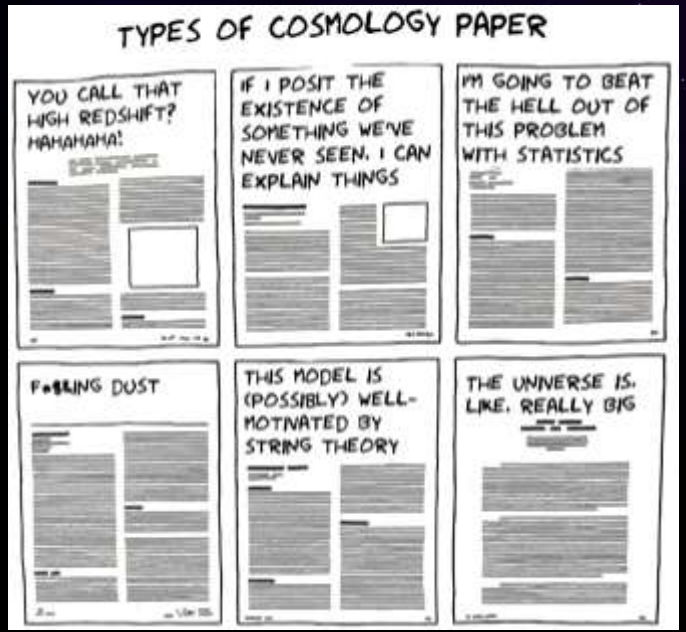
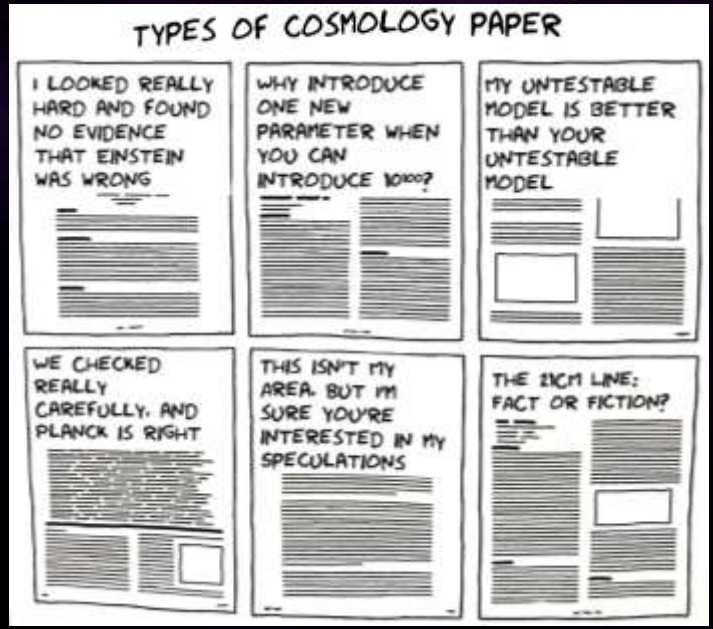
Secondary gravitational waves from cosmic inflation

Martin Teuscher with A. Barrau, R. Durrer & K. Martineau
based on arXiv **2510.00869** & **2512.14670**





[Credits: xkcd&unknown]

Common thread

Where should we seek direct probes of early Universe physics ?

Outline

01 **Motivations**

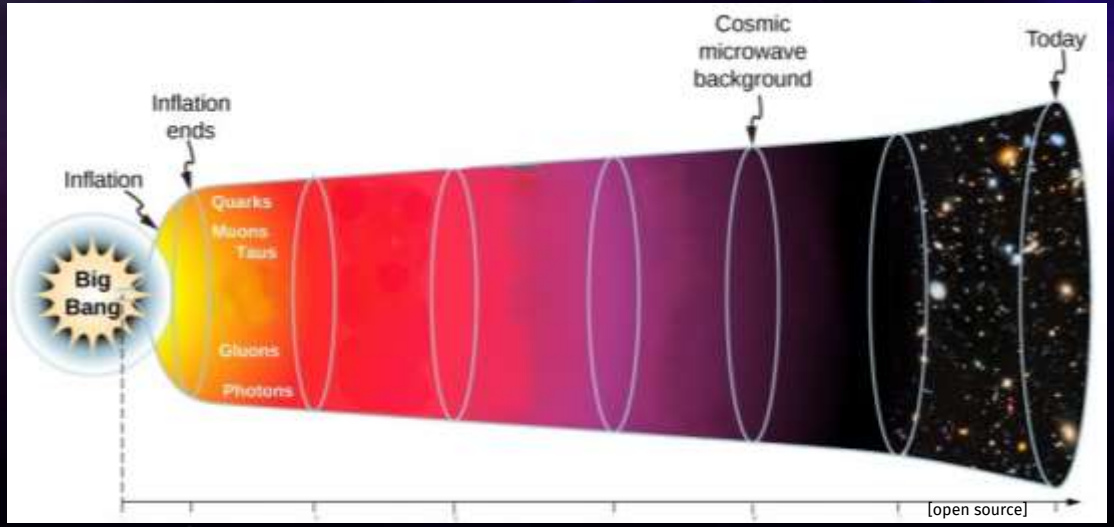
Cosmic inflation
Gravitational waves

02 General methodology

03 The E.M. field case

04 Opening : ongoing work

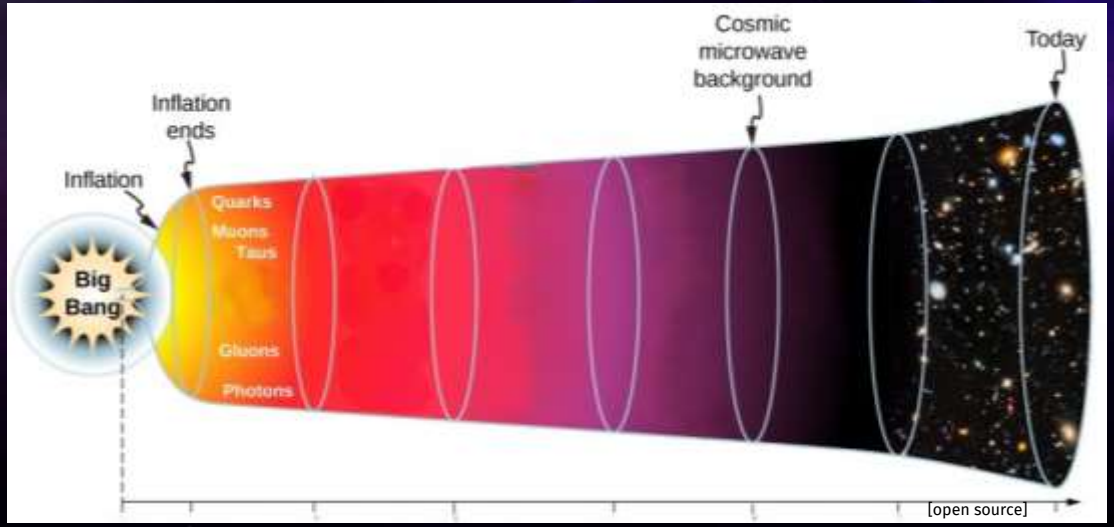
Inflation: a story of amplification



Timescale (seconds): 10^{-43} 10^{-35} 10^{+13} 10^{+17}

Universe size growth: 1 e^{60} e^{120}

Inflation: a story of amplification



Timescale (seconds): 10^{-43} 10^{-35} 10^{+13} 10^{+17}

Universe size growth: 1 e^{60} e^{120}

Same growth!

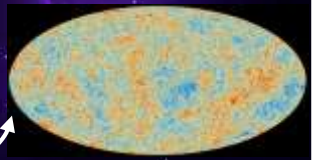
Inflation = extremely brutal event

Inflation: a story of amplification

***Why* inflation?**

- Solve flatness & horizon problems
- Explain origin of initial density fluctuations

Why this?

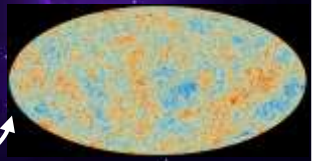


Inflation: a story of amplification

***Why* inflation?**

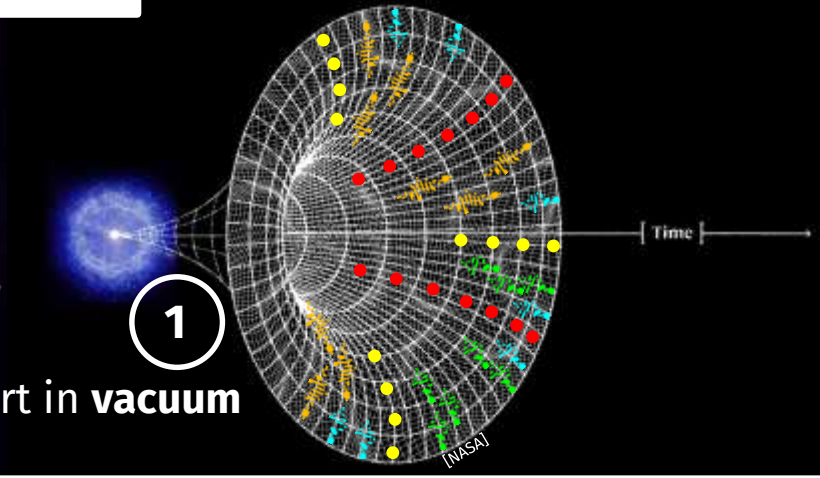
- Solve flatness & horizon problems
- Explain origin of initial density fluctuations

Why this?



***How* inflation?**

Number of particles NOT conserved in curved spacetimes!



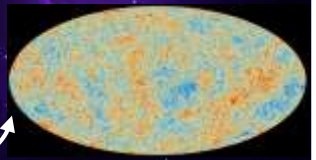
Start in **vacuum**

Inflation: a story of amplification

***Why* inflation?**

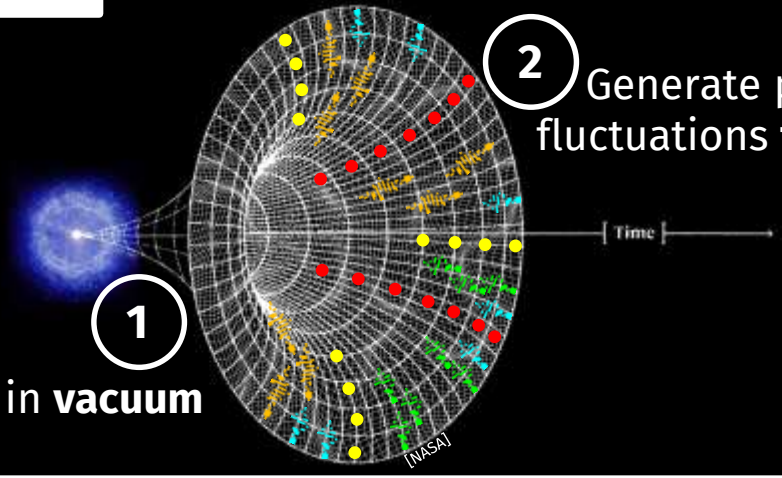
- Solve flatness & horizon problems
- Explain origin of initial density fluctuations

Why this?



***How* inflation?**

Number of particles NOT conserved in curved spacetimes!

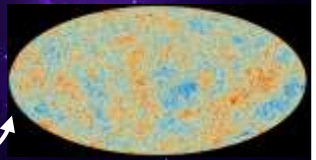


Inflation: a story of amplification

***Why* inflation?**

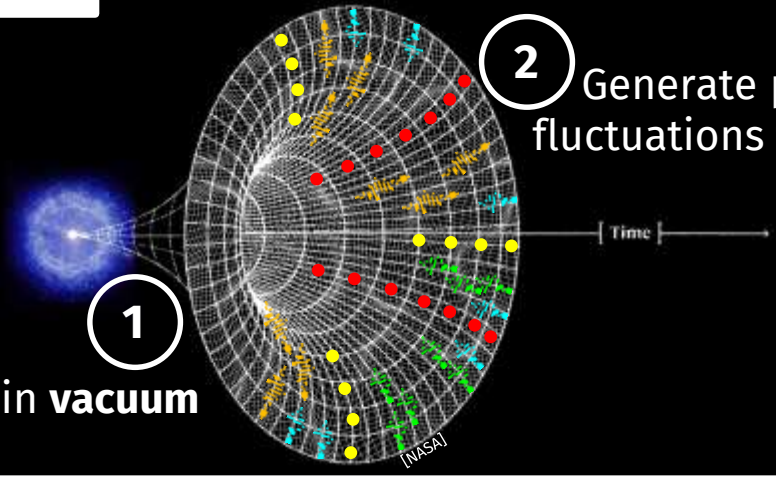
- Solve flatness & horizon problems
- Explain origin of initial density fluctuations

Why this?



***How* inflation?**

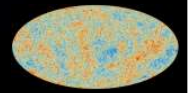
Number of particles NOT conserved in curved spacetimes!



1 Start in **vacuum**

2 Generate particles & fluctuations **from vacuum**

3 Later evolution

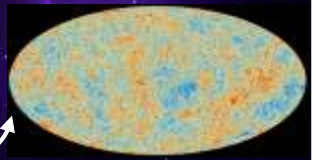


Inflation: a story of amplification

Why inflation?

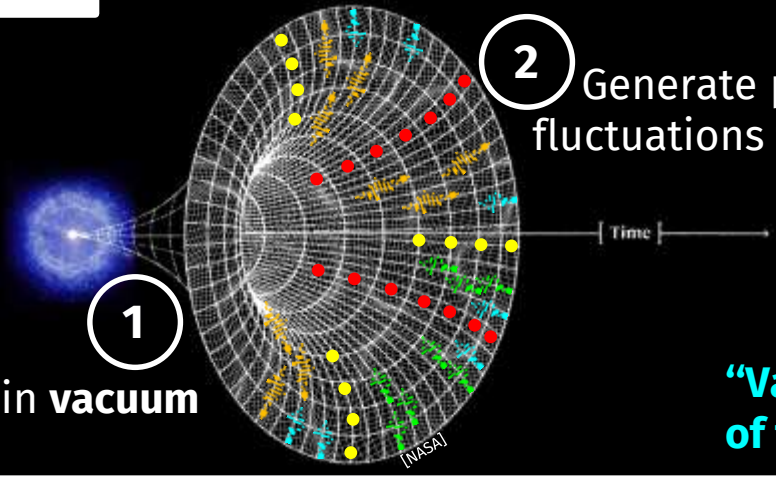
- Solve flatness & horizon problems
- Explain origin of initial density fluctuations

Why this?



How inflation?

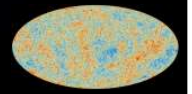
Number of particles NOT conserved in curved spacetimes!



1 Start in **vacuum**

2 Generate particles & fluctuations **from vacuum**

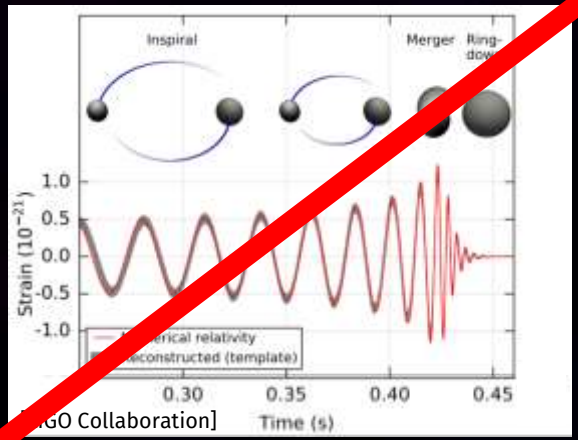
3 Later evolution



"Vacuum amplification" applies to many types of fluctuations... even gravitational waves!

Gravitational wave backgrounds

Astrophysical resolvable source

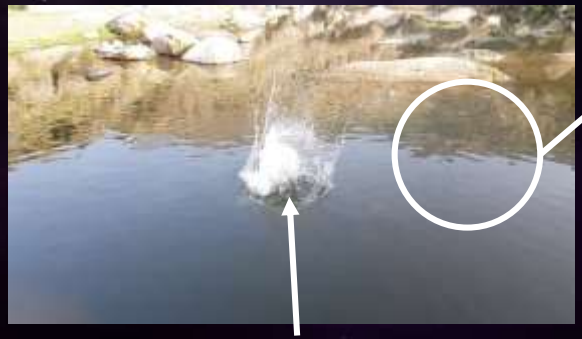


[LIGO Collaboration]

Background with **astrophysical & cosmological** contributions

Unresolvable sources: angular size in the sky $\Theta \sim 10^{-12}$ deg

Gravitational wave backgrounds

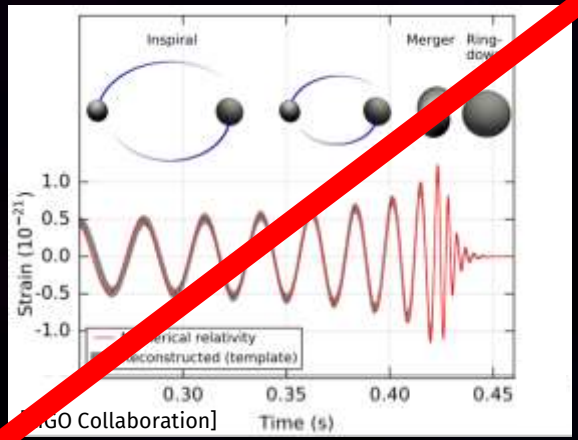


Astrophysical resolvable source

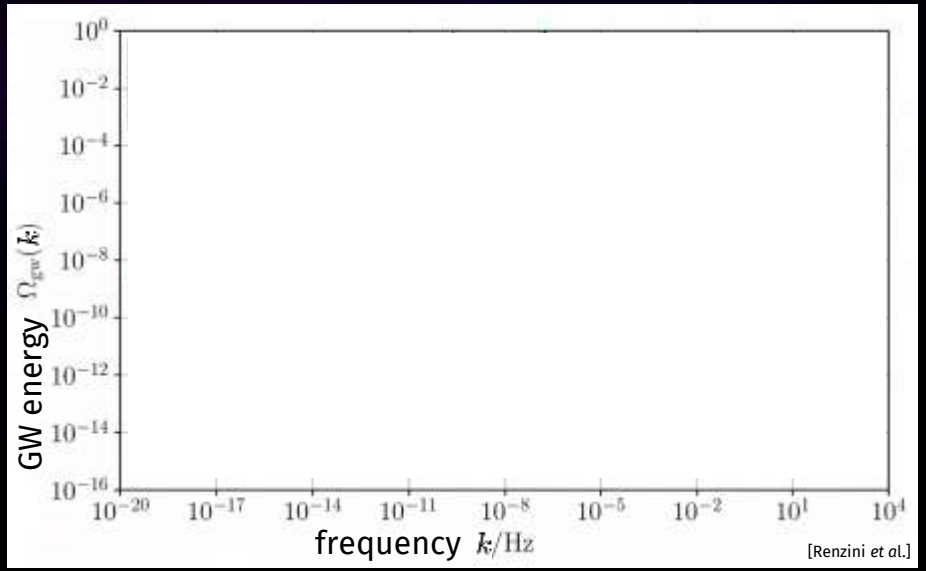
Background with **astrophysical & cosmological** contributions

Unresolvable sources: angular size in the sky $\Theta \sim 10^{-12}$ deg

GOAL: Average energy per GW frequency $\Omega_{gw}(k)$

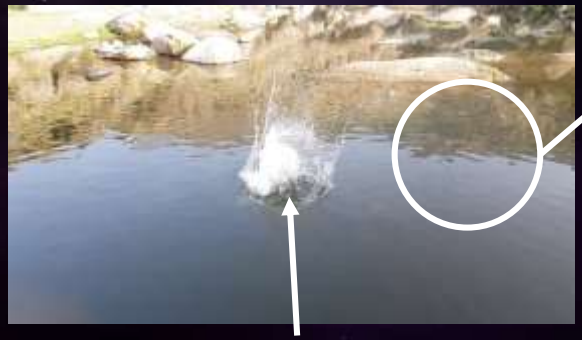


[LIGO Collaboration]

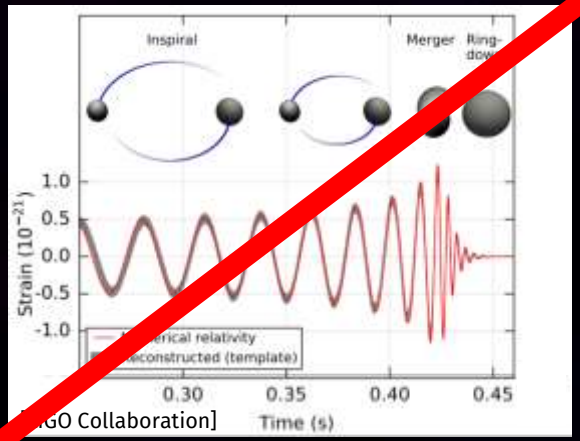


[Renzini *et al.*]

Gravitational wave backgrounds



Astrophysical resolvable source

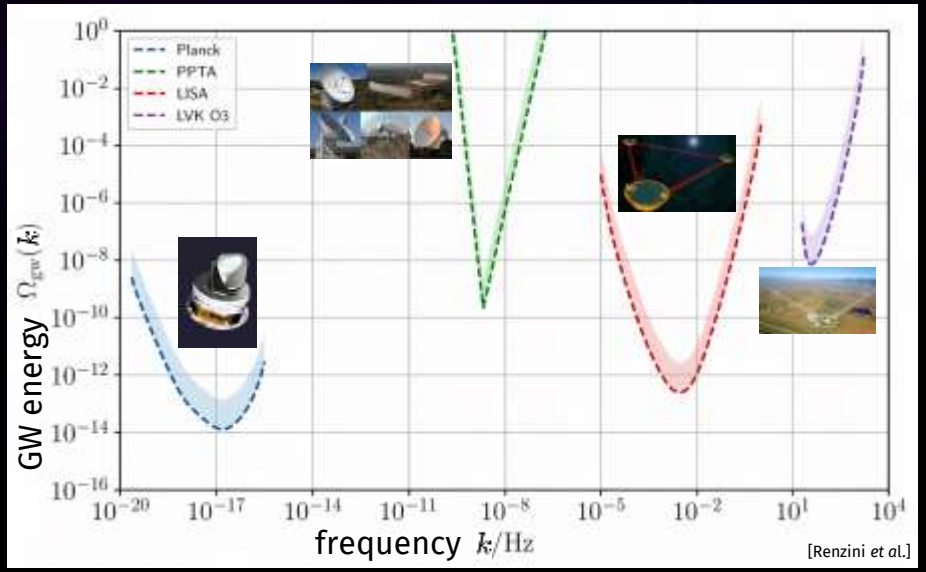


[LIGO Collaboration]

Background with **astrophysical & cosmological** contributions

Unresolvable sources: angular size in the sky $\Theta \sim 10^{-12}$ deg

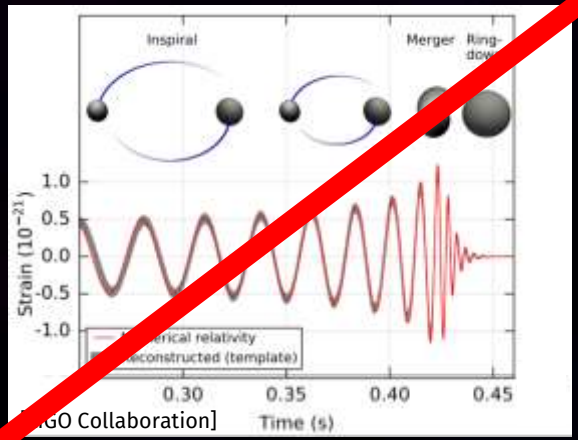
GOAL: Average energy per GW frequency $\Omega_{gw}(k)$



[Renzini *et al.*]

Gravitational wave backgrounds

Astrophysical resolvable source

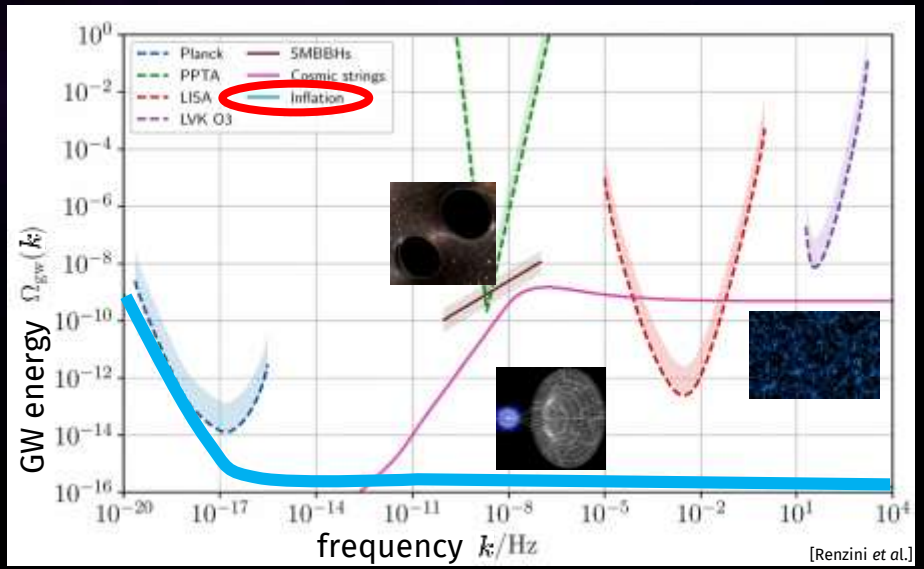


[LIGO Collaboration]

Background with **astrophysical & cosmological** contributions

Unresolvable sources: angular size in the sky $\Theta \sim 10^{-12}$ deg

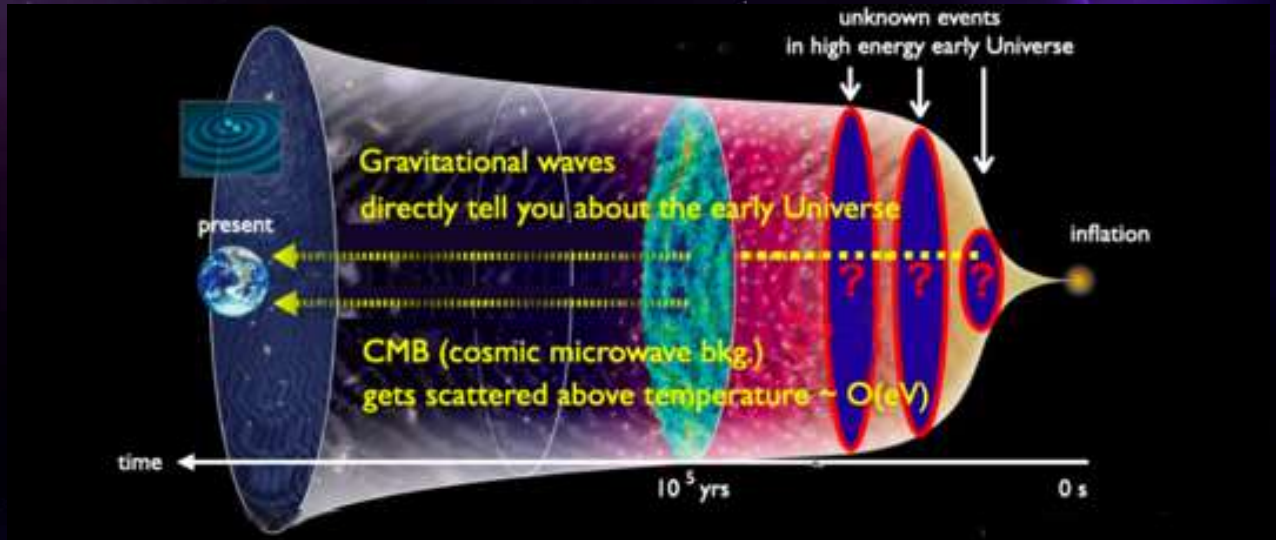
GOAL: Average energy per GW frequency $\Omega_{gw}(k)$



[Renzini *et al.*]

Why should cosmology care about primordial GW?

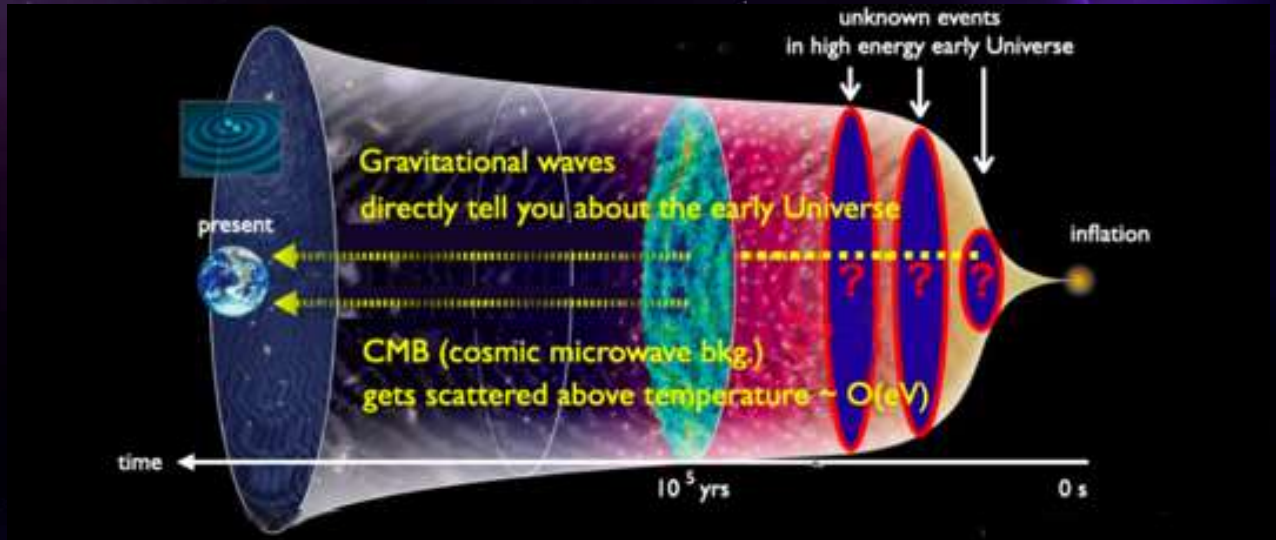
- **DIRECT probe of pre-CMB physics (!!!!)**



[https://gwpo.nao.ac.jp/en/gallery/00006 l .html]

Why should cosmology care about primordial GW?

- **DIRECT probe of pre-CMB physics (!!!!)**



[https://gwpo.nao.ac.jp/en/gallery/00006 l .html]

- *Qualitatively:* huge hint for **existence of inflation**
- *Quantitatively:* access to inflation **energy scale**

Outline

01 **Motivations**

Cosmic inflation
Gravitational waves

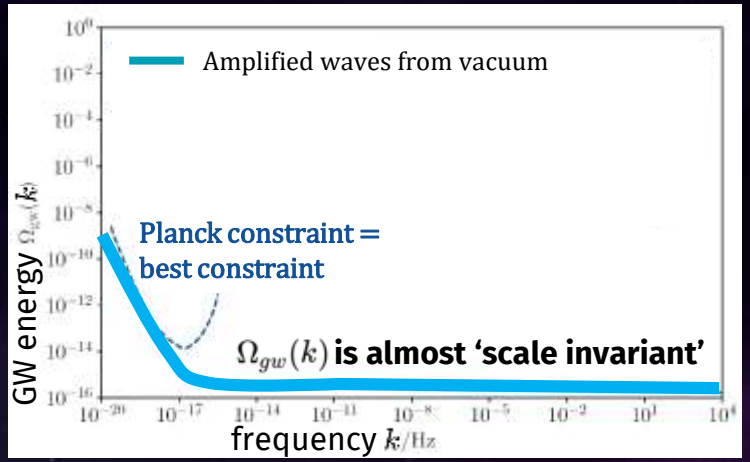
02 **General methodology**

Secondary sourced GW
Spectral index of GW signal

03 **The E.M. field case**

04 **Opening : ongoing work**

Our target?

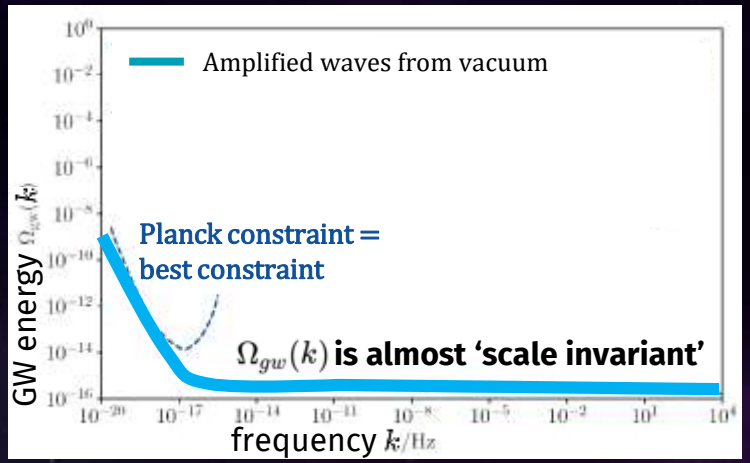


$$\Omega_{gw}^{\text{vacuum}}(k) \propto k^{n_T},\ n_T \simeq 0$$

Inflation

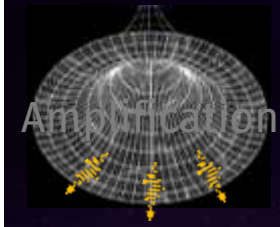
Gravitational waves production

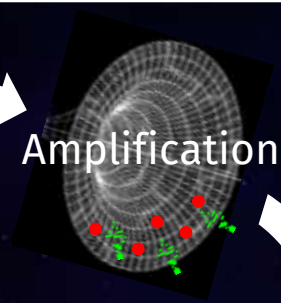
Our target: *sourced* gravitational waves



$$\Omega_{gw}^{\text{vacuum}}(k) \propto k^{n_T},\ n_T \simeq 0$$

Inflation



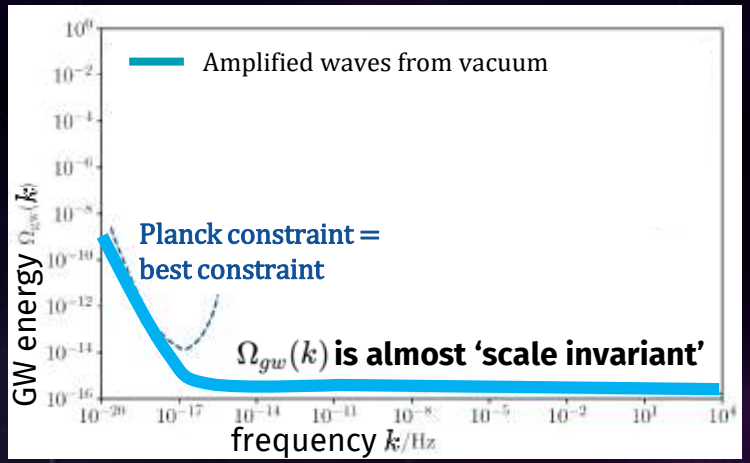


Density fluctuations of other contents (matter, radiation…)

General relativity equations

Gravitational waves production

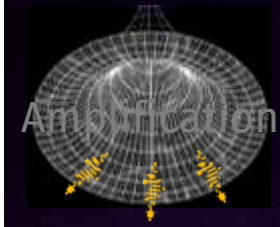
Our target: *sourced* gravitational waves

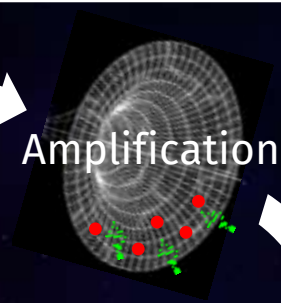


$$\Omega_{gw}^{\text{vacuum}}(k) \propto k^{n_T},\ n_T \simeq 0$$

- What is the new slope n_T ?
- Can we learn on the content?
- Is this detectable?

Inflation





Density fluctuations of other contents (matter, radiation…)

General relativity equations

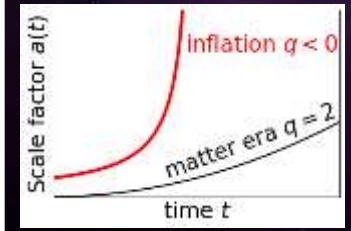
Gravitational waves production

General result on tensor index

- Existing literature: GW from specific source models
- Our work: simple formula valid for many source types!

General result on tensor index

Parameter q | Universe equation of state



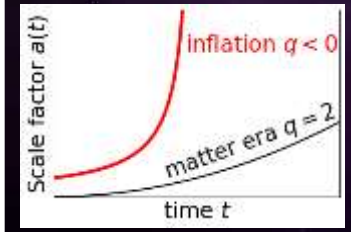
$$a(t) \propto t^q$$

Standard inflation:

$$q = -1$$

General result on tensor index

Parameter q Universe equation of state

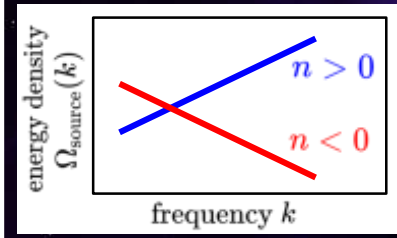


$$a(t) \propto t^q$$

Standard inflation:

$$q = -1$$

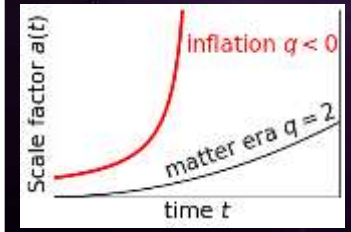
Parameter n Slope of source's spectrum



$$\Omega_{\text{source}}(k) \propto k^n$$

General result on tensor index

Parameter q Universe equation of state

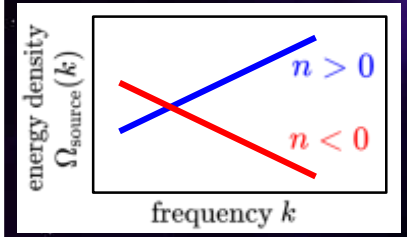


$$a(t) \propto t^q$$

Standard inflation:

$$q = -1$$

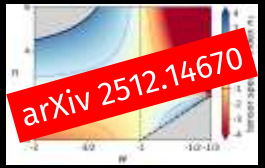
Parameter n Slope of source's spectrum



$$\Omega_{\rm source}(k) \propto k^n$$

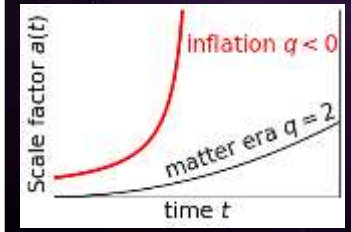
& few assumptions $\Longrightarrow$ $\Omega_{gw} \propto k^{n_T}$, $\boxed{n_T = 2(n-2)(q+1)}$

New!



General result on tensor index

Parameter q Universe equation of state

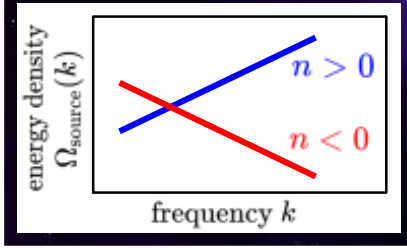


$$a(t) \propto t^q$$

Standard inflation:

$$q = -1$$

Parameter n Slope of source's spectrum

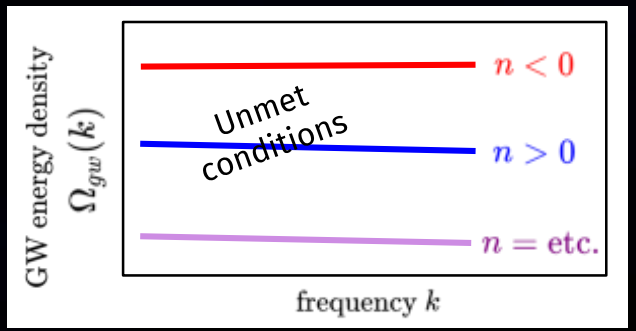


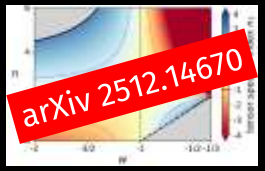
$$\Omega_{source}(k) \propto k^n$$

& few assumptions $\Longrightarrow$ $\Omega_{gw} \propto k^{n_T}$, $\boxed{n_T = 2(n-2)(q+1)}$

New!

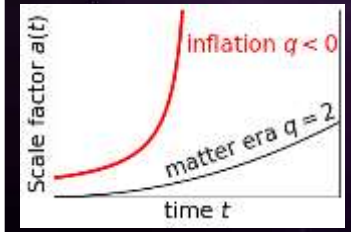
$$n_T \simeq 0 \; \forall n \; !!$$





General result on tensor index

Parameter q Universe equation of state

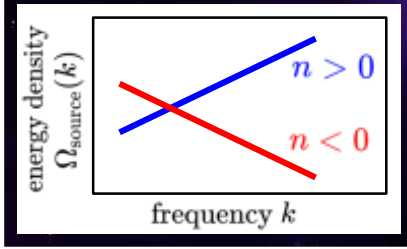


$$a(t) \propto t^q$$

Standard inflation:

$$q = -1$$

Parameter n Slope of source's spectrum

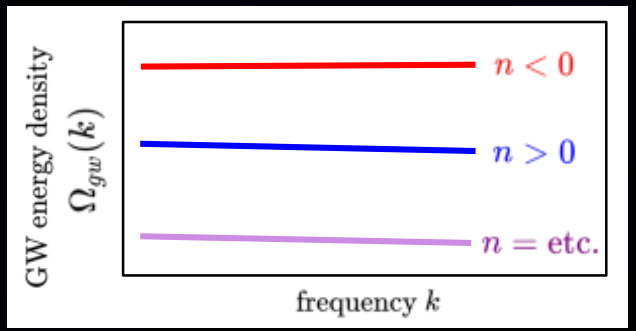


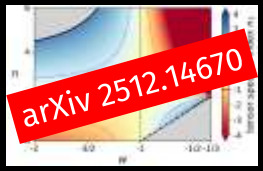
$$\Omega_{source}(k) \propto k^n$$

& few assumptions $\Longrightarrow$ $\Omega_{gw} \propto k^{n_T}$, $\boxed{n_T = 2(n-2)(q+1)}$

New!

$$n_T \simeq 0 \; \forall n \; !!$$





We have slope.
Next step: AMPLITUDE ➔

Outline

01 **Motivations**

Cosmic inflation
Gravitational waves

02 **General methodology**

Secondary sourced GW
Spectral index of GW signal

03 **The E.M. field case**

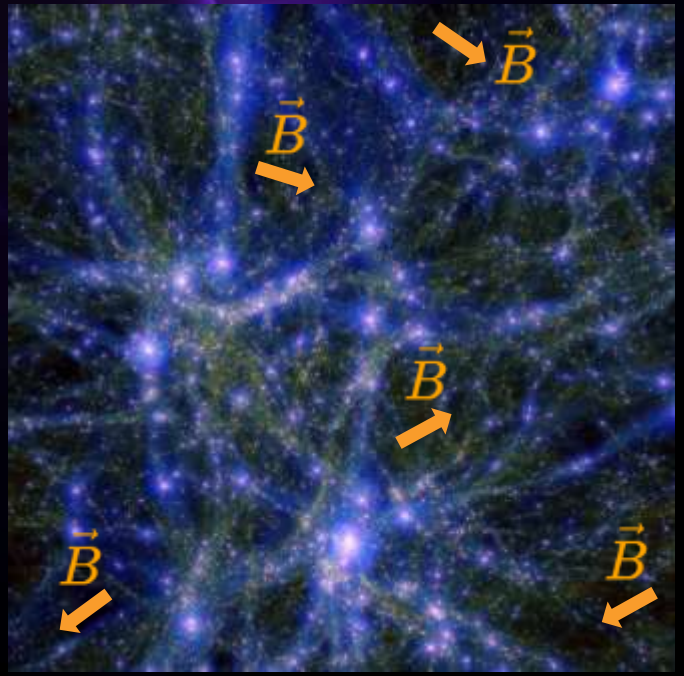
Electromagnetic amplification
Amplitude of GW signal

04 **Opening : ongoing work**

Cosmological magnetic fields

- Evidence for magnetic fields in the intergalactic ***voids*** (from light deviation)

  $\Longrightarrow$ primordial origin?

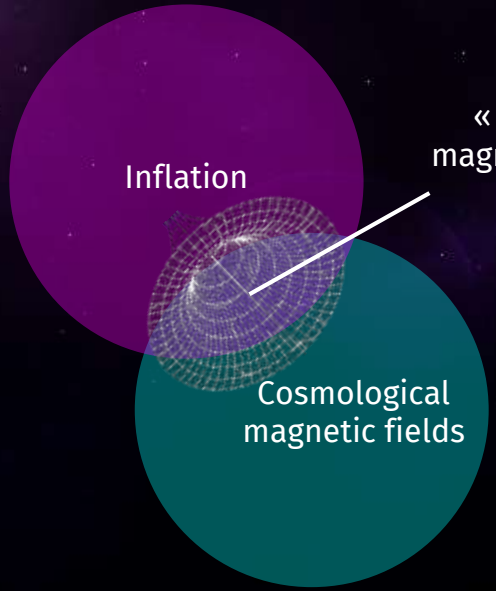


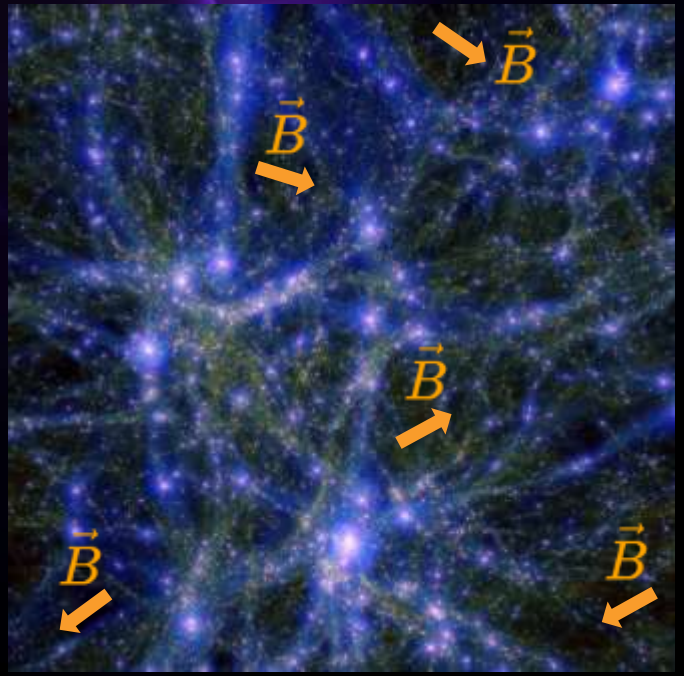
$|B| > 10^{-15}\mathrm{G}$ $\lambda_B \sim \mathrm{Mpc}$

Cosmological magnetic fields

- Evidence for magnetic fields in the intergalactic ***voids*** (from light deviation)

  $\Longrightarrow$ primordial origin?



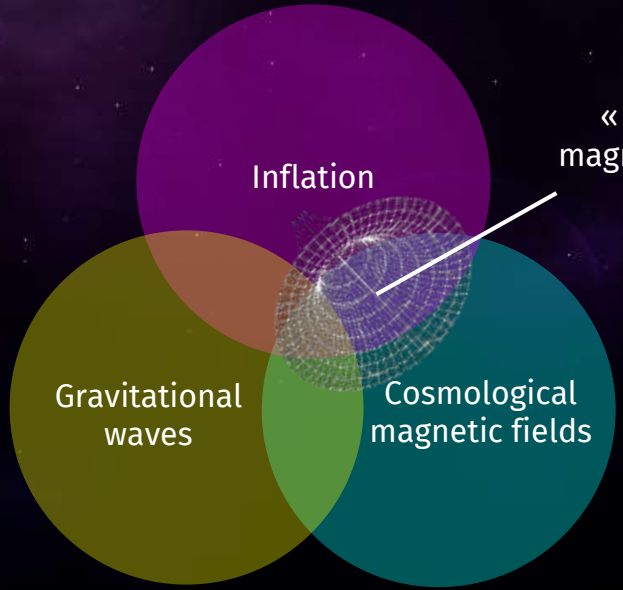


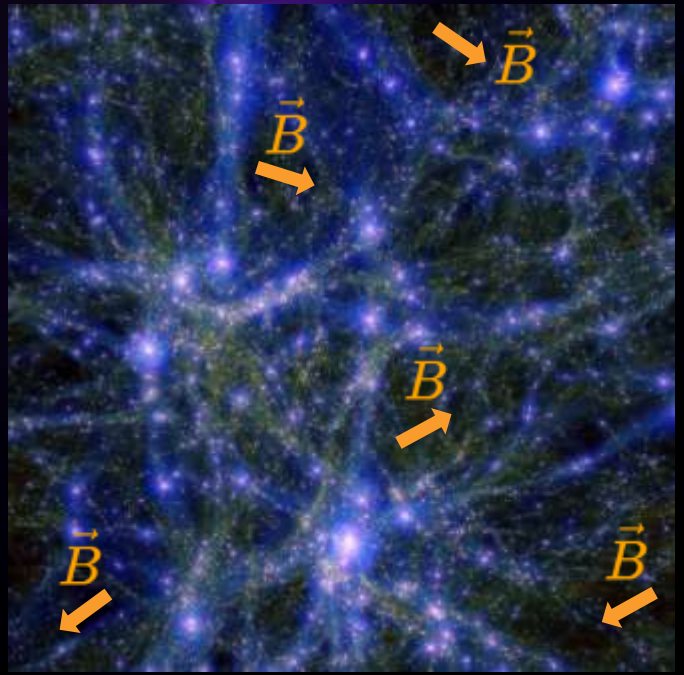
$|B| > 10^{-15}\mathrm{G}$ $\lambda_B \sim \mathrm{Mpc}$

Cosmological magnetic fields

- Evidence for magnetic fields in the intergalactic ***voids*** (from light deviation)

$\Longrightarrow$ primordial origin?



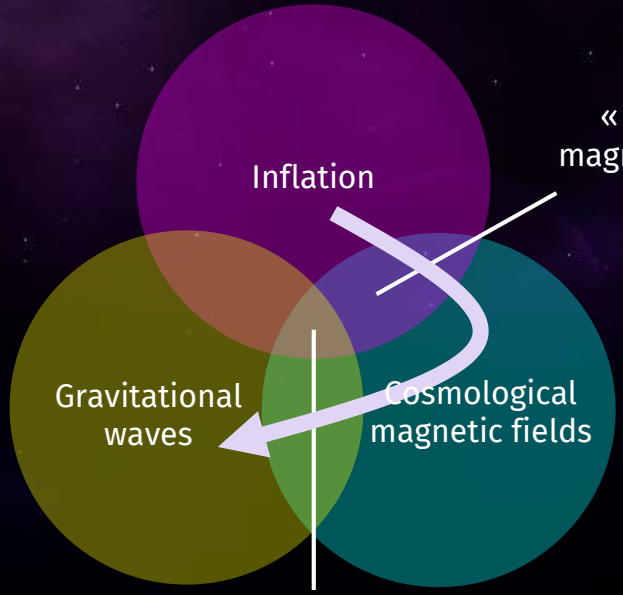


$|B| > 10^{-15}\mathrm{G}$ $\lambda_B \sim \mathrm{Mpc}$

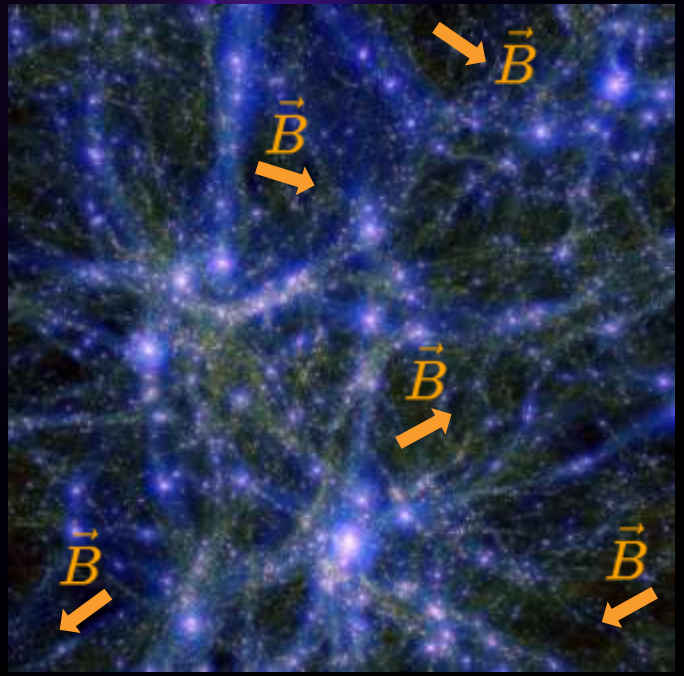
Cosmological magnetic fields

- Evidence for magnetic fields in the intergalactic ***voids*** (from light deviation)

$\Longrightarrow$ primordial origin?



GW signal produced by primordial magnetic fields ➔ combined direct probes



$|B| > 10^{-15}\mathrm{G}$ $\lambda_B \sim \mathrm{Mpc}$

To amplify or not to amplify, that is the question

Content description:

$$S = \int \sqrt{-g}\mathrm{d}^4x \left[\mathcal{L}(\phi) \right]$$

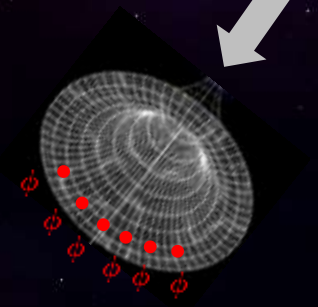
spacetime geometry inflaton

To amplify or not to amplify, that is the question

Content description:

$$S = \int \sqrt{-g}\mathrm{d}^4x \left[\mathcal{L}(\phi)\right]$$

spacetime geometry — inflaton

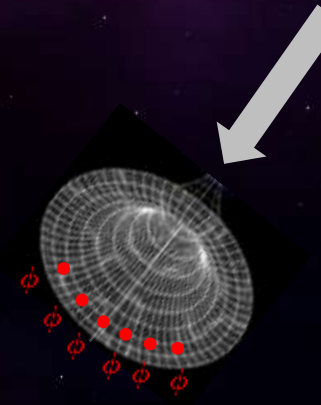


To amplify or not to amplify, that is the question

Content description:

$$S = \int \sqrt{-g}\mathrm{d}^4x \left[\mathcal{L}(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}\right]$$

spacetime geometry | inflaton | electromagnetism

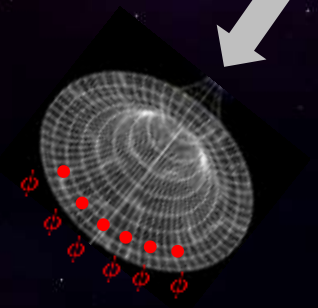


To amplify or not to amplify, that is the question

Content description:

$$S = \int \sqrt{-g}\mathrm{d}^4x \left[\mathcal{L}(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}\right]$$

spacetime geometry | inflaton | electromagnetism



No amplification!

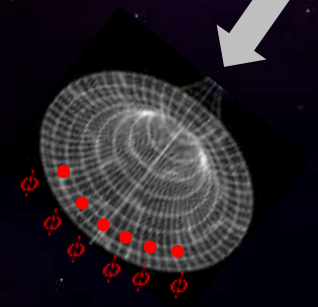
« Conformal invariance (in 4D) »
Specific to force carriers

To amplify or not to amplify, that is the question

Content description:

$$S = \int \sqrt{-g}\mathrm{d}^4x \left[\mathcal{L}(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}i_1(\phi)F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}i_2(\phi)(\star F)_{\mu\nu}F^{\mu\nu}\right]$$

spacetime geometry | inflaton | electromagnetism | “kinetic” coupling | “chiral” coupling



No amplification!

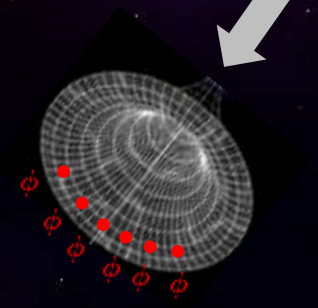
« Conformal invariance (in 4D) »
Specific to force carriers

To amplify or not to amplify, that is the question

Content description:

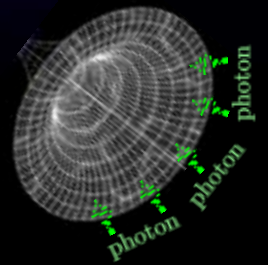
$$S = \int \sqrt{-g}\mathrm{d}^4x \left[\mathcal{L}(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}i_1(\phi)F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}i_2(\phi)(\star F)_{\mu\nu}F^{\mu\nu}\right]$$

spacetime geometry | inflaton | electromagnetism | "kinetic" coupling | "chiral" coupling



No amplification!

« Conformal invariance (in 4D) »
Specific to force carriers



Coupling-dependent amplification!

Model's parameters

Couplings $i_1(\phi), i_2(\phi) \longrightarrow$ trade for 2 real parameters:

Model's parameters

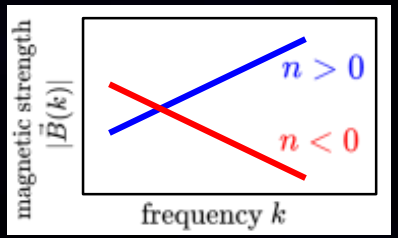
Couplings $i_1(\phi), i_2(\phi) \longrightarrow$ trade for 2 real parameters:

$$-1 \leqslant n < 3$$

Controls spectral index

Magnetic field:

$$|\vec{B}(k)|^2 \propto k^n$$



Model's parameters

Couplings $i_1(\phi), i_2(\phi) \longrightarrow$ trade for 2 real parameters:

$$-1 \leqslant n < 3$$

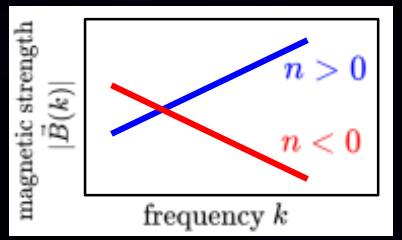
Controls spectral index

$$\gamma_2 \in \mathbb{R}$$

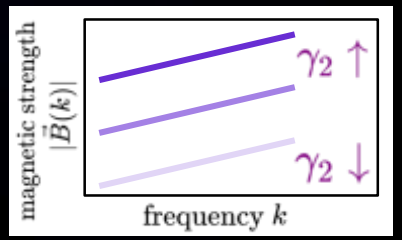
Controls polarization and amplitude

Magnetic field:

$$|\vec{B}(k)|^2 \propto k^n$$



$$|\vec{B}^+(k)|^2 - |\vec{B}^-(k)|^2 \propto \exp(\gamma_2)$$



Model's parameters

Couplings $i_1(\phi), i_2(\phi) \longrightarrow$ trade for 2 real parameters:

$$-1 \leqslant n < 3$$

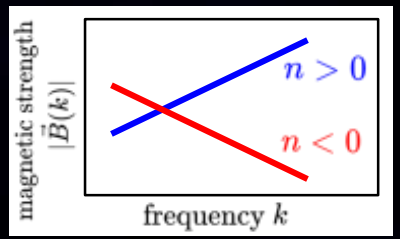
Controls spectral index

$$\gamma_2 \in \mathbb{R}$$

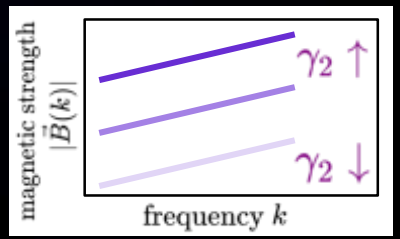
Controls polarization and amplitude

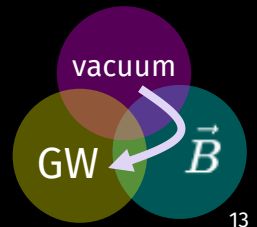
Magnetic field:

$$|\vec{B}(k)|^2 \propto k^n$$



$$|\vec{B}^+(k)|^2 - |\vec{B}^-(k)|^2 \propto \exp(\gamma_2)$$

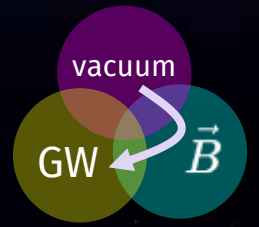




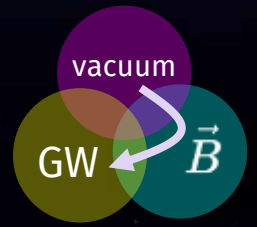
GOAL: constrain these parameters from the generated GW background!

1 – Model predictions

- **Polarized** gravitational waves

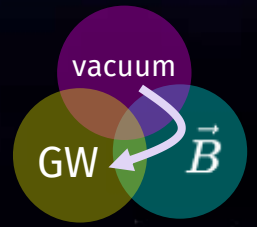


1 – Model predictions

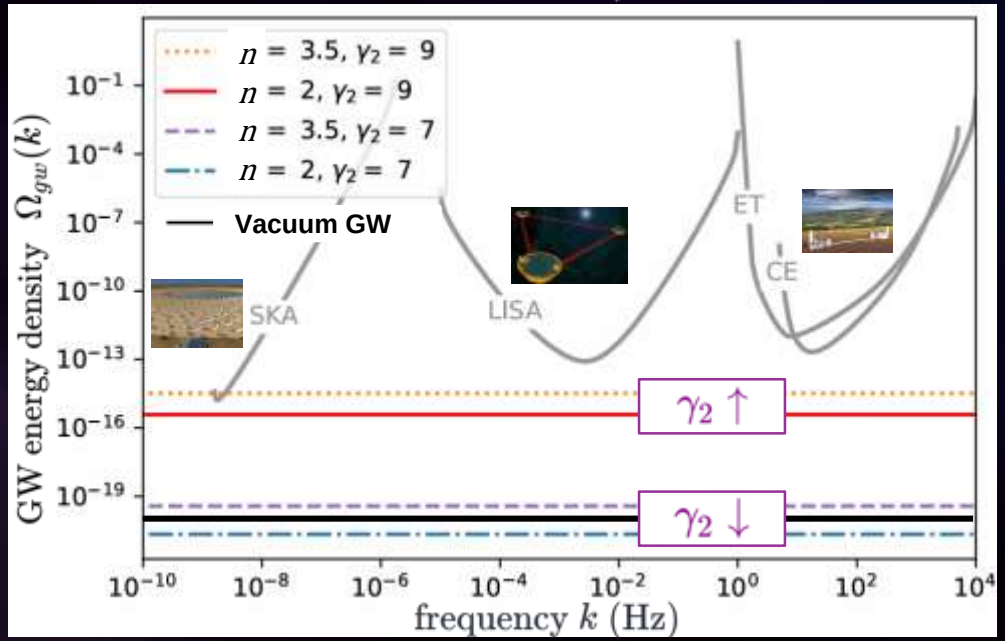


- **Polarized** gravitational waves
- **Exponentially enhanced** amplitude

1 – Model predictions

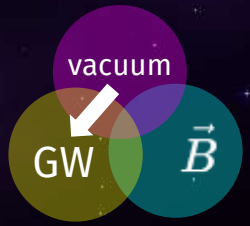


- **Polarized** gravitational waves
- **Exponentially enhanced** amplitude
- Confirmation of general law: **near scale-invariance** $\forall\, n$ (source spectrum slope)



3 – Secondary v.s. primary background

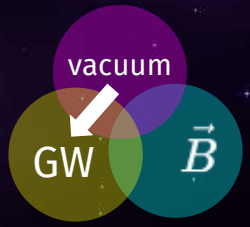
Standard inflation:



$$\Omega_{gw} \propto \left(E_{\text{inflation}}/E_{\text{Planck}}\right)^2$$

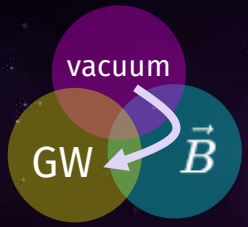
3 – Secondary v.s. primary background

Standard inflation:



$$\Omega_{gw} \propto \left(E_{\text{inflation}}/E_{\text{Planck}}\right)^2$$

Here:

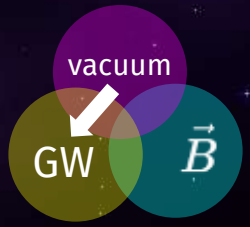


$$\Omega_{gw} \propto \left(E_{\text{inflation}}/E_{\text{Planck}}\right)^4$$

Naively less signal, but exponential boost can compensate and even reverse this trend!

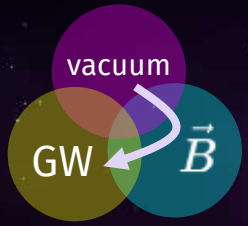
3 – Secondary v.s. primary background

Standard inflation:



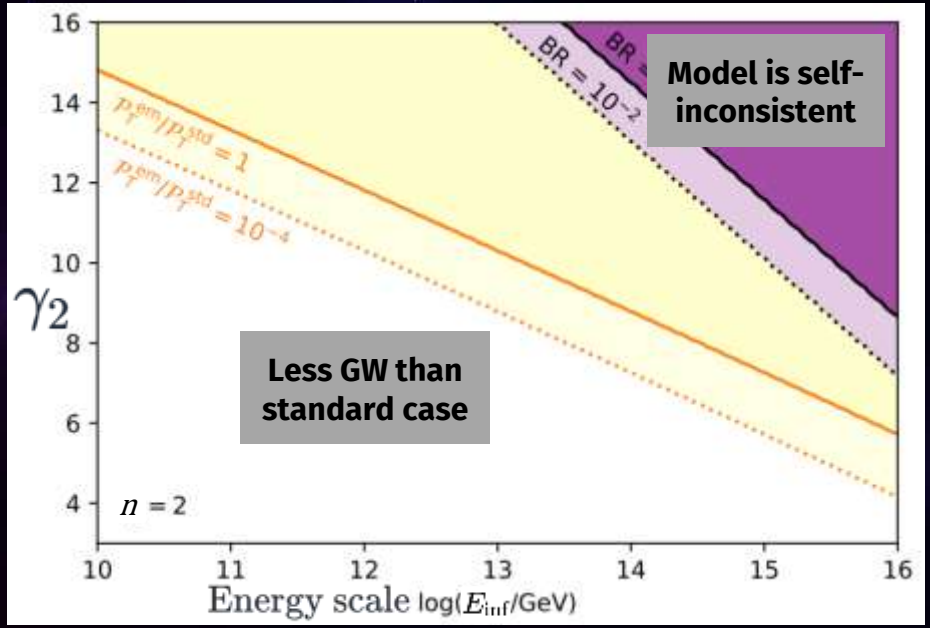
$$\Omega_{gw} \propto \left(E_{\text{inflation}}/E_{\text{Planck}}\right)^2$$

Here:



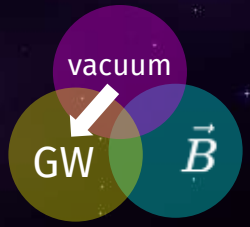
$$\Omega_{gw} \propto \left(E_{\text{inflation}}/E_{\text{Planck}}\right)^4$$

Naively less signal, but exponential boost can compensate and even reverse this trend!



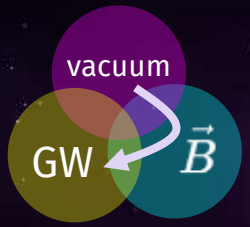
3 – Secondary v.s. primary background

Standard inflation:



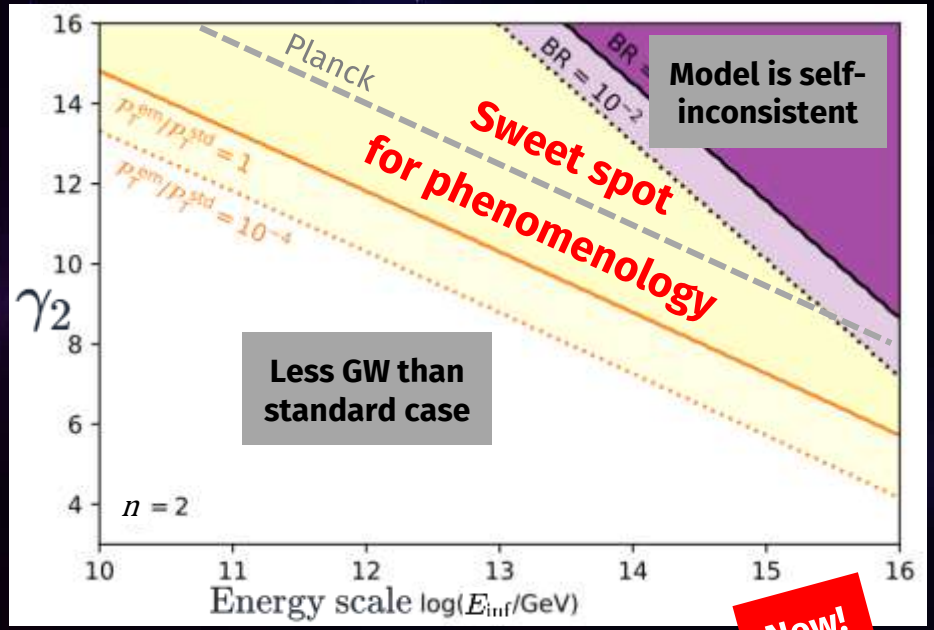
$$\Omega_{gw} \propto \left(E_{\text{inflation}}/E_{\text{Planck}}\right)^2$$

Here:



$$\Omega_{gw} \propto \left(E_{\text{inflation}}/E_{\text{Planck}}\right)^4$$

Naively less signal, but exponential boost can compensate and even reverse this trend!



JCAP 03 (2026) 43

Conclusion

Take-away 1	Gravitational waves = powerful **direct probes**

Conclusion

Take-away 1 Gravitational waves = powerful **direct probes**

Take-away 2 **New formula** to estimate GW slope index

$n_T = 2(n-2)(q+1) \longrightarrow$ great for model building

Conclusion

Take-away 1 Gravitational waves = powerful **direct probes**

Take-away 2 **New formula** to estimate GW slope index

$n_T = 2(n-2)(q+1)$ $\longrightarrow$ great for model building

Take-away 3 Do not under-estimate **secondary GW**!

Can easily overcome the standard GW signal

Outline

01 Motivations

Cosmic inflation
Gravitational waves

02 General methodology

Secondary sourced GW
Spectral index of GW signal

03 The E.M. field case

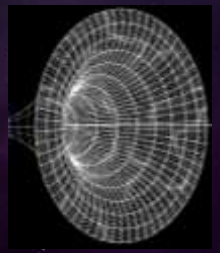
Electromagnetic amplification
Amplitude of GW signal

04 Opening : ongoing work

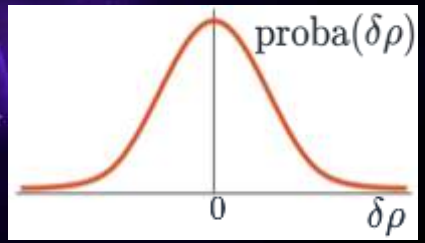
Cosmic voids
Graviton emission

Cosmic voids

Inflation



Initial density fluctuations of matter



$\delta\rho > 0$

Collapse

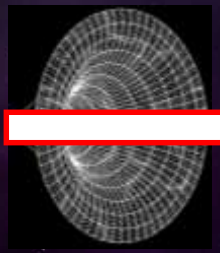
$\delta\rho < 0$

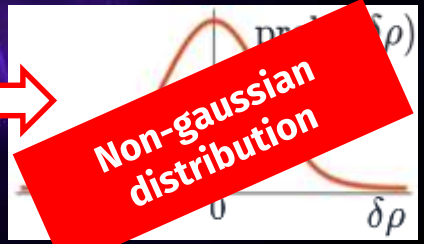
Clusters abundance

Voids abundance

Cosmic voids

Realistic inflation





Non-gaussian distribution

$\delta\rho > 0$

Collapse

$\delta\rho < 0$

Clusters abundance

Voids abundance

Ongoing work: apply advanced **random walk theory** to correct abundances, accounting for **non-perturbative non-gaussianities**

Quantum emission of gravitational waves

Light $\Leftrightarrow$ photons $\longrightarrow$ GW $\Leftrightarrow$ gravitons

Quantum emission of gravitational waves

- Light $\Leftrightarrow$ photons $\longrightarrow$ GW $\Leftrightarrow$ gravitons
- Semi-classical **number of gravitons:** $N_\omega = \dfrac{\text{signal energy}}{\text{quanta energy}} \propto \dfrac{\Omega_{gw}^{\text{classical}}(\omega)}{\hbar\omega}$

$\Longrightarrow N_\omega \sim 10^{35}$! Classical description valid ✓

Quantum emission of gravitational waves

- Light $\Leftrightarrow$ photons $\longrightarrow$ GW $\Leftrightarrow$ gravitons
- Semi-classical **number of gravitons:** $N_\omega = \dfrac{\text{signal energy}}{\text{quanta energy}} \propto \dfrac{\Omega_{gw}^{\text{classical}}(\omega)}{\hbar\omega}$

$\Longrightarrow N_\omega \sim 10^{35}$! Classical description valid ✓

- But: high frequency $\omega \Longrightarrow$ **LOW** $N_\omega \Longrightarrow$ needs proper quantum formalism

Quantum emission of gravitational waves

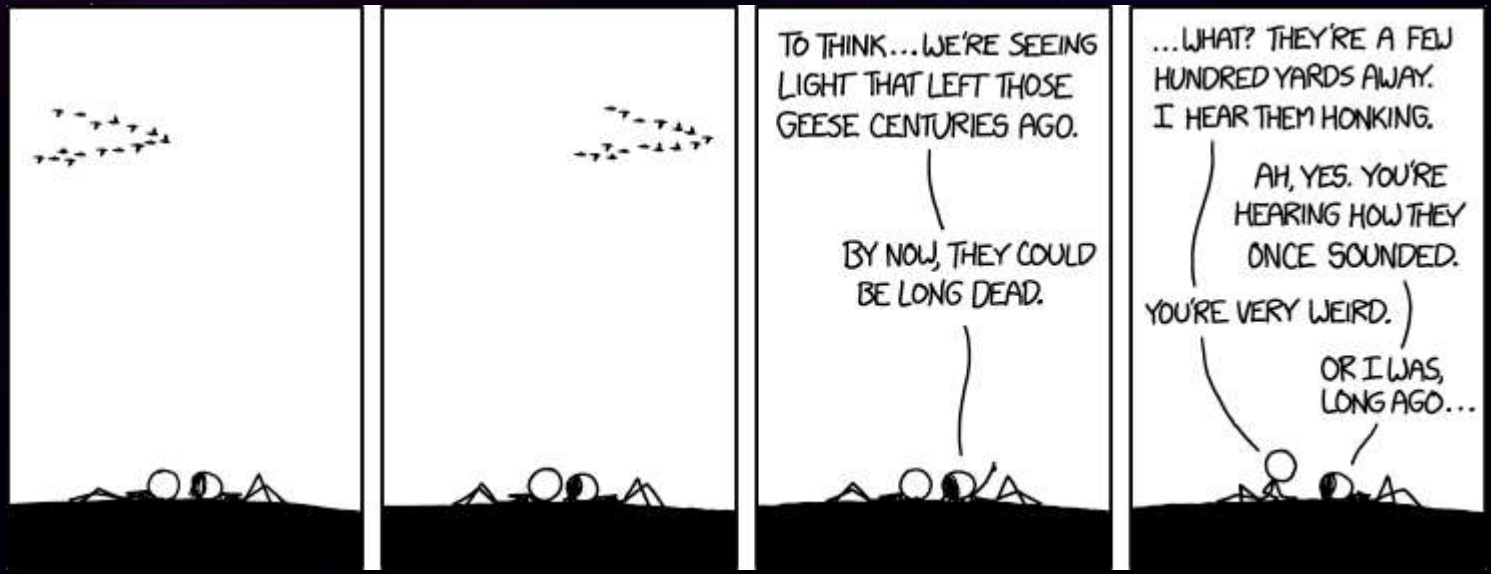
- Light $\Leftrightarrow$ photons $\longrightarrow$ GW $\Leftrightarrow$ gravitons
- Semi-classical **number of gravitons:** $N_\omega = \dfrac{\text{signal energy}}{\text{quanta energy}} \propto \dfrac{\Omega_{gw}^{\text{classical}}(\omega)}{\hbar\omega}$

$\Longrightarrow N_\omega \sim 10^{35}$! Classical description valid ✓

- But: high frequency $\omega \Longrightarrow$ **LOW** $N_\omega \Longrightarrow$ needs proper quantum formalism

Ongoing work: using formalism from **quantum optics** (Glauber), can we **reproduce semi-classical graviton number**?

Thank you!


TO THINK... WE'RE SEEING LIGHT THAT LEFT THOSE GEESE CENTURIES AGO.
BY NOW, THEY COULD BE LONG DEAD.
...WHAT? THEY'RE A FEW HUNDRED YARDS AWAY. I HEAR THEM HONKING.
AH, YES. YOU'RE HEARING HOW THEY ONCE SOUNDED.
YOU'RE VERY WEIRD.
OR I WAS, LONG AGO...

[BACK UP SLIDES WERE REMOVED FROM THIS VERSION]