Radiation from Axion Strings

with

Adaptive Mesh Refinement

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PhysRevD.105.063517, PhysRevD.107.043507 with Paul Shellard + to appear…
AMR papers in CQG and JOSS with members of GRChombo collaboration

Motivation

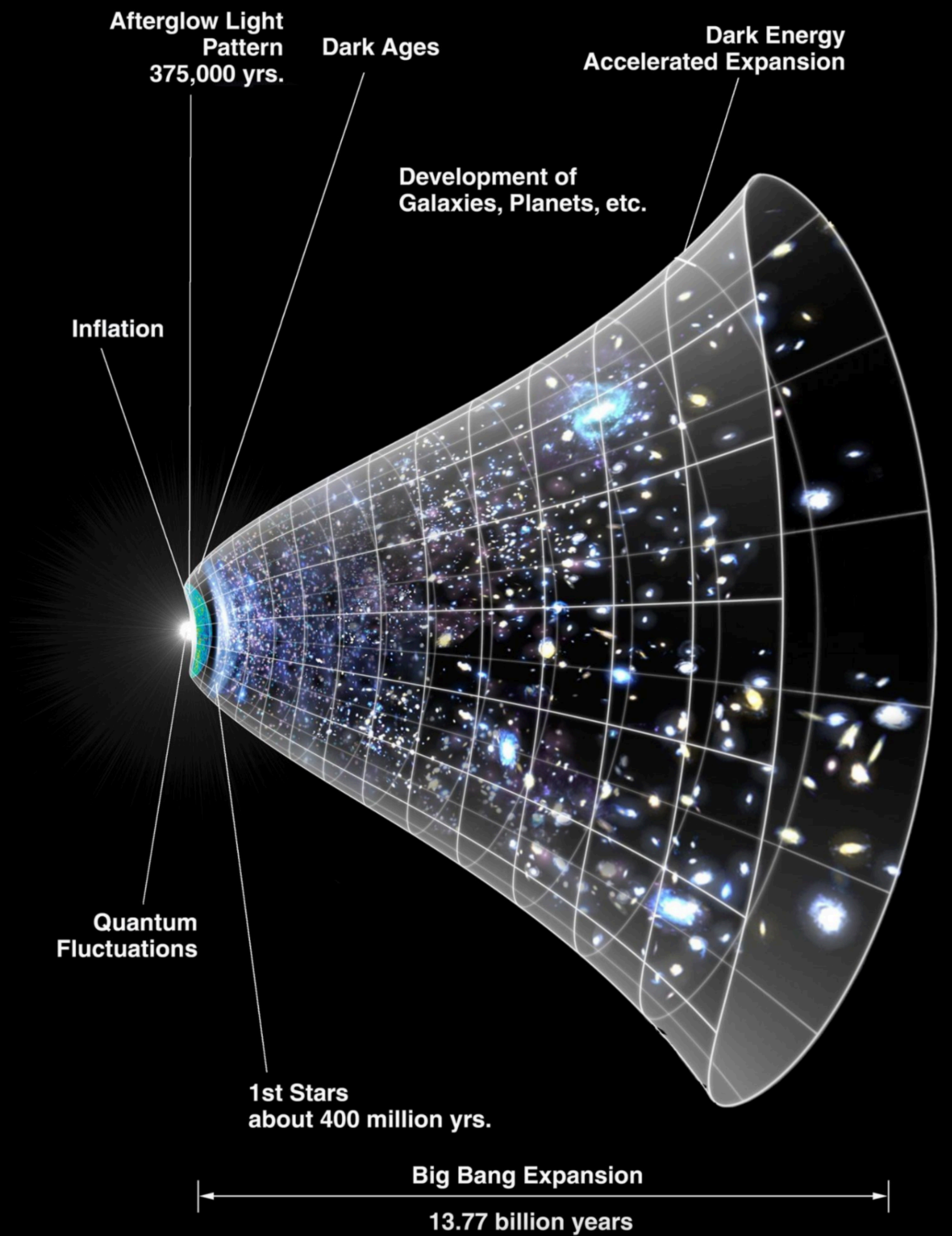
Ingredients

- ✓ Beyond Standard Model, e.g. QCD axion, ALPs, superstring theory
- ✓ Introduce complex scalar

$$\varphi = |\varphi| e^{i\frac{\vartheta}{f_a}}$$

with $U(1)$ symmetry, spontaneous symmetry breaking scale f_a

- ✓ Spontaneous symmetry breaking, Kibble mechanism, $V_{\rm eff}(\varphi, T) \to$ network of strings



Credit: NASA/WMAP Science Team

Motivation

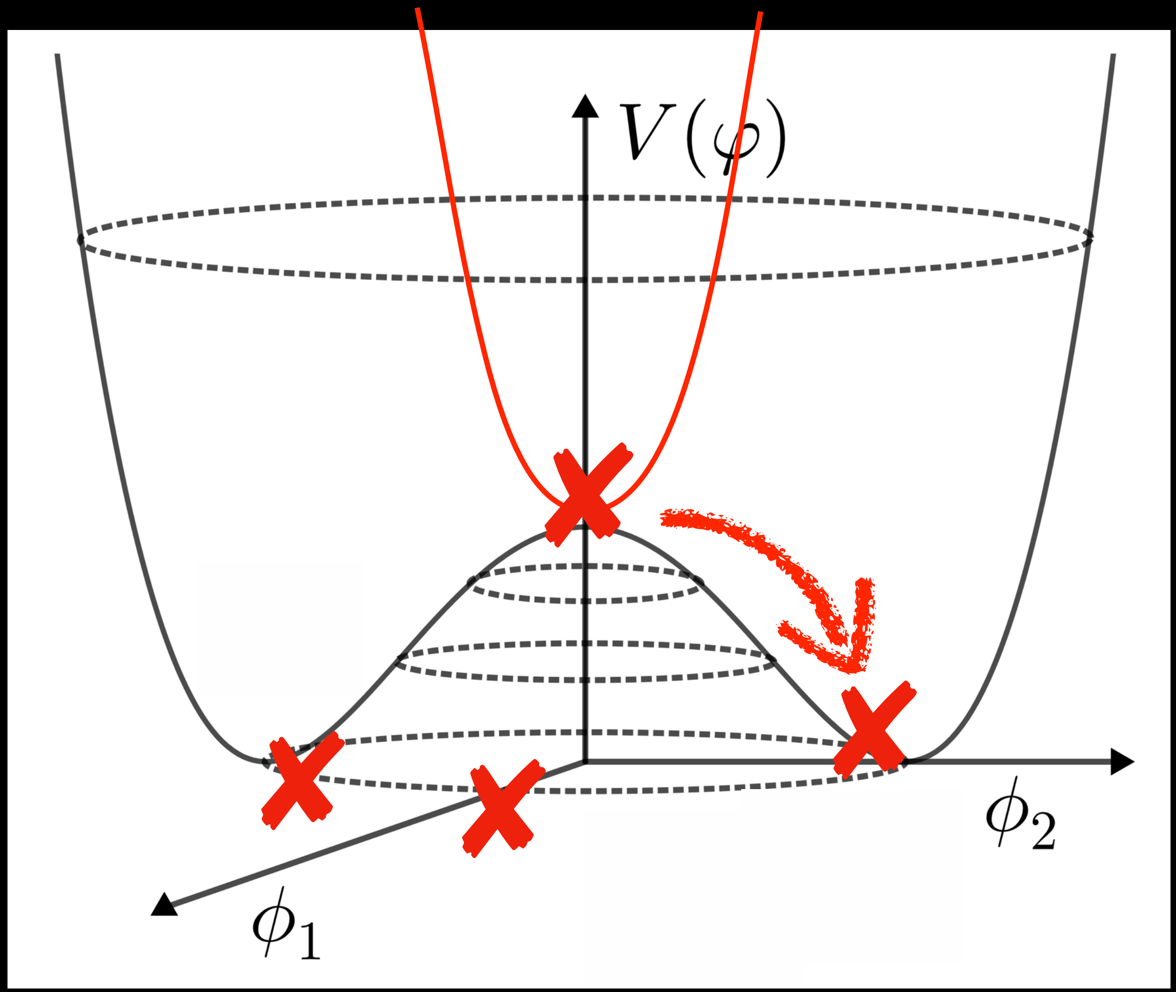
Symmetry Breaking

- ✓ Network of strings emits massive and axion radiation
- ✓ Consider post-inflationary scenario (symmetry breaking after inflation)

$$f_a < \frac{H_1}{2\pi} \; (\lesssim 10^{13}\,\mathrm{GeV})$$

(Planck/BICEP2 constraint)

- ✓ Spectrum of axion radiation from network determines later misalignment production of DM axions



$$V(\phi) = \frac{\lambda}{4}(\phi\bar{\phi} - f_a^2)^2$$

See Doddy Marsh `Axion Cosmology' Review

Motivation

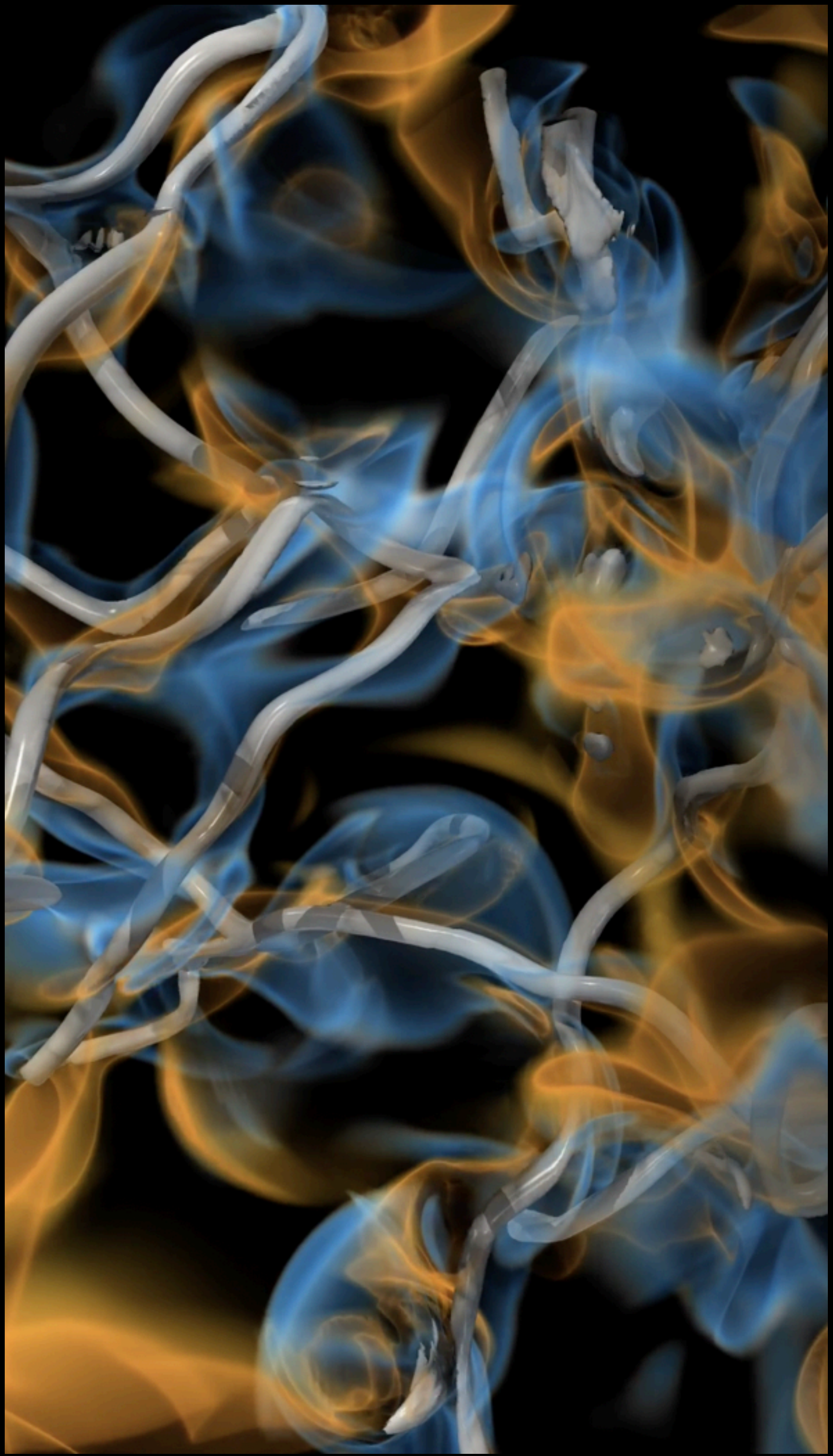
Separation of Scales

- Must understand network dynamics to predict axion spectrum and mass
- Axion string energy density

$$\mu \sim 2\pi f_a^2 \ln(m_H/H)$$

$1/H \sim$ curv. scale, $\delta \sim \sqrt{\lambda} f_a \sim m_H^{-1}$

- 'Realistic' $\ln(m_H/H) \sim 70$
- Latest sims. $\ln(m_H/H) \sim 8$ or 9 [e.g. Gorghetto et al. 2021, Buschmann et al. 2021]

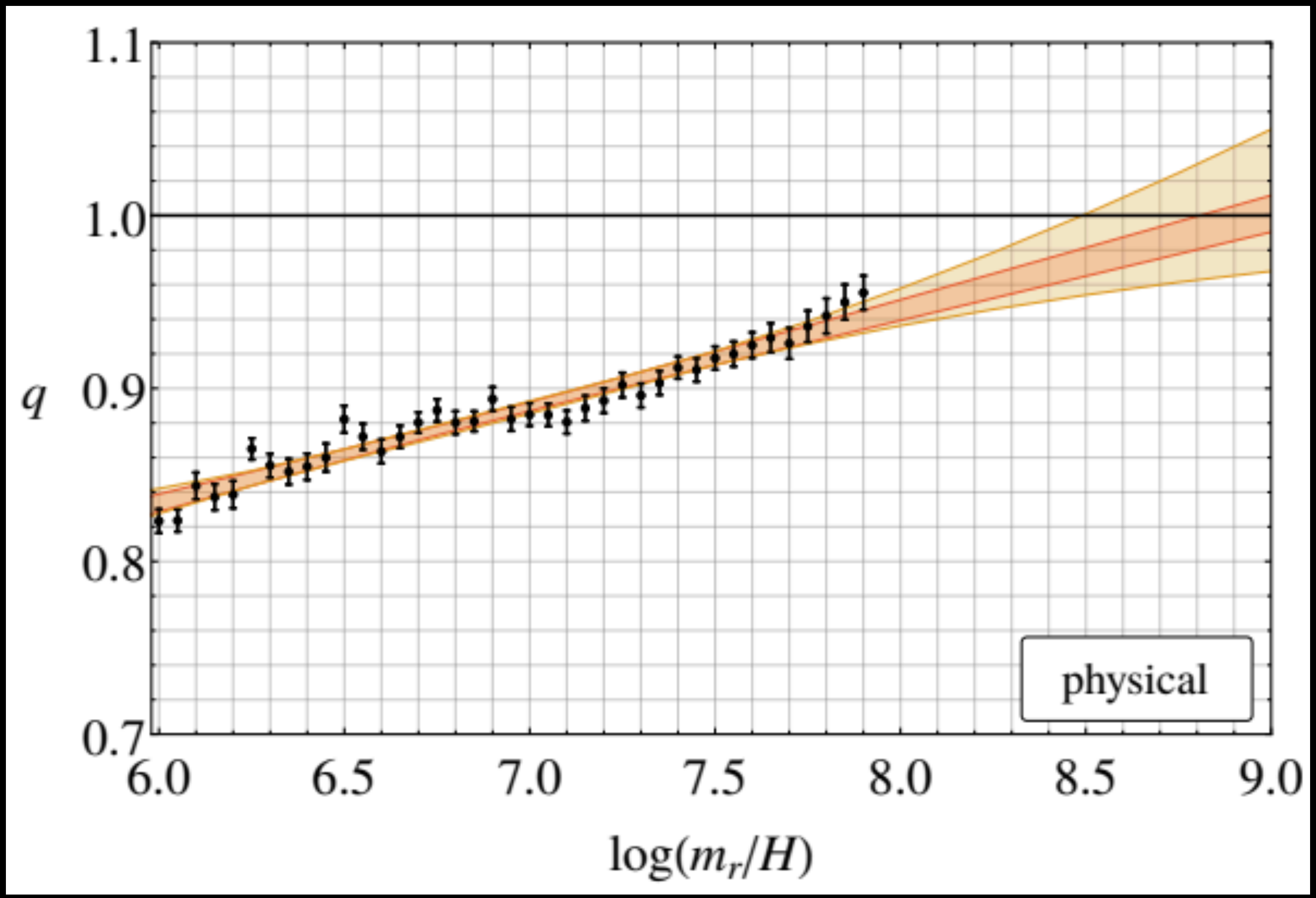


Visualisation in collaboration with Intel

Motivation

Separation of Scales

- Spectral index q depends on simulation separation of scales
- $q > 1$ IR dominated, $q < 1$ UV dominated - at crucial point

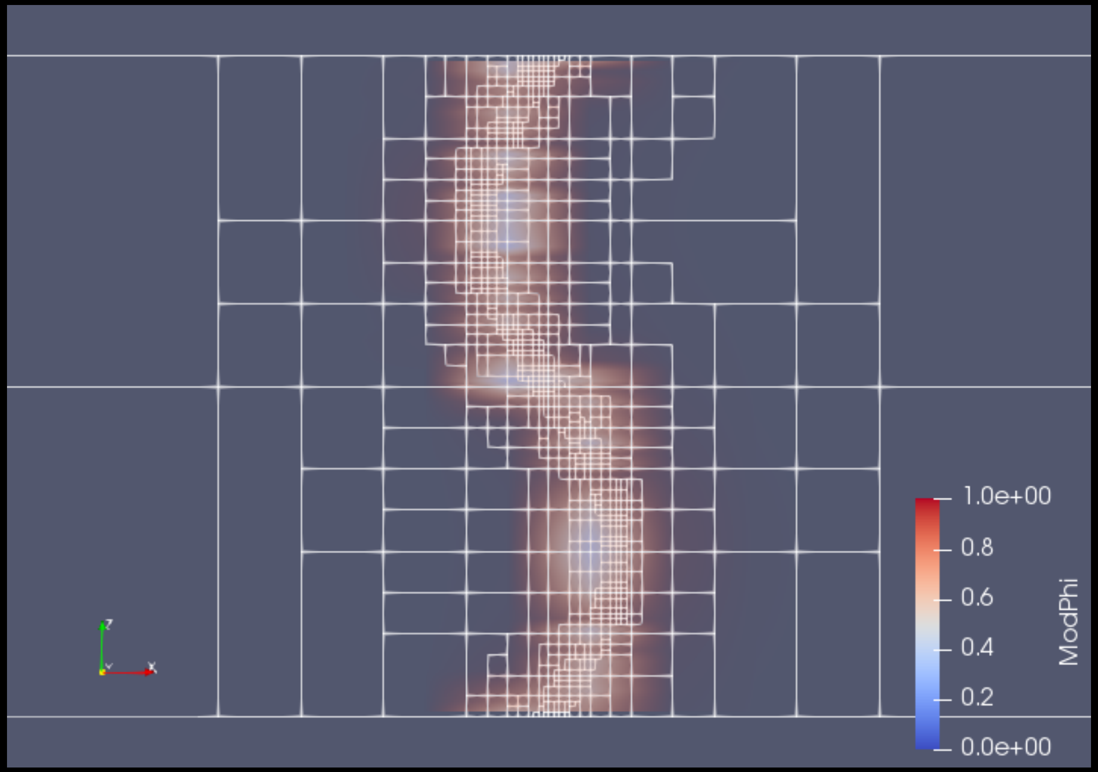


Gorghetto et al. 2021

Numerical Implementation

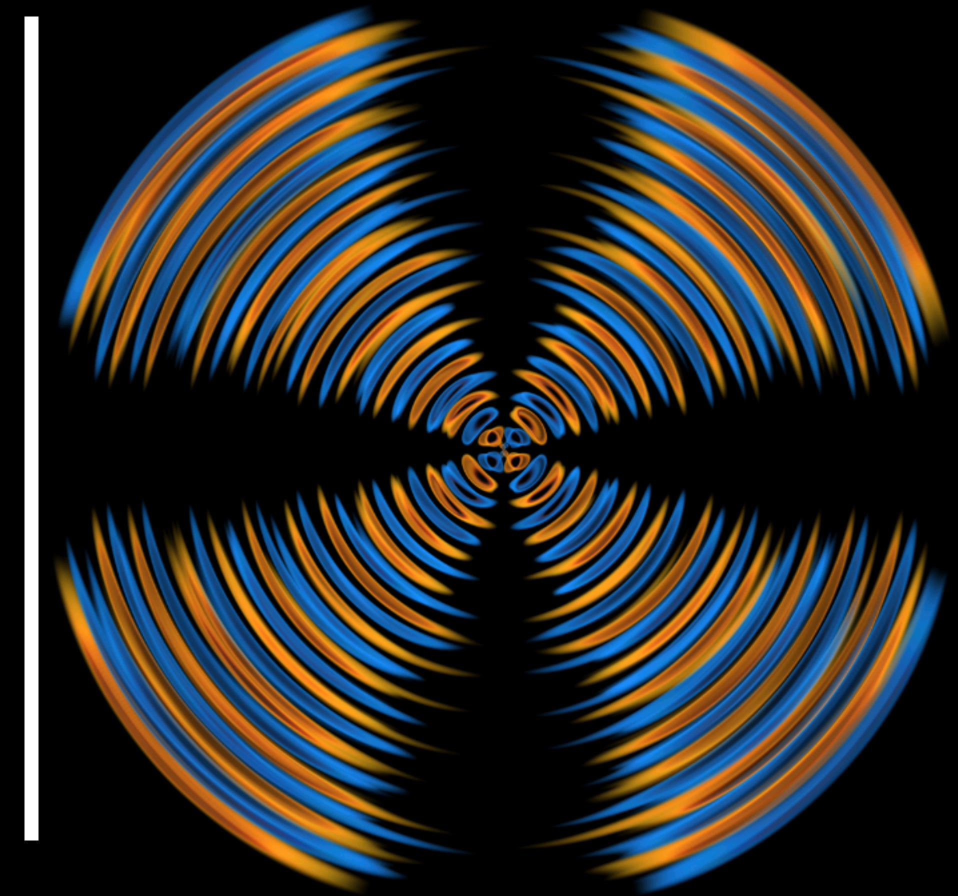
Simulation Setup

- Use adaptive mesh refinement to investigate string evolution
  - Can simulate thin strings quicker/using fewer computational resources than a fixed grid
- Concentrate on individual string configurations
- Investigate range of $\delta \approx m_H^{-1} = (\sqrt{\lambda}\eta)^{-1} \rightarrow$ implications of changing $\ln(m_H/H)$ (width or curvature)



Axion and Massive Radiation

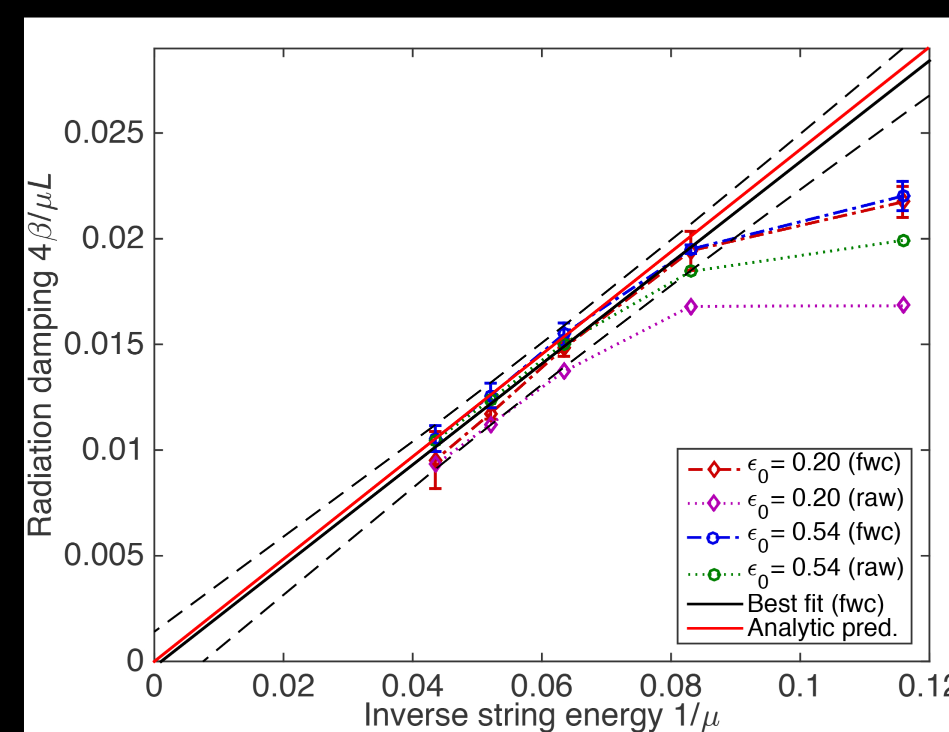
Key Results: Sinusoidal Strings



- Axion radiation emitted in harmonics of fundamental frequency Ω
- Dominated by quadrupole mode
- Higher amplitude → higher magnitude, larger proportion in high harmonics
- String backreaction described by Kalb-Ramond model (inverse square decay)

$$\frac{1}{\varepsilon^2} - \frac{1}{\varepsilon_0^2} = \frac{\beta\, t}{\bar{\mu} L}$$

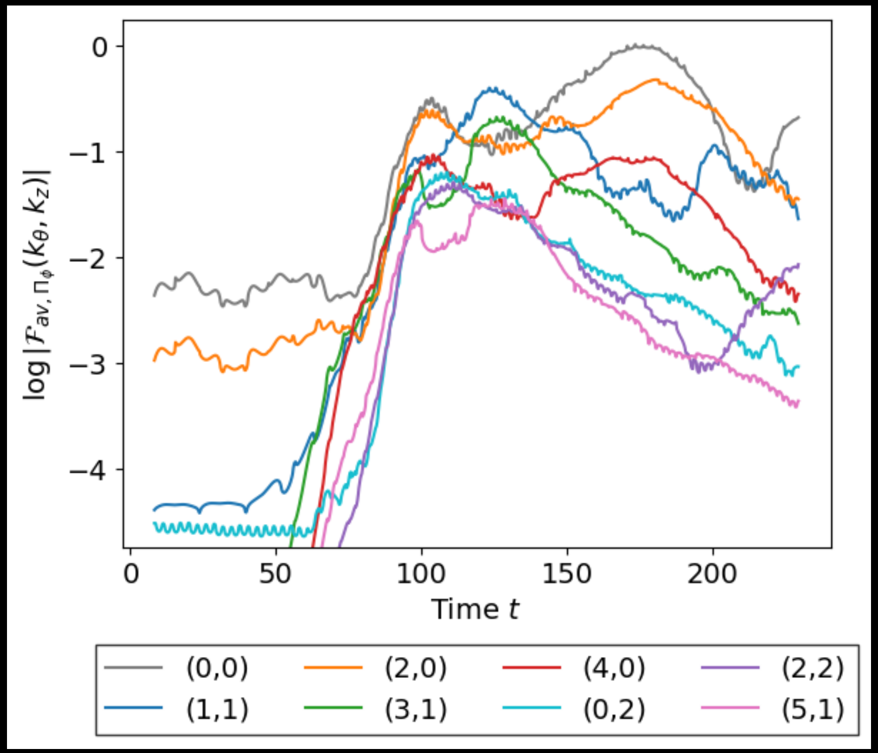
$$\bar{\mu} = \mu / f_a^2 \approx 2\pi \ln(\sqrt{\lambda} f_a R)$$

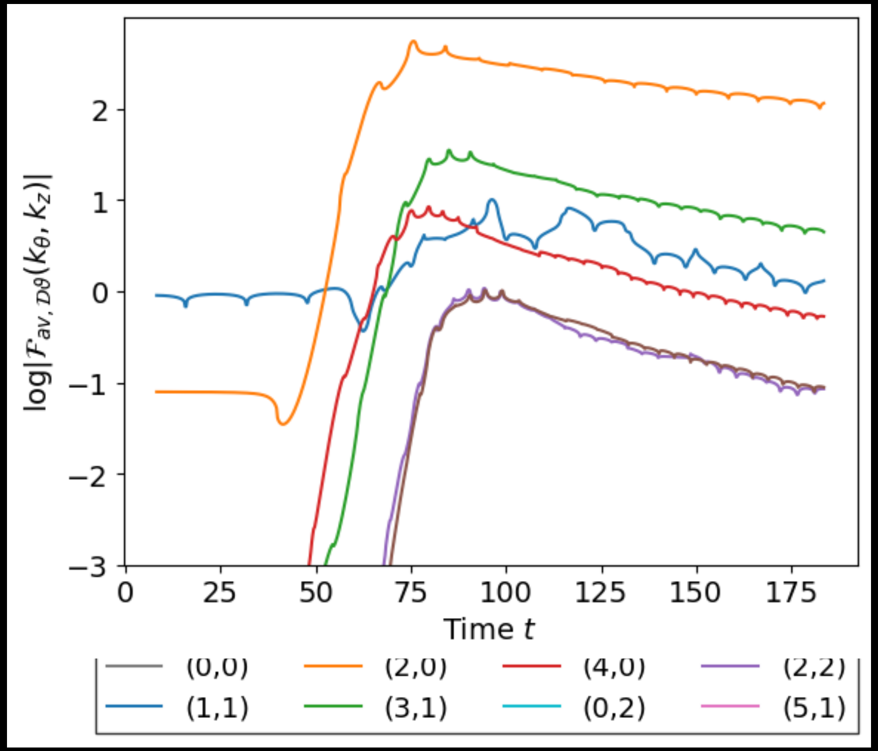


Axion and Massive Radiation

Key Results: Sinusoidal Strings

- Massive radiation suppressed compared to axion radiation by at least 100x
  - Caveat: can be comparable for highly relativistic configurations with low λ
- Suppressed significantly (exponentially) with increasing $m_H \sim \sqrt{\lambda} f_a$
- Radiates in harmonics of fundamental frequency $p_{\min} \gtrsim m_H/\Omega$



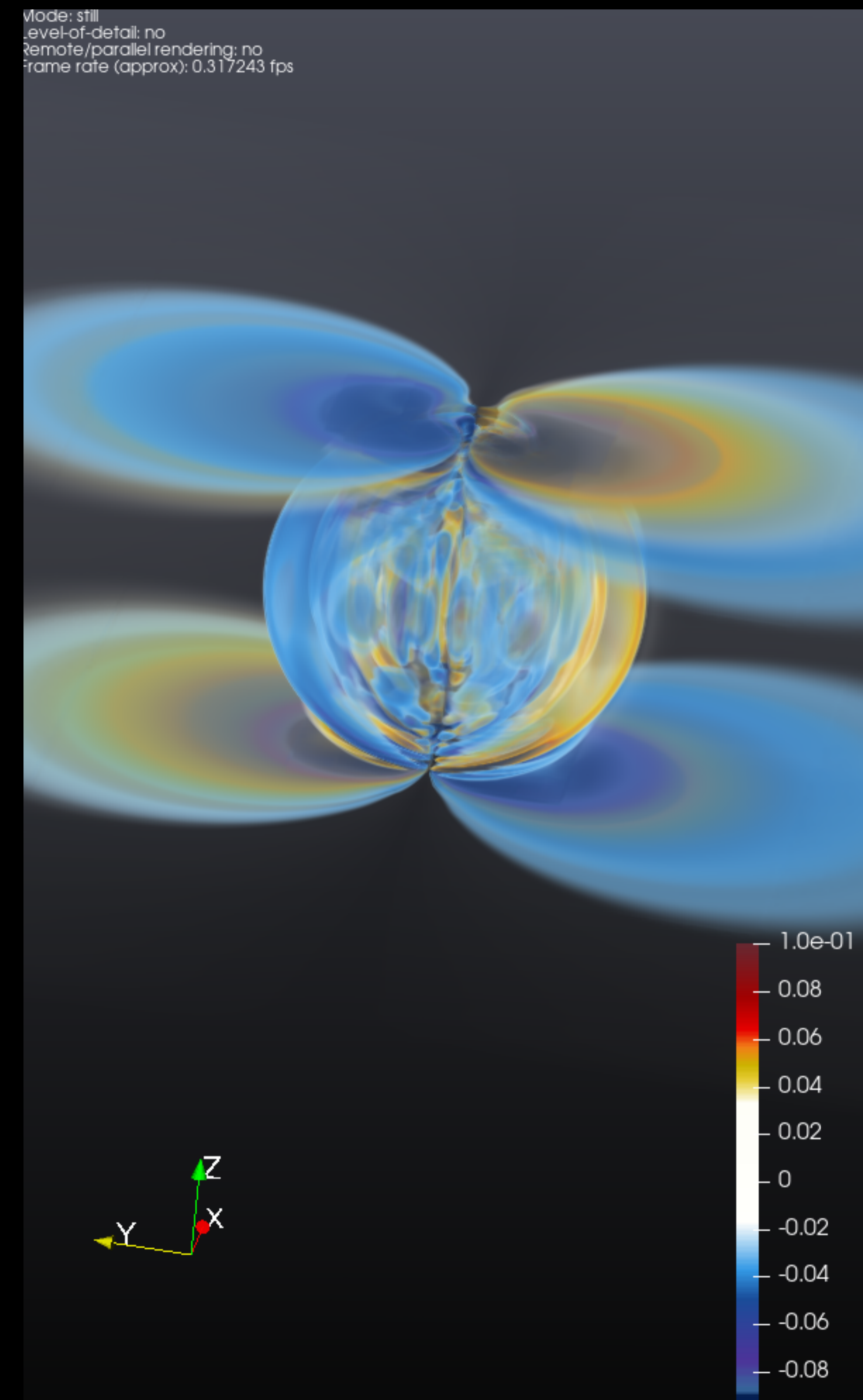


$\lambda = 1$ (top), $\lambda = 10$ (bottom), A = 4

Axion and Massive Radiation

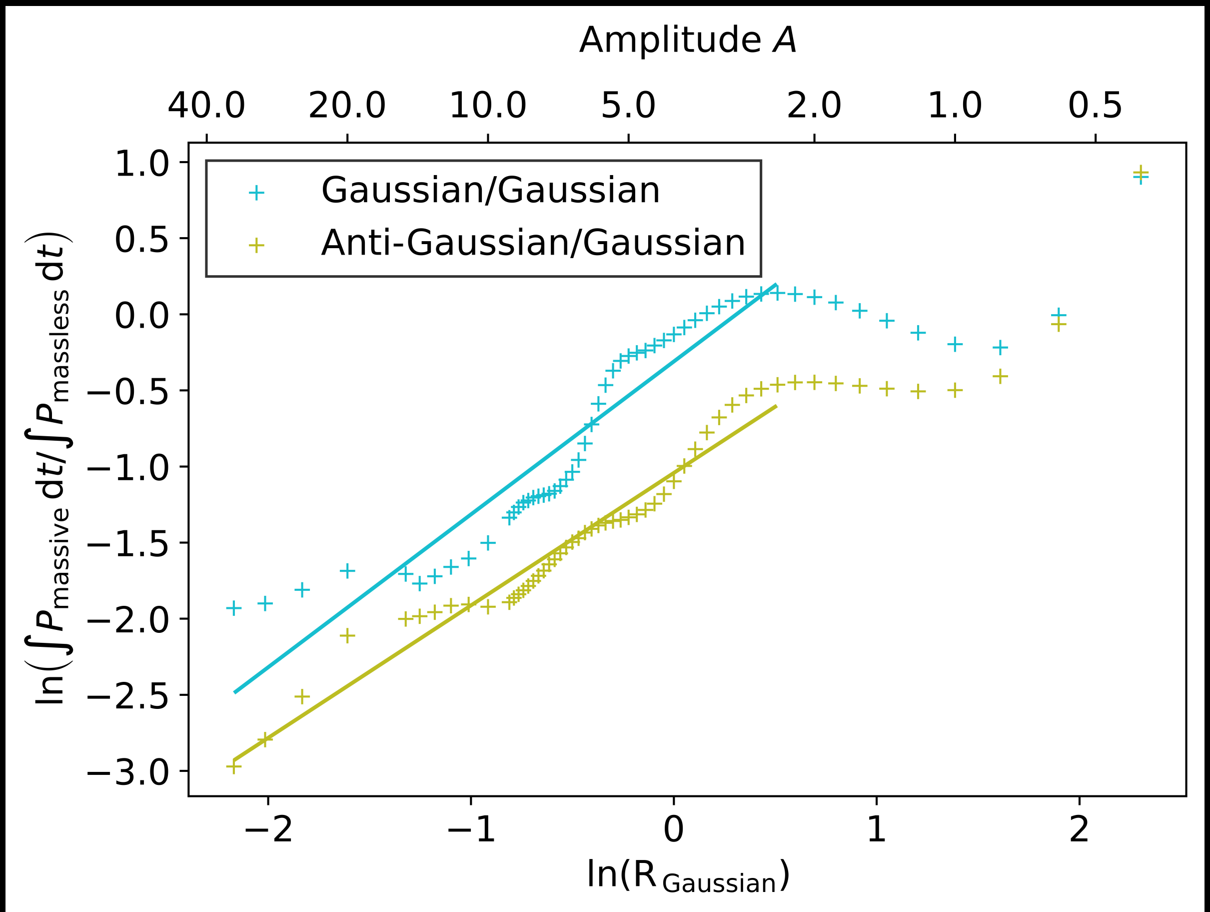
Key Results: Burst Configurations - Preliminary with T. Kinowski

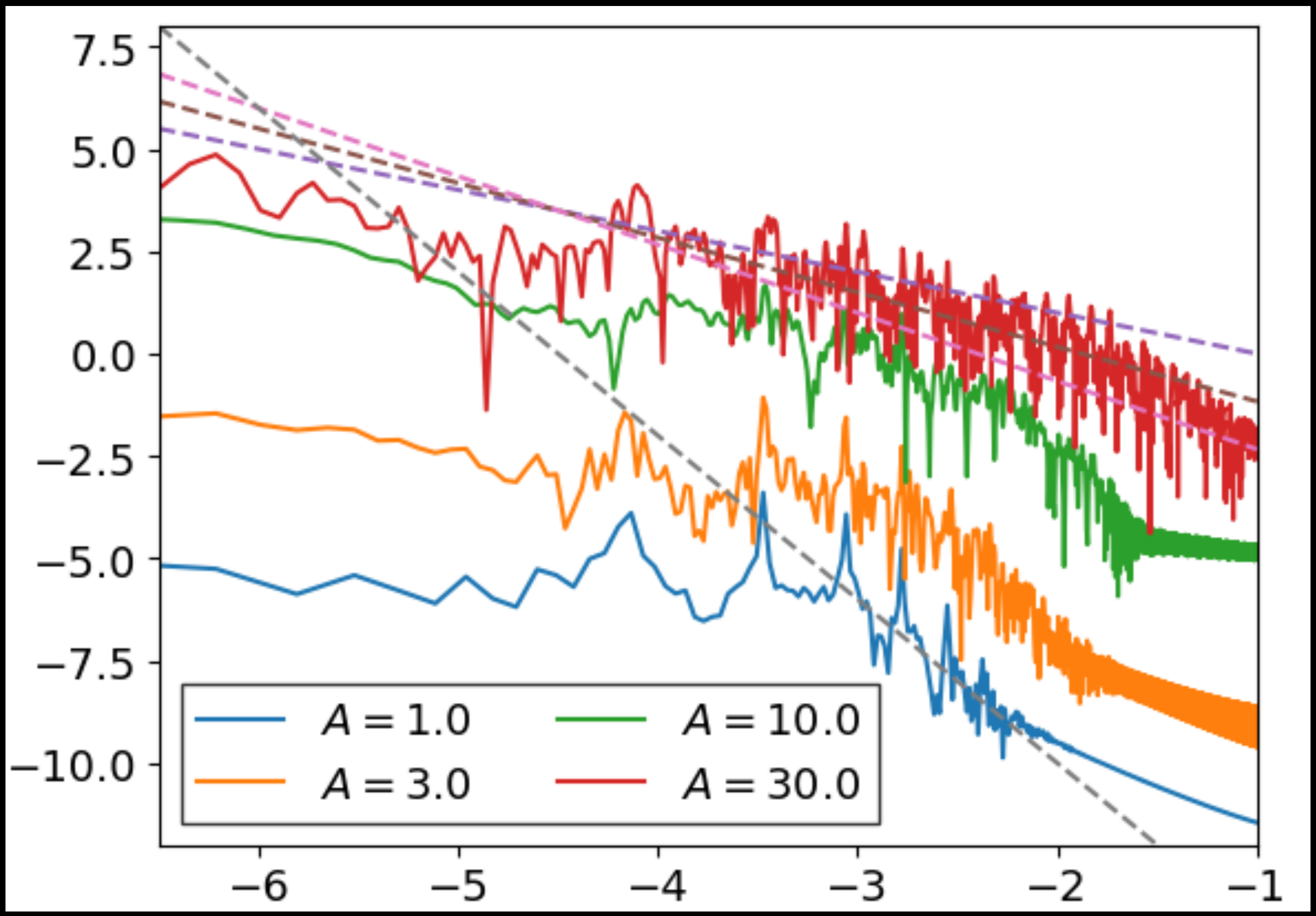
- We model dependence of each radiation mode on string radius of curvature [Vachaspati and Vachaspati 1990]
- Magnitude of both modes increases with curvature
- Ratio of massless to massive radiation increases with increased curvature
- Axion spectrum consistent with $q > 1$
- To appear very soon…



Axion and Massive Radiation

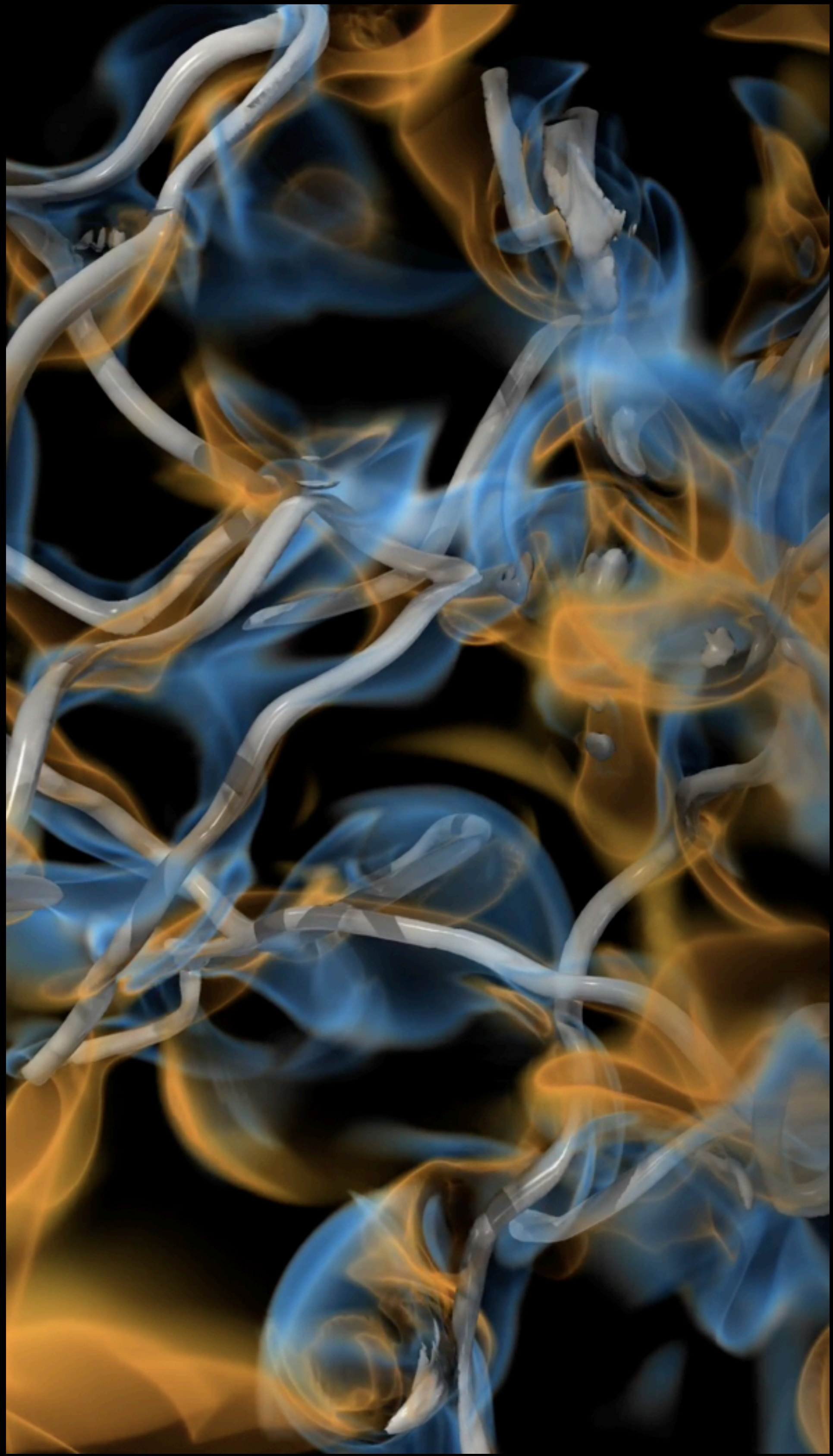
Key Results: Burst Configurations - Preliminary with T. Kinowski





To Do:

- What does this modelling mean for post-inflationary axion mass/ spectrum prediction? WG3?
- Can we incorporate this into current axion constraints?
- Is it helpful to link this to existing string network models eg. velocity one-scale model (VOS)?
- How does this link to string `scaling'?
- How does this link to cosmic string constraints?
- Many more questions to discuss with COST WGs!



Summary

- We are better understanding/ modelling axion string radiation
- Analytic models eg. Kalb-Ramond model are accurate in the linear regime
- Numerical modelling/ characterisation is needed for non-linear configurations
- Great time to build this into network simulations and astrophysical constraints