VILA DO CONDE, PORTUGAL, 29-31 MARCH, 2016

11th Iberian Cosmology Meeting

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SERIES OF MEETINGS WHICH AIM TO ENCOURAGE INTERACTIONS AND COLLABORATIONS BETWEEN RESEARCHERS WORKING IN COSMOLOGY AND RELATED AREAS IN PORTUGAL AND SPAIN.

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Scalar field dark matter and the Higgs field

Catarina M. Cosme

PhD student under the supervision of
Prof. João Rosa and Prof. Orfeu Bertolami

arXiv: 1603.06242

30 March 2016

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Introducing the problem

- **Dark matter (DM) - 26.8 %** of the mass-energy content of the Universe [Planck Collaboration 2015];

What is dark matter made of?

- We propose: oscillating scalar field as DM candidate, coupled to the Higgs boson;
- Previous works: "Higgs-portal" DM models: abundance of DM is set by the decoupling and freeze-out from thermal equilibrium $\Rightarrow$ $m \sim GeV - TeV$ (Weakly Interacting Massive Particles - WIMPs) [Silveira, Zee 1985; Bento, Bertolami, Rosenfeld 2001; Burgess, Pospelov, ter Veldhuis 2001; Tenkanen 2015];

Oscillating scalar field as dark matter candidate

Our proposal

- Oscillating scalar field, ϕ, as DM candidate;
- ϕ acquires mass through the Higgs mechanism;
- ϕ starts to oscillate when $m_\phi \sim H$, after the electroweak phase transition;
- Weakly interactions with the Higgs boson $\Rightarrow$ $m_\phi \ll eV$, extremely small self-interactions $\Rightarrow$ oscillating scalar condensate that is never in thermal equilibrium.

Oscillating scalar field as dark matter candidate

Energy density

$$\rho_{\phi,0} = \frac{1}{2}\frac{m_\phi^2}{a_0^3}\phi_i^2$$

DM abundance

$$\Omega_{\phi,0} \equiv \frac{\rho_{\phi,0}}{\rho_{c,0}}$$

$$H_{EW} \sim 10^{-5}\ eV$$

$$m_\phi(\phi_i) = \begin{cases} 2\times 10^{-5}\left(\frac{g_*}{100}\right)^{1/2}\left(\frac{\phi_i}{10^{13}\ GeV}\right)^{-4} eV, & m_\phi > H_{EW}. \\ 3\times 10^{-5}\left(\frac{g_*}{100}\right)^{1/2}\left(\frac{\phi_i}{10^{13}\ GeV}\right)^{-4} eV, & m_\phi < H_{EW}. \end{cases}$$

Initial conditions

- Light fields during inflation ⇒ quantum fluctuations do not respect the limit of the Cold Dark Matter (CDM) isocurvature perturbations.

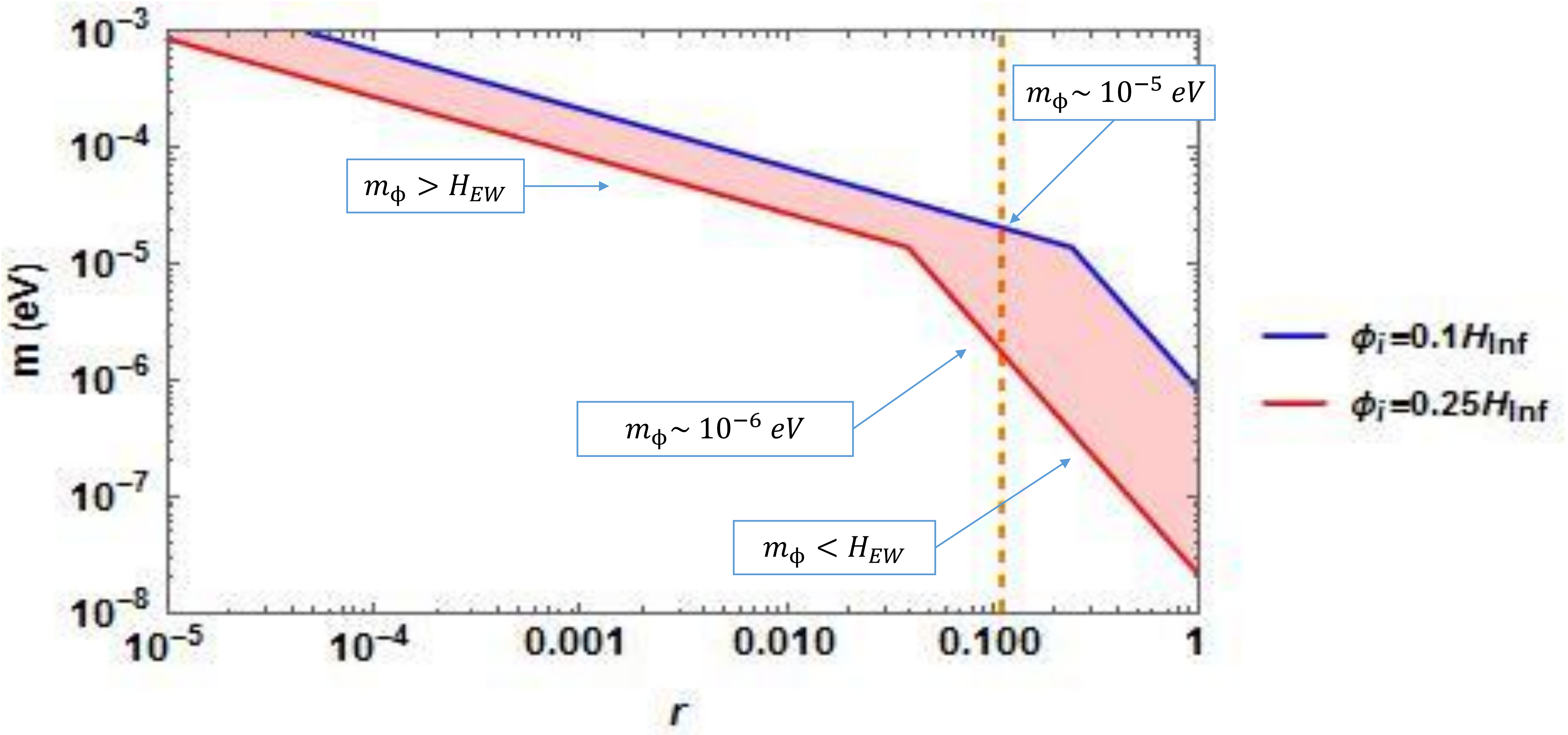
- Gravitational interactions during inflation ⇒ $\mathcal{L}_{int} = \frac{c}{2}\frac{\phi^2 V(\chi)}{M_{Pl}^2}$ ⇒ $m_\phi \sim H_{inf}$ ⇒ CDM isocurvature perturbations compatible with observations [Planck Collaboration 2015] ;

- Constraints on CDM isocurvature perturbations lead to: $\phi_i \simeq \alpha\, H_{inf}, \quad \alpha \simeq 0.1 - 0.25;$

- $H_{inf} \simeq 2.5 \times 10^{13} \left(\frac{r}{0.01}\right)^{\frac{1}{2}} GeV, \quad r < 0.11.$ [Planck Collaboration 2015].

$$r \equiv \frac{\Delta_t^2}{\Delta_{\mathcal{R}}^2}$$

Initial conditions – Results



Non-renormalizable interactions model

Hidden sector
DM field Conformal symmetry

broken by non-renormalizable operators

Heavy messengers,

Gravity

Visible sector
Higgs boson (and Standard Model fields)

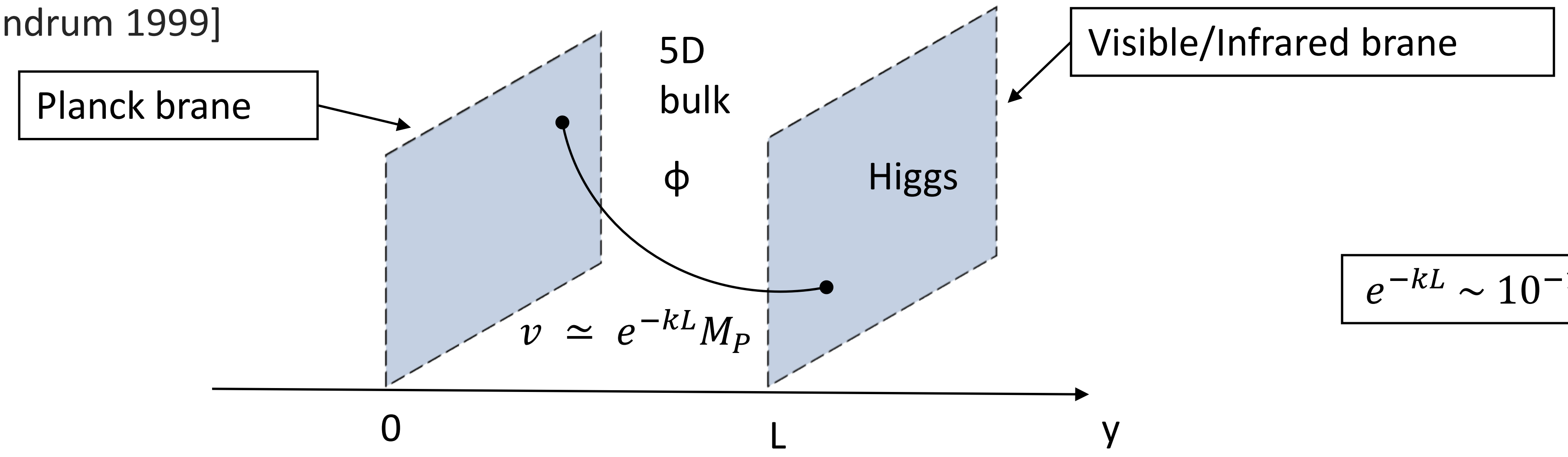
$$\mathcal{L}_{int} = \frac{a_6^2}{2}|h|^4\frac{\phi^2}{M^2} \Rightarrow m_\phi = a_6\,\frac{v^2}{M} \sim 2.5\times10^{-5}\,a_6\left(\frac{M}{M_P}\right)^{-1}\ \mathrm{eV};$$

Electroweak symmetry breaking

Warped extra-dimension model

Randall-Sundrum inspired model:

[L. Randall, R. Sundrum 1999]



$e^{-kL} \sim 10^{-16}$

Metric: $ds^2 = e^{-2k|y|} g_{\mu\nu} dx^{\mu} dx^{\nu} + dy^2$

$$S = \int d^4x \int dy \, \sqrt{-G} \left[\frac{1}{2} \, G^{MN} \partial_M \Phi \partial_N \Phi - \frac{1}{2} M_\Phi^2 \Phi^2 + \delta(y - L) \left(G^{MN} \partial_M h^\dagger \partial_N h - V(h) + \frac{1}{2} g_5^2 \Phi^2 h^2 \right) \right]$$

Warped extra-dimension model

- Decompose Φ in Kaluza-Klein modes: $\Phi(x^\mu, y) = \frac{1}{\sqrt{2L}} \sum_{n=0}^{\infty} \phi_n(x^\mu) f_n(y)$;

- $\Phi_0(x^\mu, L) = \frac{1}{\sqrt{2L}} \phi_0(x^\mu)\sqrt{2kL}$ ⟹ $\mathcal{L}_{int} = \frac{1}{2} g_5^2 k e^{-2kL} \phi_0^2 h^2$

⟹ $g_4 \sim g_5^2 k e^{-2kL} \simeq \mathcal{O}(1) \times \frac{v}{M_P} \sim 10^{-16}$

$$m_\phi \sim \frac{v^2}{M_P} \sim 10^{-5}\ \text{eV}$$

→ Mass in the required range;
In agreement with non-renormalizable interactions model.

Planck-suppressed non-renormalizable operator	⟺	Renormalizable interaction in a higher-dimensional warped geometry.

Conclusions

- DM candidate: oscillating scalar field ϕ, which acquires mass through the Higgs mechanism.
- Lower bound: $m_\phi \gtrsim 10^{-6} - 10^{-5}\, eV$;
- $m_\phi \sim \frac{v^2}{M_P} \sim 10^{-5}\, eV$ obtained through either non-renormalizable interactions between ϕ and the Higgs field or through a warped extra-dimension model.

Thank you for your attention!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Scalar field inflation in the presence of a non-minimal matter-curvature coupling

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IberiCos 2016, Vila do Conde, 30 March 2016

[†]In collaboration with Orfeu Bertolami and João Rosa

Fundação para a Ciência e a Tecnologia, SFRH/BD/102820/2014

Contents

1. Inflation
2. Alternative theories of gravity
   The non-minimal coupling between matter and curvature (NMC)
3. Scalar field inflation with a matter-curvature NMC

Why Inflation?

Hot Big Bang model:

- Evolutionary Universe;
- CMB;
- BBN...

Leaves some conundrums:

- Large scale homogeneity and isotropy (horizon problem);
- Flatness problem;
- Absence of observed topological defects (monopole problem);
- Origin of the energy density fluctuations,...

Cosmic Inflation (paradigm, not theory) provides a suitable solution for the above problems by a mechanism of accelerated expansion of the Universe at early times (between Planck and GUT epochs).

Scalar field inflation

Real scalar field with:

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0 \tag{1}$$

Inflation occurs in the so-called slow-roll approximation:

- $$V \gg \dot{\phi}^2/2 \implies \rho \approx V(\phi) \tag{2}$$
- $$V \approx const. \tag{3}$$

This is the same as stating that the slow-roll parameters are:

$$\epsilon_\phi = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1 \tag{4}$$

$$\eta_\phi = M_P^2 \frac{V''}{V} \ll 1 \tag{5}$$

Why to go beyond GR?

Successes:

- Solar System constraints;
- GPS;

But there were still some conundrums:

- Not compatible with quantum mechanics;
- Existence of singularities;
- Cosmological constant problem;
- Large scale data requires DM and DE;
- Astrophysical data requires DM.

Alternative theories of gravity:

- f(R)
- Horndeski gravity;
- Jordan-Brans-Dicke;
- NMC [Bertolami, Böhmer, Harko, Lobo 2007]...

Alternative theories of gravity: the NMC

Generalisation of $f(R)$ theories
[Bertolami, Bohmer, Harko, Lobo, 2007]:

$$S = \int \left[\kappa f_1(R) + f_2(R)\mathcal{L}\right]\sqrt{-g}d^4x \quad , \tag{6}$$

where $\kappa = M_P^2/2 = 1/16\pi G$.
Varying the action relatively to the metric $g_{\mu\nu}$:

$$\begin{aligned} 2(\kappa F_1 - F_2\rho)\left(R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R\right) =& f_2 T_{\mu\nu} + \kappa(f_1 - F_1 R)g_{\mu\nu} + \\ &+ F_2\rho R g_{\mu\nu} + 2\Delta_{\mu\nu}(\kappa F_1 - F_2\rho) \end{aligned} \tag{7}$$

One recovers GR by setting $f_1(R) = R$ and $f_2(R) = 1$.

Using the Bianchi identities, one finds the non-covariant conservation of the energy-momentum tensor:

$$\nabla_\mu T^{\mu\nu} = \frac{F_2}{f_2}\left(g^{\mu\nu}\mathcal{L} - T^{\mu\nu}\right)\nabla_\mu R \qquad (8)$$

For a perfect fluid, the extra force due to the NMC can be expressed as:

$$f^\mu = \frac{1}{\rho + p}\left[\frac{F_2}{1 + f_2}(\mathcal{L}_m - p)\nabla_\nu \mathrm{R} + \nabla_\nu p\right] h^{\mu\nu}, \qquad (9)$$

with $h^{\mu\nu} = g^{\mu\nu} + u^\mu u^\nu$ being the projection operator.

Degeneracy-lifting of the Lagrangian choice [O. Bertolami, F. S. N. Lobo, J. Páramos, 2008]

Mimicking Dark Matter (galaxies, clusters) [O. Bertolami, J. Páramos, 2010; O. Bertolami, P. Frazão, J. Páramos, 2013]

Cosmological Perturbations [O. Bertolami, P. Frazão, J. Páramos, 2013]

Preheating scenario after inflation [O. Bertolami, P. Frazão, J. Páramos, 2011]

Modified Friedmann equation [O. Bertolami, J. Páramos, 2013]

Modified Layzer-Irvine equation and virial theorem [O. Bertolami, C. Gomes, 2014]

...

Scalar field inflation in the presence of a non-minimal matter-curvature curvature

At first approximation:

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) \approx 0 \tag{10}$$

In the slow-roll regime, and for $f_1(R) = R$, we have a modified Friedmann equation:

$$H^2 \approx \frac{f_2}{1 + \frac{2F_2\rho}{M_P^2}} \frac{\rho}{3M_P^2} \tag{11}$$

Choosing the non-minimal coupling function to be:

$$f_2(R) = 1 + \left(\frac{R}{R_n}\right)^n \tag{12}$$

we find that for the large density limit:

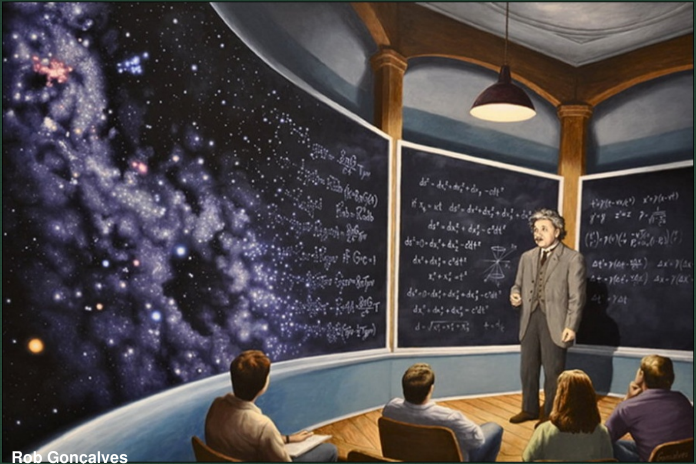
- $n = 2$ we retrieve the Friedmann equation as in GR
- $n \geq 3$ the modified Friedmann equation becomes ($A_n, B_n \in \mathbb{R}$)

$$H^2 = A_n - \frac{B_n}{\rho} \tag{13}$$

  whilst in the low density regime, this model gives a small correction to the Friedmann's equation.

We further note that modifications of the Friedmann equation have been well studied in the literature: brane models, loop quantum cosmology, ...

Thank you for your attention!



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The variation of the fine-structure constant from disformal couplings

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Instituto de Astrofísica e Ciências do Espaço

in collaboration with: Jurgen Misfud and Carsten van de Bruck, arXiv:1510.00200

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Disformal couplings

Let us consider the action

$$\mathcal{S} = \mathcal{S}_{\rm grav}\,(g_{\mu\nu},\phi) + S_{\rm matter}(\tilde{g}^{(m)}_{\mu\nu}) + S_{\rm EM}(A_\mu, \tilde{g}^{(r)}_{\mu\nu})$$

The metrics $\tilde{g}^{(m)}_{\mu\nu}$ and $\tilde{g}^{(r)}_{\mu\nu}$ are related to $g_{\mu\nu}$ via a disformal transformation:

$$\tilde{g}^{(m)}_{\mu\nu} = C_m(\phi) g_{\mu\nu} + D_m(\phi)\phi_{,\mu}\phi_{,\nu}$$

$$\tilde{g}^{(r)}_{\mu\nu} = C_r(\phi) g_{\mu\nu} + D_r(\phi)\phi_{,\mu}\phi_{,\nu}\ .$$

C_r and C_m are conformal factors
D_r and D_m are disformal factors
We can also write,

$$\tilde{g}^{(r)}_{\mu\nu} = \frac{C_r}{C_m}\tilde{g}^{(m)}_{\mu\nu} + \left(D_r - \frac{C_r D_m}{C_m}\right)\phi_{,\mu}\phi_{,\nu} \equiv A\tilde{g}^{(m)}_{\mu\nu} + B\phi_{,\mu}\phi_{,\nu}$$

Electromagnetic sector

The action

$$\mathcal{S}_{\rm EM} = -\frac{1}{4}\int d^4x\sqrt{-\tilde{g}^{(r)}}h(\phi)\tilde{g}^{\mu\nu}_{(r)}\tilde{g}^{\alpha\beta}_{(r)}F_{\mu\alpha}F_{\nu\beta} - \int d^4x\sqrt{-\tilde{g}^{(m)}}\tilde{g}^{\mu\nu}_{(m)}j_\mu A_\mu$$

- $F_{\mu\nu}$ is Faraday tensor; j^μ is the four–current;
- $h(\phi)$ is the coupling between the electromagnetism and ϕ.

In the frame in which matter is decoupled from the scalar field

$$\begin{aligned}\mathcal{S}_{\rm EM} &= -\frac{1}{4}\int d^4x\sqrt{-\tilde{g}^{(m)}}hZ\left[\tilde{g}^{\mu\nu}_{(m)}\tilde{g}^{\alpha\beta}_{(m)} - 2\gamma^2\tilde{g}^{\mu\nu}_{(m)}\phi^{,\alpha}\phi^{,\beta}\right]F_{\mu\alpha}F_{\nu\beta}\\ &\quad -\int d^4x\sqrt{-\tilde{g}^{(m)}}\tilde{g}^{\mu\nu}_{(m)}j_\mu A_\mu\end{aligned}$$

where

$$Z = \left(1 + \frac{B}{A}\tilde{g}^{\mu\nu}_{(m)}\partial_\mu\phi\partial_\nu\phi\right)^{1/2}, \qquad \gamma^2 = \frac{B}{A+B\tilde{g}^{\mu\nu}_{(m)}\partial_\mu\phi\partial_\nu\phi}$$

The field equation for A_μ

Varying the action with respect to A_μ

$$\tilde{\nabla}_\epsilon \left(hZF^{\epsilon\rho}\right) - \tilde{\nabla}_\epsilon \left(hZ\gamma^2 \phi^{,\beta} \left(\tilde{g}^{\epsilon\nu}_{(m)} \phi^{,\rho} - \tilde{g}^{\rho\nu}_{(m)} \phi^{,\epsilon}\right) F_{\nu\beta}\right) = j^\rho$$

With $\tilde{g}^{(m)}_{\mu\nu} = \eta_{\mu\nu}$, and $E^i = F^{i0}$

$$\nabla \cdot \mathbf{E} = \frac{Z\rho}{h}$$

where $\rho = j^0$. Integrating this equation over a volume $\mathcal{V}$ using, $\mathbf{E} = -\nabla V$, we get the electrostatic potential

$$V(r) = \frac{ZQ}{4\pi hr} \qquad \Rightarrow \qquad \boxed{\alpha \propto \frac{Z}{h}}$$

The fine structure constant depends on Z.

The evolution of α

For FLRW Universe,

$$Z = \left(\frac{1 - \frac{D_r}{C_r}\dot{\phi}^2}{1 - \frac{D_m}{C_m}\dot{\phi}^2} \right)^{1/2}$$

Time derivative of α,

$$\frac{\dot{\alpha}}{\alpha} = \frac{1}{Z}\left(\frac{\partial Z}{\partial \phi}\dot{\phi} + \frac{\partial Z}{\partial \dot{\phi}}\ddot{\phi} \right) - \frac{1}{h}\frac{dh}{d\phi}\dot{\phi}$$

Redshift evolution of α,

$$\frac{\Delta\alpha}{\alpha}(z) \equiv \frac{\alpha(z) - \alpha_0}{\alpha_0} = \frac{h_0 Z}{h Z_0} - 1$$

Constrains on the evolution of α

1. Atomic Clocks at $z = 0$,

$$\left.\frac{\dot{\alpha}}{\alpha}\right|_0 = (-1.6 \pm 2.3) \times 10^{-17}\ \text{yr}^{-1}$$

2. Oklo at $z \approx 0.16$,

$$\frac{|\Delta\alpha|}{\alpha} < 1.1 \times 10^{-8}$$

3. ^{187}Re meteorite at $z \approx 0.43$,

$$\frac{\Delta\alpha}{\alpha} = (-8 \pm 8) \times 10^{-7}$$

4. CMB at $z \simeq 10^3$

$$\frac{\Delta\alpha}{\alpha} = (3.6 \pm 3.7) \times 10^{-3}$$

Astrophysical constrains on the evolution of α

1. Keck/ HIRES141 absorbers (MM method) [M.T. Murphy et al. 2004]
2. VLT/ UVES154 absorbers (MM method) [J.A. King et al. 2012]
3. Keck/ HIRES Si IV absorption systems (AD method) [M.T. Murphy et al. 2001]
4. Comparison of HI 21 cm line with molecular rotational absorption spectra [M.T. Murphy et al. 2001]
5. 11 UVES absorbers [P. Molaro et al. 2013, T.M. Evans et al. 2014]

Gravity and matter field sector

Is the evolution of ϕ compatible with constraints on the evolution of α?

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(\frac{1}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right) + S_{\rm matter}(\tilde{g}^{(m)}_{\mu\nu})$$

with the equation of motion

$$\begin{aligned}\ddot{\phi} + 3H\dot{\phi} + V' &= Q_m + Q_r,\\ \dot{\rho}_m + 3H(\rho_m + p_m) &= -Q_m\dot{\phi},\\ \dot{\rho}_r + 3H(\rho_r + p_r) &= -Q_r\dot{\phi},\end{aligned}$$

where Q_m and Q_r are complicated functions of ρ_m, ρ_r, $\dot{\phi}$, C_r, C_m, D_r, D_m and their field derivatives.

Couplings and parameters

We specify to exponential couplings and potential and to linear direct coupling $h(\phi)$:

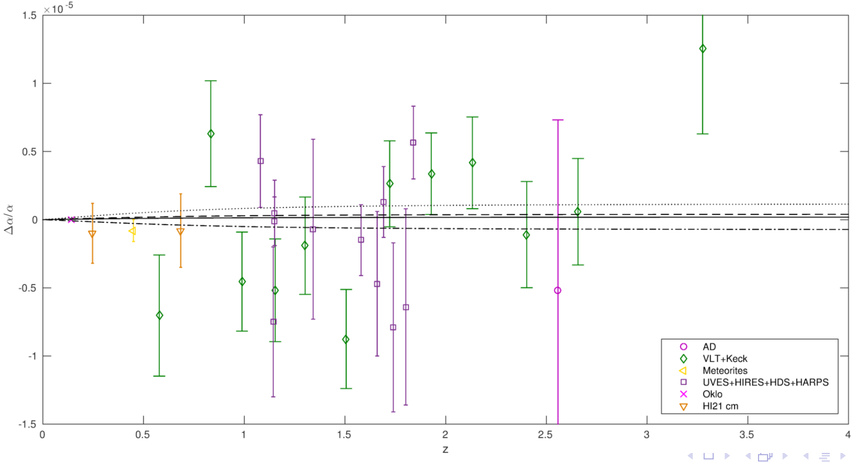
$$\begin{aligned} C_i(\phi) &= \beta_i e^{x_i\phi}, & D_i(\phi) &= M_i^{-4} e^{y_i\phi}, \\ h(\phi) &= 1-\zeta(\phi-\phi_0), & V(\phi) &= M_V^4 e^{-\lambda\phi}. \end{aligned}$$

Parameters x_i, y_i, λ, β_i, M_i, M_V and ζ are tuned such that their are in agreement with constraints on α and on the cosmological parameters from Planck.

Parameter	Estimated value
$w_{0,\phi}$	-1.006 ± 0.045
H_0	(67.8 ± 0.9) km s^{-1}Mpc^{-1}
$\Omega_{0,m}$	0.308 ± 0.012

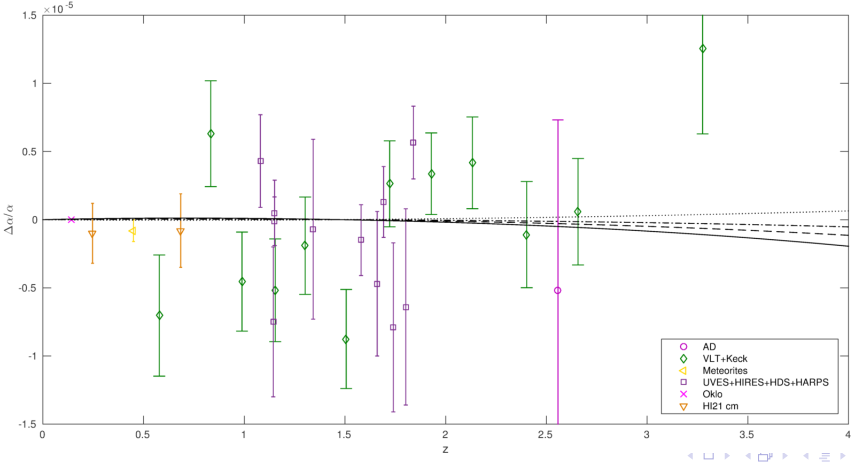
Disformal and electromagnetic couplings

M_r	M_m	M_V	β_m	x_m	$\|\zeta\|$	λ
~ 1 meV	~ 1 meV	2.69 meV	1	0	$< 5 \times 10^{-6}$	0.45



Disformal and conformal couplings

M_r	M_m	M_V	β_m	x_m	$\lvert\zeta\rvert$	λ
25-27 meV	15 meV	2.55 meV	8	0.14	0	0.45



Summary

1. A variation in the fine-structure constant can be induced by disformal couplings provided that the radiation and matter disformal coupling strengths are not identical.
2. Such a variation is enhanced in the presence of the usual electromagnetic coupling.
3. Laboratory measurements with molecular and nuclear clocks are expected to increase their sensitivity to as high as 10^{-21} yr^{-1}.
4. Better constrained data is expected from high-resolution ultra-stable spectrographs such as PEPSI at the LBT, ESPRESSO at the VLT and ELT-Hires at the E-ELT.

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Cosmic Microwave Background Anisotropies Generated by Domain Wall Networks

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arXiv:1507.01064

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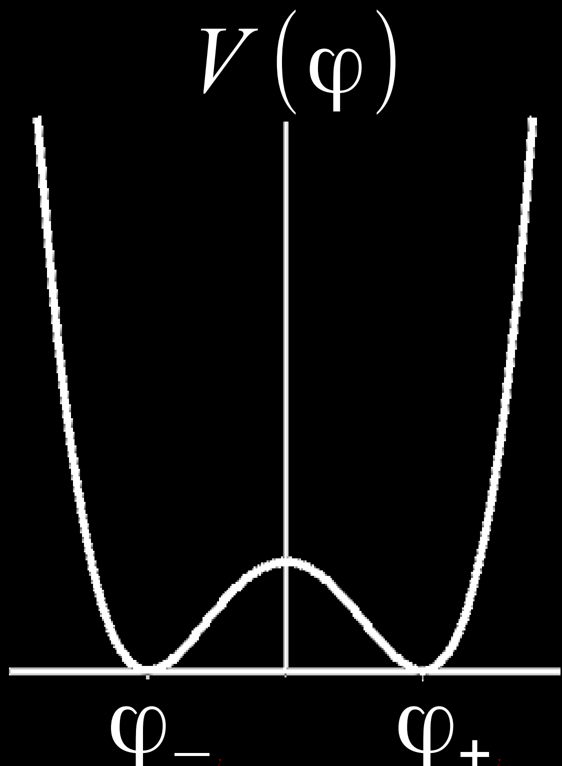
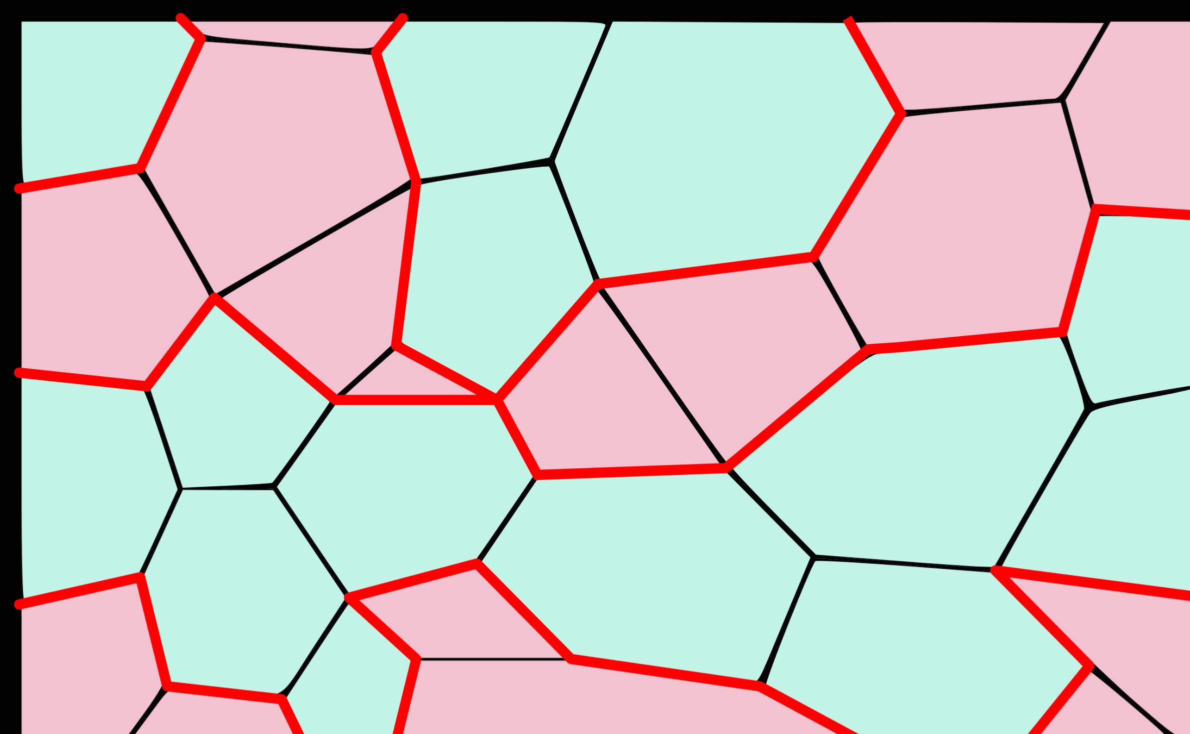
Domain Walls

Domain walls are formed when discrete symmetries are spontaneously broken in phase transitions.





DOMAIN WALLS!

Domain Wall Cmb Q&A

WHY?
- FOR EXISTING!
- REPULSIVE GRAVITY

HOW?
ACTIVE GENERATION OF PERTURBATIONS.

WHAT DOES IS MEAN?
SIGNIFICANT VECTOR CONTRIBUTIONS

WHERE?
- SUBDOMINANT CONTRIBUTIONS TO THE TEMPERATURE AND E-MODES
- POSSIBLY SIGNIFICANT B-MODE CONTRIBUTION

CMBACT CODE

PHENOMENOLOGICAL APPROACH:

ENERGY-MOMENTUM TENSOR IS CALCULATED USING THE UNCONNECTED SEGMENT MODEL:

- SET OF UNCORRELATED STRAIGHT STRING SEGMENTS;
- RANDOMLY DISTRIBUTED AND MOVING IN RANDOM DIRECTIONS;
- A FRACTION OF SEGMENTS DECAY IN EACH EPOCH (ENERGY LOSS DUE TO INTERACTIONS);
- LENGTH AND VELOCITY OF THE SEGMENTS ARE DEFINED USING THE VOS MODEL;

CMBACT CODE

PHENOMENOLOGICAL APPROACH:

ENERGY-MOMENTUM TENSOR IS CALCULATED USING THE UNCONNECTED SECTION MODEL:

- SET OF UNCORRELATED FLAT AND SQUARE DOMAIN WALL SECTIONS;
- RANDOMLY DISTRIBUTED AND MOVING IN RANDOM DIRECTIONS;
- A FRACTION OF SECTIONS DECAY IN EACH EPOCH (ENERGY LOSS DUE TO INTERACTIONS);
- AREA AND VELOCITY OF THE SECTIONS ARE DEFINED USING THE VOS MODEL;

Energy-Momentum Tensor

We need to compute the energy-momentum tensor for each of these sections.

World-volume

$$x^{\mu} = x^{\mu}(\xi^{a}), \quad \text{WITH} \quad a = 0, 1, 2$$

Nambu-Goto action: $S = -\sigma \int d^3\xi \sqrt{-h}$

$$T_{\mu\nu}\sqrt{-g} = \sigma \int d^3\xi\, \delta^4[x^{\mu} - x^{\mu}(\xi^{a})] \sqrt{-h}\, h^{ab}\, x^{\mu}_{,a}\, x^{\nu}_{,b}$$

Energy-Momentum Tensor

FORTUNATELY, IN THIS CASE

$$\underline{x} = \underline{x}_0 + \xi_1 \underline{\hat{x}}'^{(1)} + \xi_2 \underline{\hat{x}}'^{(2)} + v\tau \underline{\dot{x}}$$

ANALYTICAL SOLUTIONS:

$$\theta_{00} = 4\sigma\gamma\sqrt{2}\cos\left(\underline{k}\cdot\underline{x} + vk\tau\right)\frac{\sin\left(kl\,\hat{x}_3'^{(1)}/2\right)\sin\left(kl\,\hat{x}_3'^{(2)}/2\right)}{k^2\,\hat{x}_3'^{(1)}\,\hat{x}_3'^{(2)}}$$

$$\theta_{ij} = \theta_{00}\left[v^2\,\dot{\hat{x}}_i\,\dot{\hat{x}}_j - \left(1 - v^2\right)\hat{x}_i'^{(1)}\,\hat{x}_j'^{(1)} + \hat{x}_i'^{(2)}\,\hat{x}_j'^{(1)}\right]$$

Energy-Momentum Tensor

We now have 3 of the E-M components required by CMBFAST:

$$2\theta_S = \theta_{00}\left[v^2\left(3\,\dot{\hat{x}}_3\,\dot{\hat{x}}_3 - 1\right) - \left(1-v^2\right)\left(3\,\hat{x}_3'^{(1)}\,\hat{x}_3'^{(1)} + 3\,\hat{x}_3'^{(2)}\,\hat{x}_3'^{(2)} - 2\right)\right]$$

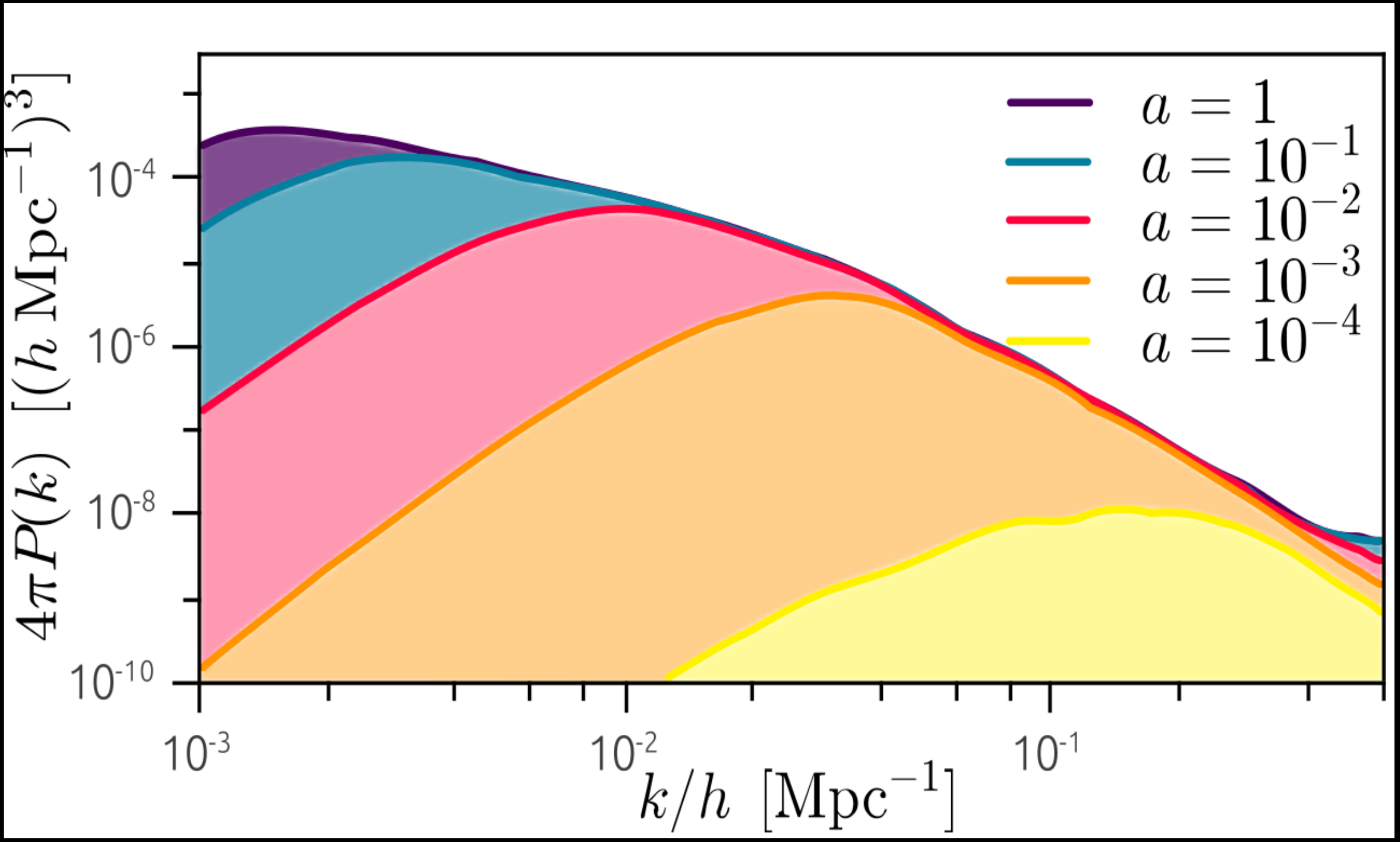
$$\theta_V = \theta_{00}\left[v^2\,\dot{\hat{x}}_1\,\dot{\hat{x}}_3 - \left(1-v^2\right)\left(\hat{x}_1'^{(1)}\,\hat{x}_3'^{(1)} + \hat{x}_1'^{(2)}\,\hat{x}_3'^{(2)}\right)\right]$$

$$\theta_T = \theta_{00}\left[v^2\,\dot{\hat{x}}_1\,\dot{\hat{x}}_2 - \left(1-v^2\right)\left(\hat{x}_1'^{(1)}\,\hat{x}_2'^{(1)} + \hat{x}_1'^{(2)}\,\hat{x}_2'^{(2)}\right)\right]$$

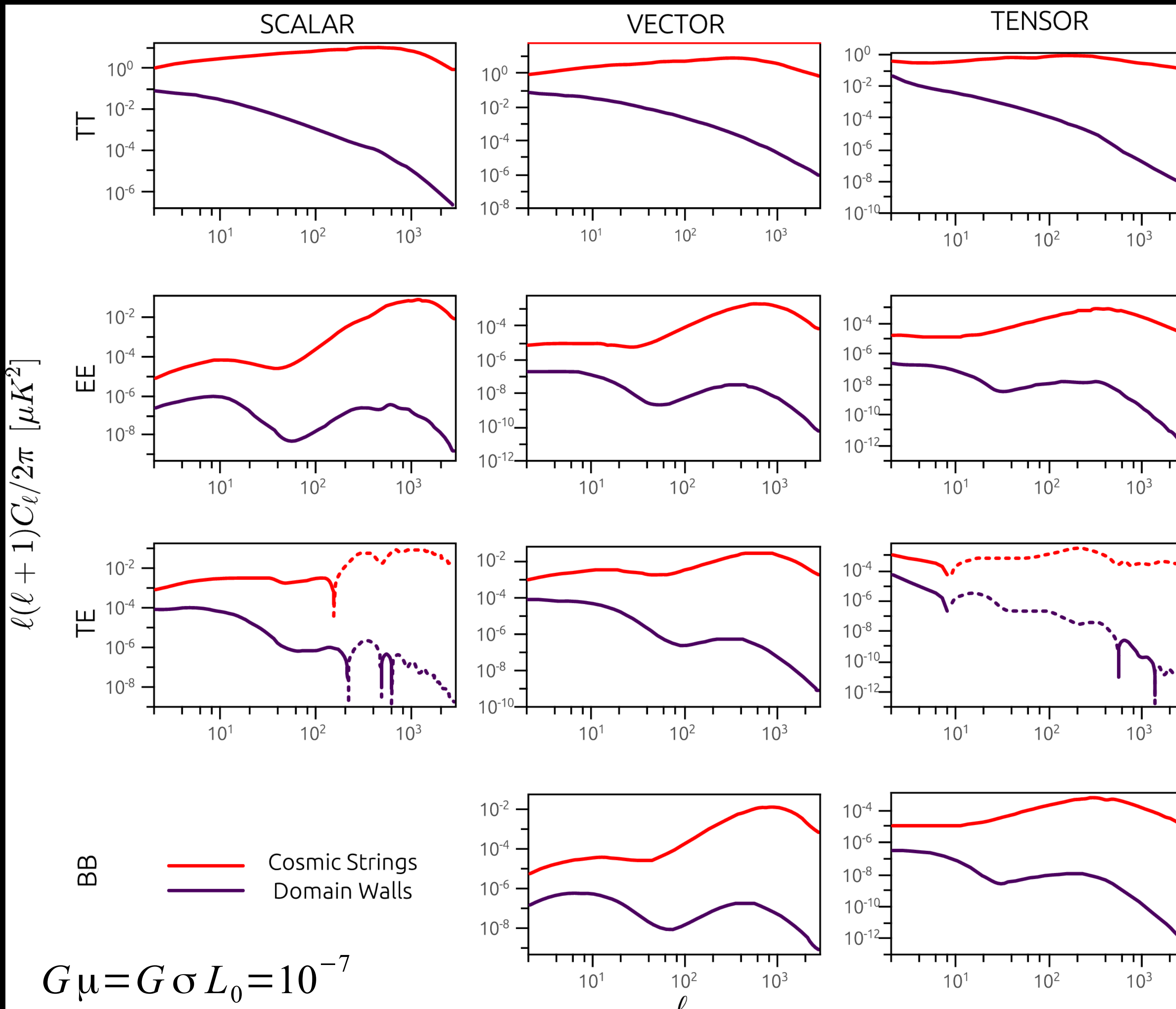
The rest follows from E-M conservation...

THE RESULTS: CDM POWER SPECTRUM

DOMAIN WALLS CONTRIBUTE MOSTLY ON LARGE SCALES…



THE RESULTS: CMB SPECTRA



THE RESULTS: CONSTRAINTS

THERE IS STILL OBSERVATIONAL ROOM FOR DOMAIN WALLS:

FRACTIONAL CONTRIBUTION TO THE TT-POWER SPECTRUM

$$f_{dw} < 0{,}2$$

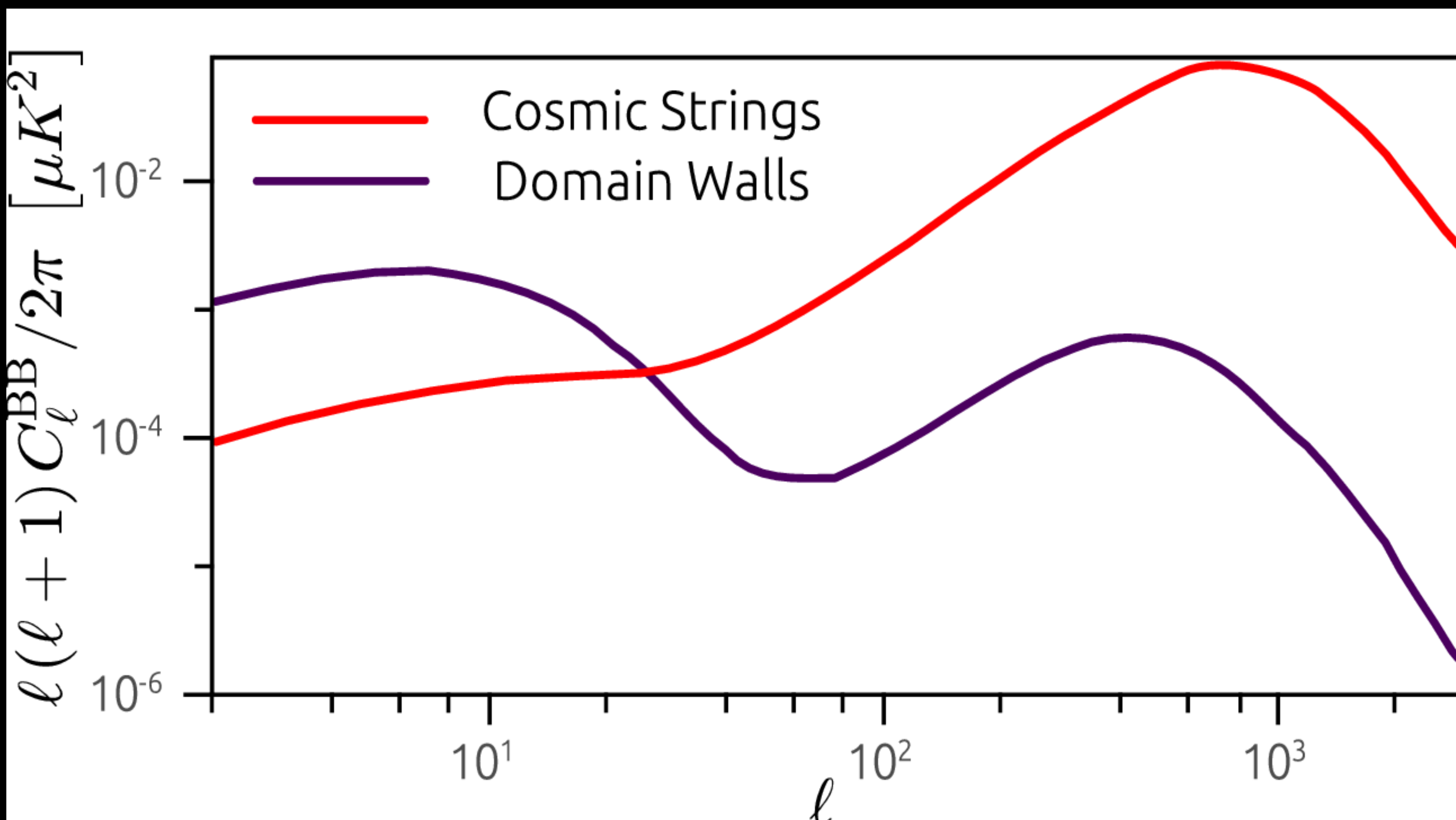
↓

ENERGY SCALE OF THE DOMAIN-WALL-FORMING PHASE TRANSITION

$$\eta < 0{,}92\ MeV$$

THE RESULTS: CONSTRAINTS

… AND THEY MAY PRODUCE SIGNIFICANT B-MODES!



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ZTF-FCT

Evolution of Semilocal String Networks:

Segment Evolution

Asier Lopez-Eiguren (UPV/EHU)

Vila do Conde, 30/03/16

In collaboration with: A. Achúcarro, A. Avgoustidis, C.J.A.P. Martins, A.S. Nunes, J. Urrestilla

Evolution of String Networks

TWO methods to analyse the evolution:

Numerical Simulations

- Evolve true eom
- High computational cost
- Limited dynamical range

Analytic Models

- Approximate models
- Simples
- More tractables
- Need input from Num. Sim.

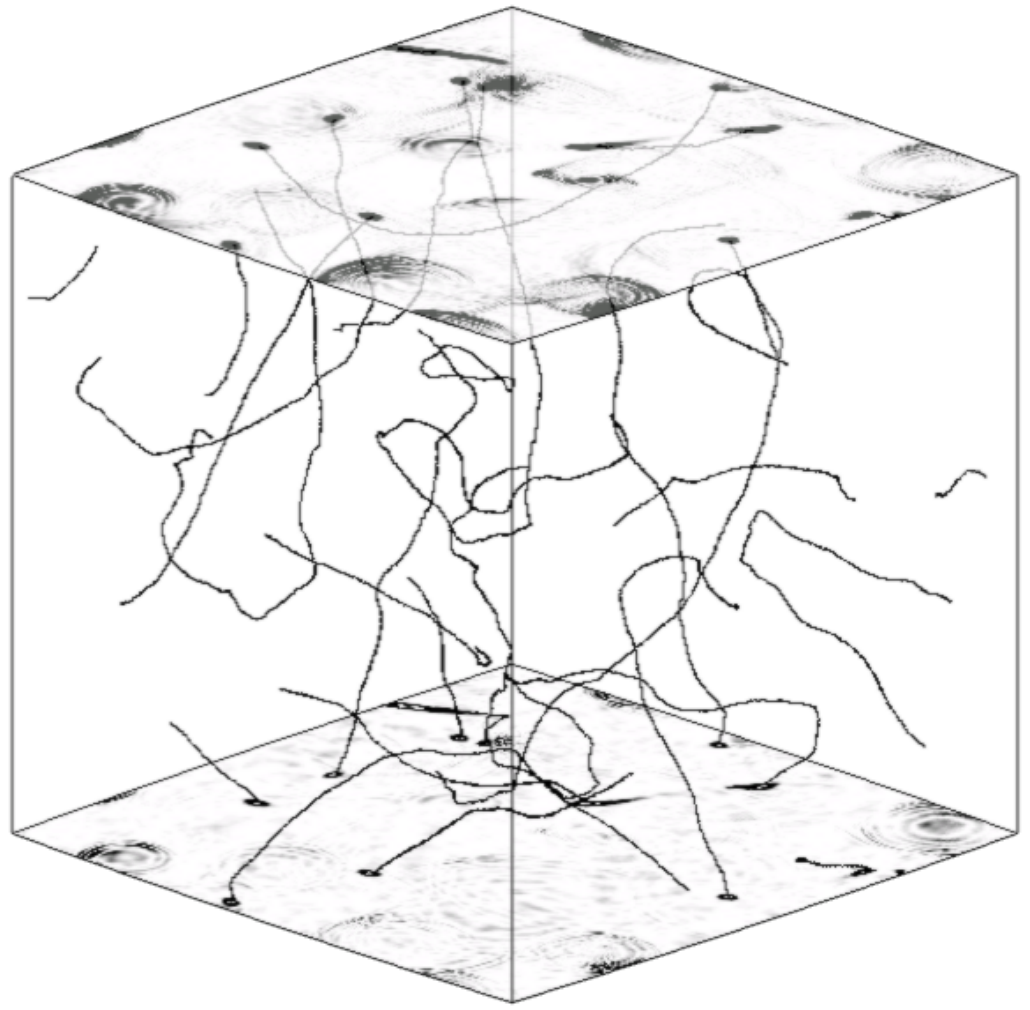
OBJECTIVE: CALIBRATE analytic models for SL

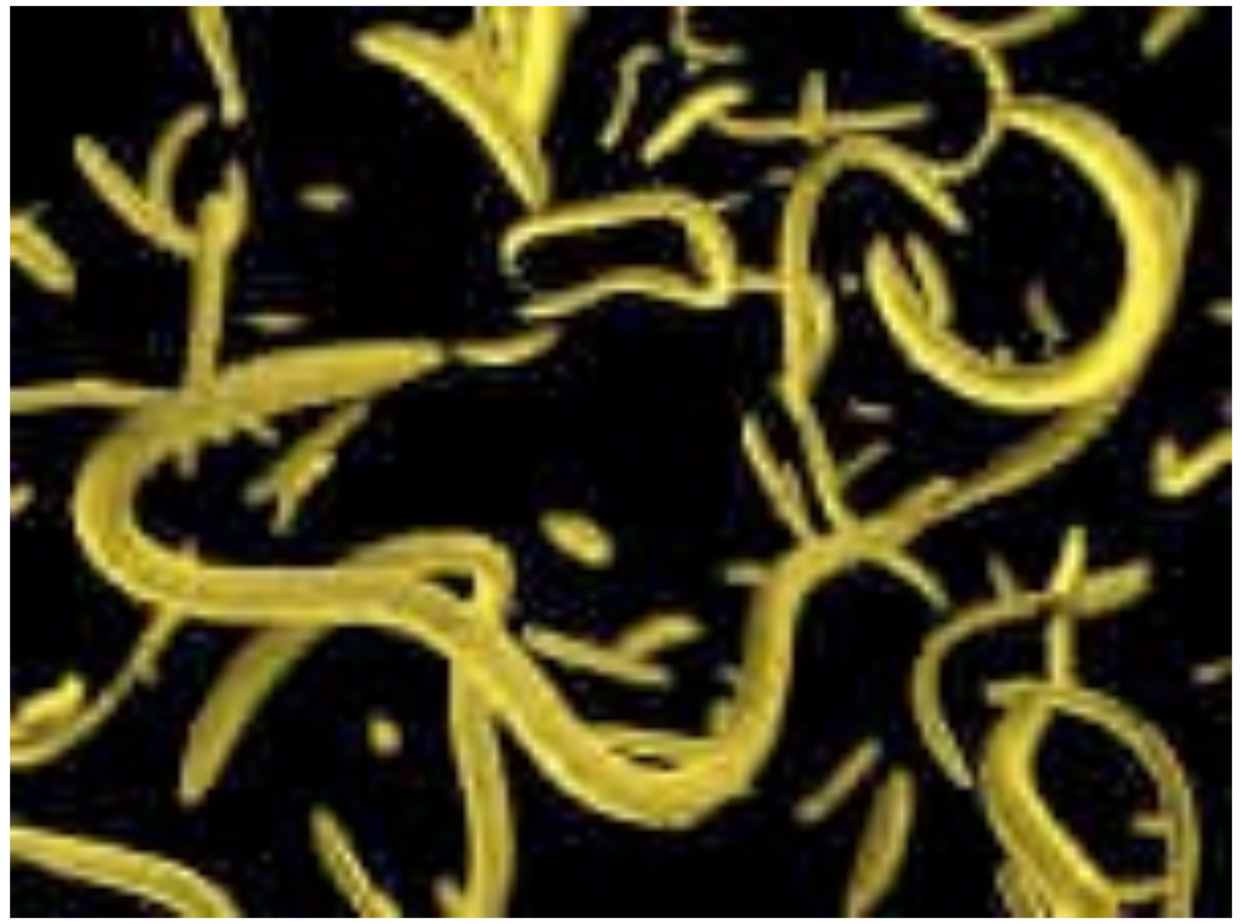
Semilocal Strings

(A. Achucarro & Vachaspati 1999)

- Extension of Abelian-Higgs (AH):
  $U(1)_l \rightarrow SU(2)_g \times U(1)_l$
- They are not topological
  - They can have ends
- This ends are effectively global monopoles

Abelian-Higgs





Semilocal

Semilocal Strings

(A. Achucarro & Vachaspati 1999)

$$\mathcal{S} = \int d^4x \Big\{ \Big[\Big(\partial_\mu - iA_\mu \Big) \Phi \Big]^2 - \frac{1}{4} F^2 - \frac{\beta}{4} (\Phi^+ \Phi - \eta^2)^2 \Big\}$$

$\Phi = (\phi, \psi), F^2 = F_{\mu\nu} F^{\mu\nu}$ *and* $F_{\mu\nu} = (\partial_\mu A_\nu - \partial_\nu A_\mu)$

- The stability of the strings depends on the parameter $\beta = m_{scalar}^2 / m_{gauge}^2$:
  - $\beta > 1$ Unstable
  - $\beta = 1$ Neutrally stable
  - $\beta < 1$ Stable
- For lower β they behave more like AH

Velocity-one-scale Model

(Martins & Shellard 1996,2002)

- Two variables:

RMS VELOCITY → $$\frac{dv}{dt} = (1 - v^2)\left(\frac{k}{L} - \frac{v}{l_d}\right)$$

TYPICAL LENGTH SCALE
INTERDEFECT DISTANCE → $$(4-n)\frac{dL}{dt} = (4-n)HL + v^2\frac{L}{l_d} + cv$$

n= dim. of defect

$$L^{4-n} = \frac{M}{\rho} \quad M \sim \rho^n$$

Damping scale

$$\frac{1}{l_d} = nH + \frac{1}{l_f}$$

particle friction

Semilocal VOS Models

Hybrid Networks: strings + monopoles

$$\frac{dl_s}{dt} = Hl_s - v_s^2 \frac{l_s}{l_d} + \sigma\left(1 - \frac{L}{l_s}\right)v_m^2$$

$$\frac{dv_s}{dt} = (1 - v_s^2)\left[\frac{k}{l_s} + f_s - \frac{v_s}{l_d}\right]$$

Model A

$$\frac{dl_s}{dt} = Hl_s - v_s^2 \frac{l_s}{l_d} + \left(d\frac{v_s l_s}{L} - k_1\right)$$

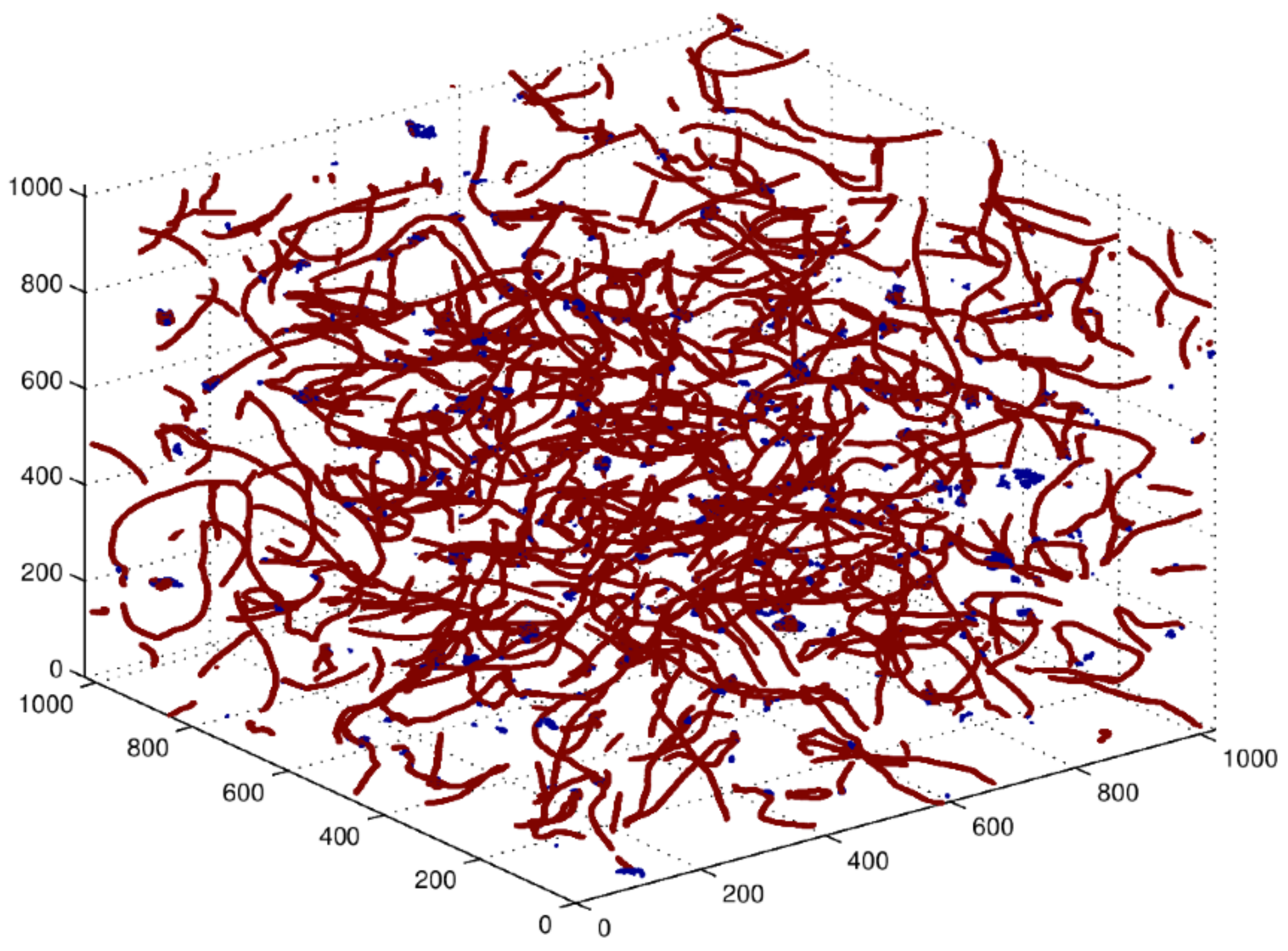
$$\frac{dv_s}{dt} = (1 - v_s^2)\left[\frac{k}{l_s} - \frac{v_s}{l_d}\right]$$

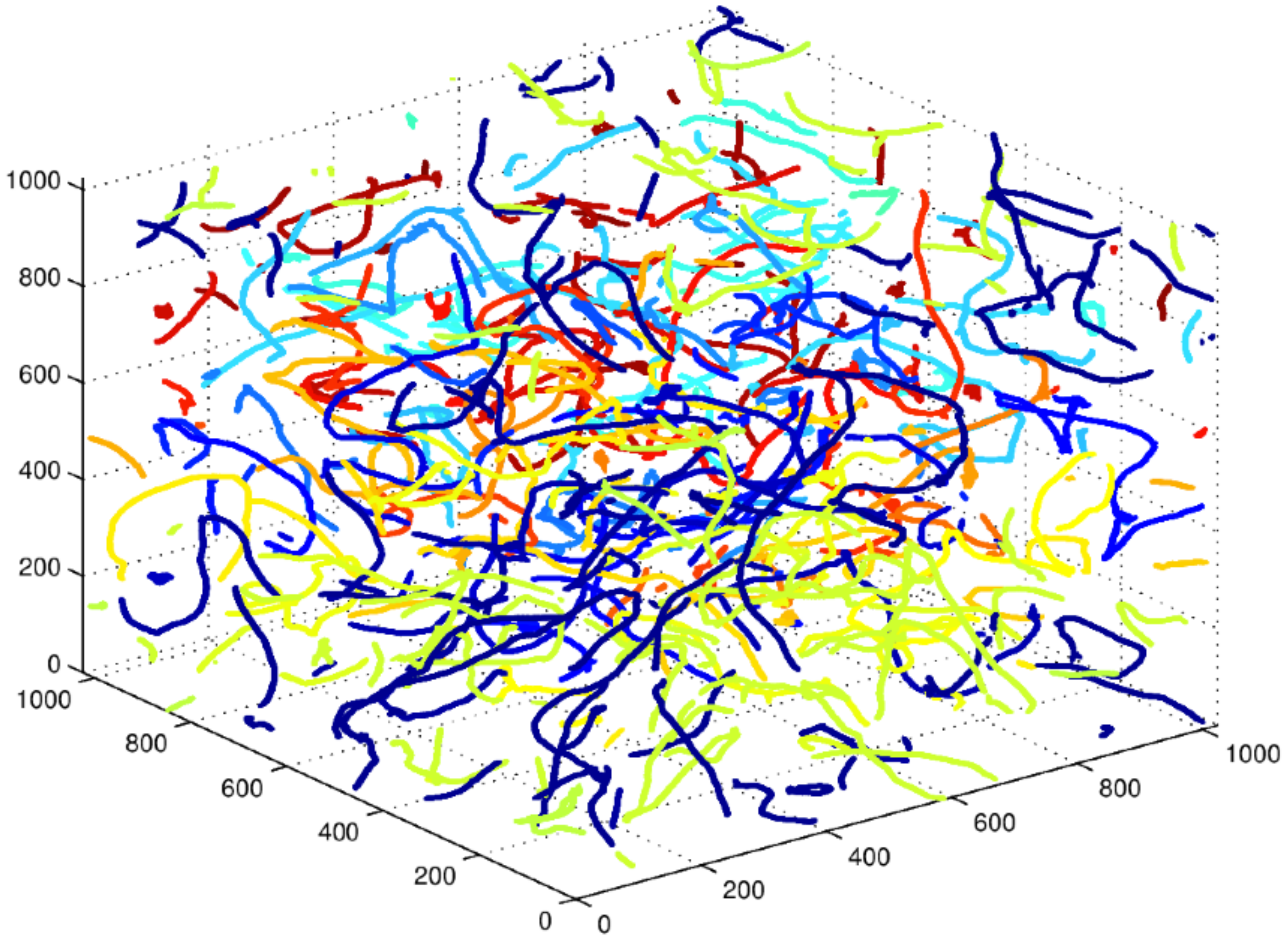
Model B

- Compare simulations with analytic models
- Obtain the best values for the parameters

Field Theory Simulations

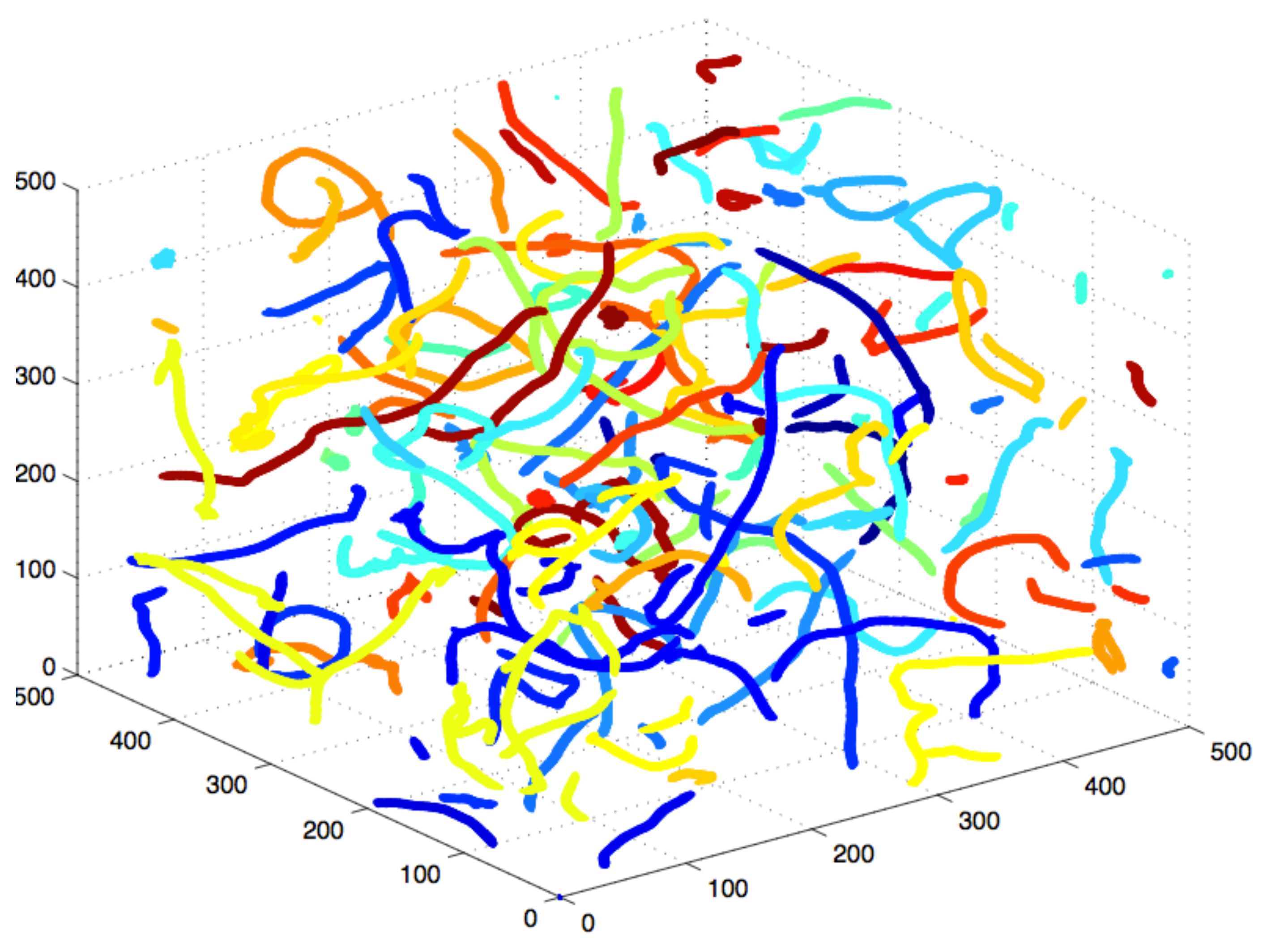
- 1024^3 lattices in radiation and matter eras in expanding universe
- Magnetic energy to detect strings





arXiv:1312.2123/PhysRevD.89.063503:
Large Scale properties were analysed

Field Theory Simulations



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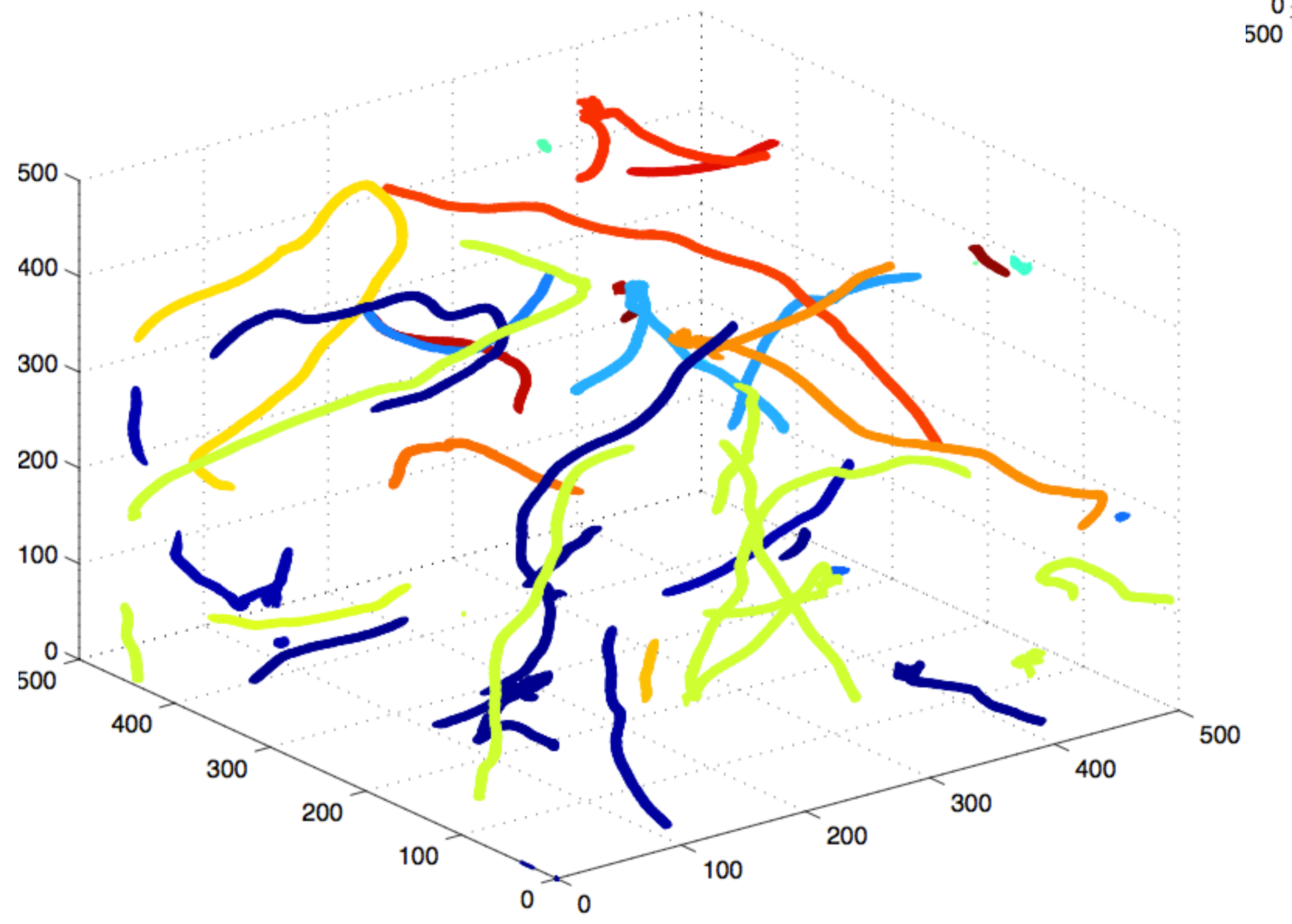

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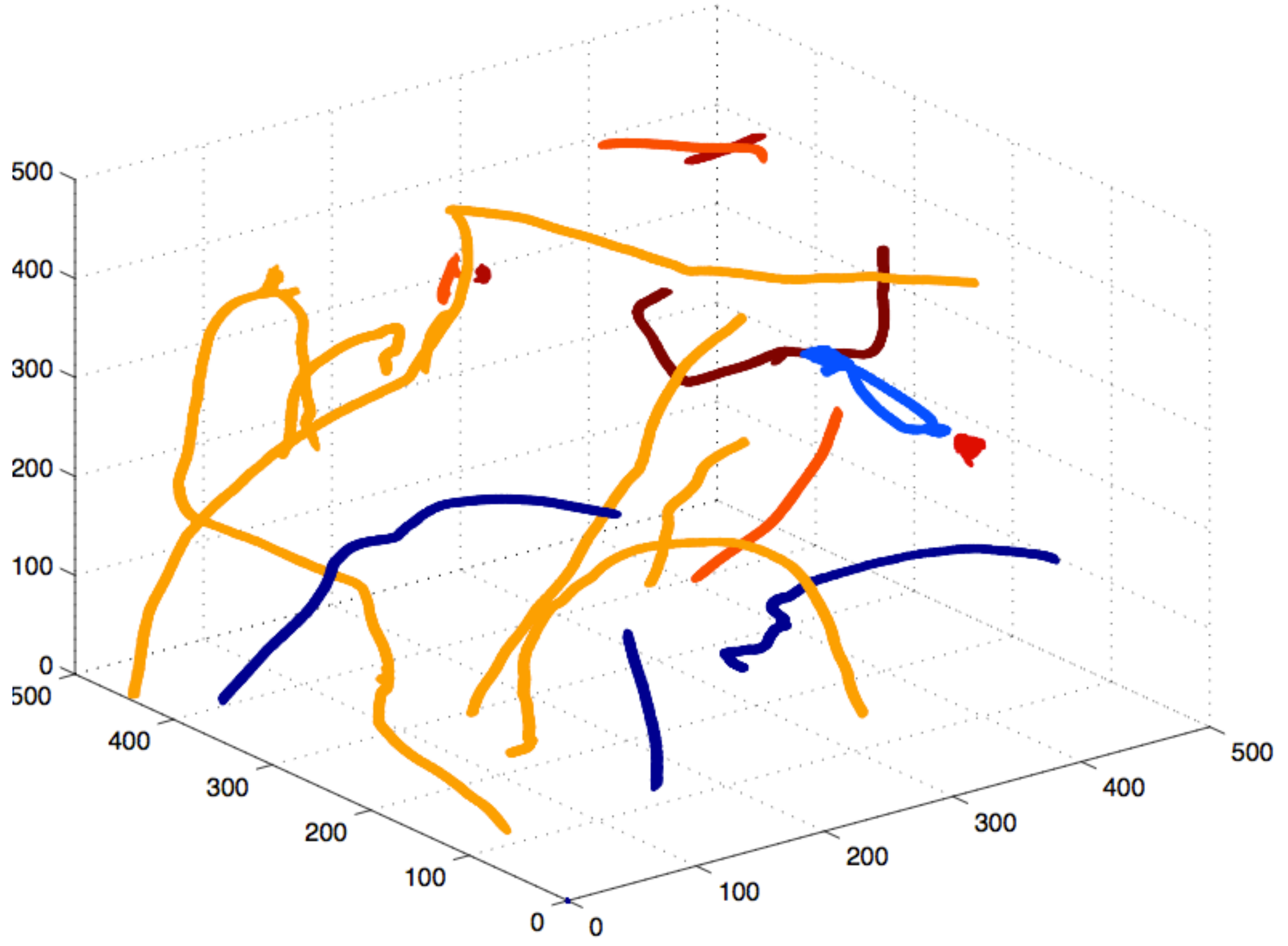

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Segment Distribution

Initial l_s seed from **simulations**

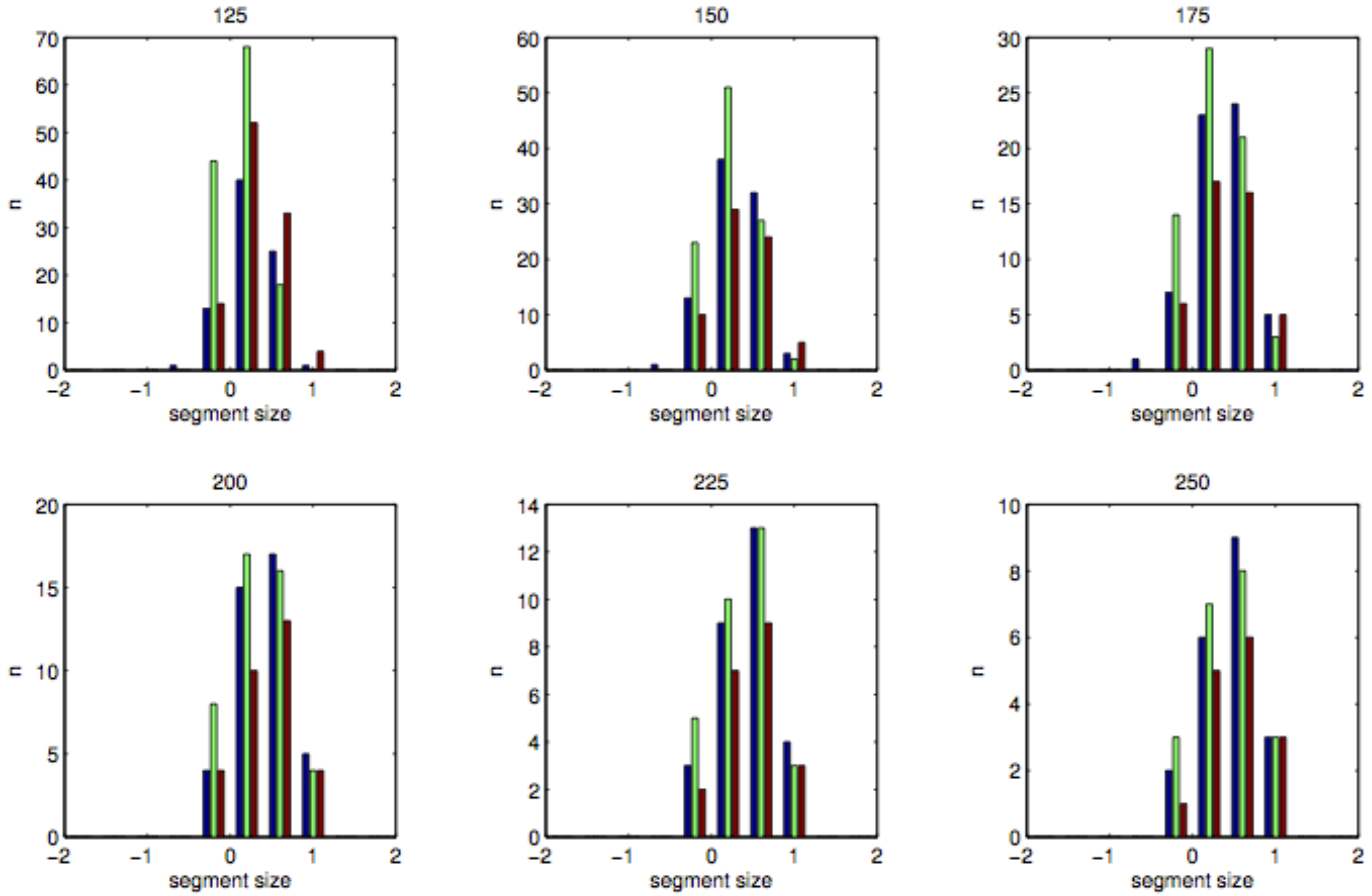
Phenomenological v_s distribution

Evolve VOS models

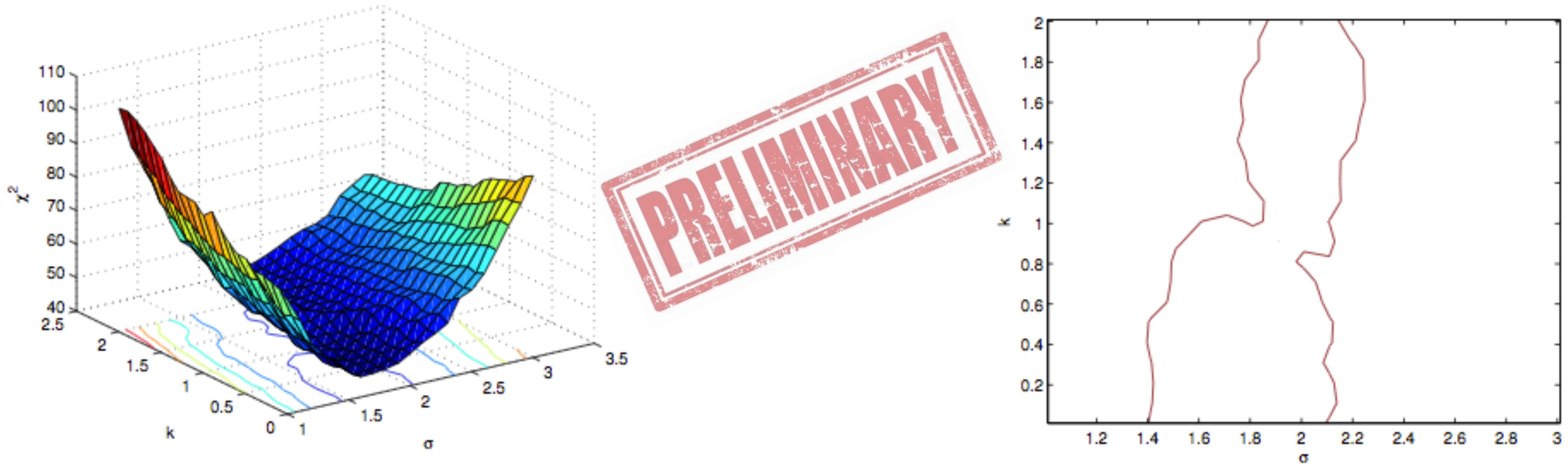
Model A

Model B

Simulations



Segment Distribution



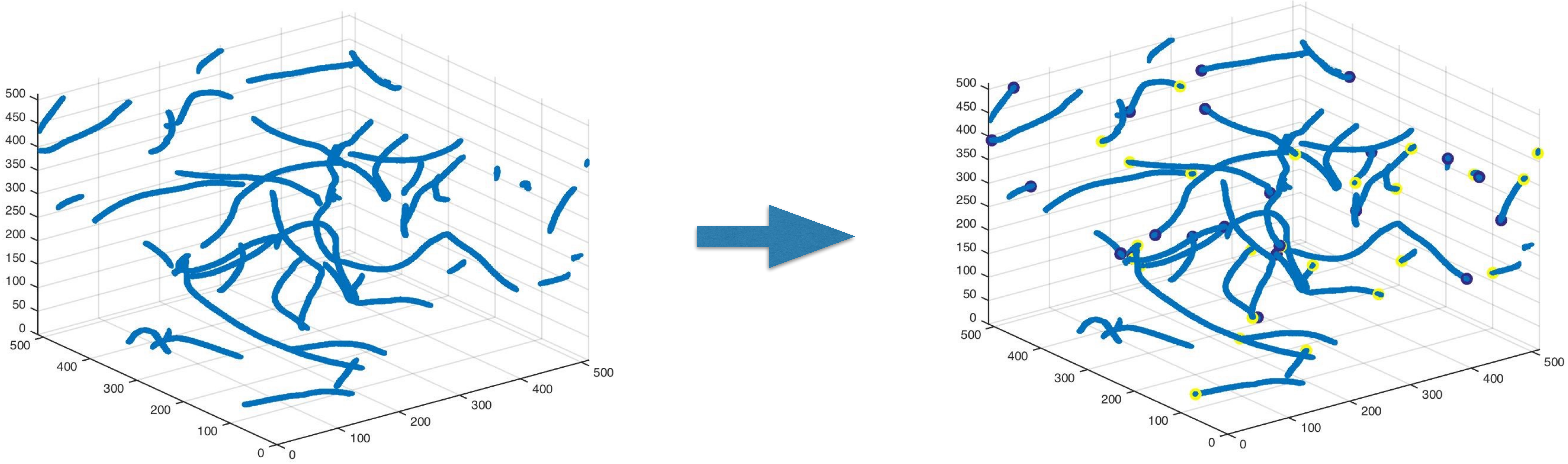
- We perform χ^2 analysis to determine the best values for the parameters

Summary

- TWO VOS models for Semilocal string networks
- We perform X^2 analysis:
  - Determine the best values of the parameters
  - Conclude which model describes better the network

Future Work

- Improve parameter analysis:
  - Obtaining v_s distribution from simulations
  - Obtain segment end (monopole) velocities

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instituto de astrofísica e ciências do espaço
FCT Fundação para a Ciência e a Tecnologia
U.PORTO
Vila do Conde

Extending the velocity-dependent one-scale model for domain walls.

I.Yu. Rybak,
CAUP, IA

in collaboration with
C.J.A.P. Martins,
A. Avgoustidis,
E.P.S. Shellard

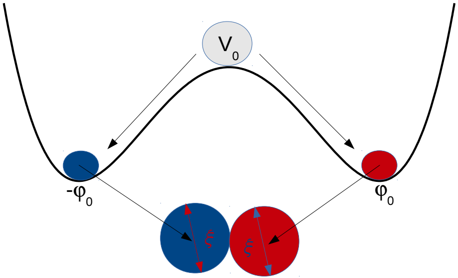
Phys.Rev.D93(2016)no.4,043534, (arxiv[hep-ph] 1602.01322)

Vila do Conde, IberiCos 2016

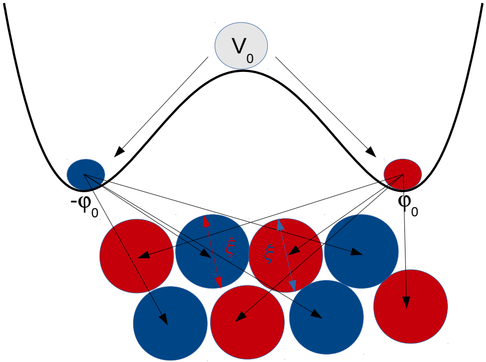
Kibble mechanism

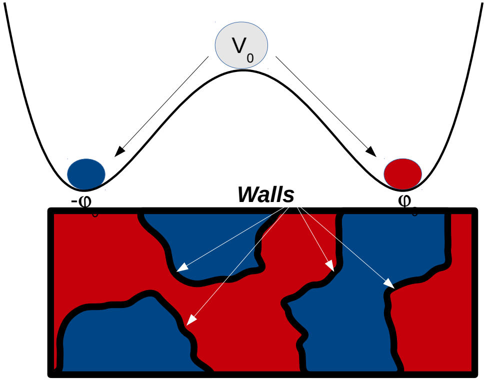
[Kibble,J.Phys.A9(1976),1387-1398ICTP/75/5]

$$L = \frac{1}{2}\left(\partial\varphi\right)^2 - V(\varphi)$$
$$V(\varphi) = V_0\left(1 - \frac{\varphi^2}{\varphi_0^2}\right)^2$$



Introduction





V_0
Walls
$-\varphi_0$
φ_0

Field theory simulation (4096^3 boxes)

Scalar field model:

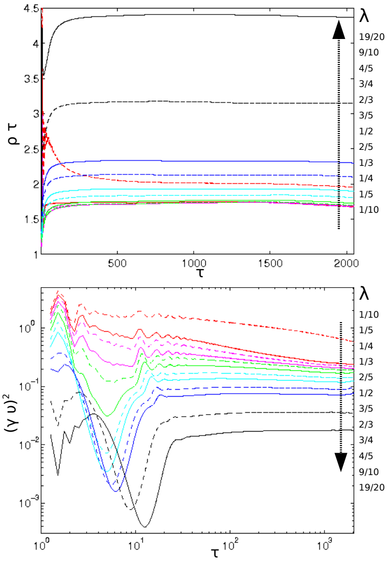
[Press,Ryden,Spergel, Astrophys.J.347,590(1989)]

$$\frac{\partial^2\phi}{\partial\tau^2} + 3\frac{d\ln a}{d\ln\tau}\frac{\partial\phi}{\partial\tau} - \frac{\partial^2\phi}{\partial x^i\partial x_i} = -\frac{\partial V}{\partial\phi},$$

Measured values (asymptotic):

- $(\gamma\upsilon)^2$ (υ - velocity).
- ξ_c/τ (ξ_c - correlation length $\sim \frac{1}{\rho}$)

(for $a \sim t^\lambda$)



Velocity-depend one scale (VOS) model

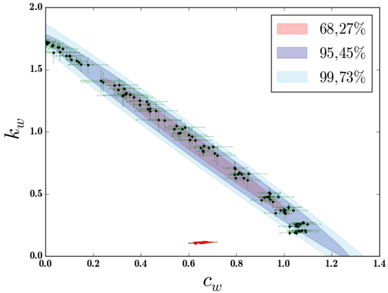
Dirac-Nambu-Goto action: $S = -\sigma_w \int \sqrt{G} d^2\sigma d\tau,$

[Sousa,Avelino,Phys.Rev.D,84,063502(2011)]

(averaged) $\Downarrow \int ... d^2\sigma$

$$\frac{dL}{dt} = \left(1 + 3v^2\right) HL + c_w v,$$
$$\frac{dv}{dt} = \left(1 - v^2\right) \left(\frac{k_w}{L} - 3Hv\right),$$

Scaling solution is: $L = \epsilon t$, v (ϵ, v - constants).



Momentum parameter for VOS model

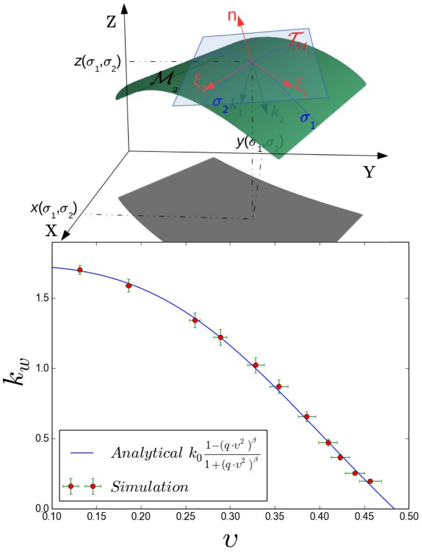
From the microscopic description

$$k_w(v) = k_0 \frac{1-(qv^2)^\beta}{1+(qv^2)^\beta}$$

Physical restrictions:

- $0 \leq k_0 \leq 2$
- $0 < \frac{1}{q} \leq v_w^2 = \frac{2}{3}$

$$k_0 = 1.73 \pm 0.01,$$
$$q = 4.27 \pm 0.10 \ (< v > \approx 0.48),$$
$$\beta = 1.69 \pm 0.08.$$



Energy loss for VOS model

Energy loss mechanisms:

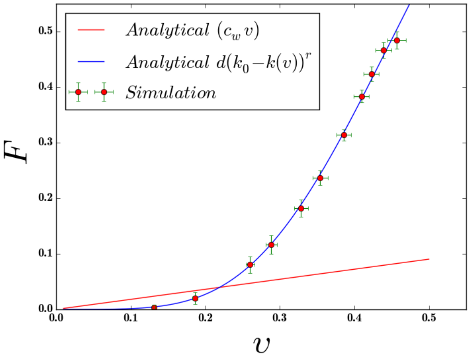
- creation of closed objects

  $c_w \upsilon$

- scalar radiation ($\sim$ *curvature*^{r})

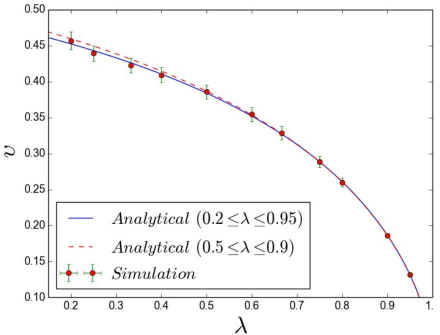
  $d\,[k_0 - k(\upsilon)]^r$

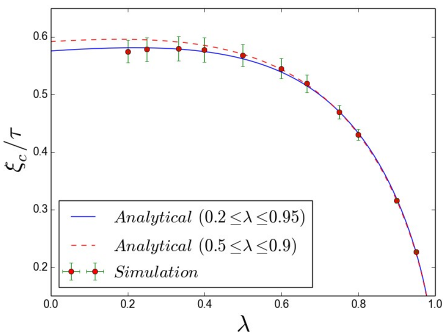
$r = 1.30 \pm 0.02,\ d = 0.28 \pm 0.01,\ c_w = 0.00 \pm 0.01.$



The whole model with found parameters

$$\frac{dL}{dt} = \left(1 + 3\upsilon^2\right) HL + c_w \upsilon + d\left(k_0 - k(\upsilon)\right)^r,$$
$$\frac{d\upsilon}{dt} = \left(1 - \upsilon^2\right)\left(\frac{k(\upsilon)}{L} - 3H\upsilon\right),$$
$$k(\upsilon) = k_0 \frac{1-\left(q\upsilon^2\right)^\beta}{1+\left(q\upsilon^2\right)^\beta}$$





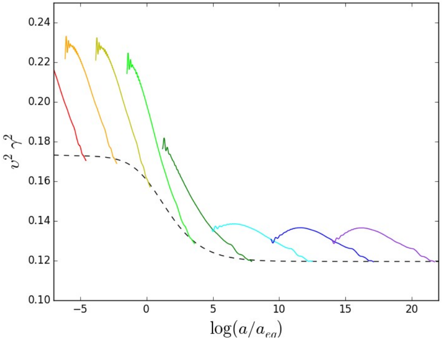
Radiation-matter transition

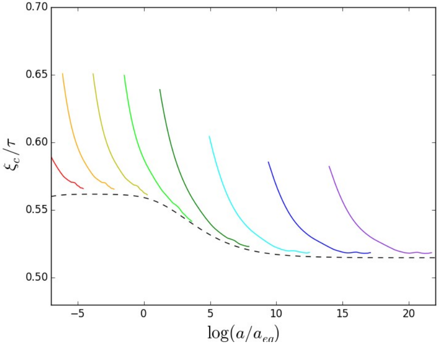
Scale factor

$$\frac{a(\tau)}{a_{eq}} = \left(\frac{\tau}{\tau_*}\right)^2 + 2\left(\frac{\tau}{\tau_*}\right),$$

where $\tau_* = \tau_{eq}/(\sqrt{2}-1)$.

Simulations with different a_eq, τ_eq to span the entire transition





Results

- The largest currently available field-theory simulations;
- Adjustment of the VOS model;
- Direct comparison of energy loss mechanisms;
- Description of the radiation-matter transition by the extended VOS model;

Interesting avenues for further study

- To extend this analysis to the case of cosmic strings for better understanding the differences between Goto-Nambu and field theory simulations;

Thank you for your attention!

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