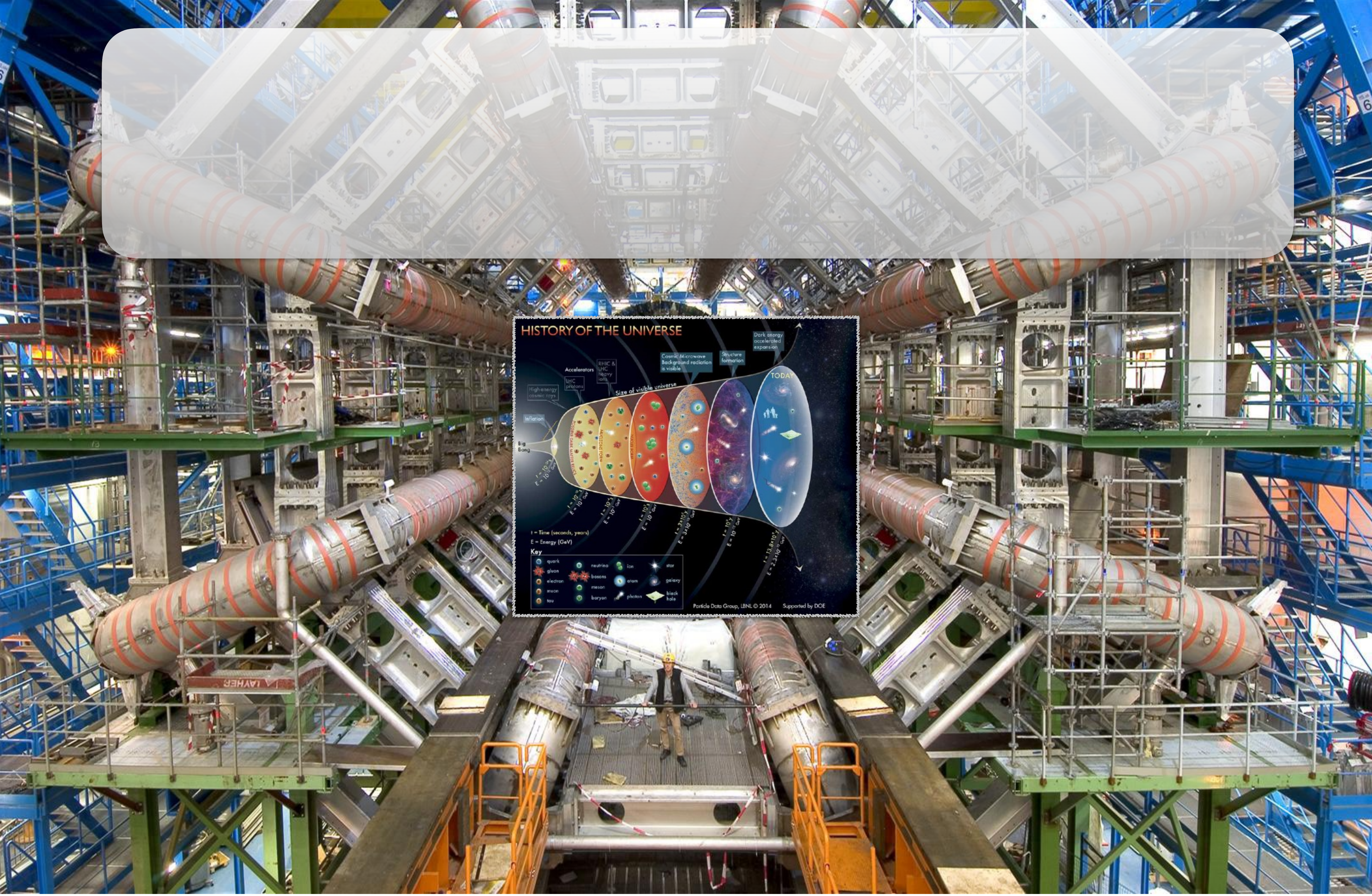


Filippo Sala

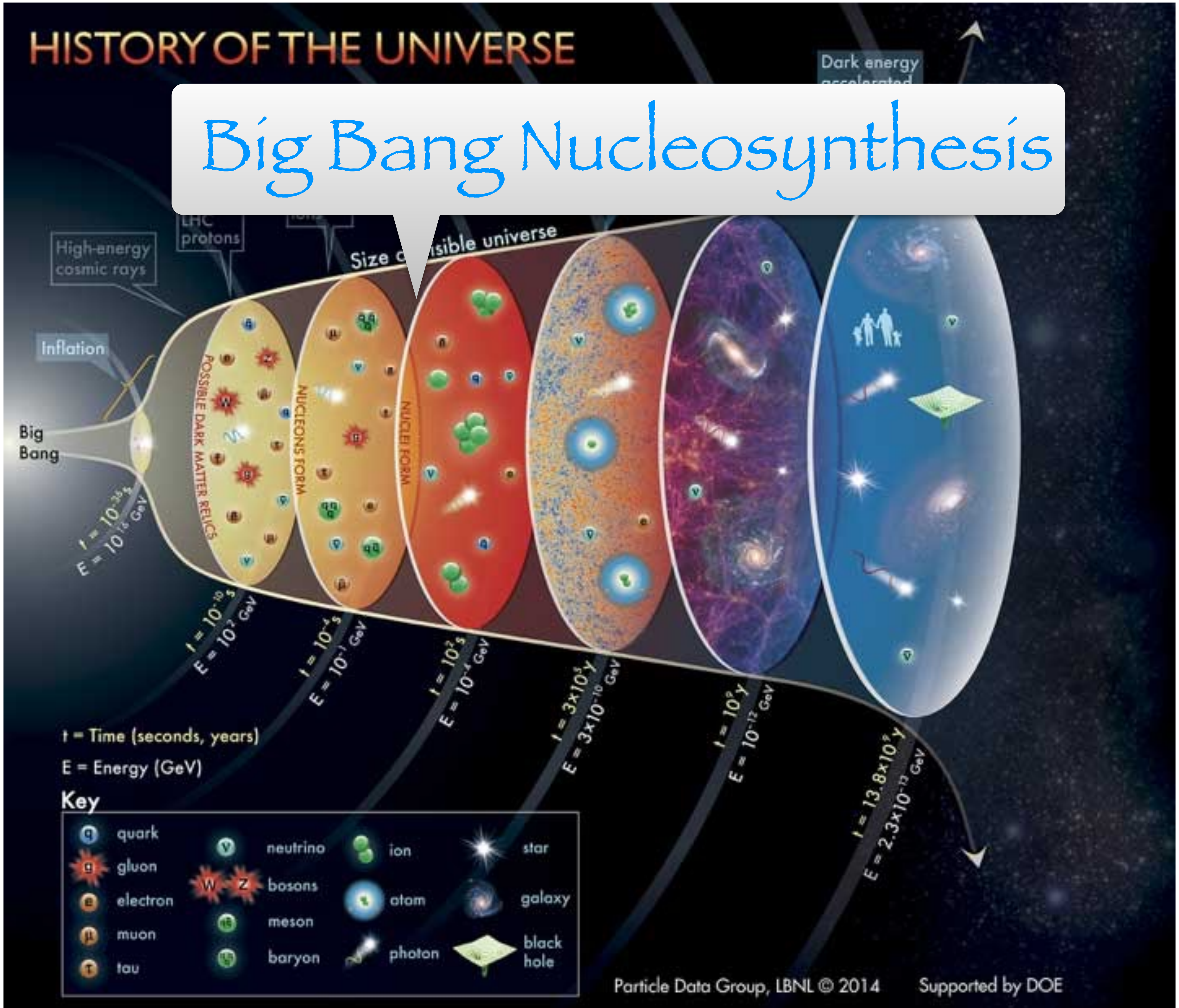
(U. Bologna)

Dark Showers Workshop
21 Jan 2025

Not Tested

Tested

Smaller Temperature



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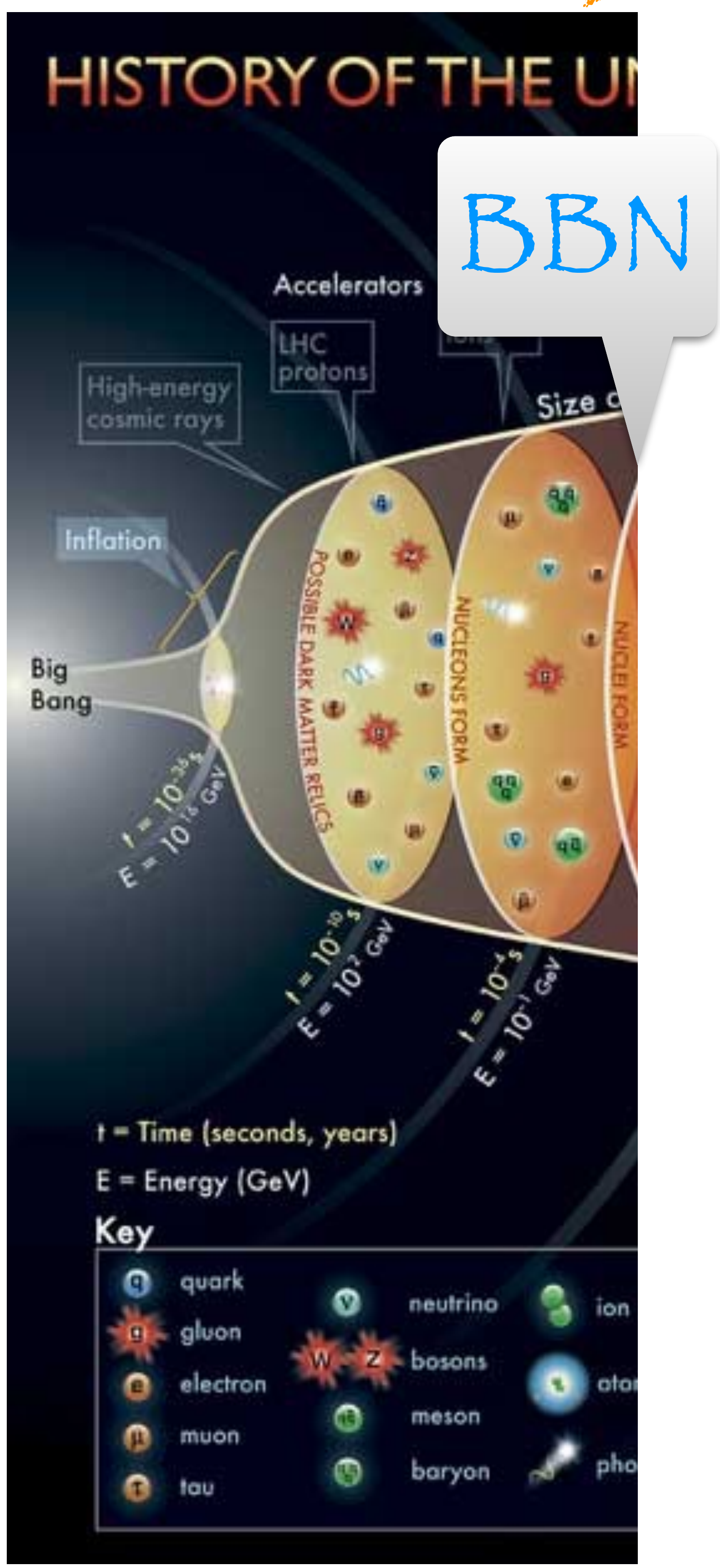
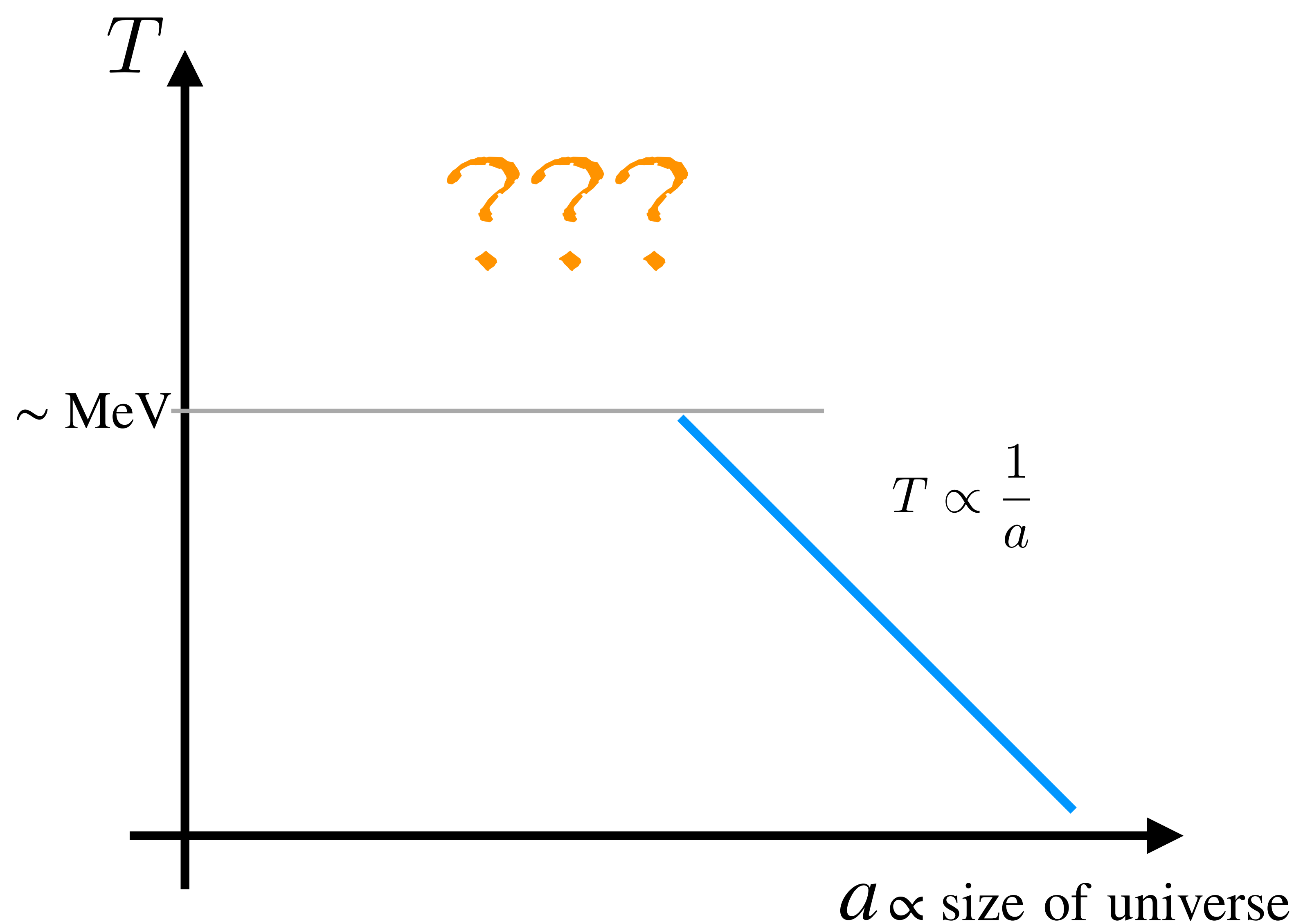
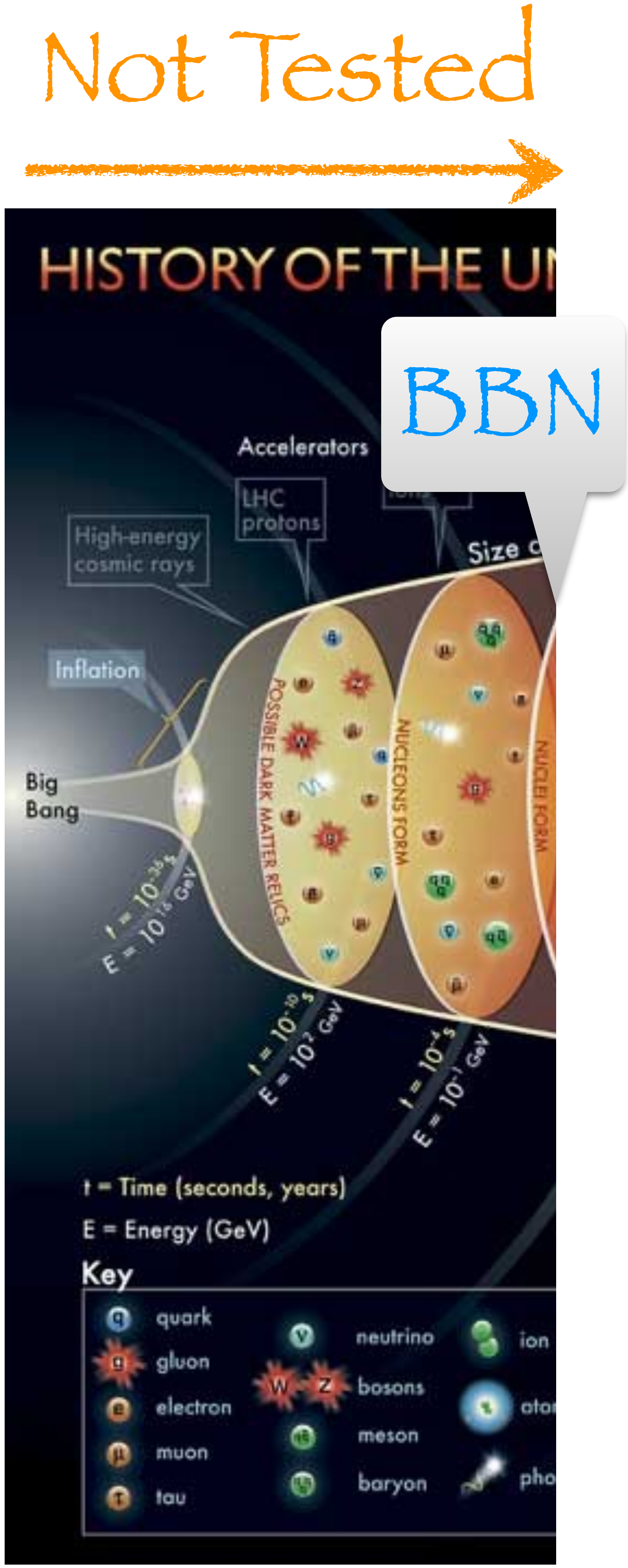

BBN
Accelerators
LHC protons
High-energy cosmic rays
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion


T
???
$\sim$ MeV
$T \propto \frac{1}{a}$
$a \propto$ size of universe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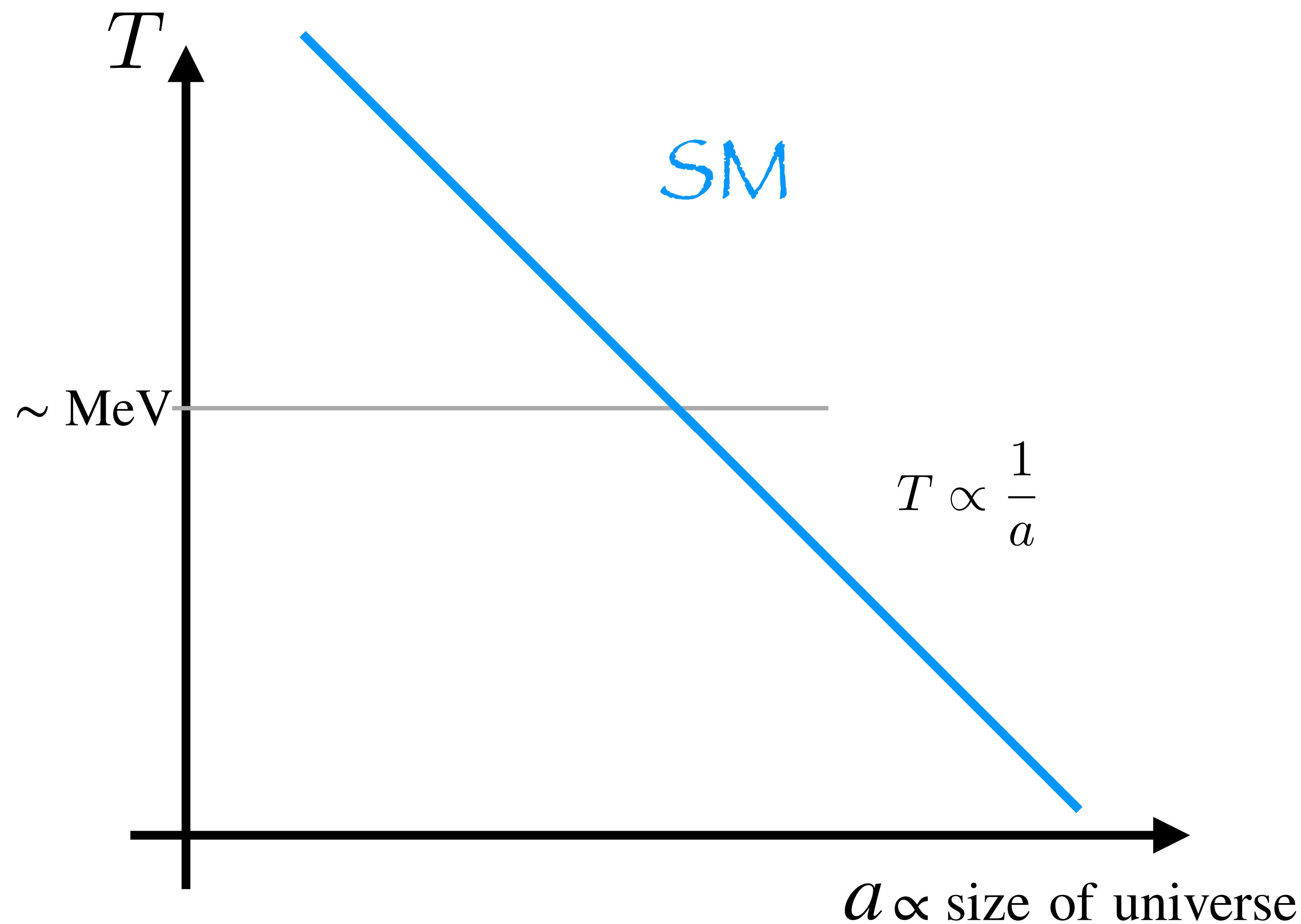
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SM
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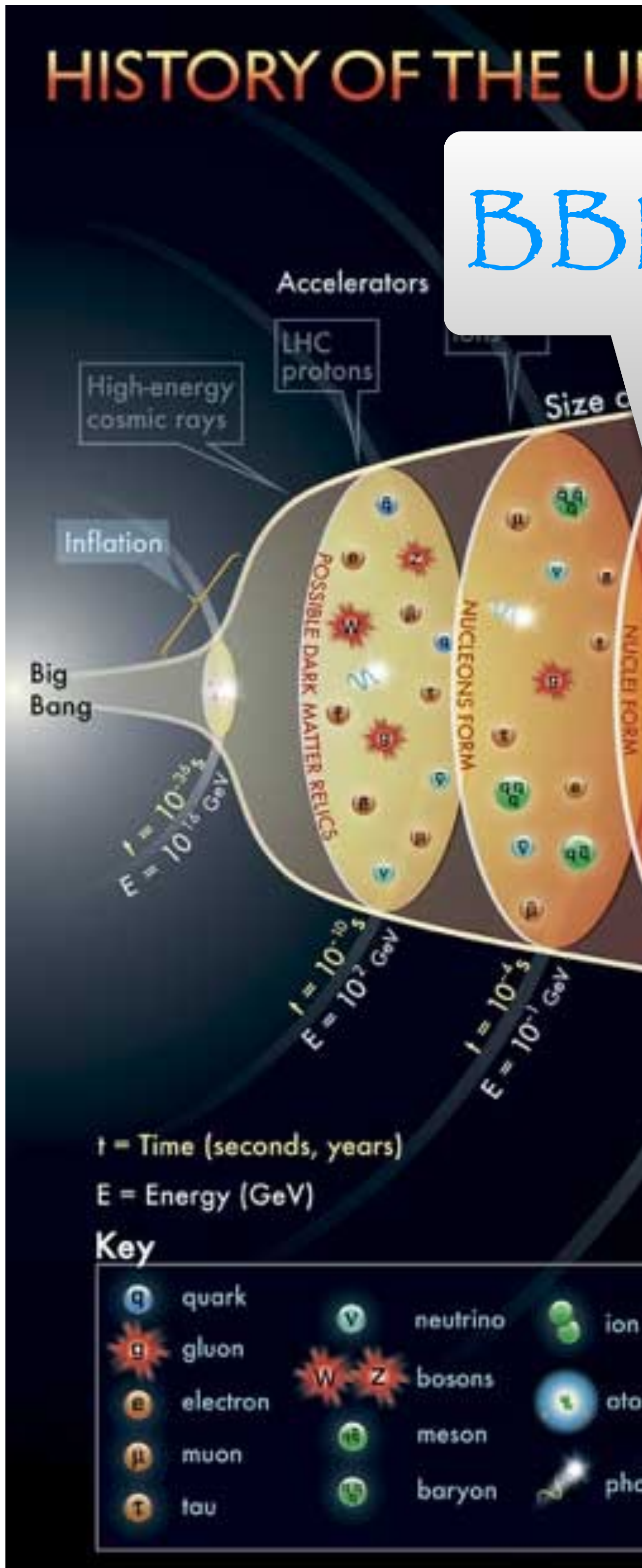

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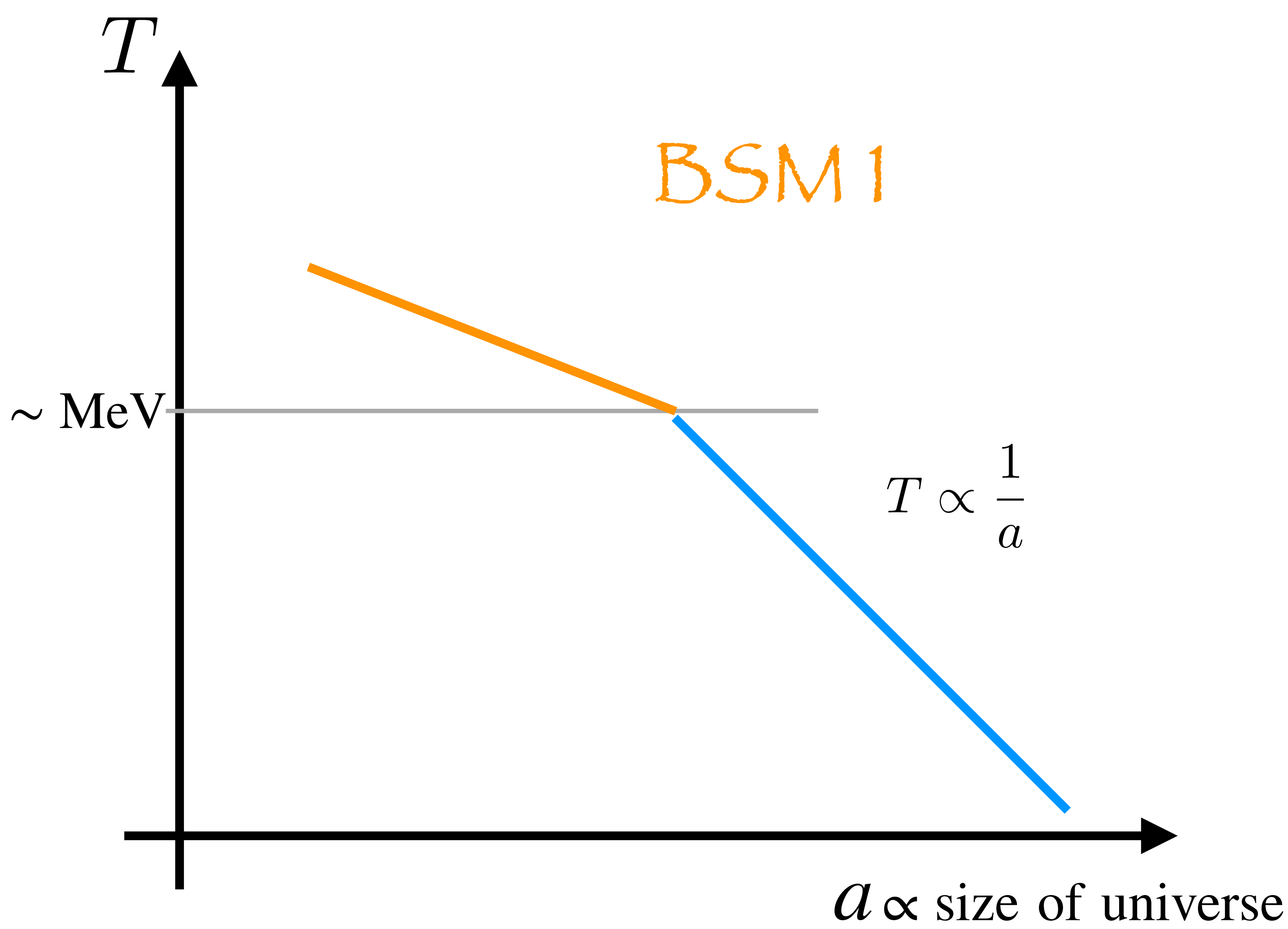

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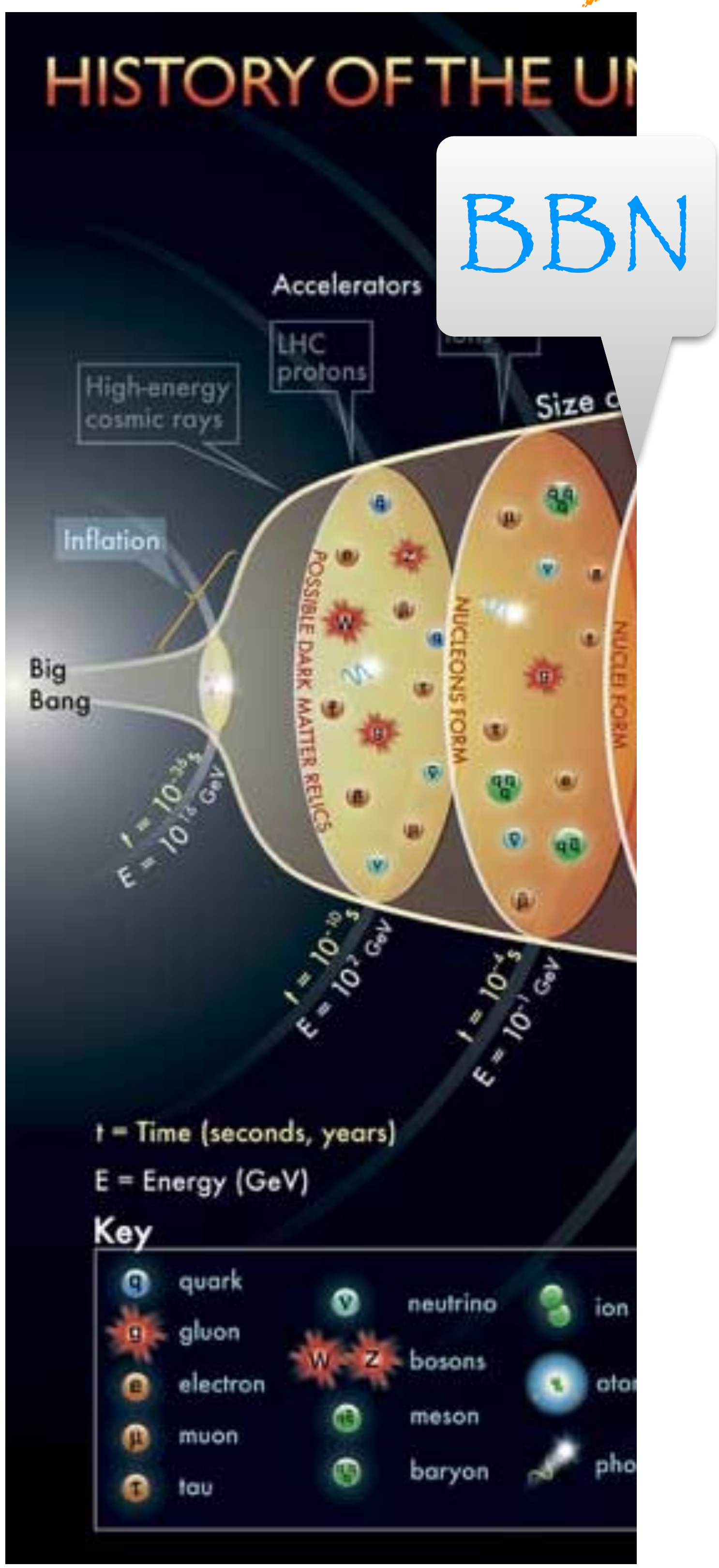
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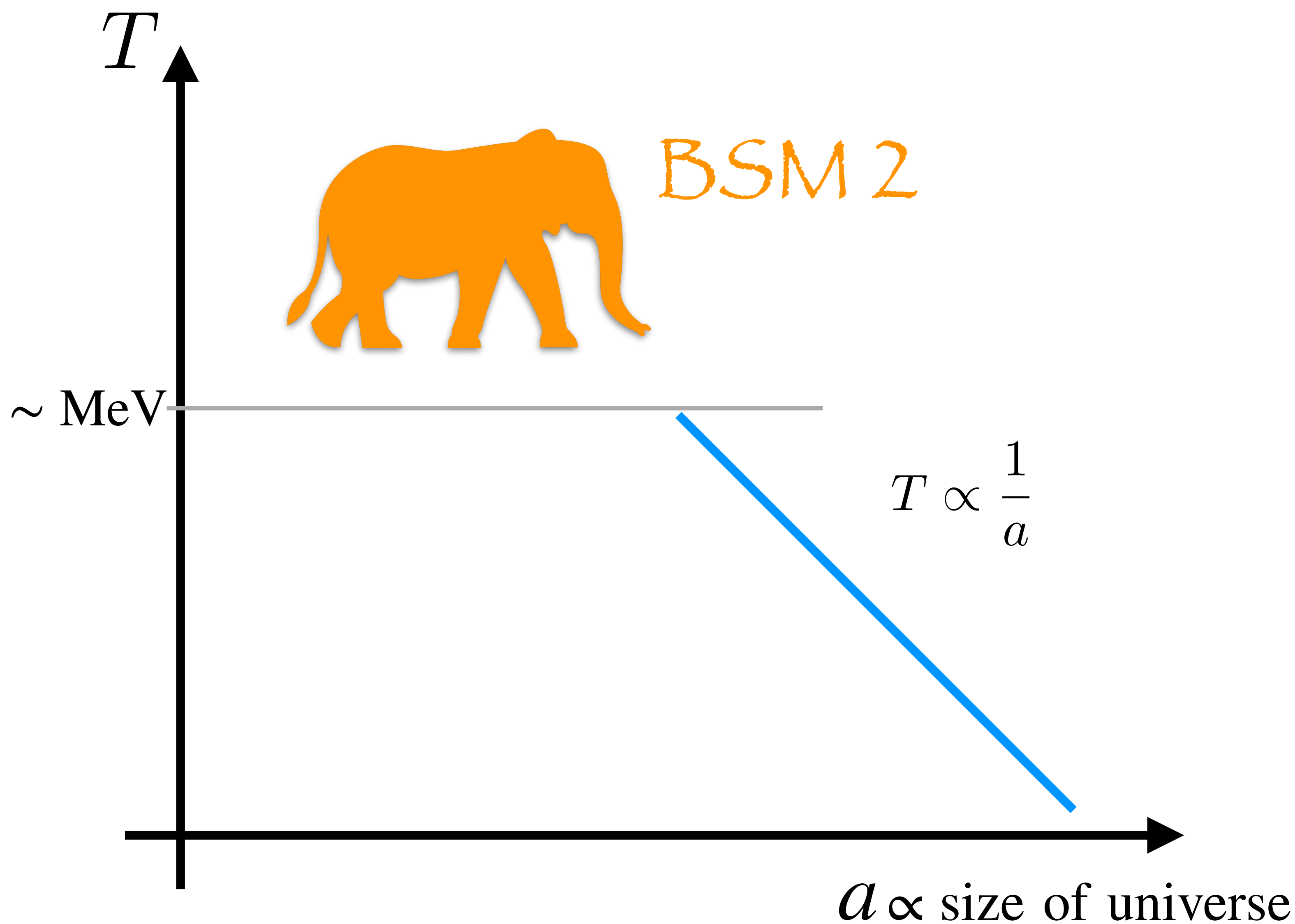
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BSM 2
$\sim$ MeV
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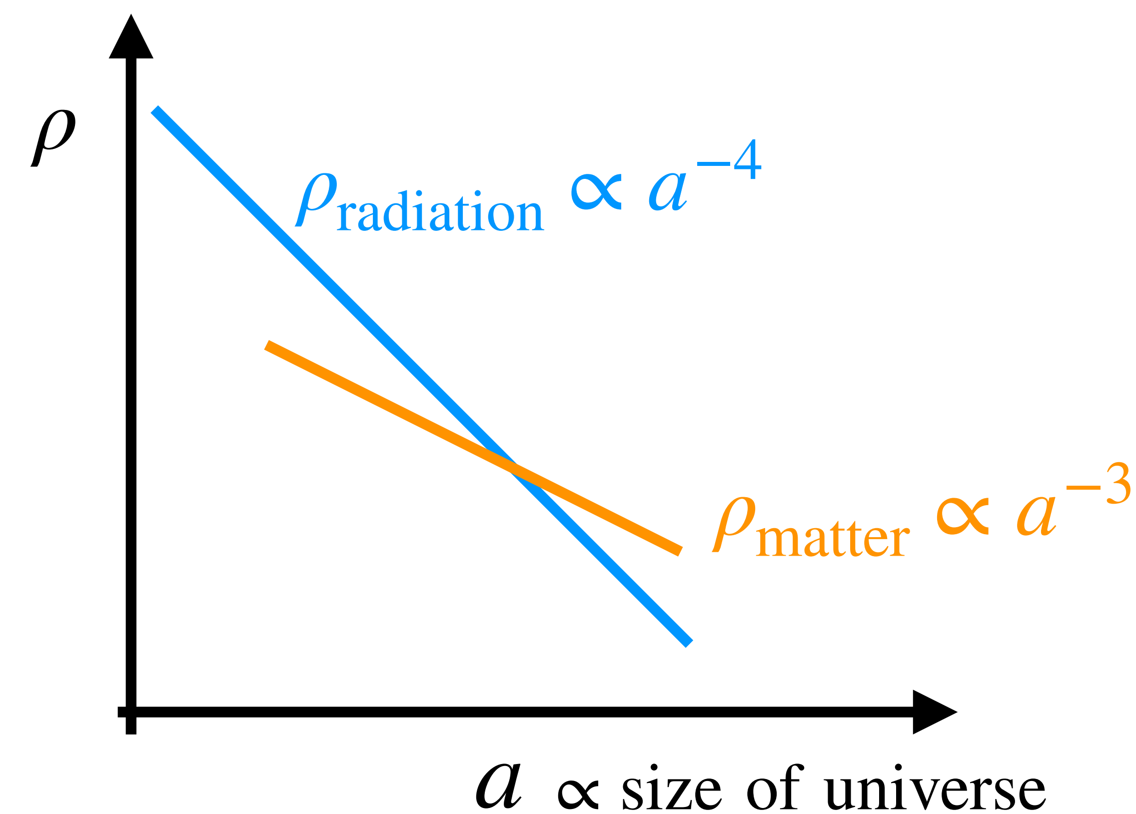
Matter Domination

Matter dominates over Radiation at late times, e.g. Dark Matter today

Matter: $m \gg T$

Radiation: $m \ll T$



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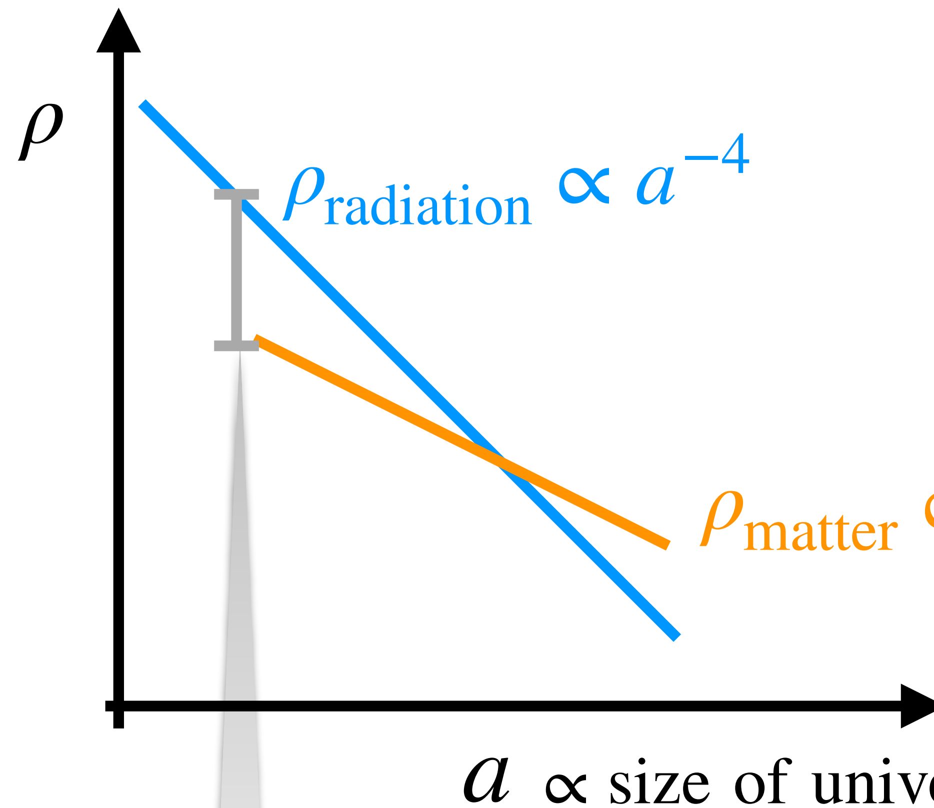

If Matter at <u>thermal equilibrium</u> -> $\rho_{\text{matter}} \propto \exp(-m/T) \lll \rho_{\text{rad}} \propto T^4$

Early Matter Domination

Add to SM particle(s) that satisfy conditions:

1) $\frac{M_{\rm Pl}}{m^2} \ll \tau \lesssim \text{sec}$

decay after becoming matter $T_{\rm decay} \ll m$

decay before spoiling BBN $T_{\rm decay} \gtrsim \text{MeV}$

2) $T_{\rm decouple} \gtrsim m$

otherwise $\rho_{\rm matter} \propto \exp(-m/T) \lll \rho_{\rm rad} \propto T^4$

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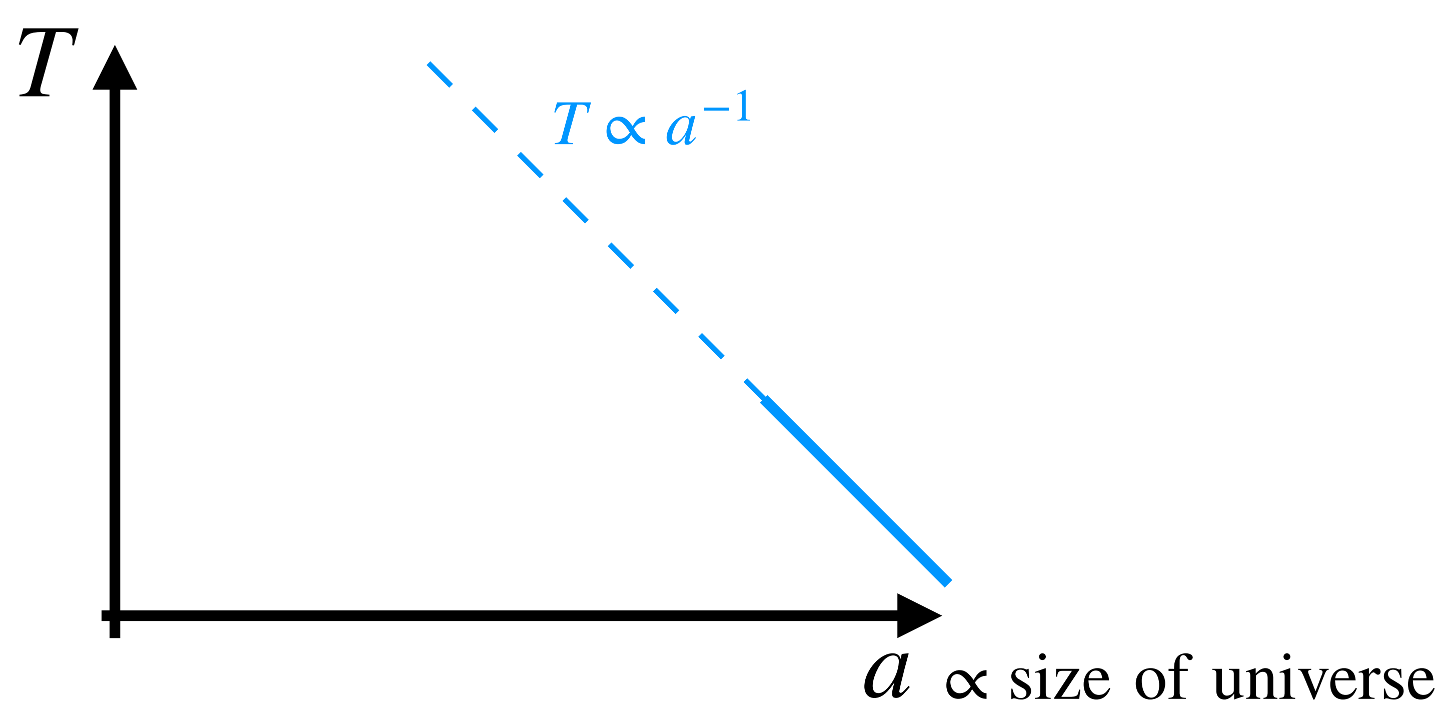

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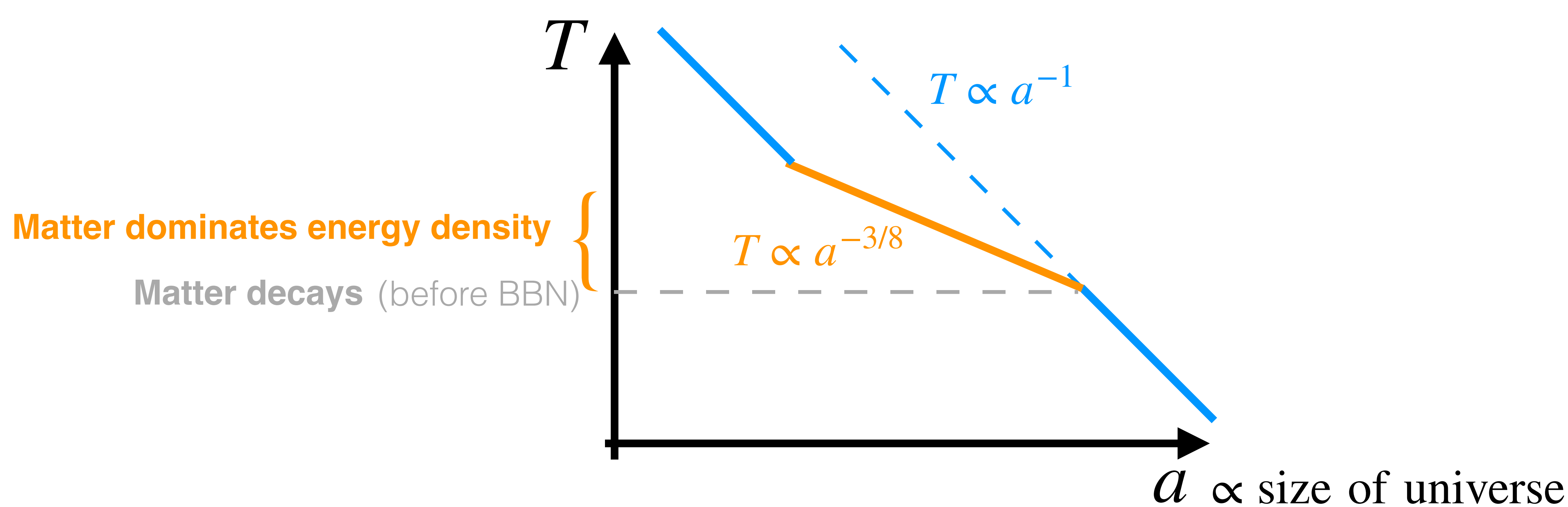

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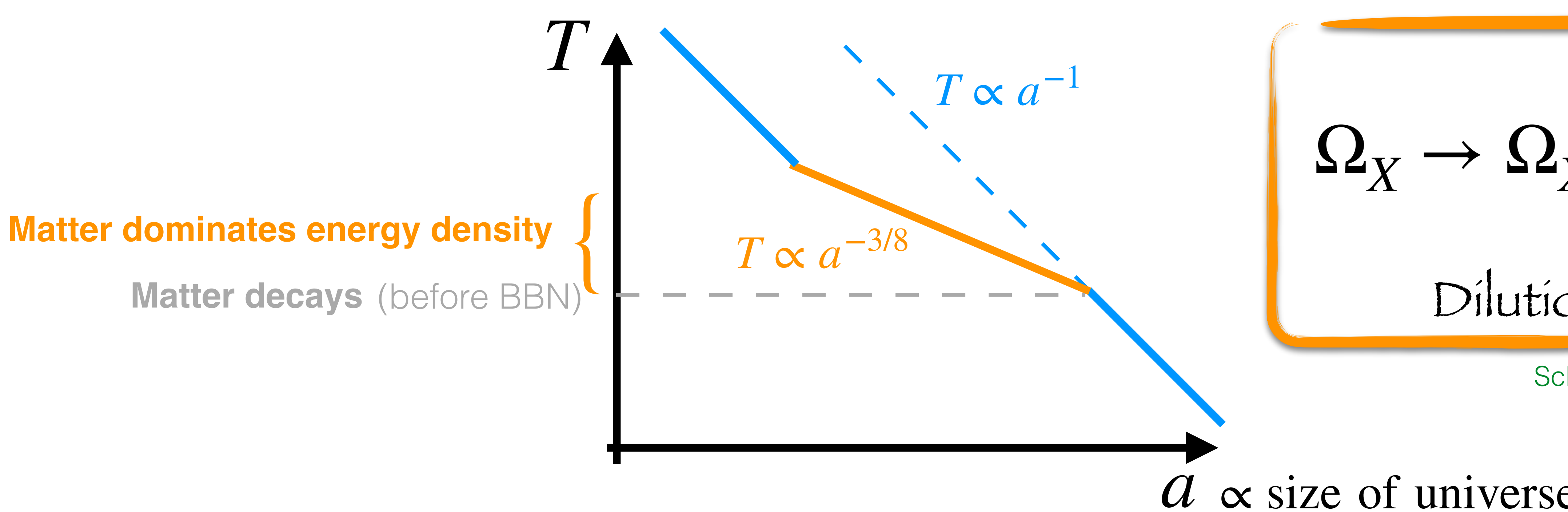


$$\Omega_X \to \Omega_X \frac{s_{\rm before}}{s_{\rm after}}$$

Dilution factor

Scherrer Turner 1985

Why Early Matter Domination?

Happens in standard cosmology after CMB...

Some theories predict it

Moduli in SUSY Banks Kaplan Nelson hep-ph/9308292, …

Lightest composite state of new confining theory
Contino+ 1811.06975,…

Some theories need it to dilute dangerous relics

Topological defects

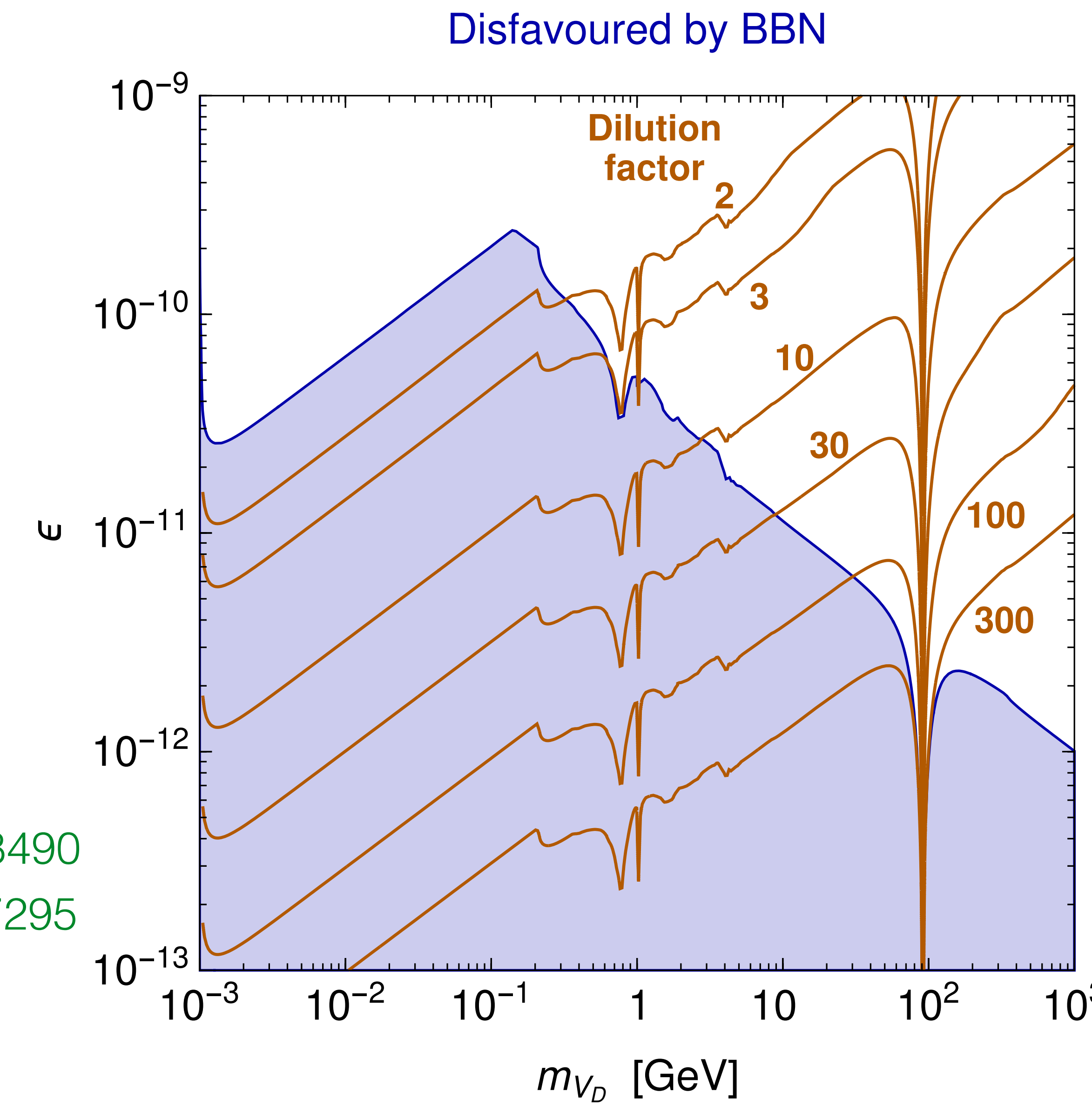
Overabundant Heavy DM Moroi Randall hep-ph/9906527
Giudice Kolb Riotto hep-ph/0005123,…

Concrete Examples

Dark Photon

$$\mathscr{L} = -\frac{1}{4}F_D^{\mu\nu}F_{D\mu\nu} - \frac{\epsilon}{2c_w}F_D^{\mu\nu}B_{\mu\nu}$$

E.g. from heavy new particles
charged under both U(1)'s



Berlin+1602.08490
Cirelli+1612.07295

BSM scalar

e.g. Glueballs of new confining sector,…

Contino+ 1811.06975,…

…

How To Test?

Early Matter Domination in the Sky

Telescopes Cosmic Rays > 100 TeV from Heavy DM annihilation

Cirelli+1612.07295
…
F. Sala + ANTARES in progress

Gravitational Waves Features in primordial spectrum from inflation, cosmic strings,…

Gouttenoire+1912.03245, …

Matter Power Spectrum Structures start to collapse earlier

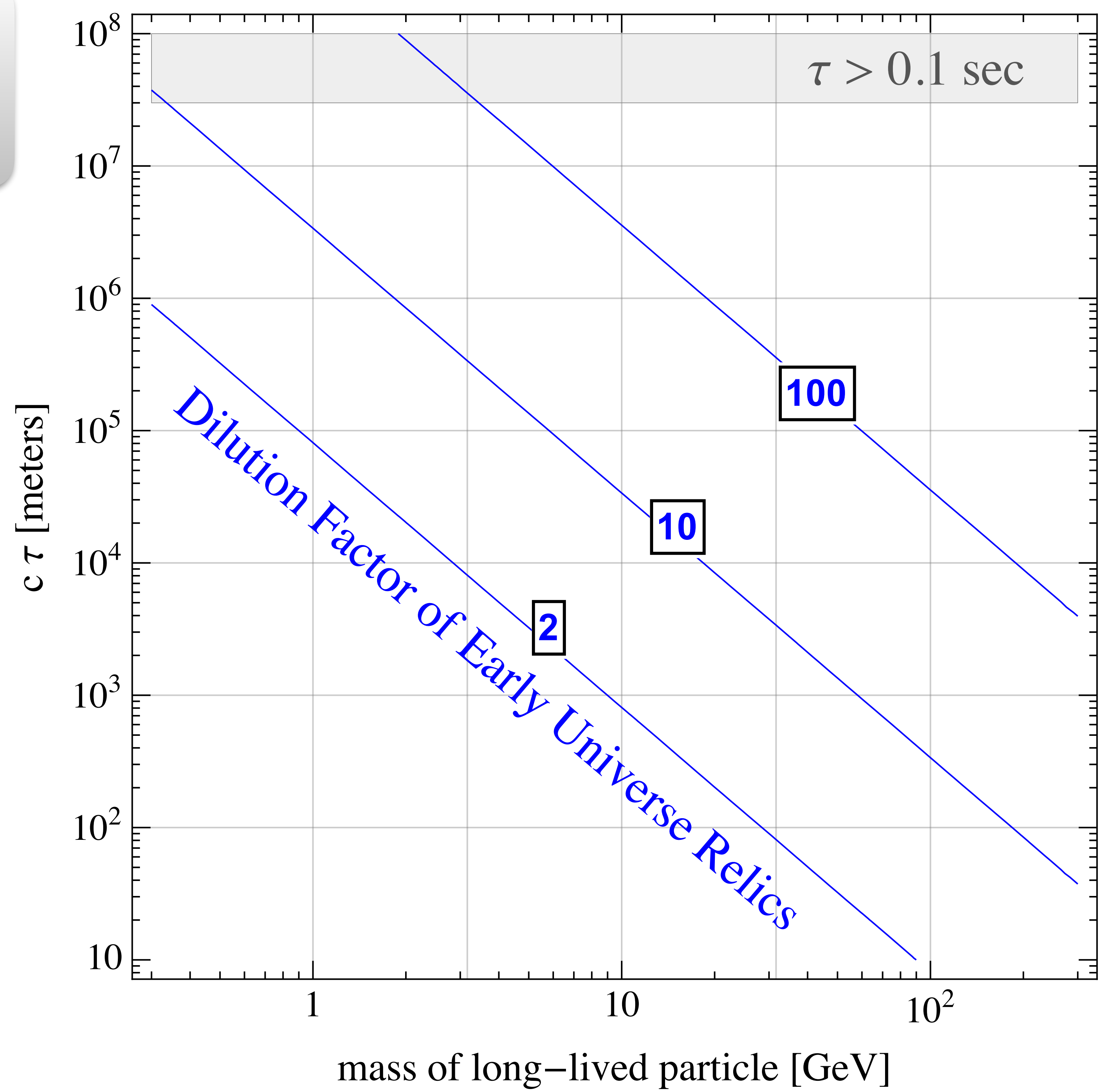
Blanco+1906.00010
Erickcek+ 2106.09041
…

Can we test in the Lab?

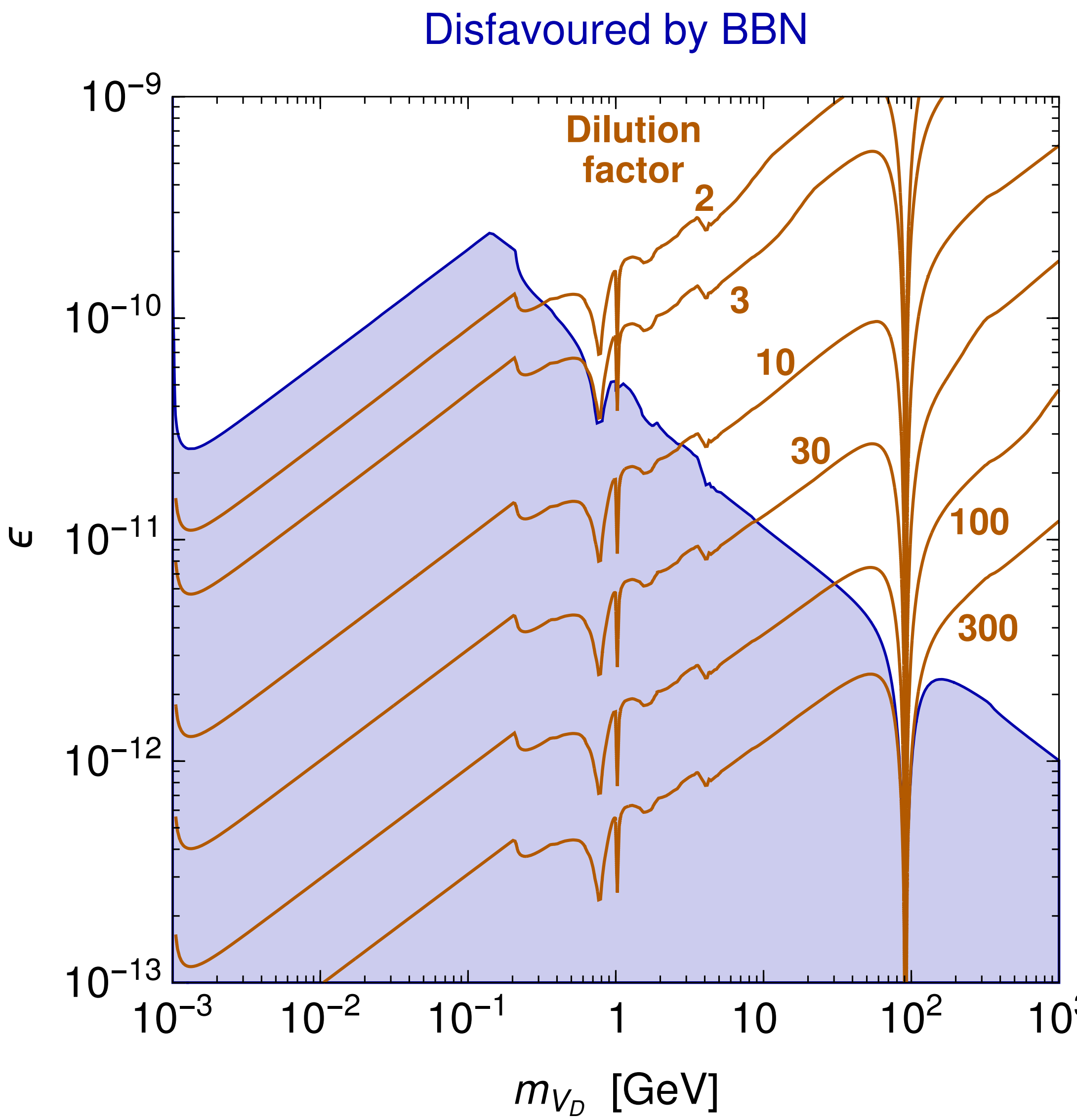
Bishara FS Schmidt-Hoberg 2401.12278

Early Matter = Long Lived Particles!

1) $$\frac{M_{\rm Pl}}{m^2} \ll \tau \lesssim \text{sec}$$

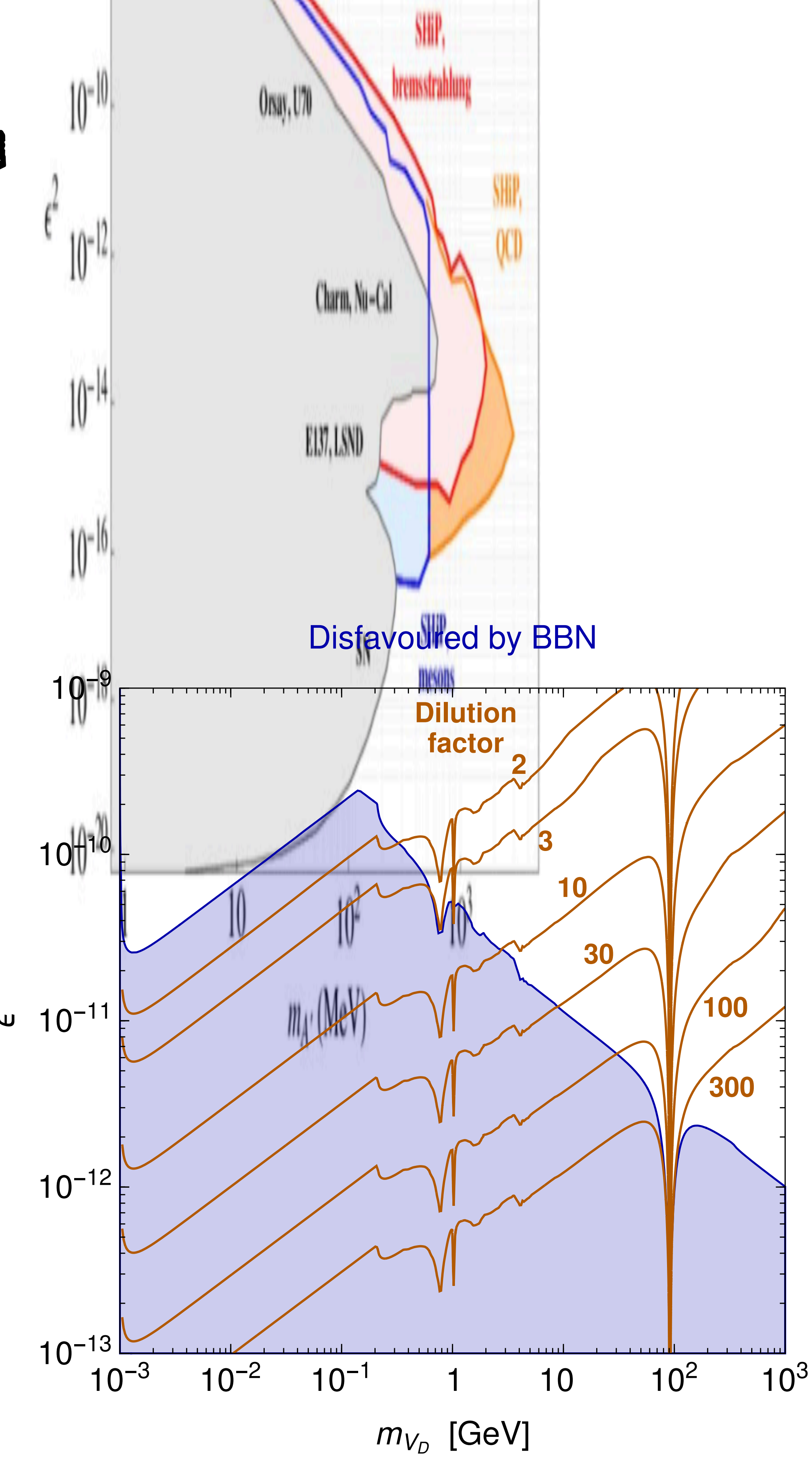


Dark Photon Domination?



Dark Photon Domination

Hard to test in the lab



Collider production vs non-equilibrium

Colliders production wants large couplings…

2) $T_{\rm decouple} \gtrsim m$ otherwise $\rho_{\rm matter} \propto \exp(-m/T)$

…but early matte domination wants small couplings

Collider production vs non-equilibrium

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…but early matte domination wants small couplings

Decouple at a phase transition!

A successful example: (dark) Glueballs

Add to the SM $SU(N_D)$ gauge group with coupling $g_D = \sqrt{4\pi\alpha_D}$

$$\mathcal{L}^{(6)} = \frac{\alpha_D}{3\pi}\frac{y^2}{M^2} H^\dagger H \, \mathrm{tr} G_{\mu\nu} G^{\mu\nu}$$

Glueball S = gluon bound state

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Glueball S = gluon bound state

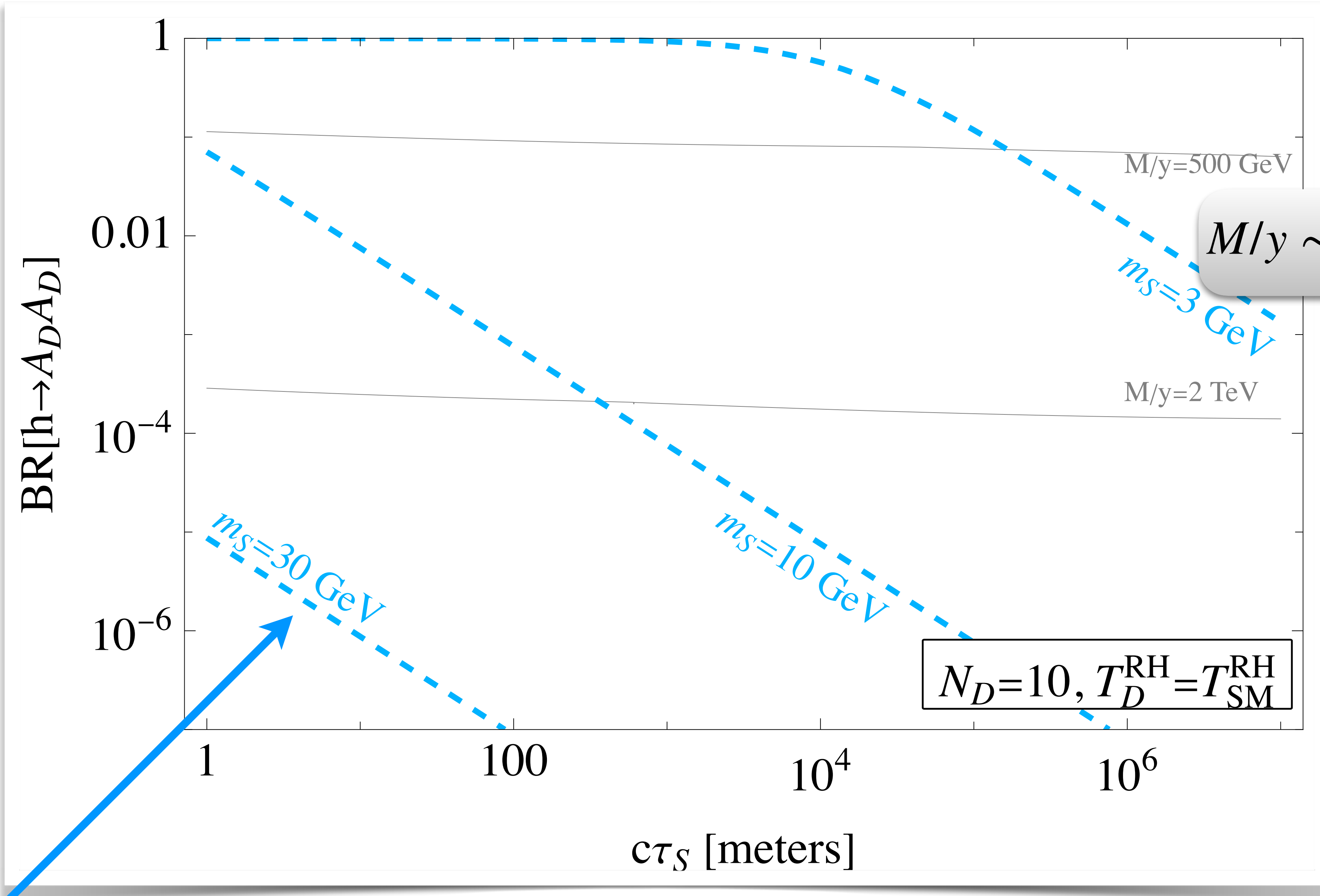
1) $\frac{M_{\mathrm{Pl}}}{m^2} \ll \tau \lesssim \mathrm{sec}$ Translates into interval of y/M

2) $T_{\mathrm{decouple}} \gtrsim m$ Decouple at confining phase transition of $SU(N_D)$

3) Production @ colliders via Higgs decays

A successful example: (dark) Glueballs

Re-parameterise as function of collider observables:



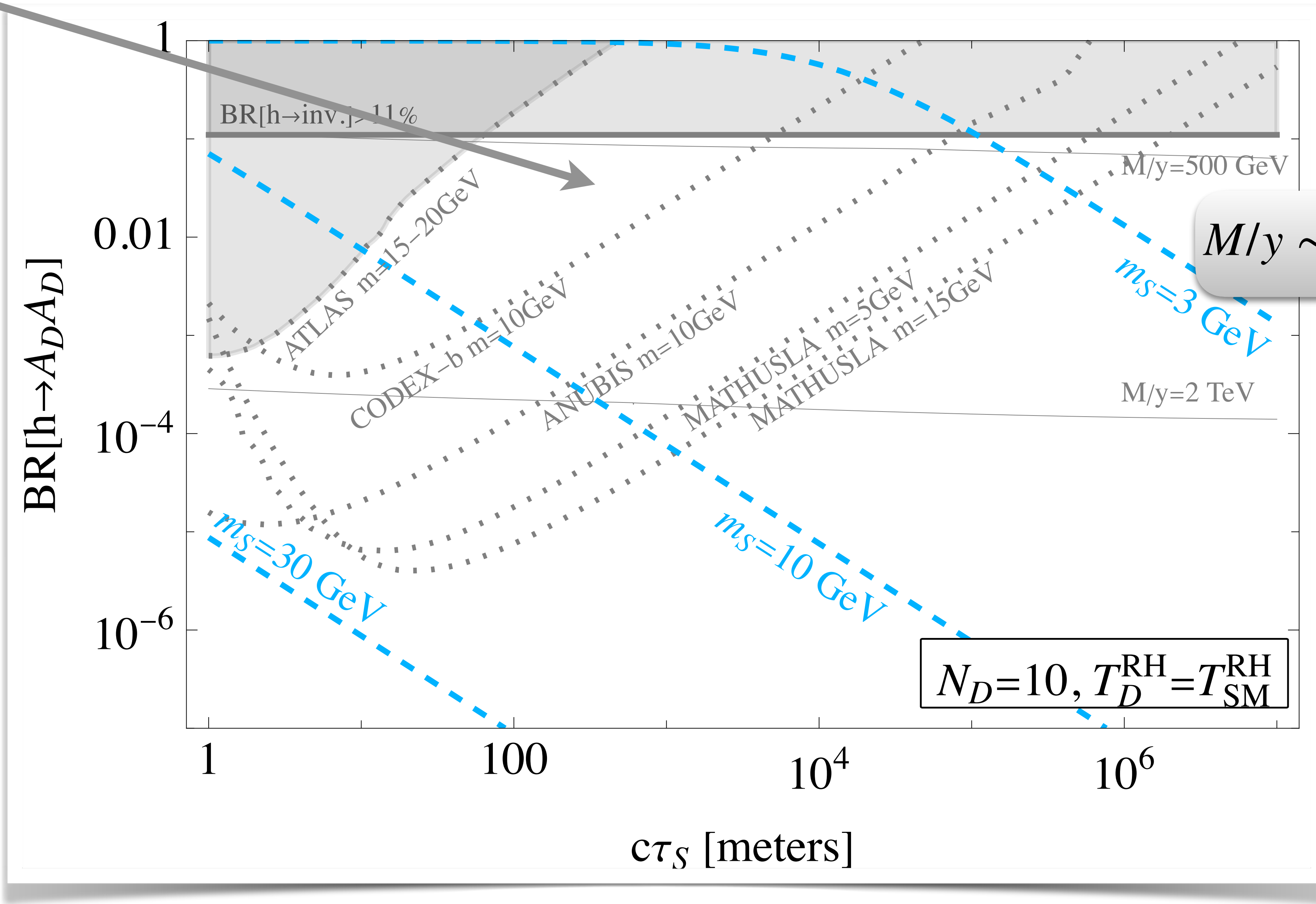
$M/y \sim f$ of Twin Higgs

m_S = Glueball mass

$$\mathcal{L}^{(6)} = \frac{\alpha_D}{3\pi} \frac{y^2}{M^2} H^\dagger H \, \mathrm{tr} G_{\mu\nu} G^{\mu\nu}$$

A successful example: (dark) Glueballs

Quirk searches could constrain region with BR > 0.01



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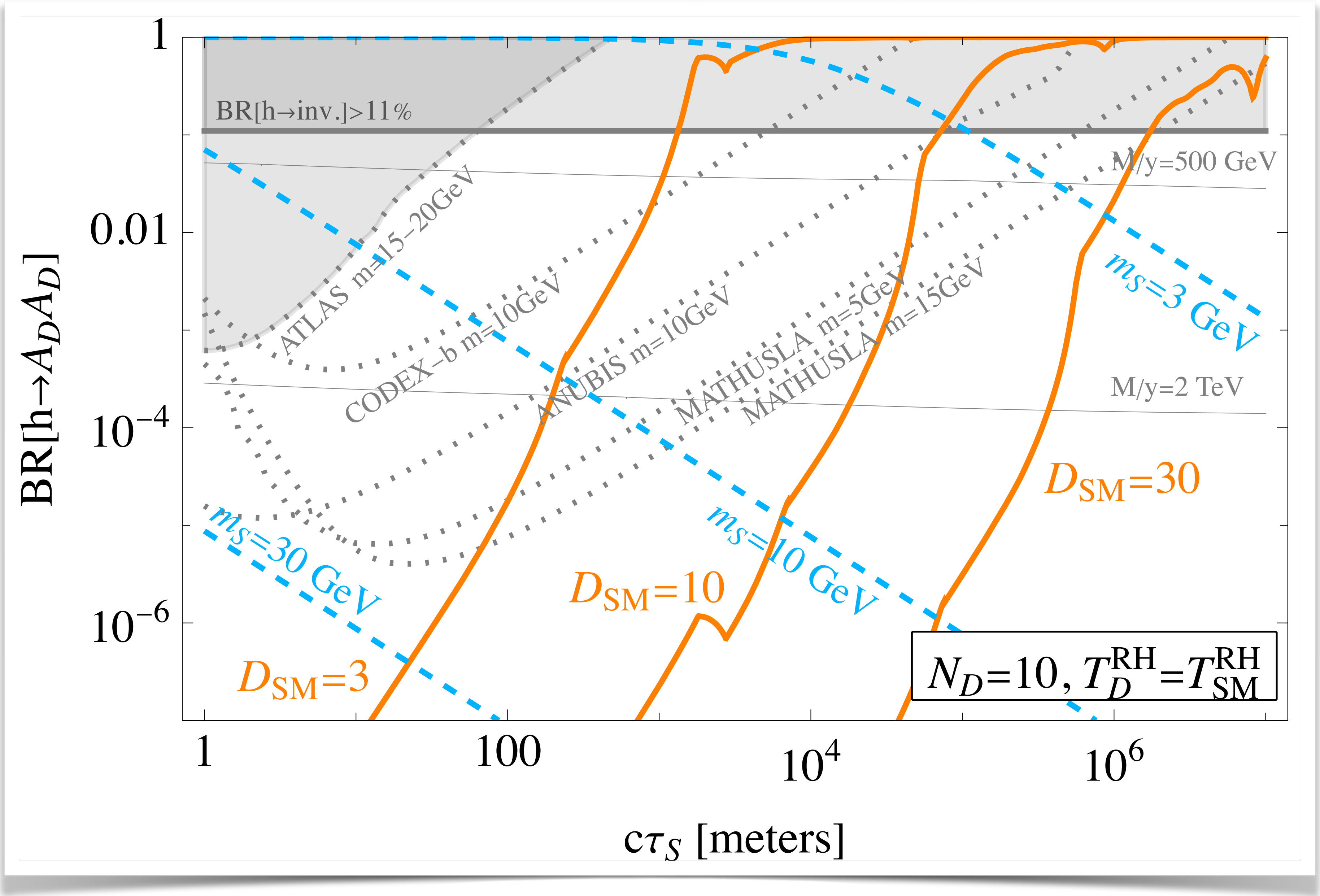
D_{SM} = Dilution of early relics (DM, GWs,...)



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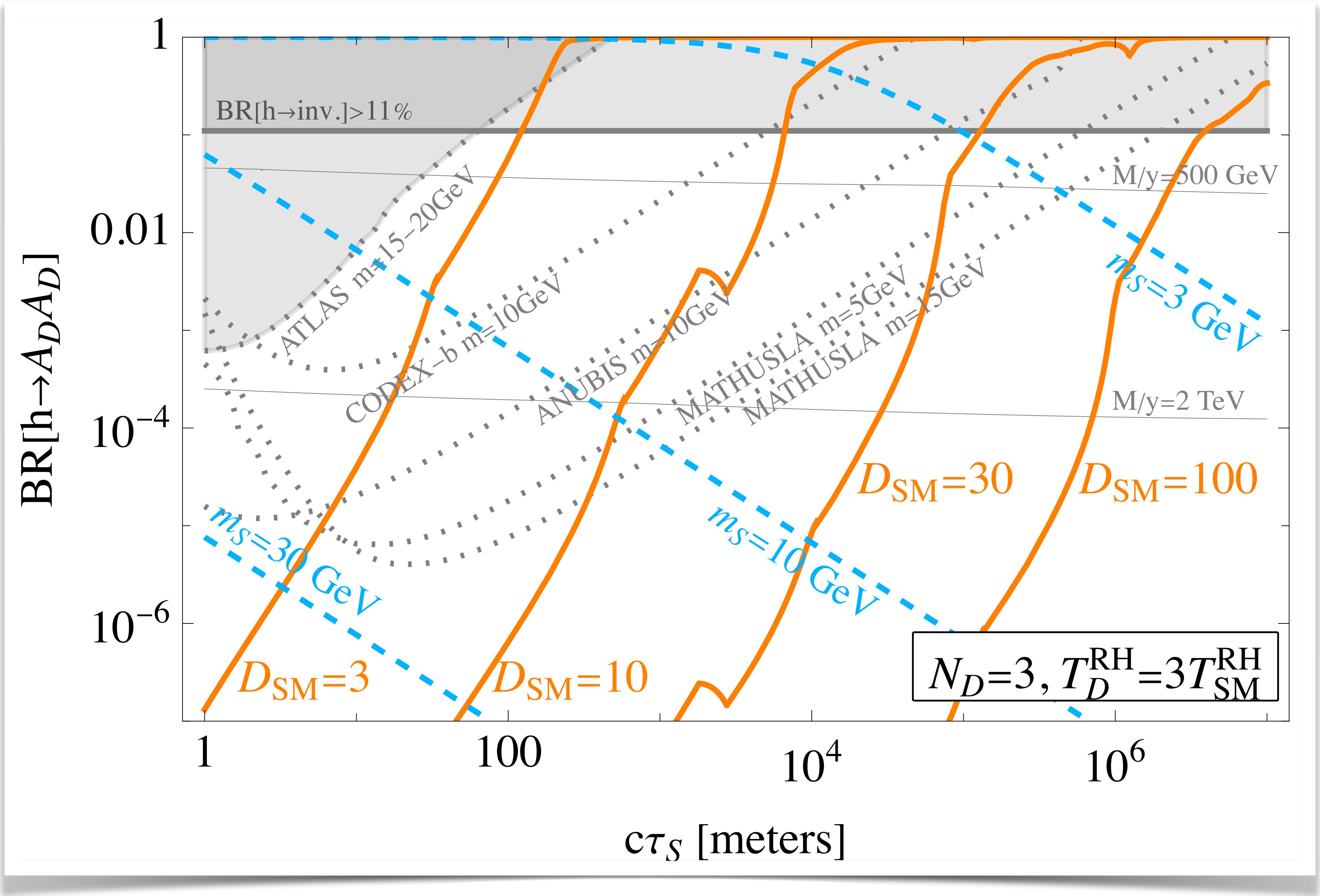

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Can we test in the Lab?

Bishara FS Schmidt-Hoberg 2401.12278

Yes!

To do/ outlook

-> Ph/Exp: dedicated searches for long-lived dark showers

-> Ph/Th/Cosmo: other collider production?

LL glueballs from VBF/heavier Higgses in progress, with D'Eramo De Marchi Sassi

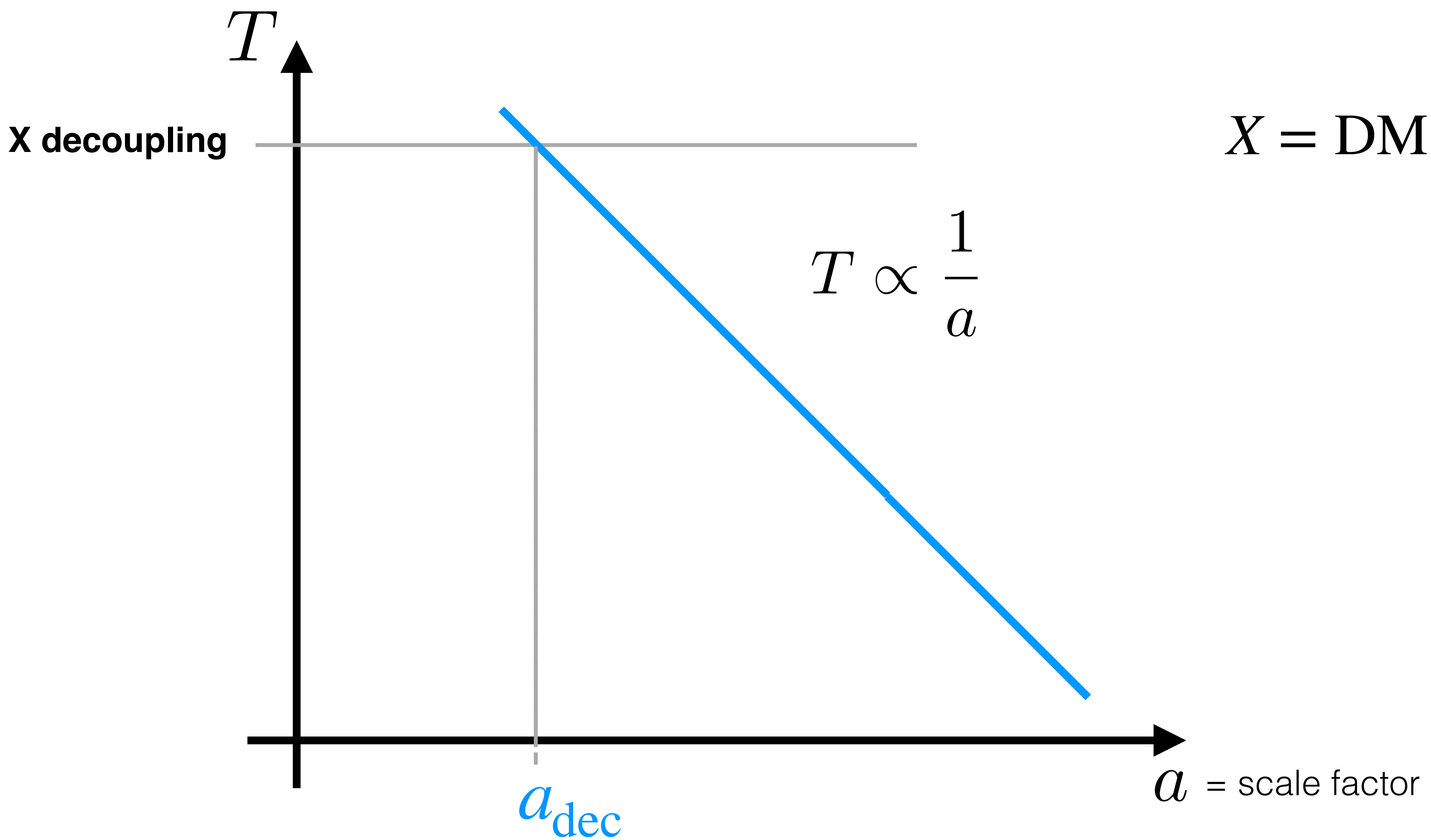
-> Ph/Th/Cosmo: ways without a phase transition?

(e.g. SUSY cascade)s?

-> ....

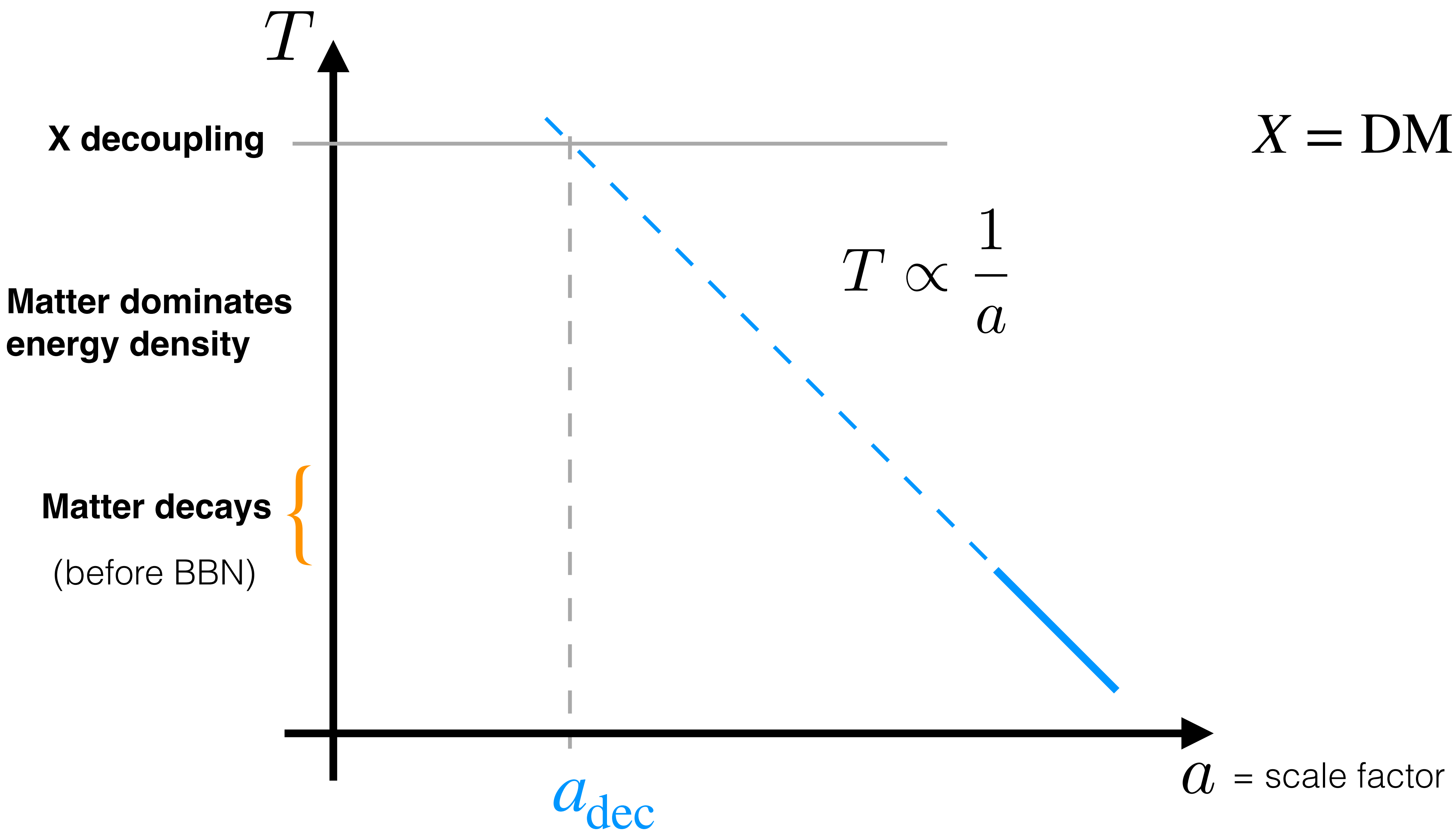
Back up

Cosmology of Early Matter Domination



$X = \mathrm{DM}, \mathrm{GW}, \ldots$

Cosmology of Early Matter Domination



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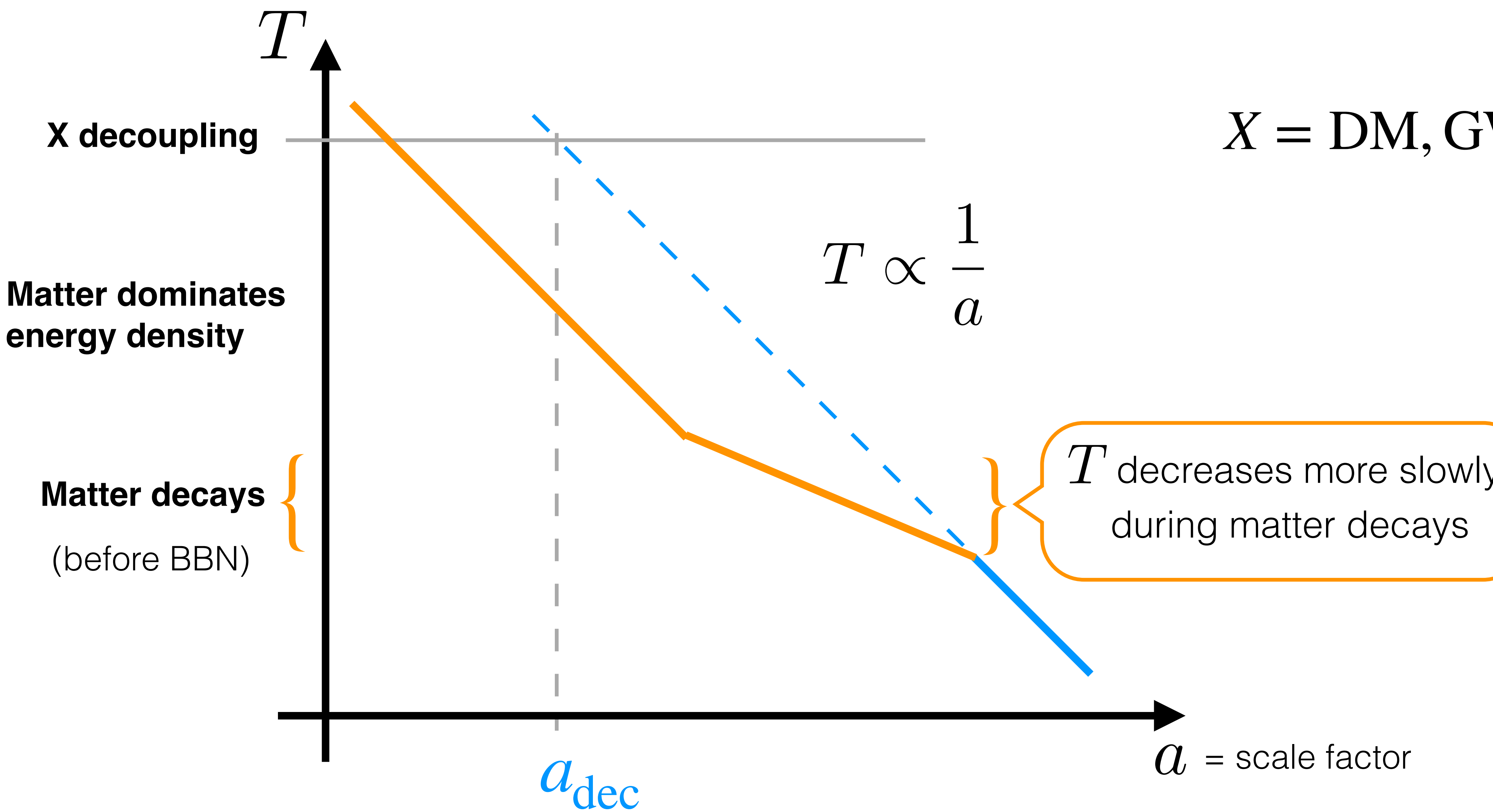

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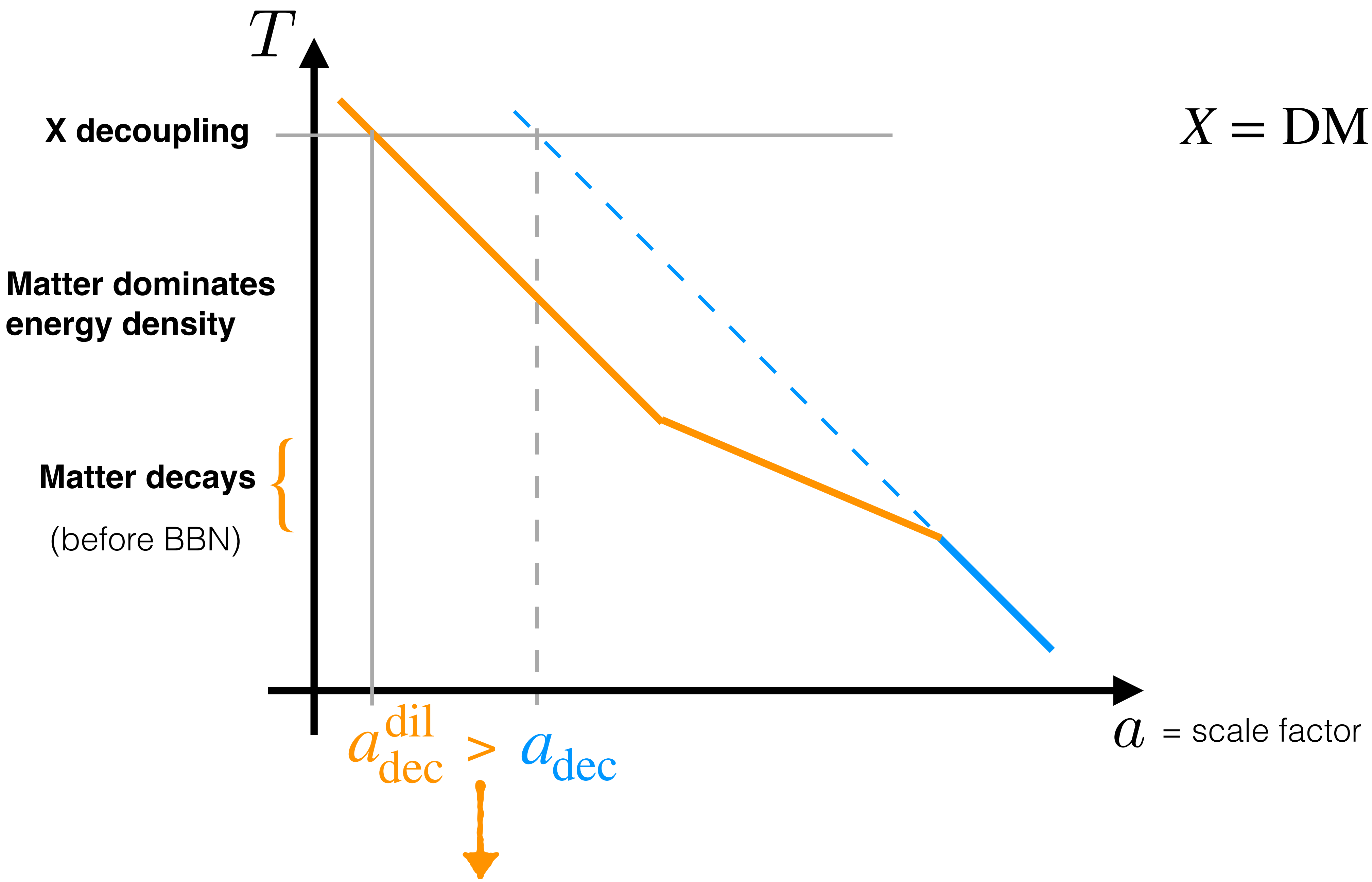

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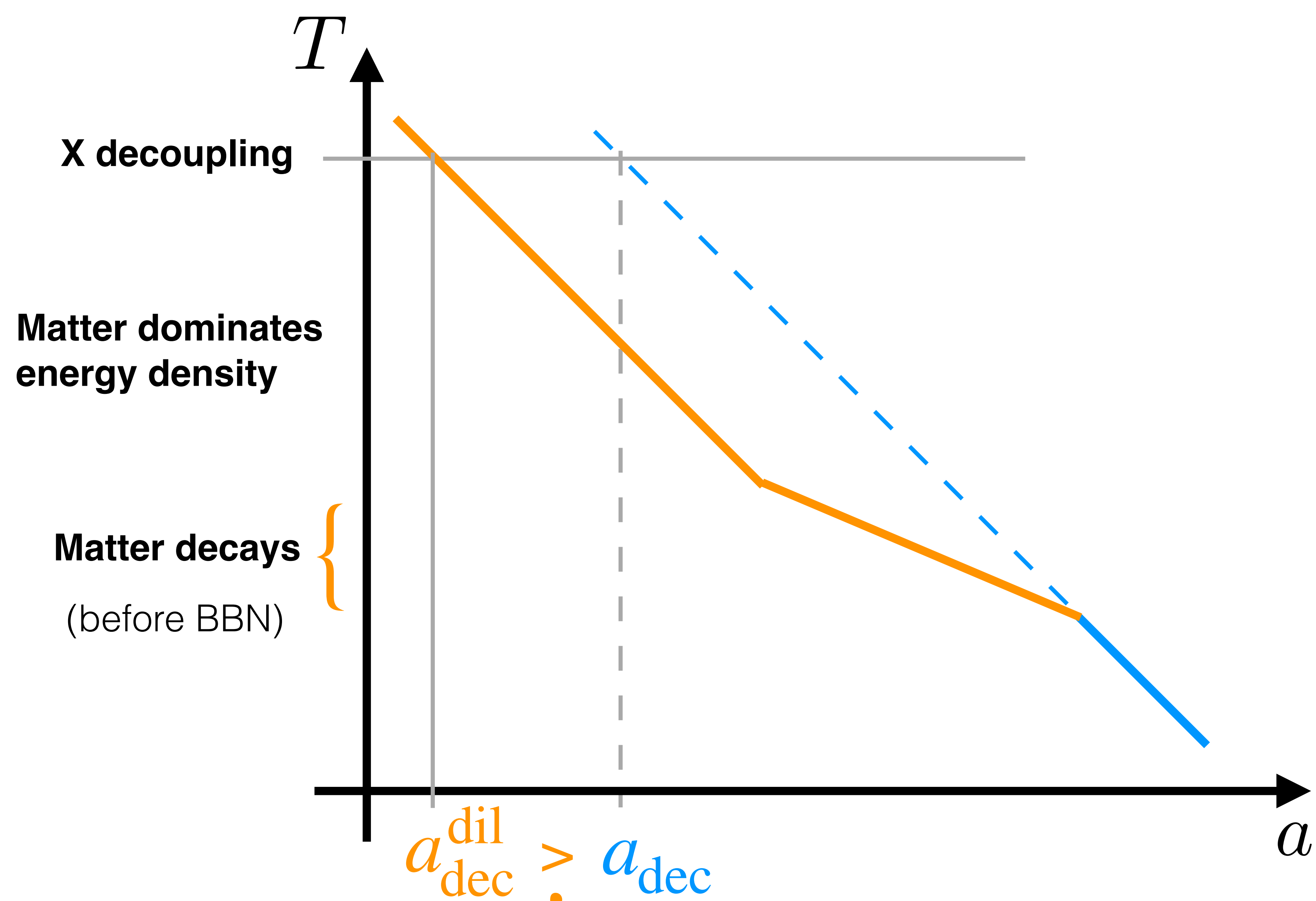
The same amount of relic X is later more diluted

Cosmology of Early Matter Domination



$X = \text{DM, GW}, \ldots$

1/dilution factor

Scherrer Turner 1985

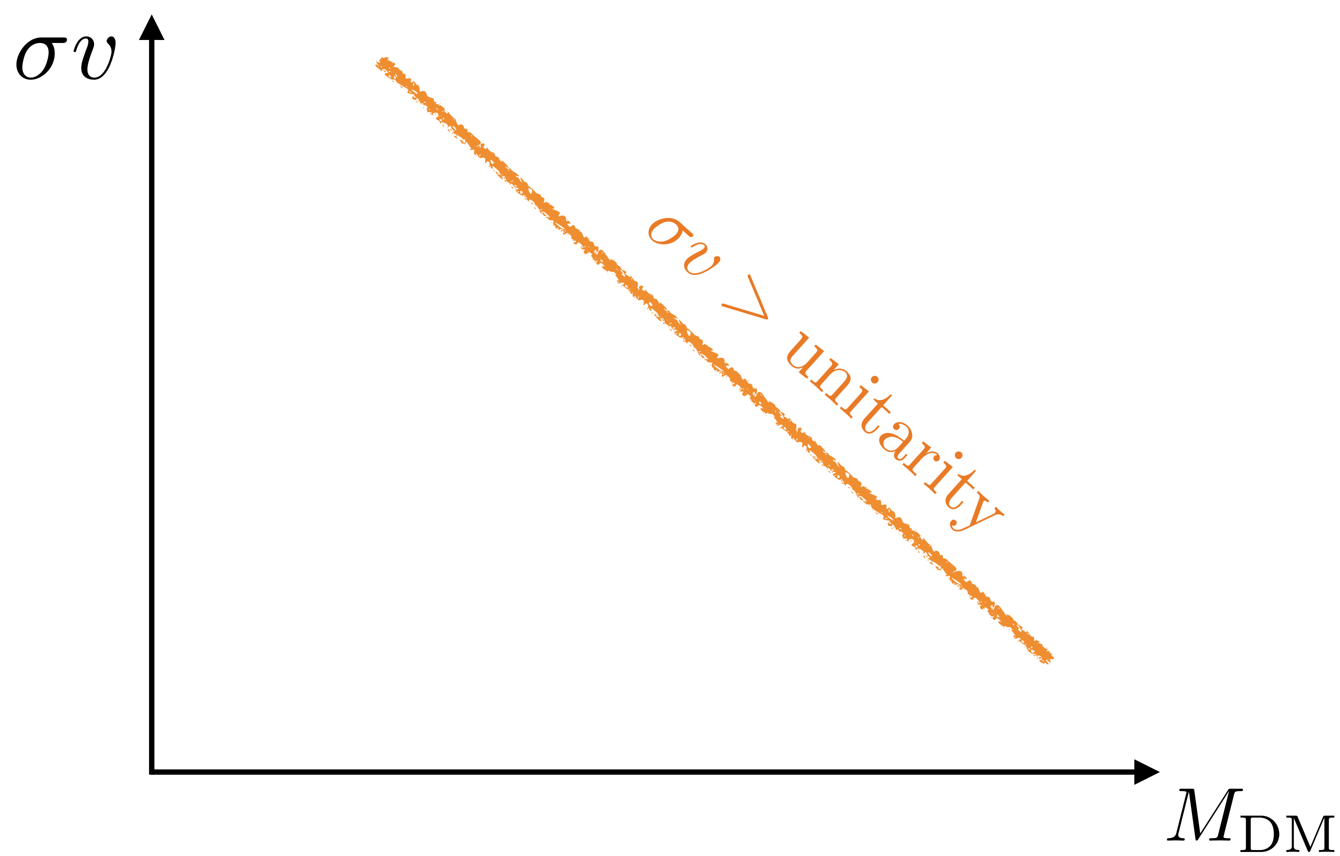
The same amount of relic X is later more diluted

$$\Omega_X \to \Omega_X \frac{s_{\rm before}}{s_{\rm after}}$$

$$\left(\Omega_X = \frac{\rho_X}{\rho_{\rm crit}} \qquad \rho_{\rm crit} = \frac{5 \text{ protons}}{\text{meter}^3} \right)$$

Early Matter and DM Unitarity Bound

$$SS^\dagger = 1 \quad \Rightarrow \quad \sigma^j v_{\rm rel} \leq \frac{4\pi(2j+1)}{v_{\rm rel}} \frac{1}{M_{\rm DM}^2}$$



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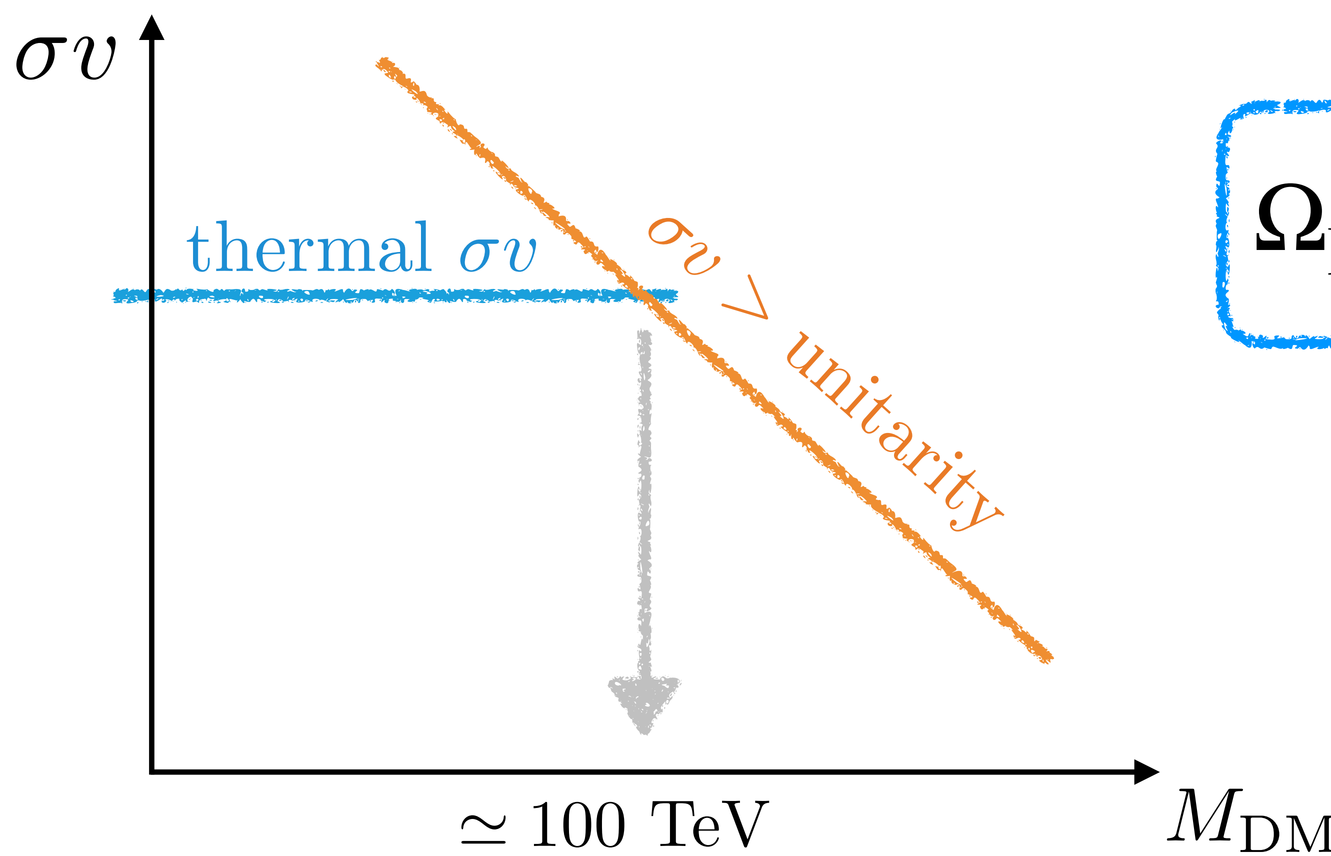

$$\Omega_{\rm DM} \propto \frac{1}{\sigma v}$$

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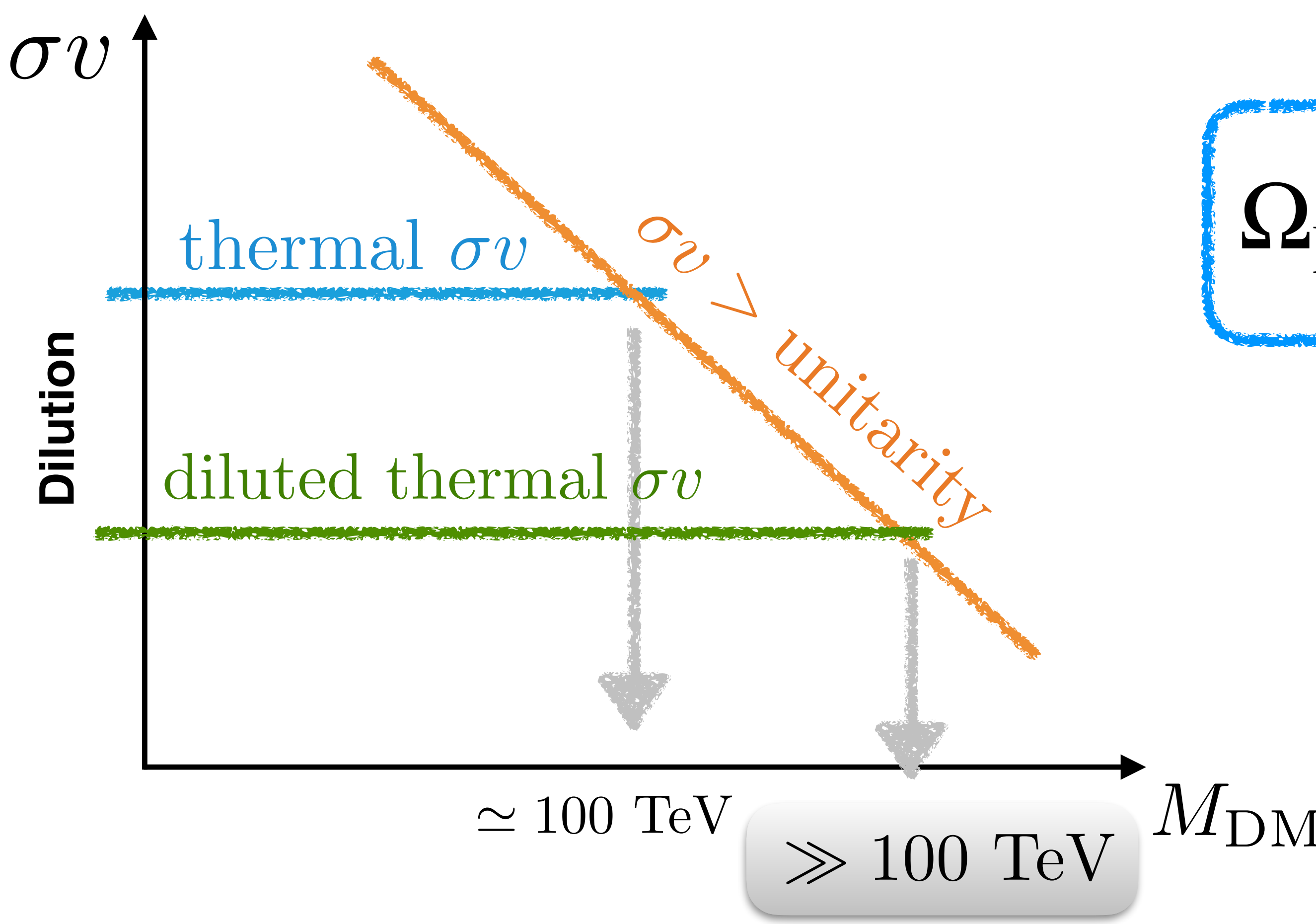
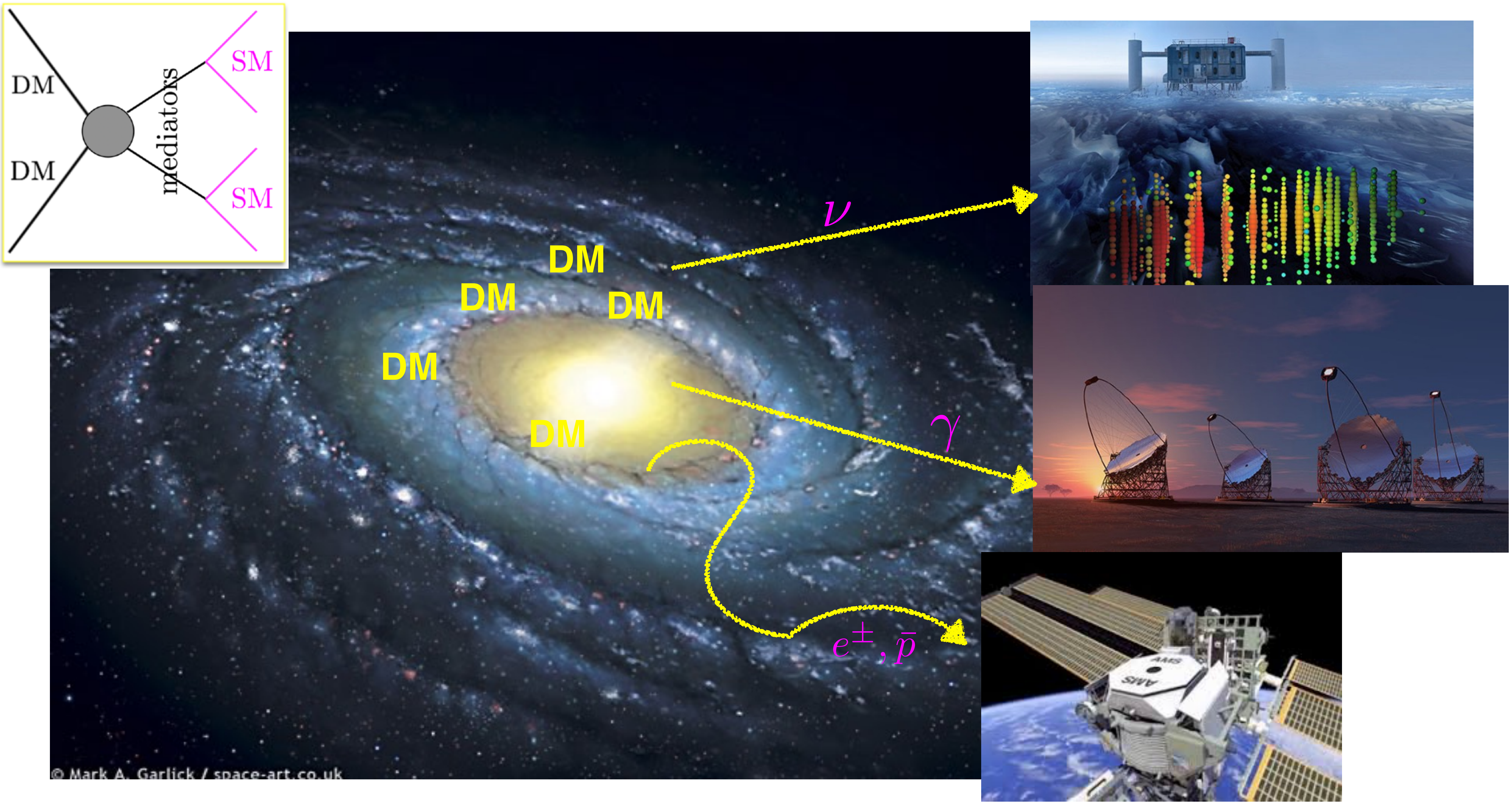


$$\Omega_{\rm DM} \propto \frac{1}{\sigma v} \frac{s_{\rm before}}{s_{\rm after}}$$

Experimental Tests

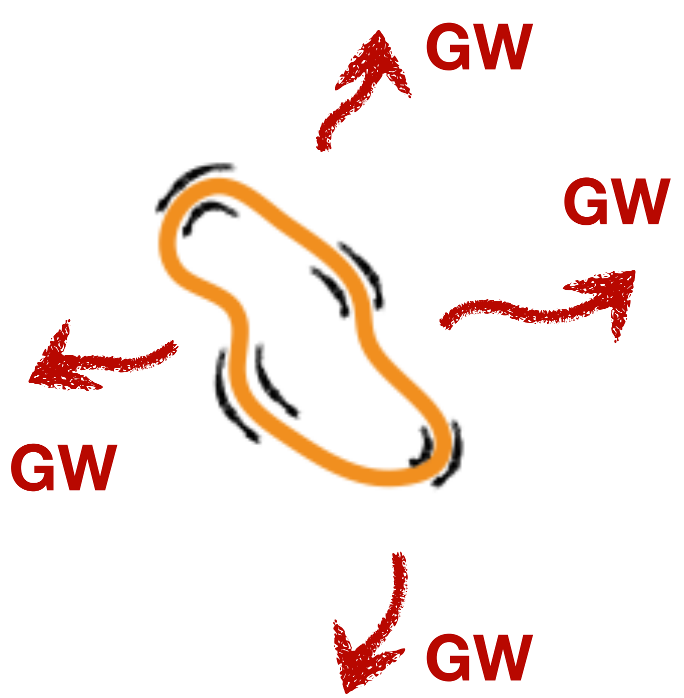
Tiny portal with the SM + Heavy → Direct Detection & Collider put no constraints

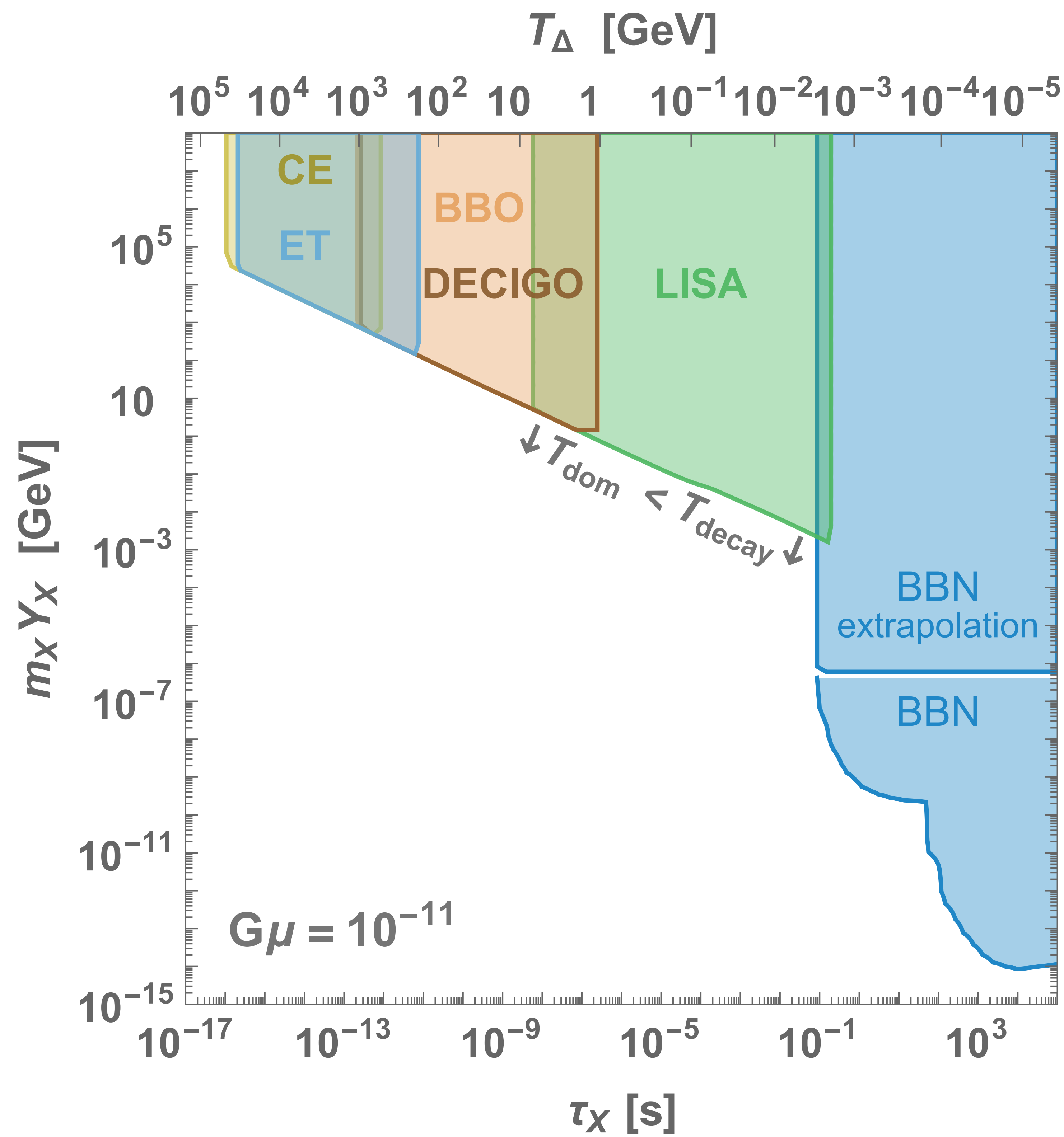


Early Matter dilutes Gravitational Waves

e.g. from cosmic strings

Gouttenoire+1912.03245

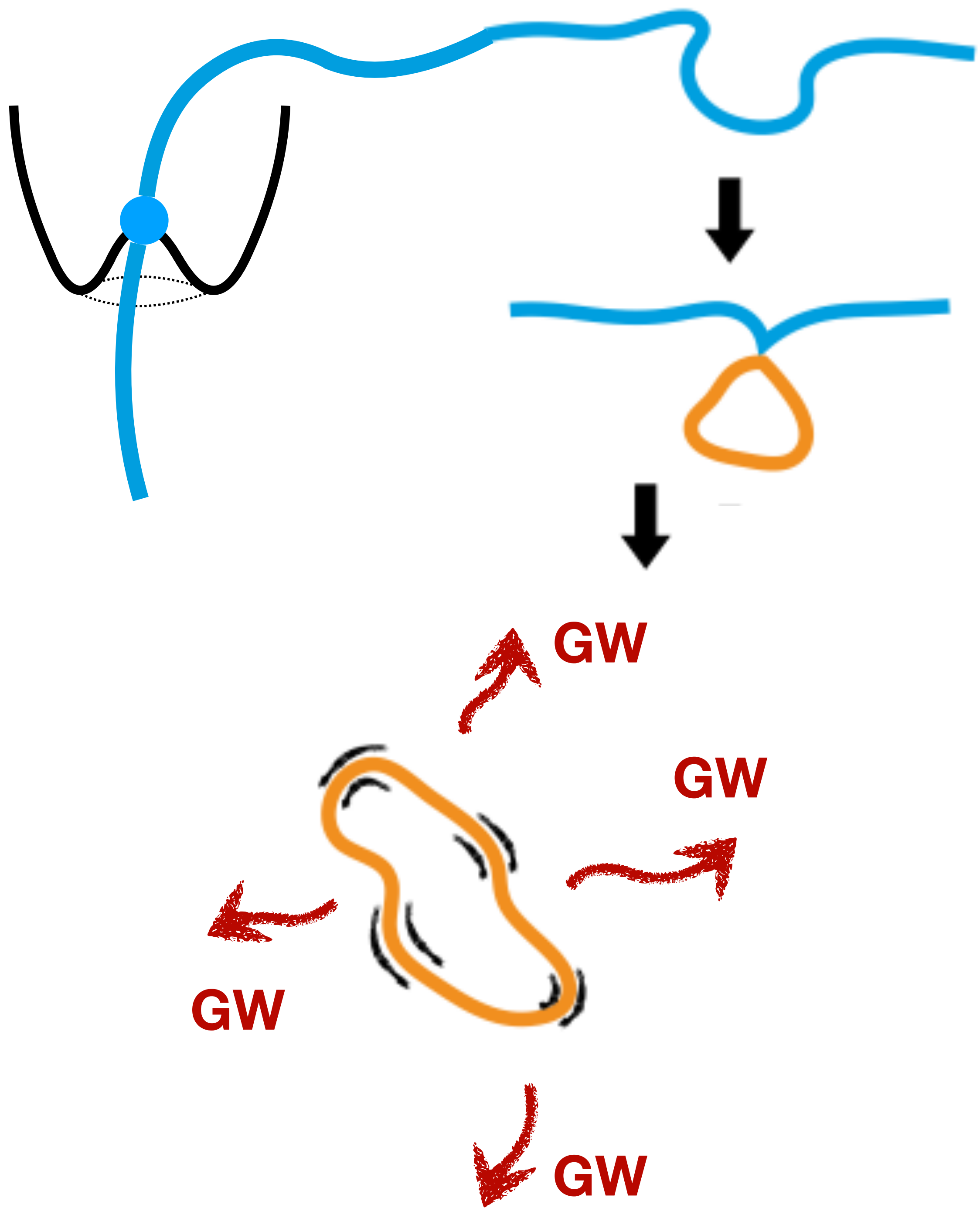




Gravitational Waves from Cosmic Strings

Gouttenoire+1912.03245

Spontaneous symmetry breaking of U(1) in Early Uni.



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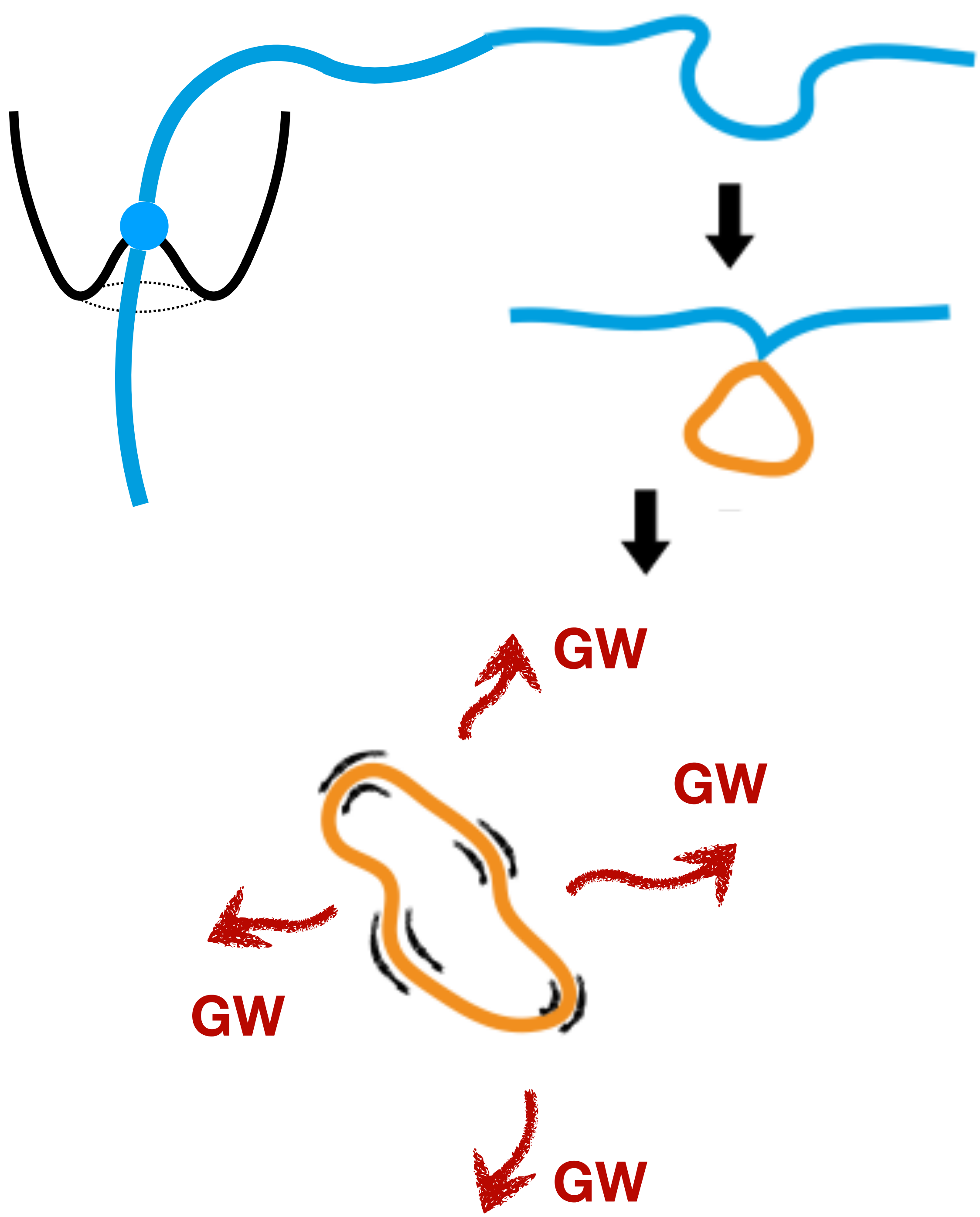
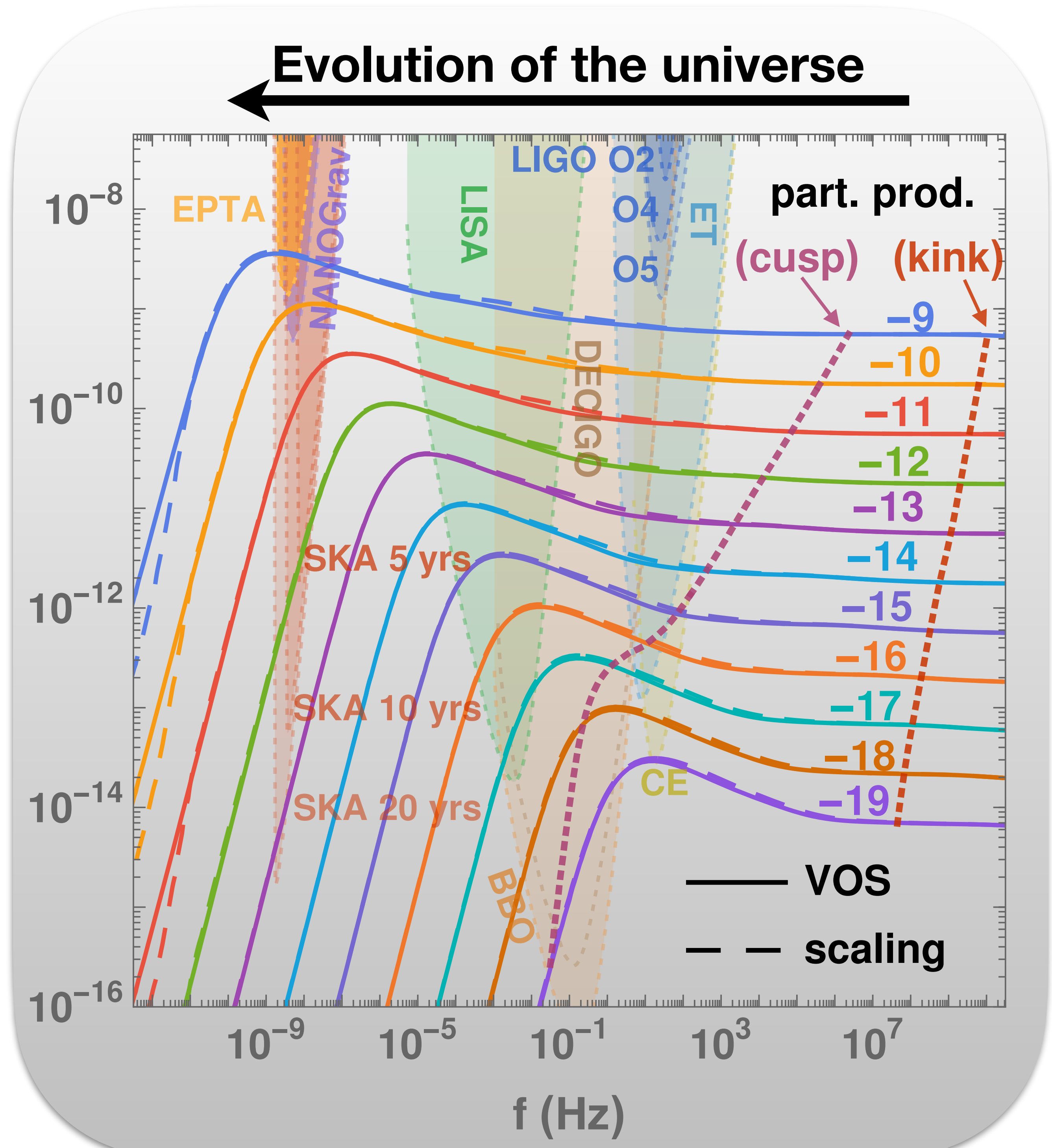




Simple Scalar Domination

Mixing with Higgs Boson

θ

from Filimonova+ 1911.03490

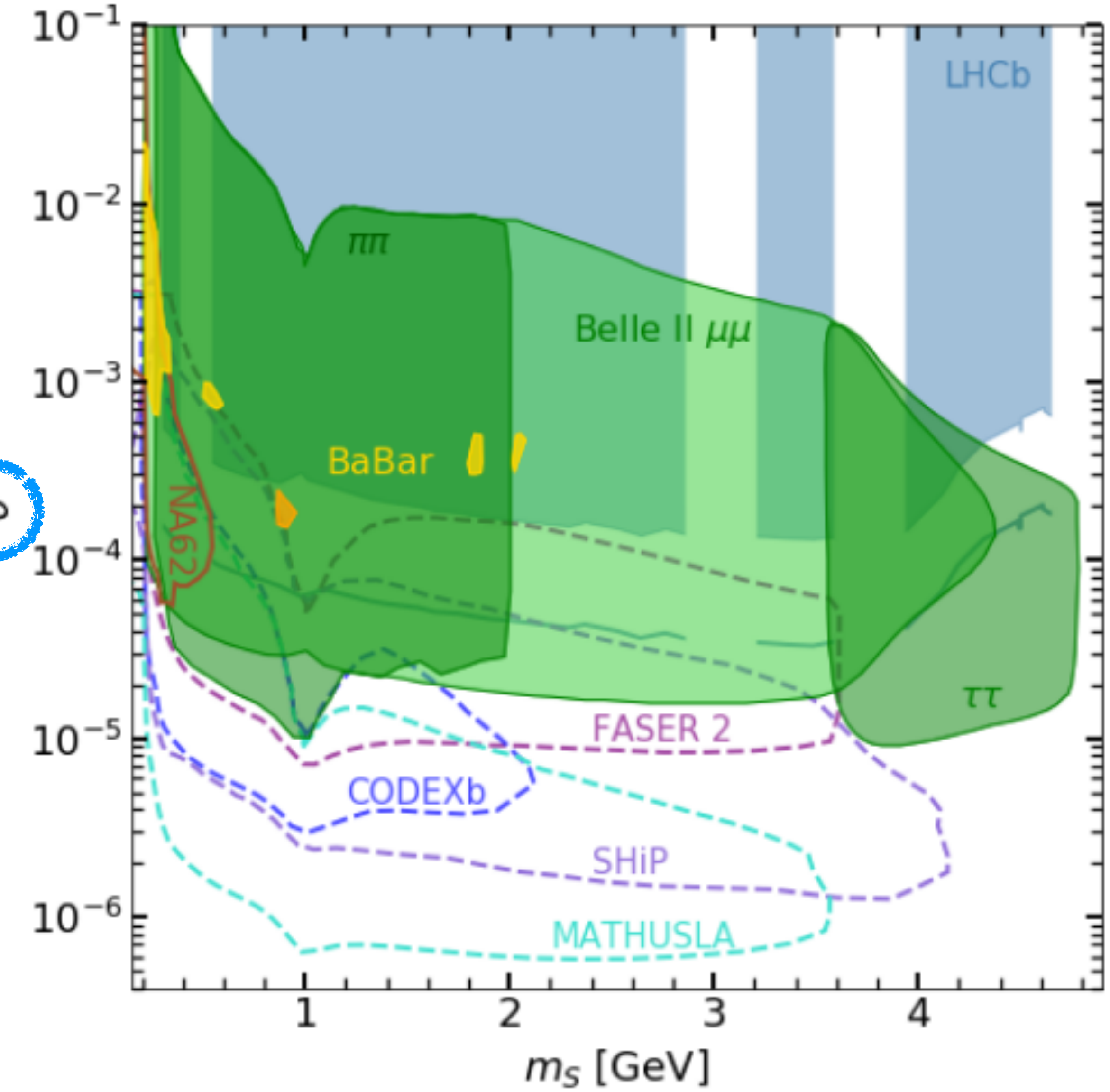
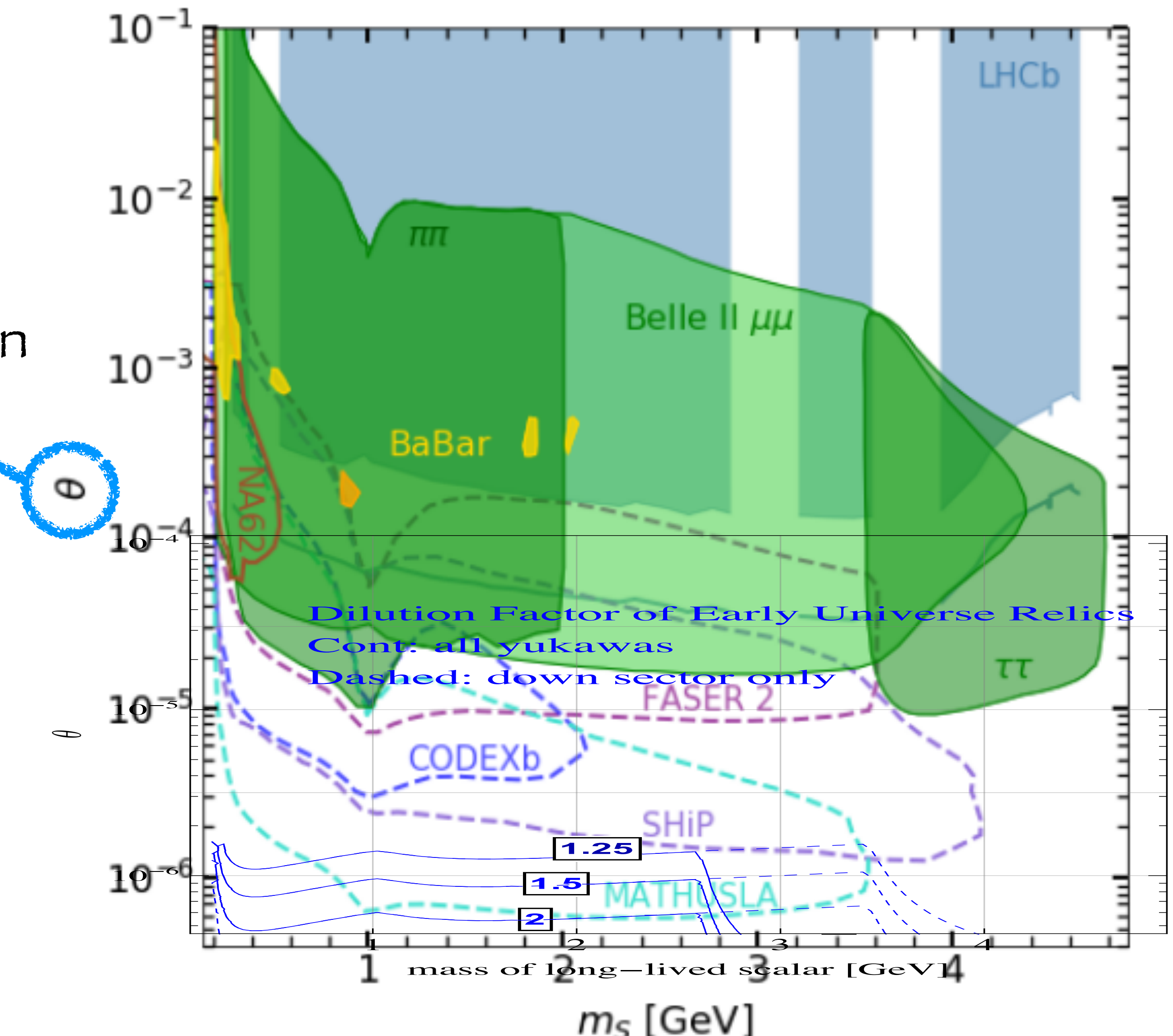


FIG. 2: Searches for dark scalars with displaced vertices. Shown are 95% CL bounds from $B^+ \to K^+ S(\to \mu\bar{\mu})$ searches at LHCb [51] (blue) and 90% CL bounds on $\mathcal{B}(B \to X_s S)\mathcal{B}(S \to f)$ with $f = \mu^+\mu^-$ (yellow) and $\pi^+\pi^-$ (orange) from an inclusive search by BaBar [52]. Regions of 3σ significance at BELLE II are shown for $B \to KS(\to f)$ with $f = \pi^+\pi^-$, $\mu^+\mu^-$ and $\tau^+\tau^-$ (green).

Simple Scalar Domination: a tiny bit

Mixing with Higgs Boson



Could work much better with inelastic models, in progress

PRELIMINARY (& UGLY)

FIG. 2: Searches for dark scalars with displaced vertices. Shown are 95% CL bounds from $B^+ \to K^+S(\to \mu\bar{\mu})$ searches at LHCb [51] (blue) and 90% CL bounds on $\mathcal{B}(B \to X_s S)\mathcal{B}(S \to f)$ with $f = \mu^+\mu^-$ (yellow) and $\pi^+\pi^-$ (orange) from an inclusive search by BaBar [52]. Regions of 3σ significance at BELLE II are shown for $B \to KS(\to f)$ with $f = \pi^+\pi^-, \mu^+\mu^-$ and $\tau^+\tau^-$ (green).

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$$\langle 0 | \mathrm{tr} G_{\mu\nu} G^{\mu\nu} | S_D \rangle \equiv F^S_{0^{++}} = \frac{3.06}{4\pi\alpha_D} m_S^3$$

0) $$D_{\rm SM} \simeq \left[1 + 0.14 \, (g_{\rm SM}^{\rm dec})^{1/3} \left(\frac{g_D}{g_{\rm SM}} \frac{m}{\sqrt{\Gamma M_{\rm Pl}}} \right)^{\frac{4}{3}} \right]^{\frac{3}{4}}$$

1) $\tau \lesssim \mathrm{sec}$

$$\Gamma_f = N_f \frac{y_f^2 \, \theta_{hS}^2}{16\pi} m_S \left(1 - \frac{4 m_f^2}{m_S^2} \right)^{\frac{3}{2}}$$

$$\theta_{hS} = \frac{3.06}{12\pi^2} \frac{y^2}{M^2} \frac{m_S^3 v}{m_h^2 - m_S^2}$$

2) $T_{\rm dec} \gtrsim m$ Decouple at confining phase transition of $SU(N_D)$

3) Production @ colliders via Higgs decays

$$\Gamma(h \to A_D A_D) = (N_D^2 - 1) \frac{\alpha_D^2}{36\pi^3} \frac{y^4 v^2}{M^4} m_h^3$$