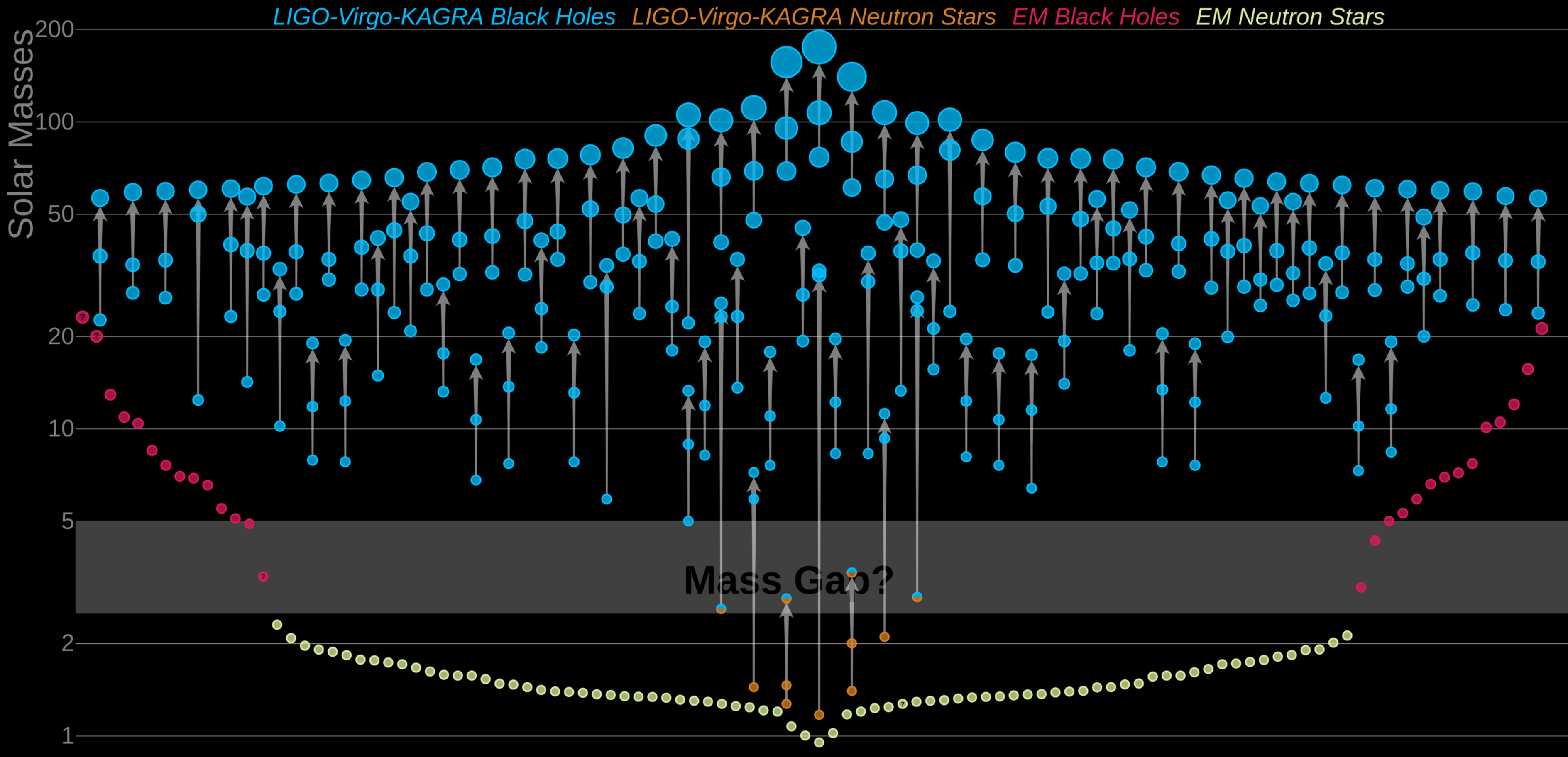
New Physics with Gravitational Waves

James Dent
Sam Houston State University

PPC – Wash. U

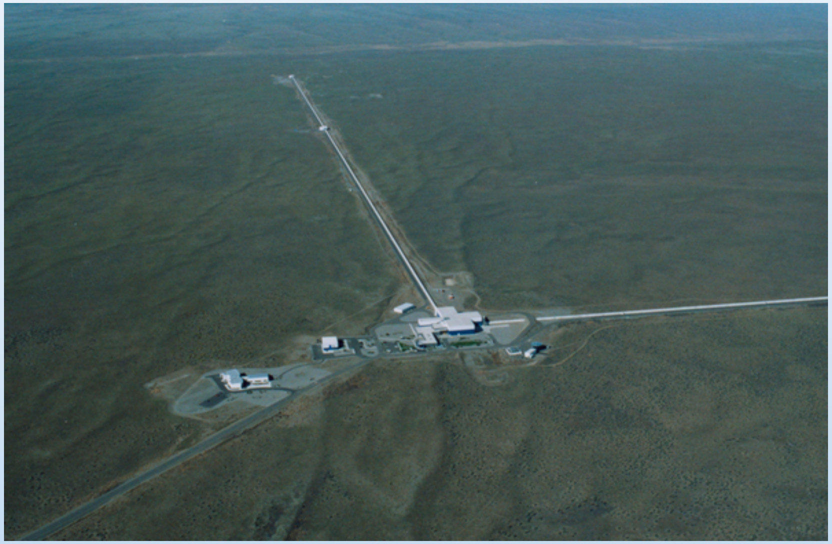
June 10, 2022

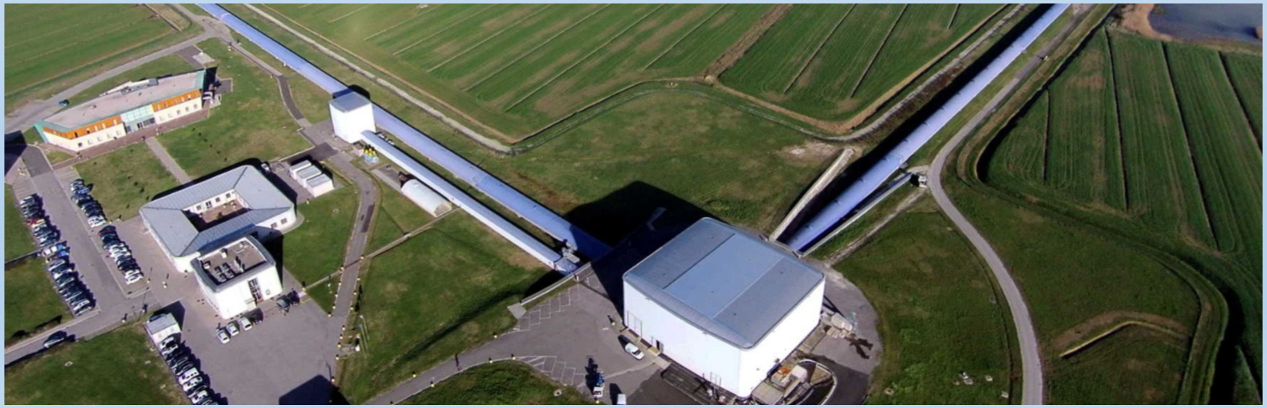
Masses in the Stellar Graveyard



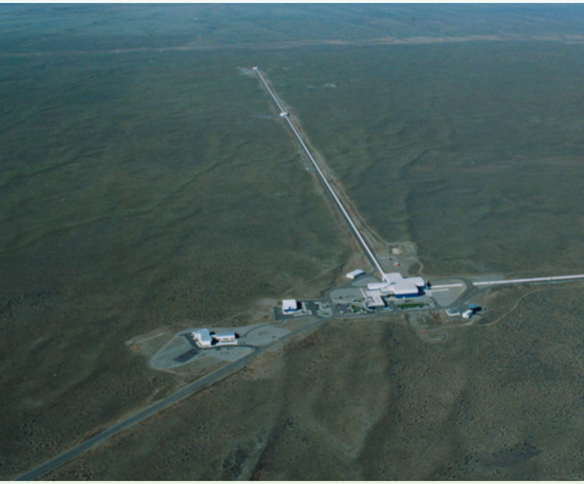
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

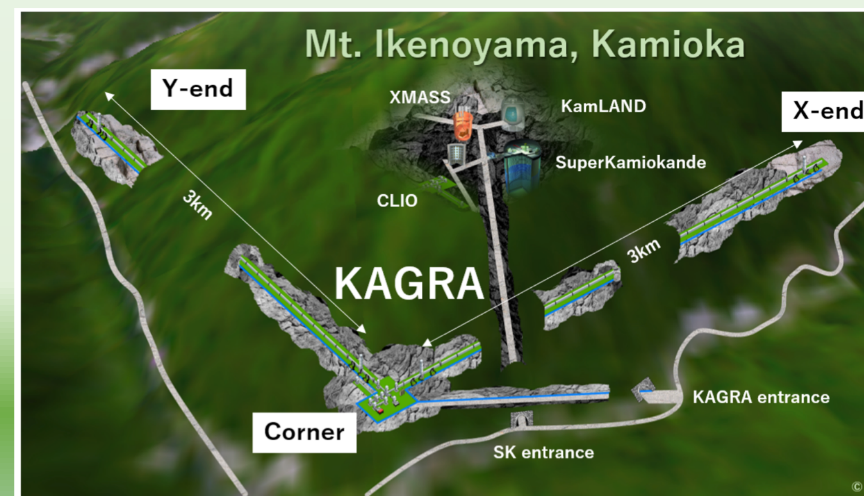
Observational Landscape



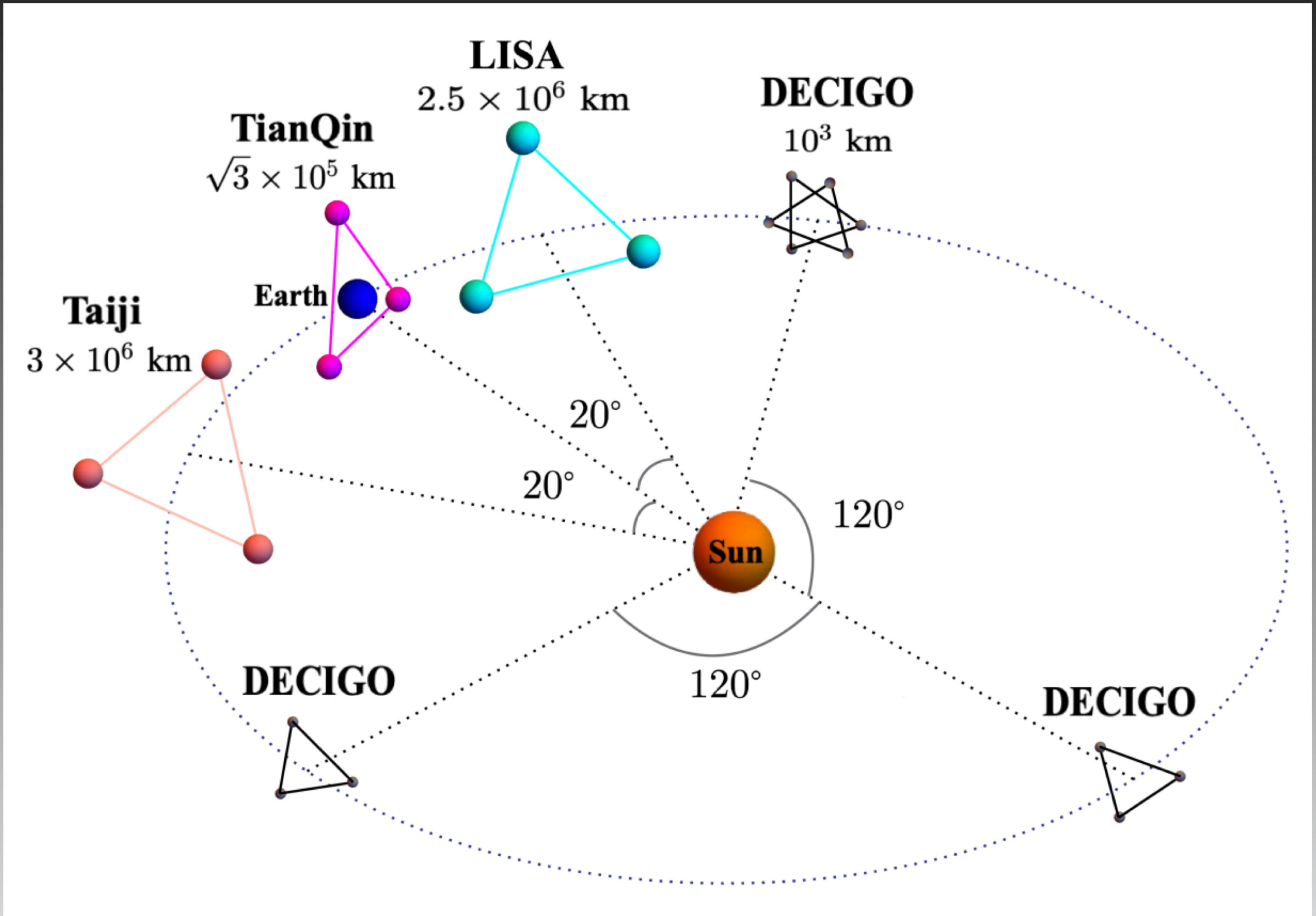


Observational Landscape





Observational Landscape -future

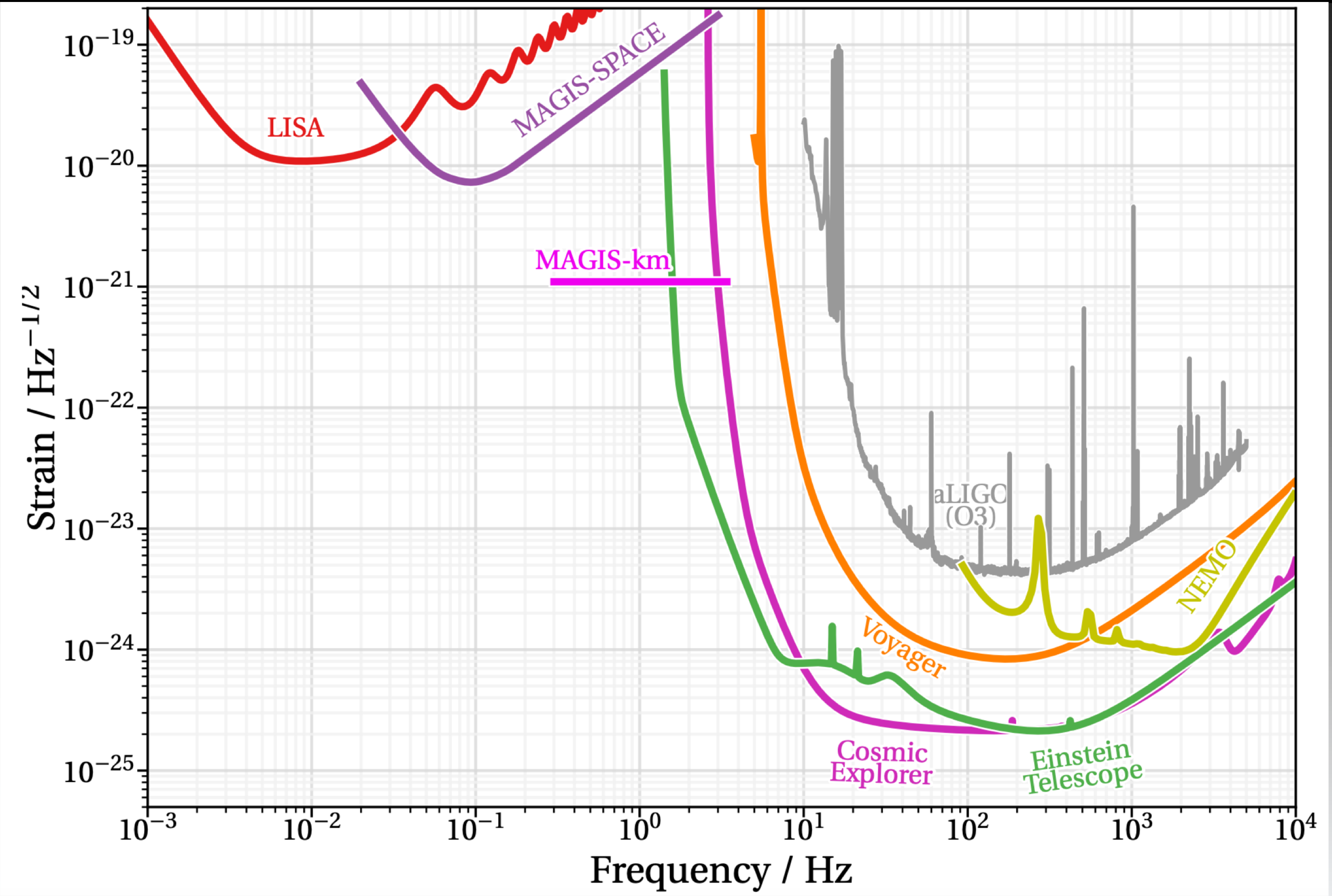


Concepts and status of Chinese space gravitational wave detection projects

Yungui Gong (Hua-Zhong U. Sci. Tech.), Jun Luo (Zhongshan U., Zhuhai and Hua-Zhong U. Sci. Tech.), Bin Wang (Shanghai Jiao Tong U. and Yangzhou U.) (Sep 15, 2021)

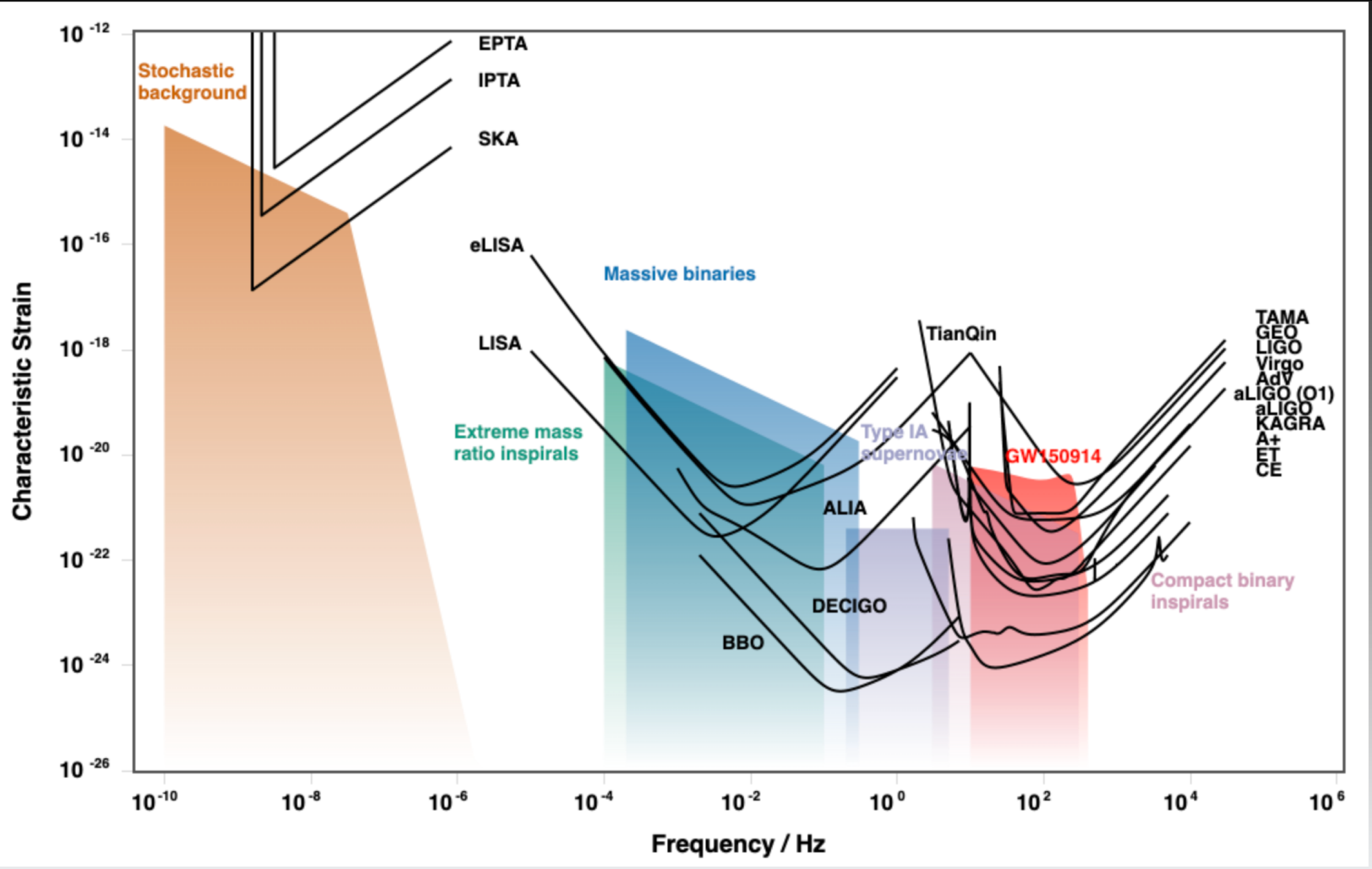
Published in: *Nature Astron.* 5 (2021) 9, 881-889 • e-Print: 2109.07442 [astro-ph.IM]

Observational Landscape -future



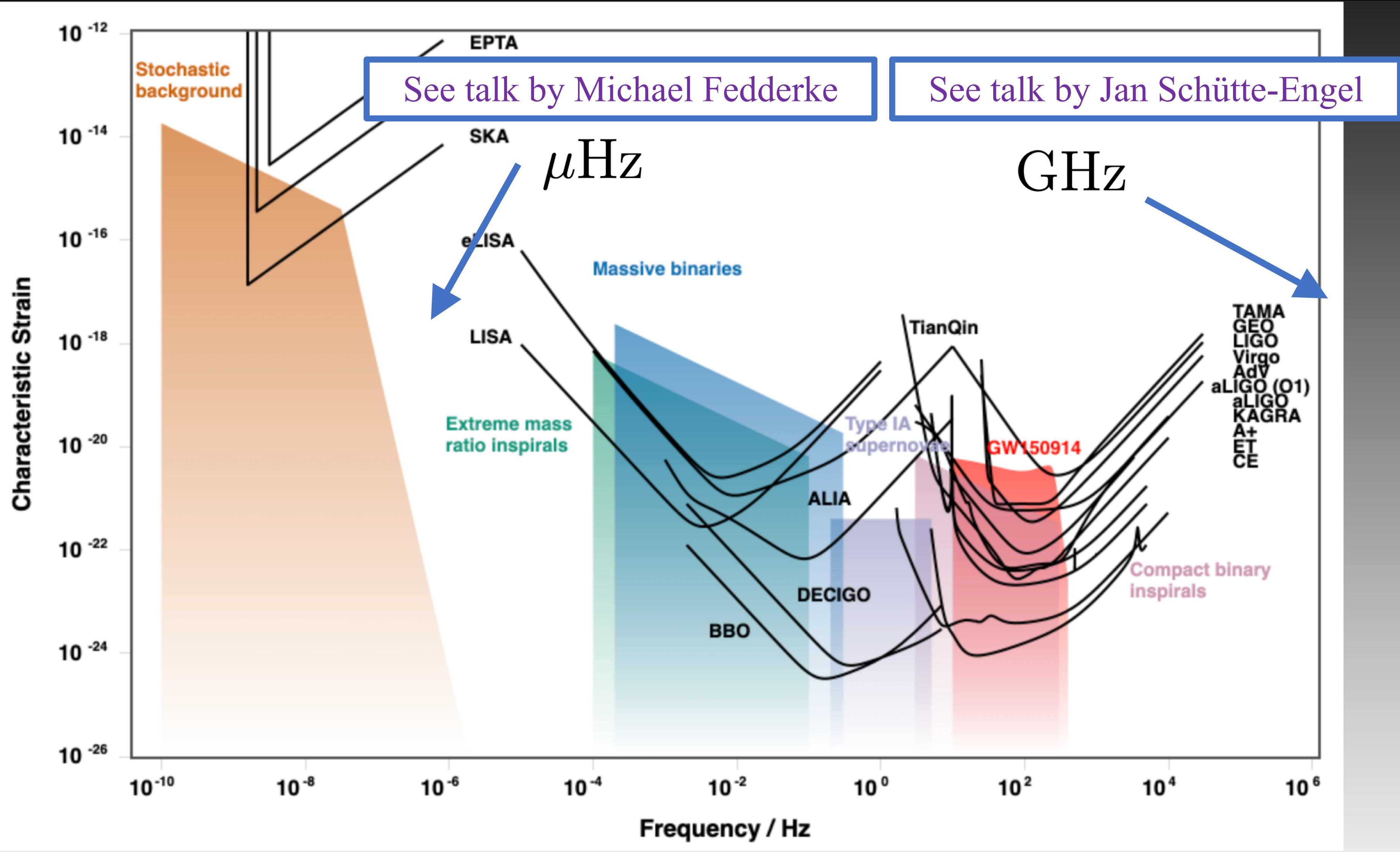
S.W.Ballmer, R.Adhikari, L.Badurina, D.A.Brown, S.Chattopadhyay, *2022 Snowmass Summer Study*, arXiv:2203.08228

Observational Landscape



C.J.Moore, R.H. Cole, and C.P.L.Berry, Class.Quant.Grav. (2015), 1408.0740, http://gwplotter.com/

Observational Landscape



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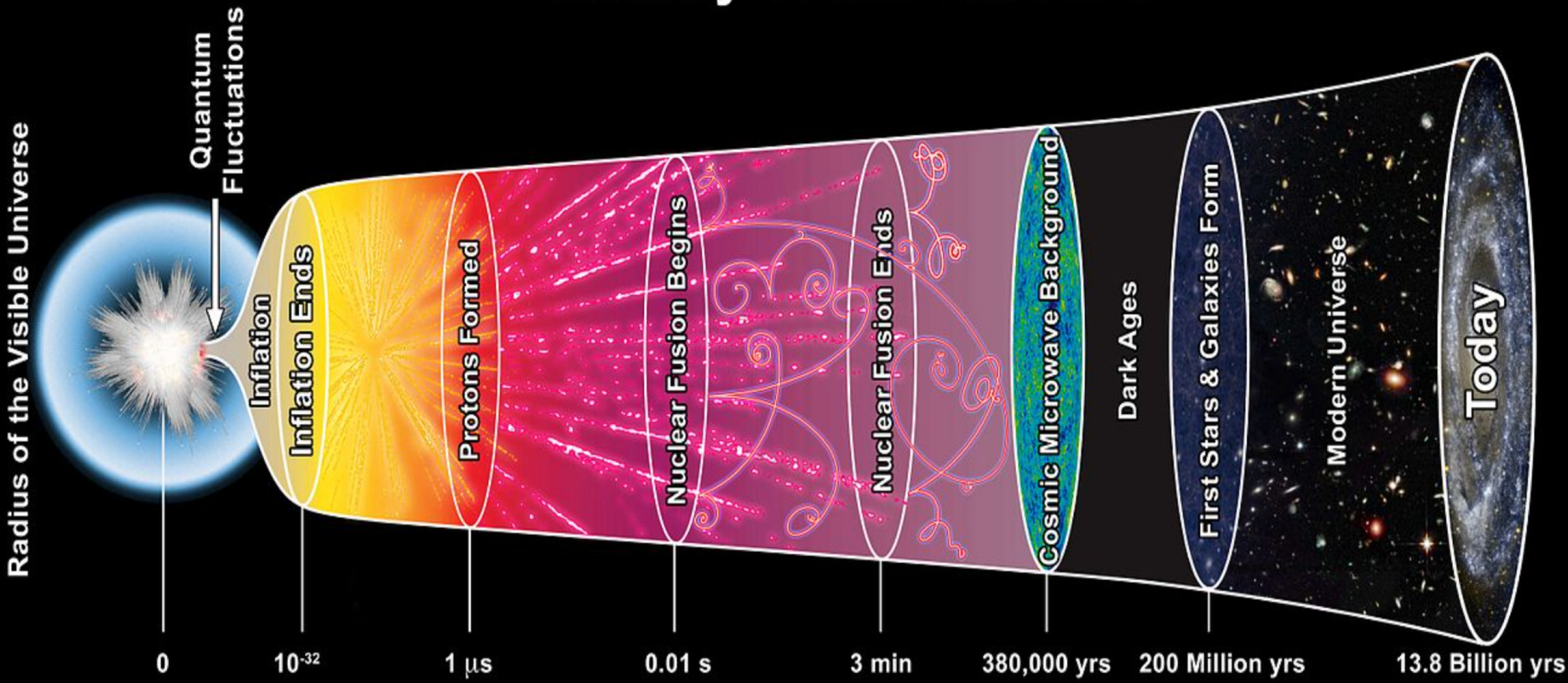
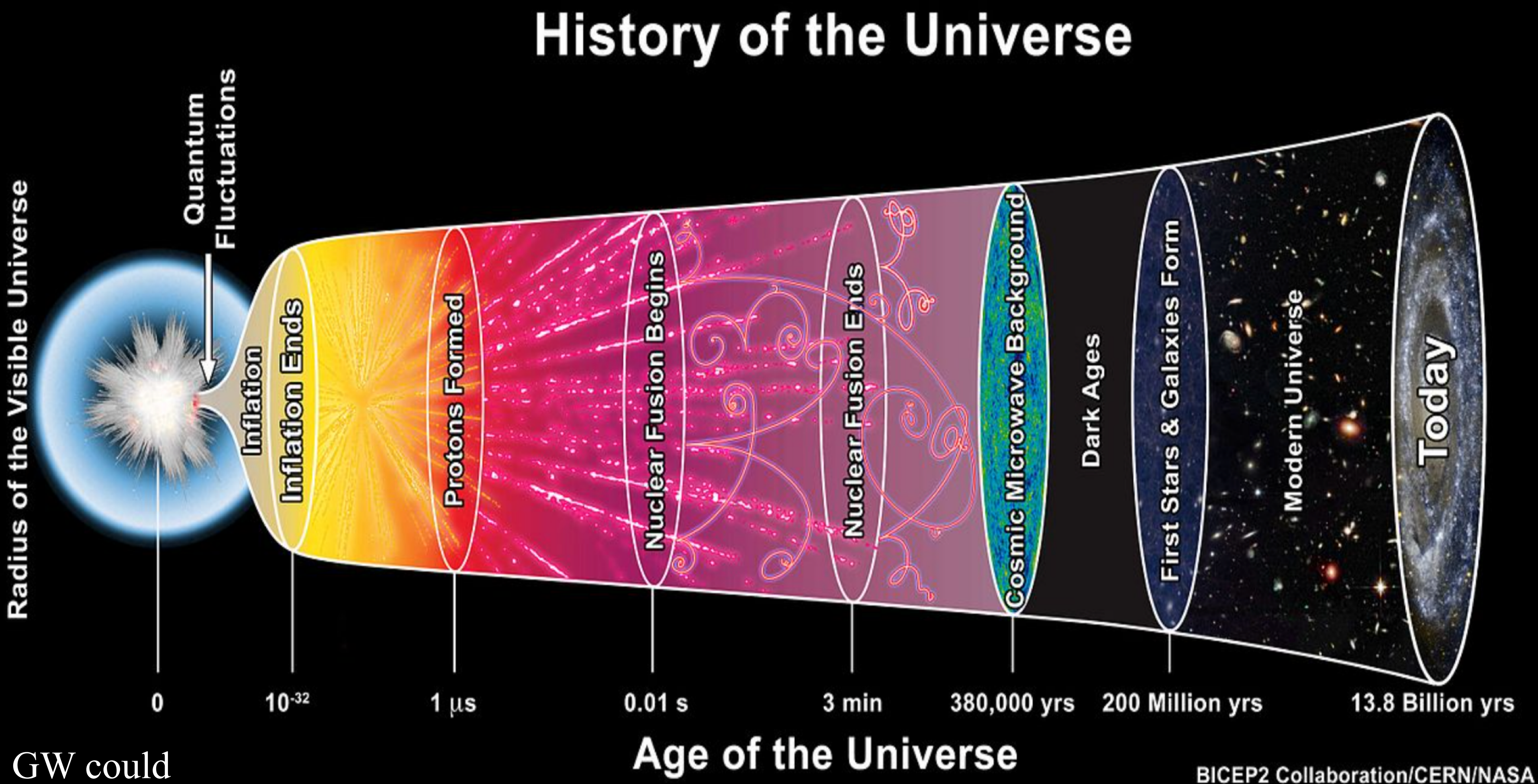
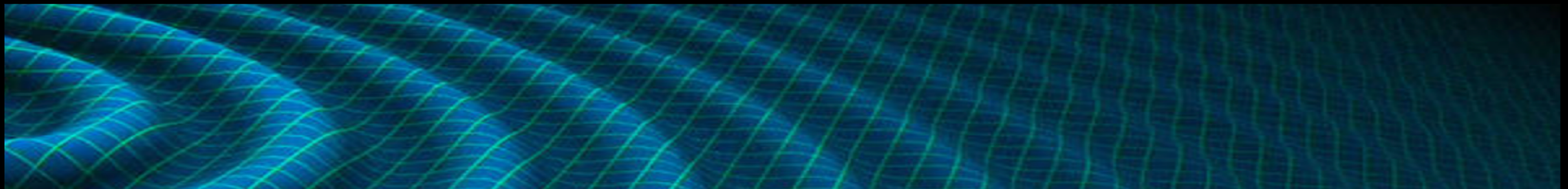
History of the Universe



BICEP2 Collaboration/CERN/NASA



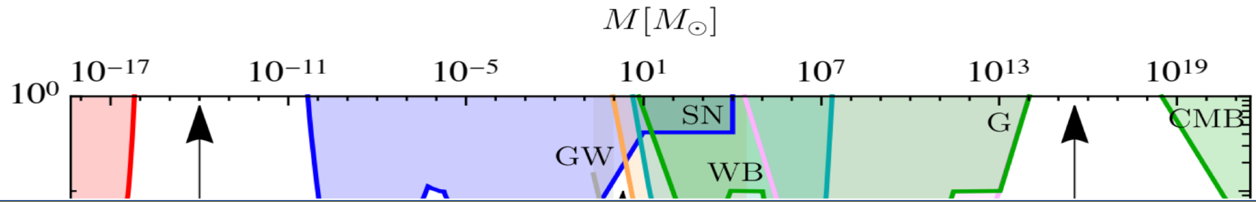
GW could probe early universe/high energies



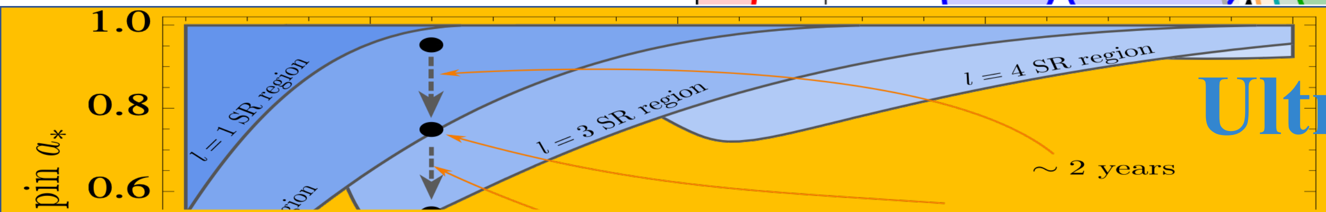
Outline of BSM physics and GW

Particle Dark Matter

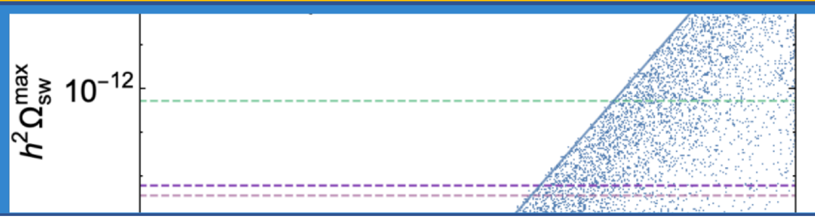
PBH

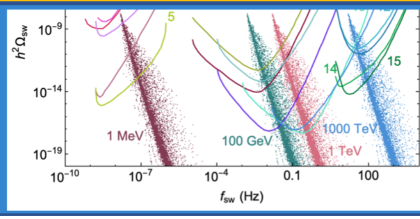


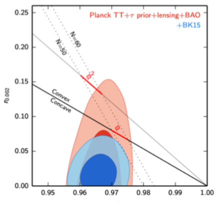
Ultralight bosons



FOPT





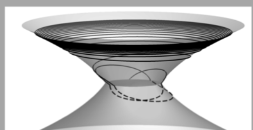


Inflation

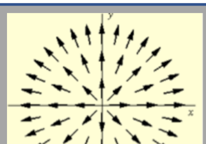
New physics with neutron star mergers

Talk by Steven Harris

ECOs



Defects



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Outline of BSM physics and GW

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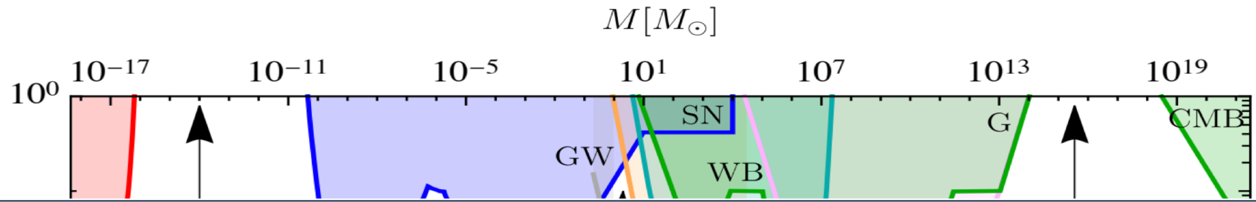
PBH



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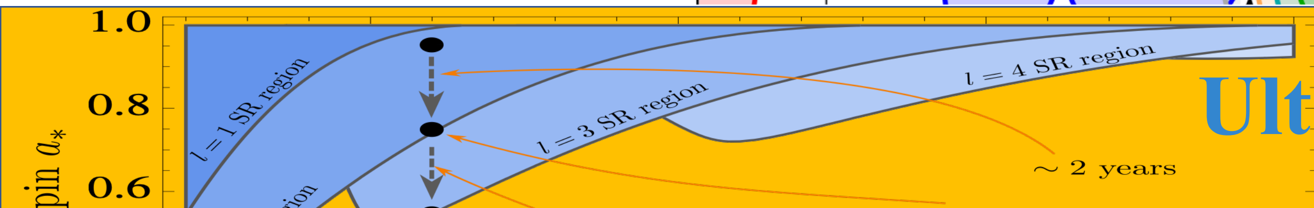

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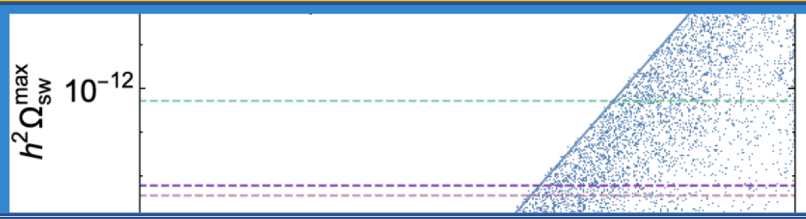

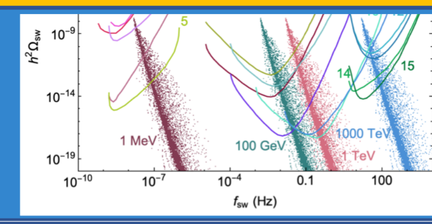

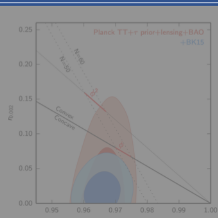

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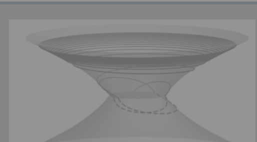

Defects

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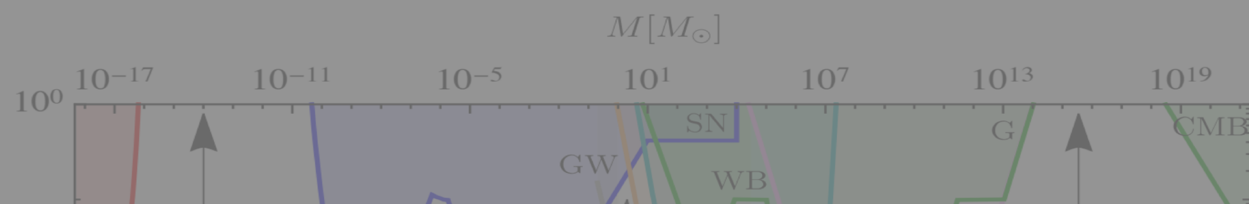

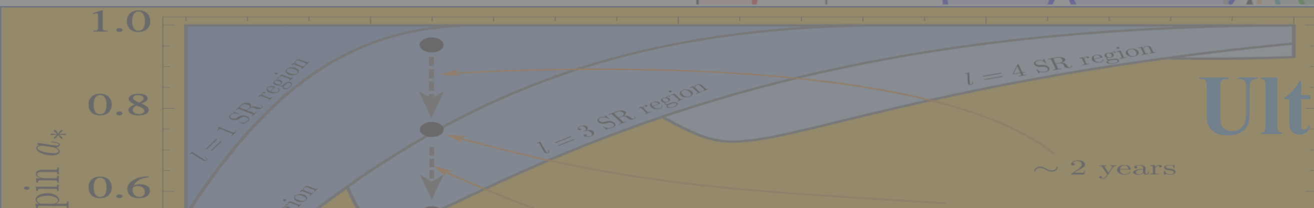

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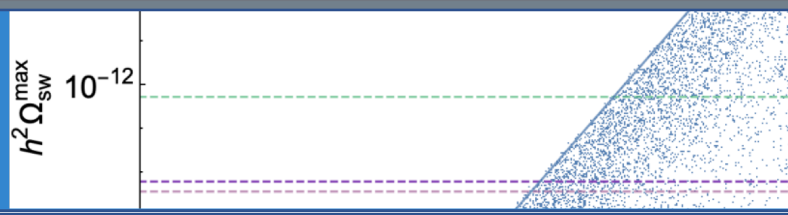

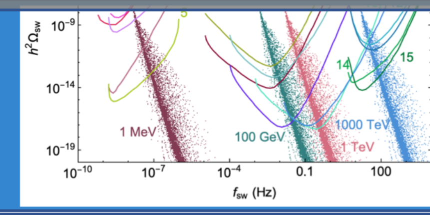

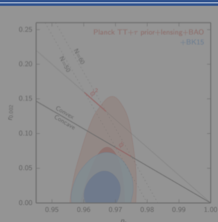

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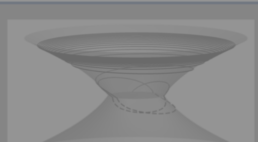

Defects

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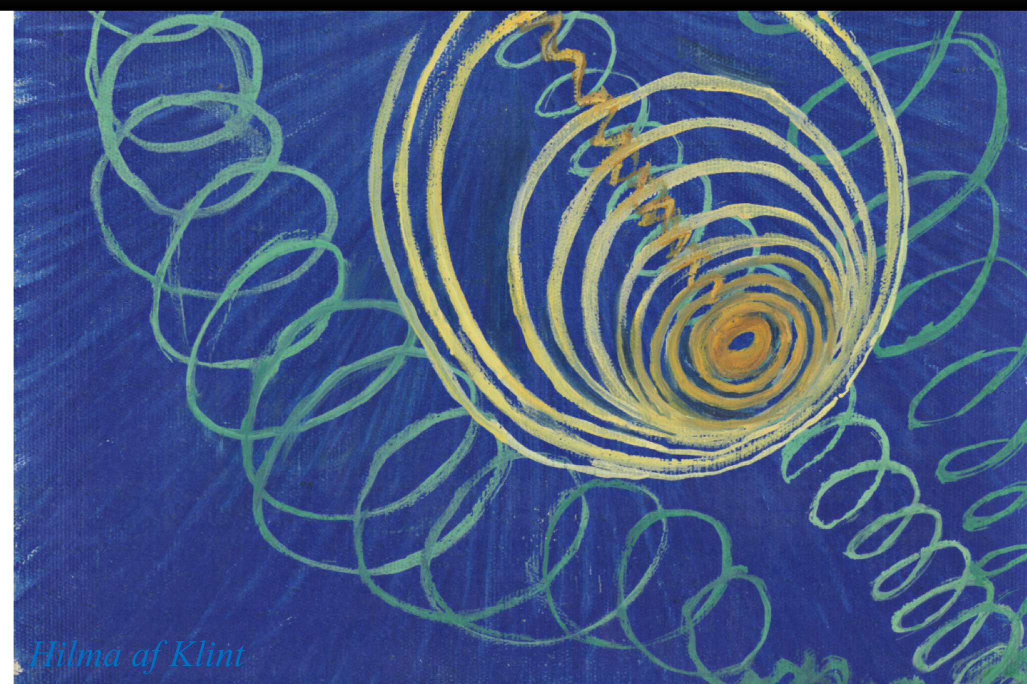
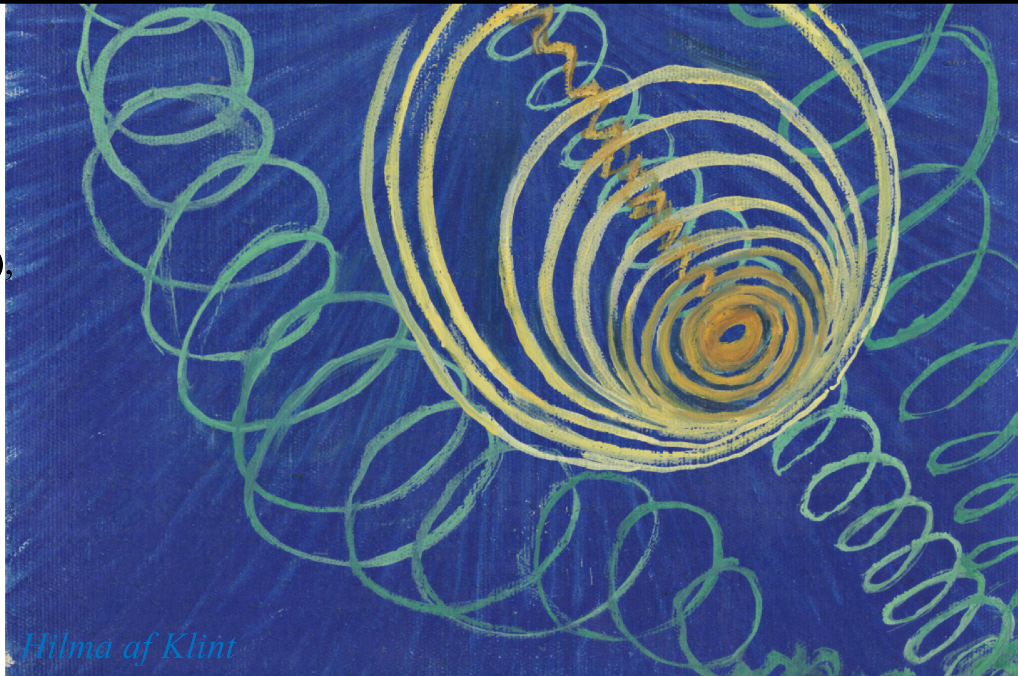
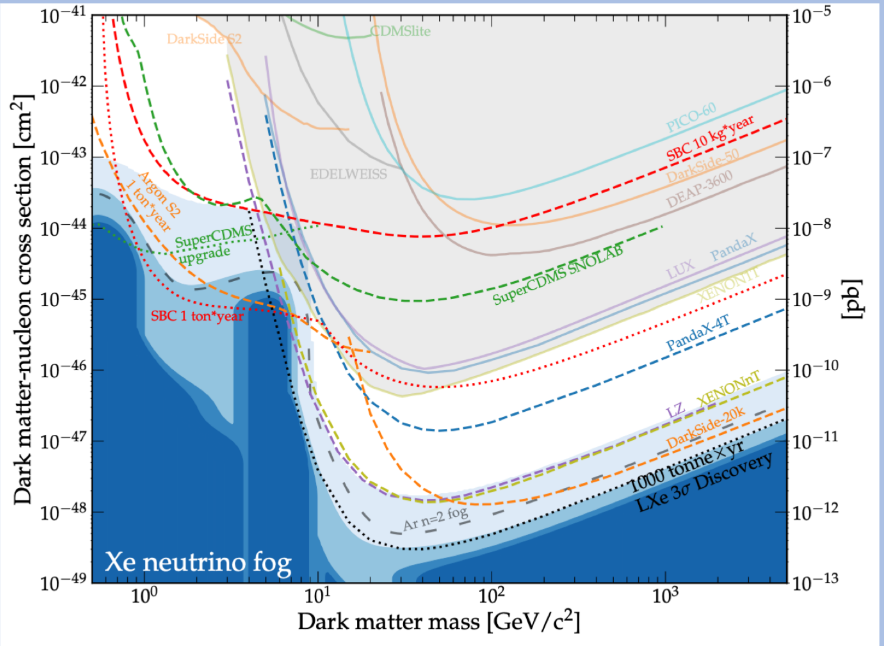
Primordial Black Holes



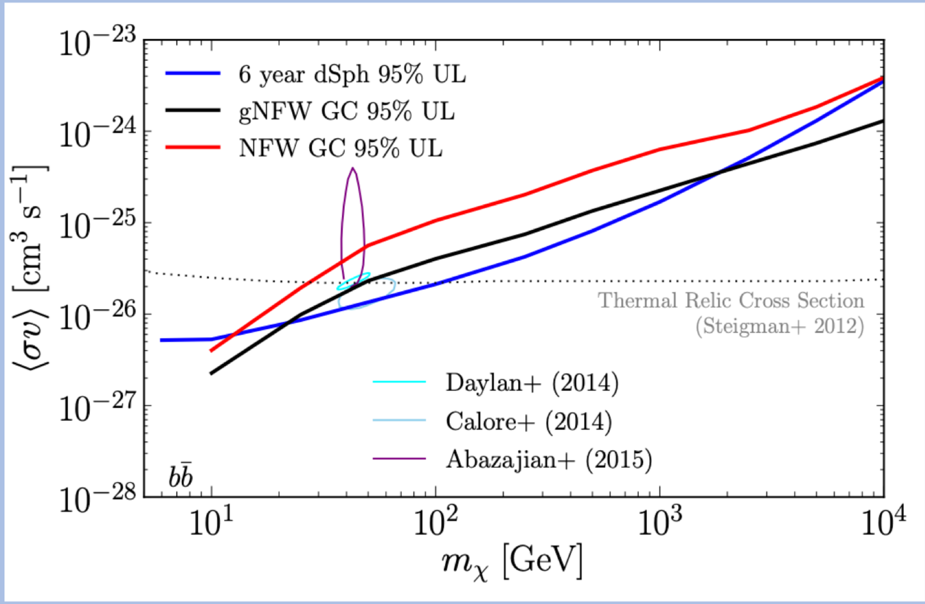
Primordial Black Holes

Y.B.Zel'dovich and I.D.Novikov, Soviet Astronomy **10** (1967)
S.Hawking, Mon.Not.Roy.Astron.Soc. **152** (1971)
B.J.Carr and S.W.Hawking, Mon.Not.Roy.Soc. **168** (1974),
B.J.Carr, Astrophys.J. **201** (1975)



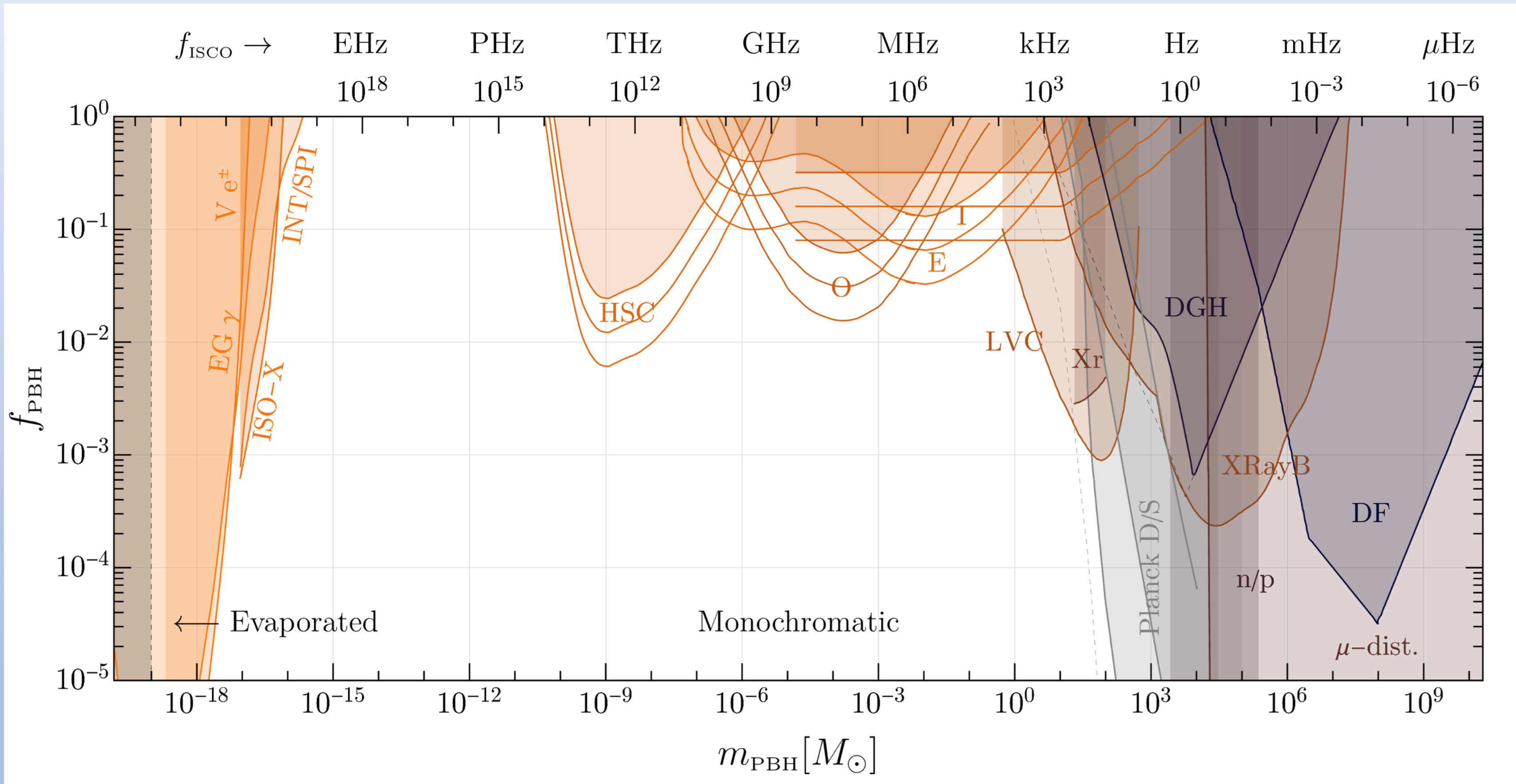


D.S. Akerib *et al.*, 2203.08084



Fermi-LAT, M.Ackermann, 1704.03910

PBH –DM mass fraction



G.Franciolini, A.Maharana, and F.Muia, 2205.02153, based on
B.Carr, K.Kohri, Y.Sendouda, and J.Yokoyama, Rept.Prog.Phys. (2021), 2002.12778.

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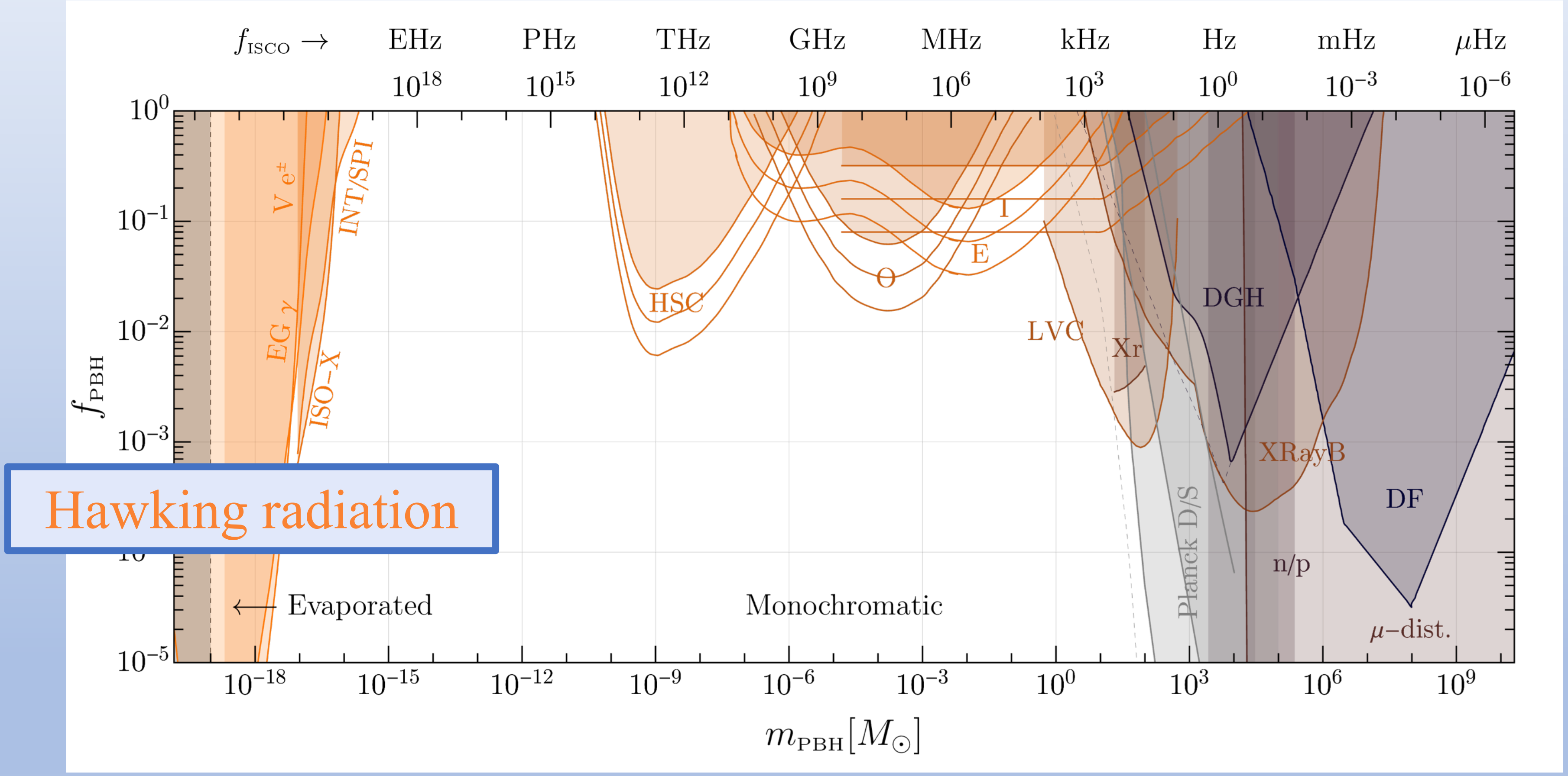

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Formation mechanisms and mass distributions

Monochromatic $$\psi_{\rm mon}(M) \equiv f_{\rm PBH}(M_c)\delta(M - M_c)$$

lognormal $$\psi(M) = \frac{f_{\rm PBH}}{\sqrt{2\pi}\,\sigma M} \exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$$

Power law $$\psi(M) \propto M^{\gamma-1}$$

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B.J.Carr, K.Kohri, Y.Sendouda, and J.Yokoyama, 0912.5297, B.J.Carr, M.Raidal, T.Tenkanen, V.Vaskonen, and H.Veermae, 1705.05567.

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See talk by Volodymyr Takhistov

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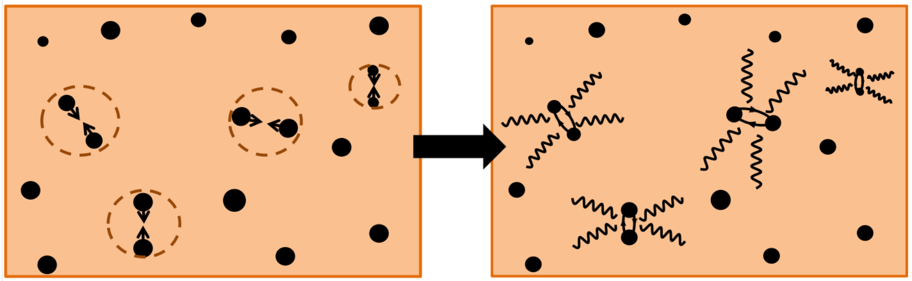
PBH – binary formation

Decouple from Hubble flow at some xcrit

Early: Three body – 2binary, 1 to torque produce binary orbits

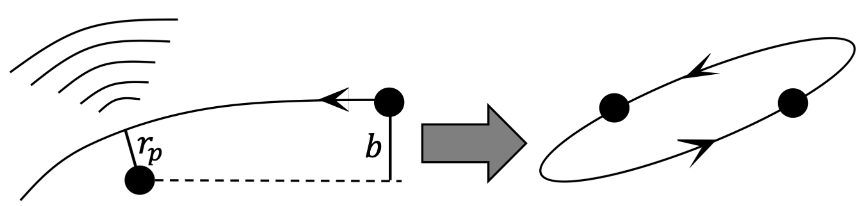


For Gaussian perturbations they are uniformly spatially distributed with Poisson number density fluctuations

$$\mathbf{F}/\mu = \underbrace{\mathbf{r}\ddot{a}/a}_{\text{Hubble flow}} - \underbrace{M\hat{\mathbf{r}}/r^2}_{\text{self-gravity}} + \underbrace{(\hat{\mathbf{r}}\cdot\mathbf{T}\cdot\mathbf{r})\hat{\mathbf{r}}}_{\text{radial tidal forces}} + \underbrace{(\mathbf{r}\times(\mathbf{T}\cdot\mathbf{r}))}_{\text{tidal torque}}\times(\hat{\mathbf{r}}/r)$$

Late: close encounters, relatively suppressed

M.Sasaki, T.Suyama, T.Tanaka, and S.Yokoyama, 1801.05235



T.Nakamura, M.Sasaki, T.Tanaka, and K.S.Thorne, astro-ph/9708060, S.Bird, I.Cholis, J.B. Muñoz, Y. Ali-Haïmoud, E.D.Kovetz, A.Raccanelli, A.G.Riess, and M.Kamionkowski, 1603.00464, M.Raidal, V.Vaskonen, and H.Veermäe, 1707.01480, Z.-C.Chen and Q.-G.Huang, 1801.10327, K.Jedamzik, 2006.11172, …

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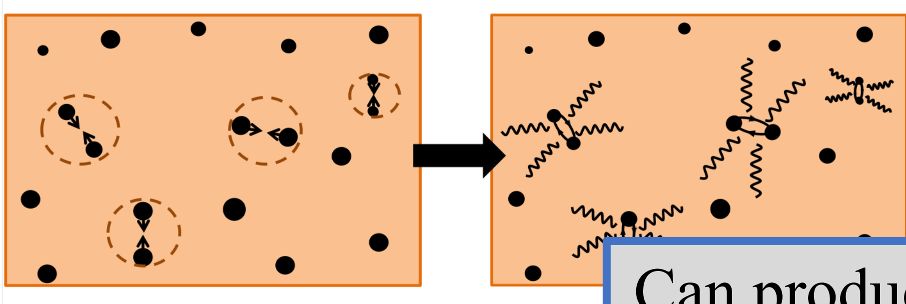


For Gaussian perturbations they are uniformly spatially distributed with Poisson number density fluctuations

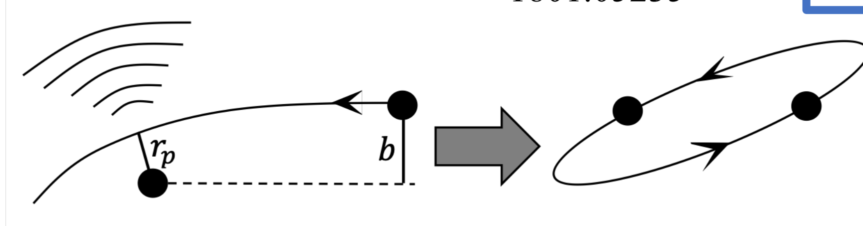
Can produce coalescence signal or SGWB

$$\mathbf{F}/\mu = \underbrace{\mathbf{r}\ddot{a}/a}_{\text{Hubble flow}} - \underbrace{M\hat{\mathbf{r}}/r^2}_{\text{self-gravity}} + \underbrace{(\hat{\mathbf{r}}\cdot\mathbf{T}\cdot\mathbf{r})\hat{\mathbf{r}}}_{\text{radial tidal forces}} + \underbrace{(\mathbf{r}\times(\mathbf{T}\cdot\mathbf{r}))}_{\text{tidal torque}}\times(\hat{\mathbf{r}}/r)$$

Late: close encounters

M.Sasaki, T.Suyama
1801.05235

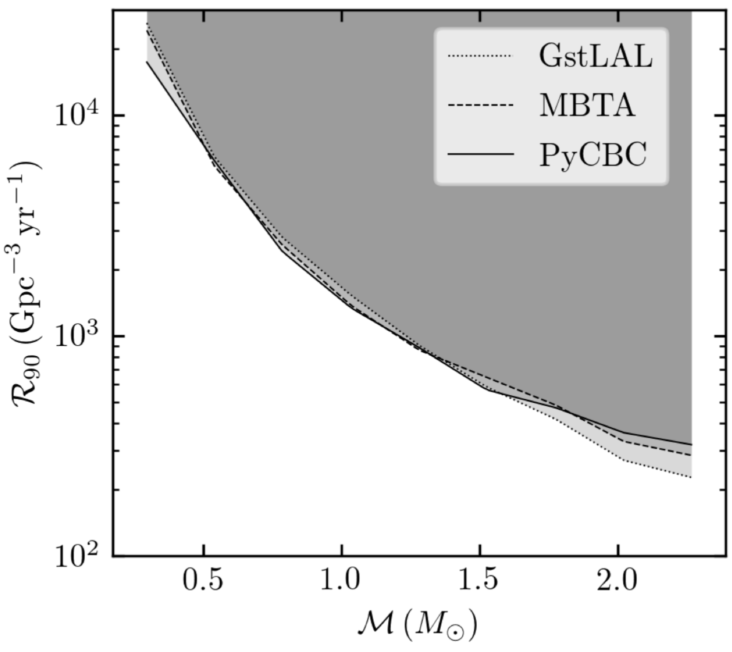
See talks by Heling Deng
Jan Schütte-Engel

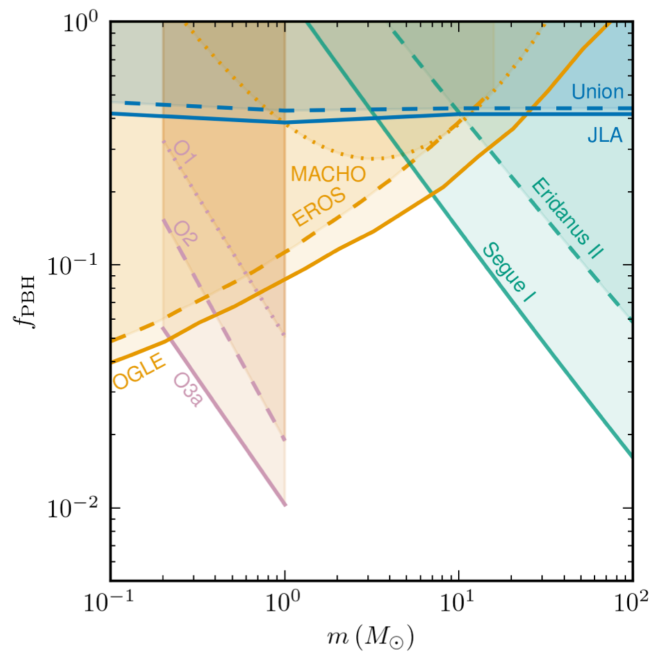


T.Nakamura, M.Sasaki, T.Tanaka, and K.S.Thorne, astro-ph/9708060, S.Bird, I.Cholis, J.B. Muñoz, Y. Ali-Haïmoud, E.D.Kovetz, A.Raccanelli, A.G.Riess, and M.Kamionkowski, 1603.00464,
M.Raidal, V.Vaskonen, and H.Veermäe, 1707.01480, Z.-C.Chen and Q.-G.Huang, 1801.10327, K.Jedamzik, 2006.11172, …

PBH – sub-solar mass merger

A possible signal of PHBs would be the detection of a merger with at least one compact sub-solar mass in the binary





LIGO, VIRGO, and KAGRA, R.Abbott *et al*., 2109.12197

PBH – Scalar Induced GW

Since PHB are formed from large density fluctuations, there exists an irreducible tensor mode induced by the scalar fluctuations at second order

$$\mathrm{d}s^2 = a(\eta)^2\left[-e^{2\Phi}\mathrm{d}\eta^2 + e^{-2\Psi}(\delta_{ij}+h_{ij})\mathrm{d}x^i\mathrm{d}x^j\right]$$

$$h^{i\,\prime\prime}_{j} + 2\mathcal{H}h^{i\,\prime}_{j} - \partial^2 h^i_j = 2\mathcal{P}^{is}_{rj}S^r_s$$

$$S^r_s = -2\Psi\partial_r\partial_s\Psi + \frac{4}{3(1+w)}\partial^r(\Psi+\mathcal{H}^{-1}\Psi')\partial_s(\Psi+\mathcal{H}^{-1}\Psi')$$

$$\mathcal{P}_h \sim \int \mathrm{d}k \int \mathrm{d}k' \left(\int \mathrm{d}t f(k,k',t)\right)^2 \mathcal{P}_\zeta(k)\mathcal{P}_\zeta(k')$$

K. Tomita. Non-linear theory of gravitational instability in an expanding universe. Prog. Theor. Phys. 37, 831 (1967), K.N.Ananda, C.Clarkson, and D.Wands, gr-qc/0612013, D.Baumann, P.J.Steinhardt, K.Takahashi, and K.Ichiki, hep-th/0703290, R.Saito and J.Yokoyama, 0812.4339, K.Kohri and T.Terada, 1804.08577,

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See talk by Keisuke Inomata

$$S^r_s = -2\Psi\partial_r\partial_s\Psi + \frac{4}{3(1+w)}\partial^r(\Psi+\mathcal{H}^{-1}\Psi')\partial_s(\Psi+\mathcal{H}^{-1}\Psi')$$

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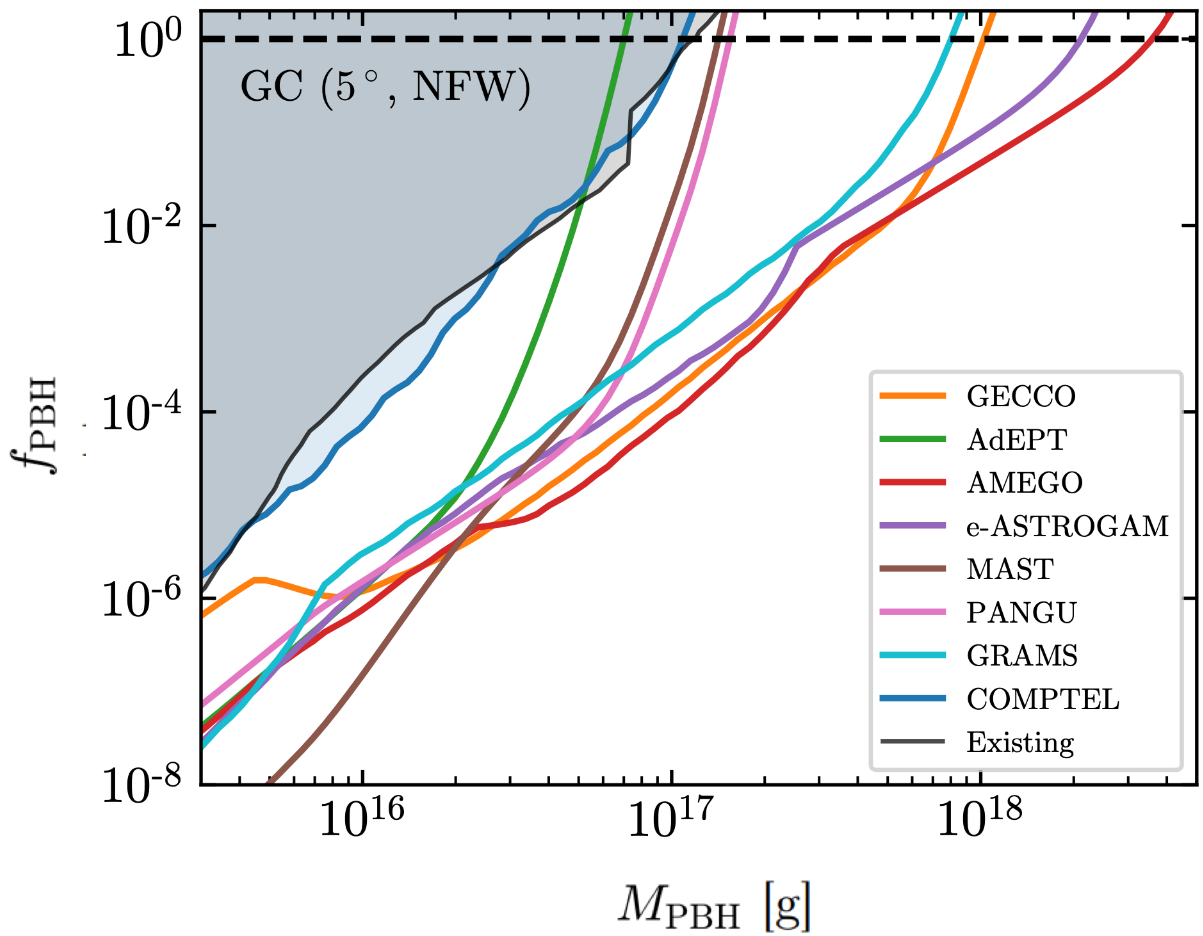
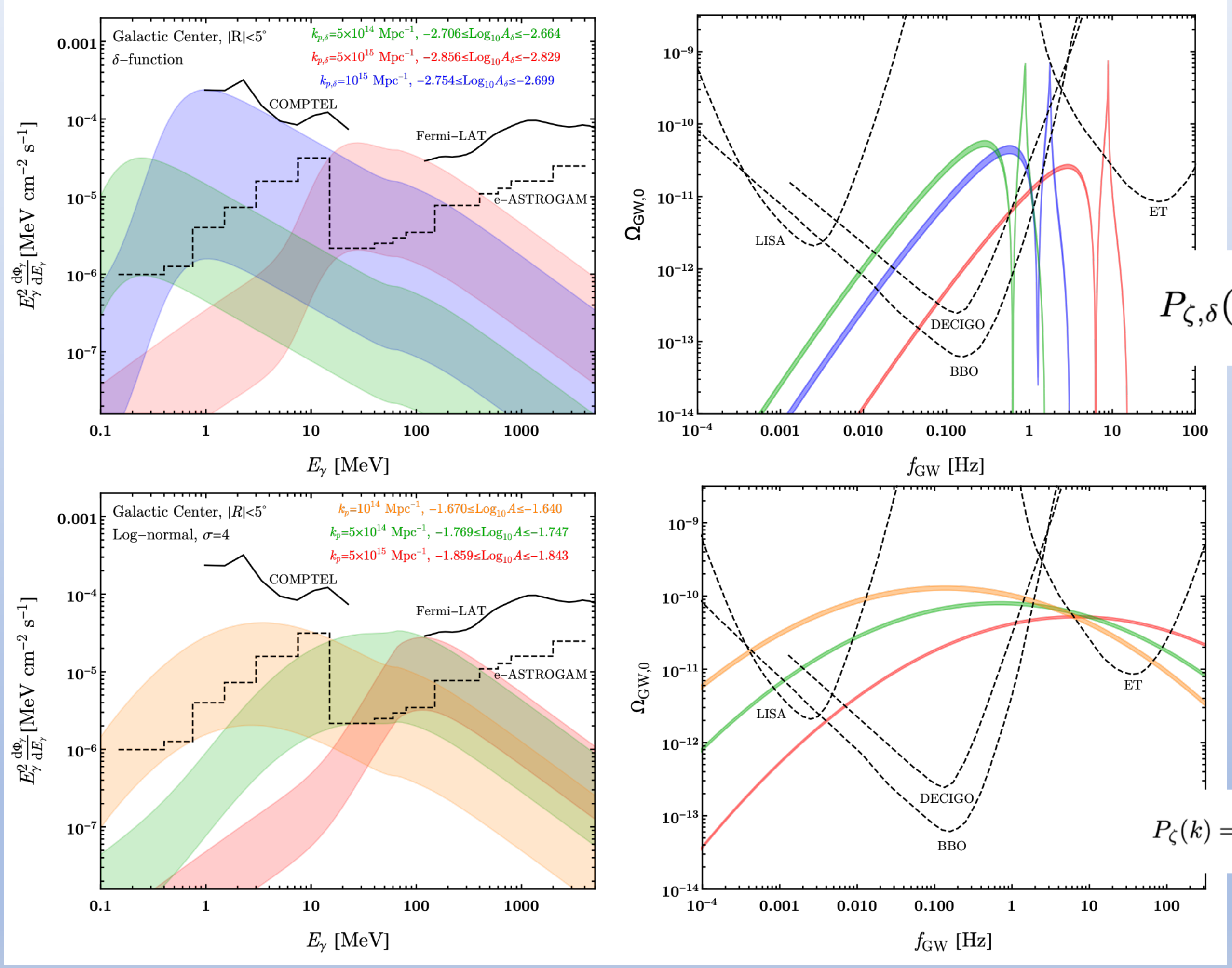
PBH – MeV Sky



A.Coogan, L.Morrison, and S.Profumo, 2010.04797
See also C.Keith, D.Hooper, T.Linden, and R.Liu, 2204.05337

$$T_H = 1/(4\pi G_N M) \simeq 1.06(10^{16}\ \text{g}/M)\ \text{MeV}$$

PBH – Scalar Induced GW – MeV Sky



$$P_{\zeta,\delta}(k) = A_\delta\,\delta\left(\log\left(\frac{k}{k_{p,\delta}}\right)\right)$$

$$P_\zeta(k) = \frac{A}{\sqrt{2\pi\sigma^2}}\,\exp\left(-\frac{(\log k - \log k_p)^2}{2\sigma^2}\right)$$

K.Agashe, J.H.Chang, S.J.Clark, B.Dutta, Y.Tsai, and T.Xu, 2202.04653
See also: V. De Luca, G. Franciolini, and A. Riotto, 2009.08268

Ultralight Bosons and Gravitational Waves

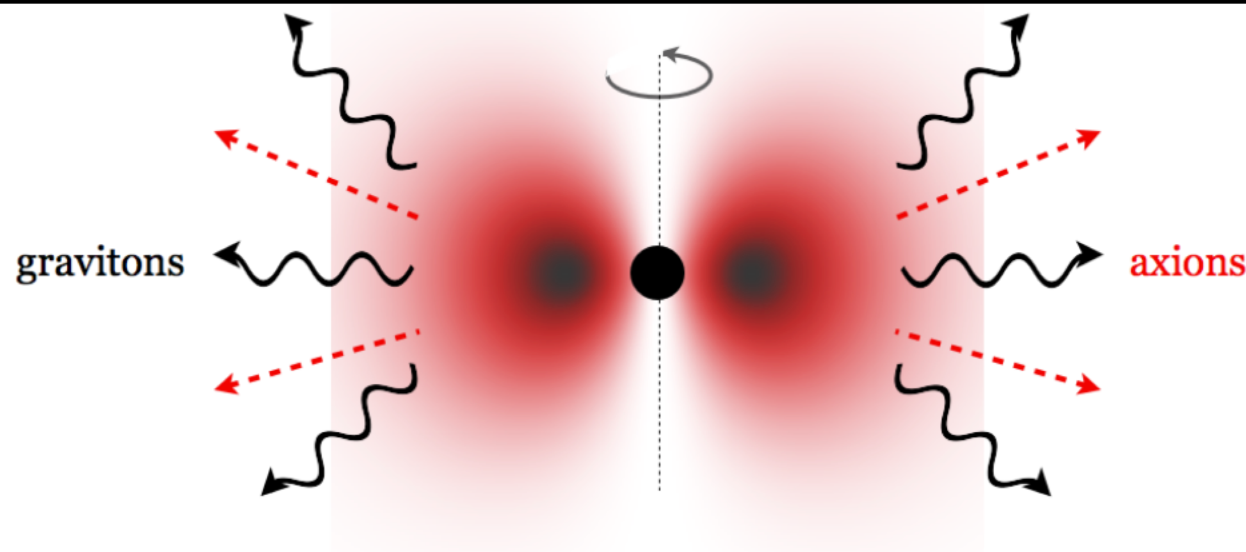
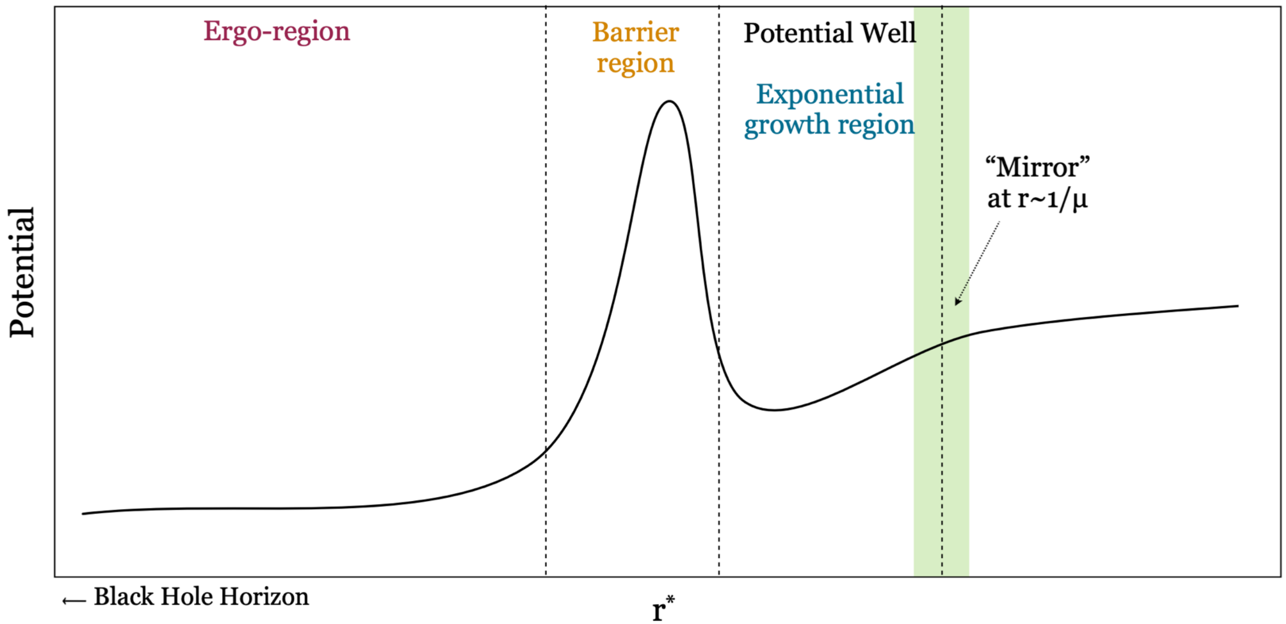


Image from: A.Arvanitaki and S.Dubovsky, 1004.3558

Superradiance - mechanism

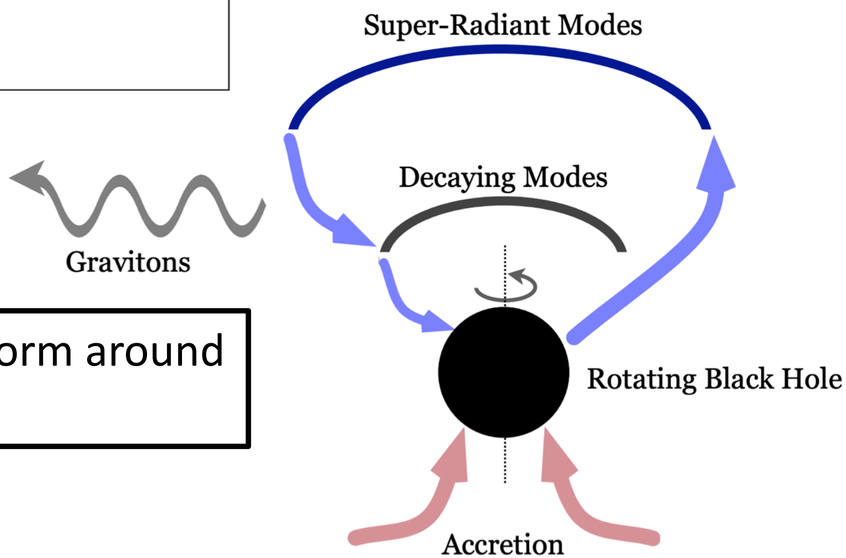


Introduces the possibility of detecting very weakly interacting particles

$$\frac{\omega}{m} < \Omega_{\mathrm{H}} = \frac{a}{2Mr_+}$$

$$r_+ \equiv M + \sqrt{M^2 - a^2}$$

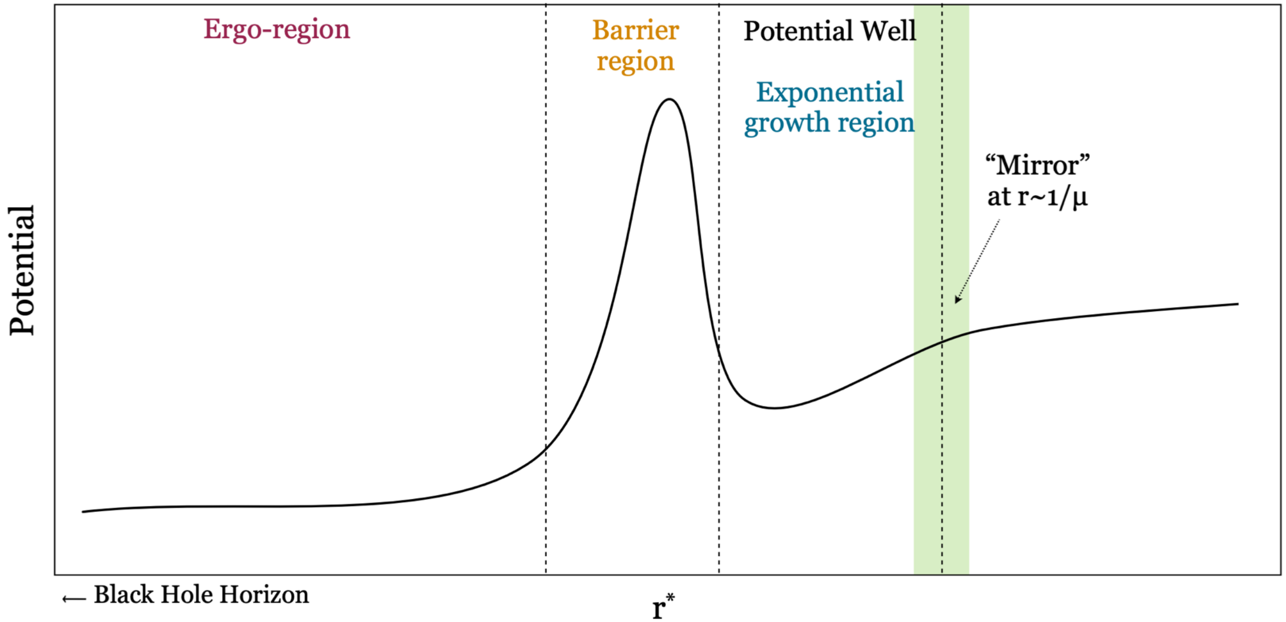
A.Arvanitaki, S.Dimopoulos, S.Dubovsky, N.Kaloper, and J.March-Russell, 0905.4720



A superradiant instability causes a bosonic cloud to form around a rotating BH

R.Penrose, *Riv.Nuovo Cim.* (1969), Y.B. Zel'dovich, *Pis'ma Zh. Eeksp. Teor. Fiz.* **14** [JETP Lett. **14** (1971)], Misner, C. W., Phys. Rev. Lett., 28, 994 (1972), W.H. Press and S.A. Teukolsky, *Nature* **238** (1972), S.L. Detweiler, PRD **22** (1980), S.R.Dolan, PRD **76** (2007), R.Brito, V.Cardoso, and P.Pani, *Lect.Notes Phys.* (2015), 1501.06570.

Superradiance - mechanism



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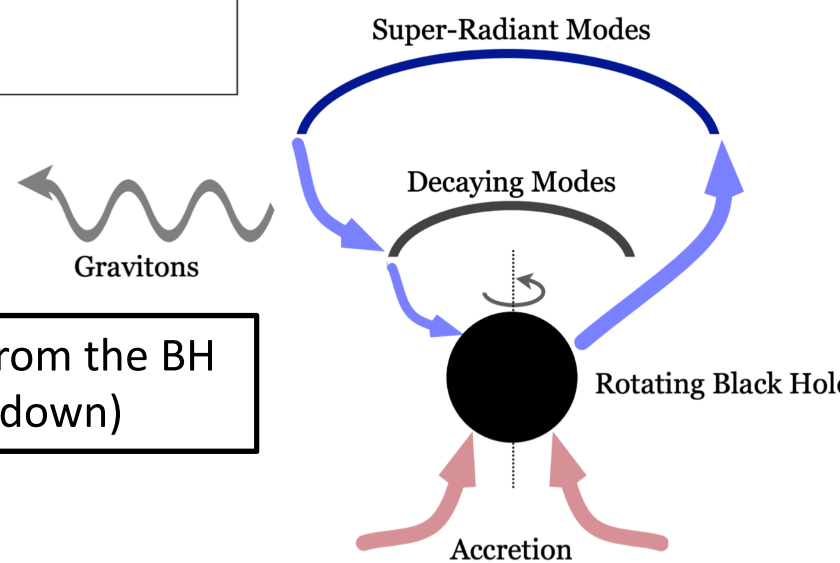
A.Arvanitaki, S.Dimopoulos, S.Dubovsky, N.Kaloper, and J.March-Russell, 0905.4720



The cloud extracts energy and angular momentum from the BH until the superradiance bound is saturated (BH spin-down)

R.Penrose, *Riv.Nuovo Cim.* (1969), Y.B. Zel'dovich, *Pis'ma Zh. Eeksp. Teor. Fiz.* **14** [JETP Lett. **14** (1971)], W.H. Press and S.A. Teukolsky, *Nature* **238** (1972), S.L. Detweiler, PRD **22** (1980), S.R.Dolan, PRD **76** (2007), R.Brito, V.Cardoso, and P.Pani, *Lect.Notes Phys.* (2015), 1501.06570.

Superradiance

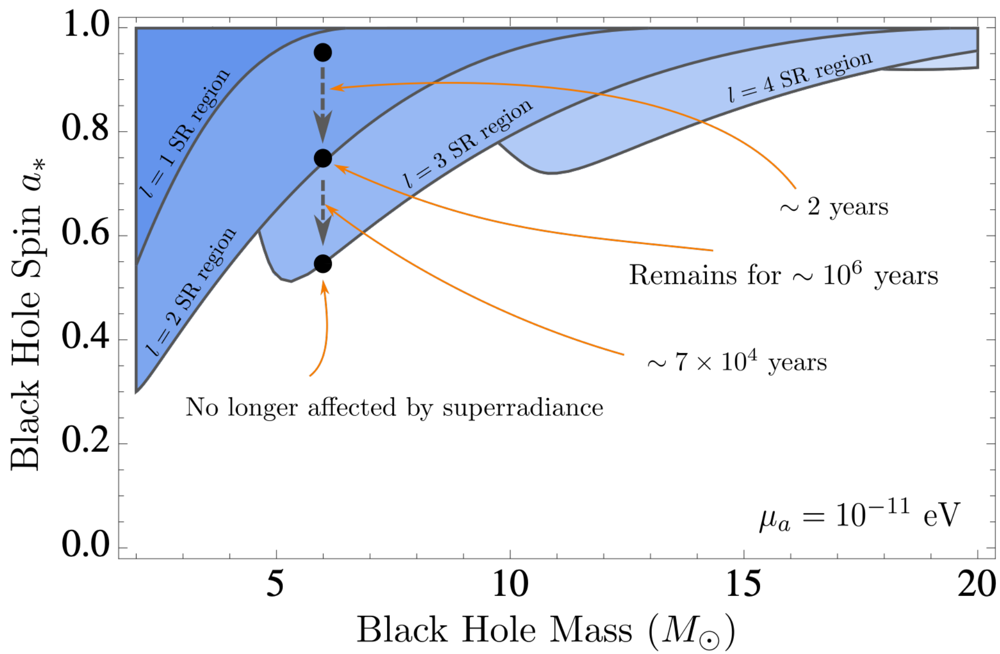
Gravitational atom

$$\psi_{n\ell m}(t,r,\theta,\phi) \simeq e^{-i(\omega-\mu)t}\bar{R}_{n\ell}(r)Y_{\ell m}(\theta,\phi)$$

$$\omega = \omega_R + i\omega_I \qquad \omega_R \simeq \mu_a\left(1-\frac{\alpha^2}{2n^2}\right)$$

Fine Structure $\alpha = r_g\mu_a, \qquad r_g \equiv G_N M,$

Superradiance Condition $\alpha/\ell \leq 1/2,$



A.Arvanitaki, M.Baryakhtar, and X.Huang, 1411.2263

Superradiance

Gravitational atom

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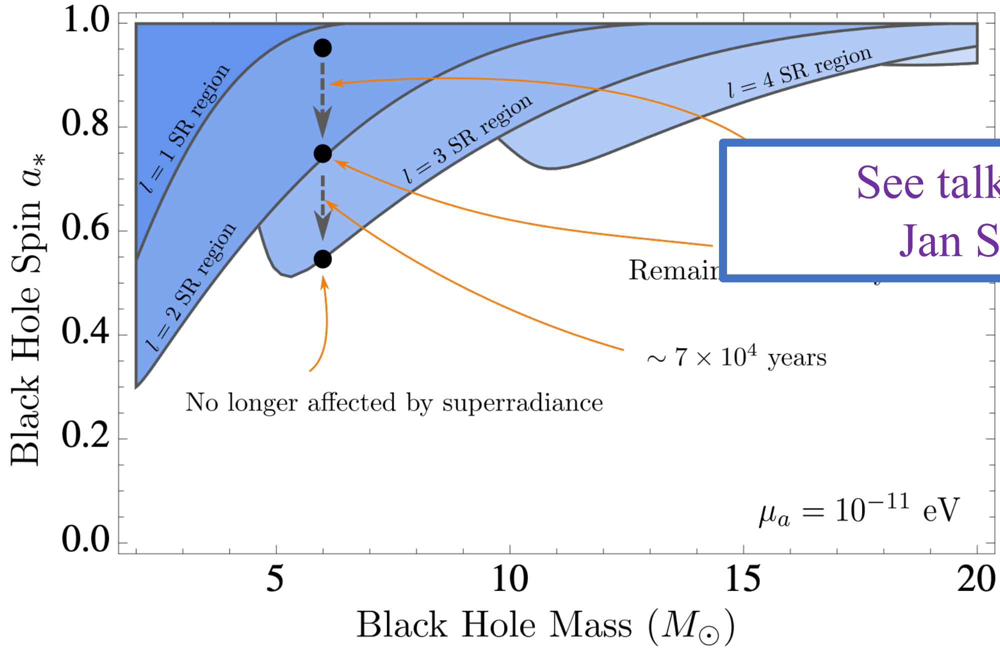
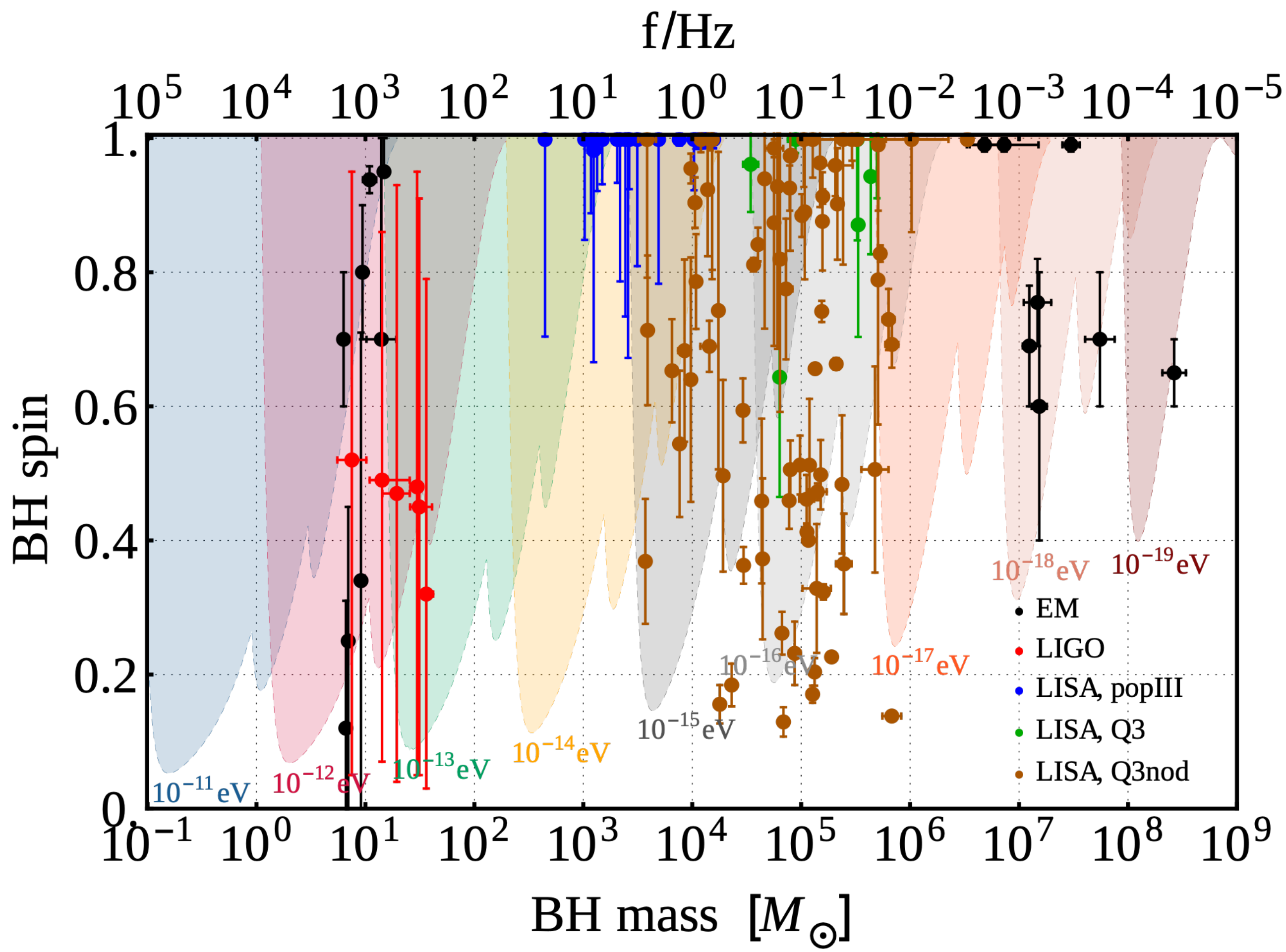


See talks by Peizhi Du
Jan Schütte-Engel

A.Arvanitaki, M.Baryakhtar, and X.Huang, 1411.2263

Superradiance – spin v. mass

Effect is strongest when the Compton wavelength is comparable to the BH size



R.Brito, S.Ghosh, E.Barausse, E.Berti, V.Cardoso, I.Dvorkin, A.Klein, and P.Pani, 1706.06311

Superradiance – time scales and frequency

The timescales for the superradiant instability

$$\tau_{\rm inst} \approx 27 \left(\frac{M_{\rm BH}}{10 M_\odot}\right) \left(\frac{\alpha}{0.1}\right)^{-9} \left(\frac{1}{\chi_i}\right) \ \text{days},$$

R.Brito, S.Ghosh, E.Barausse, E.Berti, V.Cardoso, I.Dvorkin, A.Klein, and P.Pani, 1706.06311

and for the gravitational wave emission are calculated

$$\tau_{\rm gw} \approx 6.5 \times 10^4 \left(\frac{M_{\rm BH}}{10 M_\odot}\right) \left(\frac{\alpha}{0.1}\right)^{-15} \left(\frac{1}{\chi_i}\right) \ \text{years}.$$

$$\tau_{inst} \ll \tau_{\rm gw}$$

M.Isi, L.Sun, R.Brito, A.Melatos, 1810.03812

along with the frequency of GW emission

$$f_{\rm gw} \simeq 483\,{\rm Hz} \left(\frac{m_b}{10^{-12}\,{\rm eV}}\right) \left[1 - 7 \times 10^{-4} \left(\frac{M_{\rm BH}}{10 M_\odot} \frac{m_b}{10^{-12}\,{\rm eV}}\right)\right]$$

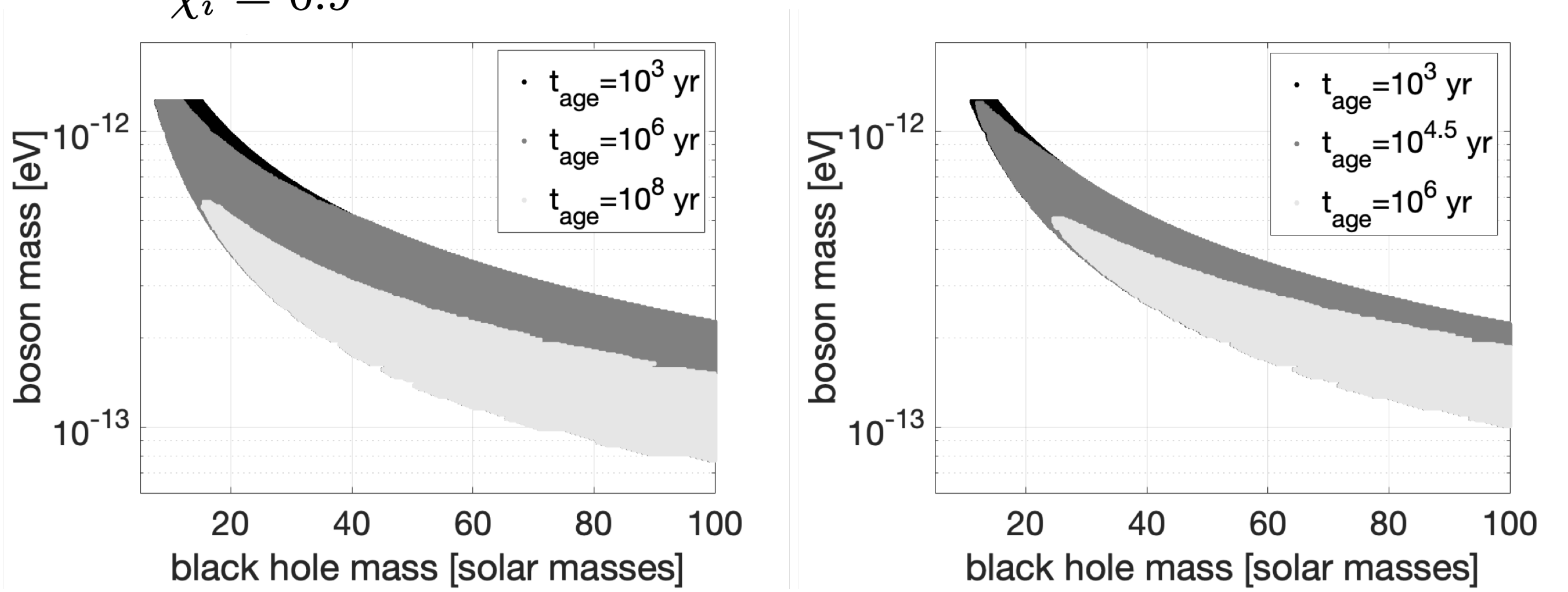
$$f_{\rm gw} \simeq \frac{\mu_b}{\pi}$$

C.Palomba, S.D'Antonio, P.Astone, S.Frasca, G.Intini, *et al.*, 1909.08854

Superradiance

All-sky for quasi-monochromatic, long-duration from scalar boson clouds

$\chi_i = 0.9$

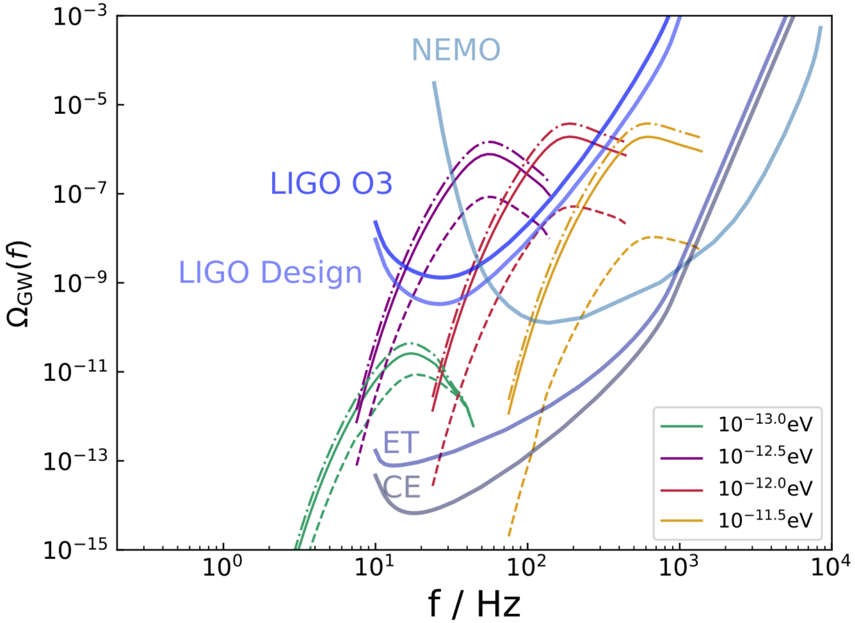


$$h_0 \approx 6 \times 10^{-24} \left(\frac{M_{\rm BH}}{10 M_\odot}\right) \left(\frac{\alpha}{0.1}\right)^7 \left(\frac{1\,{\rm kpc}}{D}\right) (\chi_i - \chi_c)$$

LIGO Scientific, Virgo, and KAGRA, R.Abbott *et al.*, 2111.15507

Superradiance – SGWB search

SGWB search with O3



χ_i	$\log \mathcal{B}$	m_s (eV)
Uniform[0, 1]	−0.27	$[1.5, 16] \times 10^{-13}$
Uniform[0, 0.5]	−0.15	$[1.9, 8.3] \times 10^{-13}$
Uniform[0.5, 1]	−0.30	$[1.3, 17] \times 10^{-13}$

TABLE I. Results of Bayesian inference and exclusion intervals for the mass of boson at 95% credible level.

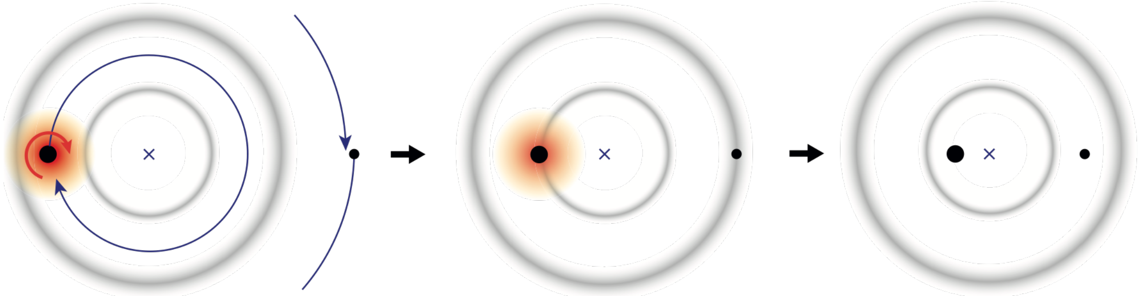
$$\Omega_{\rm GW}(f) \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\ln(f)}$$

C.Yuan, Y.Jiang, Q.-G.Huang, 2204.03482 – O3 search

C.Yuan, R. Brito, and V.Cardoso, 2106.00021 – SGWB predictions

Superradiance – further issues

Environmental effects (binaries)
Resonances, multipole
moments, etc.



D.Baumann, H.S.Chia, and R.A.Porto, 1804.03208

Self-interactions

$$\frac{g}{3!}\varphi^3 + \frac{\lambda}{4!}\varphi^4$$

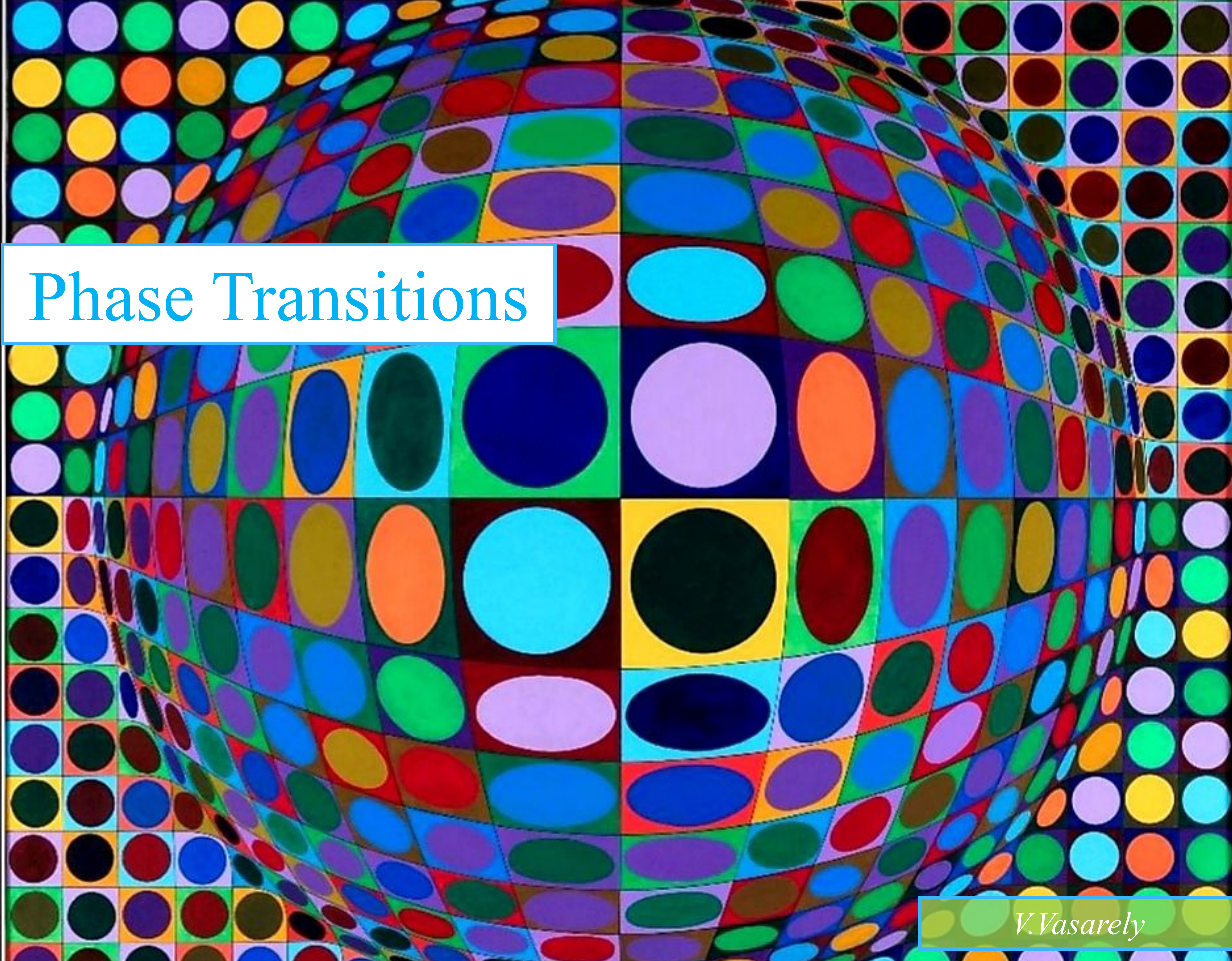
M.Baryakhtar, M.Galanis, R.Lasenby, and O.Simon, 2011.11646

Other signals – (Lasing axions?)

T.W.Kephart and J.Rosa, 1709.06581

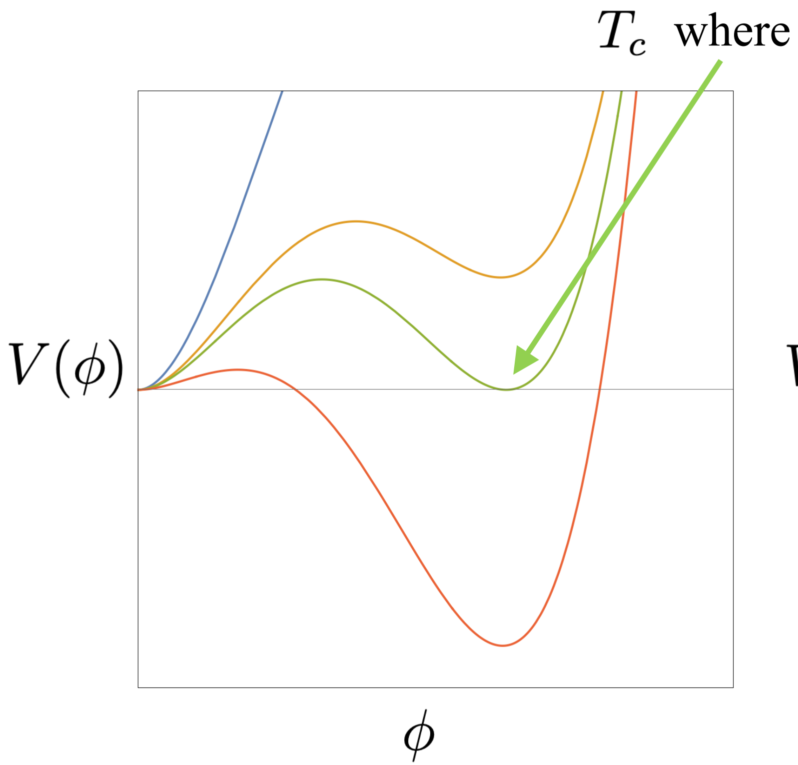
Uncertainties in mass-spin distributions

Phase Transitions

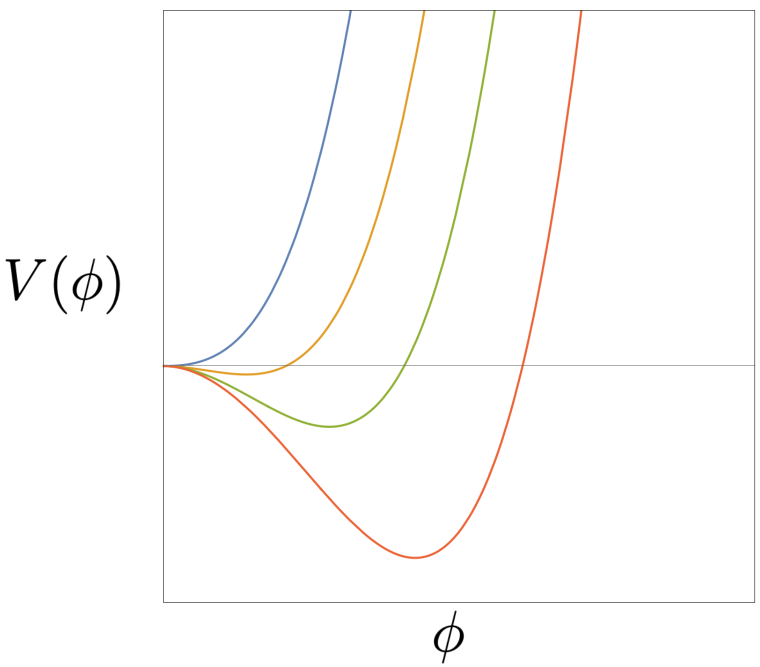


V.Vasarely

Phase Transitions

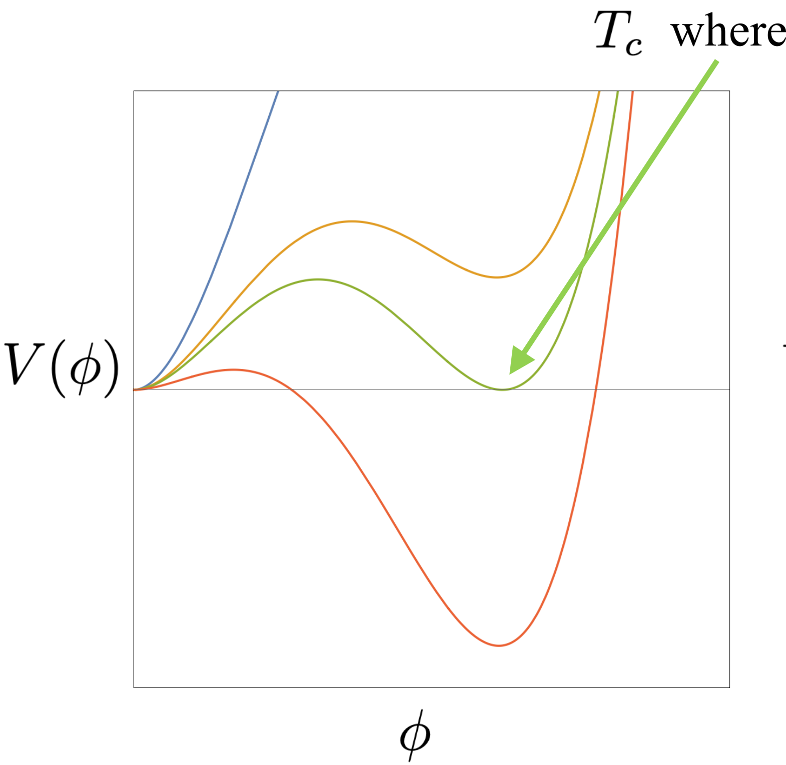


1st order

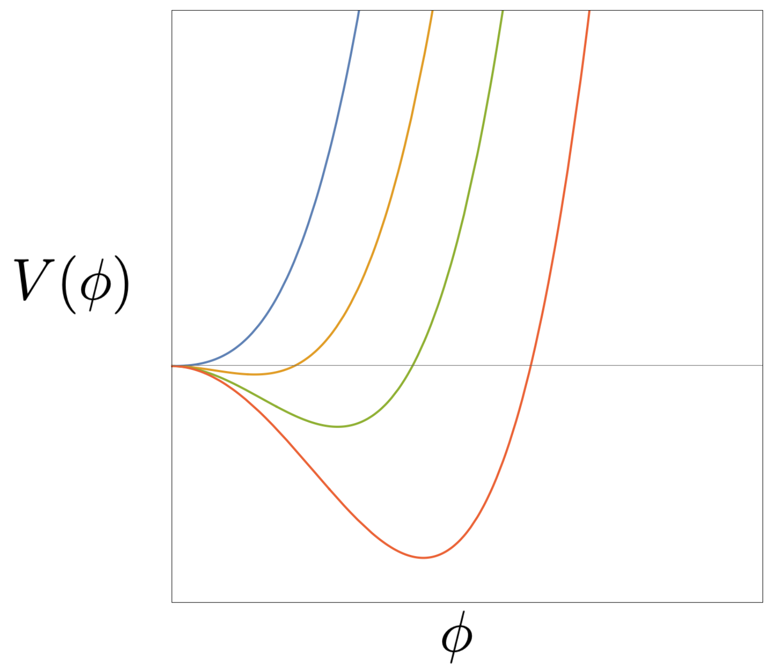


2nd order

Phase Transitions



1st order

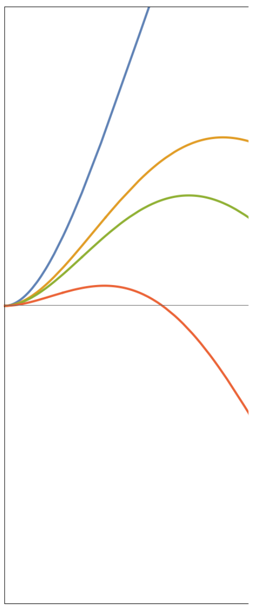


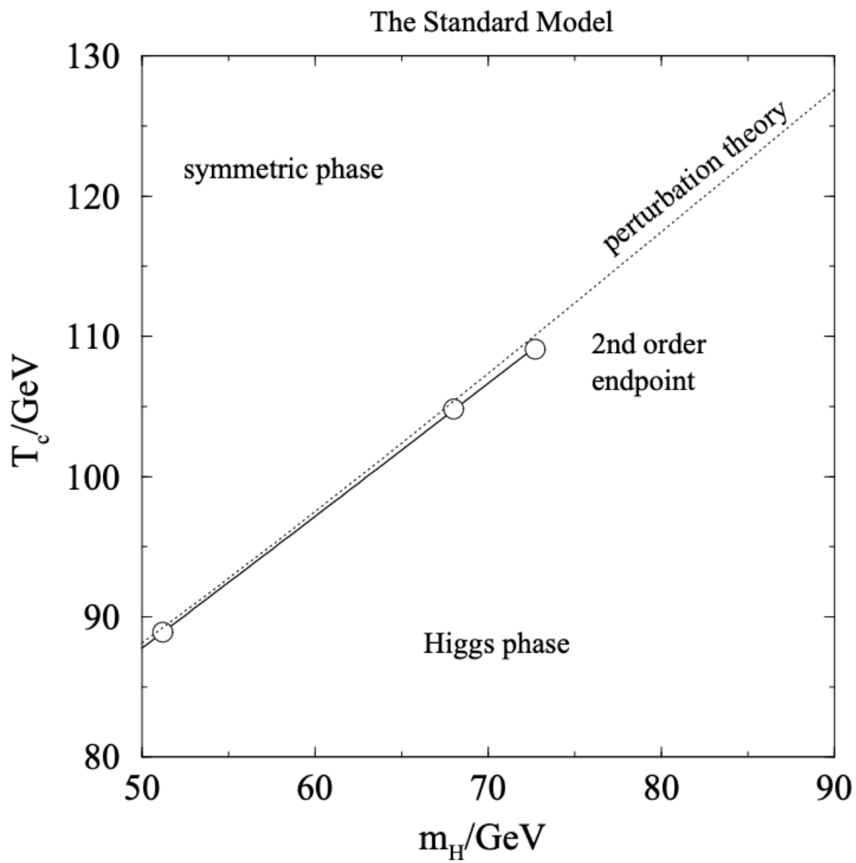
2nd order

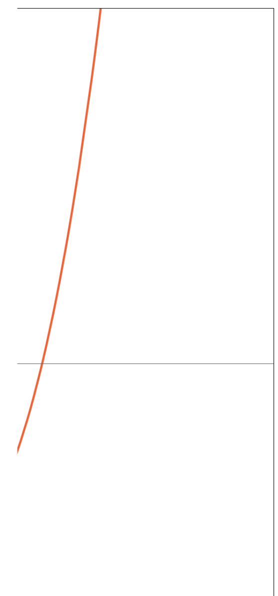
A.Kosowsky, M.S.Turner, and R.Watkins, PRL 1992, M.Kamionkowski, A.Kosowsky, and M.S.Turner, astro-ph/9310044, R.Apreda, M.Maggiore, A.Nicolis, and A.Riotto, gr-qc/0107033, C.Grojean and G.Servant, hep-ph/0607107

Phase Transitions

$V(\phi)$





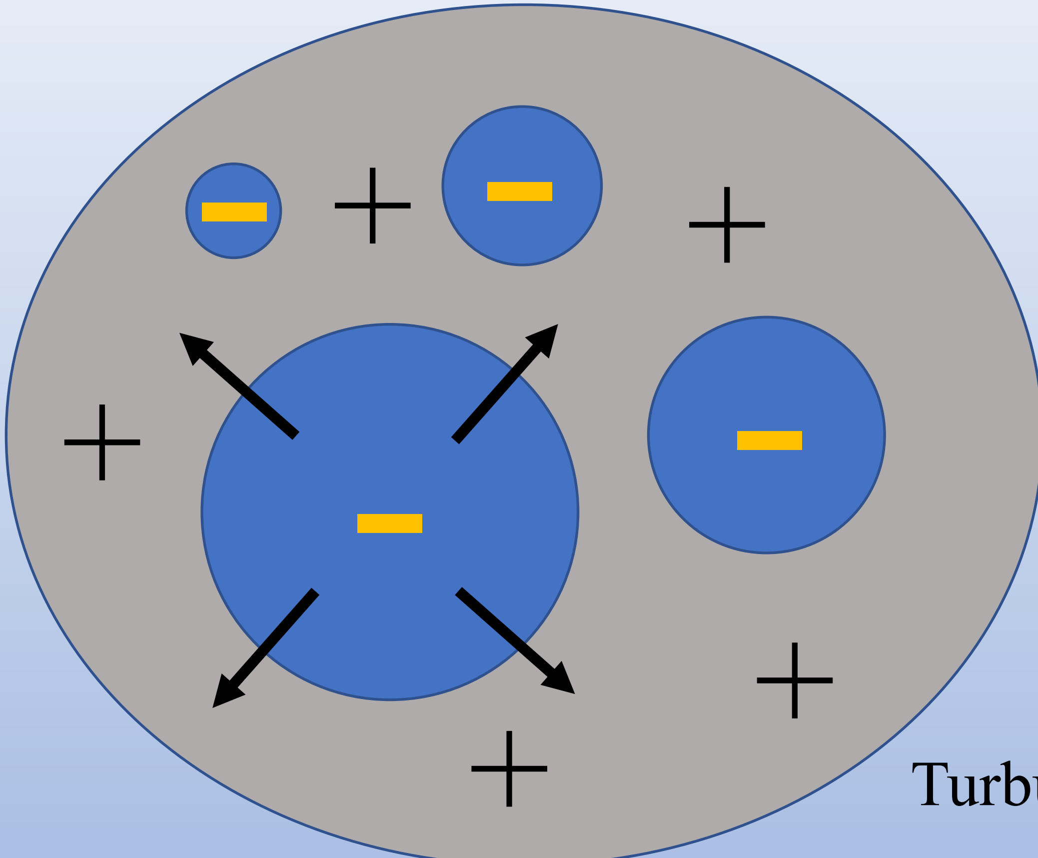


1st order

2nd order

M.Laine, K.Rummukainen, hep-lat/9809045

Phase Transitions – GW production



Bubble nucleation of the true vacuum

Bubble collisions

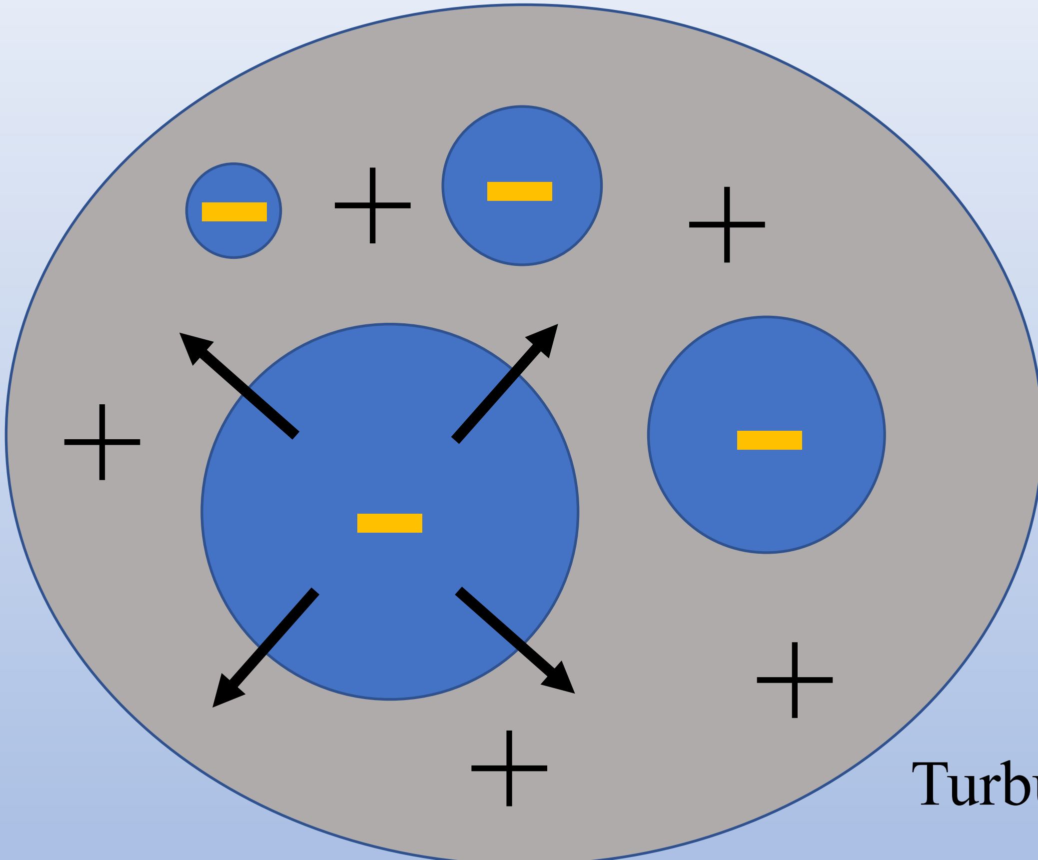
Sound Waves

Turbulence

$$\Pi_{ij}$$

SGWB: $\Omega_b + \Omega_{sw} + \Omega_t$

Phase Transitions – GW production



Bubble nucleation of the true vacuum

Bubble collisions

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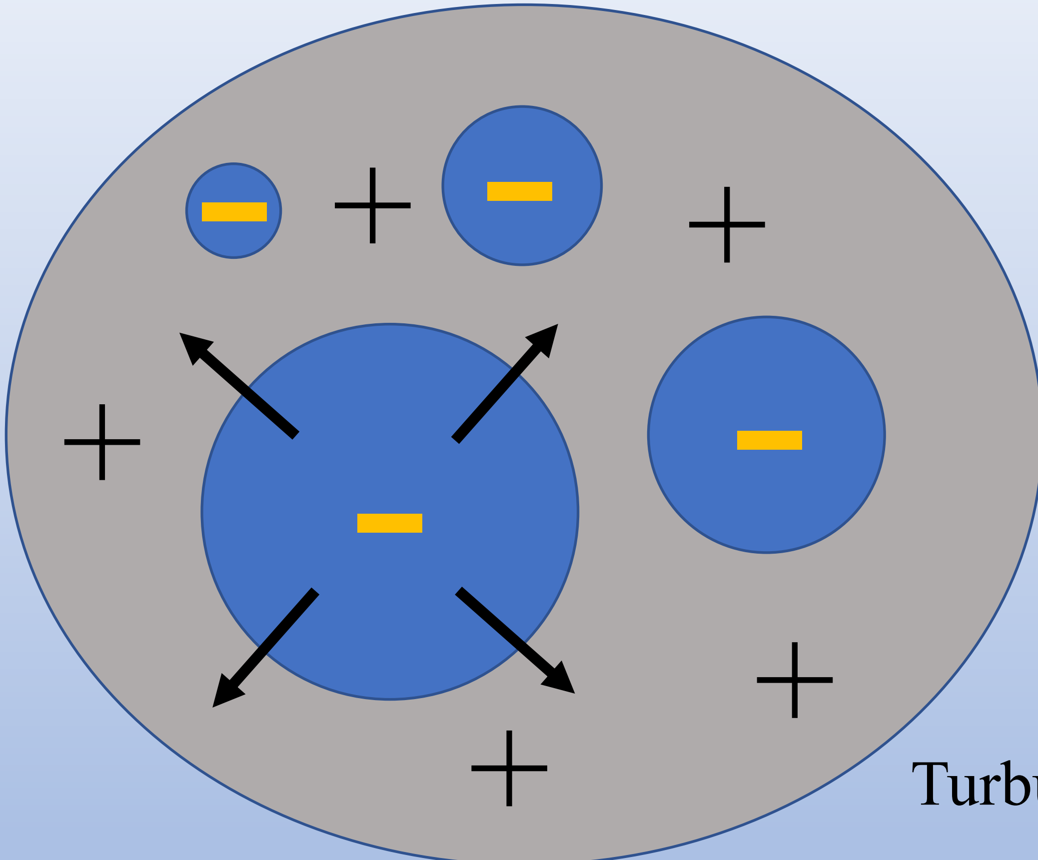
$$\Pi_{ij}$$

SGWB: $\Omega_b + \Omega_{sw} + \Omega_t$

Phase Transitions – GW production



Bubble nucleation of the true vacuum

Bubble collisions

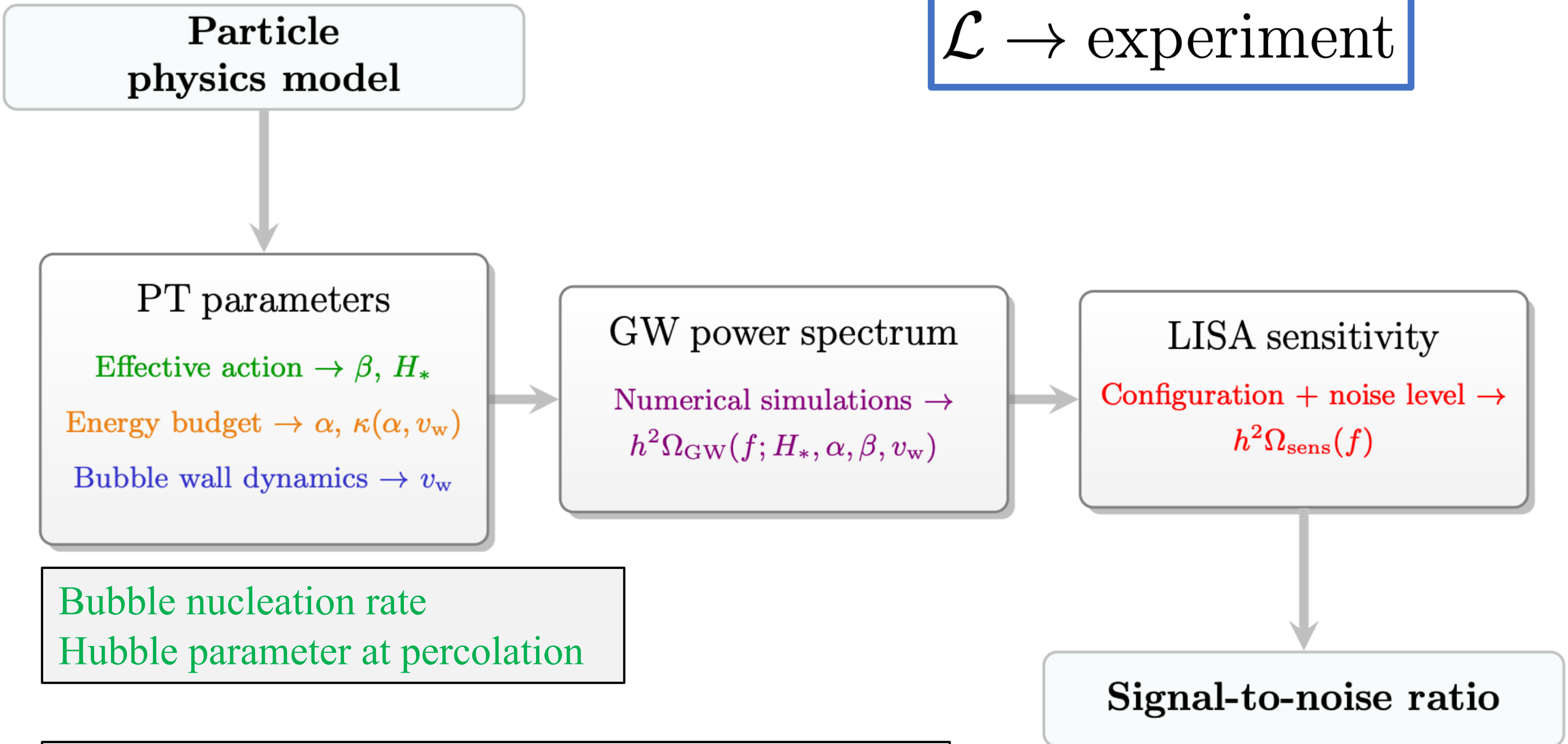
Sound Waves

Turbulence

SGWB: $\Omega_b + \Omega_{sw} + \Omega_t$

See talk by Emma Clarke

$\mathcal{L} \to$ experiment



Bubble nucleation rate
Hubble parameter at percolation

Strength of the transformation
Fractional energy converted to bubble kinetic energy
wall velocity

C. Caprini et al., "Detecting gravitational waves from cosmological phase transitions from LISA: an update", 1910.13125

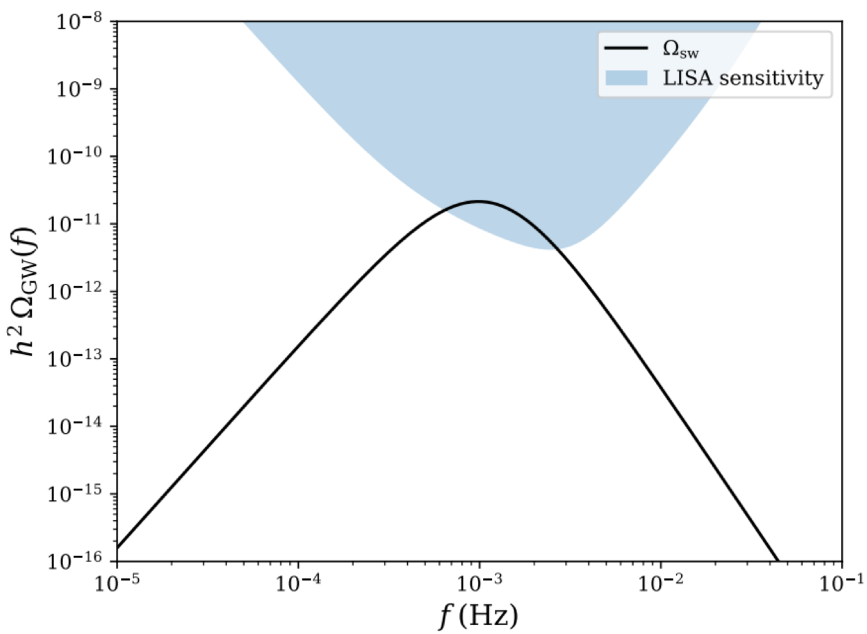
Phase Transitions – GW spectrum

$$h^2\Omega_s(f) = h^2\Omega_s^{\rm peak}(\alpha, \beta/H_*, T_*, v_w, \kappa_s)\, \mathcal{S}_s(f, f_s)\ ,$$

M.Hindmarsh, S.J.Huber, K. Rummukainen, D.J. Weir, 1704.05871
.Cutting, M.Hindmarsh, and D.J.Weir, 1802.05712

$$\mathcal{S}_s = \left(\frac{f}{f_s}\right)^3 \left[\frac{7}{4+3\,(f/f_s)^2}\right]^{7/2}$$

$$h^2\Omega_s^{\rm peak} \simeq 2.65\times 10^{-6}\left(\frac{v_w}{\beta/H_*}\right)\left(\frac{100}{g_*(T_*)}\right)^{1/3}\left(\frac{\kappa_s\,\alpha}{1+\alpha}\right)^2$$



$$f_s = 1.9\times 10^{-2}\,{\rm mHz}\left(\frac{g_*(T_*)}{100}\right)^{1/6}\left(\frac{T_*}{100\,{\rm GeV}}\right)\left(\frac{\beta/H_*}{v_w}\right)$$

Can produce GW in the region of LISA sensitivity

C. Caprini et al., 1910.13125

Phase Transitions – the parameters (simplified)

Nucleation rate per unit volume

$$p(T) = p_0 T^4 e^{-S_3/T}$$

Provides the transition rate

$$\frac{\beta}{H} = T\frac{d(S_3/T)}{dT}$$

Bounce solution

$$\frac{\partial^2\phi}{\partial r^2} + \frac{2}{r}\frac{\partial\phi}{\partial r} = \frac{\partial V_E(T,\phi)}{\partial\phi}$$

The transition strength can be calculated

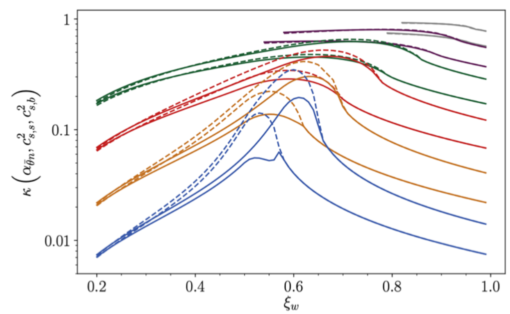
$$\alpha(T) = \frac{1}{\rho_{\rm rad}}\left(\Delta V_T - \frac{T}{4}\frac{d\Delta V_T}{dT}\right)$$

For prob ~ $O(1)$ nucleation of a bubble per Hubble volume

$$\frac{S_3(T_n)}{T_n} \simeq 140$$

Assuming radiation domination

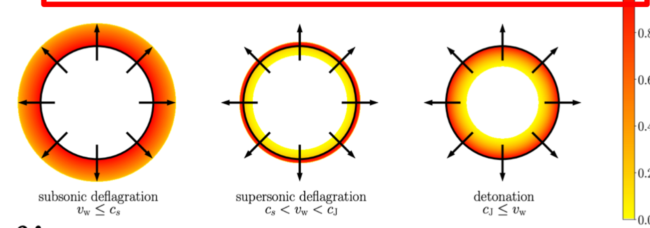
From this, the amount of available energy that is converted into bubble kinetic energy can be calculated



$$K = \frac{\rho_{\rm fl}}{e_+} = \left(\frac{\Delta\bar{\theta}}{4e_+}\right)\kappa$$

$$\kappa = \frac{4\rho_{\rm fl}}{3\alpha w_+}$$

Finally, one needs the wall velocity



v_w

There is a suppression of the signal due to the source lifetime

$$\Upsilon = 1 - \frac{1}{\sqrt{1 - 2\tau_{\rm sw} H_s}}$$

$$\tau_{\rm sw} = R_*/\bar{U}_f$$

Energy budget refs: J.R.Espinosa,T.Konstandin,J.M.No,G.Servant, JCAP 2010, 1004.4187
L.Leitao and A.Megevand,1410.3875, F.Giese, T.Konstandin, J. van de Vis, 2004.06995
F.Giese, T.Konstandin, K.Schmitz, J. van de Vis, 2010.09744

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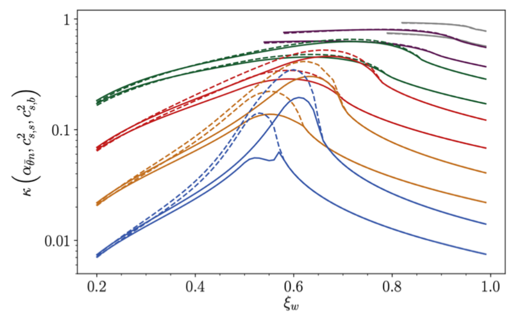

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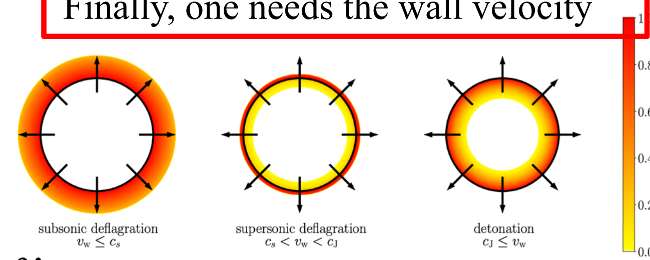

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Wall speed refs: S.Höche, J.Kozaczuk, A.J.Long, J.Turner, and Y.Wang, 2007.10343
B.Laurent and J.M.Cline 2204.13120
M.B.Hindmarsh, M.Luben, J.Lumma, and M.Pauly, *SciPost Phys.Lect.Notes* (2021), 2008.09136

Phase Transitions – Model Classes

Broadly: i) EWPT affected ii) not affected

i) xSM, EW Multiplets, 2HDM, SUSY, SMEFT
ii) Dark sector, Warped ExDim, Conformal

See talk by Arnab Dasgupta

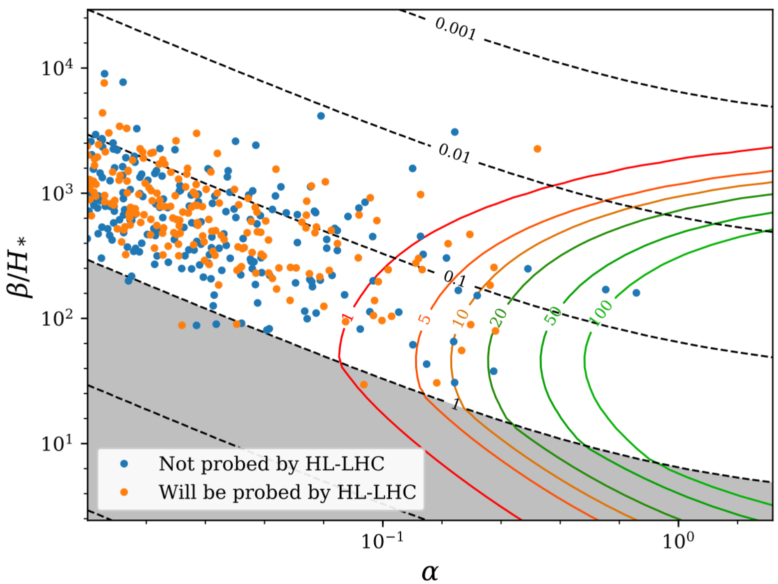
PTPlot

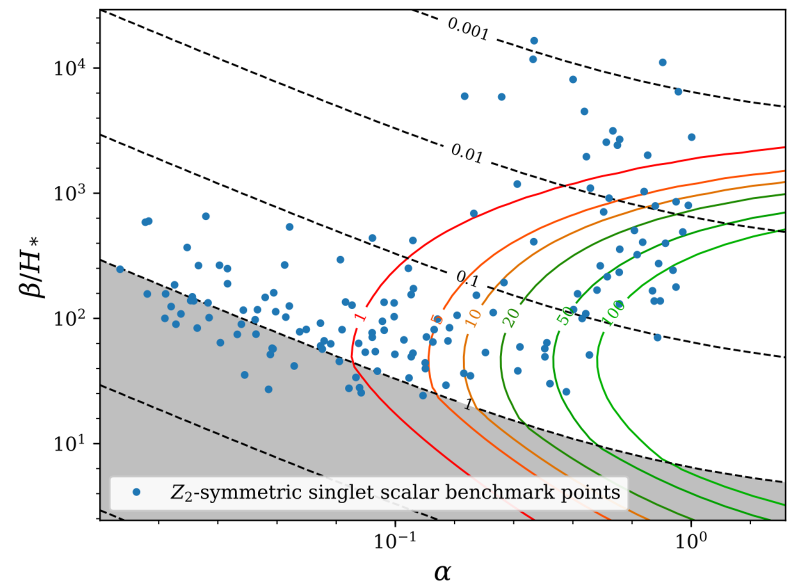
Wall velocity v_{w}**:**	0.9
Phase transition strength α_{θ}**:**	0.1
Inverse phase transition duration β/H_{*}**:**	1.1
Mission profile:	Science Requirements Document (3 years)
Transition temperature T_{*}**:**	50 GeV
Degrees of freedom g_{*}**:**	100

Submit

C. Caprini et al., *JCAP* (2020) 1910.13125

Phase Transitions – singlet scalar xSM





$$V(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2}a_1 |H|^2 S + \frac{1}{2}a_2 |H|^2 S^2 + b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4.$$

$$m_2 = 170 \text{ GeV and } 240 \text{ GeV}$$

$$v_w = 1$$

C. Caprini et al., *JCAP* (2020) 1910.13125

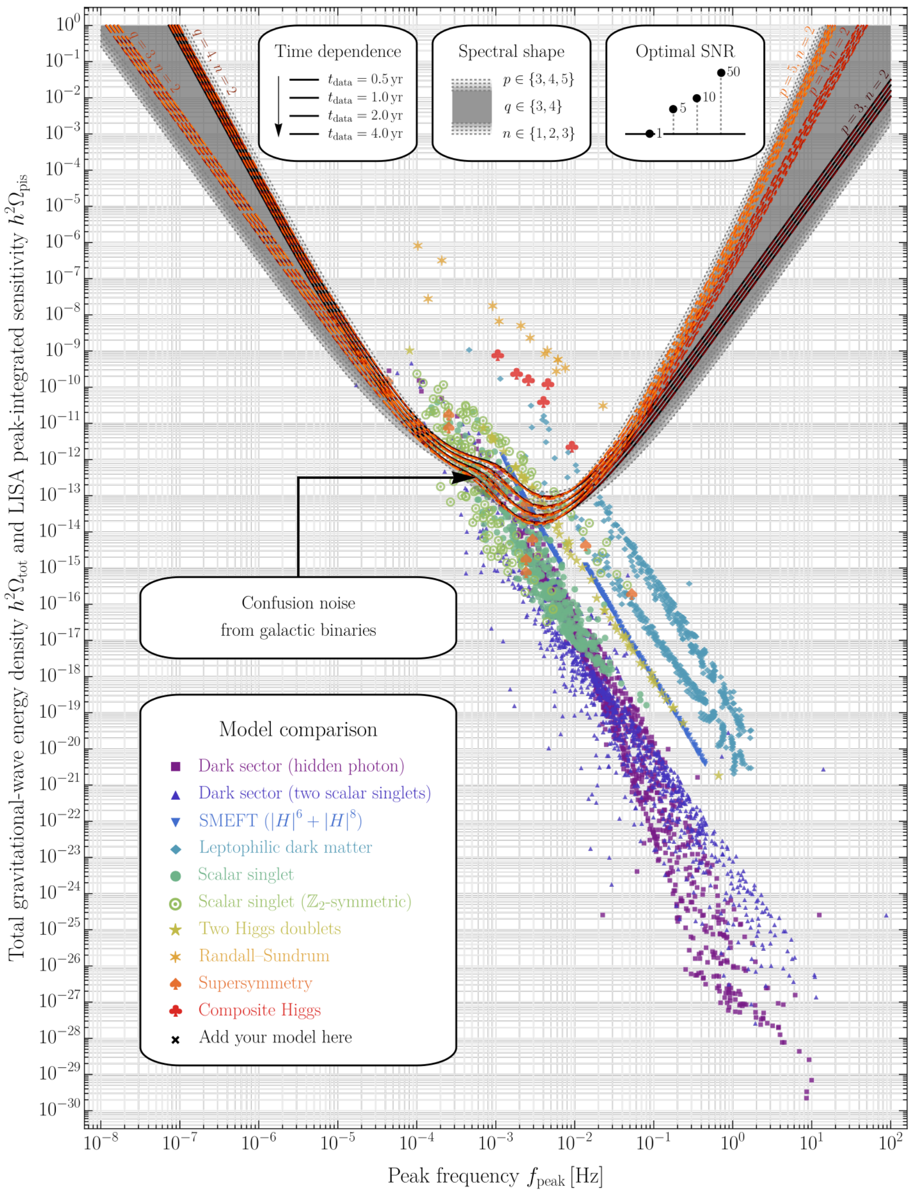
Model PISCs

3720 Benchmark Points - 10 LISA models using a general broken power law

$$\mathcal{S}(x) = \frac{1}{\mathcal{N}}\,\widetilde{\mathcal{S}}(x)\,, \quad \widetilde{\mathcal{S}}(x) = \frac{x^p}{\left[q/(p+q) + p/(p+q)\,x^n\right]^{(p+q)/n}}$$

$$\Omega_{\rm tot} = \min\{1, H_*\tau_{\rm sh}\} \times 3 \left(\frac{g_\rho^*}{g_\rho^0}\right)\left(\frac{g_s^0}{g_s^*}\right)^{4/3} \Omega_\gamma^0\,\tilde{\Omega}\,(8\pi)^{1/3}\,\frac{\max\{c_s, v_w\}}{\beta/H_*}\,K^2$$

$$f_{\rm peak} \simeq 8.9\times10^{-3}\,{\rm mHz}\left(\frac{z_{\rm peak}}{10}\right)\left(\frac{\beta/H_*}{\max\{c_s,v_w\}}\right)\left(\frac{100}{g_s^*}\right)^{1/3}\left(\frac{g_\rho^*}{100}\right)^{1/2}\left(\frac{T_*}{100\,{\rm GeV}}\right)$$



T.Alanne, T.Hugle, M.Platscher, and K.Schmitz, 1909.11356
K.Schmitz, 2002.04615 and 2005.10789

Example Sensitivity to Dark Sector Scales

Thermal effective potential that is polynomial and renormalizable

$$V(T,\phi) = \Lambda^4 \left[\left(-\frac{1}{2} + c \left(\frac{T}{v}\right)^2 \right) \left(\frac{\phi}{v}\right)^2 + b\frac{T}{v} \left(\frac{\phi}{v}\right)^3 + \frac{1}{4} \left(\frac{\phi}{v}\right)^4 \right]$$

$V(T = 0, \phi)$ has a minimum at $\phi = \pm v$ with a mass of $m^2/v^2 = 2(\Lambda/v)^4$

JBD, B.Dutta, S.Ghosh, J.Kumar, and J.Runburg, 2203.11736

Example Sensitivity to Dark Sector Scales

Thermal effective potential that is polynomial and renormalizable

$$V(T,\phi) = \Lambda^4 \left[\left(-\frac{1}{2} + c\left(\frac{T}{v}\right)^2 \right) \left(\frac{\phi}{v}\right)^2 + b\frac{T}{v}\left(\frac{\phi}{v}\right)^3 + \frac{1}{4}\left(\frac{\phi}{v}\right)^4 \right]$$

$V(T=0,\phi)$ has a minimum at $\phi = \pm v$ with a mass of $m^2/v^2 = 2(\Lambda/v)^4$

Rescale the potential, the temperature, and the field

$$\tilde{\phi} = \phi/v$$

$$\tilde{T} = T/v$$

$$\tilde{V}(\tilde{T},\tilde{\phi}) = \left(-\frac{1}{2} + c\tilde{T}^2\right)\tilde{\phi}^2 + b\tilde{T}\tilde{\phi}^3 + \frac{1}{4}\tilde{\phi}^4$$

The bounce

$$\frac{d^2\phi}{dr^2} + \frac{2}{r}\frac{\partial\phi}{\partial r} = \frac{\partial V_E(T,\phi)}{\partial\phi}$$

analytic approximation

$$\frac{S_E}{T} = \frac{4.85M^3}{E^2T^3}\left[1 + \frac{\alpha}{4}\left(1 + \frac{2.4}{1-\alpha} + \frac{0.26}{(1-\alpha)^2}\right)\right]$$

M.Dine, R.G.Leigh, P.Y.Huet, A.D.Linde, and D.A.Linde, PRD (1992), hep-ph/9203203

JBD, B.Dutta, S.Ghosh, J.Kumar, and J.Runburg, 2203.11736

Effective Potential

The criteria $\frac{\tilde{S}_E}{\tilde{T}_N} \sim 140 \left(\frac{\Lambda}{v}\right)^2$ allows the determination S_E and $\tilde{T}_N$ for any $b,$ c and $\Lambda/v.$

And subsequently, we can calculate the rate and transition strength

JBD, B.Dutta, S.Ghosh, J.Kumar, and J.Runburg, 2203.11736

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We scan over *b* and *c* ensuring:

1. Perturbativity 2.FOPT 3. nucleation rate exceeds Hubble rate.

JBD, B.Dutta, S.Ghosh, J.Kumar, and J.Runburg, 2203.11736

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We scan over *b* and *c* ensuring:

1. Perturbativity 2.FOPT 3. nucleation rate exceeds Hubble rate.

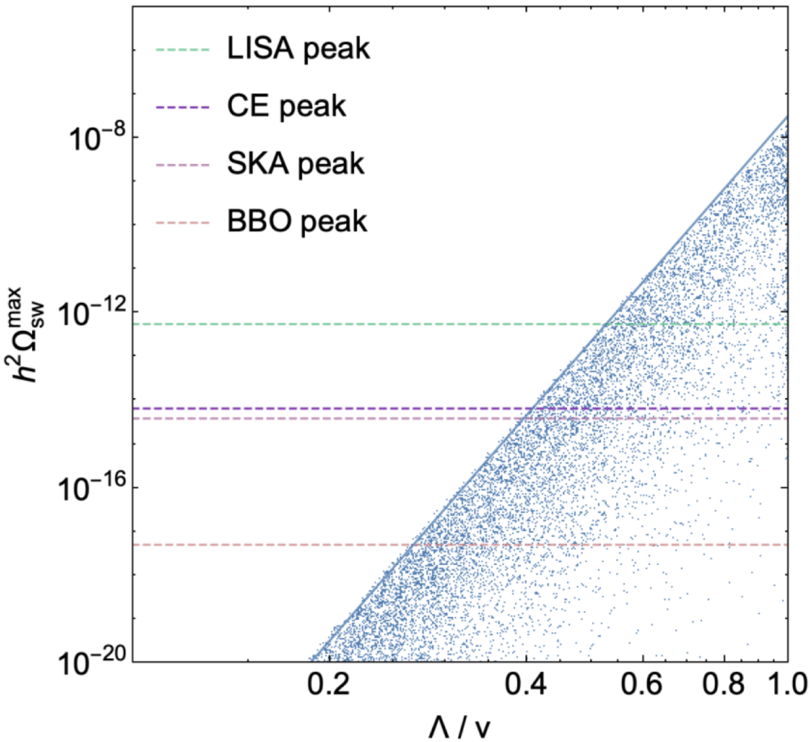
We then calculate the GW amplitude and peak *f*

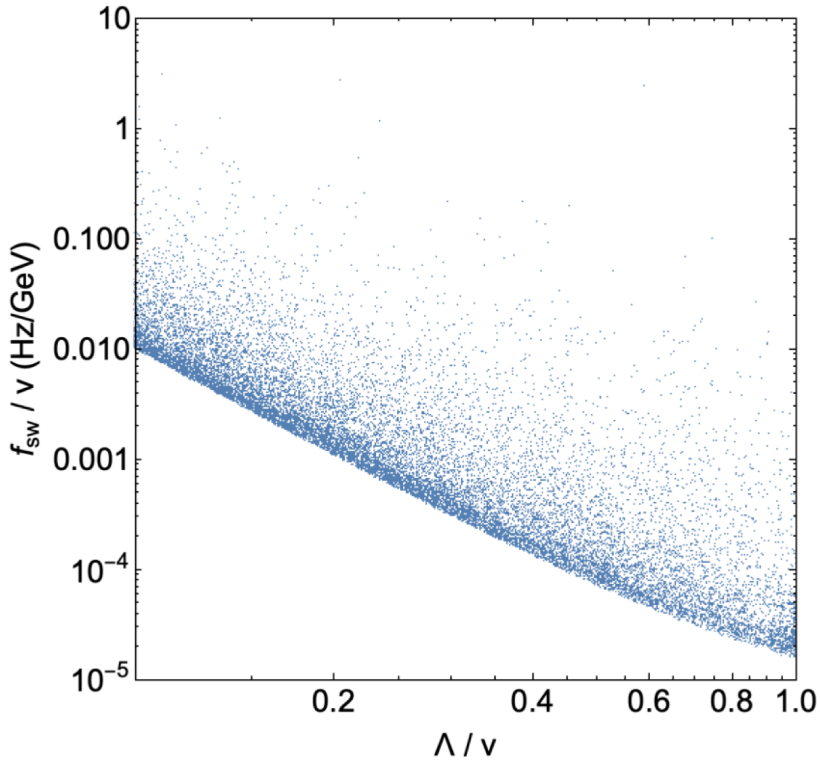
$$h^2\Omega_{sw}^{max} = h^2\tilde{\Omega}_{sw}^{max}(b, c, \Lambda/v) \times \left(\frac{\Lambda}{v}\right)^{10+8n} \left(\frac{g_*}{100}\right)^{-5/3-2n} \left[1 - \frac{1}{\sqrt{1+2\tau_{sh}H_s}}\right]$$

$$f_{sw} = \tilde{f}_{sw}(b, c, \Lambda/v) \times \left(\frac{\Lambda}{v}\right)^{-2} \left(\frac{T_N}{100\ \mathrm{GeV}}\right) \left(\frac{g_*}{100}\right)^{1/6}$$

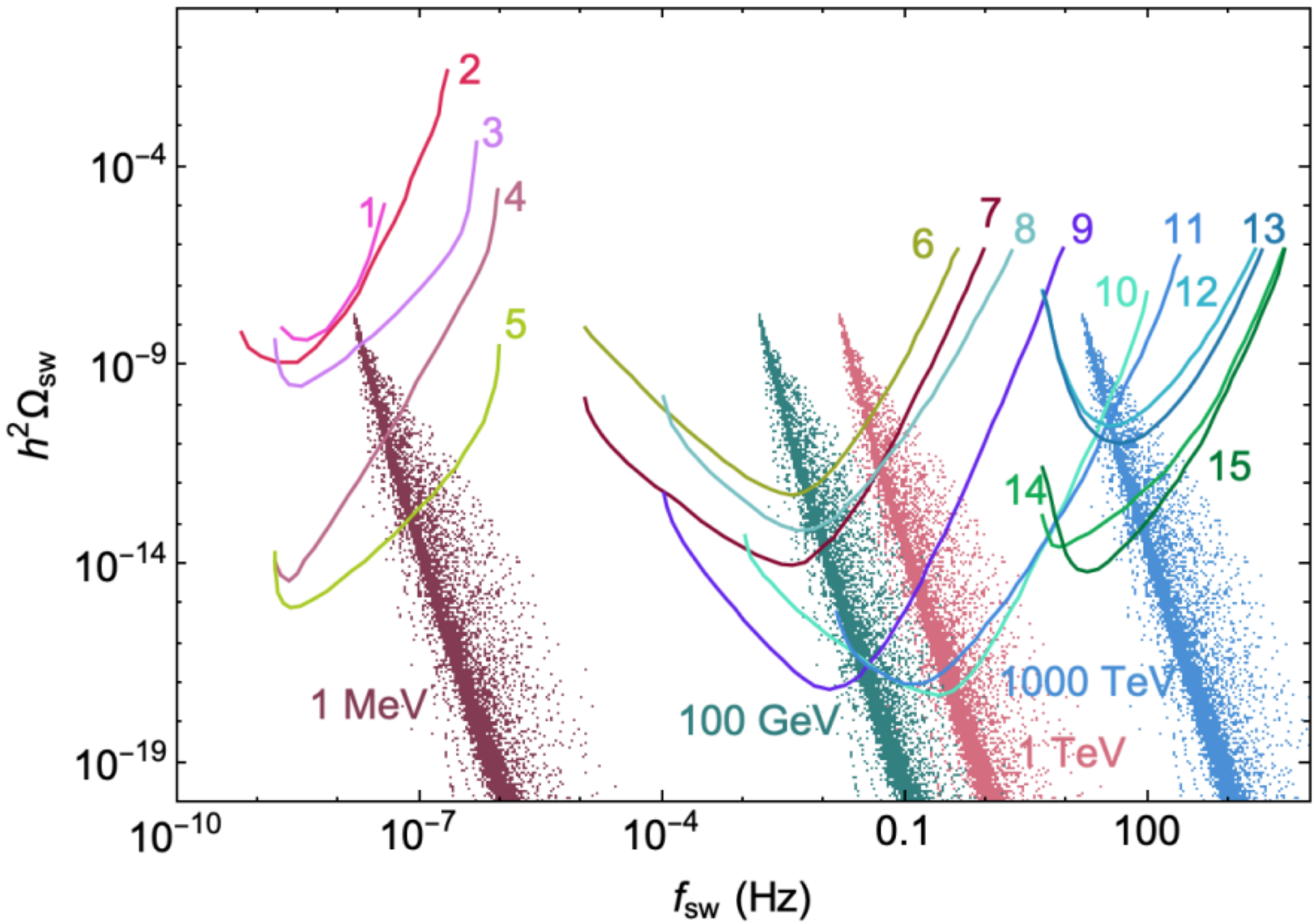
JBD, B.Dutta, S.Ghosh, J.Kumar, and J.Runburg, 2203.11736

Detectability



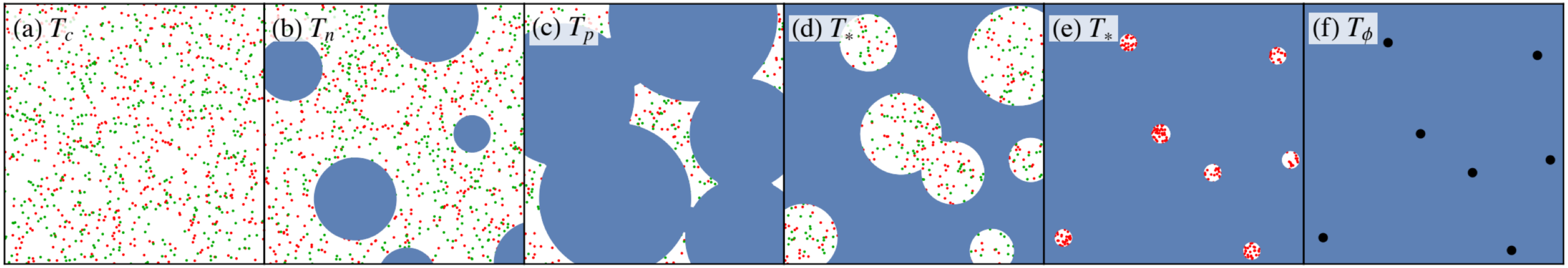


Sensitivity to Dark Sector Scales



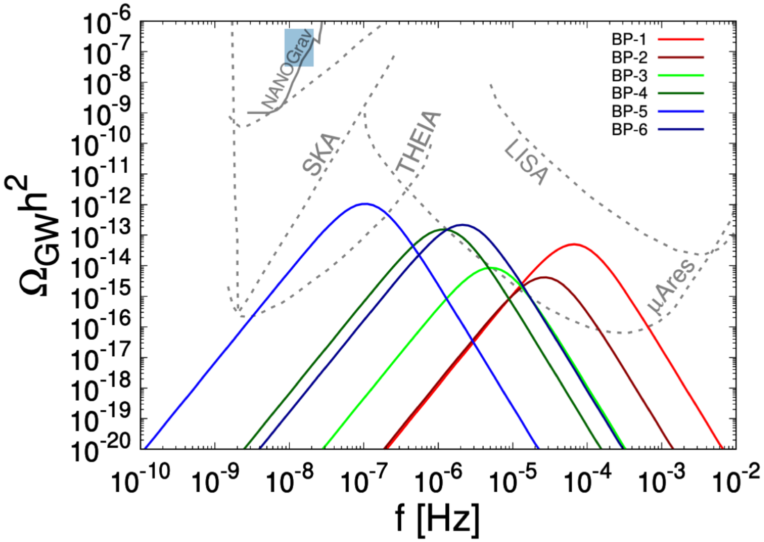
1. EPTA [133], 2. NANOGrav [134, 135], 3. Gaia [136], 4. SKA [137], 5. THEIA [138], 6. LISA [12, 139, 140], 7. Taiji [141], 8.TianQin [142], 9. ALIA [143], 10. BBO [144, 145], 11. DECIGO [146, 147], 12. aLIGO [148, 149], 13. A+ [150], 14. ET [151], 15. CE [152].

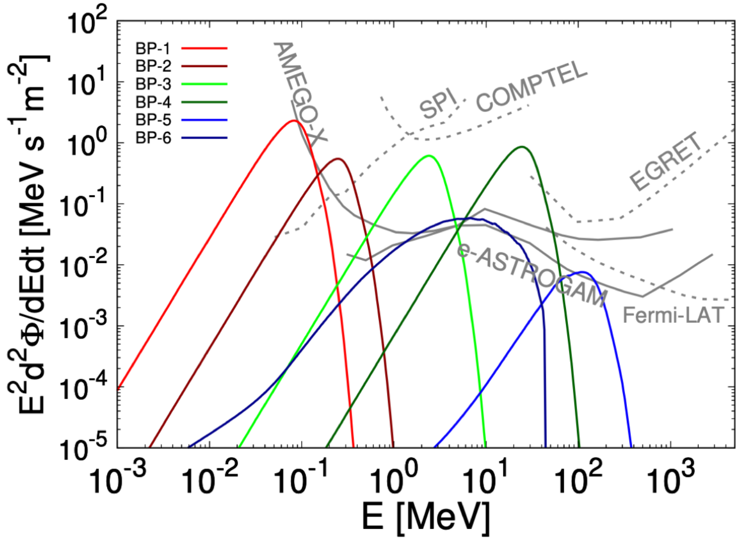
PBH and FOPT



J.-P.Hong, S.Jung, and K.-P. Xie, 2008.04430
K.Kawana, K.-P. Xie, 2106.00111

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - U(\phi) + \bar{\chi}i\partial\!\!\!/\chi - g_\chi\phi\bar{\chi}\chi$$





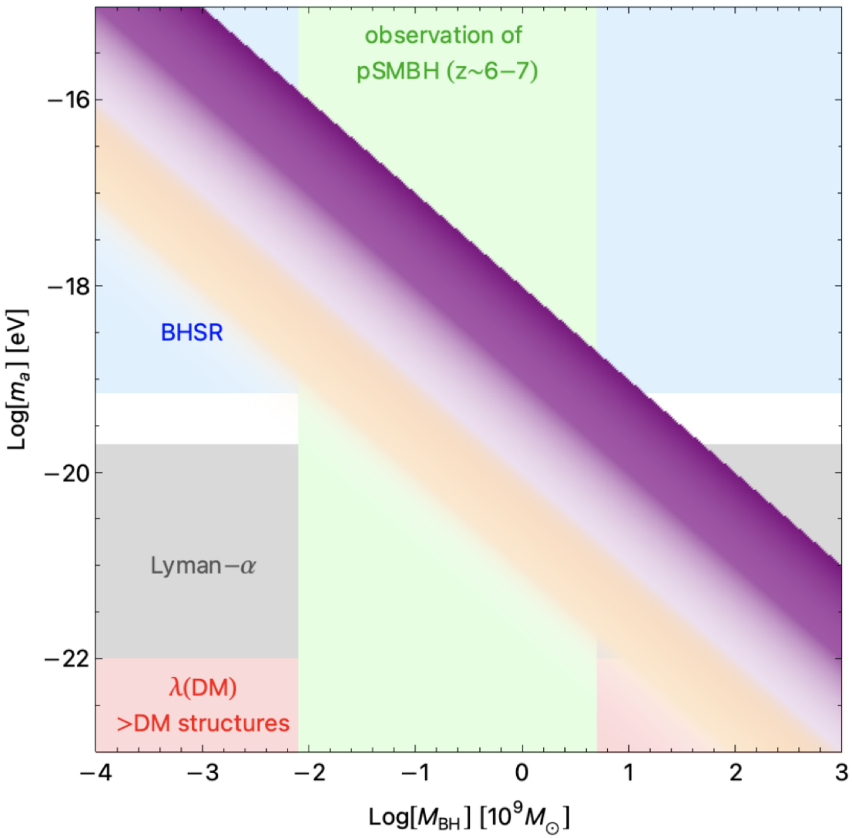
D.Marfatia, P.-Y. Seng, 2112.14588

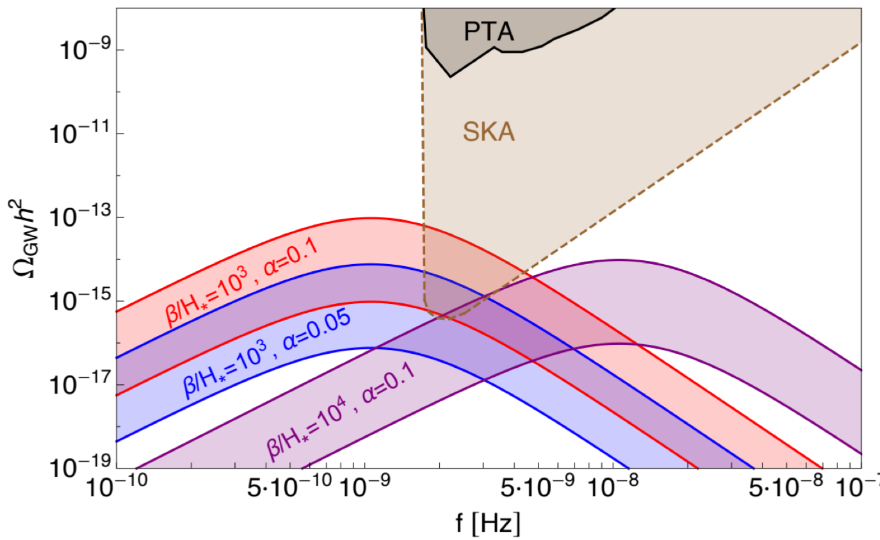
$0.1 \lesssim B^{1/4}/\text{MeV} \lesssim 10^3$

$10^{-20} \lesssim M_{\rm PBH}/M_\odot \lesssim 10^{-16}$

Superradiance and FOPT

Dark SU(3) gauge symmetry, ~10keV PT, ultralight axions connected with SMBH





$$f_{sw} = 1.1 \times 10^{-12}\ \text{Hz}\ \frac{1}{v_b}\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{10\ \text{keV}}\right)\left(\frac{g_*}{3}\right)^{1/6}$$

$$m_a = \varepsilon' \frac{M_P^3}{f_a M_{BH}}$$

$$m_a \sim \frac{\mu_a^2}{f_a} \sim 10^{-20}\ \text{eV}\left(\frac{\mu_a}{\text{keV}}\right)^2\left(\frac{10^{17}\ \text{GeV}}{f_a}\right)$$

$$f_a \in \{10^{17},\ 10^{18}\}\ \text{GeV}$$

$$\mu_a \sim T, \text{ and } R \sim 1/H$$

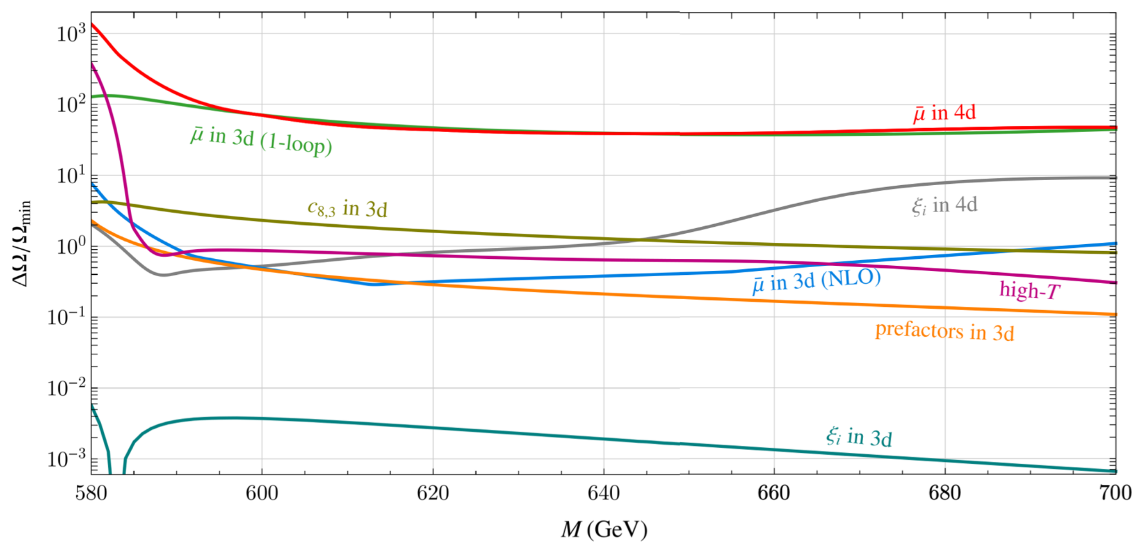
P.B.Denton, H.Davoudiasl, J.Gehrlein, 2109.01678

FOPT - Uncertainties

Thermal Parameter uncertainties

Effect	Range of error (medium)	Range of error (low)	Type of error
Transition temperature	$\mathcal{O}(10^{-4} - 10^{1})$	$\mathcal{O}(10^{-1} - 10^{0})$	Random
Mean bubble separation	$\mathcal{O}(0 - 10^{-1})$	$\mathcal{O}(10^{-1} - 10^{0})$	Suppression
Fluid velocity	$\mathcal{O}(10^{-2} - 10^{0})$	$\mathcal{O}(10^{-2} - 10^{0})$	Random
Finite lifetime	$\mathcal{O}(10^{-3} - 10^{-1})$	$\mathcal{O}(10^{1} - 10^{3})$	Enhancement
Vorticity effects	$\mathcal{O}(10^{-1} - 10^{0})$	–	Random

H.-K.Guo, K.Sinha, D.Vagie, and G.White, 2103.06993



Theory uncertainties

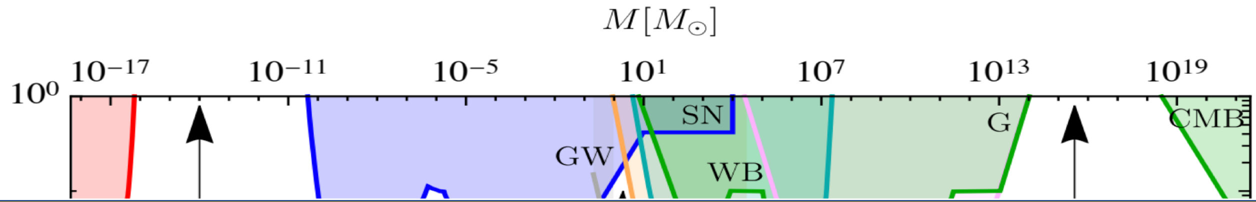
D.Croon, O.Gould, P.Schicho, T.V.I. Tenkanen, and G.White, 2009.10080

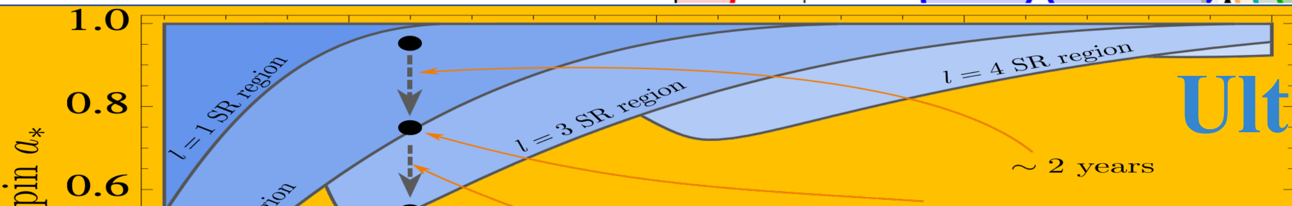
Discussion

Outline of BSM physics and GW

Particle Dark Matter

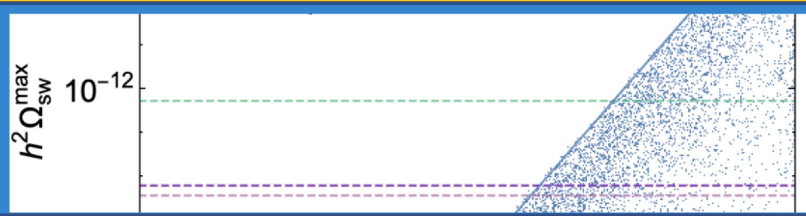
PBH

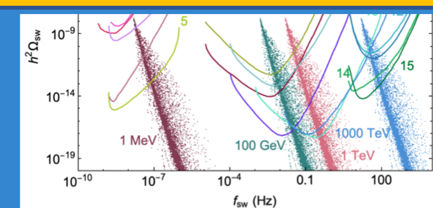


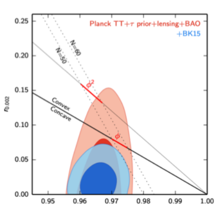


Ultralight bosons

FOPT





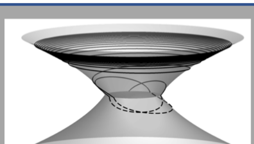


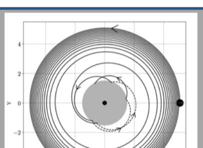
Inflation

New physics with neutron star mergers

Talk by Steven Harris

ECOs





…

Back-up Thermal parameters

Phase Transitions – the parameters (simplified)

Nucleation rate per unit volume

$$p(T) = p_0 T^4 e^{-S_3/T}$$

Provides the transition rate

$$\frac{\beta}{H} = T\frac{d(S_3/T)}{dT}$$

Bounce solution

$$\frac{\partial^2\phi}{\partial r^2} + \frac{2}{r}\frac{\partial\phi}{\partial r} = \frac{\partial V_E(T,\phi)}{\partial\phi}$$

For prob ~ $O(1)$ nucleation of a bubble per Hubble volume

$$\frac{S_3(T_n)}{T_n} \simeq 140$$

Assuming radiation domination

Phase Transitions – the parameters (simplified)

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For prob ~ $O(1)$ nucleation of a bubble per Hubble volume

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Assuming radiation domination

Percolation temperature – T_* when a fraction 1/e of space remains in the false vacuum

$$\frac{S_3(T_n)}{T_n} \simeq 141 + \log\left(\frac{A}{T_n^4}\right) - 4\log\left(\frac{T_n}{100\,\mathrm{GeV}}\right) - \log\left(\frac{\beta/H}{100}\right)$$

$$\frac{S_3(T_n)}{T_*} \simeq 141 + \log\left(\frac{A}{T_*^4}\right) - 4\log\left(\frac{T_*}{100\,\mathrm{GeV}}\right) - 4\log\left(\frac{\beta/H}{100}\right) + 3\log v_w$$

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$$\alpha(T) = \frac{1}{\rho_{\mathrm{rad}}}\left(\Delta V_T - \frac{T}{4}\frac{d\Delta V_T}{dT}\right)$$

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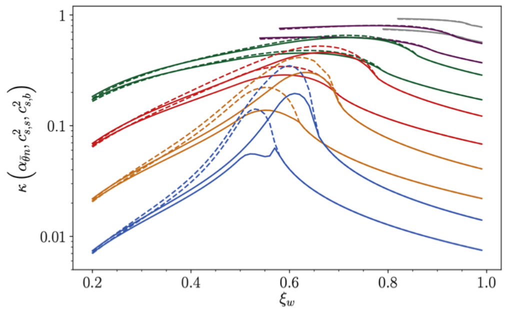
From this, the amount of available energy that is converted into bubble kinetic energy can be calculated



$$K = \frac{\rho_{\rm fl}}{e_+} = \left(\frac{\Delta\bar{\theta}}{4e_+}\right)\kappa$$

$$\kappa = \frac{4\rho_{\rm fl}}{3\alpha w_+}$$

Energy budget refs: J.R.Espinosa,T.Konstandin,J.M.No,G.Servant, JCAP 2010, 1004.4187
L.Leitao and A.Megevand,1410.3875, F.Giese, T.Konstandin, J. van de Vis, 2004.06995
F.Giese, T.Konstandin, K.Schmitz, J. van de Vis, 2010.09744

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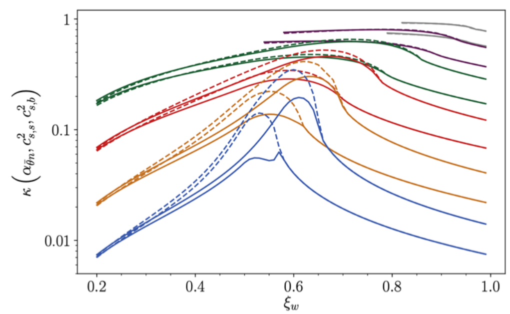

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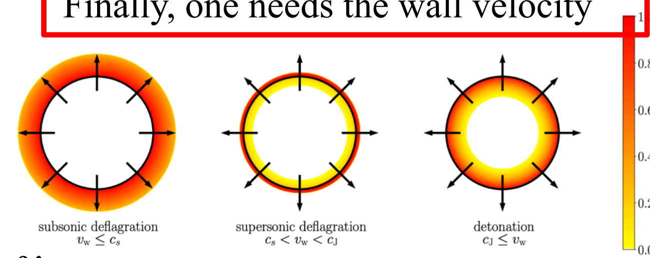
Finally, one needs the wall velocity



v_w

There is a suppression of the signal due to the source lifetime

$$\Upsilon = 1 - \frac{1}{\sqrt{1 - 2\tau_{\rm sw}H_s}}$$

$$\tau_{\rm sw} = R_*/\bar U_f$$

Wall speed refs: S.Höche, J.Kozaczuk, A.J.Long, J.Turner, and Y.Wang, 2007.10343
B.Laurent and J.M.Cline 2204.13120
M.B.Hindmarsh, M.Luben, J.Lumma, and M.Pauly, *SciPost Phys.Lect.Notes* (2021), 2008.09136