

Rescuing Overabundant Dark Matter with a First- Order Phase Transition

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Based on work with A. Medina, and C. Wagner, 2602.16822

The Usual Story

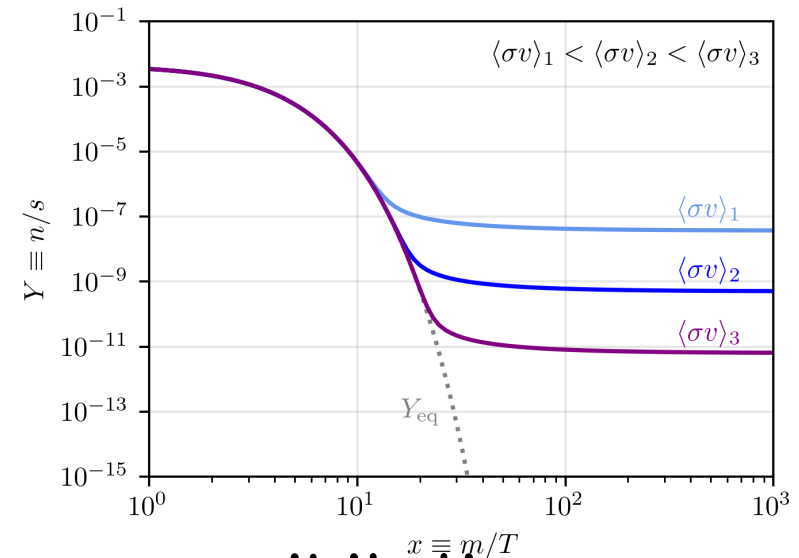
- The WMAP and Planck space observatories measured the DM relic abundance to be $\Omega h^2 = 0.12$
- For a given particle physics model, the DM relic abundance can be calculated by solving the Boltzmann Equation

$$\frac{dn}{dt} = -3Hn - \langle\sigma v\rangle [n^2 - n_{\text{eq}}^2]$$

For WIMP DM, the magic number is $\langle\sigma v\rangle \sim 10^{-26}$ cm^3/s , target for indirect detection experiments

$$\frac{dY}{dx} = -\frac{\langle\sigma v\rangle s}{Hx} [Y^2 - Y_{\text{eq}}^2]$$

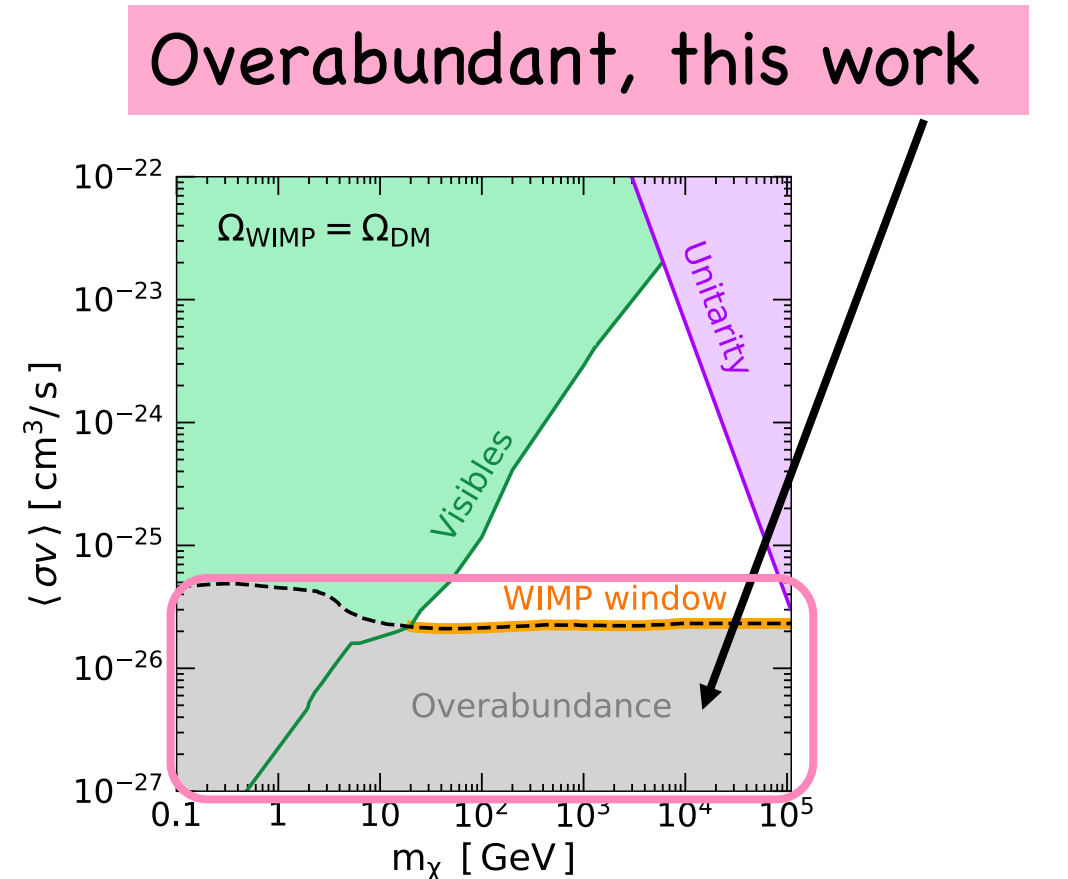
standard freezeout



Larger annihilation cross section
→ smaller relic abundance.

The Parameter Space

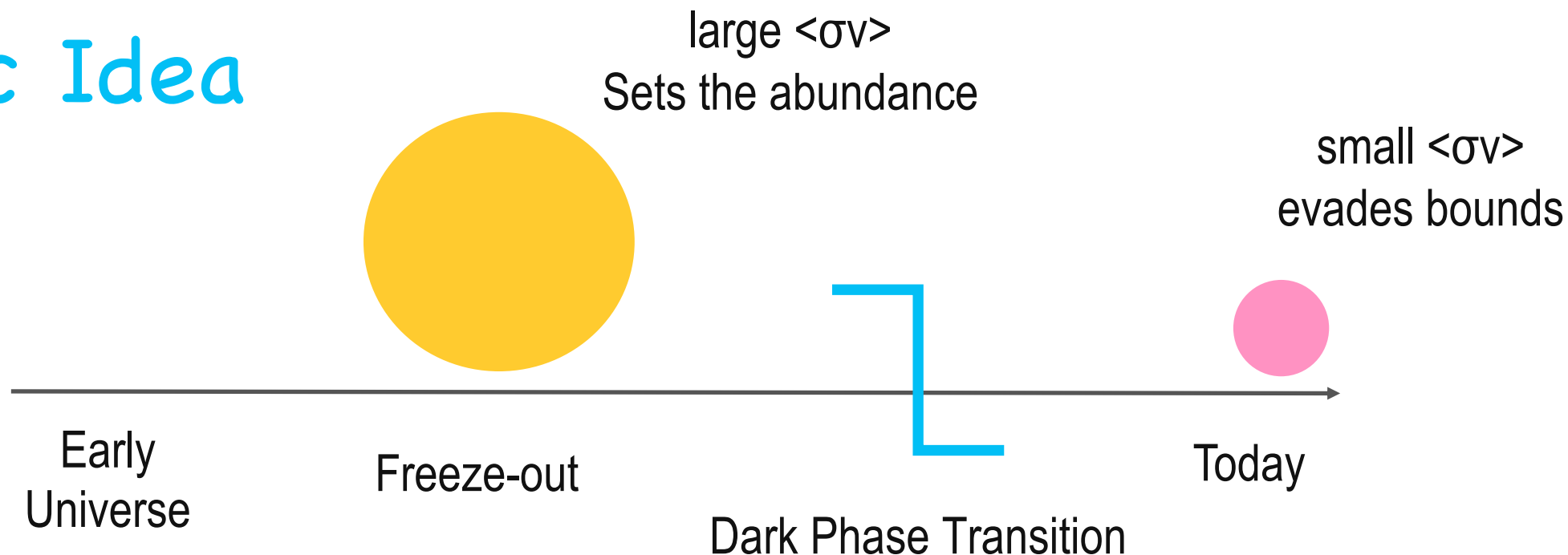
- $\langle\sigma v\rangle$ is constrained by DM indirect detection experiments
- Available parameter space is closing due to indirect searches (“visible”) and theoretical bounds (“unitarity”)
- The **WIMP window** is very narrow
- Sub-10 GeV thermal relic is already in tension with indirect detection -> nonstandard cosmological history



Leane, Slatyer, Beacom, Ng 2018

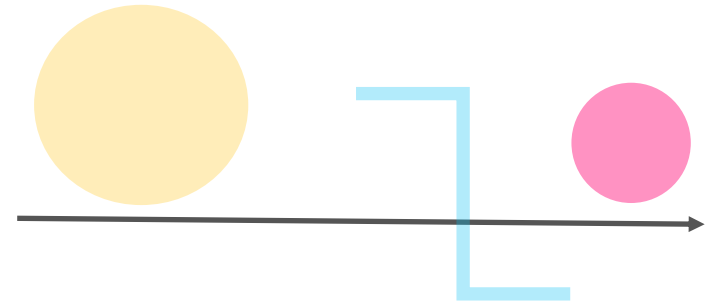
Can models with lower cross sections yield the observed DM abundance?

Basic Idea



- Annihilation Today (probed by indirect detection) \neq Annihilation at Freeze Out (sets the relic abundance)
- Idea: Have the DM annihilate efficiently early on, set the relic abundance, then a phase transition happens, after the phase transition the annihilation cross section is suppressed

Dark Photons



- Dark Sector: Dirac fermion ψ , dark photon A' , dark Higgs Φ . The dark photon has a kinetic mixing with the SM gauge boson

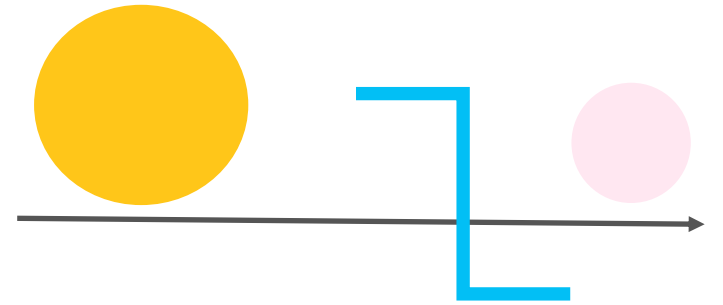
$$\Delta\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2c_W}F'_{\mu\nu}B^{\mu\nu} + \bar{\psi}(iD_\mu\gamma^\mu - m_\psi)\psi + D_\mu\Phi^*D_\mu\Phi - V(\Phi)$$

- Small kinetic mixing, and/or heavy mediator leads to small annihilation cross section today

$$\psi\bar{\psi} \rightarrow A'^* \rightarrow f\bar{f},$$

- Overabundant when inferred from indirect detection

A Dark Phase Transition



- What if the dark Higgs undergoes a phase transition?
- The early Universe is in the symmetric phase, dark photons are massless
- The annihilation is dominated by $\psi\bar{\psi} \rightarrow A' A'$
- The annihilation cross section is $\langle\sigma v\rangle = \frac{g_D^4}{16\pi m_\psi^2} + \dots$, No ϵ or m'_A dependence
- If the dark Higgs phase transition happens after the freezeout,

$$\Omega_D h^2 = \frac{2.5 \times 10^{-10} \text{ GeV}^2}{\langle\sigma v\rangle},$$

The relic abundance is set at the symmetric phase, rather than at the broken phase

Further Dilution from the Phase Transition

- The phase transition is generically strongly supercooled
- Vacuum energy release reheats the plasma and injects entropy
- Entropy injection dilutes n/s : another reduction of the relic density

Phenomenology

PH, A. Medina, and C. Wagner, 2602.16822

- For a given DM mass, calculate the dark gauge coupling by requiring the right relic abundance

$$\langle\sigma v\rangle = \frac{g_D^4}{16\pi m_\psi^2} + \dots,$$

- Require the dark sector to be in thermal equilibrium with the SM

$$\epsilon g_D \gtrsim 10^{-7} \sqrt{\frac{m_\psi}{\text{GeV}}}.$$

- Dark photon mass to be slightly above the dark matter mass, so that the $\psi\bar{\psi} \rightarrow A'A'$ is kinematically suppressed in the broken phase, and the annihilation is dominated by $\psi\bar{\psi} \rightarrow A'^* \rightarrow f\bar{f}$,
- With the dark gauge coupling, kinetic mixing, and mass of DM, and dark photon, the direct detection is easily within the current limit

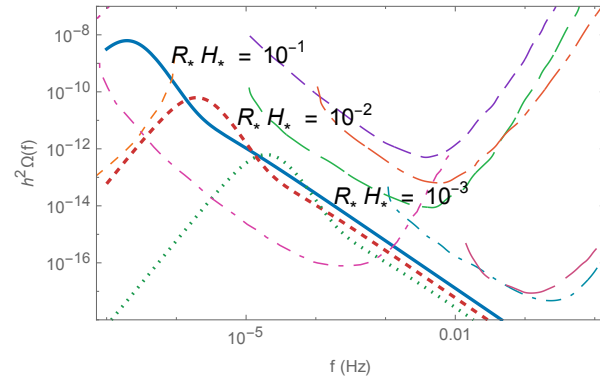
Get the right relic abundant for DM that is naively overabundant by 8–11 orders of magnitude

GW signal

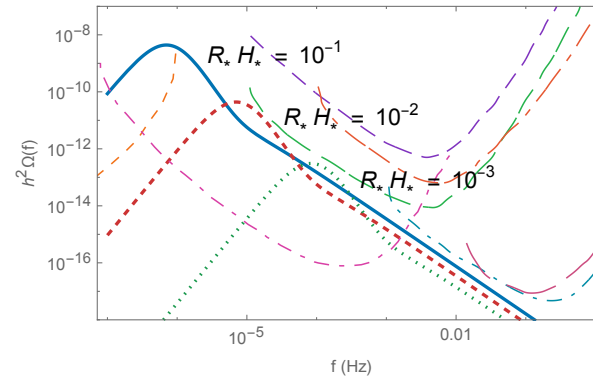
- GW signal is determined by α , β , T_{PT} , and v_W
- Phase Transition temperature. Require the phase transition happens after the freezeout, $T_{PT} \sim \frac{T_{fo}}{3} \sim \frac{m_\psi}{100}$
- Typically, large α ($m_{A'} > m_\psi \gg T_{PT}$), $\left(\frac{\alpha}{\alpha+1}\right)^2$ is saturated)
- With large α , $v_W \rightarrow 1$
- Only one free parameter, the duration of the phase transition / mean bubble separation

GW signal

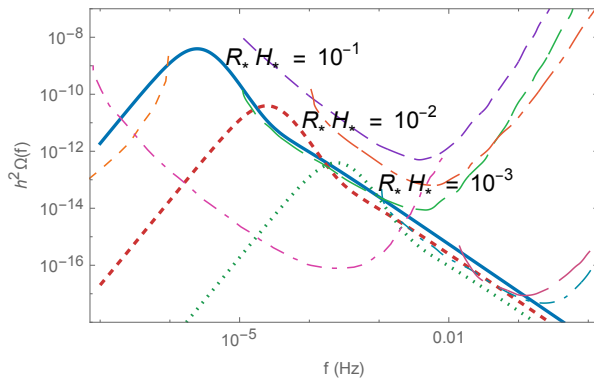
PH, A. Medina, and C. Wagner, 2602.16822



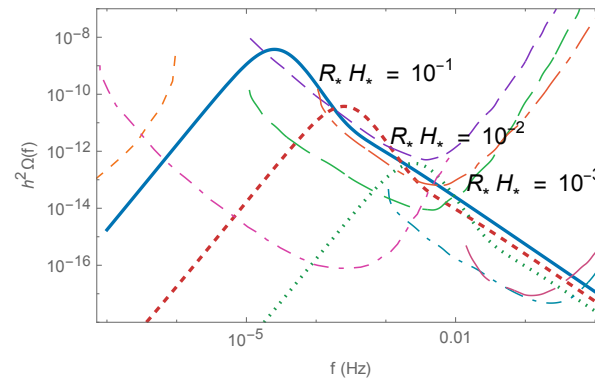
(a) $m_\psi = 10$ GeV



(b) $m_\psi = 30$ GeV



(c) $m_\psi = 100$ GeV



(d) $m_\psi = 1000$ GeV

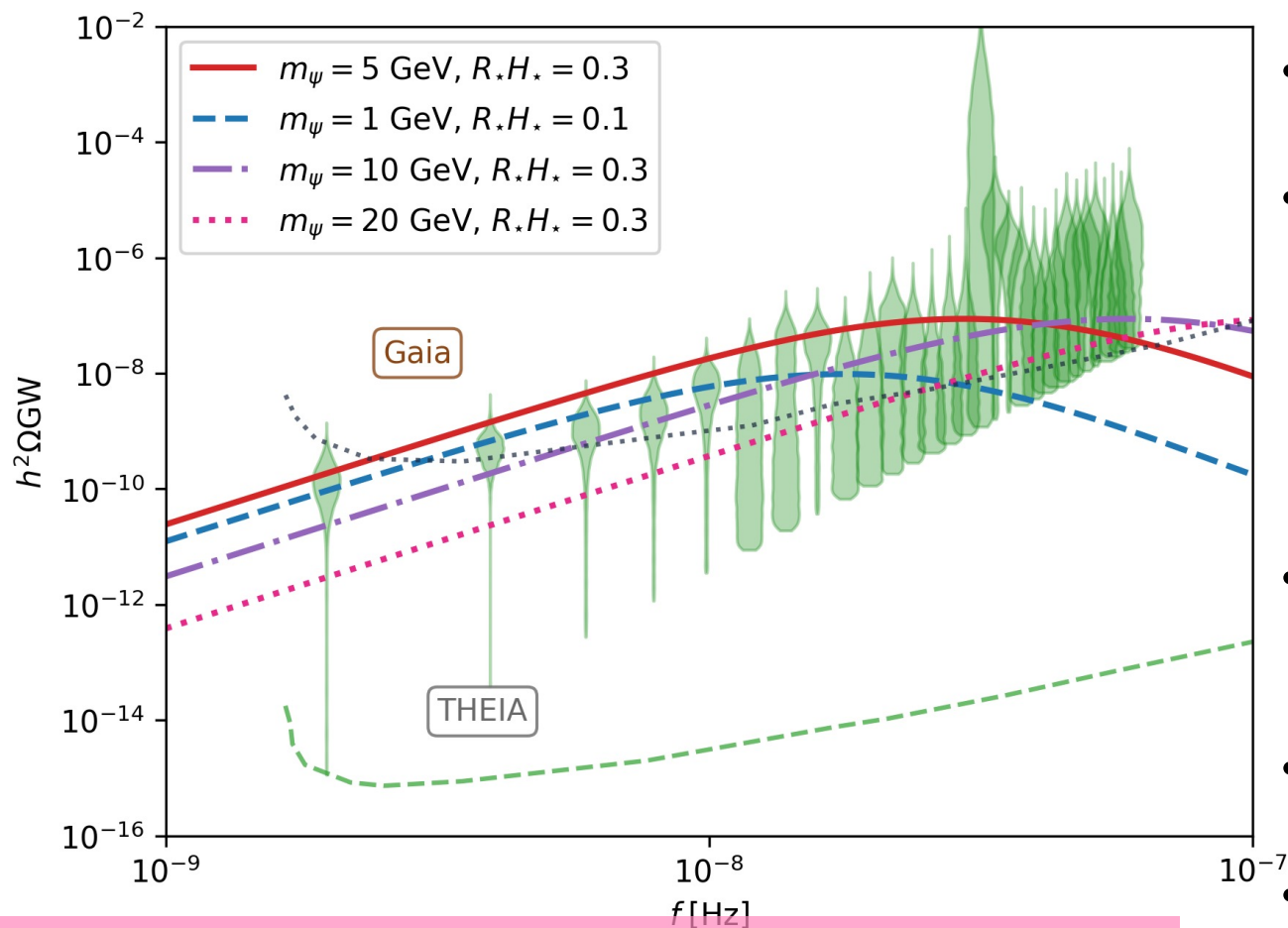
- THEIA
- μ Ares
- LISA
- Taiji
- TianQin
- BBO
- DECIGO

GW signal can be probed by upcoming experiments

Lighter DM, 1 – 10 GeV

- In this mass range, the thermal relic is under serious pressure
- The canonical $3 \times 10^{-26} \text{ cm}^3\text{s}^{-1}$ is excluded from direct detection, and a dark phase transition provides a way to suppress the late time annihilation
- Phase Transition temperature, 10 – 100 MeV, which pushes the GW into the nano-Hz frequency bands

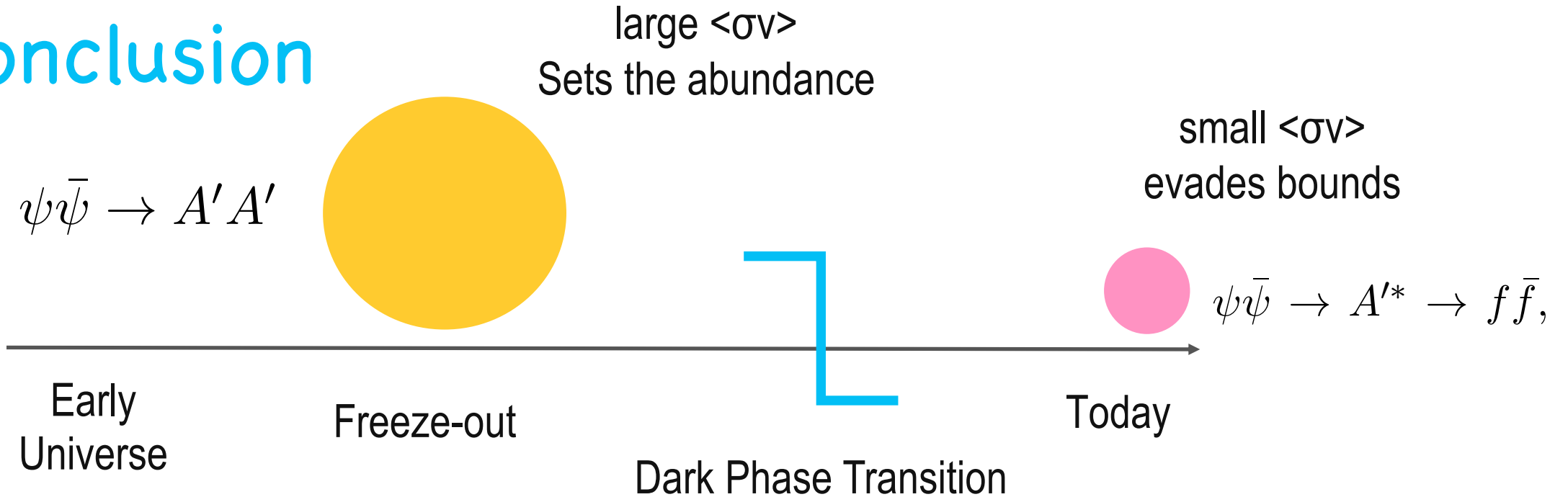
GW signal – Viable Fit to NANOGrav



- Reasonable fit for 5 GeV, and 10 GeV DM
- For 5 GeV, the peak frequency is within the observable band of Nanograv. Signal is slightly on the higher end for low frequencies and slightly on the lower end for high frequencies
- For 10 GeV, the peak frequency is higher, so the signal is slightly on the lower end for lower frequencies
- Lighter DM, can not fit the high frequencies
- Heavier DM, peak frequency is too high

A Dark phase transition link relic abundance, CMB safety, and nano-Hz GWs

Conclusion



- Propose a mechanism to suppress late-time annihilation, which suggests overabundant dark matter
- Before the phase transition, dark photon is massless, the dominant annihilation channel is $\psi\bar{\psi} \rightarrow A'A'$
- After the phase transition, dark photon is massive, and the dominant annihilation channel is instead $\psi\bar{\psi} \rightarrow A'^* \rightarrow f\bar{f}$,
- GW signal is potentially testable by future GW experiments or PTA