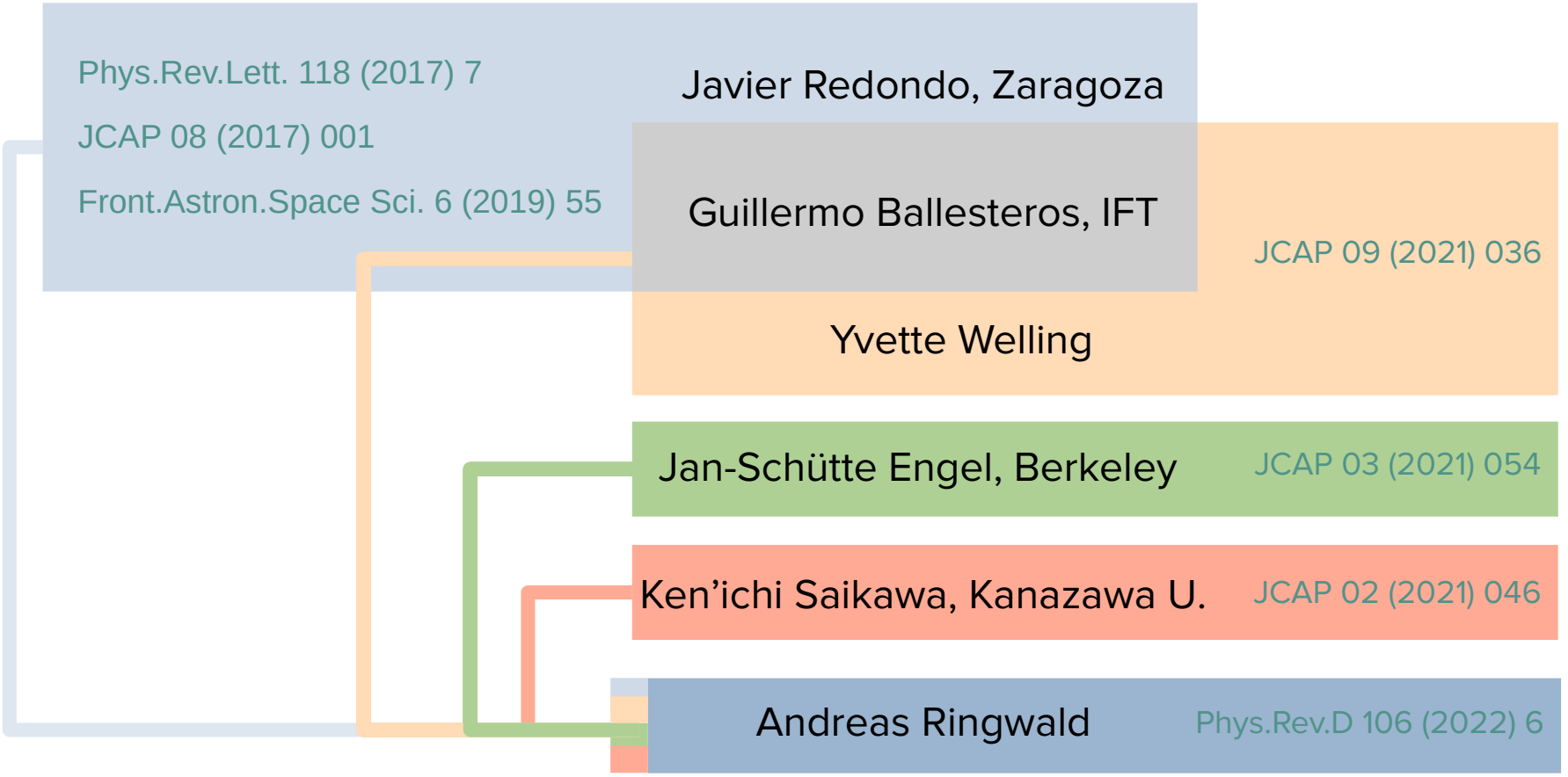
Exploring the early universe with gravitational waves

Carlos Tamarit, Johannes Gutenberg-Universität Mainz

in honour of

Andreas Ringwald


Phys.Rev.Lett. 118 (2017) 7
JCAP 08 (2017) 001
Front.Astron.Space Sci. 6 (2019) 55
Javier Redondo, Zaragoza
Guillermo Ballesteros, IFT
JCAP 09 (2021) 036
Yvette Welling
Jan-Schütte Engel, Berkeley
JCAP 03 (2021) 054
Ken’ichi Saikawa, Kanazawa U.
JCAP 02 (2021) 046
Andreas Ringwald
Phys.Rev.D 106 (2022) 6

What are gravitational waves?

Excitations of the **metric** field **sourced** by **anisotropies** in the **stress-energy** momentum tensor. In local Minkowski frame

$$ds^2 \supset -dt^2 + (\delta_{ij} + h_{ij}) dx^i dx^j,$$

$$\partial^i h_{ij} = 0$$

$$\Box \left(h_{ij} - \frac{1}{2}\delta_{ij} h \right) = \frac{2}{M_P^2} T_{ij}^{\mathrm{TT}},$$

$$T^{\mathrm{TT}}{}_i^i = 0,$$

$$\partial^i T_{ij}^{\mathrm{TT}} = 0$$

Energy density:

$$\rho_{\mathrm{gw}} = \frac{M_P^2}{4} \left\langle \dot{h}_{ij}(t, \mathbf{x})\, \dot{h}_{ij}(t, \mathbf{x}) \right\rangle$$

$$\rho_{\mathrm{crit}} = 3 H^2 M_P^2$$

$$\Omega_{\mathrm{gw}} = \frac{\rho_{\mathrm{gw}}}{\rho_{\mathrm{crit}}} \equiv \int \frac{dk}{k} \Omega_{\mathrm{gw}}(k)$$

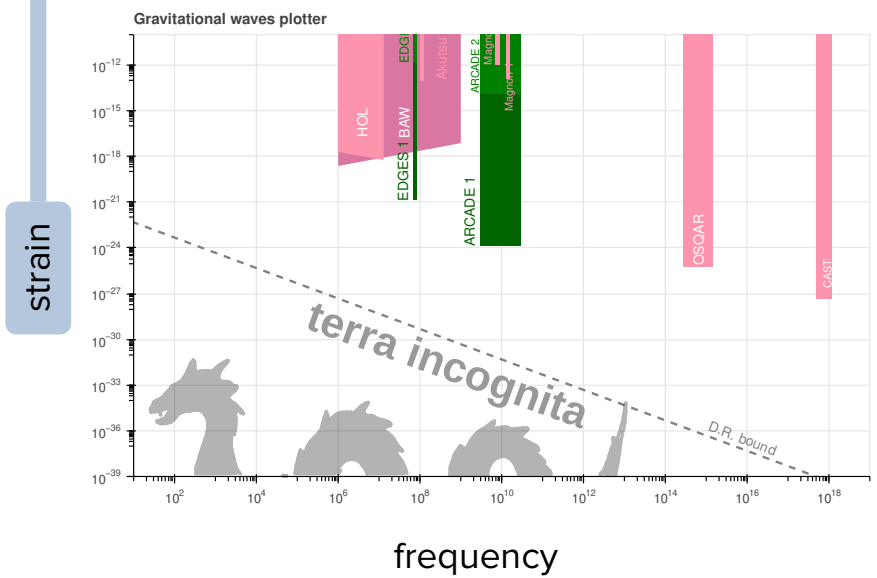
Andreas' vision: high frequency GWs

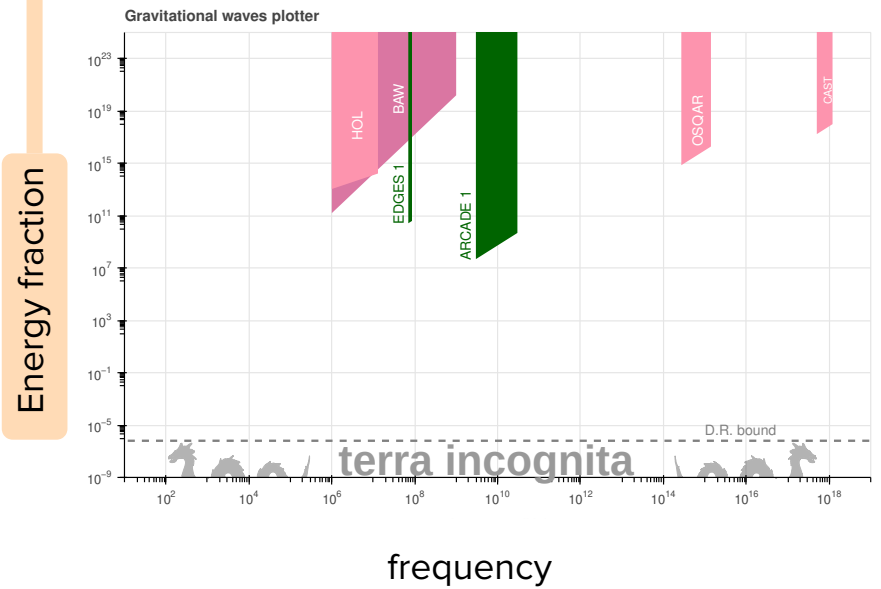
- High frequencies probe **high-energy processes** in **early universe**
- Weak interactions → waves **travel undisturbed: direct probe of primordial physics!**
- There are **no known astrophysical sources** at **very high-frequencies!**

Can we "see" the Big Bang with GWs?

Andreas' vision: high frequency GWs

$$h_c(f) = \frac{1}{f}\sqrt{\frac{3H_0\Omega_{\rm gw}^2(f)}{2\pi^2}}$$





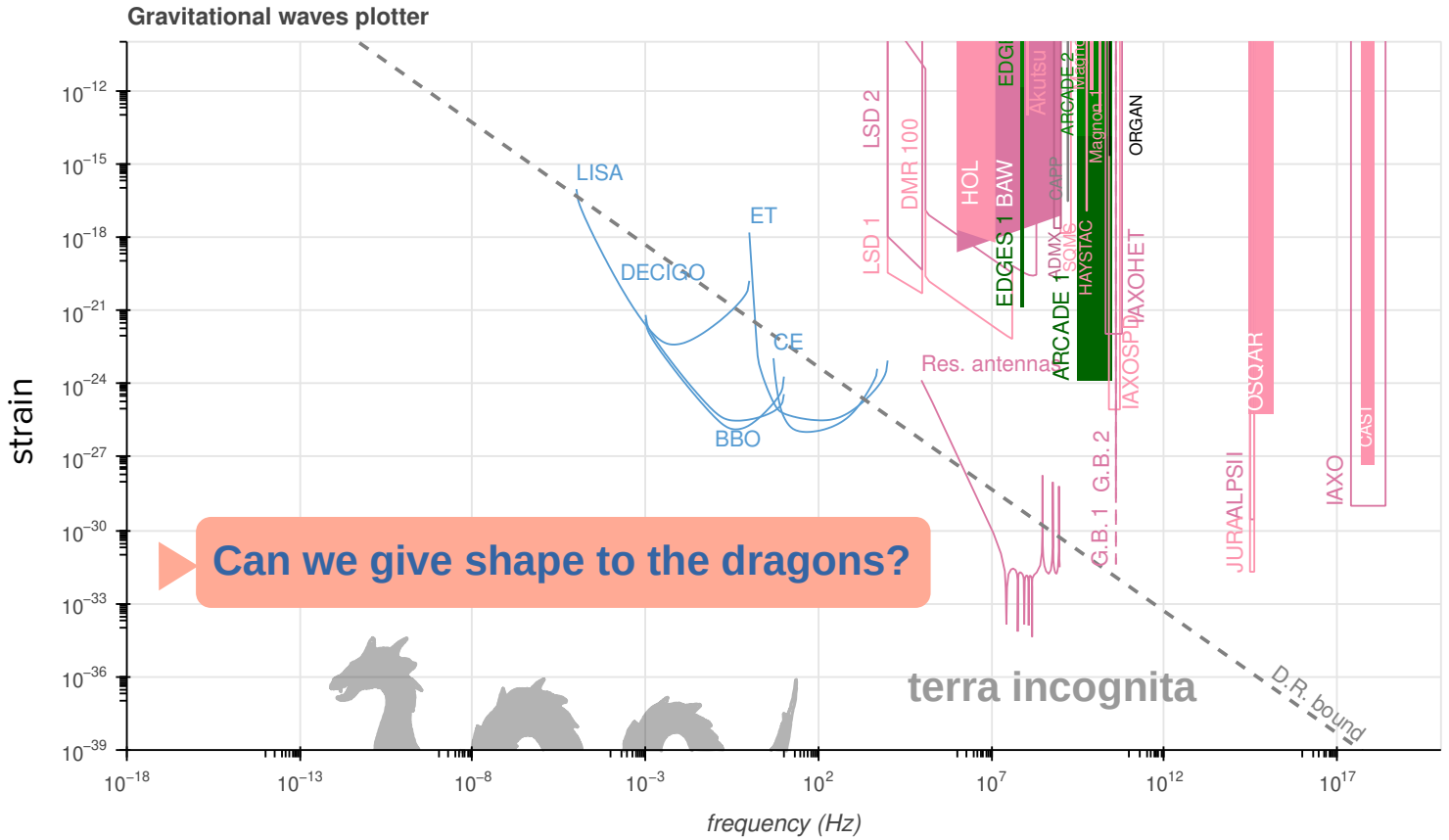
Andreas' vision: a complete spectrum?

Given a model with a **consistent cosmological history**, its **spectrum** of GWs becomes **predictable**

Andreas was excited from the beginning by the idea of calculating the **first complete spectrum of GWs,** from inflation until today, in a consistent model

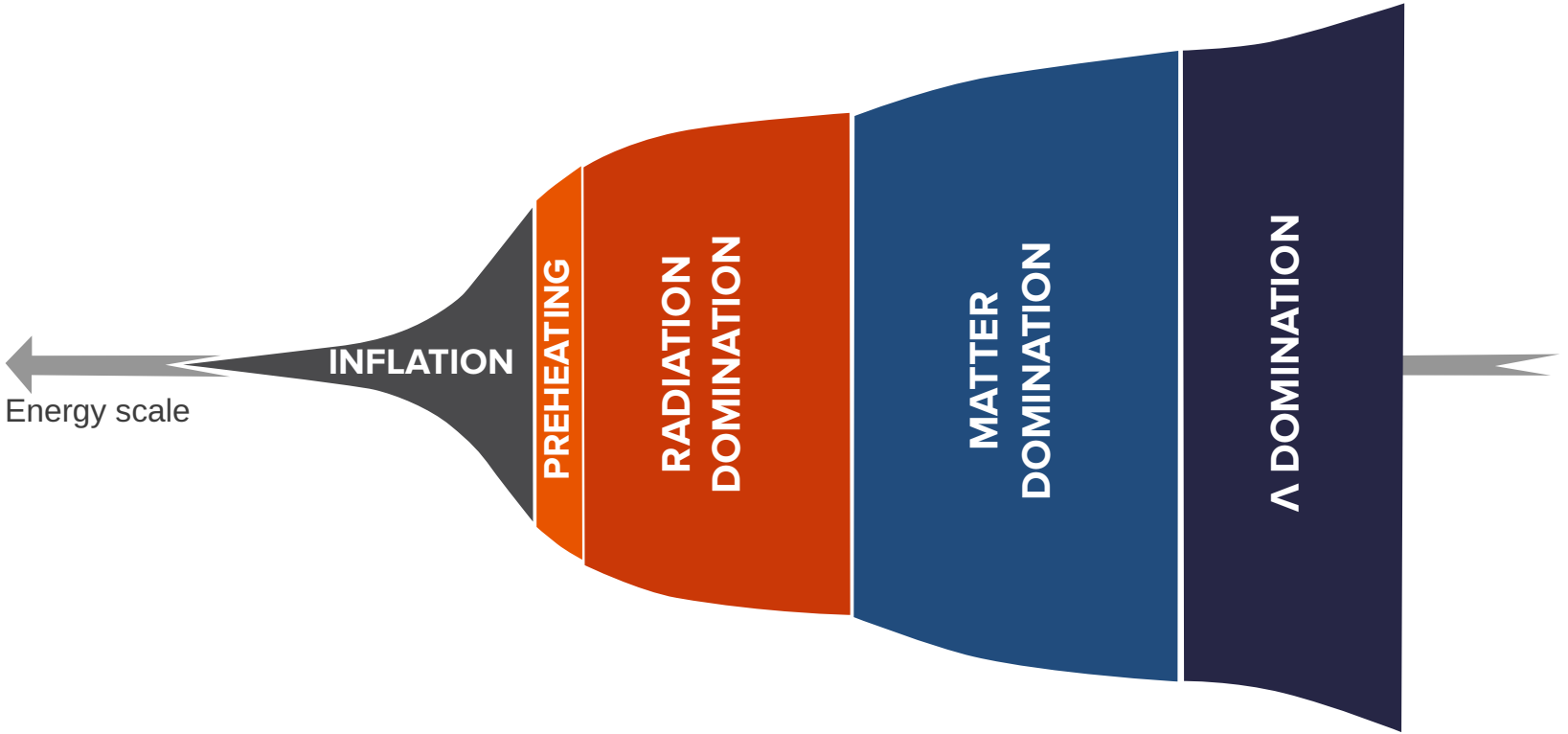
Can we calculate the complete spectrum of GWs in SMASH?

[cf. work by Buchmüller et al]

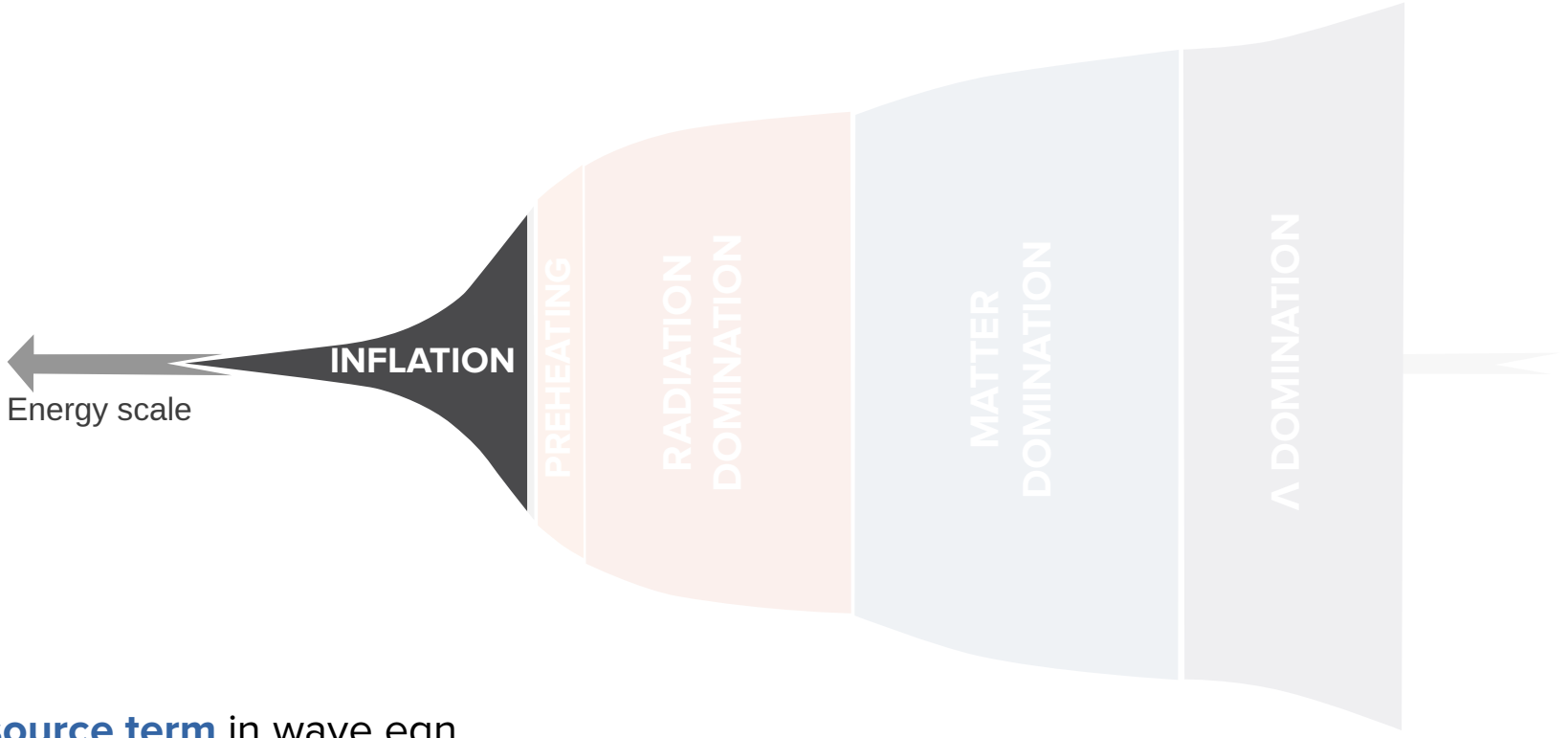

Gravitational waves plotter
strain
frequency (Hz)
LISA
ET
DECIGO
CE
BBO
LSD 2
LSD 1
DMR 100
HOL
EDGES 1
BAW
EDGES 2
Akutsu
CAPP
ADMX
SQUID
ARCADE 2
Tokyo
Magnon
HAYSTAC
ARCADE 1
ORGAN
IAXOHET
IAXOSPL
Res. antenna
G.B. 1
G.B. 2
JURA
ALPSII
OSQAR
IAXO
CAST
D.R. bound
terra incognita
Can we give shape to the dragons?

Gravity waves in SMASH

Sources of GWs in the SMASHY universe

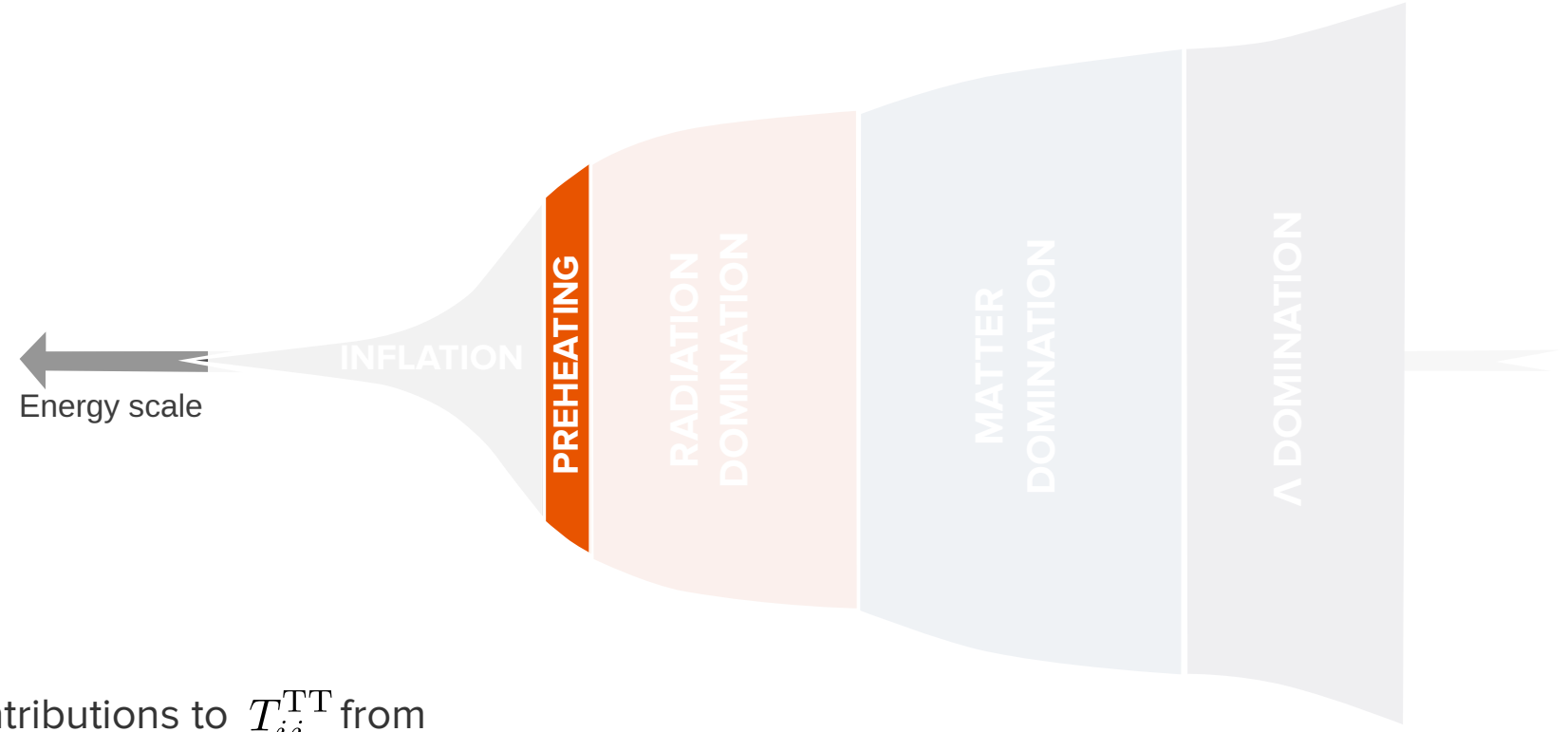


Sources of GWs in the SMASHY universe



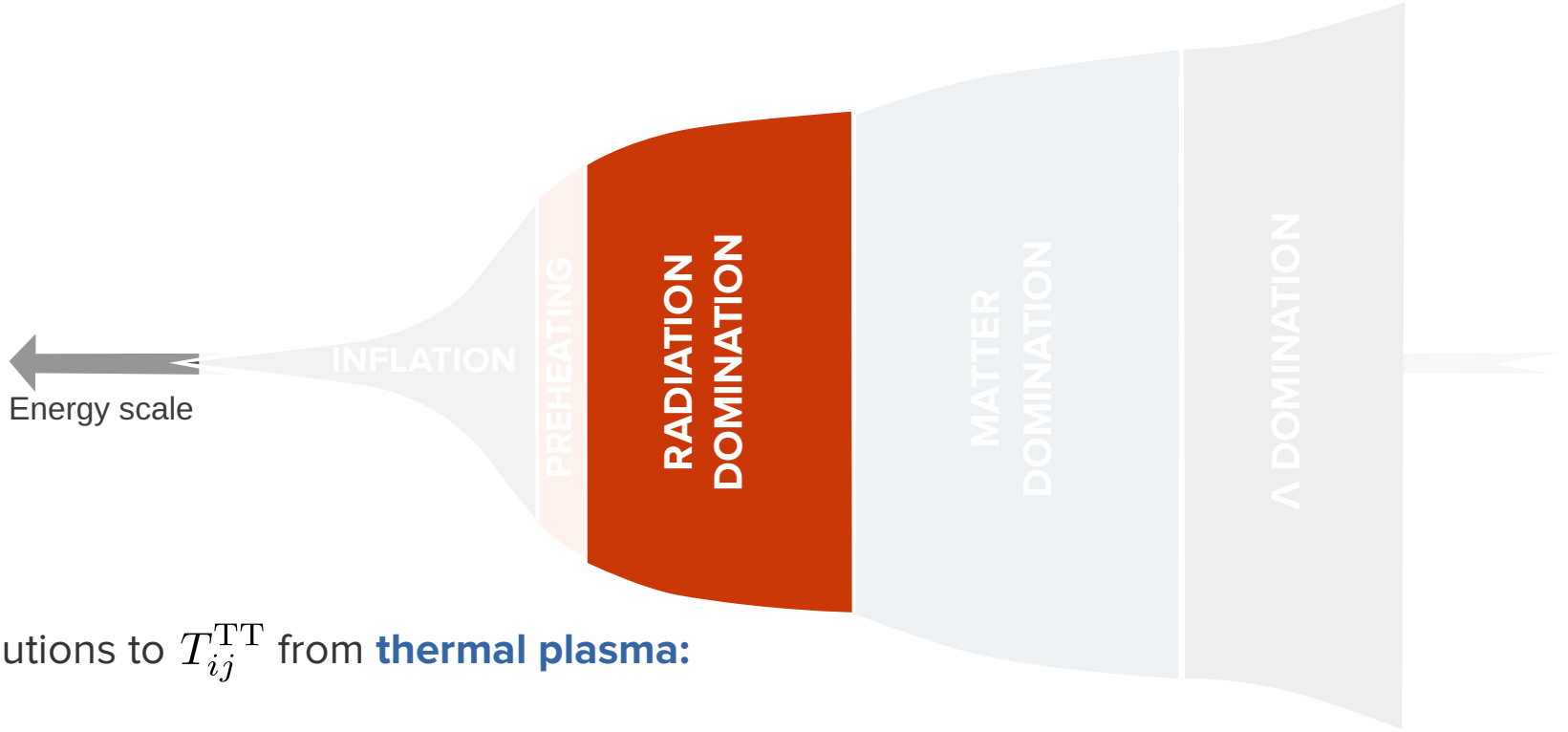
No source term in wave eqn.
Initial conditions matched to quantum field in **Minkowski** well **inside horizon**

Sources of GWs in the SMASHY universe



Contributions to T_{ij}^{TT} from
nonperturbative scalar field fuctuations (inflaton fragmentation)

Sources of GWs in the SMASHY universe



Contributions to T_{ij}^{TT} from **thermal plasma:**

Transport/viscosity
Quasi-particle excitations

Cosmic Gravitational Microwave Background (CGMB)

Interdependence between sources

Inflation

sets the initial conditions for

Reheating

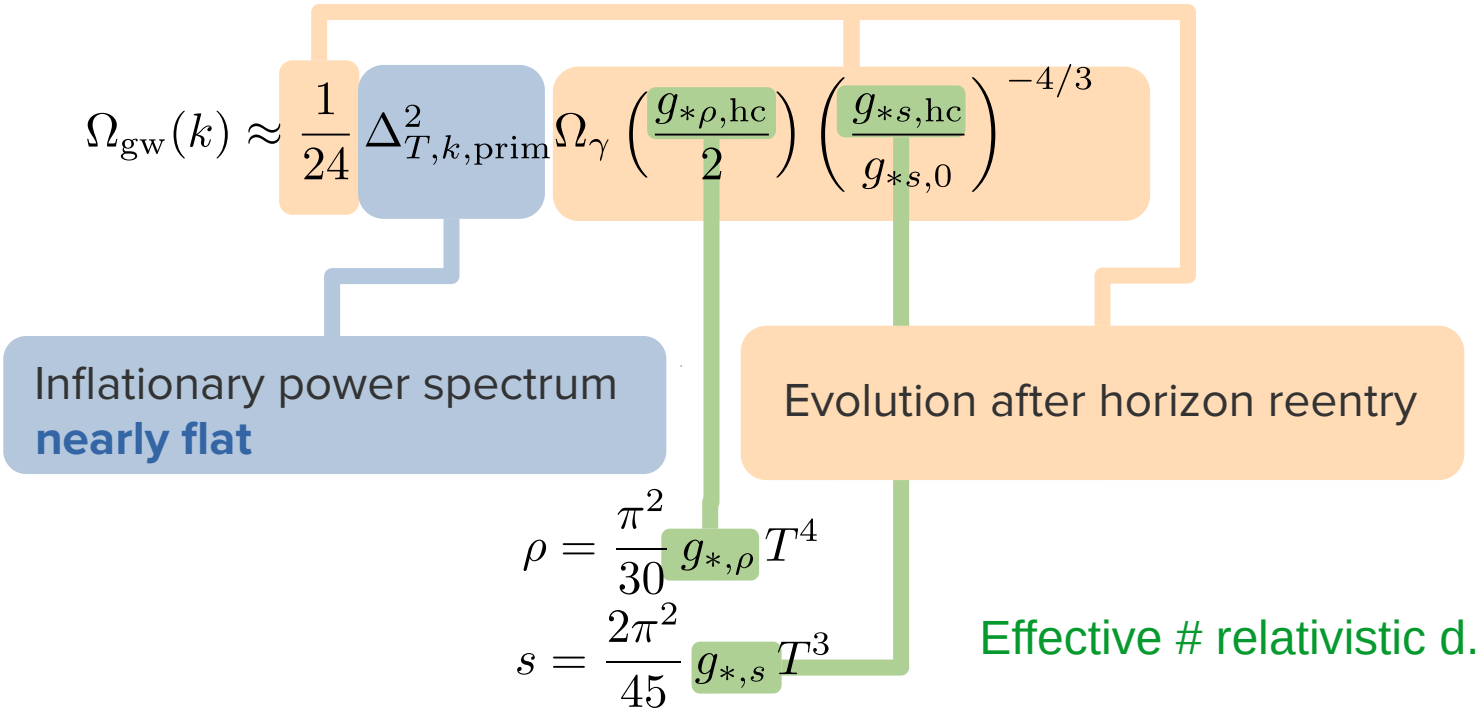
which fixes the value of the reheating temperature and the scale of

Thermal excitations

We expect correlations within SMASH of spectra coming from different sources

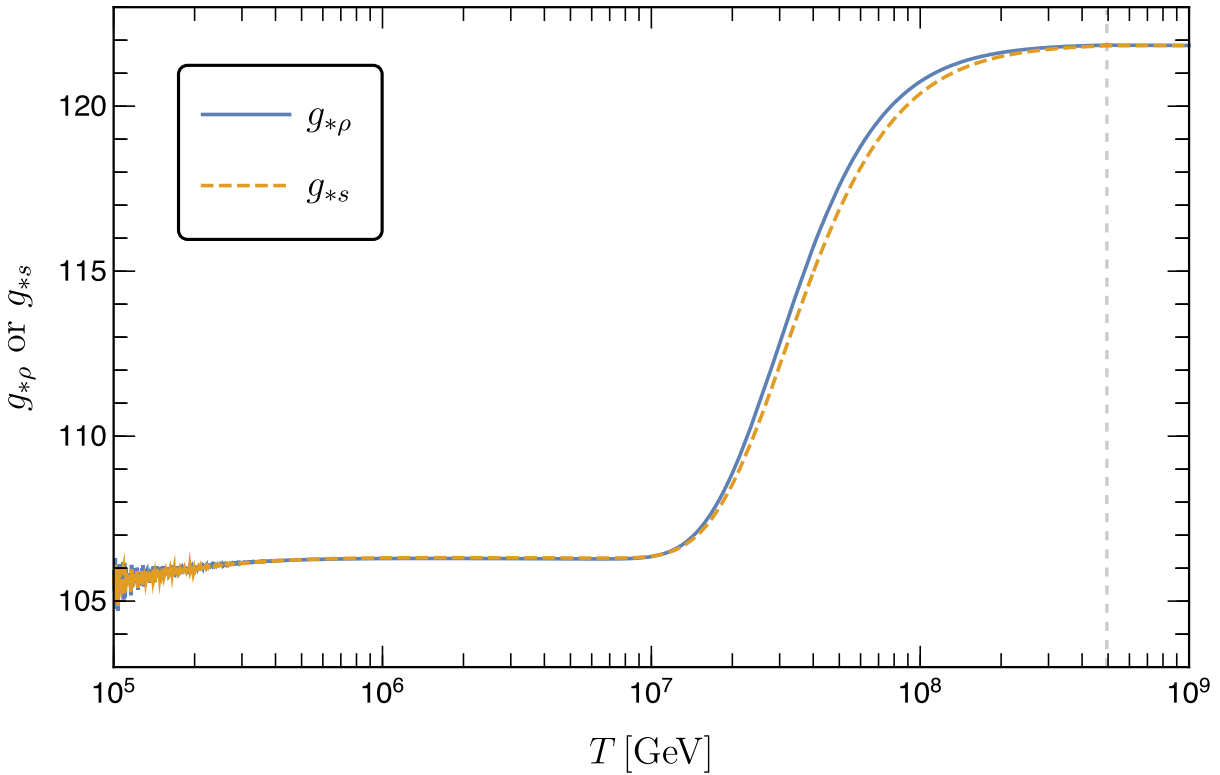
(Dragons are not arbitrary! Approx. 1 free parameter for GWs)

GWs from inflation



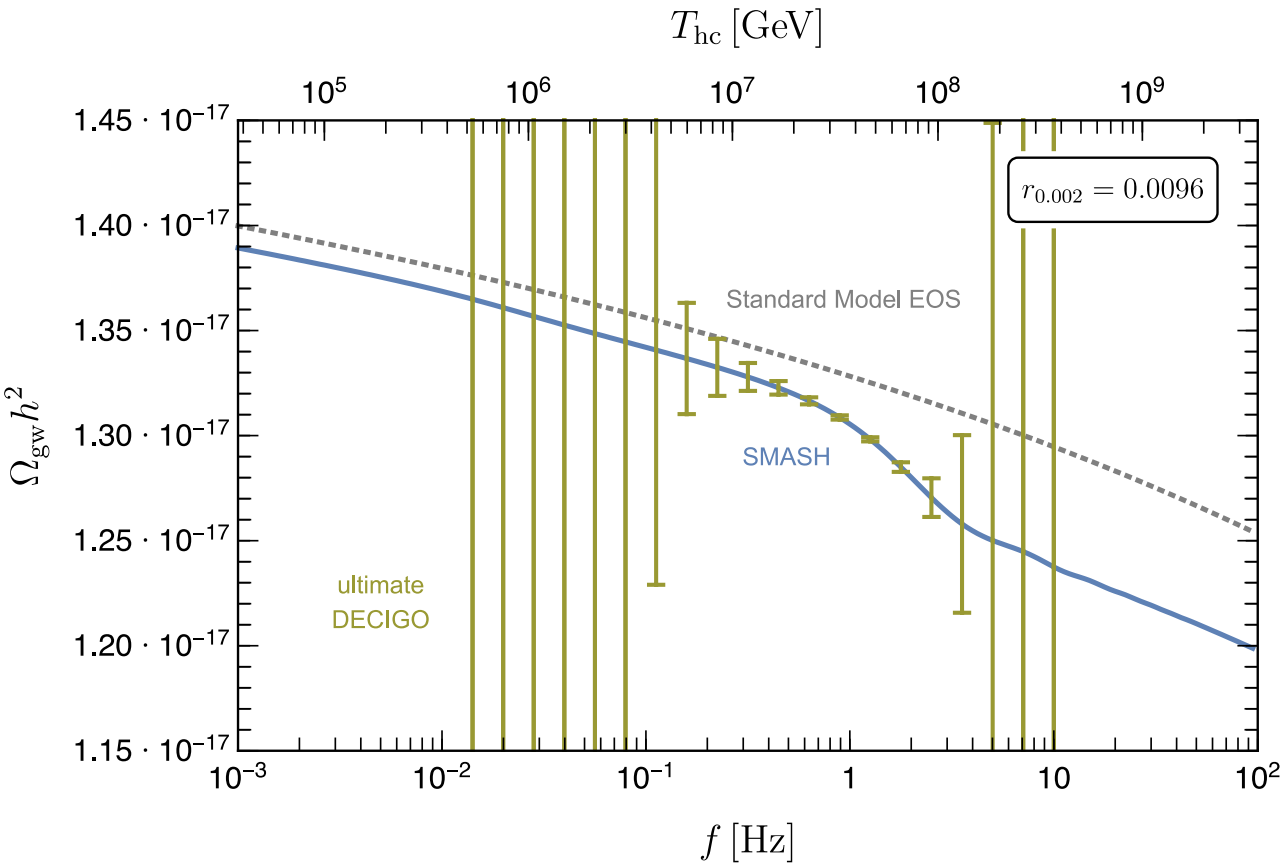
- Sudden changes in $g_{*\rho}, g_{*s}$ (as in PQ transition) can lead to **steps in power spectrum**
- **Challenge**: accurate **estimate with** $g_{*\rho}, g_{*s}$ with improved Daisy resummation

Computing $g_{*\rho}$, g_{*s} across PQ phase transition



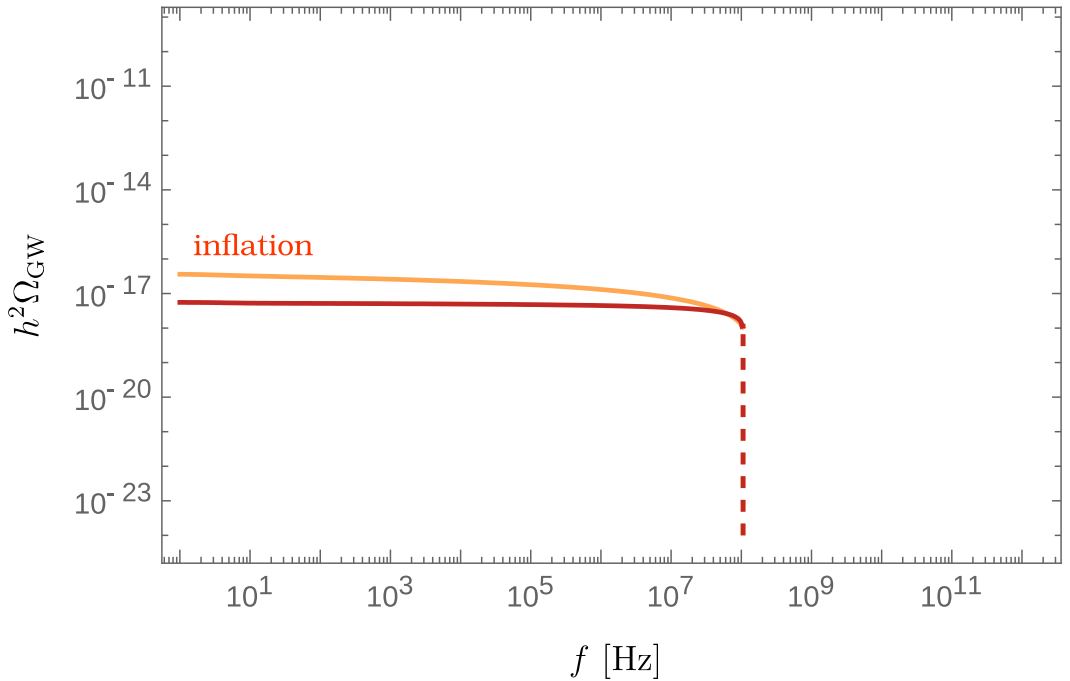
[Ringwald, Saikawa, CT]

The PQ transition affects inflationary GWs



[Ringwald, Saikawa, CT]

GWs from inflation: the bigger picture



- Spectrum tied to **Hubble scale during inflation**

GWs from preheating

[Dufaux et al]

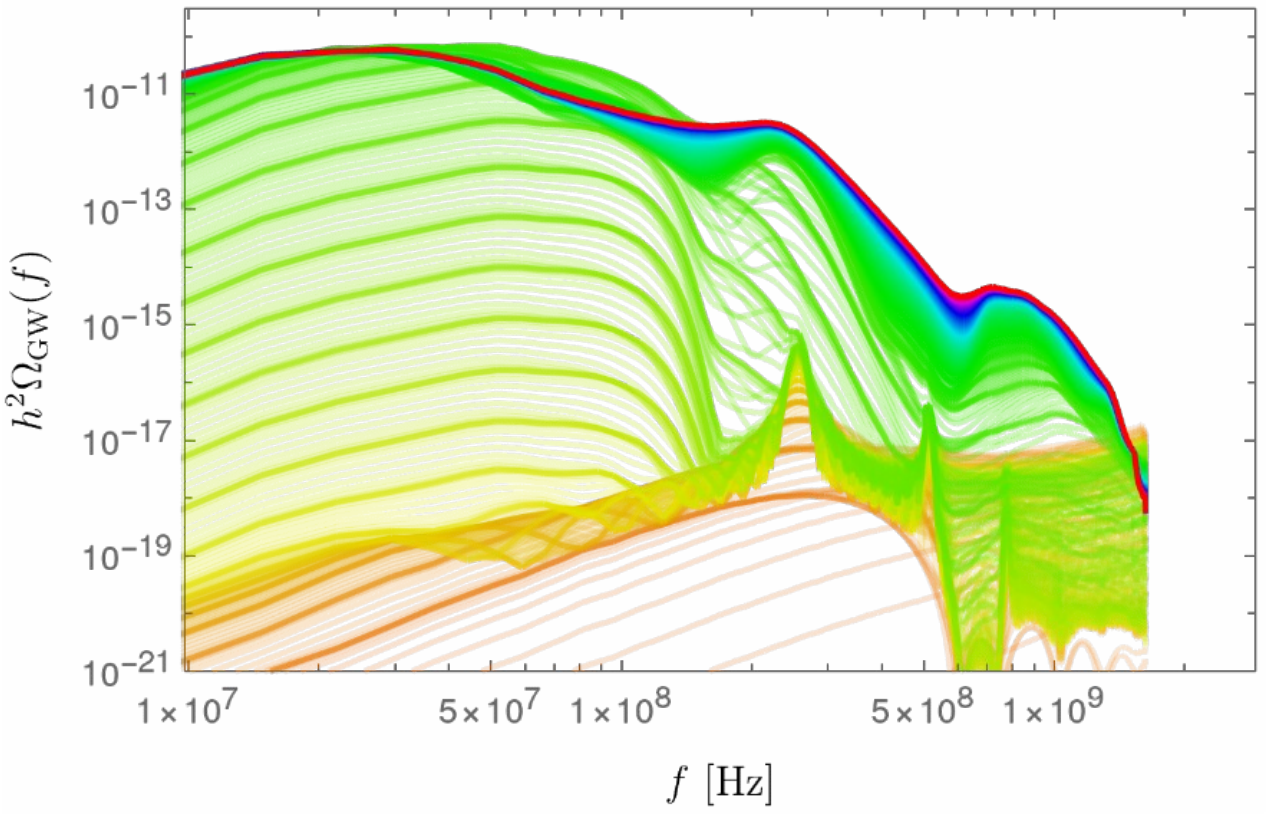
$$\left(\frac{d\rho_{\rm gw}}{d\log k}\right)_{\tau>\tau_f,\,k\gg aH} = \frac{S_k(\tau_f)}{a^4(\tau)}$$

$$S_k(\tau_f) = \frac{4\pi G k^3}{V}\int d\Omega \sum_{i,j}\Big\{ \Big|\int_{\tau_i}^{\tau_f} d\tau' \cos(k\tau')a(\tau')T^{\rm TT}_{\phi,ij}(\tau',\mathbf{k})\Big|^2 + \Big|\int_{\tau_i}^{\tau_f} d\tau' \sin(k\tau')a(\tau')T^{\rm TT}_{\phi,ij}(\tau',\mathbf{k})\Big|^2\Big\}$$

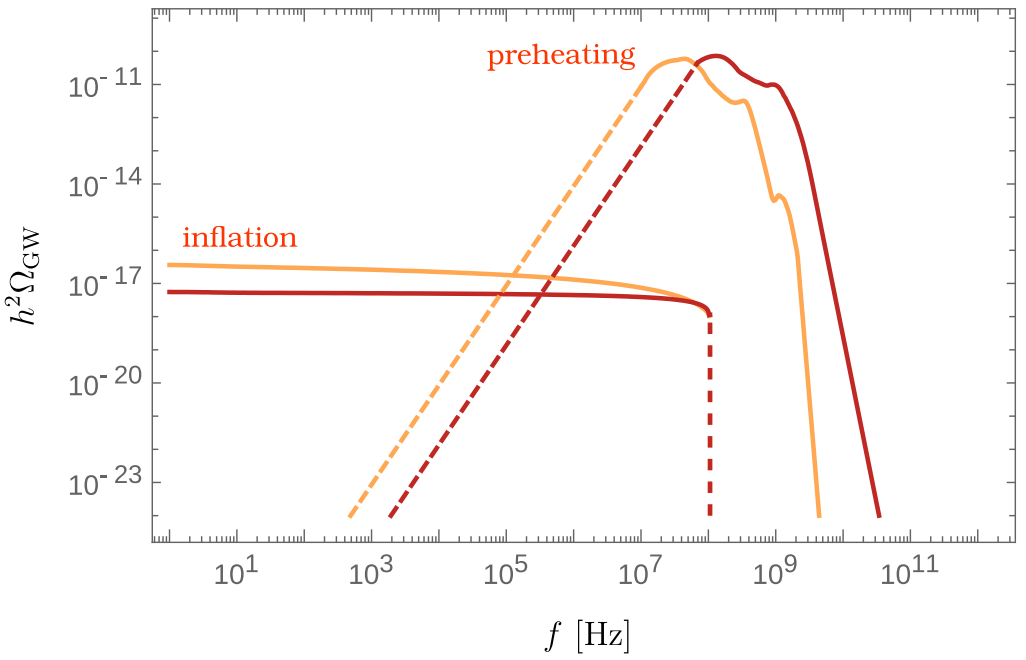
from **nonperturbative scalar dynamics**

Challenge: **lattice simulations** with **3 real scalars**, accounting for **Higgs decays**, and with a **radiation component backreacting** in scale factor

Results of simulations

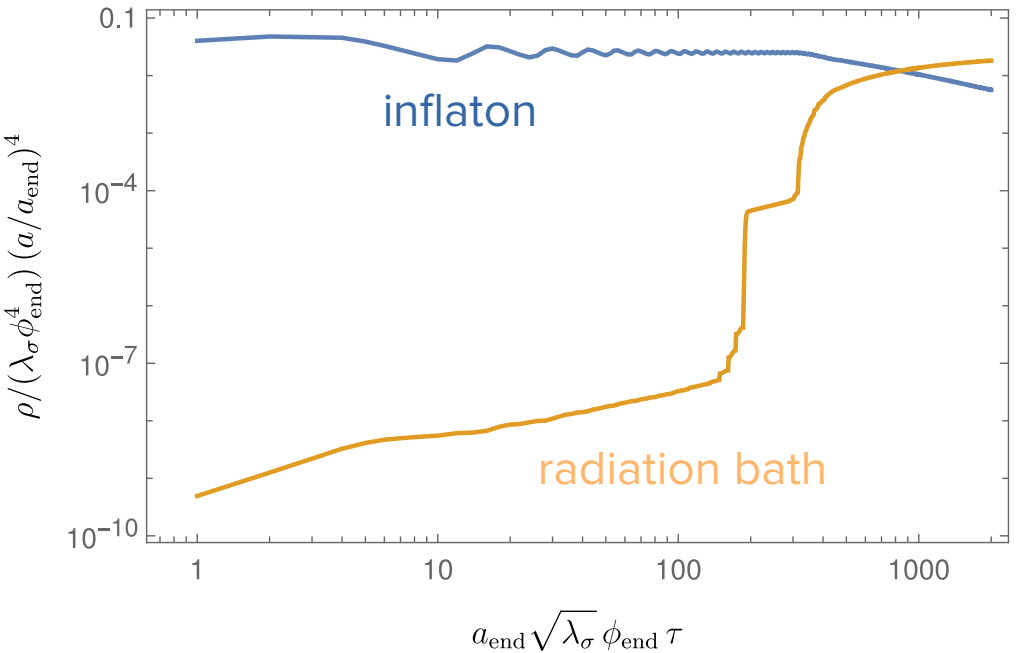


GWs from preheating: the bigger picture



- Hubble scale during inflation
- Hubble scale at inflation's end, length scale of inflaton fragmentation

Reheating temperature from simulations



$$\rho = \frac{\pi^2}{30}\, g_{*,\rho} T^4 \Rightarrow T_{\rm reheating} = 2 \times 10^{12}\ {\rm GeV}$$

GWs from thermal fluctuations

[Laine & Ghiglieri]

$$\Omega_{\rm CGMB}(f) \approx 4.03 \times 10^{-12} \left[\frac{T_{\rm max}}{M_P}\right] \left[\frac{g_{*s}(T_{\rm max})}{106.75}\right]^{-5/6} \left[\frac{f}{\rm GHz}\right]^3 \hat{\eta}\left(T_{\rm max}, 2\pi \left[\frac{g_{*s}(T_{\rm max})}{g_{*s}(\rm fin)}\right]^{1/3} \frac{f}{T_0}\right)$$

Linear effect: A **Big Bang thermometer**!

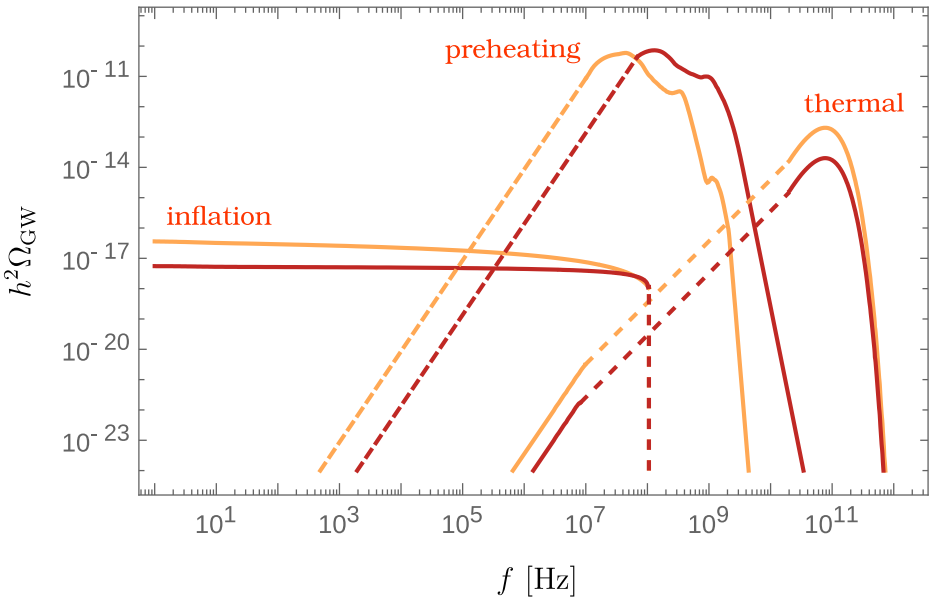
Peak frequency depending on the **number of relativistic degrees of freedom at the Big Bang**!

Challenges: **Generalization** to **arbitrary theories** beyond SM

Experimental proposal involving **Gaussian beam**

[Ringwald, Schütte-Engel, CT]

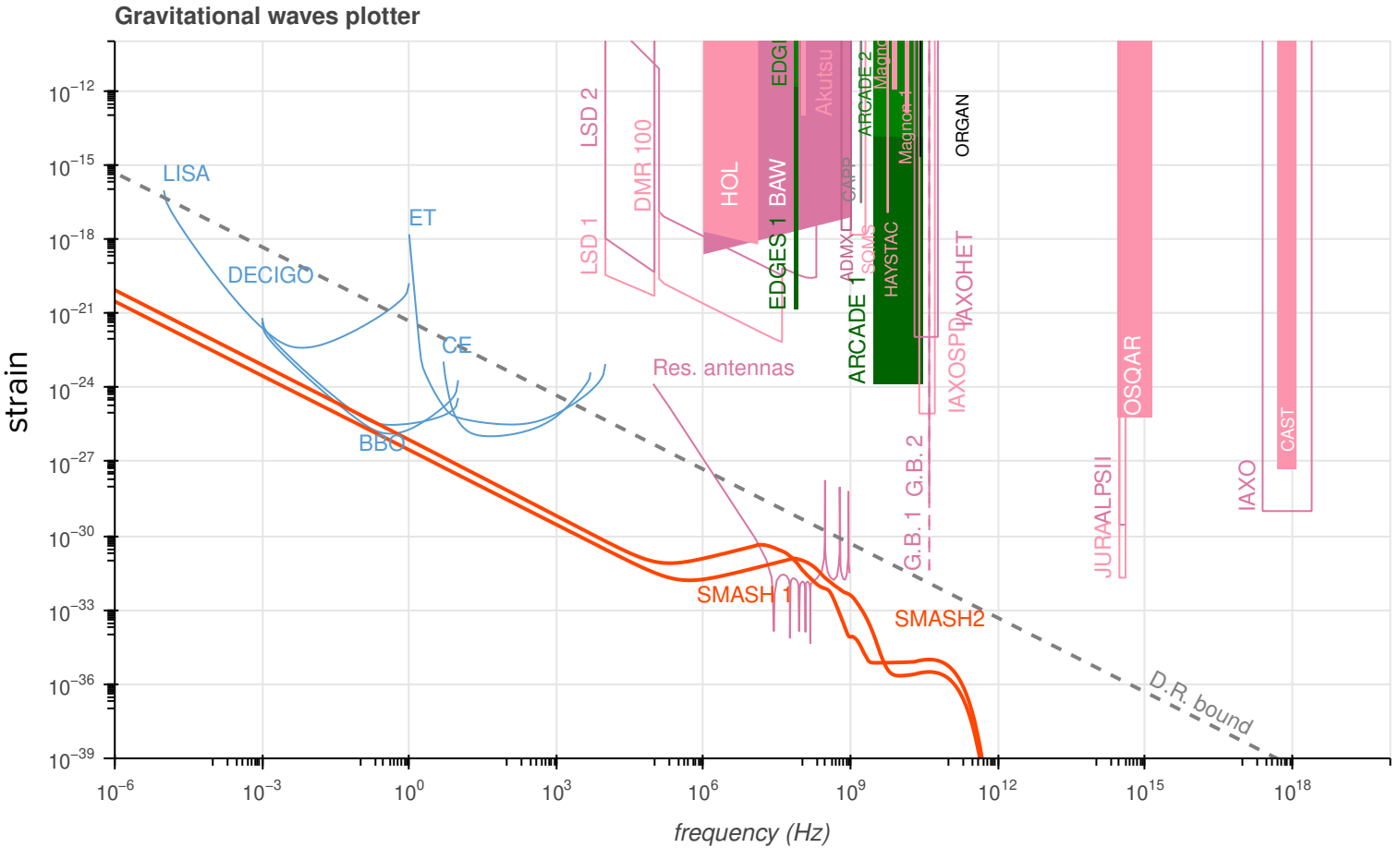
CGMB: the bigger picture



- 3 different sources potentially distinguishable!

- Hubble scale during inflation
- Hubble scale at inflation's end, length scale of inflaton fragmentation
- Tmax and number of d.o.f. in hot Big Bang

The dragon vs current and future experiments



Further visions: a new gravitational wave plotter

Gravitational Waves Plotter

http://incandenza-01.zdv.uni-mainz.de/

[Muia, Ringwald, CT]

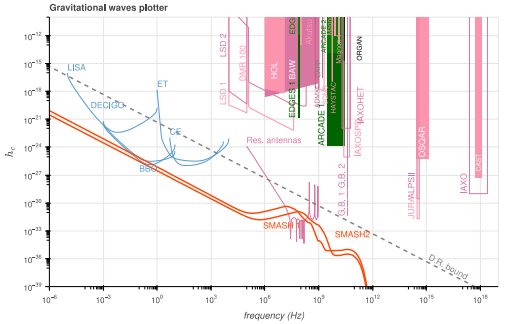
Gravitational Waves Plotter

Edited and maintained by Francesco Muia, Andreas Ringwald, and Carlos Tamarit

About

GitHub

Plot characteristic strain h_c | Plot energy fraction $h^2\,\Omega$



Plot range and size

Adjust frequency range: **1e-6 .. 1e+19**

Adjust h_c range: **1e-39 .. 1e-10**

Adjust $h^2\Omega$ range: **1e-40 .. 1e+25**

Adjust plot width: **700**

Adjust plot height: **490**

Phase transitions

Phase transition temperature (GeV): **2.00e+2**

α: **1.00e-1**

β/H: **1.00e+1**

v_w: **0.40**

CGMB

Temperature (GeV): **2.44e+18**

Global strings

String tension $G\mu$: **1.00e-11**

EDGES 1: Comment on EDGEstrong.

CAST: Comment on CAST.

Selection of bounds and signals

Theoretical Bounds

- [x] D.R. bound

Experimental Bounds

Direct Bounds	Indirect Bounds	Projected Bounds
[x] BAW	[x] ARCADE 1	[x] LSD 2
[x] OSQAR	[x] ARCADE 2	[x] LSD 1
[x] CAST	[x] EDGES 1	[x] IAXOSPD
[x] HOL	[x] EDGES 2	[x] IAXOHET
[x] Akutsu		[x] IAXO
[x] Magnon 2		[x] ALPSII
[x] Magnon 1		[x] JURA
		[x] ADMX
		[x] HAYSTAC
		[x] CAPP
		[x] SQMS
		[x] G.B. 2
		[x] G.B. 1
		[x] ORGAN
		[x] Res. antennas
		[x] DMR 8
		[x] DMR 100
		[x] BBO
		[x] CE
		[x] DECIGO
		[x] ET
		[x] LISA

Potential Signals

- [x] SMASH 1
- [x] SMASH2
- [ ] CGMB
- [ ] Global strings
- [ ] 1st-order p.t.
- [ ] Inflation-EFT
- [ ] Inflation-scalar pert.
- [ ] Inflation-extra species
- [ ] Phase trans. (env.)
- [ ] Oscillons
- [ ] Metastable strings
- [ ] Cosmic strings (env.)
- [ ] Gauge textures
- [ ] Preheating (quart.)
- [ ] Preheating (quadr.)

Conclusions

High-frequency GWs can tell us about:

Hubble scale during and at the end of inflation

Scale of inflaton fragmentation

Reheating temperature and **number of d.o.f.s** in the primordial plasma

Second-order phase transitions in the early universe

SMASH provides a **conservative benchmark** which can hopefully motivate further efforts in high-freq. GWs

Andreas' **bold physics visions** have been a constant source of **inspiration**, and will also **spur future generations** like those who will get to measure the CGMB, as Andreas named it!

Thanks Andreas for the **honour, privilege** and **fun** of our collaboration

Thank you **Guillermo Ballesteros** for connecting me to Andreas, and thanks to all the wonderful additional collaborators I got to engage with as a result:

Luca Di Luzio, Anne Ernst, Francesco Muia, Javier Redondo, Ken'ichi Saikawa, Jan Schütte-Engel, Yvette Welling

Credit: Andreas Ringwald

Always curious
Always eager
Always young