3D Quantum Bubble Collisions

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TEXAS 2015, Geneva, December 14, 2015

Based on work with Dick Bond and Laura Mersini-Houghton

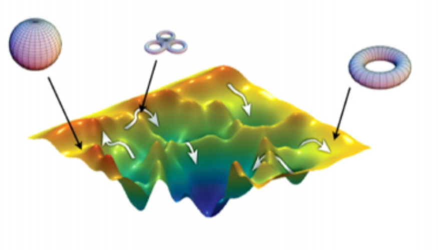
JCAP 1503 (2015) 03, 007 [arXiv:1412.5591]

JCAP 1508 (2015) 08, 048 [arXiv:1505.01857]

JCAP 1509 (2015) 09, 004 [arXiv:1505.02162]

Videos at `www.star.ucl.ac.uk/~jbraden`

The Bubbly Universe



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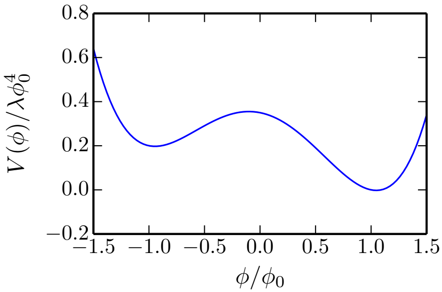

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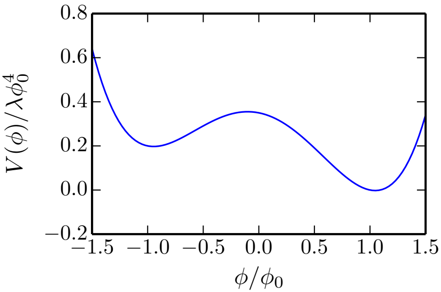
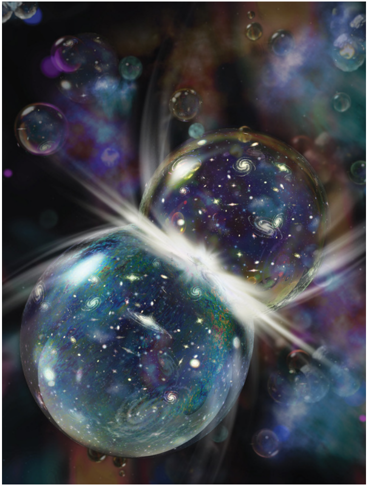




Large Literature Starting in 1982 ...

Single Bubbles

- Coleman, deLuccia
- **Hawking**, **Moss**
- Turok
- Sasaki, Linde, Tanaka, Yamamoto
- Garriga, Vilenkin, Montes, Garcia-Bellido
- Guth, Guven
- Freese, Adams
- Susskind et al
- ...

Vacuum Bubble Collisions

- **Hawking**, **Moss**, **Stewart**
- Kosowski, Turner, Watkins, Kamionkowski
- Johnson, Aguirre, Tysanner, Larfors
- Chang, Kleban, Levy, Sigurdson, Gobbetti
- Easther, Giblin, Lim, Lau
- Johnson, Lehner, Peiris,. . . (GR)
- ...

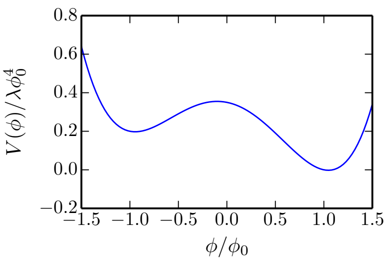
Observations

- Johnson, Peiris, Mortlock, McEwan, Feeney,...
- Smith, Senatore, Osborne

... All Based on the "Canonical" SO(2,1) Approach

New Coordinates (Minkowski)

$$t = s\cosh\psi$$
$$x = x$$
$$y = s\sinh\psi\cos\theta$$
$$z = s\sinh\psi\sin\theta$$



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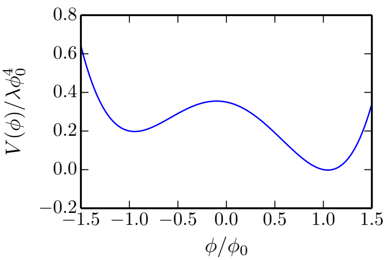

SO(2,1) Assumption: $\phi(t, x, y, z) = \phi(s, x)$

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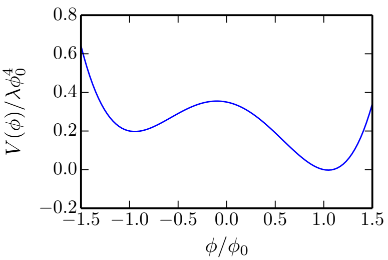

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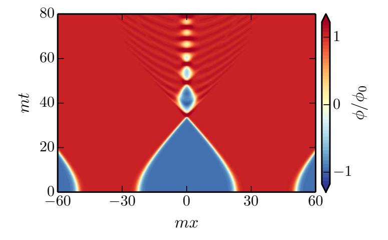
Individual Bubbles

- Perfectly Spherical
- Boost Invariant



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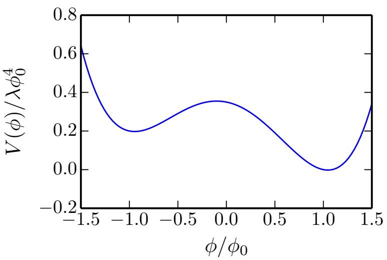

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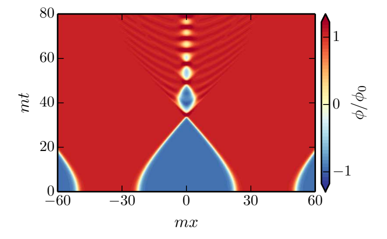
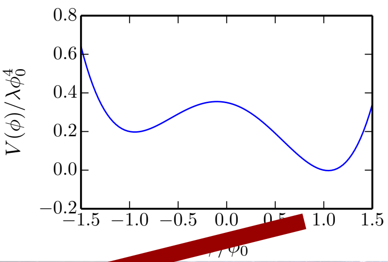


2^{nd} Bubble Breaks

- 1 Boost
- 2 Rotations

... All Based on the "Canonical" SO(2,1) Approach



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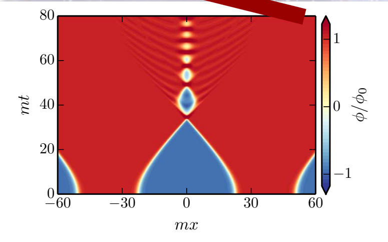
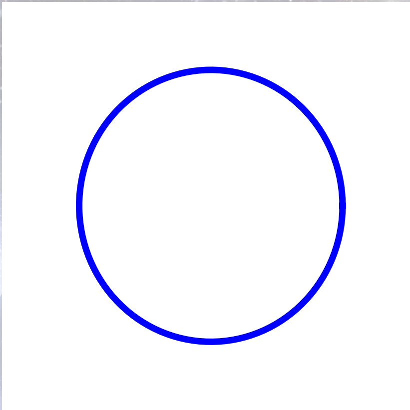


Limitations of SO(2,1) Formalism

Quantum (or Stochastic) Fluctuations

$$\phi(t,x,y,z) = \phi_{bg}(s,x) + \delta\hat{\phi}(t,x,y,z)$$



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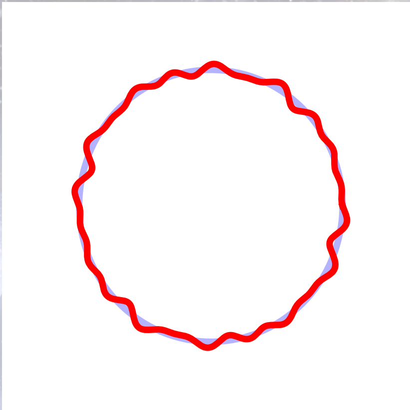


Limitations of SO(2,1) Formalism

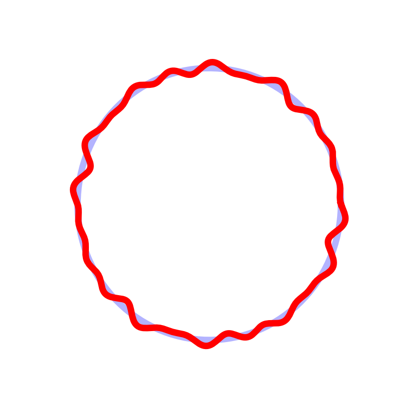
Quantum (or Stochastic) Fluctuations

$$\phi(s,x,\psi,\theta) = \phi_{bg}(s,x) + \delta\hat{\phi}(s,x,\psi,\theta)$$

$\delta\phi$ has dynamics not captured by SO(2,1) formalism

Ignoring $\delta\phi$ Breaks

- Quantum Mechanics
- Bubble Nucleation
- Inflationary perturbations



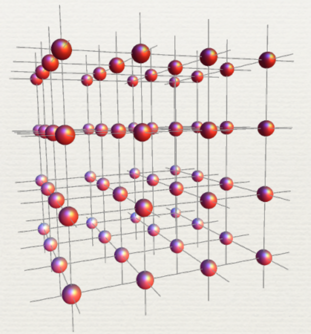
Numerical Approach is Essential [JB, in preparation]

Hybrid MPI/OpenMP Lattice Code

- Solve field equation (e.g.)

$$\ddot{\phi}_i + 3\frac{\dot{a}}{a}\dot{\phi}_i - \frac{\nabla^2\phi_i}{a^2} + V'(\vec{\phi}) = 0$$

- 10th order Gauss-Legendre integration (general) or 8th order Yoshida (nonlinear sigma models)
- Finite-difference (fully parallel) or Pseudospectral (OpenMP)
- Optional absorbing boundaries
- Quantum fluctuations $\rightarrow$ realization of random field



- Energy conservation $\mathcal{O}(10^{-9} - 10^{-14})$

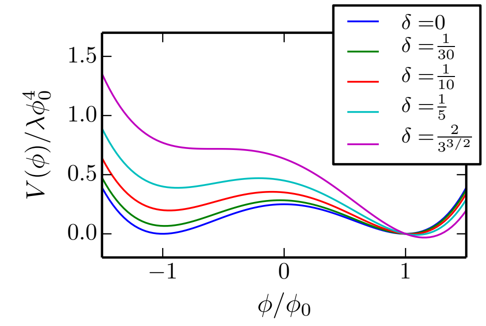
Initial Conditions I: The Bounce Solution [c.f. Coleman]

$$\frac{d^2\phi_b}{dr_E^2} + \frac{3}{r_E}\frac{d\phi_b}{dr_E} - \frac{\partial V}{\partial \phi} = 0$$

$$\phi_b(r_E = \infty) = \phi_{false} \qquad \partial_{r_E}\phi_b(r_E = 0) = 0$$

$$r_E^2 \equiv \tau^2 + x^2 + y^2 + z^2 \qquad \tau \equiv it$$

Pseudospectral Approximation



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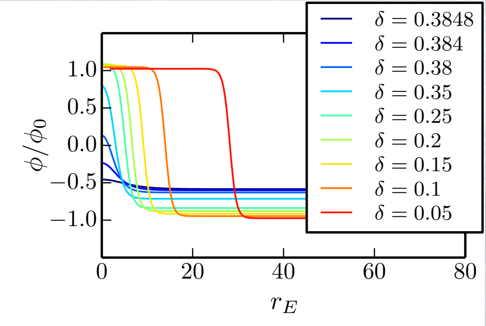
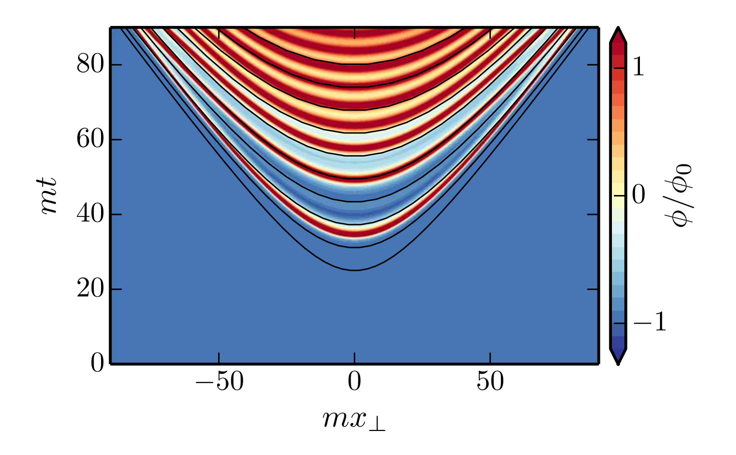


Now Some Collisions

Three-Dimensional SO(2,1) Collision

Numerical Preservation of SO(2,1) Symmetry

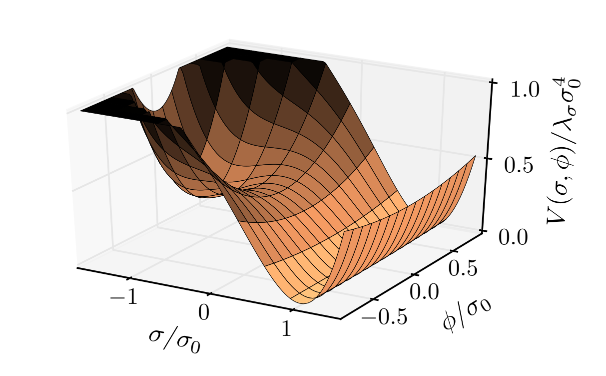


Same Collision with Fluctuations ... [JB, Bond, Mersini-Houghton, 1505.02162

... Produces Oscillons (Visible in Energy Density)

Works for multifield models supporting inflation as well

$$V(\sigma,\phi) = \frac{\lambda_\sigma \sigma_0^4}{4}\left[\left(\frac{\sigma^2}{\sigma_0^2}-1\right)^2 - \frac{\delta}{\lambda_\sigma}\frac{\sigma}{\sigma_0}\right] + \epsilon\phi + \frac{g^2}{2}\phi^2\sigma^2$$



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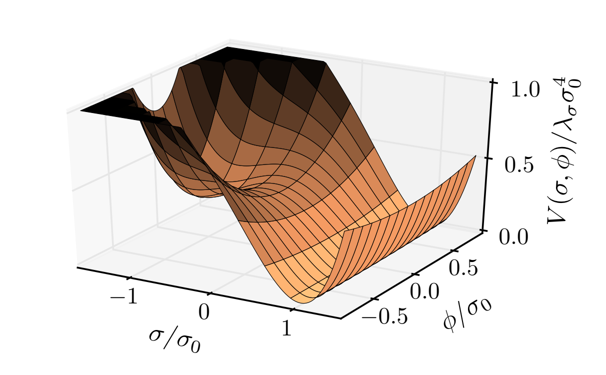
- V_{tunnel}



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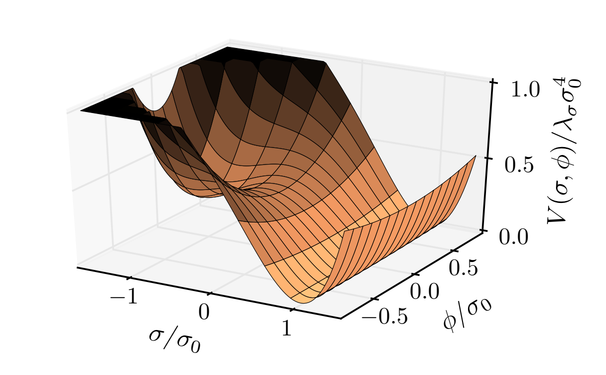
- V_{tunnel}
- $V_{inflaton}$



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- V_{tunnel}
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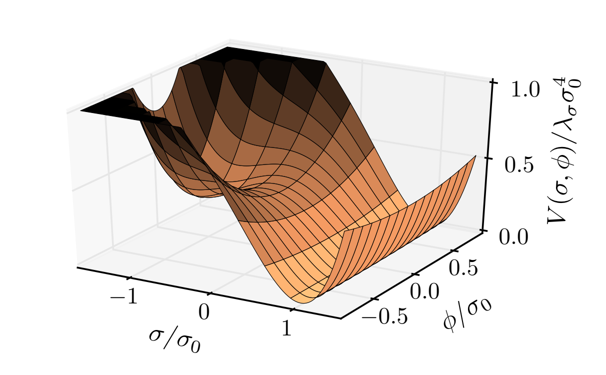
- $V_{coupling}$



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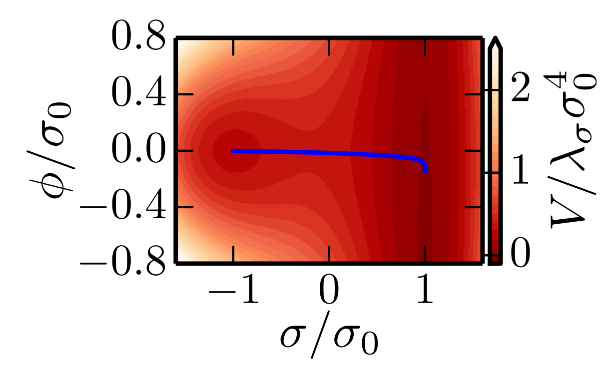


Evolution of σ and ϕ

σ Evolution

ϕ Evolution

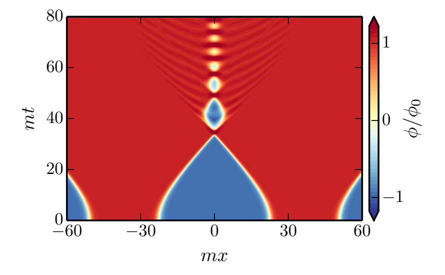
Why Does This Happen?

Linear Parametric Resonance [JB, Bond, Mersini-Houghton, 1412.5591]

Non-SO(2,1) fluctuations evolve in the symmetric background

$$\frac{\partial^2 \phi_{bg}}{\partial s^2} + \frac{2}{s}\frac{\partial \phi_{bg}}{\partial s} - \frac{\partial^2 \phi_{bg}}{\partial x^2} + V'(\phi_{bg}) = 0$$

$$\left[\frac{\partial^2}{\partial s^2} - \frac{\partial^2}{\partial x^2} - \frac{\nabla^2_{H_2}}{s^2} + V''(\phi_{bg})\right](s\delta\phi) = 0$$



Floquet Theory

c.f. Preheating [Kofman,Linde,Starobinski '97]

Oscillating $V''(\phi_{bg})$

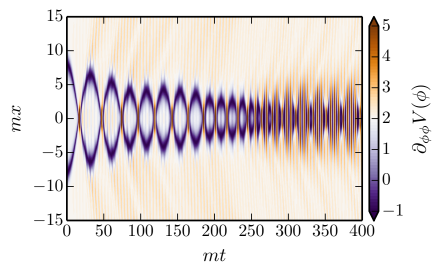
$$\Longrightarrow \quad \delta\phi \sim e^{\mu t} P(x,t)$$

Linear Parametric Resonance [JB, Bond, Mersini-Houghton, 1412.5591]

Non-SO(2,1) fluctuations evolve in the symmetric background

$$\frac{\partial^2 \phi_{bg}}{\partial t^2} - \frac{\partial^2 \phi_{bg}}{\partial x^2} + V'(\phi_{planar}) = 0$$

$$\left[\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2} + \left(k_\perp^2 + V''(\phi_{planar})\right)\right] \delta\tilde{\phi}_{k_\perp} = 0$$



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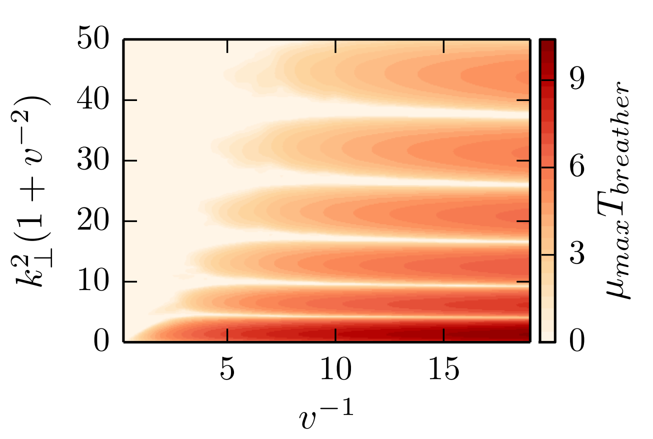
Oscillating $V''(\phi_{bg})$

$$\implies \delta\phi \sim e^{\mu t} P(x,t)$$

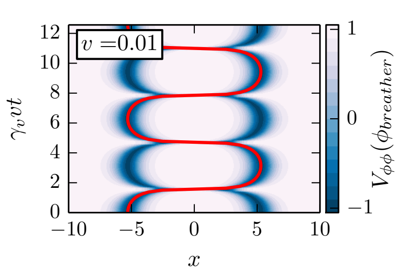
Exponentially Growing Modes Exist

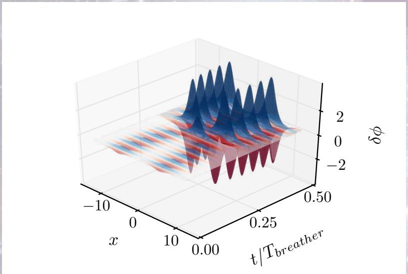
$$V(\phi) = 1 - \cos(\phi)$$

$$\phi_{breather} = 4\tan^{-1}\left(\frac{\cos(\gamma_v v t)}{v\cosh(\gamma_v x)}\right) \qquad \gamma_v \equiv (1+v^2)^{-1/2}$$



Broad Resonance for Colliding Walls





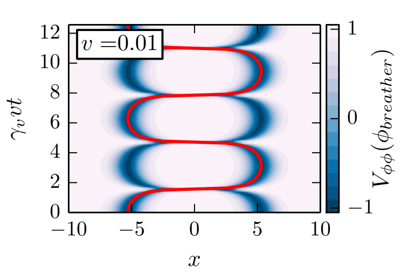
$v = 0.01$

Generic Instability

- Goldstones of Spontaneously Broken Translation Invariance
- Time-dependent wall "tension"

Broad Resonance for Colliding Walls

$$n_k^{eff} \propto \frac{1}{2k_\perp}\int_{-\infty}^{\infty} dx \left(\delta\dot{\phi}_k^2 + k_\perp^2\delta\phi^2\right)$$



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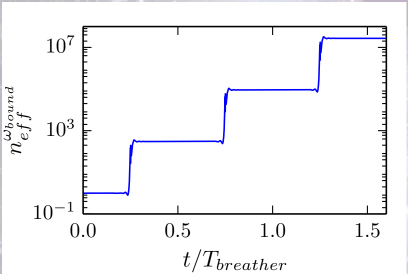

Generic Instability

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- Time-dependent wall “tension”

Implications

SO(2,1) symmetry can be badly broken

Observables don't necessarily have azimuthal symmetry

- Beam smoothing versus inhomogeneity scale
- Tensor modes are produced by fracturing of walls
- Inhomogeneous start to inflation in some regions
- Sign of $\zeta = \delta \ln(a)$ in one field versus two field model

Qualitative conclusions don't depend on inflationary scenario

- Oscillons as nonequilibrium environment for baryogenesis?
- Oscillons dilute as $a^{-3} \rightarrow$ perturbed EOS during phase transition?
- Application to braneworlds with colliding walls
- Preheating in unwinding inflation?
- Bubble baryogenesis

These signals are spatially **intermittent**