Theory Priors in the Search For Light Dark Matter

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September 8, 2022

GUINEAPIG Workshop on Light Dark Matter

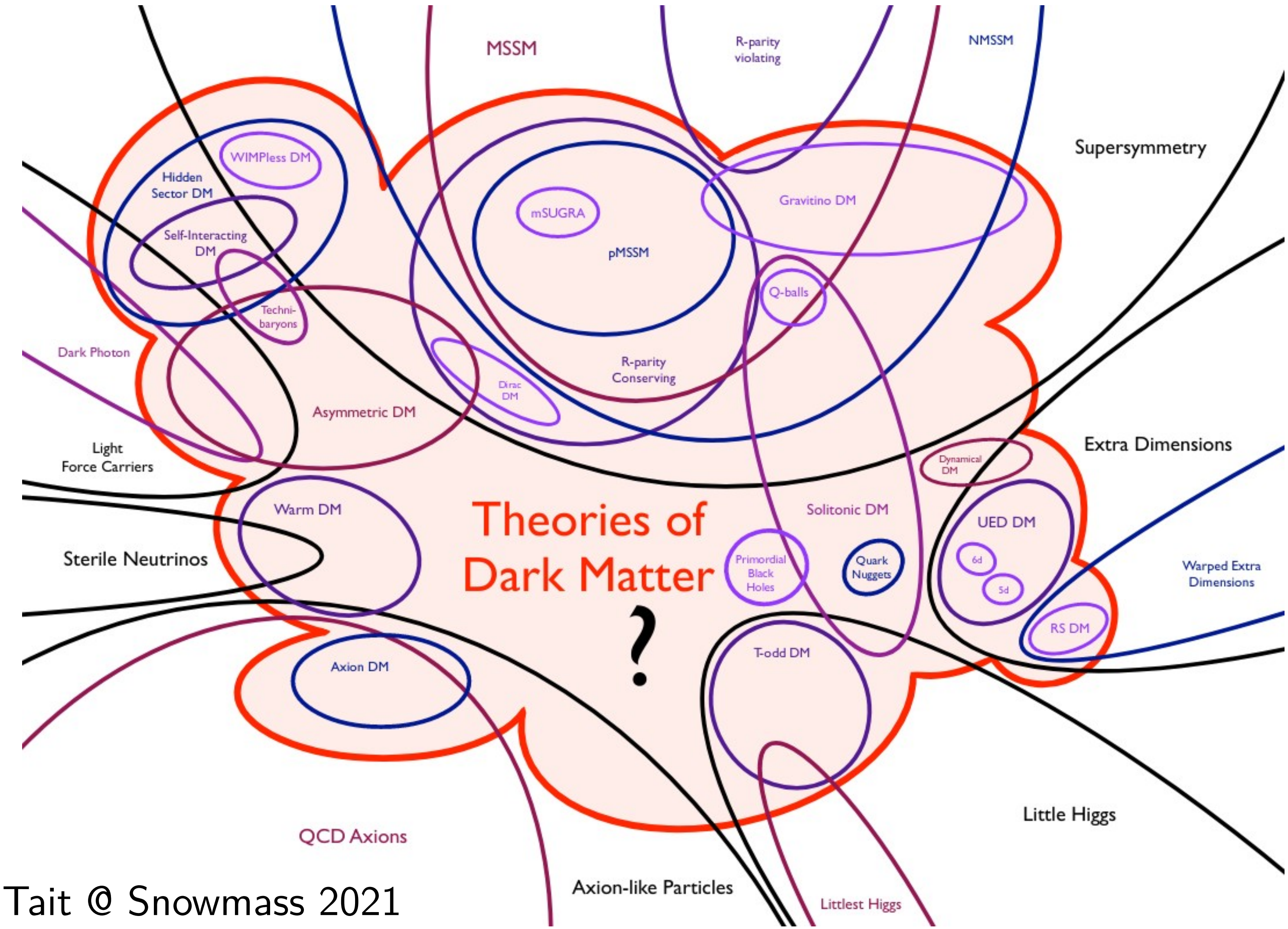
University of Victoria

Dark Matter: **Exists.**

Particle Physicists:

Dark Matter: **Exists.**

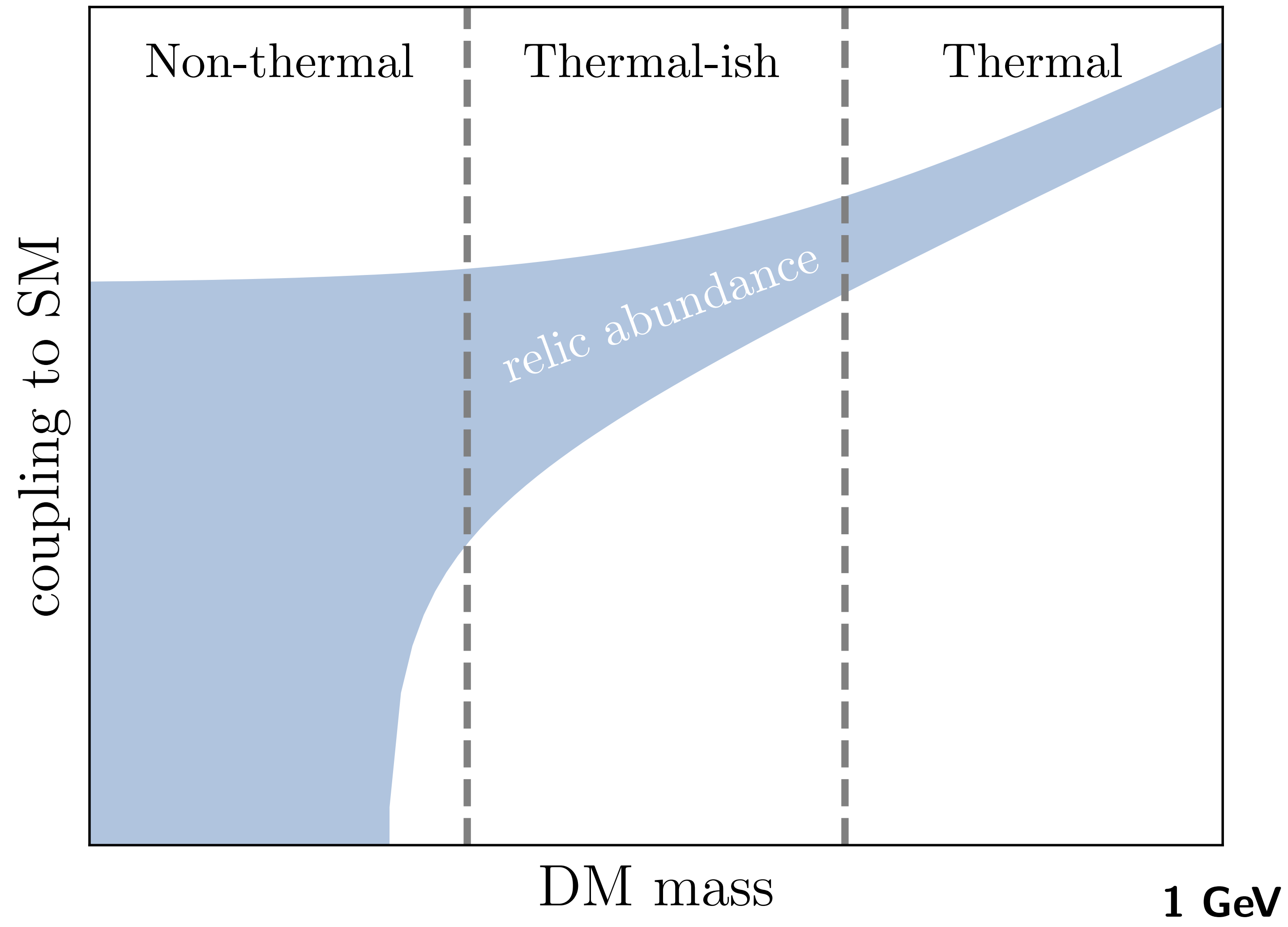
Particle Physicists:



Tim Tait @ Snowmass 2021

Taxonomy of Detectable DM

DM production provides a useful framework for organizing many scenarios



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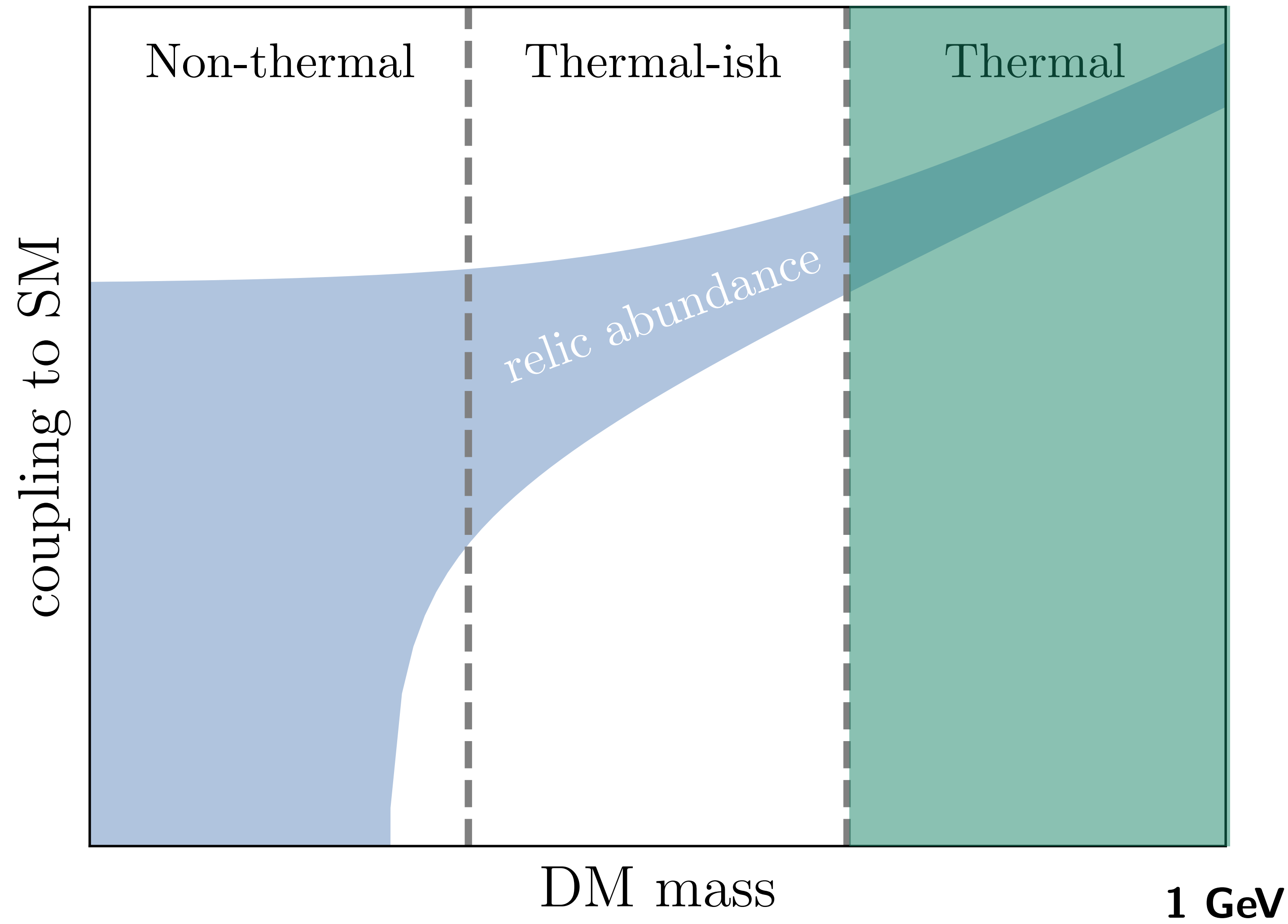
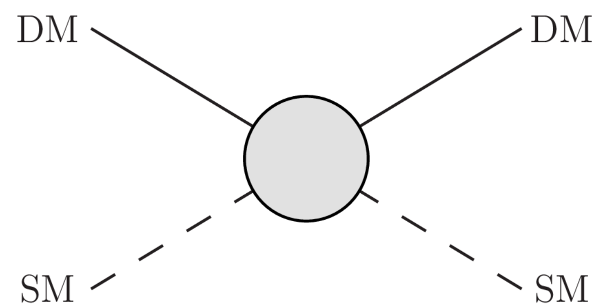


DM and Thermal Equilibrium

At sufficiently large DM-SM couplings, DM is in thermal equilibrium with the SM.

Kinetic equilibrium

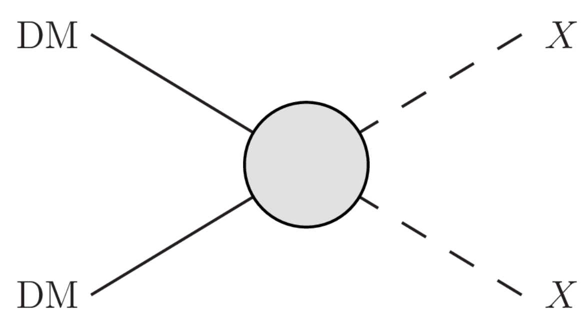
$$T_{\rm DM} = T_\gamma$$



Chemical equilibrium

$$n_{\rm DM} \sim n_\gamma \quad (T \gg m_{\rm DM})$$

$$n_{\rm DM} \sim n_\gamma \exp(-m_{\rm DM}/T) \quad (T < m_{\rm DM})$$

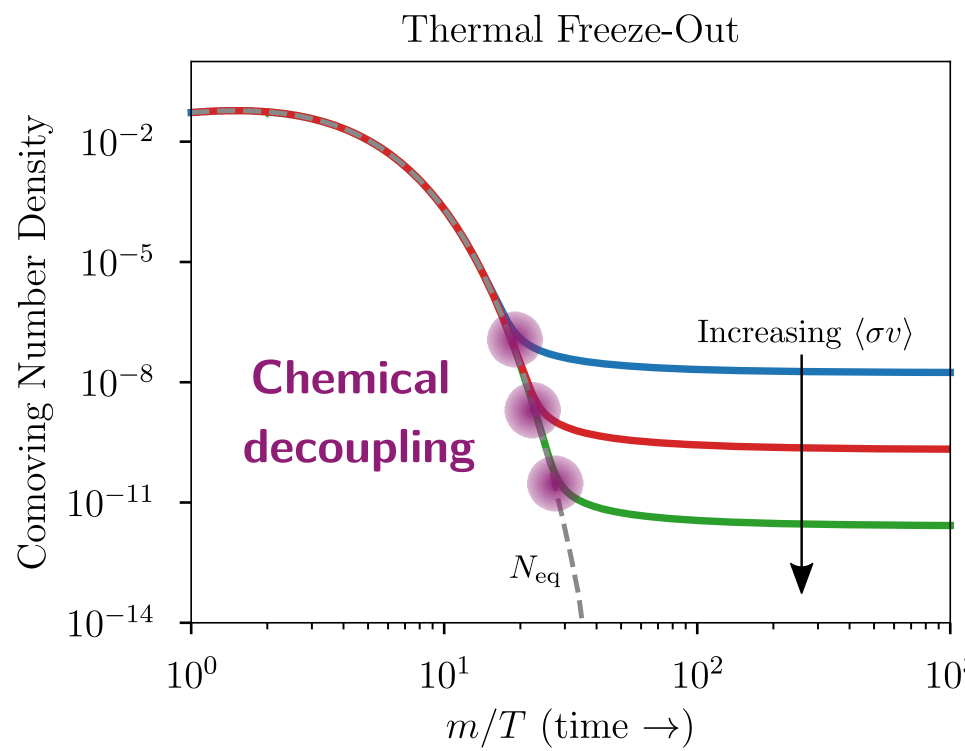


If equilibrium persists: too much or too little DM!

There must be a chemical decoupling

Freeze-out

Chemical decoupling (= freeze-out) must occur to get just the right amount of DM



Correct abundance if

$$\langle \sigma v \rangle \approx \left(\frac{1}{20 \text{ TeV}} \right)^2$$

At large masses (>> 1 GeV) – SM gauge interactions, or couplings to the Higgs enough

How can sub-GeV DM interact with SM to enter and exit equilibrium?

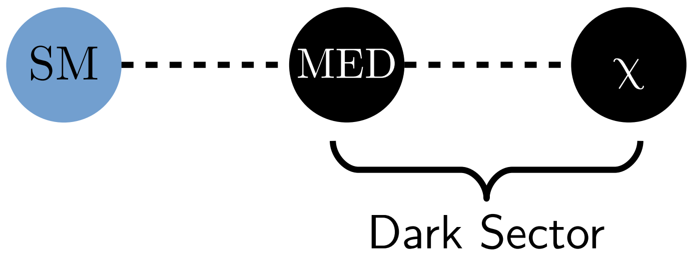
Light Thermal DM and Dark Sectors

For light DM, SM interactions insufficient

$$\langle \sigma v \rangle_{\rm SM} \sim \frac{\alpha^2 m_\chi^2}{m_Z^4} < \left(\frac{1}{20\ \text{TeV}} \right)^2$$

Lee & Weinberg ‘77

Boehm & Fayet ‘04



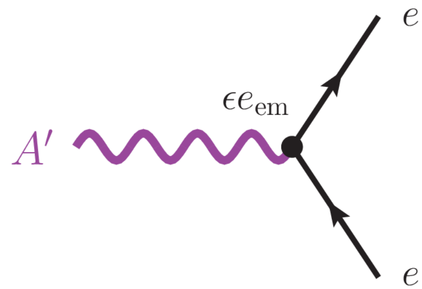
Light thermal DM requires a new mediator that interacts with SM

How can such particles interact with familiar matter?

Portals to the Dark Sector

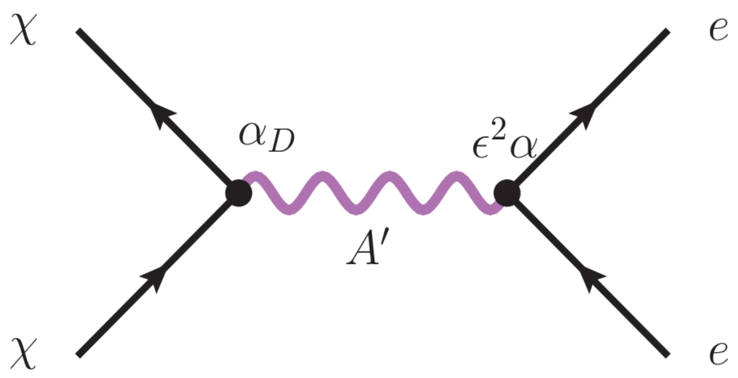
Only a handful of low-dimensional connections to potential new particles – study these first!

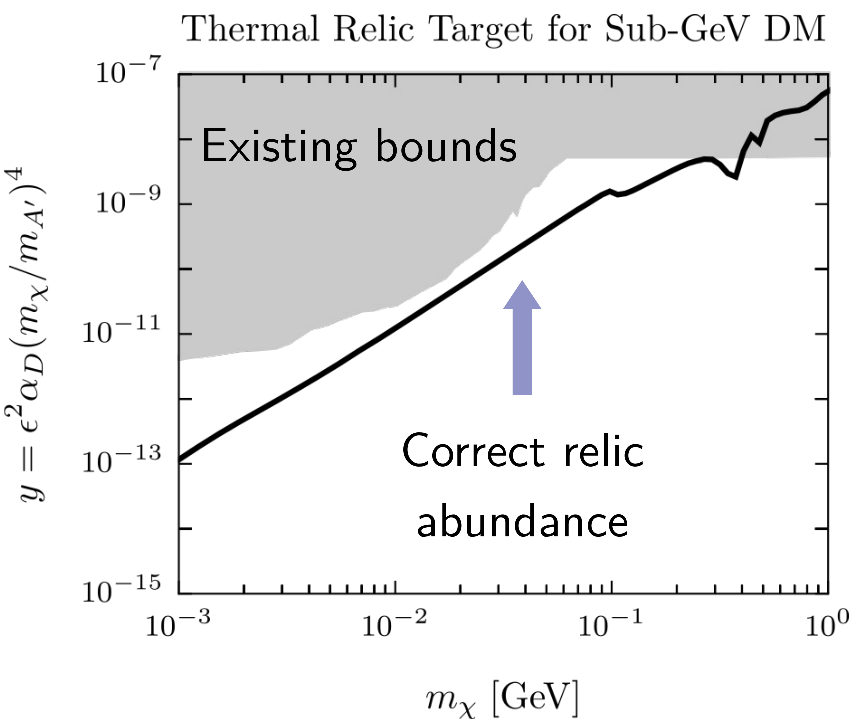
$A'_\mu J^\mu_{\text{EM}}$	Dark photon	$\Rightarrow$	Coupling to electromagnetism
$\lvert H\rvert^2 \phi^2$	Higgs portal scalar	$\Rightarrow$	Coupling to fermions
$L H N_R$	Right-handed neutrino	$\Rightarrow$	Coupling to neutrinos
$a F_{\mu\nu} \widetilde{F}^{\mu\nu}$	Pseudo-scalar	$\Rightarrow$	Coupling to electromagnetism
$\vdots$			



A Predictive Model

Dark matter coupled to the dark photon can annihilate directly into SM particles





$$\langle \sigma v \rangle \propto \frac{\epsilon^2 \alpha \alpha_D m_\chi^2}{m_{A'}^4} \equiv \frac{y}{m_\chi^2}$$

These models are weakly coupled, in the sense $\alpha_D < 1$

Other Approaches to Chemical Decoupling

Chemical equilibrium and decoupling are generic – **many** other implementations!

E.g. Strongly Interacting Massive Particles (SIMPs)

Carlson, Machacek and Hall (1992); Hochberg, Kuflik, Volansky and Wacker (2014)

Chemical equilibrium (within the DM) **Kinetic equilibrium (with the SM)**

Explicit separation between processes responsible for chemical and kinetic equilibrium

Specific examples: see, e.g., Hochberg, Kuflik & Murayama (2015); Berlin, NB, Gori, Schuster & Toro (2018); Hochberg, Kuflik, McGehee, Murayama & Schutz (2018)++

Big Question 1: Thermal Contact

Were there new states in kinetic and/or chemical equilibrium with the Standard Model?

Limits to Thermal Equilibrium

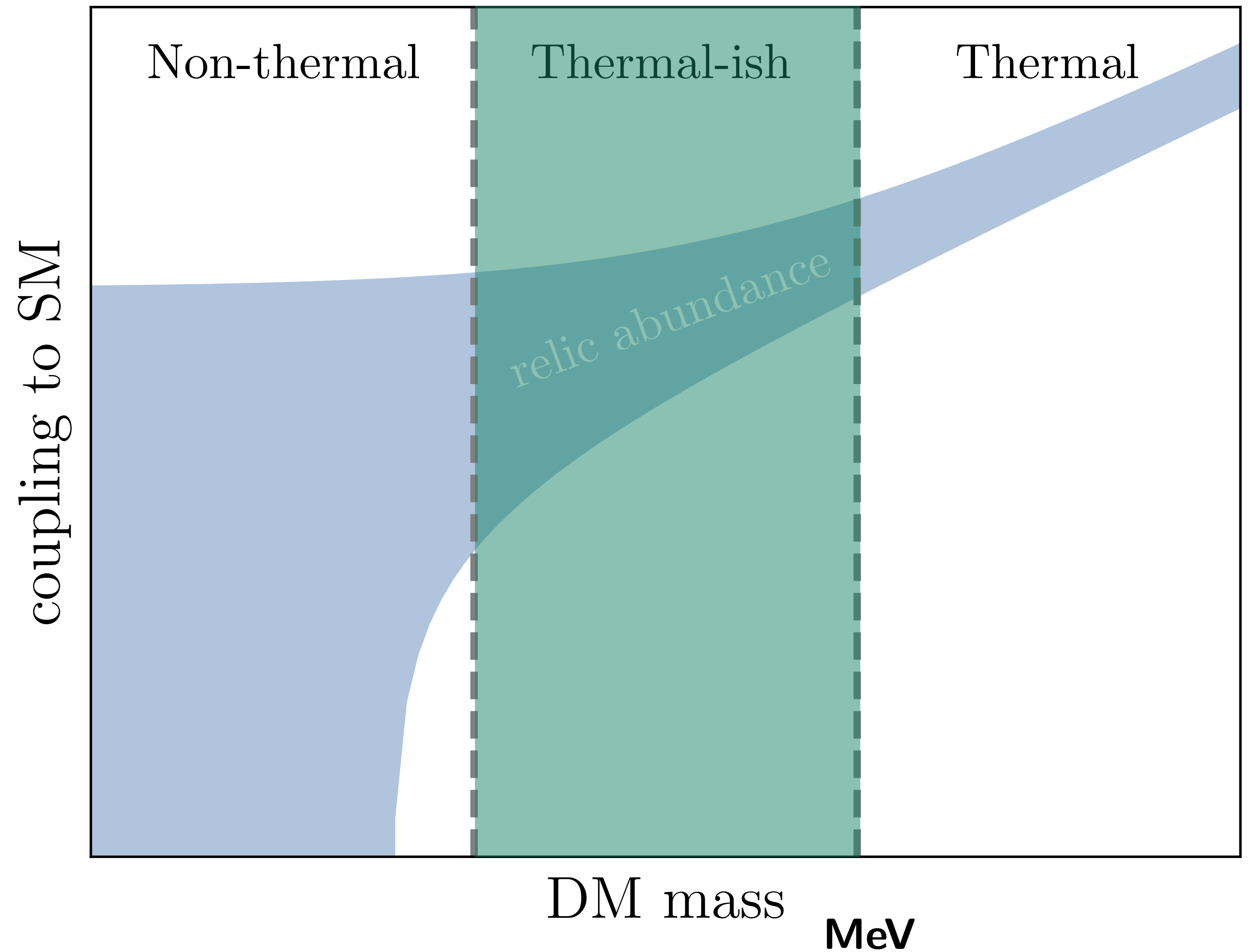
Thermal equilibrium implies DM (and associated particles) were once as abundant as photons and neutrinos.

At mass scales near MeV this leads to observational problems:

see Saniya's talk

Below the MeV scale must consider smaller couplings and "less-than-thermal" scenarios

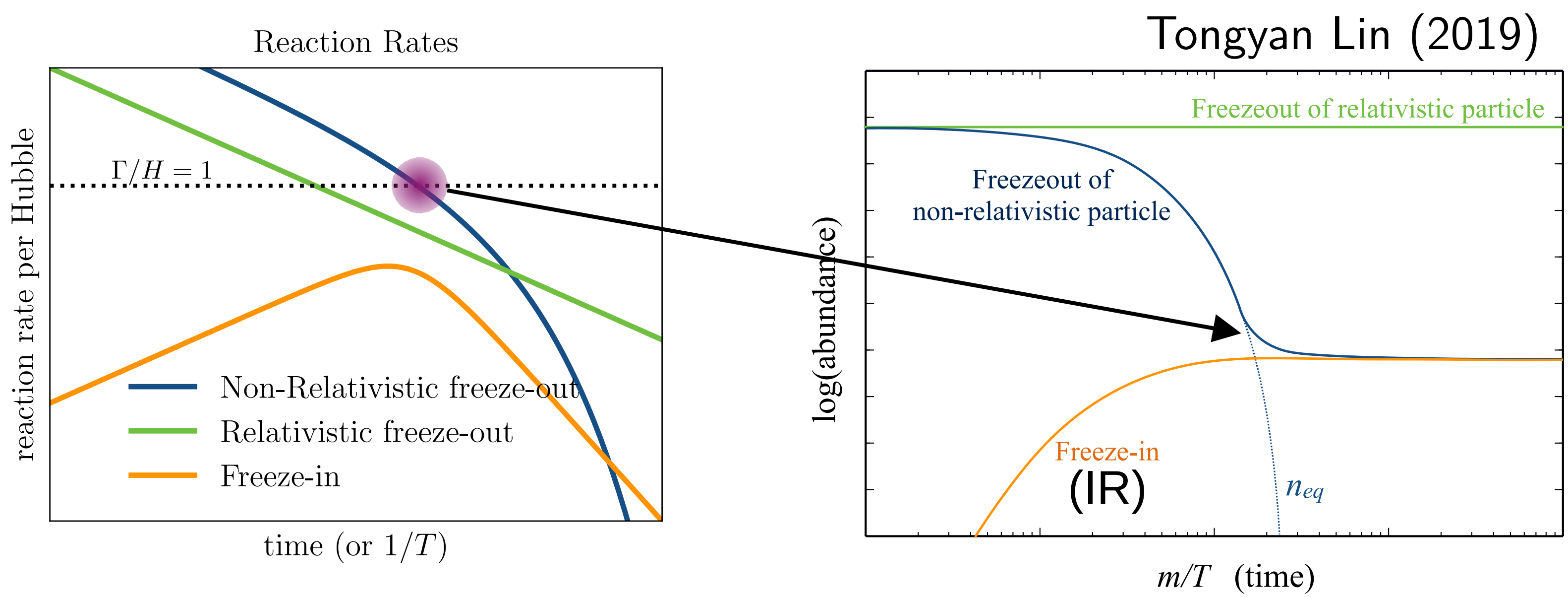
Thermal-ish: Feeble Contact with the SM



Freeze-in

Coupling to SM too weak for equilibrium: $\Gamma/H \ll 1$

$$n_{\rm DM} \ll n_\gamma$$



Dodelson and Widrow (1993); Hall, Jedamzik, March-Russell and West (2009)

DM density builds up gradually but still tied to SM-DM interaction

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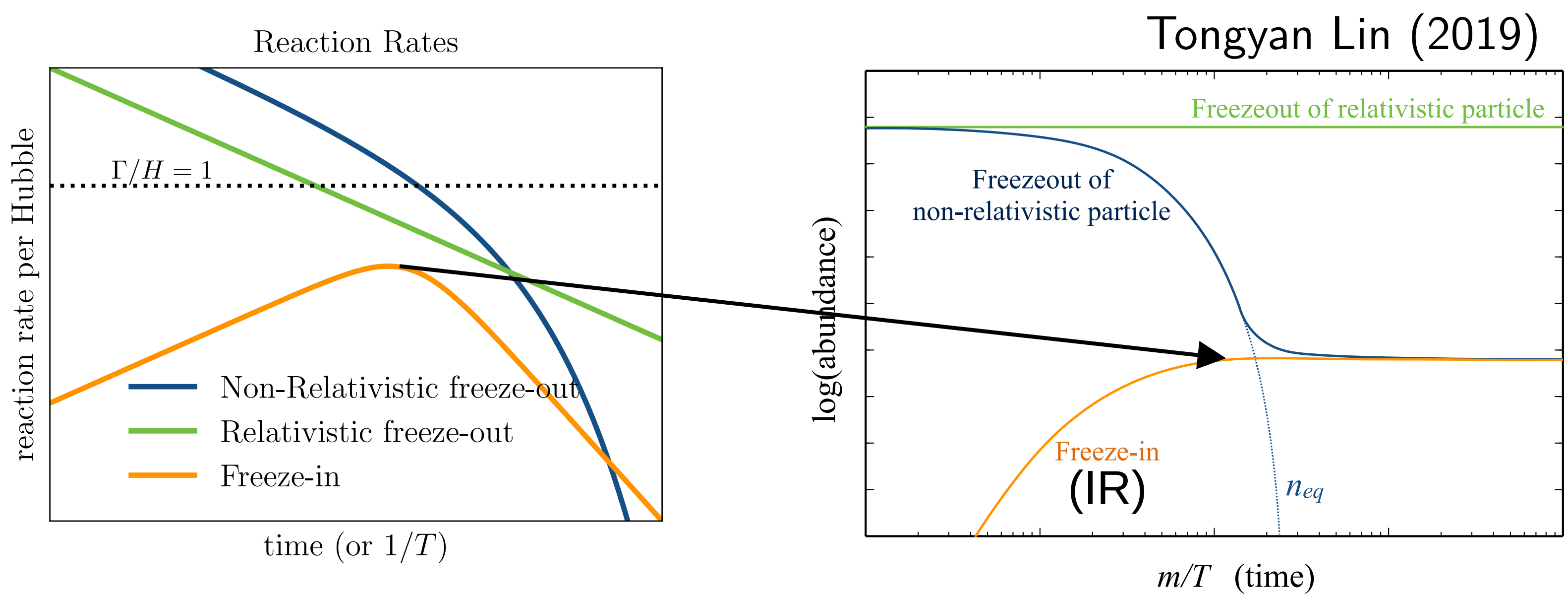


Dodelson and Widrow (1993); Hall, Jedamzik, March-Russell and West (2009)

DM density builds up gradually but still tied to SM-DM interaction

Freeze-in Phenomenology

Abundance from SM-DM interaction $\rightarrow$ generic and predictive

but hidden assumption: initial abundance tiny

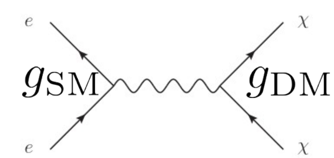
$\Rightarrow$ non-trivial constraint on cosmology, see Adshead, Cui & Shelton (2016)

Features tiny couplings*, detectable models tend to have ultralight mediators, e.g. photon/dark photon

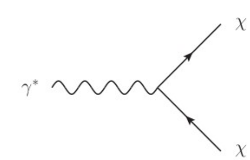
$$\Omega_\chi \sim \Omega_{cdm} \left(\frac{g_{\rm DM} g_{\rm SM}}{10^{-12}} \right)^2$$

$$\mathcal{L} \supset e Q_\chi \bar{\chi} \gamma_\mu \chi A^\mu, \quad Q_\chi \ll 1$$

Annihilation



Plasmon decay



*Can be enhanced in different cosmologies: see
Berlin, NB, Krnjaic, Schuster & Toro (2018); Banerje & Chowdhury (2022)

Freeze-in Phenomenology

Abundance from SM-DM interaction → generic and

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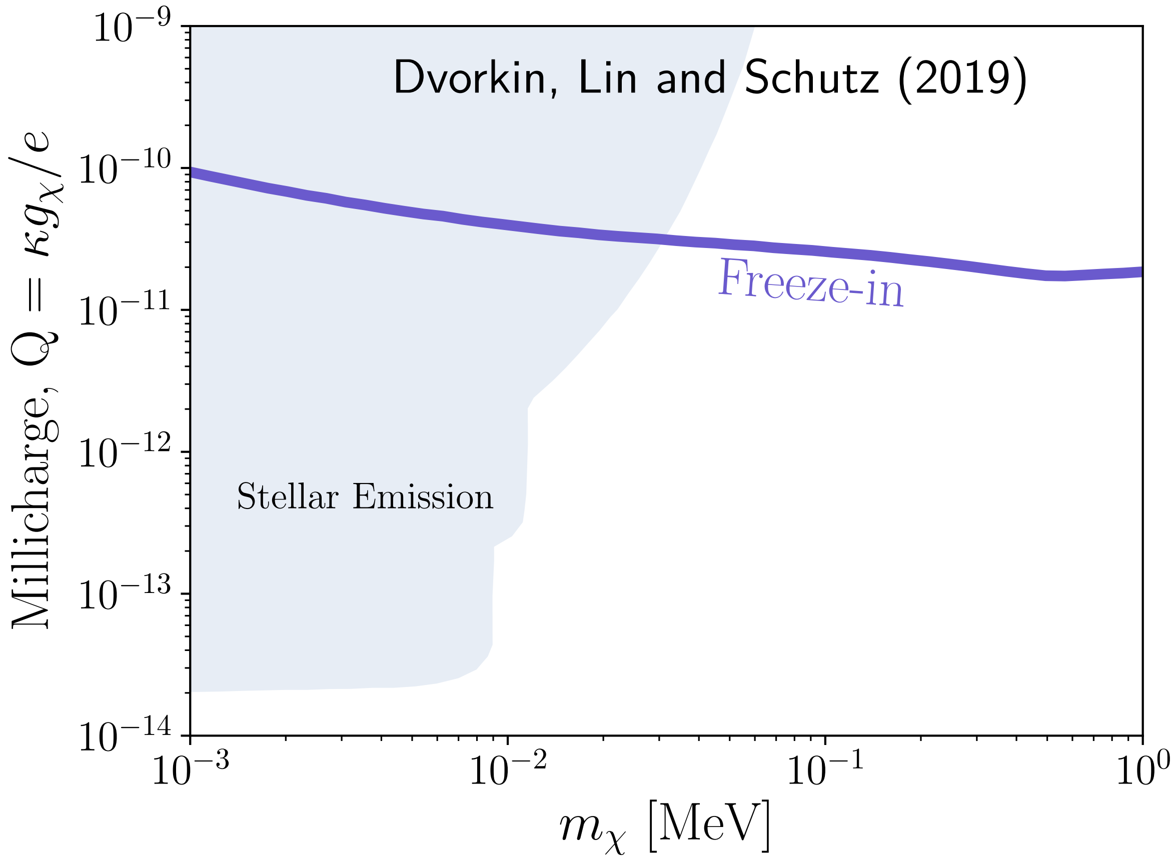
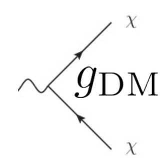


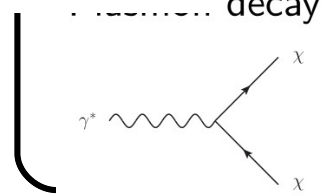
Ω

ation



$\mathcal{L}$

decay



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Berlin, NB, Krnjaic, Schuster & Toro (2018); Banerje & Chowdhury (2022)

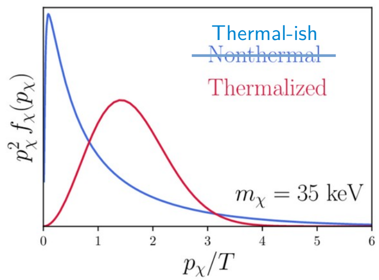
Big Question 2: Feeble Interactions with SM

Did interactions with the SM, even ultra-weak ones, play any role in producing the DM?

Limits to Thermal-ish Production

DM produced through freeze-in inherits a thermal-ish distribution from the SM: some fraction of DM is "fast"

High-velocity DM particles wash out small-scale structure



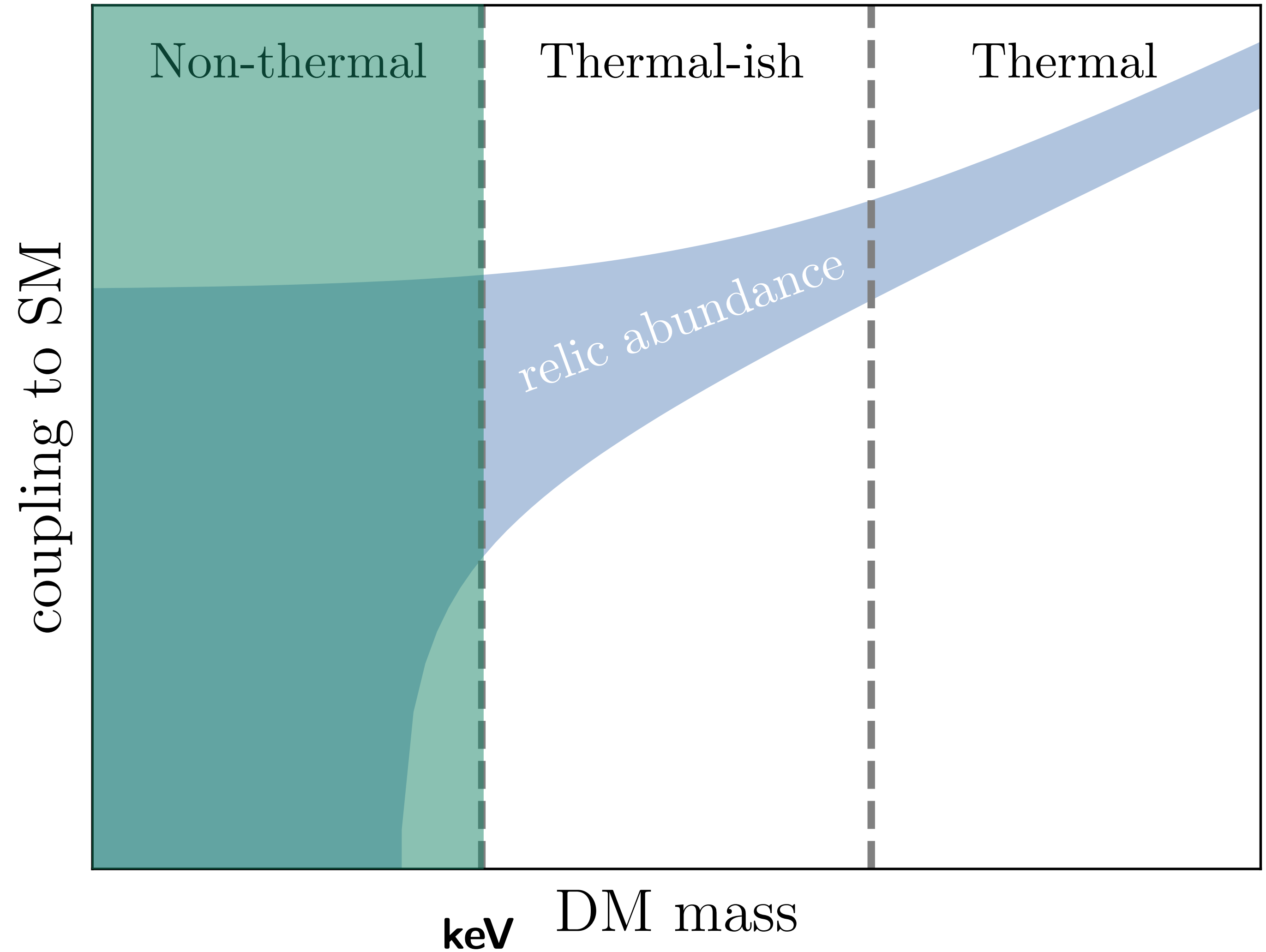
Freeze-in: Dvorkin, Lin and Schutz (2020);
D'Eramo & Lenoci (2021)
Dodelson-Widrow: Nadler, Drlica-Wagner et al (2021)

see Saniya's talk

Below the ∼10 keV scale must consider non-thermal scenarios

Below keV: bosons only! Fermions don't pack into dwarf galaxies -Boyarsky, Ruchayskiy & Iakubovskyi (2008)

Non-Thermal Production

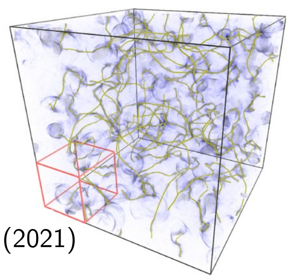


Production of Ultralight DM

Many non-thermal/non-equilibrium processes can produce relic DM

Decays of other relics

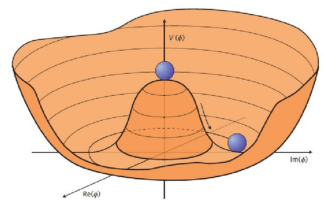
(Moduli, saxions, topological defects...)



Buschmann et al (2021)

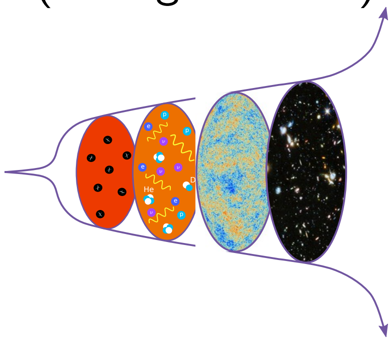
Phase transitions

(misalignment)



Gravitational particle production

(during inflation)



Note:

1) No reliance on SM coupling (but can still sometimes identify “targets”)

2) Mechanisms can be mixed and matched (cf. QCD axion)

Simplest example: **misalignment** of **axion-like particles**

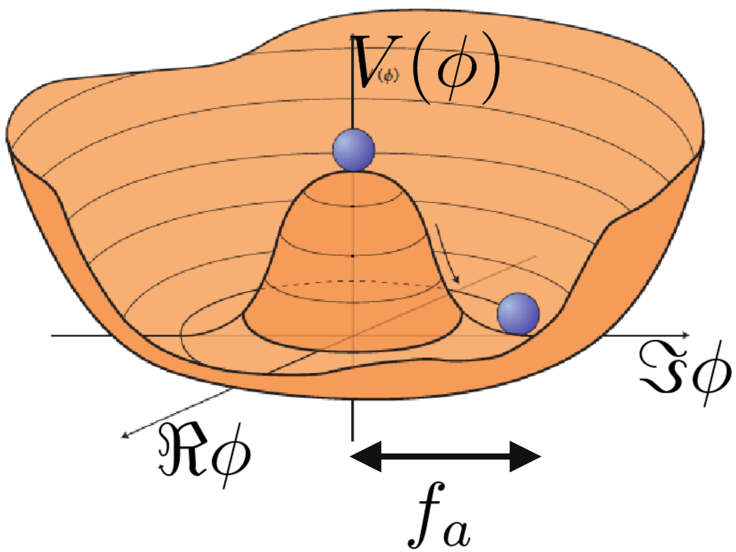
Misalignment

- Generic mechanism for light bosonic DM: axions, **axion-like particles (ALPs)**, moduli,...
- Field displaced from the origin of its potential with $a_i = \theta_0 f_a$
- Mass protected by symmetry $\rightarrow$ naturally light; interactions scale w/ f_a

$$\mathcal{L} \supset \frac{\hat{c}_{\gamma\gamma}}{f_a} a F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

ALP Misalignment

Ellis, Gaillard & Nanopoulos (2012)



Scale of symmetry breaking

Evolution after Misalignment

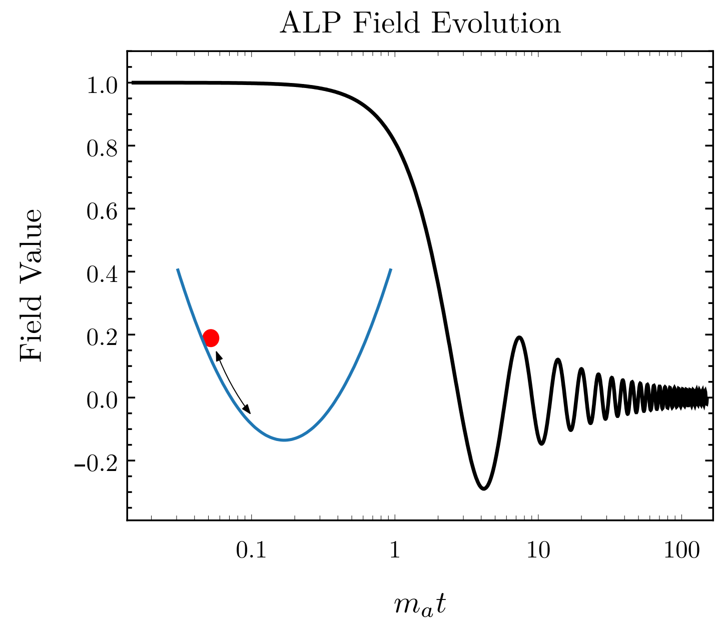
- Field begins to oscillate in its potential when

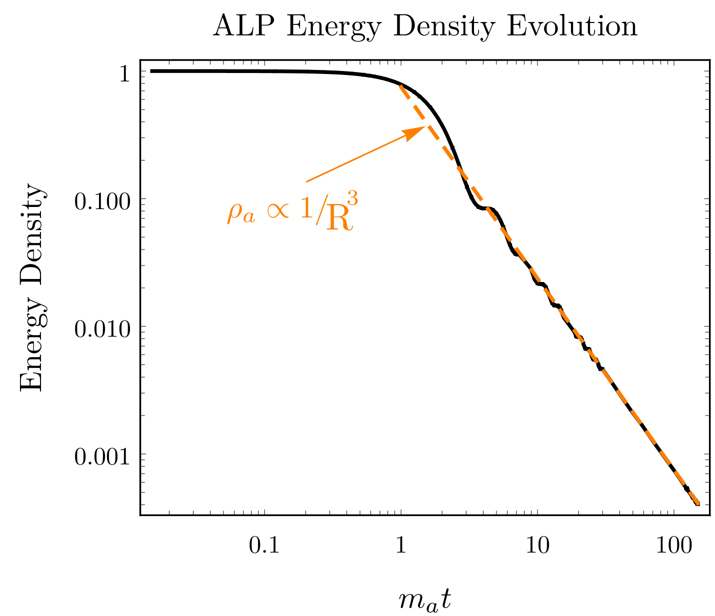
$$m_a \sim H(t)$$

- Time-averaged energy density in oscillations scales like CDM

$$\rho_a \sim 1/R(t)^3$$

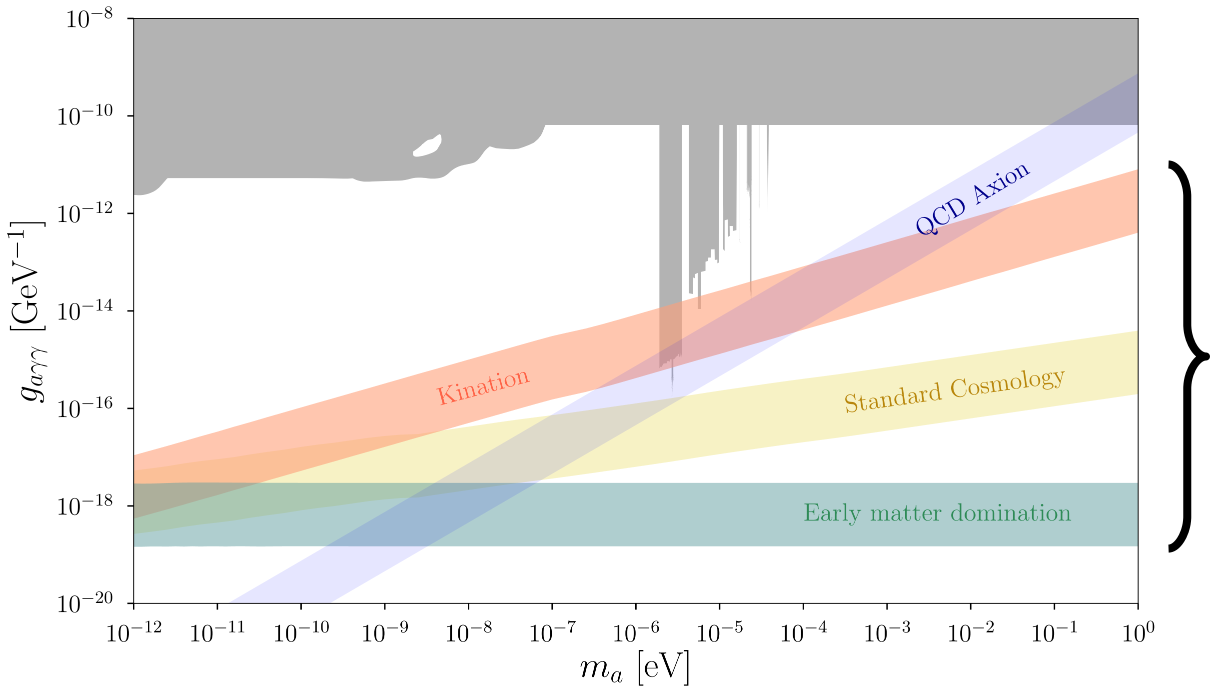
↑ FRW scale factor





Sensitivity to Initial Conditions

- **Abundance** depends on initial misalignment angle (but expect it to be O(1) generically)
- **Abundance** and **spatial distribution** sensitive to cosmological evolution before nucleosynthesis

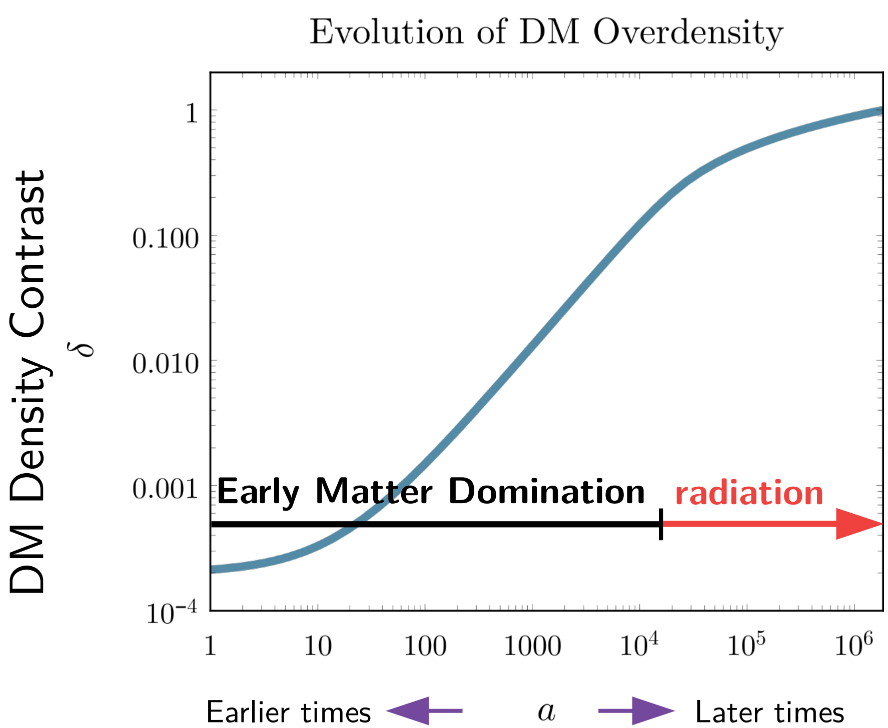


Dependence on pre-BBN universe

Visinelli & Gondolo (2009)+; NB, Dolan, Draper & Kozaczuk (2019)

Spatial Distribution of DM

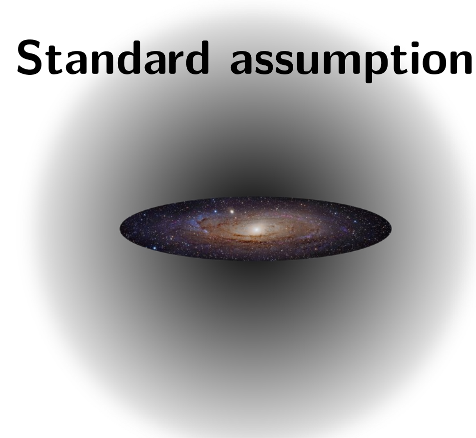
Small scale distribution of non-thermal DM depends sensitively on pre-nucleosynthesis cosmology



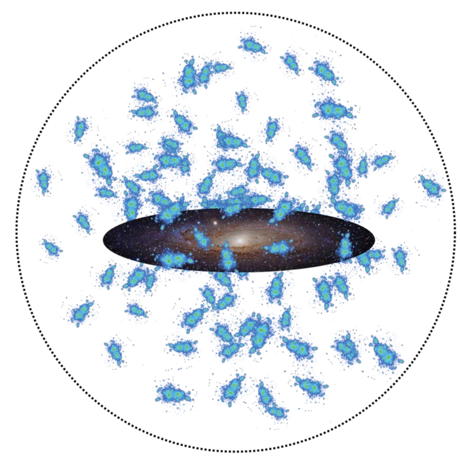
Erickcek, Sigurdson '11

NB, Dolan, Draper '20

NB, Dolan, Draper, Shelton '21



EMD before BBN



Big Question 3: Initial Conditions

Does non-thermal DM abundance and spatial distribution hold clues about conditions in the pre-nucleosynthesis universe?

Conclusion

The zoo of DM models can be (usefully) classified by their production mechanisms

Particle & Early Universe theory prioritizes representatives in these classes

- organizes viable interactions through effective field theory

- provides experimental targets

- relates specific searches to fundamental questions:

Particles in equilibrium or in feeble contact with SM? Non-standard cosmological evolution? Light particles during inflation?

Disclaimer & Exceptions

I focused on models accessible to traditional direct detection: far from a complete list! E.g.

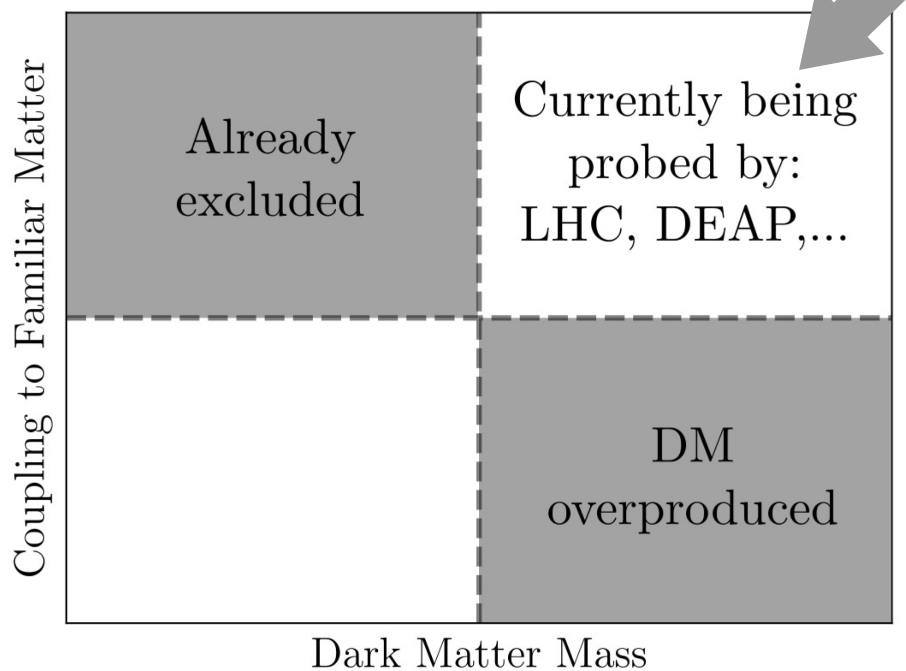
- Strong interactions with SM particles – shielded from DD
- Tuned parameters allowing large/small couplings and viable thermal freeze-out
- DM with sub-components that are easier to detect
- No interactions with SM (other than gravity) – not a nightmare scenario (for astrophysicists)!
- ...

Thank you/Merci!

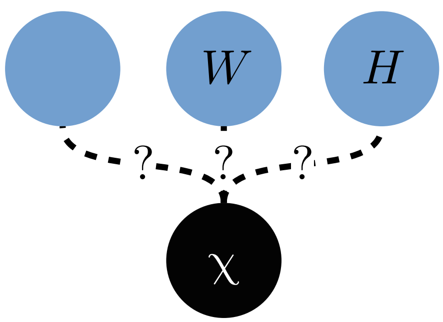
Appendix

Light Thermal Dark Matter

$$\langle \sigma v \rangle \approx \left(\frac{1}{20\ \text{TeV}} \right)^2 \sim \frac{y}{m_\chi^2} \Rightarrow \quad y \sim \alpha_{\text{em}}^2, \quad m_\chi \sim 100 m_{\text{proton}}$$



Weakly-Interacting Massive Particle



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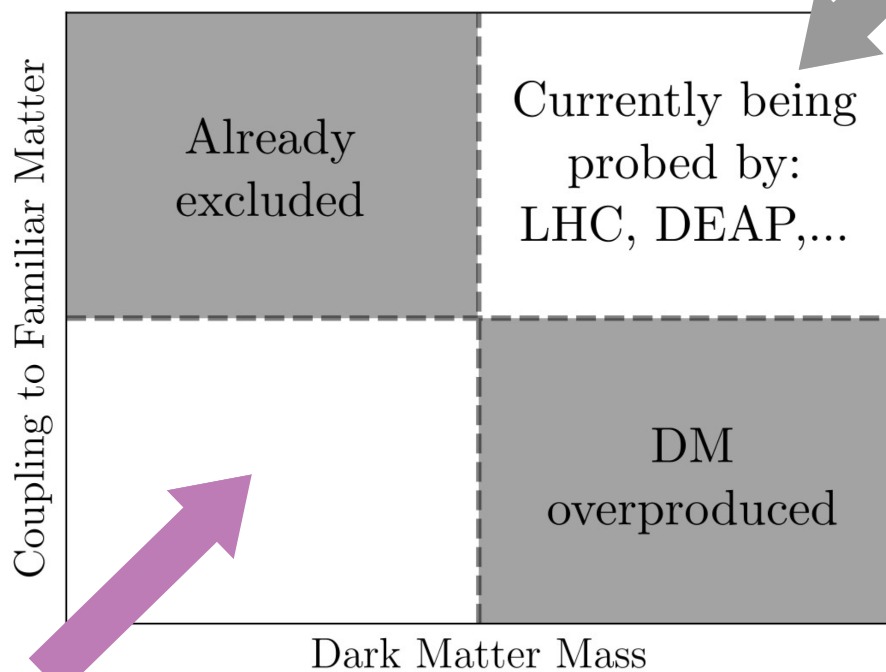

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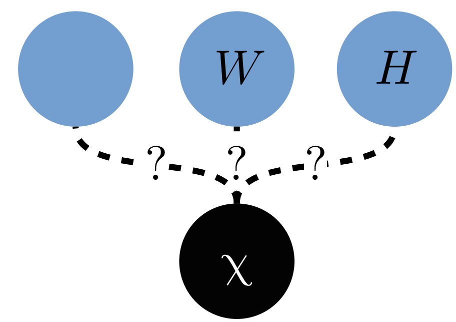
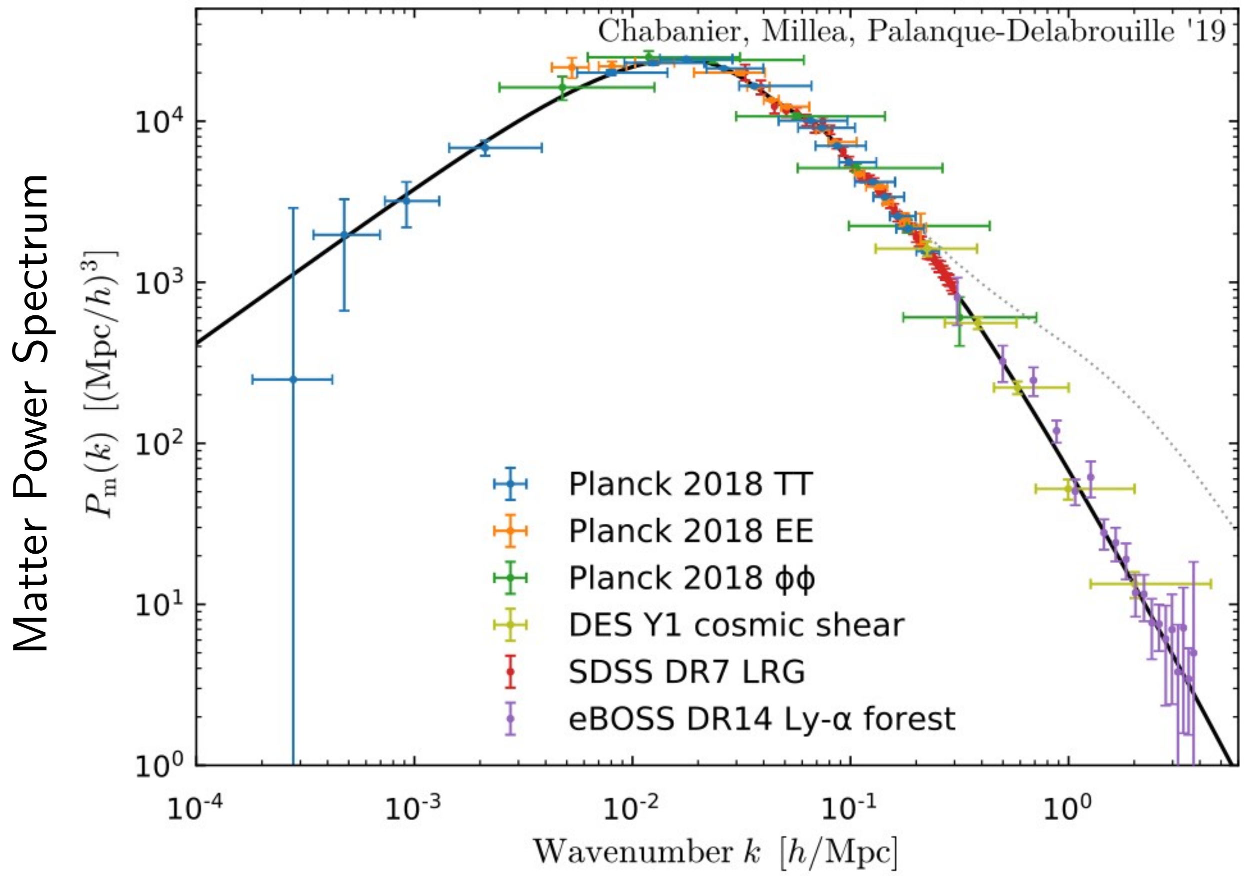
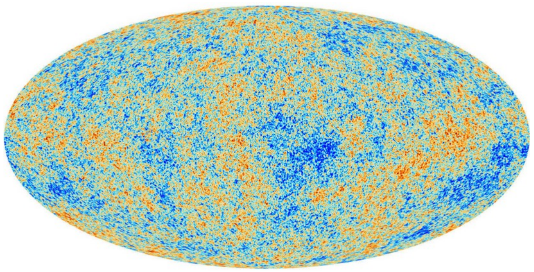


$$y \ll \alpha_{\text{em}}^2, \quad m_\chi \lesssim m_{\text{proton}}$$

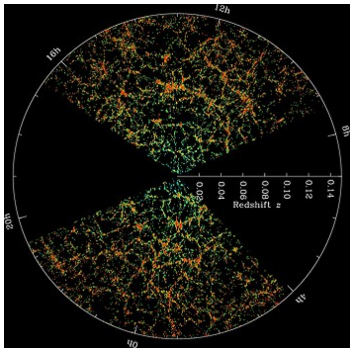
“Light” Dark Matter

Distribution of Dark Matter: Large Scales

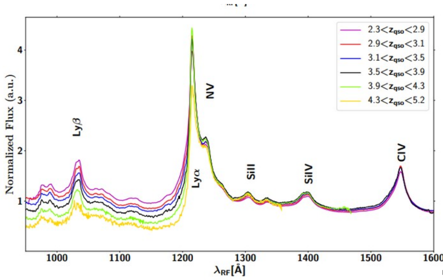




Planck '18



SDSS



eBOSS

Inflationary Vector Production 1

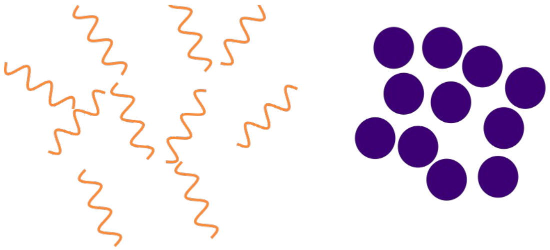
If DM is a light ($m < H_I$) spectator during inflation, it acquires an independent set of fluctuations

Minimally-coupled Vector Field

$$S = \int d^4x \sqrt{-g} \left[-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} m^2 A_\mu A^\mu \right] \Rightarrow \Delta^2_{A_L} = \left(\frac{k H_I}{2\pi m} \right)^2 \quad A_L = \hat{k} \cdot \vec{A}$$

Scale-*dependent* non-adiabatic fluctuations

$$\delta_{dm} \neq \delta_{rad} \sim \delta_{bar}$$



Graham, Mardon & Rajendran ‘15

Ema, Nakayama & Tang ‘19

Ahmed, Grzadkowski & Socha ‘20

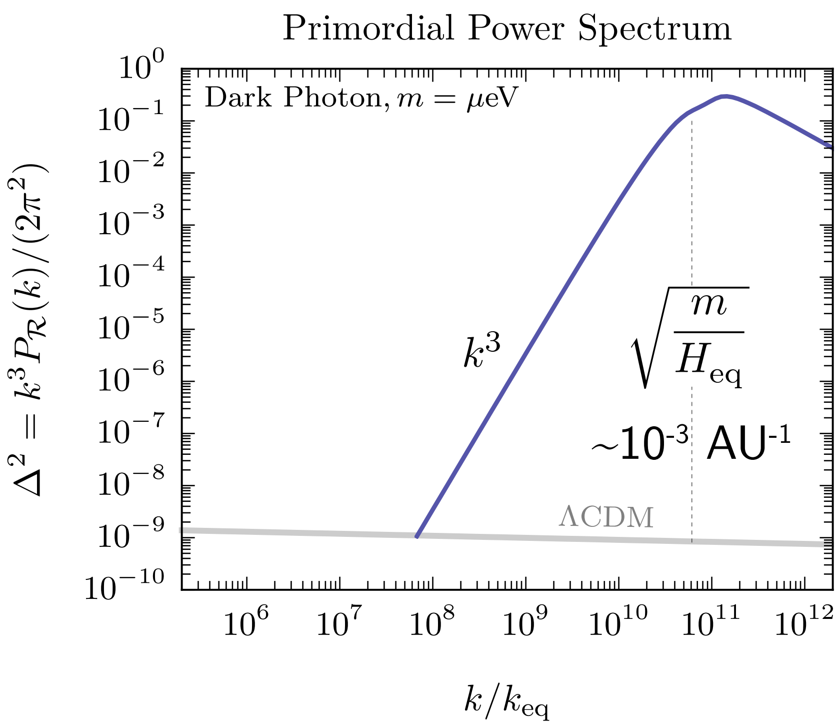
Long & Kolb ‘20

Inflationary Vector Production 2

- More power at small scales – **DM is born clumpy**
- Location of peak tied to particle mass

$$k_*/k_{eq} \approx \sqrt{\frac{m}{H_{\rm eq}}}$$

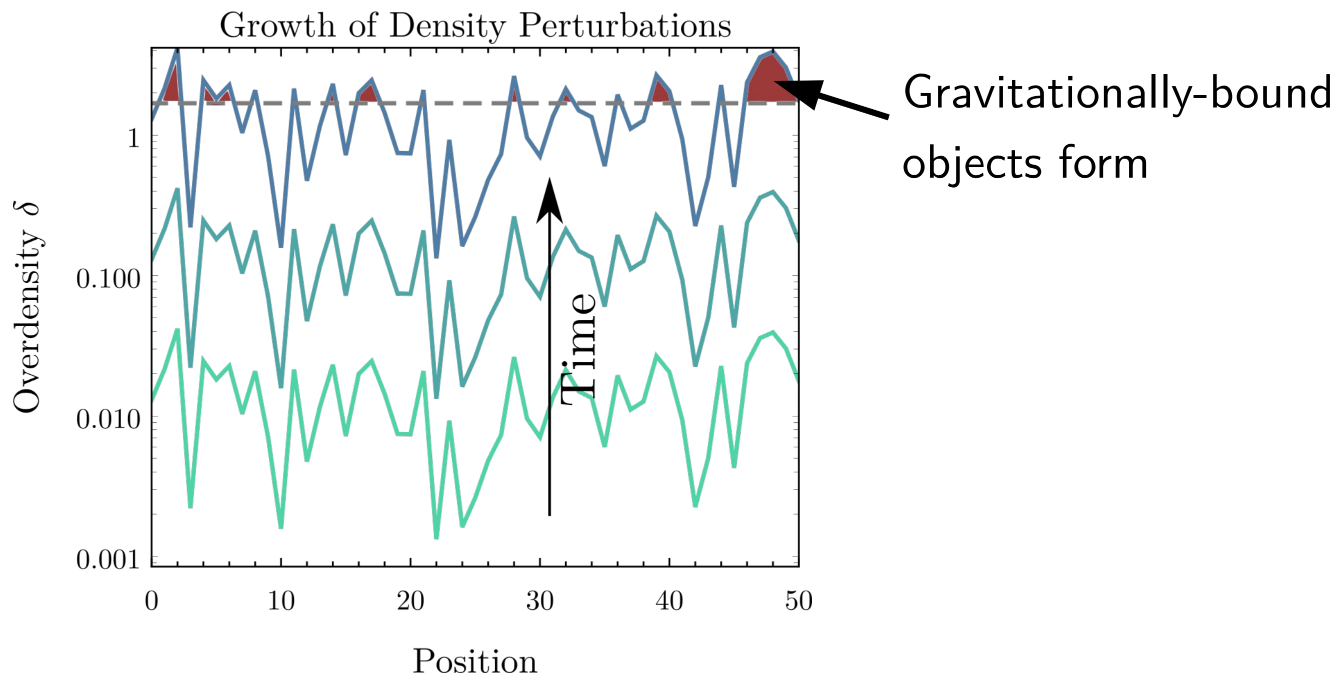
- Slope of PS follows from field evolution, i.e. particle nature and cosmology!



Graham, Mardon & Rajendran (2015)

Non-Linear Evolution & Collapse

Density perturbations are enhanced by several orders of magnitude during EMD or inflationary production



EMD or Inflationary boost leads to much earlier collapse compared to standard assumptions

Going Non-Linear

- (Linear) Perturbation theory no longer valid – how do we learn about DM distribution at late times?

(Semi) analytics: Press-Schechter

Statistical properties of DM halos and formation from linear theory

Pros:

- Intuition for structure formation

  Erickcek, Sigurdson '11, **NB**, Dolan, Draper '20

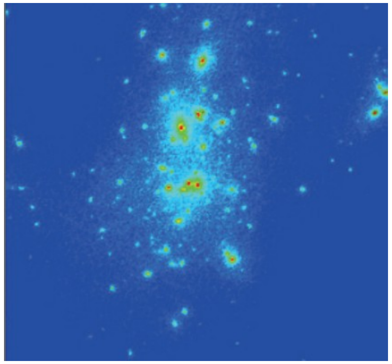
- Quick exploration of models

  NB, Dolan, Draper & Shelton '21

Cons:

- Untested on small scales
- Tidal disruption not included

Numerics: N-body simulations



Erickcek & Waldstein '17

Detailed halo properties & survival

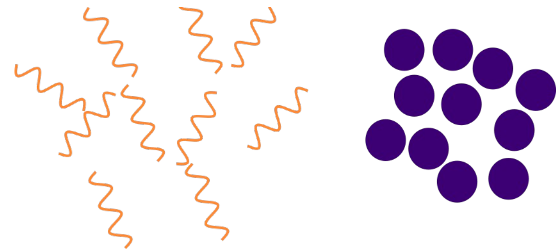
See work by Sten Delos et al '17, '18, '19;

Axions: Eggemeier '19, Xiao et al '21, Buschmann et al '19 ++

Other Light Fields

If DM is a light ($m < H_I$) spectator during inflation, it acquires an independent set of fluctuations

Minimally-coupled Scalar Field



$$S = \frac{1}{2}\int d^4x\sqrt{-g}\left[(\partial\phi)^2 - m^2\phi^2\right] \Rightarrow \ \Delta_\phi^2 = \left(\frac{H_I}{2\pi}\right)^2$$

Scale-*independent* non-adiabatic fluctuations $\delta_{dm} \neq \delta_{rad} \sim \delta_{bar}$

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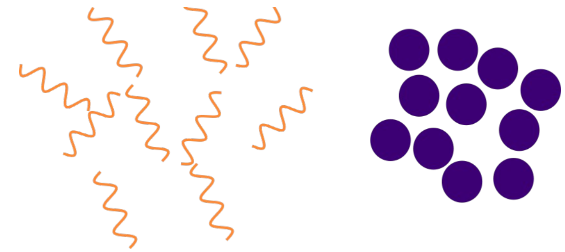

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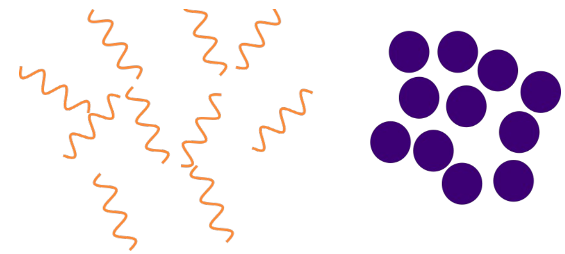
Other Light Fields

If DM is a light (m $<$ H_I) spectator during inflation, it acquires an independent set of fluctuations



Minimally-coupled Scalar Field

$$S = \frac{1}{2}\int d^4x\sqrt{-g}\,[(\partial\phi)^2 - m^2\phi^2] \Rightarrow \Delta_\phi^2 = \left(\frac{H_I}{2\pi}\right)^2$$

Scale-*independent* non-adiabatic fluctuations $\delta_{dm} \neq \delta_{rad} \sim \delta_{bar}$

Minimally-coupled Vector Field

$$S = \int d^4x\sqrt{-g}\left[-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m^2A_\mu A^\mu\right] \Rightarrow \Delta_{A_L}^2 = \left(\frac{kH_I}{2\pi m}\right)^2 \quad A_L = \hat{k}\cdot\vec{A}$$

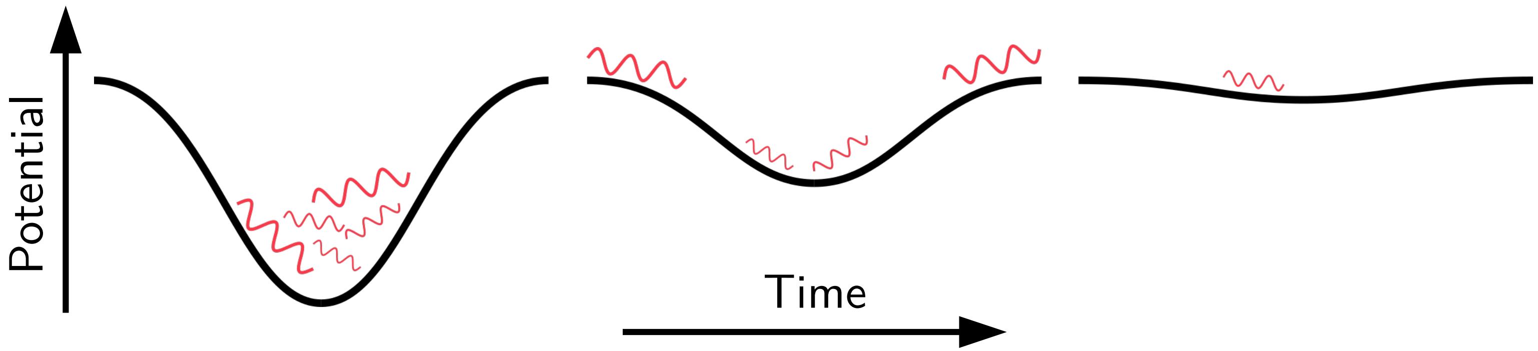
Scale-*dependent* non-adiabatic fluctuations

Graham, Mardon & Rajendran '15
Ema, Nakayama & Tang '19
Ahmed, Grzadkowski & Socha '20
Long & Kolb '20

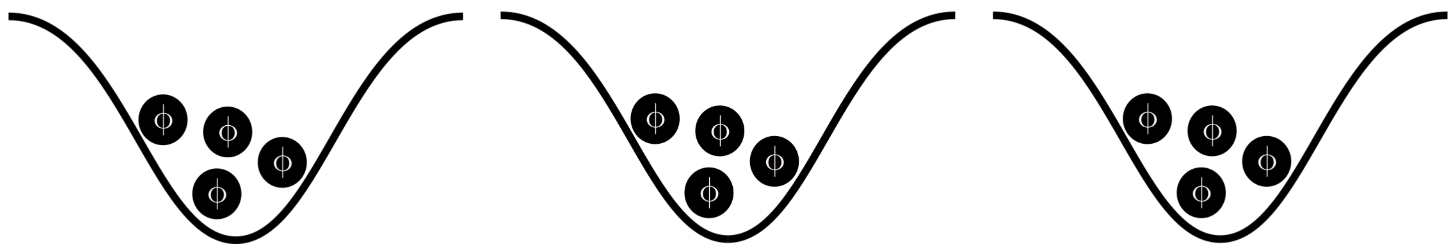
EMD: Impact on Small-Scale Structure

Modified cosmology also changes the growth of density perturbations

- *Radiation domination*: gravitational potentials decay



- *(Early) Matter domination*: gravitational potentials stay constant



Beyond Radiation Domination

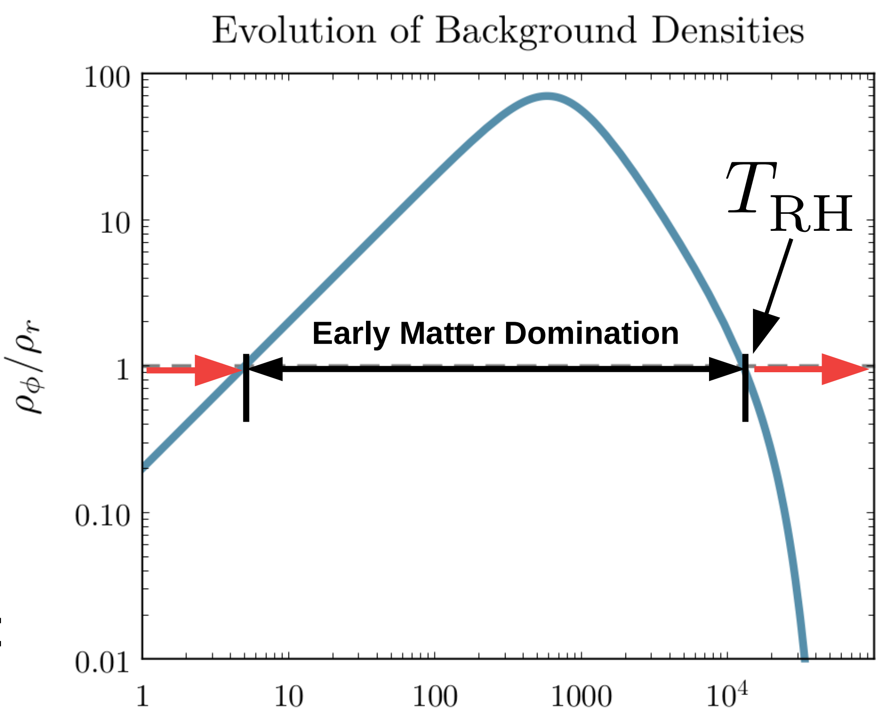
Non-radiation-dominated evolution generic beyond the SM

$$\rho_X/\rho_{\rm rad} \propto a^{1-3w_X}$$

A semi-stable species X with

$$w_X < 1/3$$

will dominate if you wait long enough



Scale factor a
(arbitrary normalization)

Early Matter Domination (EMD):

$$w_X = 0$$

SUSY/String Moduli
Coughlan et al '83
Banks, Kaplan & Nelson '94
de Carlos, Casas, Quevedo & Roulet '93
Moroi & Randall '99
++

Dark Sectors
Yue Zhang '15
Dror et al '16 & '17
Berlin, Hooper & Krnjaic '16
Erickcek, Ralegankar & Shelton '20 & '21
++

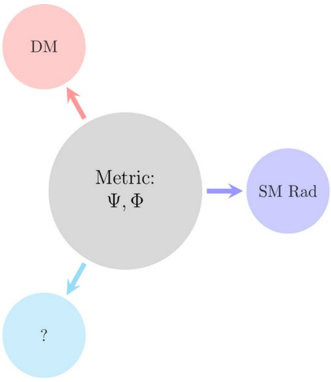
Evolution of Density Perturbations

Initial density fluctuations need to be evolved to late times

Evolution of DM density perturbation governed by energy/momentum conservation + gravity $\delta = [\rho_{dm}(x) - \bar{\rho}_{dm}]/\bar{\rho}_{dm}$

$$\ddot{\delta} + \mathcal{H}\dot{\delta} + \cdots = -k^2\Psi - 3\ddot{\Phi}$$

Background cosmology



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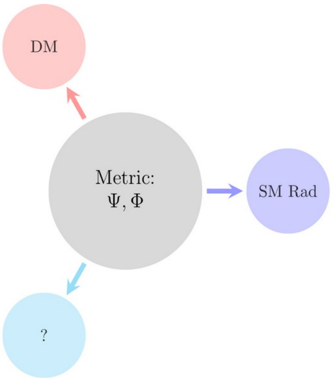

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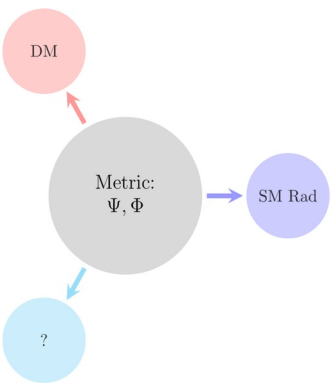
Scale-dependent effects:

Radiation pressure, wave effects

Gravitational driving



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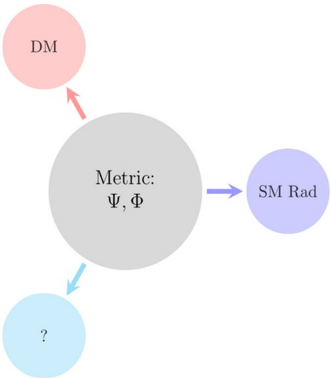
Background cosmology

Scale-dependent effects:
Radiation pressure, wave effects

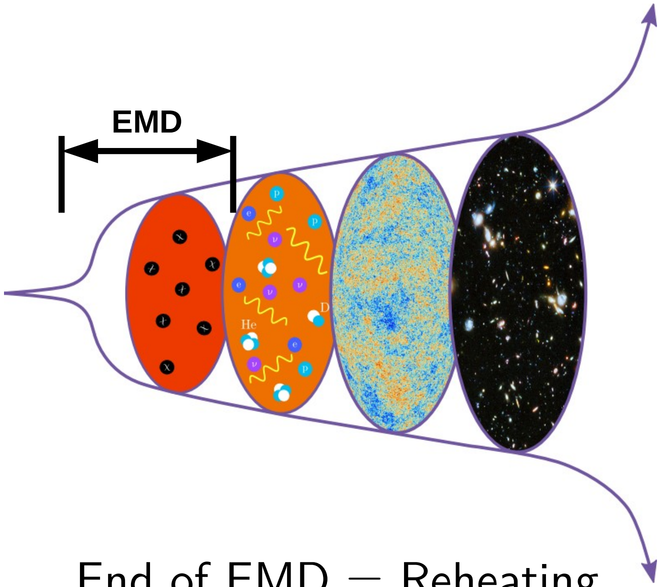
Gravitational driving

$$\delta \propto \begin{cases} a & \text{matter dom.} \\ \ln a & \text{radiation dom.} \end{cases}$$

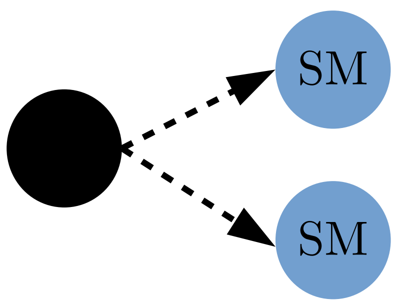


Early Matter Domination (EMD)

Pre-BBN ($T > 5$ MeV) universe dominated by **matter** instead of radiation



End of EMD = Reheating



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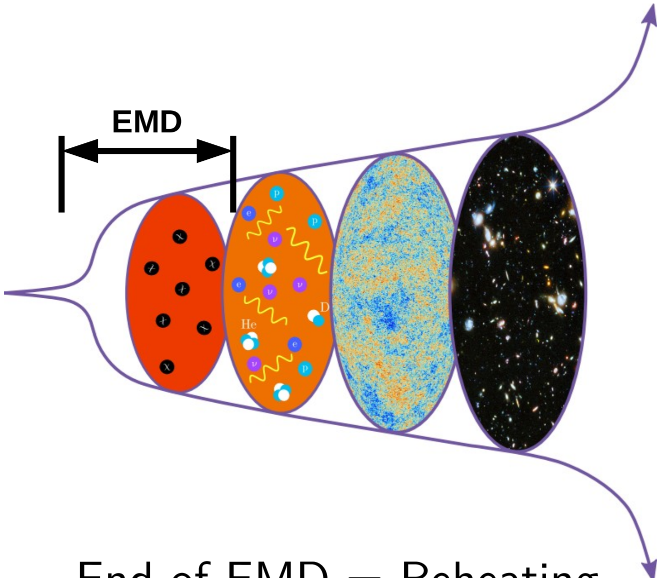

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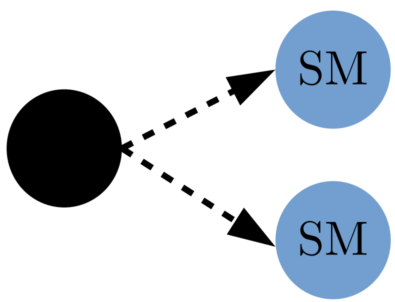
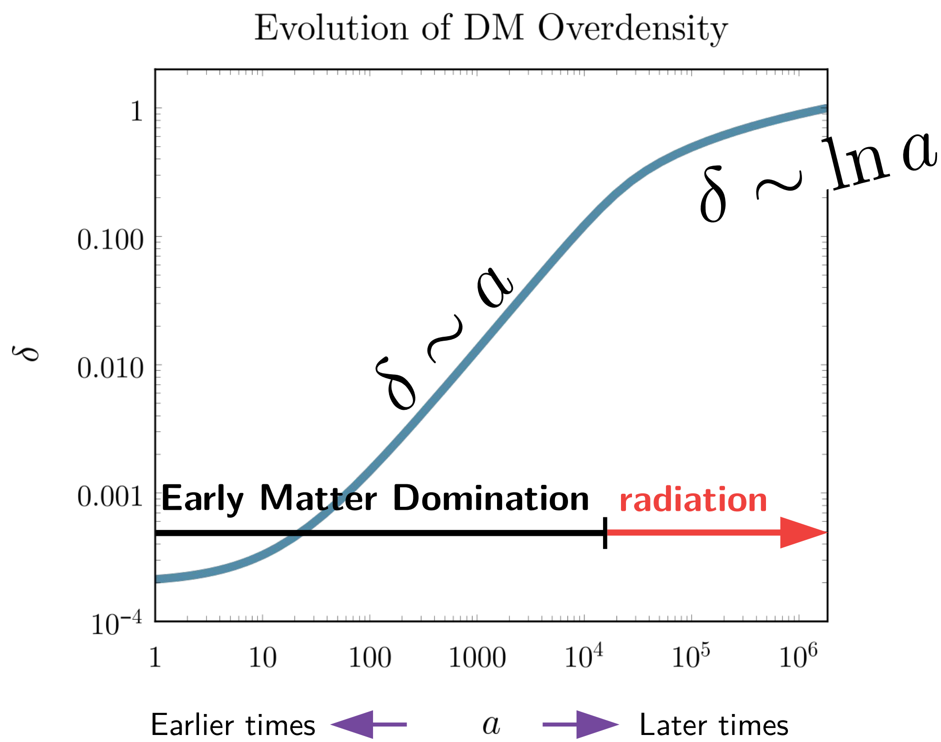




CDM & WIMPs: Erickcek, Sigurdson '11

ALPS: **NB**, Dolan, Draper '20

EMD enhances growth of small-scale density perturbations

Misalignment Abundance (RD)

$$\Omega_a = \frac{1}{2}\frac{m_a^2 f_a^2 \theta_0^2}{\rho_c}\left(\frac{R_{\rm osc}}{R_0}\right)^3$$

Dilution factor $R_{\rm osc}/R_0$ estimated *assuming* radiation-domination and using entropy conservation between $T_{\rm osc}$ and T_0:

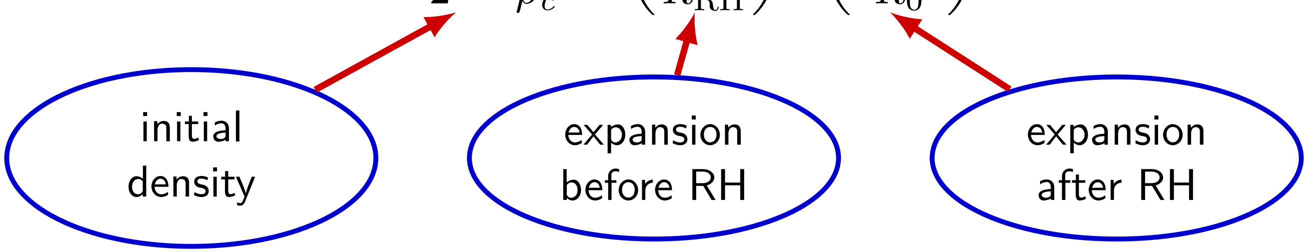
$$m_a \sim H(T_{\rm osc}) \quad \Rightarrow^* \; T_{\rm osc} \sim 85\ {\rm GeV}\sqrt{\frac{m_a}{10^{-5}\ {\rm eV}}}$$

$$\left(\frac{R_{\rm osc}}{R_0}\right)^3 = \frac{s(T_0)}{s(T_{\rm osc})}$$

* temperature independent m_a

Misalignment Abundance (Non-RD)

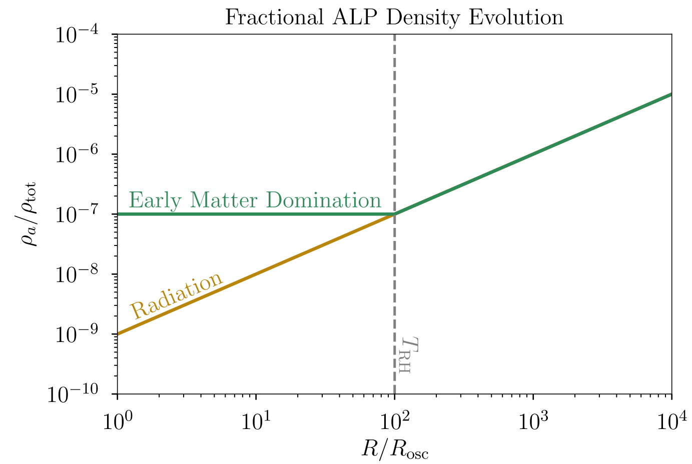
$$\Omega_a = \frac{1}{2}\frac{m_a^2 f_a^2 \theta_0^2}{\rho_c}\left(\frac{R_{\rm osc}}{R_{\rm RH}}\right)^3\left(\frac{R_{\rm RH}}{R_0}\right)^3$$



Dilution factor $R_{\rm osc}/R_{\rm RH}$ obtained via $H \propto \sqrt{\rho_{\rm tot}} \sim R^{-3/2}$:

$$\left(\frac{R_{\rm osc}}{R_{\rm RH}}\right)^3 = \left(\frac{H(T_{\rm RH})}{H(R_{\rm osc})}\right)^2 \sim \frac{T_{\rm RH}^2}{M_{\rm Pl} m_a^2}$$

Estimating the Relic Abundance (RD)

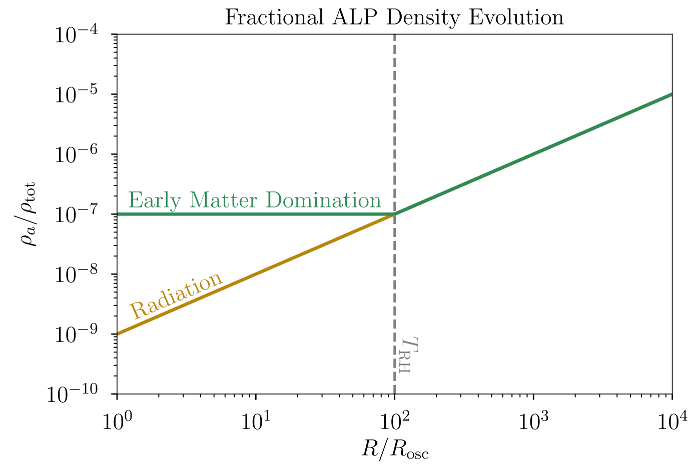


Visinelli & Gondolo (2009)+; NB, Dolan, Draper & Kozaczuk (2019)

Standard Cosmology (and T-independent mass): $\rho_{\rm tot} \propto 1/R^4$

$$\Omega_a h^2 \simeq 0.12 \left(\frac{f_a \theta_0}{1.9 \times 10^{13}\,\mathrm{GeV}} \right)^2 \left(\frac{m_a}{1\,\mu\mathrm{eV}} \right)^{1/2}$$

Estimating the Relic Abundance (EMD)



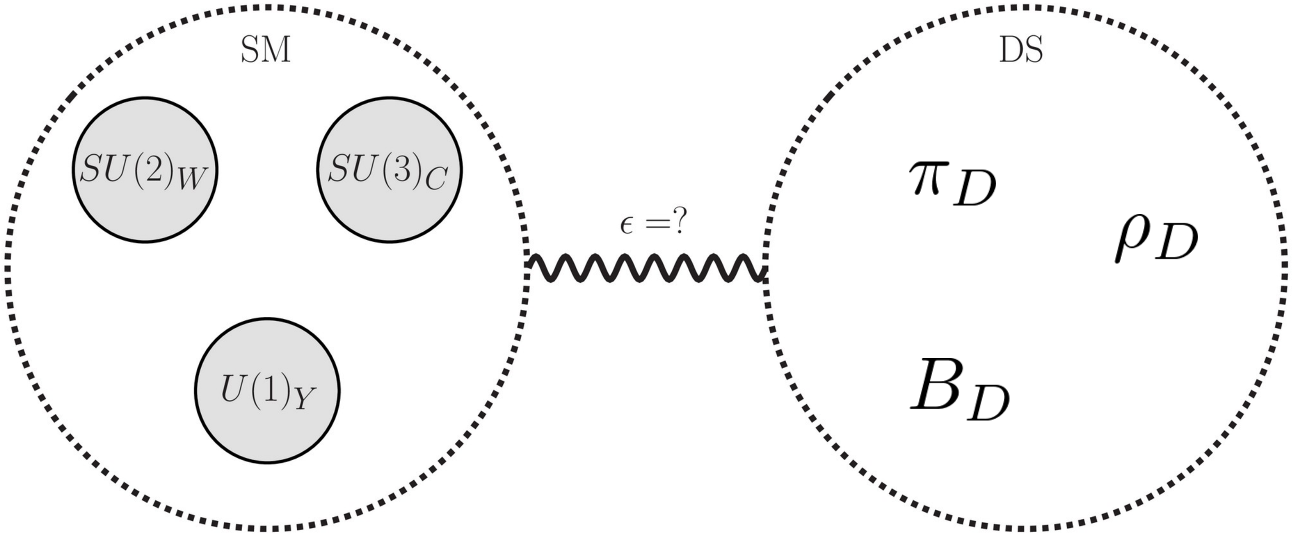
Visinelli & Gondolo (2009)+; NB, Dolan, Draper & Kozaczuk (2019)

Early Matter Domination (and T-independent mass): $\rho_{\rm tot} \propto 1/R^3$

$$\Omega_a h^2 \simeq 0.12 \times \left(\frac{f_a \theta_0}{9 \times 10^{14}\,\mathrm{GeV}}\right)^2 \times \left(\frac{T_{\rm RH}}{10\,\mathrm{MeV}}\right)$$

SIMPs

Natural in **strongly-interacting** (QCD-like) dark sectors. E.g. DM = pions of a dark QCD — Hochberg, Kuflik and Murayama (2015)

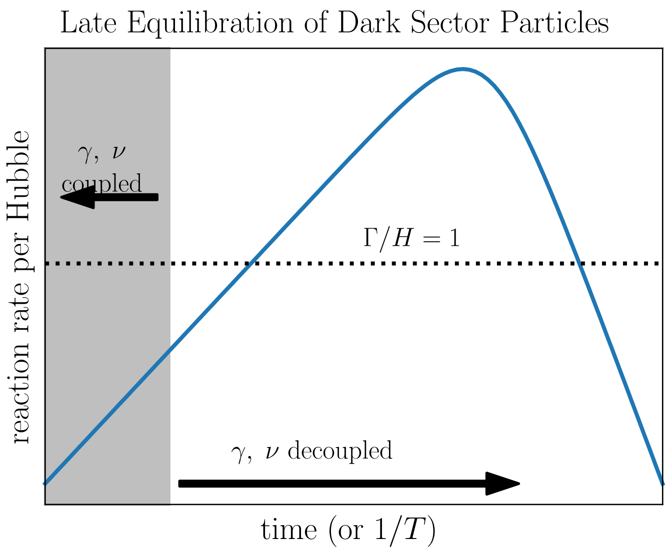


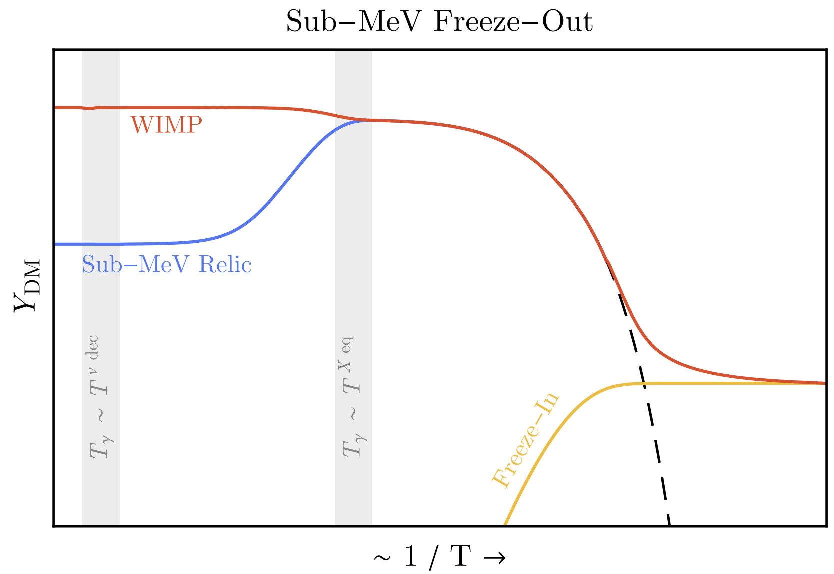
An alternative implementation of chemical and kinetic equilibrium in early universe! Phenomenology depends on mediator choice: Dark photons: Hochberg, Kuflik & Murayama (2015); Berlin, NB, Gori, Schuster & Toro (2018)

ALPs: Hochberg, Kuflik, McGehee, Murayama & Schutz (2018)

Late Equilibration

An intermediate regime: a delayed, brief period of equilibrium with SM



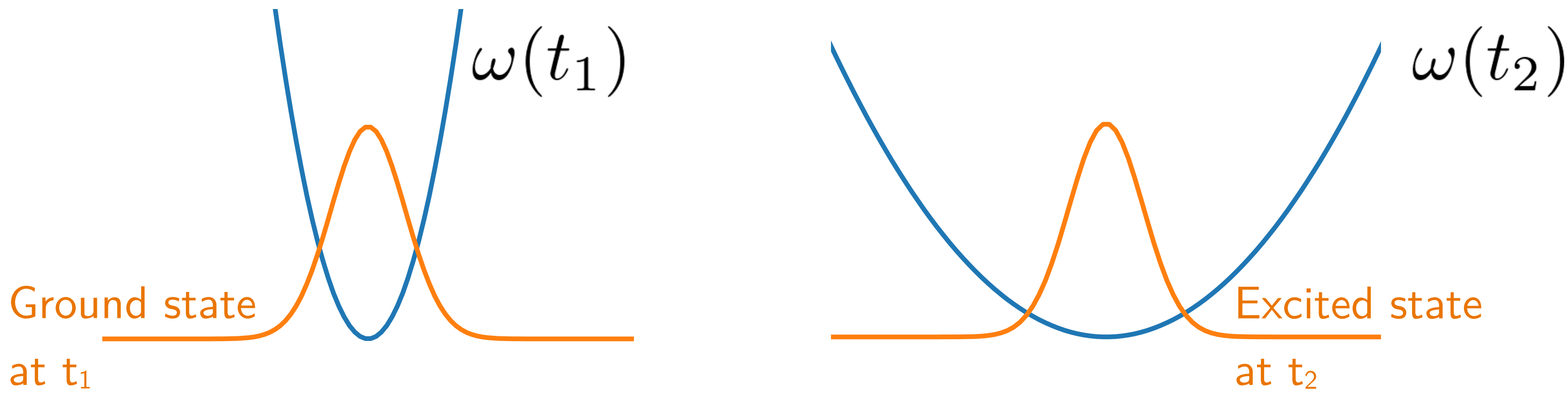


Berlin, NB (2017,2018); Berlin, NB & Li (2018)

Minimizes cosmological impacts (compared to thermal ∼MeV scale relics) but only viable implementation through neutrino portal

Inflationary Particle Production

Rapidly expanding universe gives rise to non-adiabatic evolution of fields; a harmonic oscillator analogy



A free quantum field has $\omega^2 = k^2 + m^2 a(t)^2 + \ldots$

$$a(t) = e^{H_{inf} t}$$

An initially empty universe evolves into one filled with potentially stable relics!

Dark Photon DM

Gravitational particle production relates DM mass, scale of inflation and abundance

$$\Omega_A = \Omega_{cdm}\sqrt{\frac{m_A}{6\times 10^{-6}\ \mathrm{eV}}}\left(\frac{H_{inf}}{10^{14}\ \mathrm{GeV}}\right)^2$$

Graham, Mardon & Rajendran '15; Ema, Nakayama & Tang '19; Ahmed, Grzadkowski & Socha '20; Long & Kolb '20

DM born clumpy at very small scales $\rightarrow$ possible enhancement or suppression of DD rates!