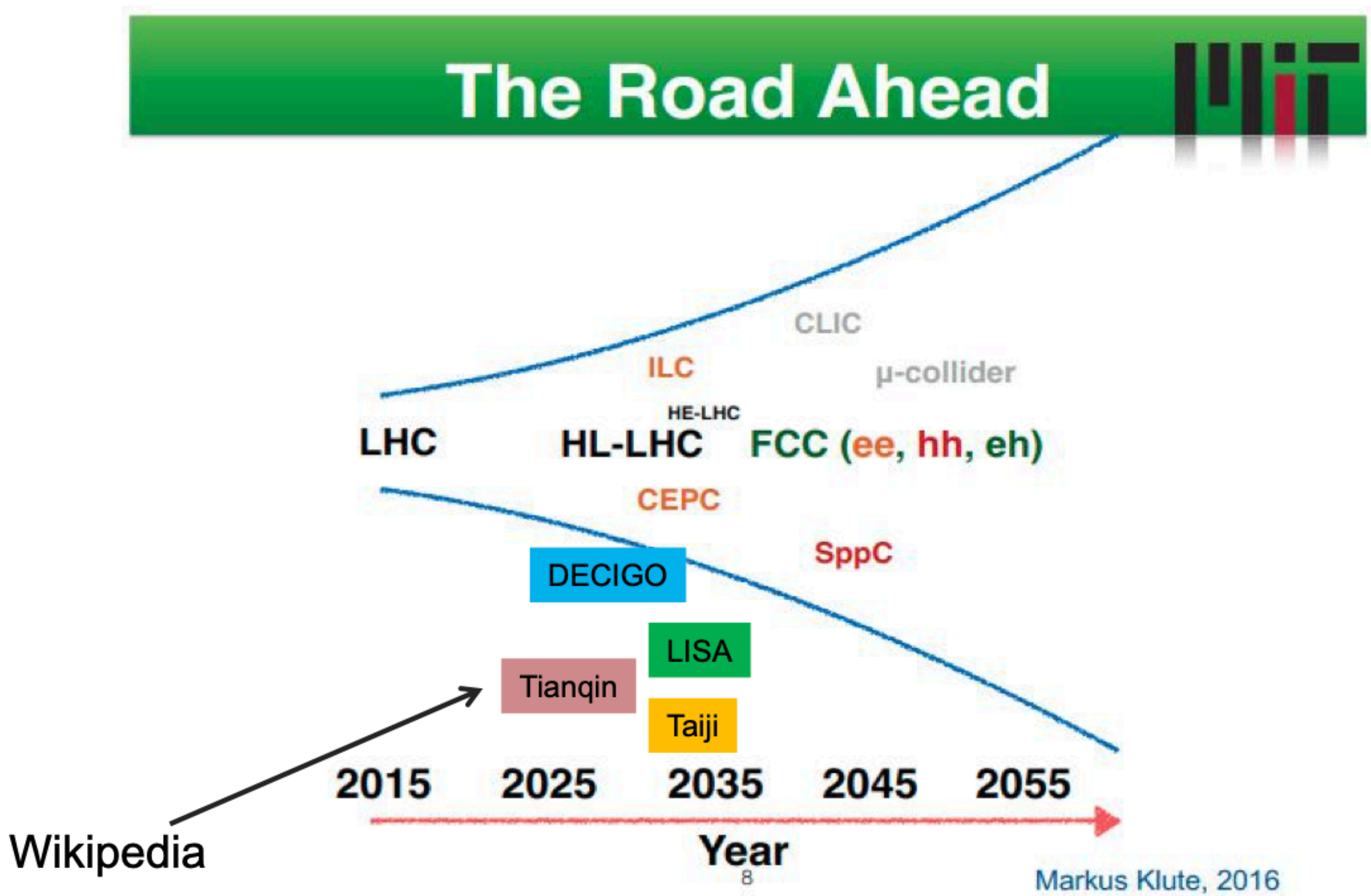
BSM Physics
at
Gravitational Wave Detectors

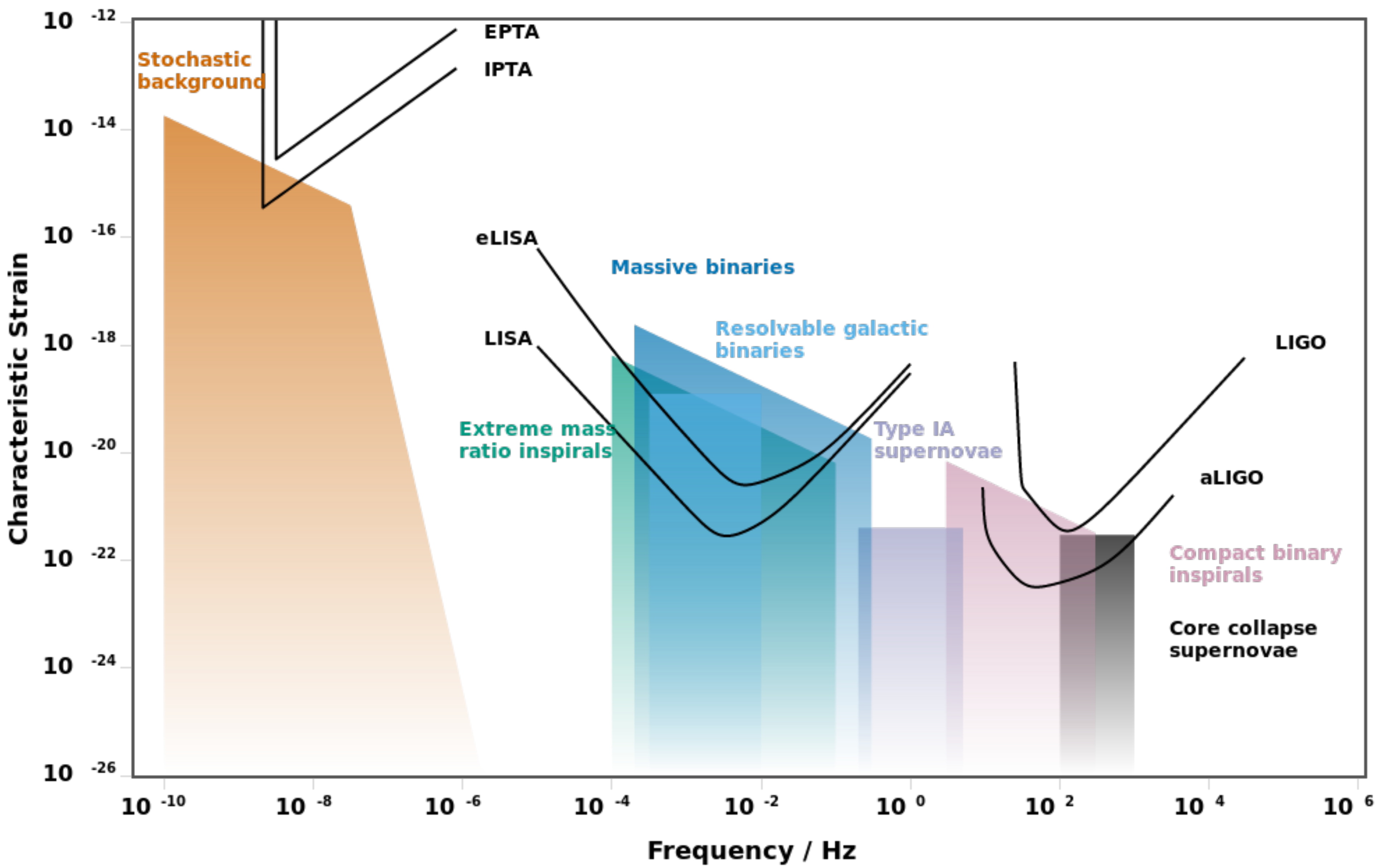
Mitchell Workshop 2024

Kuver Sinha
University of Oklahoma

Data's coming, folks



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.

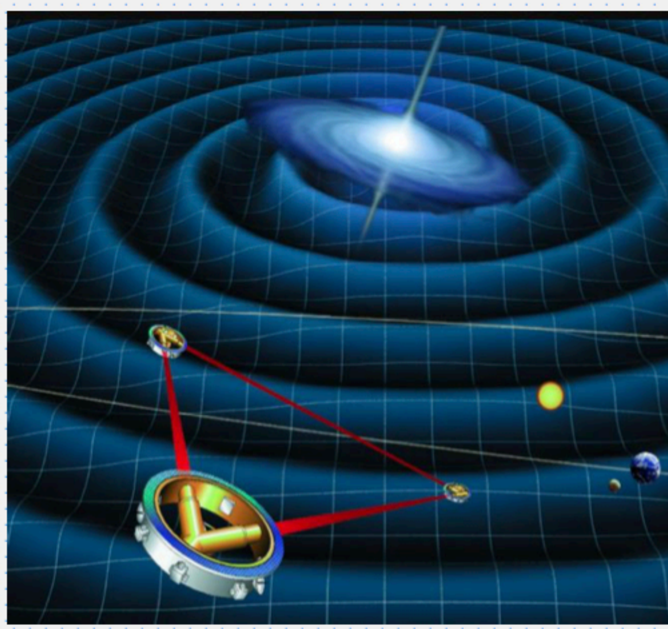
lots of interesting work by our community!

Check out Dorival Goncalves's talk

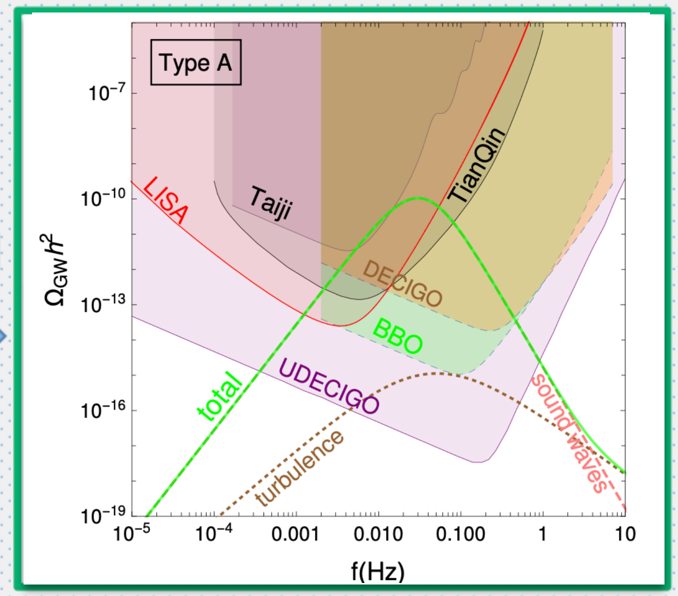
A. Alves, T. Ghosh, D. Goncalves, H. Guo, KS (JHEP03 2020)
A. Alves, T. Ghosh, H. Guo, KS (JHEP04 2019)
A. Alves, T. Ghosh, H. Guo, KS (JHEP12 2018)

Workflow: Phase Transitions

theoretical calculation of gravitational wave spectrum and detector simulation



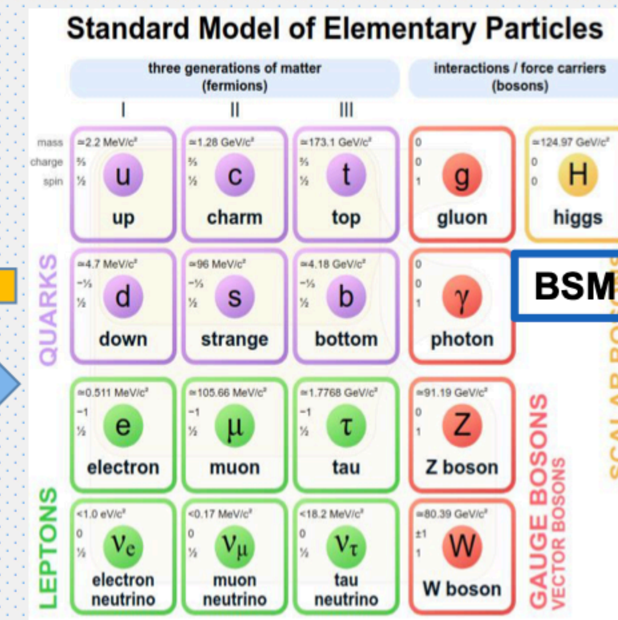
LIGO, LISA, Taiji, Tianqin...



Gravitational Wave Spectrum

α
β
v_w
T_*
g_s
...

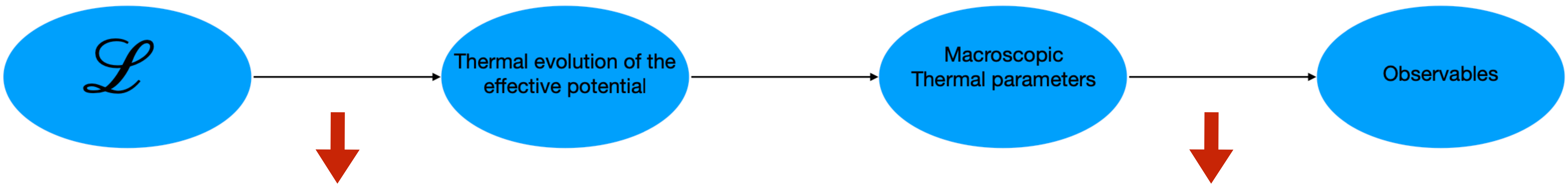
Phase Transition Parameters



Particle Physics Model

data analysis, constraints or discovery(parameter estimation)

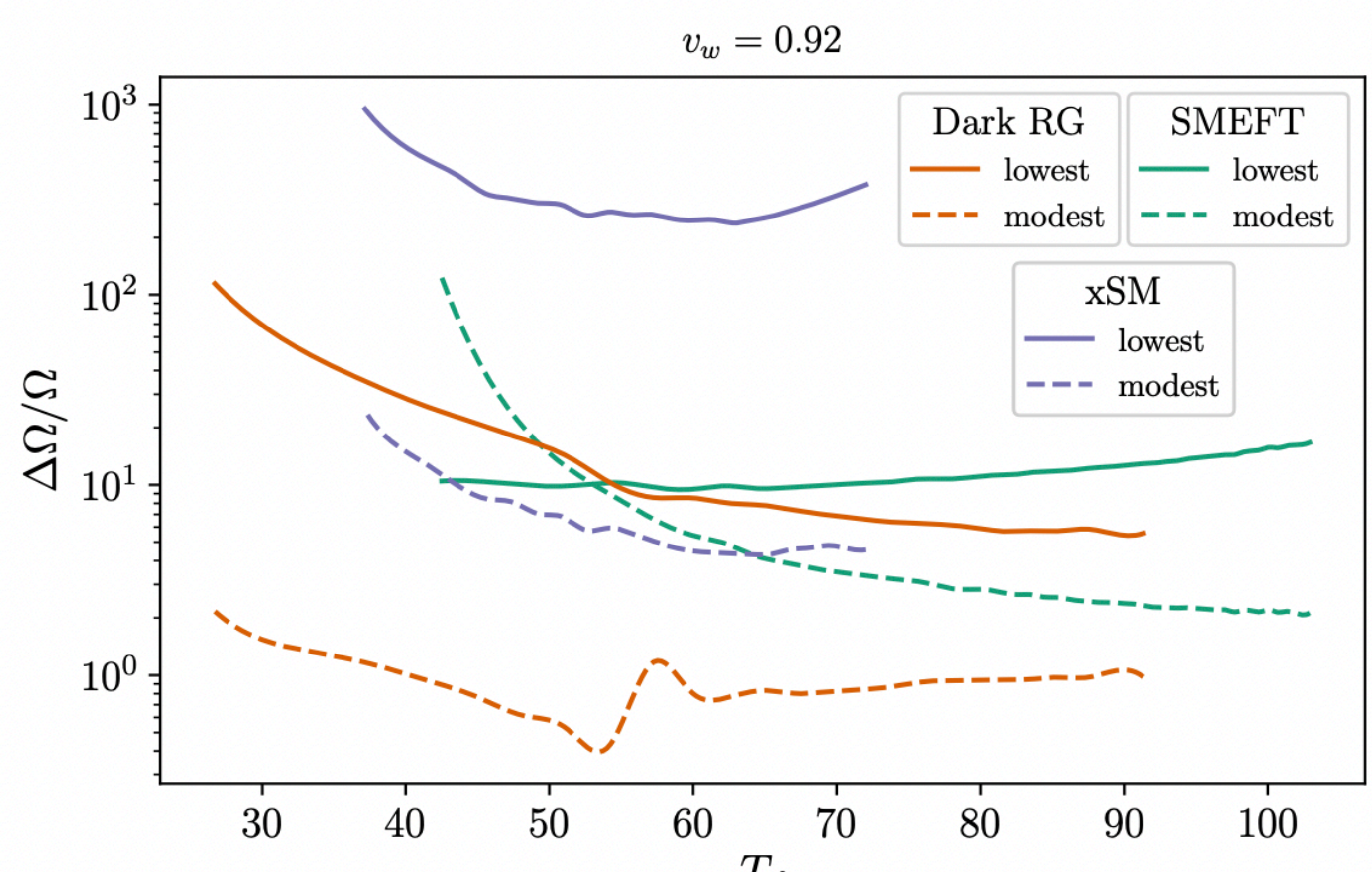
Uncertainties in Phase Transition Calculations



$\Delta\Omega_{GW}/\Omega_{GW}$	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)

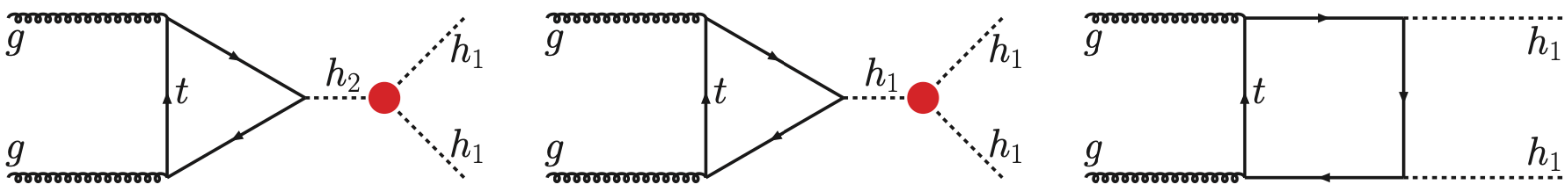
H. Guo, KS, G. White, D. Vagie (JHEP06 2021)

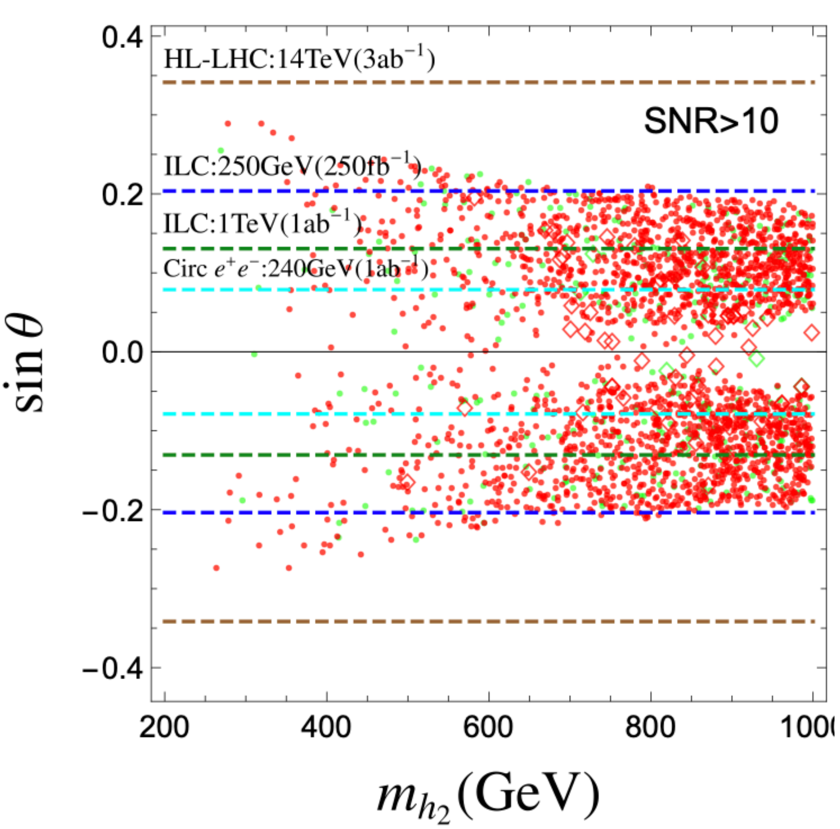
H. Guo, KS, G. White, D. Vagie (JCAP01 2021)

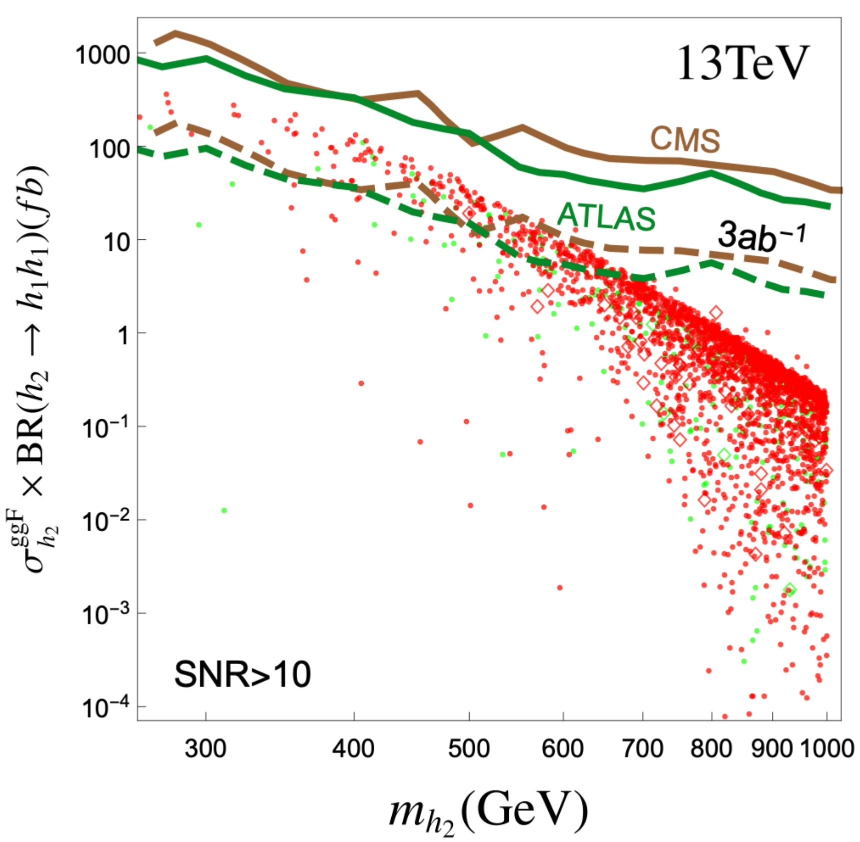
Complementarity

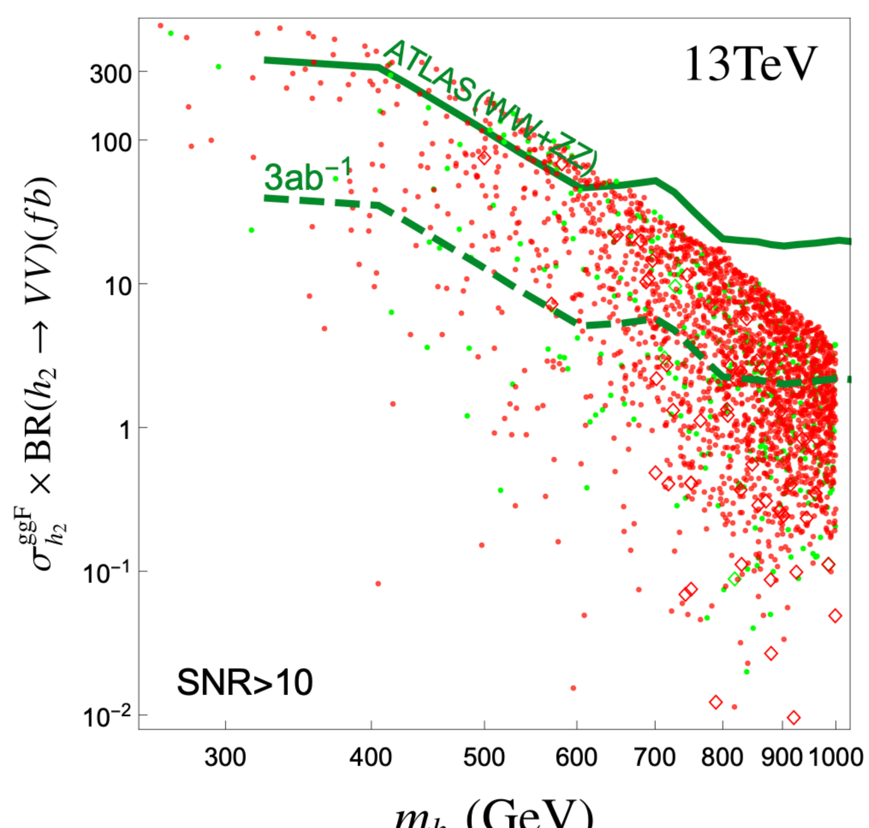
$$V(H,S) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{a_1}{2} H^\dagger H S + \frac{a_2}{2} H^\dagger H S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

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)

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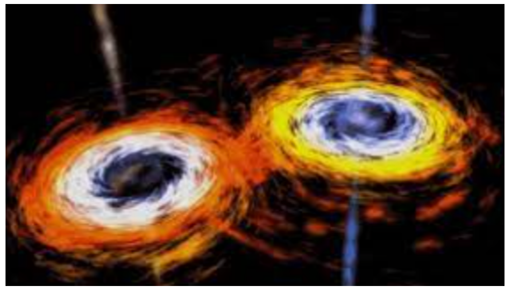
Source is astrophysical, serves as a clock (multimessenger)

Binary Inspiral

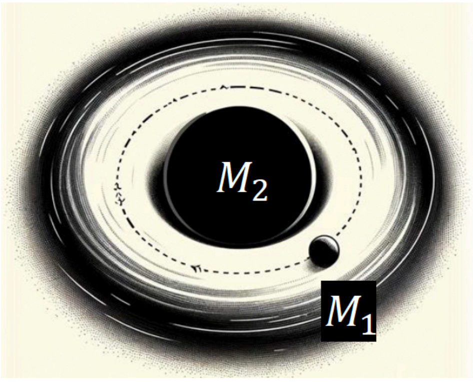
Binary inspirals can serve as probes of light dark mediators, under the assumption that they accumulate dark charge

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

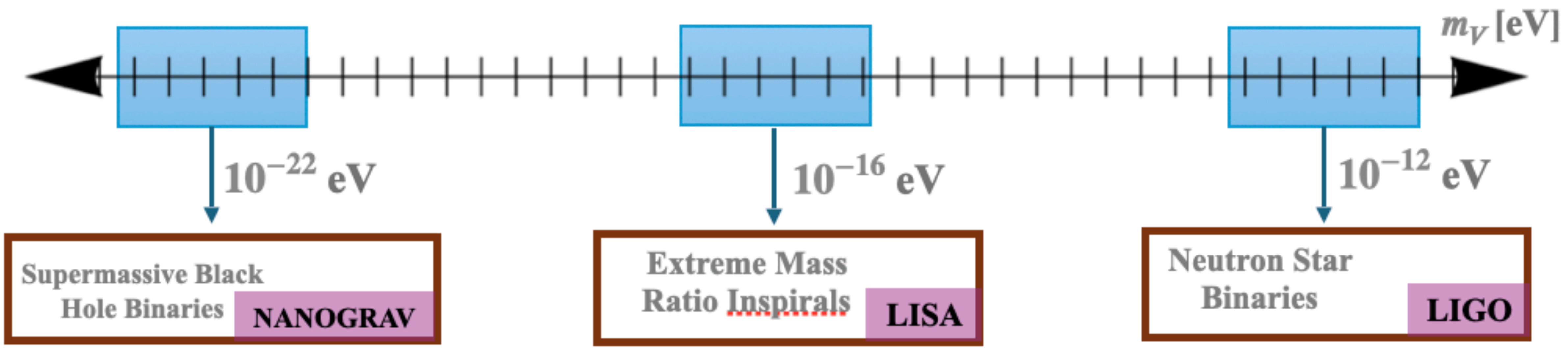
Dror, Lehmann, Profumo (PRD104 2021)



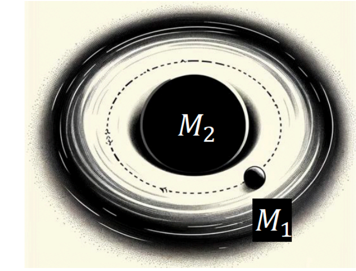
Bhalla, KS, Xu (2024)



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



EMRIs, Dark Forces



$$|\vec{F}_{\rm total}| = \frac{G M_1 M_2}{r^2}[1 + \tilde{\alpha}' e^{-m_V r}(1 + m_V r)],$$

time evolution of orbital frequency

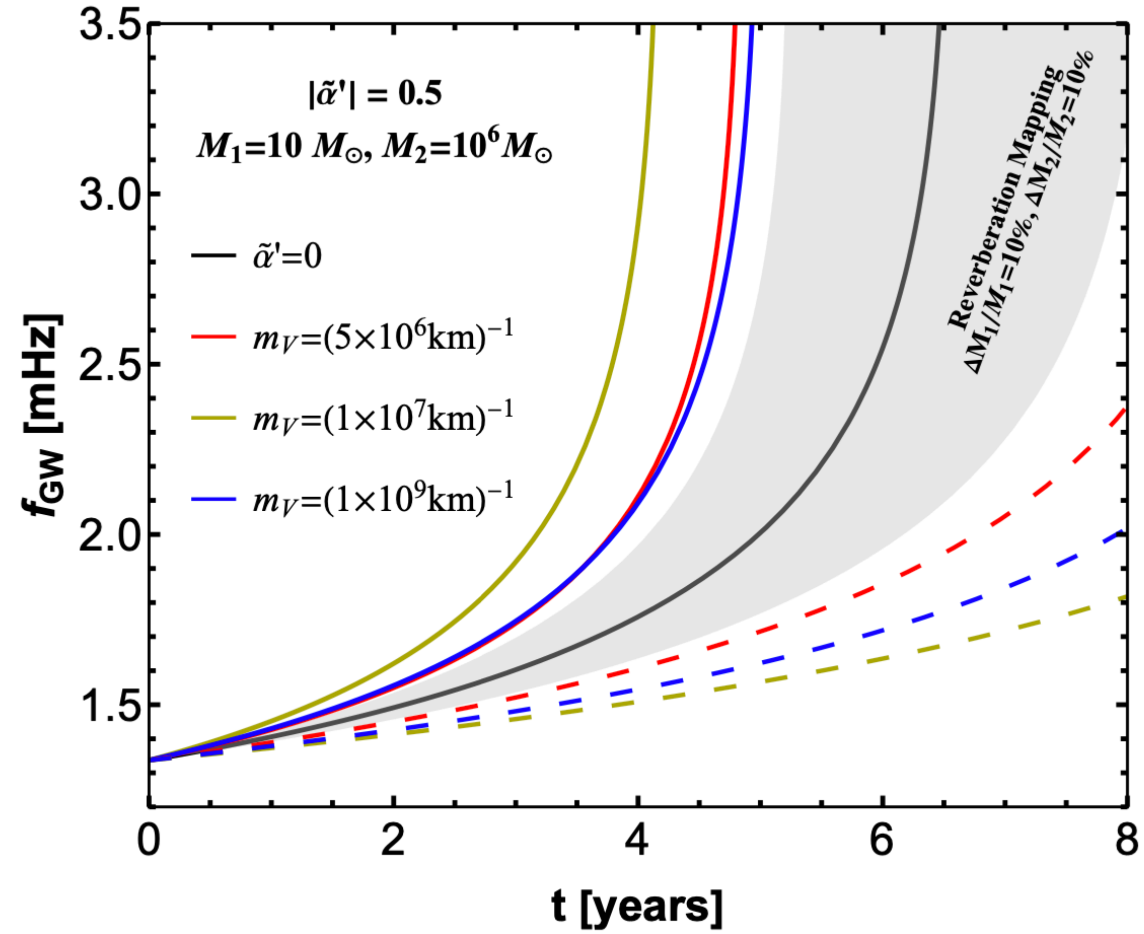
$$\frac{d\omega}{dt} = -\frac{32}{5} G\,\mu\,\omega^5\,r^2\,g\,\mathcal{N}^{-1}.$$

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

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

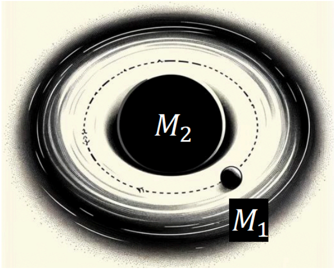
$$F_{TOTAL} = \frac{G M_1{}' M_2{}'}{r^2}$$

Reverberation mapping, dynamical tracers



Bhalla, KS, Xu (2024)

EMRIs, Dark Forces

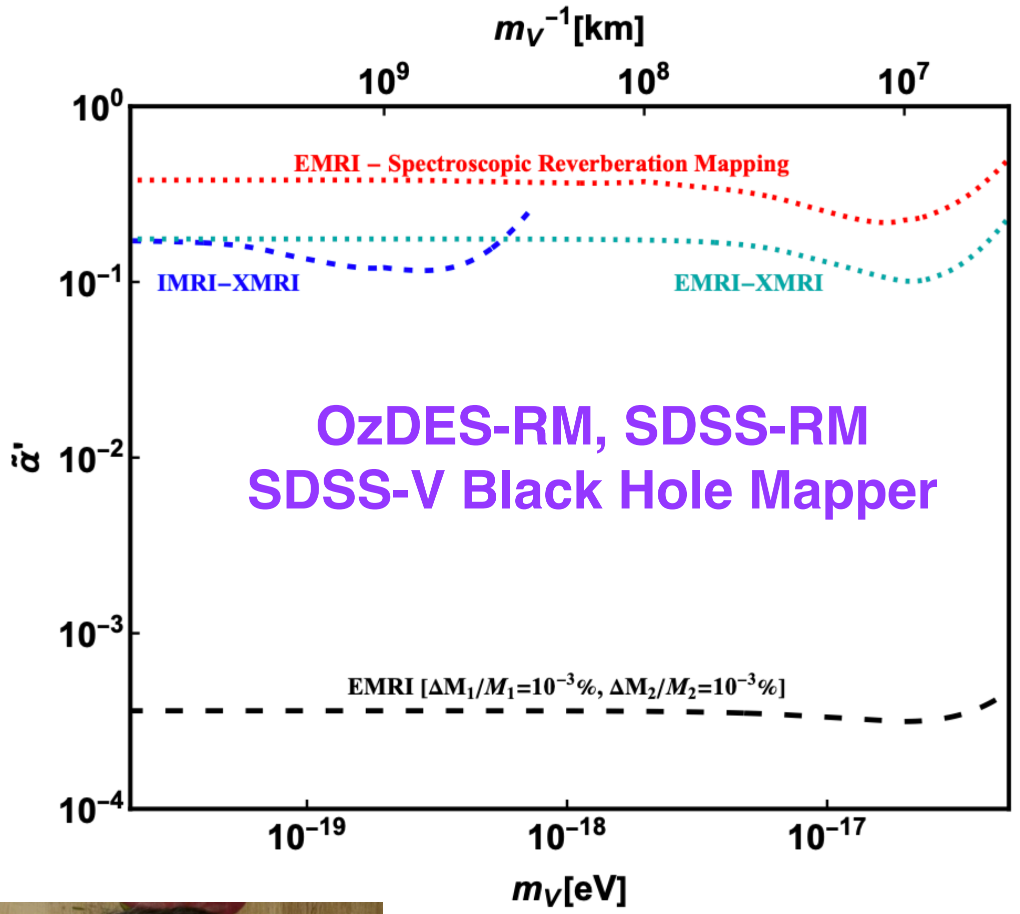


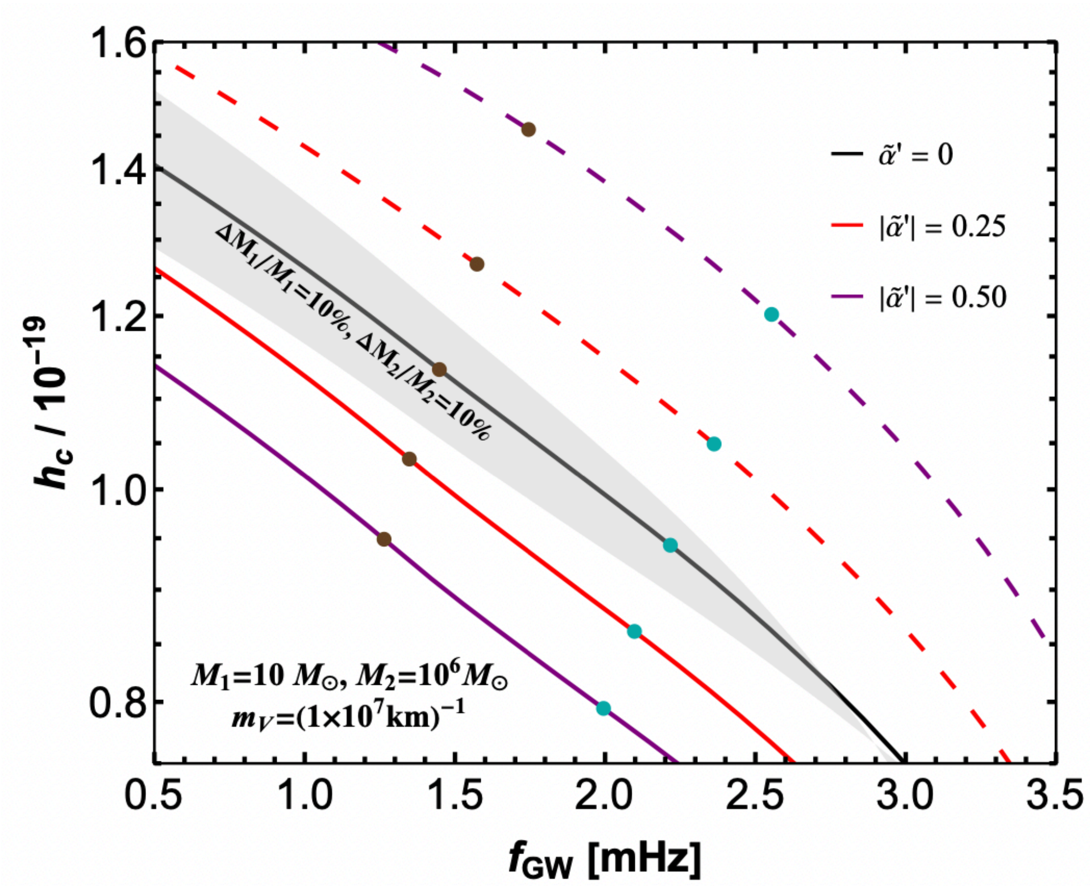
The rms amplitude of the GW emitted for the dominant m=2 mode

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

dL is the luminosity distance from Earth

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





Badal Bhalla

BSM at Source

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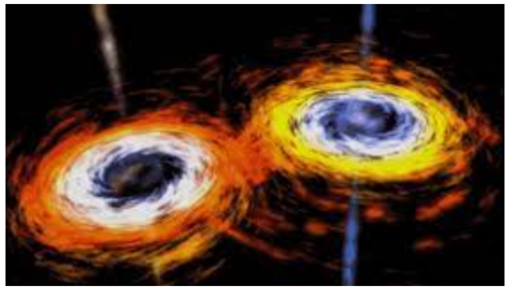
Binary Probes Environment



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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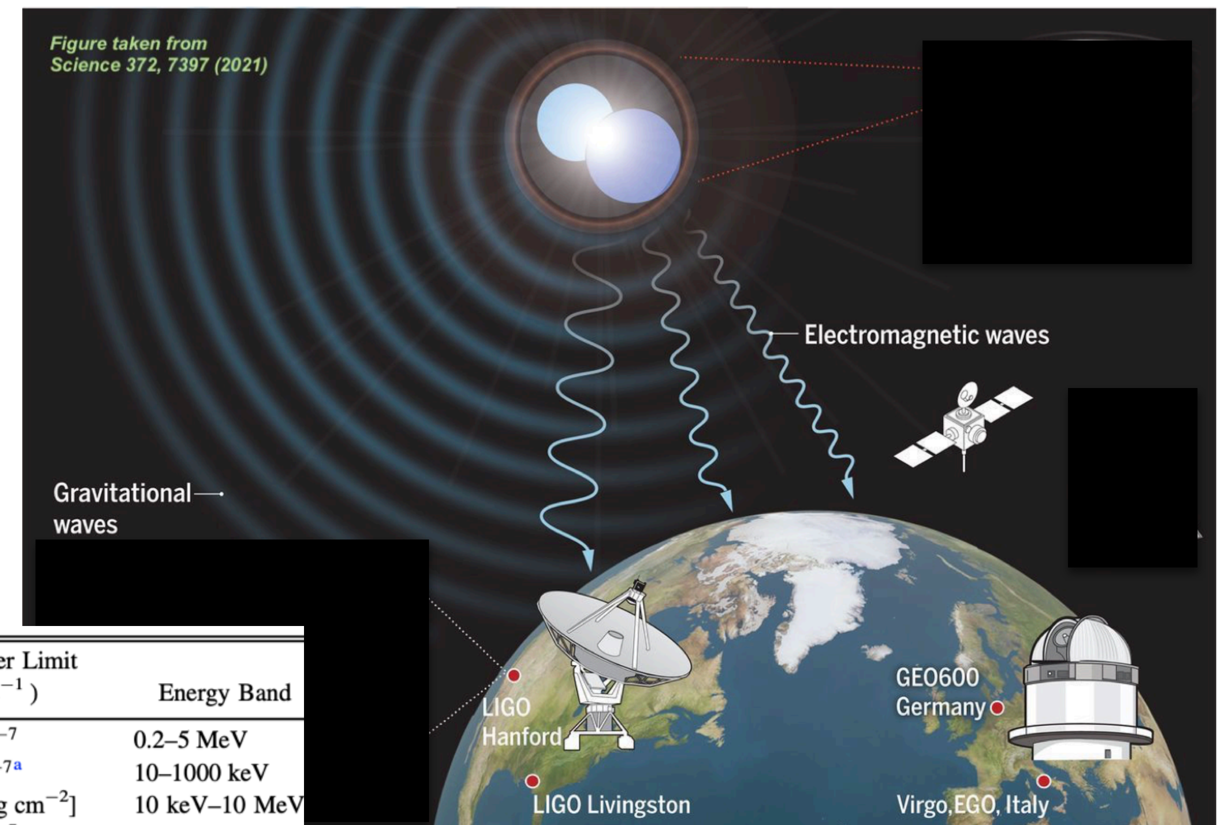
Neutron Star Mergers

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



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)

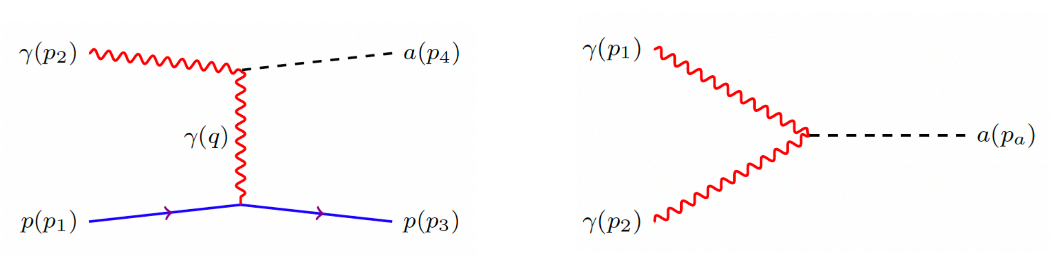
Dev, Fortin, Harris, KS, Zhang (JCAP 01, 2022)

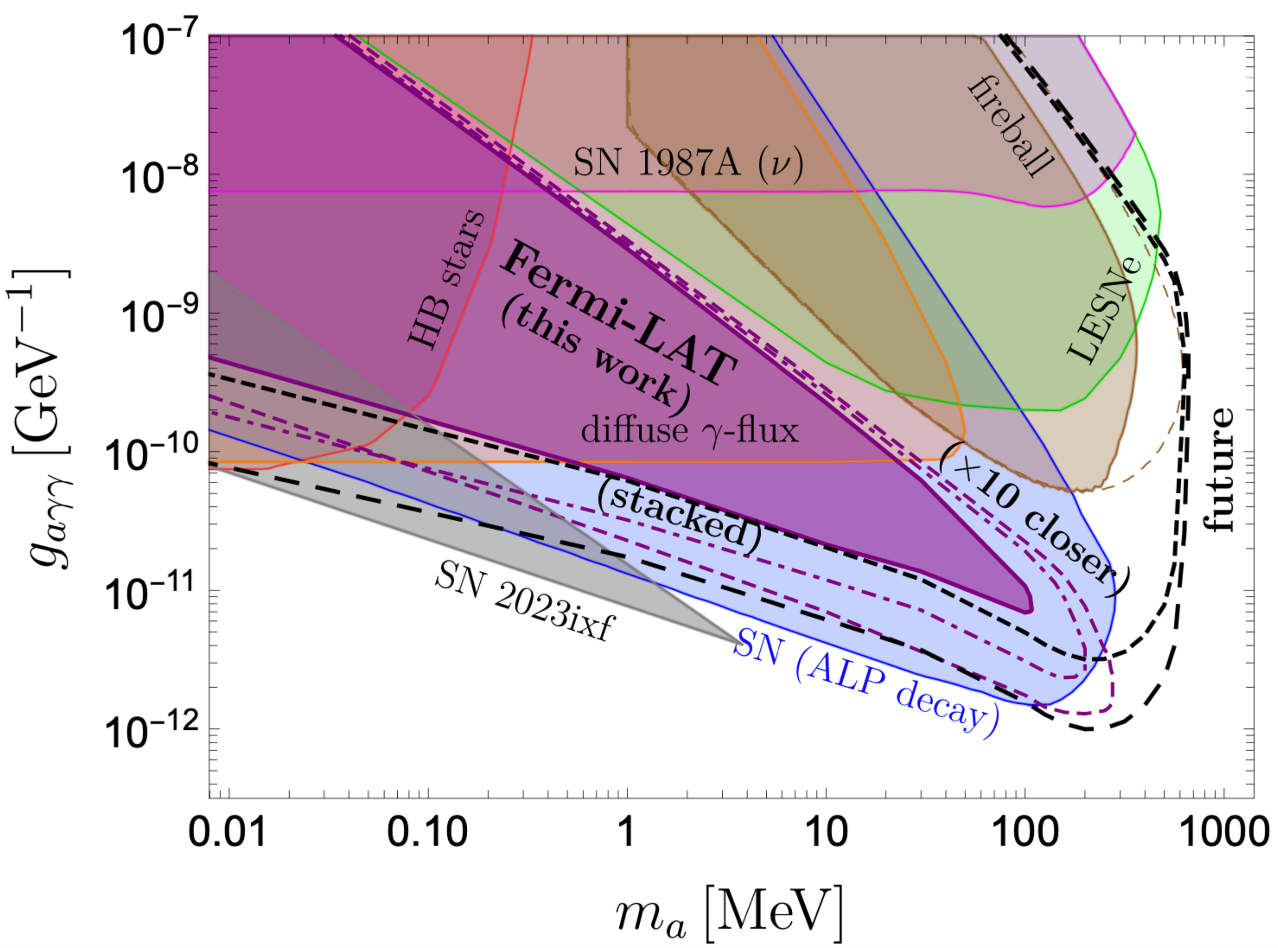
Dev, Fortin, Harris, KS, Zhang (PRL 132, 2024)

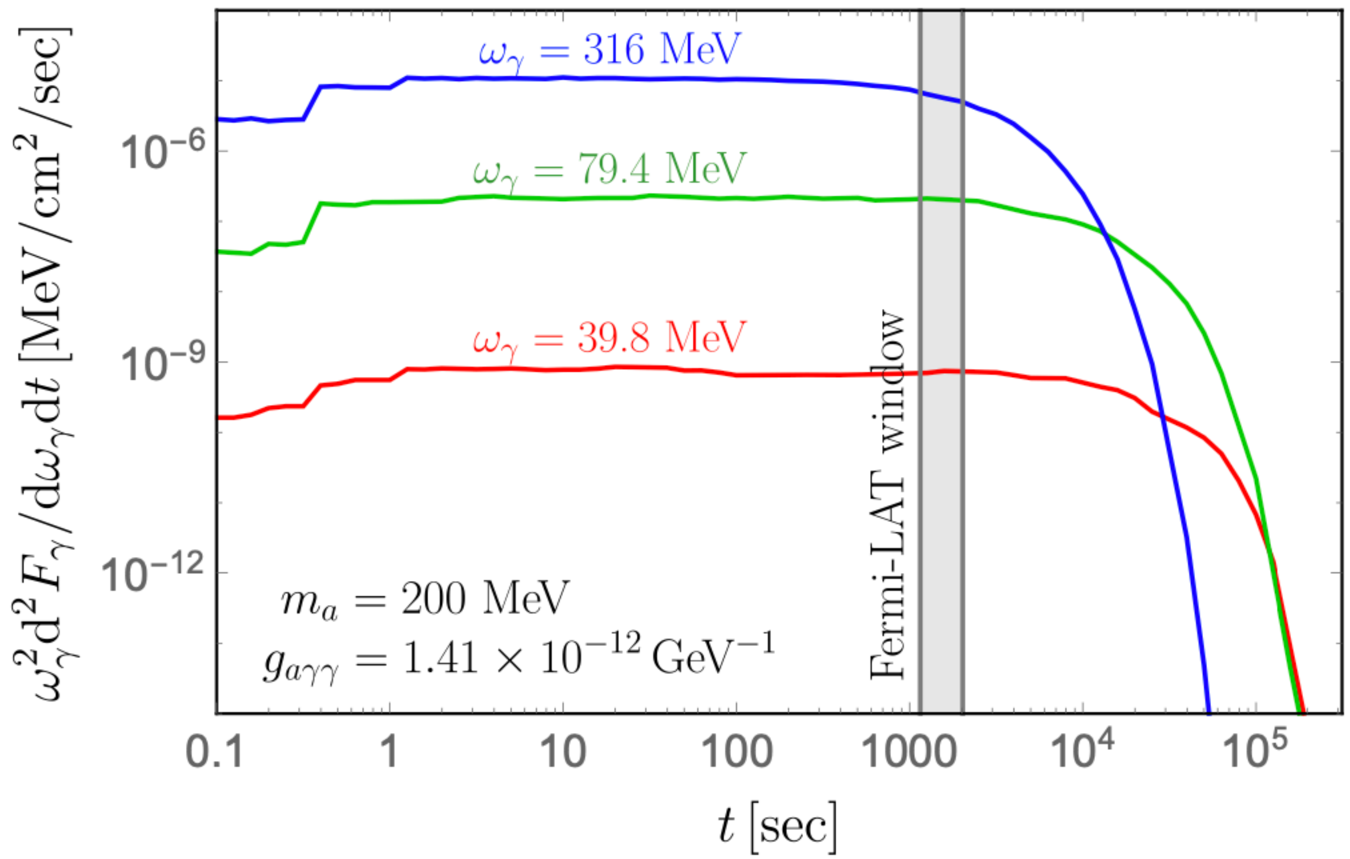
Neutron Star Mergers

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)

Check out Fazlollah Hajkarim's talk

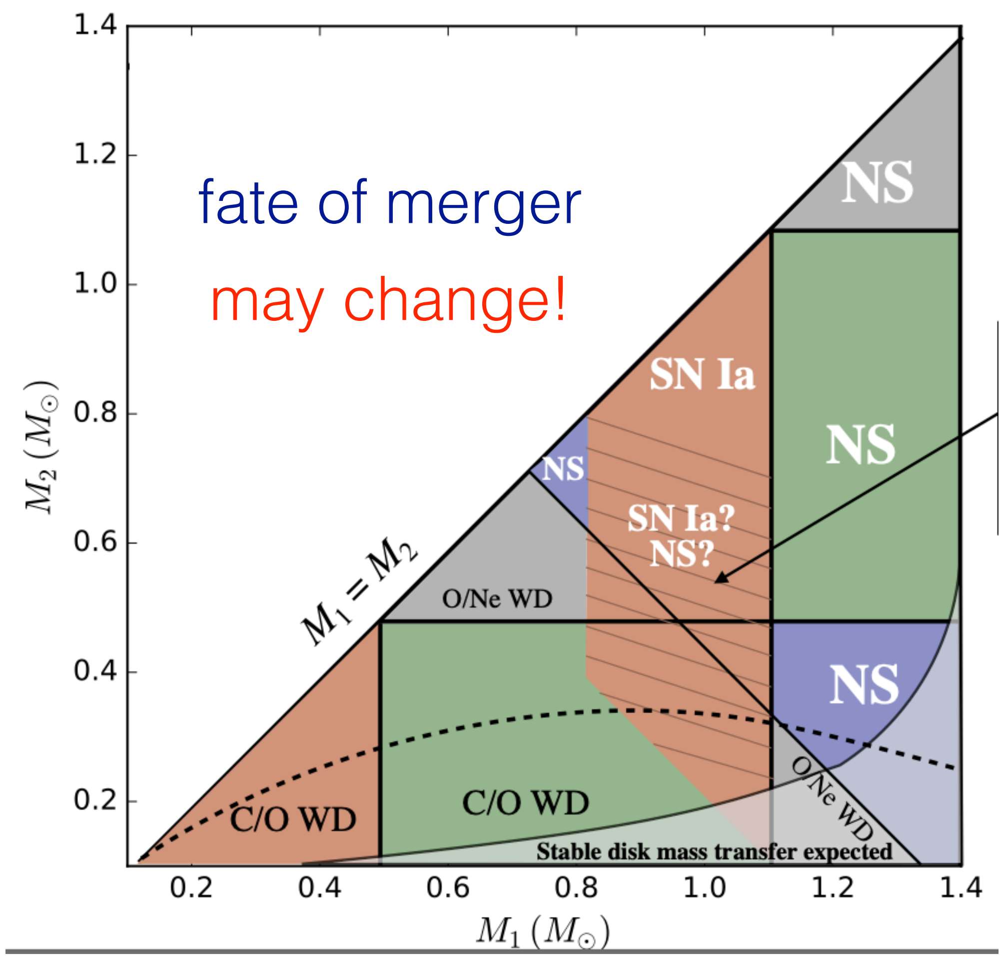
White Dwarf Mergers

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

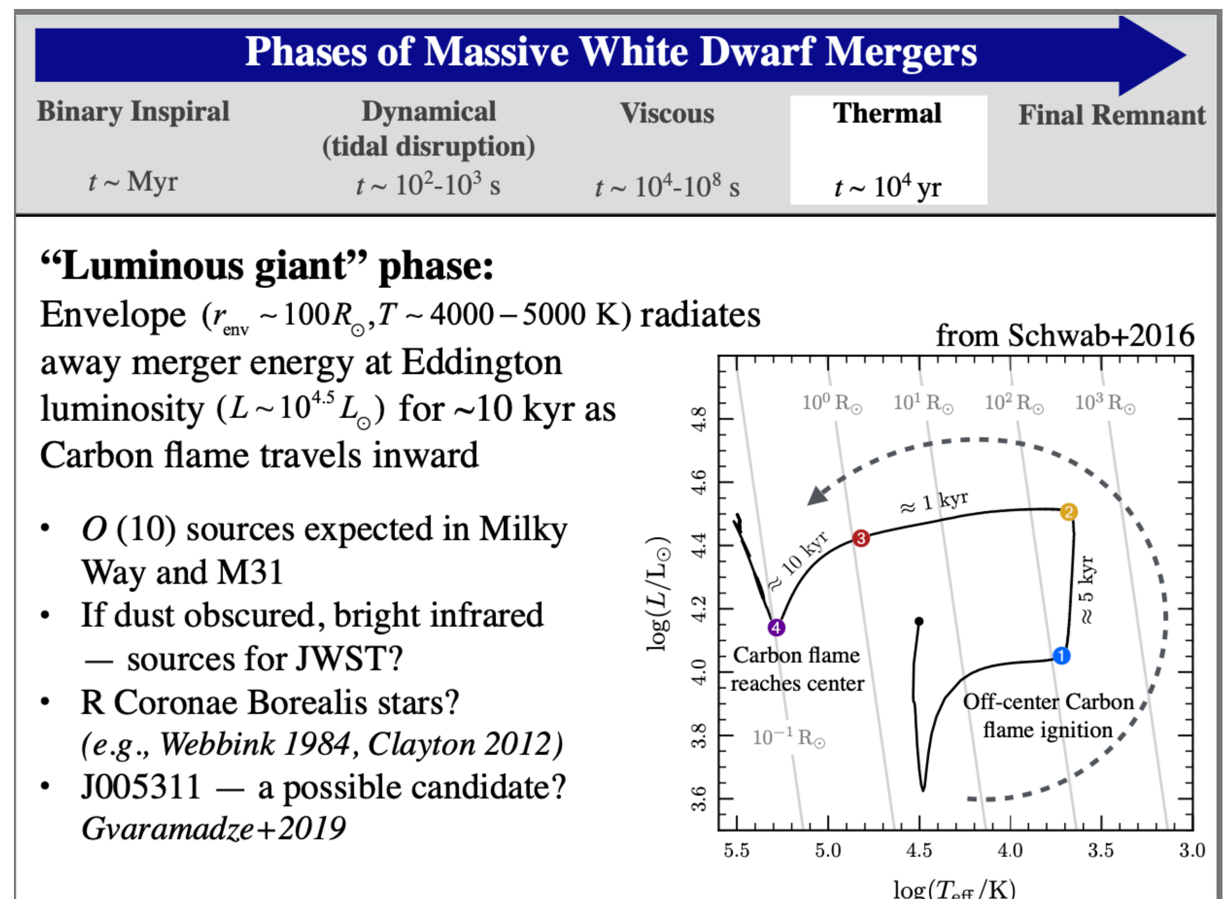
e.g., Nelemans+2001, Ruiter+2010, Nissanke+2012, Lamberts+2019, Breivik+2020

TJ Gehrman - the stellar physics guru

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



Shen et. al. (2015)



Kremer et. al. (2023)

White Dwarf Mergers

GW signal sets an alarm clock t=0

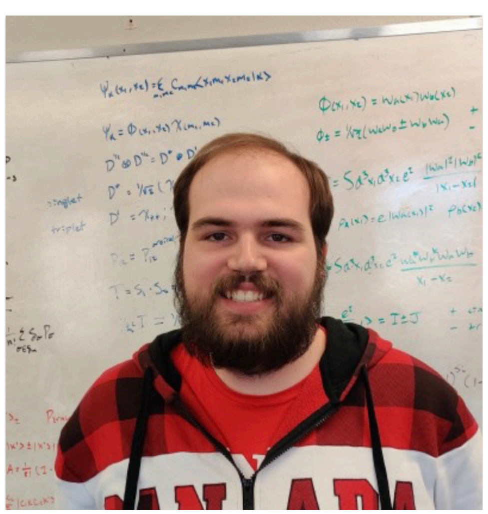
look for *disappearance*

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!

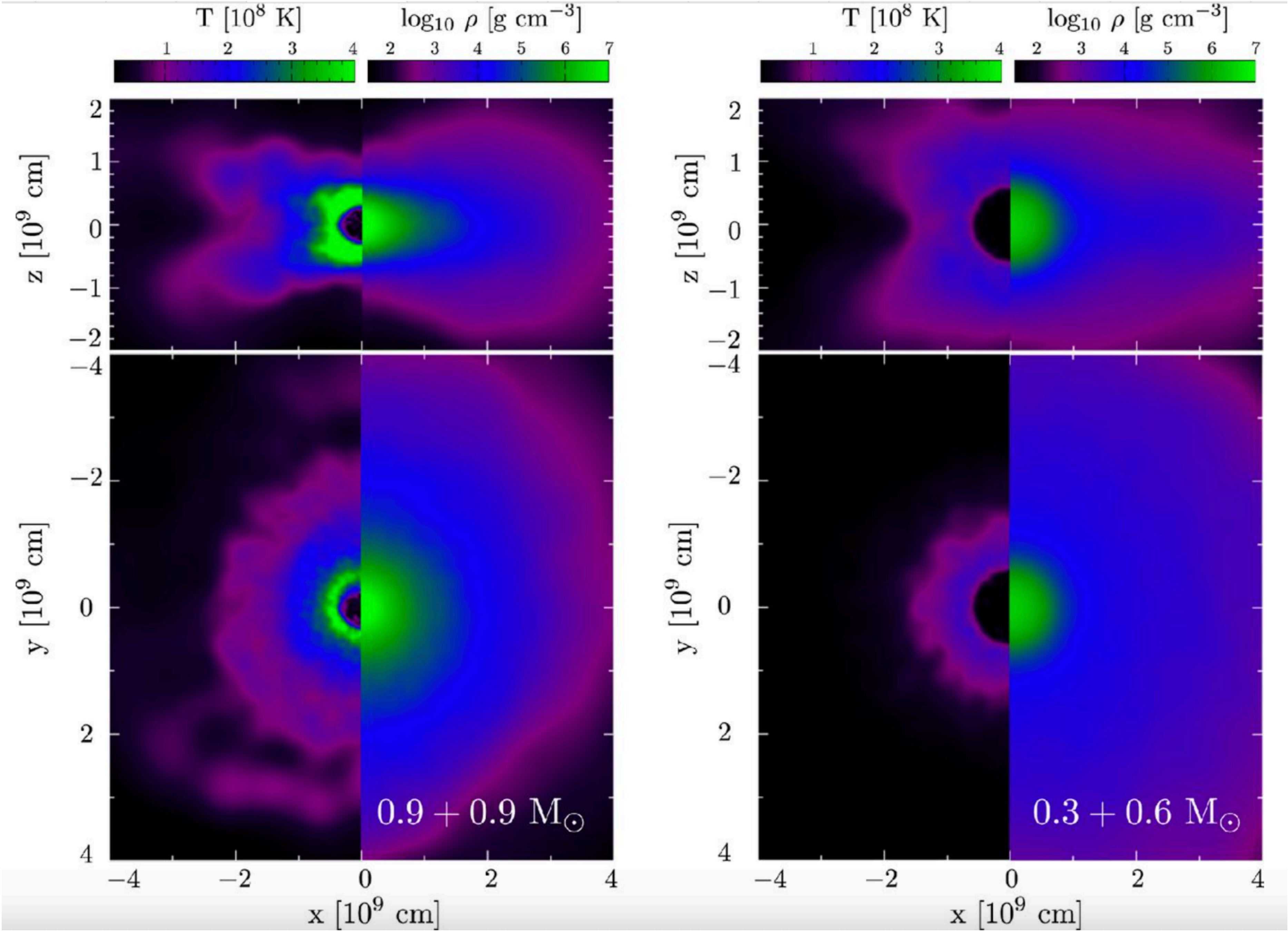


Teddy Walsh

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

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

White Dwarf Mergers



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

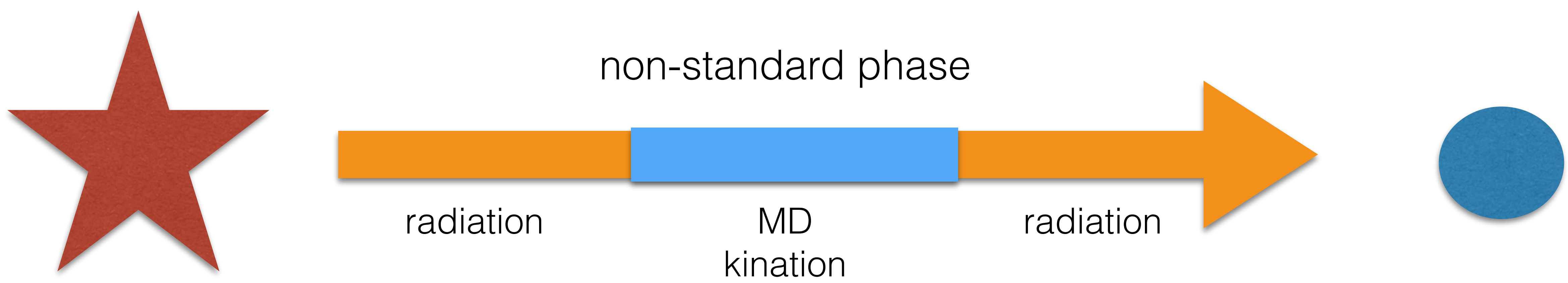
BSM on the way

BSM on the way

Source is BSM, deformation due to new cosmology

Source is astrophysical, deformation due to new stuff

Gameplan



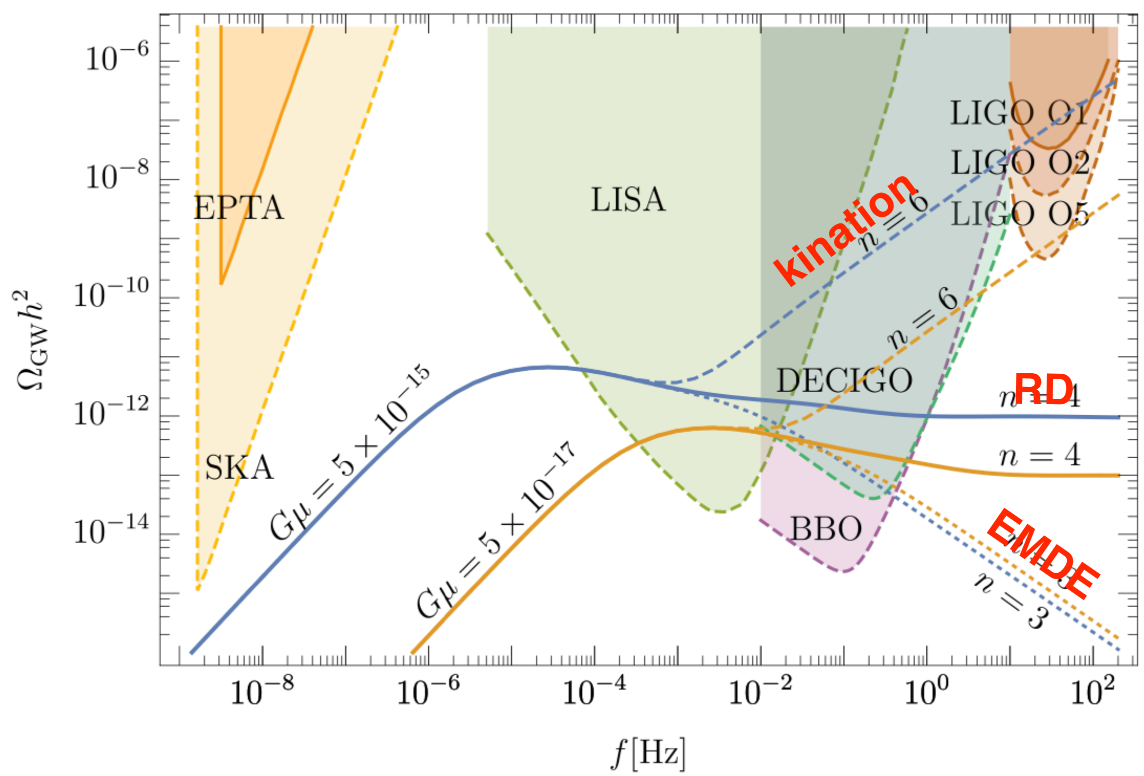
Insert favorite early Universe BSM source:
cosmic strings
phase transitions
2nd order GWs

cosmological distance

deformed GW waveform

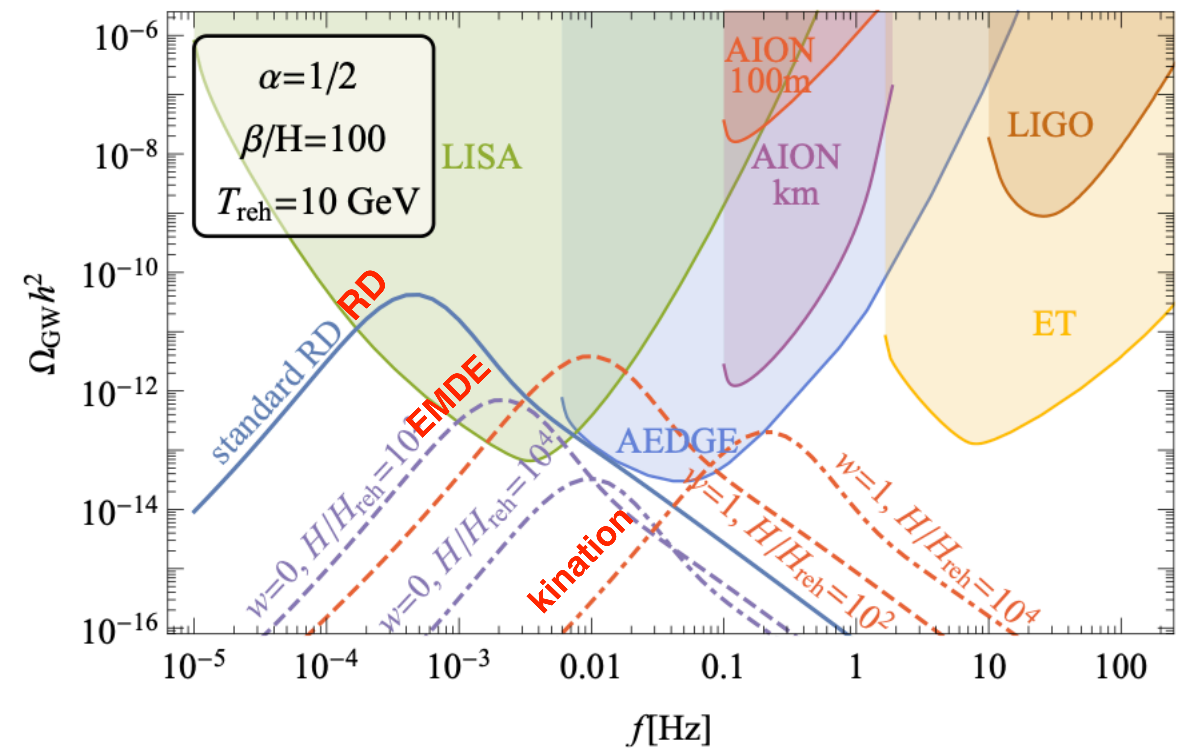
Study Non-Standard Histories

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

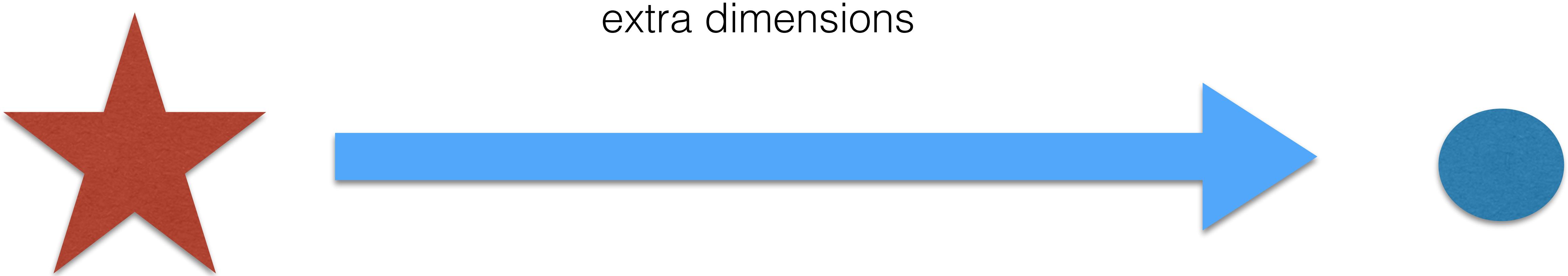
BSM on the way

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

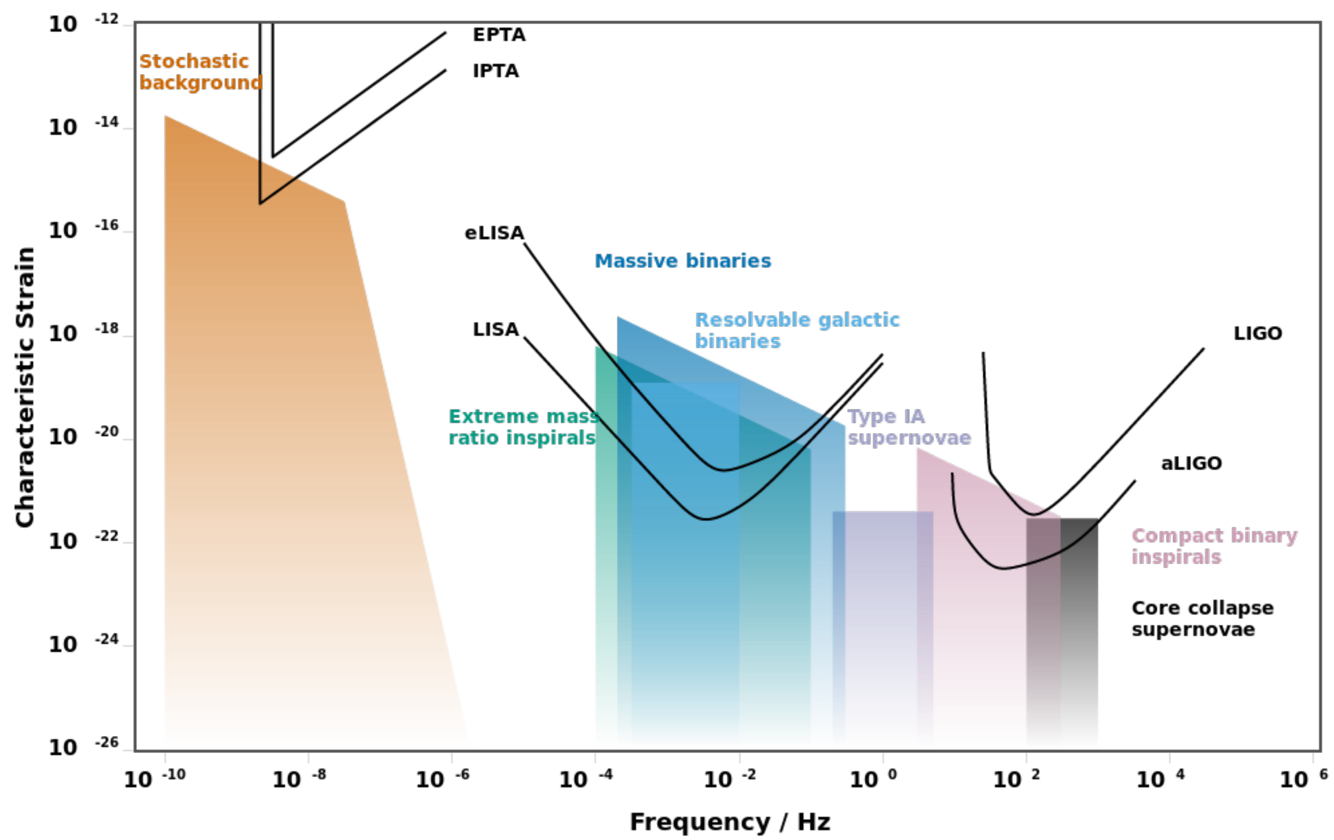
Invitation

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

TJ Gehrman

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)