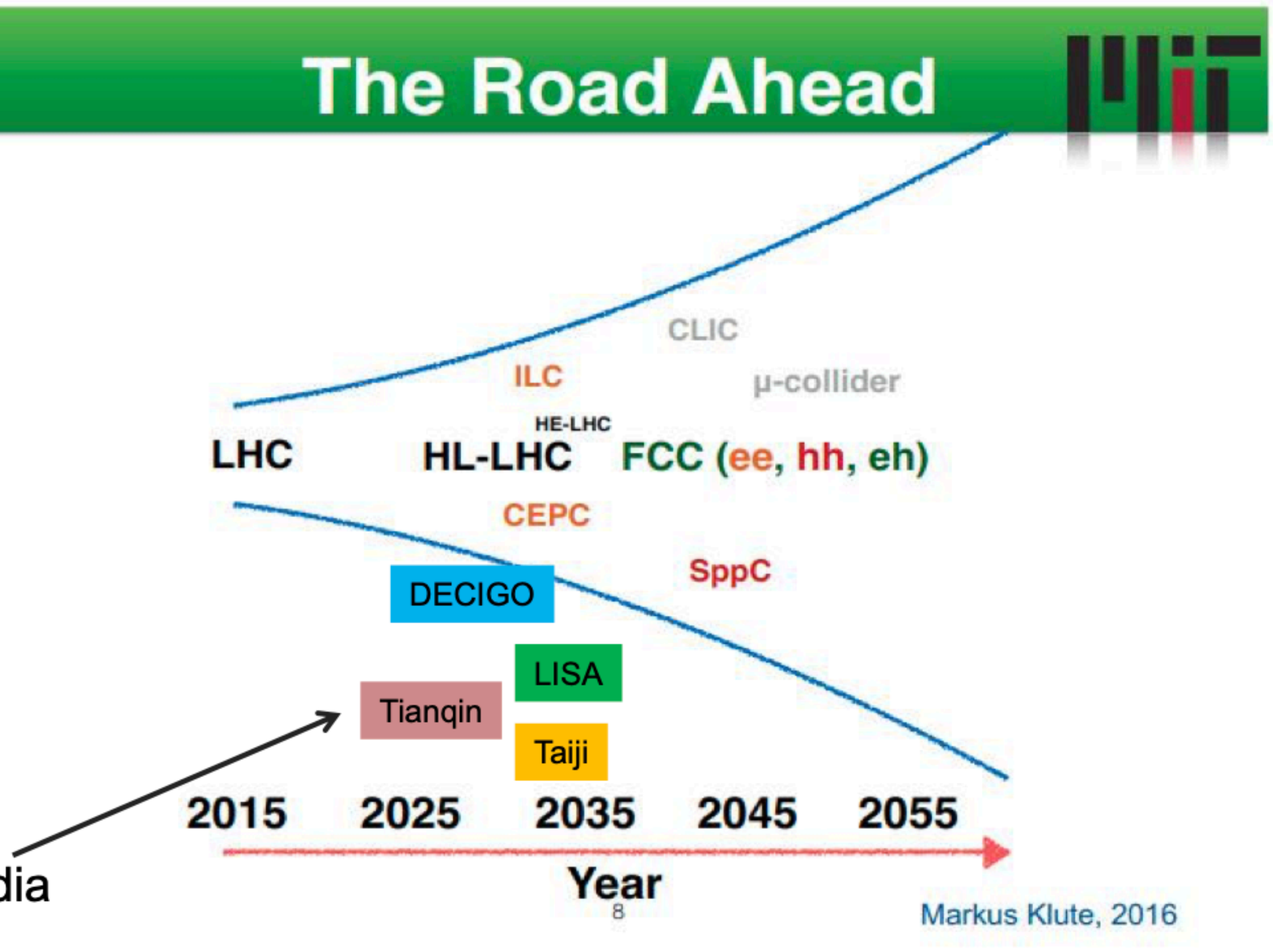
BSM Physics
at
Gravitational Wave Detectors

CETUP* Workshop 2024

Kuver Sinha
University of Oklahoma

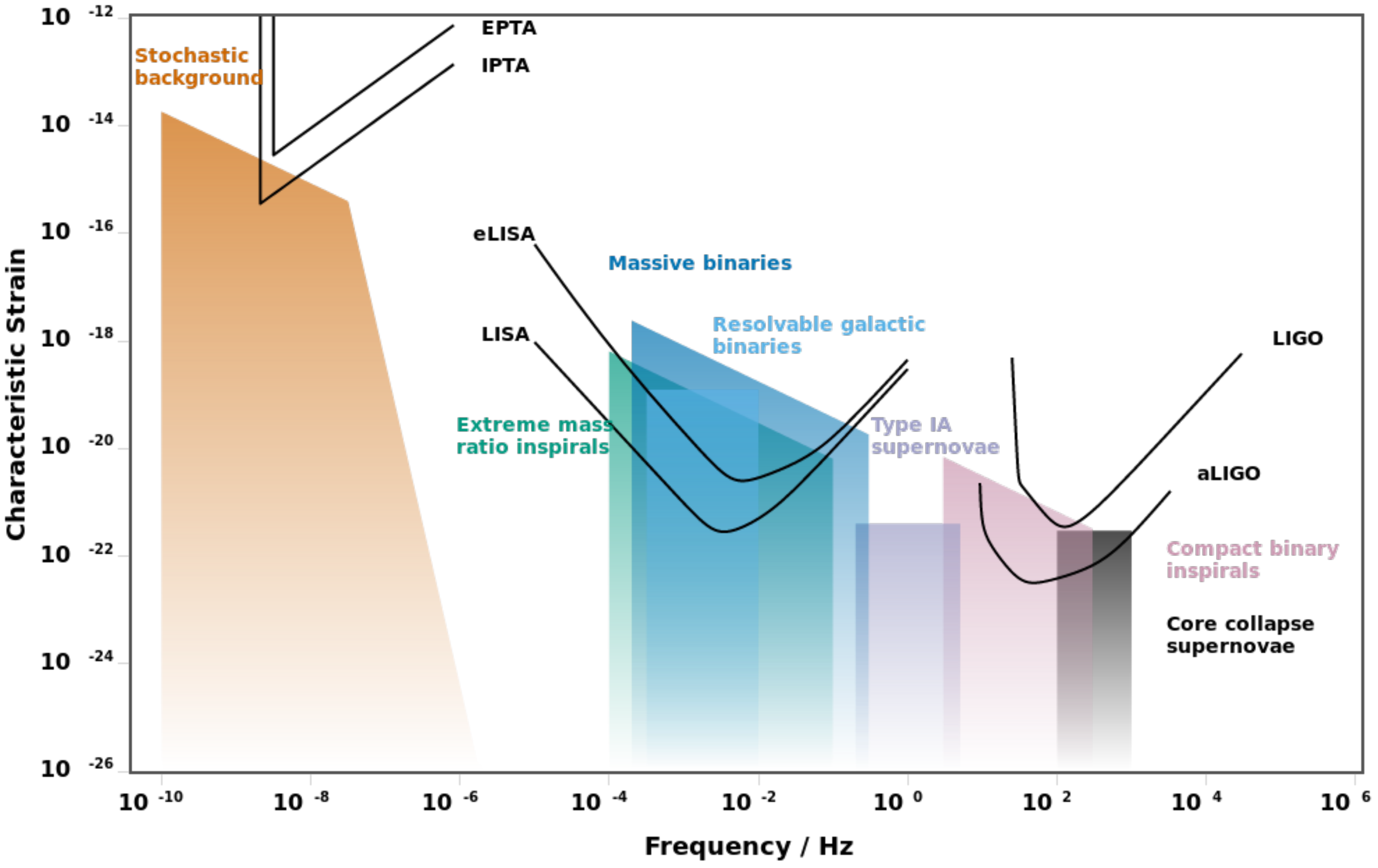
Data’s coming, folks



Wikipedia

Markus Klute, 2016

Data’s coming, folks



How do we leverage this to explore BSM physics?

BSM choices

Do you want to study BSM at the source?

or (and)

Do you want to study BSM in what happens on the way?

BSM at the Source

BSM at Source

Source itself is due to BSM physics (phase transitions)

Source is astrophysical, BSM exchange deforms signal

Source is astrophysical, probes BSM in its environment

Source is astrophysical, serves as a clock (multimessenger)

Source: Phase Transition

Take the simplest template (xSM) and obtain robust GW predictions

mass resummation in thermal field theory

modeling of relativistic hydrodynamics for sound waves in plasma

needs a lot of work

H. Guo, J.No, F. Hajkarim, KS, G. White (JHEP06 2021)
H. Guo, KS, G. White, D. Vagie (JHEP06 2021)
H. Guo, KS, G. White, D. Vagie (JCAP01 2021)

Take various particle physics models and obtain GW predictions

deformed Higgs sectors, extra scalars, SSB of gauge groups, etc.

connect to dark sectors, baryogenesis, flavor physics, etc.

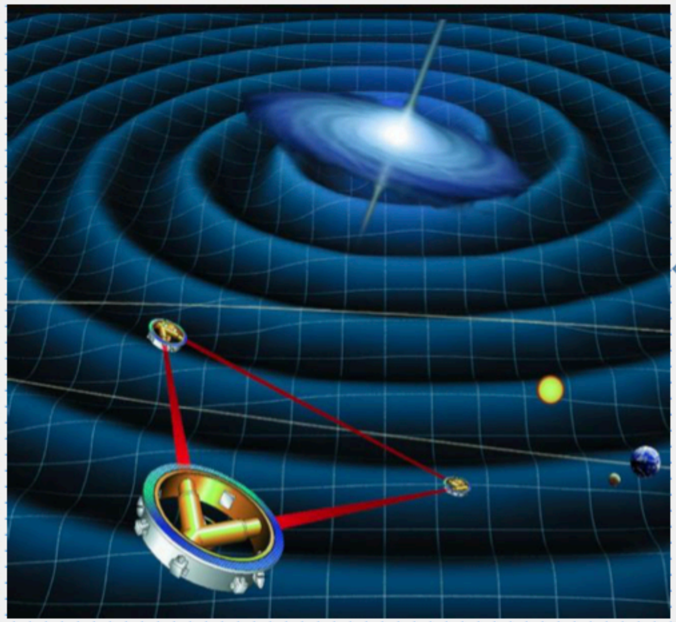
typically use fit functions for GW spectrum

lots of interesting work by our community!

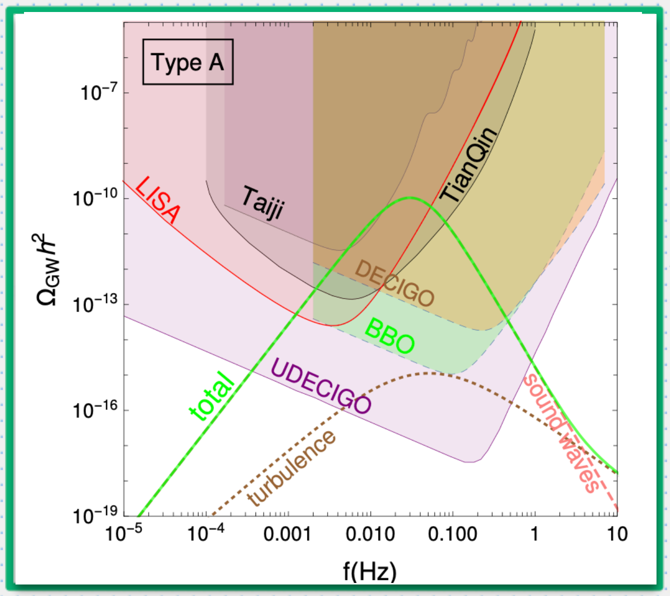
A. Alves, T. Ghosh, D. Goncalves, H. Guo, KS (JHEP03 2020)
A. Alves, T. Ghosh, H. Guo, KS (JHEP04 2019)
A. Alves, T. Ghosh, H. Guo, KS (JHEP12 2018)

Workflow: Phase Transitions

theoretical calculation of gravitational wave spectrum and detector simulation



LIGO, LISA, Taiji, Tianqin...



Gravitational Wave Spectrum

α

β

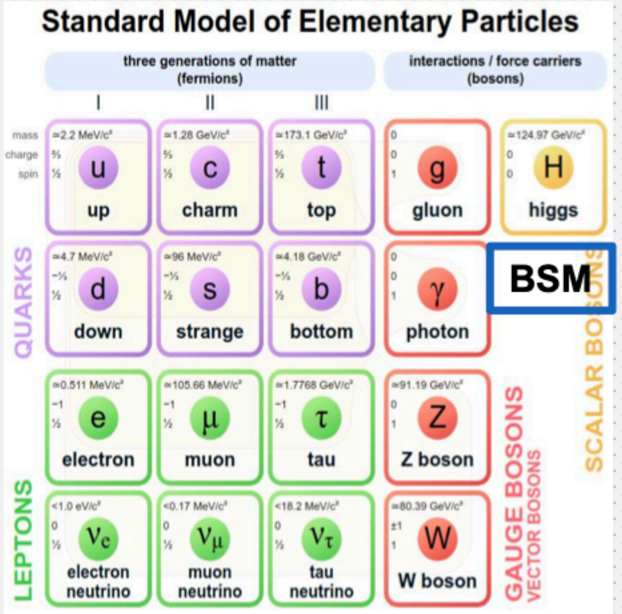
v_w

T_*

g_s

...

Phase Transition Parameters



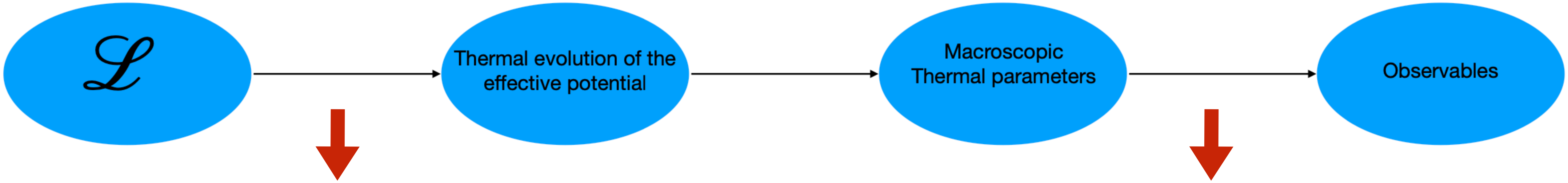
Standard Model of Elementary Particles

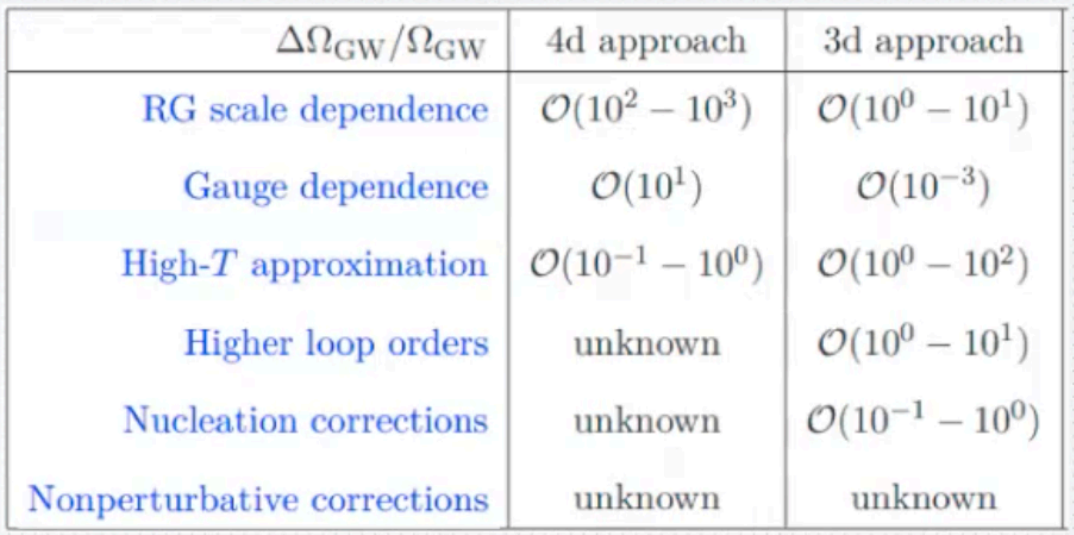
three generations of matter (fermions) I	II	III	interactions / force carriers (bosons)	
≈2.2 MeV/c² ⅔ ½ u up	≈1.28 GeV/c² ⅔ ½ c charm	≈173.1 GeV/c² ⅔ ½ t top	0 0 1 g gluon	≈124.97 GeV/c² 0 0 H higgs
≈4.7 MeV/c² −⅓ ½ d down	≈96 MeV/c² −⅓ ½ s strange	≈4.18 GeV/c² −⅓ ½ b bottom	0 0 1 γ photon	**BSM**
≈0.511 MeV/c² −1 ½ e electron	≈105.66 MeV/c² −1 ½ μ muon	≈1.7768 GeV/c² −1 ½ τ tau	≈91.19 GeV/c² 0 1 Z Z boson	
<1.0 eV/c² 0 ½ ν_e electron neutrino	<0.17 MeV/c² 0 ½ ν_μ muon neutrino	<18.2 MeV/c² 0 ½ ν_τ tau neutrino	≈80.39 GeV/c² ±1 1 W W boson	

Particle Physics Model

data analysis, constraints or discovery(parameter estimation)

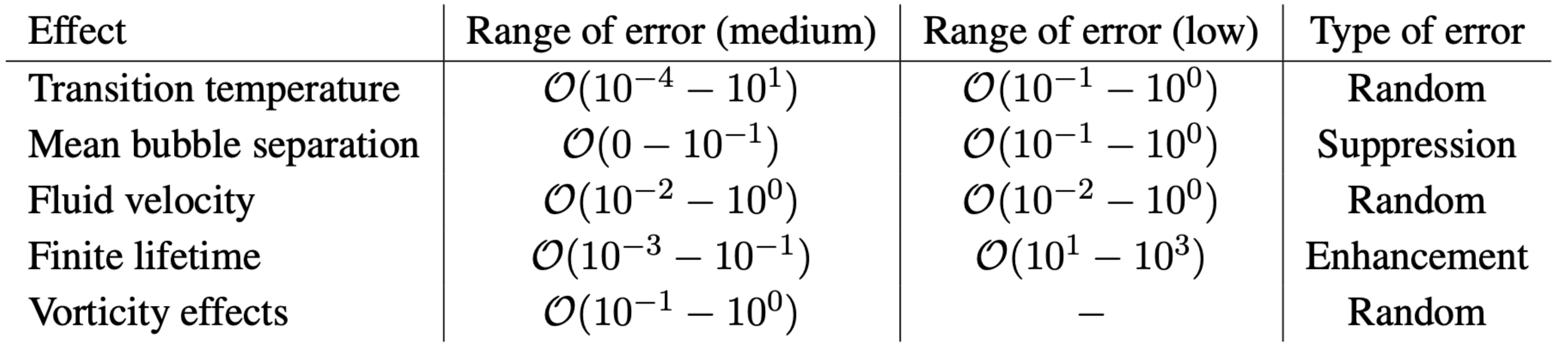
Uncertainties in Phase Transition Calculations



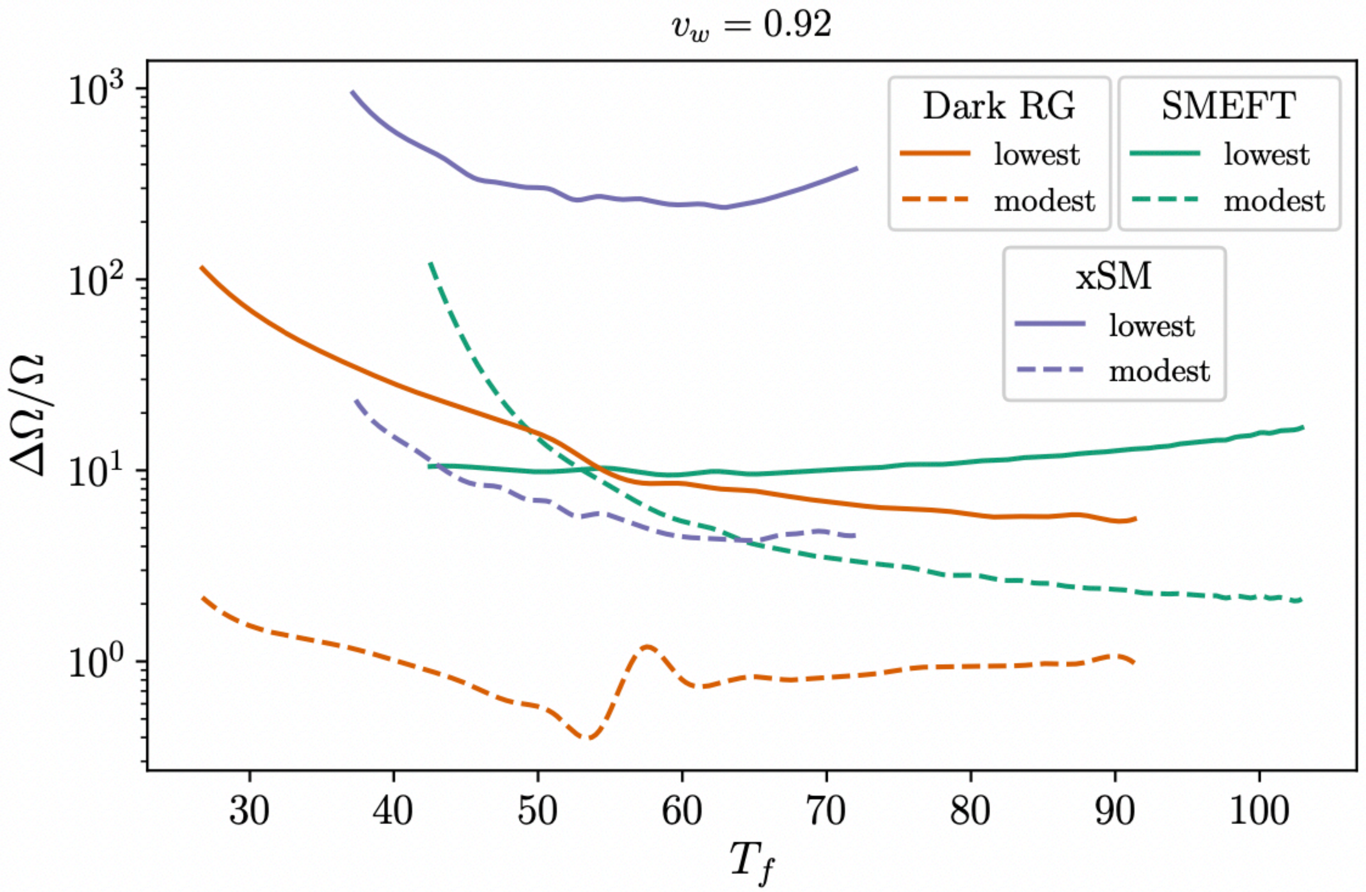


$\Delta\Omega_{\rm GW}/\Omega_{\rm GW}$	4d approach	3d approach
RG scale dependence	$\mathcal{O}(10^2 - 10^3)$	$\mathcal{O}(10^0 - 10^1)$
Gauge dependence	$\mathcal{O}(10^1)$	$\mathcal{O}(10^{-3})$
High-T approximation	$\mathcal{O}(10^{-1} - 10^0)$	$\mathcal{O}(10^0 - 10^2)$
Higher loop orders	unknown	$\mathcal{O}(10^0 - 10^1)$
Nucleation corrections	unknown	$\mathcal{O}(10^{-1} - 10^0)$
Nonperturbative corrections	unknown	unknown

Croon, Gould, Schicho, Tenkanen, White, JHEP04(2021)055



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. Guo, J.No, F. Hajkarim, KS, G. White (JHEP06 2021)

H. Guo, KS, G. White, D. Vagie (JHEP06 2021)

H. Guo, KS, G. White, D. Vagie (JCAP01 2021)

Precision GW Calculations

False vacuum fraction

H. Guo, KS, G. White, D. Vagie (JHEP06 2021)

The false vacuum fraction at $t > t_c$ in an expanding universe is defined as

$$g(t_c, t) = \exp\left[-\frac{4\pi}{3}\int_{t_c}^{t} dt' p(t') a^3(t') r(t', t)^3\right] \equiv \exp\left[-I(t)\right], \tag{2.16}$$

where $I(t)$ represents the volume of nucleated bubbles per comoving volume, double counting the overlapped space between bubbles and virtual bubbles within others [112]. The comoving radius of a bubble nucleated at t' and measured at t is

$$r(t', t) = \int_{t'}^{t} dt'' \frac{v_w}{a(t'')} = v_w\left(\eta' - \eta\right), \tag{2.17}$$

False vacuum fraction - function of temperature

$$r(T', T) = \frac{v_w}{a_c}\int_{T}^{T'} \frac{dT''}{T''}\frac{1}{\gamma H(T'')}\left(\frac{T_c}{T''}\right)^{-1/\gamma}, \tag{2.24}$$

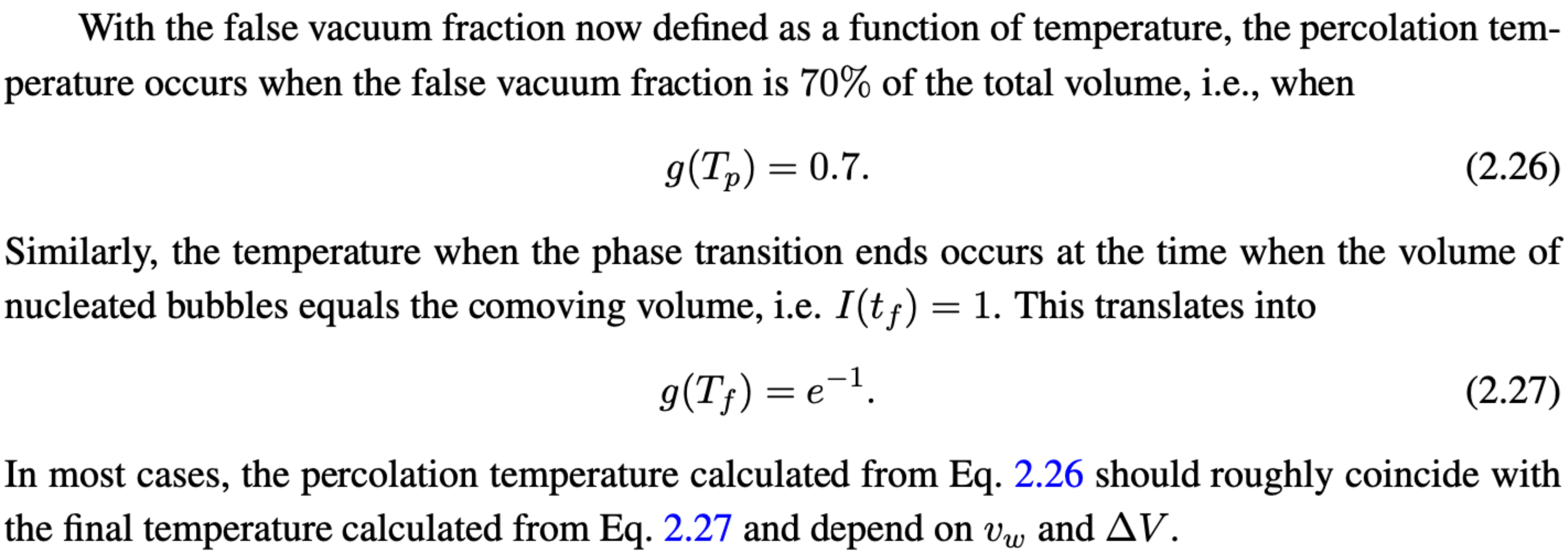
$$I(T) = \frac{4\pi}{3}\int_{T}^{T_c} \frac{dT'}{T'}\frac{1}{\gamma H(T')}\bar{p}_0 T'^4 \exp\left[-\frac{S_3(T')}{T'}\right]\left(\frac{T_c}{T'}\right)^{3/\gamma}\left[a_c r\left(T', T\right)\right]^3, \tag{2.25}$$

with $g(T_c, T) = \exp\left[-I(T)\right]$.

Precision GW Calculations

Percolation temperature

H. Guo, KS, G. White, D. Vagie (JHEP06 2021)



With the false vacuum fraction now defined as a function of temperature, the percolation temperature occurs when the false vacuum fraction is 70% of the total volume, i.e., when

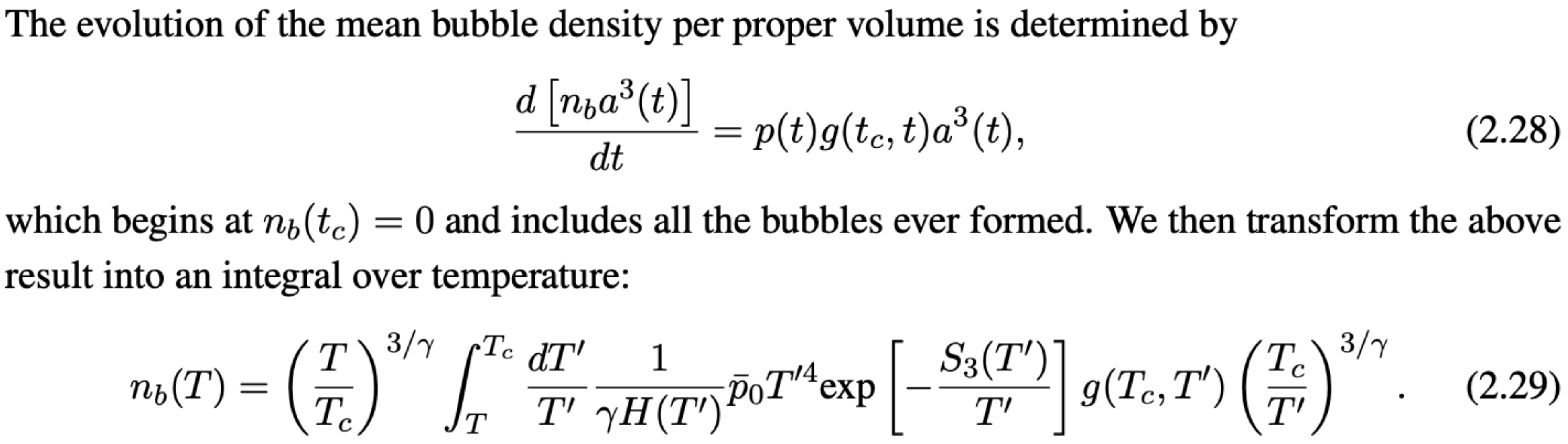
$$g(T_p) = 0.7. \tag{2.26}$$

Similarly, the temperature when the phase transition ends occurs at the time when the volume of nucleated bubbles equals the comoving volume, i.e. $I(t_f) = 1$. This translates into

$$g(T_f) = e^{-1}. \tag{2.27}$$

In most cases, the percolation temperature calculated from Eq. 2.26 should roughly coincide with the final temperature calculated from Eq. 2.27 and depend on v_w and ΔV.

Bubble number density



The evolution of the mean bubble density per proper volume is determined by

$$\frac{d\left[n_b a^3(t)\right]}{dt} = p(t) g(t_c, t) a^3(t), \tag{2.28}$$

which begins at $n_b(t_c) = 0$ and includes all the bubbles ever formed. We then transform the above result into an integral over temperature:

$$n_b(T) = \left(\frac{T}{T_c}\right)^{3/\gamma} \int_T^{T_c} \frac{dT'}{T'} \frac{1}{\gamma H(T')} \bar{p}_0 T'^4 \exp\left[-\frac{S_3(T')}{T'}\right] g(T_c, T') \left(\frac{T_c}{T'}\right)^{3/\gamma}. \tag{2.29}$$

Precision GW Calculations

Calculation of mean bubble separation

The mean bubble separation R_* is related to the mean bubble number density and is given by

$$R_* = \left(\frac{1}{n_b}\right)^{1/3}. \tag{2.31}$$

Calculation of \beta

$$R_*(\eta) = \frac{a(\eta)}{a(\eta_f)}(8\pi)^{1/3}\frac{v_w}{\beta(v_w)}, \tag{2.38}$$

where $R_{*,c} = R_*/a(\eta)$ and $\beta_c = a(\eta_f)\beta$. The above result can be transformed into a function of temperature using a relation similar to Eq. 2.21 to give

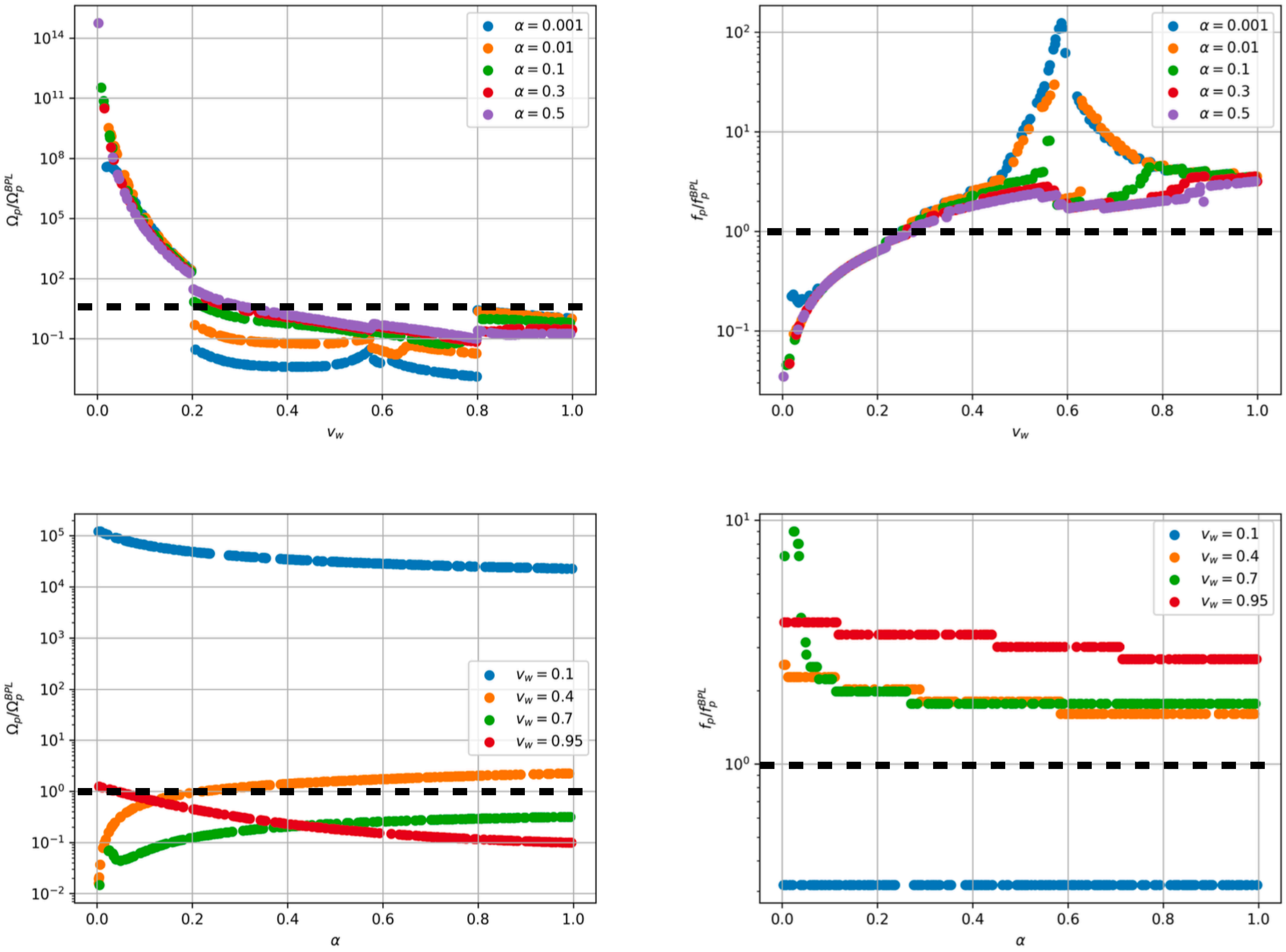
$$\frac{a(\eta)}{a(\eta_f)} = \left(\frac{T_f}{T}\right)^{1/\gamma}. \tag{2.39}$$

The procedure to calculate the inverse time duration of the phase transition at T_f for a fixed v_w is

1. Find T_f from the false vacuum fraction $g(T_c, T)$ for when $I(T_f) = 1$;
2. Calculate $n_b(T_f)$;
3. Use $R_*(T_f) = \left(\frac{1}{n_b(T_f)}\right)^{1/3}$;
4. Solve Eq. 2.38 using Eq. 2.39 to get $\beta(v_w)$.

H. Guo, KS, G. White, D. Vagie (JHEP06 2021)

Uncertainties in Phase Transition Calculations

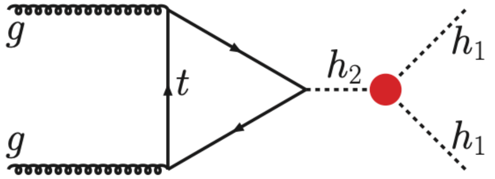


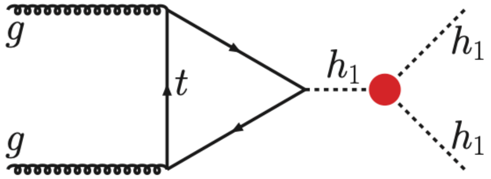
F. Hajkarim, H. Guo, KS, G. White (in progress)

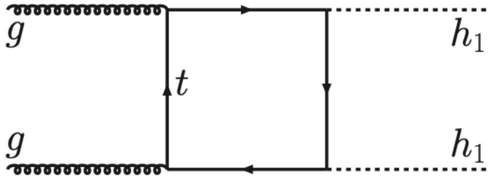
Complementarity

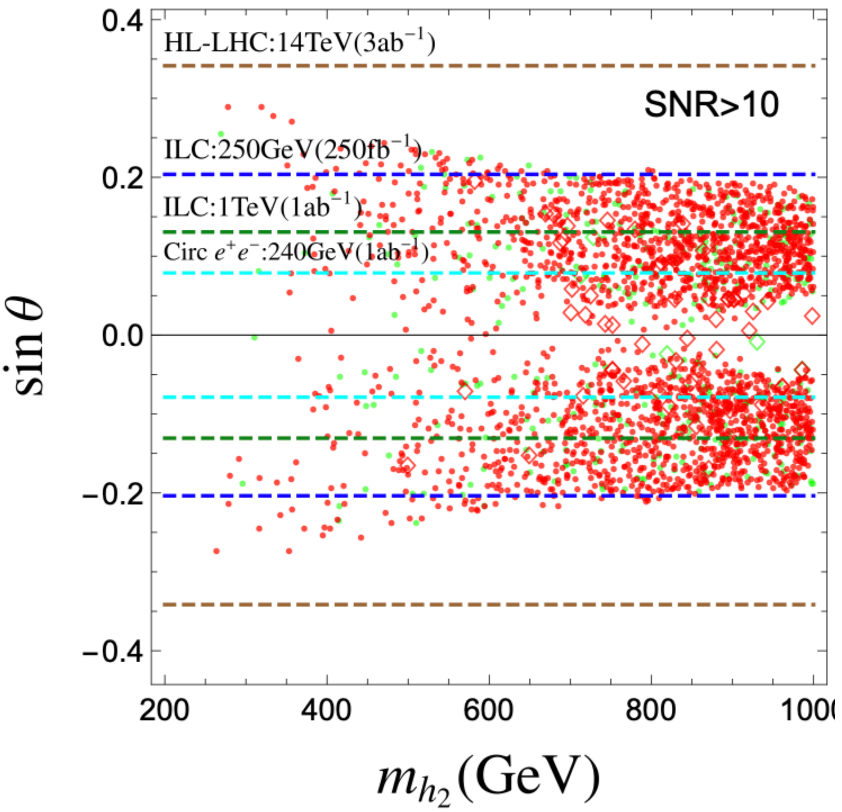
$$V(H,S) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{a_1}{2} H^\dagger H S + \frac{a_2}{2} H^\dagger H S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

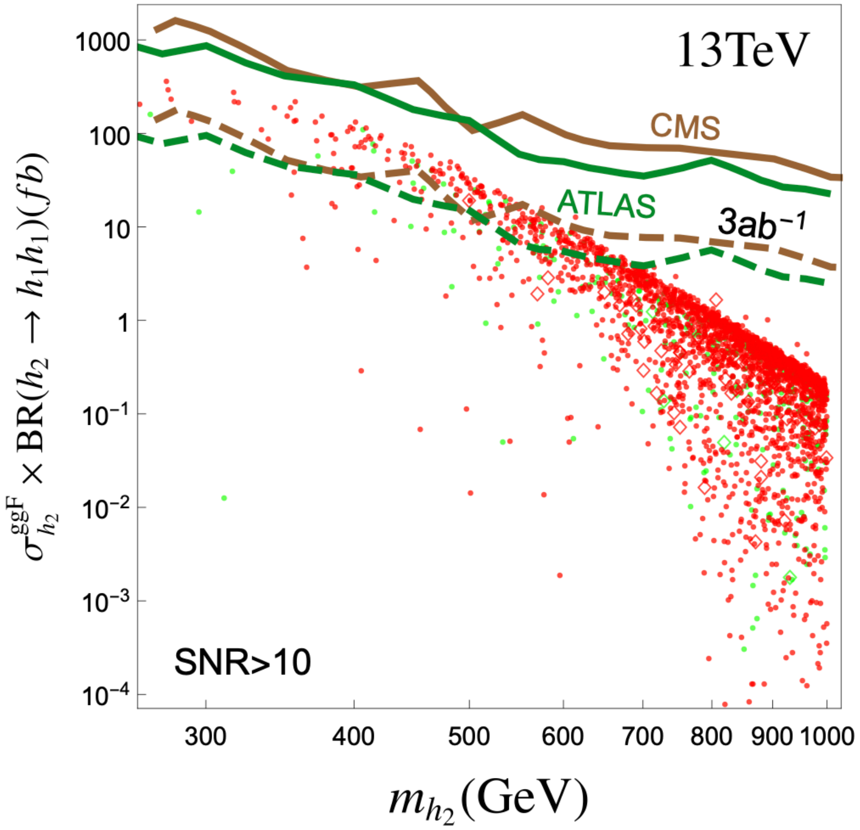
A. Alves, T. Ghosh, D. Goncalves, H. Guo, KS (PLB818 2021)
A. Alves, T. Ghosh, D. Goncalves, H. Guo, KS (JHEP03 2020)
A. Alves, T. Ghosh, H. Guo, KS (JHEP04 2019)
A. Alves, T. Ghosh, H. Guo, KS (JHEP12 2018)

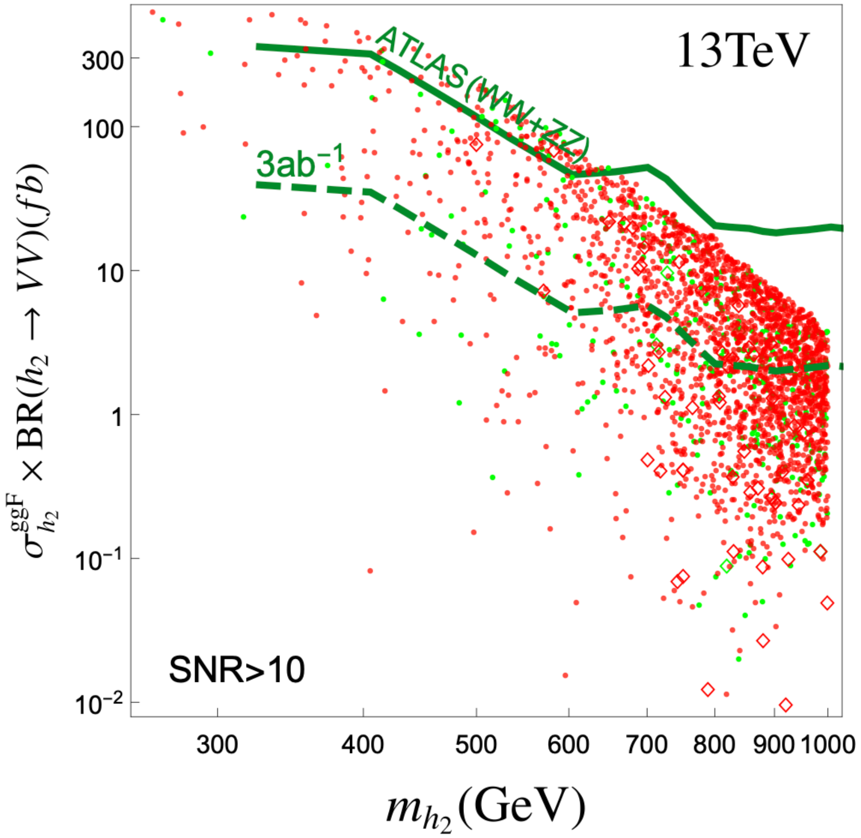












BSM at Source

Source itself is due to BSM physics (phase transitions)

Source is astrophysical, BSM exchange deforms signal

Source is astrophysical, probes BSM in its environment

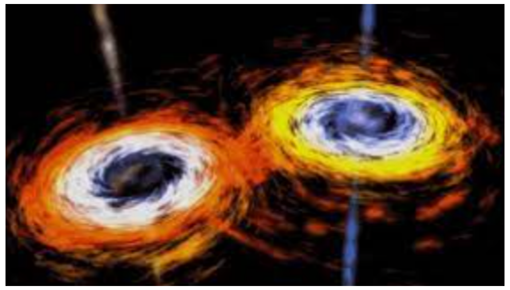
Source is astrophysical, serves as a clock (multimessenger)

Binary Inspiral

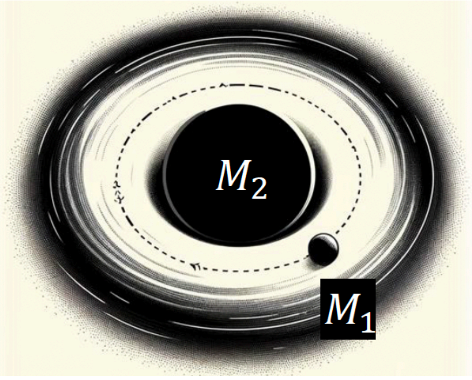
Binary inspirals can serve as probes of light dark mediators, under the assumption that they accumulate dark charge

The wavelength of the mediator that can be probed is primarily fixed by the length scale of the binary system

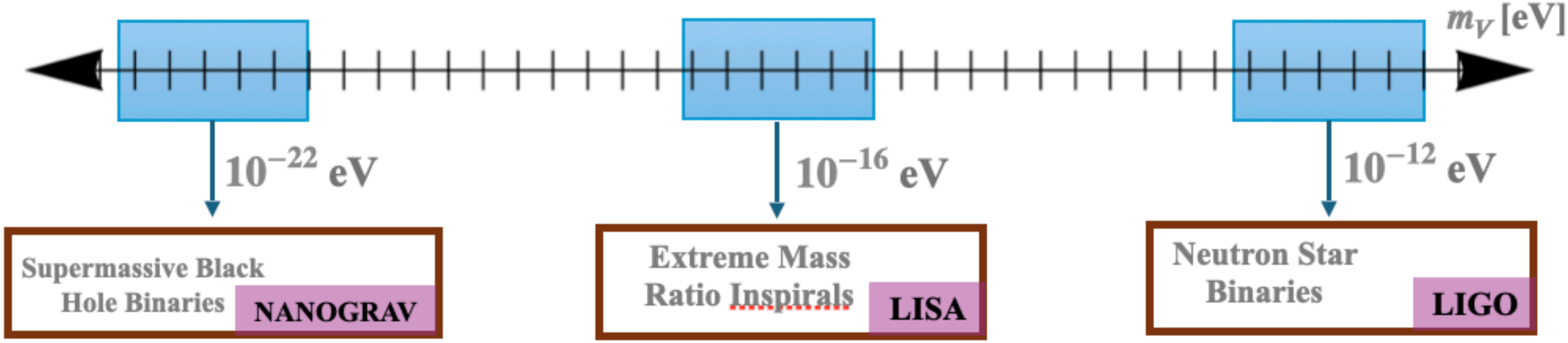
Dror, Lehmann, Profumo (PRD104 2021)



Bhalla, KS, Xu (2024)



Dror, Laha, Opferkuch (PRD102, 2020)
Kopp, Laha, Opferkuch, Shepherd (JHEP 11, 2018)
Croon, Nelson, Sun, Walker (APJL 858,2018)



m_V [eV]

10^{-22} eV

Supermassive Black Hole Binaries **NANOGRAV**

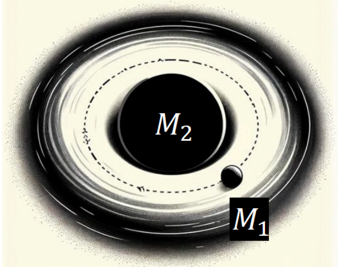
10^{-16} eV

Extreme Mass Ratio Inspirals **LISA**

10^{-12} eV

Neutron Star Binaries **LIGO**

EMRIs, Dark Forces

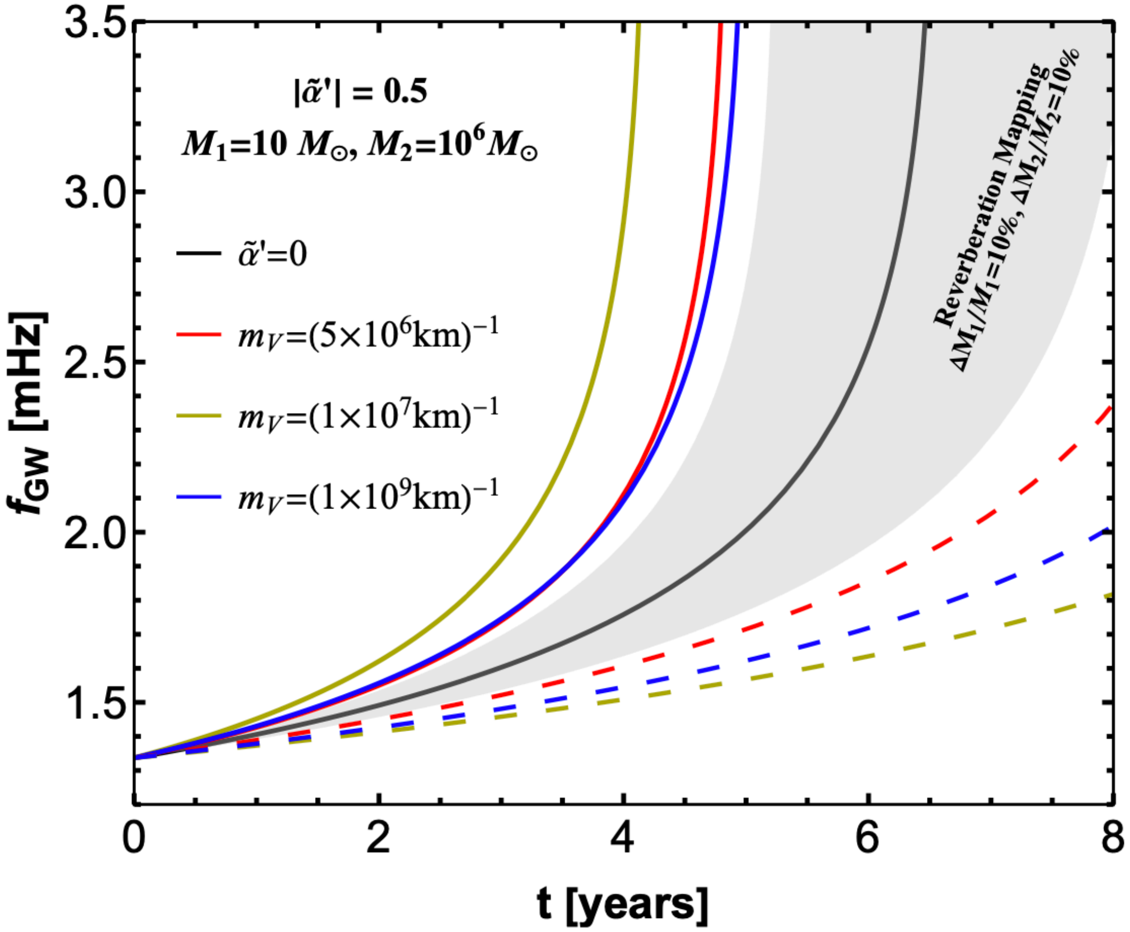


$$|\vec{F}_{\text{total}}| = \frac{GM_1M_2}{r^2}[1+\tilde{\alpha}'e^{-m_V r}(1+m_V r)],$$

time evolution of orbital frequency

$$\frac{d\omega}{dt} = -\frac{32}{5}G\,\mu\,\omega^5\,r^2\,g\,\mathcal{N}^{-1}.$$

$$g = -\frac{3+\tilde{\alpha}'e^{-m_V r}\,(3+m_V r(3+m_V r))}{1+\tilde{\alpha}'e^{-m_V r}\,(1+m_V r(1-m_V r))}$$



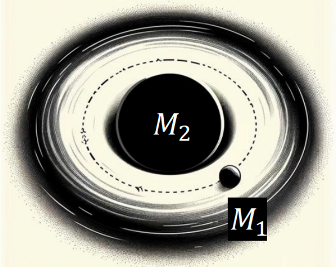
Multimessenger studies needed since rescaling the binary component masses can mimic the dark force

$$F_{TOTAL} = \frac{GM_1{}'M_2{}'}{r^2}$$

Reverberation mapping, dynamical tracers

Bhalla, KS, Xu (2024)

EMRIs, Dark Forces

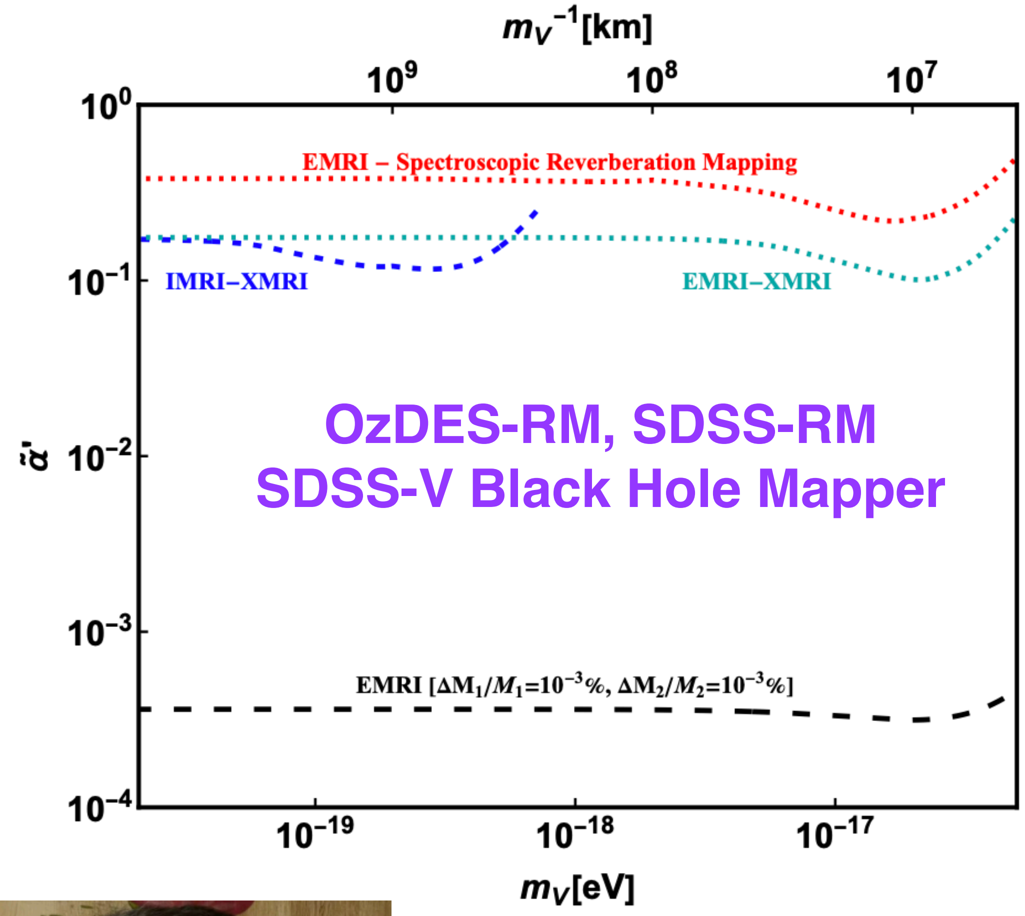


The rms amplitude of the GW emitted for the dominant m=2 mode

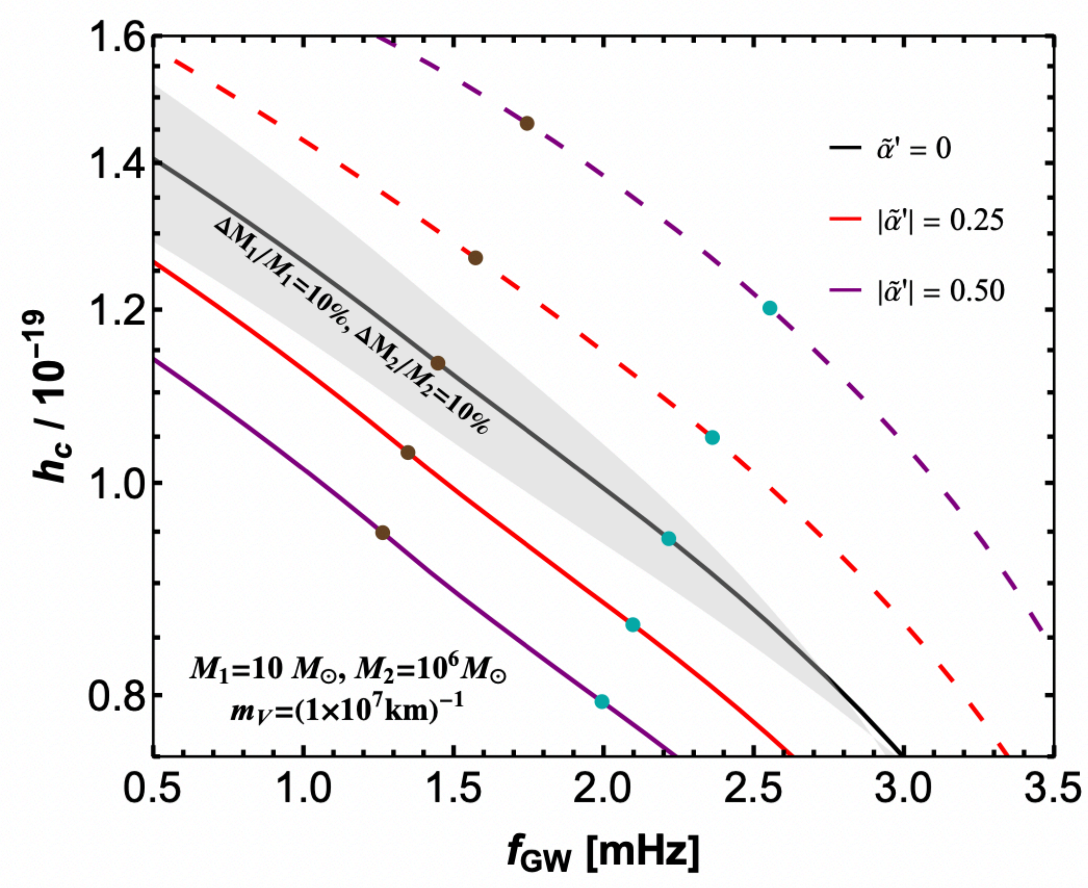
$$h_{o,2} = \sqrt{\frac{32}{5}}\,\frac{\eta\, G\, M_2}{d_L}\,(G\, M_2\, \omega)^{2/3}\,\mathcal{H}_{o,2}.$$

dL is the luminosity distance from Earth

$$h_{c,m} \equiv h_{o,m}\sqrt{2 f_{\mathrm{GW},m}^2 / \dot{f}_{\mathrm{GW},m}}$$



OzDES-RM, SDSS-RM
SDSS-V Black Hole Mapper



Badal Bhalla

BSM at Source

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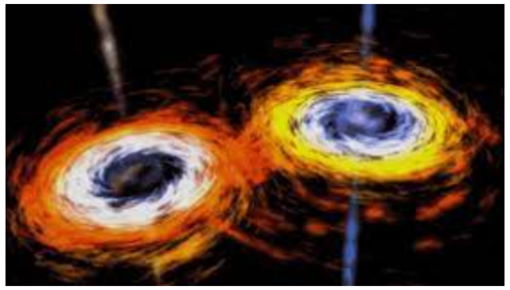
Binary Probes Environment



A stellar black hole or neutron star will accumulate a dark matter spike around it

The spike distorts the GW waveform from binary inspiral: “dark dressed black holes”

Kavanaugh, Bertone et.al. (2020 -)

SMBH binaries exist at the centers of merging galaxies

In a sense, you can think of NANOGrav is an instrument for probing galactic centers

SMBH binaries inspire an “existence problem”: why do they exist and how did they get so close?

The seed problem (exacerbated by JWST) and the final parsec problem

Can you speed up accretion? How about bigger seeds? PBH seeds don’t work…

Final parsec: dynamical friction increased by SIDM? BEC 3-body encounters?

Bromley, Sandick, Shams Es Haghi (2023)

Alvarez, Cline, Dewar (2024)

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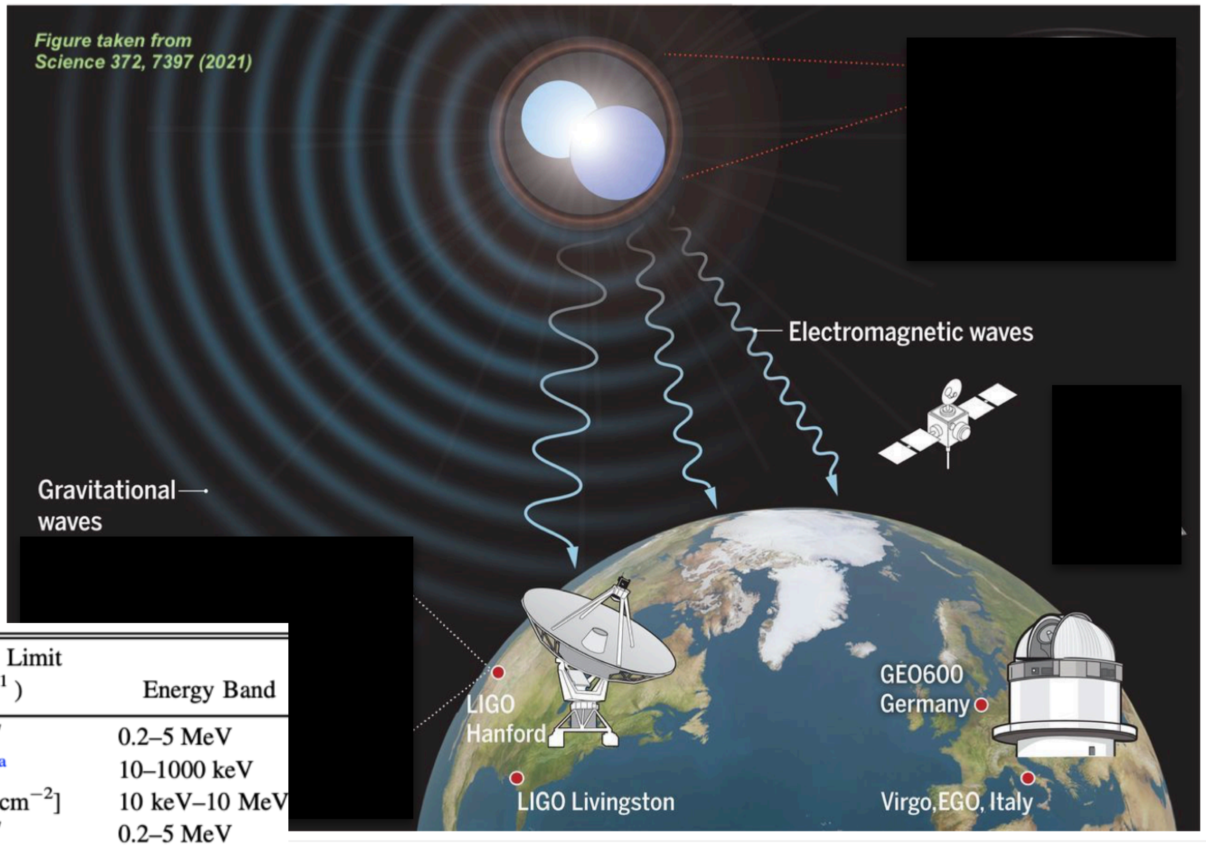
Neutron Star Mergers

GW signal sets an alarm clock t=0

If your BSM signal has time dependence from moment of emission (eg due to decay lifetime), use multiessenger studies

The energy of your emission dictates facility you want to use

Multi-messenger Observation of Binary Neutron Star Merger GW170817



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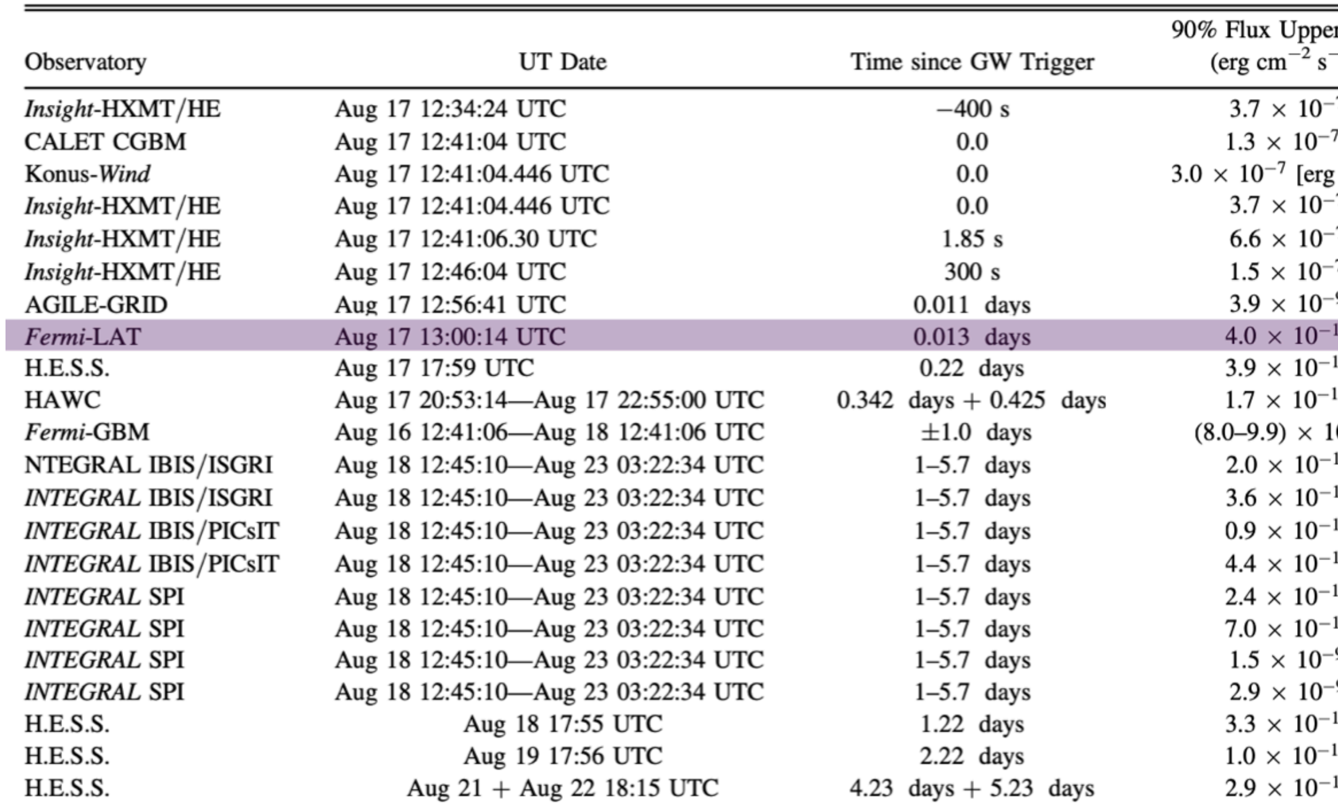
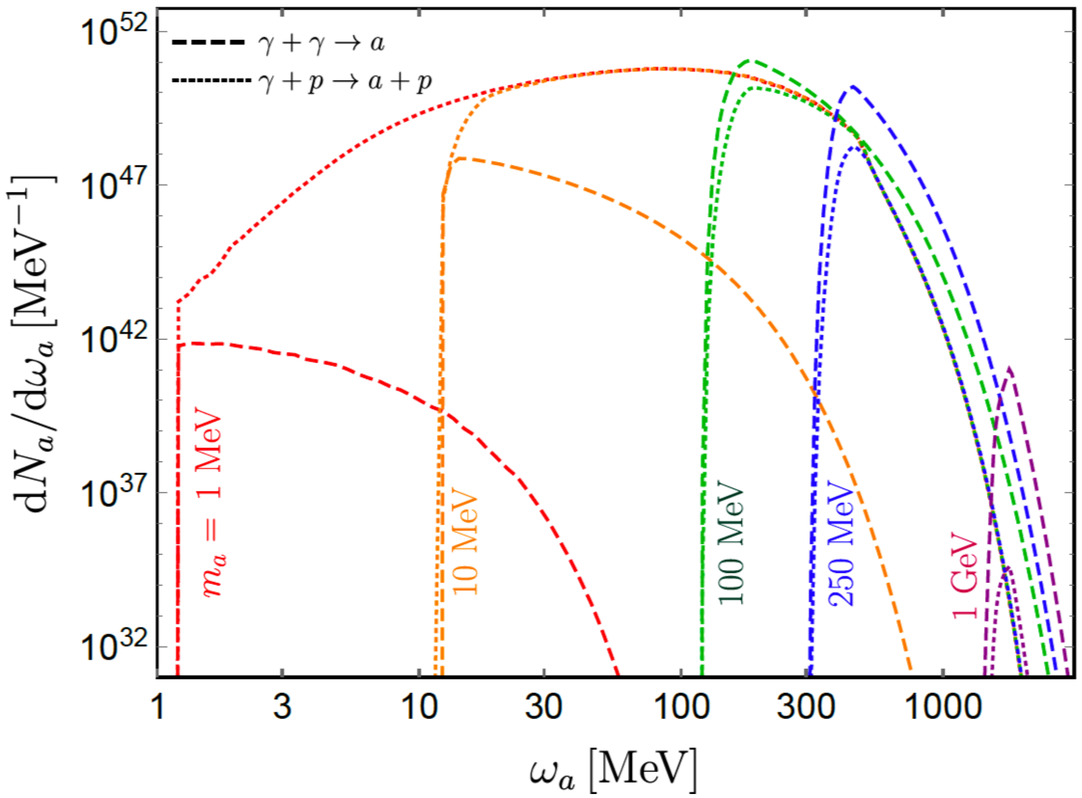


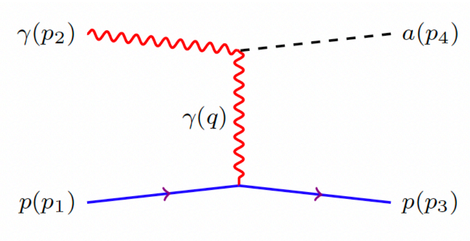
Observatory	UT Date	Time since GW Trigger	90% Flux Upper Limit (erg cm^{-2} s^{-1})	Energy Band
Insight-HXMT/HE	Aug 17 12:34:24 UTC	−400 s	3.7×10^{-7}	0.2–5 MeV
CALET CGBM	Aug 17 12:41:04 UTC	0.0	1.3×10^{-7}[a]	10–1000 keV
Konus-*Wind*	Aug 17 12:41:04.446 UTC	0.0	3.0×10^{-7} [erg cm^{-2}]	10 keV–10 MeV
Insight-HXMT/HE	Aug 17 12:41:04.446 UTC	0.0	3.7×10^{-7}	0.2–5 MeV
Insight-HXMT/HE	Aug 17 12:41:06.30 UTC	1.85 s	6.6×10^{-7}	0.2–5 MeV
Insight-HXMT/HE	Aug 17 12:46:04 UTC	300 s	1.5×10^{-7}	0.2–5 MeV
AGILE-GRID	Aug 17 12:56:41 UTC	0.011 days	3.9×10^{-9}	0.03–3 GeV
Fermi-LAT	Aug 17 13:00:14 UTC	0.013 days	4.0×10^{-10}	0.1–1 GeV
H.E.S.S.	Aug 17 17:59 UTC	0.22 days	3.9×10^{-12}	0.28–2.31 TeV
HAWC	Aug 17 20:53:14—Aug 17 22:55:00 UTC	0.342 days + 0.425 days	1.7×10^{-10}	4–100 TeV
Fermi-GBM	Aug 16 12:41:06—Aug 18 12:41:06 UTC	±1.0 days	$(8.0–9.9) \times 10^{-10}$	20–100 keV
NTEGRAL IBIS/ISGRI	Aug 18 12:45:10—Aug 23 03:22:34 UTC	1–5.7 days	2.0×10^{-11}	20–80 keV
INTEGRAL IBIS/ISGRI	Aug 18 12:45:10—Aug 23 03:22:34 UTC	1–5.7 days	3.6×10^{-11}	80–300 keV
INTEGRAL IBIS/PICsIT	Aug 18 12:45:10—Aug 23 03:22:34 UTC	1–5.7 days	0.9×10^{-10}	468–572 keV
INTEGRAL IBIS/PICsIT	Aug 18 12:45:10—Aug 23 03:22:34 UTC	1–5.7 days	4.4×10^{-10}	572–1196 keV
INTEGRAL SPI	Aug 18 12:45:10—Aug 23 03:22:34 UTC	1–5.7 days	2.4×10^{-10}	300–500 keV
INTEGRAL SPI	Aug 18 12:45:10—Aug 23 03:22:34 UTC	1–5.7 days	7.0×10^{-10}	500–1000 keV
INTEGRAL SPI	Aug 18 12:45:10—Aug 23 03:22:34 UTC	1–5.7 days	1.5×10^{-9}	1000–2000 keV
INTEGRAL SPI	Aug 18 12:45:10—Aug 23 03:22:34 UTC	1–5.7 days	2.9×10^{-9}	2000–4000 keV
H.E.S.S.	Aug 18 17:55 UTC	1.22 days	3.3×10^{-12}	0.27–3.27 TeV
H.E.S.S.	Aug 19 17:56 UTC	2.22 days	1.0×10^{-12}	0.31–2.88 TeV
H.E.S.S.	Aug 21 + Aug 22 18:15 UTC	4.23 days + 5.23 days	2.9×10^{-12}	0.50–5.96 TeV

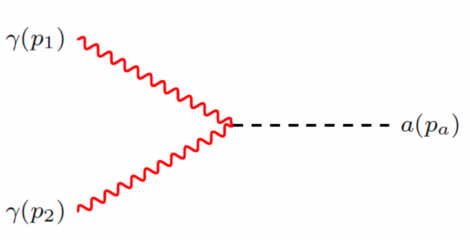
Target: axions

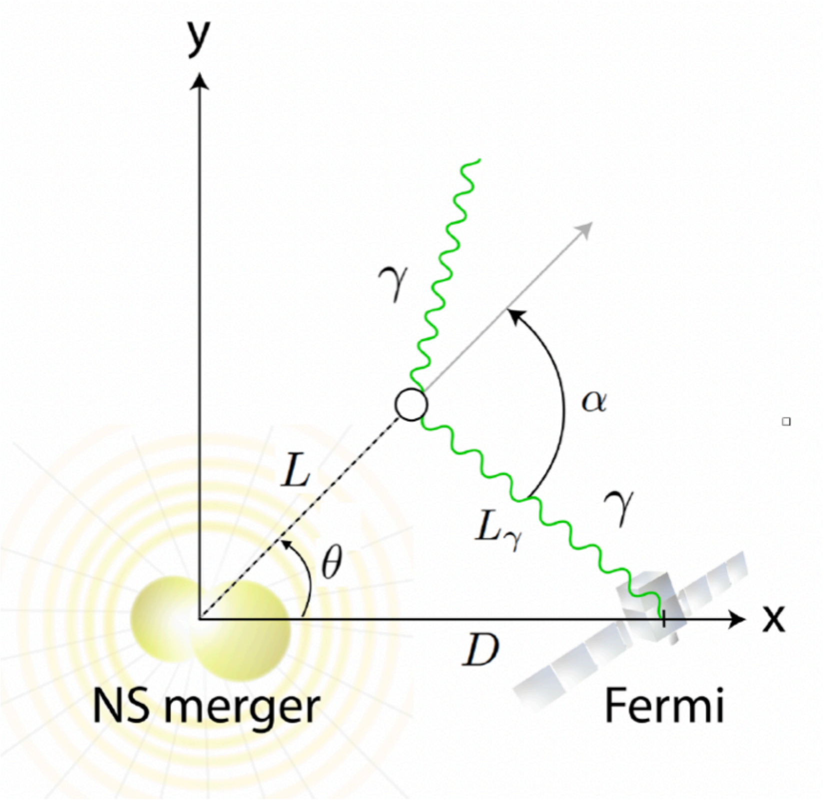
Alford, Fortin, Harris, KS (JCAP 07, 2020)
Dev, Fortin, Harris, KS, Zhang (JCAP 01, 2022)
Dev, Fortin, Harris, KS, Zhang (PRL 132, 2024)

Neutron Star Mergers





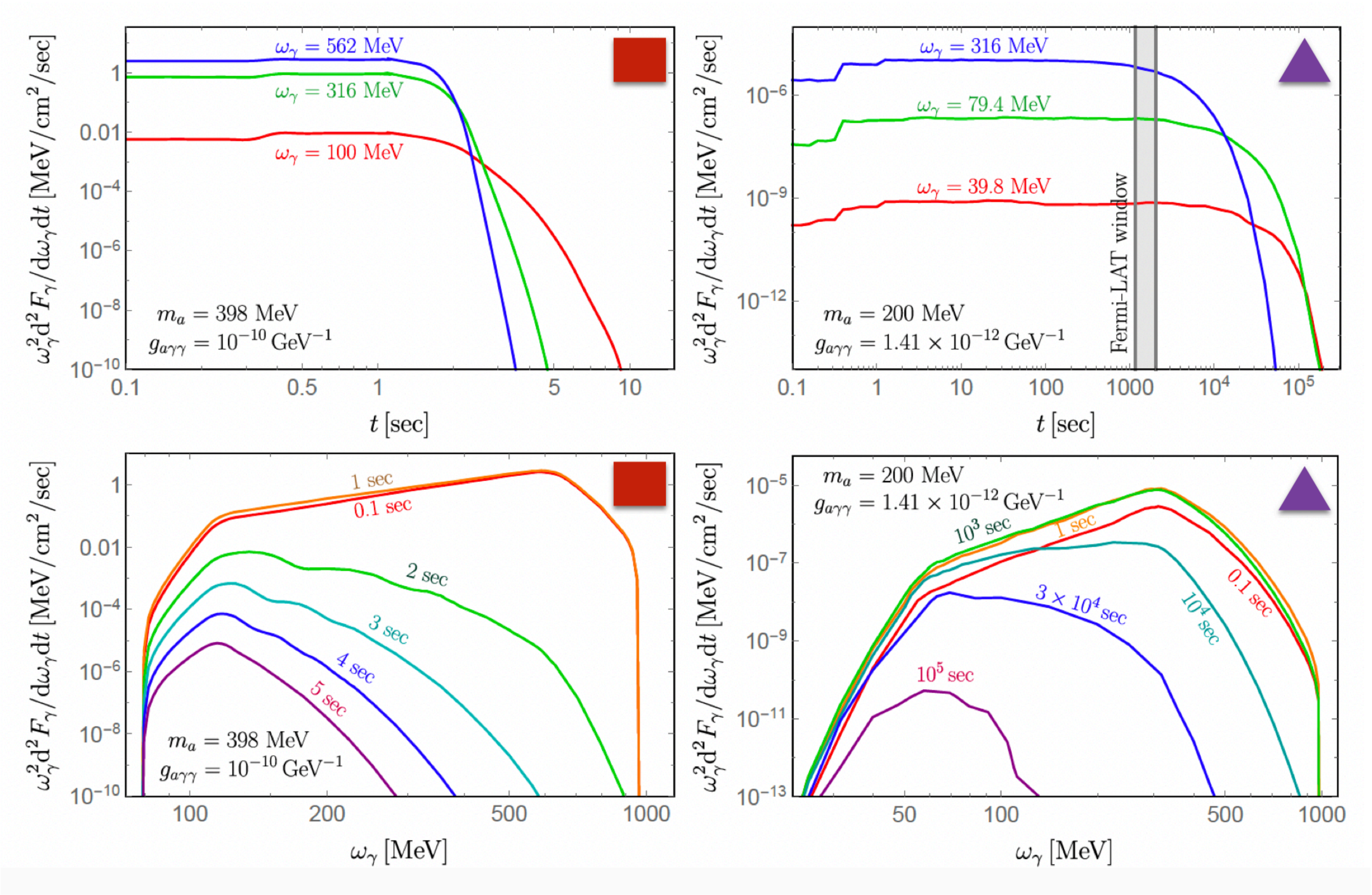




$$\omega_\gamma^2 \frac{\mathrm{d}^2 F_\gamma}{\mathrm{d}\omega_\gamma \mathrm{d}t}(\omega_\gamma, D+t) = \int_{-1}^{1} \mathrm{d}z \int_0^\infty \mathrm{d}L \, \frac{\omega_\gamma^2}{4\pi D(L_\gamma + Lz)} \frac{\mathrm{d}^2 N_a}{\mathrm{d}\omega_a \mathrm{d}t}(\omega_a, D + t - L/\beta_a - L_\gamma) \mathrm{Jac}(\omega_a, \omega_\gamma)$$
$$\times \frac{m_a^2}{\omega_a^2 (1-\beta_a z)^2} \frac{\exp\left(-L/\ell_a\right)}{\ell_a} \Theta(L - R_\star)\Theta(L - D/\sqrt{1-z^2})\,.$$

Dev, Fortin, Harris, KS, Zhang (PRL 132, 2024)

Neutron Star Mergers

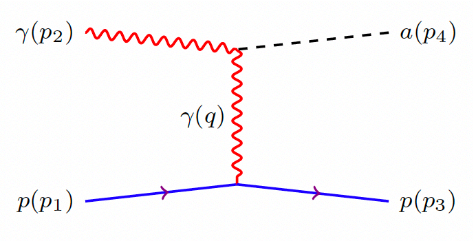


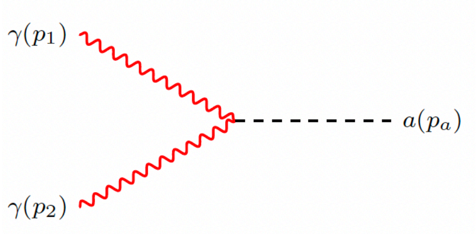
Dev, Fortin, Harris, KS, Zhang (PRL 132, 2024)

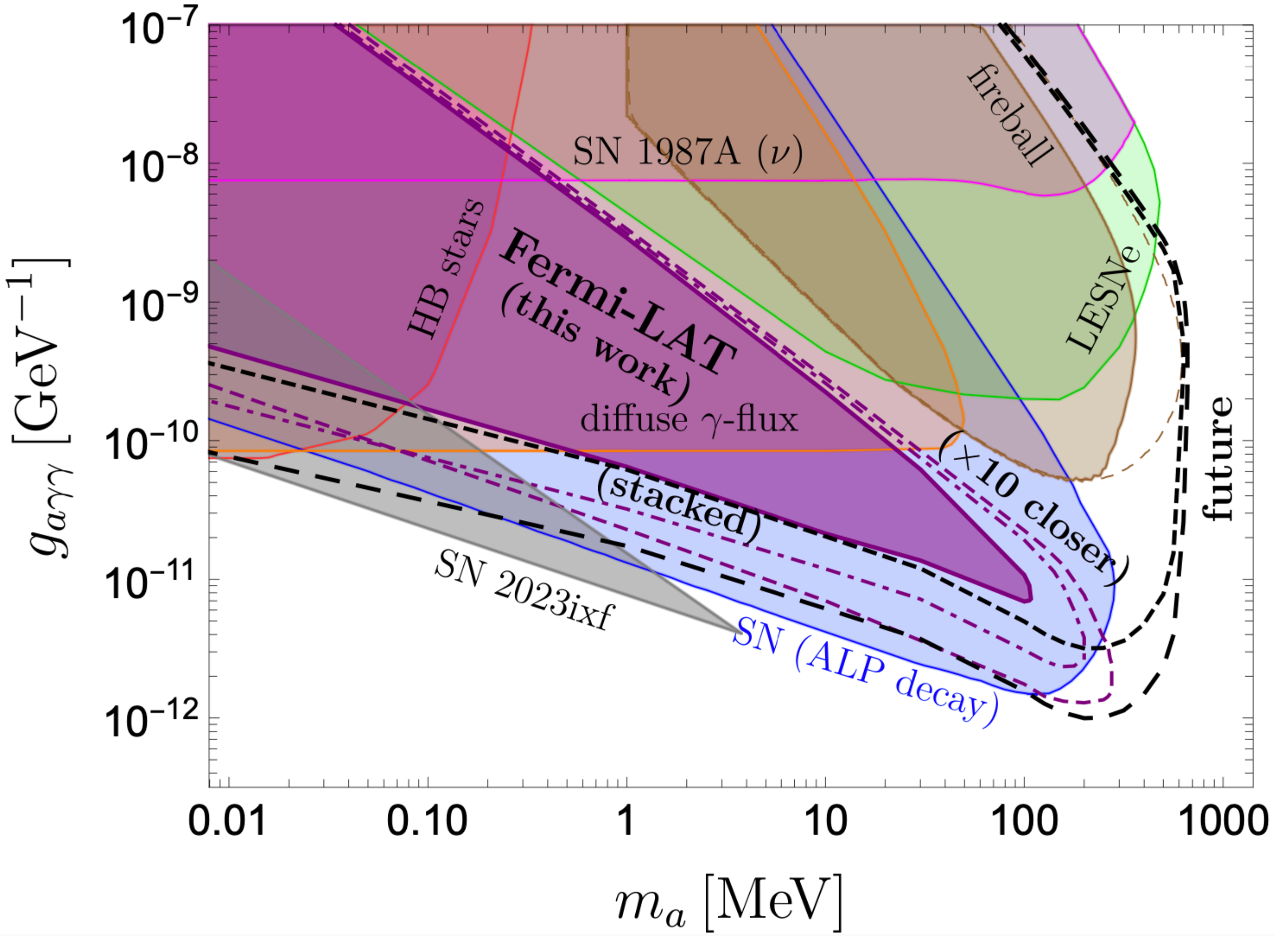
Neutron Star Mergers

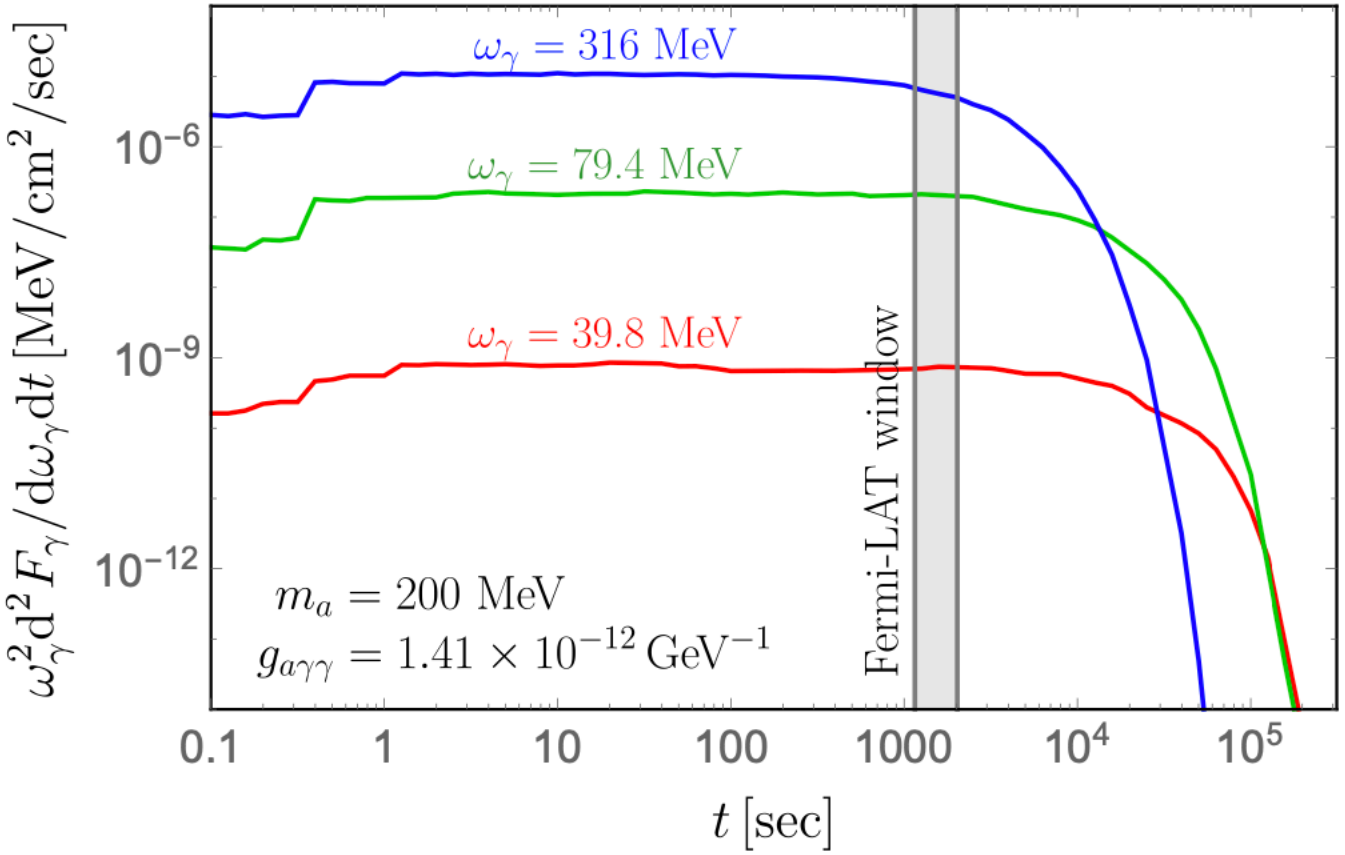
Multimessenger is key

Localization of source is important









you're looking at a baby magnetar

generally, you want to look at near-Earth,
hot, young magnetars if you want to constrain axions

Fortin, Harris, KS, + various (2017-2024)

Gau, Hajkarim, Fortin, Harris, KS (JCAP 07, 2020)

Diamond, Marques-Tavares (2024)

White Dwarf Mergers

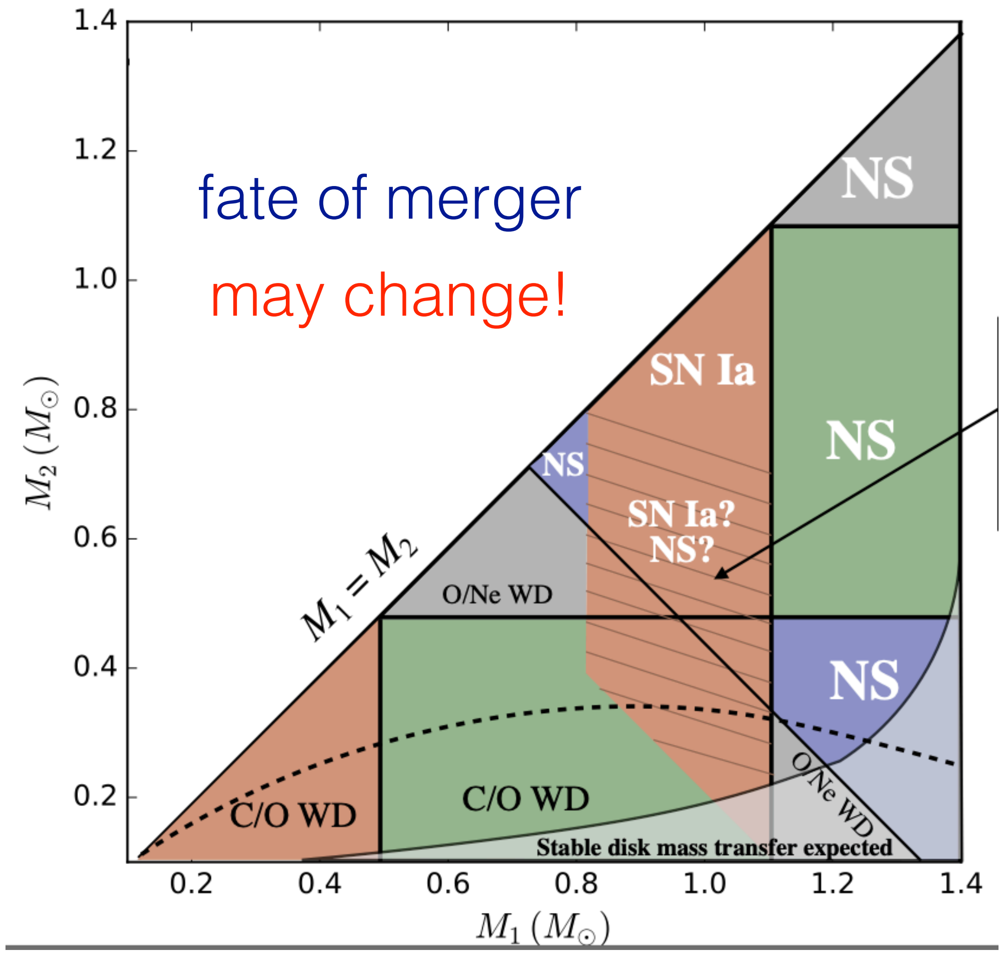
- Total white dwarf binaries in Milky Way: ~ 5 x 10^8
- Total with $f_{GW} > 10^{-4}$ Hz: ~ 6 x 10^7
- Total individually resolvable: ~ 10^3 - 10^4

e.g., Nelemans+2001, Ruiter+2010, Nissanke+2012, Lamberts+2019, Breivik+2020

TJ Gehrman -
the stellar physics guru

Dev, Fortin, Harris, KS, Walsh, Zhang (in progress)

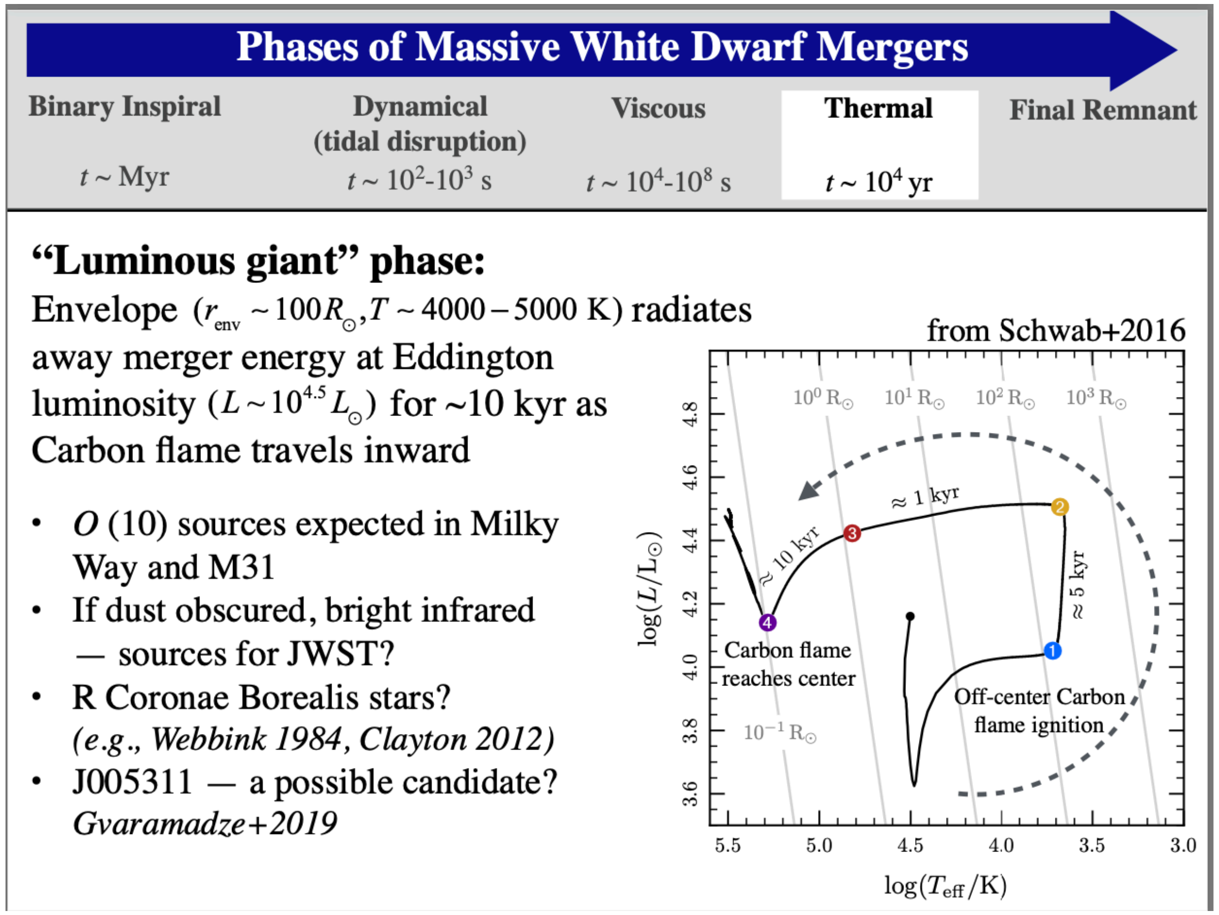
Gehrman, Sandick, KS, Walsh, Xu (in progress)



fate of merger

may change!

Shen et. al. (2015)



Phases of Massive White Dwarf Mergers

Binary Inspiral	Dynamical (tidal disruption)	Viscous	Thermal	Final Remnant
$t \sim$ Myr	$t \sim 10^2$-10^3 s	$t \sim 10^4$-10^8 s	$t \sim 10^4$ yr	

"Luminous giant" phase:

Envelope ($r_{\rm env} \sim 100 R_\odot, T \sim 4000-5000$ K) radiates away merger energy at Eddington luminosity ($L \sim 10^{4.5} L_\odot$) for ~10 kyr as Carbon flame travels inward

- O (10) sources expected in Milky Way and M31
- If dust obscured, bright infrared — sources for JWST?
- R Coronae Borealis stars? *(e.g., Webbink 1984, Clayton 2012)*
- J005311 — a possible candidate? *Gvaramadze+2019*

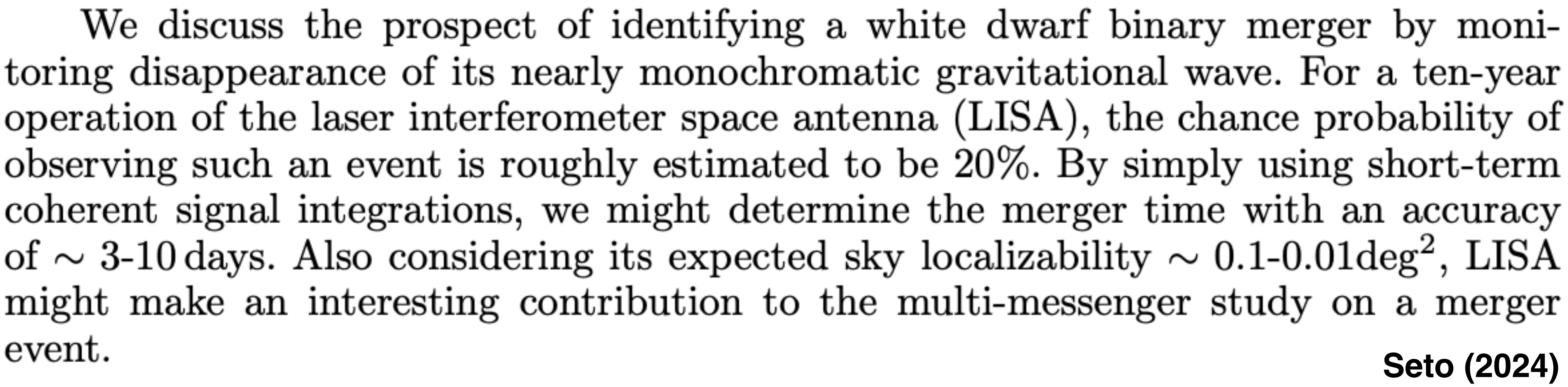
from Schwab+2016

Kremer et. al. (2023)

White Dwarf Mergers

GW signal sets an alarm clock t=0

look for *disappearance*

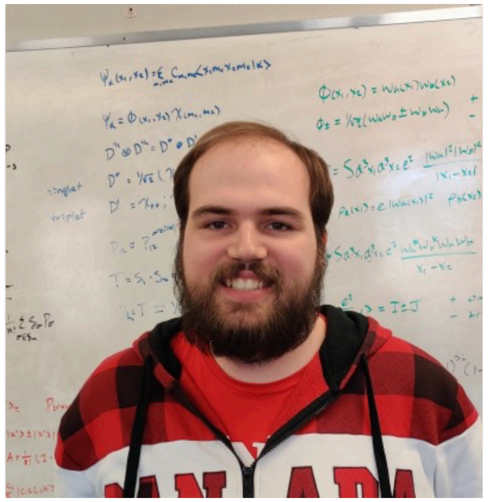


We discuss the prospect of identifying a white dwarf binary merger by monitoring disappearance of its nearly monochromatic gravitational wave. For a ten-year operation of the laser interferometer space antenna (LISA), the chance probability of observing such an event is roughly estimated to be 20%. By simply using short-term coherent signal integrations, we might determine the merger time with an accuracy of $\sim$ 3-10 days. Also considering its expected sky localizability $\sim$ 0.1-0.01deg^2, LISA might make an interesting contribution to the multi-messenger study on a merger event.

Seto (2024)

you're looking at a baby white dwarf!

or a baby super-Chandrasekhar mass star!



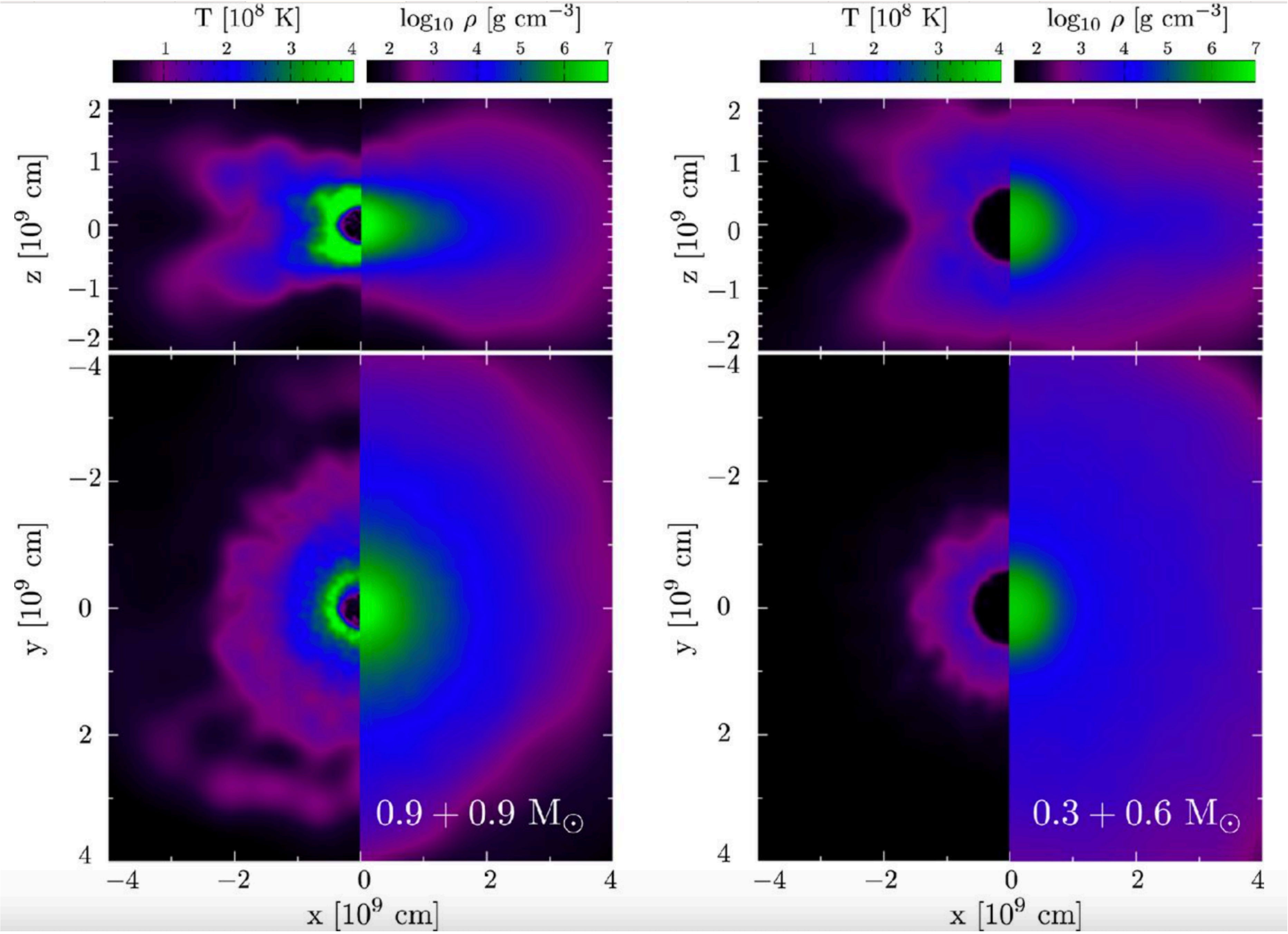
Teddy Walsh

$$\frac{L_a}{L} \sim 1.6 \times 10^{-4} \left(\frac{g_{aee}}{10^{-13}}\right)^2 \left(\frac{M_{\rm WD}}{1M}\right) \left(\frac{T_c}{10^7 K}\right)^4$$

Gehrman, Sandick, KS, Walsh, Xu (in progress)

Dev, Fortin, Harris, KS, Walsh, Zhang (in progress)

White Dwarf Mergers



Dan, Rosswog, Bruggen, Podsiadlowski (MNRAS, 2014)

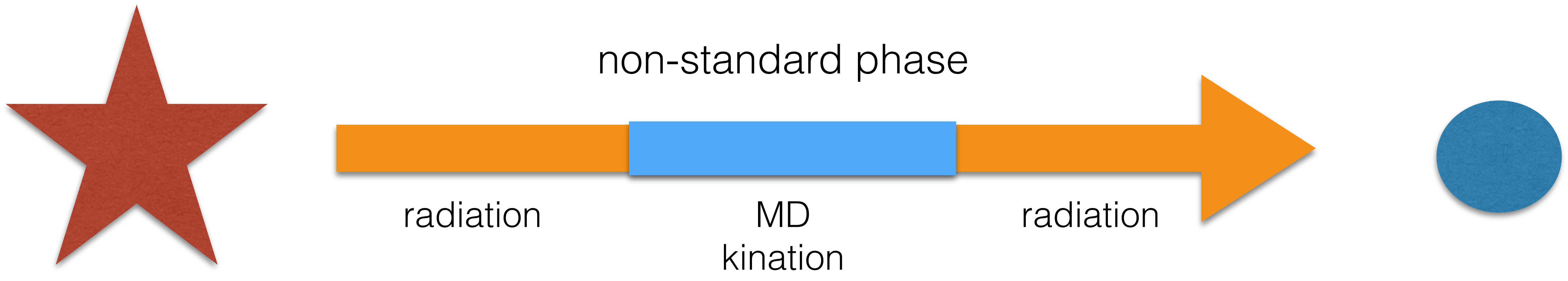
BSM on the way

BSM on the way

Source is BSM, deformation due to new cosmology

Source is astrophysical, deformation due to new stuff

Gameplan



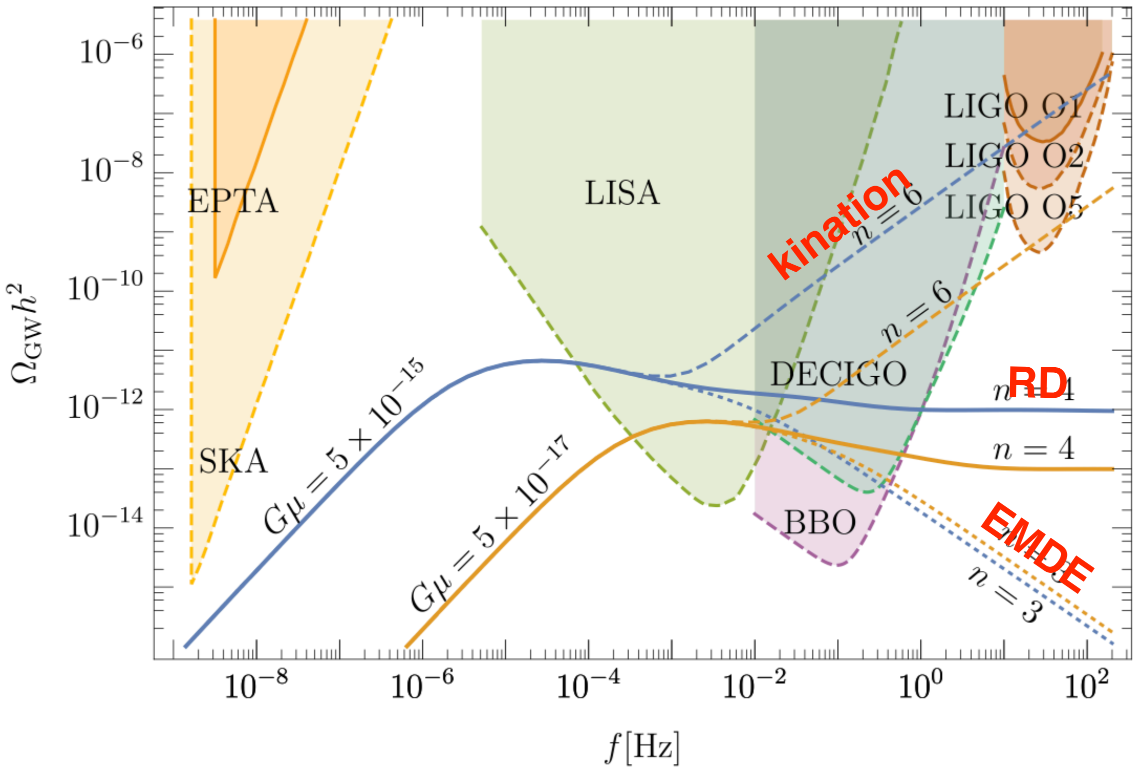
Insert favorite early Universe
BSM source:
cosmic strings
phase transitions
2nd order GWs

cosmological distance

deformed GW
waveform

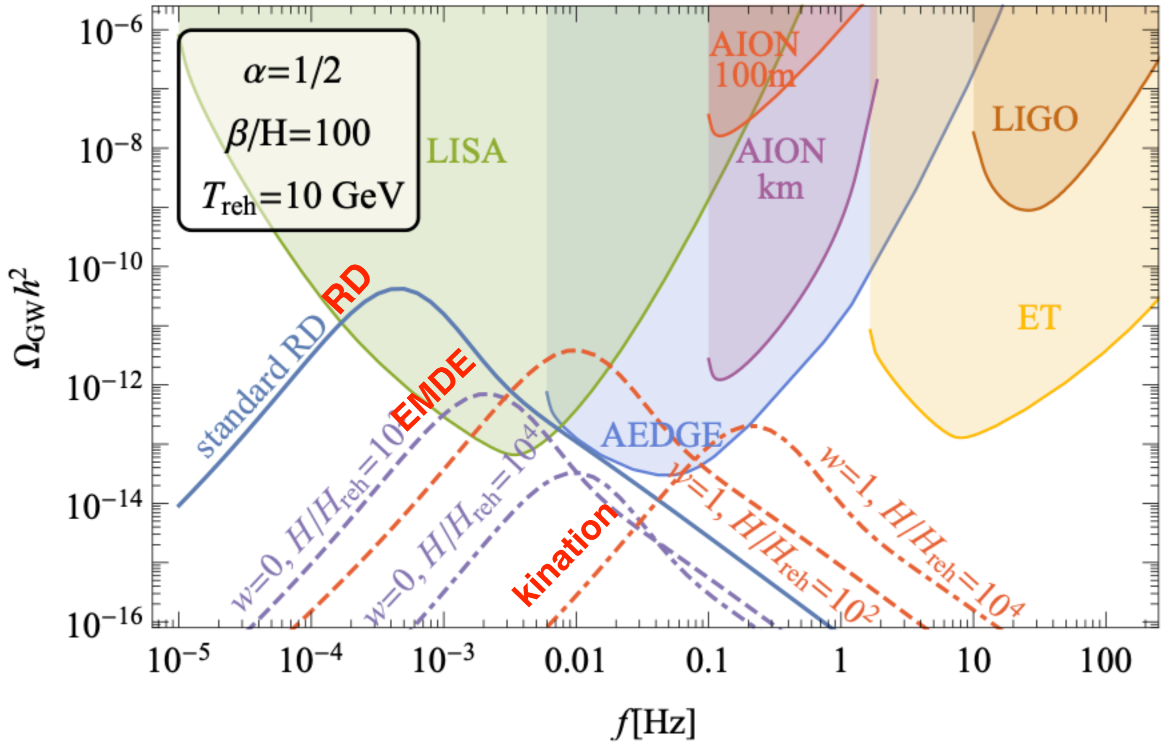
Study Non-Standard Histories

example: source = cosmic strings



Cui, Lewicki, Morrissey, Wells (2016)
Gouttenoire, Servant, Simakachorn (2020)

example: source = phase transition



Figueroa et. al. (2020)

source = primordial GWs, induced GWs, etc.

Bernal, Hajkarim (2018)
Domenec et. al. (2020)

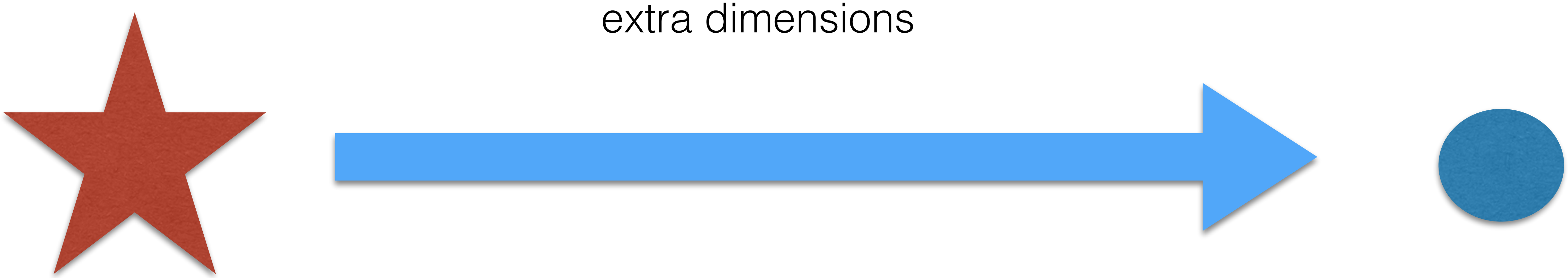
Personally, I only trust modifications of the causal k^3 tail. It is universal

BSM on the way

Source is BSM, deformation due to new cosmology

Source is astrophysical, deformation due to new stuff

Gameplan



massive graviton
modified GR
extra dimensions

dark matter

Insert favorite late Universe astrophysical source:
NS merger
BH merger
EMRI

deformed GW waveform

Check out Tao Xu’s talk

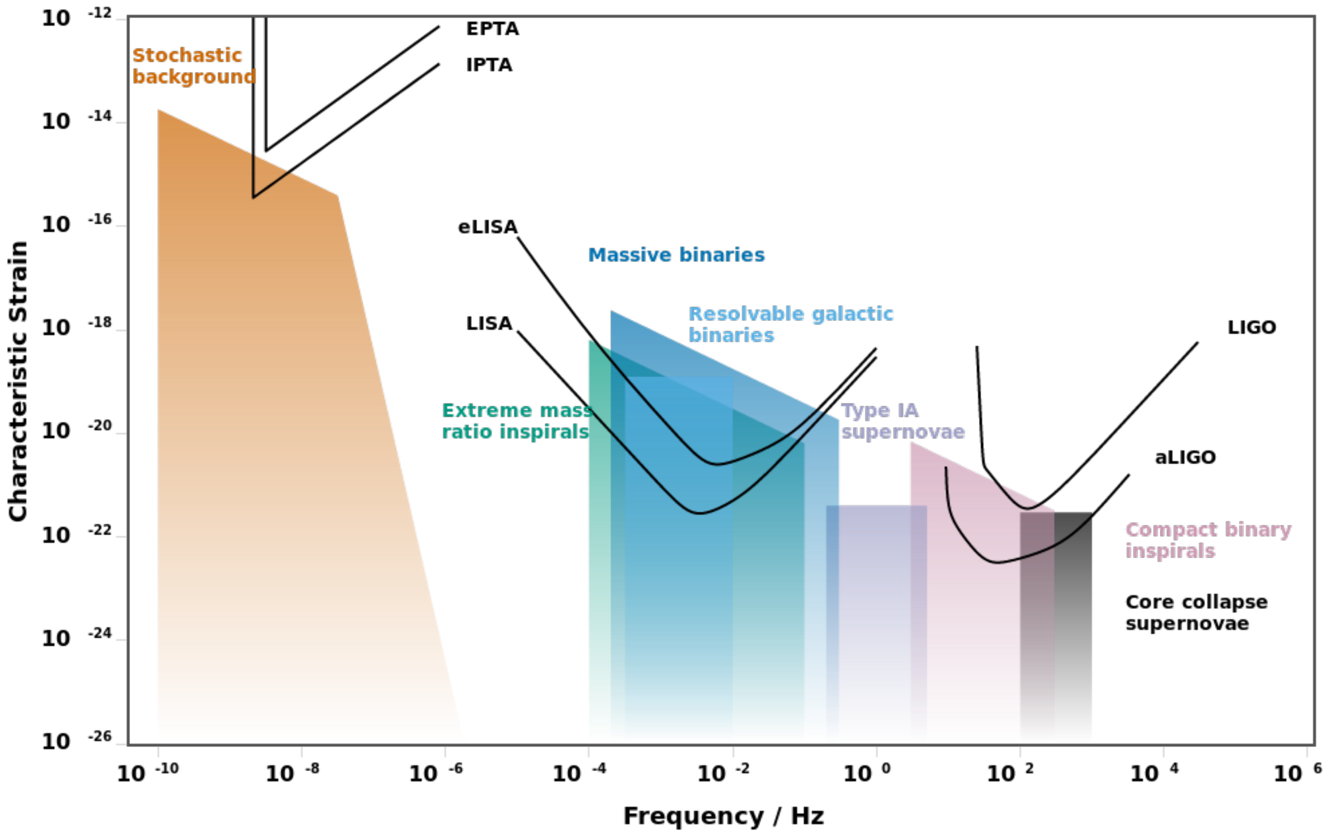
Invitation

Low f GW

High f GW

N. Aggarwal et. al. (2020)

V. Domcke et. al. (2020-)



Secular drift of pulsars?

DeRocco, Dror (2023)

SMBH inspirals

PBH + baryogenesis + dark matter

TJ Gehrman, Shams, KS, Xu (*JCAP* 03 2024)

TJ Gehrman, Shams, KS, Xu (*JCAP* 02 2023)

TJ Gehrman, Shams, KS, Xu (*JCAP* 10 2023)

Reheating

Easther, Giblin, Lim (2006)