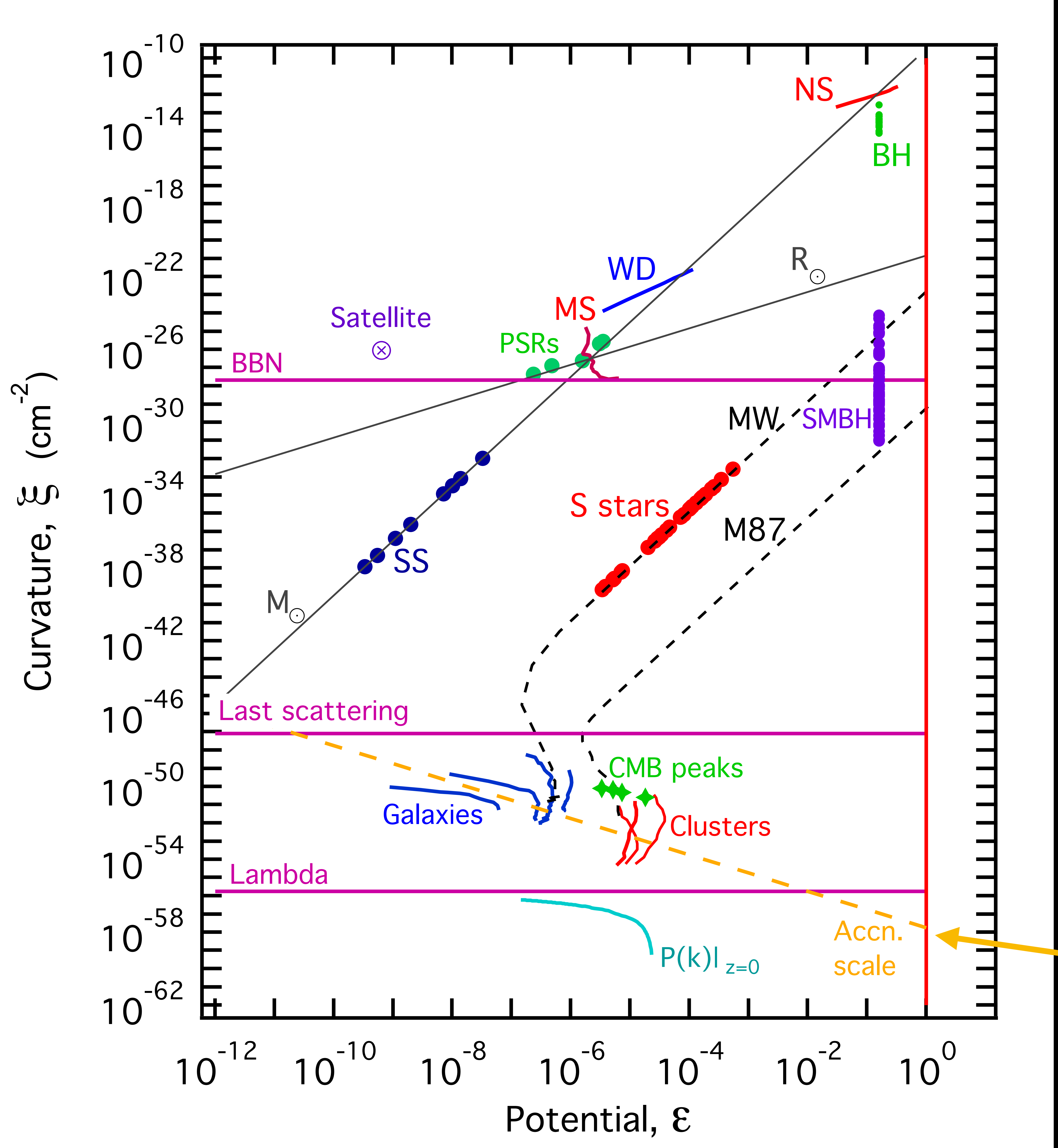
MOND@40, University of St Andrews, 9/6/23

Twin Tests of Gravity

Gravitational waves & large-scale structure

Tessa Baker
Queen Mary University of London

Where have we probed gravity?



1.2 X 10^{-10} ms^{-2}

TB, Psaltis & Skordis (2015)

Outline

- A framework for testing deviations from GR.
- Bounds from gravitational waves (GWs).
- Simulating large-scale structure (LSS) beyond GR.

Bartolomeo Fiorini

Ashim sen Gupta

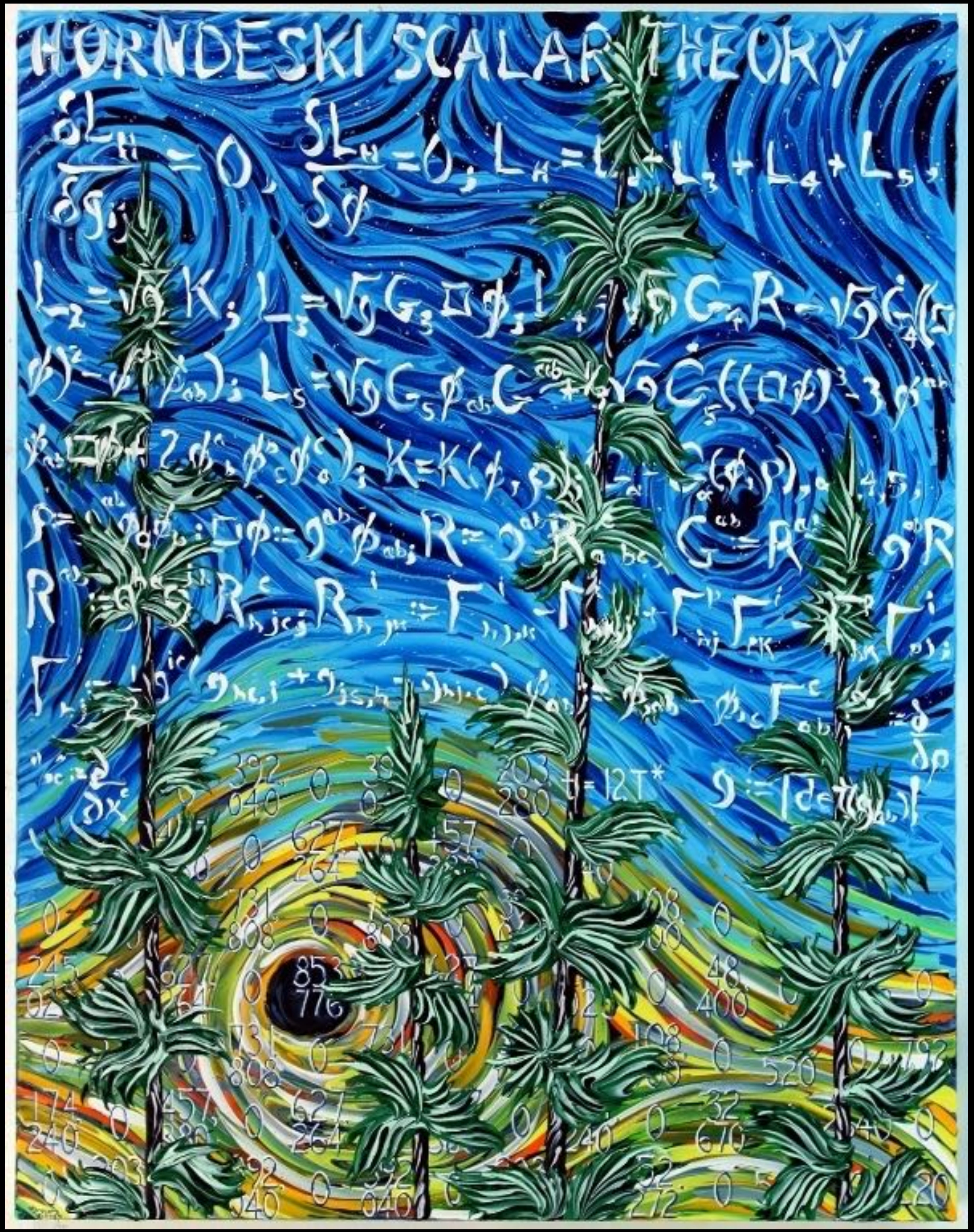
Konstantin Leyde (joining soon)

Charlie Dalang

Anson Chen

Stefano Zazzera

Frameworks for Testing Gravity

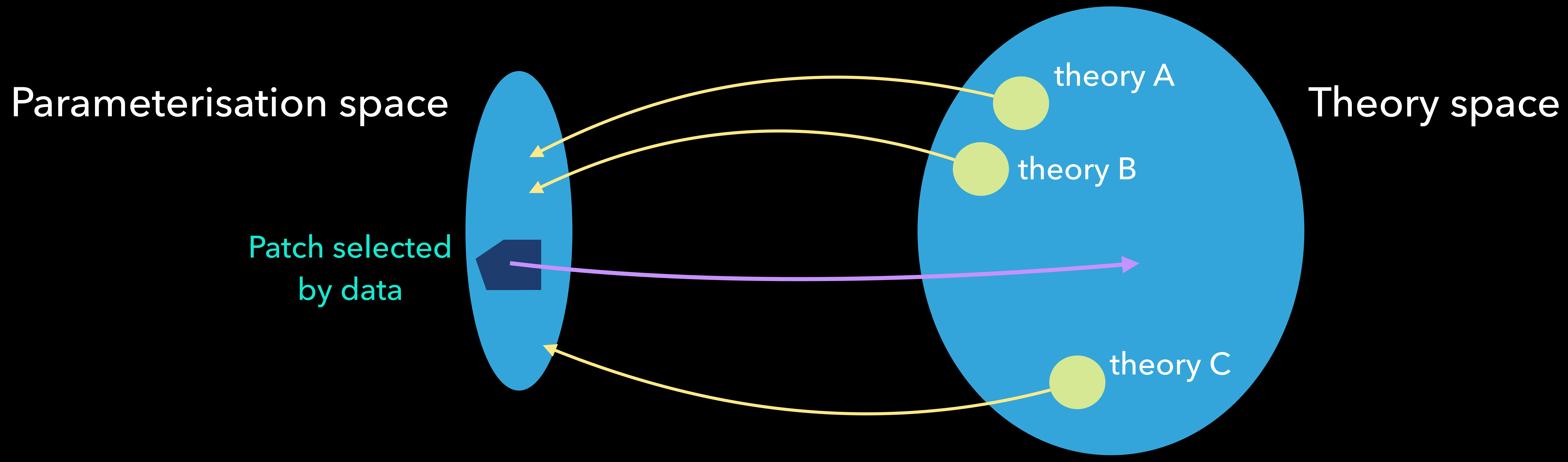


`Horndeski Scalar Theory--Past, Present & Future', G. Horndeski

Parameterised frameworks

Constraining individual gravity theories beyond GR is hugely inefficient.

⇒ Try to map multiple models onto a common set of parameters.



No 100% perfect solution, but can build parameterisations for new scalar, vector and tensor degrees of freedom.

1404.3713
1604.01386

Horndeski gravity — a family beyond GR

EFT mindset: write down most general action for gravity + extra d.o.f., with symmetries.

Today: one scalar only → **Horndeski gravity**.

$$S = \int d^4x \sqrt{-g} \left[\text{Messy function of } \varphi \text{ and } g_{\mu\nu} \right] + S_{\text{Matter}}$$

↓

Take linearised equations about a smooth, expanding universe (FRW)

$$\alpha_K(z),\ \alpha_B(z),\ \alpha_M(z),\ \alpha_T(z)$$

Horndeski 'alpha' parameters.

The Horndeski 'Alpha' Parameters

Quantify typical features of non-GR behaviour from scalar fields:

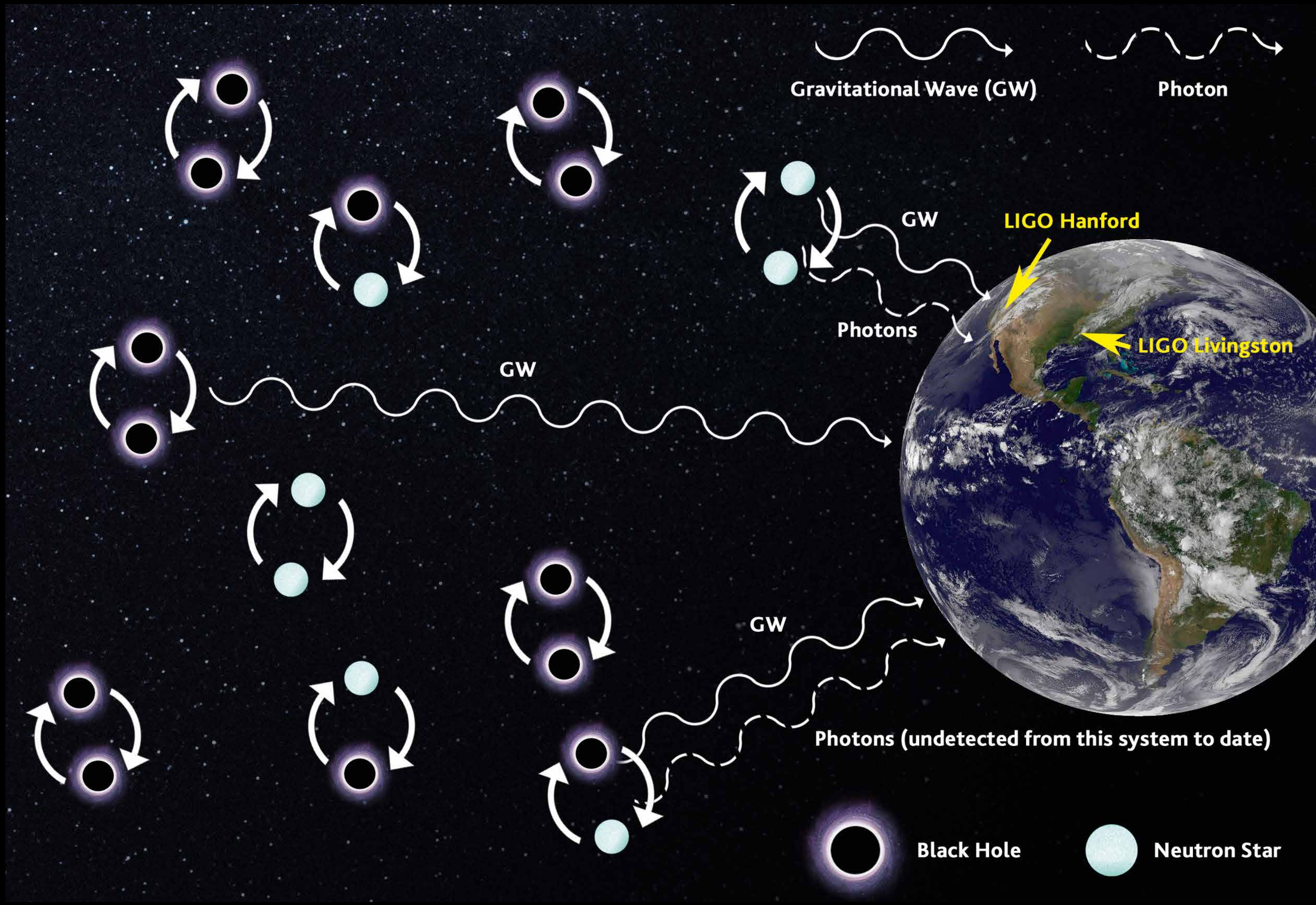
$\alpha_T(z)$ speed of gravitational waves, $c_T^2 = 1 + \alpha_T$.

$\alpha_M(z) = \frac{1}{H}\frac{d\ln M^2(t)}{dt}$ running of effective Planck mass.

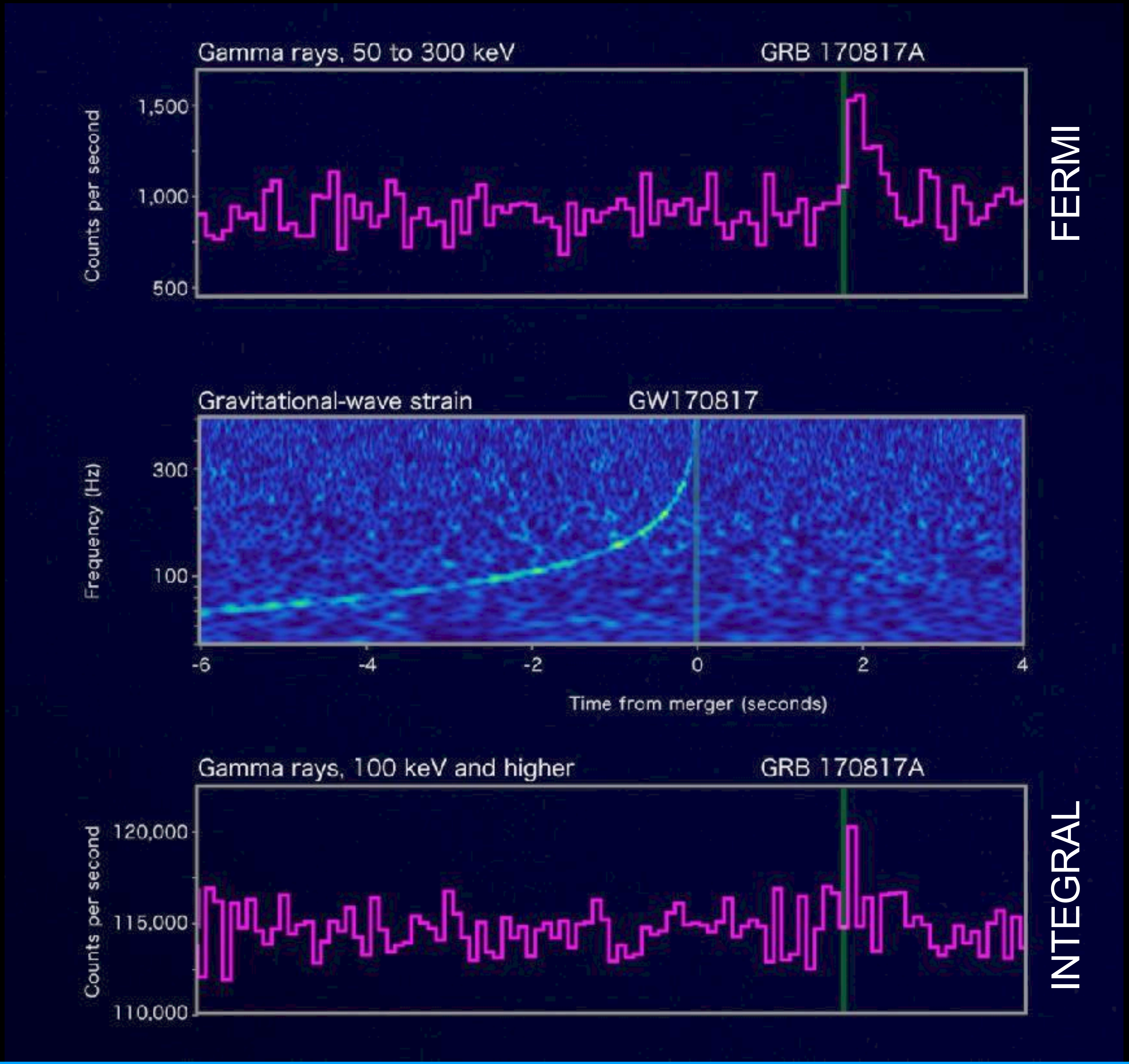
$\alpha_B(z)$ \`braiding' – mixing of scalar + metric kinetic terms.

$\alpha_K(z)$ kinetic term of scalar field.

Bounds from Gravitational Waves



GW propagation speed with GW170817



- Propagation speed of GWs was constrained by GW170817 & GRB170817a.
- $\Delta t = t_{GW} - t_{GRB} = 1.7s$
- Recall: $c_T^2 = 1 + \alpha_T$

$$\Rightarrow |\alpha_T| \lesssim 10^{-15}$$

- Rules out the most complicated parts of the Horndeski Lagrangian.
- Photons & GWs propagate on geodesics of the same metric (Boran et al. 1710.06168).

The Horndeski 'Alpha' Parameters

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GW Propagation

GW propagating on FRW background in GR:

$$h''_{ij} + 2\,\mathcal{H}\,h'_{ij} - \nabla^2 h_{ij} = 0$$

Hubble factor

Contains +, X polarisation modes.

GW Propagation

GW propagating on FRW background in Horndeski gravity:

$$h''_{ij} \; + 2\,(1 + \alpha_M)\,\mathcal{H}\,h'_{ij} \; - \; c_T^2\,\nabla^2 h_{ij} \; = \; 0$$

Modified `friction'
→ changes GW amplitude

Luminosity distance-redshift relation

$$\tilde{h}_{+,\times}(f) \propto \frac{\mathcal{M}_z^2}{d_L} (\pi \mathcal{M}_z f)^{-\frac{7}{6}} \times \text{(polarisation angles)} \times \text{(inclination factor)}$$

Luminosity distance $$d_L(z) = (1+z)\int_0^z \frac{d\tilde{z}}{H(\tilde{z})}$$

Standard sirens allow us to measure both d_L and redshift.

⇒ Constrain (for example) the Hubble constant.

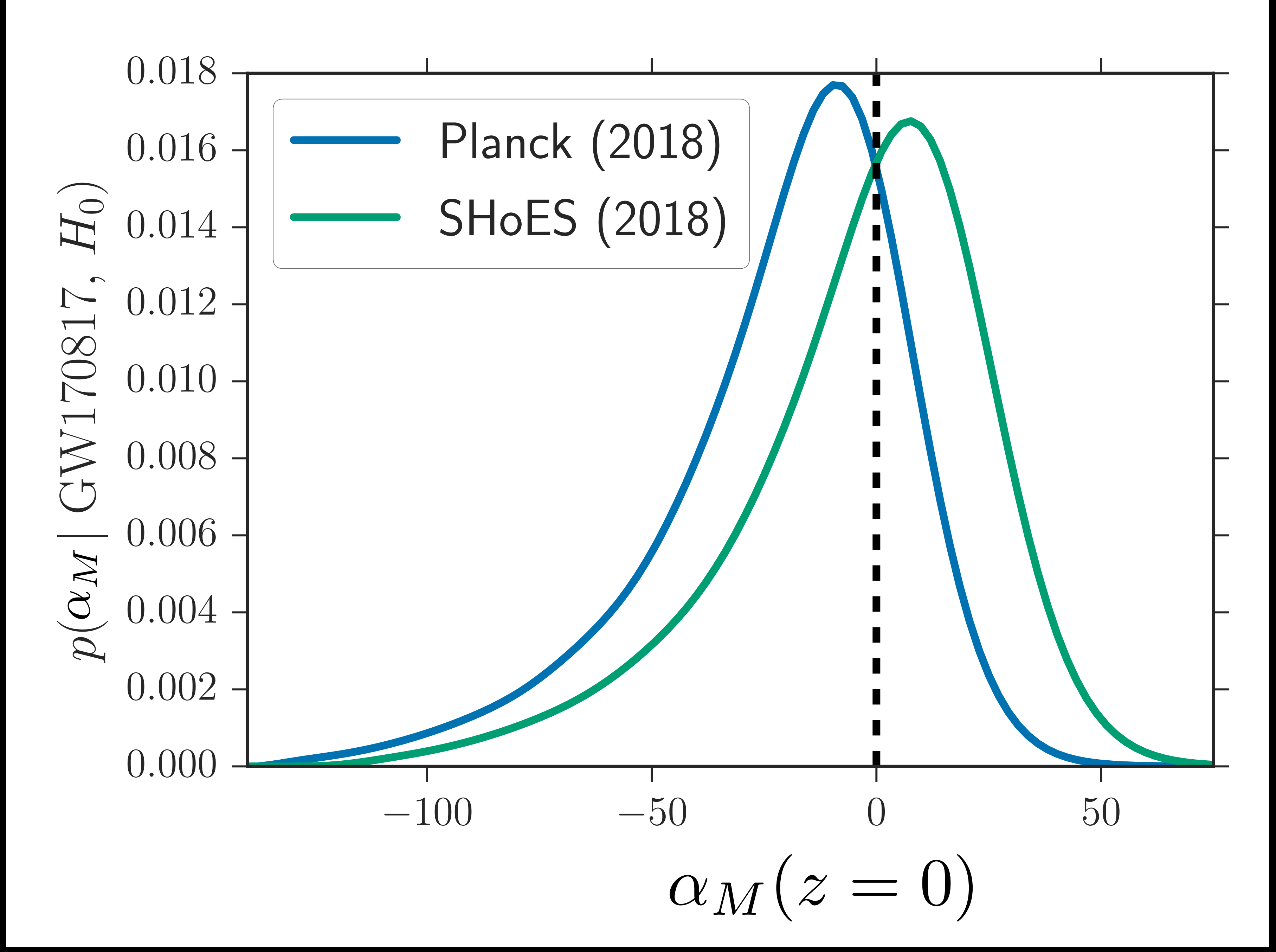
Luminosity distance-redshift relation

$$\tilde{h}_{+,\times}(f) \propto \frac{\mathcal{M}_z^2}{d_{\rm GW}} (\pi \mathcal{M}_z f)^{-\frac{7}{6}} \times \text{(polarisation angles)} \times \text{(inclination factor)}$$

GW Luminosity distance / Normal Luminosity distance

$$\frac{d_{\rm GW}}{d_L} \neq \exp\left[\int_0^z \frac{\alpha_M(\tilde{z})}{1+\tilde{z}}\, d\tilde{z}\right]$$

Lagos et al. (2018)



Deviations from GR affect the luminosity distance-redshift relation.

Now we get d_{GW} from the GW, still redshift from EM counterpart.

→ Constrain α_M with GW170817?

Dark Sirens to the rescue

Results are poor because $\frac{d_{\rm GW}}{d_L} \rightarrow 1$ at low redshift – so departures from GR are tiny/zero.

We need GWs that have travelled larger distances.

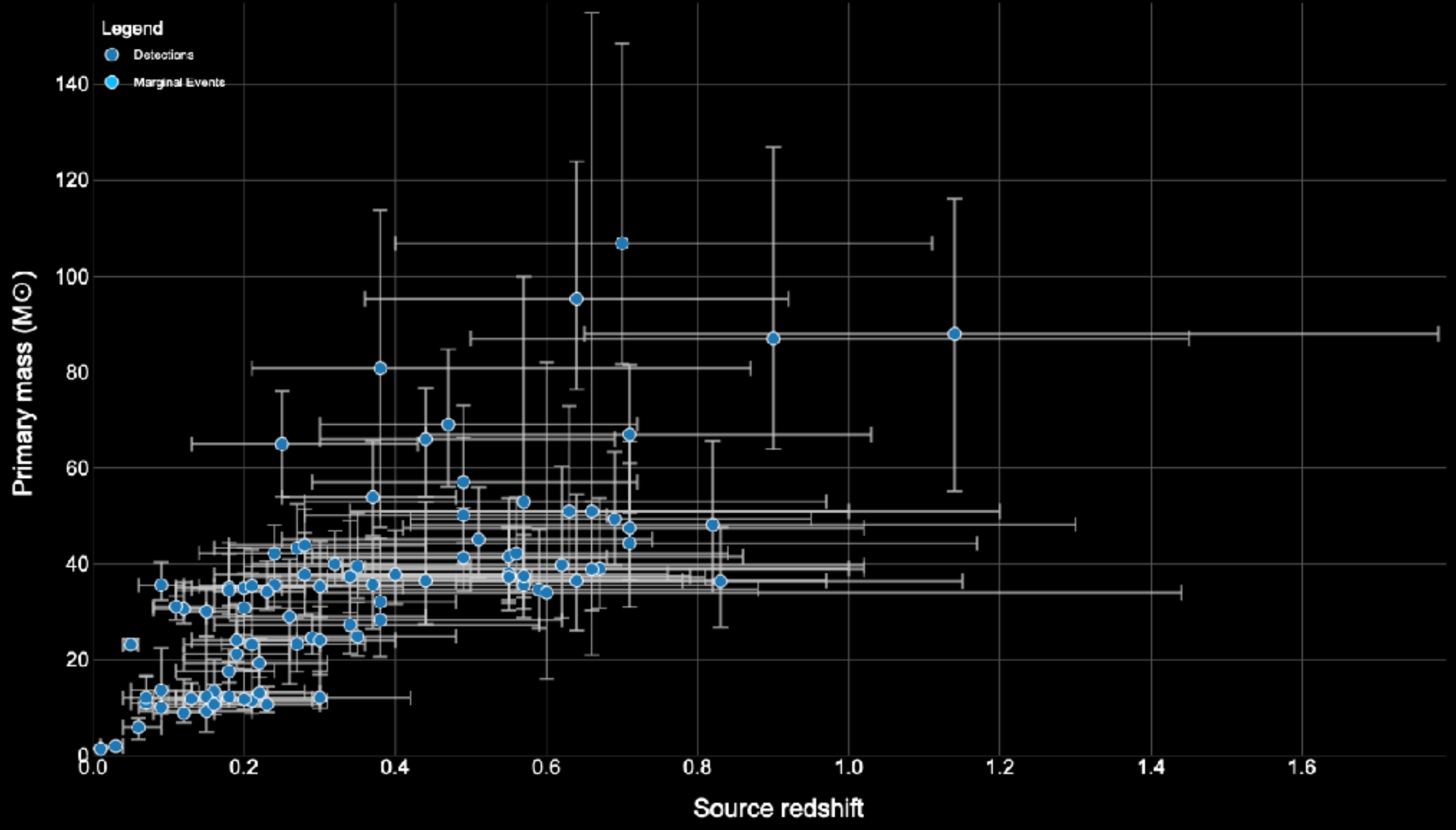
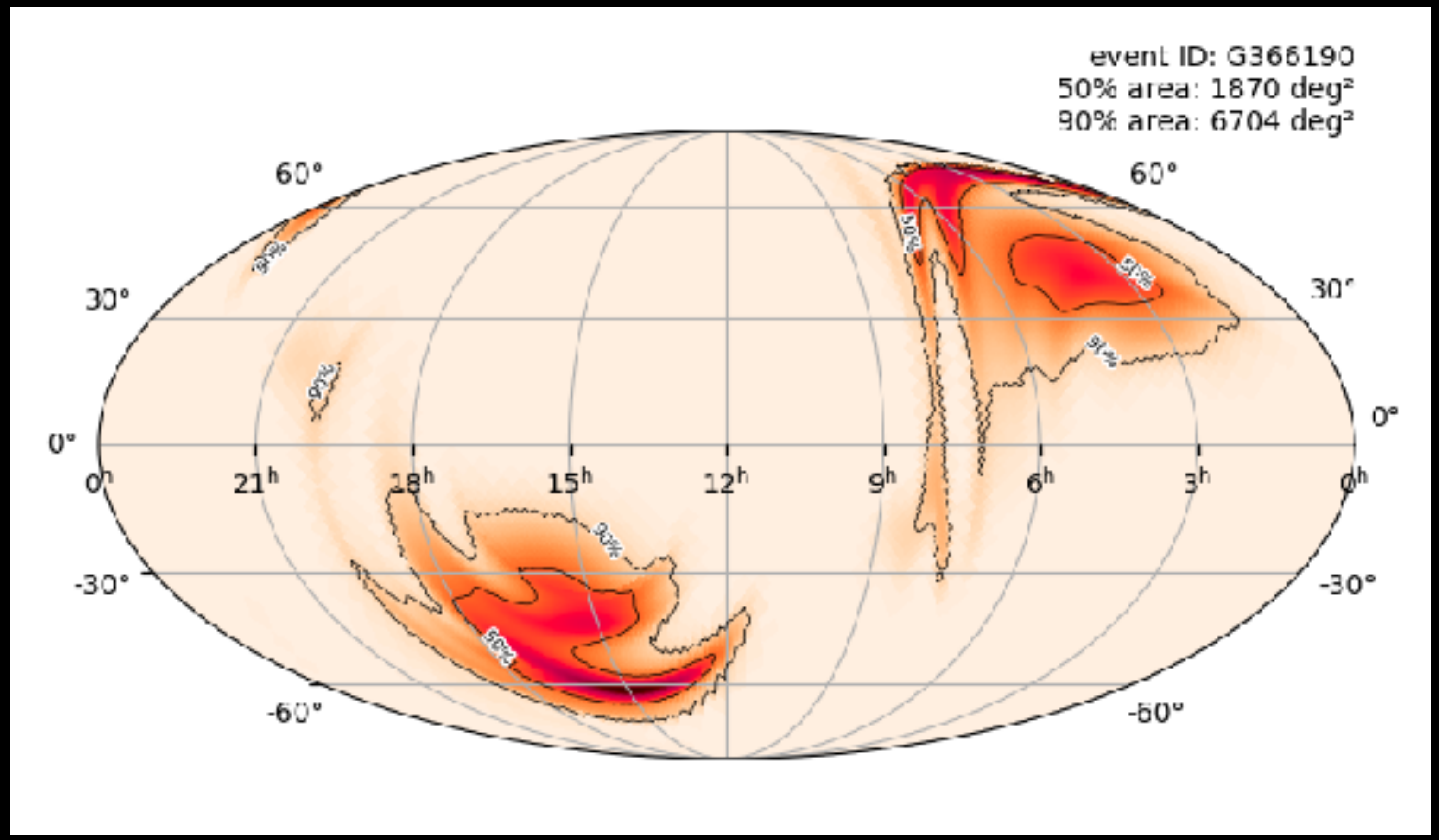
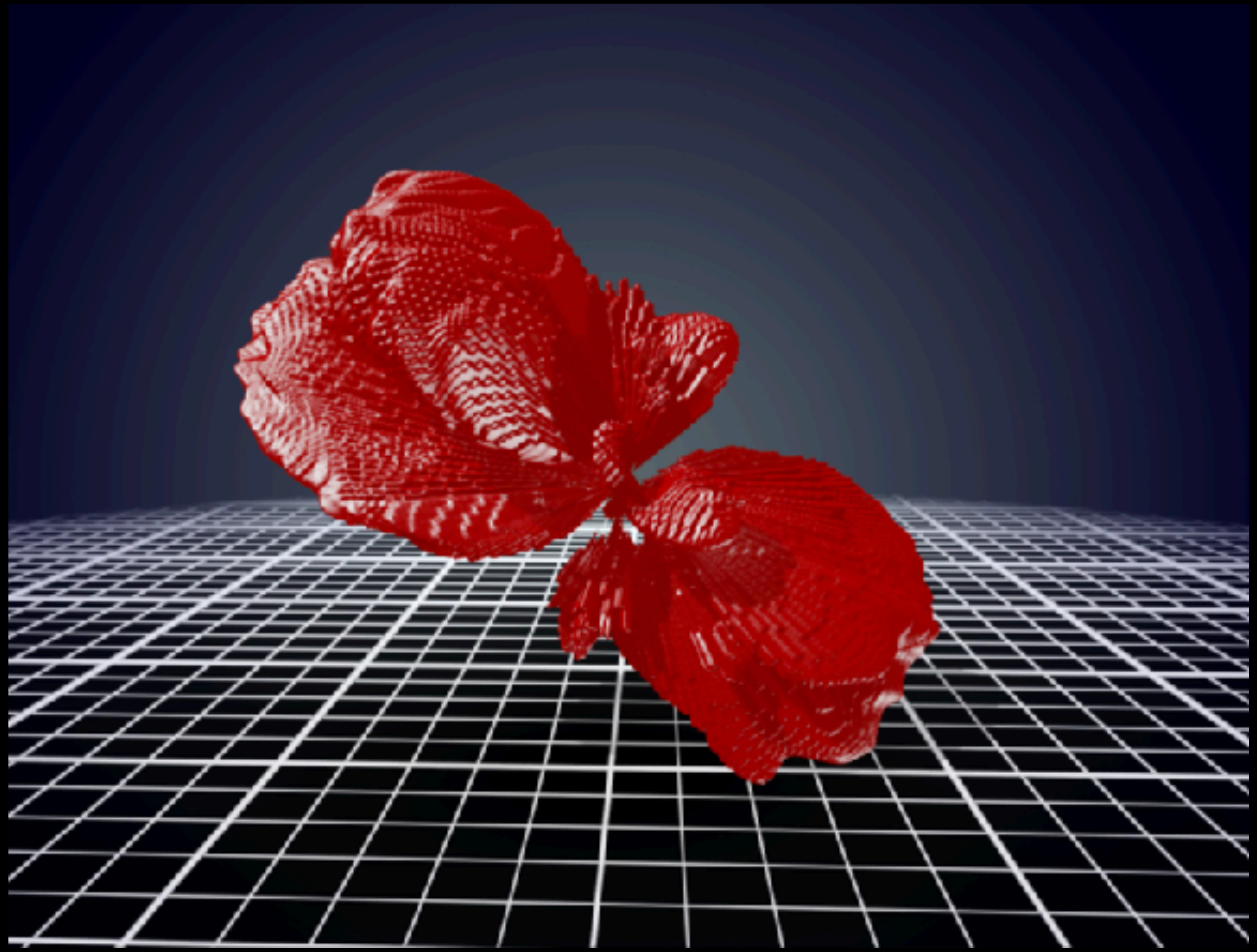


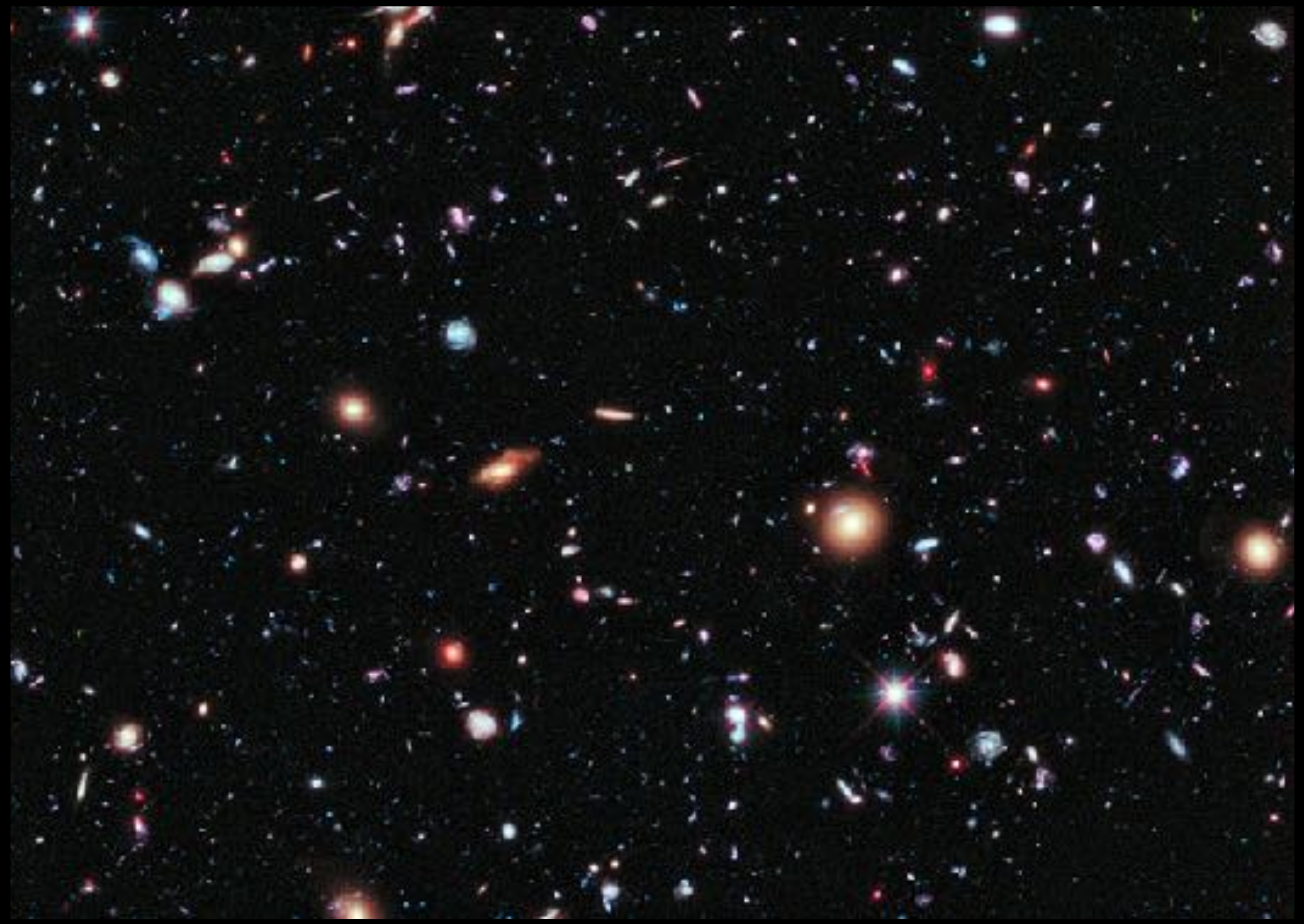
Figure from
catalog.cardiffgravity.org

Dark Sirens



https://chirp.sr.bham.ac.uk/alert/S200302c





NASA Hubble

Dark Sirens = substitute EM counterpart with catalog of galaxies

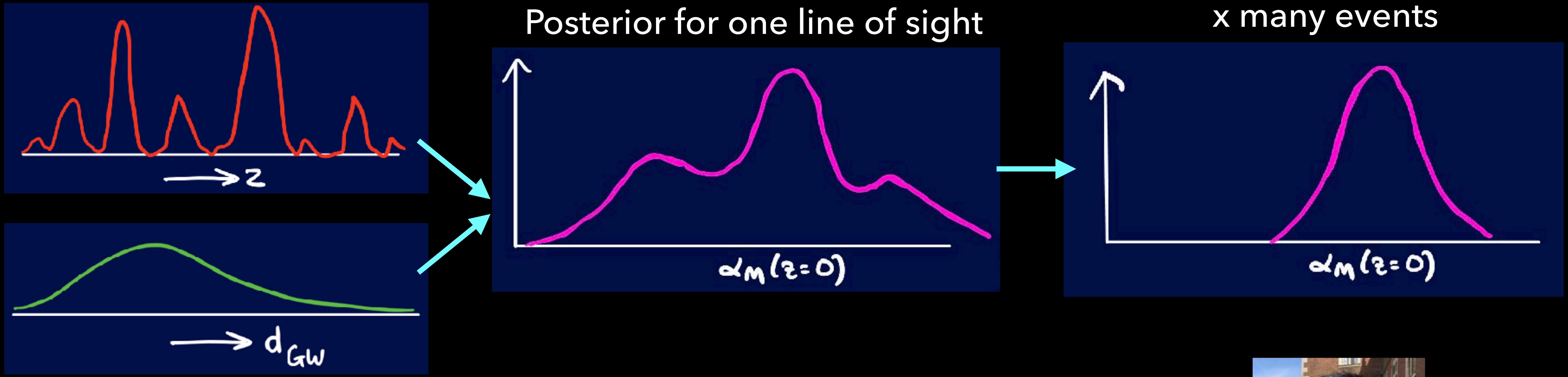
- Con: more costly analysis .
- Pro: use all GW data, no waiting for special events.
- Pro: GW data from higher redshifts → better suited to GR tests.

Dark Sirens

Galaxy distribution

Posterior for one line of sight

x many lines of sight
+
x many events



GW data

Anson Chen

Fantastic work by Anson Chen & Rachel Gray to develop *gwcosmo* to handle departures from GR.

Results with GWTC-3 BBHs

Parameters describing black hole mass distribution

A different MG parameter ~ equivalent to α_M
It's GR value is 1.

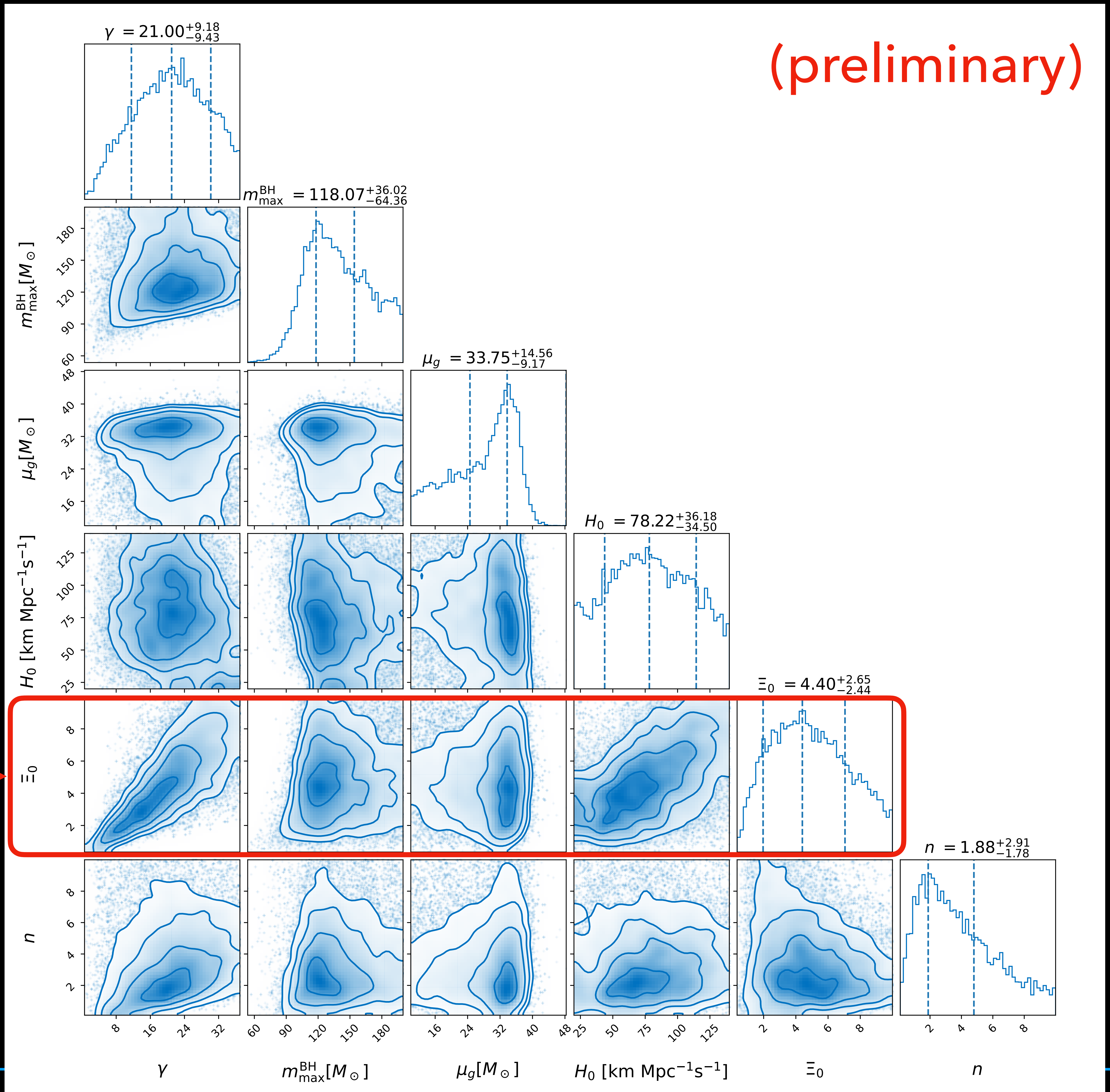


Figure: Anson Chen

Look out for our results in the O4 observing run 👍

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Quantify typical features of non-GR behaviour from scalar fields:

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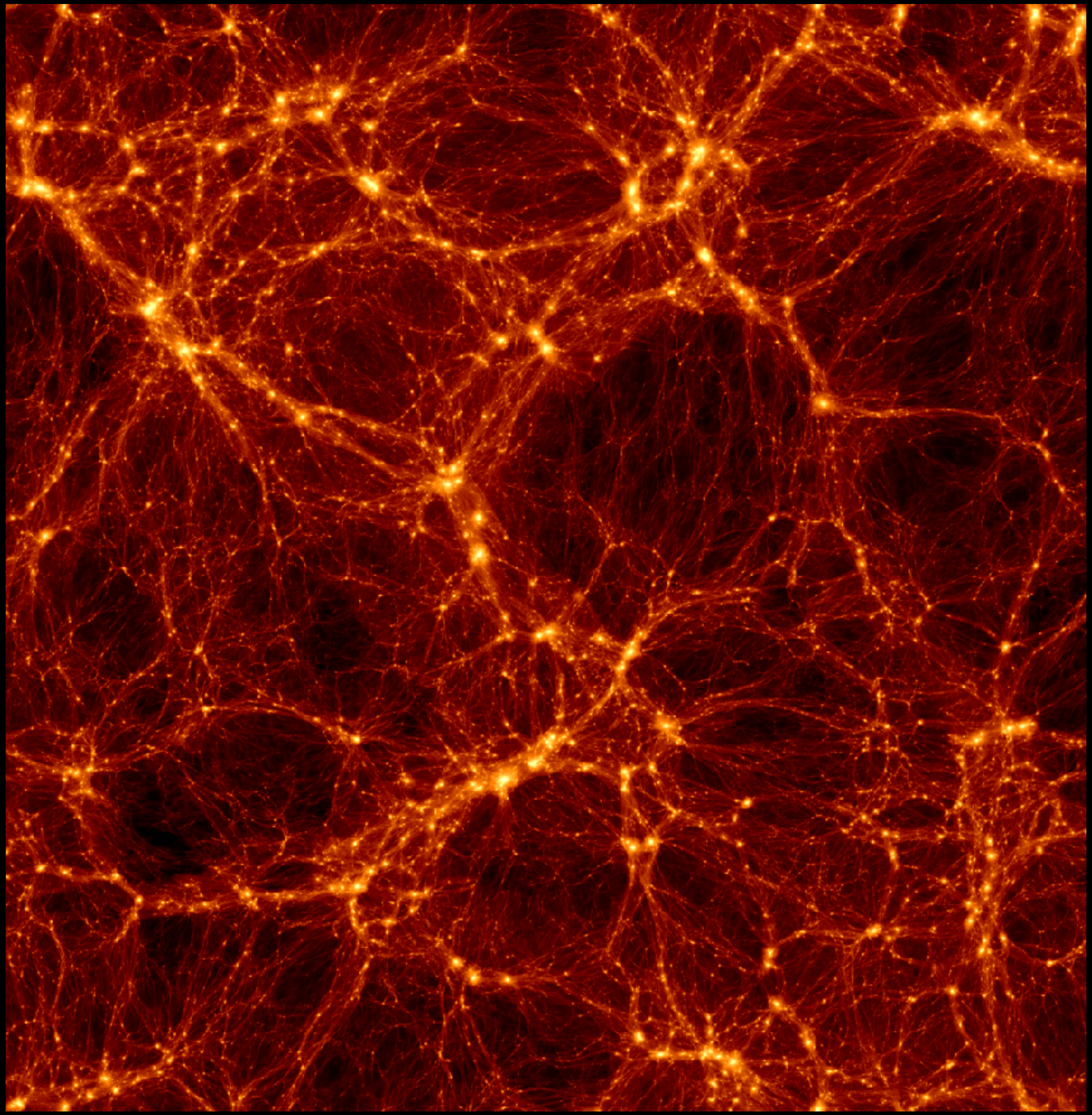
$\alpha_M(z)$ running of effective Planck mass.

- Weak / no constraint from GW170817
- Constraints from Dark Sirens method ~O(1-10)

$\alpha_B(z)$ `braiding' – mixing of scalar + metric kinetic terms.

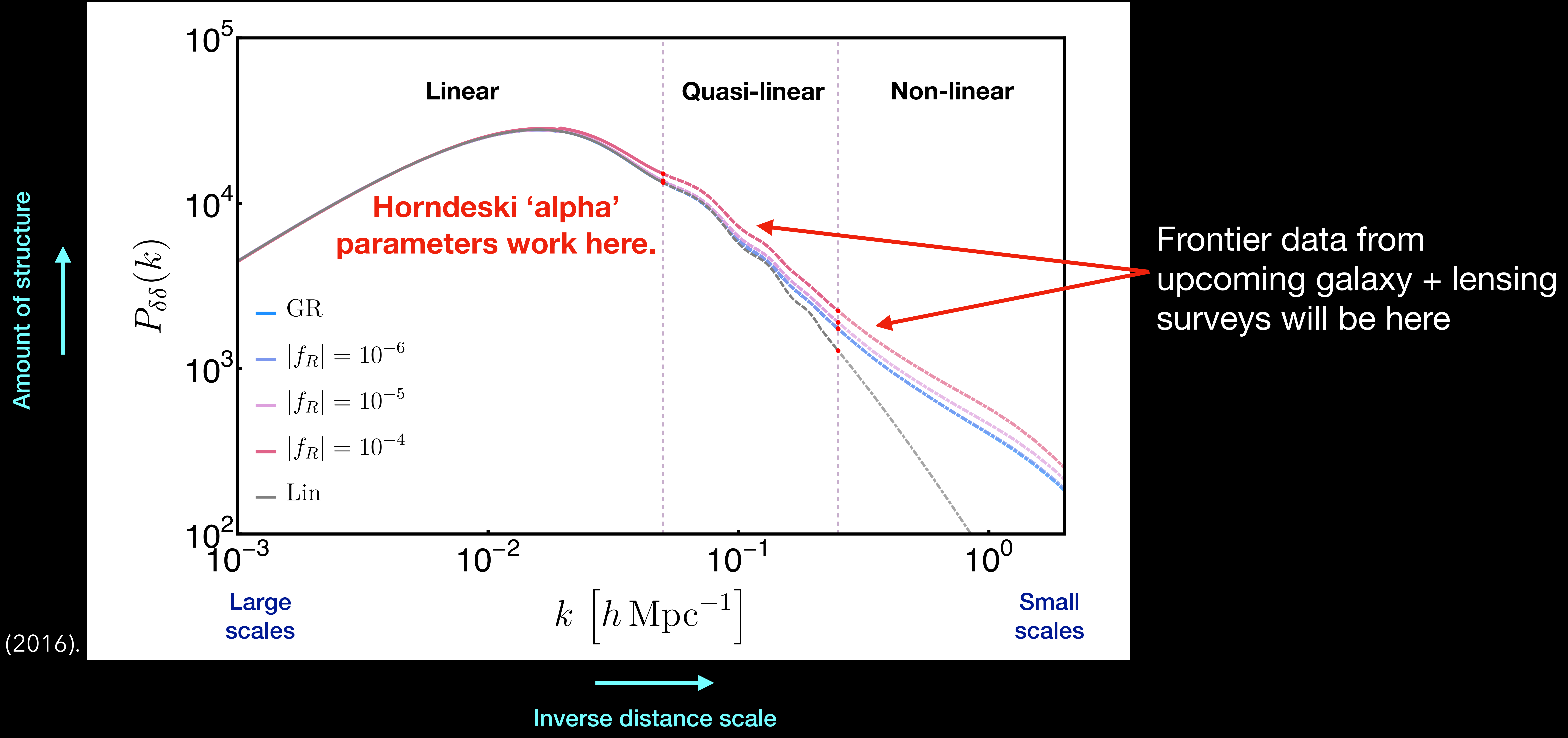
$\alpha_K(z)$ kinetic term of scalar field.

Simulating Large-Scale Structure (LSS) Beyond GR



The matter power spectrum of LSS

Example: f(R) gravity.



Pratten et al. (2016).

Full (nonlinear) Horndeski

Imposing $c_T = 1$ from GW170817, the Horndeski Lagrangian becomes:

Gravity, GR if $G_4 = M_P^2/2$

Fancy scalar self-interactions

$$S = \int d^4x \sqrt{-g}\,[G_4(\phi)R + K(\phi, X) - G_3(\phi, X)\Box\phi] + S_M$$

Fancy generalisation of a kinetic term

Standard matter

where X = kinetic term of scalar field

G_4, K and G_3 are the real, 'grown up' versions of the alpha parameters.

Simulating LSS in Horndeski gravity

Nonlinear scales require simulations.

How do you build a simulation for a general *family* of gravity models?

Hi-COLA = Horndeski in COLA

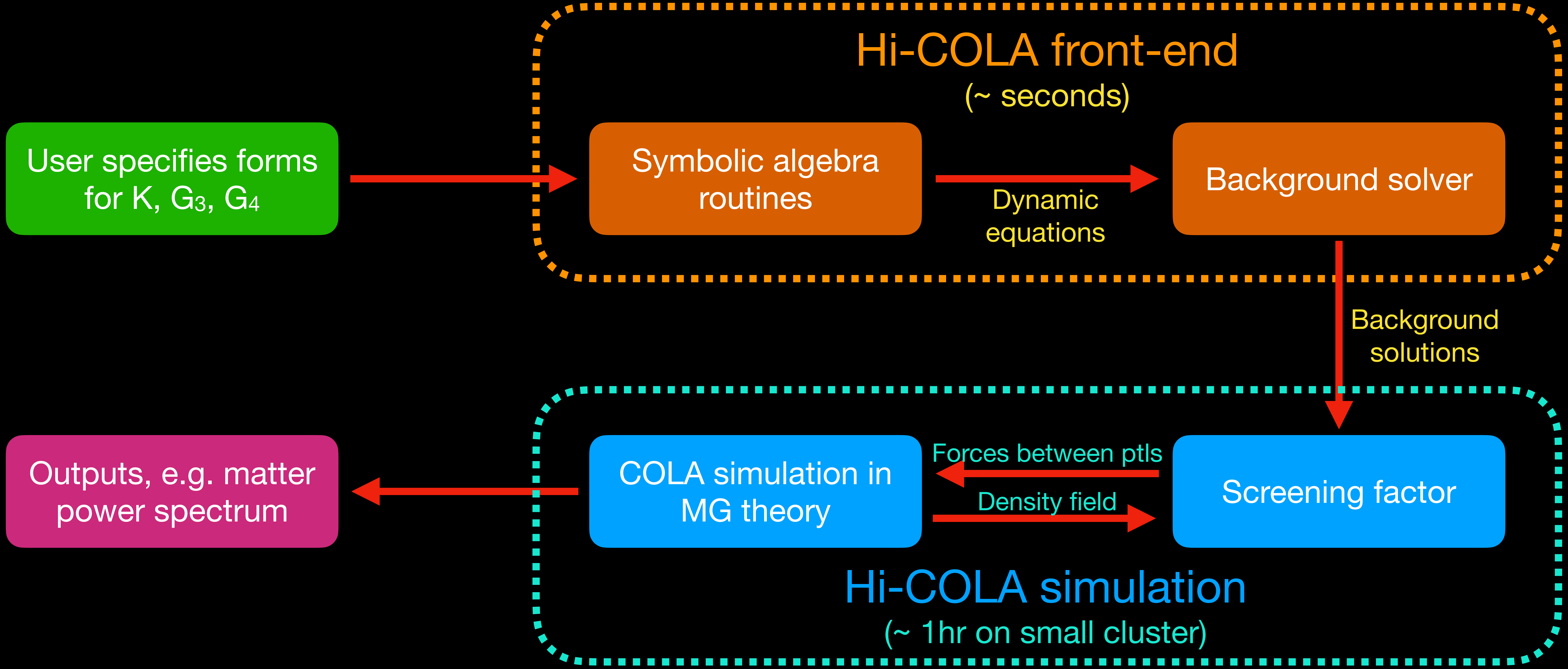
COLA = COmoving Lagrangian Acceleration

Bart Fiorini

Ashim Sen Gupta

Hi-COLA is the first LSS simulation code that is fully flexible with respect to gravitational laws.

Inside Hi-COLA



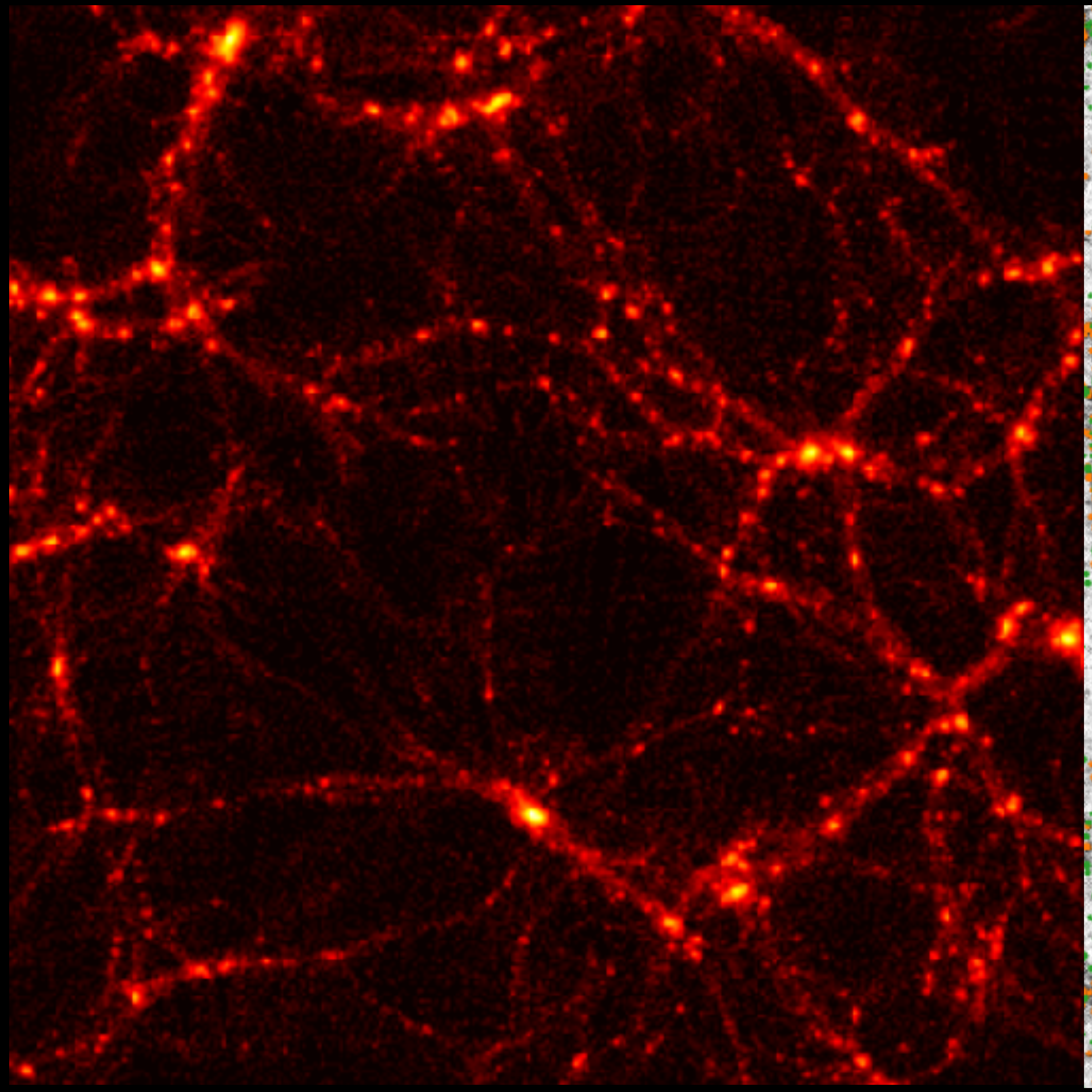
2209.01666

LSS with Hi-COLA

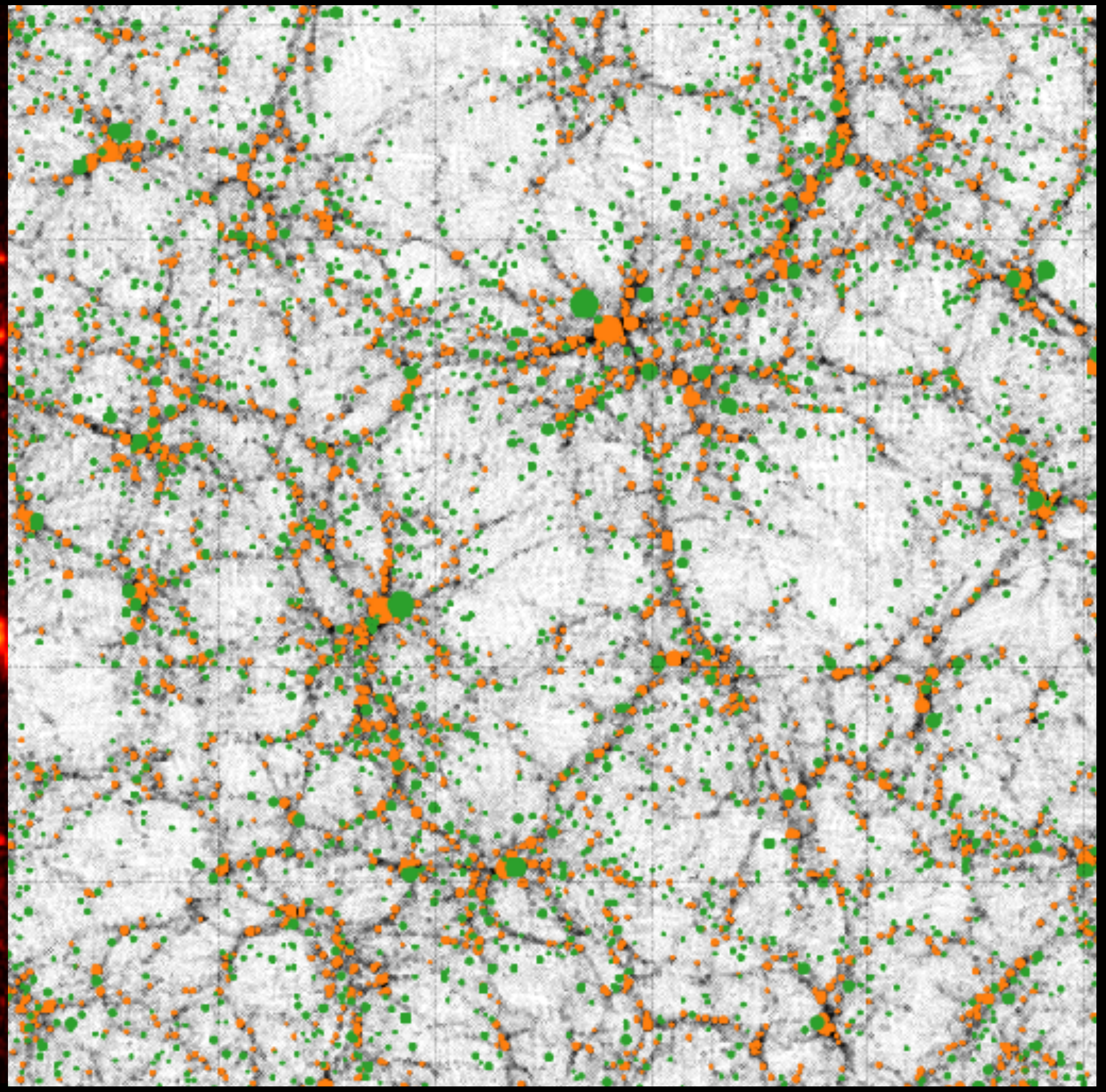
Code is publicly available, incl. documentation, quick start guide, mathematical appendices.

github.com/Hi-COLACode

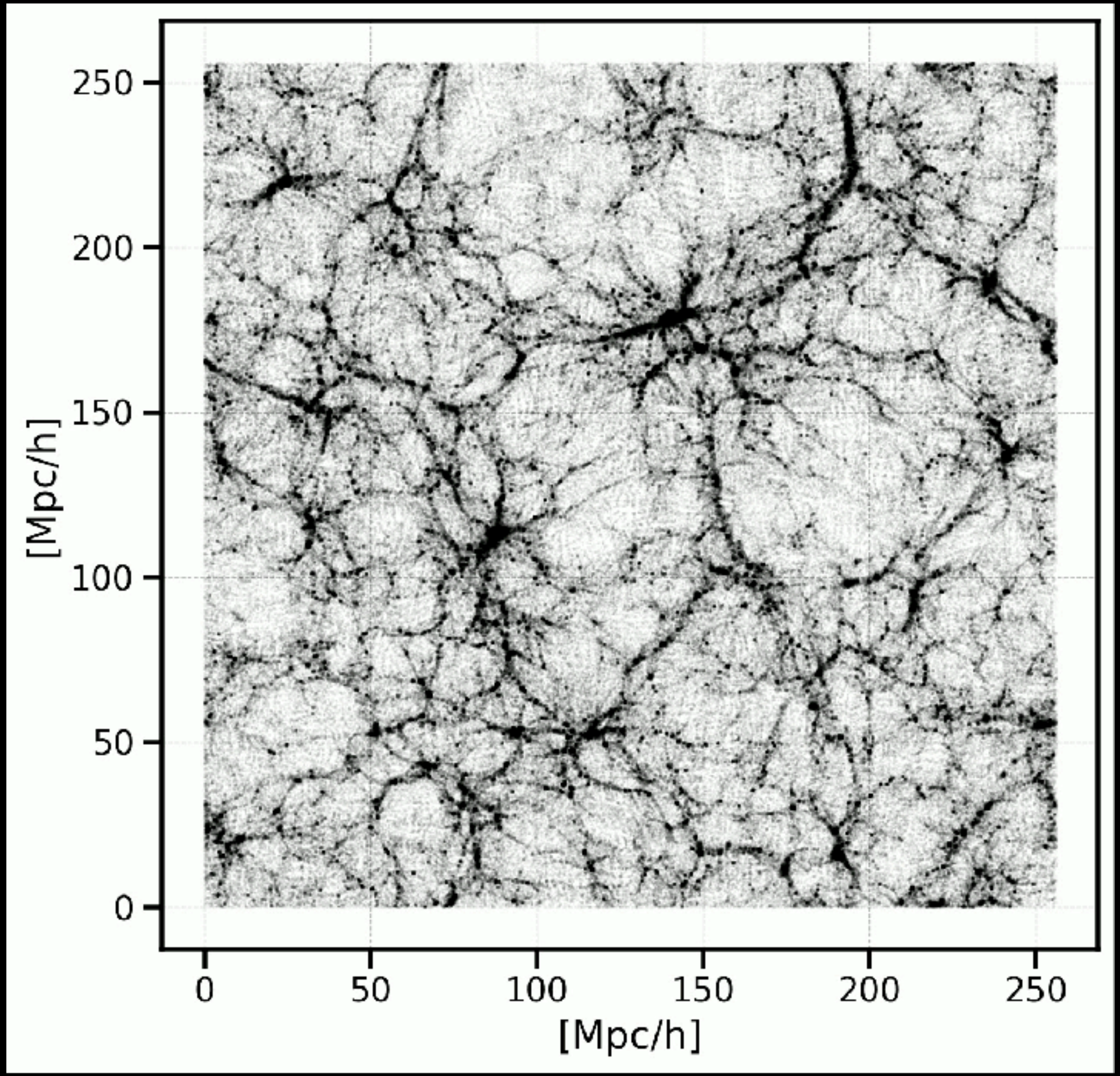
Fig: B. Fiorini



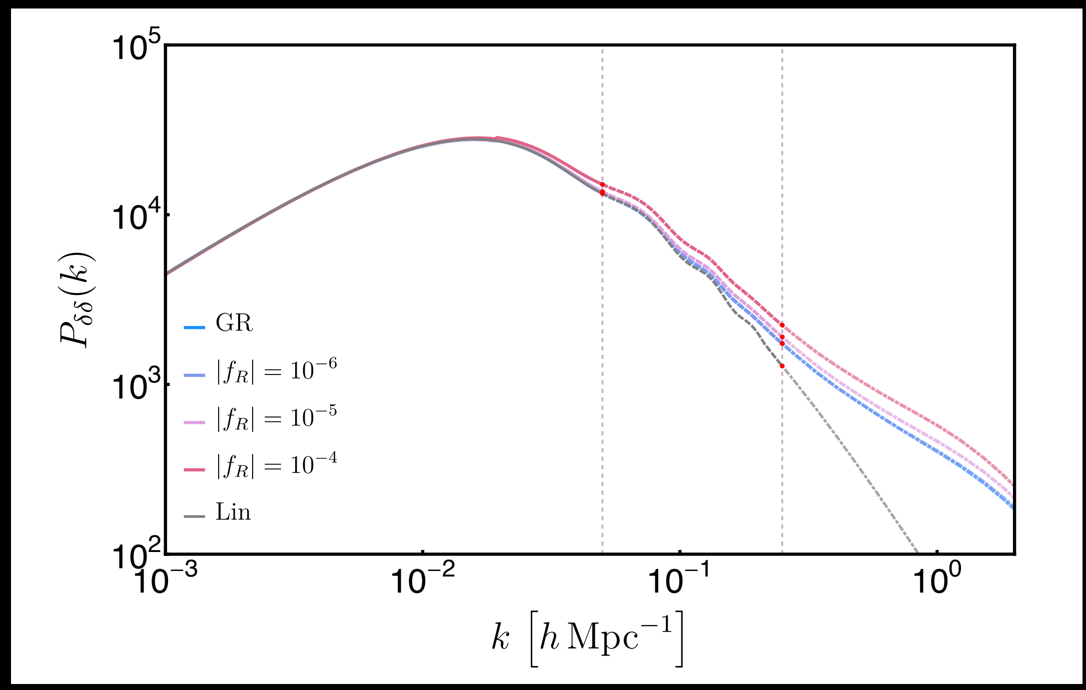
Dark matter



Halos & proto-halos



Reminder: dark matter power spectrum



LSS with Hi-COLA

Example: power spectrum of dark matter in Cubic Galileon gravity.

NB: as a ratio to LCDM predictions

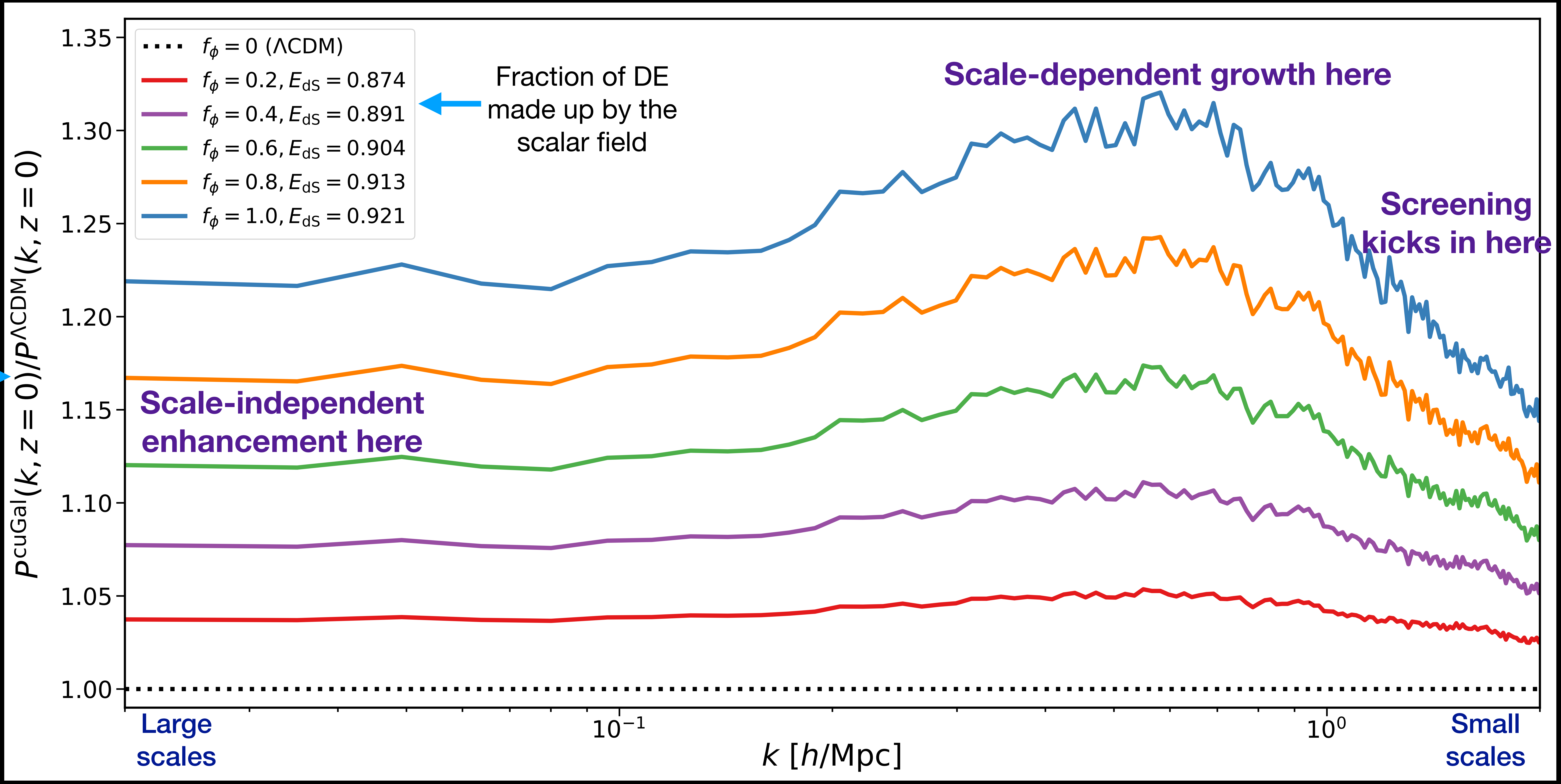


Fig: B. Wright

+ thousands (more?) gravity models, each generated in ~1 hr → analysis with upcoming stage IV surveys.

Horndeski 'Alpha' Parameters - Final Status

$\alpha_T(z)$ Strongly constrained by GW speed bounds (but! Loopholes exist)

$\alpha_M(z)$ Weak / no constraint from GW170817

Constraints from Dark Sirens method ~O(1-10)

Both could/should improve in LVK O4 run

$\alpha_B(z)$ Constraints ~O(1) from linear LSS – largely saturated

$\alpha_K(z)$ Unconstrained by linear LSS

Horndeski 'Alpha' Parameters - Final Status

$\alpha_T(z)$ Strongly constrained by GW speed bounds (but! Loopholes exist)

$\alpha_M(z)$ Constraints from Dark Sirens method ~O(1-10)

To improve these, we really need to constrain the 'full' versions.

$\alpha_B(z)$

$\alpha_K(z)$

$$S = \int d^4x \sqrt{-g}\,[G_4(\phi)R + K(\phi, X) - G_3(\phi, X)\Box\phi] + S_M$$

Data from:

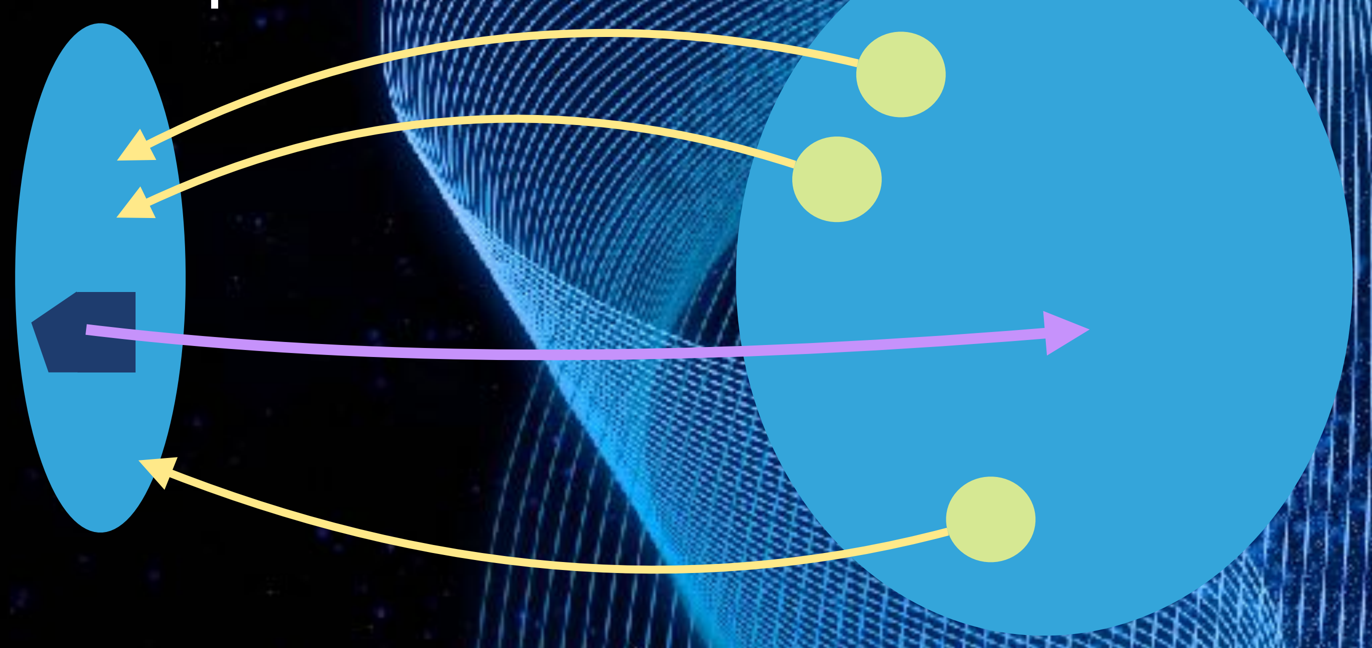
Vera Rubin Observatory

DESI

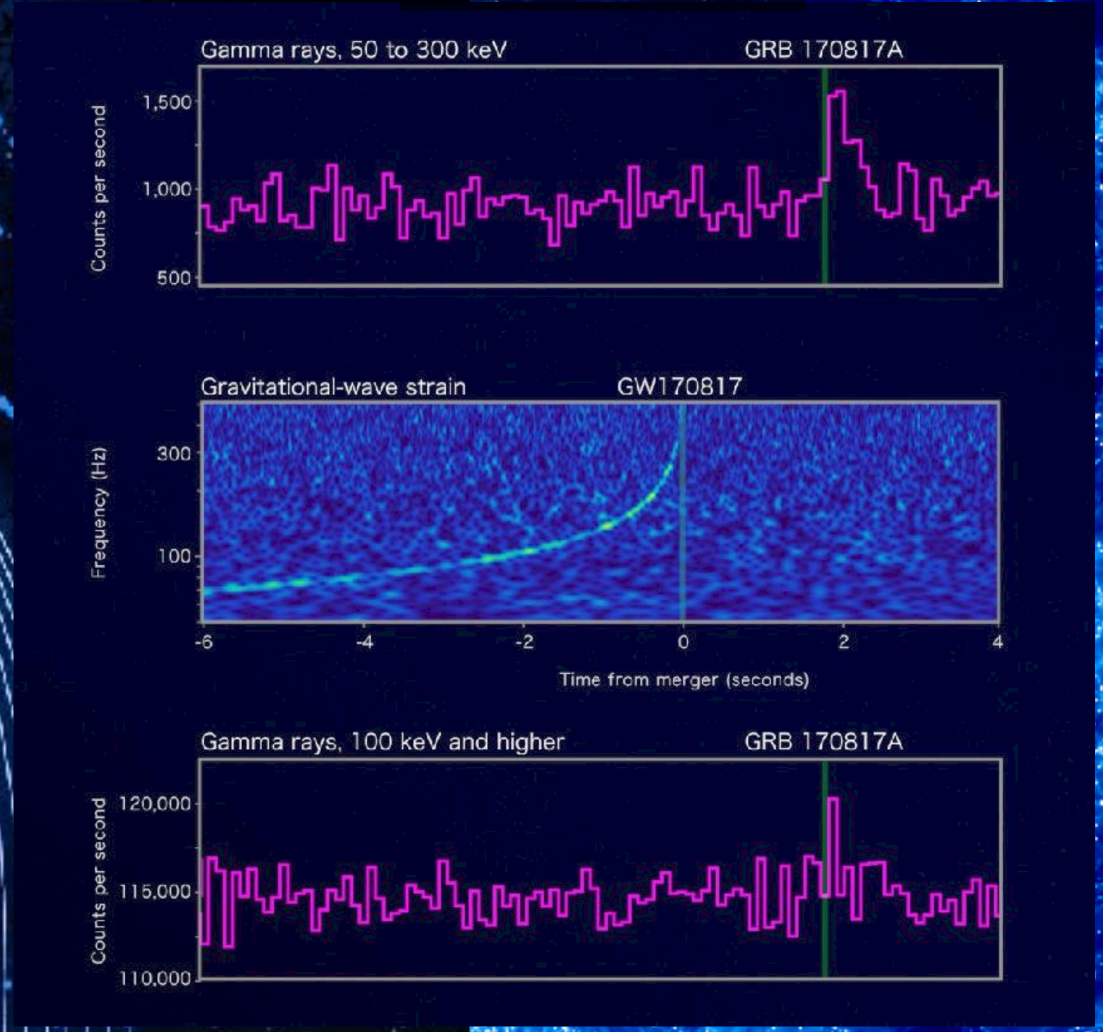
Euclid

@Tessa_M_Baker
t.baker@qmul.ac.uk

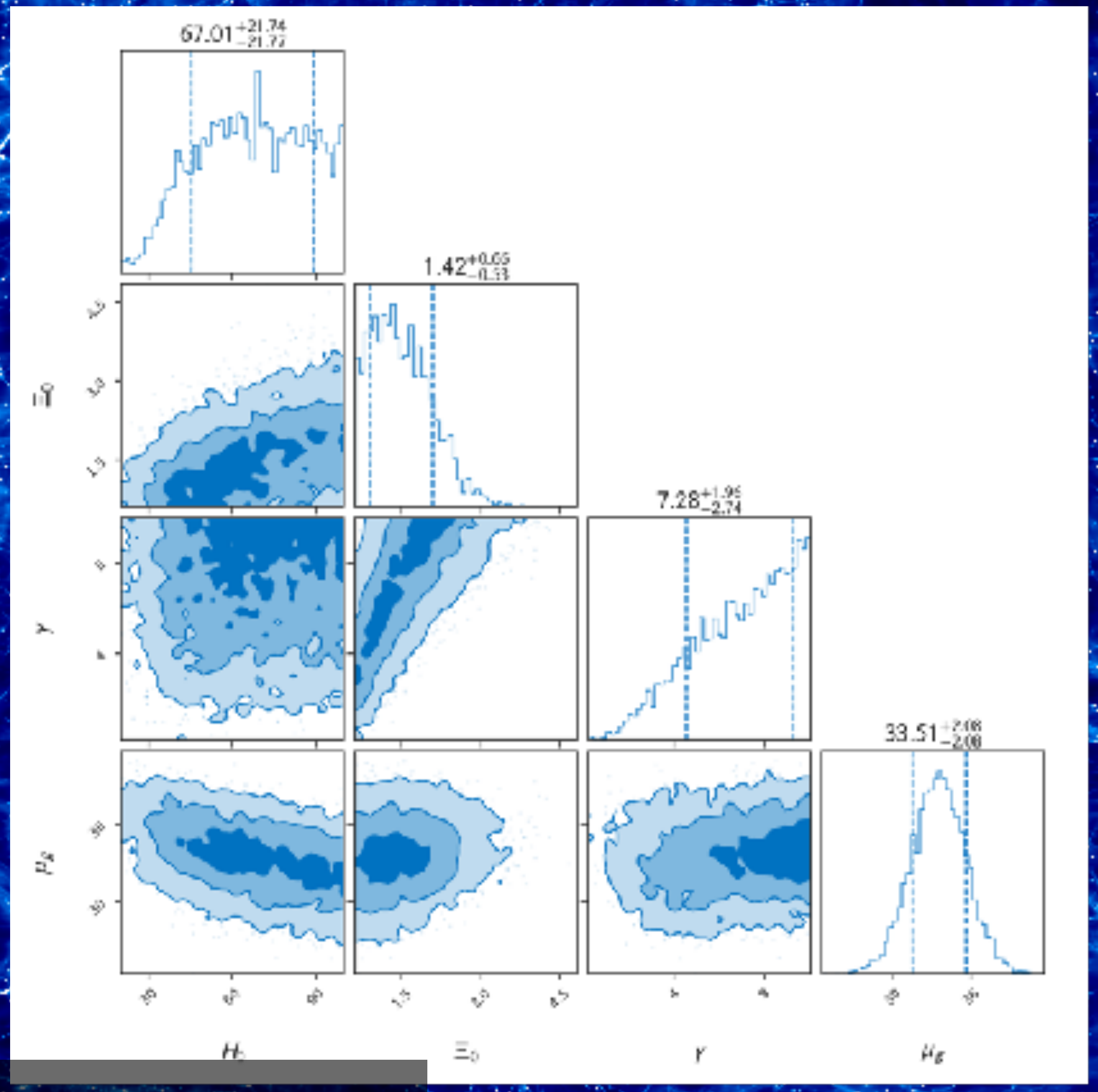
Conclusions

1\. 

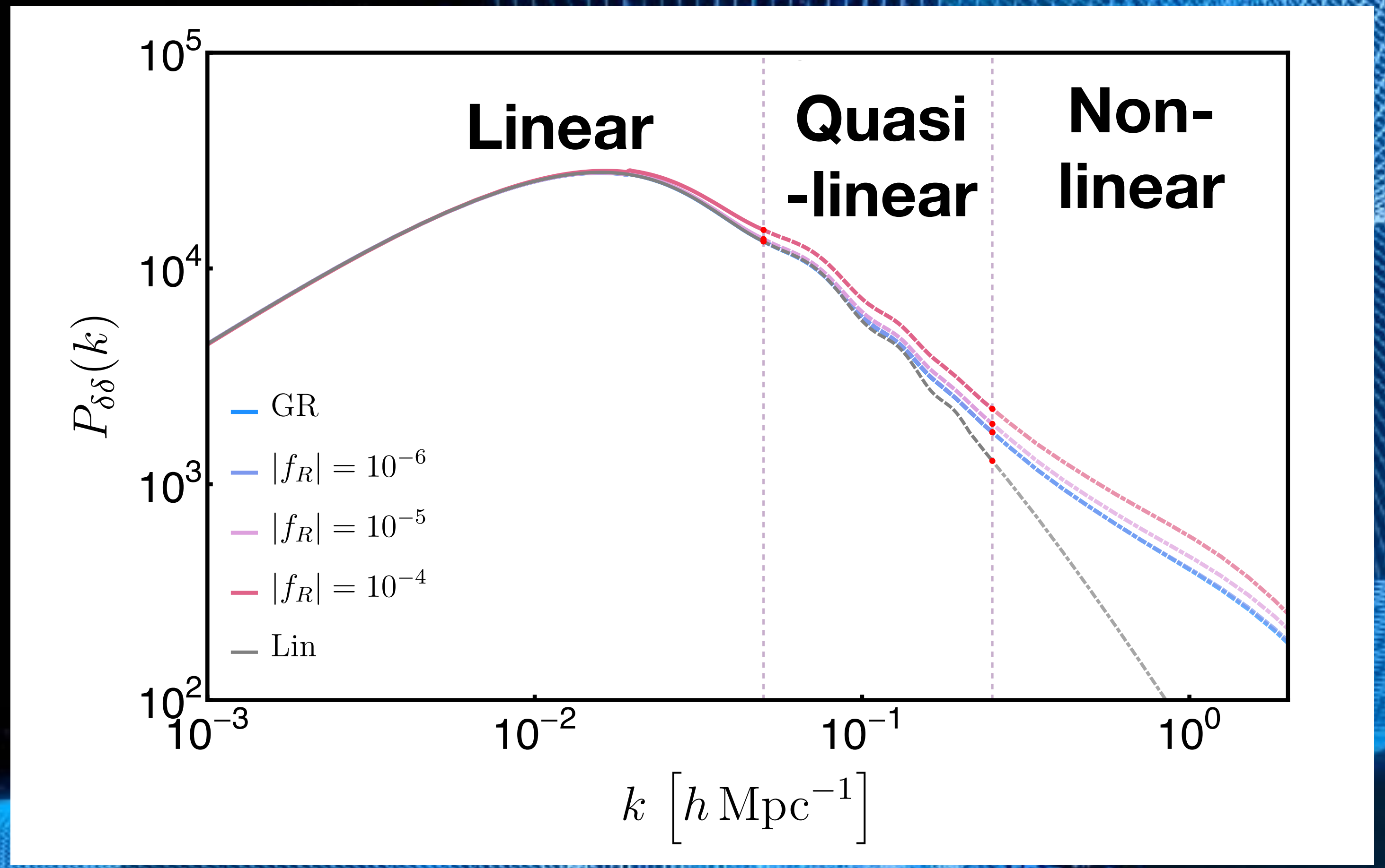
$\alpha_T(z)$

2\. 

$\alpha_M(z)$

3\. 

$\alpha_B(z)$, $\alpha_K(z)$ → G_4, K, G_3

4\. 

5\.