Reconstructing Non-standard Cosmologies with Dark Matter

Paola Arias, NB, Alan Herrera, Carlos Maldonado – arXiv:1906.04183 [hep-ph]
NB, Fazlollah Hajkarim – arXiv:1905.10410 [astro-ph.CO]
NB, Catarina Cosme, Tommi Tenkanen, Ville Vaskonen – arXiv:1806.11122 [hep-ph]
NB, Catarina Cosme, Tommi Tenkanen – arXiv:1803.08064 [hep-ph]

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MOCa
October 1st, 2019

Reconstructing the Equation of State of the Early Universe

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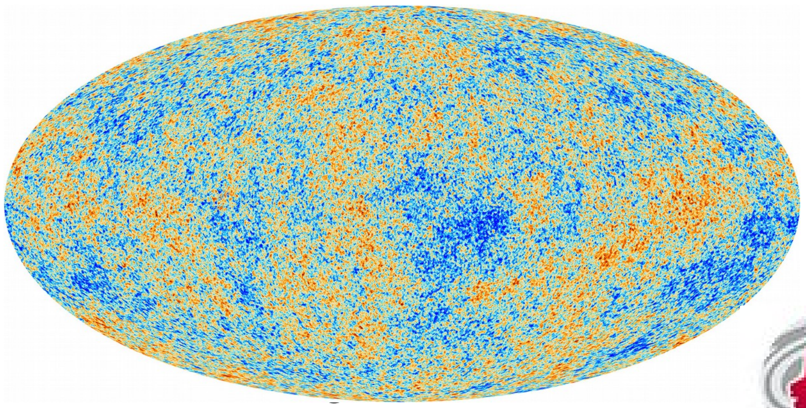
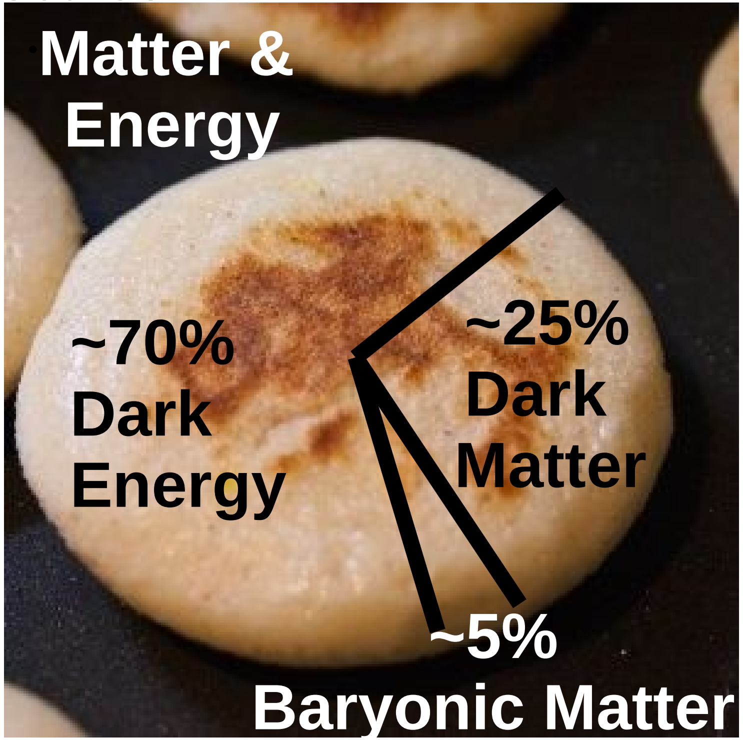
Evidences for Dark Matter

Several observations indicate the existence of non-luminous Dark Matter (missing force) at very different scales!

* Galactic rotation curves
* RC in Clusters of galaxies
* Clusters of galaxies
* CMB anisotropies





planck

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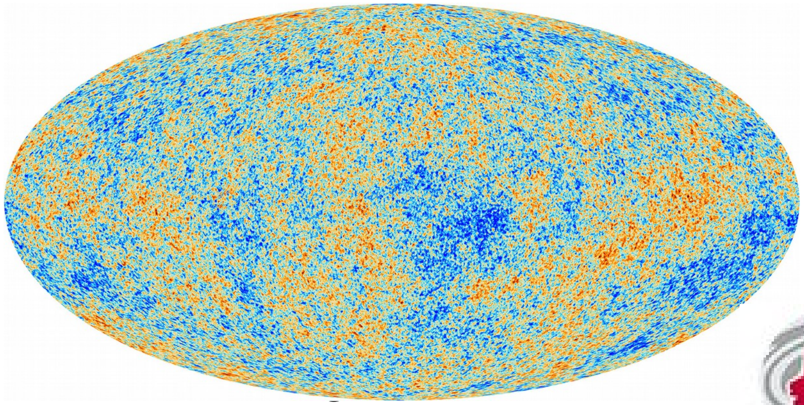
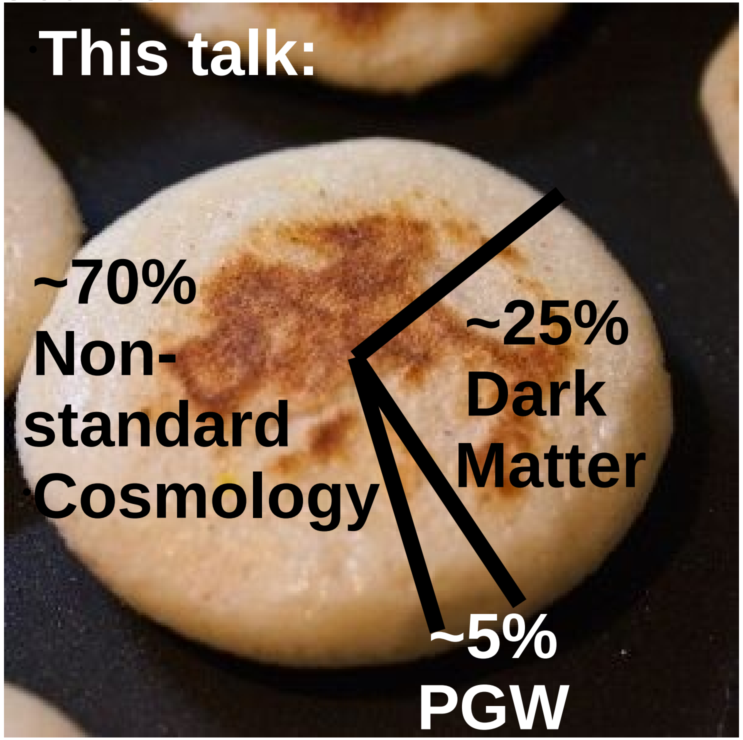
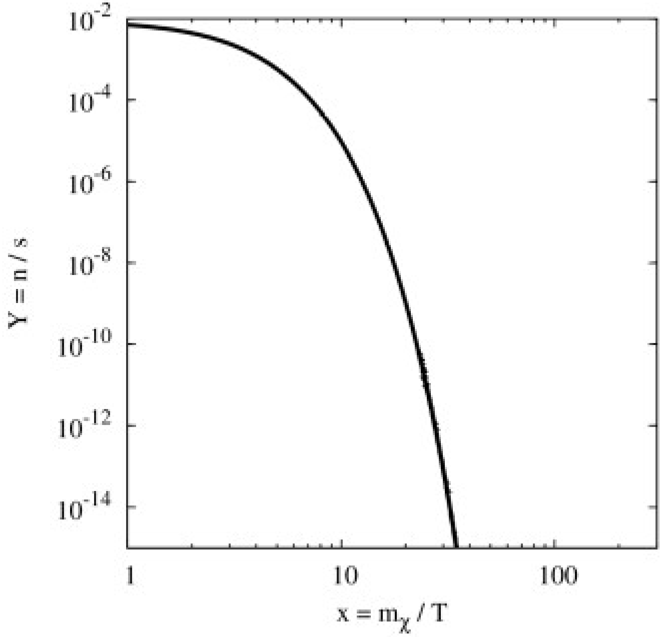


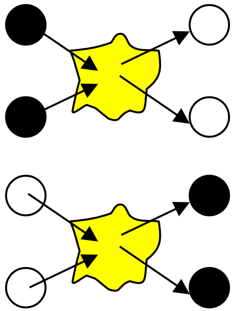


How was Dark Matter produced in the Early Universe?

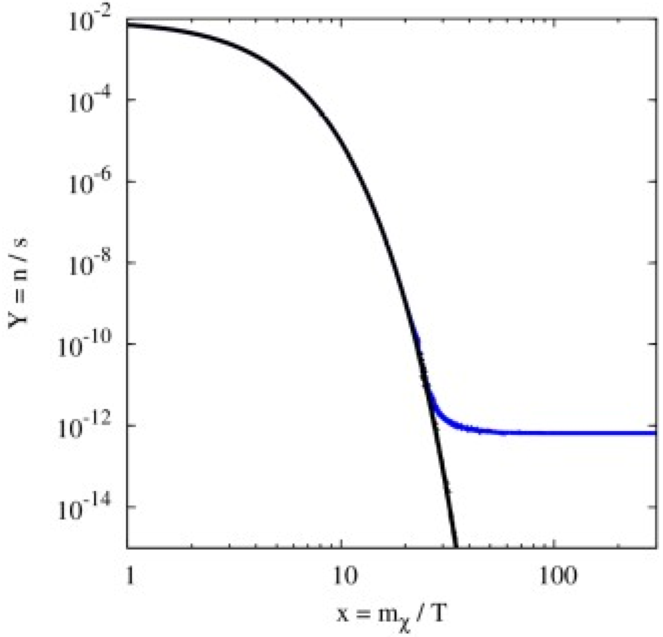
WIMP Dark Matter



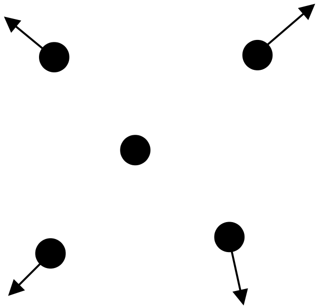
Early Universe:
DM in full **thermal equilibrium**
with the Standard Model.



WIMP Dark Matter

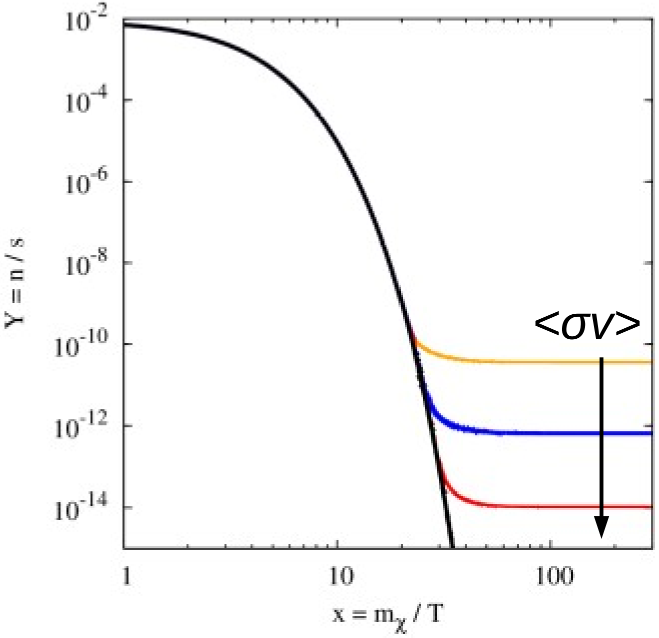


Due to the expansion of the Universe DM particles fall **out of chemical equilibrium** and cannot annihilate anymore.



A relic density of DM is obtained which remains constant.

WIMP Dark Matter



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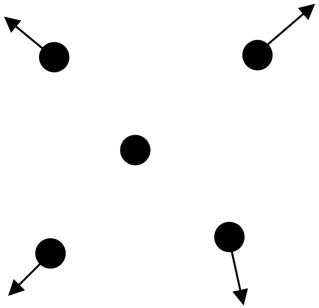
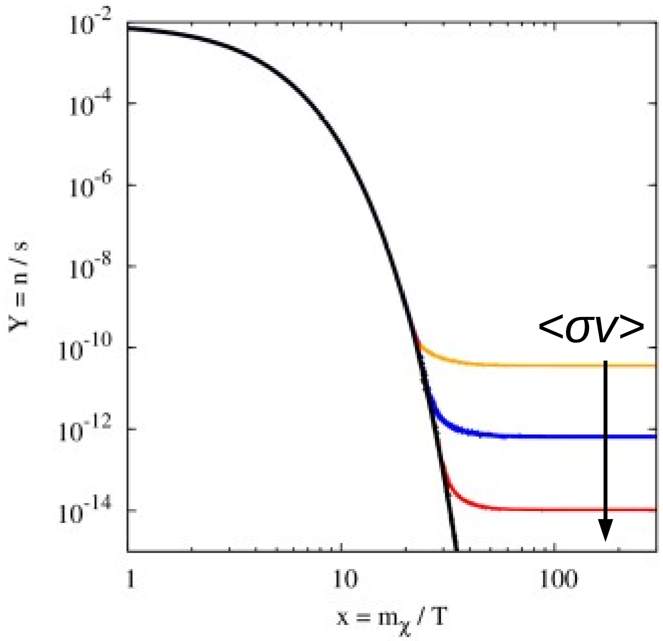


A particle with very weak interactions decouples earlier, having a larger relic density.

A relic density of DM is obtained which remains constant.

A particle with stronger interactions keeps in equilibrium for longer, and is more diluted.

WIMP Dark Matter



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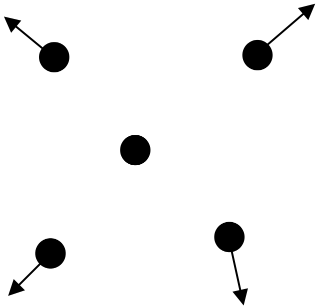

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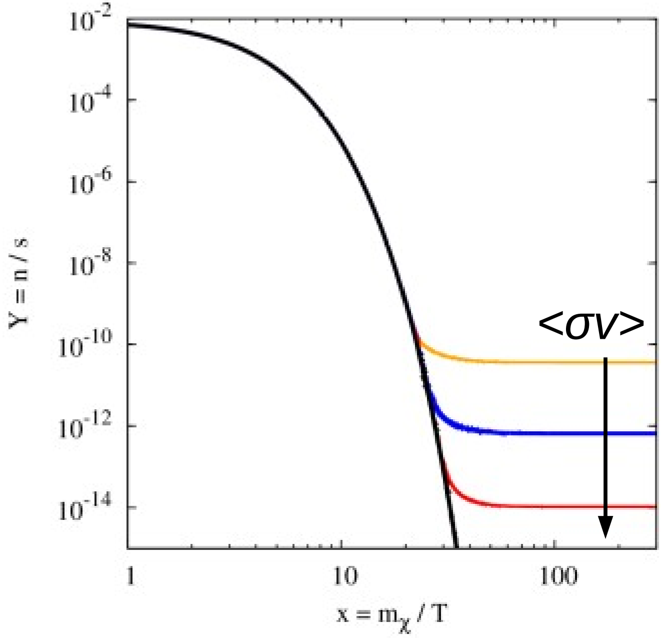
→ ***Collisionless cold WIMP*** Dark Matter

WIMP Dark Matter



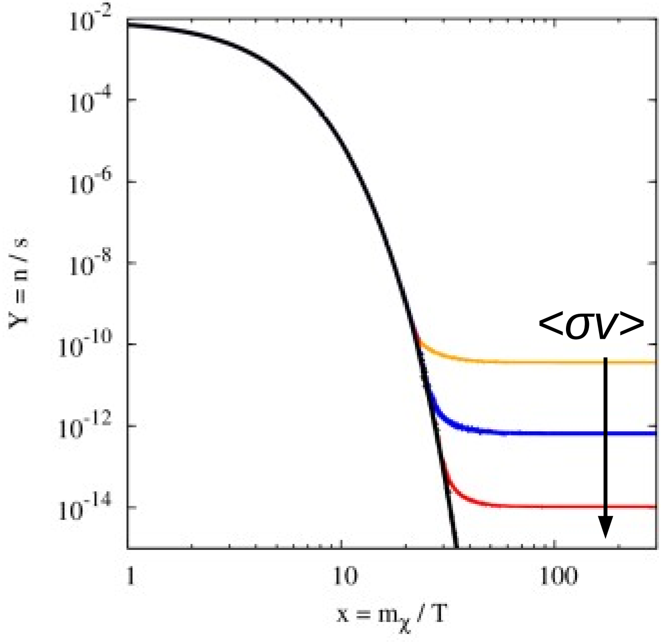
WIMP DM typically requires:

$\langle \sigma v \rangle$ ~ few 10^{-26} cm^3/s

* GeV to TeV masses
* *O*(1) couplings DM-SM

→ Independent from initial conditions!

WIMP Dark Matter



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$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$

WIMP Dark Matter

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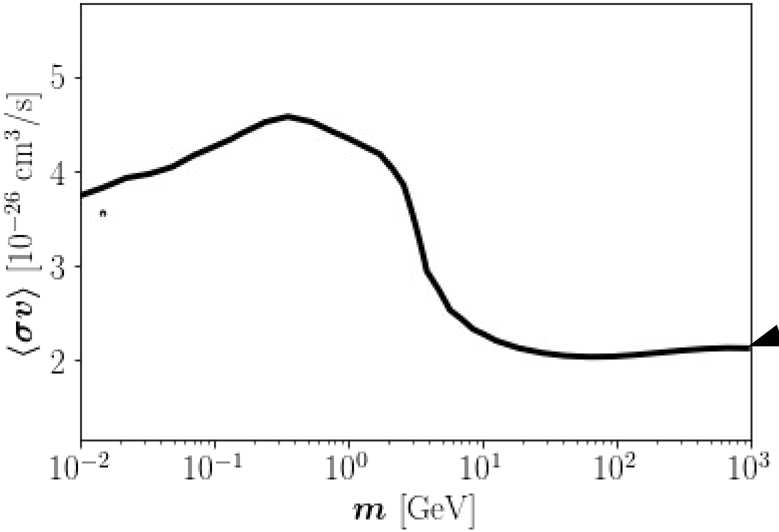
Common lore:



* <σv> ~ 10^{-26} cm^3/s:
Standard WIMP mechanism

WIMP Dark Matter

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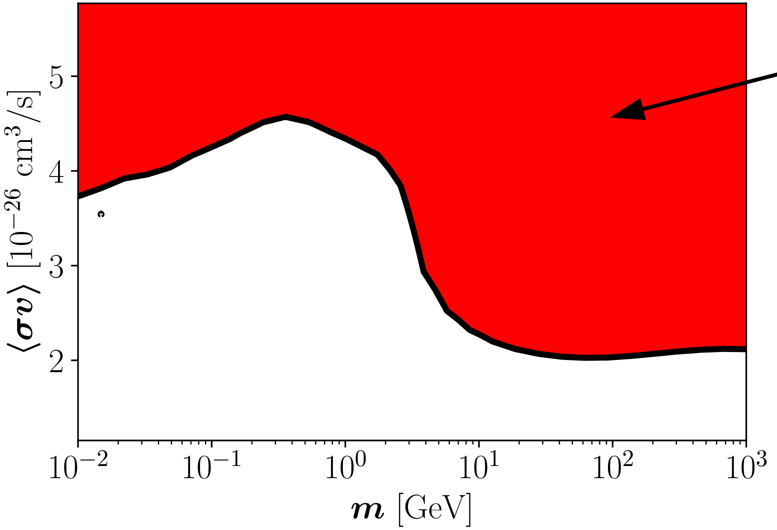

Common lore:

* <σv> >> 10^{-26} cm^3/s:
  DM underproduction
  → Multi-component DM

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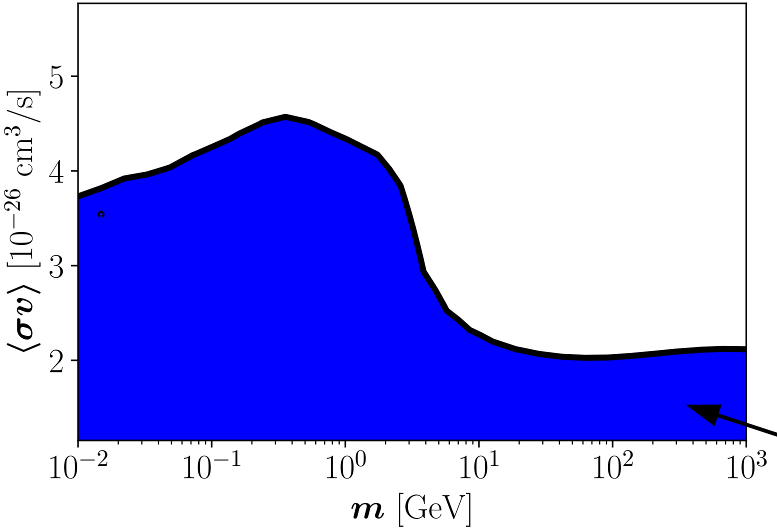
WIMP Dark Matter



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Common lore:

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  DM underproduction
  → Multi-component DM

* <*σv*> ~ 10^{-26} cm^3/s:
  Standard WIMP mechanism

* <*σv*> << 10^{-26} cm^3/s:
  DM overproduction = Universe overclosed
  → Non-standard Cosmology

“Standard” Cosmology

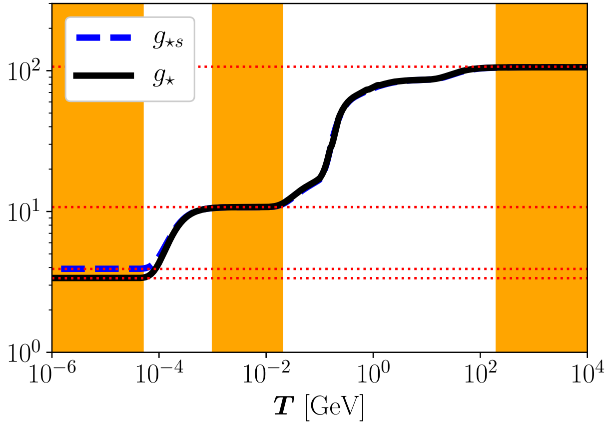
→ **Early Universe dominated by SM radiation**

$$\rho_R(T) \equiv \frac{\pi^2}{30}\, g_\star(T)\, T^4$$

Hubble expansion rate $$H = \sqrt{\frac{\rho_R}{3\, M_P^2}}$$

Entropy is conserved $$s(T) = \frac{2\pi^2}{45}\, g_{\star s}(T)\, T^3,$$

Temperature scaling $$T \propto \frac{1}{a}$$



Non-standard Cosmology

→ **Early Universe dominated by a non-SM component ϕ**

ω: equation of state

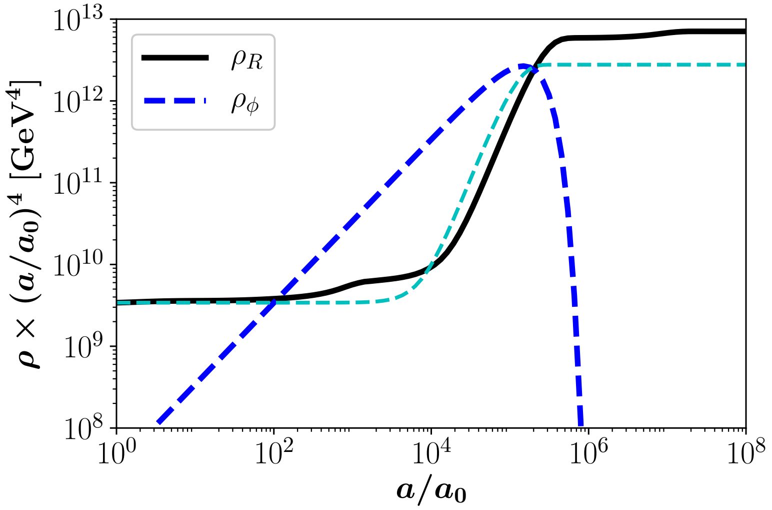
Γ_ϕ: total decay width into SM radiation

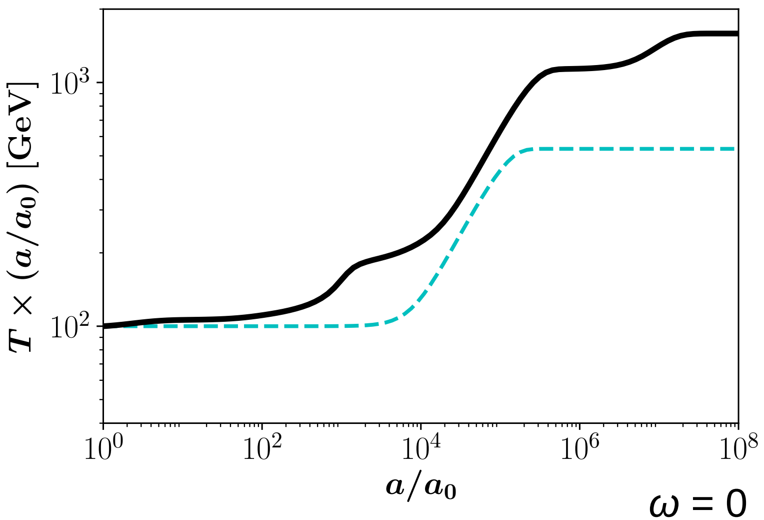
$$\frac{d\rho_\phi}{dt} + 3(1+\omega)\, H\, \rho_\phi = -\Gamma_\phi\, \rho_\phi$$

$$\frac{d\rho_R}{dt} + 4\, H\, \rho_R = +\Gamma_\phi\, \rho_\phi$$

Hubble expansion rate $H = \sqrt{\frac{\rho_\phi + \rho_R}{3\, M_P^2}}$

Non-standard Cosmology



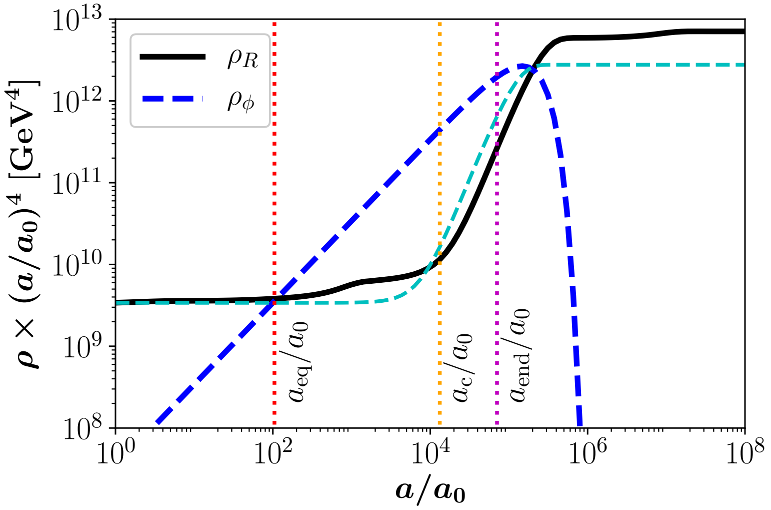


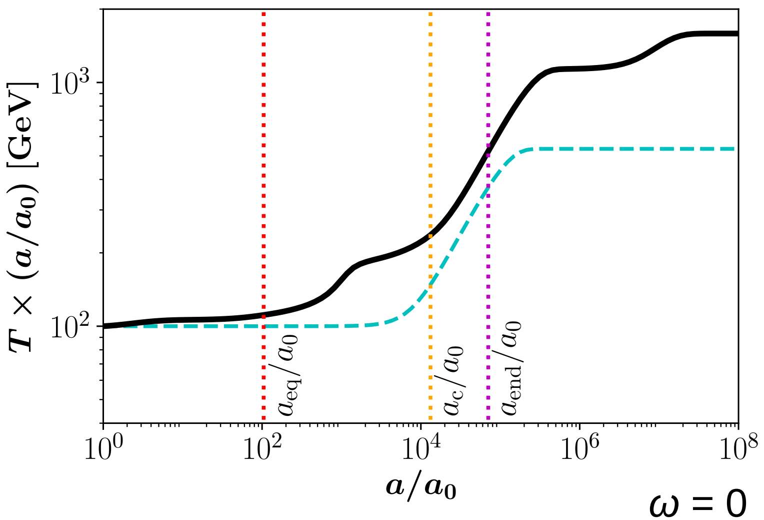
ω = 0
(non-relativistic matter)

$$\frac{d\rho_\phi}{dt} + 3(1+\omega)\, H\, \rho_\phi = -\Gamma_\phi\, \rho_\phi$$

$$\frac{ds}{dt} + 3\, H\, s = +\frac{\Gamma_\phi\, \rho_\phi}{T}$$

Non-standard Cosmology

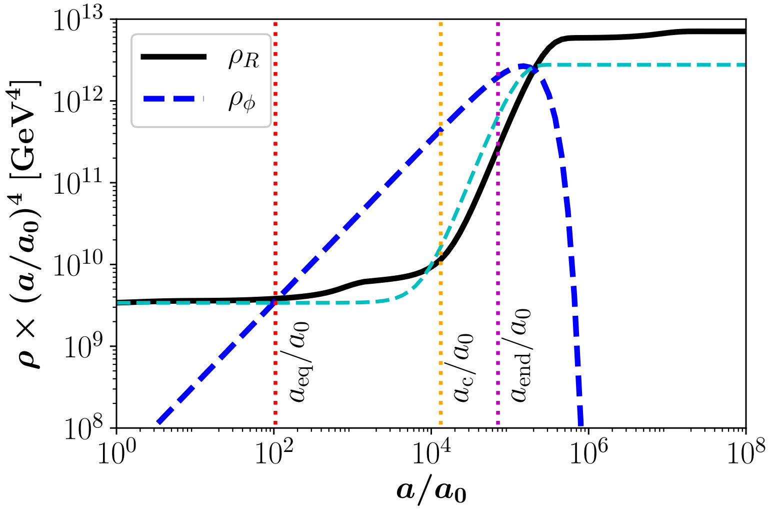


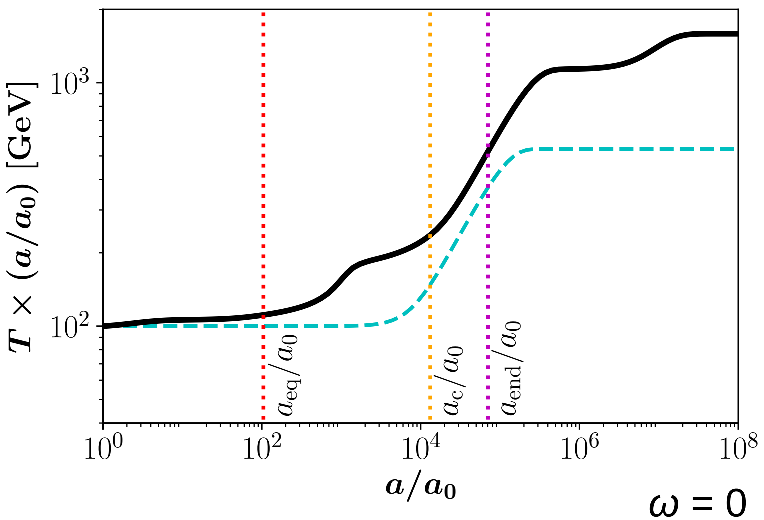


$\omega = 0$
(non-relativistic matter)

- $\boldsymbol{a}_{\mathbf{eq}}$: equality $\rho_\phi = \rho_R$
- $\boldsymbol{a}_{\mathbf{c}}$: ϕ starts to decay
- $\boldsymbol{a}_{\mathbf{end}}$: end of ϕ domination era
  ($H = \Gamma_\phi$ at $T=T_{\rm end}$)

Non-standard Cosmology





ω = 0
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$$\rho_R(a) \propto \begin{cases} a^{-4} & \text{for } a \ll a_c, \\ a^{-\frac{3}{2}(1+\omega)} & \text{for } a_c \ll a \ll a_{end}, \\ a^{-4} & \text{for } a_{end} \ll a, \end{cases}$$

$$T(a) \propto \begin{cases} a^{-1} & \text{for } a \ll a_c, \\ a^{-\frac{3}{8}(1+\omega)} & \text{for } a_c \ll a \ll a_{end}, \\ a^{-1} & \text{for } a_{end} \ll a. \end{cases}$$

DM in Non-standard Cosmologies

$$\frac{d\rho_\phi}{dt} + 3(1+\omega)\, H\, \rho_\phi = -\Gamma_\phi\, \rho_\phi$$

$$\frac{ds}{dt} + 3\, H\, s = +\frac{\Gamma_\phi\, \rho_\phi}{T}$$

$$\frac{dn}{dt} + 3\, H\, n = -\langle \sigma v \rangle \left(n^2 - n_{\mathrm{eq}}^2\right)$$

Free parameters:

- Particle physics
  * DM mass m
  * annihilation cross section $\langle \sigma v \rangle$
- Cosmology
  * $\kappa = \rho_\phi / \rho_R$ at $T = m$
  * $T_{\mathrm{end}} > 4$ MeV
  * equation of state $\omega \in [-1, 1]$

WIMP Paradigm in Non-standard Cosmologies

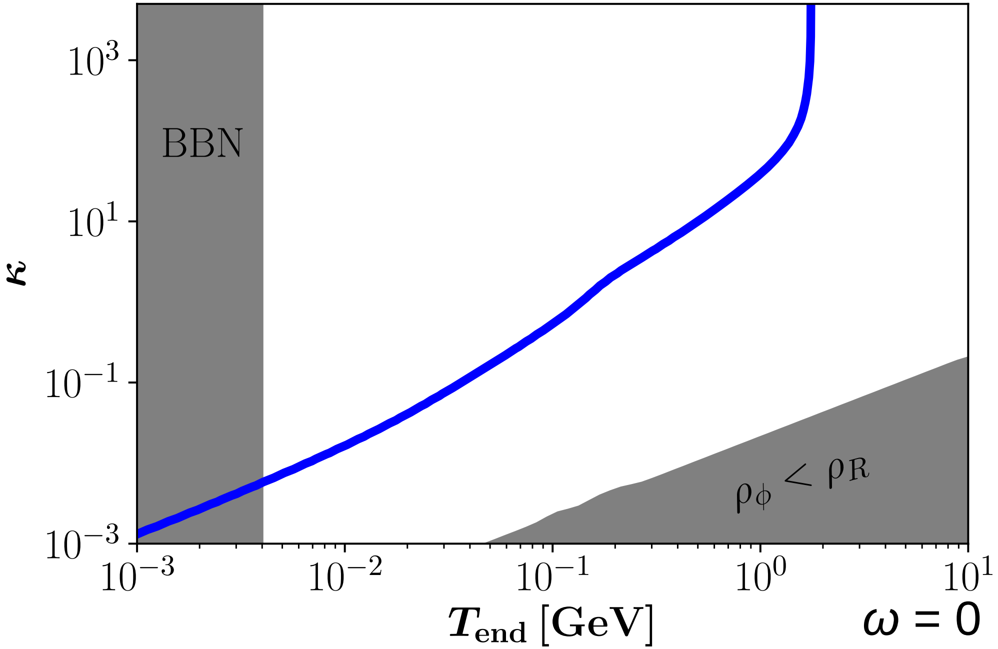
Suppose DM is discovered
and its particle physics properties are reconstructed

- If $<\sigma v> \sim 10^{-26}$ cm^3/s → standard WIMP
- If $<\sigma v> \ll 10^{-26}$ cm^3/s → standard WIMP mechanism fails!

* Can non-standard cosmologies revive the WIMP paradigm?
* which non-standard cosmologies are compatible?

Reconstructing Cosmological Parameters

For m = 100 GeV and $\langle\sigma v\rangle = 3 \times 10^{-28}$ cm^3/s



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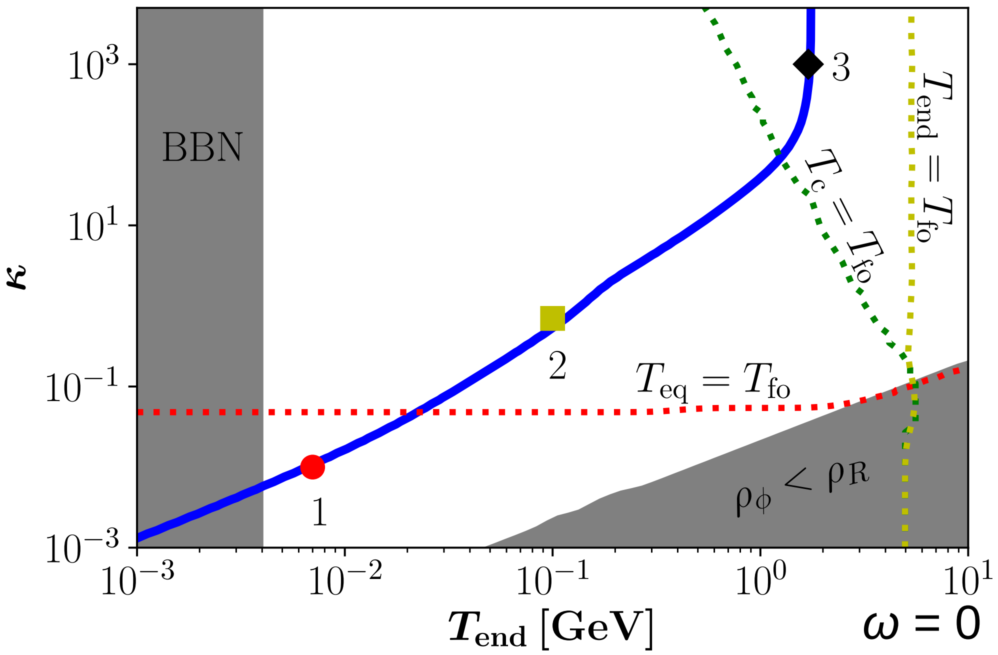

$\omega = 0$

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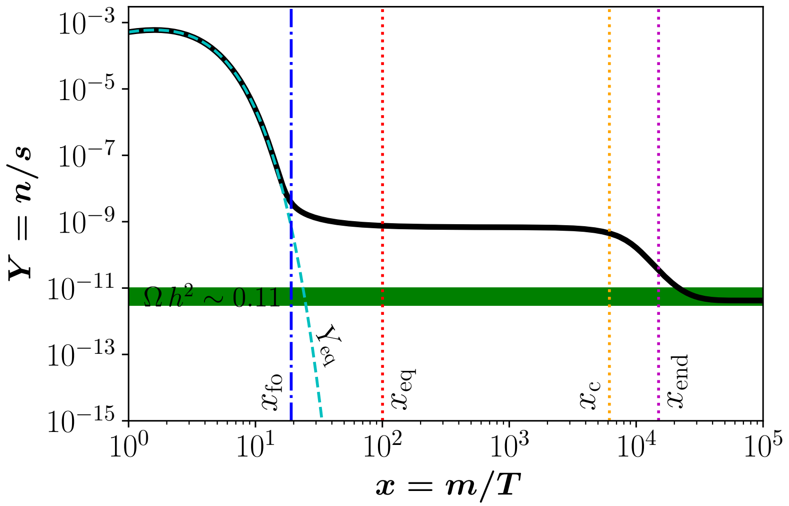
Case 1: $T_{eq} << T_{fo}$



Usual case with a late entropy injection

* SM energy density dominant during freeze-out
  → Hubble rate dominated by SM radiation

* Entropy conserved during freeze-out
  → $T \sim a^{-1}$

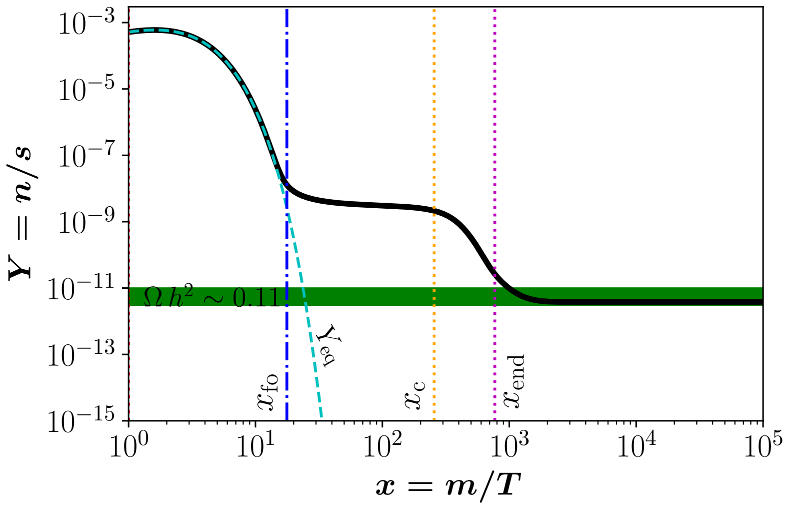
* Late DM dilution when ϕ decays

$$\frac{dY}{dx} = -\frac{\langle\sigma v\rangle\, s}{H\, x}\left(Y^2 - Y_{eq}^2\right)$$

$$Y_{obs} = \frac{Y_0}{D} \simeq \frac{15}{2\pi\sqrt{10\, g_\star}}\frac{x_{fo}}{m\, M_P\, \langle\sigma v\rangle}\left[\frac{1}{\kappa}\left(\frac{T_{end}}{m}\right)^{1-3\omega}\right]^{\frac{1}{1+\omega}}$$

Cosmology: $\kappa \propto T_{end}^{1-3\omega}$

Case 2: $T_c << T_{fo} << T_{eq}$



Case with a late entropy injection

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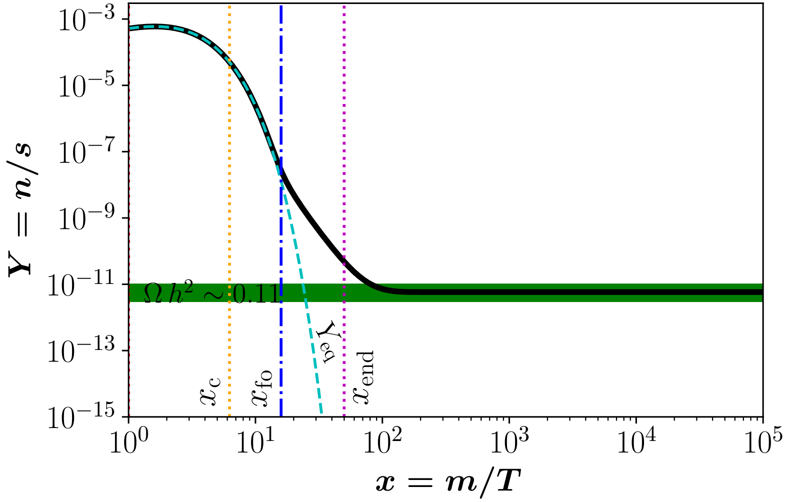
$$\frac{dY}{dx} = -\frac{\langle\sigma v\rangle\, s}{H\, x}\left(Y^2 - Y_{eq}^2\right)$$

$$Y_{obs} = \frac{Y_0}{D} \simeq \frac{45(1-\omega)}{4\pi\sqrt{10 g_\star}}\frac{\sqrt{\kappa}}{m\, M_P\, \langle\sigma v\rangle}\, x_{fo}^{\frac{3}{2}(1-\omega)}\left[\frac{1}{\kappa}\left(\frac{T_{end}}{m}\right)^{1-3\omega}\right]^{\frac{1}{1+\omega}}$$

Cosmology: $\kappa \propto T_{end}^{2\frac{1-3\omega}{1-\omega}}$

Case 3: $T_{\text{end}} << T_{\text{fo}} << T_{\text{c}}$



Freeze-out and decay happen simultaneously

* ϕ energy density dominant during freeze-out
  → Hubble rate dominated by ϕ

* Entropy in <u>not</u> conserved during freeze-out
  → $T \sim a^{-3(1+\omega)/8}$

* DM is diluted while produced

$$\frac{dY}{dx} = -\frac{\langle\sigma v\rangle\, s}{H\, x}\left(Y^2 - Y_{\text{eq}}^2\right)$$

$$\frac{dN}{da} = -\frac{\langle\sigma v\rangle}{H\, a^4}\left(N^2 - N_{\text{eq}}^2\right)$$

$$Y_{\text{obs}} = \frac{N_0}{s\, a^3} = \frac{45(1-\omega)}{4\pi}\sqrt{\frac{1}{10 g_\star}}\frac{1}{M_P\langle\sigma v\rangle}\left[T_{\text{fo}}^{4(\omega-1)}\, T_{\text{end}}^{3-5\omega}\right]^{\frac{1}{1+\omega}}$$

Cosmology: independent on κ

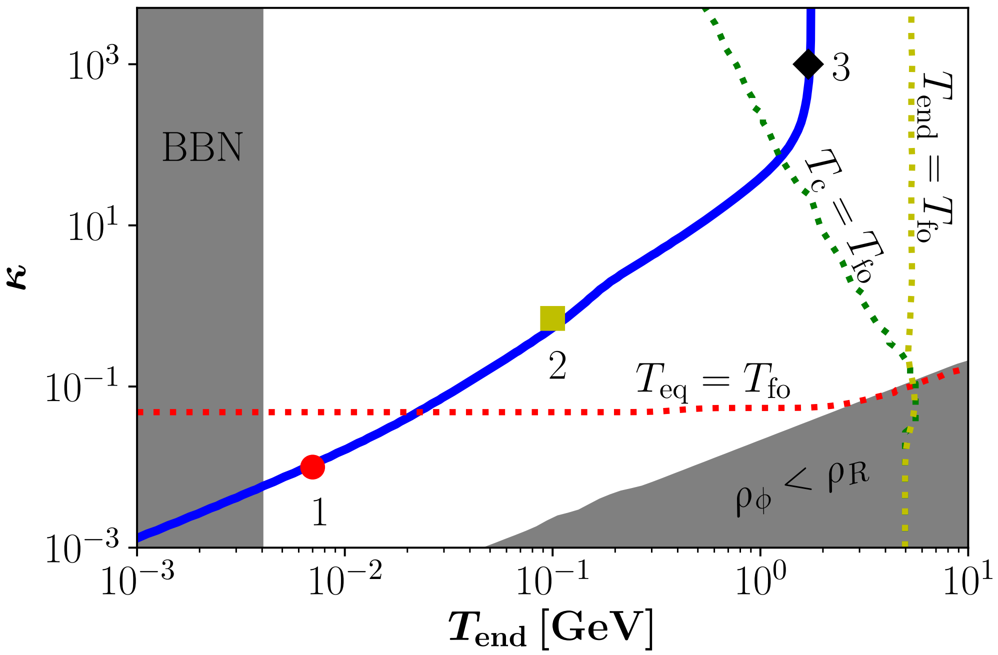
Case 4: $T_{\mathrm{fo}} \ll T_{\mathrm{end}}$

Freeze-out in standard cosmology!

ϕ decays at very high temperatures,
when DM is still in equilibrium with the SM.

Reconstructing Cosmological Parameters

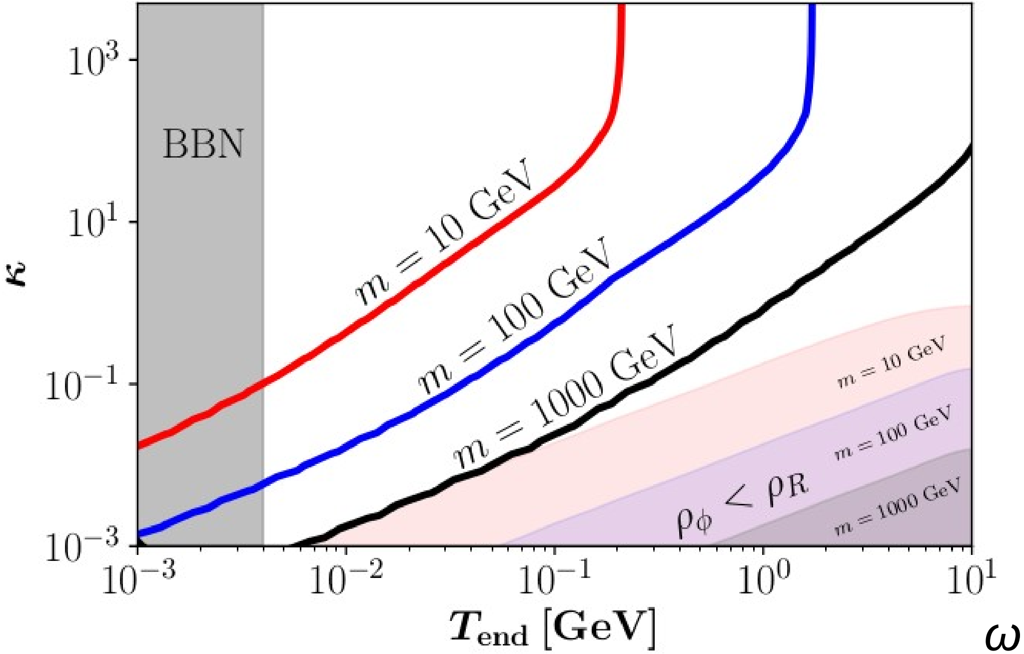
For m = 100 GeV and $\langle\sigma v\rangle$ = 3 x 10^{-28} cm^3/s



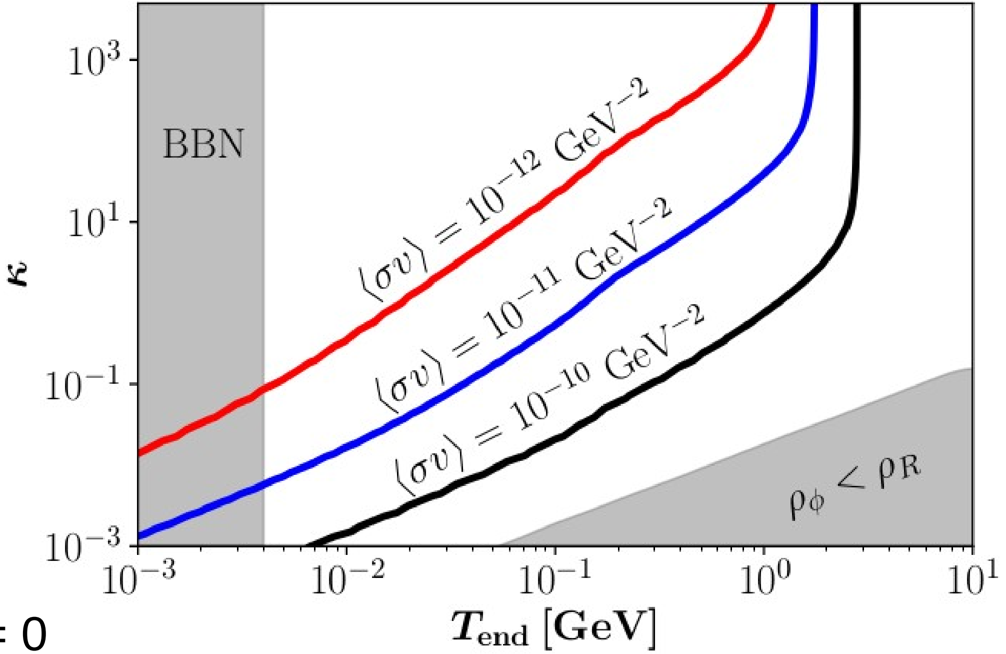
$\omega = 0$

Varying the Particle Physics

<σv> = 3 x 10^{-28} cm^3/s



m = 100 GeV



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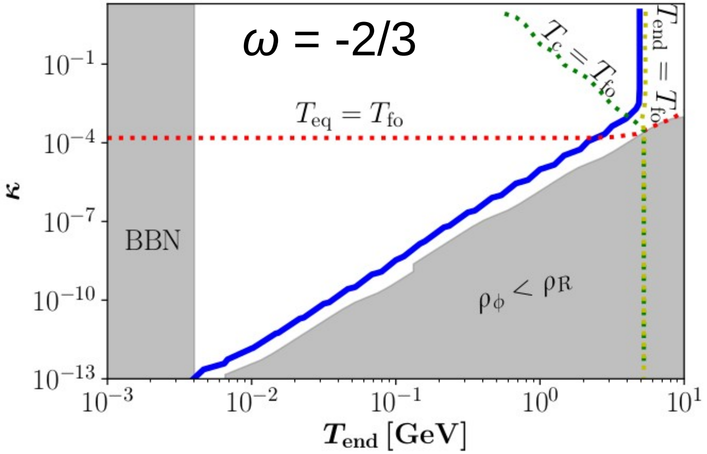
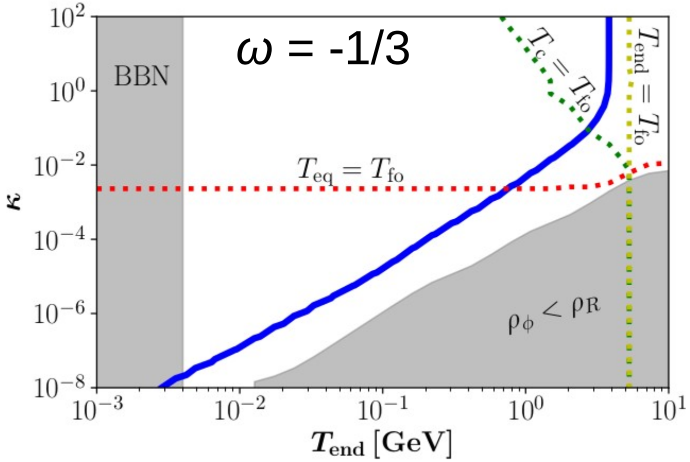
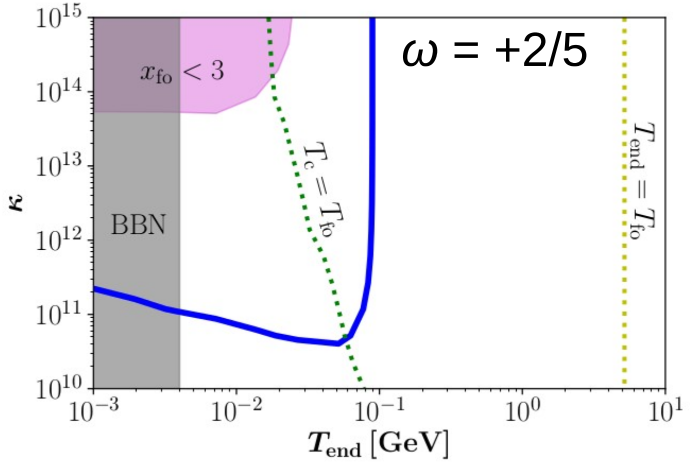
Varying the Cosmology







m = 100 GeV

<*σv*> = 3 *x* 10^{-28} cm^3/s

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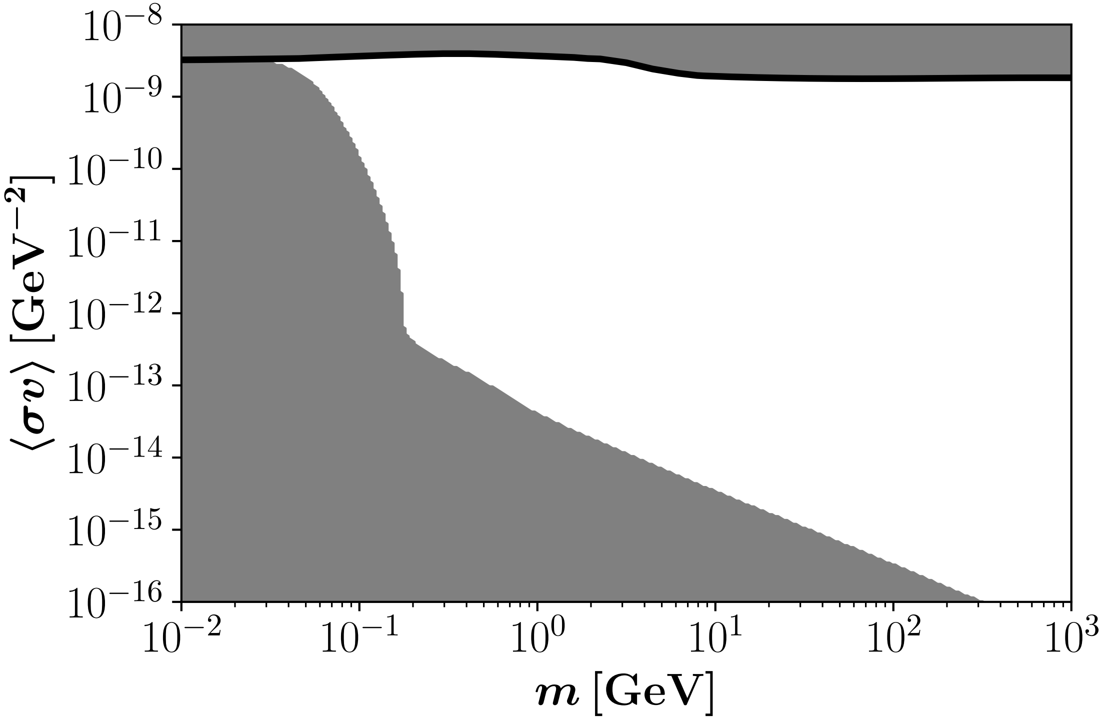
Varying the Cosmology

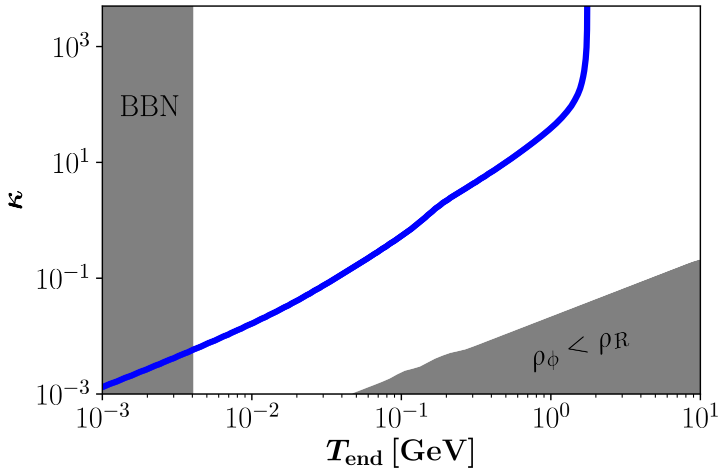


* $\omega = 0$

* Non-relativistic freeze-out:
  $x_{fo} > 3$
* $T_{end} > 4$ MeV

Breaking the Degeneracy

2 free parameters and 1 observable:
κ and T_{end} are degenerated



→ Another observable is needed

GWs as probes of the early Universe

- GWs decouple upon production
- GWs spectrum:
  * Primordial spectrum at production
  * Propagation
- But difficult to detect :-/

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→ **GWs do probe the early Universe**

Primordial Gravitational Waves

- GW are represented by spatial metric perturbations (transverse & traceless).
- The evolution of GWs is described by the linearized Einstein eq.

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} - \frac{\nabla^2}{a^2} h_{ij} = 16\pi\, G\, \Pi_{ij}^{TT}$$

Π^{TT} is the transverse-traceless part of the anisotropic stress tensor $\Pi_{ij} = \frac{T_{ij} - p\, g_{ij}}{a^2}$

- Primordial GW spectrum

$$\Omega_{\rm GW}(t,k) = \frac{1}{\rho_c(t)} \frac{d\rho_{\rm GW}(t,k)}{d\ln k} = \frac{1}{12\, a^2(\eta)\, H^2(\eta)} \mathcal{P}_T(k) \, \left[X'(\eta,\, k)\right]^2$$

with the primordial tensor power spectrum $\mathcal{P}_T(k) = A_T \left(\frac{k}{\tilde{k}}\right)^{n_T}$

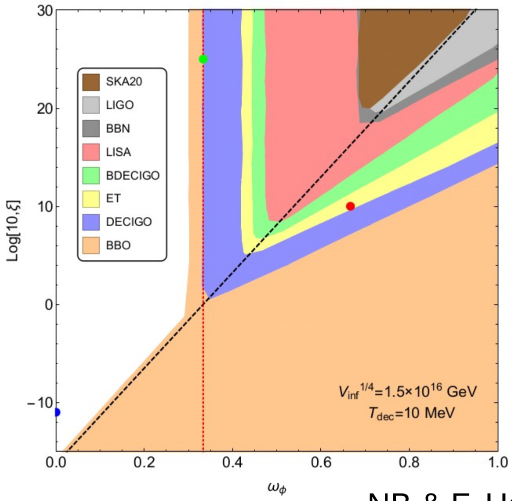
and the transfer function $\frac{d^2X(u)}{du^2} + \frac{2}{a(u)} \frac{da(u)}{du} \frac{dX(u)}{du} + X(u) = 0,$

Breaking the Degeneracy

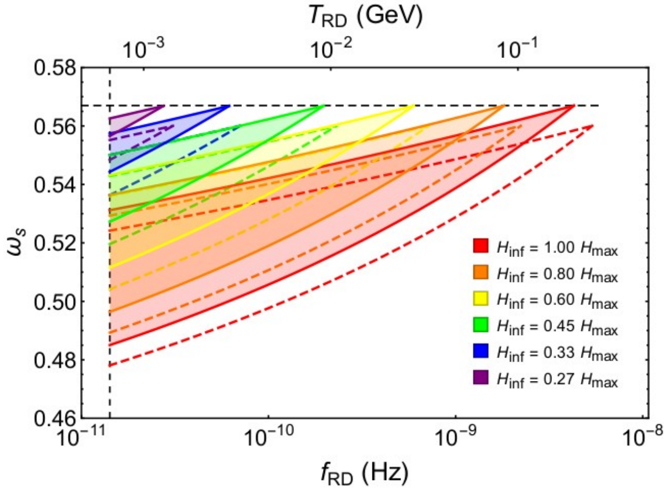
2 free parameters and 1 observable:
κ and T_{end} are degenerated

→ Another observable is needed

Primordial Gravitational Waves are sensitive to the expansion rate of the Universe!



NB & F. Hajkarim
1905.10410



D. Figueroa & E.H. Tanin
1905.11960

Conclusions & Outlook

- Dark Matter exists
- The nature of Dark Matter is still unknown
- Understanding Dark Matter is one of the major problems in particle physics
- WIMP paradigm is by far the favorite scenario
- We do not know much for the cosmology before BBN
- Non-standard cosmologies are completely plausible and *well-motivated scenarios*!
- Expansion of the early Universe could have been driven by an *extra component* ϕ
- *Non-standard cosmologies* open up the particle physics parameter space beyond the canonical $\langle\sigma v\rangle$ = few 10^{-26} cm^3/s
- Non-standard cosmologies with $\omega = 0$ (dust) can make the WIMP mechanism viable for ***m* > 30 MeV**.
- Need other observables sensitive to the cosmology: → PGW

Muchas gracias ve!

Non-standard Cosmology

→ **Early Universe dominated by a non-SM component ϕ**

ω: equation of state

Γ_ϕ: total decay width into SM radiation

$$\frac{d\rho_\phi}{dt} + 3(1+\omega)\, H\, \rho_\phi = -\Gamma_\phi\, \rho_\phi$$

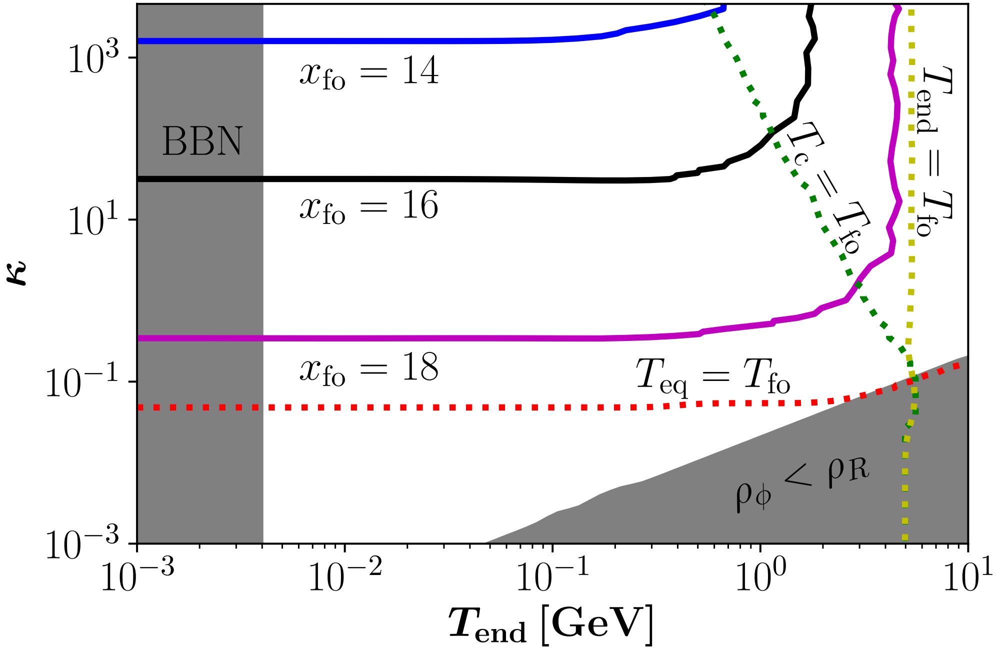
$$\frac{ds}{dt} + 3\, H\, s = +\frac{\Gamma_\phi\, \rho_\phi}{T}$$

(just to keep track of the relativistic degrees of freedom!)

Hubble expansion rate $$H = \sqrt{\frac{\rho_\phi + \rho_R}{3\, M_P^2}}$$

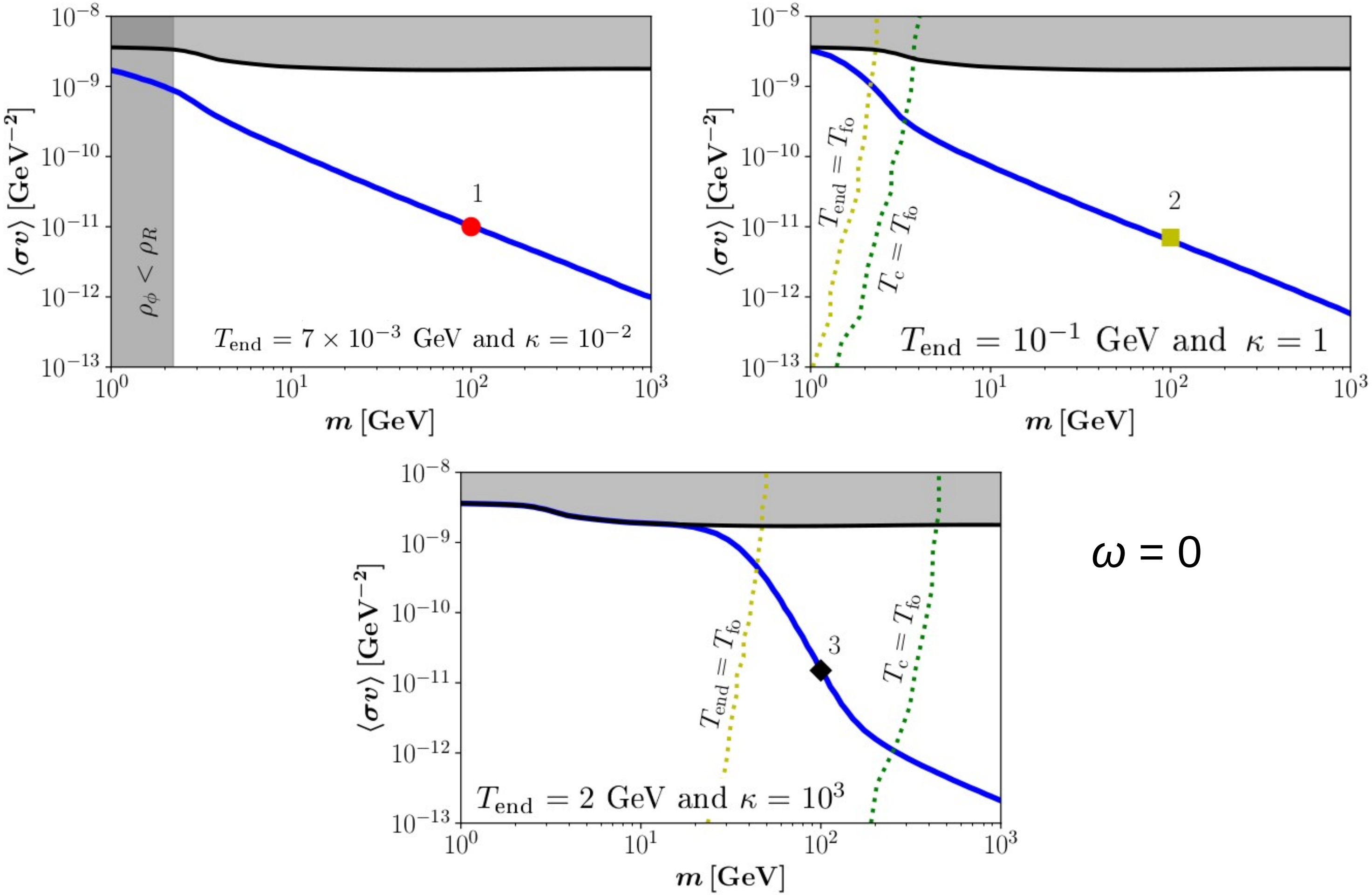
DM freeze-out in Non-standard Cosmologies

For m = 100 GeV and $\langle\sigma v\rangle = 3 \times 10^{-28}$ cm^3/s



$\omega = 0$

Varying the Cosmology



$\omega = 0$