場の理論的シミュレーションに基づく
アクシオン宇宙ひもの解析

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arXiv:1012.5502

with 平松尚志(YITP), 川崎雅裕(ICRR), 山口昌英(TITech), 横山順一(RESCEU)

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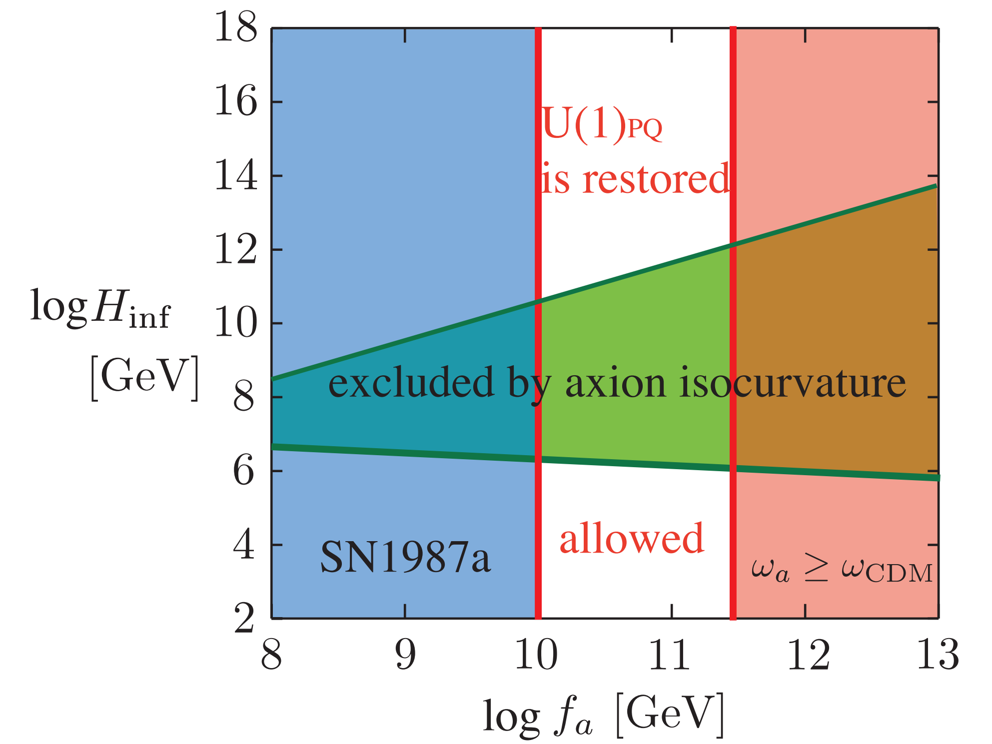
Outline

- Introduction
- Field theoretic simulation of axionic strings
- Scaling property of the string network
- Energy spectrum of radiated axions
- Constraint on the axion decay constant
- Summary

1. Introduction

- Axion:
  - Pseudo-NG boson of the spontaneously broken anomalous Peccei-Quinn U(1) symmetry.
  - Rich implications in cosmology:
    - A candidate of CDM
    - Isocurvature perturbations

$$H_{\rm inf} \lesssim 10^7 \ {\rm GeV}$$



[Kawasaki & Sekiguchi (08)]

(as long as the PQ symmetry is not restored...)

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$$\epsilon = \frac{1}{2M_{\rm Pl}^2}\left(\frac{V_\phi}{V}\right)^2 \lesssim 10^{-14}$$

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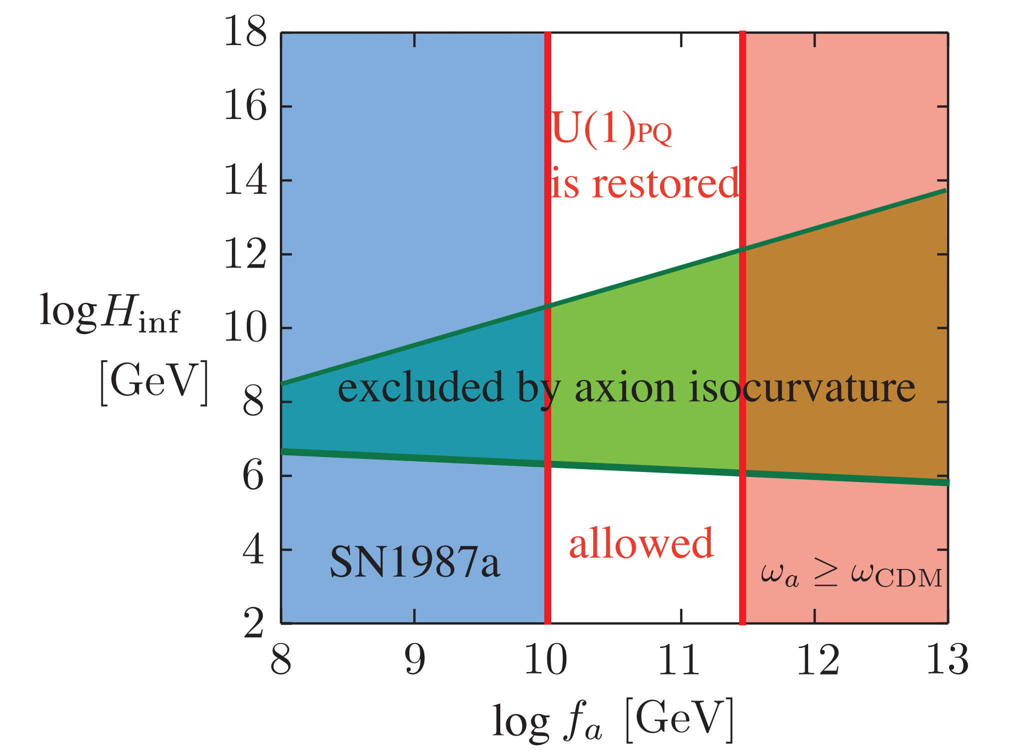

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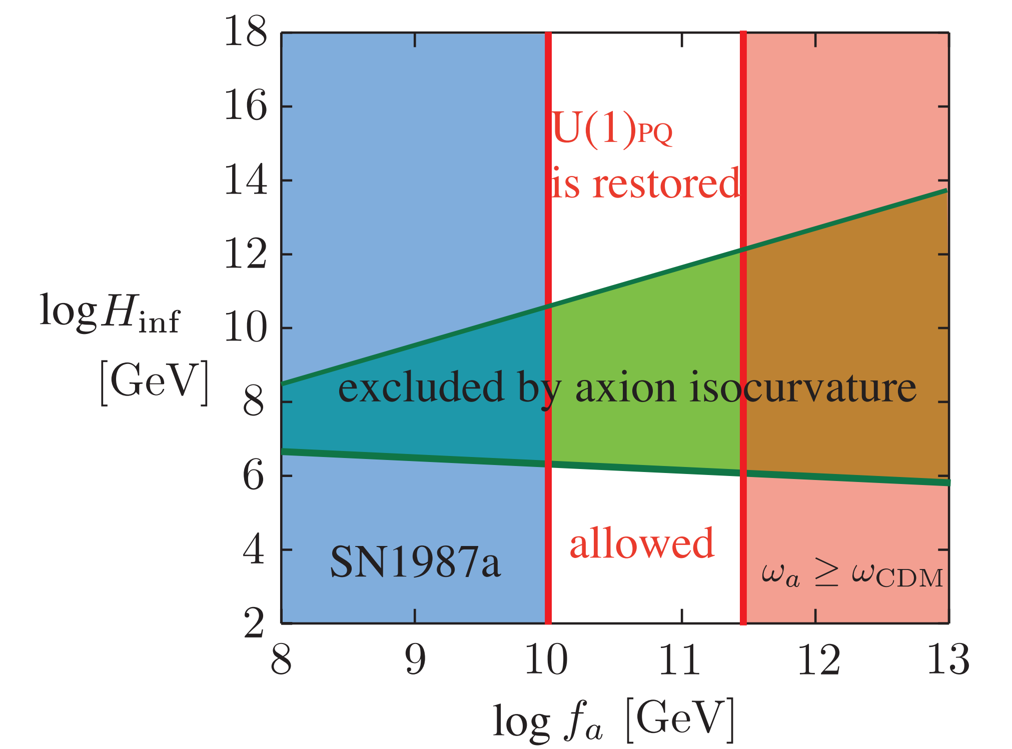

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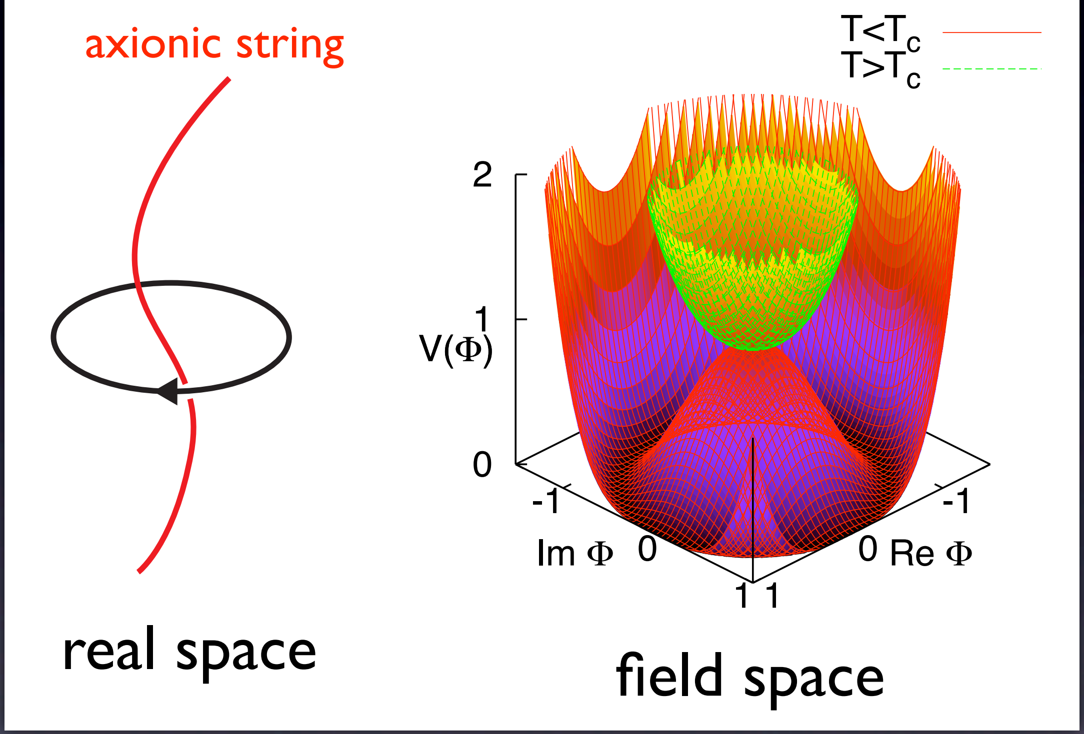
⇒Another possibility: the PQ symmetry restores in the early Universe.

Axionic string

- Since the PQ symmetry is a global U(1) symmetry, when U(1)PQ breaks spontaneously, 1-dim topological defect (axionic string) can form.



potential:

$$V(\Phi) = \frac{\lambda}{2}(|\Phi|^2 - \eta^2)^2 + \frac{\lambda}{3}T^2|\Phi|^2$$

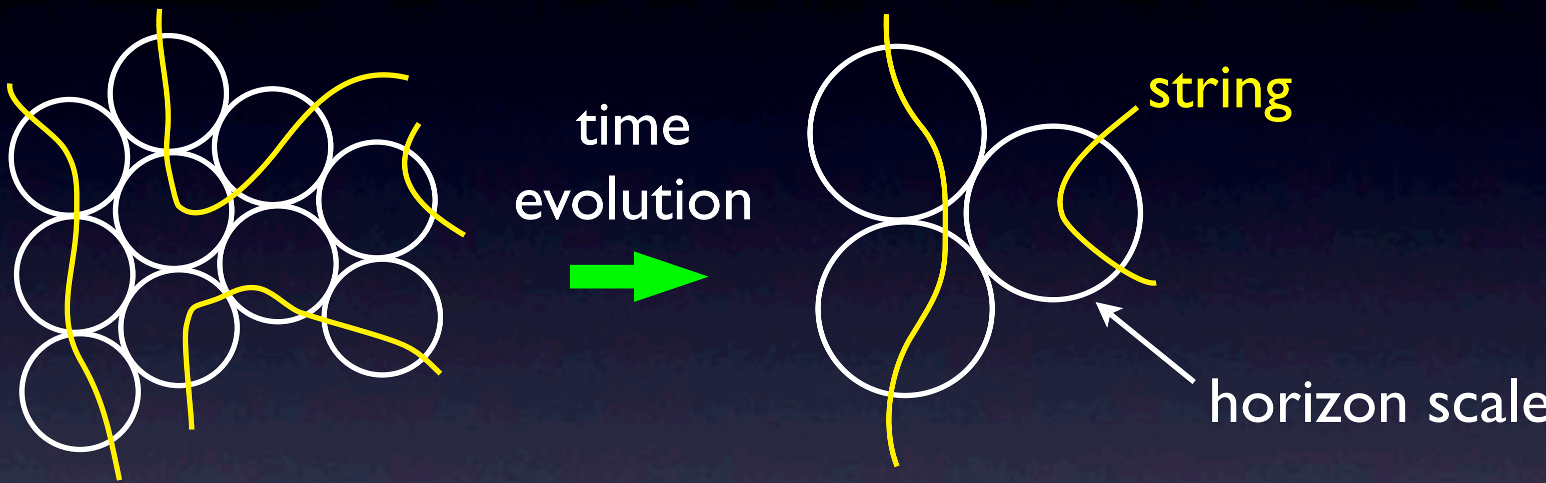
η : PQ scale

Phase transition occurs at temperature $T_{\rm crit} = \sqrt{3}\eta$.

- If the SSB of U(1)PQ occurs in the early Universe, a cosmological network of axionic strings is generated.

Fate of cosmological axionic strings

- Scaling solution
  - Number of strings in a horizon stays constant.



- At QCD phase transition, axionic domain walls (DWs) bounded by axionic strings are generated, and both of them quickly disappear if $N_{\rm DW} = 1$.
- Strings lose their energy by emitting massless axions.
  - Emitted axions finally become CDM.

$$\bar{\rho}_{\rm axion}(t_0) = m_{\rm axion}\bar{n}_{\rm axion}(t_0)$$

Energy spectrum of radiated axions

- Number density of radiated axions:

$$\bar{n}_{\rm axion}(t) = \int \frac{dk}{2\pi^2}\frac{R(t)}{k}P(k,t).$$

R(t): scale factor

k: comoving momentum

- Energy spectrum of radiated axions: P(k)
  - At small momenta, P(k) peaks at the horizon scale ~1/H.
  - At higher momenta...

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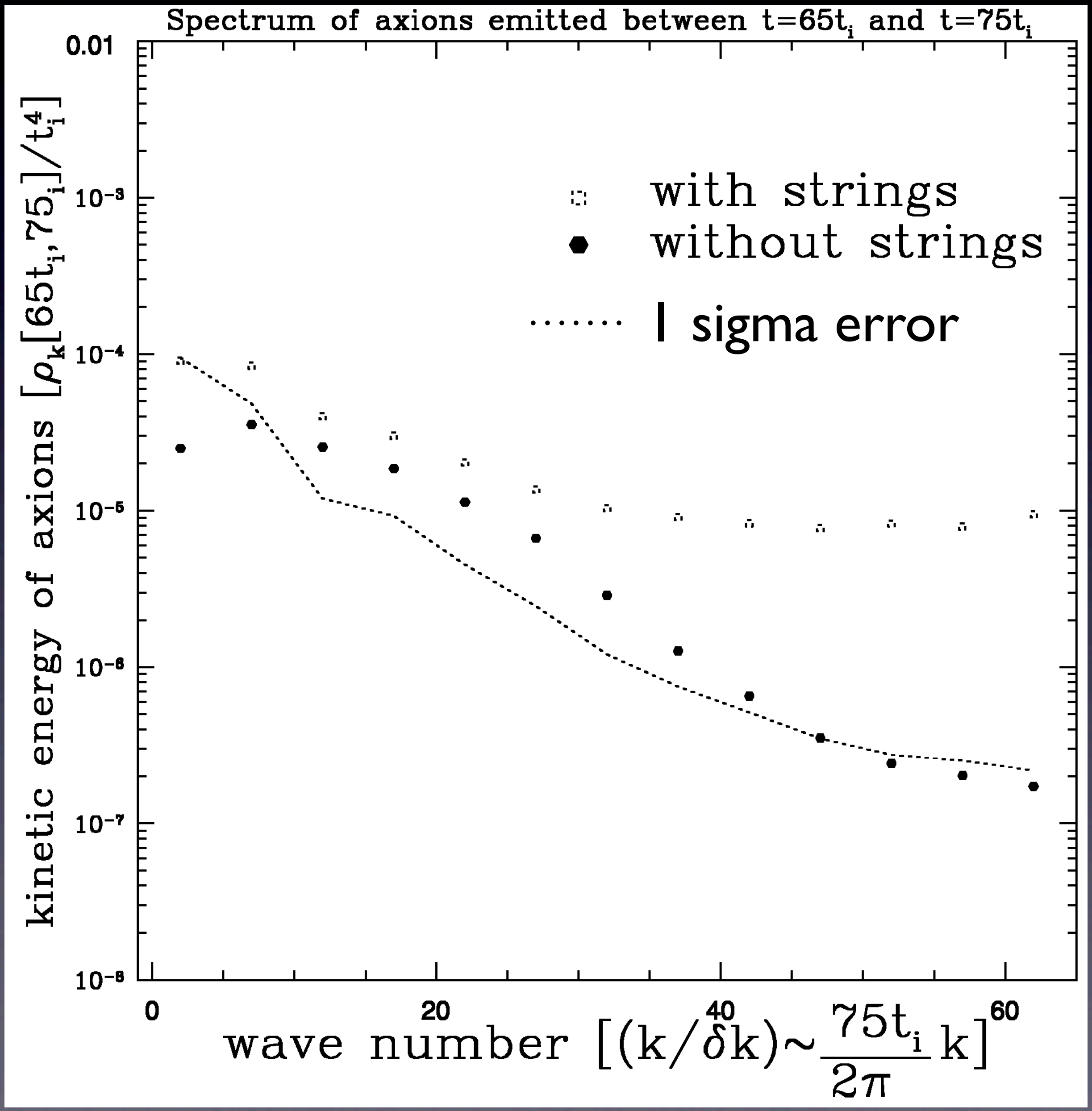
⇒ There has been a controversy!

A previous study

- A solution to the controversy was given by Yamaguchi, Kawasaki & Yokoyama (99).
  - A field theoretic lattice simulation of the PQ scalar is performed.
  - The result supports the claim of Davis & Shellard.
  - Uncertainties are large, due to the limitation of statistics.



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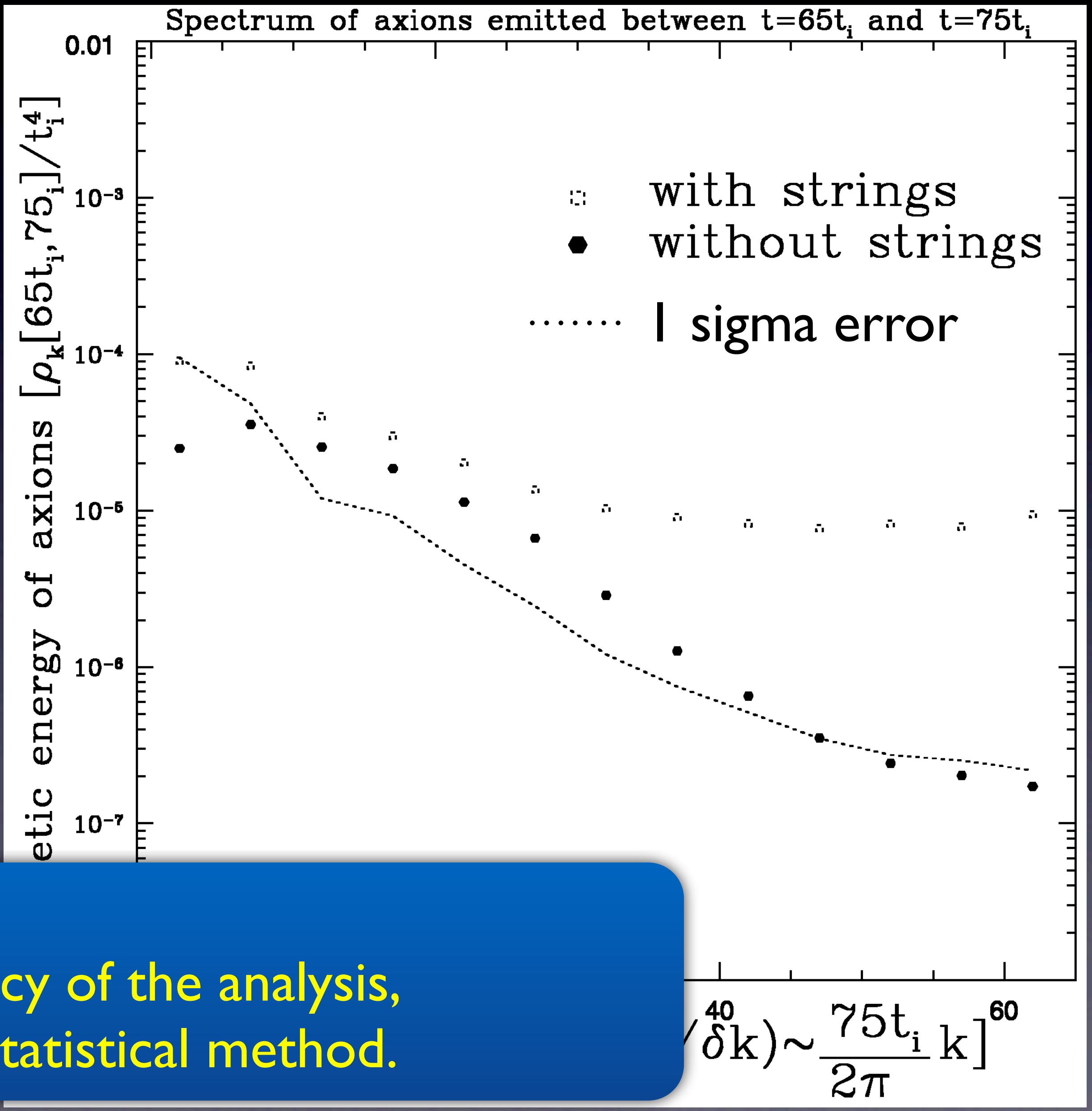

Main purpose:
To improve the accuracy of the analysis, using a sophisticated statistical method.

2. Field theoretic simulation of axionic strings

- Field theoretic simulation
  - Axionic strings are not well-localized. (cf. string-based Nambu-Goto action used for local strings)
  - First-principles calculation, free from theoretical uncertainties.

$$\ddot{\Phi}(\vec{x},t) + 3H(t)\Phi(\vec{x},t) - \frac{1}{R(t)^2}\nabla^2\Phi(\vec{x},t) = -\frac{\partial V[\Phi,T]}{\partial \Phi^*}$$

  - Dynamical range is limited.

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two requirements

1. Resolve inner structure of strings

   ⇒ comoving size $\propto 1/R(t)$.

2. Simulation box > a horizon volume

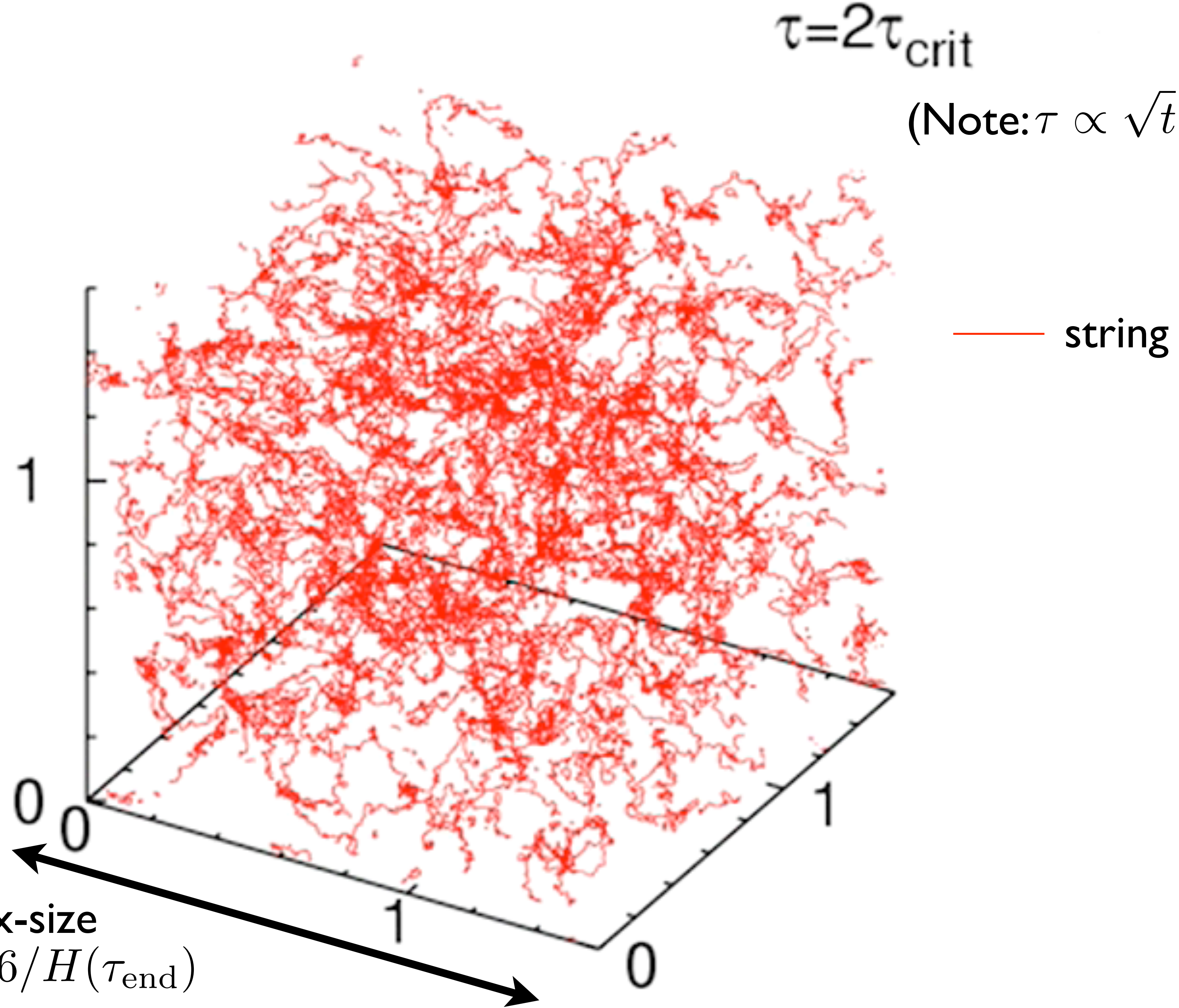
   ⇒ comoving size $1/R(t)H(t) \propto R(t)$

Details of simulation

- Parameters
  - PQ scale: $\eta = 10^{16}\mathrm{GeV}$
  - coupling constant: $\lambda = 1$
  - number of relativistic dof: $g_* = 1000$
  - comoving size of simulation box at final time: $L = 1.6/H(\tau_{\mathrm{end}})$
  - number of grids: $N_{\mathrm{grid}} = 512^3$
  - time range: $t_{\mathrm{ini}} = 0.25 t_{\mathrm{crit}},\ t_{\mathrm{end}} = 25 t_{\mathrm{crit}}$
  - spacial resolution: $R(t_{\mathrm{end}})\Delta x = 0.7 d_{\mathrm{string}}$, with $d_{\mathrm{string}} = 1/\sqrt{2}\eta$
- Initial condition is randomly drawn from the thermal distribution.
- Equation of motion is integrated using the leap-frog method.

Numerical simulation $(N_{\rm grid} = 512^3)$

(Note: $\tau \propto \sqrt{t}$)

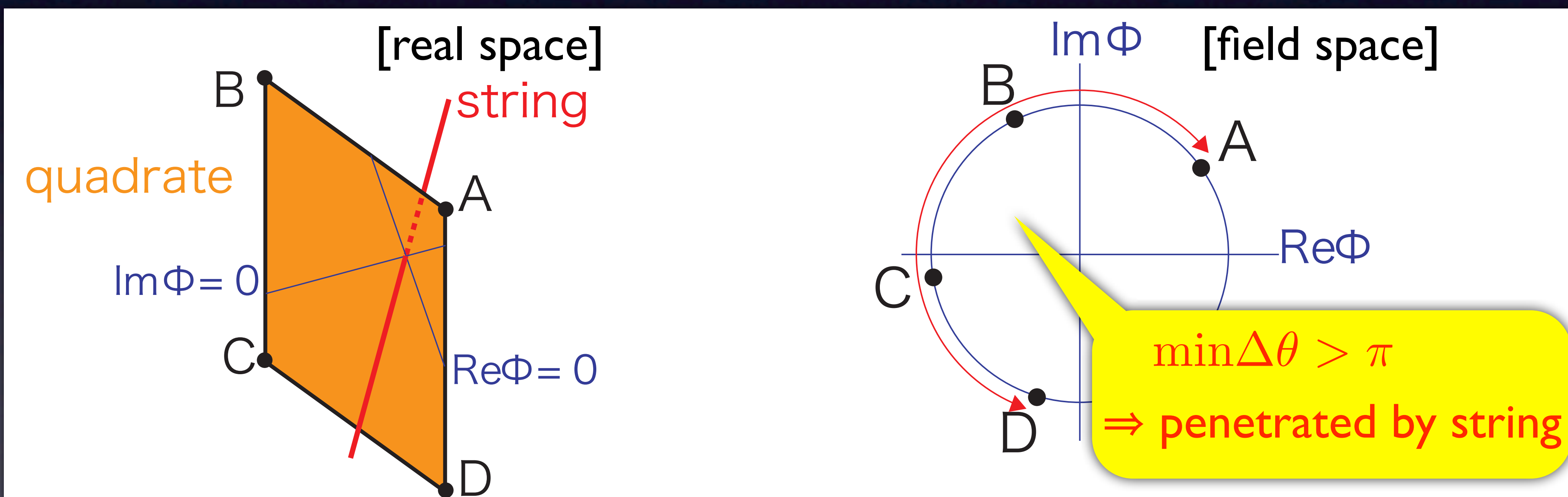


comoving box-size
$L = 1.6/H(\tau_{\rm end})$

Identification of strings

- Non-trivial task!! Only $\Phi(\vec{x},t)$ at discrete lattice points are known.
- We developed a completely new method for identification of strings:

> If a string penetrates a (sufficiently small) quadrate, the minimal range that contains phases at 4 vertices should be larger than π.



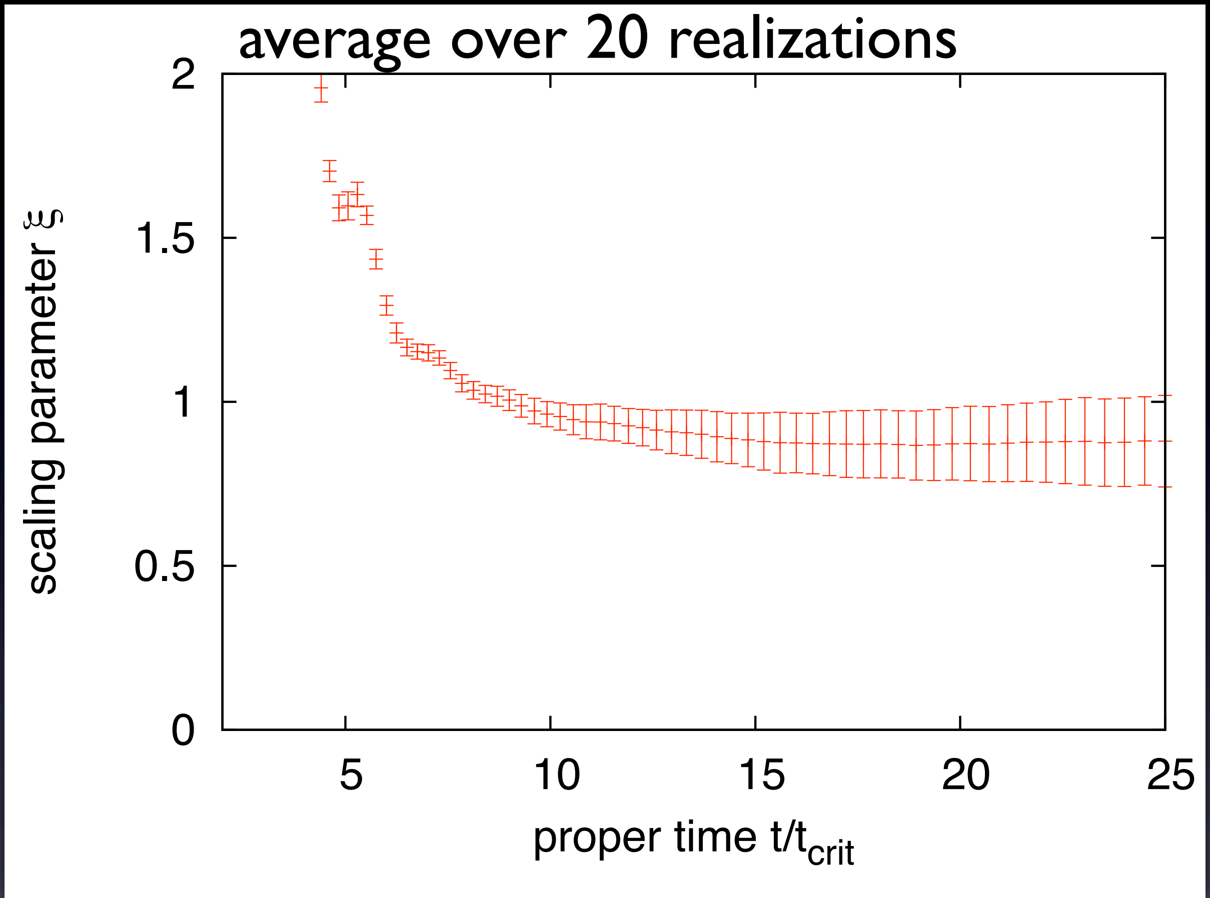
- We can determine >99% of string positions in quadrates penetrated by strings.

3. Scaling property

- Scaling parameter

$$\xi \equiv \frac{\rho_{\rm string} t^3}{\mu_{\rm string} t}$$

= (# of strings in a horizon volume)



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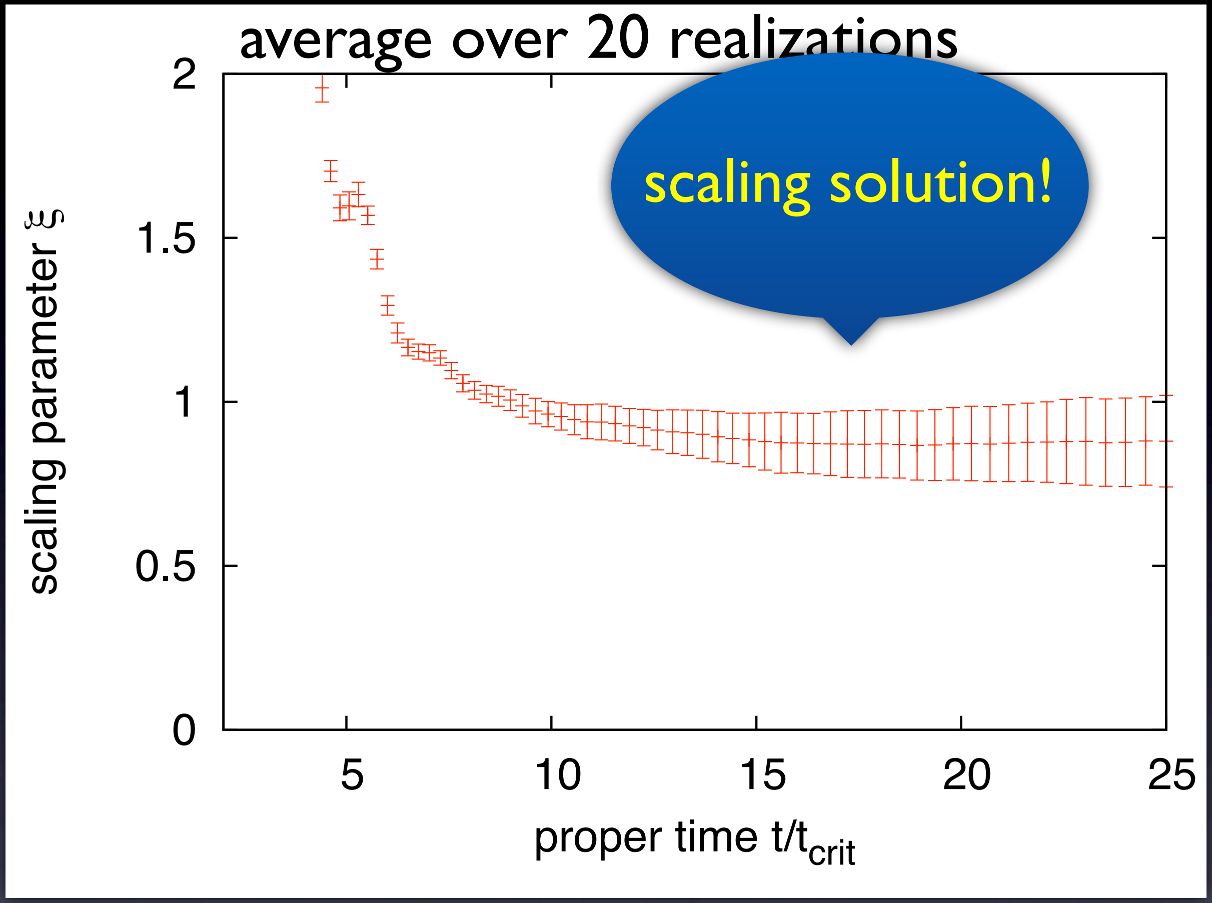

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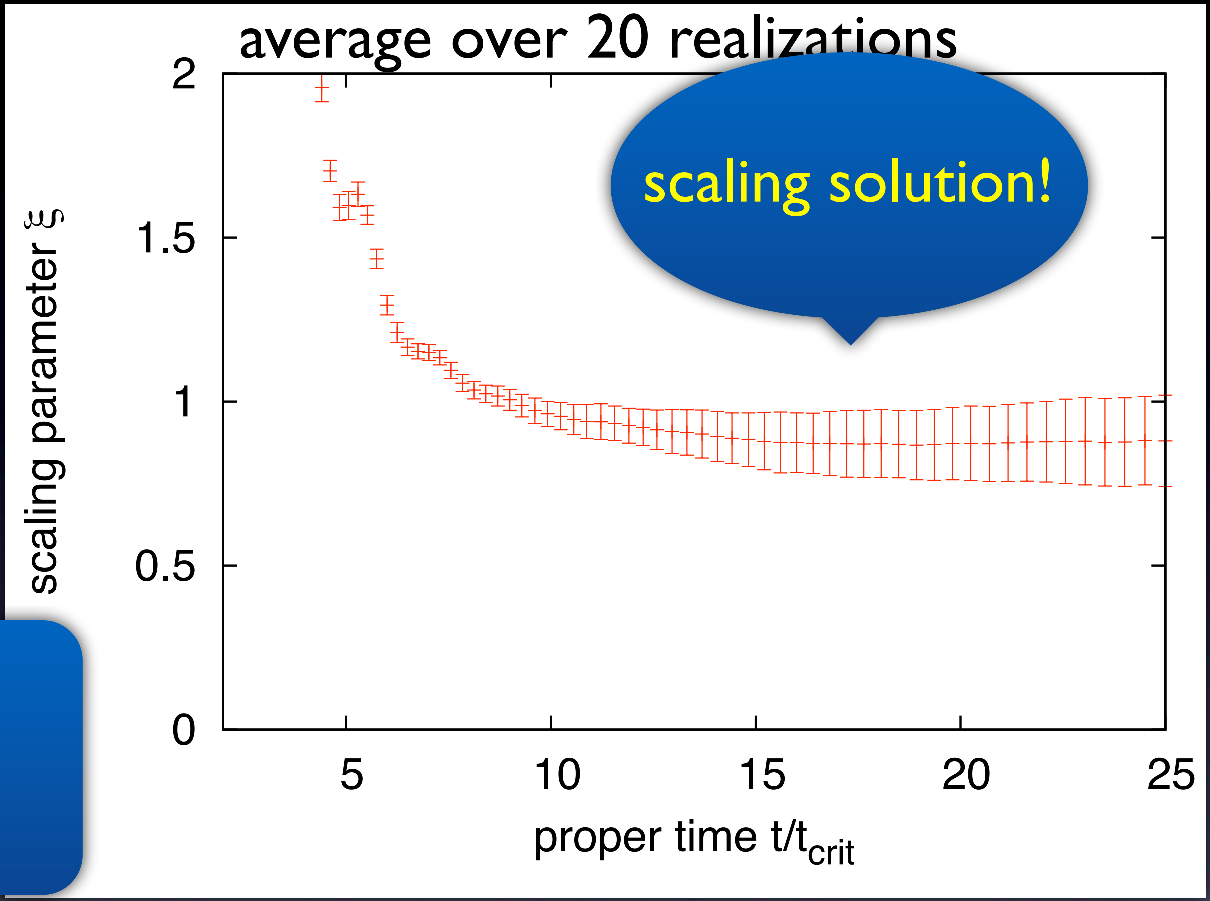

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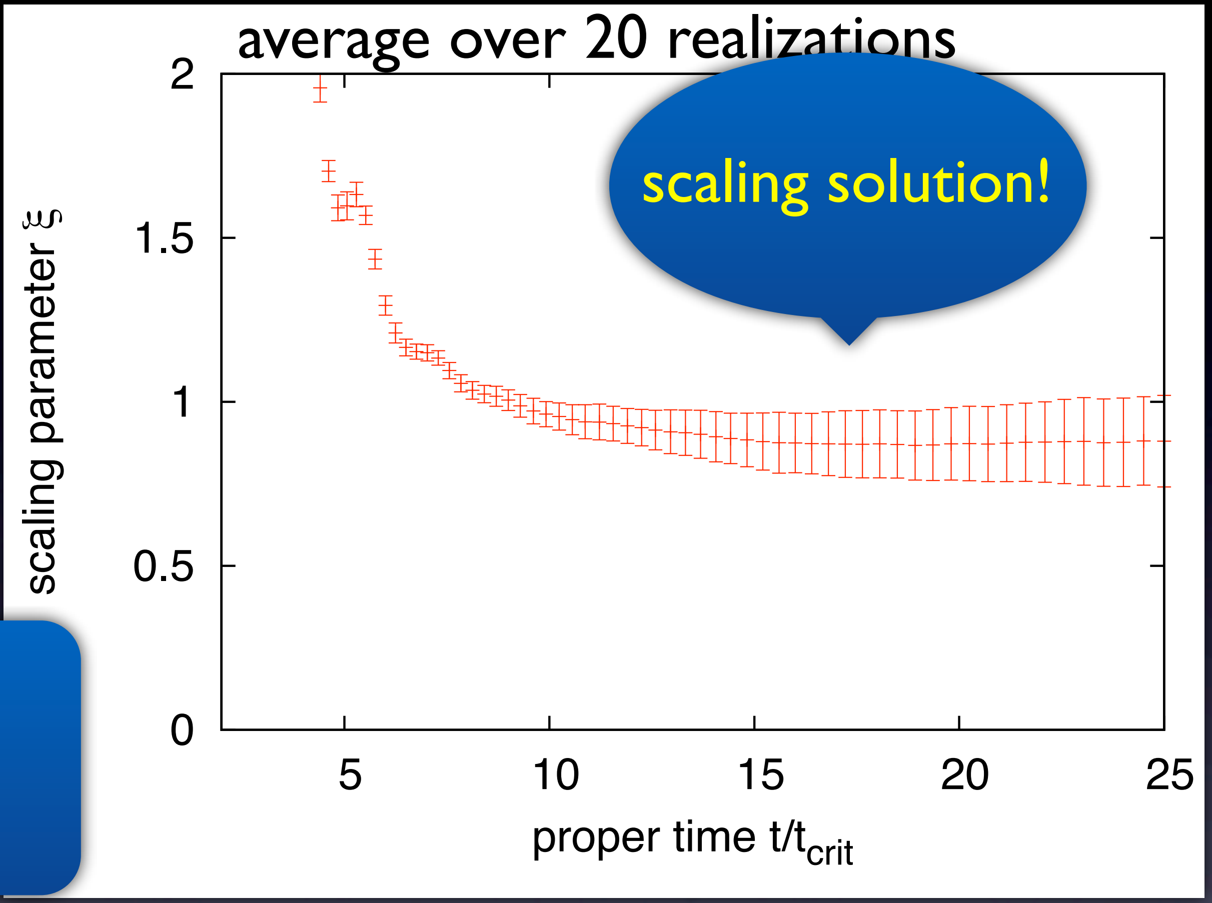

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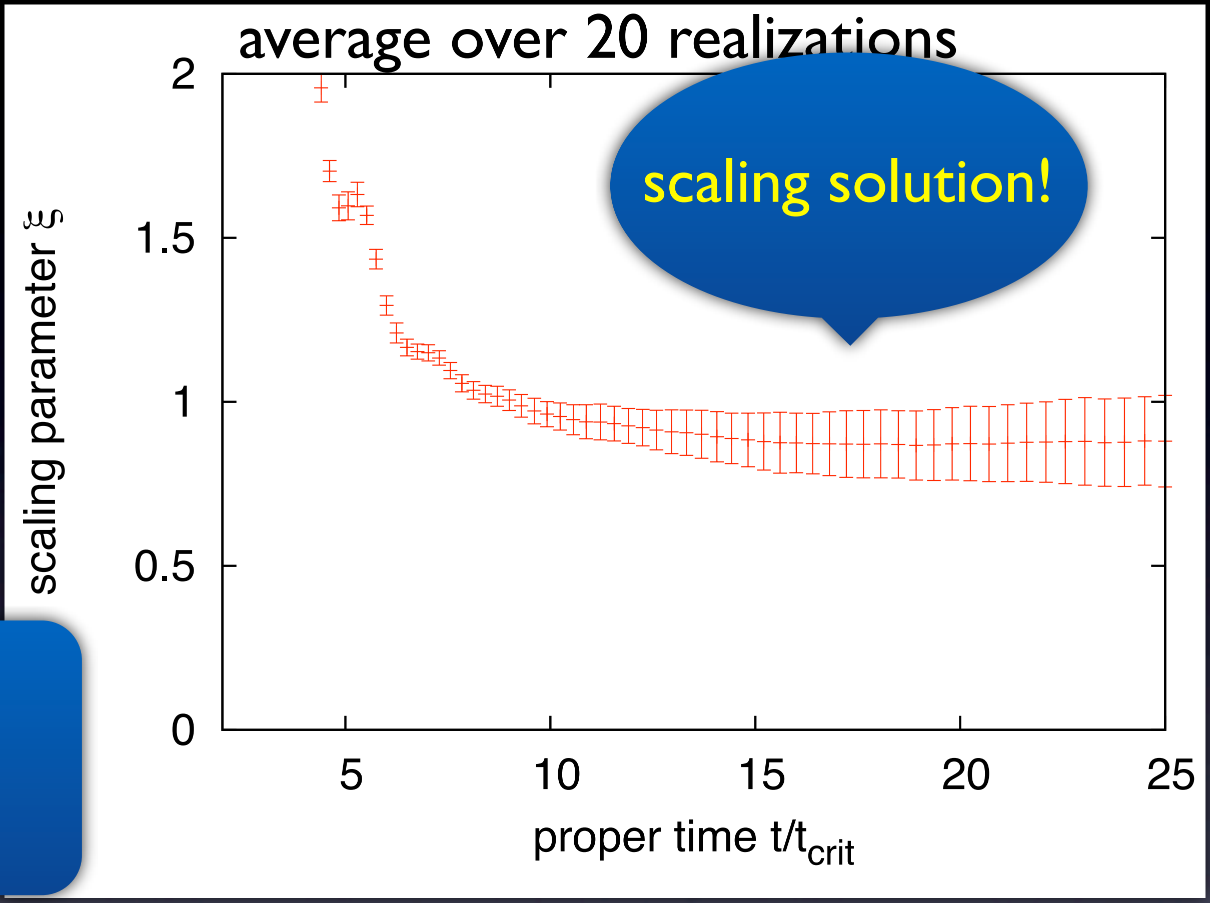

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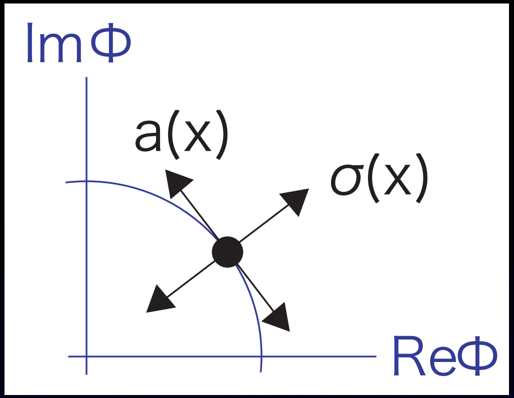
- Cf. For local string, $\xi \simeq 13$. [Bennett & Bouchet (90), Allen & Shellard (90), ...]

4. Energy spectrum of radiated axion

- Axion is the phase of the PQ scalar



$$\Phi(\vec{x},t) = \left(\eta + \frac{\sigma(\vec{x},t)}{2}\right)\exp\left[i\frac{a(\vec{x},t)}{\sqrt{2}\eta}\right].$$

- Mean kinetic energy of axion is given by

$$\bar{\rho}_{\mathrm{axion}}(t) = \frac{1}{V}\int d^3x \frac{1}{2}\left[\frac{da}{dt}(\vec{x},t)\right]^2 = \int \frac{d^3k}{(2\pi)^3}\frac{1}{2V}\left|\frac{da}{dt}(\vec{k},t)\right|^2.$$

- Energy spectrum:

$$P(k,t) = \int \frac{d\hat{k}}{4\pi}\frac{k^2}{2V}\left|\frac{da}{dt}(\vec{k},t)\right|^2$$

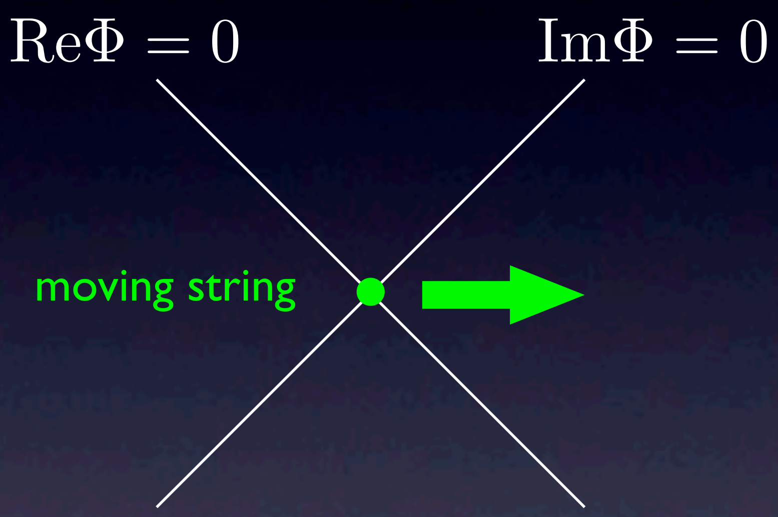
- Number density:

$$\bar{n}_{\mathrm{axion}}(t) = \int \frac{dk}{2\pi^2}\frac{R(t)}{k}P(k,t).$$

Effects of string cores

- Near a moving axionic string, the phase changes rapidly and the energy of the axion field can be arbitrary large.

[field configuration]



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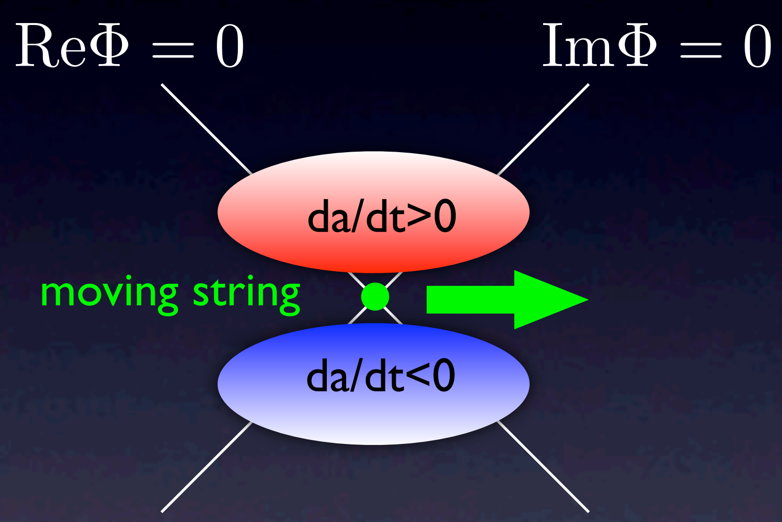

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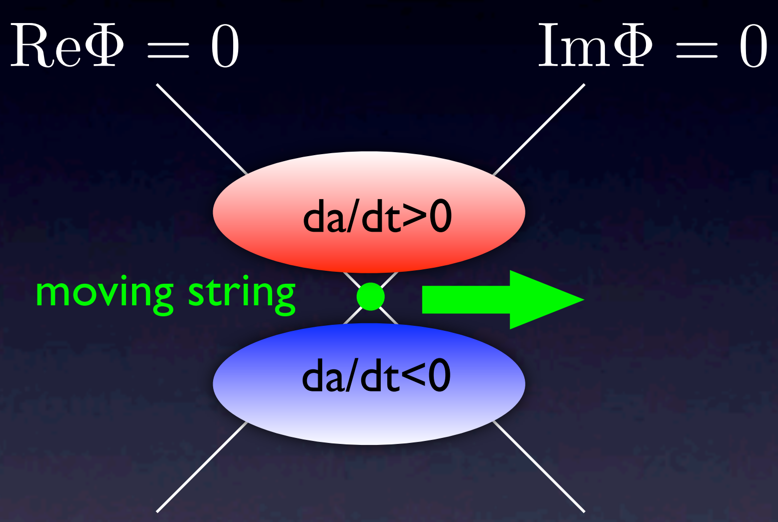

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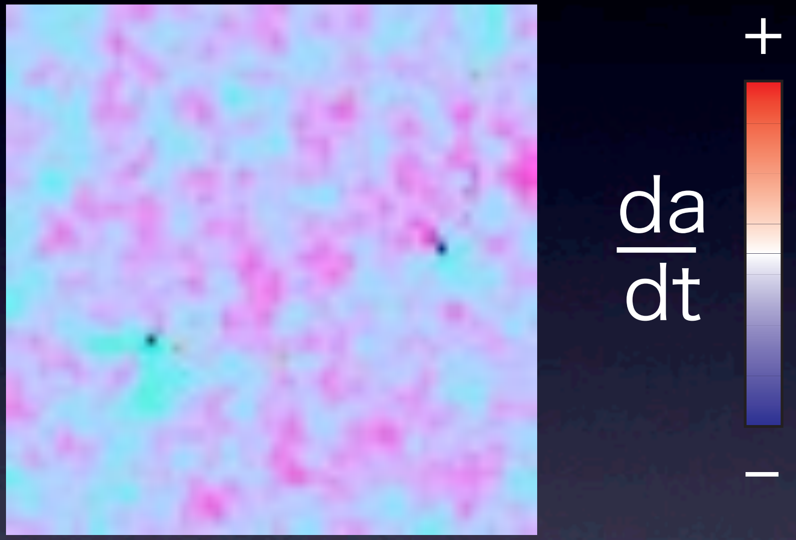

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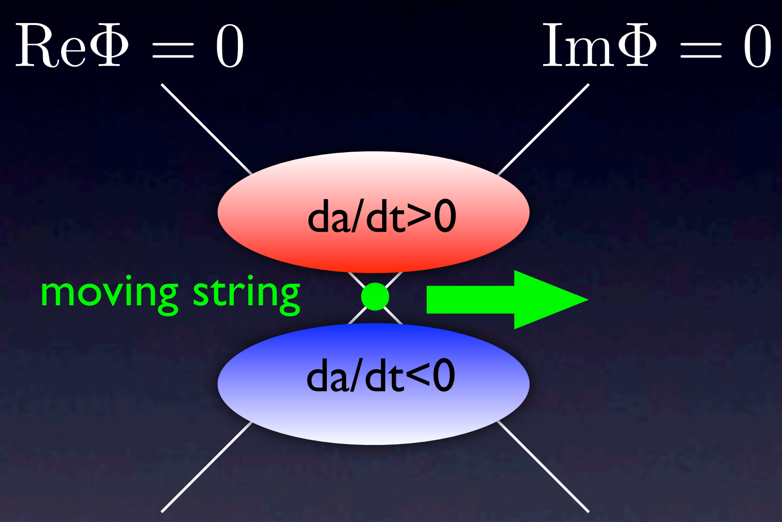

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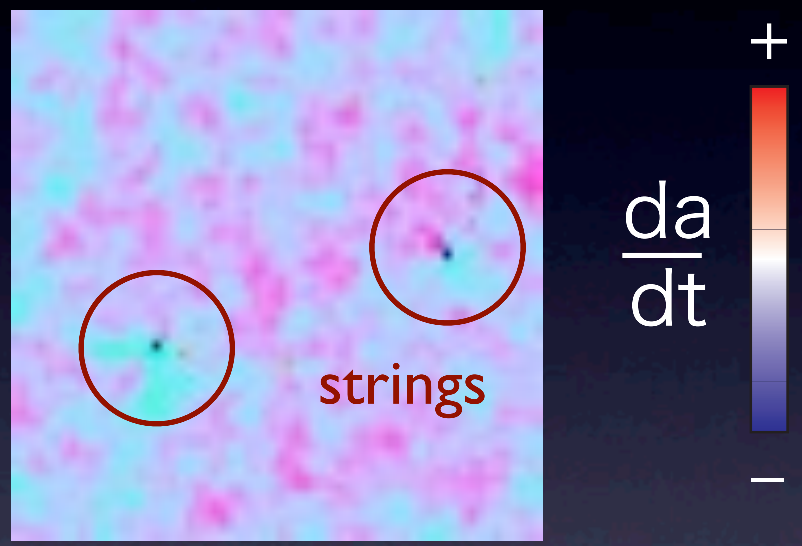

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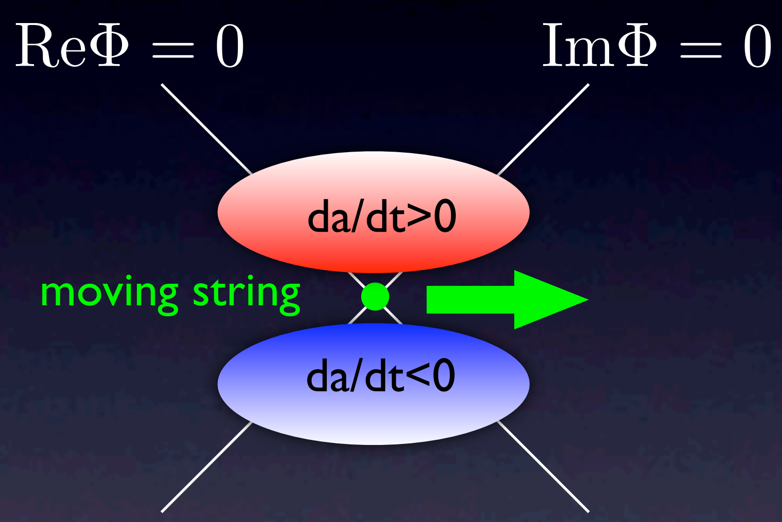

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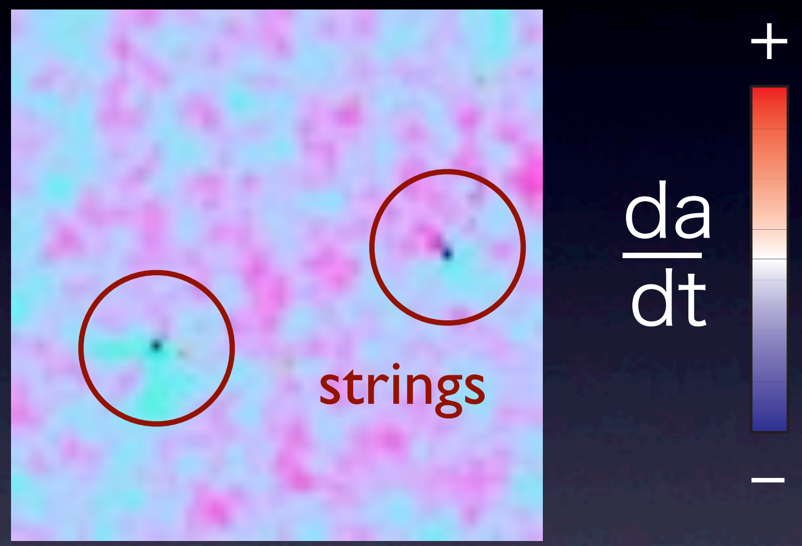

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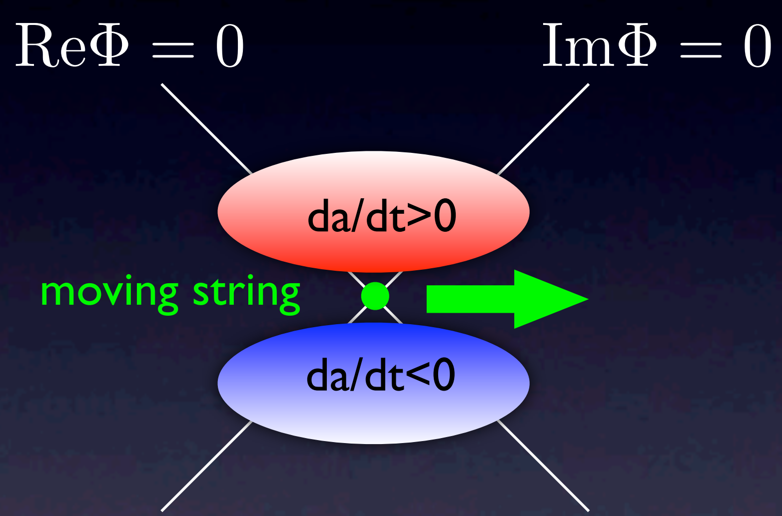

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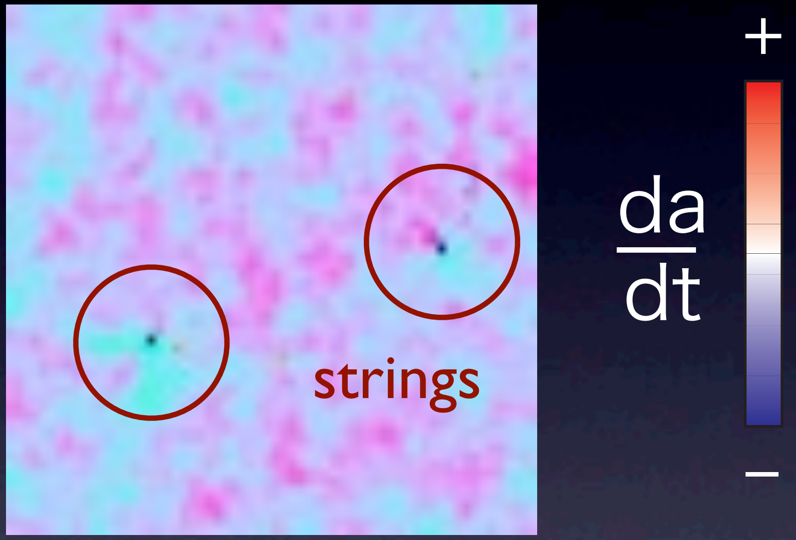

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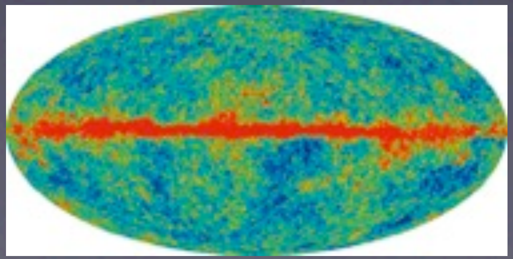
- We adopted the pseudo-power spectrum estimator (PPSE), which is often used in data analysis of CMB.



Pipeline

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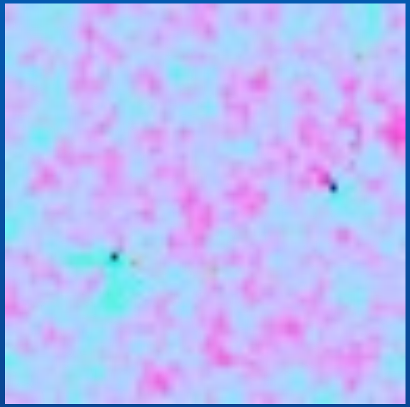
$$\dot{a}(\vec{x}) = \dot{a}_{\rm free}(\vec{x}) + (\text{string contribution})$$



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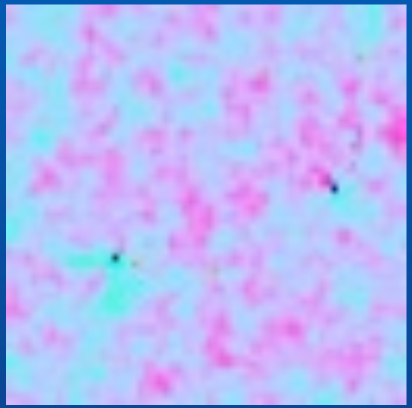

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• Window function

$$W(\vec{x}) = \begin{cases} 0 & (\text{near strings}) \\ 1 & (\text{elsewhere}) \end{cases}$$

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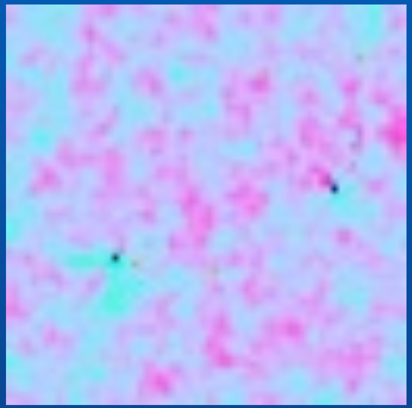

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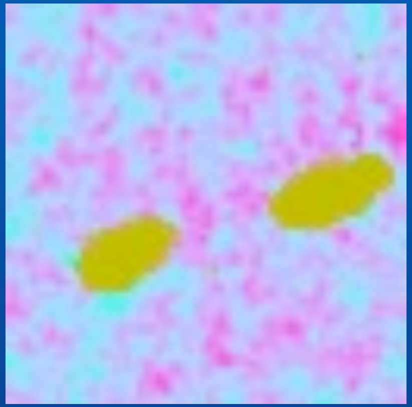

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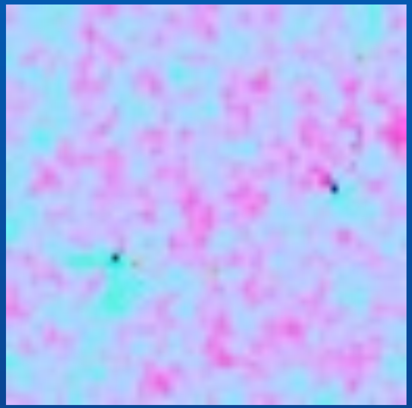

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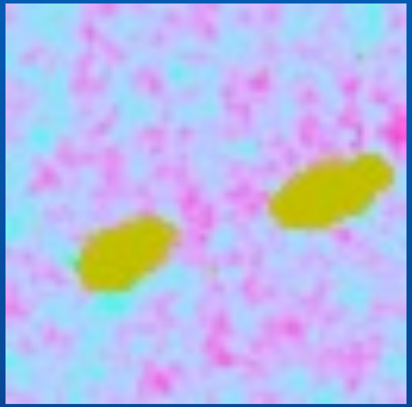

4. Spectrum of masked fluctuation

$$\tilde{P}(k) \approx \int \frac{d\hat{k}}{4\pi} \left|\tilde{\dot{a}}(\vec{k})\right|^2$$

- Biased due to masking

$$\langle \tilde{P}(k) \rangle \neq P_{\rm free}(k)$$

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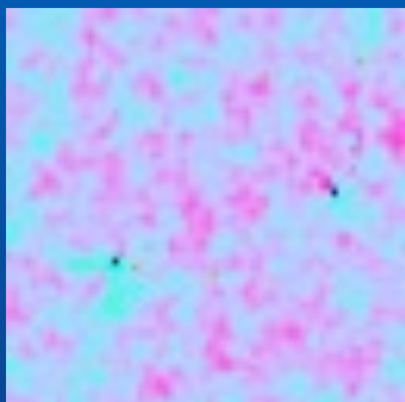

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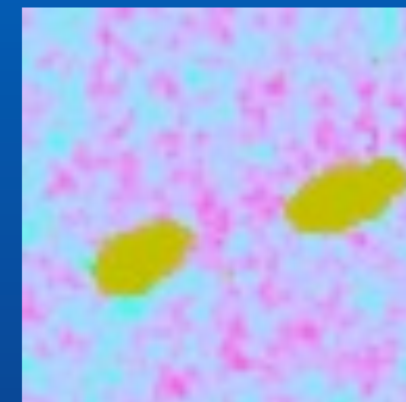

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5. Pseudo-power spectrum estimator

$$\hat{P}(k) \approx \int dk M^{-1}(k,k')\tilde{P}(k')$$

with

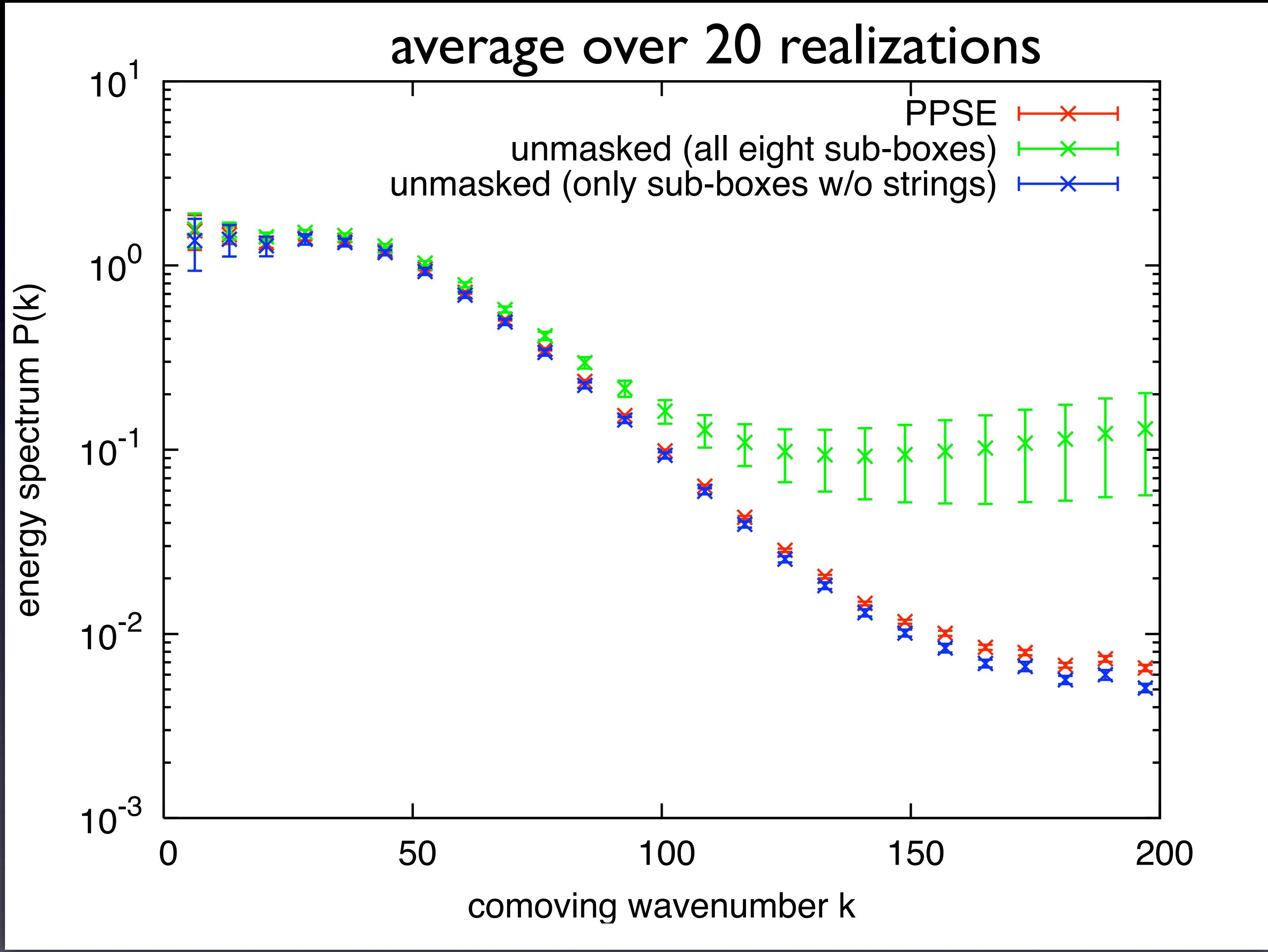
$$M(k,k') \equiv \int \frac{d\hat{k}}{4\pi}\frac{d\hat{k}'}{4\pi} \left|W(\vec{k}-\vec{k}')\right|^2$$

- PPSE is unbiased!

$$\langle \hat{P}(k) \rangle = P_{\rm free}(k)$$

Validity check of PPSE

- Energy spectra are estimated in eight sub-boxes with a same size.



- Total box size

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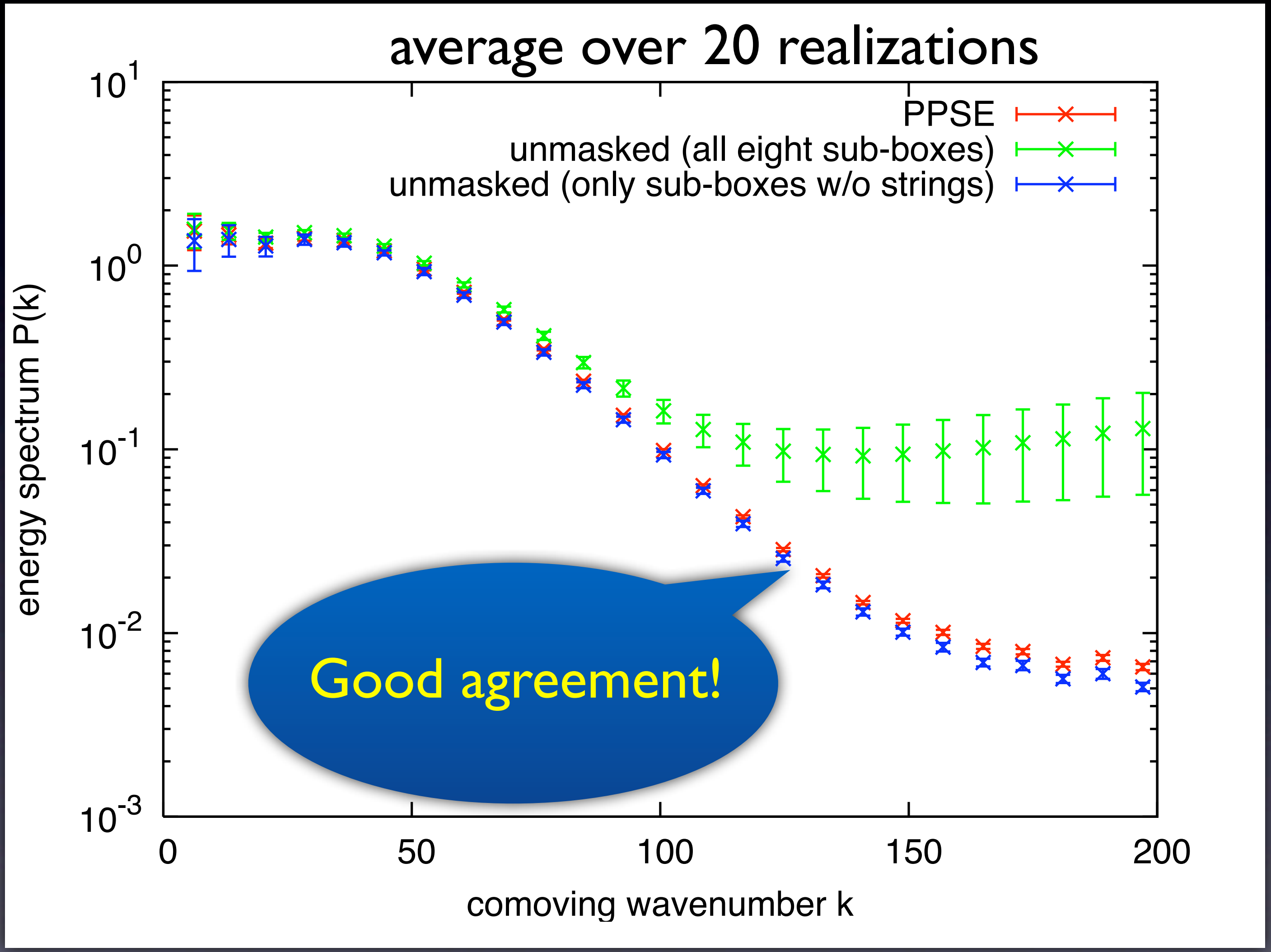

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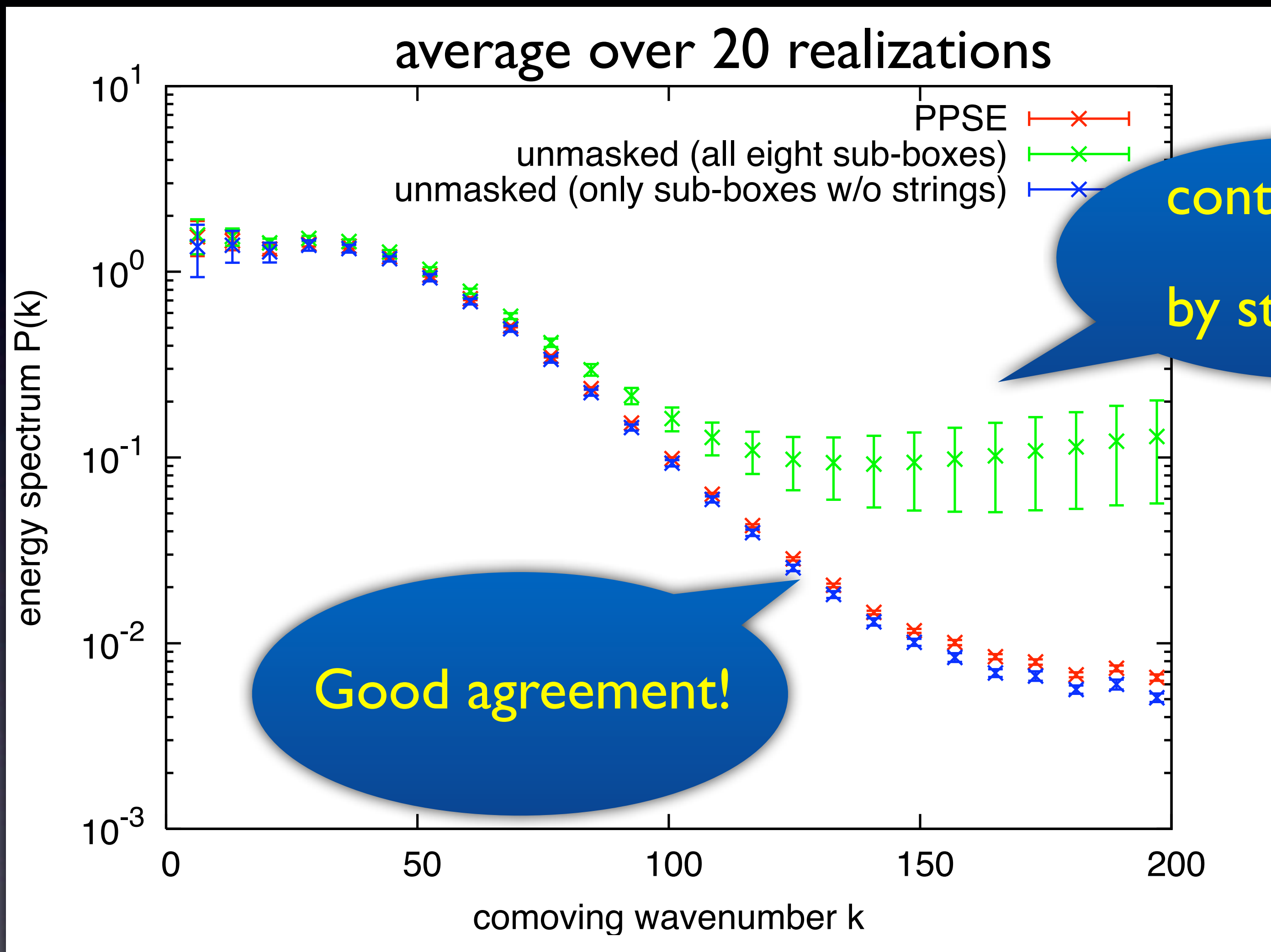

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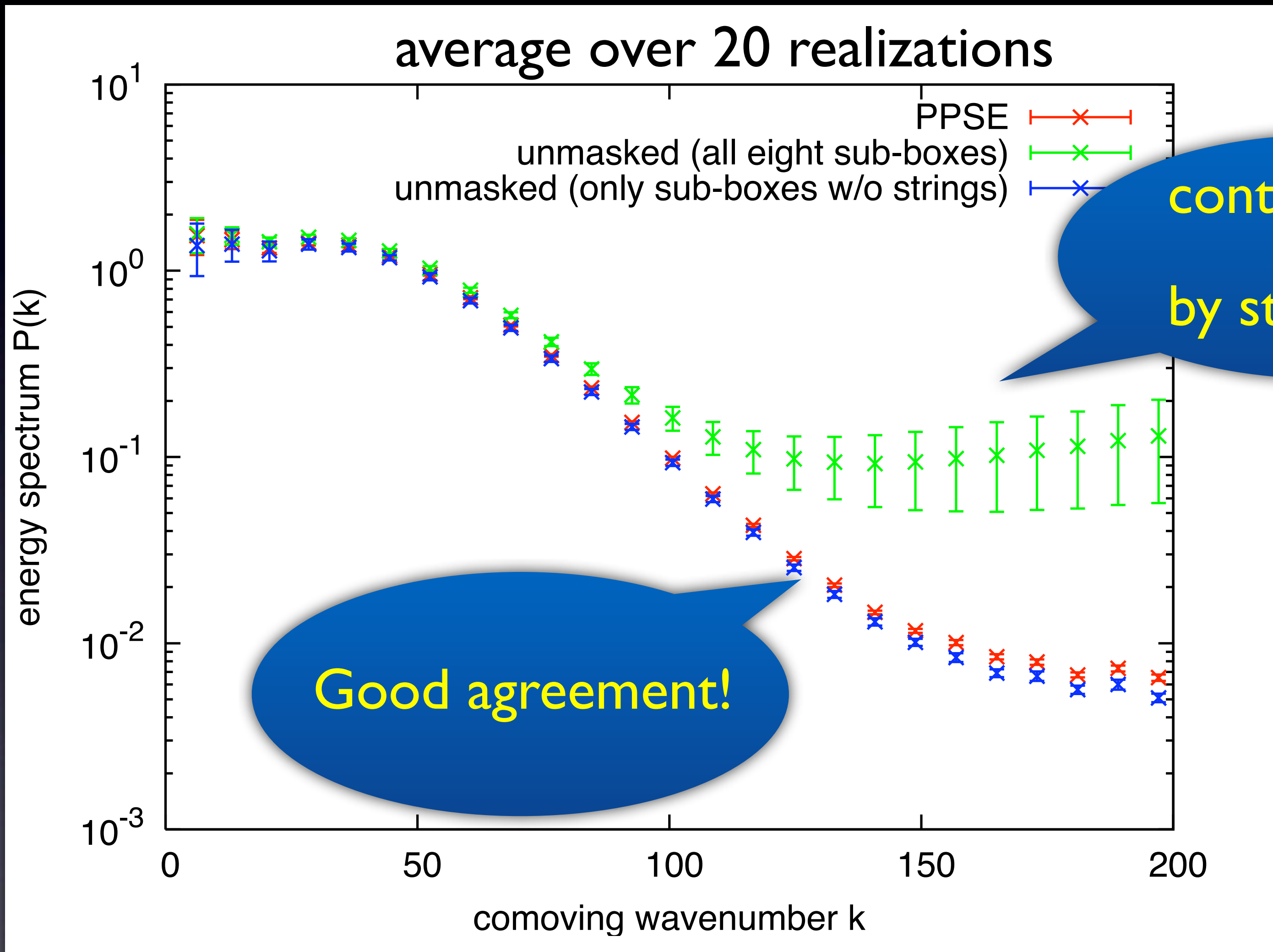

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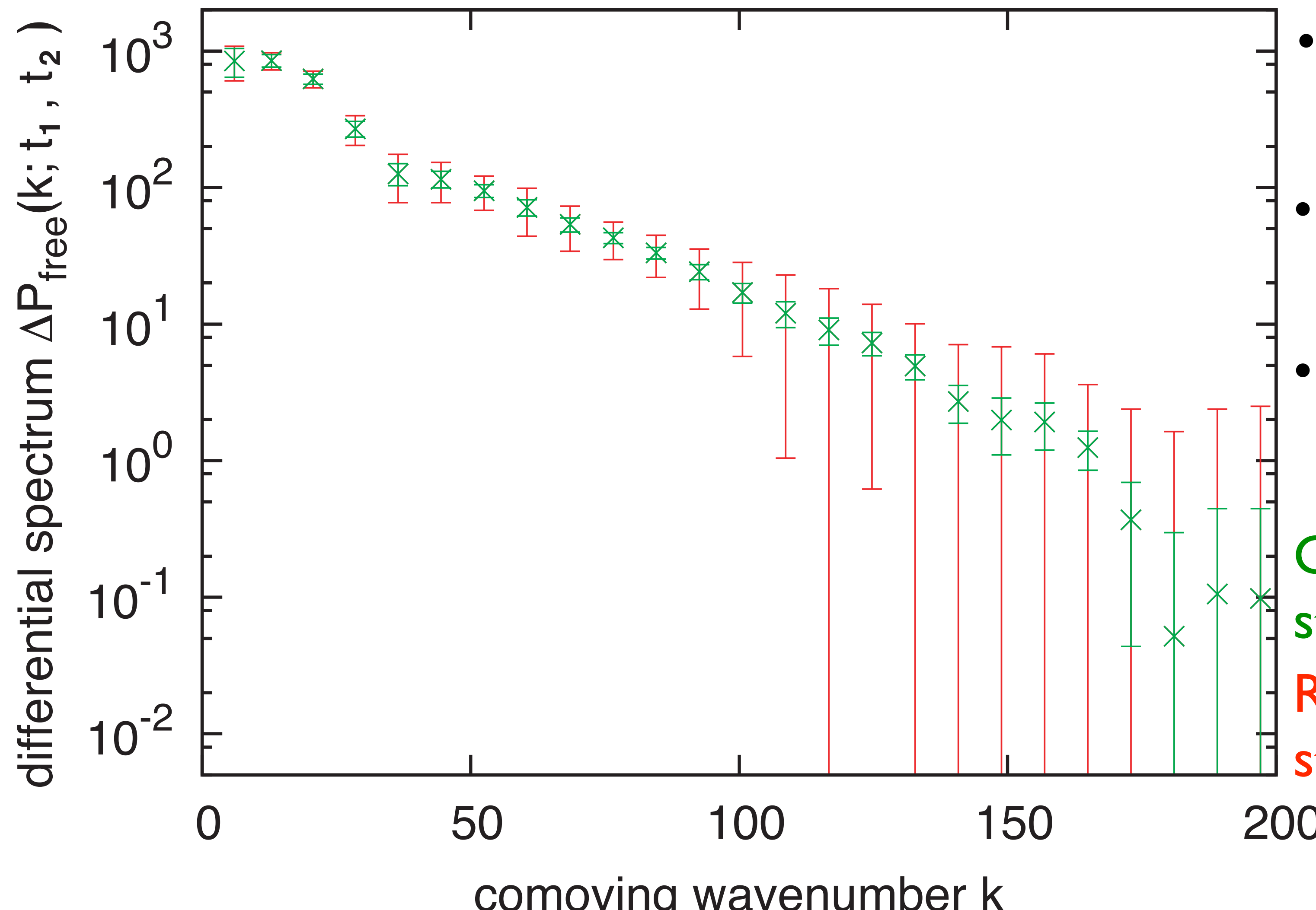
- PPSE successfully removes the string contaminations!

Result: Differential spectrum

- Differential spectrum (= energy spectrum of net radiated axions)

$$\Delta\hat{P}(k;t_1,t_2) = R(t_2)^4\hat{P}(k,t_2) - R(t_1)^4\hat{P}(k,t_1)$$



- averaged over 20 realizations
- box size:

$$L = 1.6/H(t_2)$$

- resolution:

$$d_{\text{string}} = 1.4 \times R(t_2)\Delta x$$

Green: statistical error alone

Red: statistical + systematic

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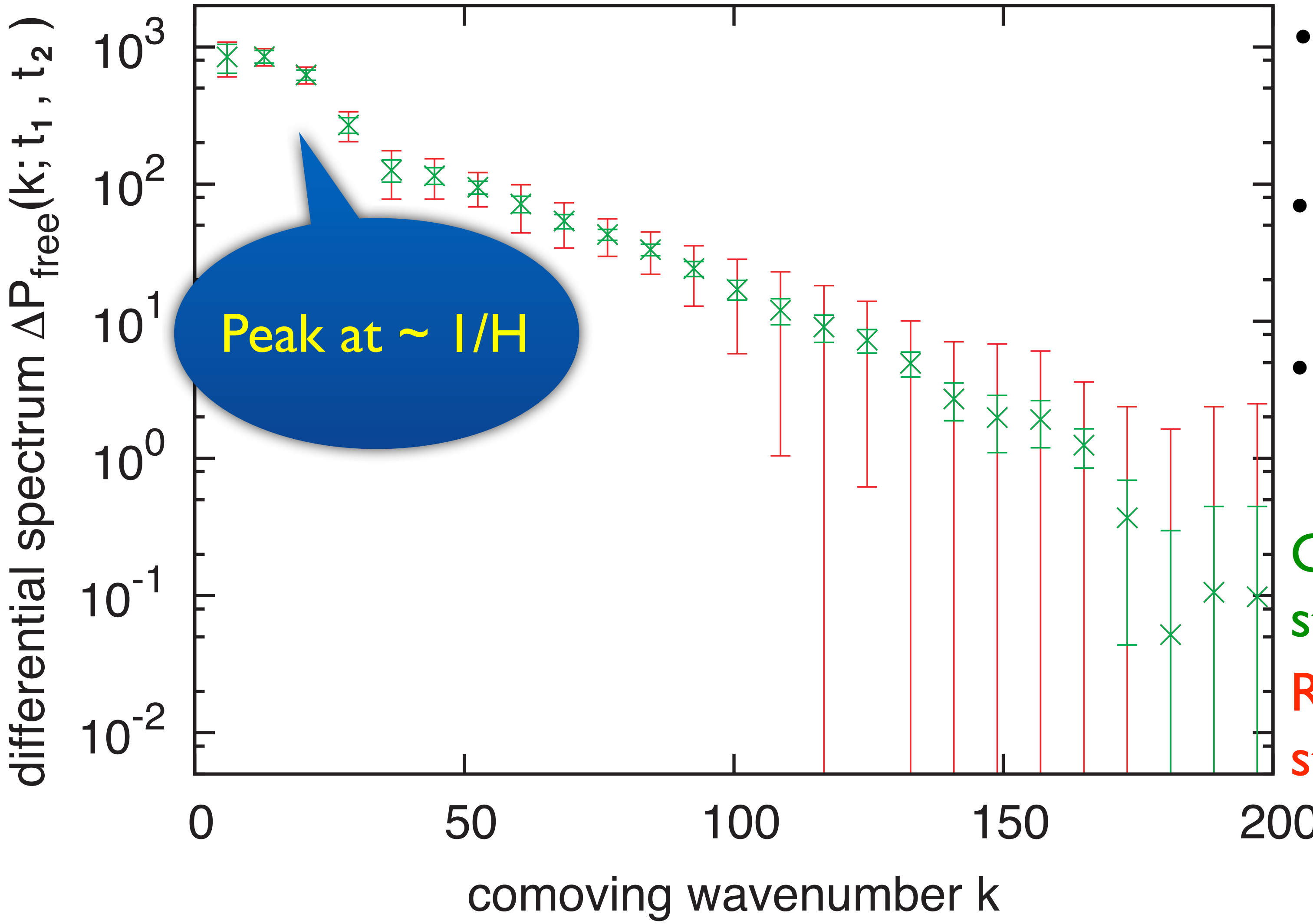

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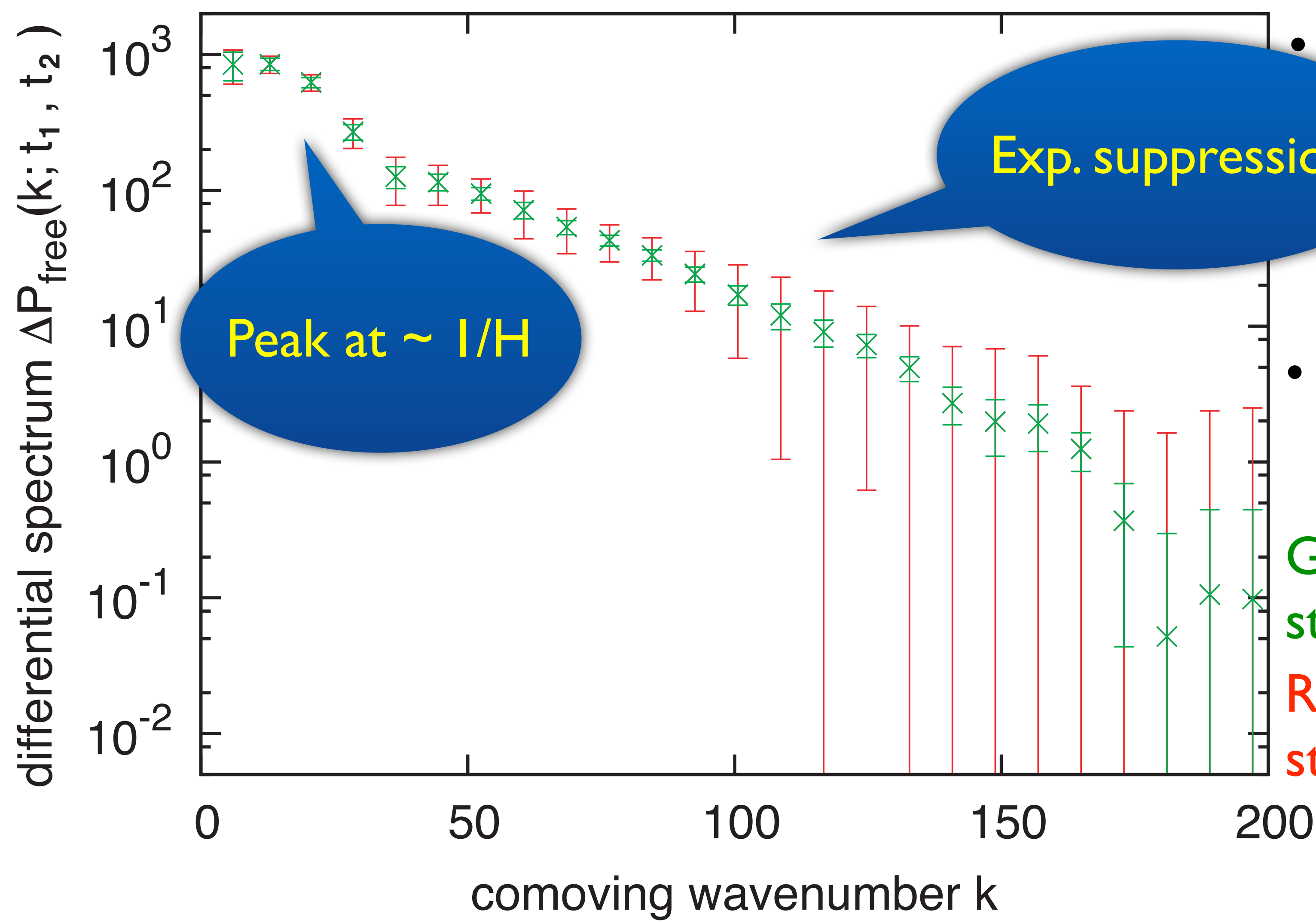

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Energy dependence of radiated axions

- Energy spectrum of radiated axion P(k):
  - Sharply peaks around the horizon scale.
  - Suppressed exponentially toward higher momenta k.
  - Consistent with the previous YKY99 and supports the claim of Davis & Shellard.

- Mean momentum of radiated axions:

$$\overline{k(t)} = \frac{\int dk \Delta P_{\rm free}(k,t)}{\int dk \frac{1}{k} \Delta P_{\rm free}(k,t)} = \frac{\Delta[\bar{\rho}_{\rm axion} R^4]}{\Delta[\bar{n}_{\rm axion} R^3]}$$

- $\overline{k(t)}$ ~ Hubble scale,

$$\overline{k(t)}^{-1} = 0.23 \pm 0.02 \frac{t}{R(t) 2\pi}.$$

⇒ consistent with 0.25±0.18 in YKY99.

5. Constraint on the axion decay constant

- Extrapolate our result down to $\eta = f_a \simeq 10^{12}\mathrm{GeV}$.
- In the scaling regime, the energy density of strings are given by

$$\bar{\rho}_{\mathrm{string}}(t) = \frac{\xi}{t^2} 2\pi f_a^2 \ln\left(\frac{t}{\sqrt{\xi} d_{\mathrm{string}}}\right), \qquad \text{with } d_{\mathrm{string}} = f_a/\sqrt{2}.$$

- Axionic strings lose their energy via emitting axions:

$$\left[\frac{d\bar{\rho}_{\mathrm{axion}}}{dt}\right] = -\left[\frac{d\bar{\rho}_{\mathrm{string}}}{dt}\right].$$

⇒ Net energy density of radiated axions:

$$\frac{1}{R(t)^4}\frac{d[R(t)^4\bar{\rho}_{\mathrm{axion}}(t)]}{dt} \simeq \frac{\xi}{t^3} 2\pi f_a^2 \ln\left(\frac{f_a t}{\sqrt{2\xi}}\right)$$

- Number of radiated axions in a unit comoving volume:

$$R(t)^3\bar{n}_{\mathrm{axion}}(t) = \int^t dt \overline{k(t)}^{-1} \frac{d[R(t)^4\bar{\rho}_{\mathrm{axion}}(t)]}{dt}.$$

Constraint on the axion decay constant(cont'd)

- Strings continue emitting axions till the wall domination occurring at

$$T_w \simeq 0.67\ \mathrm{GeV}\left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{-0.12}.$$

← $m_{\rm axion} \propto f_a^{-1} T^{-3.39}$

[Wantz & Shellard (09)]

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- The energy density of CDM axions from strings

$$\Omega_{\mathrm{axion}} h^2 \simeq 8.7 \left(\frac{\xi}{\epsilon}\right)\left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{1.19} \quad \text{with} \quad \begin{cases} \xi = 0.87 \pm 0.14 \\ 1/\epsilon = 0.23 \pm 0.02 \end{cases}$$

- Constraint on the decay constant of axion:

$$f_a \lesssim 1.3 \times 10^{11} \mathrm{GeV}$$

← $\Omega_{\mathrm{CDM}} h^2 = 0.11$ [Komatsu+(10)]

Other sources of axion CDM

- Emission from DWs [Hagmann & Sikivie (91), Lyth (92), Nagasawa & Kawasaki (94), ...]
  - DWs quickly disappear after formation.

$$\Omega_{\rm axion} h^2 \simeq \frac{1.8}{\gamma} \left(\frac{f_a}{10^{12}{\rm GeV}} \right)^{1.19}$$

γ : Lorentz factor of radiated axions

  - Numerical simulation gives $\gamma \simeq 7$. [Chang, Hagmann & Sikivie (98)]

$$\Rightarrow \quad f_a \lesssim 4.9 \times 10^{11} {\rm GeV}.$$

- Coherent oscillation

$$\Omega_{\rm axion} h^2 \simeq 0.10 \, \theta_i^2 \left(\frac{f_a}{10^{12}{\rm GeV}} \right)^{1.19}$$

θ_i : initial misalignment

  - The canonical value is $\langle \theta_i^2 \rangle = \pi^2/3$.

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- Constraints from other sources are comparable. $\Rightarrow f_a \lesssim 10^{11}$ GeV.

Summary

- We performed a field theoretic simulation of cosmological axionic strings of the largest scales ($N_{\rm grid} = 512^3$) so far.
- We developed a new method for identification of strings, which allows determination of string positions with >99% efficiency.
- We estimated the energy spectrum of radiated axions from strings, using the pseudo-power spectrum estimator. We successfully removed contributions from string cores and achieved precise estimation of the spectrum.
- The spectrum is consistent with YKY99, showing exponential damping at large momenta. Our result supports the claim of Davis & Shellard.
- We obtained a constraint on the axion decay constant,

$$f_a \lesssim 10^{11} \ {\rm GeV}.$$

Result: Energy spectrum

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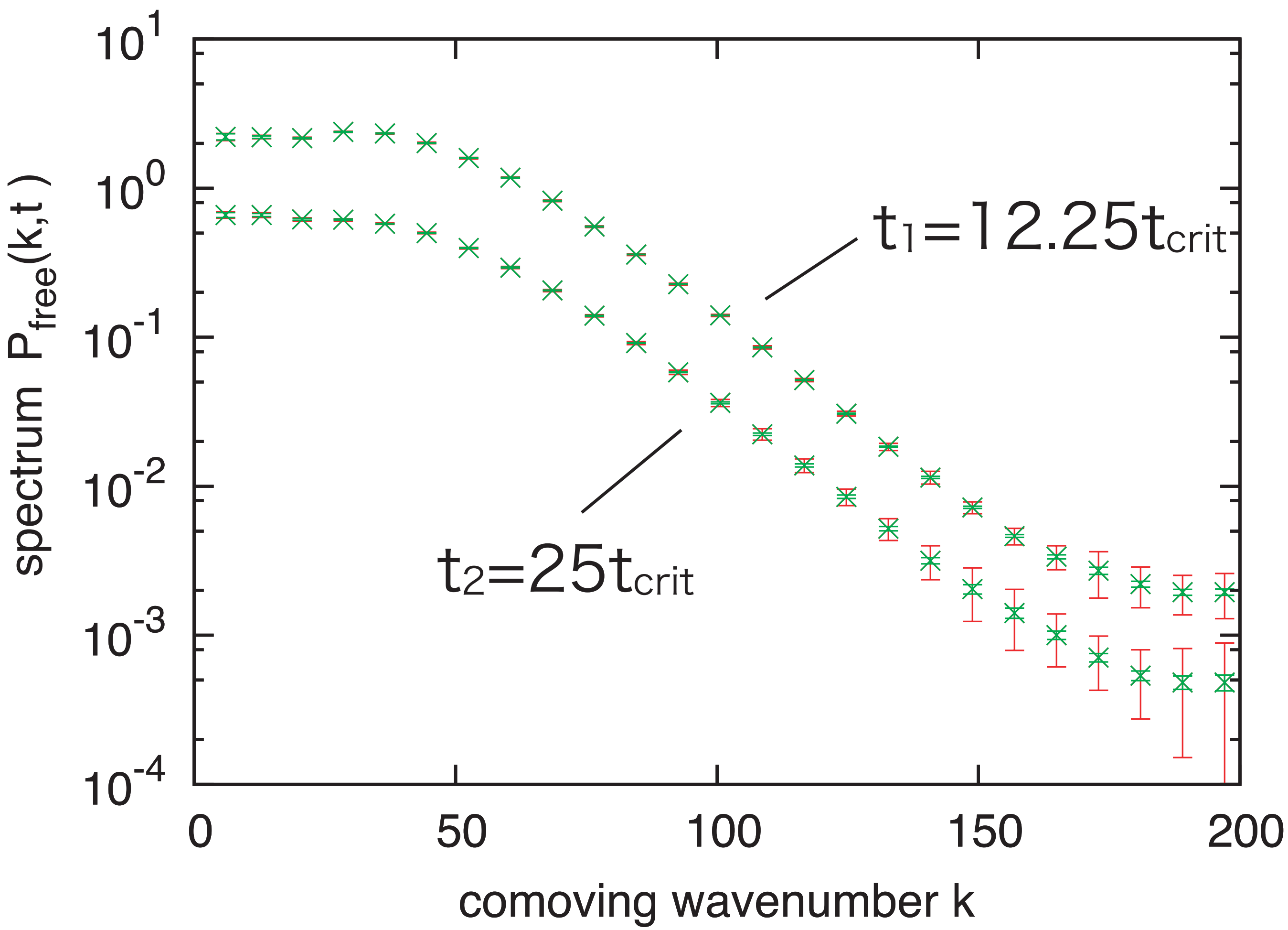

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Note!! Not all of axions are emitted within the scaling regime.