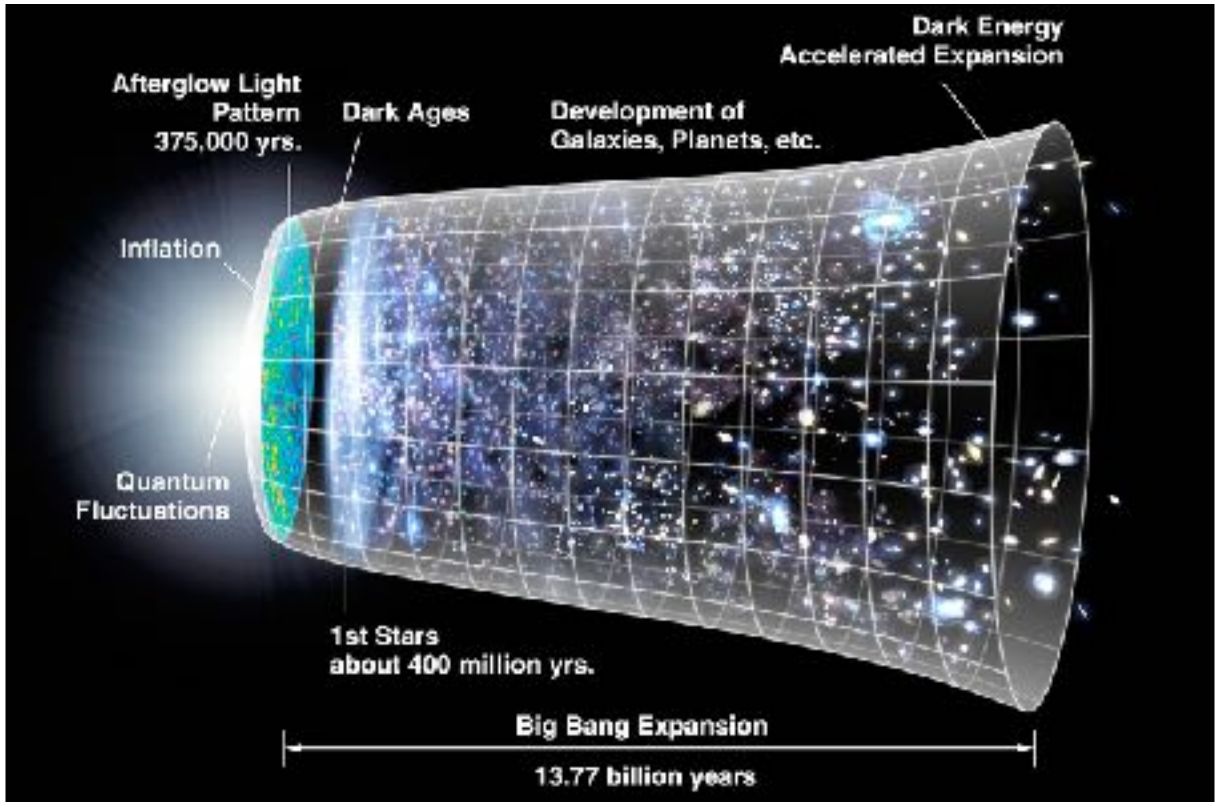
Cosmology @ APC



Simone Mastrogiovanni, Leila Haegel, *Pierre Auclair*, Konstantin Leyde,
Eric Chassande-Mottin, Matteo Barsuglia, Danièle Steer, …

Stas Babak, *Chiara Caprini,* Ed Porter, *Sylvain Marsat,* Alberto Mangiagli, Alberto Roberto Pol,
Alexandre Toubiana…

Close contact with theory group (modified gravity, PBHs, topological defects…)

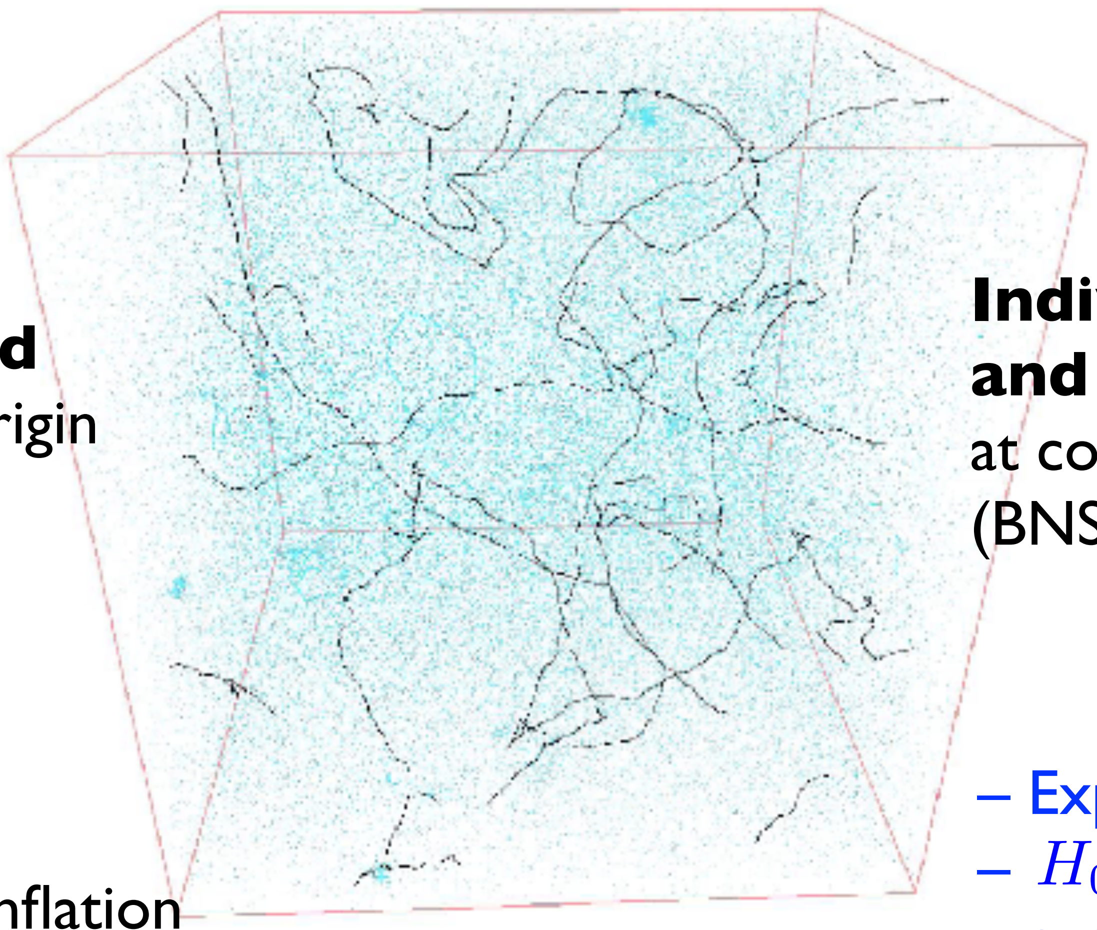
Gravitational wave cosmology

Very early universe

$t \gtrsim t_{Pl}$

Stochastic background
of GWs of cosmological origin

- quantum processes during inflation
- primordial black holes
- Phase transitions in early universe
- topological defects: cosmic strings
- …..



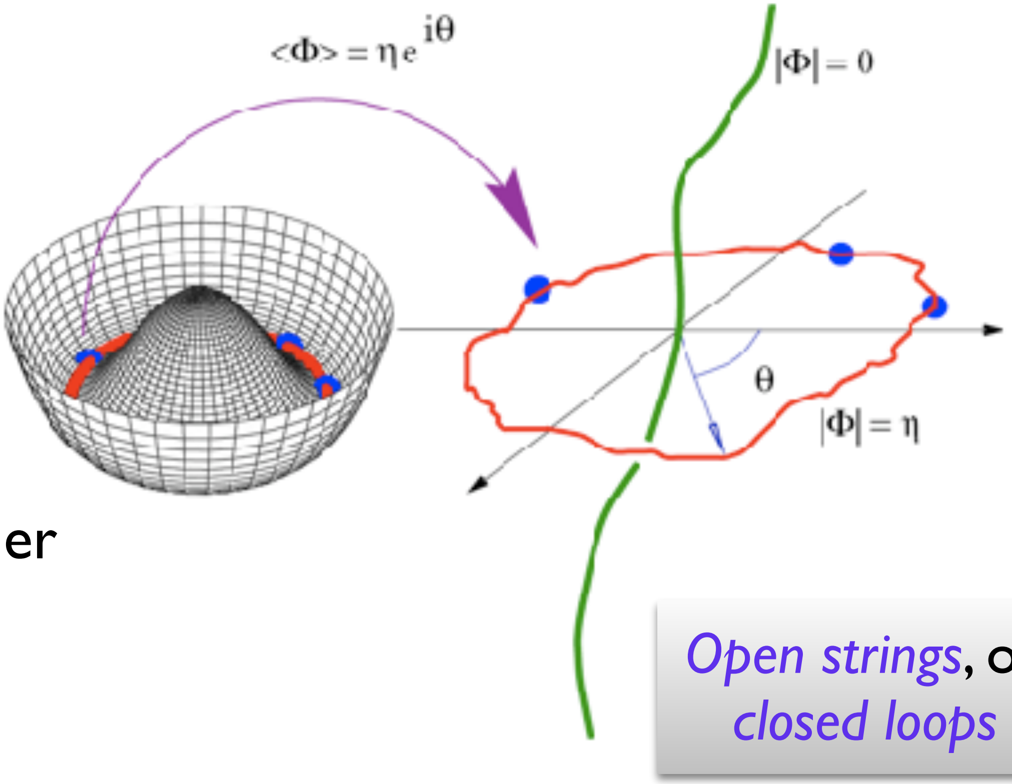
late-time universe

Individual sources
and populations of sources
at cosmological distances
(BNS, BBH, NS-BH…)

- Expansion rate $H(z)$
- H_0, Hubble constant
- cosmological parameters Ω_m
- beyond $\Lambda\mathrm{CDM}$
  dark energy $w(z)$,
  modified gravity (modified GW propagation)
- astrophysics: BH populations….

Primordial cosmology: cosmic strings

Steer, Auclair, Leyde…



Open strings, or *closed loops*

– line-like *topological defects* formed in a symmetry breaking phase transition

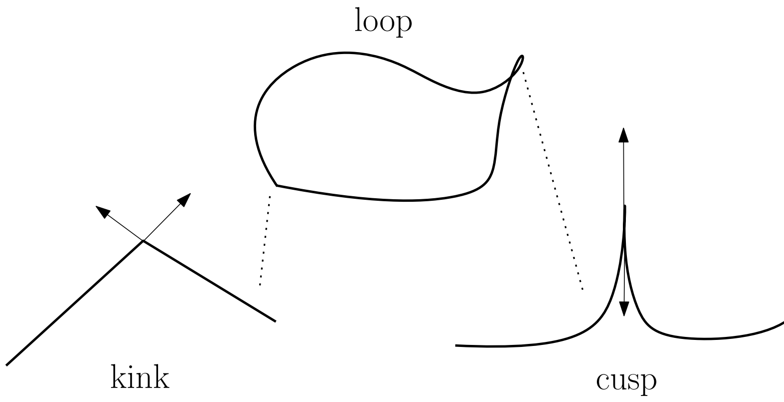
– **Loops** loose energy through GW radiation (& possibly other particle radiation) through their periodic oscillations, and short high-frequency bursts at "kinks" and "cusps"

– Expertise:

- string network modeling and loop number density $n(\ell, t)$

the crucial quantity to calculate all observation signatures in GWs,

- detectability of bursts in O1, O2 etc.
- calculation of the stochastic GW background



– Aim : either a detection, or a constraint on the dimensionless string tension

$$G\mu \sim 10^{-6}\left(\frac{\eta}{10^{16}\ \mathrm{GeV}}\right)^2$$

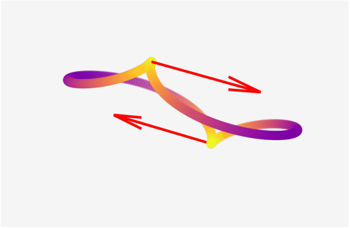
1) GW emission is the dominant decay mode:

Observables: SGWB and search for individual GW bursts

$\frac{\mathrm{d}\ell}{\mathrm{d}t}$ = rate at which a cosmic string loop of loses energy

2) other decay channels, into both GWs and particles

Observable effects on both SGWB and diffuse gamma-ray background



cusps, kinks

Network modeling: *[Cosmic string loop production functions, JCAP 06 (2019) 015, Auclair, Steer et al]*

Development of new models: *[Impact of the small-scale structure on the Stochastic Background of Gravitational Waves from cosmic strings, JCAP 11 (2020) 050, P.Auclair]*

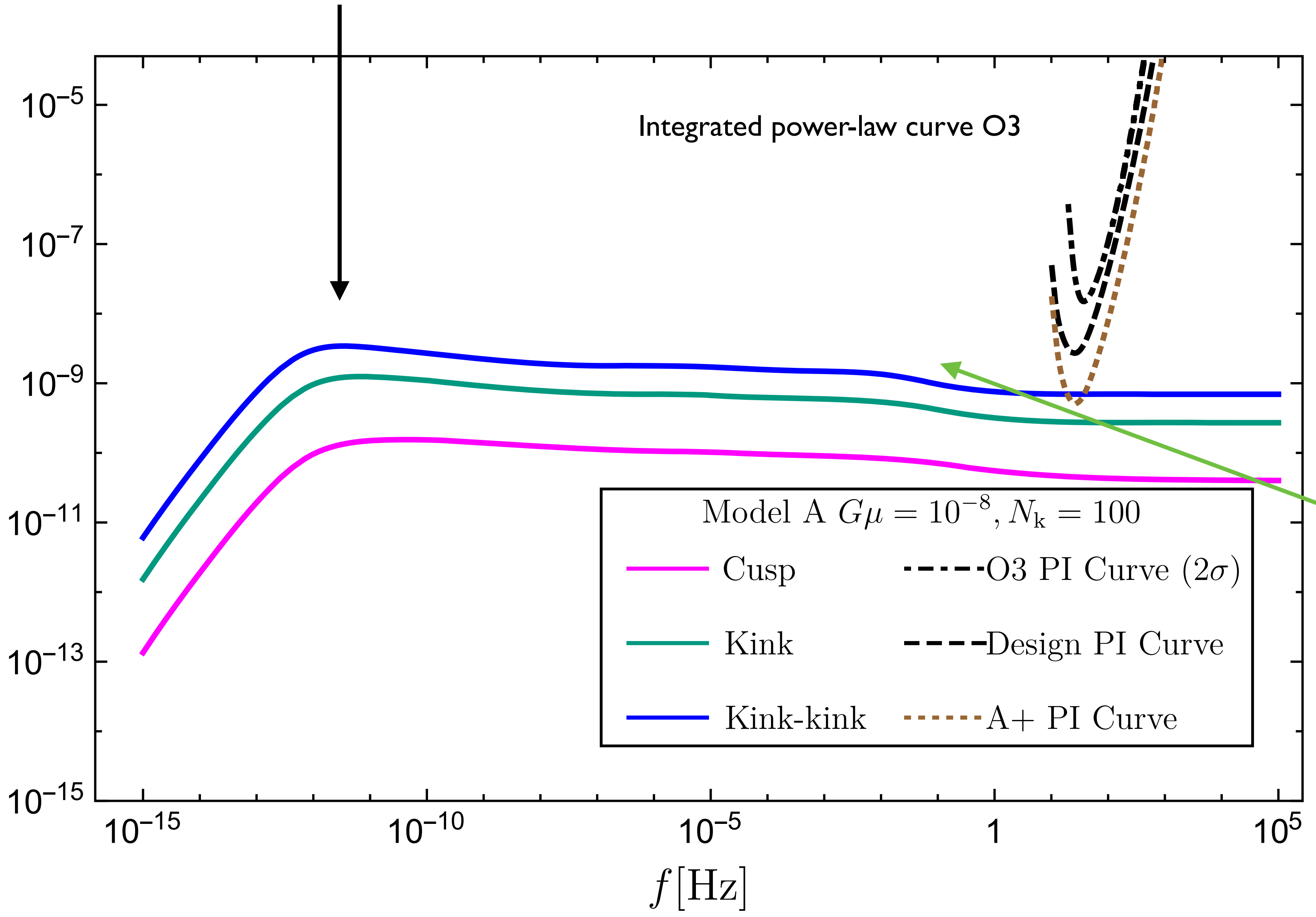
LVK O3 paper: *[Constraints on Cosmic Strings Using Data from the Third Advanced LIGO–Virgo Observing Run, Phys.Rev.Lett. 126 (2021) 24, 241102, Auclair et al]*

Contributions:

- Written new code for SGWB & burst search
- new models proposed by our group analysed,
- paper writing team.

Generic shape (Model A)

$$f_{\rm peak} \sim H_m (\Gamma G\mu)^{-1}$$



emission in *radiation era* -> *flat spectrum* (exact compensation between redshifting of GW energy density, and loop production required for network to scale)

QCD phase
transition
T~100 GeV

emission in *matter era* (less loop production, redshifting of GW energy density "wins")

Flat LCDM

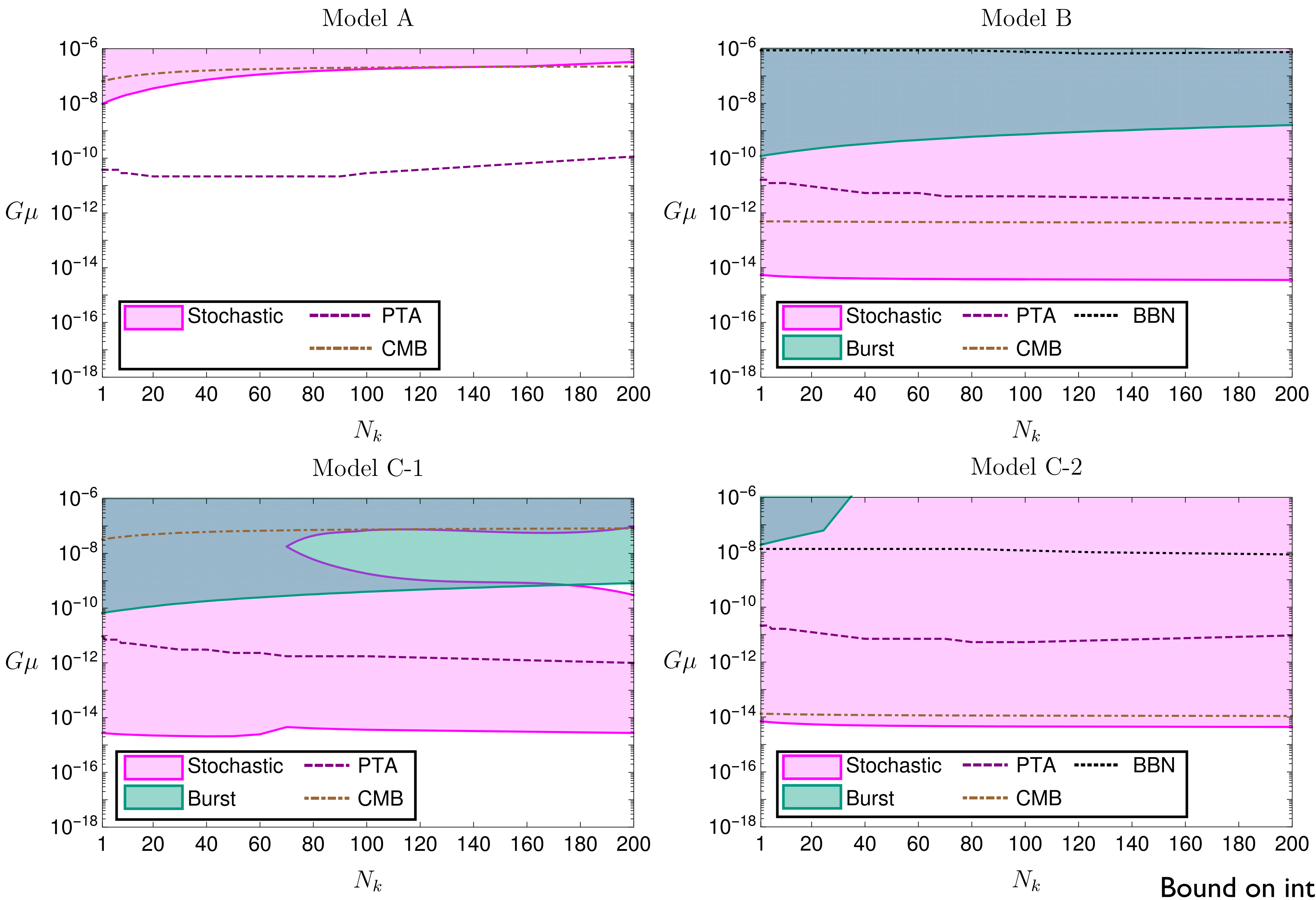
Standard Model numbers of degrees of freedom as given by microMEGAS

$$H(z) = H_0 \mathcal{H}(z)$$

$$\mathcal{H}(z) = \sqrt{\Omega_\Lambda + \Omega_{\rm mat}(1+z)^3 + \Omega_{\rm rad}\mathcal{G}(z)(1+z)^4}$$

[Constraints on Cosmic Strings Using Data from the Third Advanced LIGO–Virgo Observing Run, Phys.Rev.Lett. 126 (2021) 24, 241102, Auclair et al]

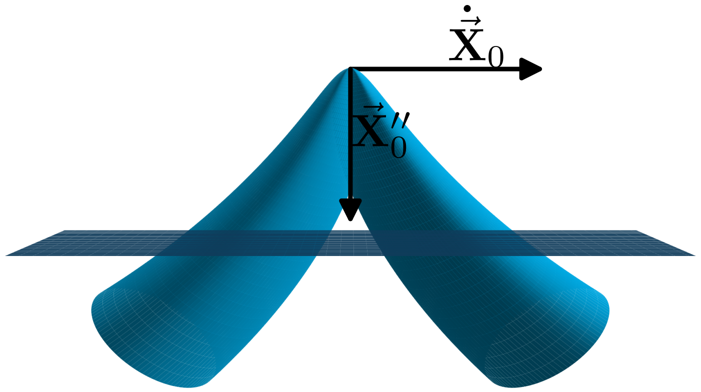
Exclusion plots: strongest constraints on strings to date



Bound on integrated GW energy density generated before BBN, and before photon decoupling

- Relative to O1 and O2 analysis (Nk=1), constraints on Gmu stronger by 2 orders of magnitude for model A, and by 1 for model B

Recent ideas



- At kinks and cusps, a realistic string can "overlap" leading to other forms of energy loss: emission of particles

- Including this gives the new loop distribution.

- Emitted particles decay into standard model Higgs particles, of which a fraction cascade down into gamma-rays -> contribute to the **diffuse gamma-ray background:**

$$\boxed{\omega_{\rm DGRB}^{\rm obs} \lesssim 5.8 \times 10^{-7}\ {\rm eVcm}^{-3}}$$

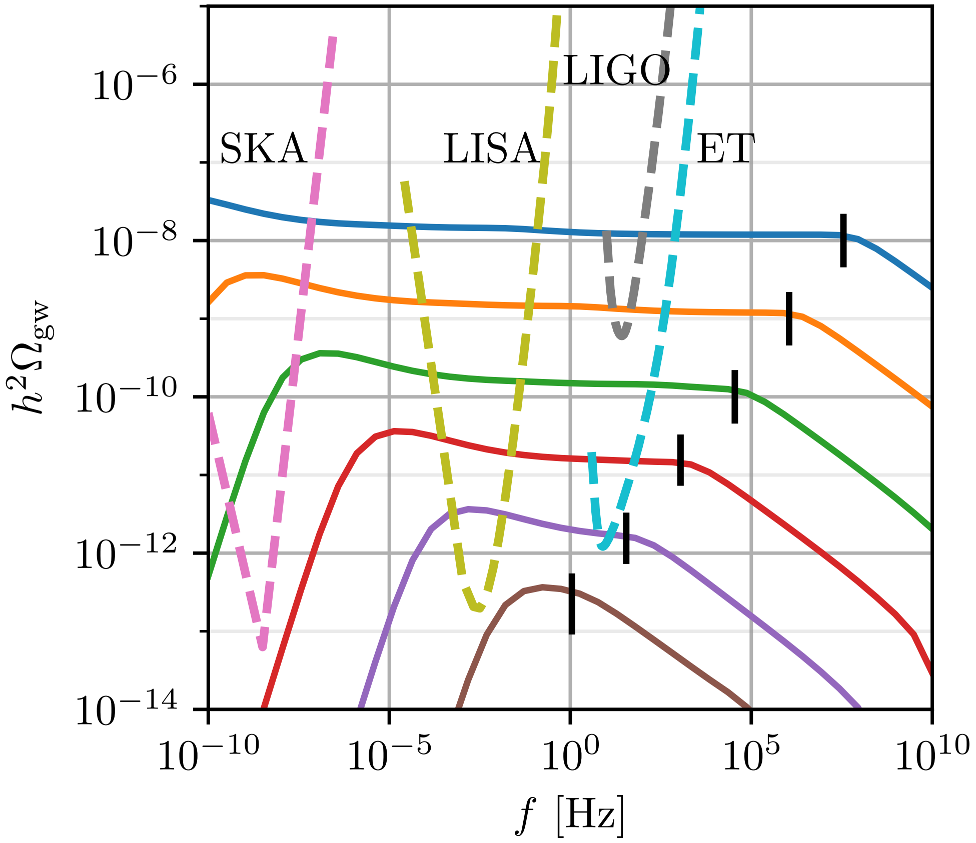
A. A. Abdo et al. (Fermi-LAT),

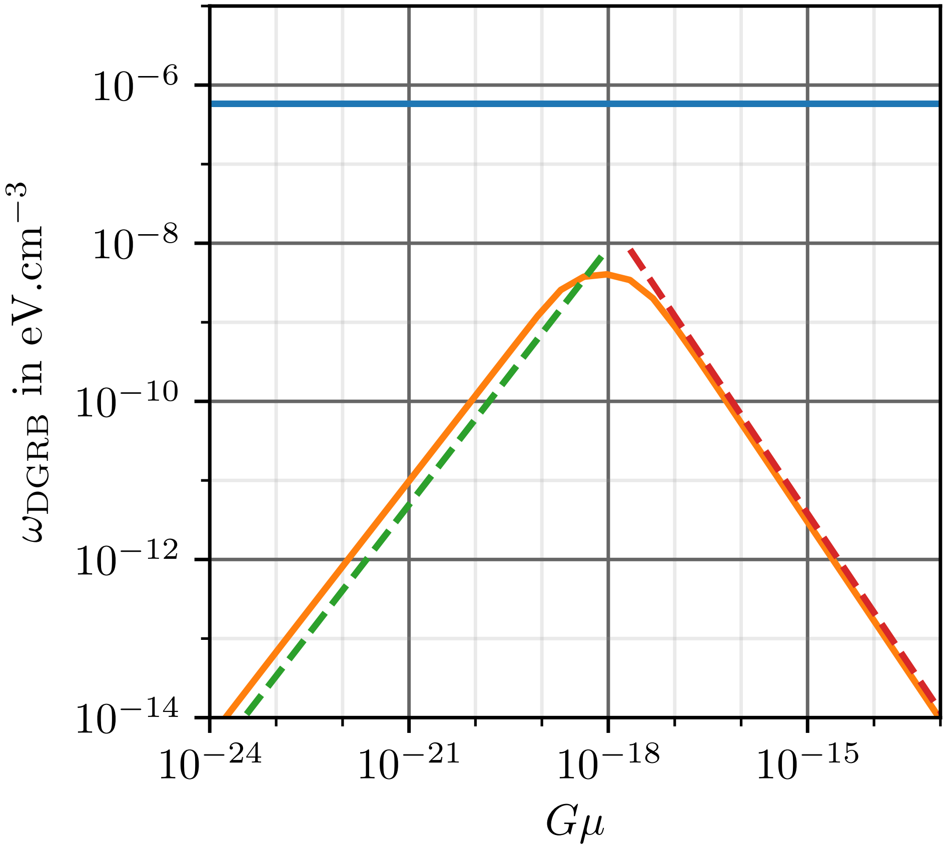
total EM energy injected since universe became transparent to GeV gamma-rays $t_\gamma \simeq 10^{15}{\rm s}$

- combined with GW constraints -> possibly new constraints

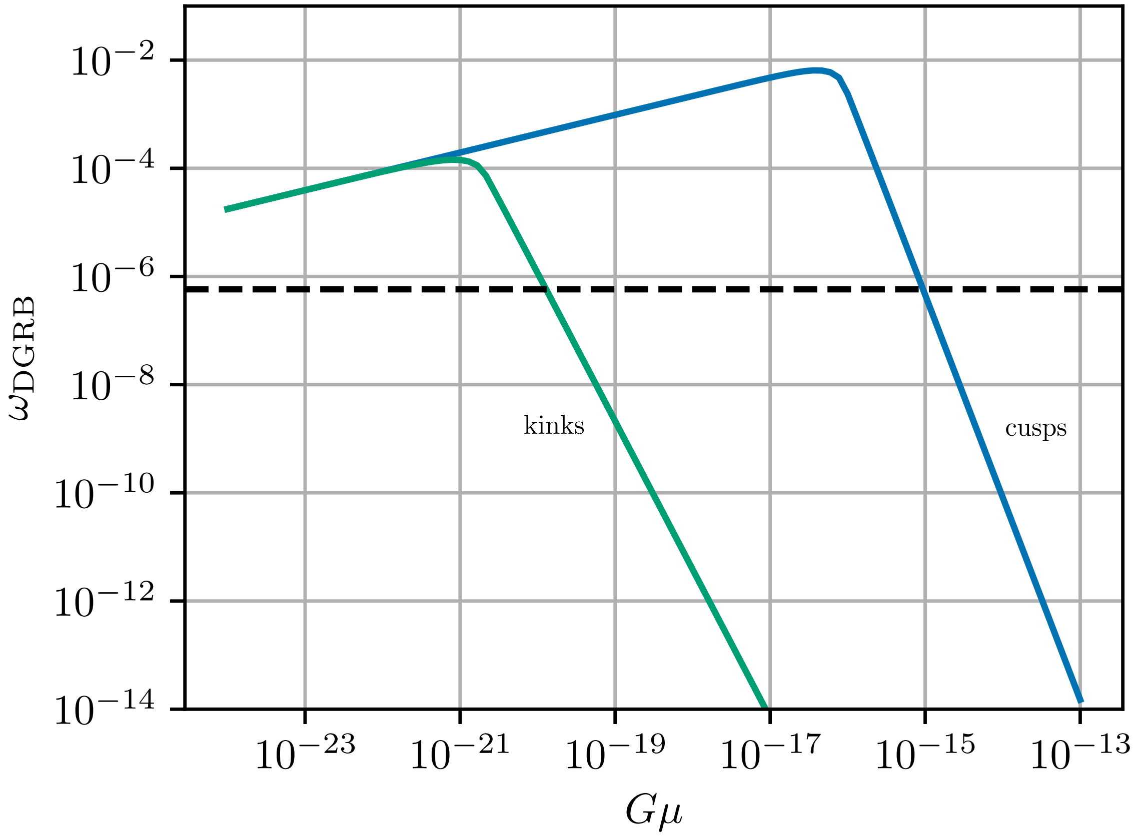
[Particle emission and gravitational radiation from cosmic strings: observational constraints, Phys.Rev.D 101 (2020) 8, 083511, Auclair, Steer etc]

For model A:





For model B: *[Auclair, Leyde, Steer, 2021]*



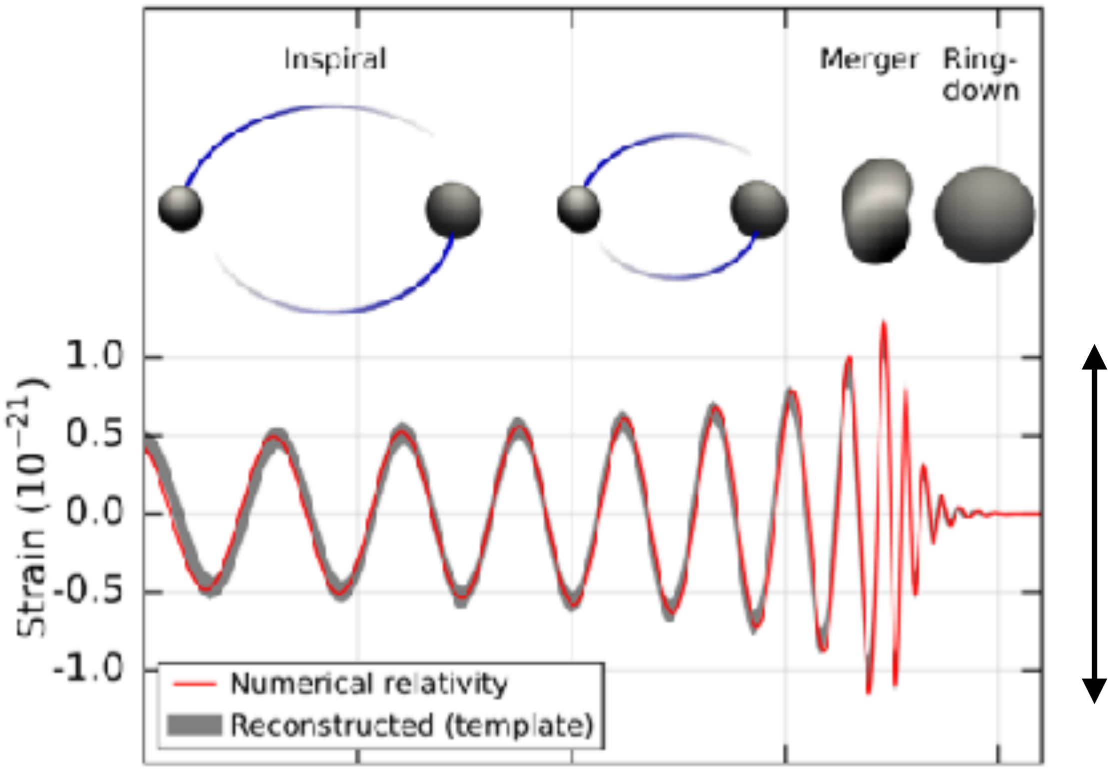
$$10^{-15} \lesssim (G\mu)_{\rm cusps} \lesssim 4.0 \times 10^{-15}$$

gamma rays

GWs

- Future O4/O5 observations will most certainly rule out model B…or discover cosmic strings

Gravitational wave cosmology



$\mathrm{fn}(d_L; \mathcal{M}_z)$

$\longrightarrow$ $\mathrm{fn}(t; \mathcal{M}_z)$

late-time universe

$\updownarrow$

Individual sources
and populations of sources
at cosmological distances
(BNS, BBH, NS-BH…)

$\downarrow$

– Expansion rate $H(z)$
– H_0, Hubble constant
– cosmological parameters Ω_m
– beyond ΛCDM
  dark energy $w(z)$,
  modified gravity (modified GW propagation)
– astrophysics: BH populations….

- Two main axes

1) **Developing, understanding & refining methods to extract redshift of the source**

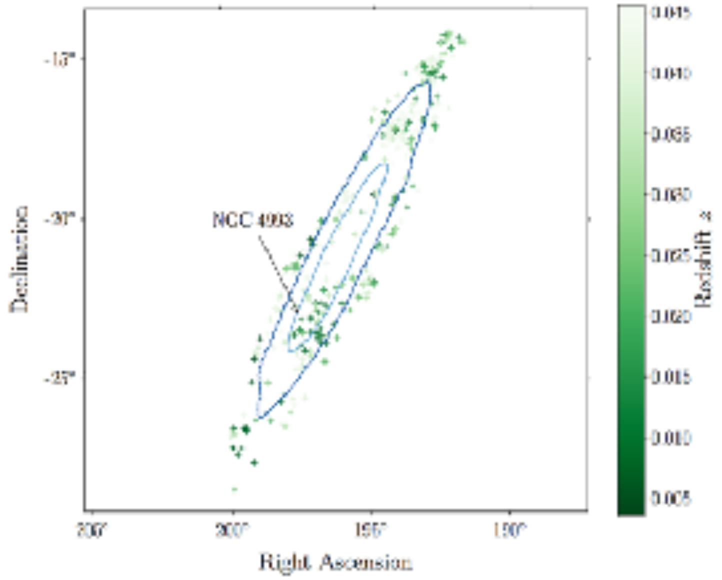
- A direct EM counterpart with an associated redshift measurement *[B.Schutz, '86]*
- A collection of galaxies localized in the GW localization volume (i.e. galaxy catalogues *[B.Schutz, 86]*
- Knowledge of the *source frame mass distribution* (dark sirens)
- ….

[Measuring cosmological parameters with gravitational waves", S.Mastrogiovanni and D.A.Steer, "Handbook of Gravitational Wave Astronomy" Springer 2022.]

[The potential role of binary neutron star merger afterglows in multimessenger cosmology, S.Mastrogiovanni, E.Chassande-Mottin…Astron.Astrophys. 652 (2021) A1]

[Cosmological Inference using Gravitational Wave Standard Sirens: A Mock Data Challenge, R.Gray, … S.Mastrogiovanni…D.Steer, Phys. Rev. D 101, 122001 (2020)]

- study of galaxy catalogue method,
- explore how the incompleteness of catalogs affects the final measurement of Hubble constant
- effect of weighting each galaxy's likelihood of being a host by its luminosity
- Theoretical study used for O2 cosmology paper



GW170817 99% localisation area with 408 galaxies from GLADE catalogue

$$H_0 = 77^{+37}_{-18}\ \mathrm{km/Mpc/s}$$

- Two main axes

1) **Developing, understanding & refining methods to extract redshift of the source**

- A direct EM counterpart with an associated redshift measurement *[B.Schutz, '86]*
- A collection of galaxies localized in the GW localization volume (i.e. galaxy catalogues *[B.Schutz, 86]*
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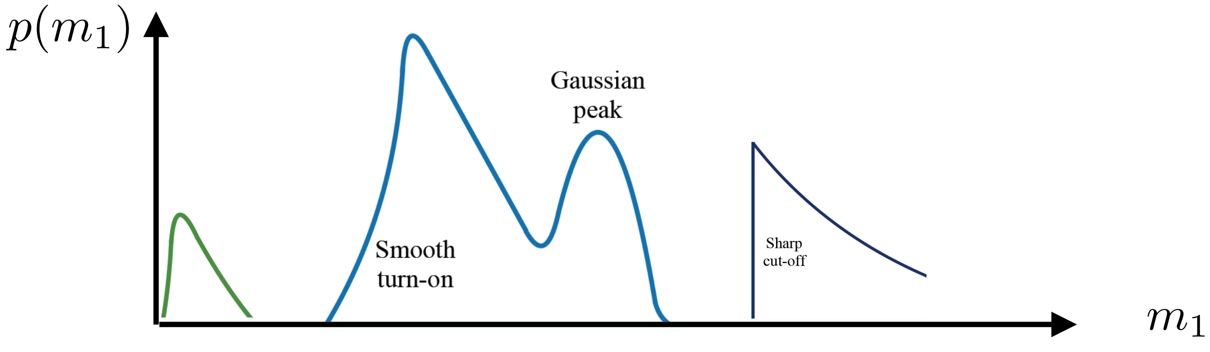
- ….

Development of IcaroGW code (Simone)



$$m_{1,2}^{\mathrm{det}} = [1 + z(d_L, H_0, \ldots)] m_{1,2}^{\mathrm{source}}$$

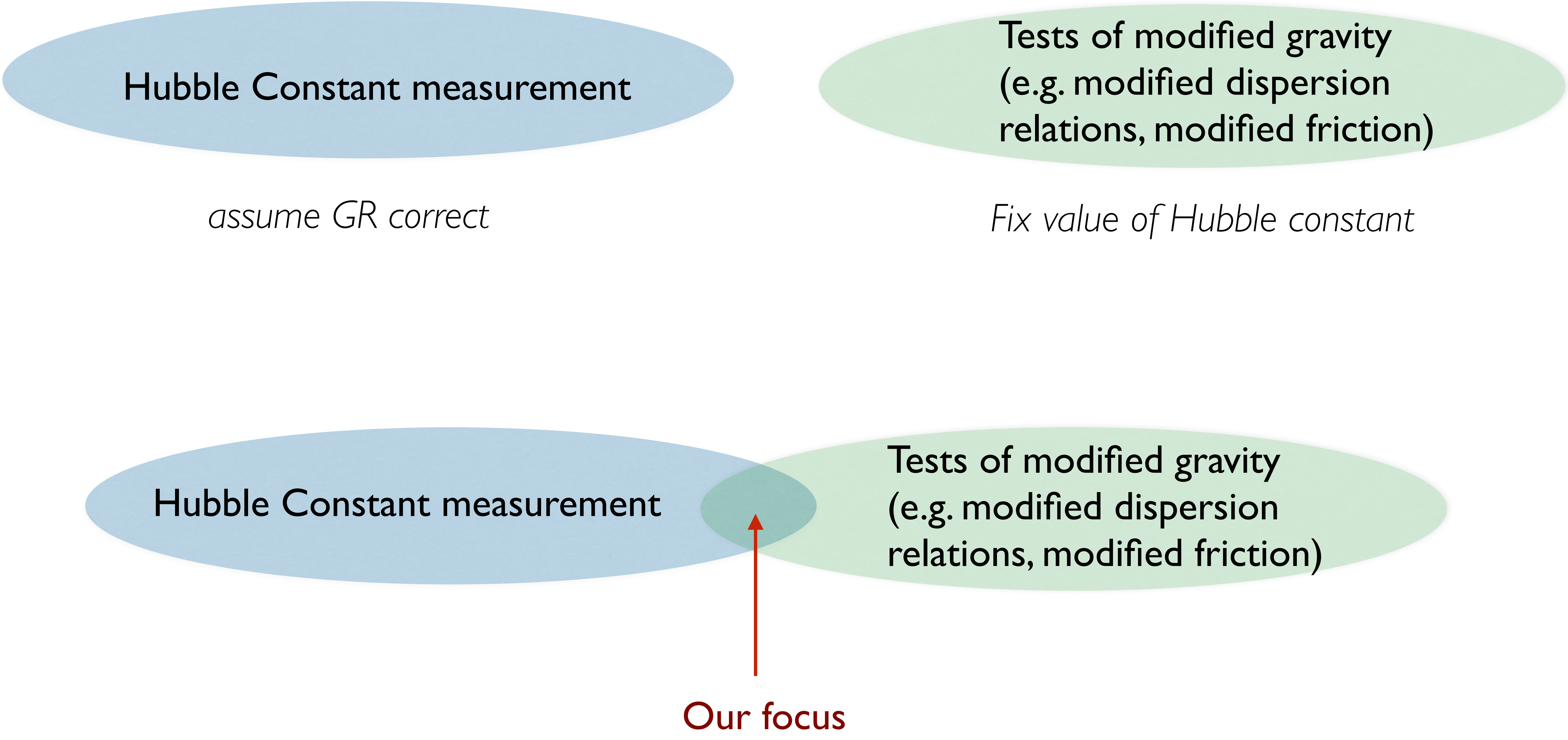
[Cosmology in the dark: On the importance of source population models for gravitational-wave cosmology, S. Mastrogiovanni et al, Phys.Rev.D 104 (2021) 6, 062009]

– tight correlation between estimation of source frame mass spectrum + cosmo parameters.

– Effect of fixing the underlying mass model with **incorrect** parameters
(e.g. m_{max} in a range around its true value)

2) **Testing modified gravity and cosmology**

$$h'' + 2[1+\alpha_M(\eta)]\frac{a'}{a}h' + k^2 c_T^2(\eta, k/a)h = 0,$$



Hubble Constant measurement

assume GR correct

Tests of modified gravity (e.g. modified dispersion relations, modified friction)

Fix value of Hubble constant

Hubble Constant measurement

Tests of modified gravity (e.g. modified dispersion relations, modified friction)

Our focus

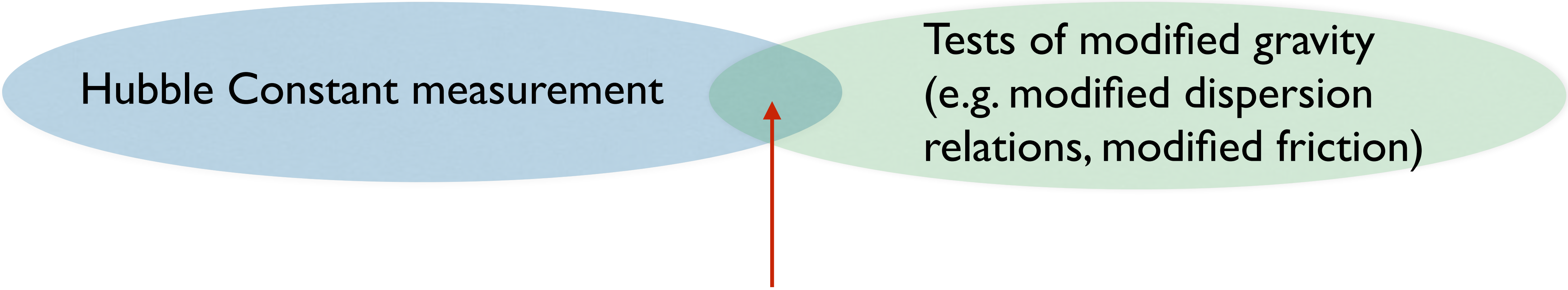
- Degeneracy between H0 and parameters of modified gravity theories?
- Do we need to perform a joint analysis of GR modifications and H0 together (to avoid for eg biases?)

2) **Testing modified gravity and cosmology**

[Probing modified gravity theories and cosmology using gravitational-waves and associated electromagnetic counterparts, Simone, Matteo, D.S, Phys.Rev.D 102 (2020) 4, 044009]

[Gravitational wave friction in light of GW170817 and GW190521, S.Mastrogiovanni, L. Haegel, C.Karathanasis, I.Magana Hernandez, and D.A.Steer, JCAP 02 (2021) 043.]

[Current and future constraints on cosmology and modified gravitational wave friction from binary black holes, K.Leyde S.Mastrogiovanni, D.A.Steer, E.Chassande-Mottin, C.Karathanasis 2202.00025 [gr-qc]]



Hubble Constant measurement

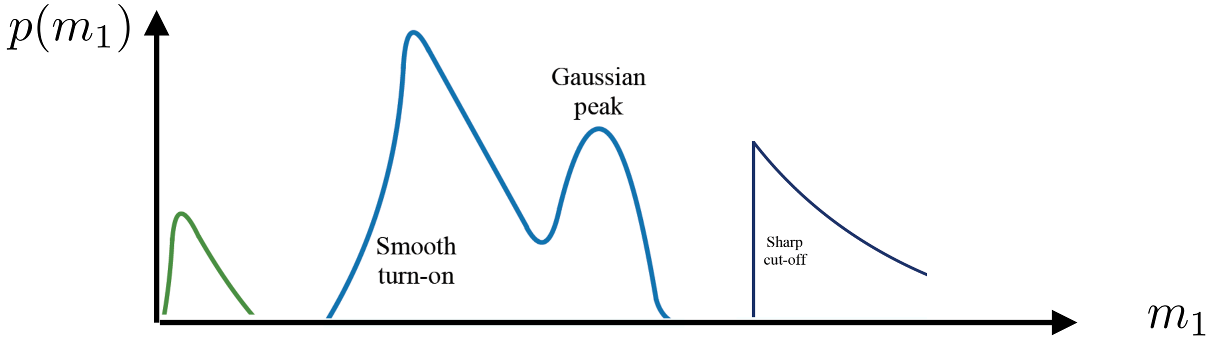
Tests of modified gravity (e.g. modified dispersion relations, modified friction)

Our focus

With dark sirens

[Current and future constraints on cosmology and modified gravitational wave friction from binary black holes, K.Leyde S.Mastrogiovanni, D.A.Steer, E.Chassande-Mottin, C.Karathanasis 2202.00025 [gr-qc]]

Extension of IcaroGW-TGR code



$$\boxed{h'' + 2[1+\alpha_M(\eta)]\frac{a'}{a}h' + k^2 c_T^2(\eta, k/a)h = 0,}$$

- Simplest assumption : no modified dispersion relation, so gravitons are massless and propage with cT=1 at all frequencies (e.g. certain Horndeski, DHOST..) theories

- Modified luminosity distance:

$$d^{\mathrm{GW}}(z) = d_{\mathrm{EM}}(z)\exp\left[\int_0^z \frac{\alpha_M(z)}{1+z}dz\right]$$

M. Lagos et al Phys. Rev. D 99, 083504 (2019),

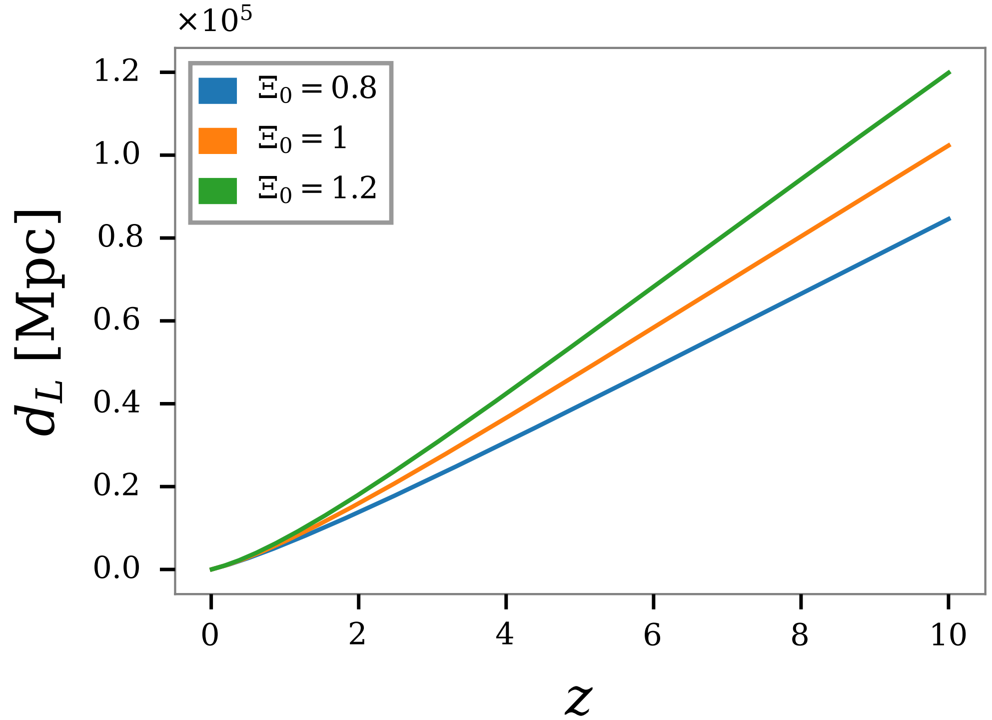
Consider 3 parametrisations:

a) Phenomenological model suggested in *[1906.01593]*

$$d_L^{\mathrm{GW}} = d_L^{\mathrm{EM}}\left(\Xi_0 + \frac{1-\Xi_0}{(1+z)^n}\right)$$

GR: $\Xi_0 = 1$

Ξ_0 characterises early time behaviour



b) Assume friction term is linked to dark energy content of the universe *[1404.3713…]*

$$\alpha_M(z) = c_M \frac{\Omega_\Lambda(z)}{\Omega_\Lambda(0)},$$

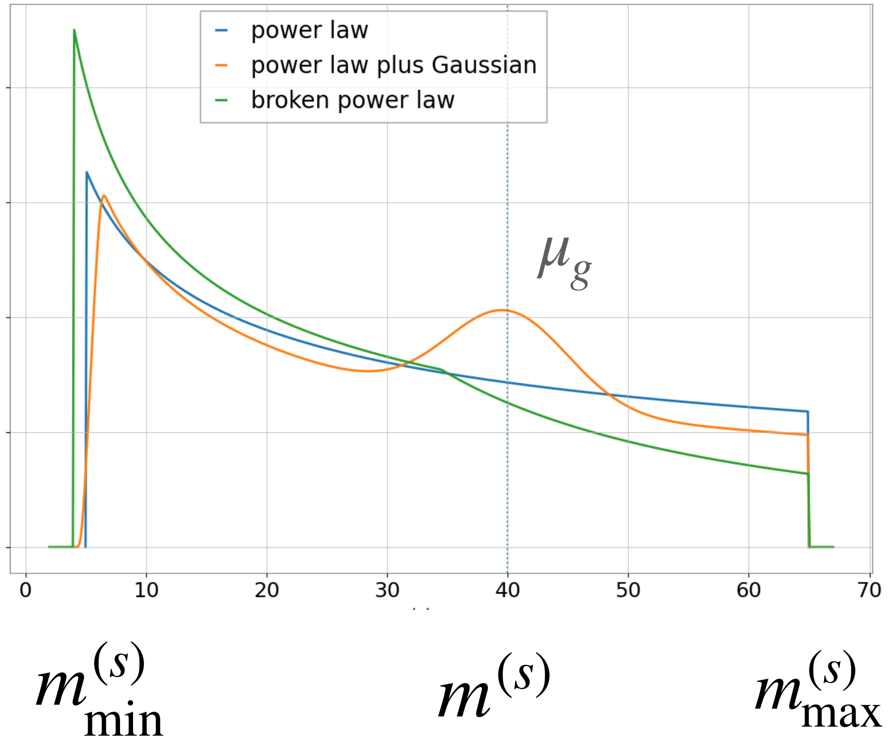
$$d_L^{\mathrm{GW}} = d_L^{\mathrm{EM}} \exp\left[\frac{c_M}{2\Omega_{\Lambda,0}} \ln \frac{1+z}{\Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0}}\right]$$

c) Model an extra dimensional universe with screening scale, motivated from e.g. DGP *[0709.0003, 2109.08748]*

$$d_L^{\mathrm{GW}} = d_L^{\mathrm{EM}} \left[1 + \left(\frac{d_L^{\mathrm{EM}}}{(1+z)R_c}\right)^n\right]^{\frac{D-4}{2n}}$$

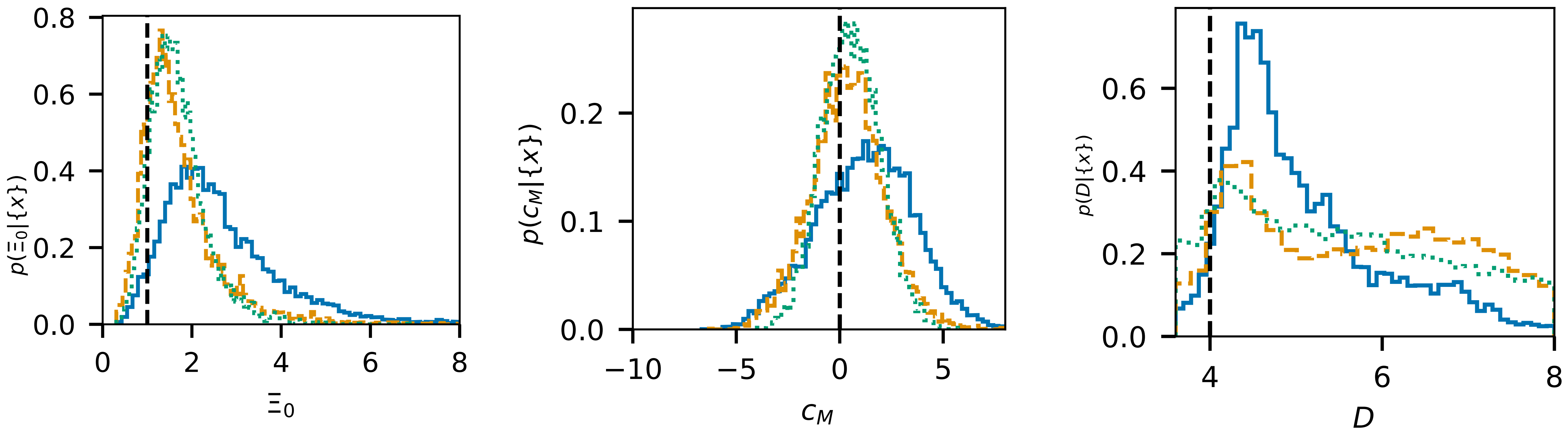
Consider 4 different source mass population models, motivated from 2010.14533, and estimate jointly, using O3 data

- the cosmological parameters (H_0, Ω_m)
- source mass parameters $(m_{\mathrm{min}}^{(s)}, m_{\mathrm{max}}^{(s)}, \ldots)$
- parameters describing luminosity distance



Results using O3 data :

- Comparing Bayes factors: GR with multi-peak model is preferred!

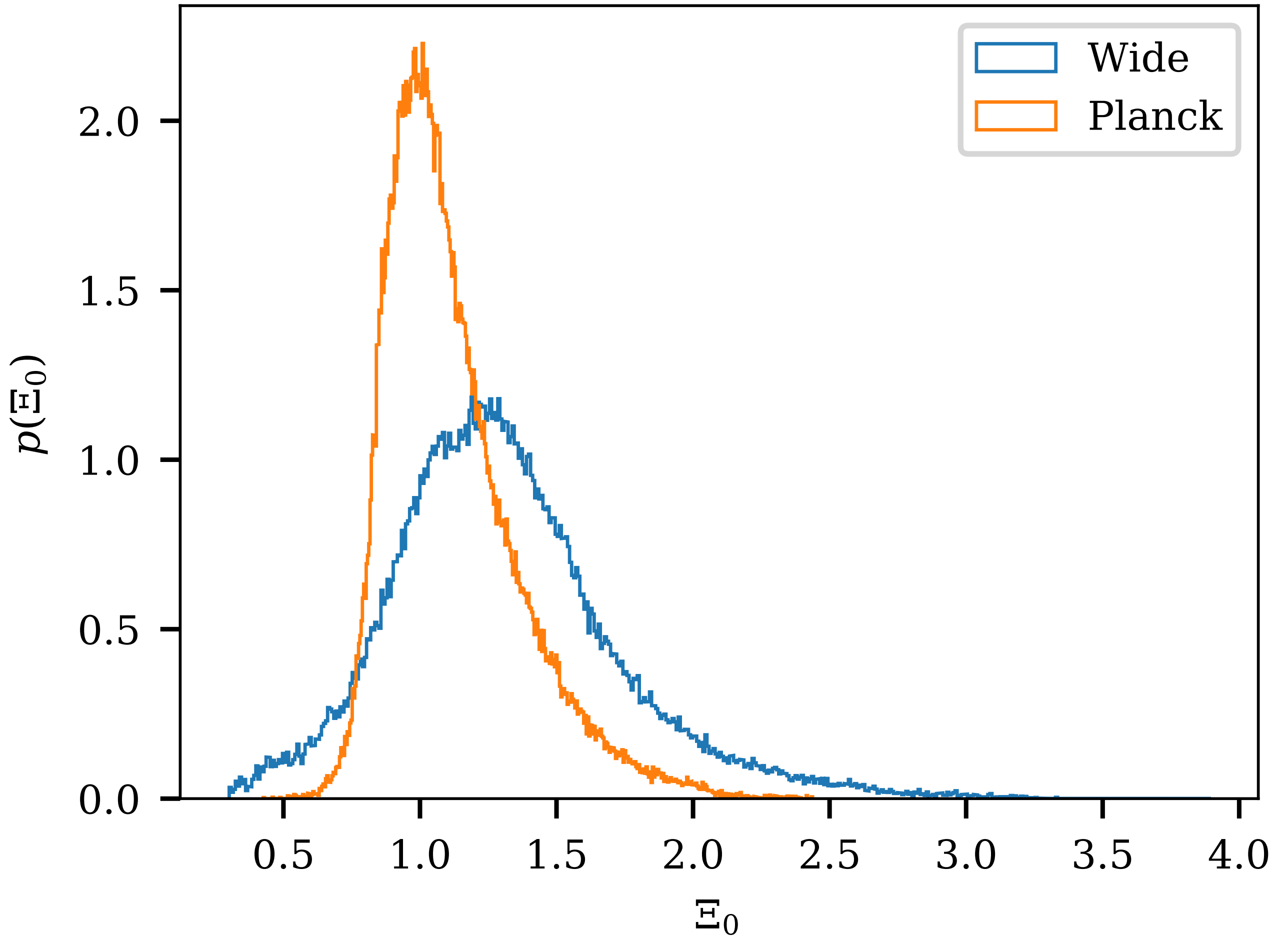


Blue: SNR >11, Orange SNR >12, green SNR >10

- For all modified gravity models, values of parameters are compatible with their GR values at 90% confidence level!

Forecasts for O4 and O5 :

- Simulate expected data, with 87 events for O4, and 423 for O5 (1 year of data)



Blue = agnostic priors on the cosmological parameters
Orange = narrow priors.

	Agnostic	*From Planck*
H_0	$\mathcal{U}(30, 130)$	$\mathcal{U}(66.07, 68.47)$
Ω_M	$\mathcal{U}(0.05, 0.4)$	$\mathcal{U}(0.3082, 0.3250)$