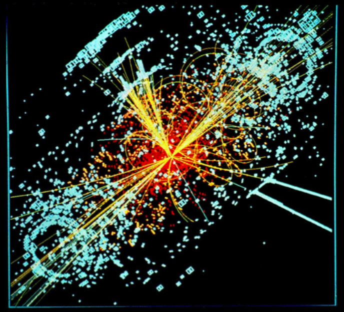

Searching for new physics
with
Gravitational Waves

Djuna Lize Croon

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Brighton,

November 2018

Based on work with

G. White [JHEP, arXiv:1803.05438]

V. Sanz and G. White [JHEP, arXiv:1806.02332]

M. Gleiser, S. Mohapatra, C. Sun [PLB, arXiv:1802.08259]

J. Fan, C. Sun, [arXiv:1810.01420]

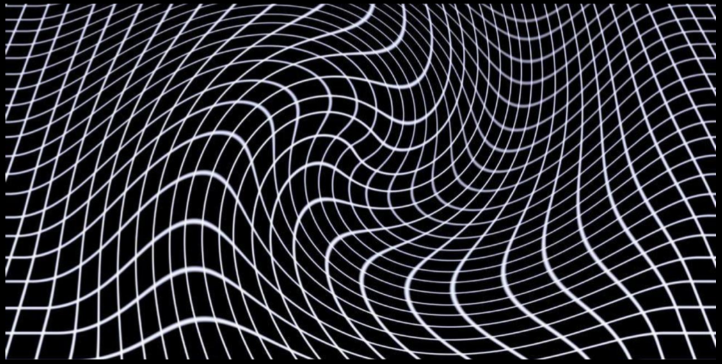
Gravitational Waves: unique probes of New Physics

- A memory of the past

  Information about the source is not washed out by thermal equilibration

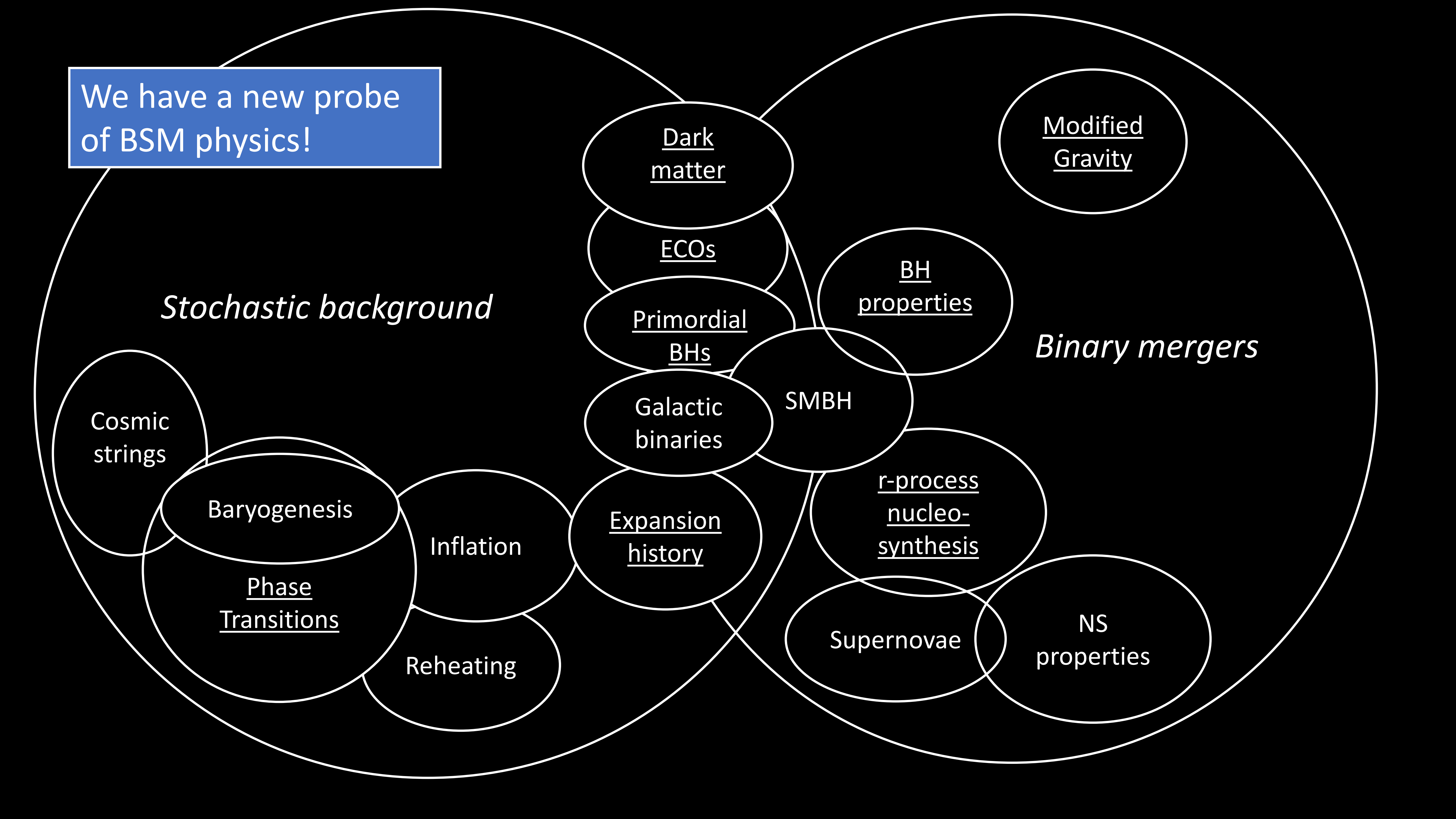
- A detector of the far

  The Universe is (almost) transparent to GW

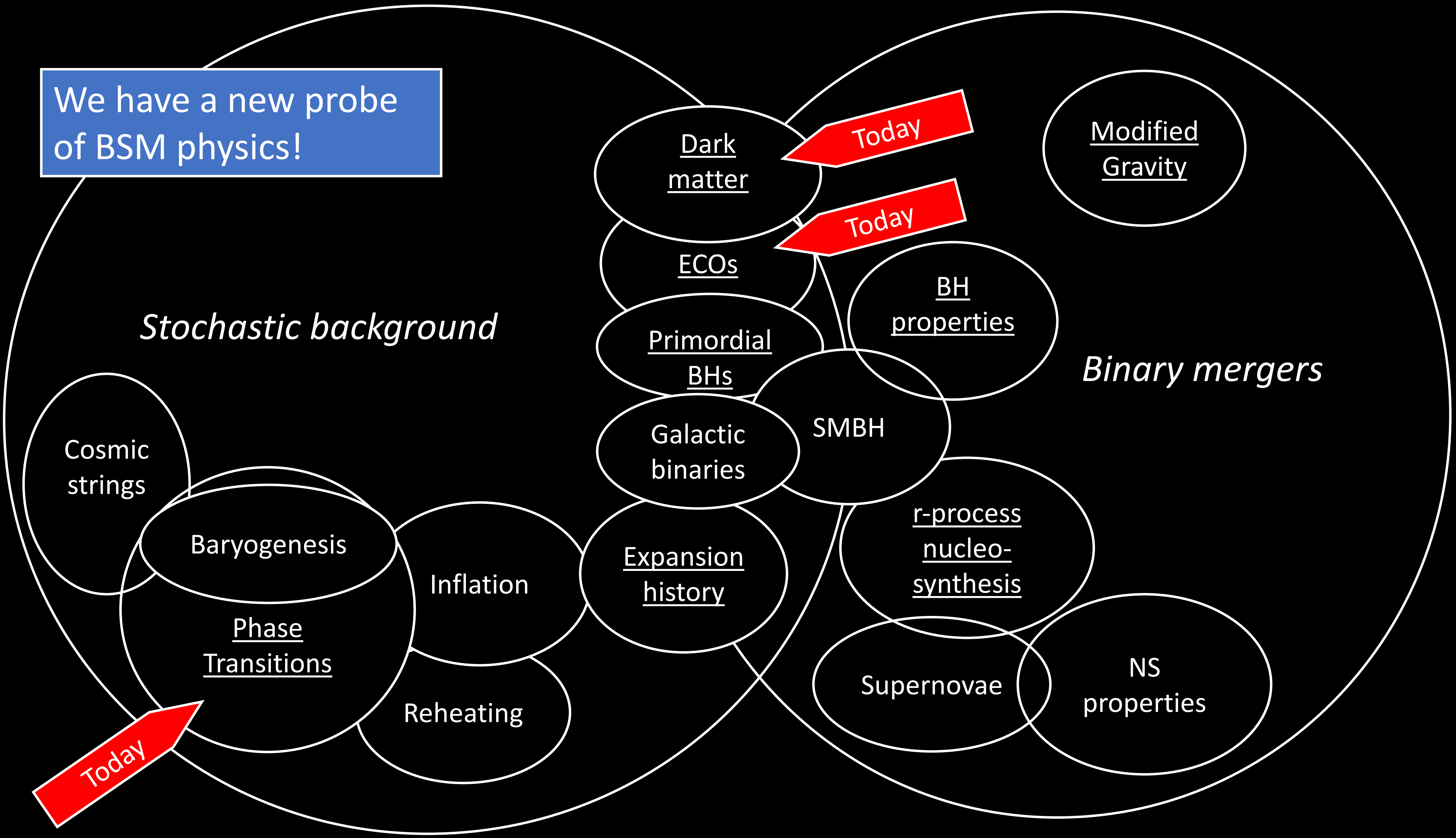


- A probe of the dark

  Gravitational interactions are a defining property of Dark Matter


We have a new probe of BSM physics!
Stochastic background
Binary mergers
Dark matter
ECOs
Primordial BHs
Galactic binaries
SMBH
Modified Gravity
BH properties
Cosmic strings
Baryogenesis
Phase Transitions
Inflation
Reheating
Expansion history
r-process nucleo-synthesis
Supernovae
NS properties

We have a new probe of BSM physics!



What is a gravitational wave?*

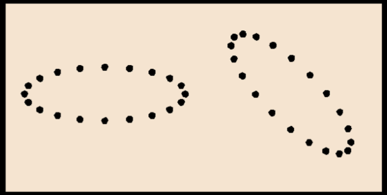
- Perturbations around flat space: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ — 10 components
- Einstein equations (Lorentz gauge):

$$\boxed{\Box\, \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}}$$

6 components

- Outside the source, $T_{\mu\nu} = 0$
  - → Transverse-traceless gauge fixes residual gauge freedom — 2 components
  - → Single plane wave:

$$h_{ab}^{TT}(t, z) = \begin{pmatrix} h_+ & h_\times \\ h_\times & -h_+ \end{pmatrix} \cos\left(\omega(t - z/c)\right)$$



*In linearized GR

What is a gravitational wave?*

- Perturbations around flat space: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ 10 components
- Einstein equations (Lorentz gauge):

$$\boxed{\Box \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}} \longrightarrow h_{ab}^{TT} = [h_{ab}^{TT}]_{\text{quad}} + \dots$$

changing quadrupole moment of $T_{\mu\nu}$

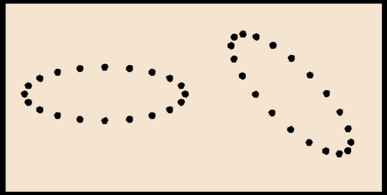
- Outside the source, $T_{\mu\nu} = 0$

2 components

→ Transverse-traceless gauge fixes residual gauge freedom

→ Single plane wave:

$$h_{ab}^{TT}(t,z) = \begin{pmatrix} h_+ & h_\times \\ h_\times & -h_+ \end{pmatrix} \cos\left(\omega(t - z/c)\right)$$



*In linearized GR

From metric perturbation to detector response

- Plane wave decomposition:

Polarization tensor
(A=+,x)

$$h_{ab}(t,\vec{x}) = \int_{-\infty}^{\infty} df \int_{S^2} d^2\Omega_{\hat{k}} \sum_A e_{ab}^A(\hat{k}) h_A(f,\hat{k}) e^{2i\pi f(t-\hat{k}\cdot\vec{x}/c)}$$

Plane waves

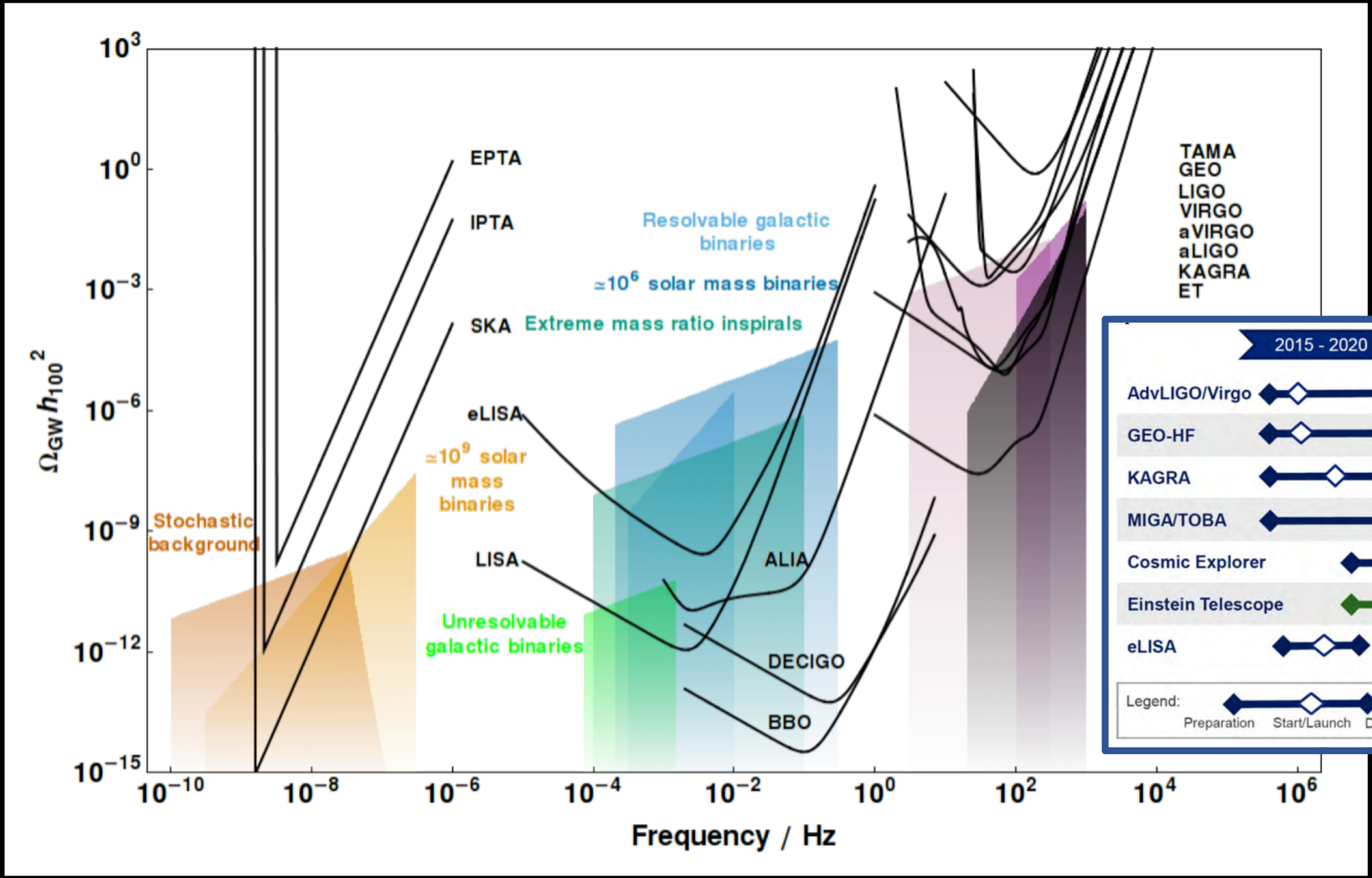
- Schematically, for unpolarized isotropic GRB (this talk):

$$\langle h_A h_{A'}^* \rangle \propto S_h(f) = \frac{3H_0}{2\pi^2}\frac{\Omega_{GW}(f)}{f^3}$$

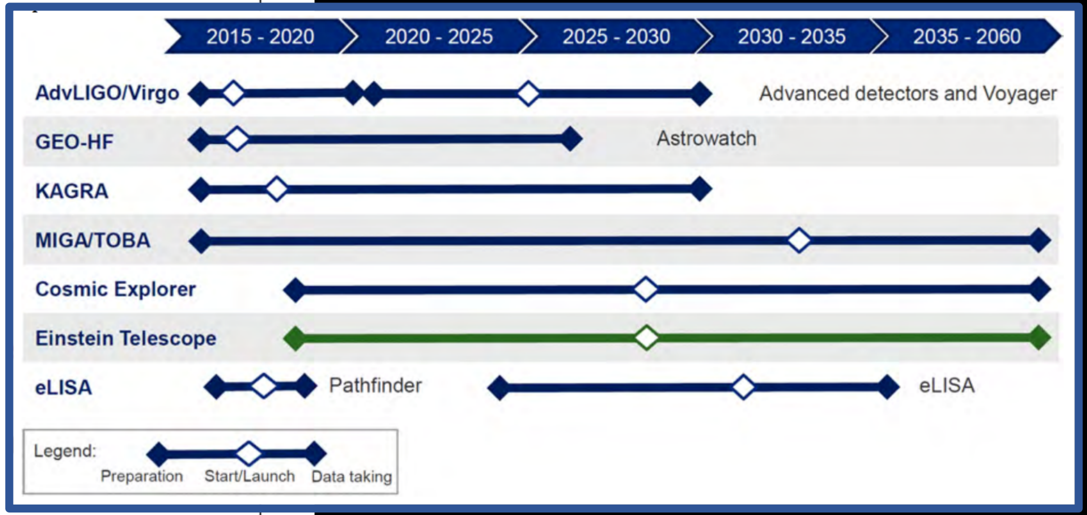
Fractional energy density

$$\boxed{\Omega_{\rm GW}(f) \equiv \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}}$$

Experimental strain-noise sensitivity bands



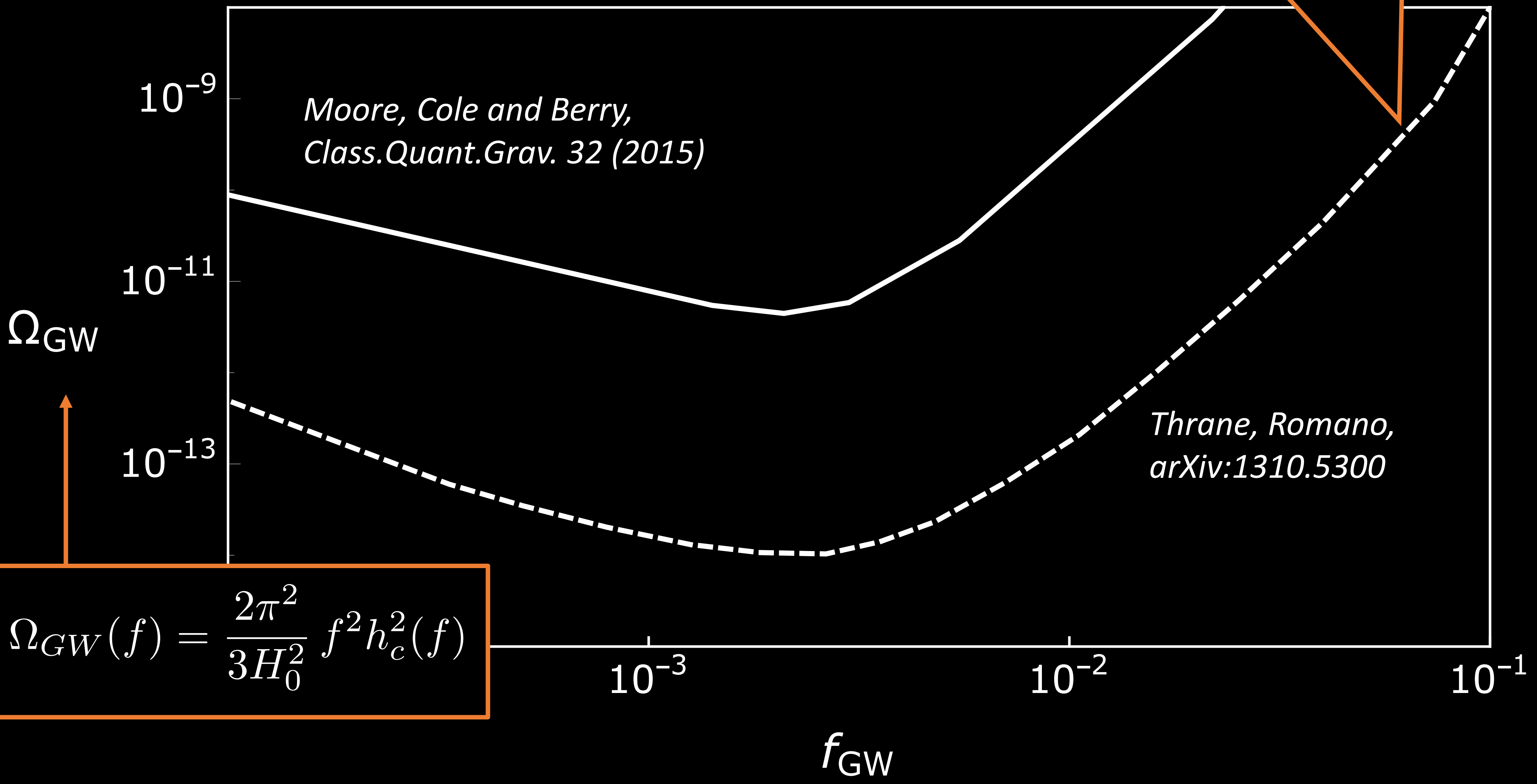
Moore, Cole and Berry, Class.Quant.Grav. 32 (2015)



KNAW: ET on the national roadmap

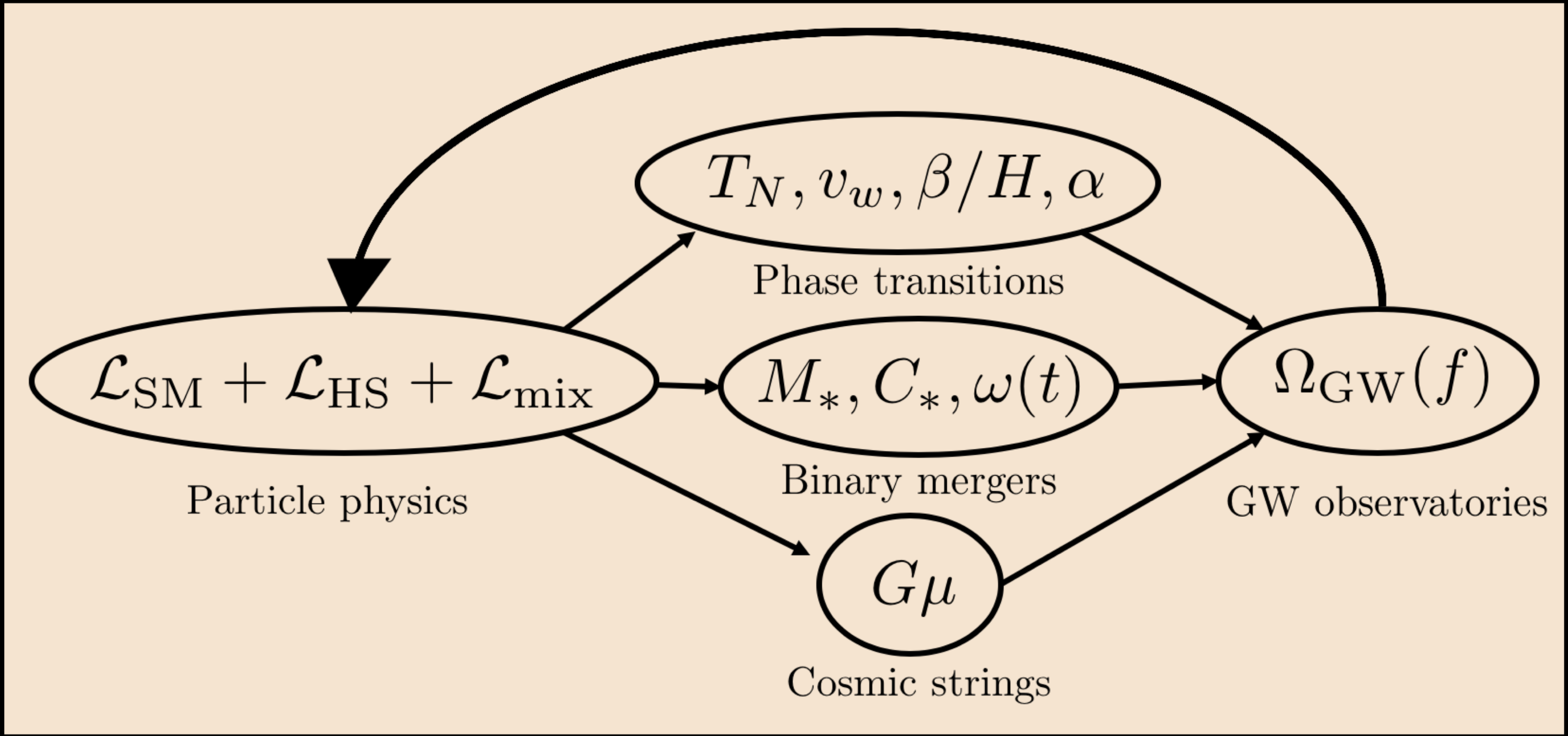
LISA sensitivity curves

Integration over frequency gives power-law integrated curves



$$\Omega_{GW}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2(f)$$

The road ahead: solving the inverse problem



BSM physics in Binary mergers

Modified waveform of BNS or BBH mergers

Mergers of exotic compact objects

Resolvable mergers: wave form analysis

$$\Phi(t) = 2\pi \int dt\, f_{\rm GW}(t)$$

$$h(t) = A\left[\pi f_{{\rm GW}(t)}\right]^{2/3} \cos\left[\Phi(f_{\rm GW}(t)) + \varphi\right]$$

- Distance to the binary $(A \propto 1/r)$
- Inclination of the orbital plane
- Detector response
- Chirp mass

$$\boxed{f_{\rm GW}(t) = \frac{\omega(t)}{\pi}}$$

DC, A. Nelson, C. Sun, D. Walker, Z. Xianyu, ApJ, arXiv:1711.02096 [hep-ph]

Example: Dark matter spectroscopy in BNS mergers

- A generic model of an interacting asymmetric dark sector,

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_V + \mathcal{L}_\chi + \mathcal{L}_{mix}, \quad \begin{cases} \mathcal{L}_V = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu \\ \mathcal{L}_\chi = \bar{\chi} \left(\gamma^\mu (i\partial_\mu - g' V_\mu) - m_\chi\right) \chi \,. \end{cases}$$

$$\alpha' = g'^2/4\pi$$

- Can produce observable features at LIGO for ultralight mediators,

$$m_V^{-1} = \{10\mathrm{km}, 1000\mathrm{km}\} \longleftrightarrow m_V = \{10^{-13}\mathrm{eV}, 10^{-11}\mathrm{eV}\}$$

DC, A. Nelson, C. Sun, D. Walker, Z. Xianyu, ApJ, arXiv:1711.02096 [hep-ph]

Example: Dark matter spectroscopy in BNS mergers

- Dark Repulsion:
  - Modified frequency from Yukawa potential
  - Switches on from $r \sim m_V^{-1}$
  - Can be interpreted as a modified chirp mass m_c

$$\omega^2 = \frac{Gm}{r^3}\left(1 - \tilde{\alpha}' e^{-m_V r}\right),$$

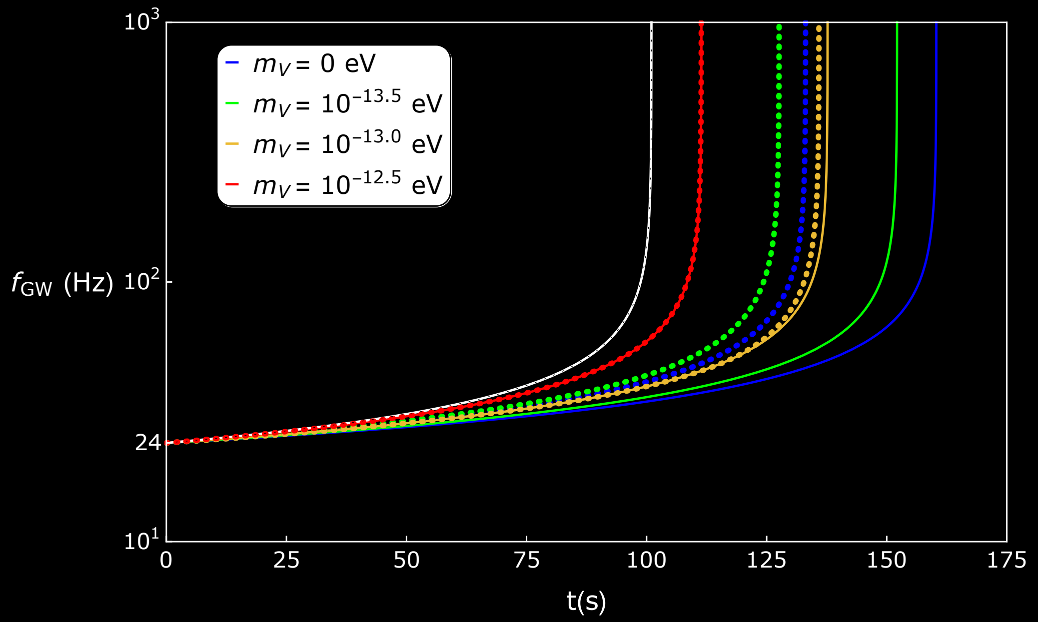
$$\tilde{\alpha}' \equiv \frac{\alpha' q_1 q_2}{G m_1 m_2}$$

- Dark Radiation:
  - For unequally charged NS, a dark dipole moment is generated
  - Dark radiation dissipates for light mediator $m_V c/\omega < 1$

dipole

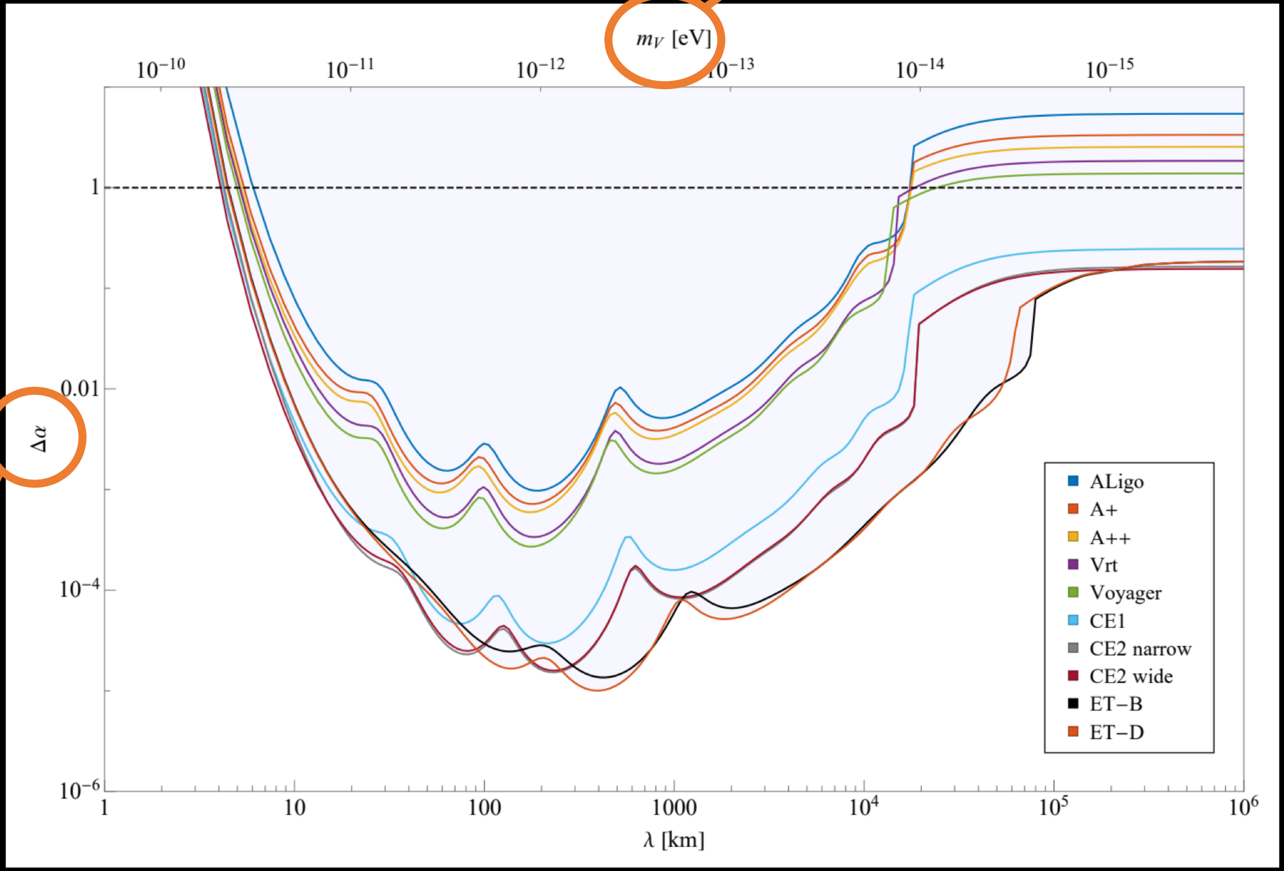
$$\dot{E} = -\left(P_{GW} + P_{dark}\right)$$

quadrupole



DC, A. Nelson, C. Sun, D. Walker, Z. Xianyu, ApJ, arXiv:1711.02096 [hep-ph]

Mediator mass



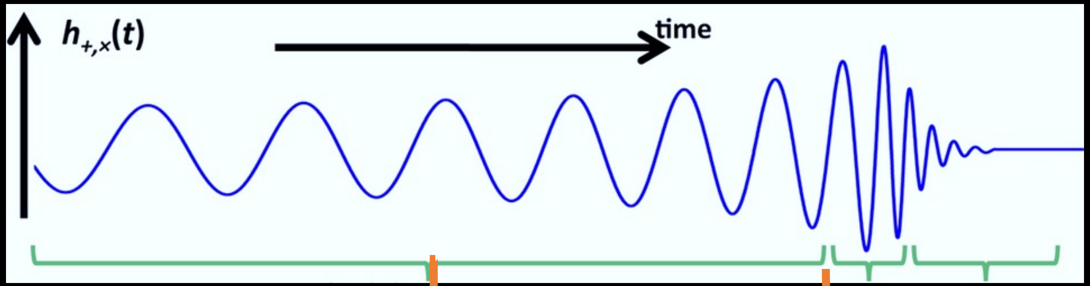
Effective coupling

$$\tilde{\alpha}' \equiv \frac{\alpha' q_1 q_2}{G m_1 m_2}$$

S. Alexander, E. McDonough, R. Sims, N. Yunes, arXiv:1808.05286 [hep-ph]

Observing binary merger events

- Dominant contribution from the inspiral phase $\Omega_{\mathrm{GW}} \propto f^{2/3}$
- Ends in f_{ISCO} ~ peak frequency



$$f(t) = \frac{5^{3/8}}{8\pi}(G_N m_c)^{-5/8} t^{-3/8}$$

$$m_c = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$$

$$f_{\mathrm{ISCO}} = \frac{C_*^{3/2}}{3^{3/2}\,\pi\, G_N (M_1 + M_2)}$$

What ECOs can be observed?

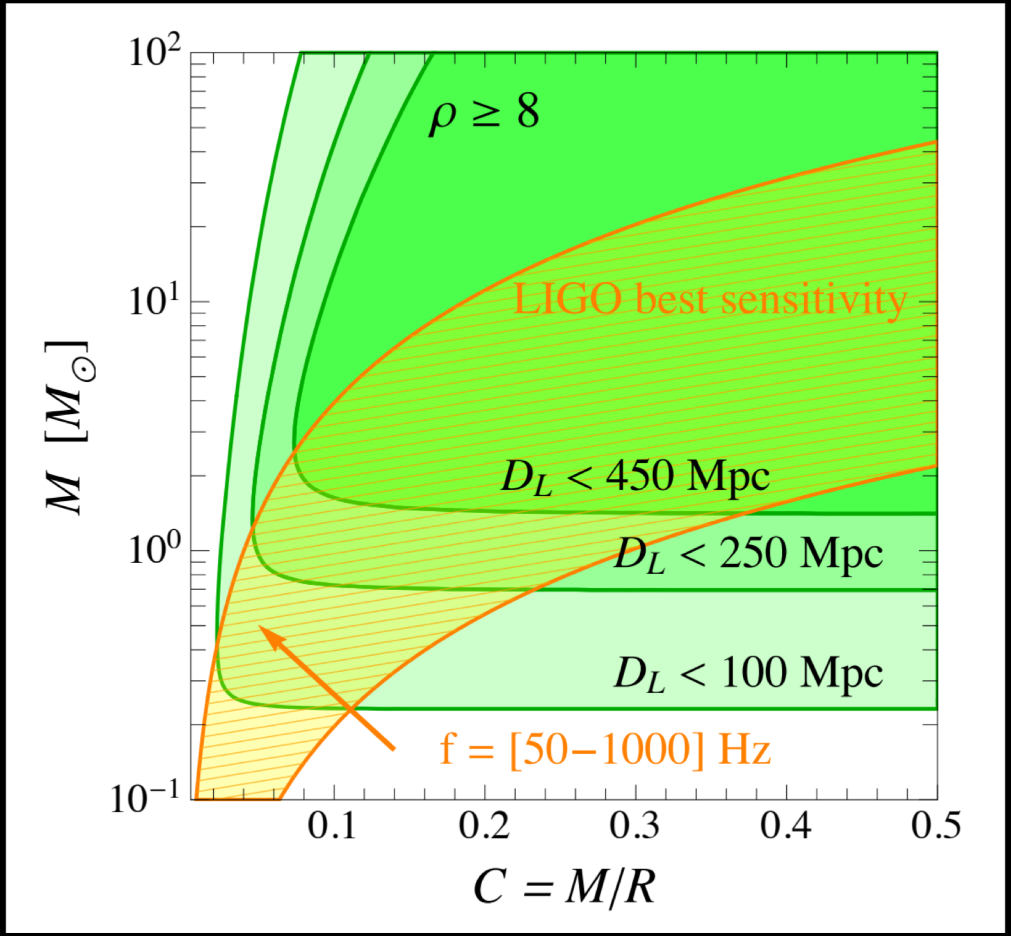
- Best detection prospects for $f_{\min} < f_{\rm ISCO} < f_{\max}$

- Defines an ECO sensitivity band

$$f_{\rm ISCO} = \frac{C_*^{3/2}}{3^{3/2}\,\pi\, G_N (M_1 + M_2)}$$

$$C_* = \frac{G_N M_*}{R_*}$$

- Important: masses and compactness of constituent objects

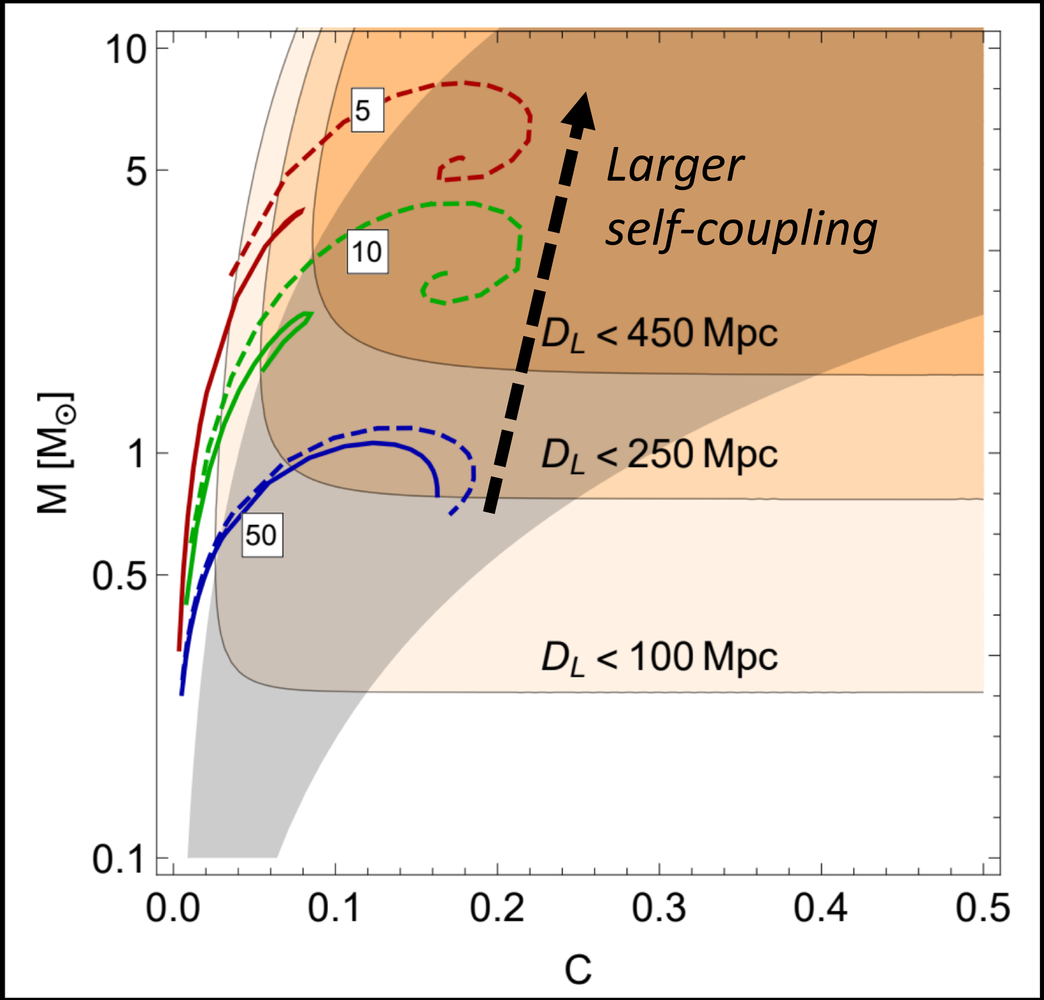


Giudice, McCullough, Urbano 1605.01209

Example: boson stars with repulsive self-interaction

- Solving the Einstein-Klein-Gordon system
  - Einstein equations (spherically symmetric metric)
  - Scalar EOM (harmonic ansatz)

$$\left.\begin{aligned} R_{\max} &\propto \sqrt{\lambda}\,\frac{M_p}{m^2} \\ M_{\max} &\propto \sqrt{\lambda}\,\frac{M_p^3}{m^2} \end{aligned}\right\} C_{\max} \approx 0.16.$$



DC, Fan, Sun, 1810.01420

Stochastic Background (from binary mergers)

$$\boxed{\Omega_{\mathrm{GW}}(f) \equiv \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}}$$

$$\Omega_{\mathrm{GW}}(f, M_*, f_{BBS}) = \frac{f}{\rho_c H_0}\int_0^{z_{max}} \frac{R_m(z, M_*, f_{\mathrm{BBS}})}{(1+z)\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}\,\frac{dE}{df_s}\; dz$$

LIGO, PRL 120, 091101

Stochastic Background (from binary mergers)

$$\Omega_{\rm GW}(f) \equiv \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$$

Observed frequency

$f_s = (1+z)f$

Merger rate

$$\Omega_{\rm GW}(f, M_*, f_{BBS}) = \frac{f}{\rho_c H_0}\int_0^{z_{max}} \frac{R_m(z, M_*, f_{\rm BBS})}{(1+z)\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}\frac{dE}{df_s}dz$$

Differential energy emitted by a single source

LIGO, PRL 120, 091101

The Merger Rate

$$R_m(t, M_*, f_{\rm BBS}) = \int_{\Delta t_{min}}^{\Delta t_{max}} R_{\rm BBS}(t - \Delta t, M_*)\, p(\Delta t)\, d\Delta t.$$

Binary formation rate

Ansatz: the boson star formation rate tracks the luminous star formation rate,

$$R_{\rm BBS}(z_f, M_*) = f_{\rm BBS} \times {\rm SFR}(z_f, M_*).$$

Time delay distribution

Probability that two stars initially separated by a are gravitationally bounded:

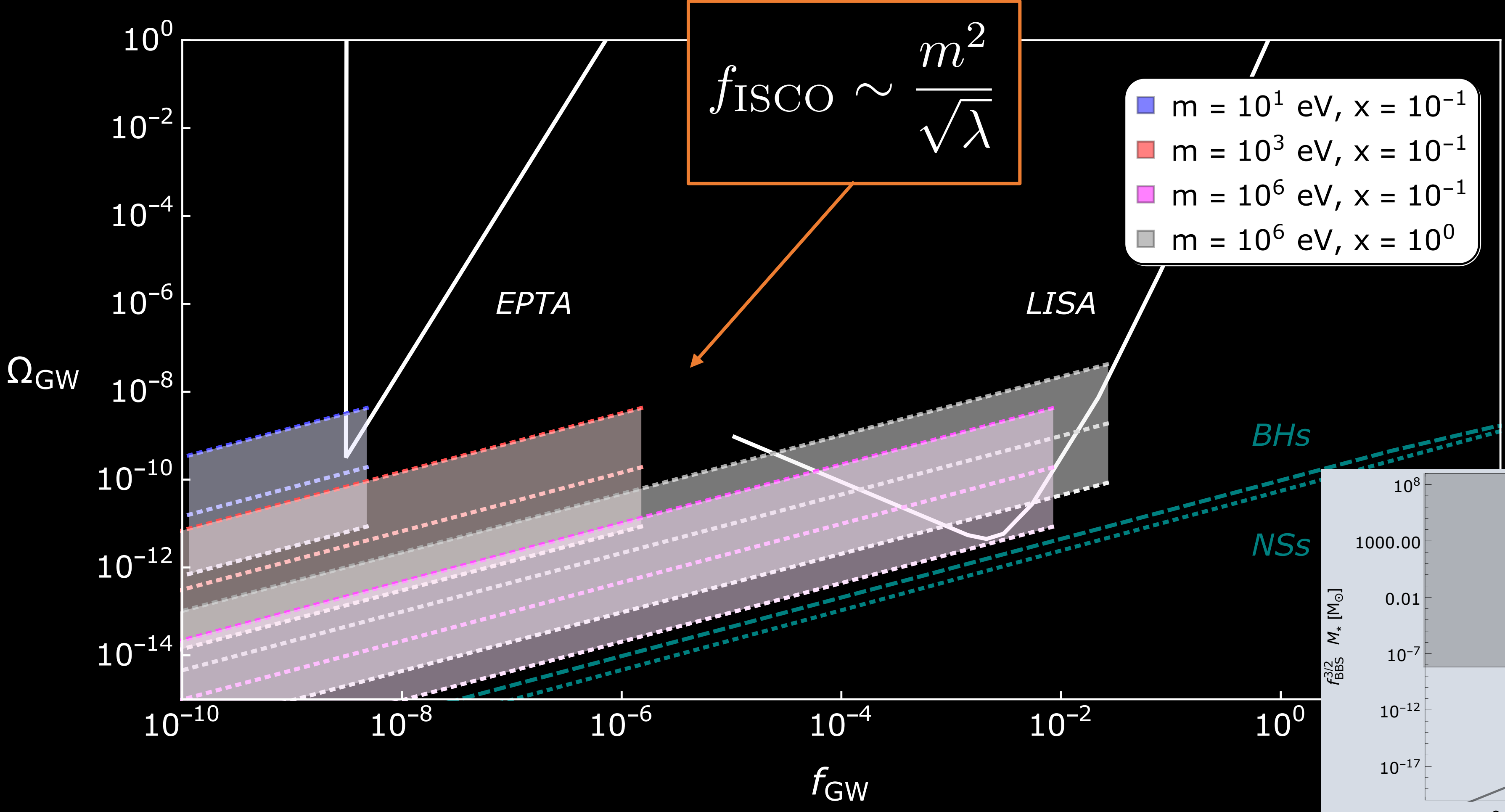
$$p(a) = \binom{N(a)}{2}^{-1} = \frac{2}{N(a)(N(a)-1)} \propto a^{-6}$$

$$N(a) = \rho\pi a^3/6$$

$$\Delta t \sim a^4$$

Inspiral phase

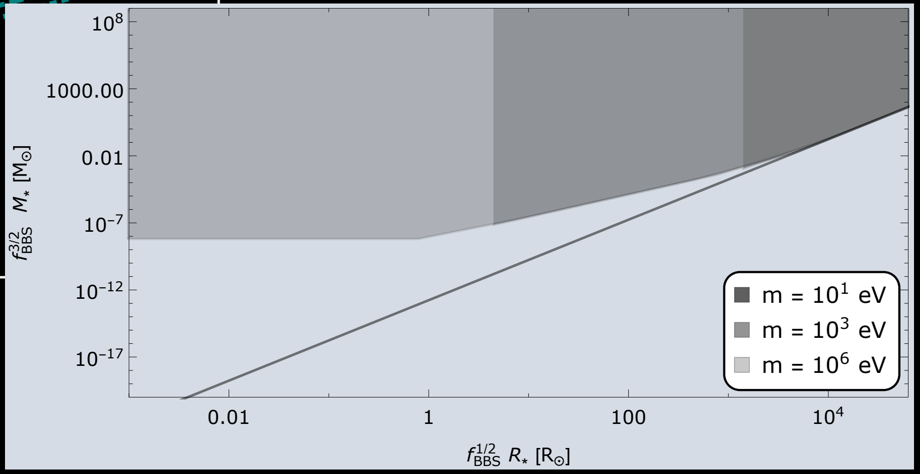
Example: boson stars with repulsive self-interaction



$$\Omega_{\rm GW} \sim \frac{\lambda^{1/3}}{m^{5/6}}$$

Bullet Cluster:

$$\lambda \lesssim 10^{-11} \left(\frac{m}{\rm eV}\right)^{3/2}$$



DC, Gleiser, Mohapatra, Sun [PLB, arXiv:1802.08259]

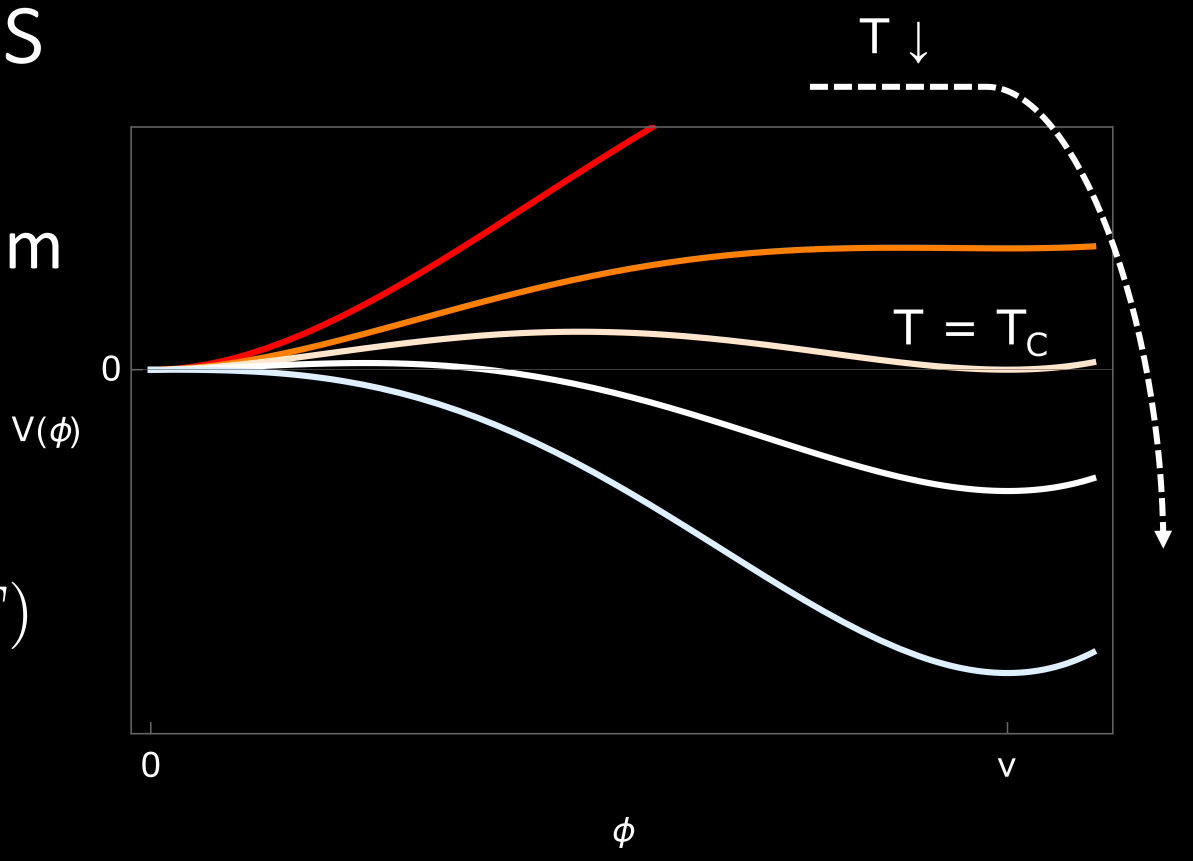
First order Phase Transitions

Electroweak PT in an extended Higgs sector

Hidden sector PT

Exotic signatures

Cosmic Phase Transitions



Inhomogeneous and out-of-equilibrium

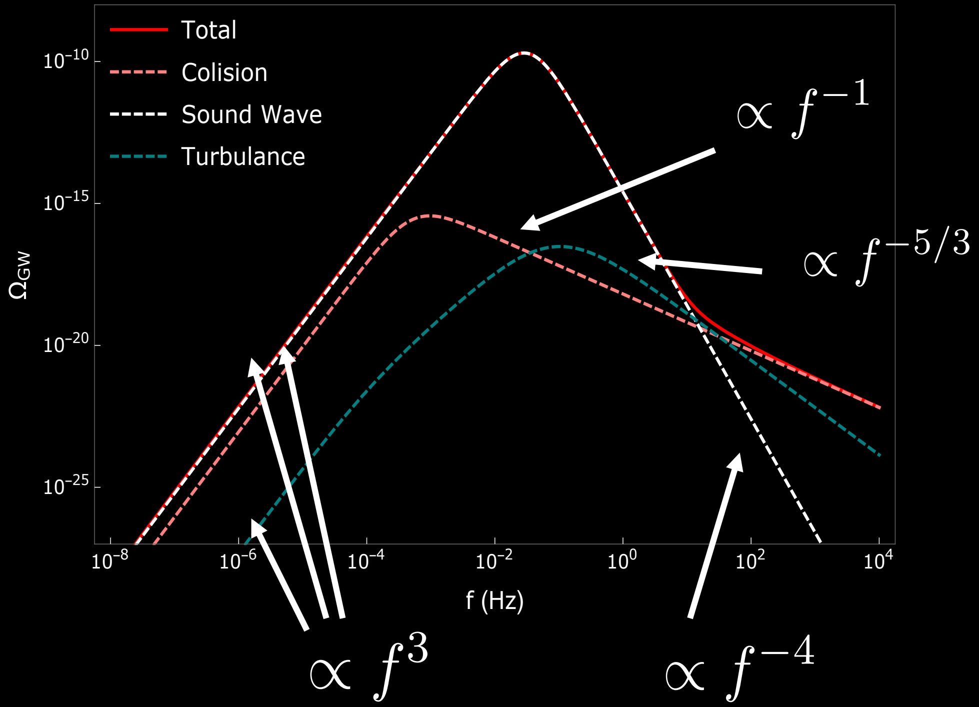
Thermal phase transitions:

$$V(\phi,T) = V_0(\phi) + V_{\rm CW}(\phi,\mu) + V_T(\phi,T)$$

Vacuum decay by tunneling:
Solve for *bounce solutions* and thermal parameters of the PT

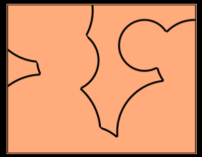
Coleman, De Luccia, PRD 1980

Gravitational Wave spectra from a Cosmic PT



Three contributions: $\Omega_{\mathrm{GW}} = \Omega_{\mathrm{env}} + \Omega_{\mathrm{sw}} + \Omega_{\mathrm{turb}}$

- Collisions of the bubble shells (the envelope approximation)
  Dominant for runaway bubbles



- Sound shells in the fluid kinetic energy
  Dominant for non-runaway bubbles

- Turbulence: modeled using Kolmogorov's theory
  Subdominant (usually)

See for example:
Weir, [1705.01783]
Hindmarsh, PRL, [1608.04735]
Hindmarsh, Huber, Rummukainen, Weir, PRL, [1304.2433]

GW spectra from thermal parameters

- Most PTs of interest are non-runaway

Bodeker, Moore, JCAP, [1703.08215]

$$\Omega_{\rm sw}\Big|_{\rm peak} = \Omega_{\rm sw}\left(\alpha, \frac{\beta}{H}, v_w\right)$$

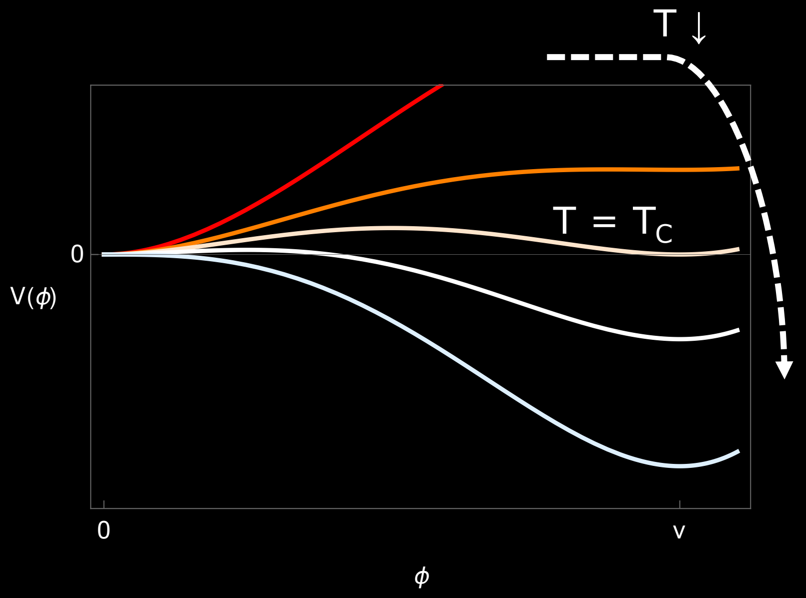
$$f_{\rm sw}\Big|_{\rm peak} = f_{\rm sw}\left(T_N, \frac{\beta}{H}, v_w\right)$$

α = latent heat
v_w = wall velocity
β/H = transition rate parameter
T_N = nucleation temperature

- The sound wave spectrum is defined by just two parameters:
  - $\mathbf{\Omega}(f)$ and f
  - Or: peak amplitude and frequency
- Given this degeneracy, how much model discrimination is possible?

Example: Effective models for a first order PT

- Minimal model for a PT: double well potential → three terms in the effective potential, with relative signs



- Limiting cases:
  1. $V(h_D, T) = \frac{1}{2}m(T)^2 h_D^2 - c_3(T)h_D^3 + \frac{1}{4}\lambda(T)h_D^4$
  2. $V(h_D, T) = \frac{1}{2}m(T)^2 h_D^2 - \frac{1}{4}\lambda(T)h_D^4 + c_6(T)h_D^6$

- Models: SSB in a dark gauge sector

SSB: SU(N) → SU(N-1) through h_D getting a VEV
N_f coupled fermions

Aside: EWPT

- Up to dimension-6 operators, models of the EWPT can be captured by the previous potential

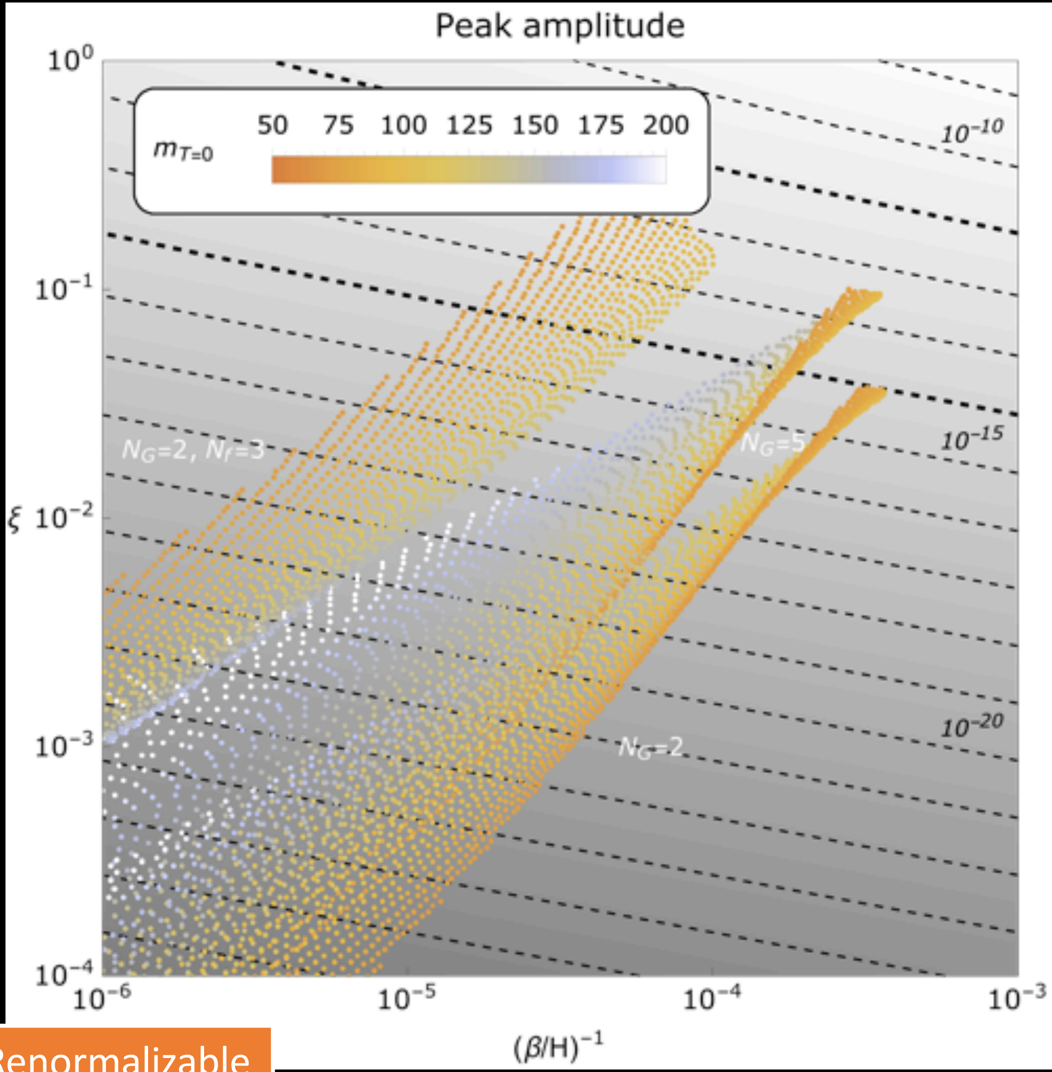
$$V_6(h,T) = \left(a_T T^2 - \frac{\mu^2}{2}\right) h^2 + \left(b_T T^2 - \frac{\lambda}{4}\right) h^4 + \frac{1}{8\Lambda_6^2} h^6$$

$$a_T = \frac{y_t^2}{8} + 3\frac{g^2}{32} + \frac{g\prime^2}{32} - \frac{\lambda}{4} + \frac{v_0^2}{\Lambda_6^2}\frac{3}{4}$$

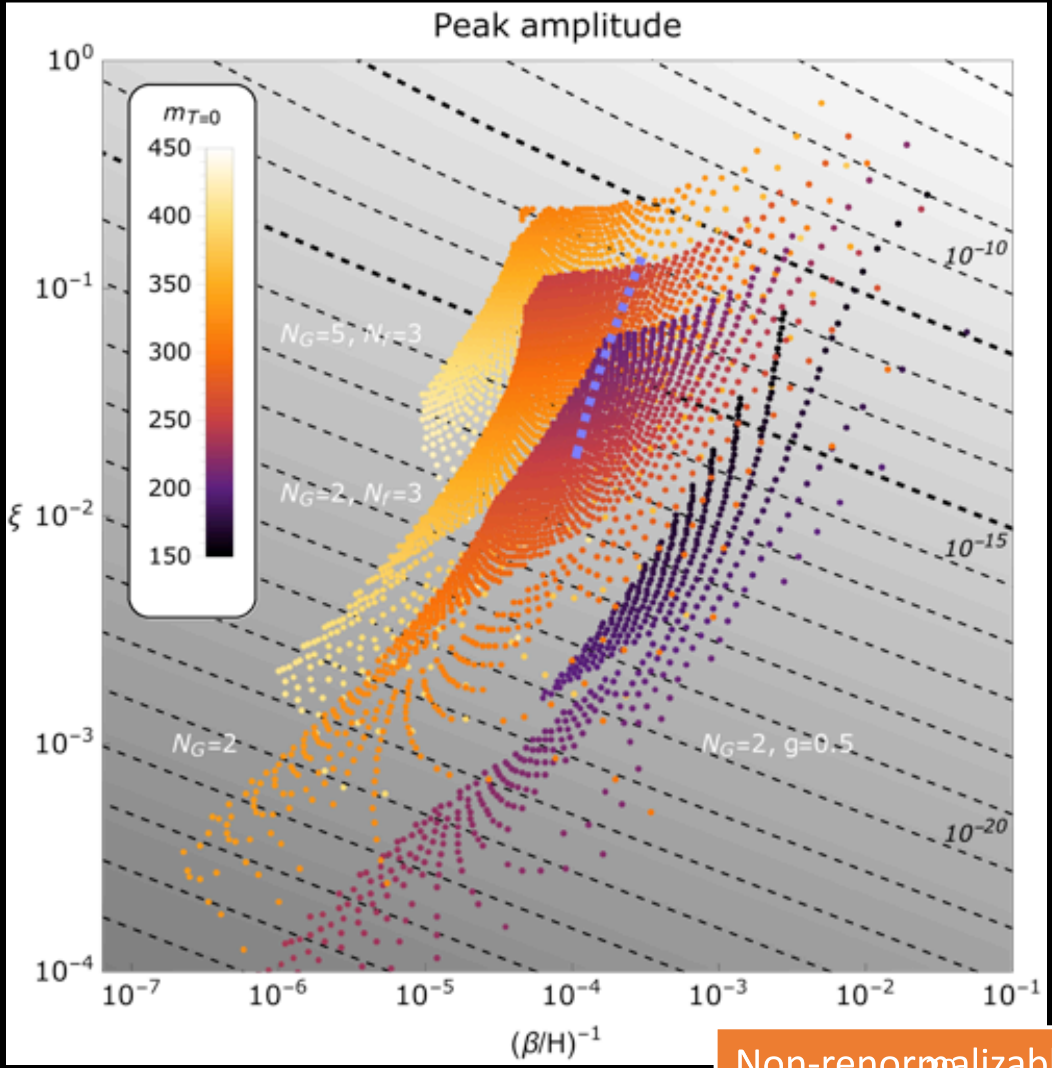
$$b_T = \frac{1}{4}\frac{1}{\Lambda_6^2}$$

Scale of new physics; a singlet, an extra doublet, …

Peak amplitude



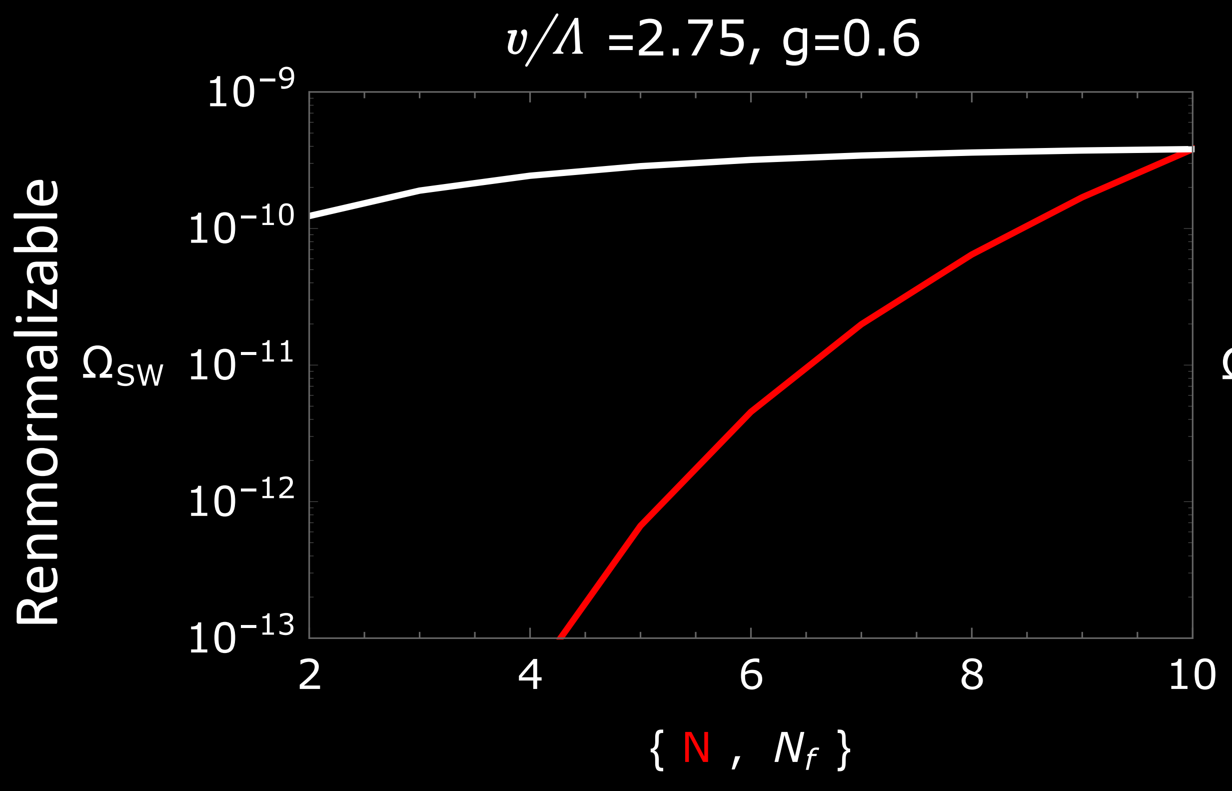
Renormalizable

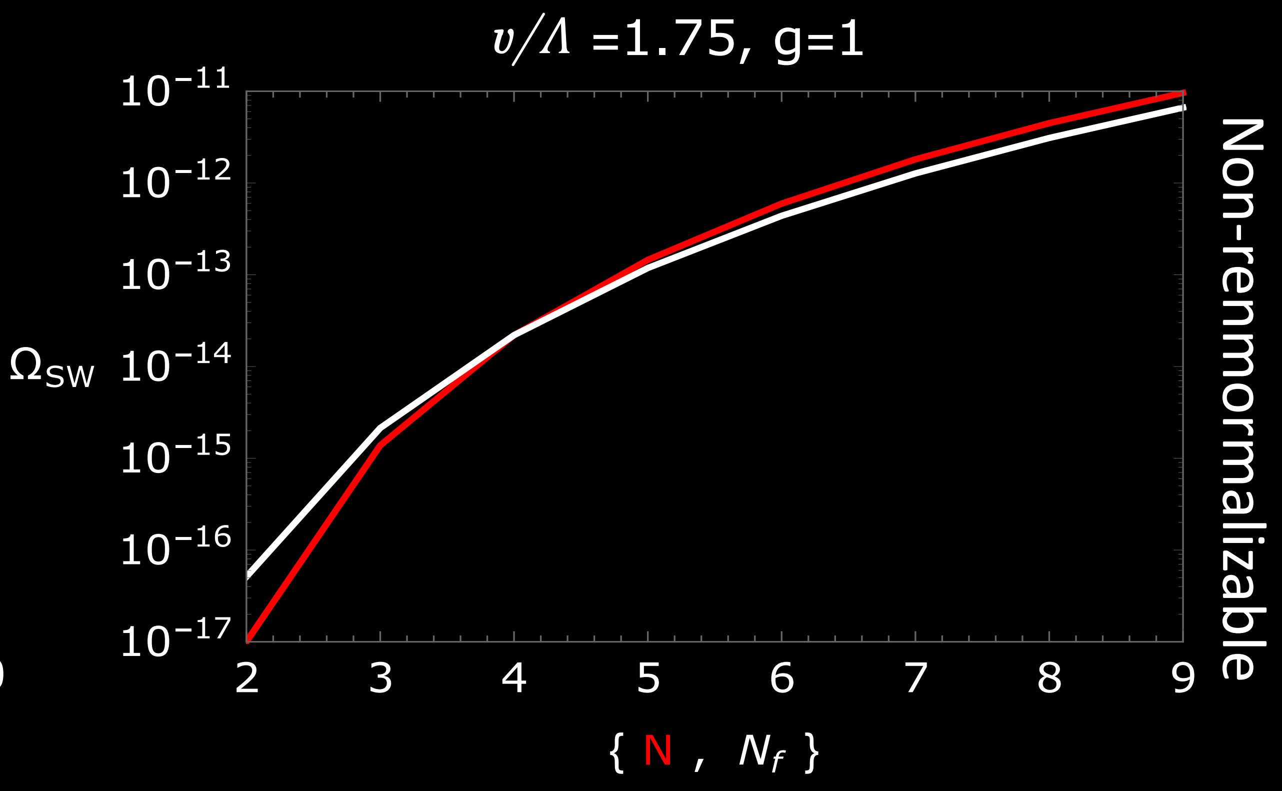


Non-renormalizable

Peak amplitude

$$V(h_D, T) = \frac{1}{2}m(T)^2 h_D^2 - c_3(T)h_D^3 + \frac{1}{4}\lambda(T)h_D^4$$
$$V(h_D, T) = \frac{1}{2}m(T)^2 h_D^2 - \frac{1}{4}\lambda(T)h_D^4 + c_6(T)h_D^6$$





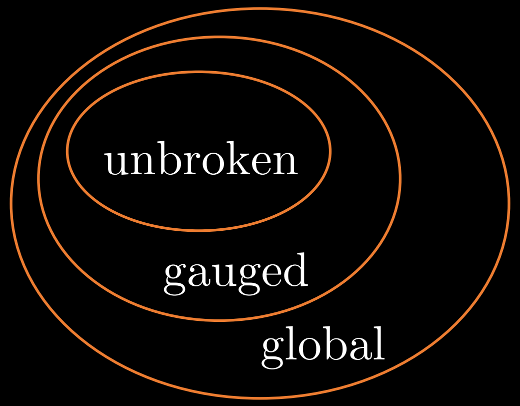
Some qualitative lessons

- Most thermal parameters are sensitive to the ratio v/Λ

- Extra fermions ($N_f\ y^2$), and a larger gauge group (N_G),
  - Enhance the amplitude of the signal
  - Sensitive to heavier scalars (effective zero temperature mass)

- The effective non-renormalizable potential yields better detection prospects
- Other sources of the GRB (with similar f): cosmic strings (~flat GW profile), binary mergers (~$f^{2/3}$)

Example: Composite Dark Matter models

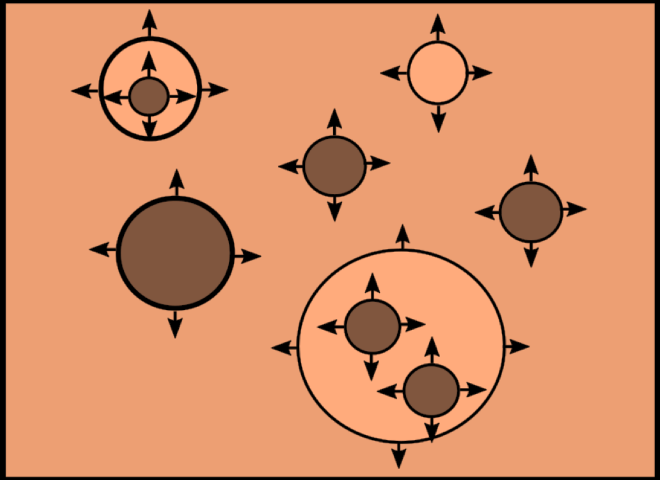


- Dark matter candidate as the lightest bound state of a confining gauge group (Goldstone boson)

- Light states are sensitive to an effective scalar potential at the 1-loop level, which in turn initiates a further breaking (pseudo-Goldstone boson)

- The couplings in such scenarios correspond to loop integrals in the UV theory

Example: exotic spectra



What if? A multi-step PT actually occurs simultaneously:

$T_f^A < T_N^B < T_N^A$

1	$(0,0) \to (v_A, 0)$	"First transition"
2	$(v_A,0) \to (v_A, v_B)$	"Bubble in a bubble"
3	$(0,0) \to (v_A, v_B)$	"Immediate transition"

Observations:

- First PT does not reach $f_1(T) = 1$
- Transitions 2) and 3) correspond to different thermal parameters

$$\Omega_{GW} = \sum_i w_i \, \Omega_{GW}^{(i)} \left(\Omega_0^{(i)}, f^{(i)}, \Upsilon_i, v_w^{(i)}, \frac{\beta^{(i)}}{H}, T_N^{(i)} \right)$$

To conclude,

- Gravitational waves are new independent probes of particle physics!

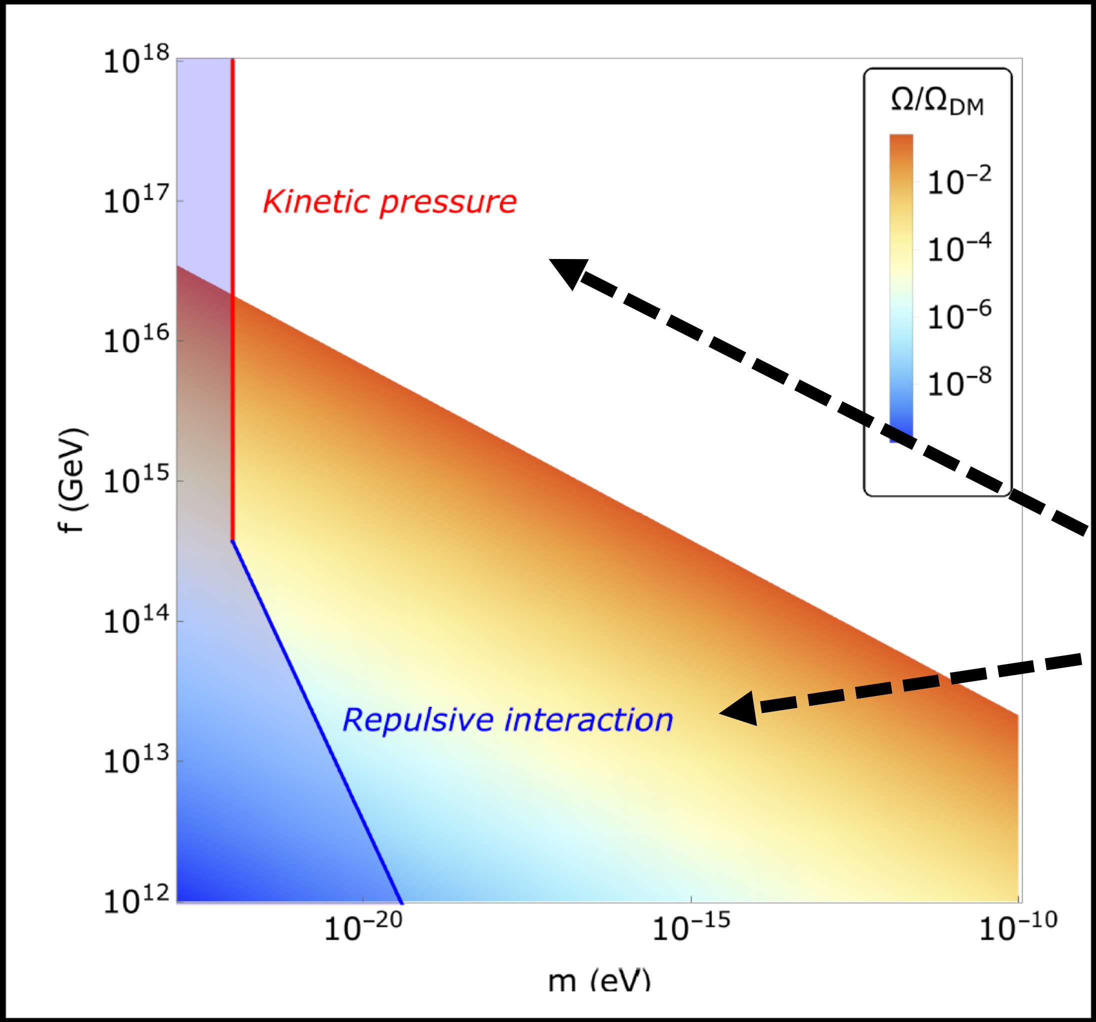
- New physics in binary merger signals
  - Modified waveforms
  - Mergers of ECOs
- New physics in first order phase transition signals
  - Dark phase transitions can mimic an EWPT signal
  - More exotic signals may break the degeneracy

Thank you!

Back up slides:

- The misalignment mechanism
- The difference between Q-balls and Boson Stars
- Power-law integrated sensitivity
- Constraints on ultra-light vector bosons

Misalignment production of NR bosons



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

Matter power spectrum modified

Q-balls and boson stars (nomenclature)

- Q-balls: non-topological solitons, *no gravity*
  - Very specific potentials with ϕ^6 interaction
  - Conserved charge Q, global ($Q = N_{particles}$) or gauged ($Q = g \times current$)

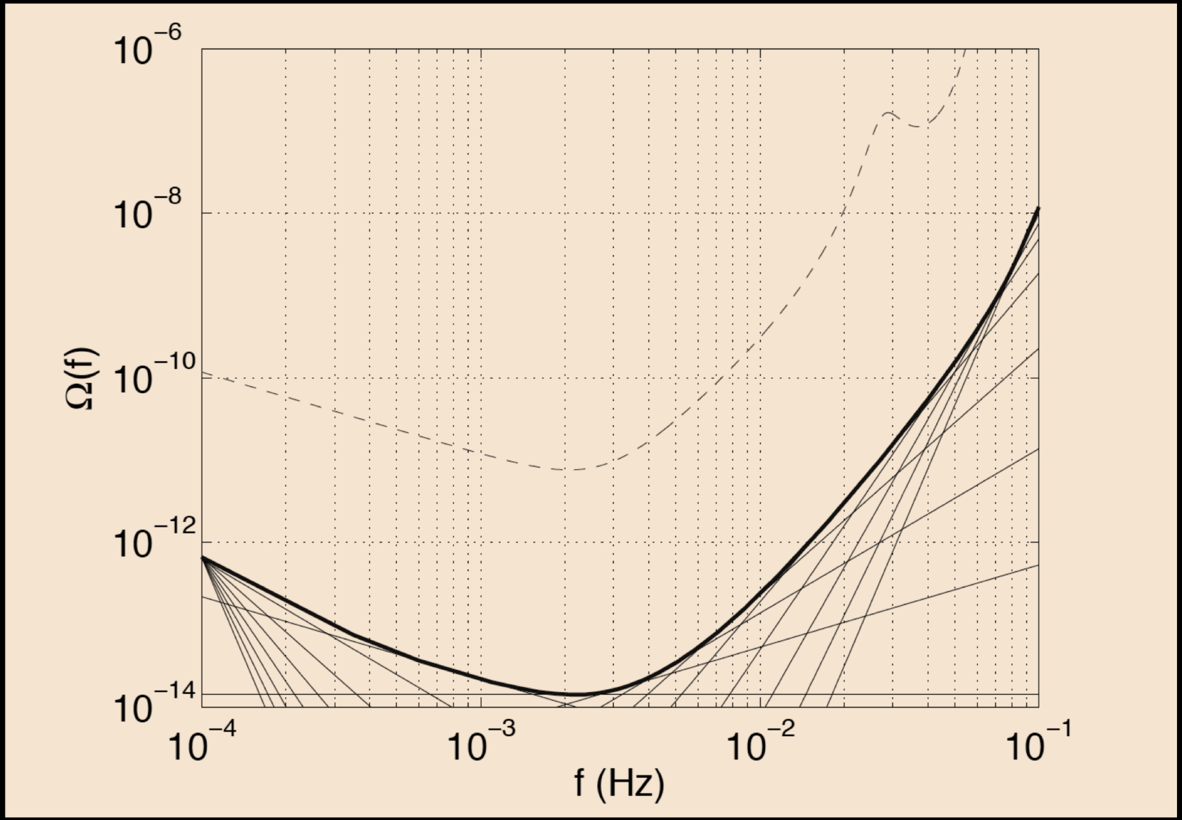
- Boson stars: *gravity*
  - Global symmetry with $Q = N$
  - Solutions exist with many families of potentials

Power-law integrated sensitivity

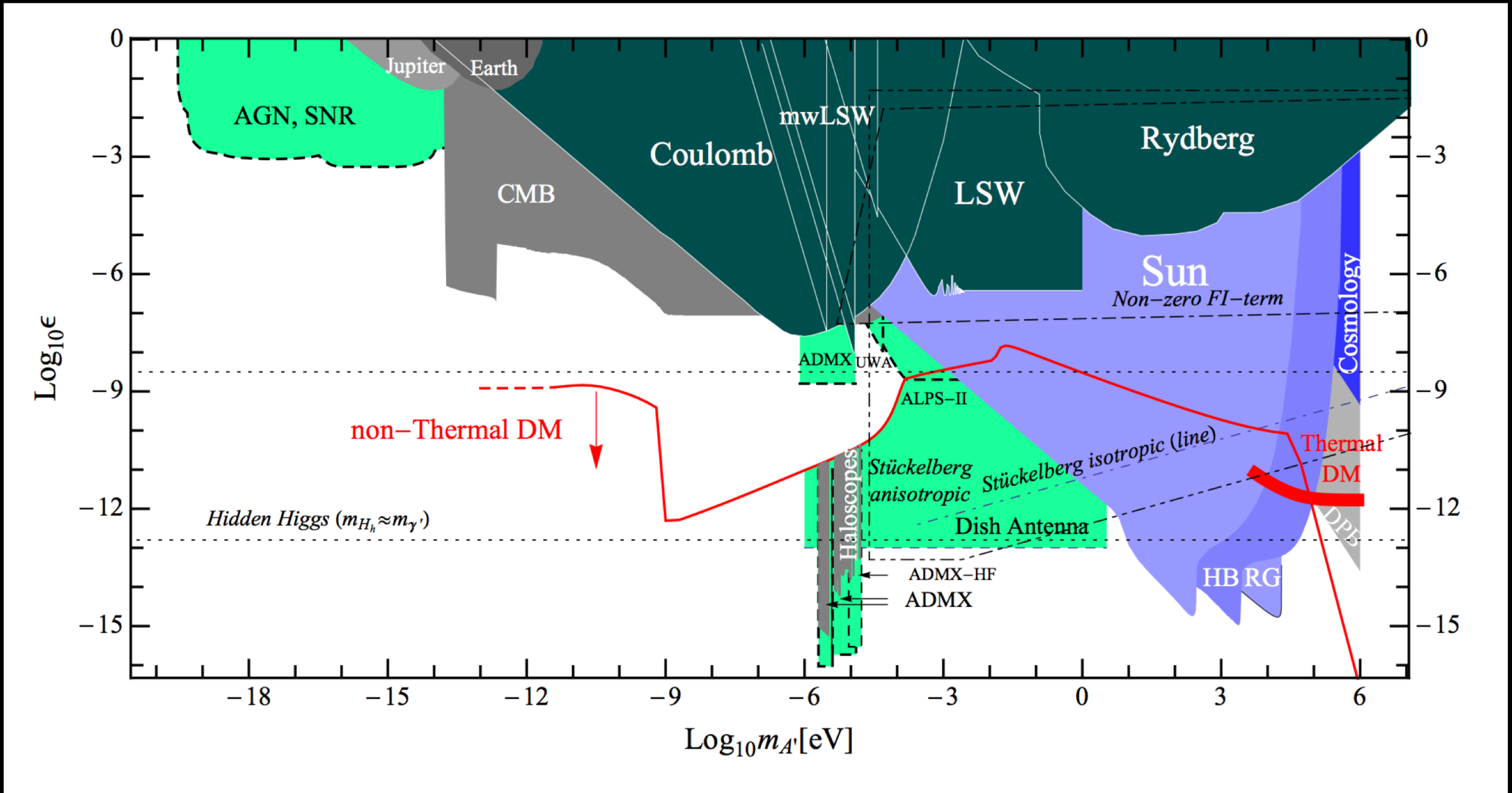
- For power-law spectra,

$$\Omega_{GW}(f) = \Omega_\beta \left(\frac{f}{f_{\mathrm{ref}}}\right)^\beta$$

- Define the bandwidth of the detector (f_{min} , f_{max})
- For a set of indices $\boldsymbol{\beta}$, calculate $\boldsymbol{\Omega_\beta}$ (integration over f) such that the signal-to-noise has some fixed value



Constraints on ultralight dark vector bosons



Snowmass community report, 2013