Axion dark matter mass

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17-21 Oct 2022

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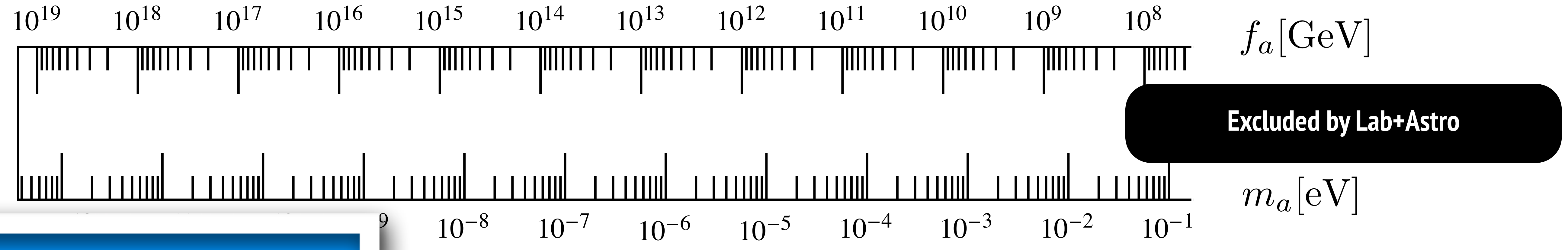
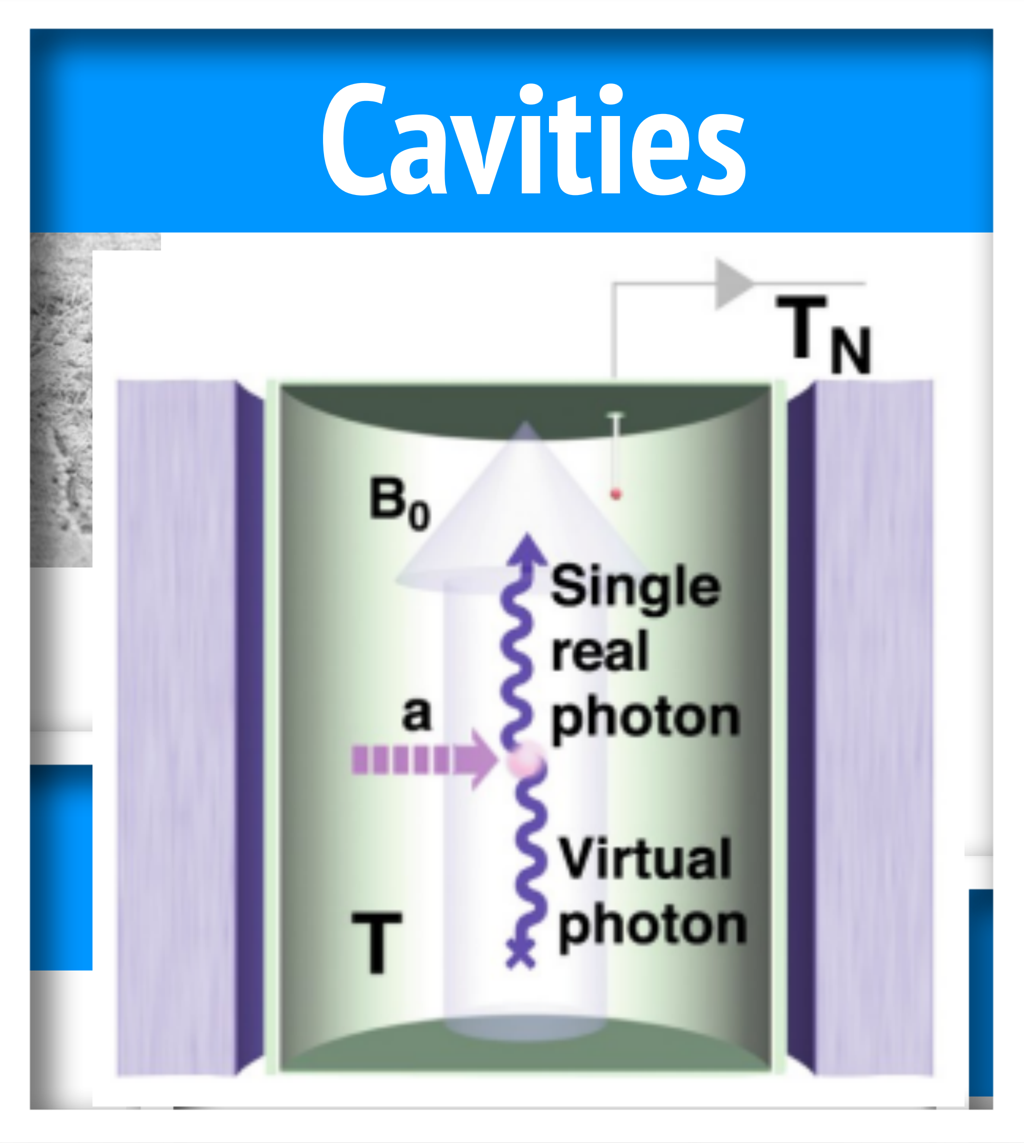
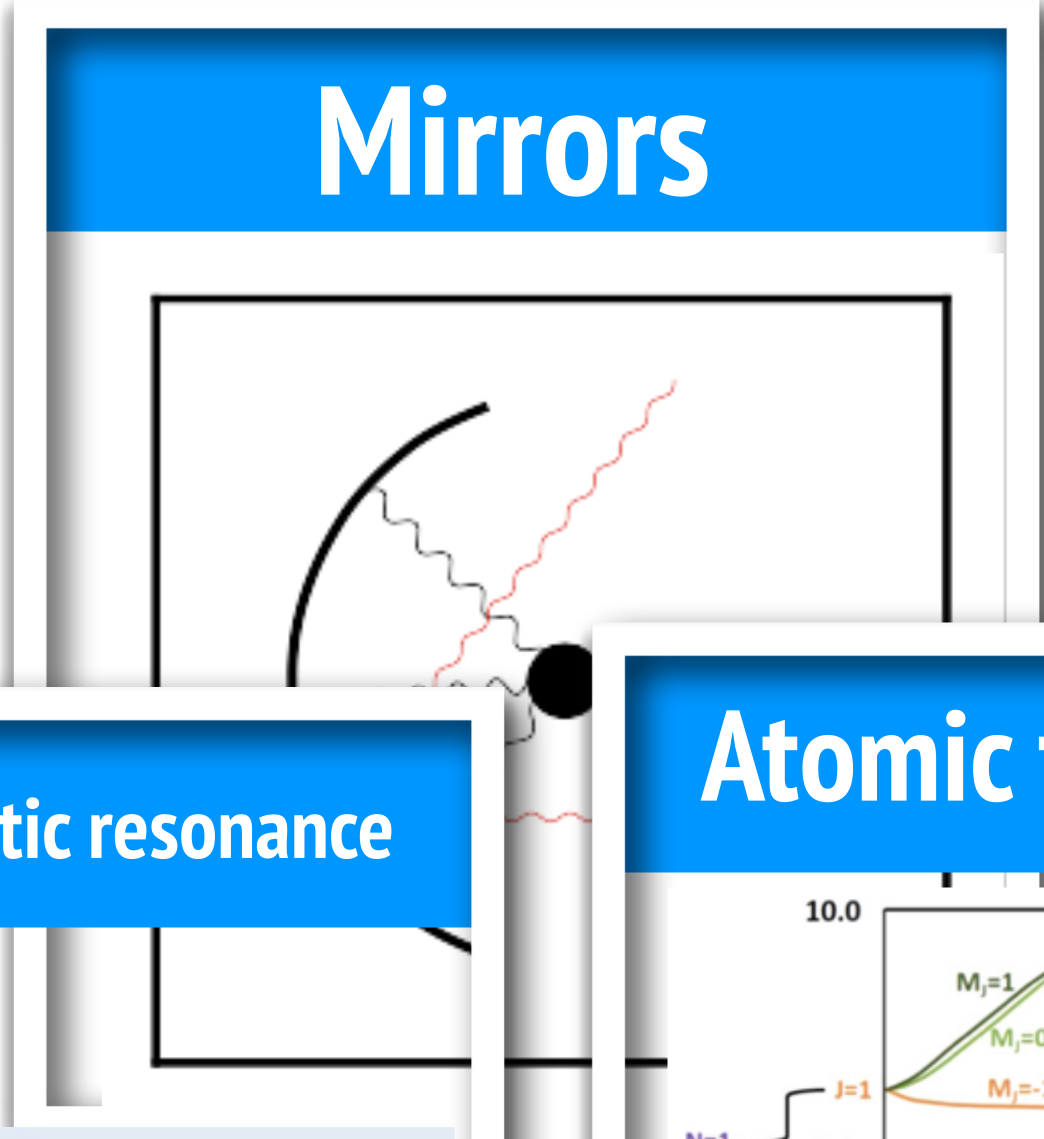
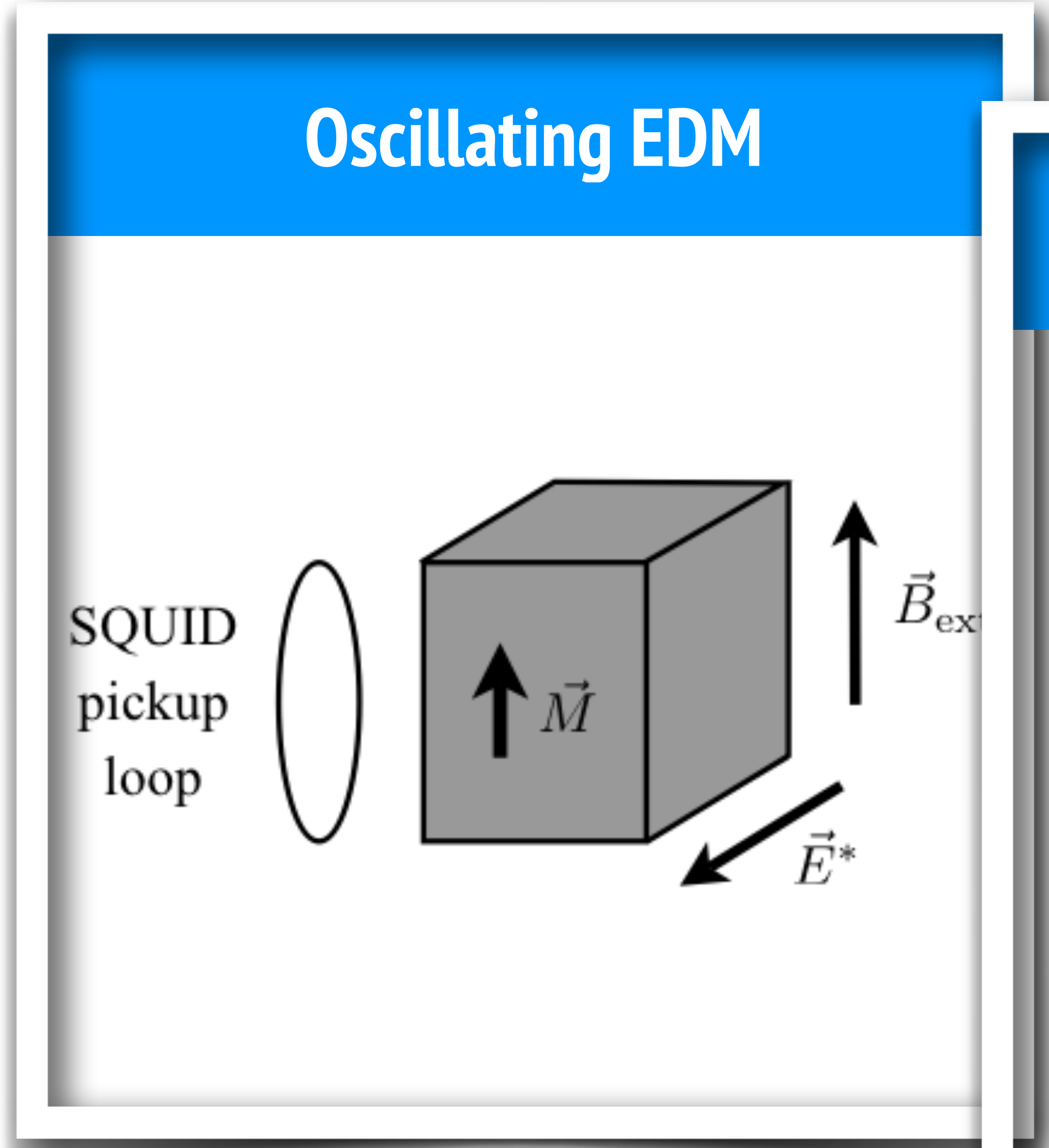
axion DM experiments need to scan its mass ... they could use a hint

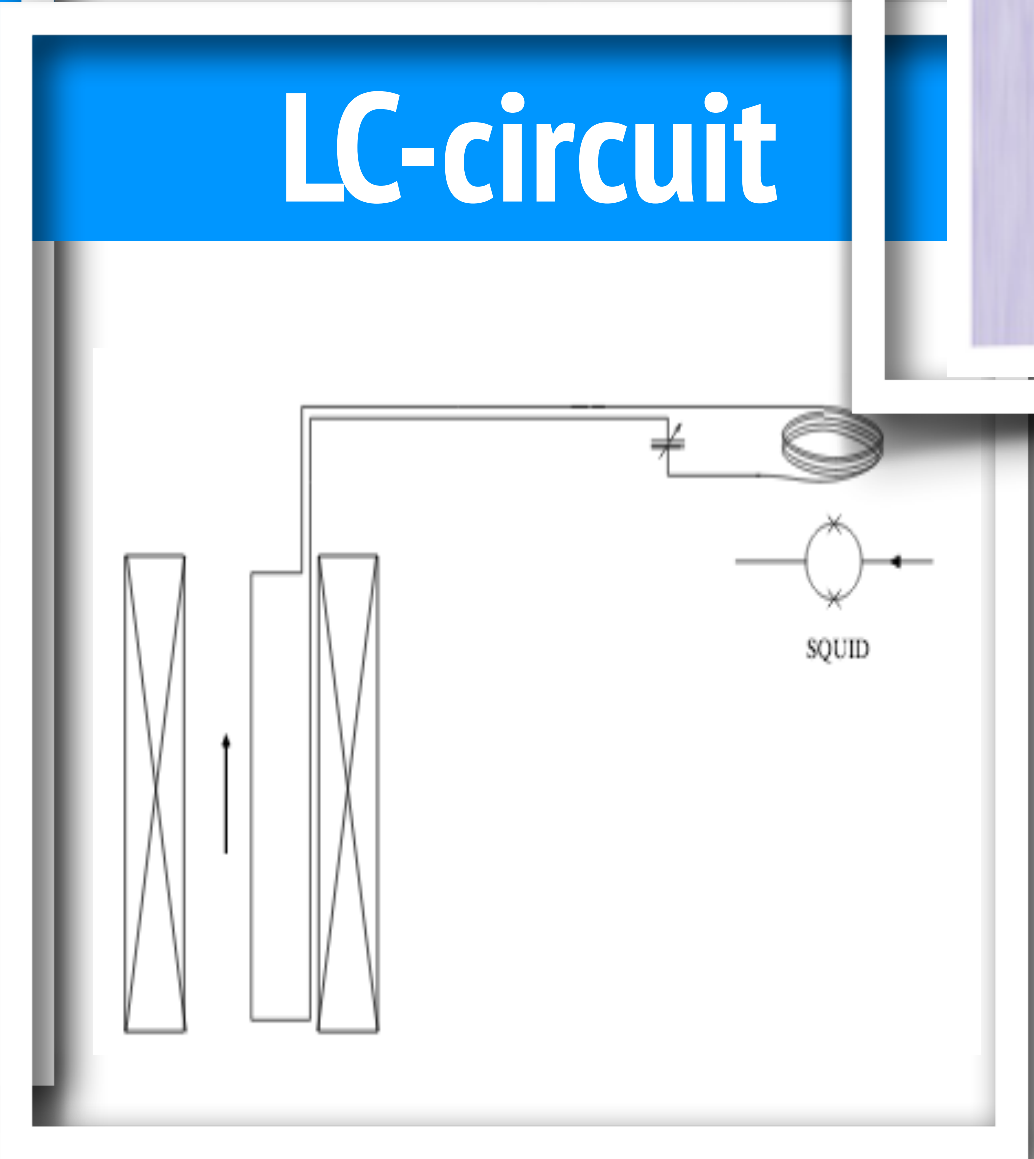
- From $f_a \sim 10^{19}\,\mathrm{GeV}$ to $f_a \sim 10^{8}\,\mathrm{GeV}$ 11 orders of magnitude in axion mass to scan ...
10^{17} channels in mass ....

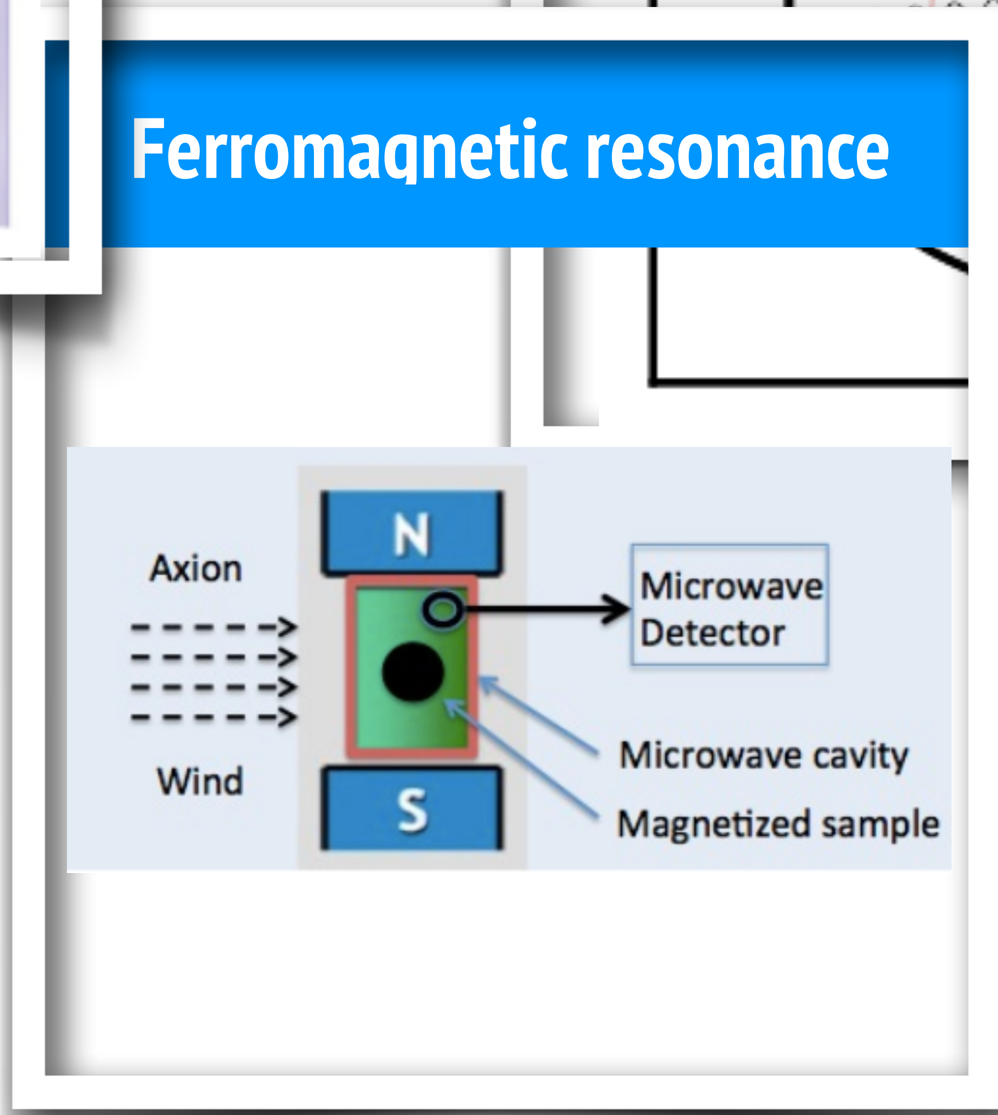


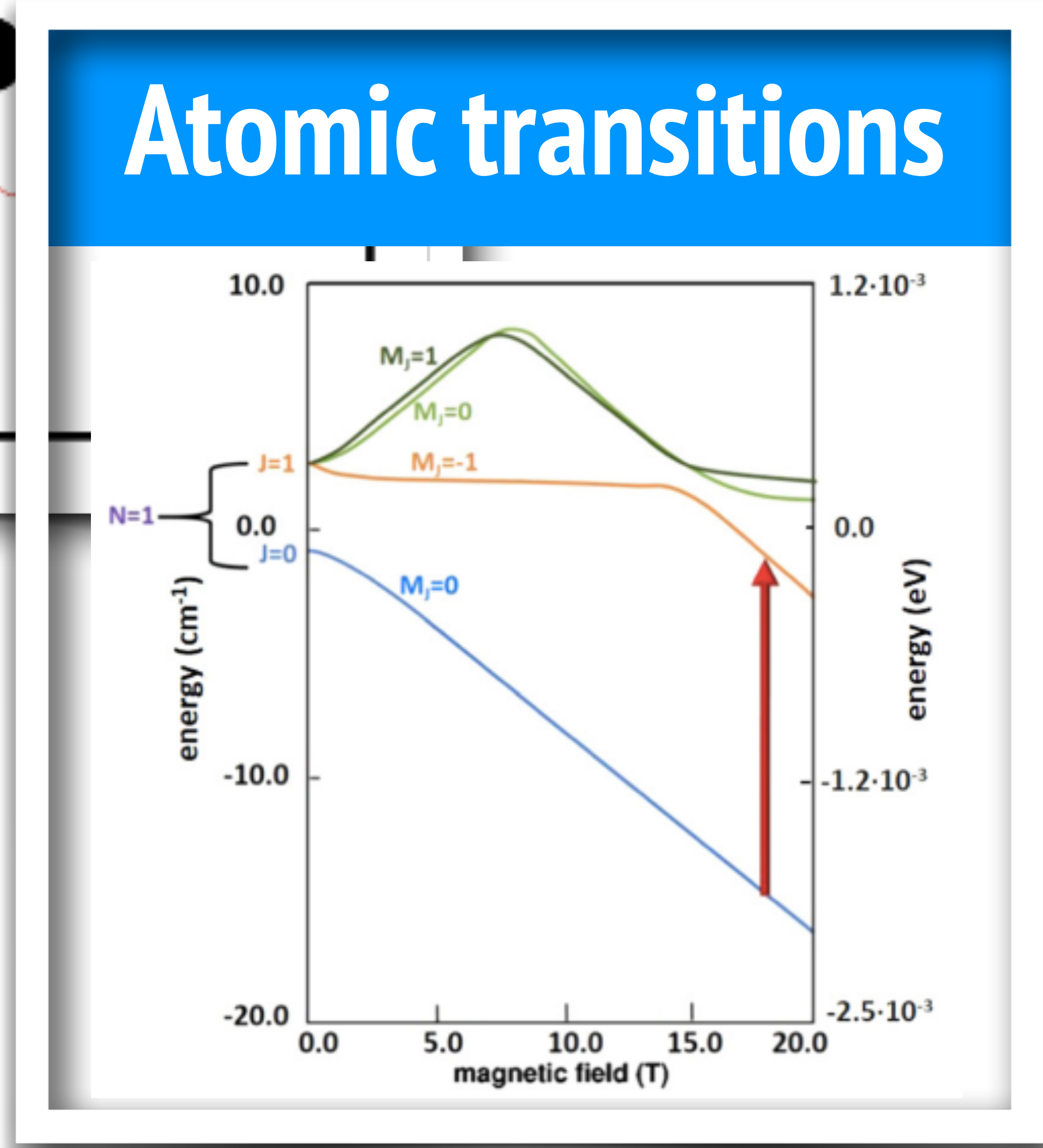












any theory bias?

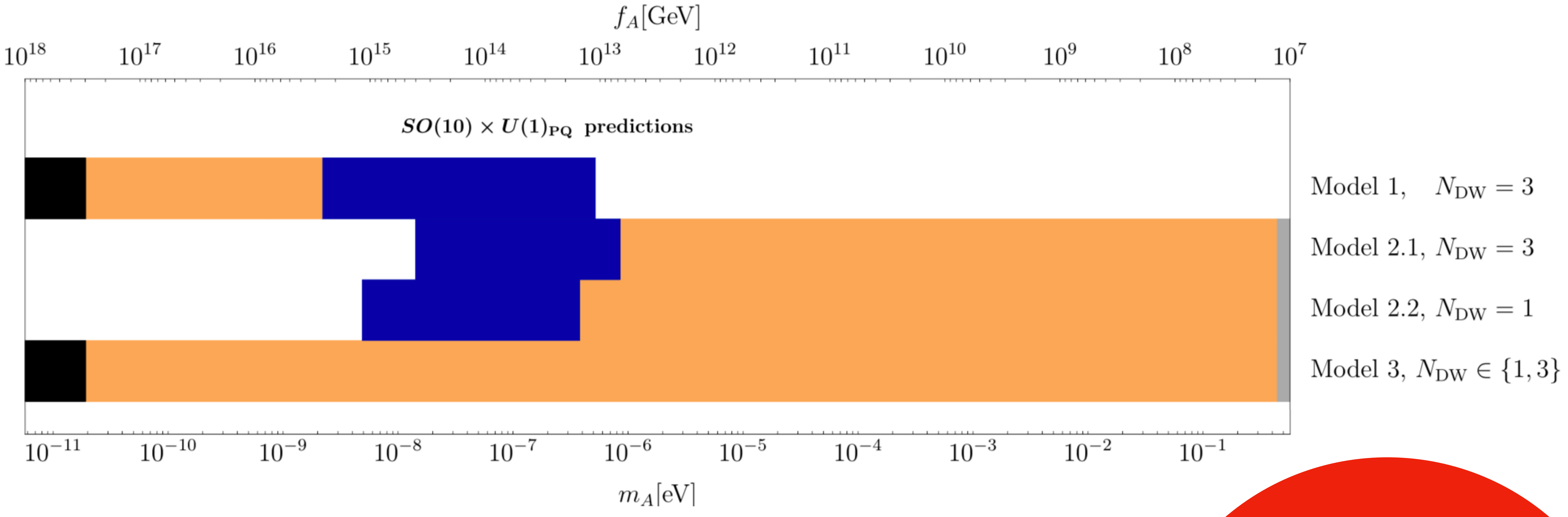
- String theory?

- weakly coupled heterotic string $f_A \simeq 1.1 \times 10^{16}\text{GeV}$ $m_A \simeq 5.2 \times 10^{-10}\text{eV}$ *Witten 1985*

- ... plenty of other posibilities *See e.g. Svrček 2006*

- Grand Unified Theories

see e.g. Ernst 2018



- Supersymmetry

- No strong theory bias, mostly pheno

- Simple complete-models PP+Cosmo (SMASH-like) *Ballesteros 2017*

- Motivations are pheno

any bias from phenomenology?

- Measurement available

- Axion DM abundance $\Omega_A(m_A)h^2 \leq 0.12$ → $m_A \geq 42\,\mathrm{tbc}$ *tbc, to be confirmed units*

- Measurements possible in the future

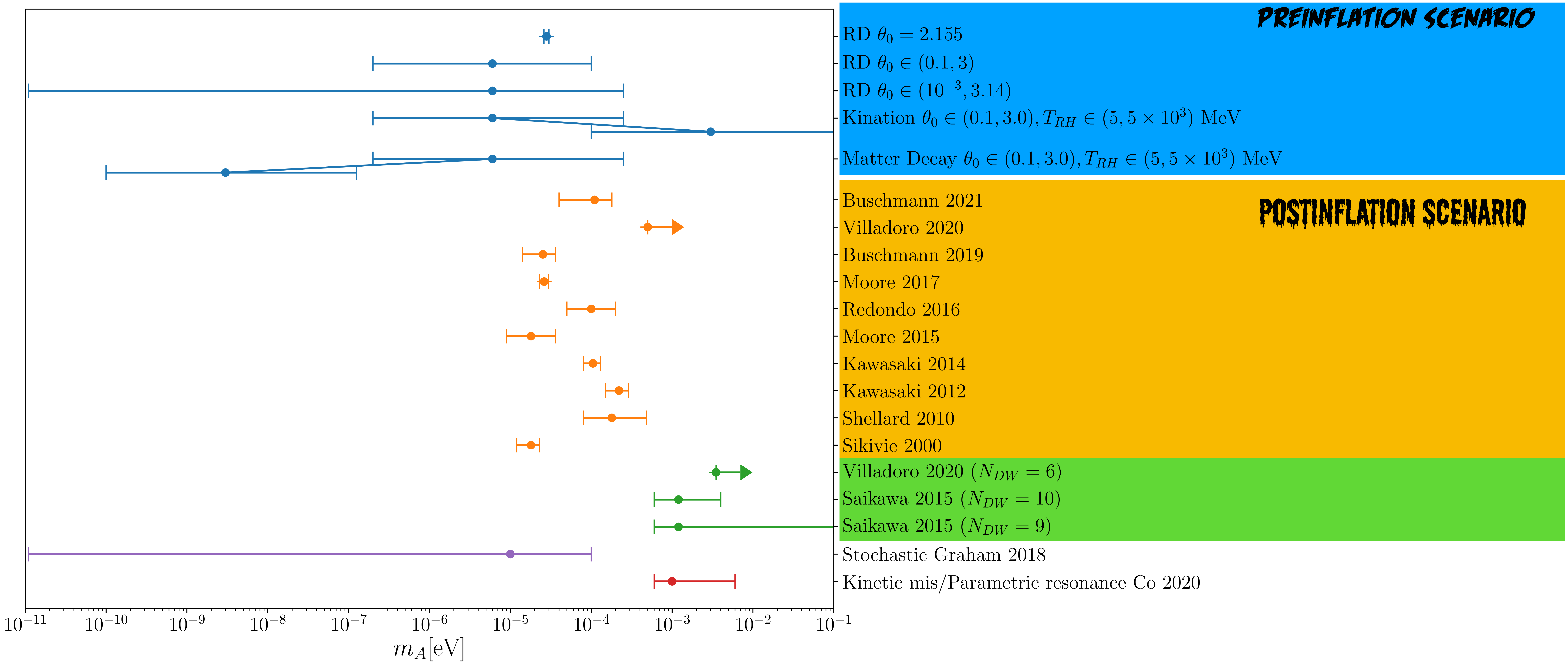
-Observed galactic/extragalactic MW lines from axion DM decay ?

-Black hole spin depletion?

-Microlensing/femtolensing/other type of events from axion miniclusters?

-birefringence/dichroism?

Axion DM mass: ICs and Cosmology



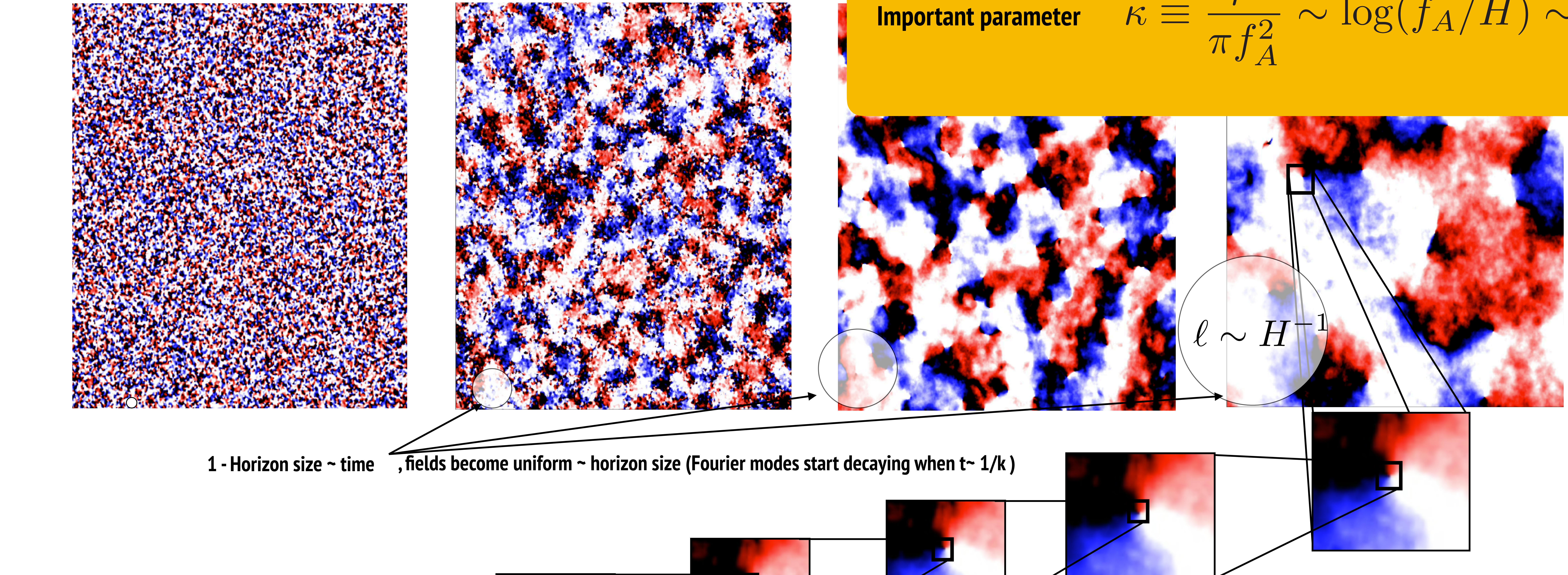
post-inflationary scenario N=1

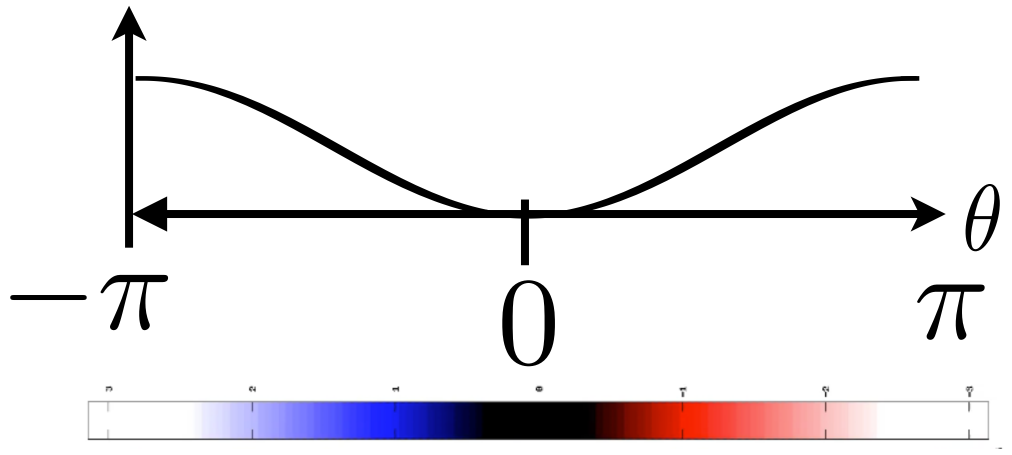
Postinflation scenario, the problem

- Axion strings form by Kibble mechanism
- Energy logarithmically distributed around, tension $\mu \simeq \pi f_A^2 \log\left(\frac{f_A}{H}\right)$

- SIMULATION REQUIRES DYNAMICAL RANGE $\sim f_A/H \sim 10^{30}$ (available $\sim 10^3$)

Important parameter $\kappa \equiv \dfrac{\mu}{\pi f_A^2} \sim \log(f_A/H) \sim 70$



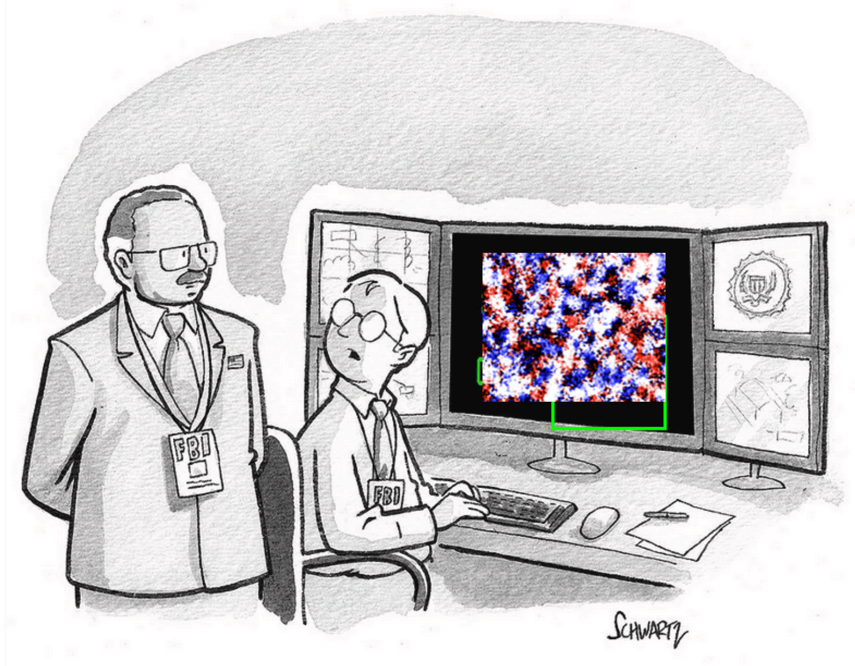


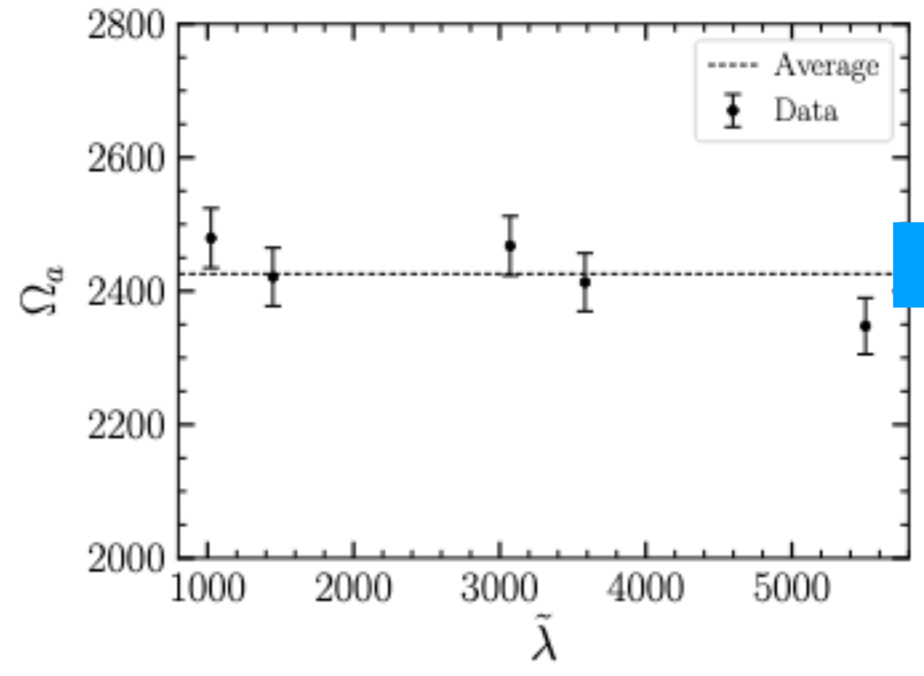
How to tackle the energy problem (get the right axion number)

Two approaches:

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

Moore, Redondo, Buschmann

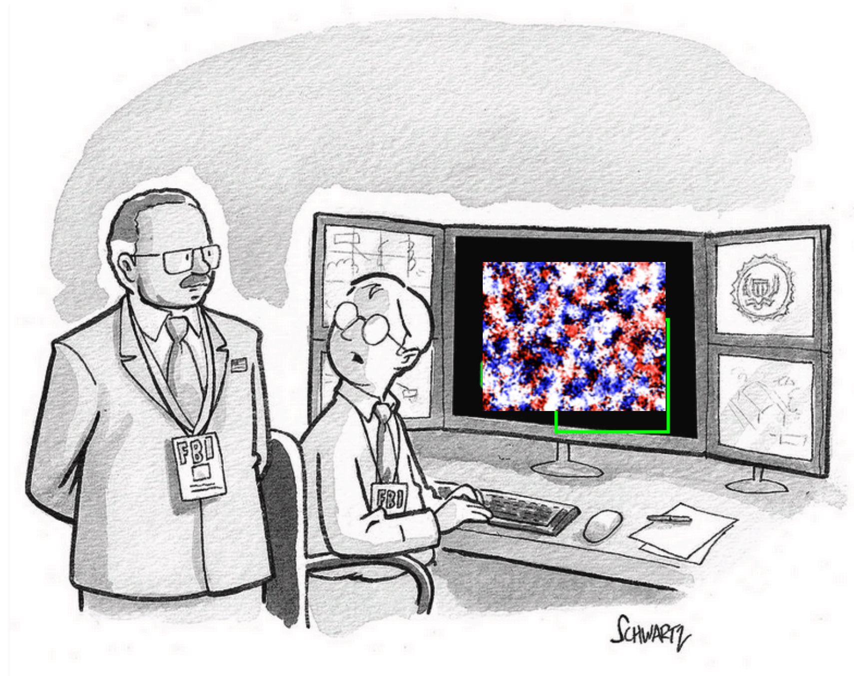


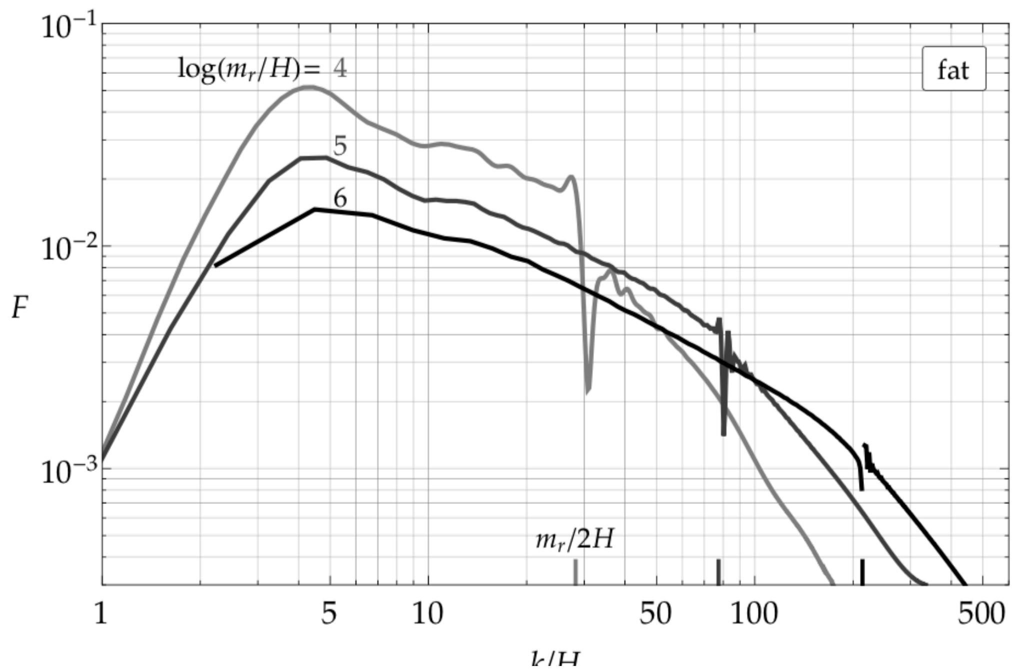


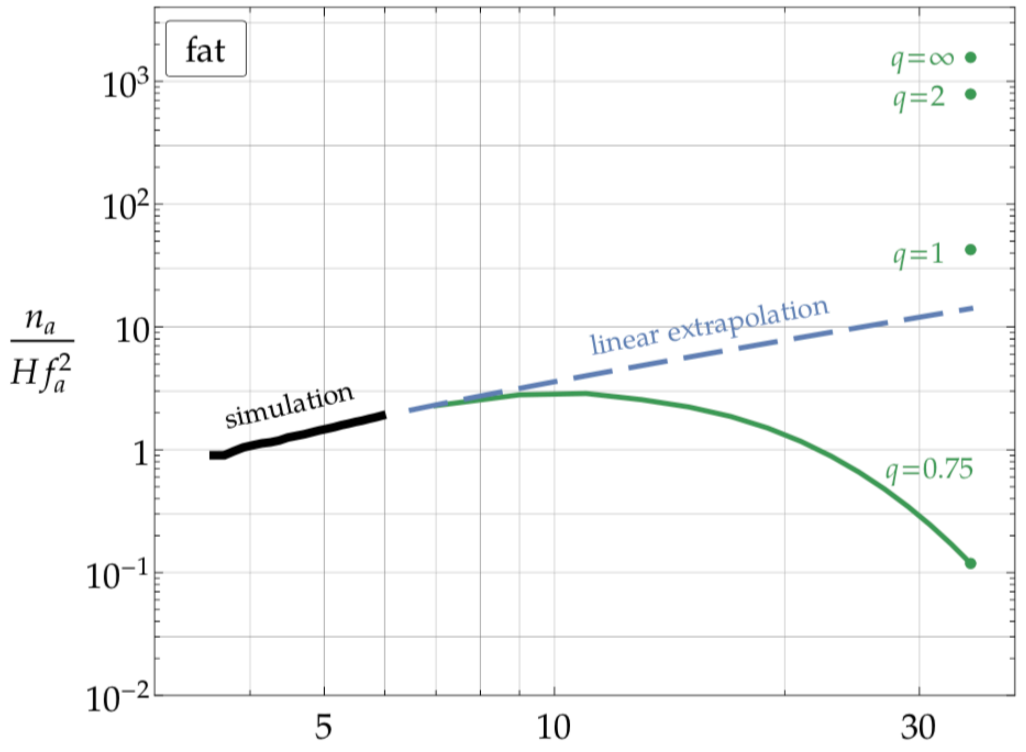
$\kappa \sim \log(\lambda)$

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

Kawasaki, Gorghetto, Buschmann

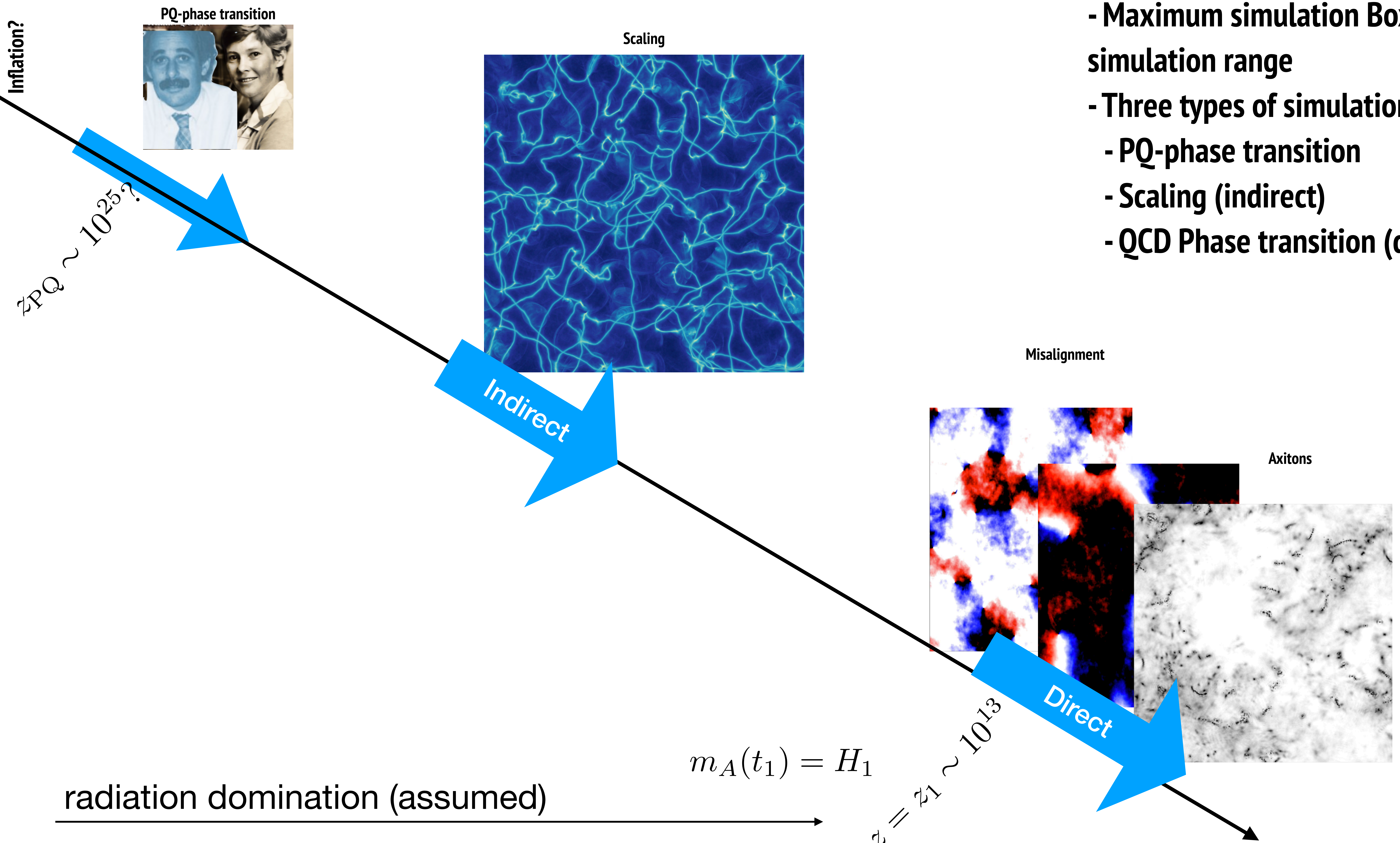






post-inflationary scenario, simulations

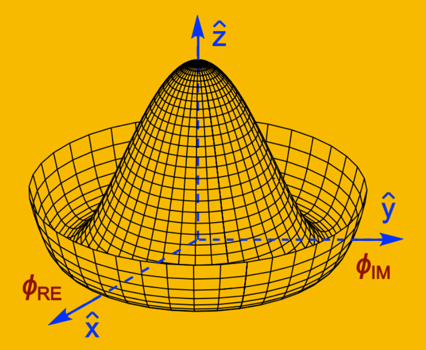
- Maximum simulation Boxes of 10^4, limited simulation range
- Three types of simulations:
  - PQ-phase transition
  - Scaling (indirect)
  - QCD Phase transition (direct)



Direct simulations

Two approaches:

Usual U(1) global string



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

$f_A \sim v$

$$\kappa \sim \log(v/H)$$

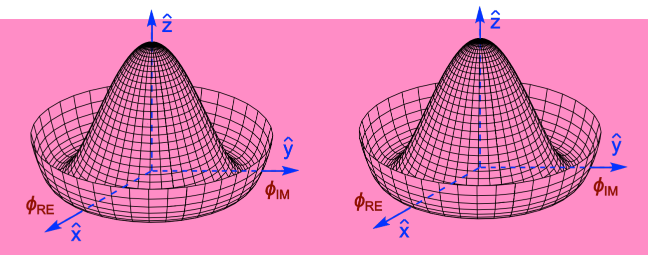
Moore, Redondo, Buschmann

1 extra degree of freedom (radial mode, saxion)

unphysical DW destruction

PRS trick (enhanced tension at early times)

Moore tension string



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

$f_A \sim v/\sqrt{q_1^2+q_2^2}$

$$\kappa \sim 2(q_1^2 + q_2^2)$$

Moore

2+3 extra degrees of freedom (two higgs, 1 vector field)

fA/v parametrically suppressed by gauge charges

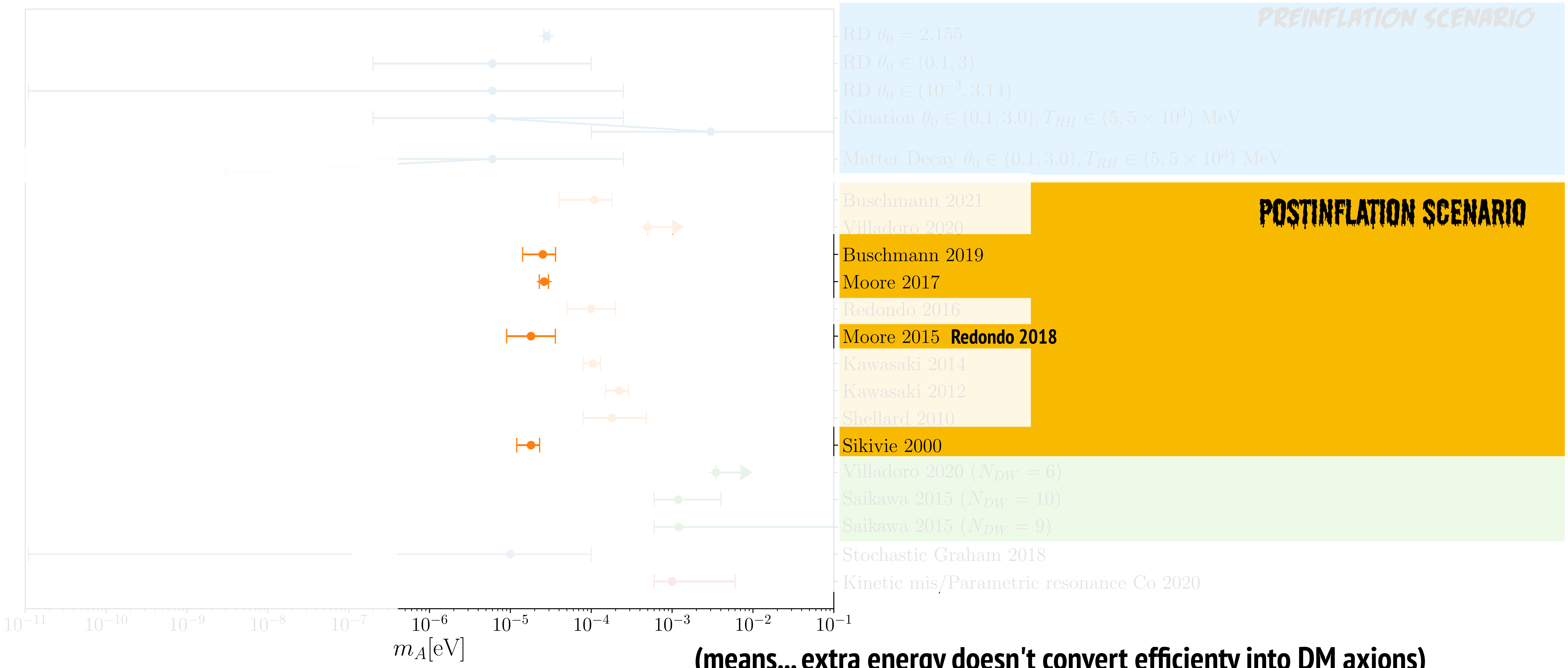
large effective tension

no unphysical DW destruction

PRS trick (enhanced tension at early times)

Direct simulations

Relatively good agreement of direct simulations



(means... extra energy doesn't convert efficienty into DM axions)

"UV energy stays in the UV"

Indirect simulations: the axion spectrum

- Goal: understand how energy is transfered from strings to axions

- String network density, scaling solution (O(1) string length/Hubble vulume)

$$\rho_s = \xi \frac{\mu}{t^2} \quad \left(\sim \frac{\mu \ell}{\ell^3}\right)_{\ell\sim t} \sim \mathcal{O}\left(\xi H^2 f_A^2 \kappa\right)$$

Kibble, Vilenkin

$$\xi \sim 1$$

Yamaguchi '99, Hiramatsu '11

Implies an energy loss rate $\Gamma_{st\to A} = \dfrac{\xi\mu}{t^3}$

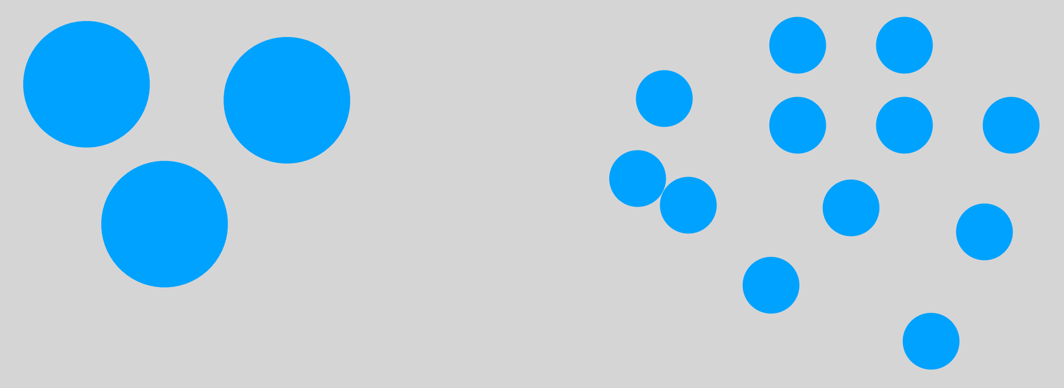
- Axion ENERGY produced at that rate ... $\dot{\rho}_A + 4H\rho_A = \Gamma_{st\to A}$

$$\rho_A \sim \frac{1}{2}\langle|\dot{A}|^2\rangle \sim \mathcal{O}(\xi\kappa H^2 f_A^2)$$

- BUT Axion NUMBER is the adiabatic invariant!

- Axion number depends on the spectrum $n_A(t) \sim \int_0^t dt' \left(\frac{R'}{R(t)}\right)^3 \int \frac{dk}{k}\frac{\partial\rho_A}{\partial t\partial k}$

depends on the mean energy



few high-E axions

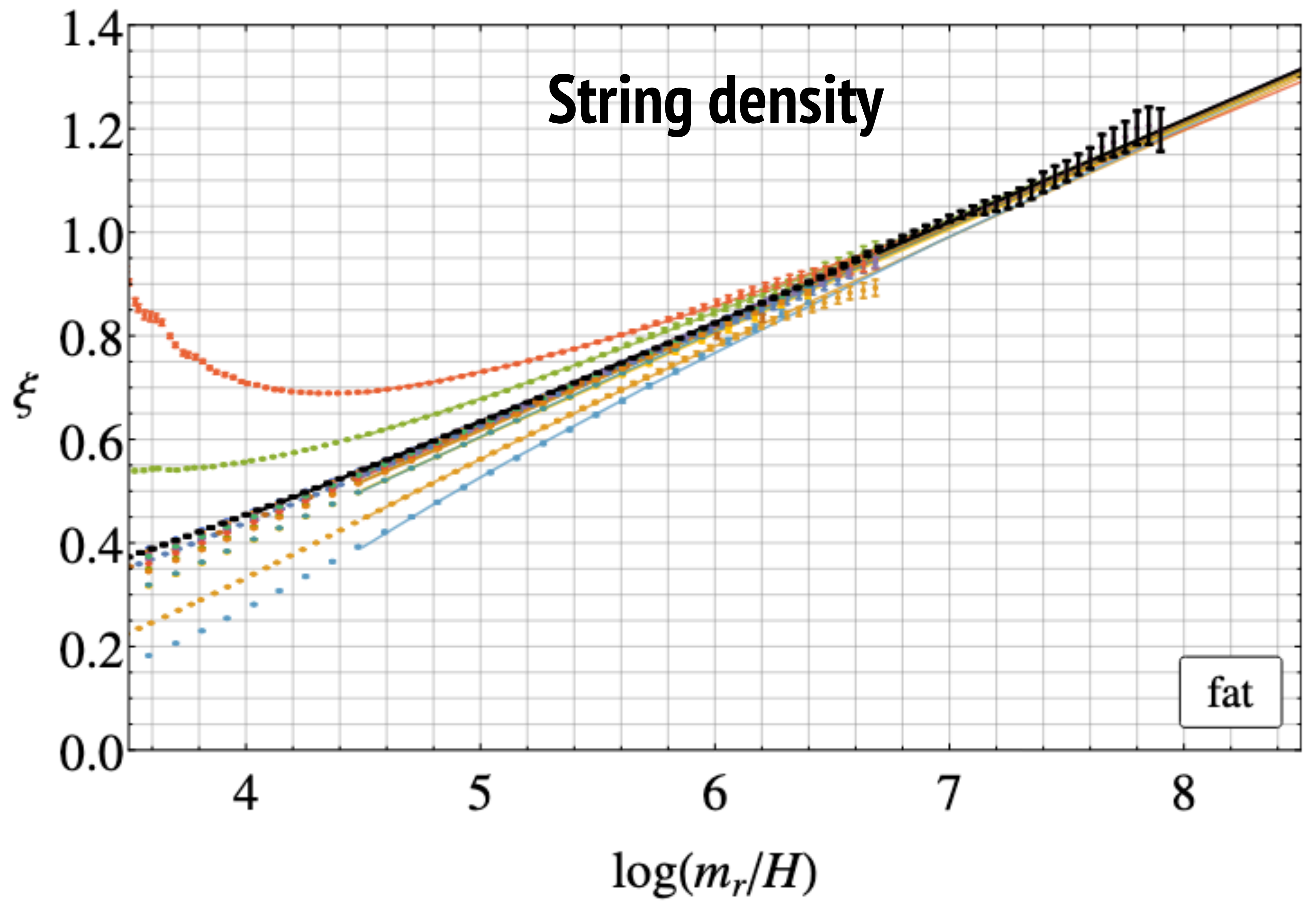
many low-E axions

String network evolution

- Studied in many papers at low tension (k<9)
- O(1) with small logarithmic increase *Gorghetto, Viladoro, Hardy*
- Extrapolates to O(15) *Gorghetto, Viladoro, Hardy20 , Buschman 21*
- Small controversy, 1p vel model *Hindmarsh 21*

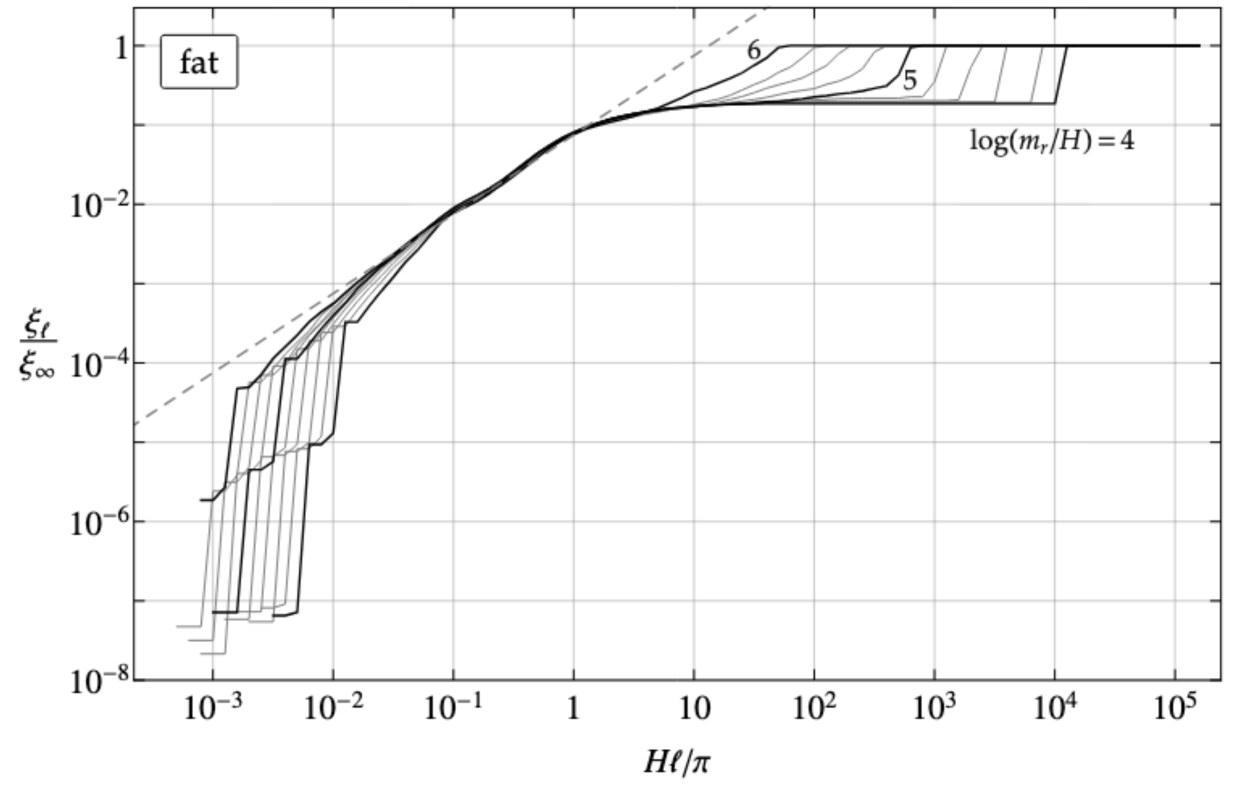
string-length per

causal horizon



log fA/H (distance between strings/string core)

The fraction of the total string length ξ`/ξ∞ that is contained in loops smaller than l for different time shots.



Spectrum of string radiated axions

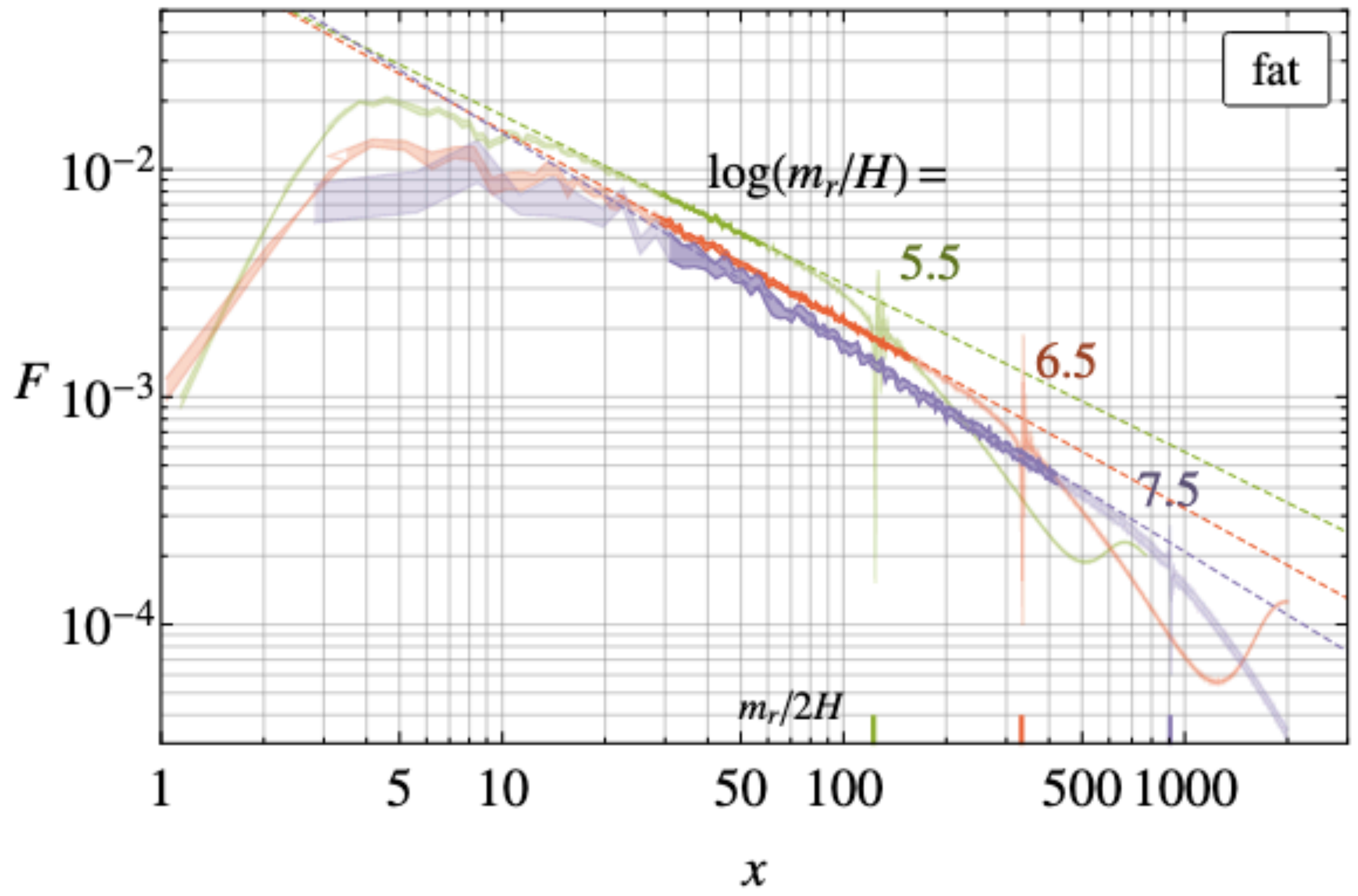
Gorghetto, Viladoro, Hardt

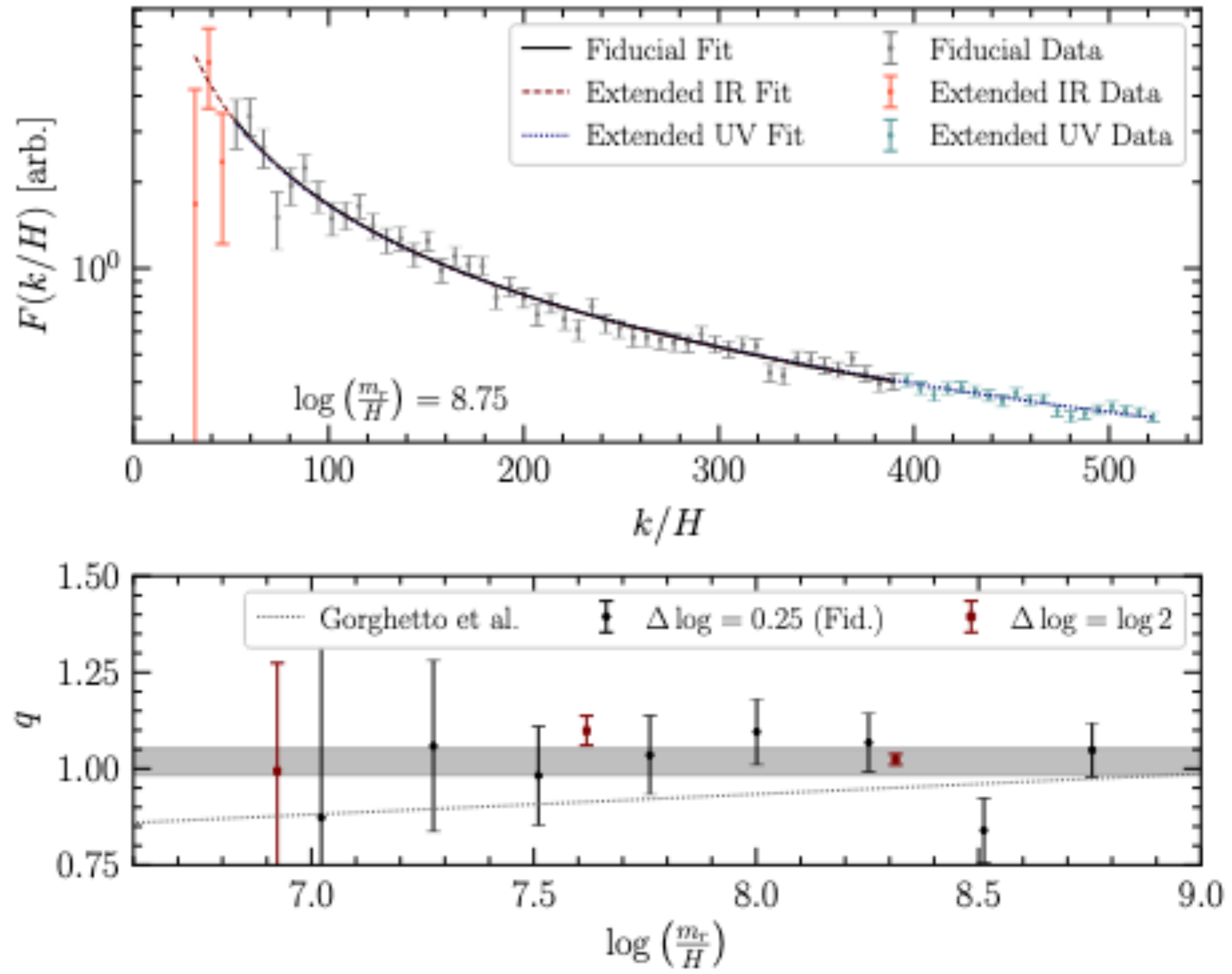
- Time-derivative of the spectrum $F \sim \dfrac{\partial^2 \rho_a}{\partial t \partial k}$

- Power-law between IR (limited by causality) and UV (fA) cut-offs

$$1/k^q$$

- Several attempts in the literature, differ mostly in :
  ICs, statistics, and analysis details *Hiramatsu, VGH, Redondo, Buschman*



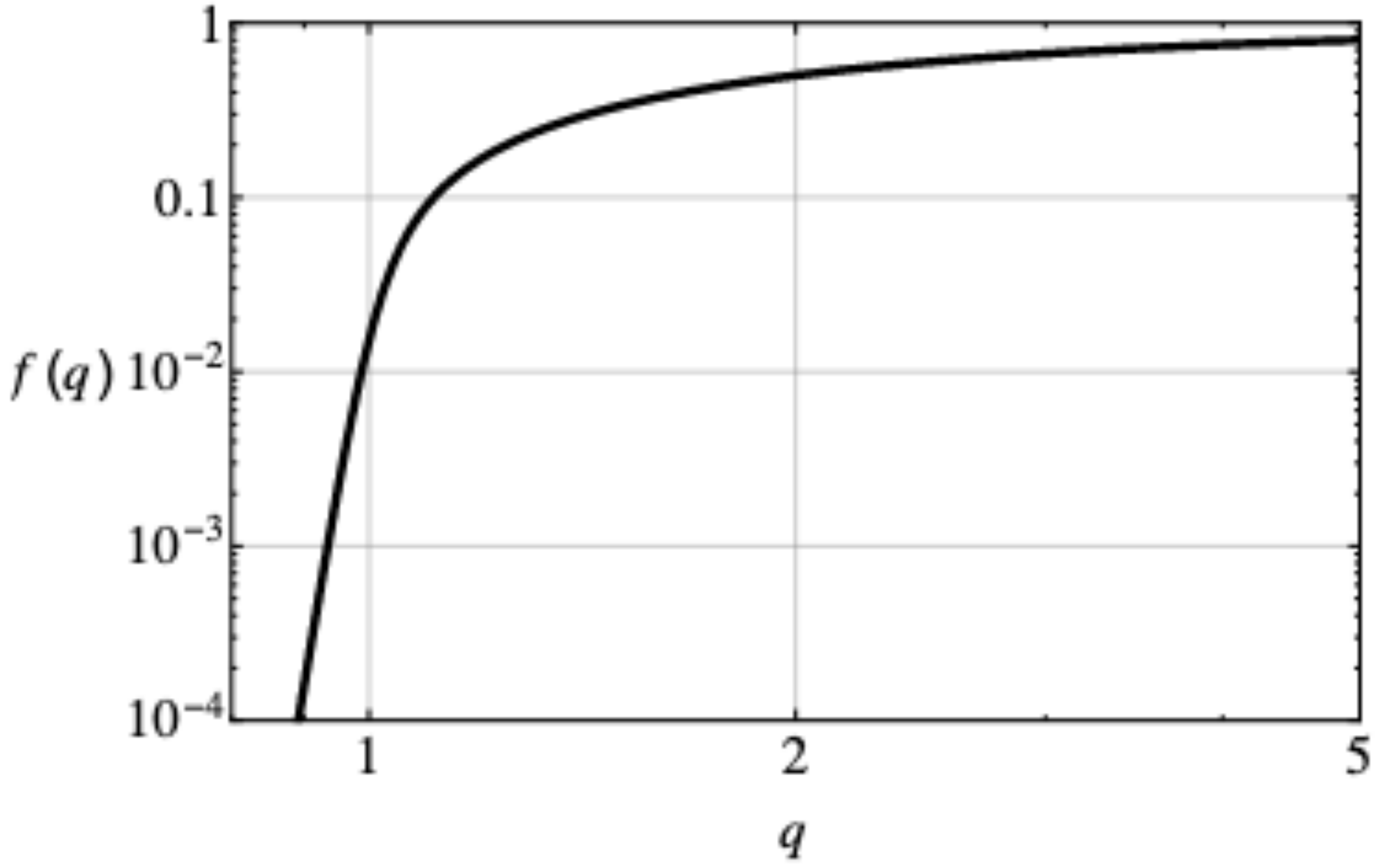


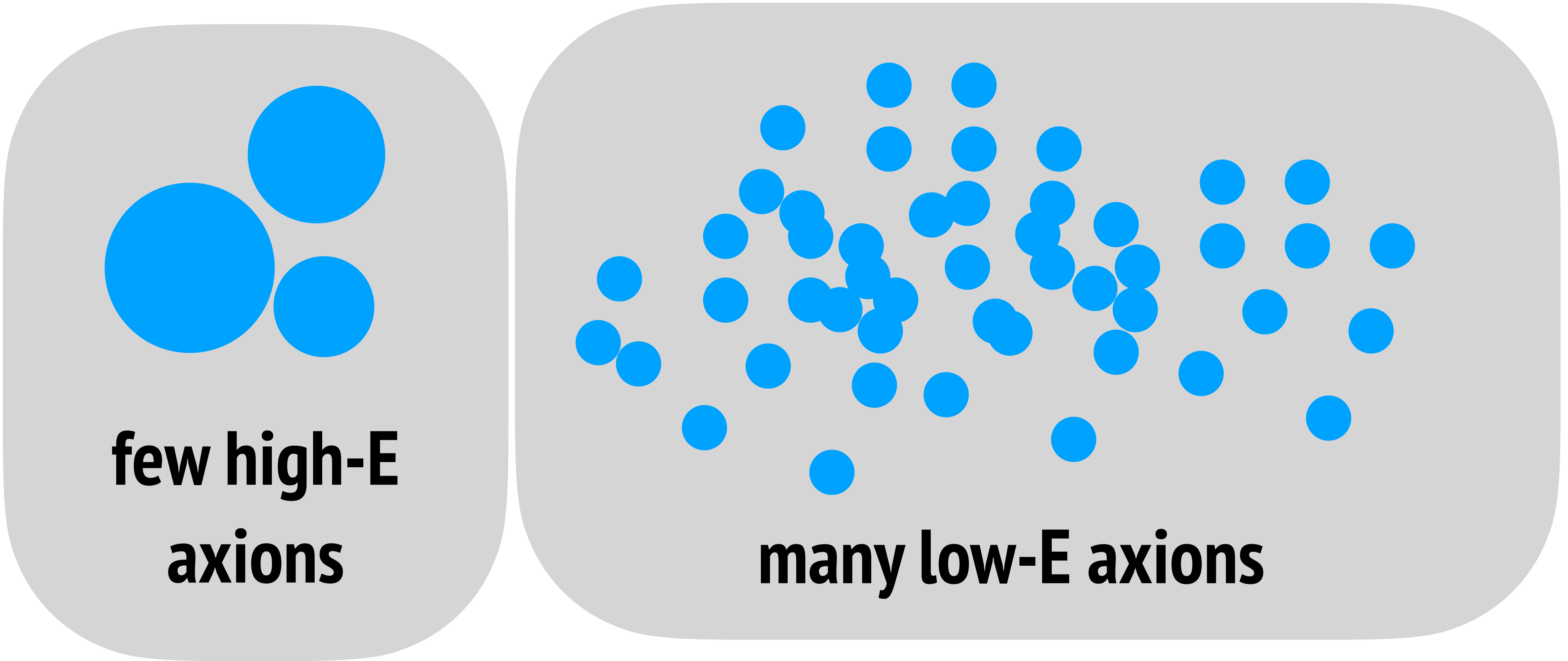
the impact of q

- Model spectrum like a power law $1/k^q$

$$F[x,y] = \begin{cases} \frac{1}{x_0}\left(\frac{x_0}{x}\right)^q \frac{q-1}{1-\left(\frac{x_0}{y}\right)^{q-1}} & x_0 < x < y \\ 0 & x < x_0 \vee x > y\,, \end{cases}$$

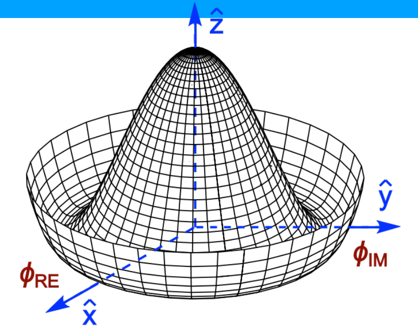
$$n_a(t) \approx \frac{8H\xi(t)\mu_{\rm eff}(t)}{x_0} \times \begin{cases} 1 - 1/q & q > 1 \\ \frac{1}{\log\left(\frac{m_r}{Hx_0}\right)} & q = 1 \\ \frac{1-q}{q(2q-1)}\left[\frac{Hx_0}{m_r}\right]^{1-q} & \frac{1}{2} < q < 1\,, \end{cases}$$





the value of q

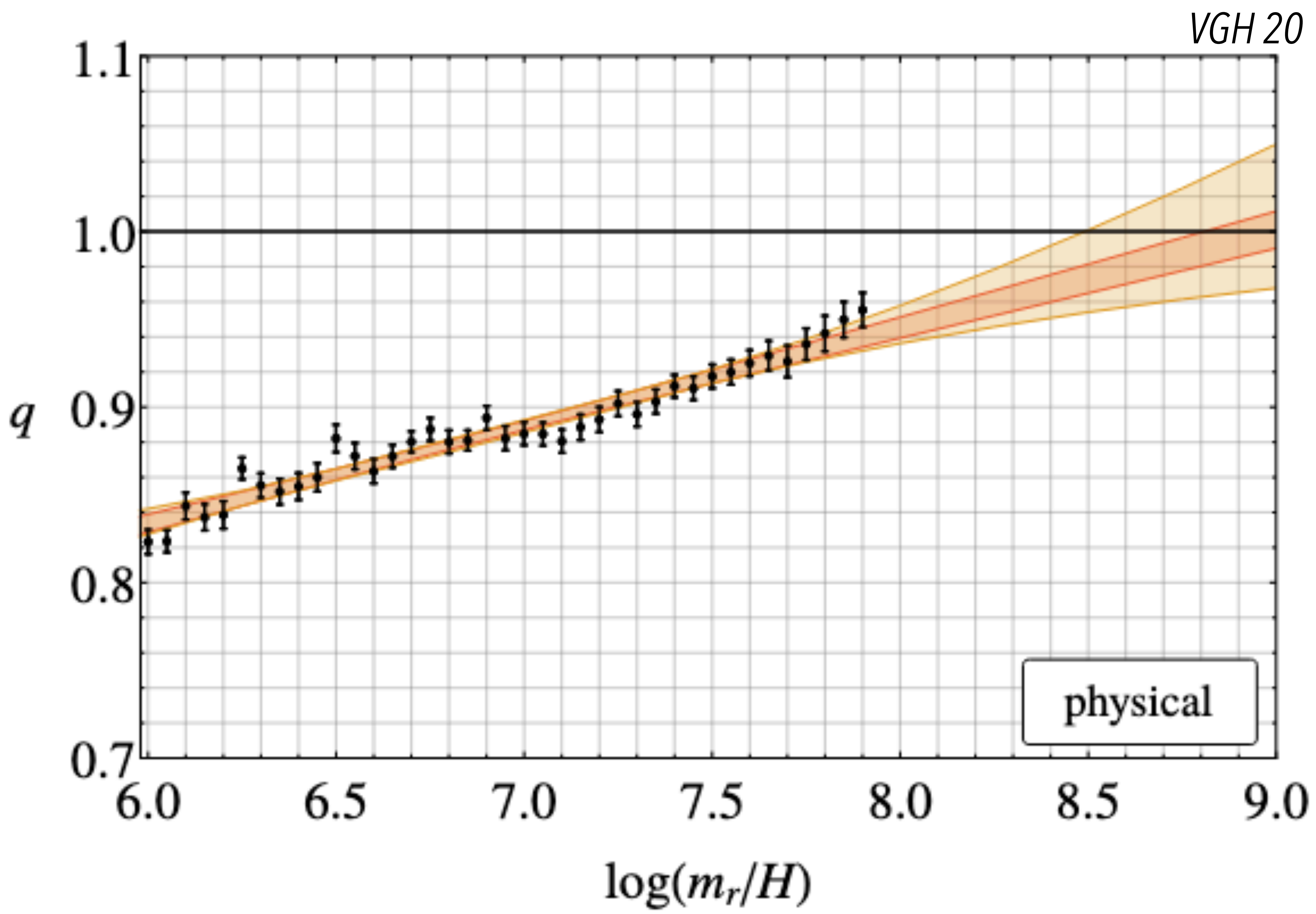
- VGH 20



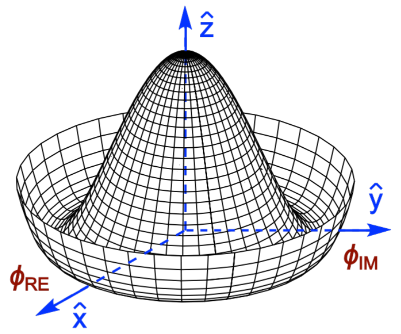
  - ICs in the atractor solution
  - O(100) simulations
  - find q<1 but increasing
  - theoretical expectations
  - Compatible with similar simulations (in particular mine…)

(Redondo, Saikawa, Vaquero to appear)

VGH 20

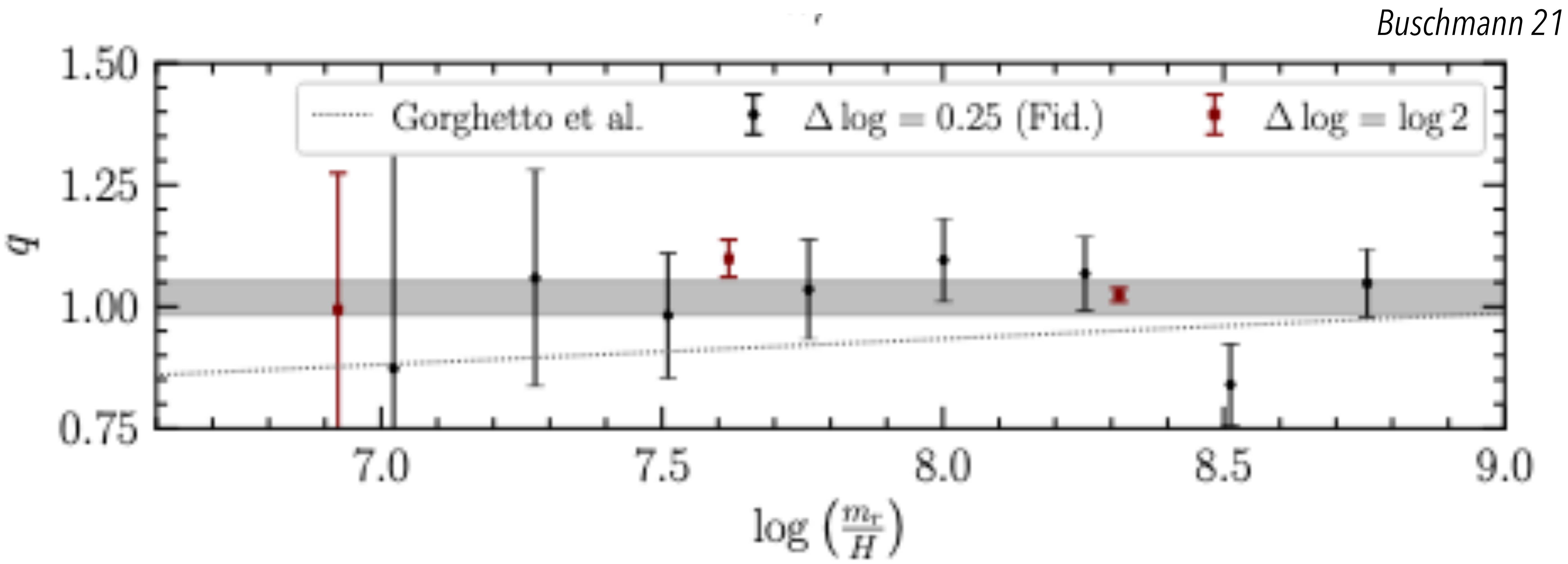


- Buschmann 21

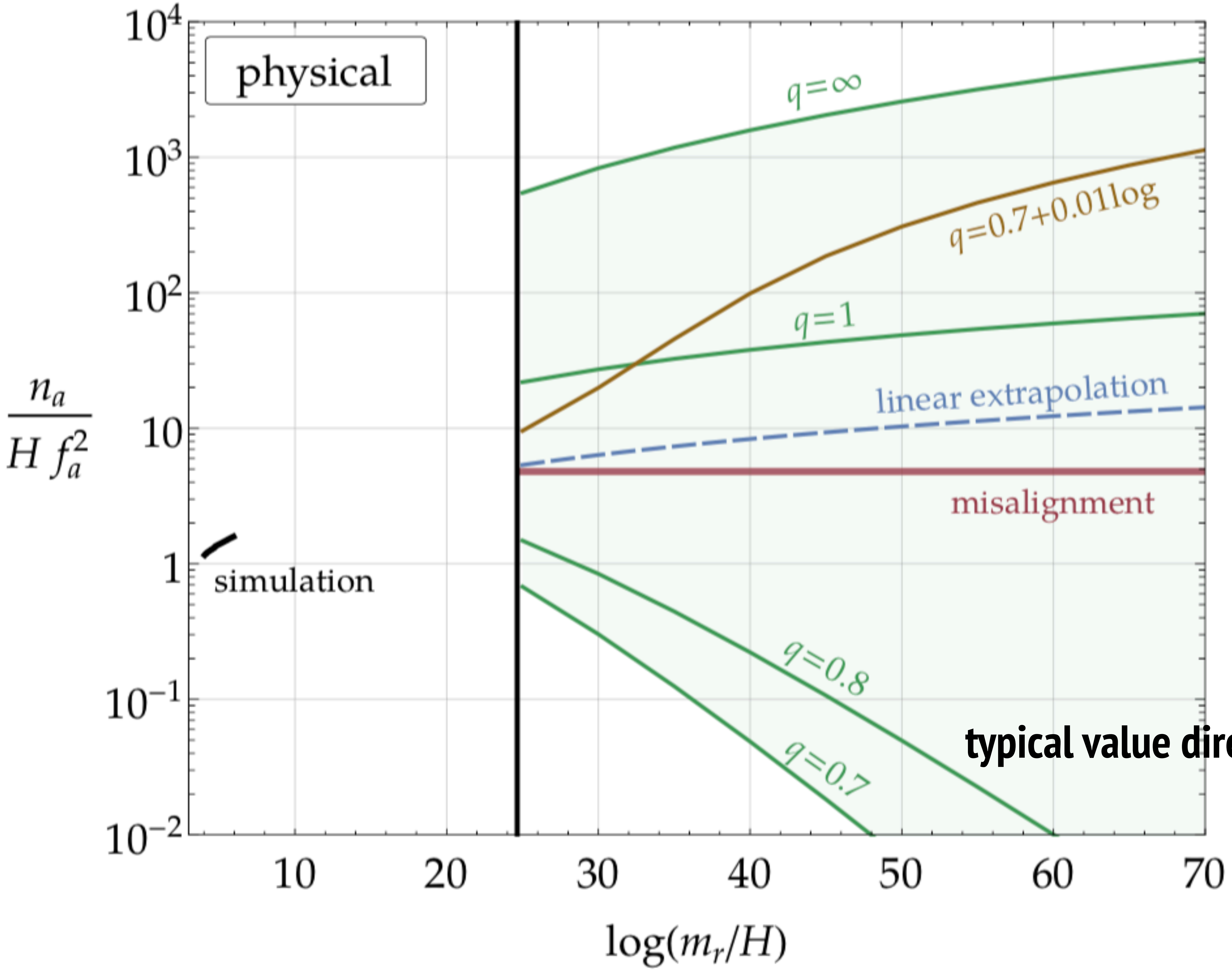


  - ++AMR to increase dynamical range!!
  - ICs with a PQ phase transition (parameters?)
  - 1 huge simulation
  - Very conservative analysis
  - find q~1 NOT INCREASING
  - some theoretical reasoning

Buschmann 21



Extrapolation



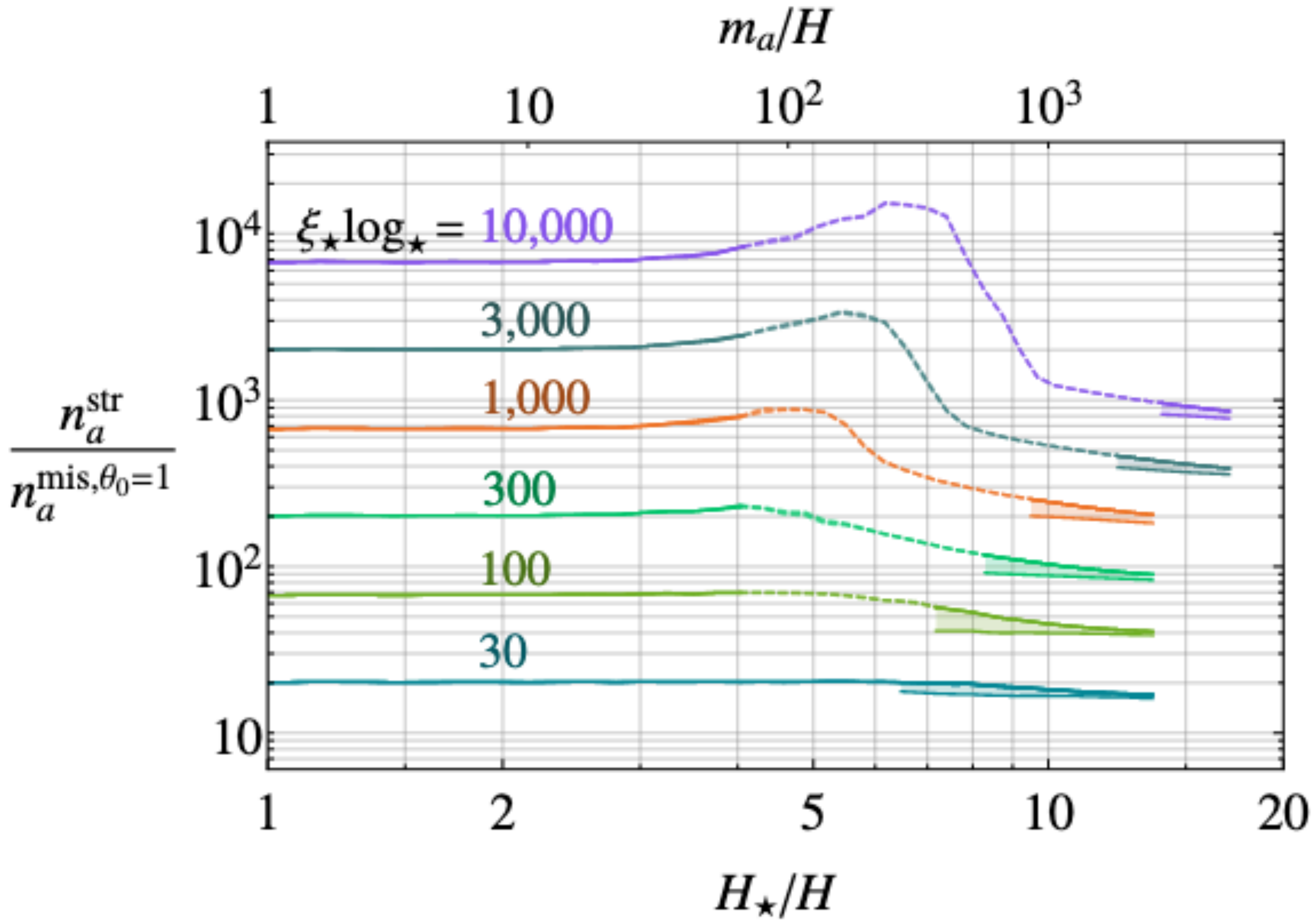
VGH 21

Buschmann 21

typical value direct simulations, strings do not matter

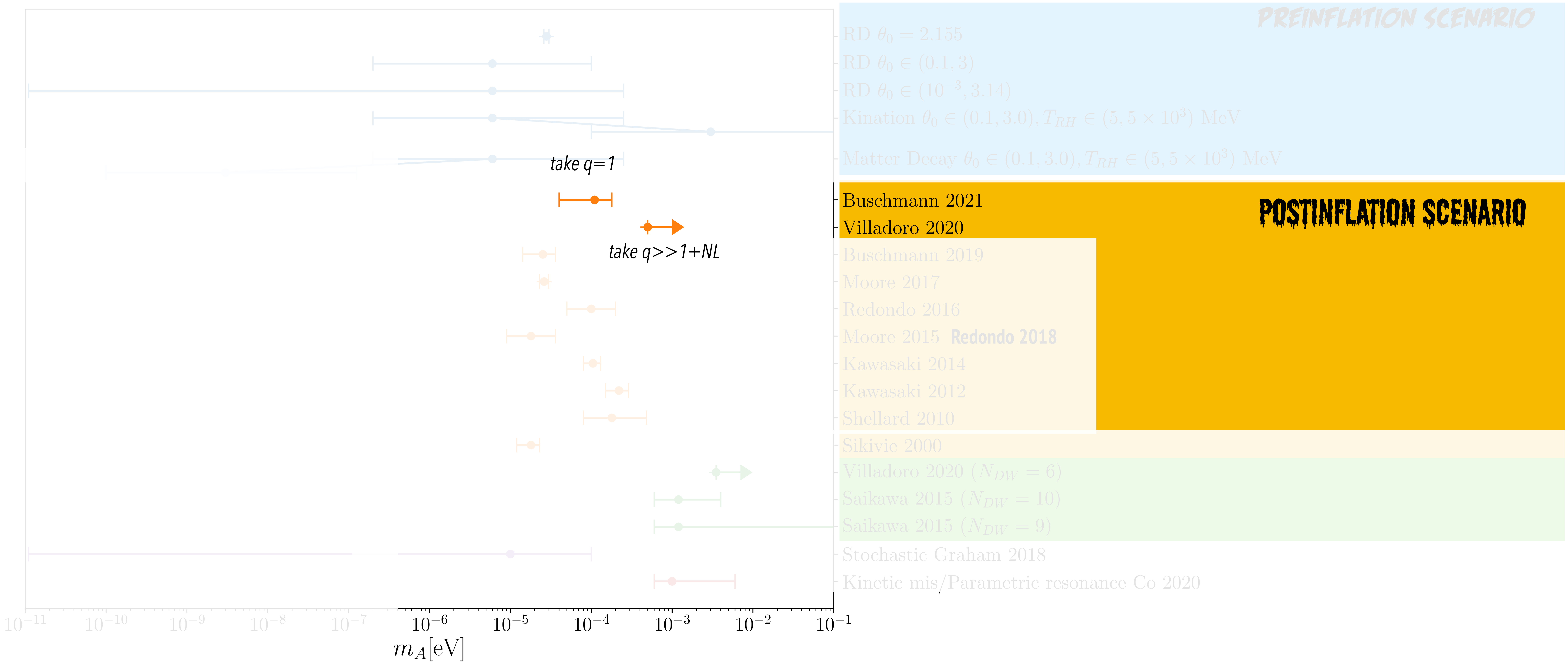
Non-linearities at large axion production

- Scaling analysis give a value of nA around the QCD phase transition,
- QCD potential is non-linear, DWs destroy string network … how does this affect?
- Leading effects at large nA studied by VGH21, strong SQRT reduction
- Very important for VGH21 assumption (q>>1), less so for Buschmann 21 (q~1)



Direct simulations

Very good agreement of direct simulations



Conclusions

- New generation of numerical simulations are getting closer to tackle the axion DM mass

- Main problem is **dynamical range**

- Direct attempt: **more or less convergent results** (need to reduce errors) [have xi~O(1), q<1], k~8-70! **UV stays in the UV**

- Indirect attempt:

  - VGH atractor solution suggests q>>1 ... although the growing trend could stagnate at q=1 (then why not xi too?)

  - Buschmann 21 finds q=1 with **1 simulation** and **different ICs, no NL evolution under QCD**

- Need to increase dynamical range, statistics and use similar ICs to be sure of extrapolation.

- Note: Direct attempt is only justified if q<~1, xi~O(1) by the indirect attempt