Thermal production of gravitational waves in the early universe

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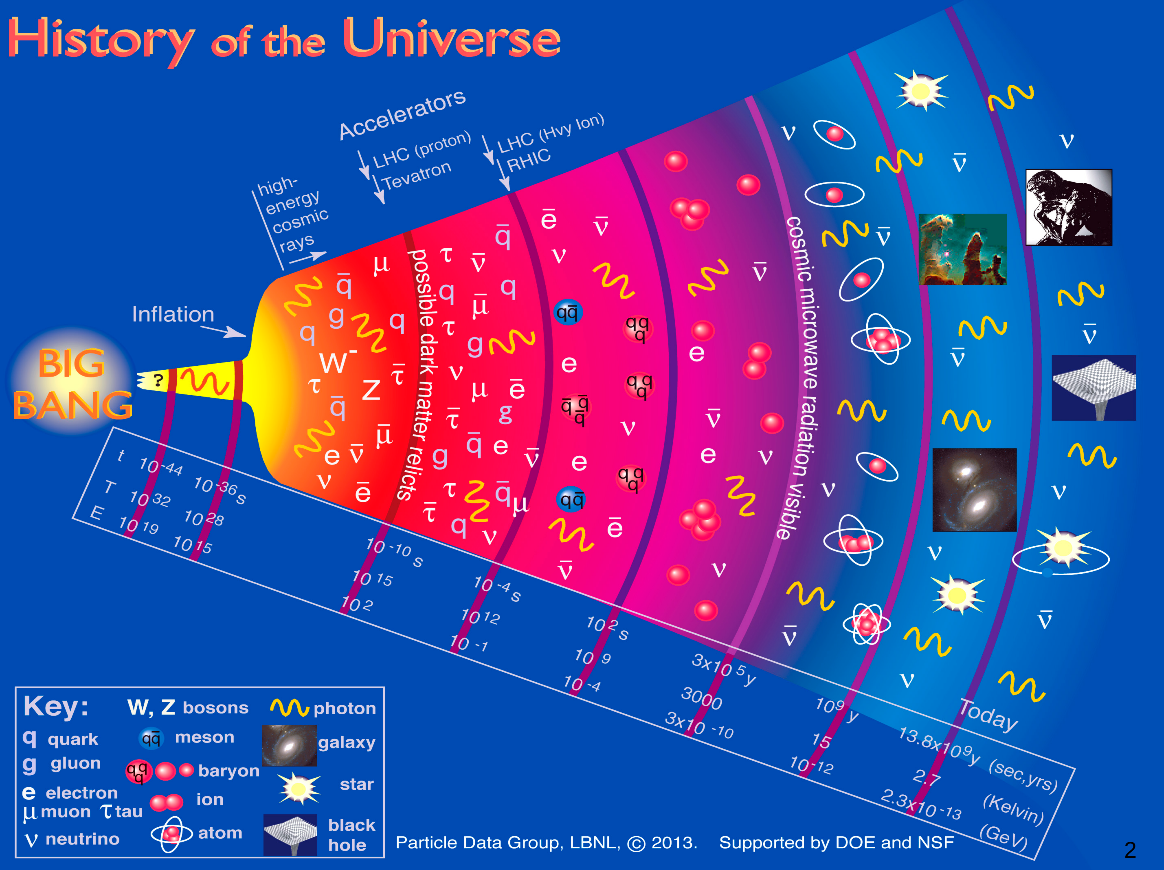
https://xunjiexu.github.io/

Based on 2503.10756 and 2505.08868 (JHEP$\times$2)

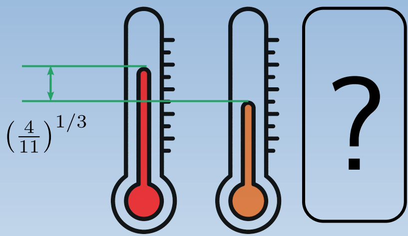
International Joint Workshop on the Standard Model and Beyond, Taipei, Dec 9 – 12, 2025
https://indico.phys.sinica.edu.tw/event/301/


History of the Universe
Accelerators
LHC (proton)
Tevatron
LHC (Hvy Ion)
RHIC
high-energy cosmic rays
Inflation
BIG BANG
?
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-36 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-4 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
13.8x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
μ muon τ tau
atom
black hole
ν neutrino
Particle Data Group, LBNL, © 2013. Supported by DOE and NSF

the lightest species: $\gamma \to$CMB, $\nu \to$CNB, graviton/GW $\to$CGWB?

observation ✓
$\Rightarrow$ modern cosm.

predicted, not detected yet



CMB | CNB | CGWB

2.7 K | 1.9 K

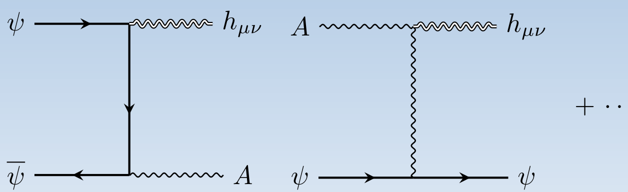
$\underbrace{\qquad\qquad}$

theoretically ✓

because
known interactions
known thermal history

$$\boxed{S = \int d^4x\sqrt{-g}\left(\tfrac{1}{2}M_P^2\mathcal{R} + \mathcal{L}_{\rm SM} + \cdots\right)}$$

$\hookrightarrow$ gravitons,
with known interactions



hot SM $\xrightarrow[\text{high E}]{\text{scattering}}$ $h_{\mu\nu}$ $\xrightarrow{\text{red shift}}$ CGWB

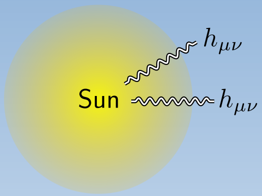
Just like CMB/CNB, CGWB $\in$ thermal relics

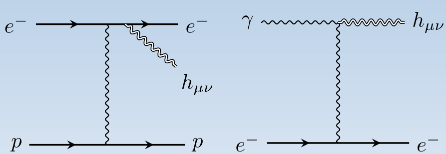
Main diff: ~~equilibrium~~
abundance $\Leftarrow$ thermal production

PHYSICAL REVIEW VOLUME 140, NUMBER 2B 25 OCTOBER

Infrared Photons and Gravitons*

STEVEN WEINBERG†
Department of Physics, University of California, Berkeley, California
(Received 1 June 1965)





The solar gravitational radiation power is then

$$P_\odot \simeq 6\times 10^{14}\ \text{erg/sec}. \tag{4.24}$$

$= 6 \times 10^7$ Watt

Although this is not much more power than used by the city of Berkeley, it nevertheless compares favorably with the gravitational radiation from previously considered classical sources like planetary motion. A planet of mass m moving in a circular orbit of radius R around a star of mass M emits gravitational radiation with power

$$P = (32/5)Gc^{-5}m^2R^4(GM/R^3)^3. \tag{4.25}$$

For the Jupiter-Sun system this is 7.6×10^{11} erg/sec. Venus and the Earth radiate comparable amounts, and the other planets considerably less, so the thermal gravitational radiation (4.14) from the Sun appears to be the dominant source of gravitational radiation from the solar system. A binary star like Sirius A and B radiates more classically—in this case Eq. (4.25) gives 8×10^{14} erg/sec—but it also radiates more thermally. Thus thermal collisions possibly may provide the most important source of gravitational radiation in the universe. I have no idea what it is good for.

Recently recalculated by
Camilo Garcia-Cely, Andreas Ringwald, PRL
[2407. 18297]

CGWB from SM: from LLO (leading-log order) to complete LO

Gravitational wave background from Standard Model physics: Complete leading order #1
J. Ghiglieri (SUBATECH, Nantes), G. Jackson (U. Bern, AEC), M. Laine (U. Bern, AEC), Y. Zhu (Munich, Tech. U.) (Apr 23, 2020)
Published in: *JHEP* 07 (2020) 092 • e-Print: 2004.11392 [hep-ph]
pdf DOI cite claim reference search 89 citations

LO

Gravitational wave background from Standard Model physics: Qualitative features #2
J. Ghiglieri (U. Bern, AEC), M. Laine (U. Bern, AEC) (Apr 10, 2015)
Published in: *JCAP* 07 (2015) 022 • e-Print: 1504.02569 [hep-ph]
pdf DOI cite claim reference search 95 citations

LLO

Not an easy task
… even t-channel only

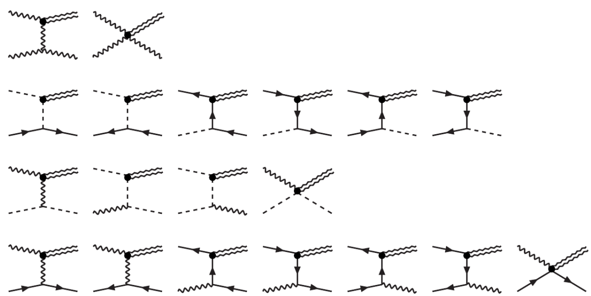
IR divergence
Debye screening
…

$\Phi_{g(g)} \Leftrightarrow$

$\Phi_{s(f)} + \Phi_{f(s)} + \Phi_{s|f} \Leftrightarrow$

$\Phi_{s(g)} + \Phi_{g(s)} + \Phi_{s|g} \Leftrightarrow$

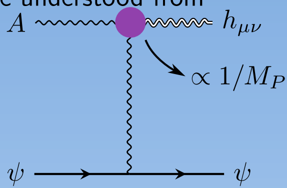
$\Phi_{f(g)} + \Phi_{g(f)} + \Phi_{f|g} \Leftrightarrow$



How does CGWB look like? — similar to CMB

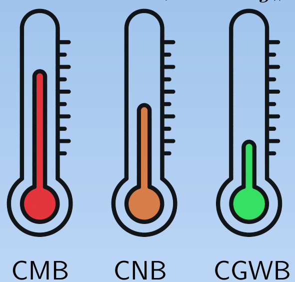
Height:

... can be understood from

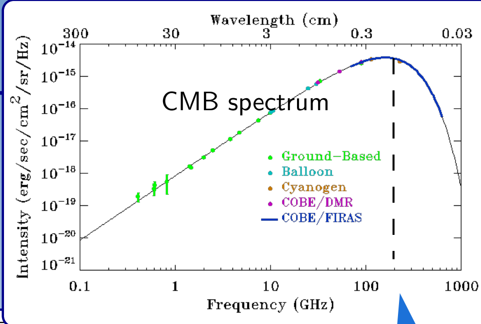


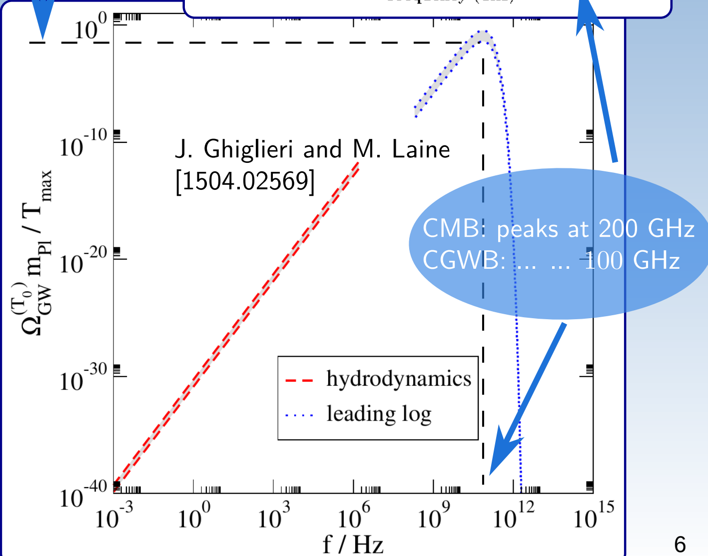
f_{peak}:

... colder than CMB, due to $g_\star$



Height $\propto \frac{T}{M_P}$

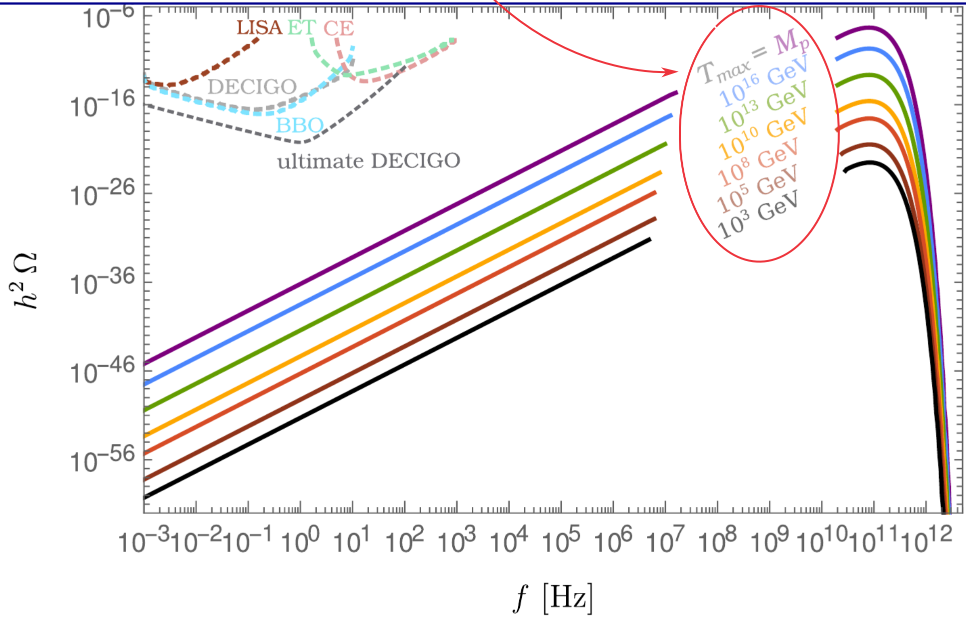




Gravitational Waves as a Big Bang Thermometer #1

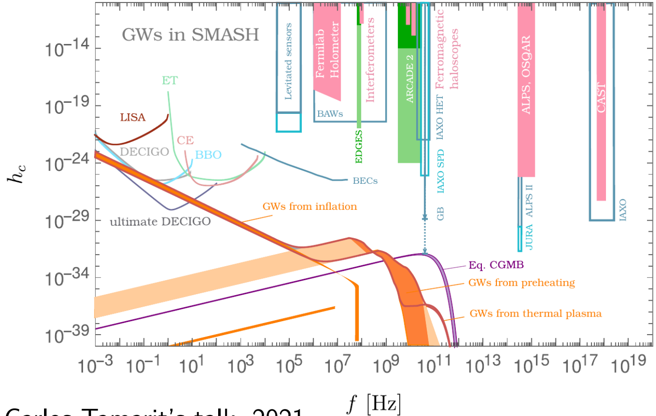
Andreas Ringwald (DESY), Jan Schütte-Engel (Hamburg U. and Illinois U., Urbana), Carlos Tamarit (Munich, Tech. U.) (Nov 9, 2020)

Published in: *JCAP* 03 (2021) 054 • e-Print: 2011.04731 [hep-ph]

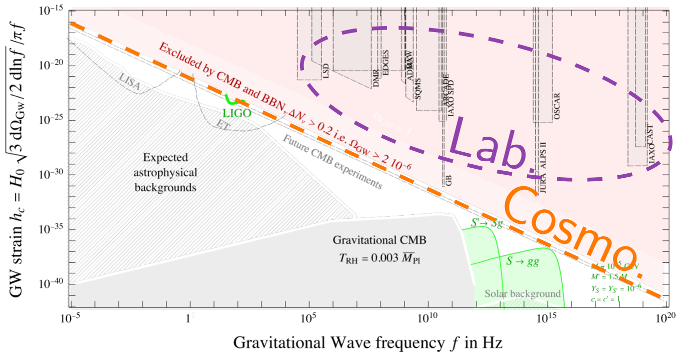


Detection? 

- interferometer not suitable
  - (LIGO, LISA, ET, ...) $\lesssim$ kHz
  - CGWB $\gtrsim$ GHz
- high-frequency GW?
  - axion experiments
    ... way above expected signals
  - cosmo. probe: $N_{\rm eff}$, BBN
  - no lab. bounds exceed cosmo.



Carlos Tamarit's talk, 2021.
https://indico.cern.ch/event/1074510/contributions/4519382/

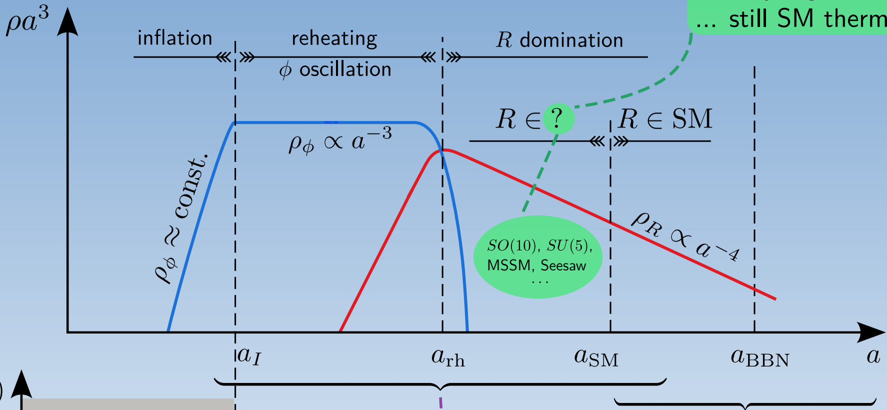


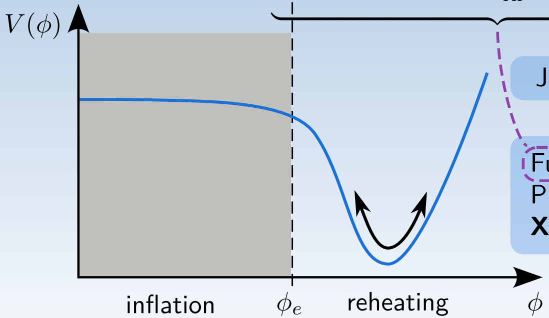
A. Strumia, G. Landini, [2501.09794]

How high has T ever reached?

🤔 ... should think about inflation ...

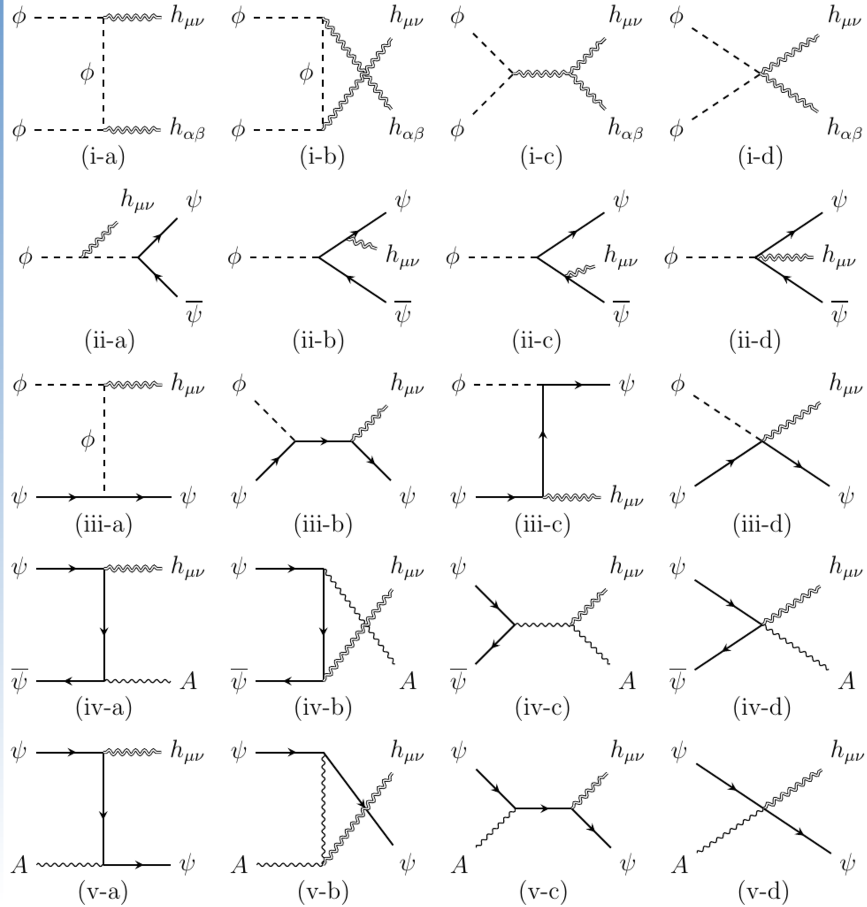
At very high T...
... still SM thermal plasma?





J. Ghiglieri, M. Laine, *et al*, JHEP07(2020)092

Full-Spectrum Analysis of Gravitational Wave Production from Inflation to Reheating
XJX, Y. Xu, Q. Yin, J. Zhu, JHEP10(2025)141.


(i-a)
(i-b)
(i-c)
(i-d)
(ii-a)
(ii-b)
(ii-c)
(ii-d)
(iii-a)
(iii-b)
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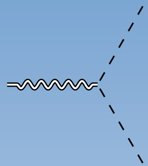
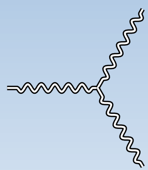
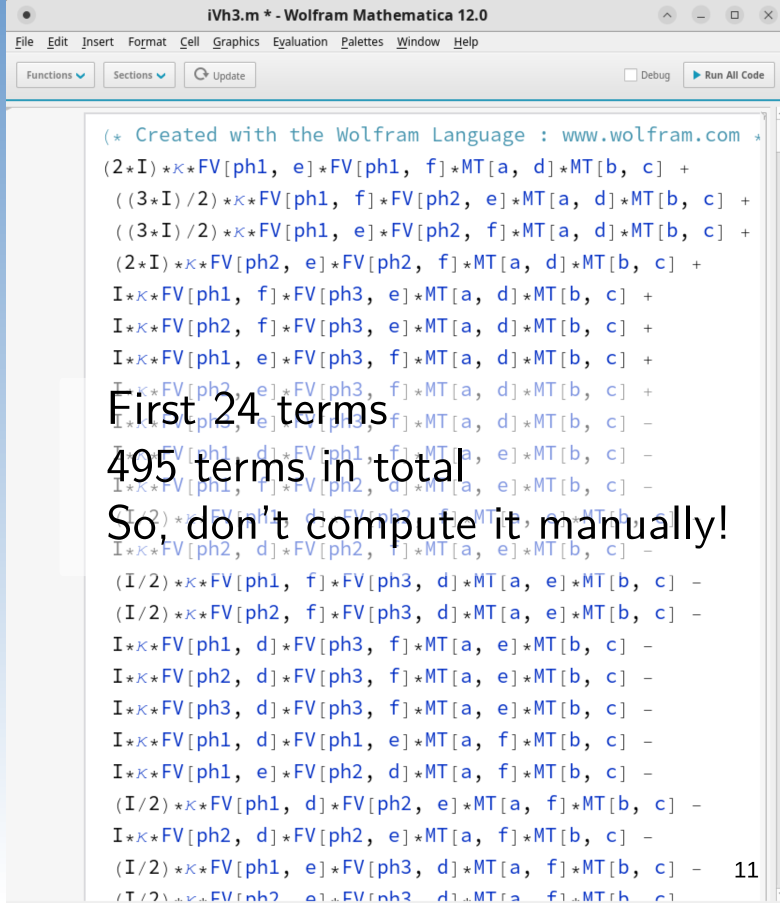
(v-a)
(v-b)
(v-c)
(v-d)



$$= -\frac{i}{M_P}\left[p_1^\mu p_2^\nu + p_1^\mu p_2^\nu - \eta^{\mu\nu}\left(p_1 \cdot p_2 - m_\phi^2\right)\right]$$



$=$



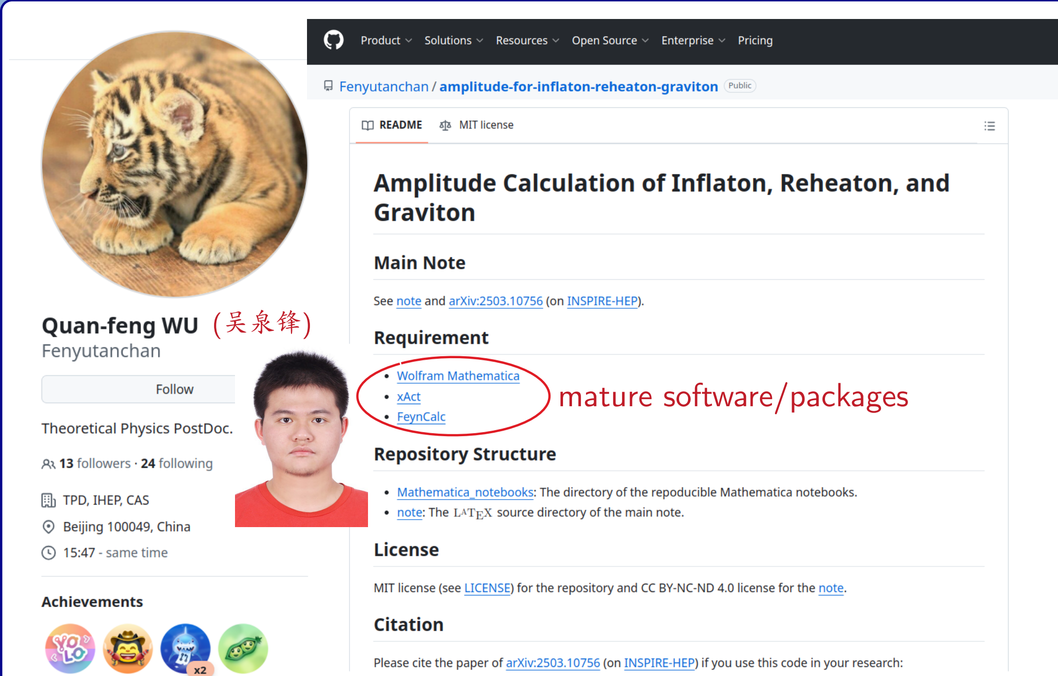
First 24 terms

495 terms in total

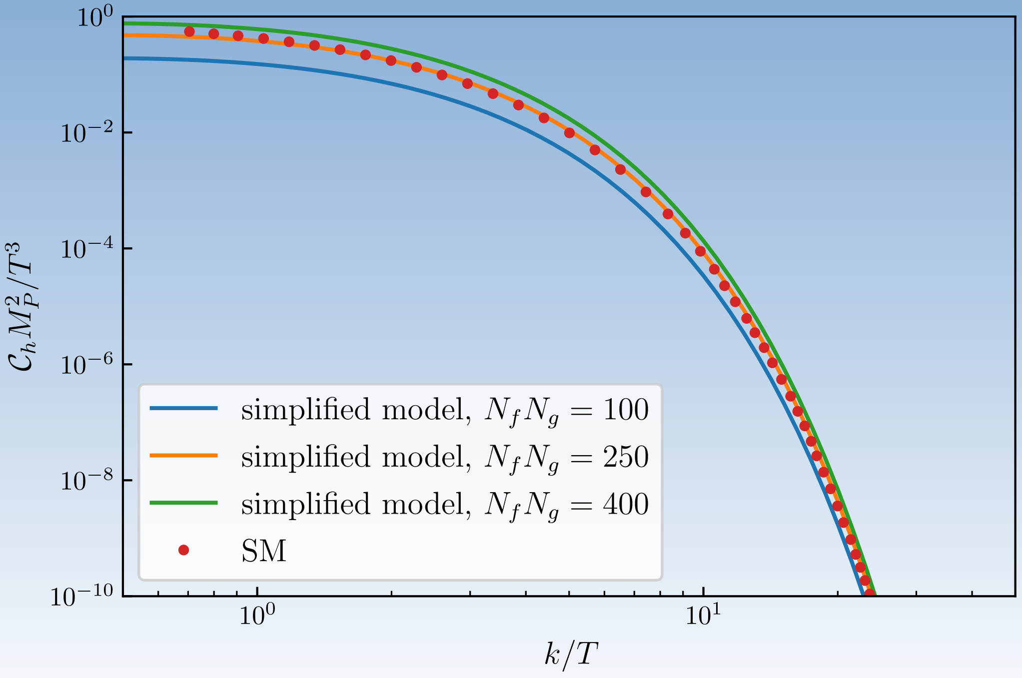
So, don't compute it manually!

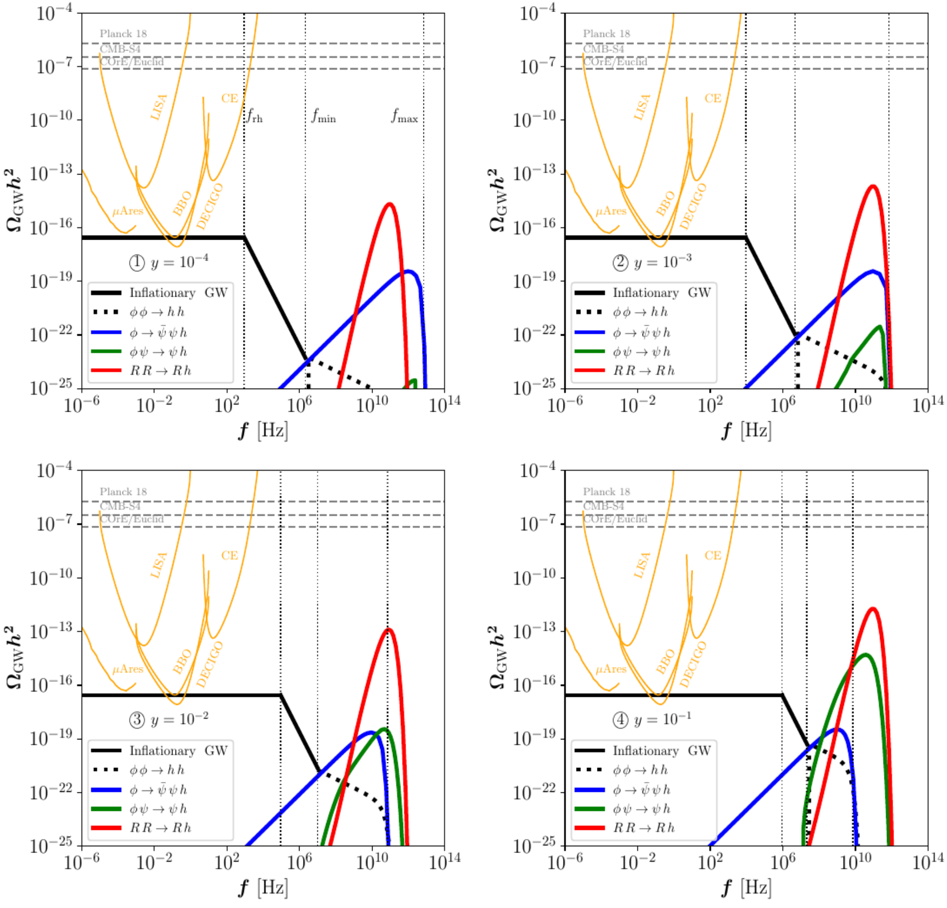
A few words about tools:

- FeynGrav [2406.14872] is useful, but ...
- Anna Tokareva's lecture [2412.08690] and github (github.com/tokareva90) very useful!
- We rebuilt the tool to automatically derive Feynman rules and calculate diagrams



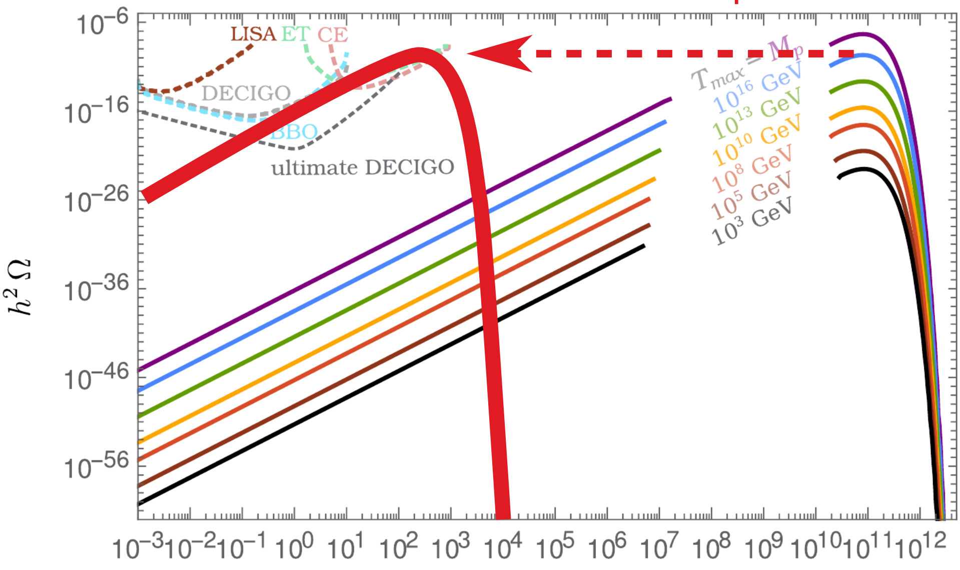
https://github.com/Fenyutanchan/amplitude-for-inflaton-reheaton-graviton


10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^0
10^1
k/T
$\mathcal{C}_h M_P^2/T^3$
simplified model, $N_f N_g = 100$
simplified model, $N_f N_g = 250$
simplified model, $N_f N_g = 400$
SM



Planck 18
CMB-S4
COrE/Euclid
LISA
CE
BBO
DECIGO
μAres
$f_{\rm rh}$
$f_{\rm min}$
$f_{\rm max}$
① $y = 10^{-4}$
② $y = 10^{-3}$
③ $y = 10^{-2}$
④ $y = 10^{-1}$
Inflationary GW
$\phi\,\phi \to h\,h$
$\phi \to \bar{\psi}\,\psi\,h$
$\phi\,\psi \to \psi\,h$
$R\,R \to R\,h$
$\Omega_{\rm GW}h^2$
f [Hz]

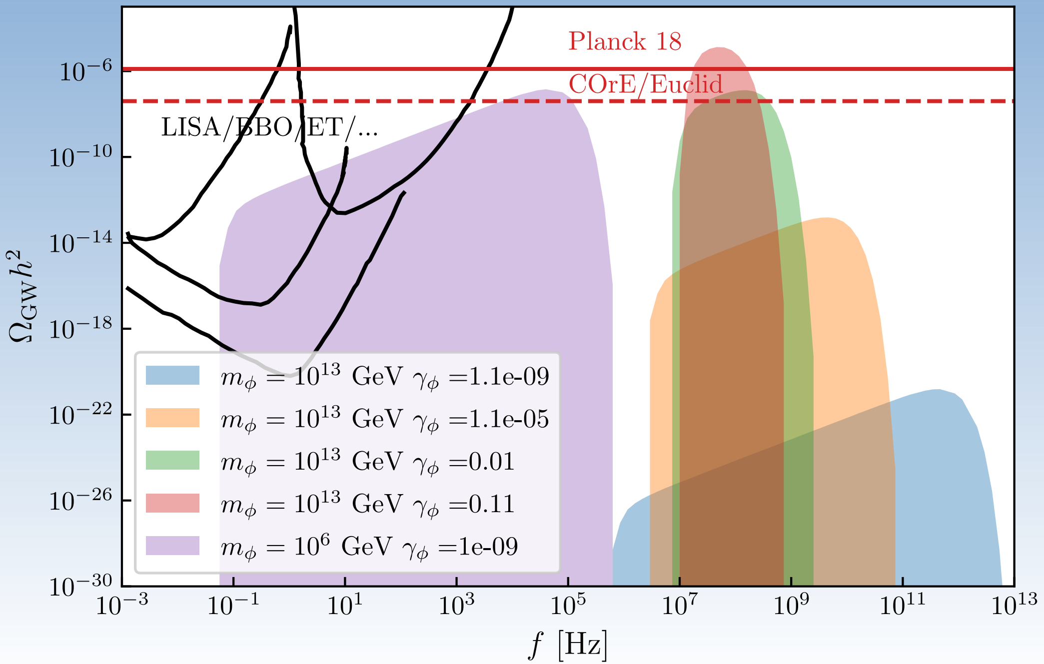
Can we shift CGWB to lower frequencies?



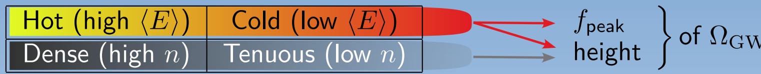
Andreas Ringwald, et al, 2011.04731v2

Yes, if inflatons are light but dense ...

Nicolás Bernal, Quan-feng Wu, XJX, Yong Xu,
Pre-thermalized Gravitational Waves, [2503.10756].



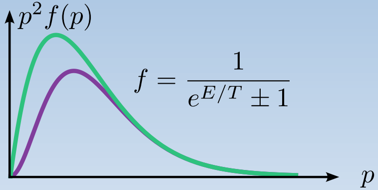
Relations between GW properties and thermal plasma properties:



Want high Ω_{GW} at lower f_{peak}? Take "Cold+Dense"!

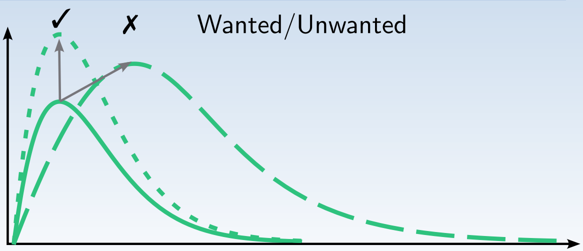
Is it possible to increase n without increasing T?

Yes, bosons only, fermions always $f \le 1$ (Pauli blocking)



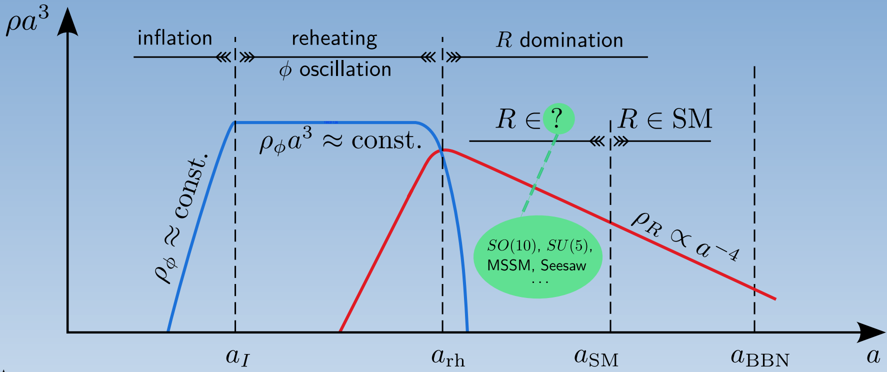
$$f = \frac{1}{e^{E/T} \pm 1}$$

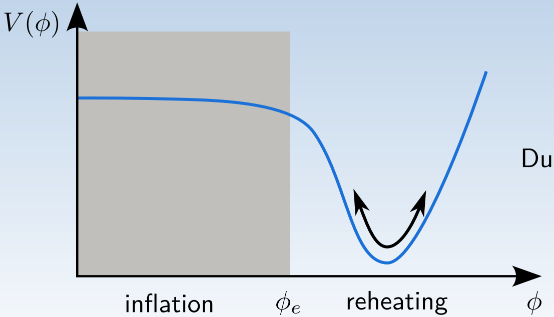
$$n = \frac{\zeta(3)}{\pi^2} T^3 \times \begin{cases} 1 & \text{(BE)} \\ 3/4 & \text{(FD)} \end{cases}$$



- typically, $f \lesssim 1$.
- Therefore, $n \sim 0.1 T^3$
- Can we have $n = 1000 T^3$?

... cold but dense ...
How?



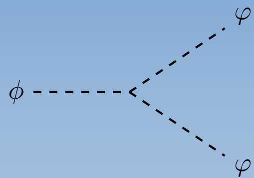


During reheating, inflaton itself is cold & dense.

Can radiation (R) inherit this feature?

Consider ...

inflaton (ϕ) decay to bosonic radiation (φ, massless)



$$\langle p_\varphi \rangle = \frac{1}{2} m_\phi$$
$$n_\varphi = 2 n_\phi$$

Inflaton is cold ($p_\phi = 0$), and can be dense ($n_\phi \gg \frac{1}{\pi^2} m_\phi^3$).

The produced radiation would inherit "cold & dense" from it:

$$n_\varphi \gg \frac{2}{\pi^2} m_\phi^3 \gg \frac{1}{\pi^2} \langle p_\varphi \rangle^3$$

very small m_ϕ $\rightarrow$ $\boxed{n_\varphi = 10000000000 T^3}$

e.g. 10^{10} GeV

So far, so good ...

However,

$$n_\varphi / T^3 \gg 1 \xrightarrow[\text{kinetic equilibrium}]{\text{chemical equilibrium}} ???$$

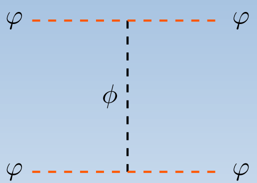
However, $\boxed{n_\varphi/T^3 \gg 1} \xrightarrow[\text{kinetic equilibrium}]{\text{chemical equilibrium}} \boxed{n_\varphi/T^3 = 0.1}$

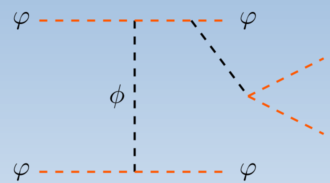
KEQ $\Leftarrow$ sufficient collisions to exchange momentum

CEQ $\Leftarrow$ sufficient $\not{N}_\varphi$ collisions to change particle number

Can φ reaches KEQ and CEQ?

Leading order





Yes & No, depending on ...

We choose coupling $\rightarrow$ No KEQ

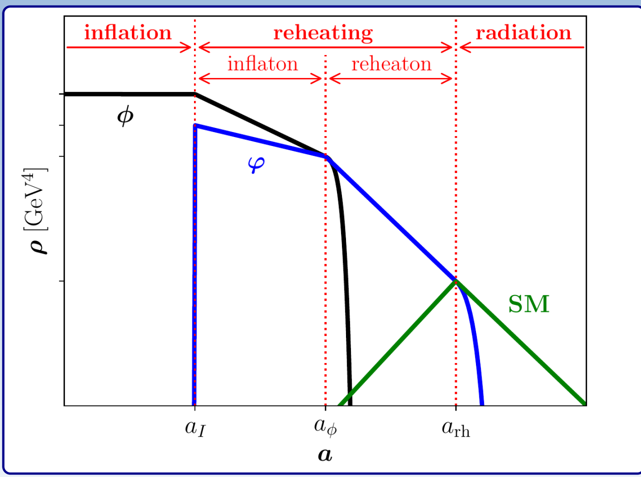
No! Too much suppressed

Adding reheaton φ to the game

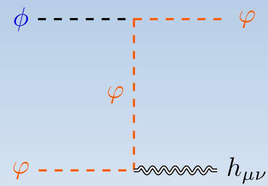
$$\text{Reheaton } (\varphi) \begin{cases} \text{to connect } \phi \text{ and SM} \\ \text{to inherit “cold\&dense” from } \phi \end{cases}$$

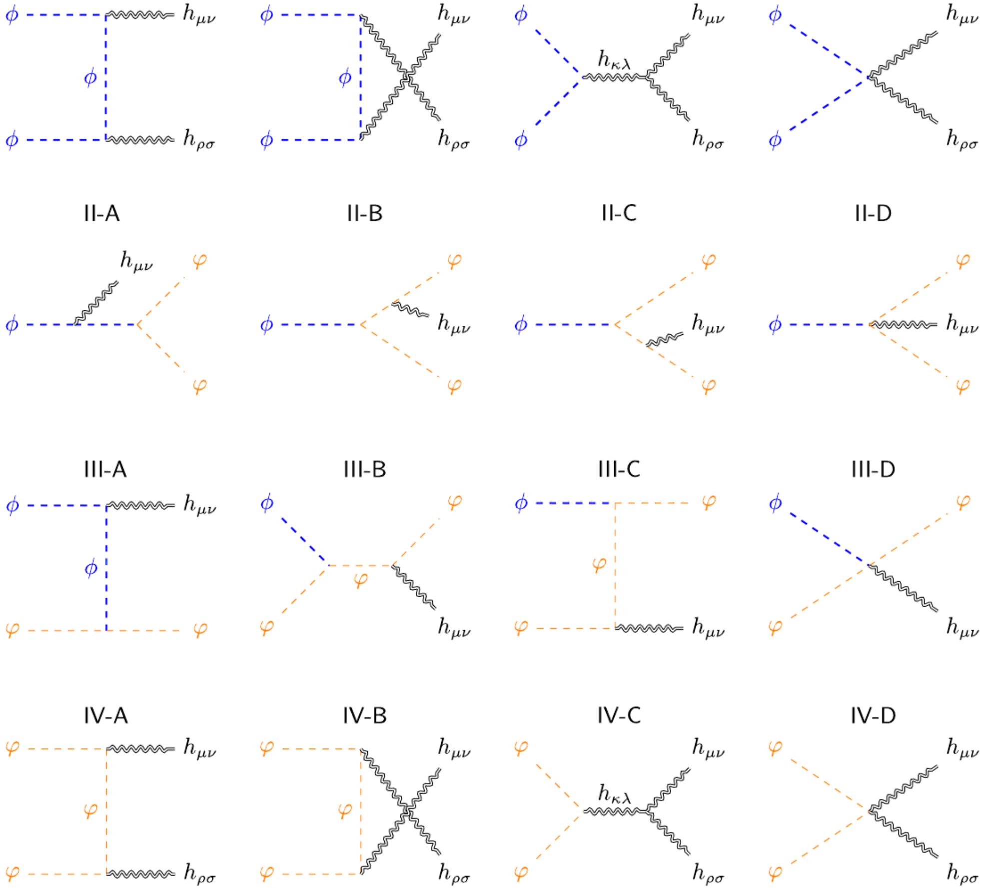
Requirement:

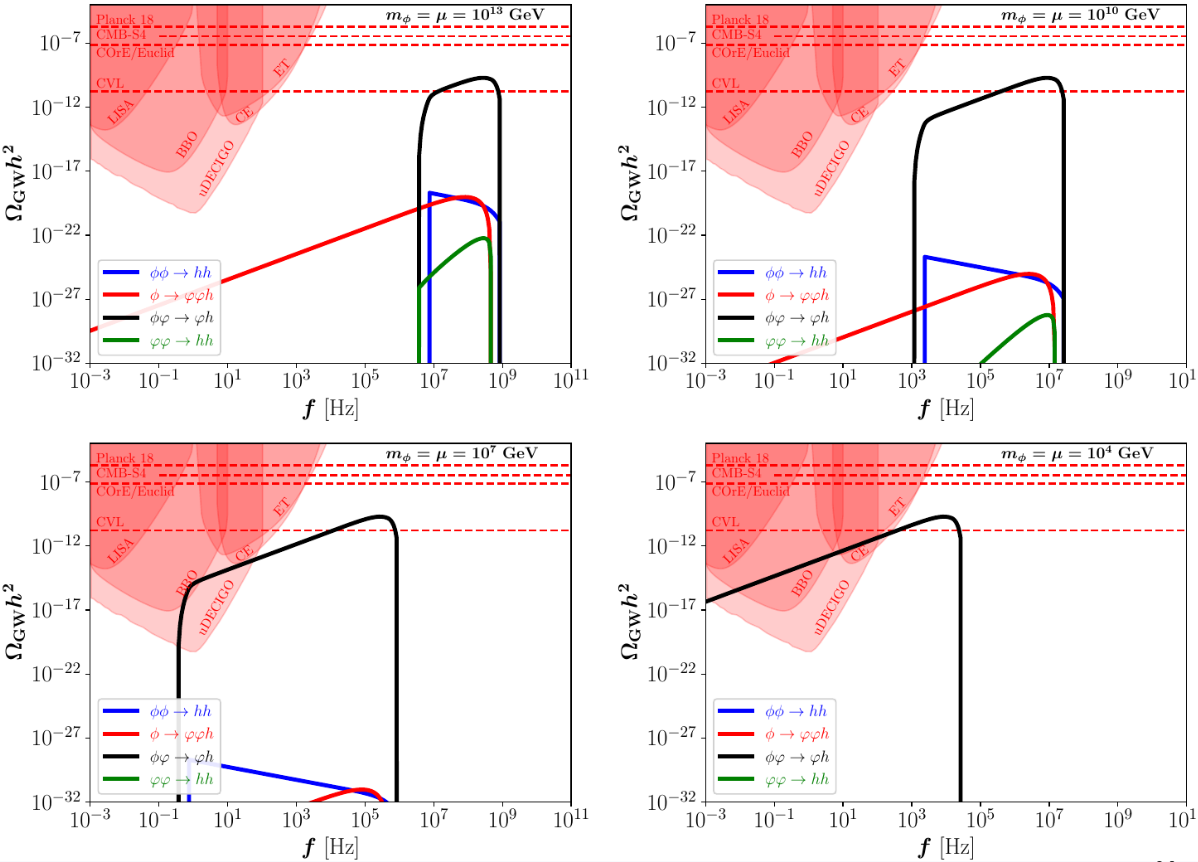
- interacts weakly
- behaves as radiation



One of the dominant GW production channels



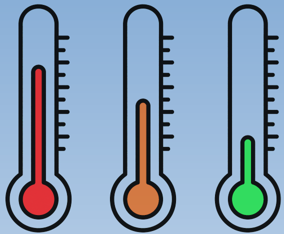

II-A
II-B
II-C
II-D
III-A
III-B
III-C
III-D
IV-A
IV-B
IV-C
IV-D



$m_\phi = \mu = 10^{13}$ GeV
$m_\phi = \mu = 10^{10}$ GeV
$m_\phi = \mu = 10^{7}$ GeV
$m_\phi = \mu = 10^{4}$ GeV
Planck 18
CMB-S4
COrE/Euclid
CVL
LISA
BBO
uDECIGO
CE
ET
$\phi\phi \to hh$
$\phi \to \varphi\varphi h$
$\phi\varphi \to \varphi h$
$\varphi\varphi \to hh$
$\Omega_{\rm GW} h^2$
f [Hz]

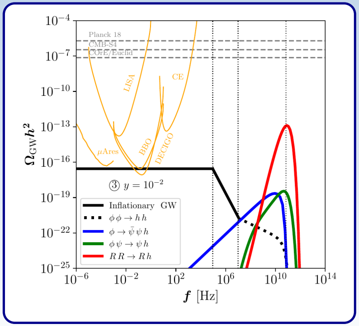
Summary

- CGWB = Cosmic Gravitational Wave Background
  - guaranteed background
  - the only assumption: the Universe was hot and dense
  - peaks at ~ 100 GHz
- Taking inflation into account
  - finite $T_{\max}$
  - transition from inflation $\to$ reheating $\to$ SM

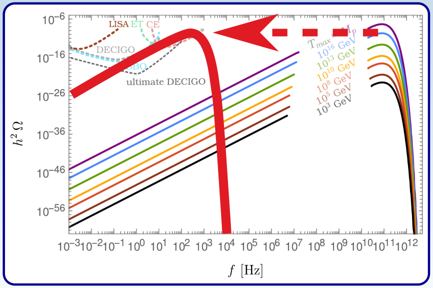


CMB CNB CGWB

Full-spectrum analysis



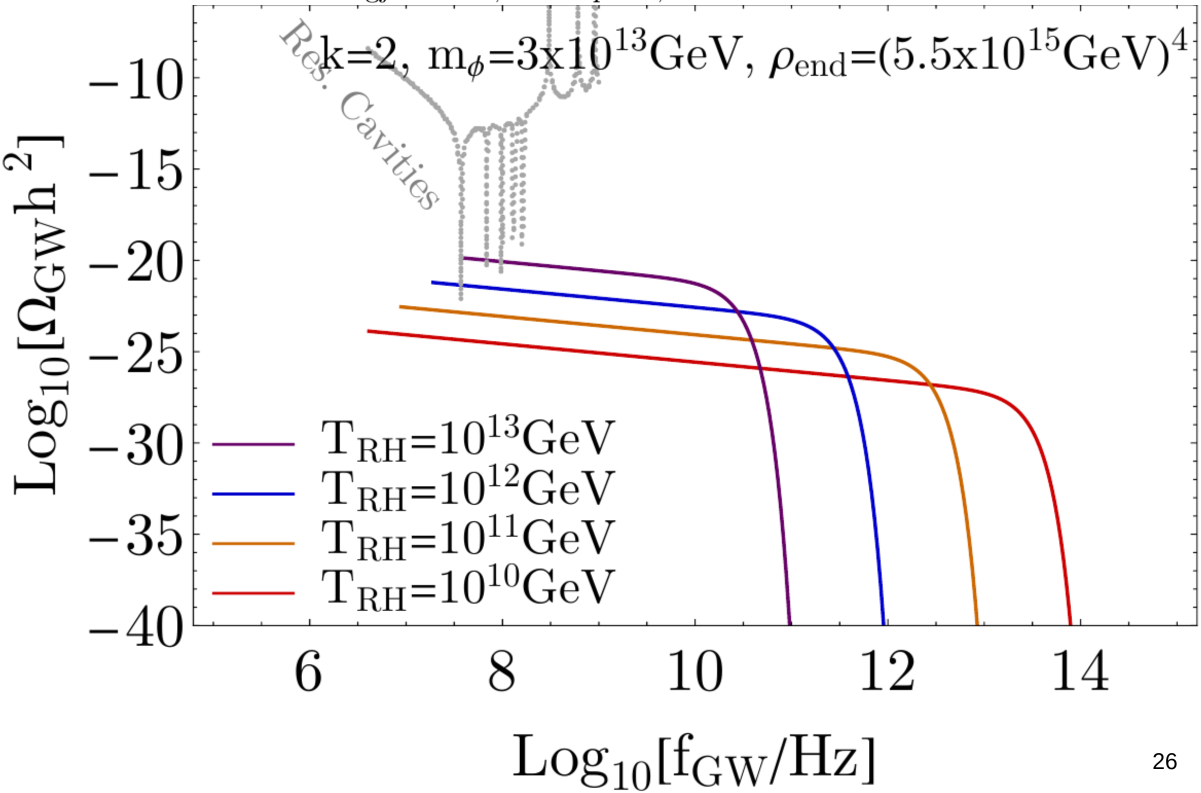
- If ... "cold&dense" ...
  - motivated/achieved by reheaton



Backup

Minimal Production of Prompt Gravitational Waves during Reheating

Gongjun Choi,* Wenqi Ke,† Keith A. Olive‡ 2402.04310



A slide taken from Carlos Tamarit's talk.

https://indico.cern.ch/event/1074510/contributions/4519382/

How to detect high-freq gravitational waves?

Direct searches

Interferometers [Nishizawa et al, Akutsu et al, Chou et al]

Cavity experiments measuring **rotation of polarization** [Cruise & Ingley]

Experiments measuring **resonant spin precession** of electrons [Ito et al]

Inverse Gertsenshtein effect: Partial conversion of gravitational waves into electromagnetic radiation

Can use **axion experiments** featuring photon-axion conversion! [Cruise, Ellji et al]

Indirect searches

Gertsenshtein effect can modify the **CMB** spectrum! [Domcke & Cely]