# Dark Matter and Gravity Waves from a Dark Big Bang

Martin W. Winkler

in collaboration with K. Freese

based on arXiv:2208.03330

The University of Texas at Austin
Department of Physics
College of Natural Sciences

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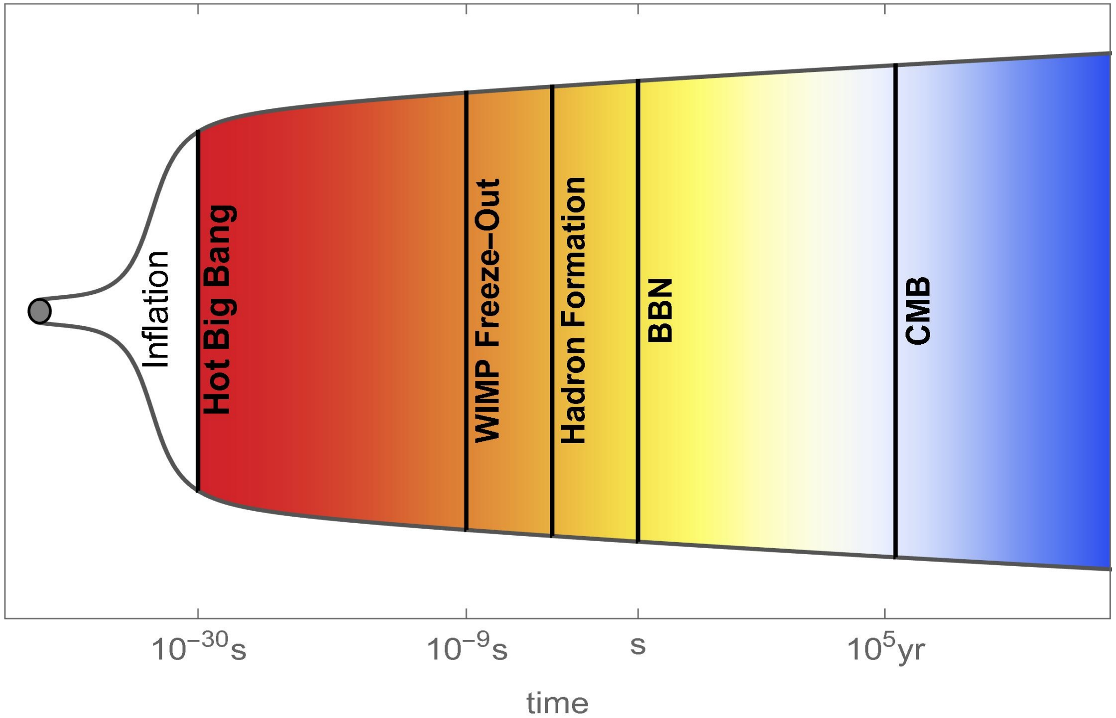
Stockholm University

# Hot Big Bang Cosmology




<u>Hot Big Bang</u>

vacuum energy

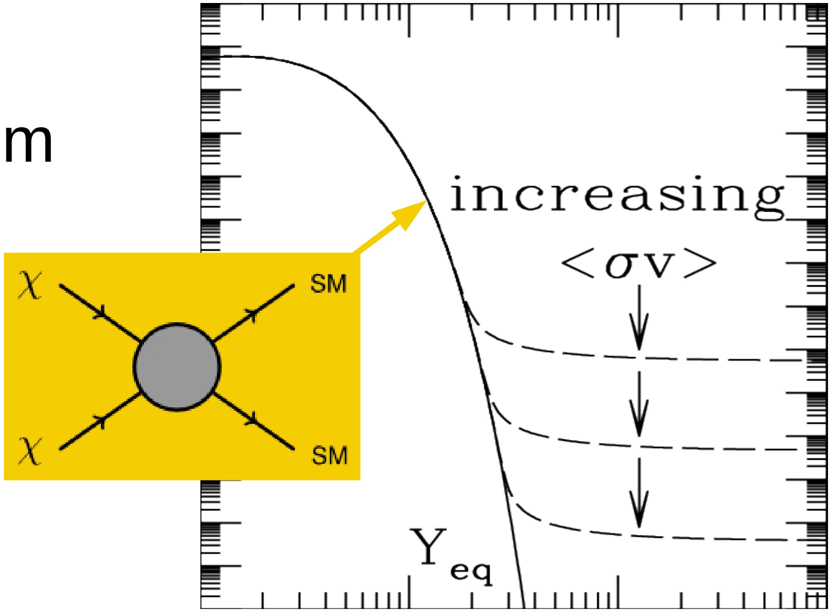
↓

hot plasma of quarks, leptons, gauge bosons, DM

early universe: DM in thermal equilibrium

$$H \propto T^2 \qquad \Gamma \propto \langle \sigma v \rangle e^{-m_\chi/T}$$

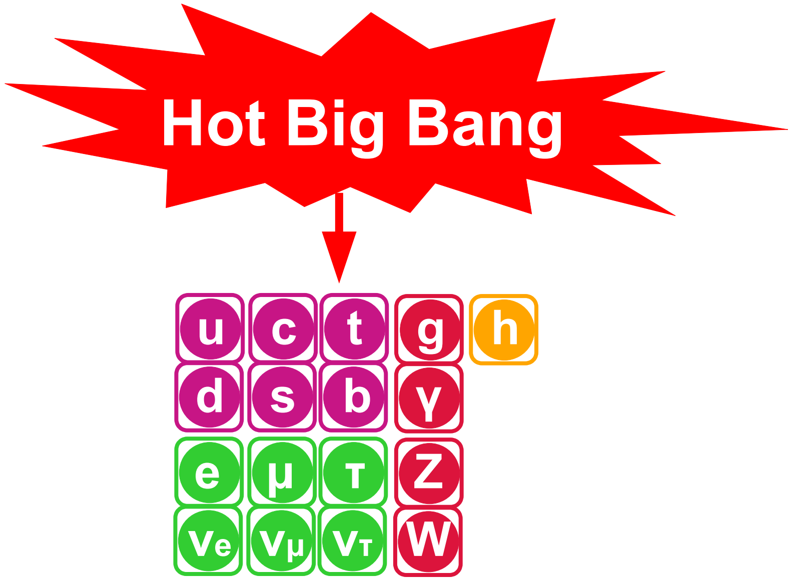
**expansion** **annihilation**



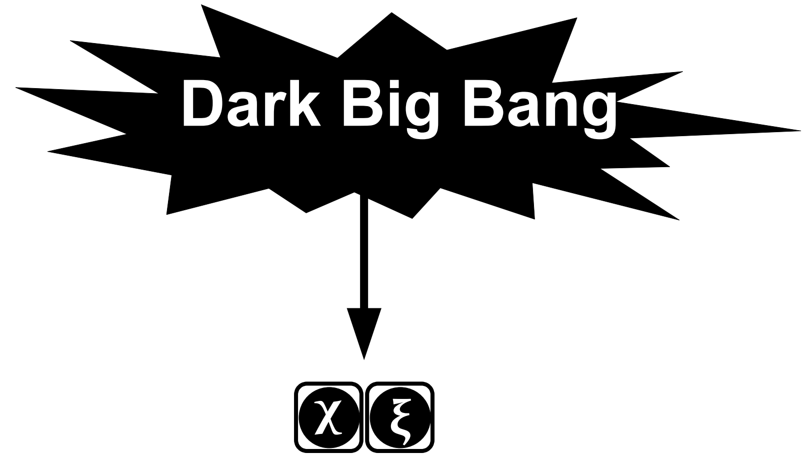

freeze-out: $H \simeq \Gamma$

Dicus et al. 1977, Lee, Weinberg, 1977

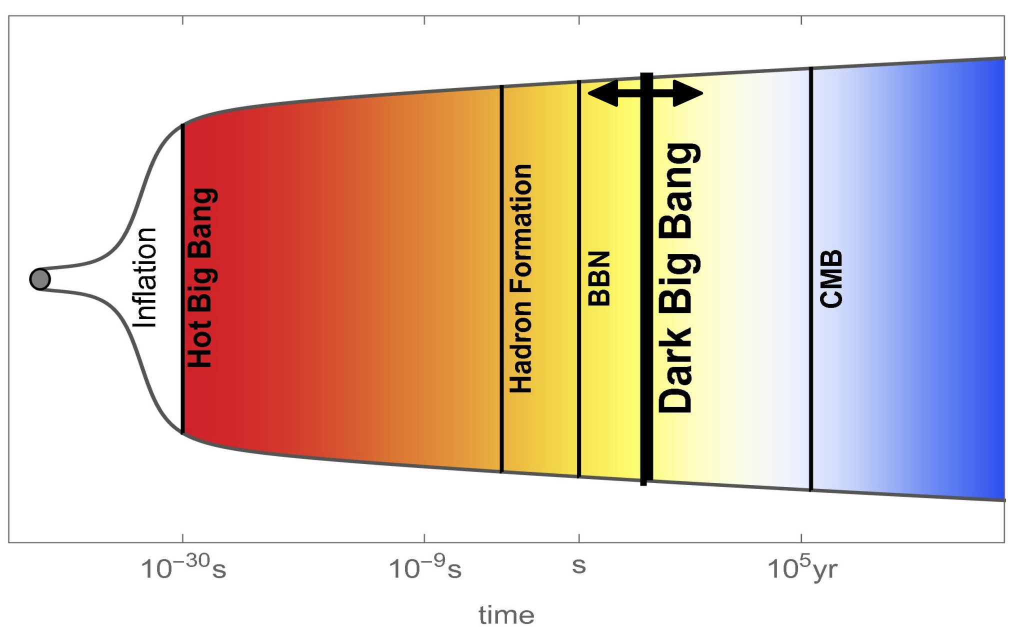
# Dark Big Bang Cosmology




**radiation, matter**




**dark matter, dark radiation**




Earliest probes of DM from structure formation.

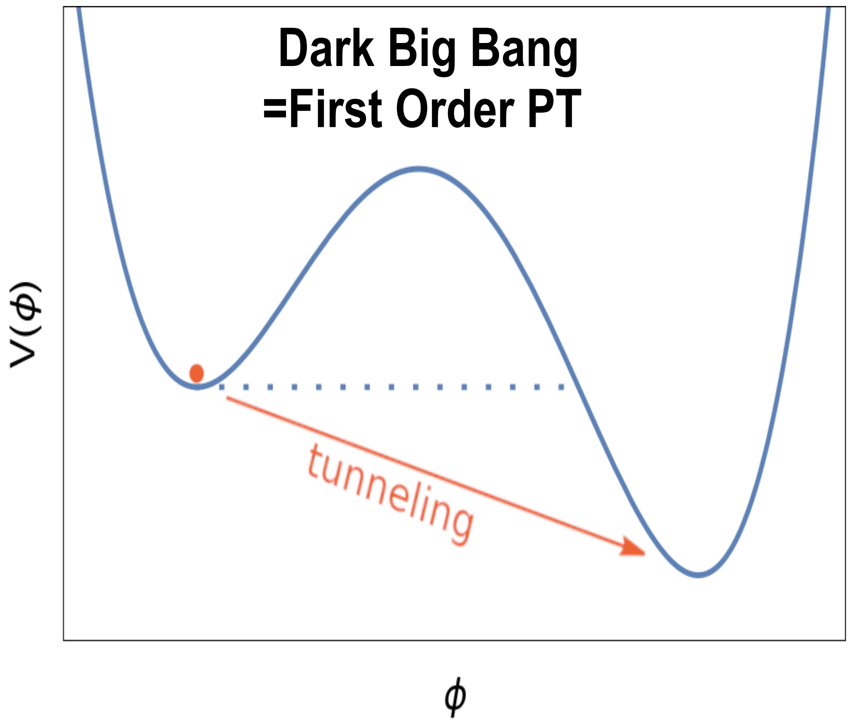
▶ Late Dark Big Bang?

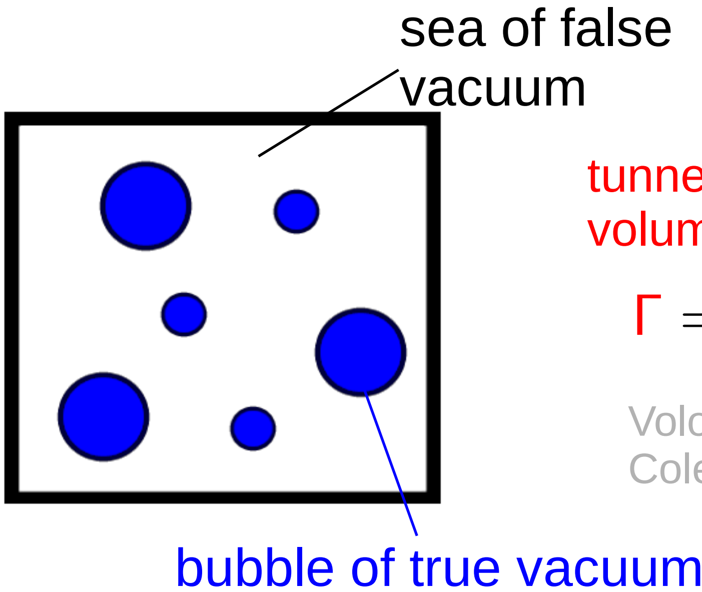
$$\mathcal{L} = \mathcal{L}_{\text{Inflation}} + \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}}$$

decoupled

$$\mathcal{L}_{\text{DS}} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{i}{2}\bar{\chi}\not{\partial}\chi - V(\phi) - y\,\phi\bar{\chi}\chi - \frac{m_\chi^2}{2}\bar{\chi}\chi\left( + \mathcal{L}_{\text{DR}}(\xi)\right)$$

$\phi$ = tunneling field $\chi$ = dark matter $\xi$ = dark radiation




tunneling rate per volume and time”

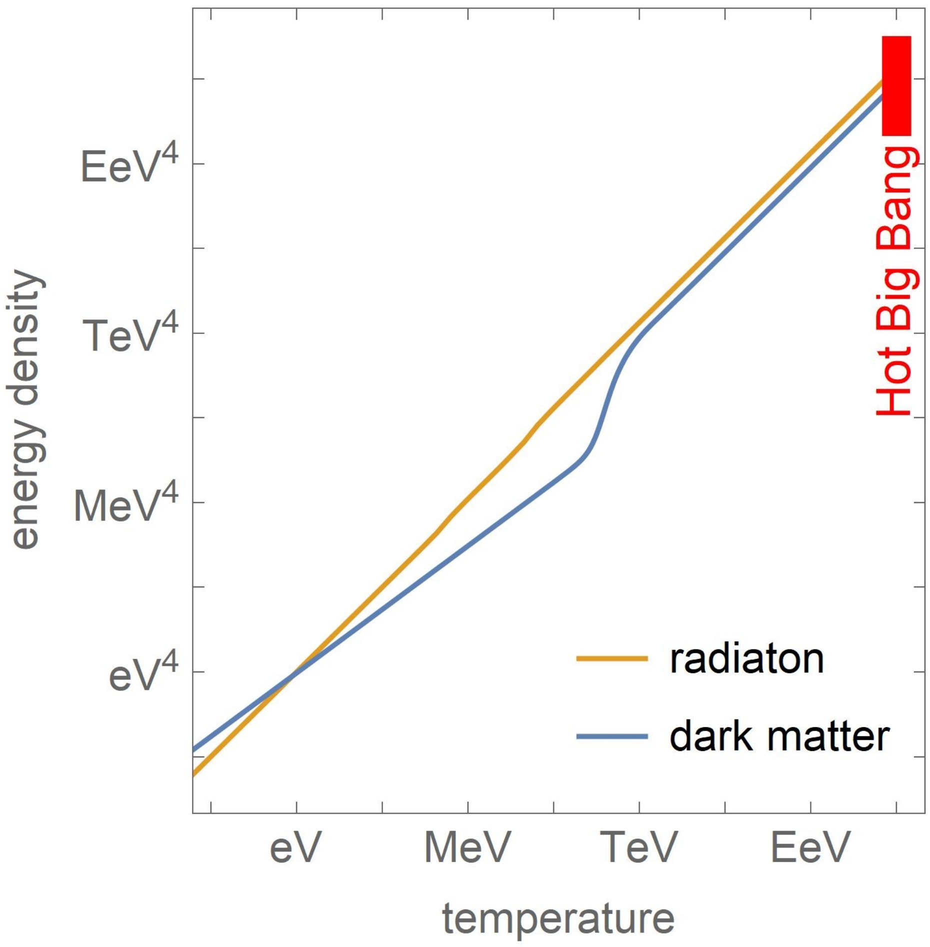
$$\Gamma = Ae^{-S/\hbar}$$

Voloshin et al. 1974, Coleman 1977

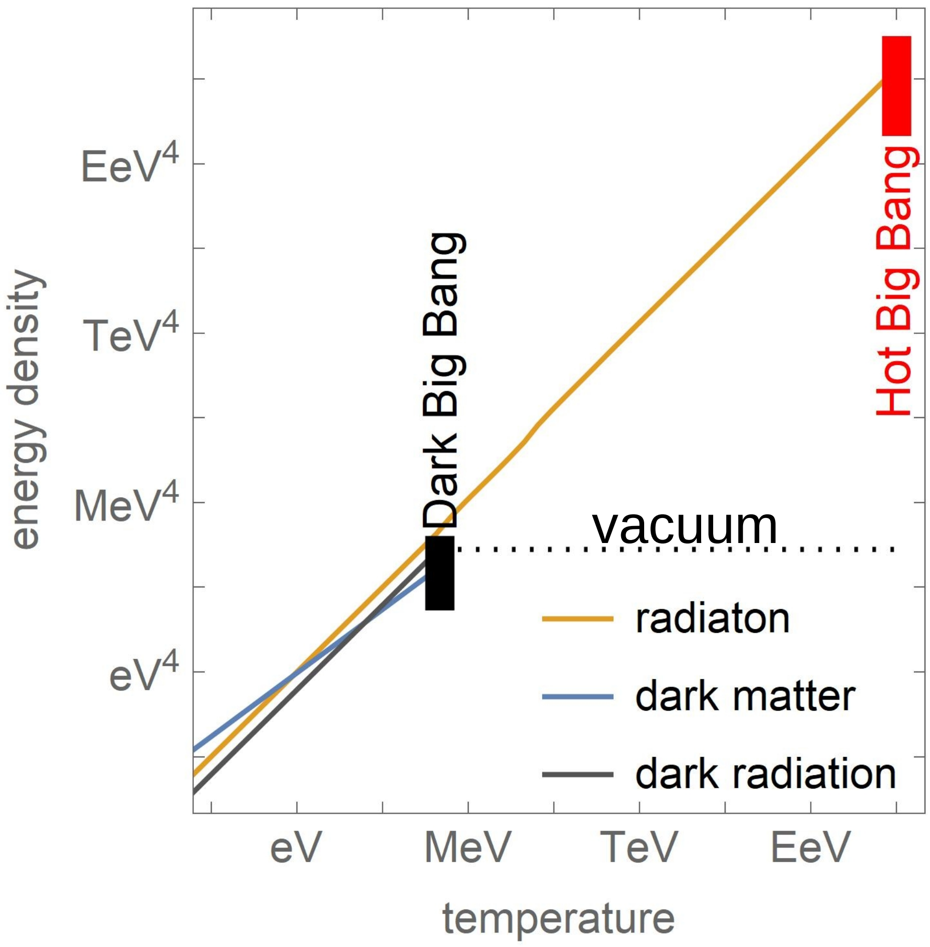
bubble collisions induce plasma of dark particles ϕ, χ, ξ

# Energy Densities

## Standard Cosmology




## Dark Big Bang Cosmology



# Strength of the Dark Big Bang

dark reheating temperature:

$$T_{d*} = \alpha^{1/4} \frac{g_{\text{eff}}(T_*)}{g_d(T_{d,*})} T_* \qquad \alpha = \frac{\rho_{\text{vac}}}{\rho_{\text{rad}}(T_*)}$$

entropies of visible and dark sector are separately conserved, hence

$$\frac{T_d}{T} = \left(\frac{g_{\text{eff}}(T)}{g_{\text{eff}}(T_*)}\right)^{1/3} \left(\frac{g_d(T_{d*})}{g_d(T_d)}\right)^{1/3} \frac{T_{d*}}{T_*}$$

dark radiation contributes to the effictive neutrino number at CMB

Nakai et al. 2020

$$\Delta N_{\text{eff}} = 0.63 \times \left(\frac{\alpha}{0.1}\right) \left(\frac{10}{g_{\text{eff}}(T_*)}\right)^{1/3} \left(\frac{g_d(T_{d*})}{g_d(T_d)}\right)^{1/3}$$

Planck + $H_0$ data: $\Delta N_{\text{eff}} = 0.22 \pm 0.15 \implies \boldsymbol{\alpha \lesssim 0.1}$

Aghanim et al. 2021

# Phase Transition Properties

probability of a point to remain in false vacuum:

Guth, Weinberg 1981

$$P(t) = e^{-I(t)} \qquad I(t) = \frac{4\pi}{3}\int_0^t dt'\,\Gamma\, \underbrace{a^3(t')}_{\text{scale factor}}\, \underbrace{r_c(t,t')}_{\text{comoving radius of past light cone}}$$

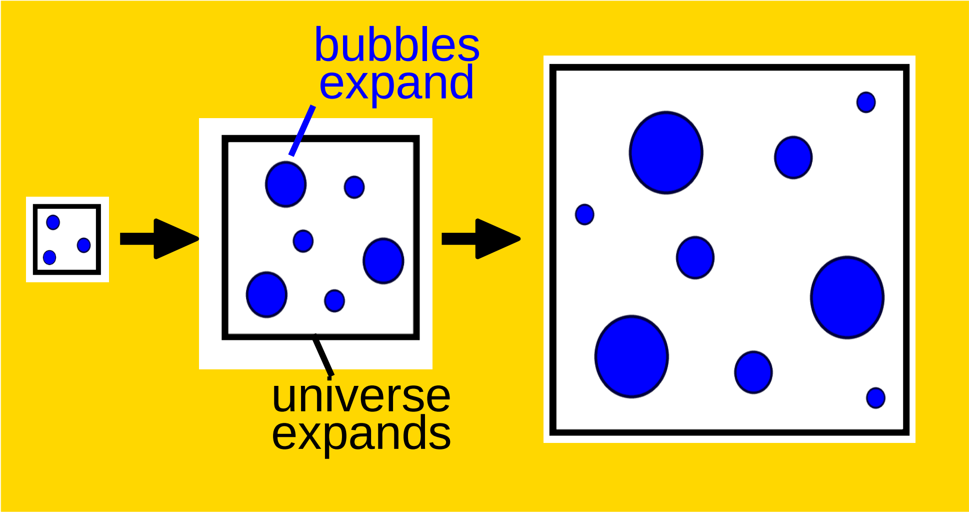
time, duration of phase transition:

$$I(t_*) = 1 \qquad \Delta t = \left(dI/dt\right)^{-1}\Big|_{t=t_*}$$

percolation condition:

Turner, Weinberg, Widrow 1992

$$\left.\frac{d(a^3P)}{dt}\right|_{t=t_*} < 0 \implies \Delta t < \frac{1}{3H_*}$$




Dark Big Bang with constant Γ during radiation-domination:

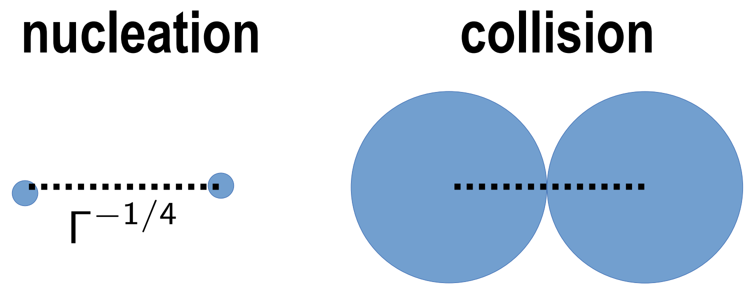
$$t_* = \left(\frac{105}{8\pi\Gamma}\right)^{1/4} = 1.4\,\Gamma^{-1/4} \qquad \Delta t = \frac{1}{8\,H_*}$$

# How late can the Dark Big Bang occur

typical comoving size of the true-vacuum bubbles at collision:

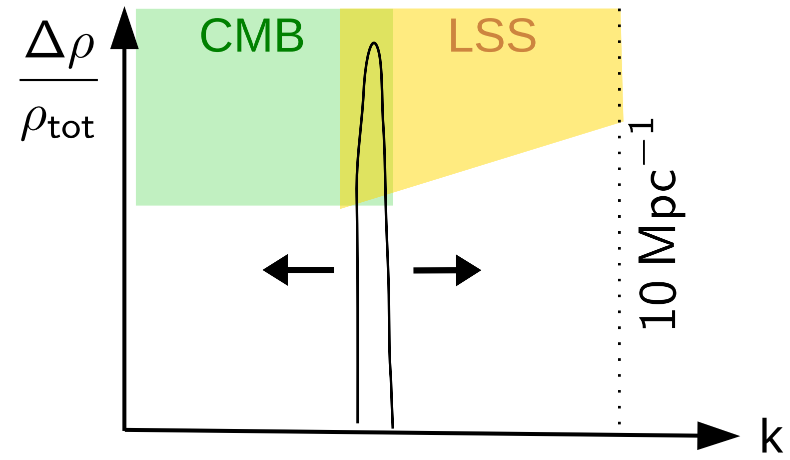
Niedermann, Sloth 2021, Freese, Winkler 2021

$$d \sim \frac{\Gamma^{-1/4}}{a_*} \sim \frac{t_*}{a_*}$$




Dark Big Bang induces density anisotropies peaked at scale

$$k \sim \frac{2\pi}{d} \sim 20\ \mathrm{Mpc}^{-1} \times \left(\frac{\mathrm{yr}}{t_*}\right)^{1/2}$$




peak below CMB & LSS resolution requires

$$\mathbf{t_* \lesssim few \quad years}$$

# Adiabatic Perturbations

during radiation-domination (super-horizon regime)

Bardeen 1980

$$\delta\dot{\rho}_r = -4\rho\delta H - 3H\delta\rho_r$$

$$\delta\dot{H} = -2H\delta H - \frac{1}{6}\delta\rho - \cancel{\frac{\nabla^2\delta P}{12\rho_r}}$$

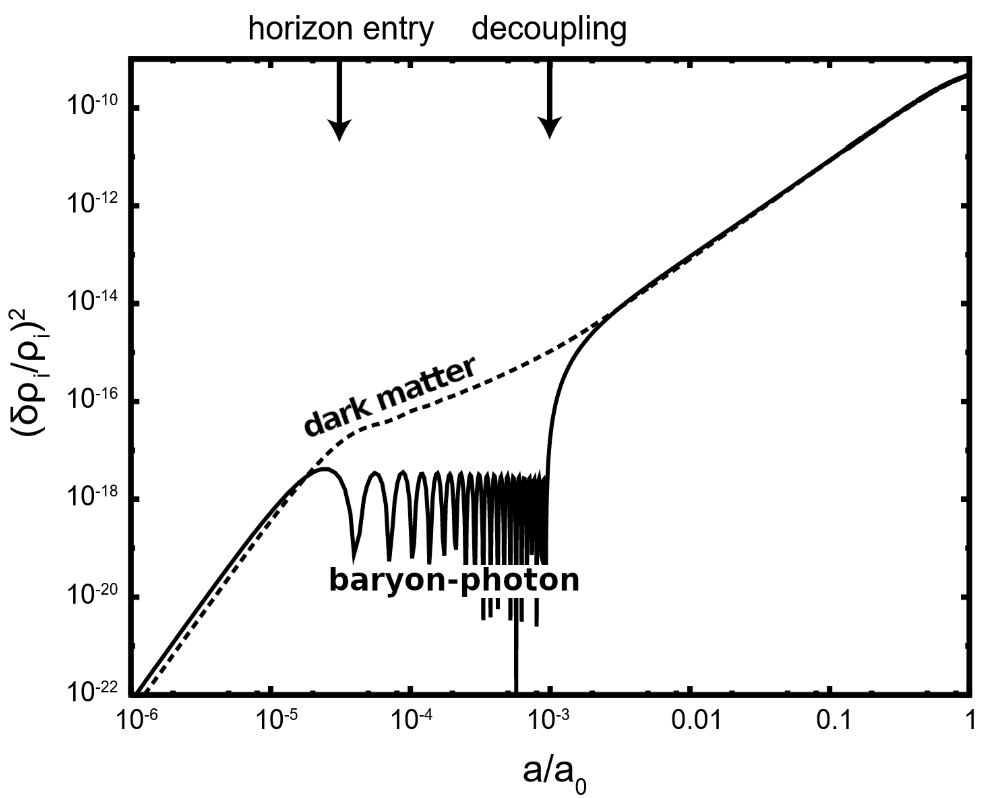
$$\frac{\delta\rho_{r,k}}{\rho_r} = -4\frac{\delta H_k}{H} = \frac{4}{9}\left(\frac{k}{aH}\right)^2\mathcal{R}_k$$

quickly reach asymptotic solution

after dark matter is produced by the Dark Big Bang it quickly picks up the right adiabatic perturbations

$$\delta\dot{\rho}_\chi = -6\rho_\chi\delta H - 3H\delta\rho_\chi$$

$$\Rightarrow \quad \frac{\delta\rho_{\chi,k}}{\rho_\chi} = \left(\frac{1}{3} - \frac{t_*}{3t}\right)\left(\frac{k}{aH}\right)^2\mathcal{R}_k$$




observable modes (LSS) must be be super-horizon at Dark Big Bang

$$\mathbf{t_* \lesssim few\ \ years\ \ (again)}$$

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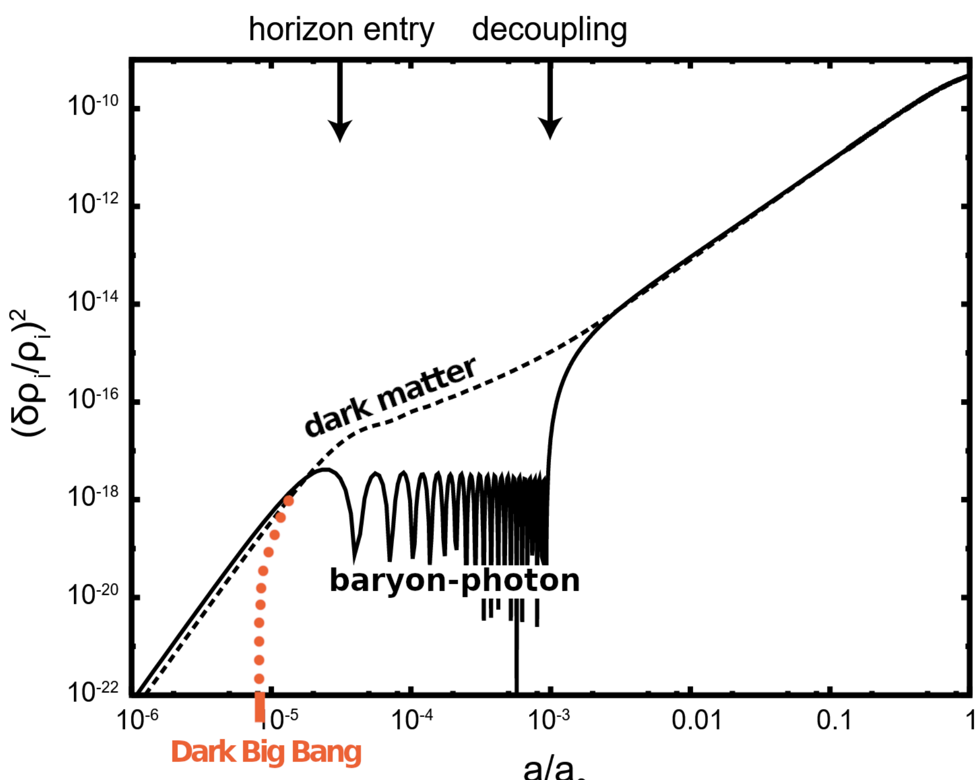
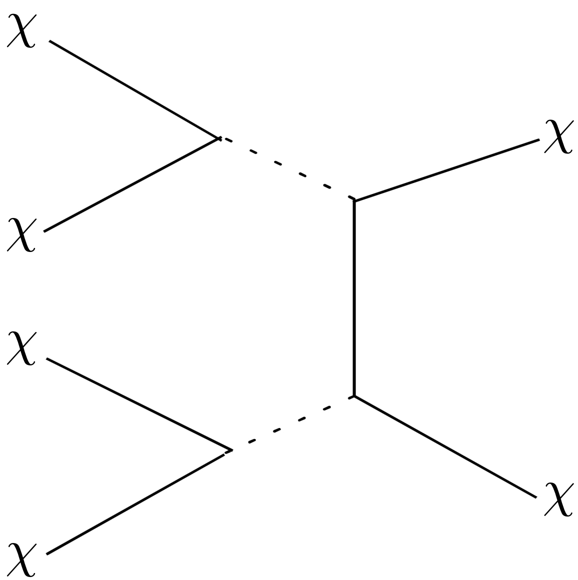


# Light Dark Matter

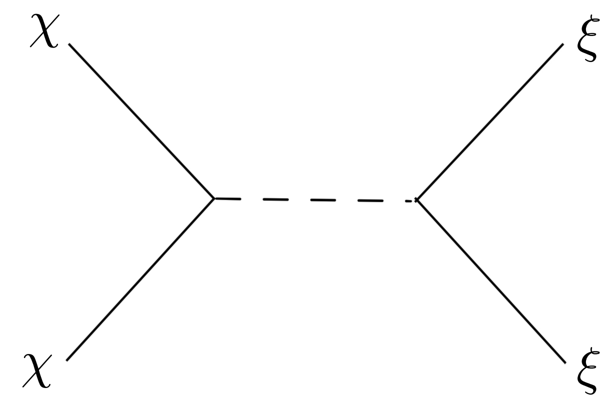
light dark matter ($m_\chi \lesssim T_{d*}$) typically enters thermal equilibrium after the Dark Big Bang

**case 1: only dark matter**




$$\Gamma_{4\to2} = \langle \sigma_{4\to2} v^3 \rangle n_\chi^3$$

**case 2: dark matter + dark radiation**



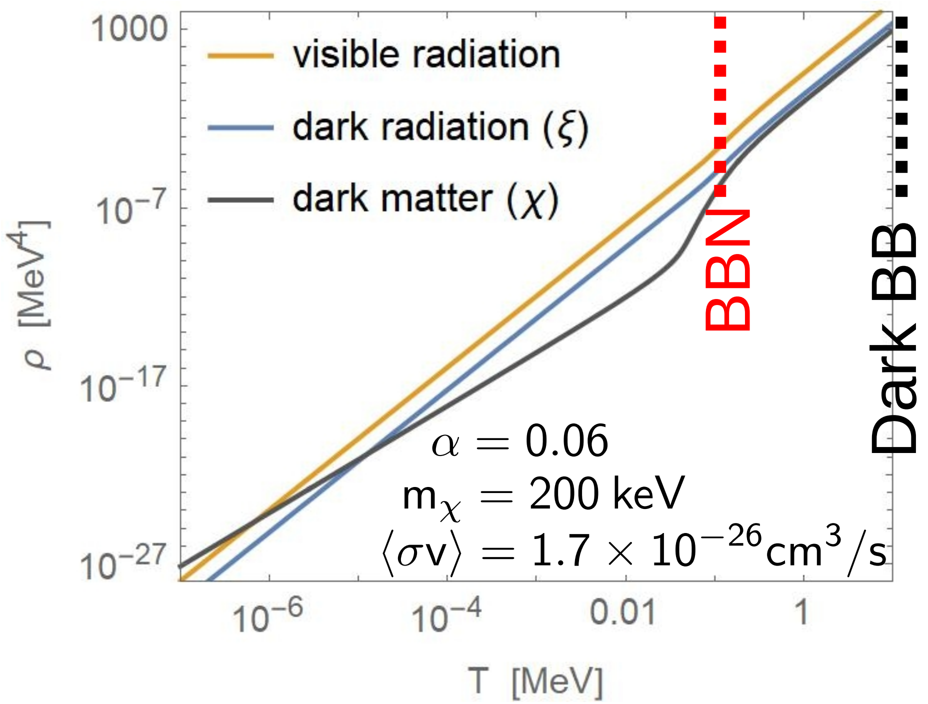

$$\Gamma_{2\to2} = \langle \sigma_{2\to2} v \rangle n_\chi$$

freeze-out from thermal equilibrium when: $\Gamma_{4,2\to2} \simeq H$

# Dark WIMPs

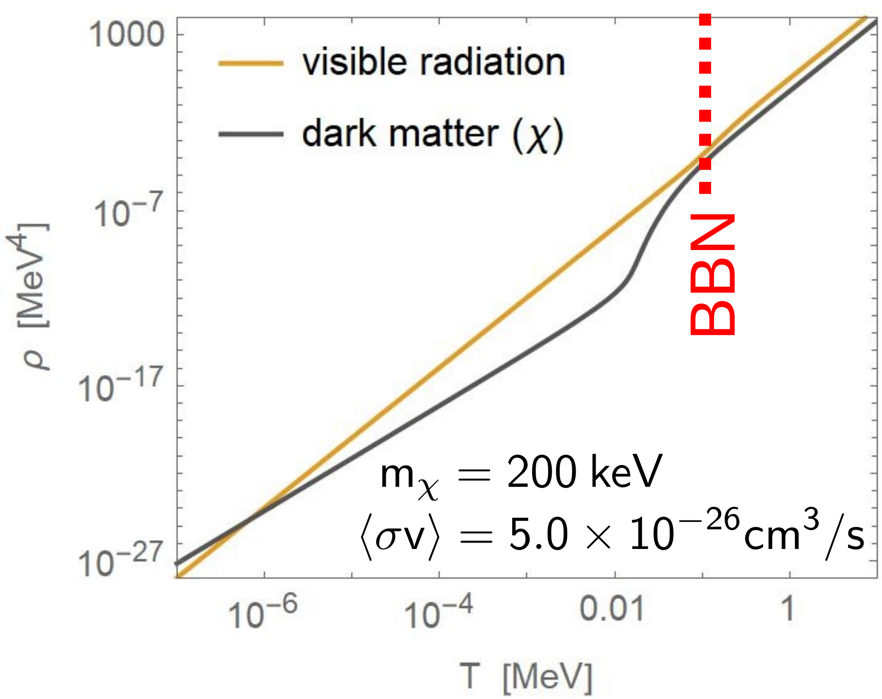
Boltzmann equation: $\dot{n}_\chi + 3H(T)n_\chi = -\langle\sigma v\rangle(n_\chi^2 - n_{\chi,eq}^2(T_d))$

**Dark WIMP**




$$\mathbf{\Delta N_{eff} = 0.4}$$

**WIMP**




$$\mathbf{\Delta N_{eff}(BBN) \simeq 2}$$

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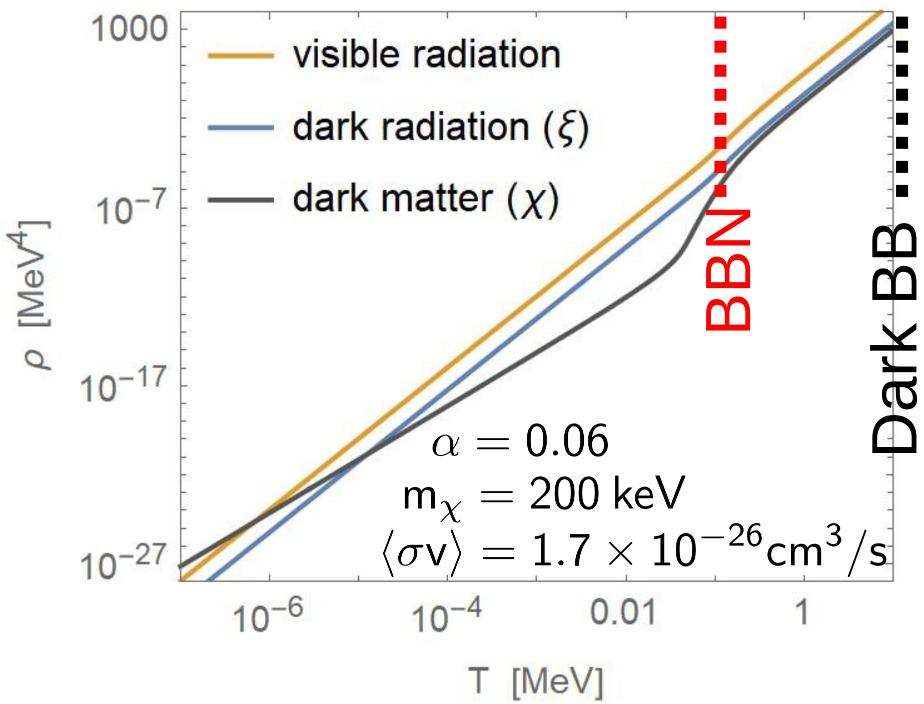


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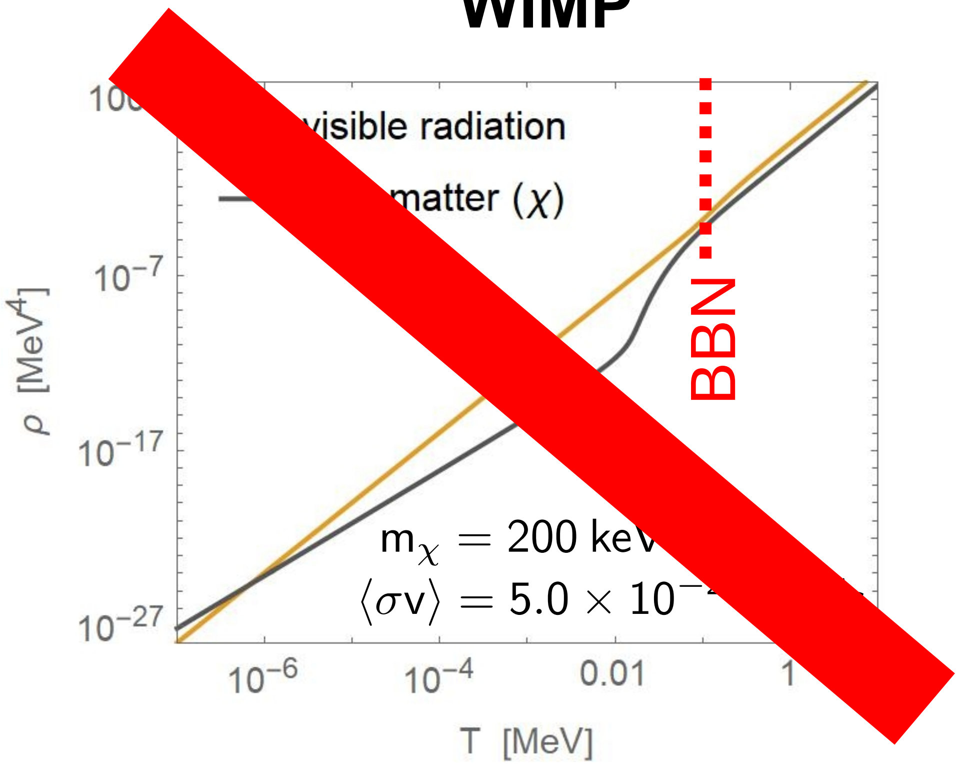



$\mathbf{\Delta N_{eff}(BBN) \simeq 2}$

# Darkzillas (Ultra-Heavy Dark Matter)

Dark Big Bang induces "runaway bubbles"

$$\gamma_w \simeq \frac{R}{R_0} \sim \frac{\Gamma^{-1/4}}{m_\phi^{-1}} \sim \alpha^{1/4}\frac{M_P}{T_*} \sim \mathbf{10^{21}} \times \alpha^{1/4}\frac{\text{MeV}}{T_*}$$

- extremely heavy dark matter accessible $m_{\chi,\text{max}} \sim \gamma_w m_\phi$
  Chung, Kolb, Riotto 1998

dark matter energy/ area (bubble walls treated as external source)
Watkins, Widrow 1992, Falkowski, No 2013

$$\frac{\varepsilon}{A} = \frac{1}{4\pi^2}\int_{4m_\chi^2}^{s_{\text{max}}} ds\, s^{1/2}\, f(s) \int d\Pi_2 |\mathcal{M}(\phi \to \chi\chi)|^2$$

encodes details of bubble collisions: $\propto s^{-2}$ (elastic limit)

matrix element $\propto s$

for perfectly elastic bubble collisions ultraheavy dark matter particles ($m_\chi \sim 10^{16}$ GeV) can be produced efficiently.

# Gravitational Waves from the Dark Big Bang

bubble collisions induce gravity waves with energy density and peak frequency,

$$\rho_{\mathrm{GW},*} \sim \frac{\rho_{\mathrm{vac}}^2 (\Delta t)^2}{M_P^2} \qquad f_* \sim \frac{1}{\Delta t} \quad \frac{1}{8H_*} \text{ for Dark Big Bang}$$

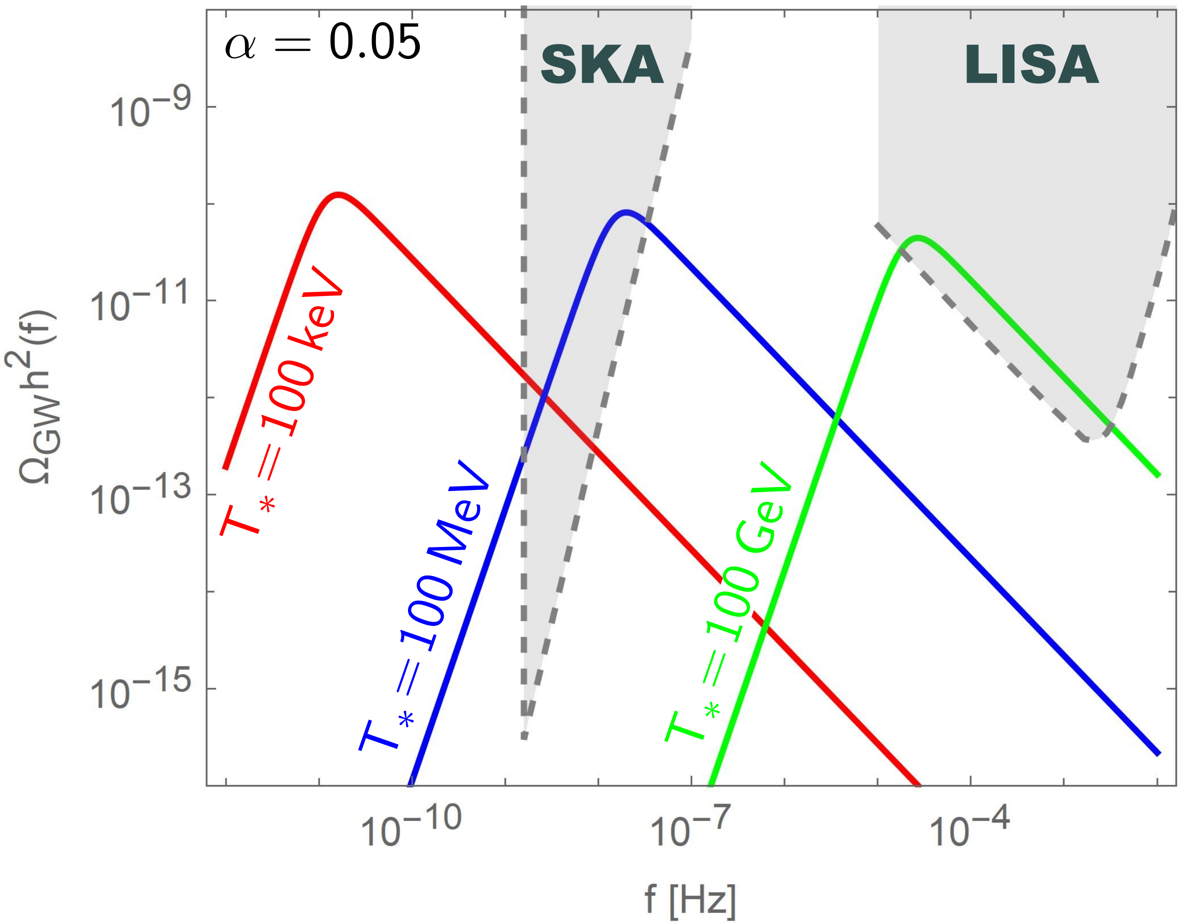
redshifted and expressed in terms of critical density

$$\Omega_{\mathrm{GW}} h^2 (f_*^0) \sim 4 \times 10^{-8} \alpha^2$$

$$f_0^* \sim 2\,\mathrm{nHz} \times \frac{T_*}{10\,\mathrm{MeV}}$$

simulations suggest broken power law spectrum ("envelope approximation")

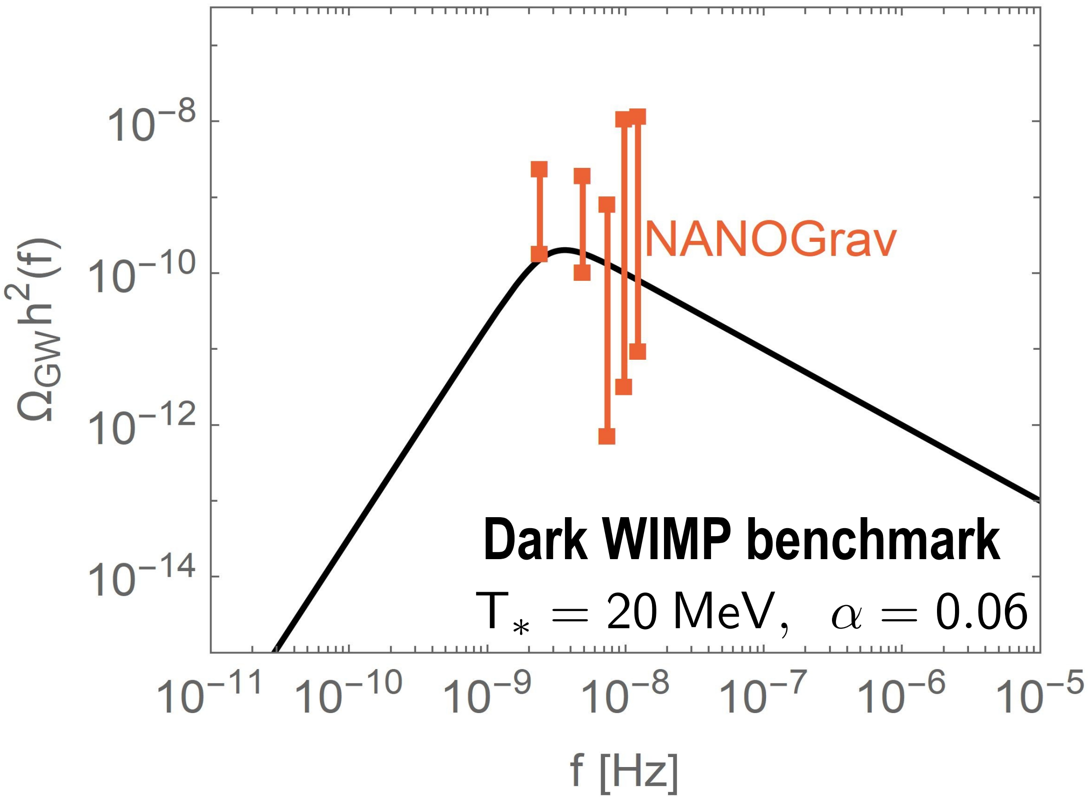
Kosowsky, Turner, Watkins 1993, Huber, Konstandin 2008

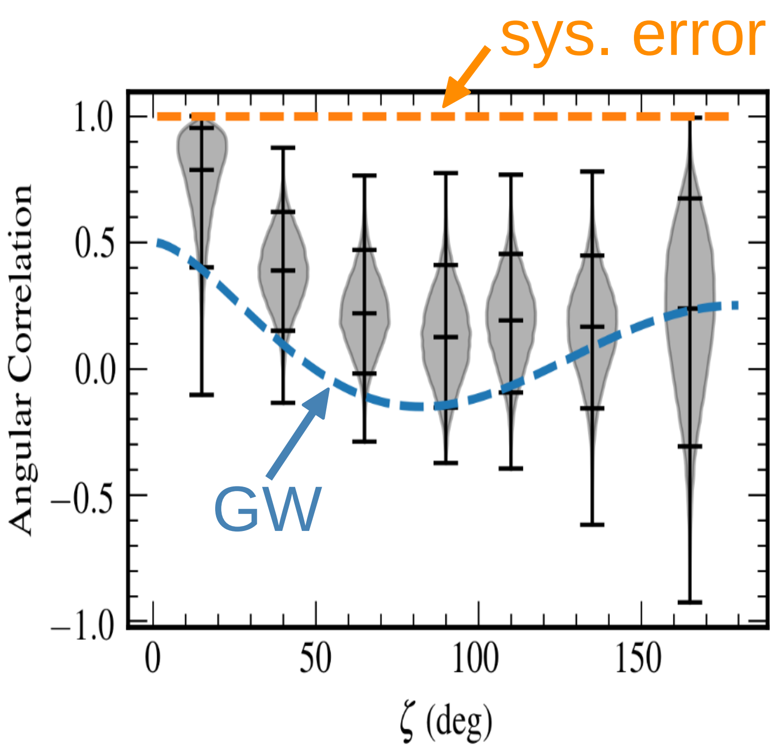


# Pulsar Timing Signals

tentative observation of a stochastic gravitational wave background by the NANOGrav, PPTA and EPTA pulsar timing array experiments

Arzoumanian et al. 2020, Goncharov et al. 2021, Chen et al. 2021




Dark Big Bang at $T_* \sim 10$ MeV can explain PTA signals, dark matter density, ameliorate Hubble tension (through $\Delta N_{\rm eff} \sim 0.3$)

# Summary

- dark matter and dark radiation could stem from a first order phase transition in the dark sector = Dark Big Bang
- Dark Big Bang at $\mathrm{t}_* \lesssim \mathrm{year}$ consistent with CMB
- correct relic density by dark freeze-out (Dark WIMPs) or through bubble collisions (Darkzillas)
- no signal in indirect or direct dark matter detection
- Dark Big Bang testable through gravitational wave signal. Tentative signal at several PTAs consistent with $\mathrm{t}_* \sim \mathrm{ms}$
- dark radiation induced by Dark Big Bang testable through $\Delta N_{\mathrm{eff}}$