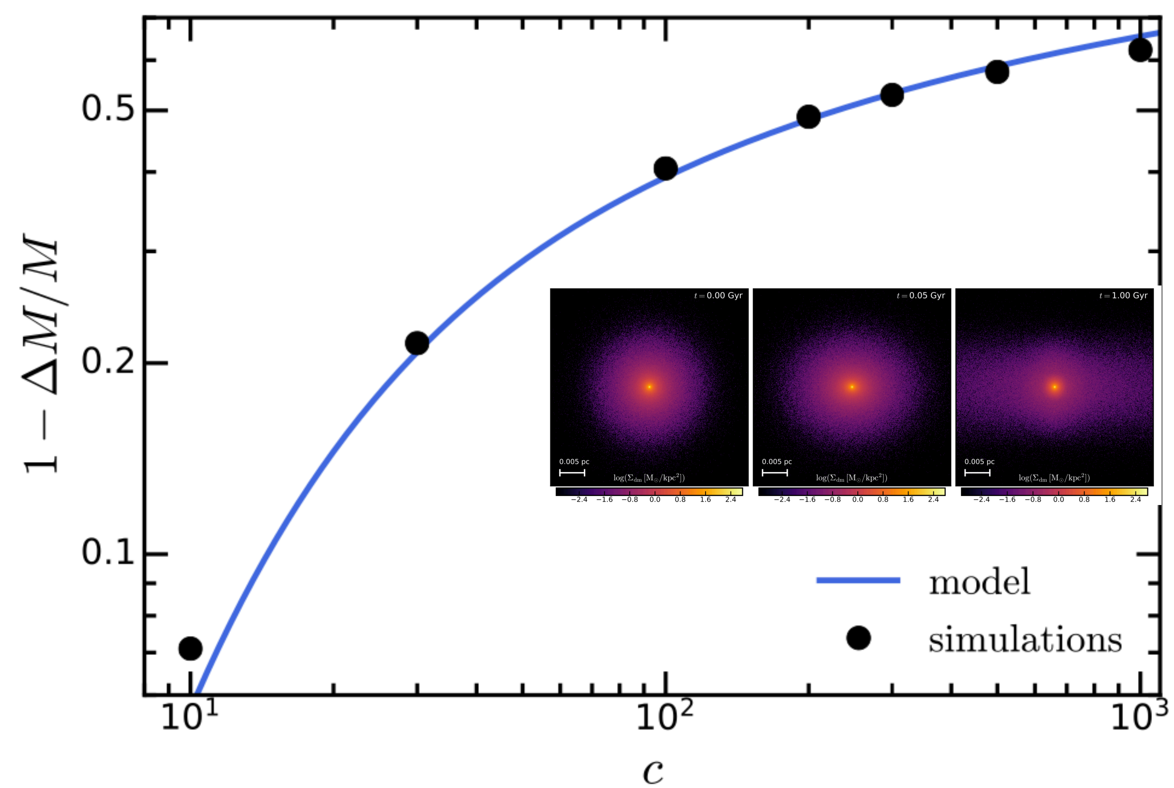
Hyerarchical growth

Survival in the galaxy

Dukuchaev 17, Kavanagh 21, Dandoy 22, Zurek 22

Theoretical, montecarlo, numerical simulations, but not (much) feedback from Early Universe SIM-motivated properties (HMF, density profiles*, etc..





Small structure

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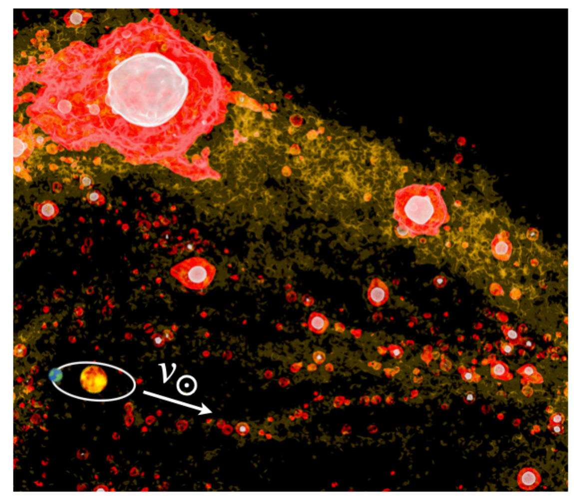
Seeds in early Universe:

Gravitational collapse arounc

Hyerarchical growth

Survival in the galaxy

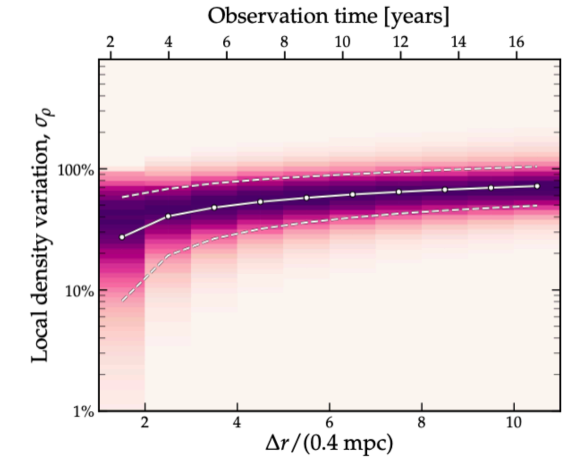
Volume rendering



$v_\odot \sim 220$ km/s

$\mathcal{O}(10^5)$ trajectories

$$\sigma_\rho(r) = \frac{1}{\langle\rho(r)\rangle_{\rm traj}}\sqrt{\frac{1}{n_r}\sum_{i=1}^{n_r}(\rho(r_i) - \langle\rho(r)\rangle_{\rm traj})^2}$$



Expected variation of 20–30% for an observing time of $\mathcal{O}(1)$ year

Almost 100% on even longer timescales

Eggemeier, O'Hare, GP, Redondo, Wong, 2022

DM field in the galaxy (voids?) see talk of Giovanni Pierobon

Relevant question for Direct Dark matter, first steps

Microlensing

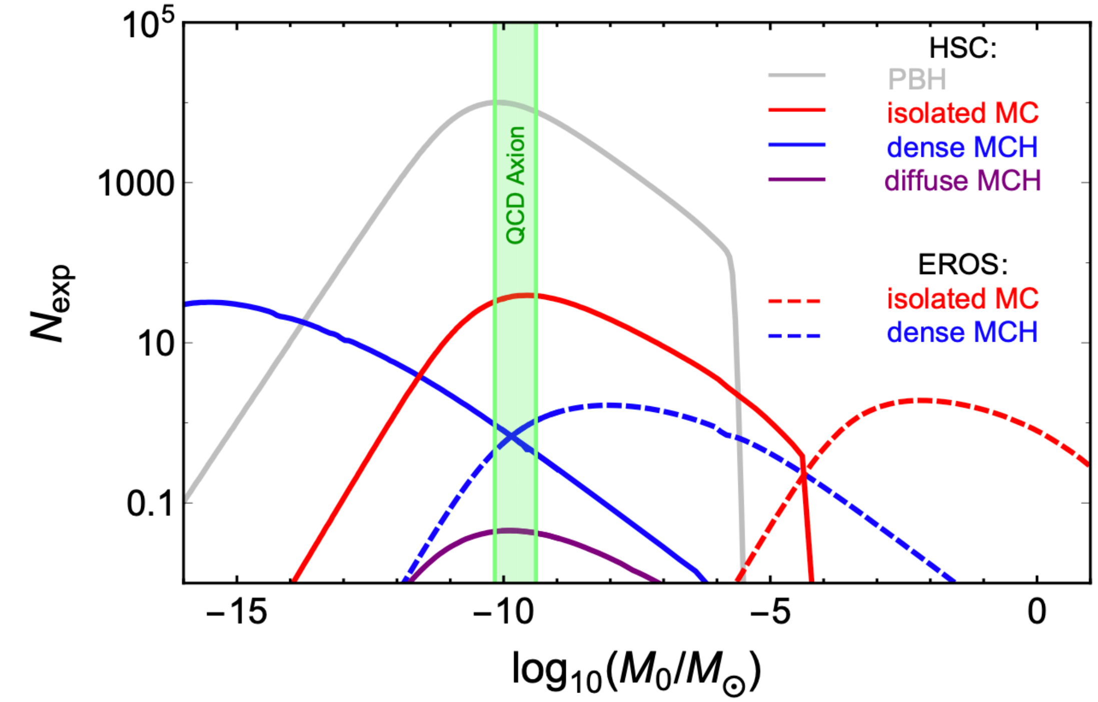
Collisions with compacts, radio signals

Small structure

Axion minihalos and axion stars (same for dark photons)

Fairbairn 17

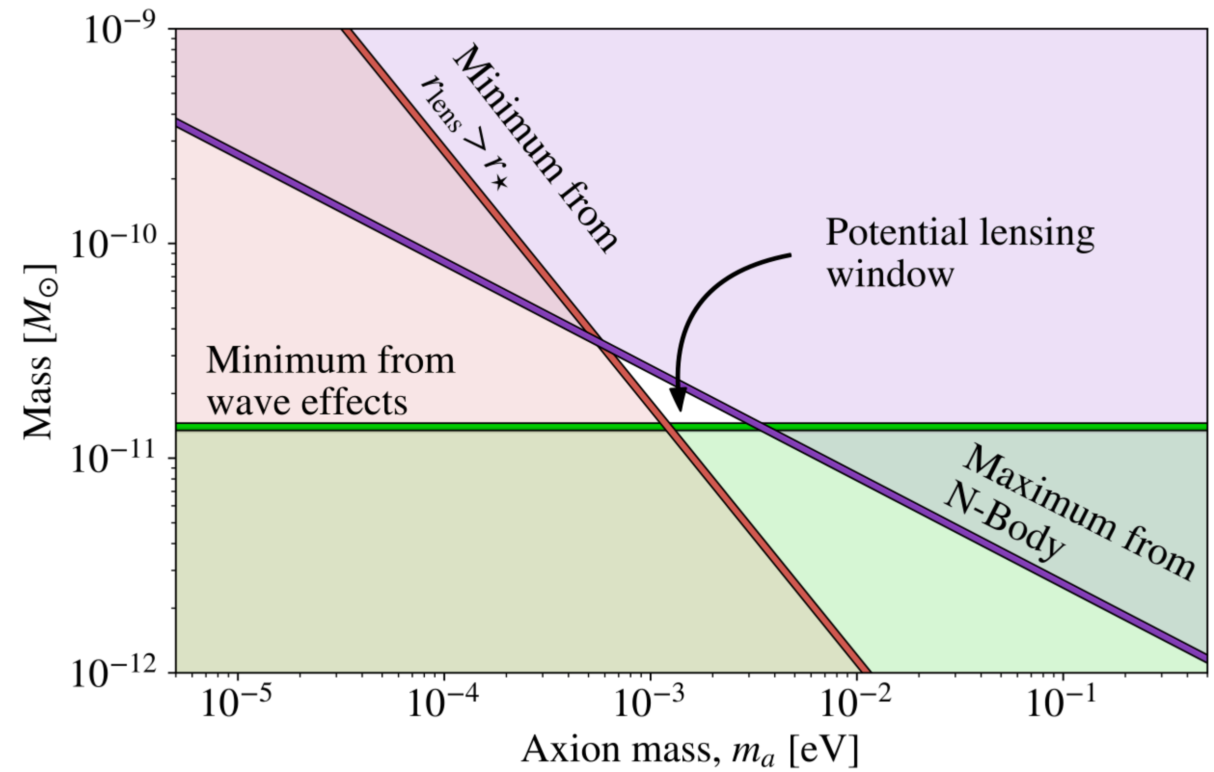
Theory expectations based on
O(1) analytical properties
were very optimistic



Ellis 22

Microlensing

Expectations based on
analytical properties from numerical
simulations make it much harder
BUT STILL the num. sims. are not FINAL

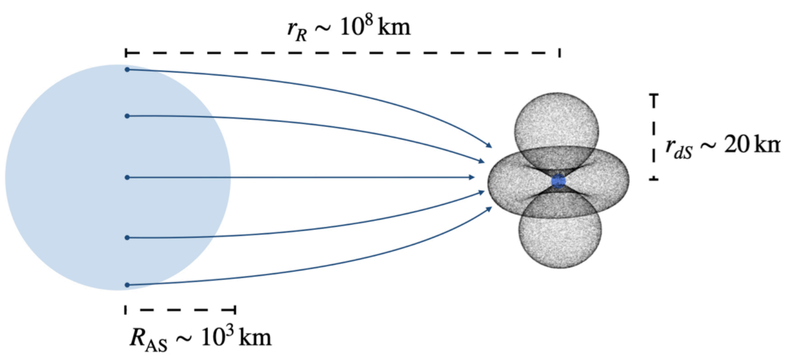


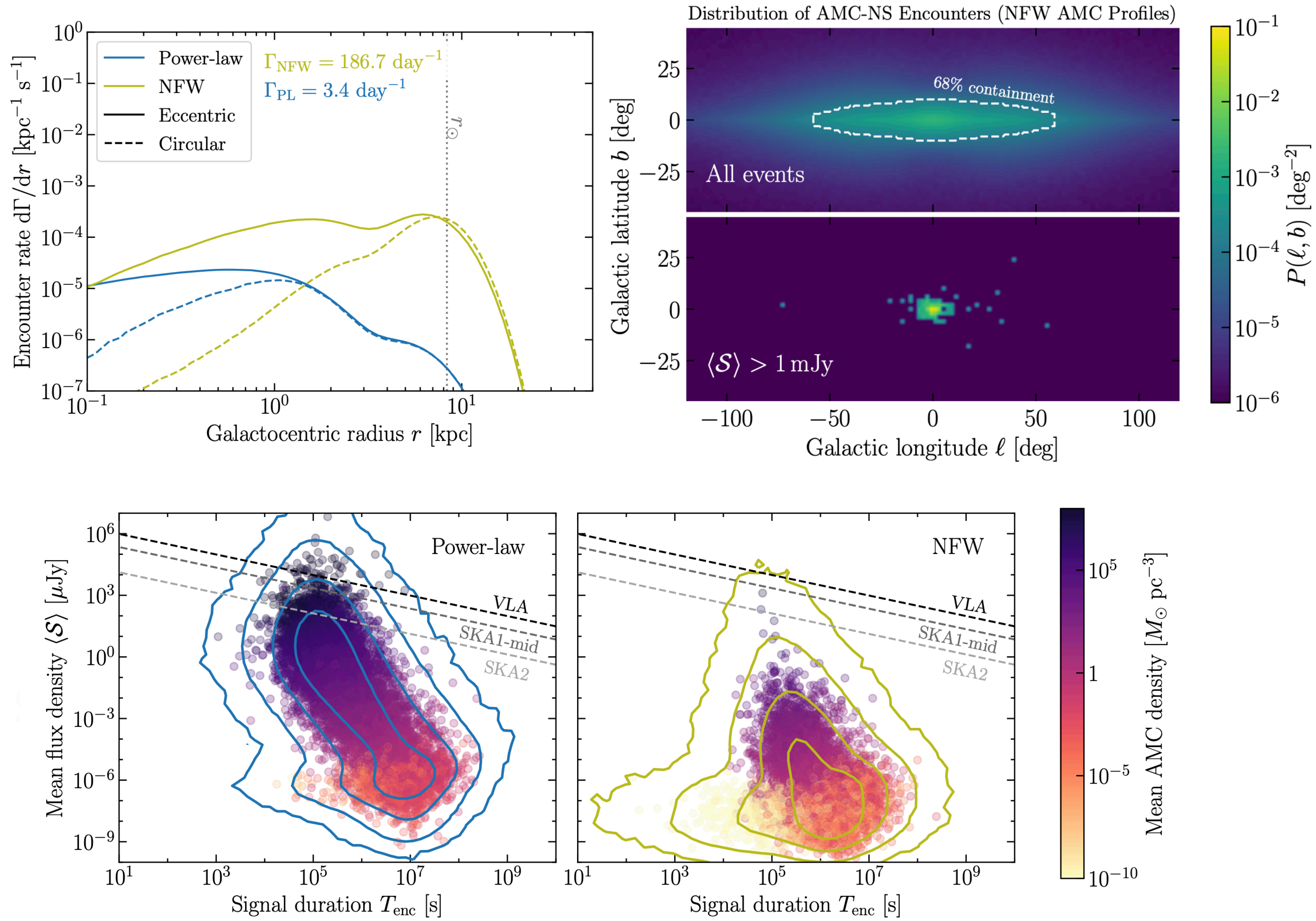
Small structure

Axion minihalos and axion stars (same for dark photons)

Edwards 21

transient radio signals from MCs, axion starts in the B-field of neutron-stars





Collisions with compacts, radio signals

More recent assesment *Witte 22*

Small structure

Axion minihalos and axion stars (same for dark photons)

Seeds in early Universe:

Gravitational collapse

Hyerarchical growth

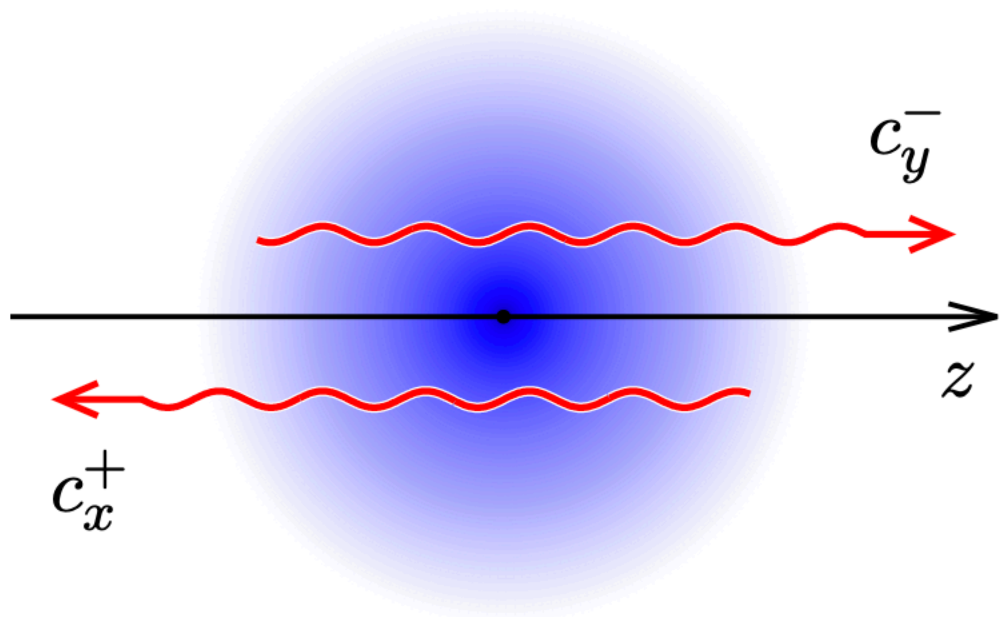
Survival in the galaxy

DM field in the galaxy (voids?) s

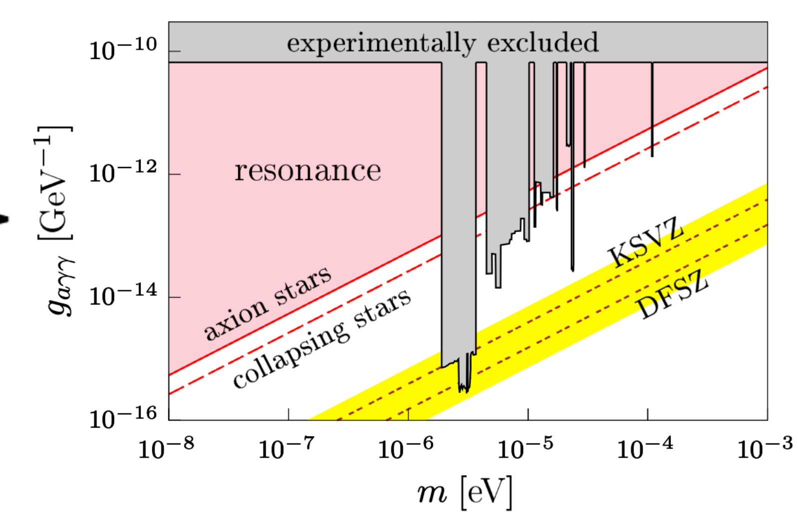
Microlensing

Collisions with compacts, radio s

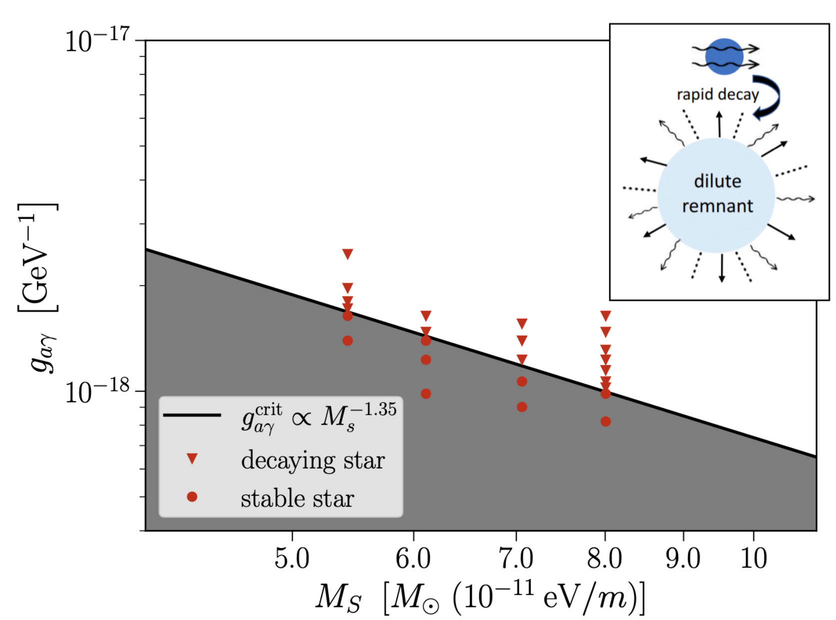
Parametric resonance



Levkov 21



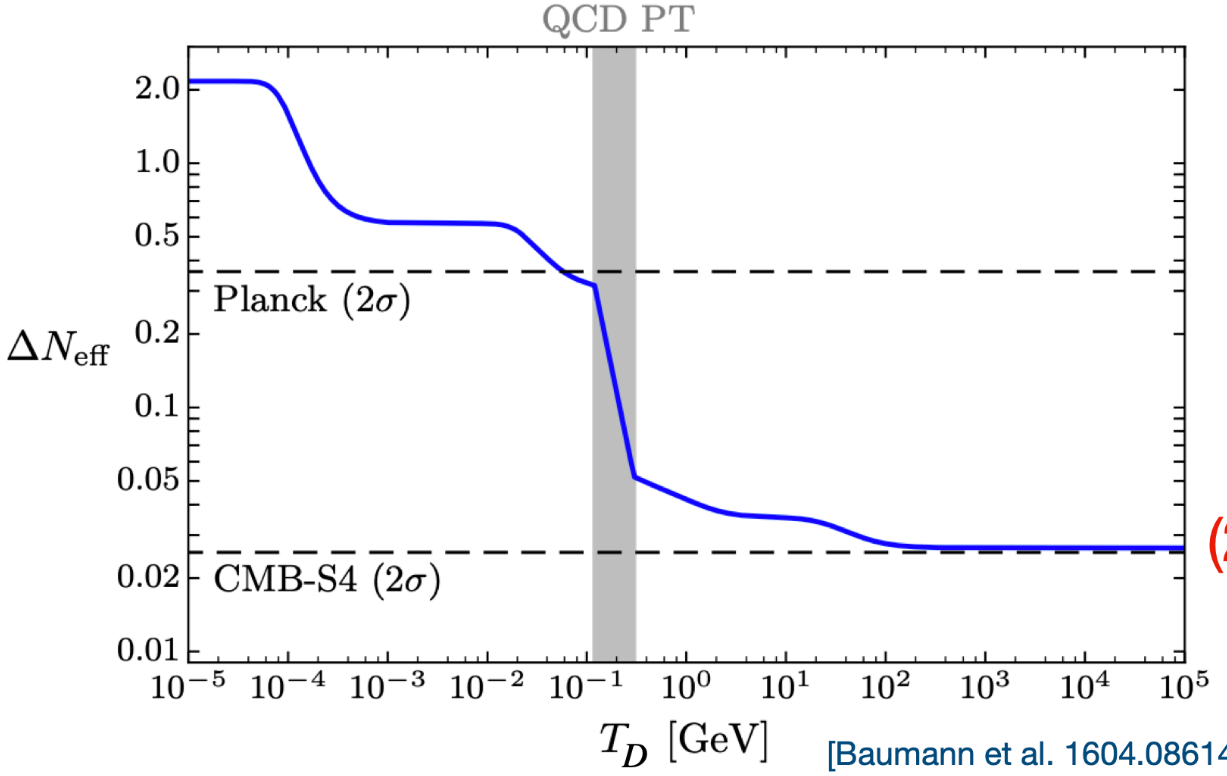
Jukko 23



Radio emission from axion stars

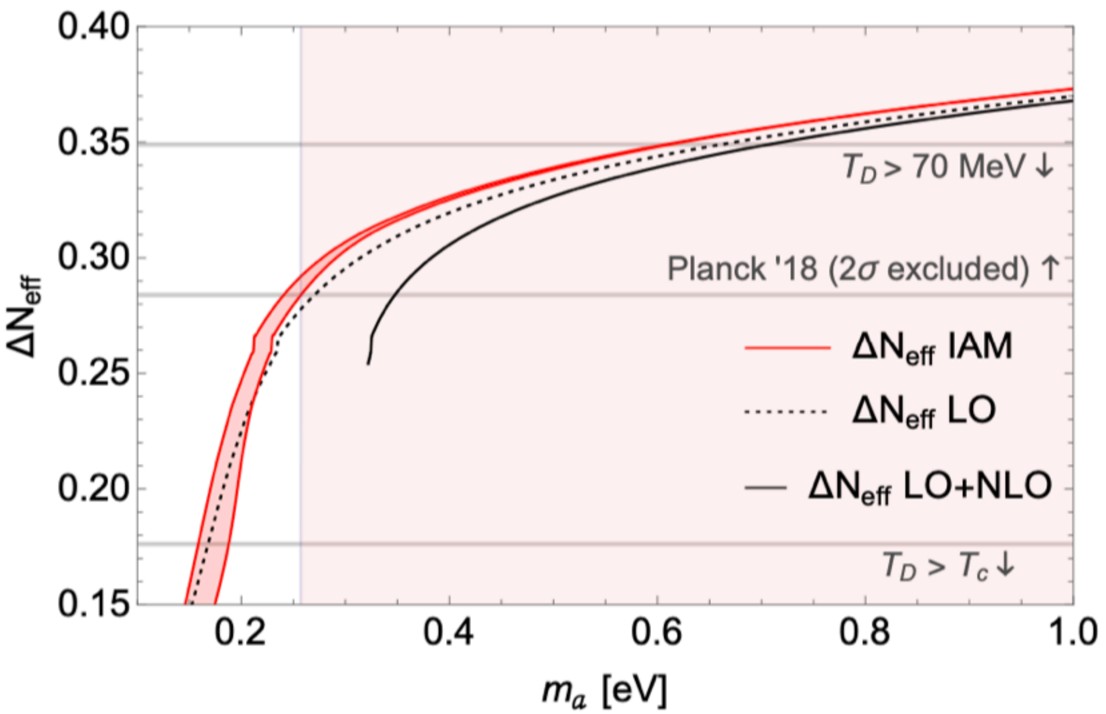
hot DM

- CMB data can pinpoint dark radiation levels to Neff ~ thermal axions decoupled above EWPT



[Baumann et al. 1604.08614]

- Calculations of decoupling around QCD PT were not reliable (LO CHPT) improved by Unitarisation



✦ LO and NLO ChPT reliable up to $T_D = 70$ MeV

✦ IAM valid up to $T_c \simeq 155$ MeV, gives a bound $m_a \leq 0.26$ eV

Additional corrections needed for future sensitivities, K's, f0(880), thermal effects

Large scale structure

- ``Large" mass WISPs

    Strings outside the horizon (preinflation) *Kaplan*

    warm DM suppression of PS

    ...

- Ultra-light WISPs

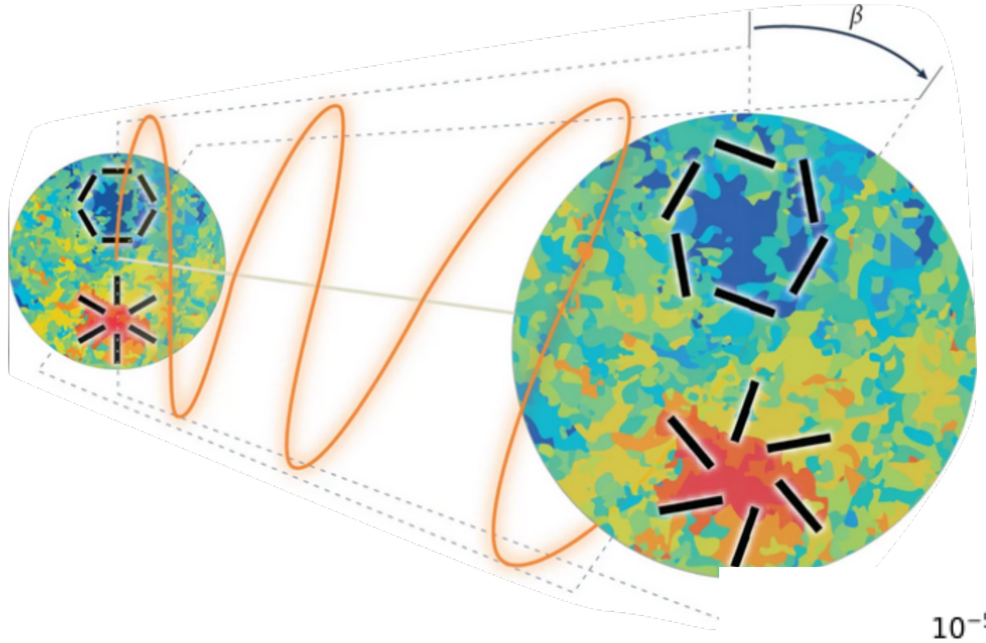
    Ly-alpha
    Power spectrum

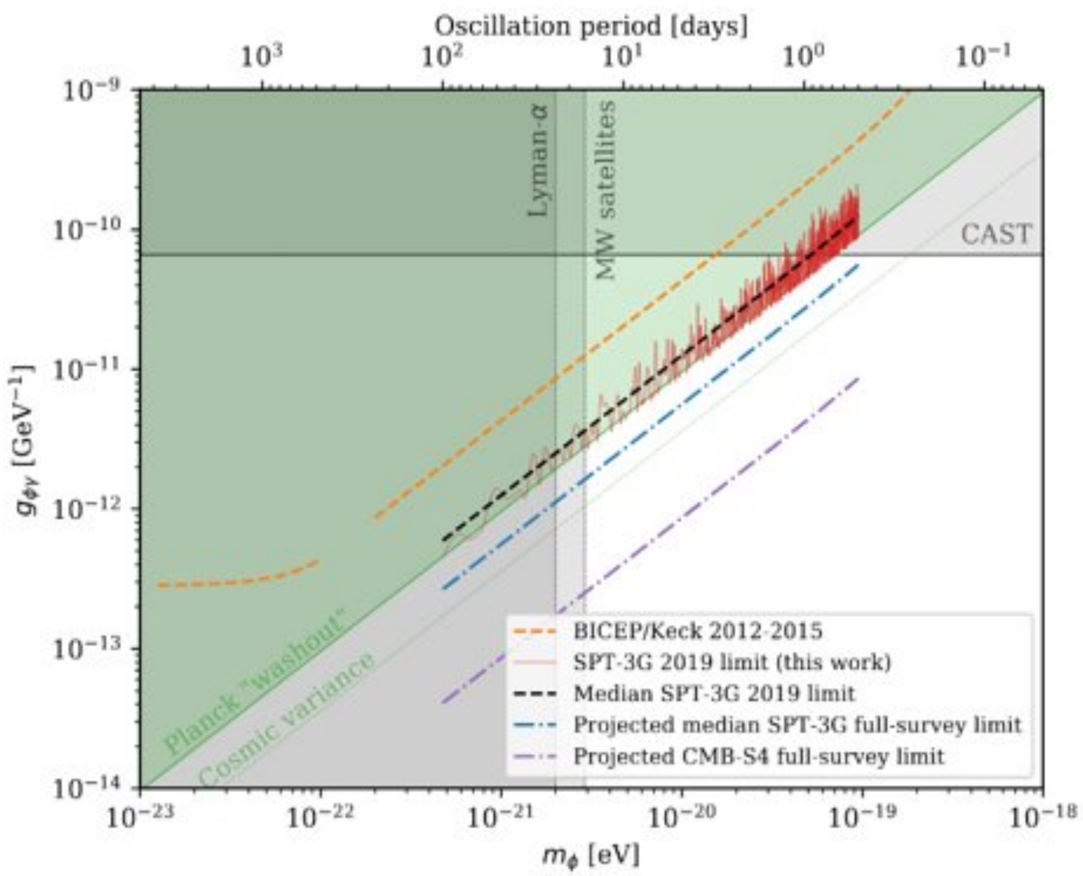
    ...

Cosmic birefringence

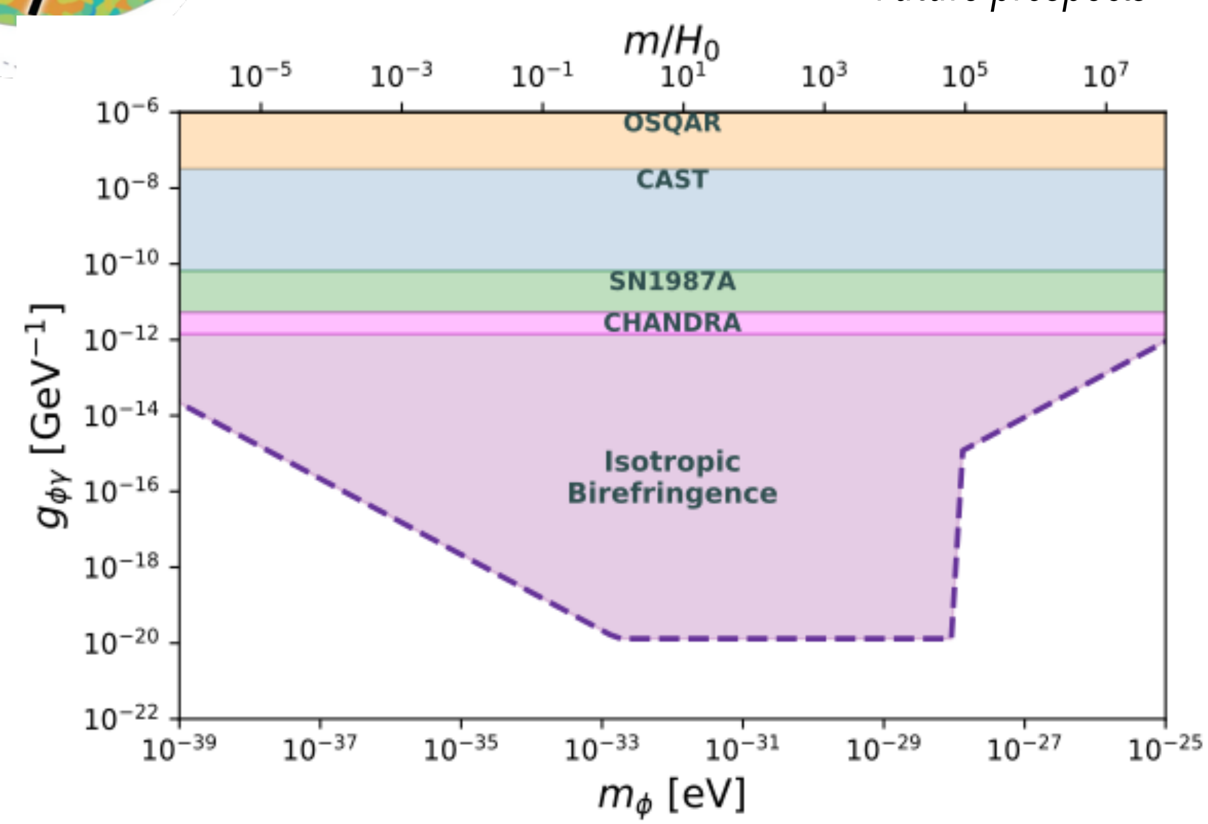
ALP DM coupled to photons with extremely low mass rotates polarisation of CMB

See talk of P. Diego





Future prospects



What to expect in the near future:

- High-precision CMB polarisation data is on the way (SPT-3G, BICEP3, SO, LiteBIRD)
- Improved artificial calibrators are being deployed [exciting results coming soon from BICEP3!]
- Better understanding of Galactic dust EB

Conclusions

- Extremely exciting prospects and opportunities

- I have been quite biased (the art is broader than this meagre statement)

- QCD axion is somewhow nicely covered by up-to-date studies but other WISPs much less