Probing High Energy Particle Physics with Gravitational Waves

Jan Schütte-Engel
March 25 2024

The Future of High Energy Physics: A New Generation, A New Vision
Aspen Center for Physics

Berkeley UNIVERSITY OF CALIFORNIA
N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries PHYSICS FRONTIER CENTER
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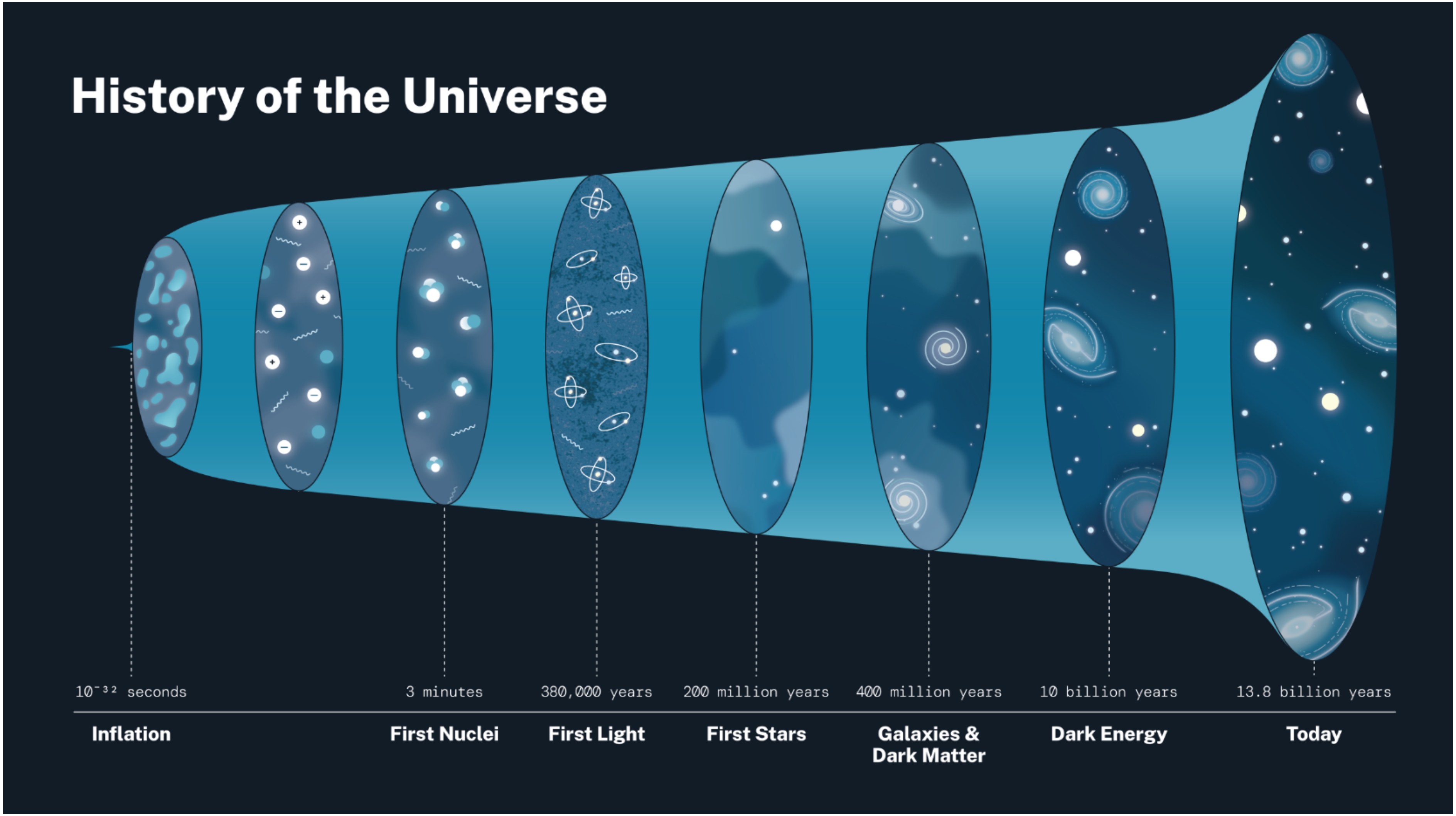
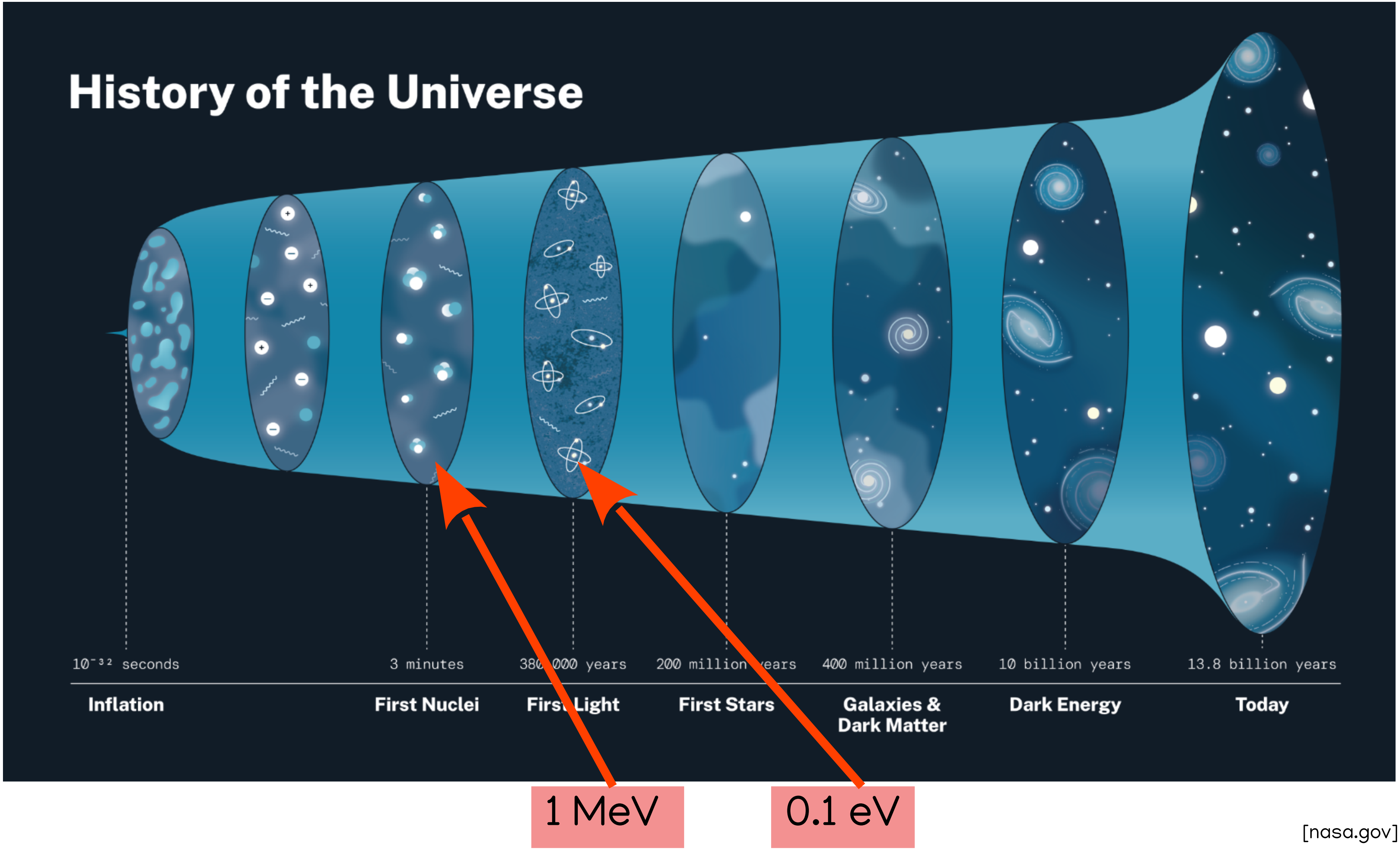

History of the Universe
10^{-32} seconds
3 minutes
380,000 years
200 million years
400 million years
10 billion years
13.8 billion years
Inflation
First Nuclei
First Light
First Stars
Galaxies & Dark Matter
Dark Energy
Today

[nasa.gov]



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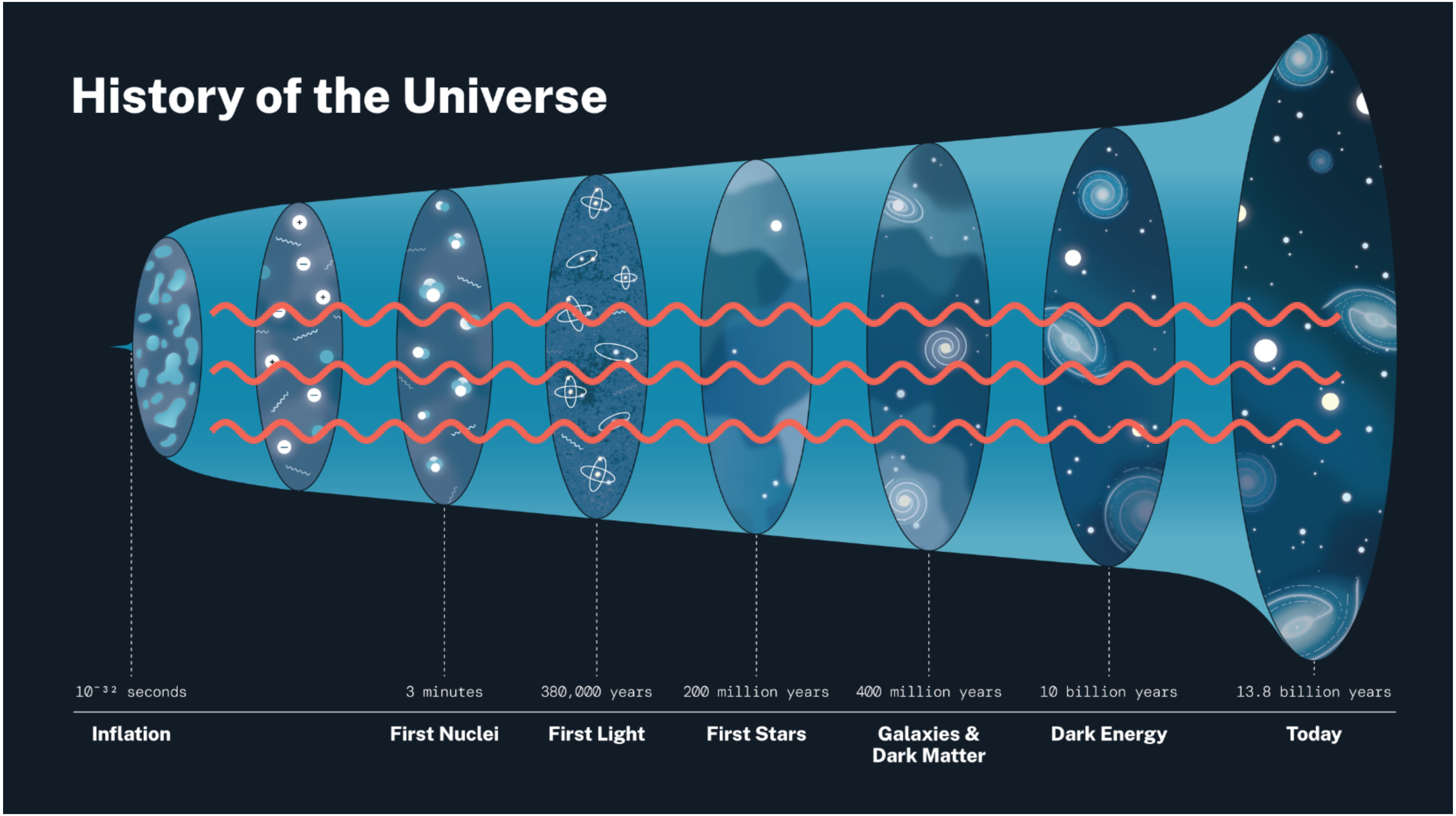
1 MeV
0.1 eV

[nasa.gov]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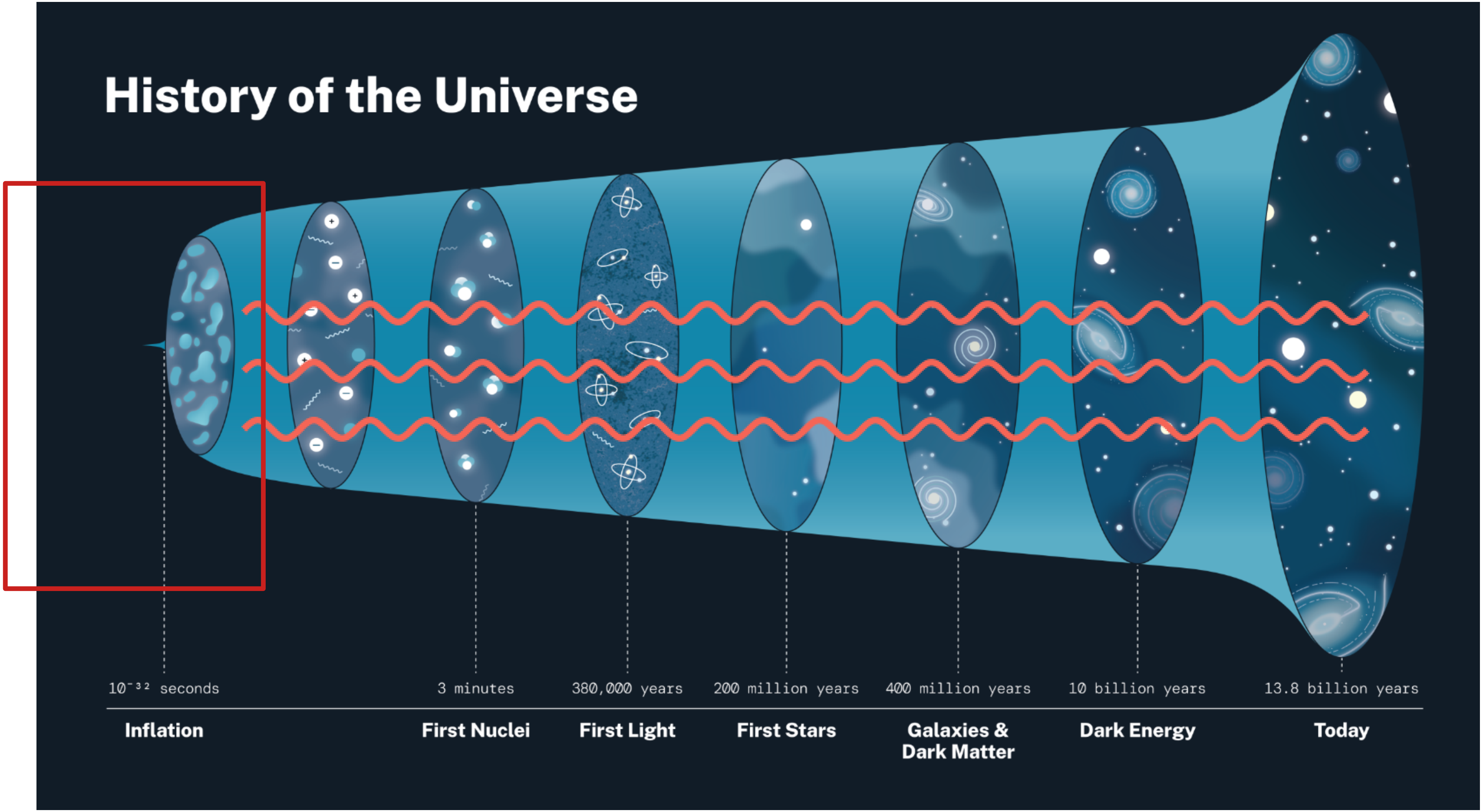
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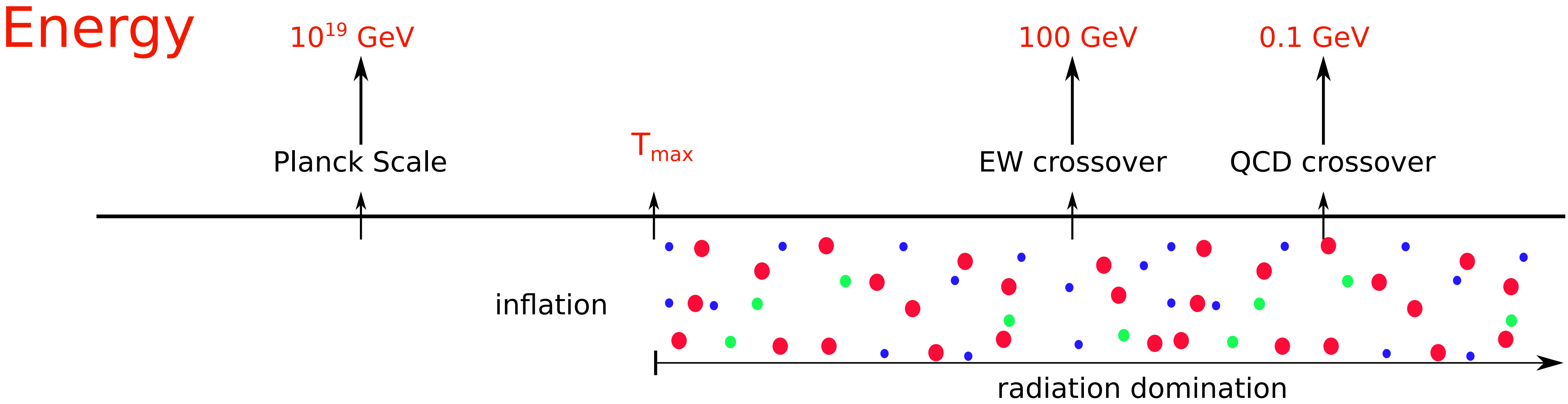
[nasa.gov]

GWs from the early universe



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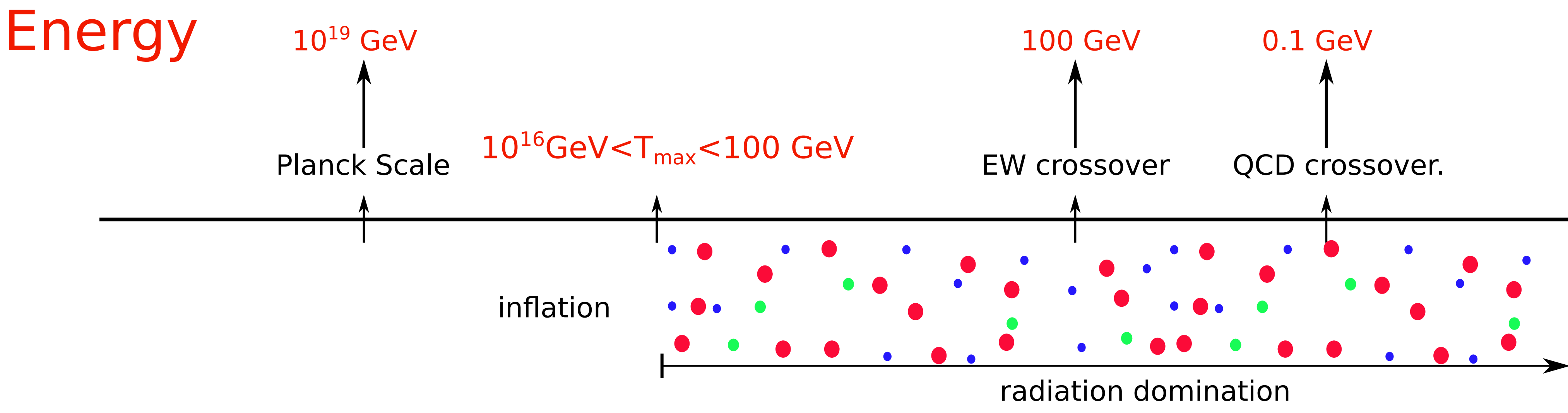

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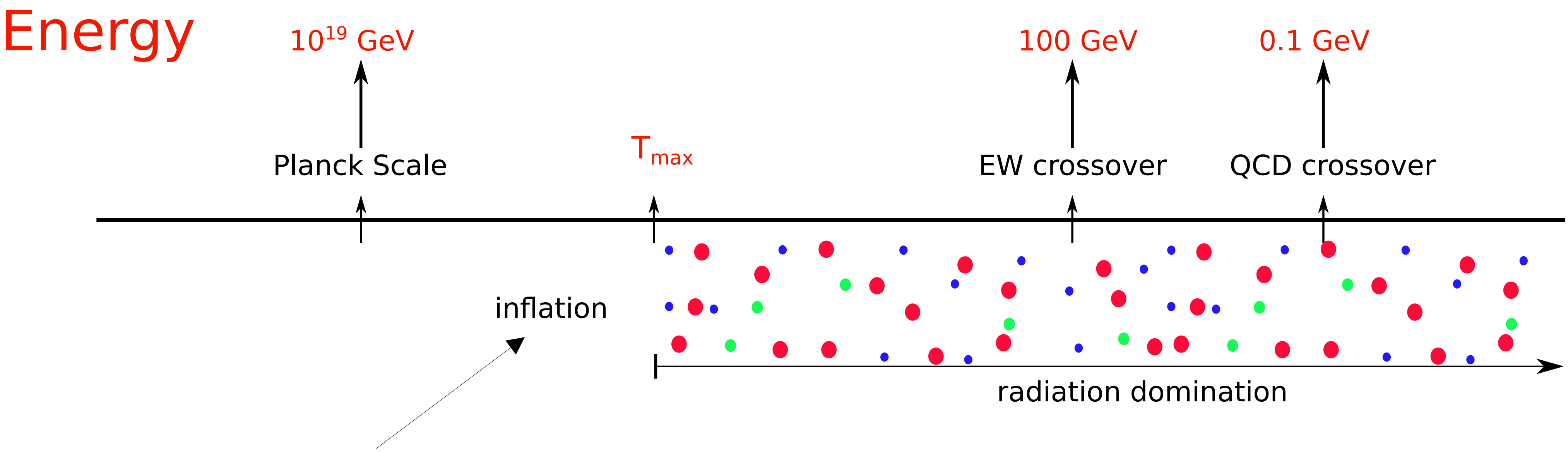
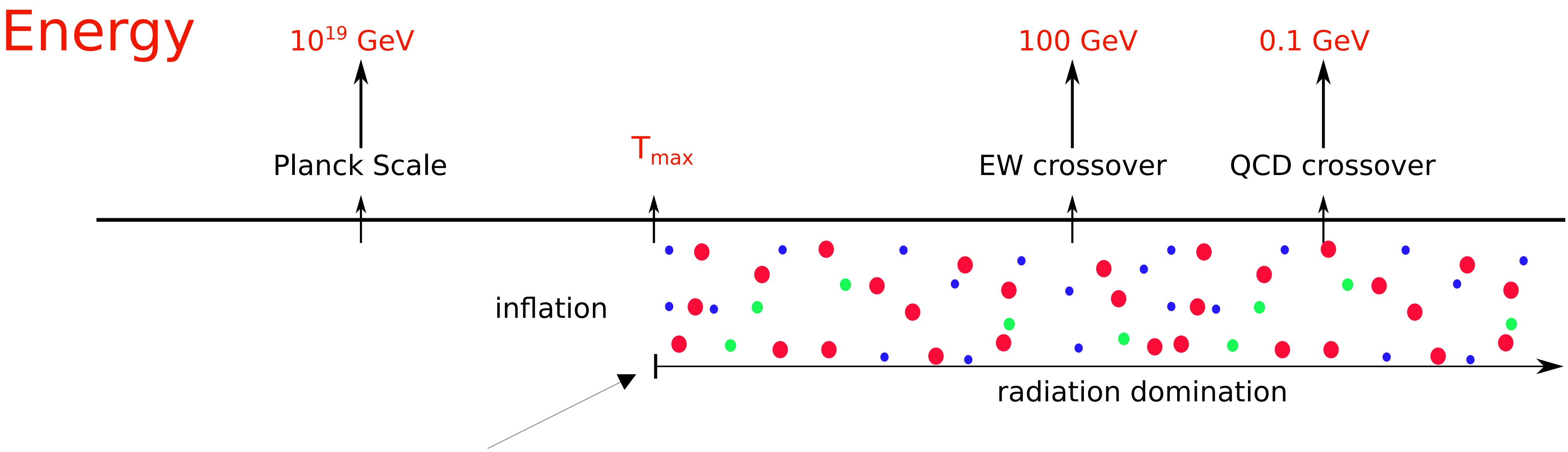


GWs from inflation

GWs due to the tensor modes generated
by quantum fluctuations during inflation

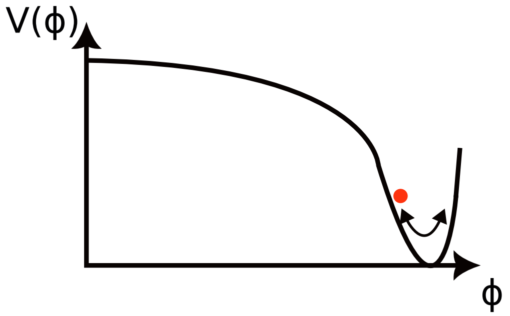
[Grishchuk,75], [Starobinskii, 79],
[Rubakov, Sazhin, Veryaskin, 82]

GWs from the early universe

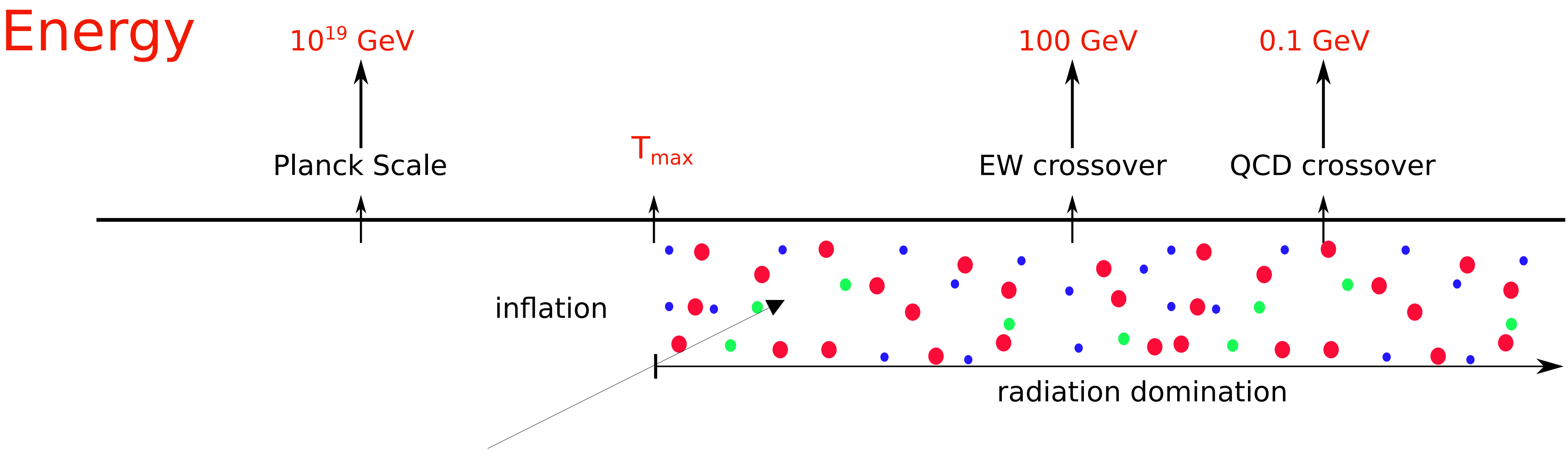


GWs from (p)reheating

[Khlebnikov, Tkachev, 97], [Lozanov, 2020]

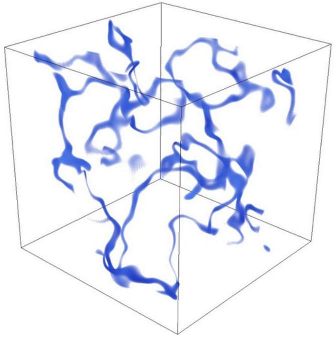


GWs from the early universe



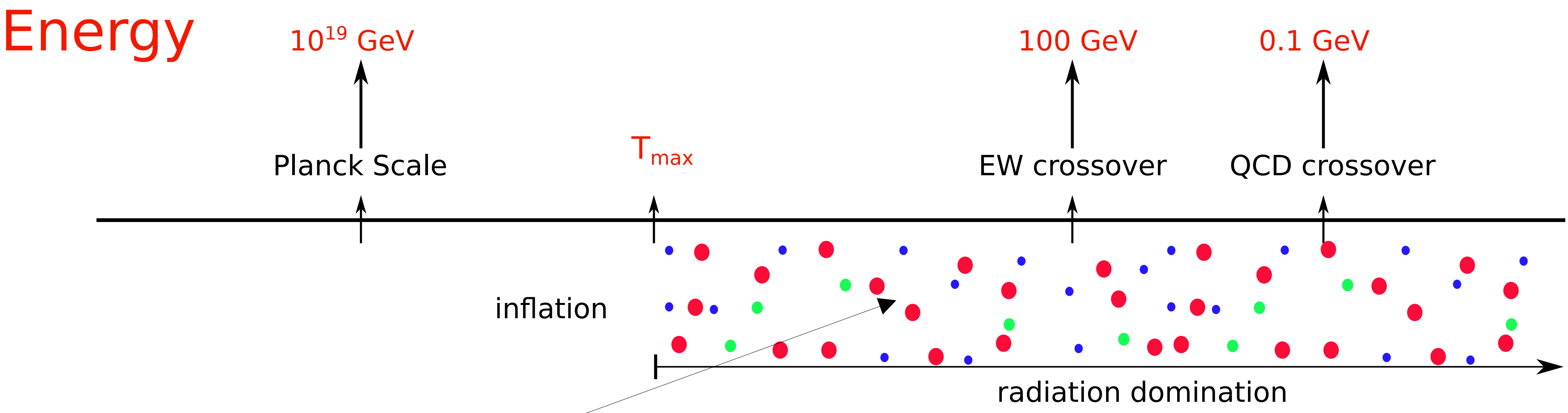
Cosmic strings

[Damour, Vilenkin, 20]



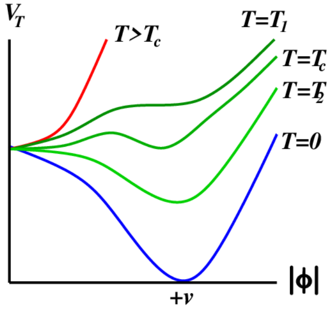
[Frolov, 2010]

GWs from the early universe



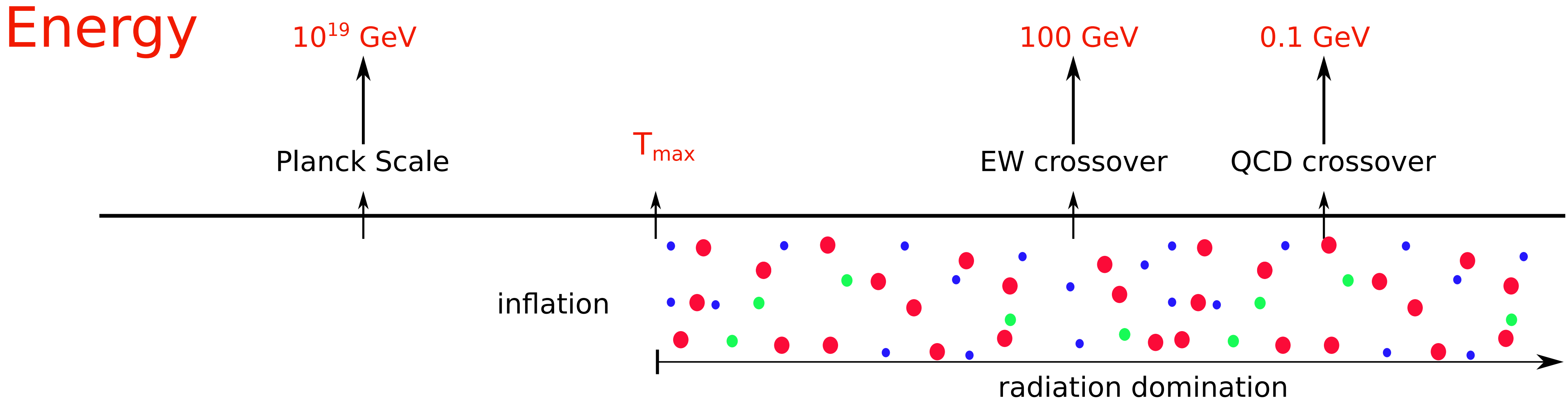
First order phase transitions

[Witten, 84], [Hogan, 86]

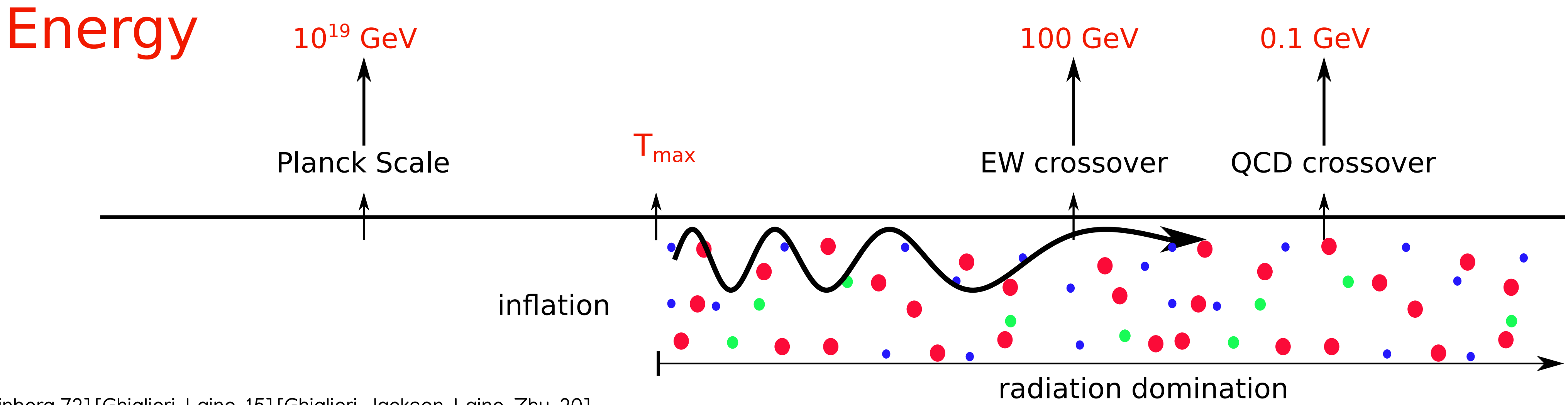


[Hindmarsh , Lüben, Lumma, Pauly 2020]

GWs from the early universe



GWs from the thermal plasma



[Weinberg 72] [Ghiglieri, Laine, 15] [Ghiglieri, Jackson, Laine, Zhu, 20]
[Ringwald, **JSE**, Tamarit 20], [Ghiglieri, **JSE**, Speranza, 22],
[Laine, Ghiglieri, **JSE**, Speranza, 24]

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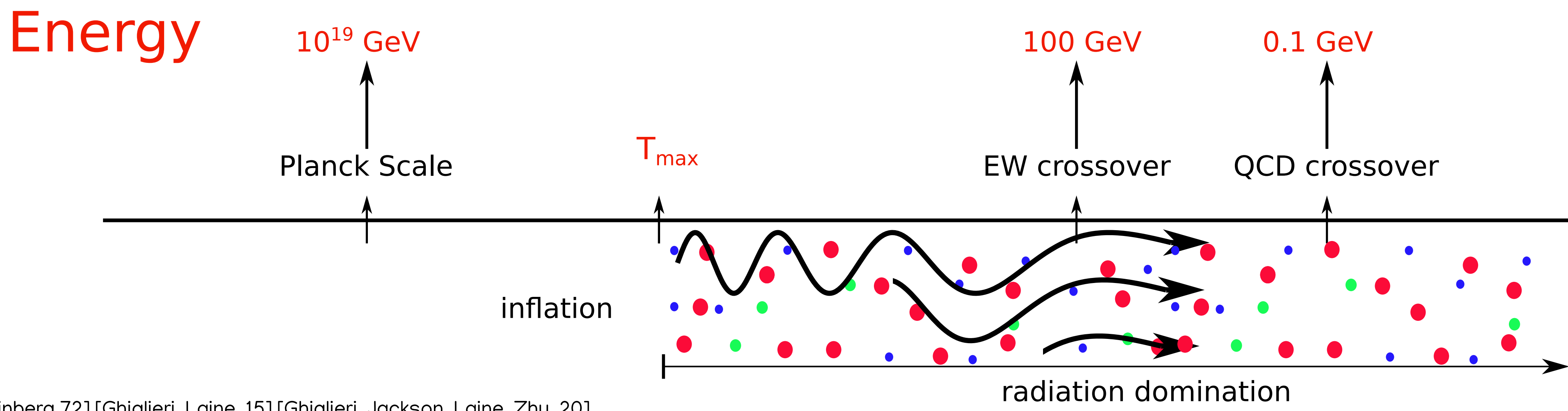

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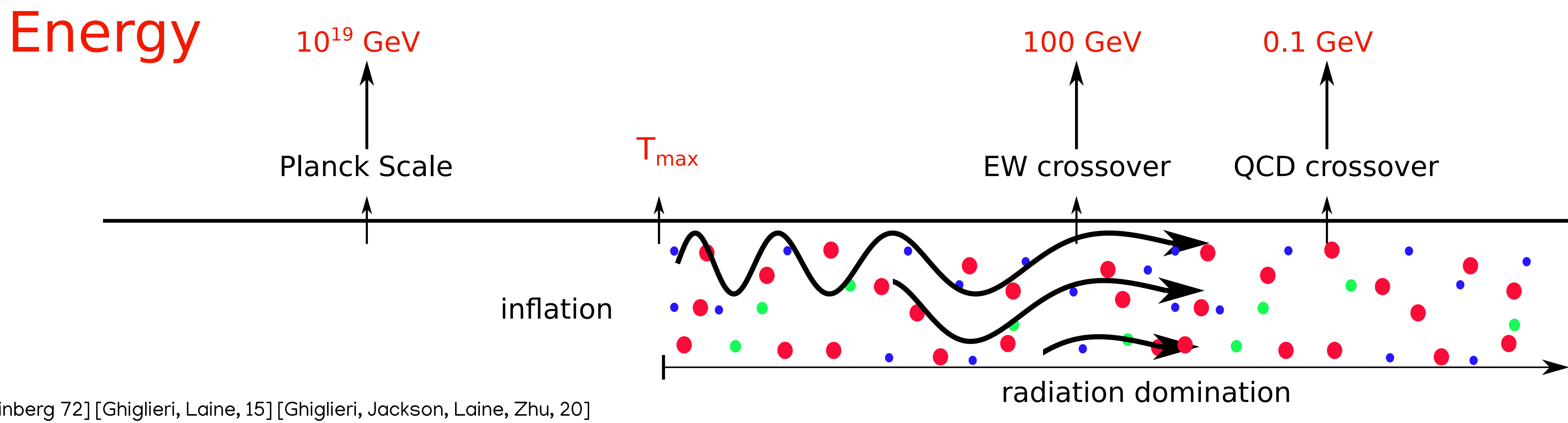

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$$\omega_g^{\text{today}} = \left(\frac{g_{*s}(T_0)}{g_{*s}(T)}\right)^{\frac{1}{3}} \frac{k}{T} T_0$$

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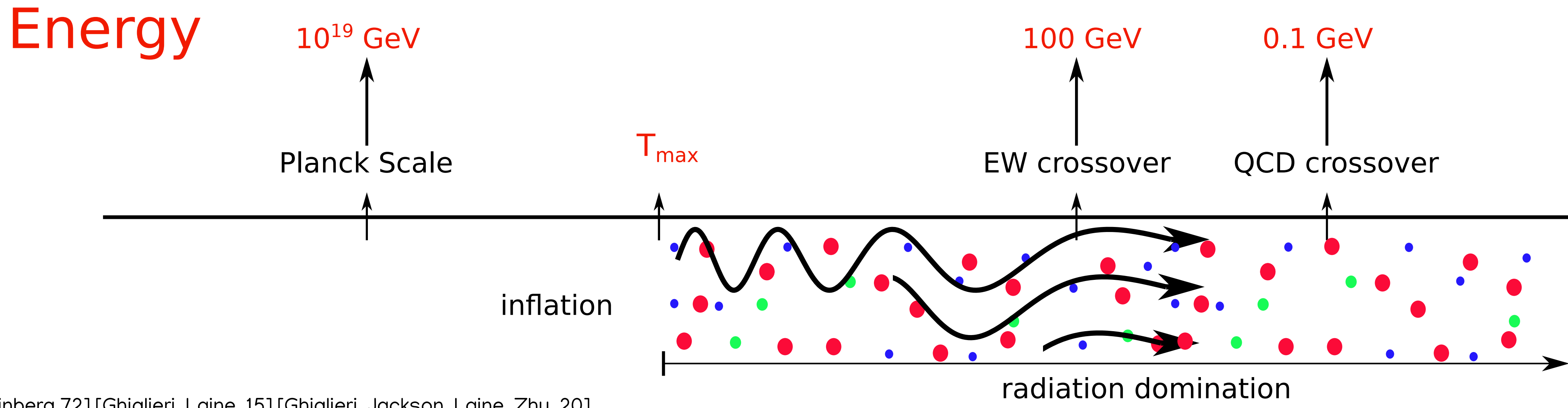

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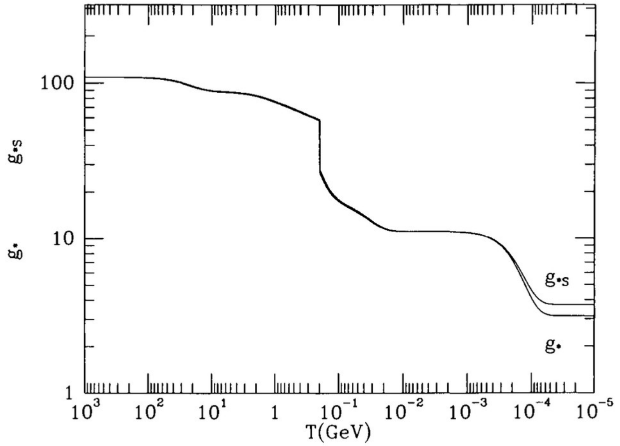

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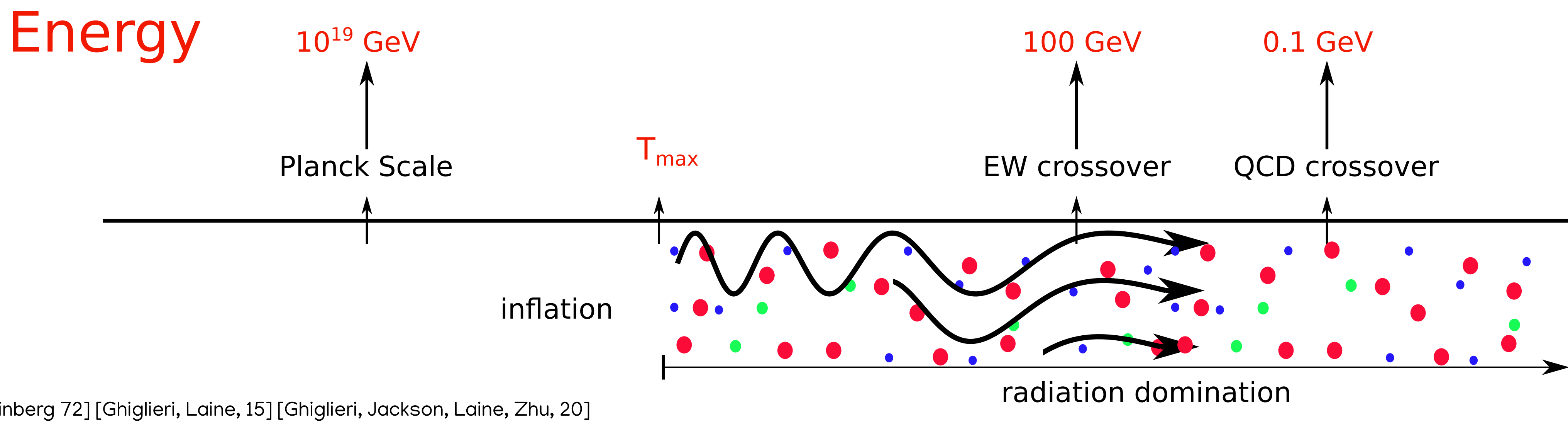

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Cosmic Gravitational Microwave Background (CGMB)

Outline

- Scalar model: $\mathcal{L} = -\partial_\mu \phi^\dagger \partial^\mu \phi + \frac{\lambda}{4}|\phi|^4$
- Standard Model (SM): $\mathcal{L} = \mathcal{L}_{\mathrm{SM}}$
- Beyond the SM (BSM) theories: $\mathcal{L} = \mathcal{L}_{\mathrm{BSM}}$

$$f_\phi(k) = n_{\rm B}(k) + \cdots\,, \quad n_B = \frac{1}{e^{k/T}-1}$$

$$f_h(k) = 0\cdots$$

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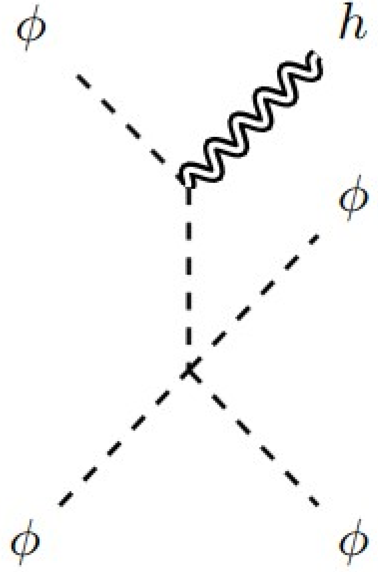
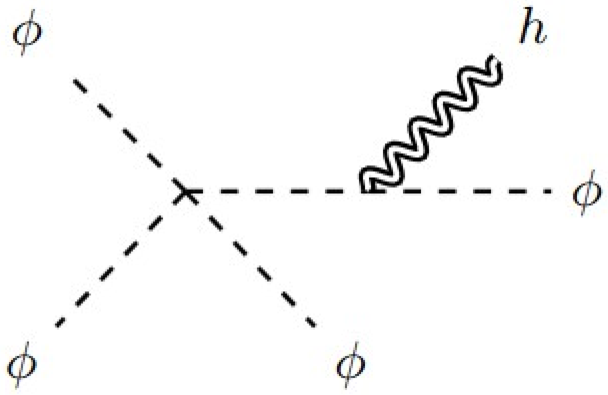
$$f_h(k) = 0 + f_h^{(2,2)}(k) + \cdots$$

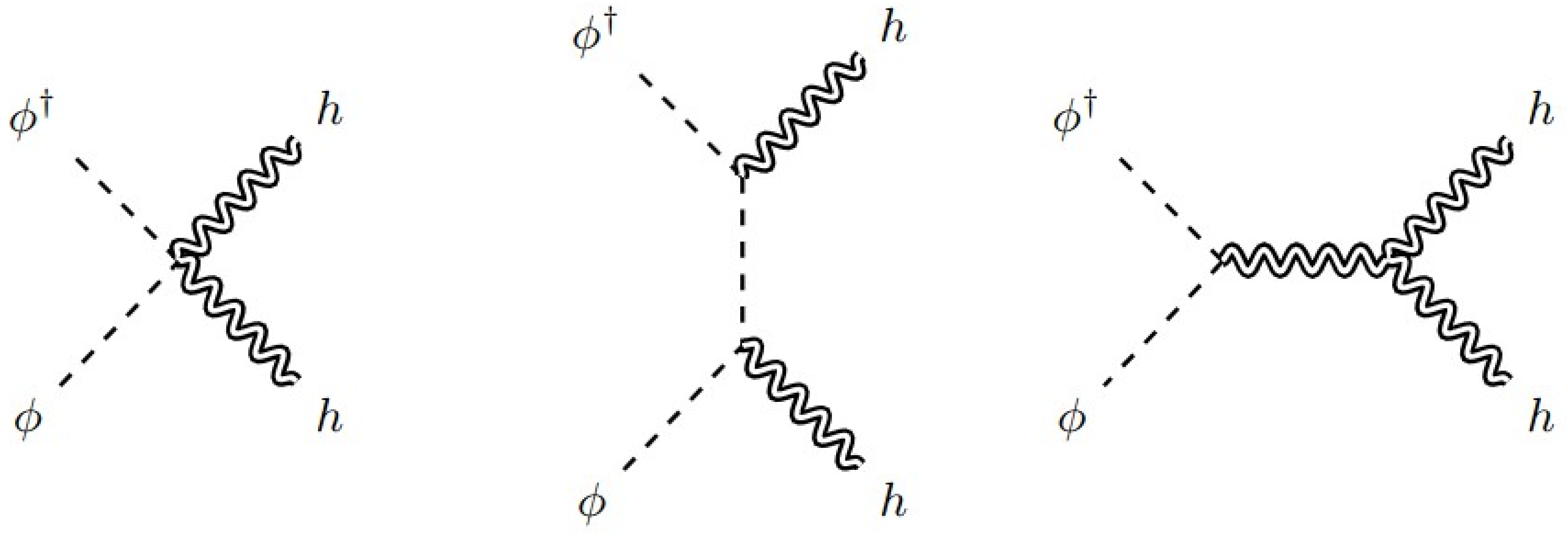




$$|\mathcal{M}|^2 \sim \lambda^2 \left(\frac{1}{m_p}\right)^2$$

$$f_\phi(k) = n_{\mathrm{B}}(k) + \cdots$$

$$f_h(k) = 0 + f_h^{(2,2)}(k) + f_h^{(0,4)}(k) + \cdots$$



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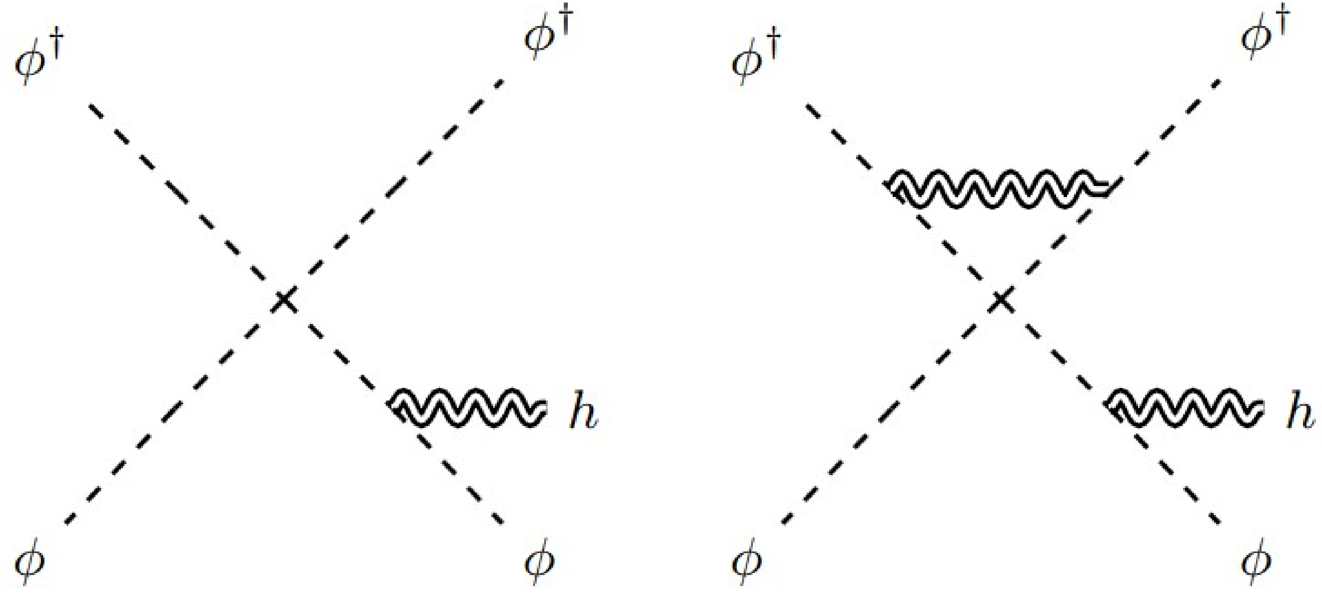

$$|\mathcal{M}|^2 \sim \lambda^2 \left(\frac{1}{m_p}\right)^4$$

$$h_0^2\Omega_{\rm gw}(f_g) \sim \frac{T_{\rm max}}{m_p} n_{\rm B}(y_{\rm max}) \left(\lambda^2 \psi^{(2,2)}(y_{\rm max}) + \frac{1}{3}\left(\frac{T_{\rm max}}{m_p}\right)^2 \psi^{(0,4)}(y_{\rm max}) + \frac{1}{3}\lambda^2 \left(\frac{T_{\rm max}}{m_p}\right)^2 \psi^{(2,4)}(y_{\rm max}) + \cdots \right)$$

$$y_{\rm max} \equiv \frac{2\pi f_g}{T_0}\left(\frac{g_{*s}(T_{\rm max})}{g_{*s}(T_0)}\right)^{1/3} = 0.14\left(\frac{f_g}{10^{10}\ {\rm Hz}}\right)\left(\frac{g_{*s}(T_{\rm max})}{2}\right)^{1/3}$$

ψ –functions encode information about microscopic particle physics model

$$h_0^2\Omega_{\rm gw}(f_g) \sim \frac{T_{\max}}{m_p} n_{\rm B}(y_{\max}) \left(\lambda^2 \psi^{(2,2)}(y_{\max}) + \frac{1}{3}\left(\frac{T_{\max}}{m_p}\right)^2 \psi^{(0,4)}(y_{\max}) + \frac{1}{3}\lambda^2 \left(\frac{T_{\max}}{m_p}\right)^2 \psi^{(2,4)}(y_{\max}) + \cdots \right)$$

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Single graviton production dominates if

$$10\,\frac{T_{\max}}{m_p} < \lambda$$

$$h_0^2\Omega_{\rm gw}(f_g) \sim \frac{T_{\max}}{m_p} n_{\rm B}(y_{\max}) \left(\lambda^2 \psi^{(2,2)}(y_{\max}) + \frac{1}{3}\left(\frac{T_{\max}}{m_p}\right)^2 \psi^{(0,4)}(y_{\max}) + \frac{1}{3}\lambda^2 \left(\frac{T_{\max}}{m_p}\right)^2 \psi^{(2,4)}(y_{\max}) + \cdots \right)$$

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Quantum gravity effects are small corrections. They suppressed by a factor

$$\left(\frac{T_{\max}}{m_p}\right)^2$$

$$h_0^2\Omega_{\rm gw}(f_g) \sim \frac{T_{\rm max}}{m_p} n_{\rm B}(y_{\rm max}) \left(\lambda^2 \psi^{(2,2)}(y_{\rm max}) + \frac{1}{3}\left(\frac{T_{\rm max}}{m_p}\right)^2 \psi^{(0,4)}(y_{\rm max}) + \frac{1}{3}\lambda^2 \left(\frac{T_{\rm max}}{m_p}\right)^2 \psi^{(2,4)}(y_{\rm max}) + \cdots \right)$$

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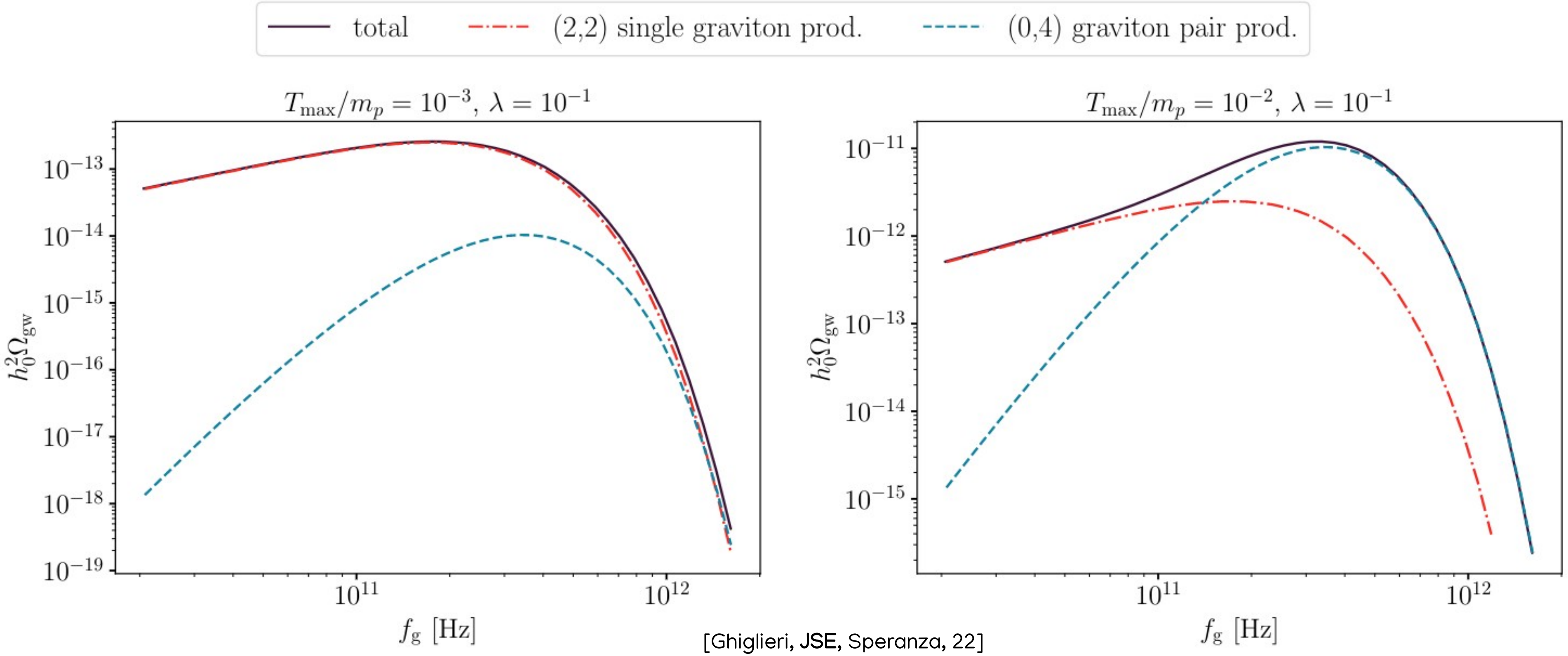

[Ghiglieri, **JSE**, Speranza, 22]

GWs from the thermal plasma in SM

$$h_0^2\Omega_{\rm gw}(f_g) \sim \frac{T_{\rm max}}{m_p} n_{\rm B}(y_{\rm max}) \left(g^2 \psi^{(2,2)}(y_{\rm max}) + \frac{1}{3}\left(\frac{T_{\rm max}}{m_p}\right)^2 \psi^{(0,4)}(y_{\rm max}) + \cdots \right)$$

SM gauge couplings

GWs from the thermal plasma in SM

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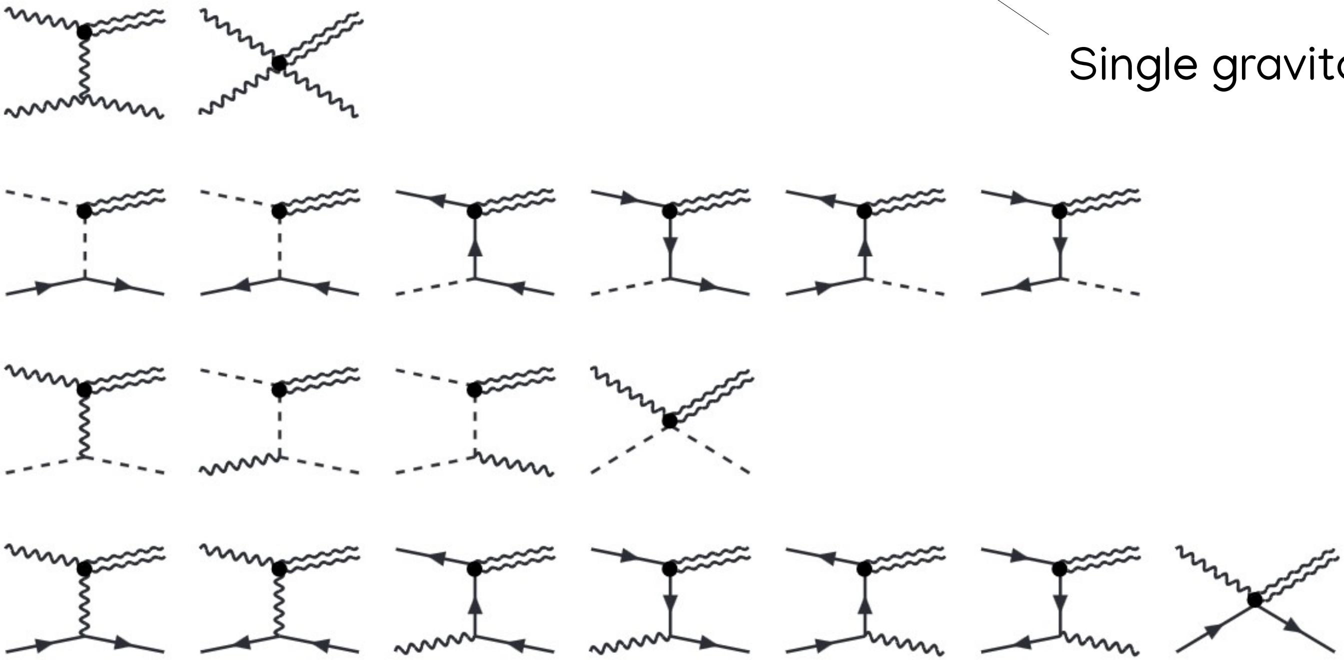
Single graviton production processes

$$|\mathcal{M}|^2 \sim g^2 \frac{1}{m_p^2}$$



[Ghiglieri, Jackson, Laine, Zhu, 20]

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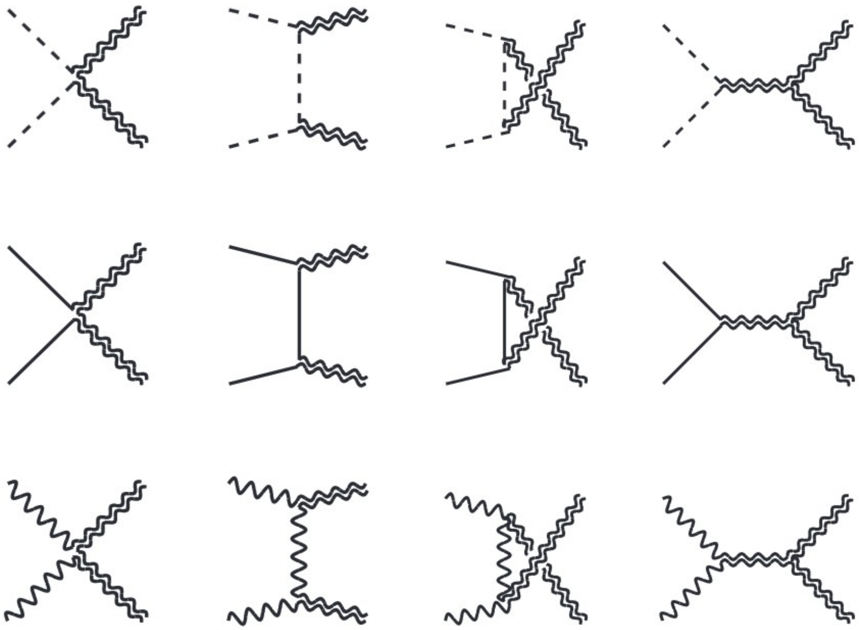


[Laine, Ghiglieri, **JSE**, Speranza, 22]

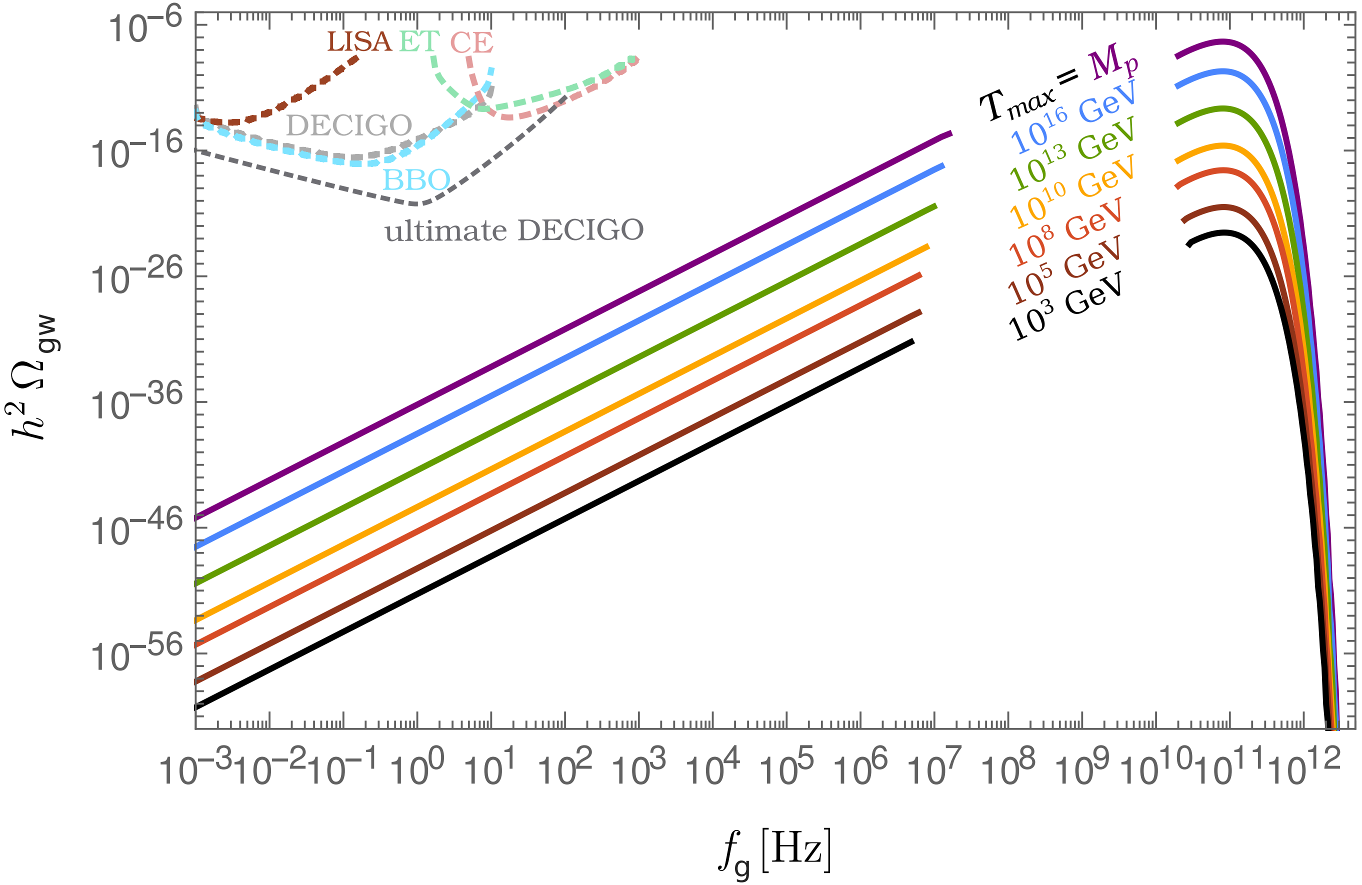
Graviton pair production processes

$$|\mathcal{M}|^2 \sim \frac{1}{m_p^4}$$

In SM double graviton production dominates if

$$\frac{T_{\rm max}}{m_p} > 0.4$$

GWs from the thermal plasma



$$f_{\rm peak} \sim \left(\frac{1}{g_{*s}(T_{\rm max})}\right)^{\frac{1}{3}}$$

	SM	MSSM
$g_{*s}(T_{\rm max})$	106.75	228

$$\Omega_{\rm gw} \sim \frac{T_{\rm max}}{m_p}$$

From BBN and CMB:

$$h^2\Omega_{\rm gw} < 10^{-6}$$

[Ringwald, **JSE**, Tamarit, 20]

Conclusions

- CGMB is guaranteed stochastic GW background which peaks in GHz regime
- Powerful probe of particle physics models
- Peak amplitude determines maximum temperature
- Quantum gravity effects are encoded as small corrections in the GW spectrum

Backup

Distribution functions

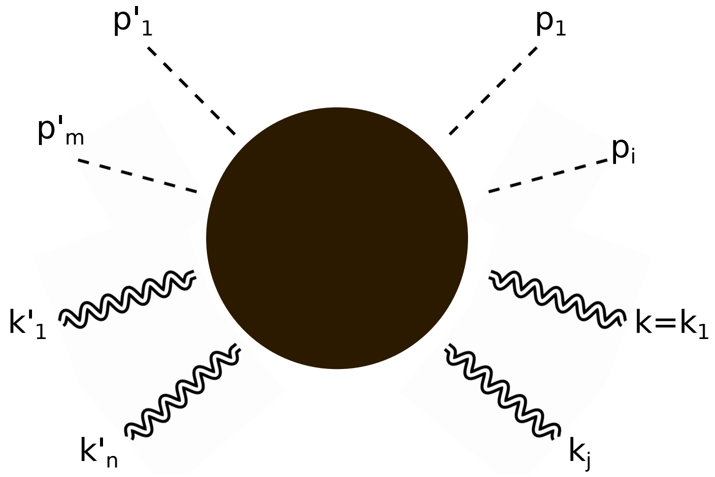
$$f_\phi(t,k) \equiv \frac{\text{Number of } \phi\text{-states with momentum } k \text{ in } d^3k \text{ interval}}{V\, d^3k/(2\pi)^3}$$

$$f_h(t,k) \equiv \frac{\text{Number of gravitons with momentum } k \text{ in } d^3k \text{ interval}}{V\, d^3k/(2\pi)^3}$$

Evolution equations

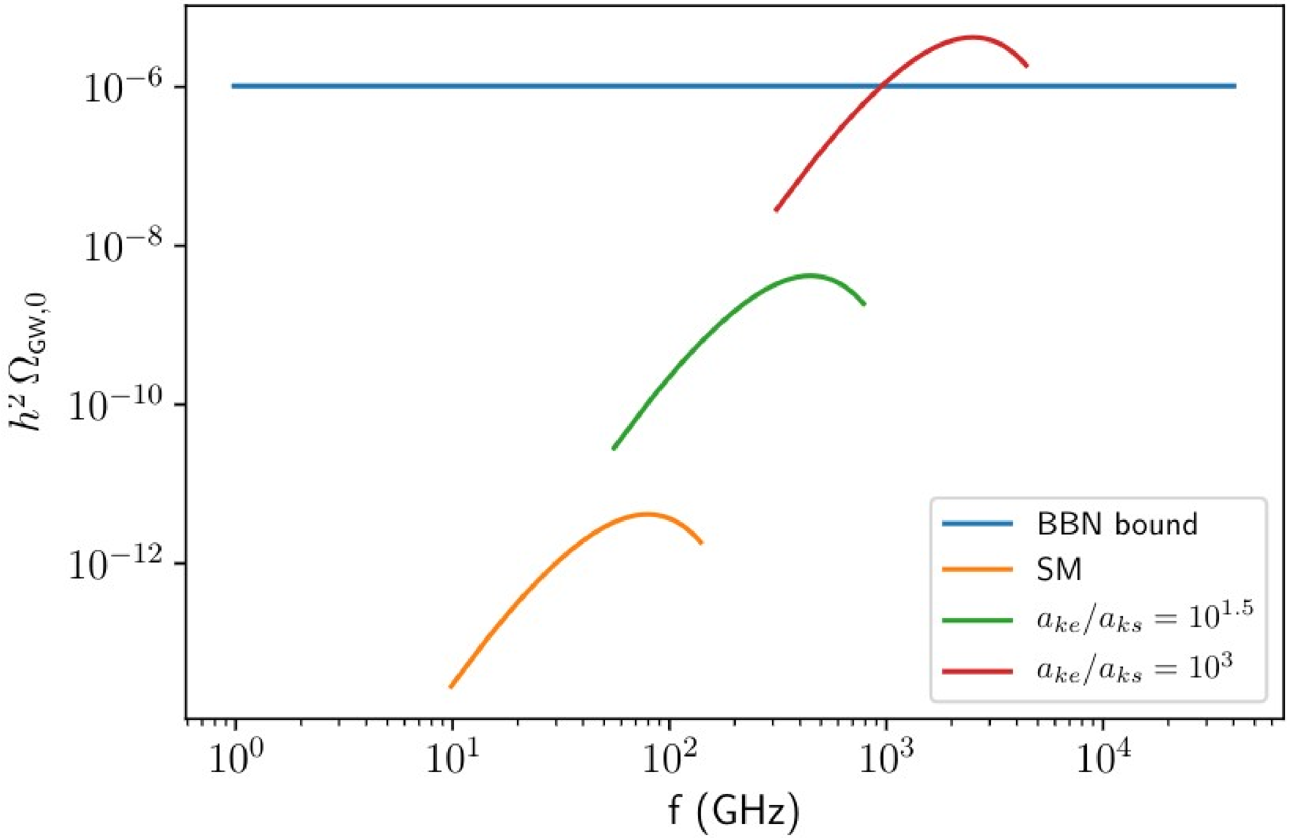
$$\dot{f}_\phi(t,k) = G_\phi(t,k) - L_\phi(t,k)$$

$$\dot{f}_h(t,k) = G_h(t,k) - L_h(t,k)$$



$$G_h(t,k) = \frac{1}{4k} \sum_{\substack{\text{all processes } r \\ \text{with at least one} \\ \text{final state graviton}}} S_r \int d\Omega_r \, |\mathcal{M}_r|^2 \times f_\phi(p'_1)\cdots f_\phi(p'_m)\, f_h(k'_1)\cdots f_h(k'_n) \times$$
$$\times (1+f_\phi(p_1))\cdots(1+f_\phi(p_i))\ (1+f_h(k))\cdots(1+f_h(k_j))$$

CGMB in modifierd cosmology



[Muia, Quevedo, Schachner, Villa 23]

Sensitivity to stochastic GWs

$$\mathrm{SNR} = \frac{S_{\mathrm{sig}}}{S_{\mathrm{noise}}} = \frac{\omega_n Q}{4\pi T} \left|\eta\right|^2 B_0^2 V_{\mathrm{cav}} S_h(\omega)$$

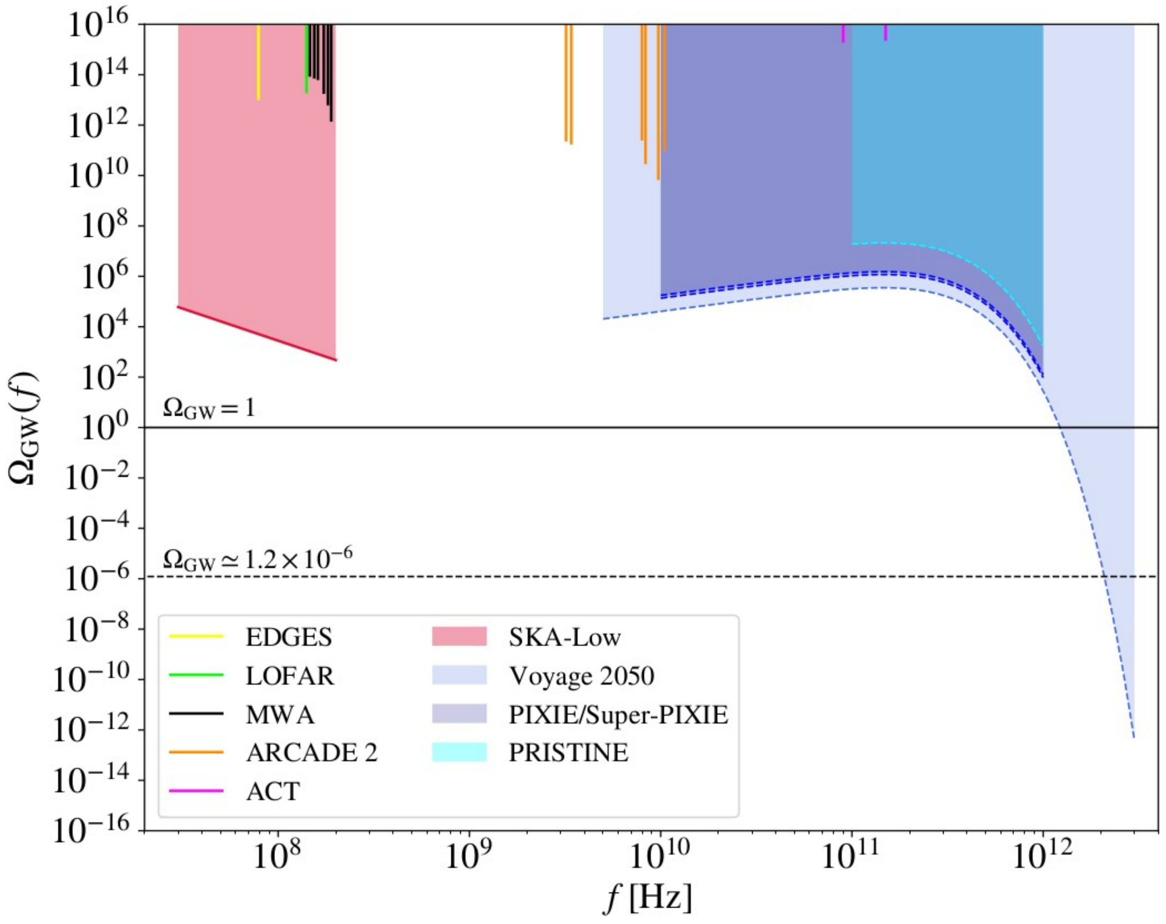
We can only constrain: $\Omega_{\mathrm{GW}} > 1$

BUT

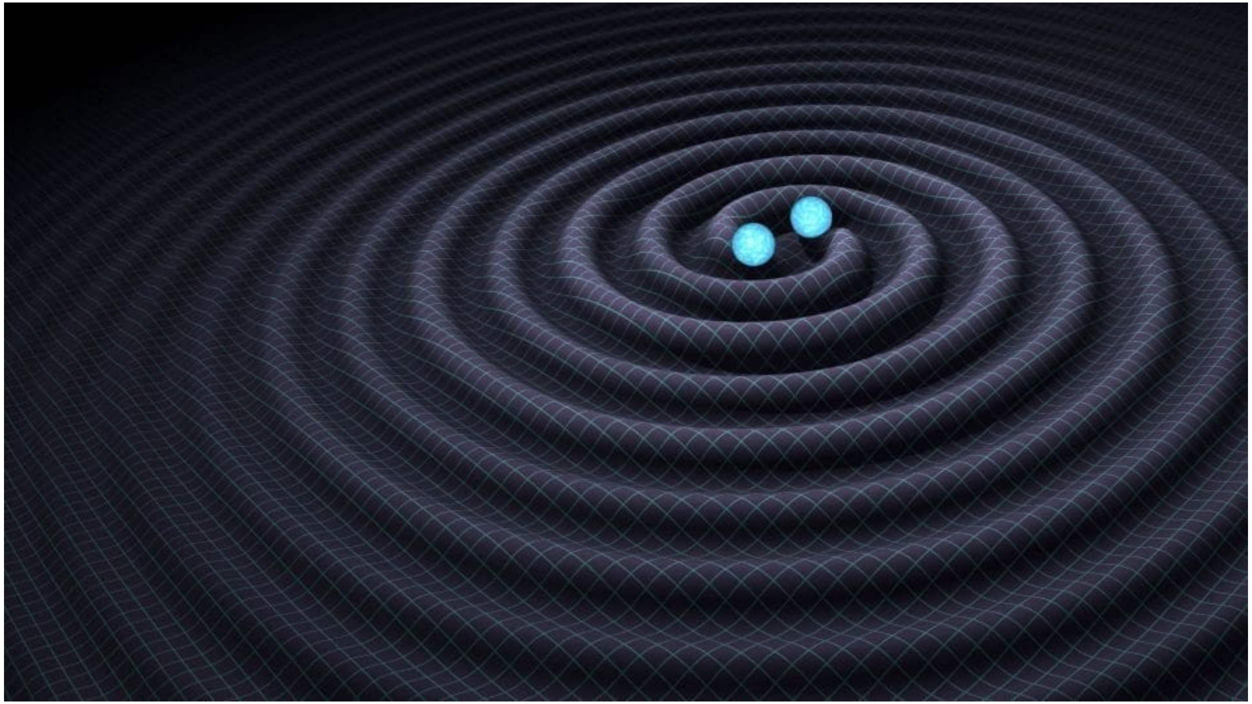
From BBN and CMB: $\Omega_{\mathrm{GW}} < 10^{-6}$

Graviton photon conversion in galactic or earth magnetic field seems more promising...

Astrophysical detection of Stochastic GWs



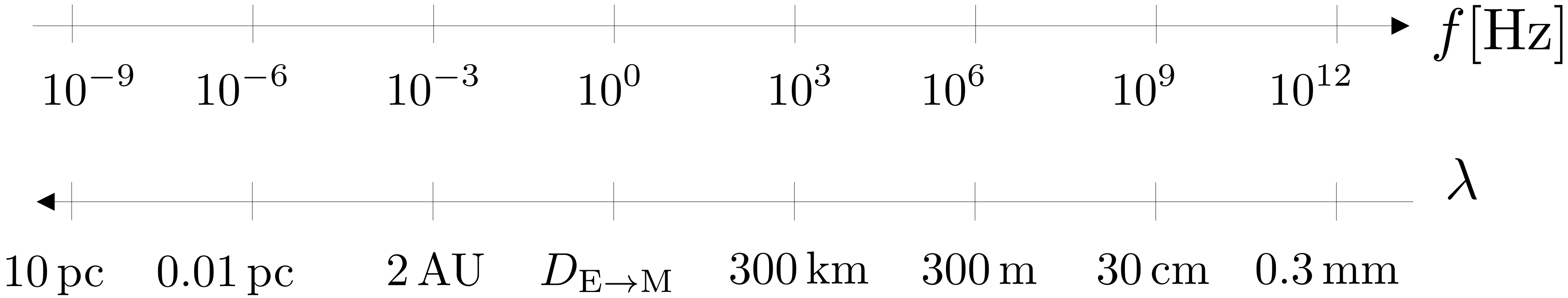
[He, Giri, Sharma, Mtchedlidze, Georgiev, 23]


[R. Hurt, Caltech-IPAC]

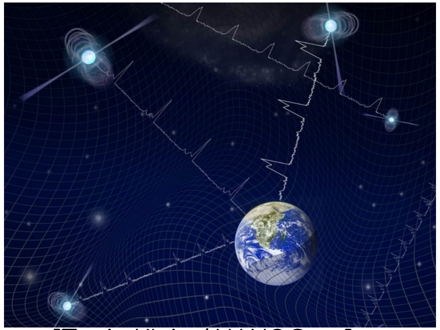
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\Box h_{\mu\nu} = -16\pi G T_{\mu\nu}$$

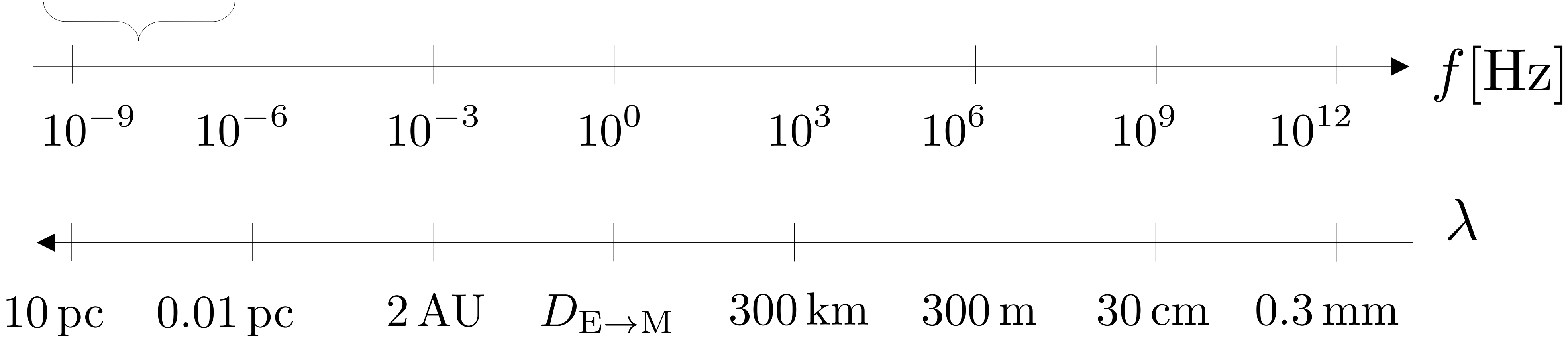

$f\,[\mathrm{Hz}]$
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
λ
$10\,\mathrm{pc}$
$0.01\,\mathrm{pc}$
$2\,\mathrm{AU}$
$D_{\mathrm{E}\to\mathrm{M}}$
$300\,\mathrm{km}$
$300\,\mathrm{m}$
$30\,\mathrm{cm}$
$0.3\,\mathrm{mm}$

Pulsar timing arrays

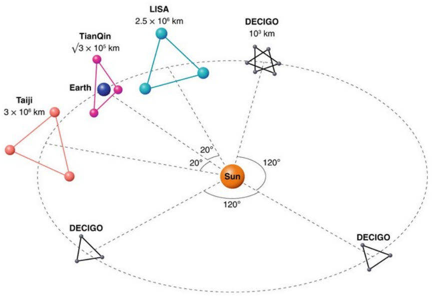


[Tonia Klein / NANOGrav]

Possible sources:
- Supermassive black hole mergers
- First order phase transition
- etc.

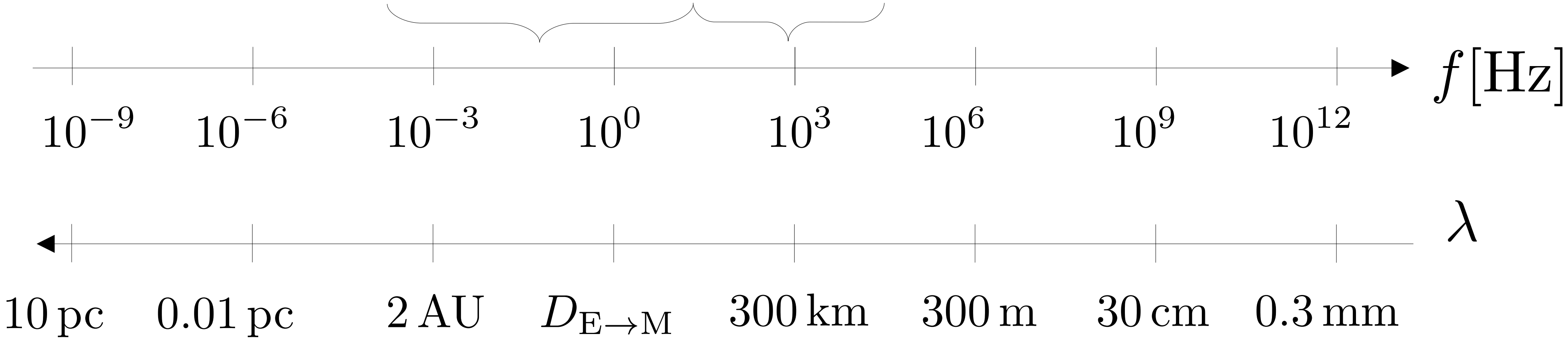


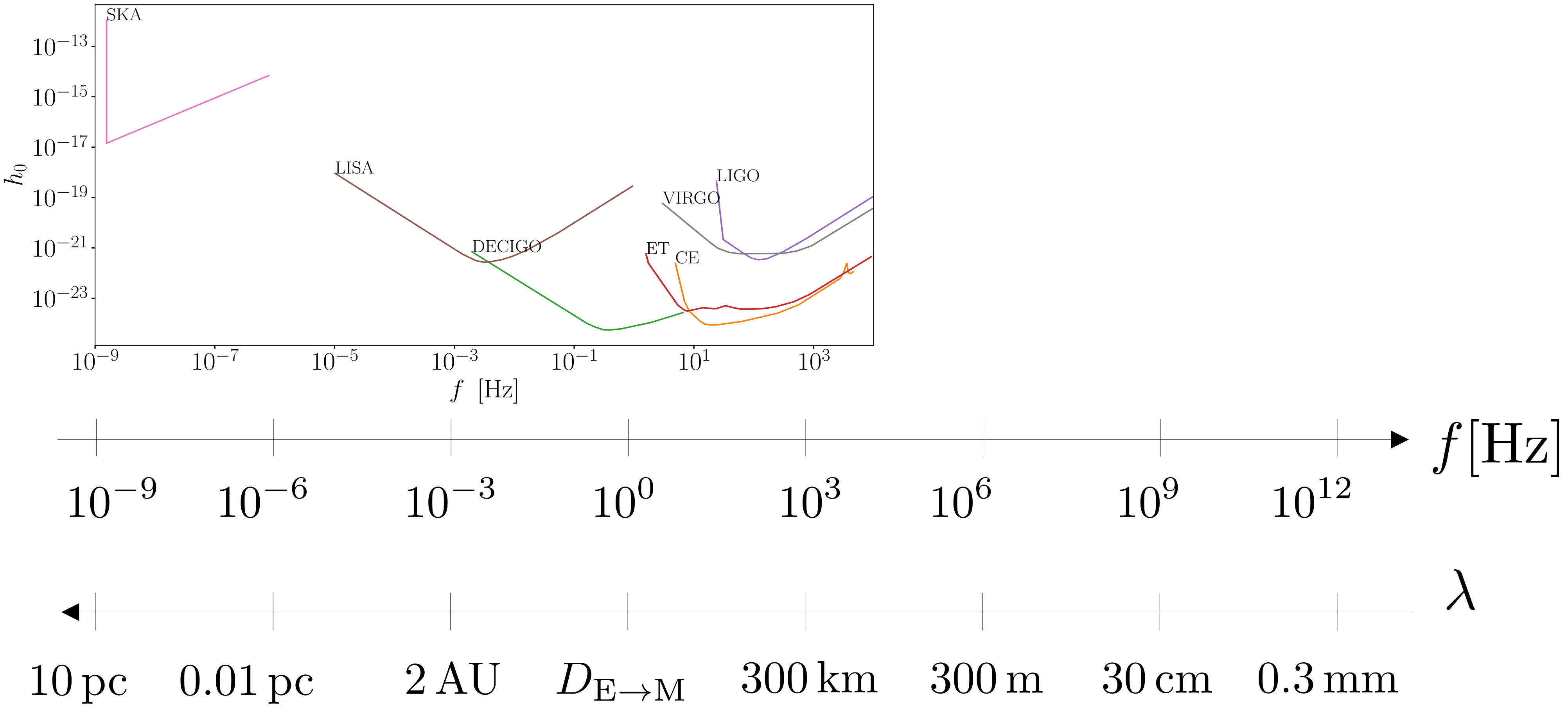
Space and Earth based interferometers

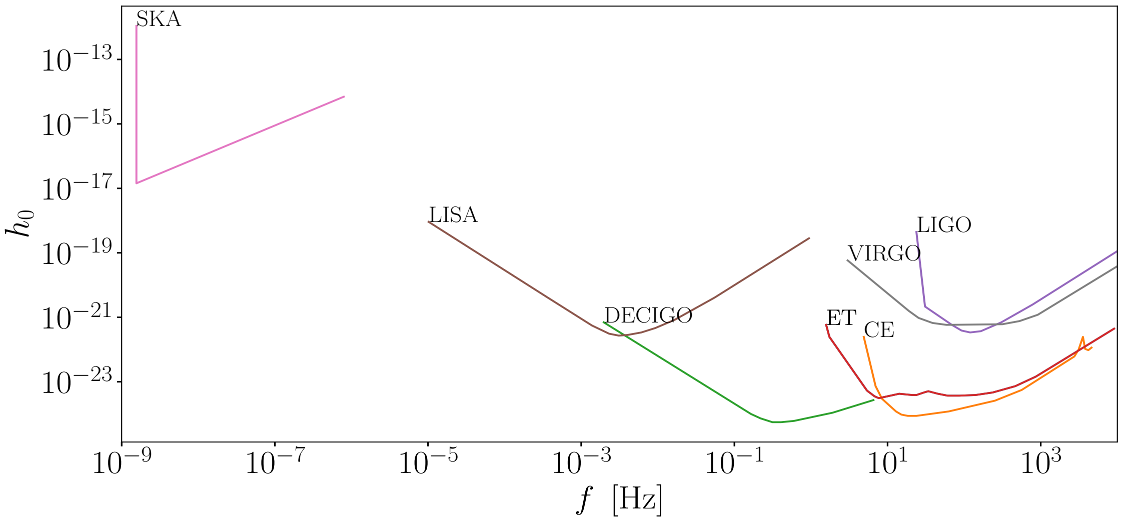


[Gong, Luo, Wang, 21']

Possible sources:
- Massive binaries
- Supernovae
- Stochastic background from inflation
- GWs from early universe
- etc.




SKA
LISA
DECIGO
ET
CE
VIRGO
LIGO
h_0
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-23}
10^{-9} 10^{-7} 10^{-5} 10^{-3} 10^{-1} 10^{1} 10^{3}
f [Hz]
f [Hz]
10^{-9} 10^{-6} 10^{-3} 10^{0} 10^{3} 10^{6} 10^{9} 10^{12}
λ
10 pc
0.01 pc
2 AU
$D_{\mathrm{E}\to\mathrm{M}}$
300 km
300 m
30 cm
0.3 mm



High frequency GW regime

$$f > 10^4 \text{ Hz}$$

Why look into it?

1. interesting sources
2. GWs exist and we probe unexplored parameter-space. We see surprises in LIGO.