The 10th Annual
Large Hadron Collider Physics Conference
May 16-21, 2022

Probing the Higgs sector with gravitational waves

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ICEX Departamento de Física

UFMG

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Outline

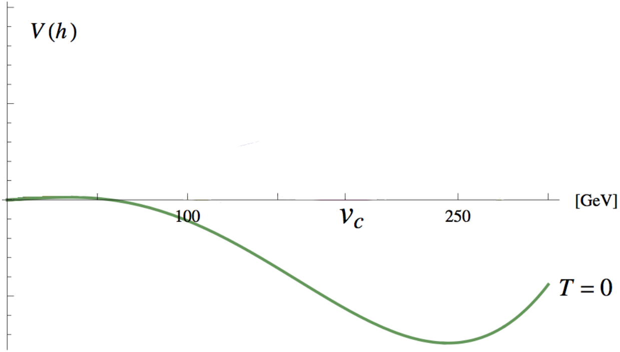
Probing the Higgs sector with gravitational waves

- Electroweak phase transition
  The bridge between the Higgs and gravitational wave physics
- LISA: the Laser Interferometer Space Antenna
  …and the possibility of detecting these GWs
- Probing BSM physics with GWs: a 2HDM example
- Conclusions and outlook

The electroweak phase transition

Cold, nearly empty Universe ($T \approx 0$)

Higgs mechanism proceeds as in textbooks



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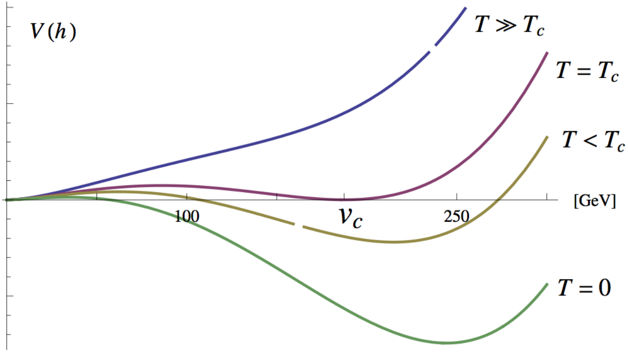
But the early Universe is hot!

Higgs immersed in plasma
Thermal corrections to *effective* potential

$$V_{\text{eff}} \overset{\text{high T}}{\approx} V_0 + \sum_i g_i \frac{T^2}{24} m_i^2 \underbrace{- \frac{T}{12\pi} m_i^3}_{\text{bosons only}} + \dots$$



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Barrier between vacua
⇓
bubbles!
The Universe boils!

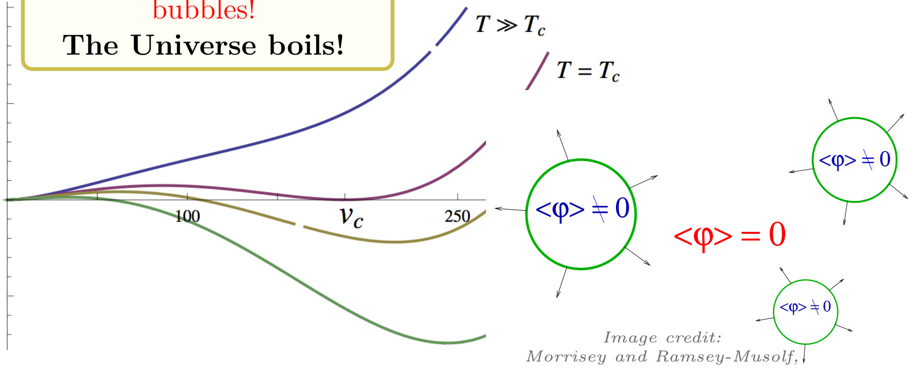
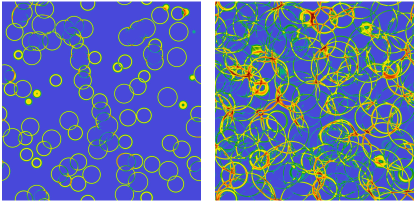


Image credit: Morrisey and Ramsey-Musolf, New J. Phys. **14** *(2012) 125003*

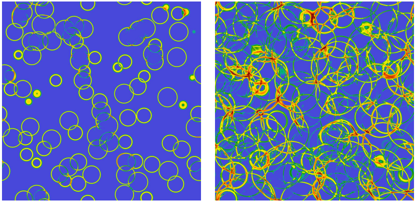
Gravitational waves



Hindmarsh, Huber, Rummukainen and Weir
Phys. Rev. D **92**, *123009*

Collisions break spherical symmetry
$\Downarrow$
quadrupole moment (sources GWs)!
(kinetic energy, sound waves, turbulence)

Gravitational waves



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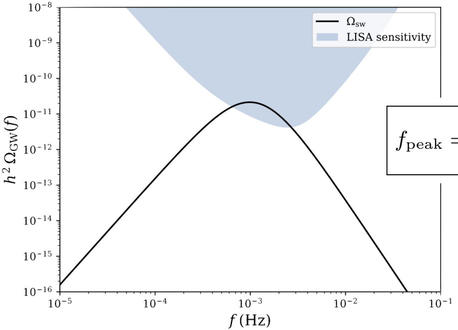
Long distances

sources causally disconnected

white noise $\implies$ $\Omega_{\text{GW}} \sim k^3$

Density parameter

$$\frac{d\Omega_{\text{GW}}}{d\ln k} = \frac{1}{12H^2}\frac{k^3}{2\pi^2}P_{\dot{h}}(\mathbf{k},t)$$



Total GW energy is finite:
spectrum decreases for $k \gtrsim k_*$

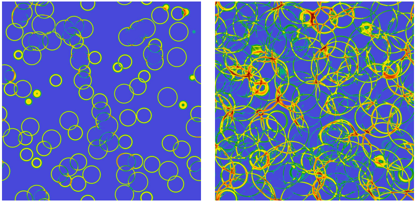
$$f_{\text{peak}} = 16.5 \times 10^{-3}\ \text{mHz}\ \left(\frac{g_{s*}}{100}\right)^{1/6} \frac{T_*}{100\ \text{GeV}} \left(\frac{f_*}{H_*}\right)$$

Typically

$$f_*/H_* \simeq 100 - 1000 \ \Rightarrow \boxed{f_{\text{peak}} \simeq \mathcal{O}(\text{mHz})}$$

$$T_* \simeq 100\ \text{GeV}$$

Gravitational waves



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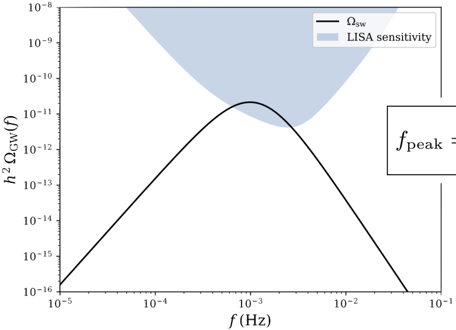

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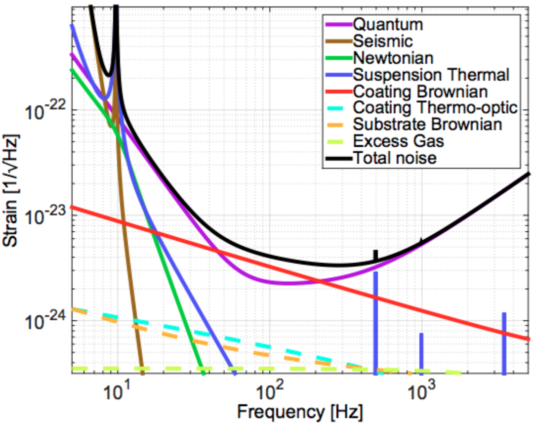
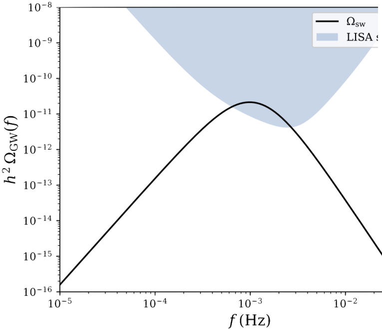
Gravitational waves

Ground-based interferometers

Low f sensitivity limited by seismic, thermal, Earth's gravity gradients

LIGO noise budget (LIGO Document T1800044-v5)





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Must go to space!

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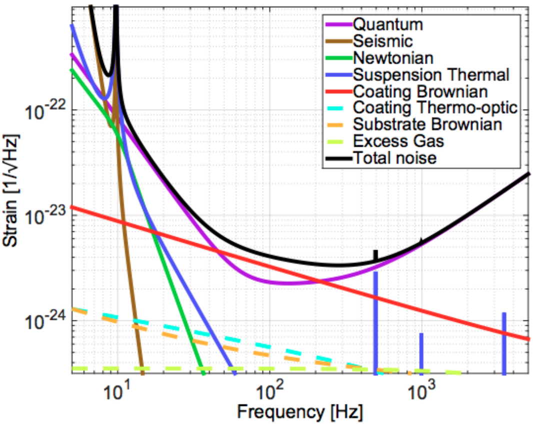

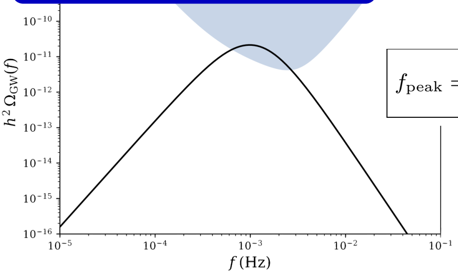

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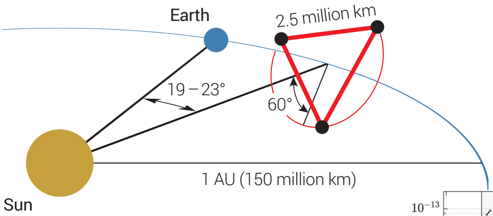
LISA

Laser Interferometer Space Antenna

LISA: Laser Interferometer Space Antenna

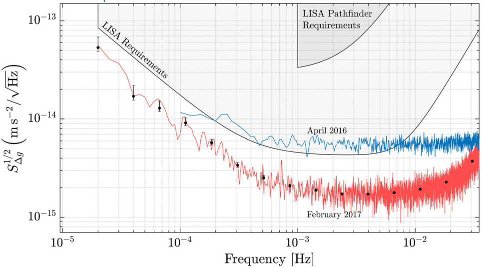


3 free-falling spacecrafts
preserving equilateral shape
while orbiting the sun(!)

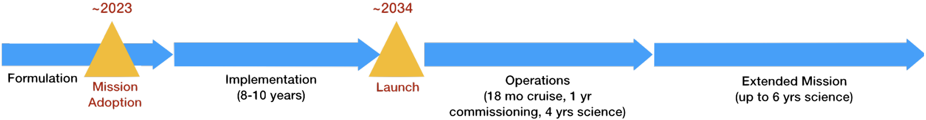
Sensitive to variations of
1 part in 10^{22} arm lengths

Gravitons decouple much earlier than photons from plasma!

Detection of GWs from EWPT give us a “picture” of the Universe at 10^{-12} s after “Big Bang” (CMB: 380,000 years!)



LISA Pathfinder
PRL **120**, *061101 (2018)*



~2023

~2034

Formulation

Mission Adoption

Implementation (8-10 years)

Launch

Operations (18 mo cruise, 1 yr commissioning, 4 yrs science)

Extended Mission (up to 6 yrs science)

Astro2020 Whitepaper, arXiv:1907.06482 [astro.ph-IM]

GWs as complementary probes of BSM physics

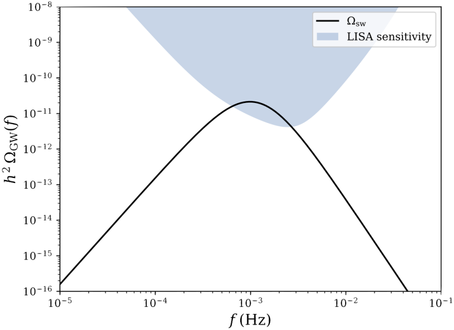
Accurate prediction of spectrum from BSM

$\Updownarrow$

test BSM physics with GWs!

Key parameters:

- $\alpha \equiv \dfrac{\text{energy released}}{\text{total energy in radiation}}$
- $\beta^{-1} \equiv$ characteristic timescale of phase transition; $\Gamma = \Gamma_* \, e^{-\beta\,(t-t_*)}$
- $T_* \equiv$ temperature
- $v_w \equiv$ velocity of bubble expansion



A CONCRETE EXAMPLE: THE 2HDM CASE

Two-Higgs-doublet models

GCD, Huber, Mimasu, No, PRL **113** *(2014) 21, 211802*
GCD, Huber, Mimasu, No, PRD **93** *(2016) 11, 115033*
Caprini, Chala, GCD et al., JCAP **03** *(2020) 024*

- Minimal SM extensions:
  - Two $SU(2)_L$ scalar doublets: Φ_1 and Φ_2 .
  - Motivated by many SM extensions (e.g. SUSY, Composite Higgs).
  - Various heavy scalars $(h_0, H_0, A_0, H^{\pm})$ increase EWPT strength.
  - 7 parameters: 4 scalar masses, overall mass scale of Φ_2, 2 mixing angles

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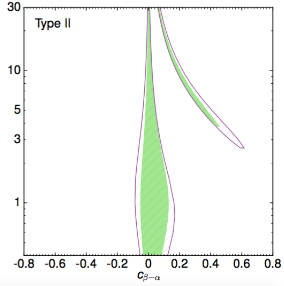

Fix $m_{h_0} = 125$ GeV

Higgs measurements: $\boxed{h_0 \approx h_{\rm SM}}$

EWPO $\Longrightarrow$ approx. degeneracy

$$\boxed{m_{H^\pm} \approx m_{A^0} \text{ or } m_{H^0}}$$

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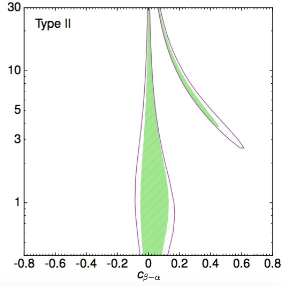

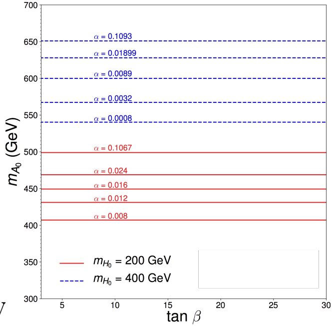

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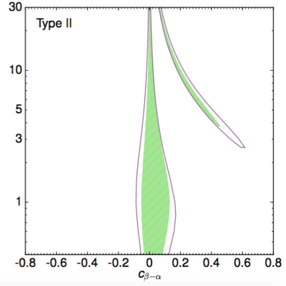

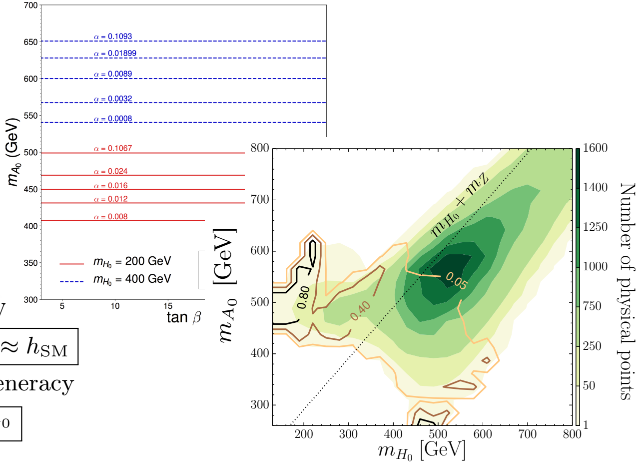

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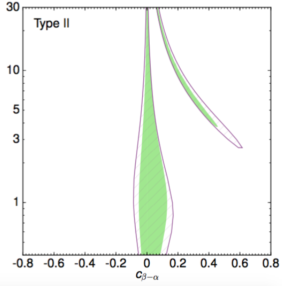
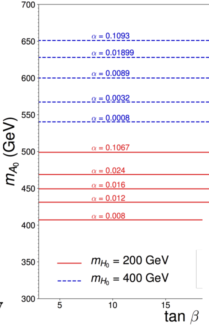
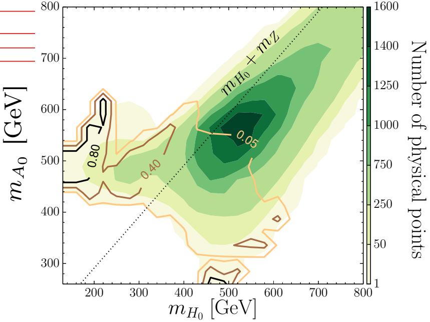
Dialogical aspect

Cosmological phase transition
$\Downarrow$
implications for collider searches





This motivated a search for
$A/H \to ZH/A$
by CMS and ATLAS



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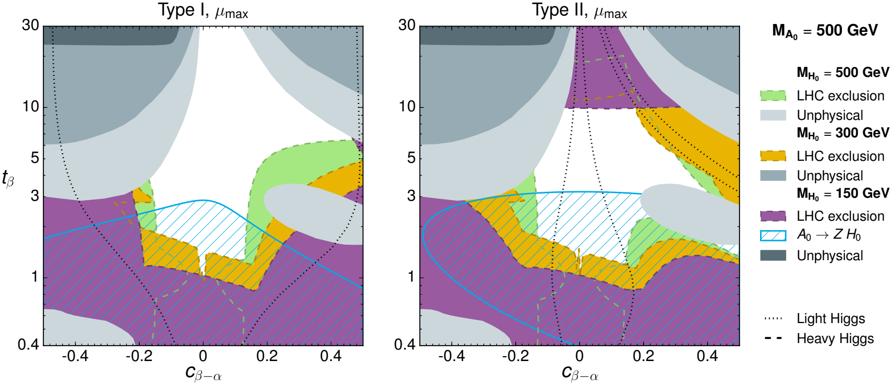
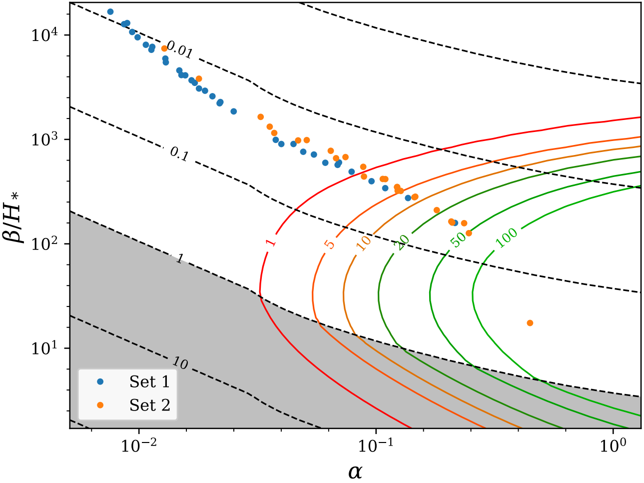


See also Kling, Su and Su, JHEP **06** *(2020) 163*

LISA as a probe for BSM physics

Complementary aspect

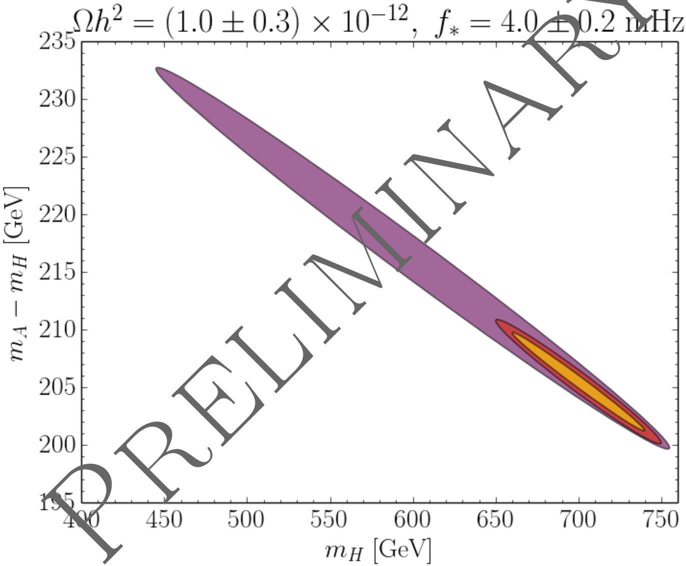
Caprini, Chala, GCD et al., JCAP **03** *(2020) 024*



Orange: 2HDM Type-II excluded at LHC (but not Type-I)

Blue: Not excluded by LHC

LISA as a probe for BSM physics



BUBBLE WALL VELOCITY:

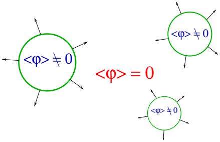
A COMMENT ON RECENT DEVELOPMENTS

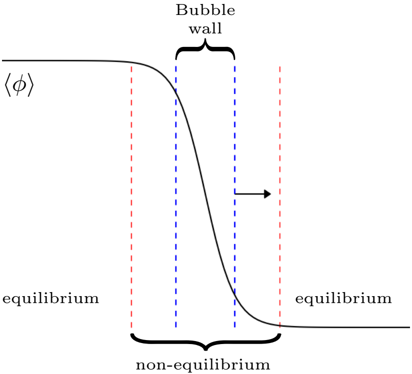
Bubble wall velocity and Boltzmann equation

*GCD, Huber, Konstandin, JCAP **04** (2022) 04, 010*

GW spectrum determined by 4 thermodynamical parameters:

$$\underbrace{\alpha,\quad \beta,\quad T_*}_{\substack{\text{equilibrium physics}\\ \text{analysis of free-energy}}} \qquad \text{and} \qquad \underbrace{v_w}_{\text{non-equilibrium}}$$





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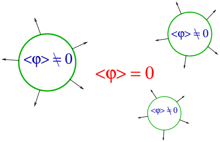

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v_w computed from Klein-Gordon equation

$$-\phi'' + \frac{dV_T}{d\phi} + \underbrace{\sum_i \frac{dm_i^2}{d\phi} \int \frac{d^3p}{(2\pi)^3 2E_i} \delta f_i(x^\mu, p^\mu)}_{\text{friction}} = 0$$

δf from Boltzmann equation

$$p^\mu \partial_\mu \, \delta f_i(x^\mu, p^\mu) = \mathcal{S}[f_j] + \mathcal{C}[f_j]$$

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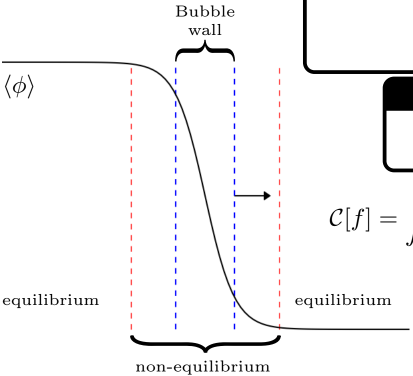

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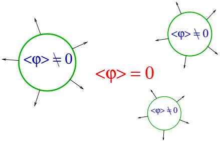

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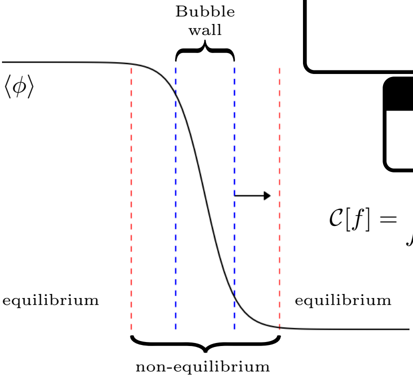


How can we solve this integro-differential equation?

Current debate: continuous *vs.* discontinuous friction

Fluid Ansatz (90's)

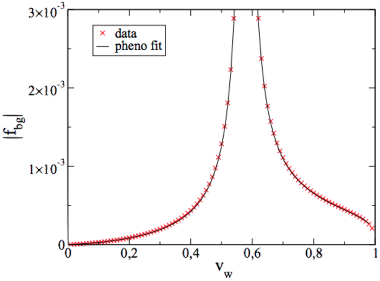
$$f(x,p) = \frac{1}{e^{\beta p^\mu (u_\mu + \delta u_\mu) - \mu} \pm 1}$$

Moore, Prokopec, PRD ***52*** *(1995) 7182*

3 fluctuations: $\mu, \quad \delta u_0 \equiv \delta T/T, \quad \delta u_z \equiv \delta v$

Discontinuous friction

Konstandin, Nardini, Rues, JCAP ***09*** *(2014) 028*



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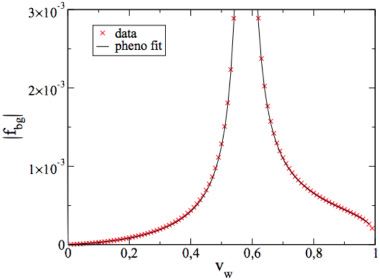


Recently proposed

$$f(x,p) = \frac{1}{e^{\beta p^\mu u_\mu - \mu} \pm 1} + \delta f$$

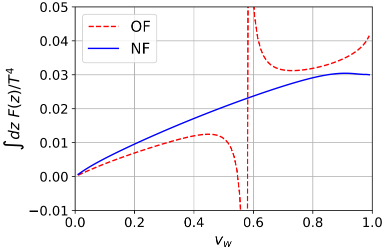
Cline, Kainulainen
PRD ***101*** *(2020) 063525*

ad hoc factorization property:

$$\langle X \delta f \rangle \sim \left\langle \frac{p_z}{E} \delta f \right\rangle \times \int d^3p \, \frac{E}{p_z} X \, f_{\rm eq}$$

Leaves 2 fluctuations: μ and $u \equiv \langle (p_z/E)\delta f \rangle$

Laurent, Cline, PRD ***102*** *(2020) 063516*

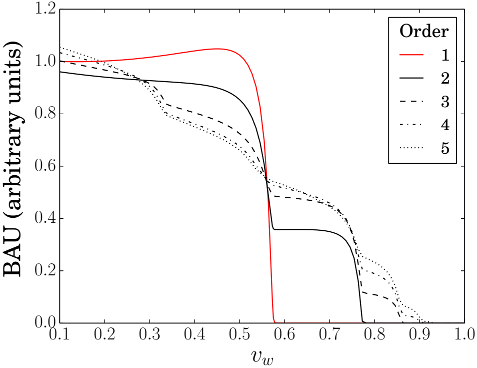


Could the discontinuity be an artifact of truncating the fluid Ansatz (i.e. including only 3 perturbations)?

This happens for the baryon asymmetry

GCD, Huber, Konstandin

*JCAP **08** (2021) 020*



Extended fluid Ansatz

GCD, Huber, Konstandin, JCAP ***04*** (2022) 04, 010

$$f(x,p) = \frac{1}{e^{\beta p^\mu u_\mu + \delta} \pm 1}$$

with

$$\delta = w^{(0)} + p^\mu w^{(1)}_\mu + p^\mu p^\nu w^{(2)}_{\mu\nu} + \cdots$$

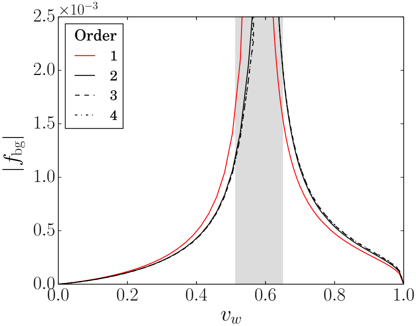
Linearized Boltzmann equation

$$p^\mu \partial_\mu \, \delta f_i(x^\mu, p^\mu) = \mathcal{S}[f_j] + \mathcal{C}[f_j]$$

$$\Downarrow$$

$$A \cdot q' + \Gamma \cdot q = S$$

with $q = (w^{(0)}, w^{(1)}_0, w^{(1)}_z, \ldots)^T$



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*GCD, Huber, Konstandin, JCAP **04** (2022) 04, 010*

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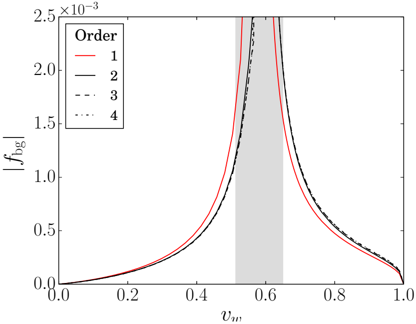
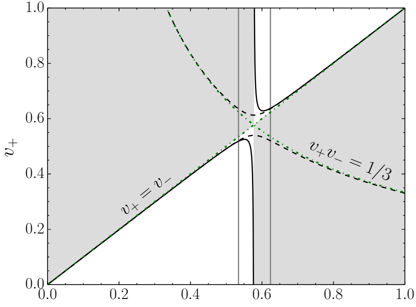
Important!

A discontinuity is expected from energy-momentum conservation!





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GCD, Huber, Konstandin, JCAP ***04*** *(2022) 04, 010*

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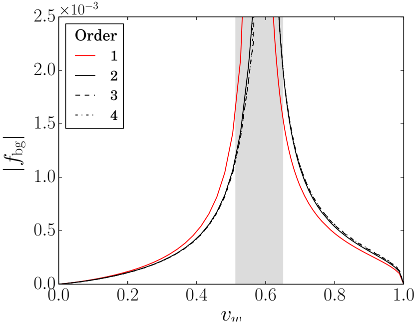
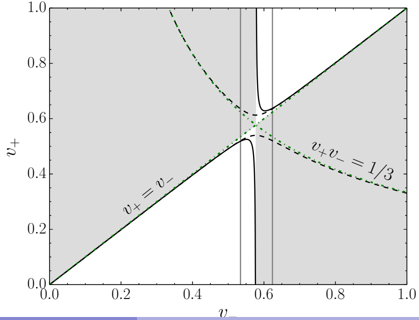
Discontinuity recovered in non-linearized approaches

Laurent, Cline, arXiv:2204.13120





Conclusions

- We live in a golden age for Cosmology
  (precision measurements, GW detection, new experiments in sight…)

- Cosmological observations can be used to constrain BSM Particle Physics.
  The Early Universe reached higher energies than any accelerator we could dream of building in the foreseeable future.

- The study of the EWPT provides a rich Particle-Cosmology interface.
  EW epoch $\longleftrightarrow$ physics @ EW scale (relevant at current colliders!)

- Room for improvement in estimate of thermodynamical parameters
- Application of extended fluid Ansatz to specific models
  (computation of v_w from first principles)
- Improvement in implementation (collision terms) and solution of Boltzmann equation

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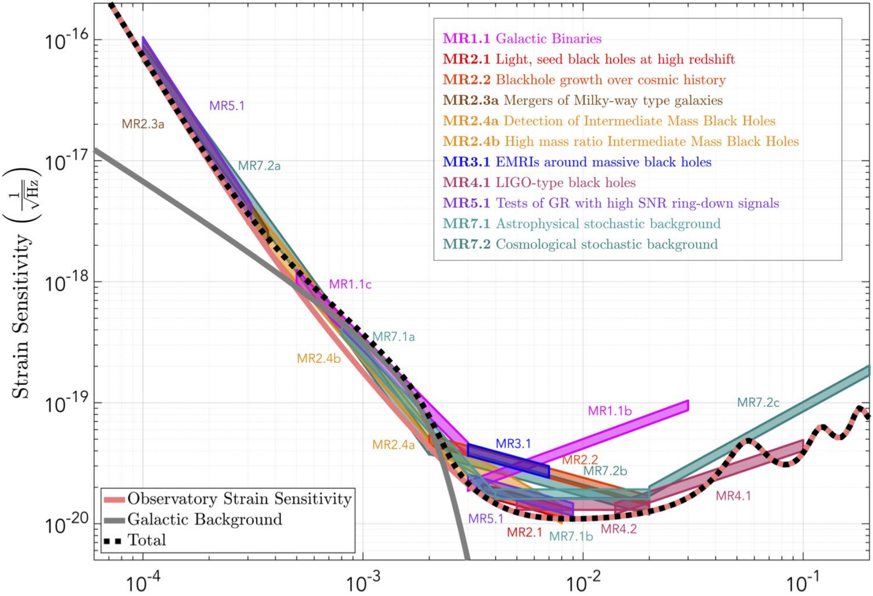
THANK YOU!

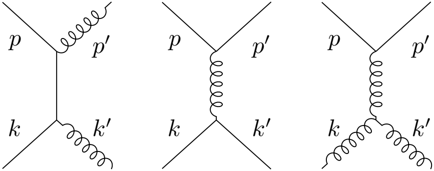
APPENDICES

LISA Science Objectives

LISA Mission Proposal L3



Collision terms



Singular behaviour ⟵ kinetic term
but
collisions important for convergence

$$\boxed{\text{coll.} \sim \delta_p + \delta_k - \delta_{p'} - \delta_{k'}}$$

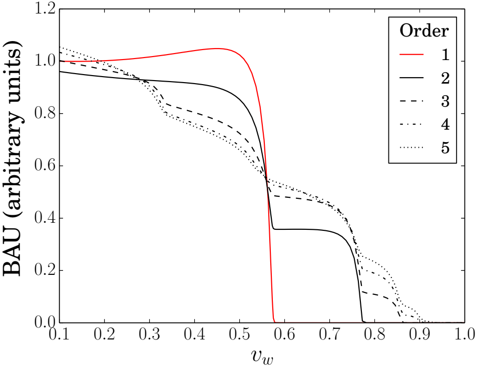
Annihilations

$$|\mathcal{M}|^2 \sim -g_s^4 \frac{st}{(t - m_q^2)^2}$$

$$t = -2p \cdot p' = -2|\mathbf{p}||\mathbf{p}'| \cos\theta_{pp'}$$

$$\int_p p^\mu \dots p^\nu \mathcal{C}[f] \simeq \int_p \int_k \int_{p'} \int_{k'} \frac{st}{(t - m_q^2)^2} \delta^4(\dots) p^\mu \dots p^\nu f_p f_k (1 \pm f_{p'})(1 \pm f_{k'}) \times$$
$$\times \left[\dots + w^{(2)}_{\rho\sigma}(p^\rho p^\sigma + k^\rho k^\sigma) + \dots\right]$$

Results: Supersonic baryogenesis

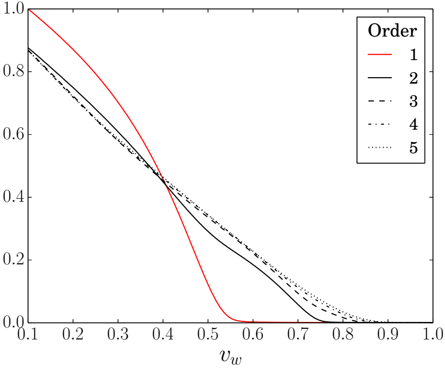


$\alpha_s = 0.01$

BAU suppressed for $v_w > c_s$, but
not prohibitively small!
(except for $v_w \to 1$)

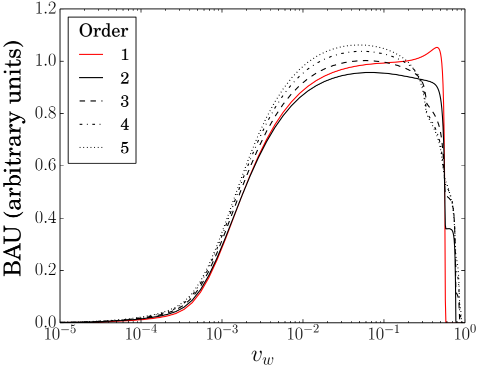
convergence parameter $\sim \frac{T}{\Gamma} \sim D\,T$

$\alpha_s = 0.06$



Continuous along v_w
similar to found recently in
Cline & Kainulainen
*PRD **101** (2020) no. 6, 063525*

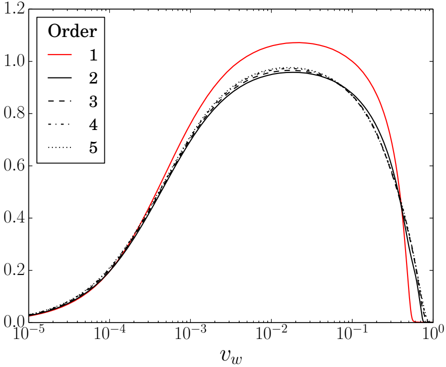
Results: small v_w



$$\alpha_s = 0.01$$

BAU can be either enhanced or suppressed relative to 1st order

$$\alpha_s = 0.06$$



Either way the discrepancy is $\sim \mathcal{O}(20\%)$ for subsonic walls

$\Downarrow$

3-fluid reasonably reliable in this regime