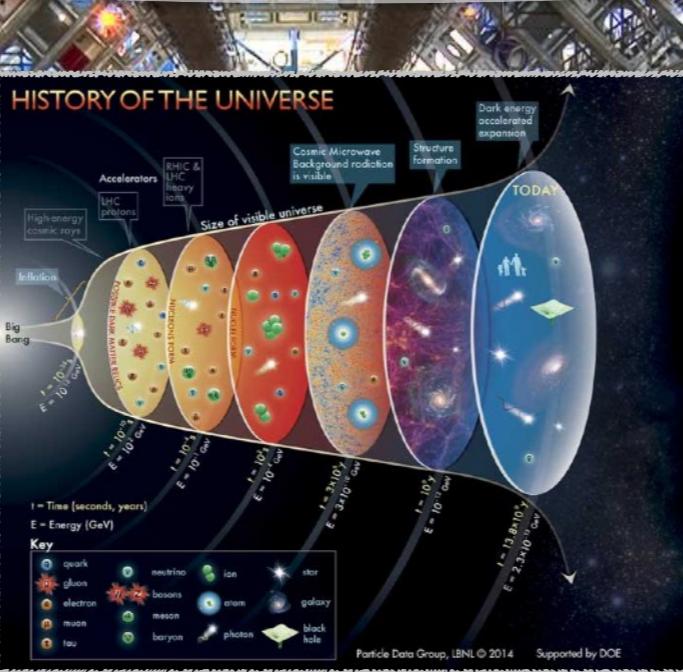


Early Matter Domination at Colliders



Filippo Sala

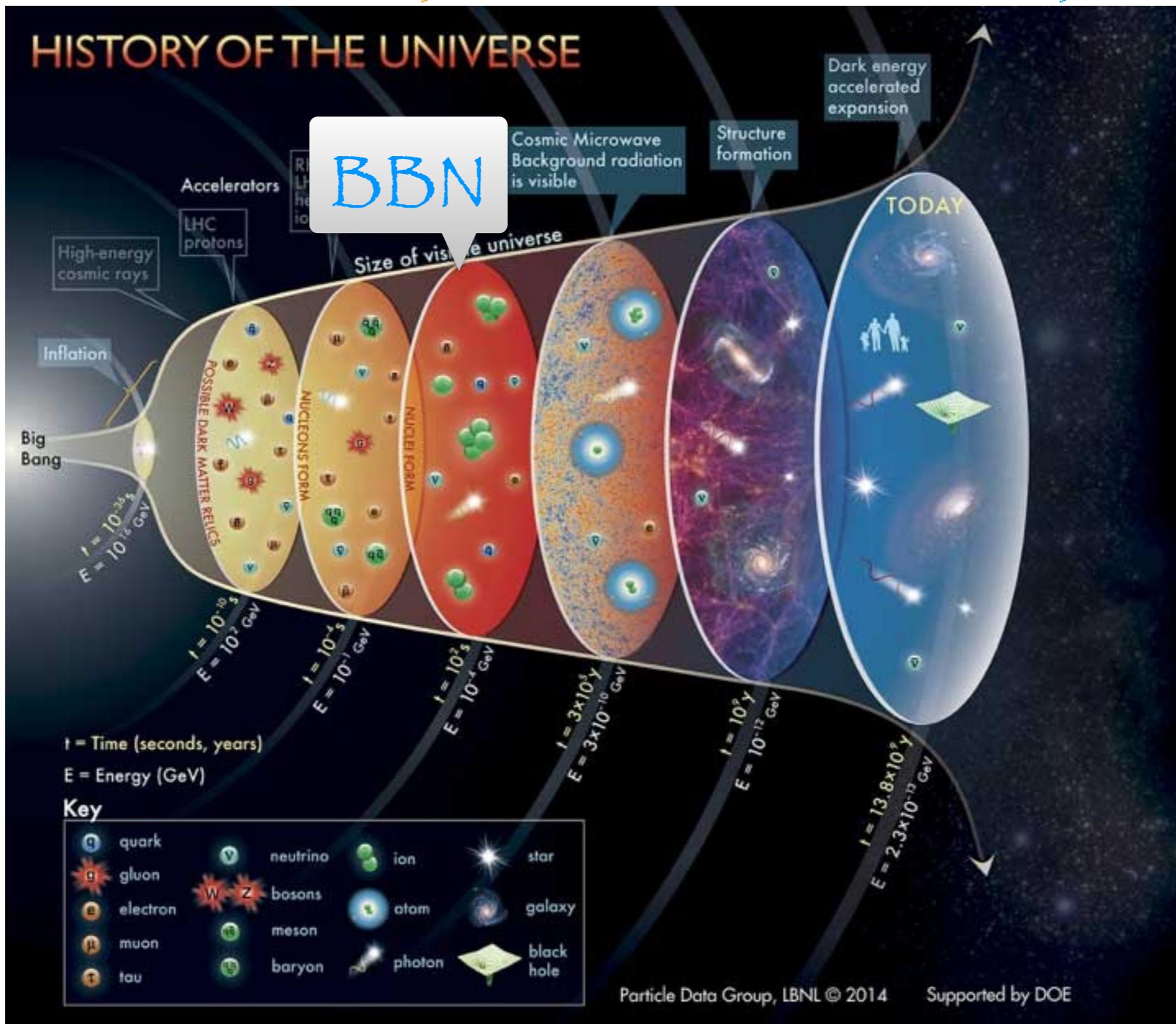
GDR intensity frontier, LPNHE Paris, 15 Nov 2021



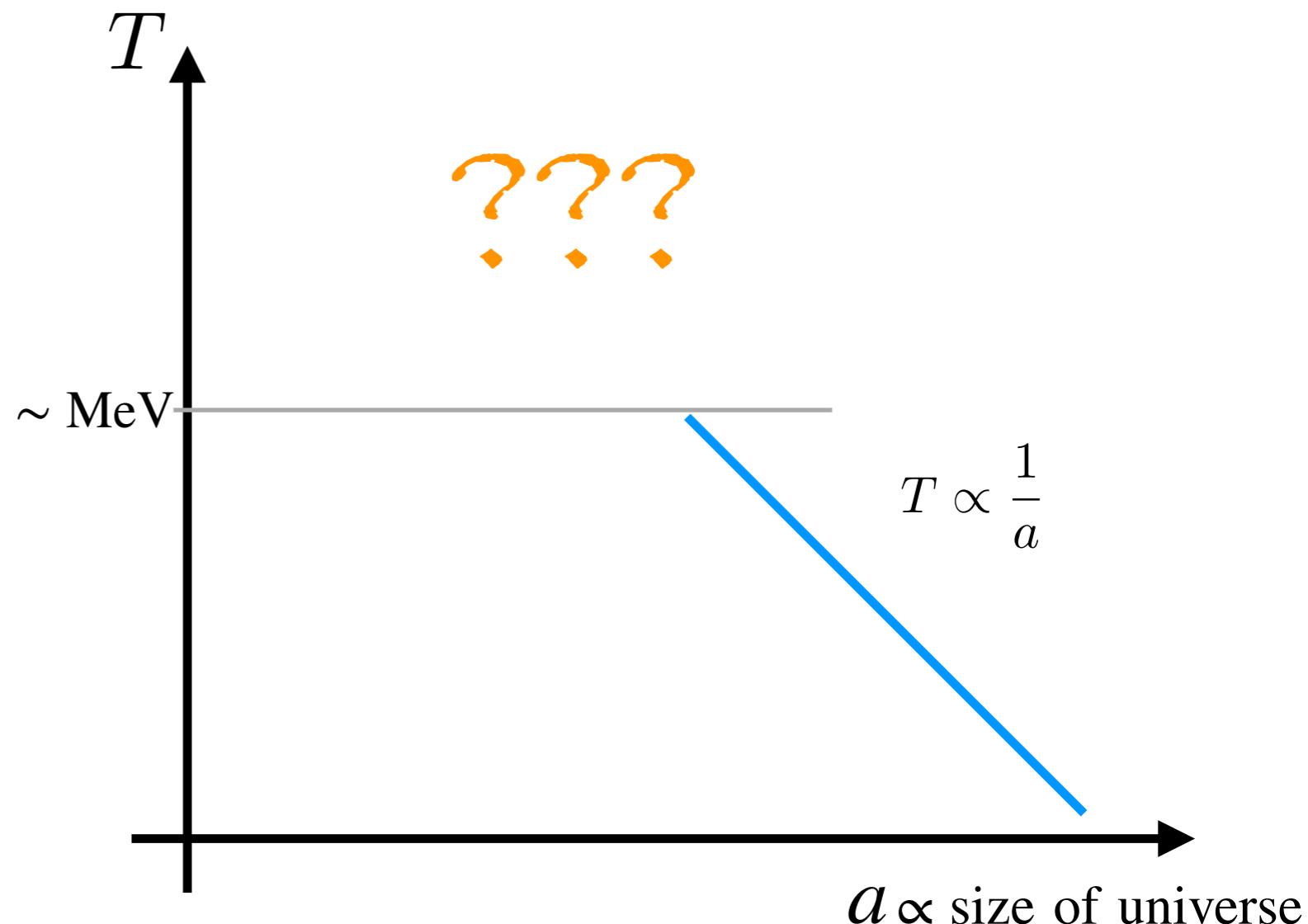
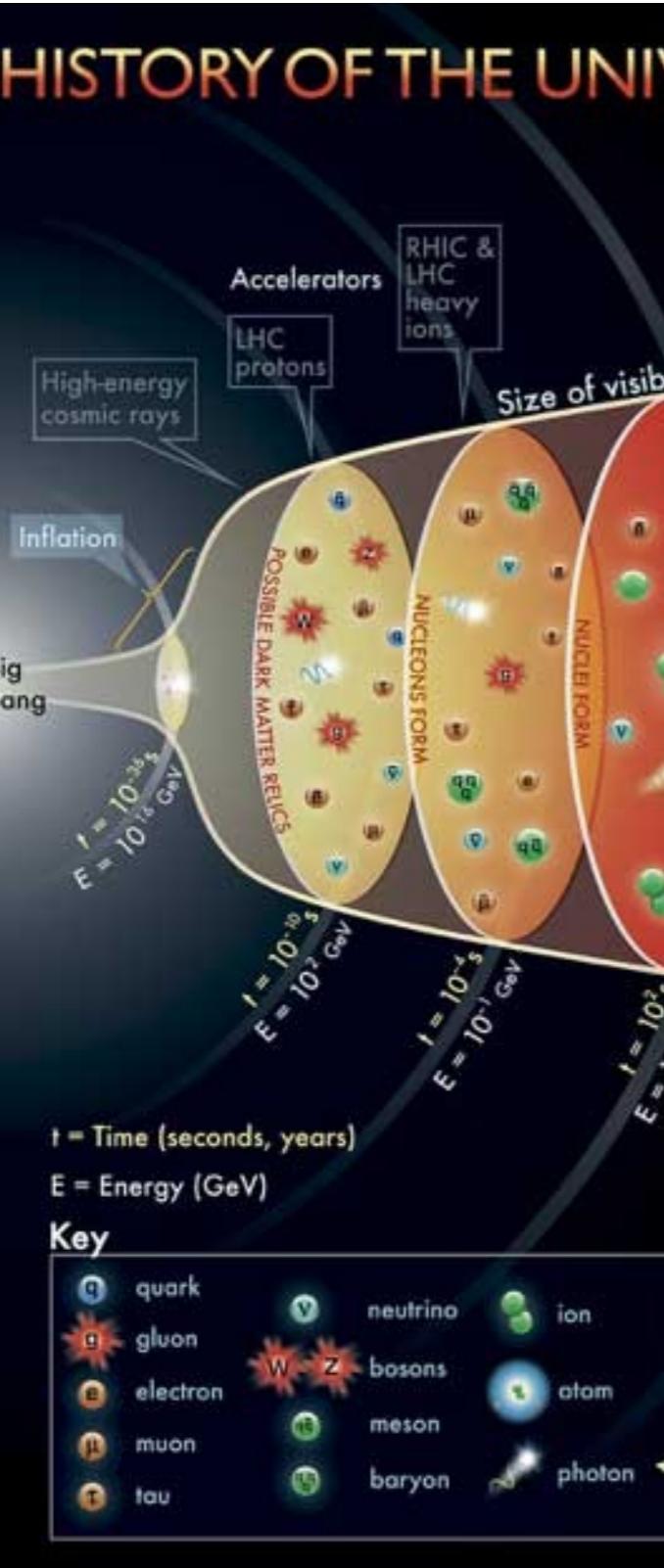
Not Tested

Tested

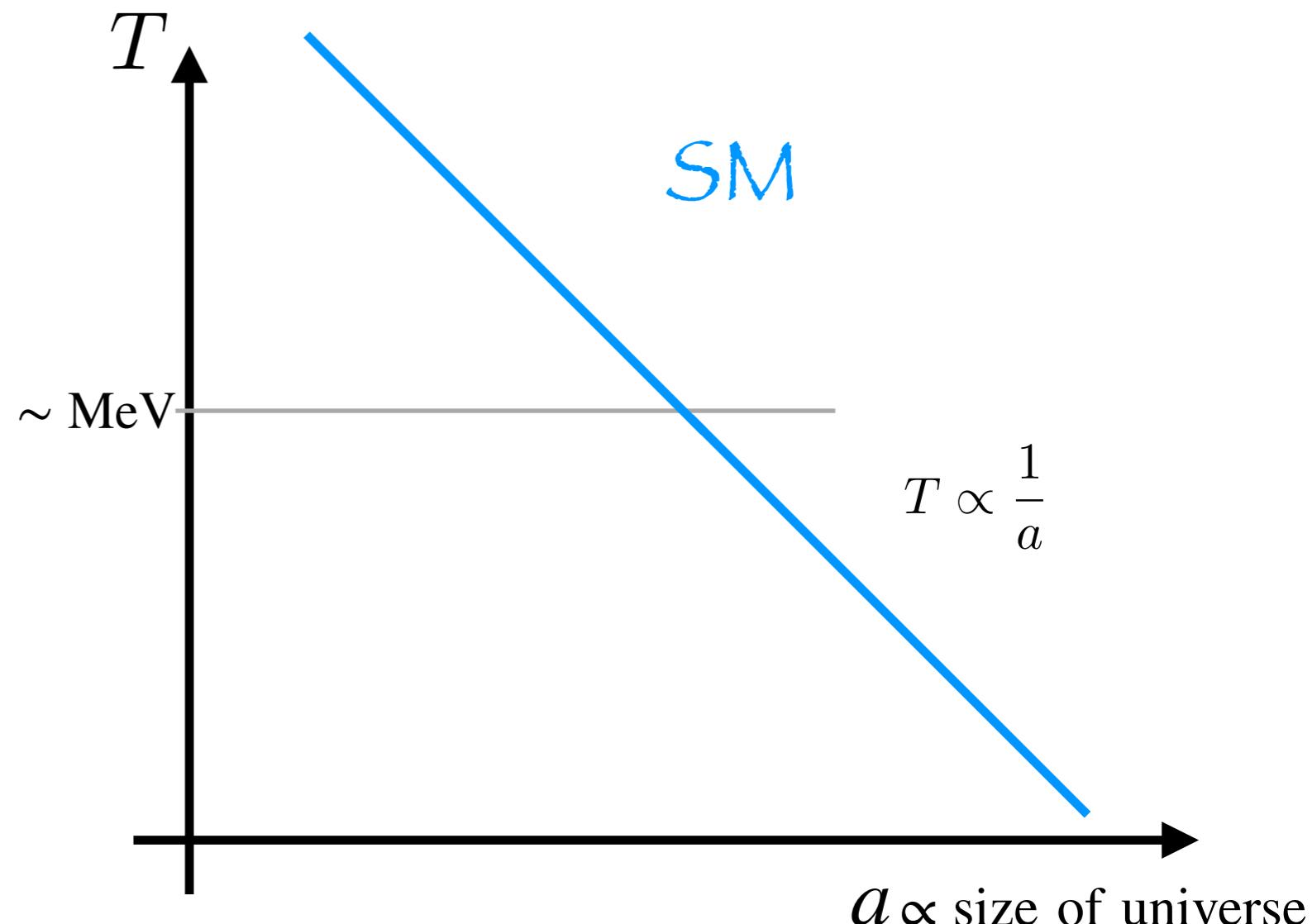
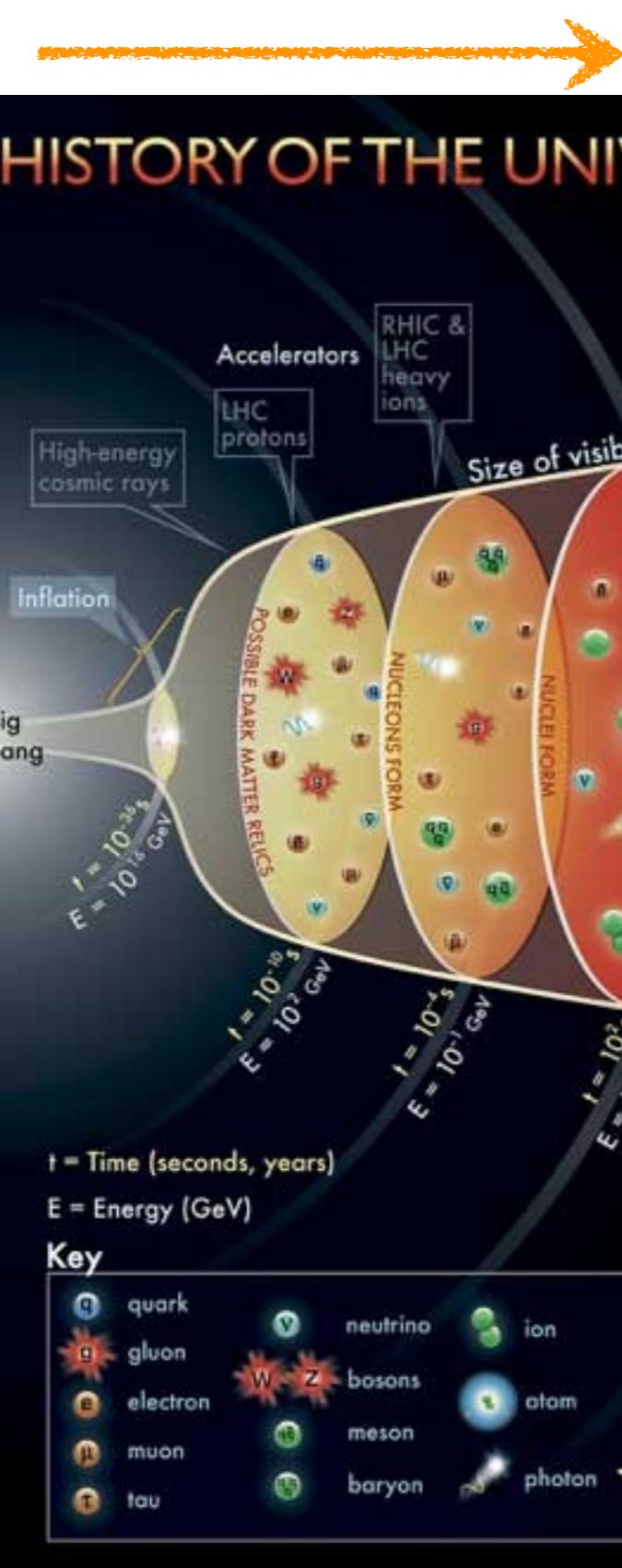
Smaller Temperature



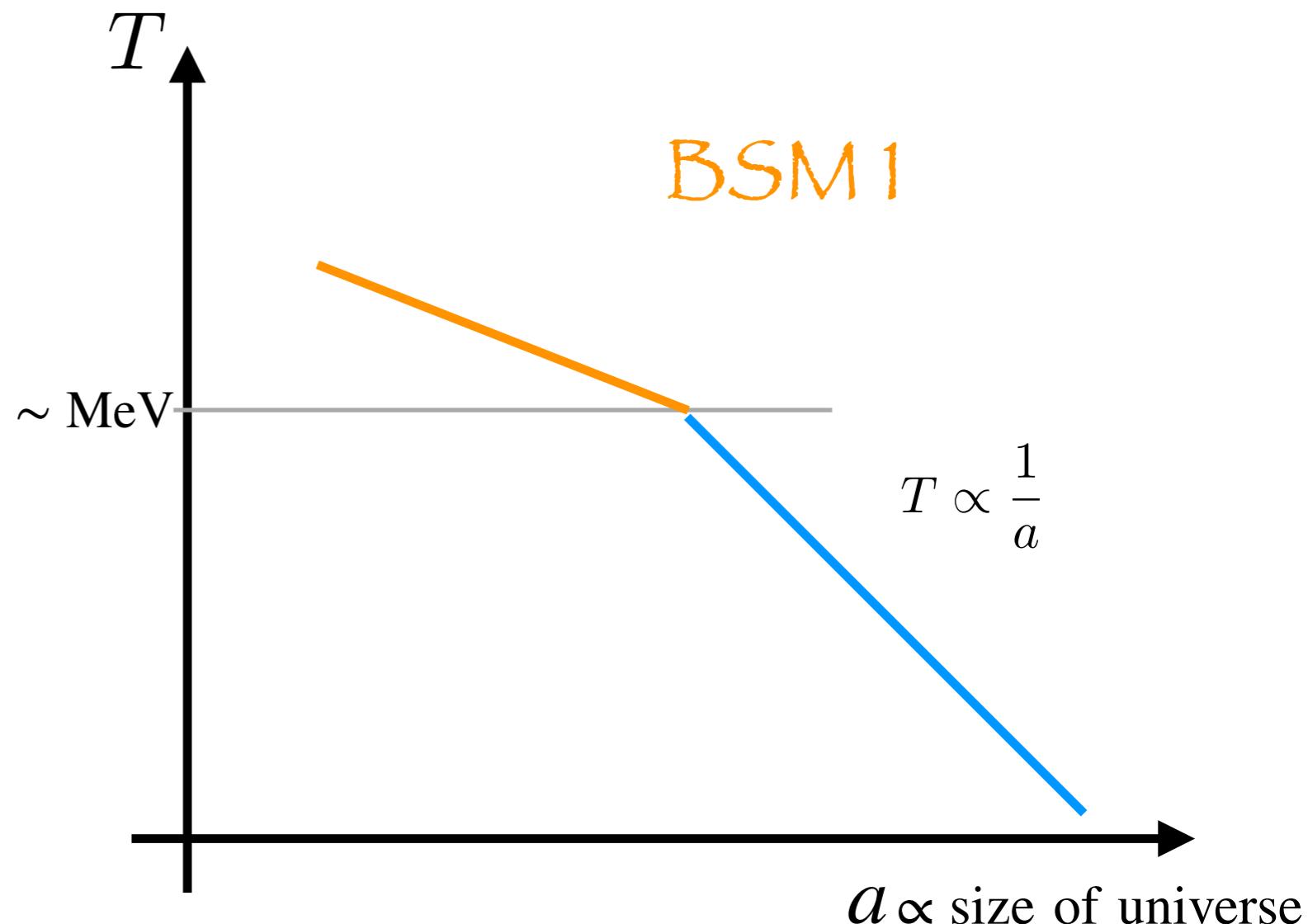
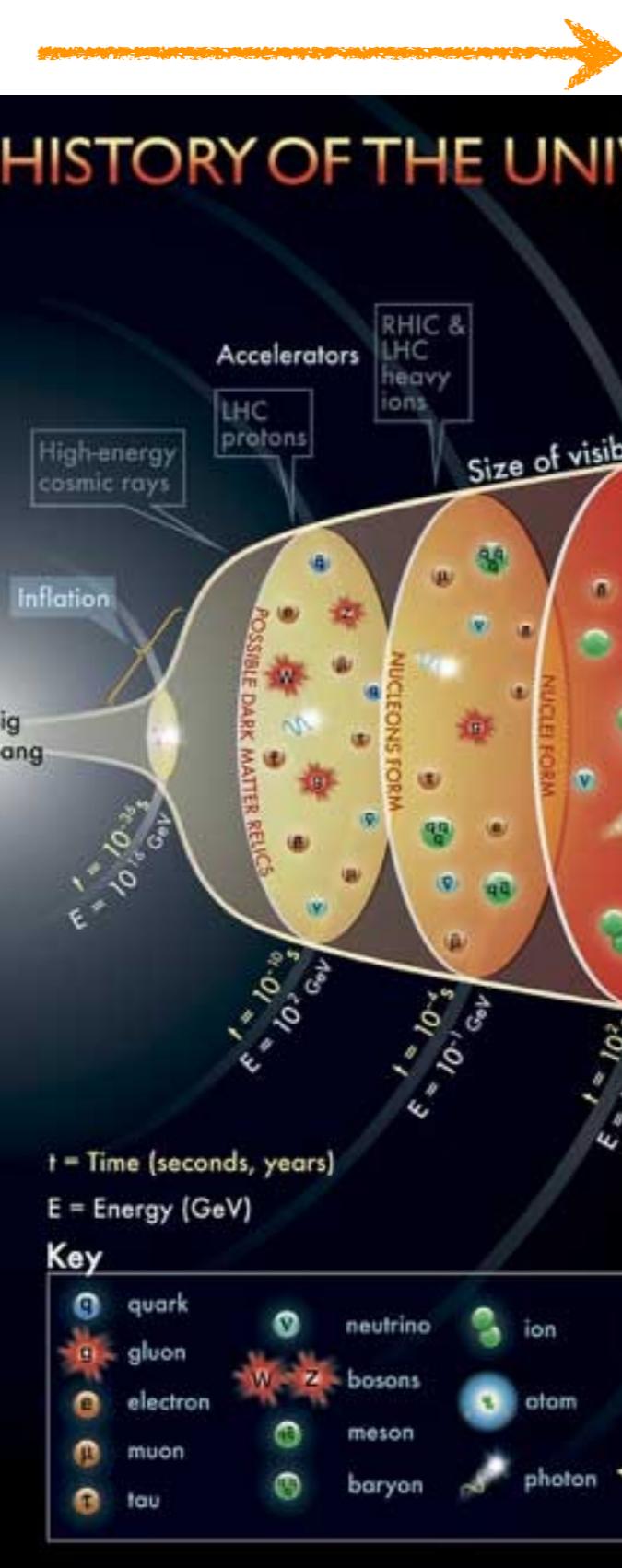
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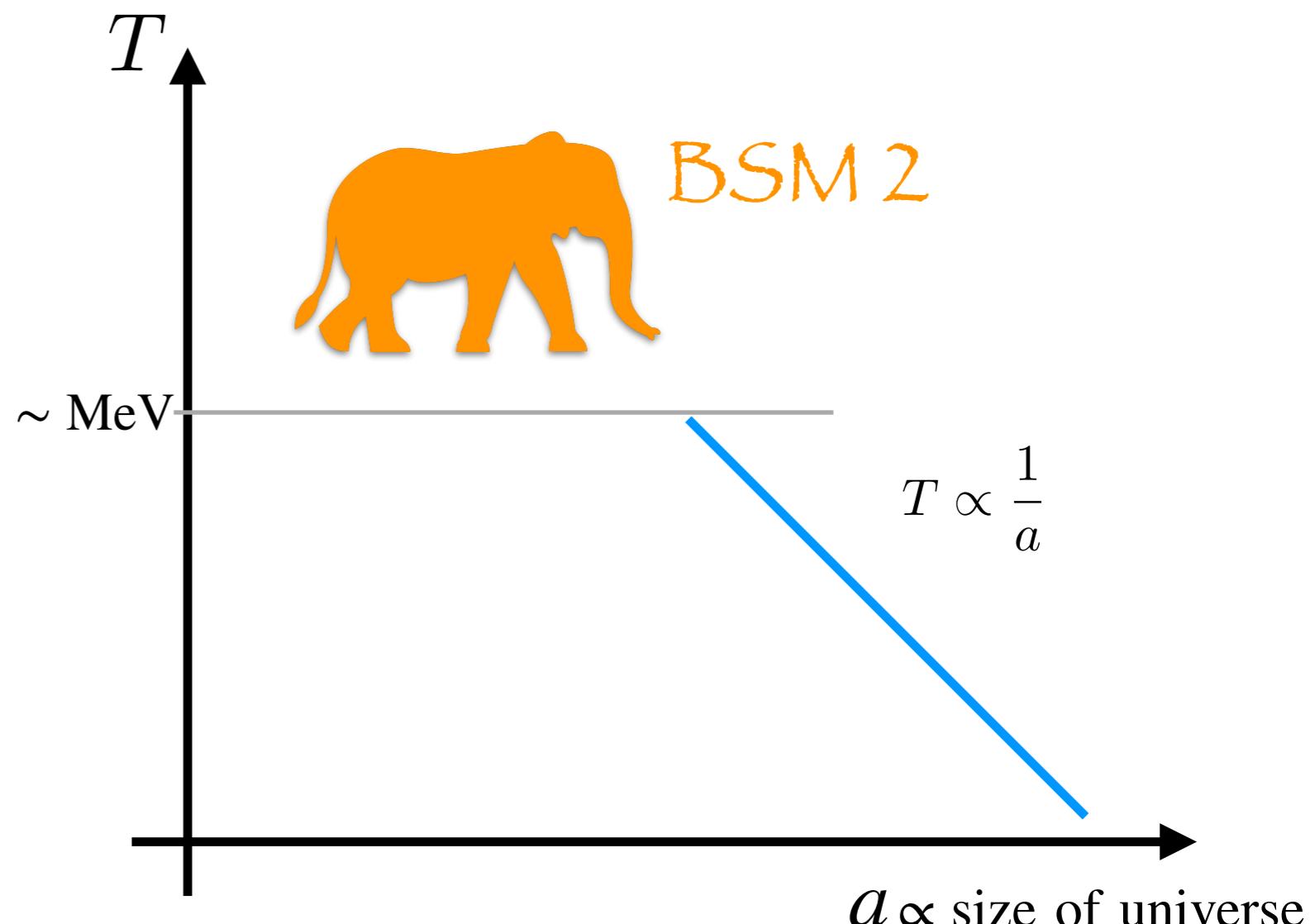
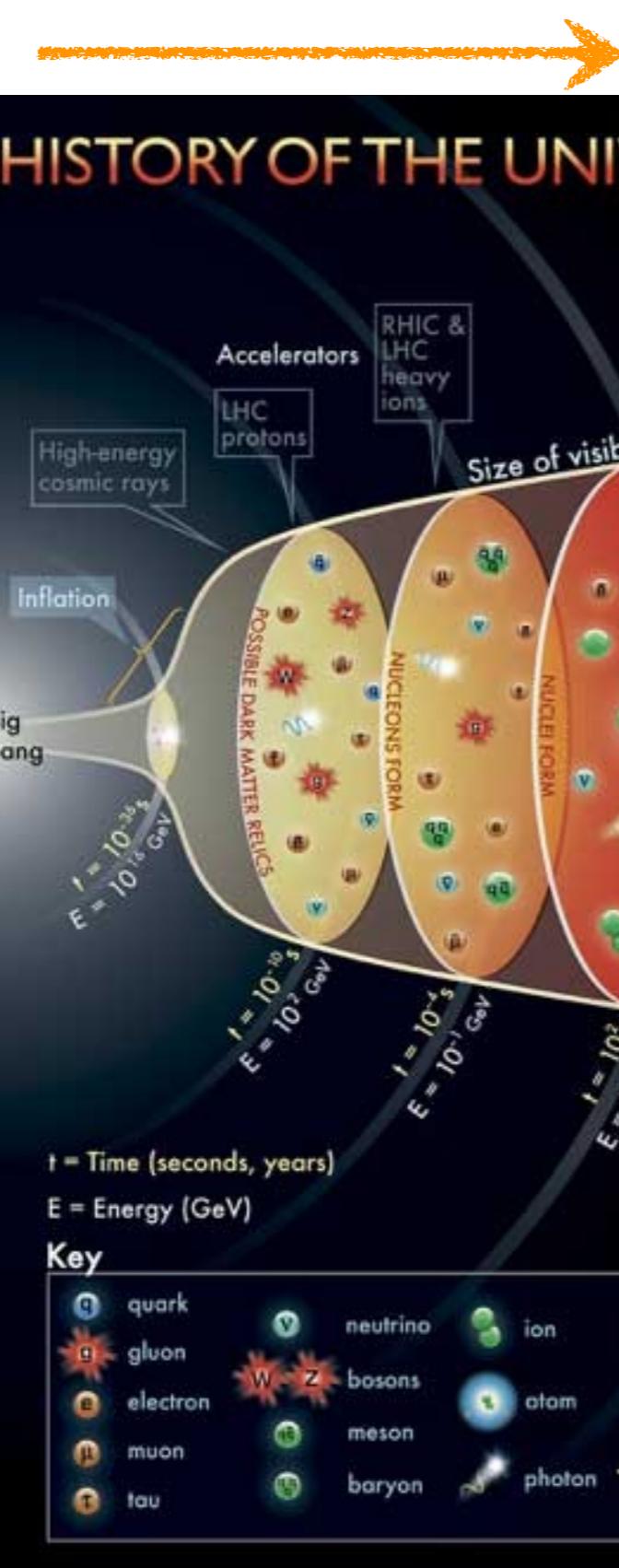
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Not Tested



Not Tested

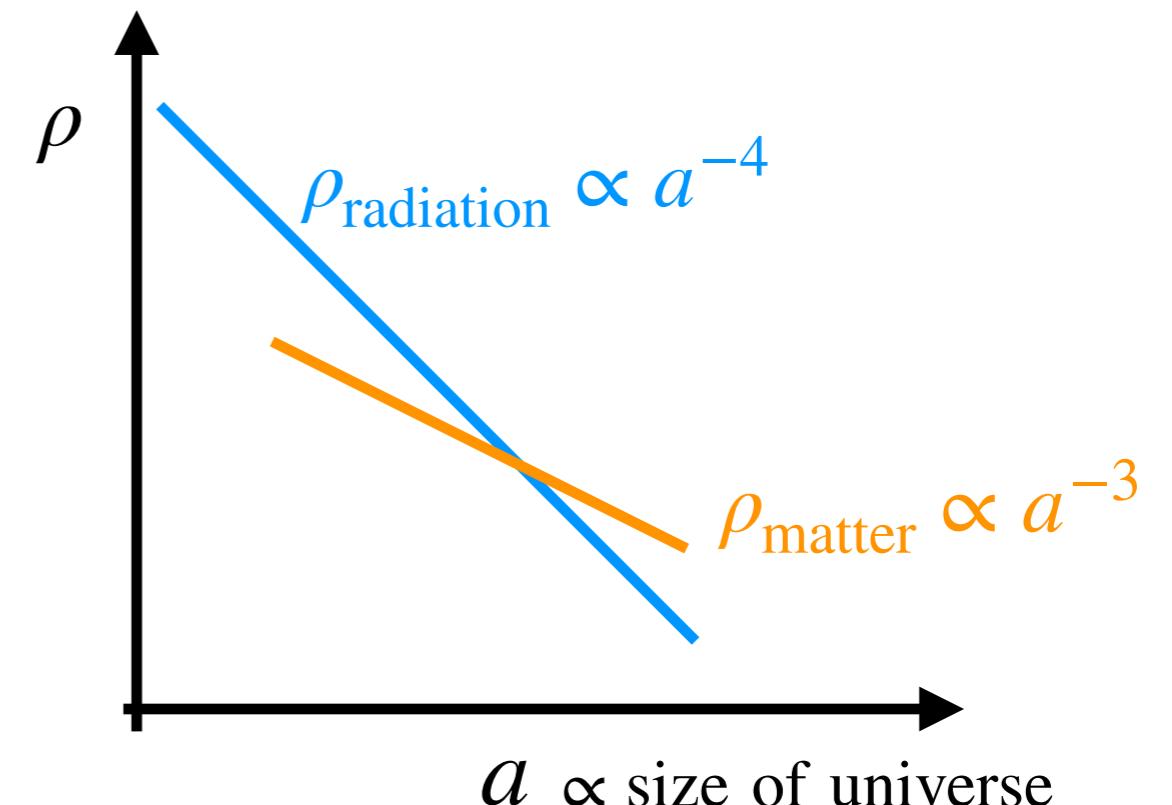


Matter Domination

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

Matter: $m \gg T$

Radiation: $m \ll T$

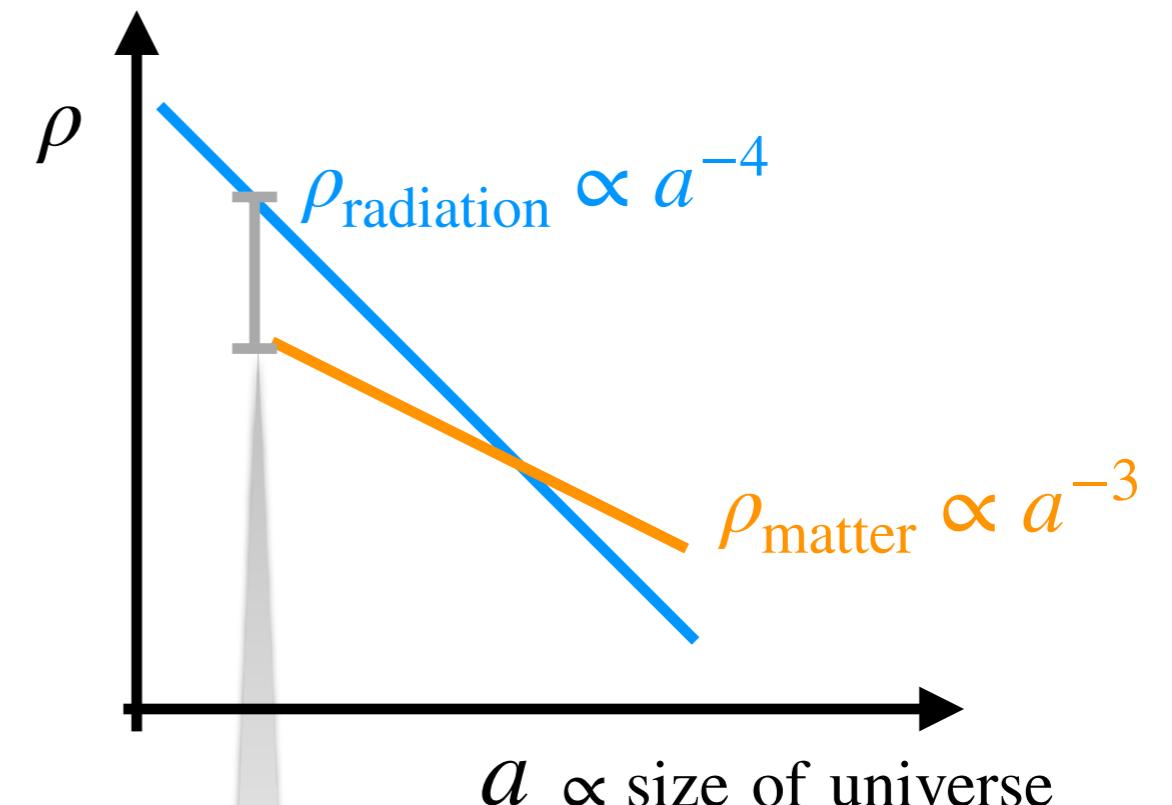


Matter Domination

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

Matter: $m \gg T$

Radiation: $m \ll T$



If Matter at thermal equilibrium $\rightarrow \rho_{\text{matter}} \propto \exp(-m/T) \ll \rho_{\text{rad}} \propto T^4$

Early Matter Domination

Add to SM particle(s) that satisfy conditions:

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

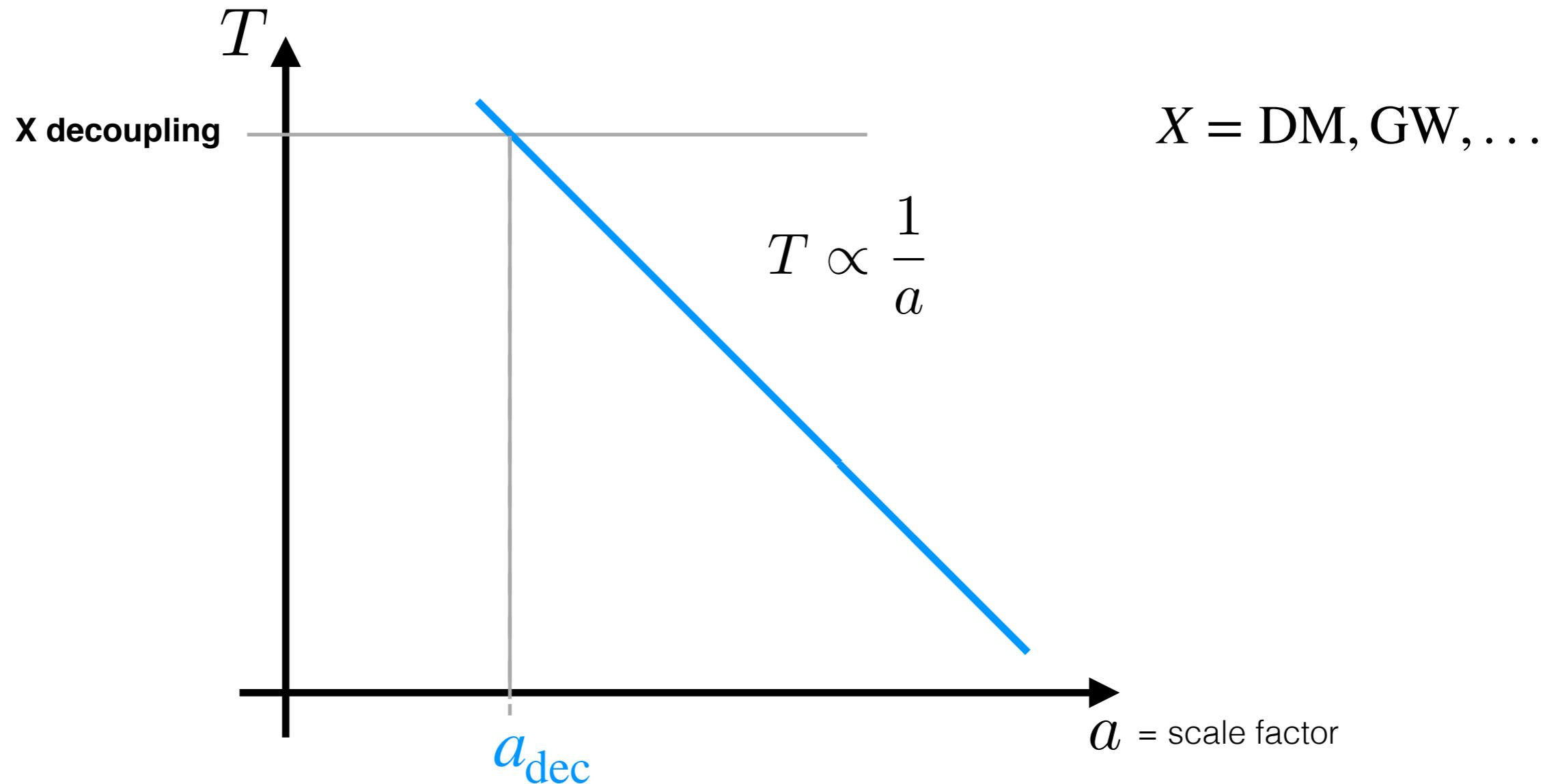
We know Universe is **radiation dominated** for $T \gtrsim \text{MeV}$
so Matter should decay before

2) $T_{\text{dec}} \gtrsim m$

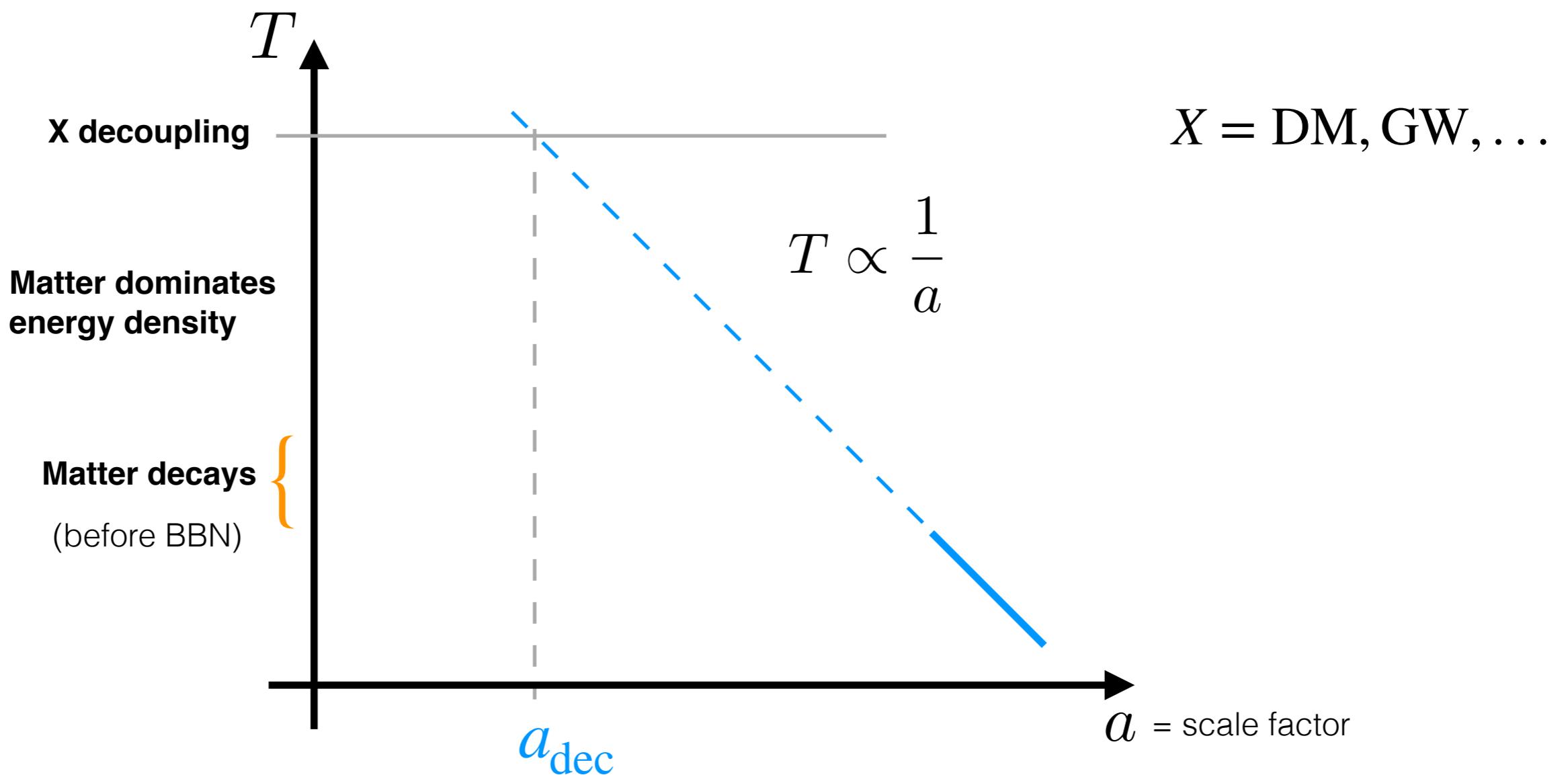
Matter should thermally decouple early

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

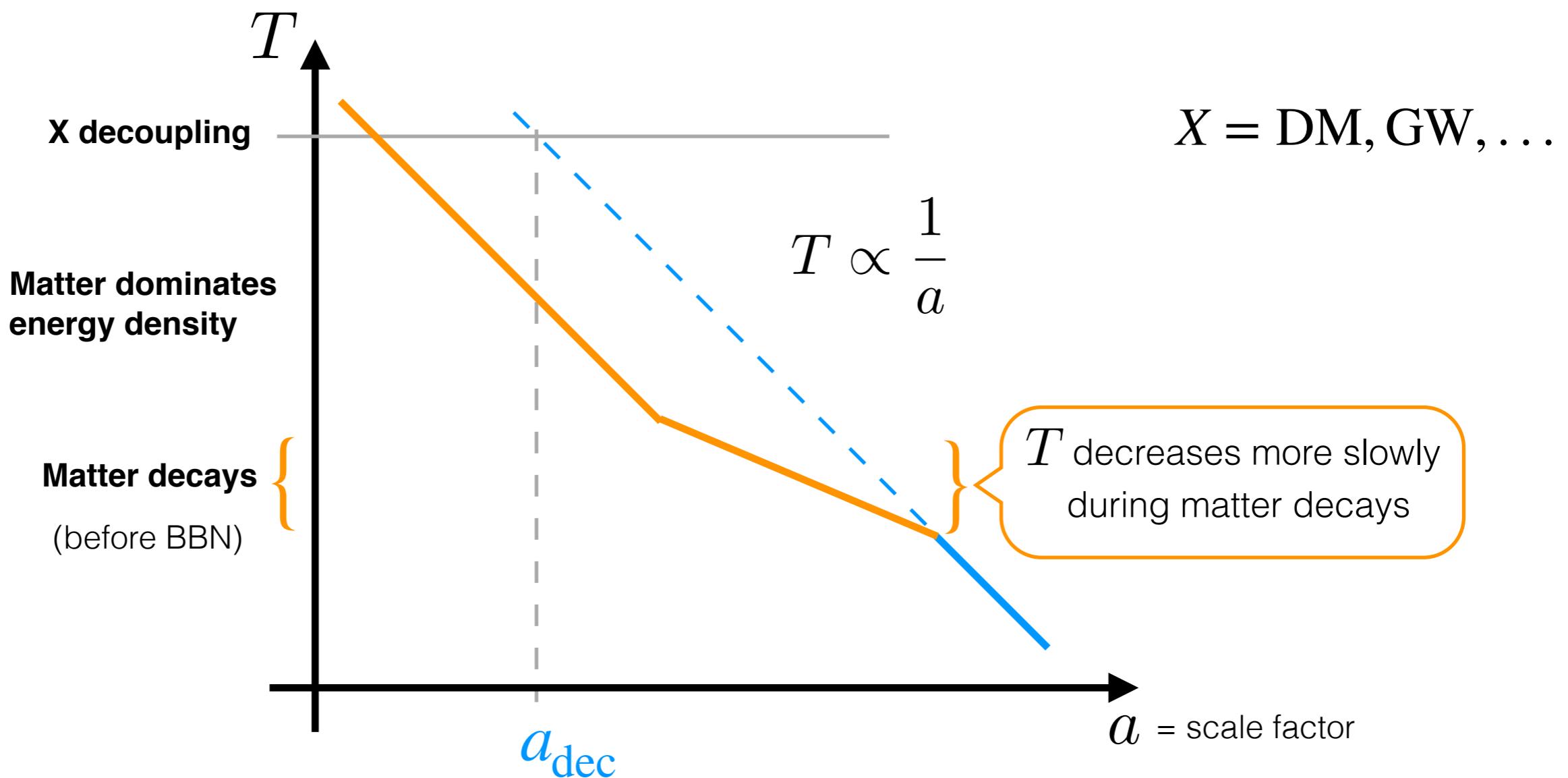
Cosmology of Early Matter Domination



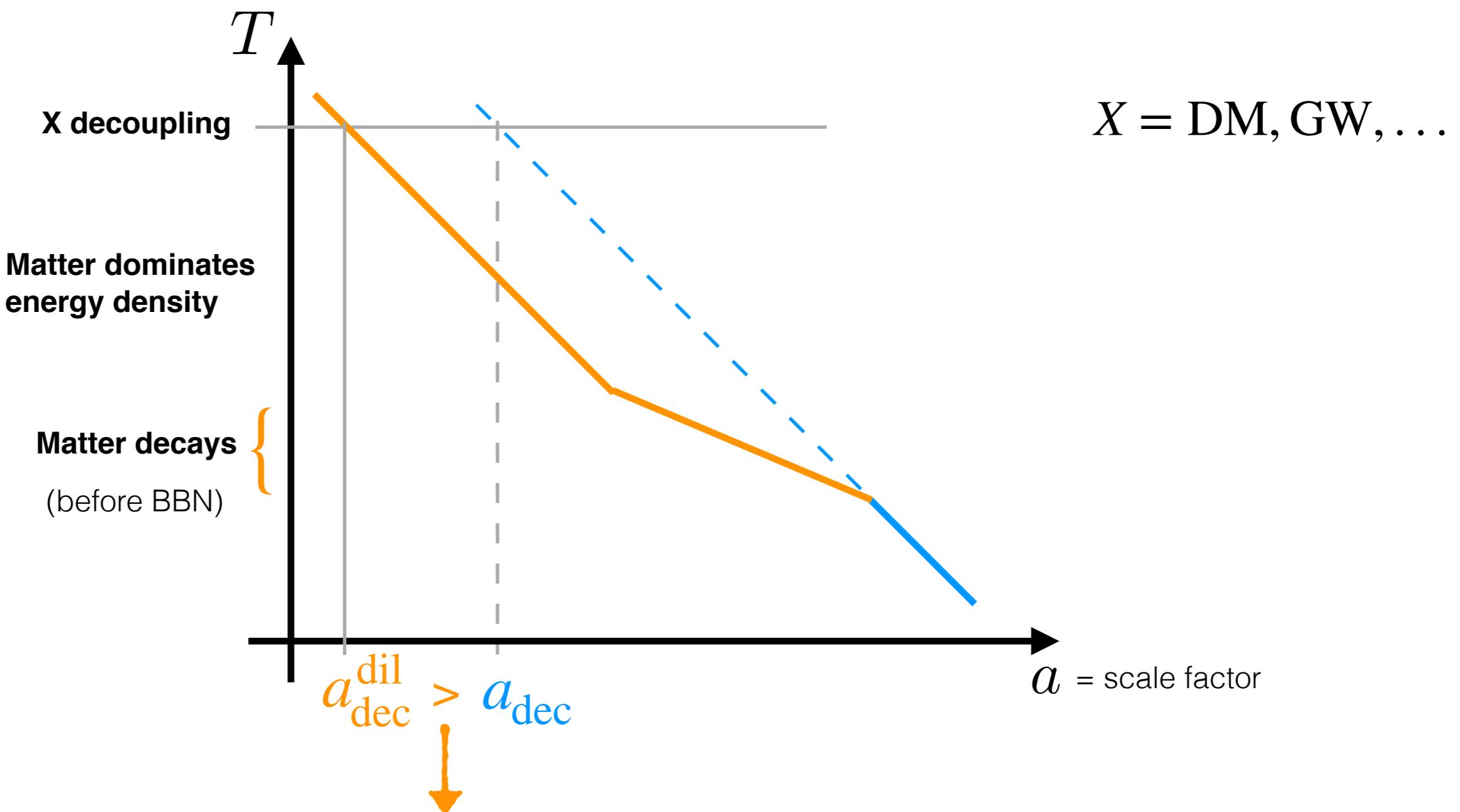
Cosmology of Early Matter Domination



Cosmology of Early Matter Domination

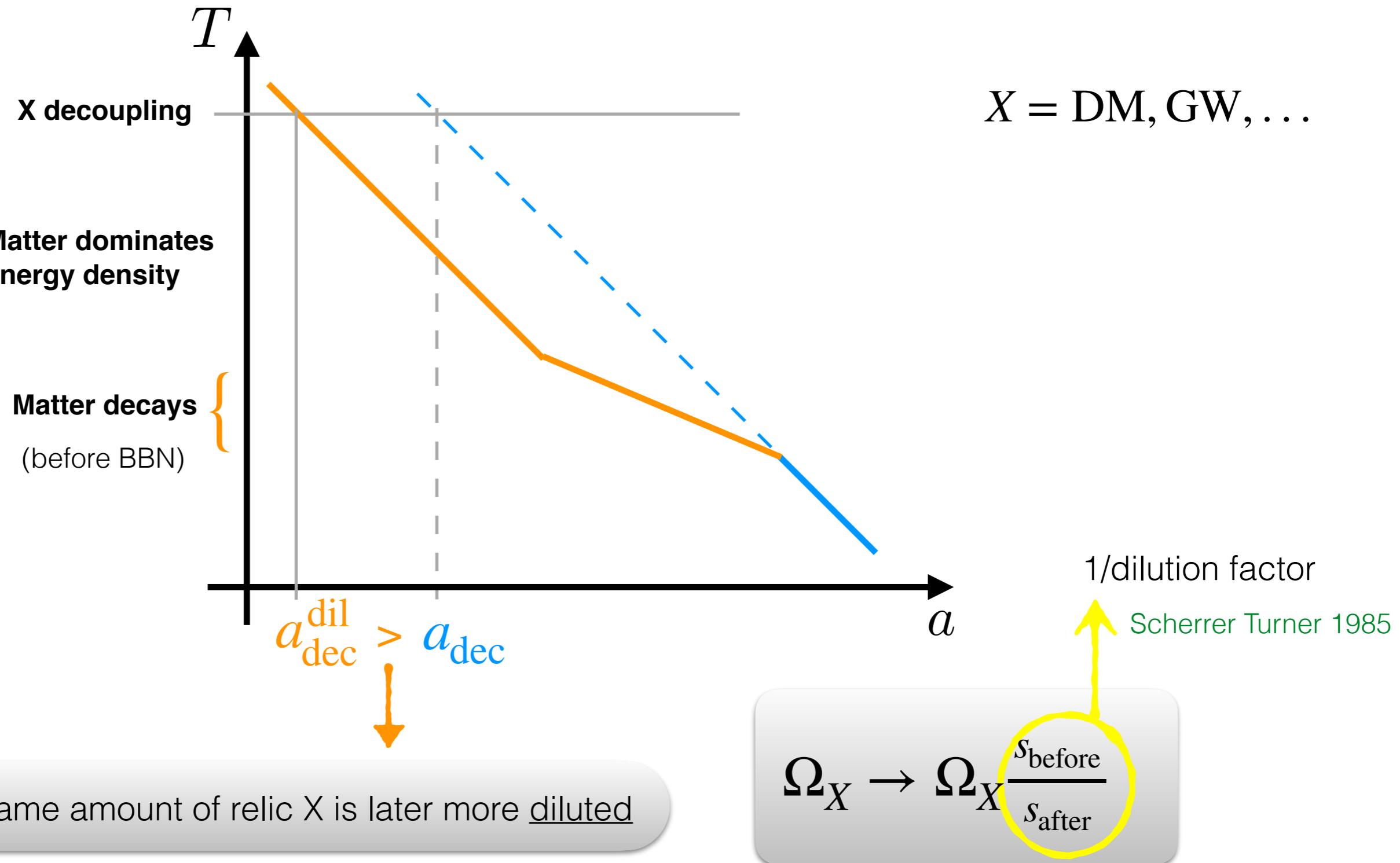


Cosmology of Early Matter Domination



The same amount of relic X is later more diluted

Cosmology of Early Matter Domination



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

Why Early Matter Domination?

Why not? After all, matter dominates 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, ...

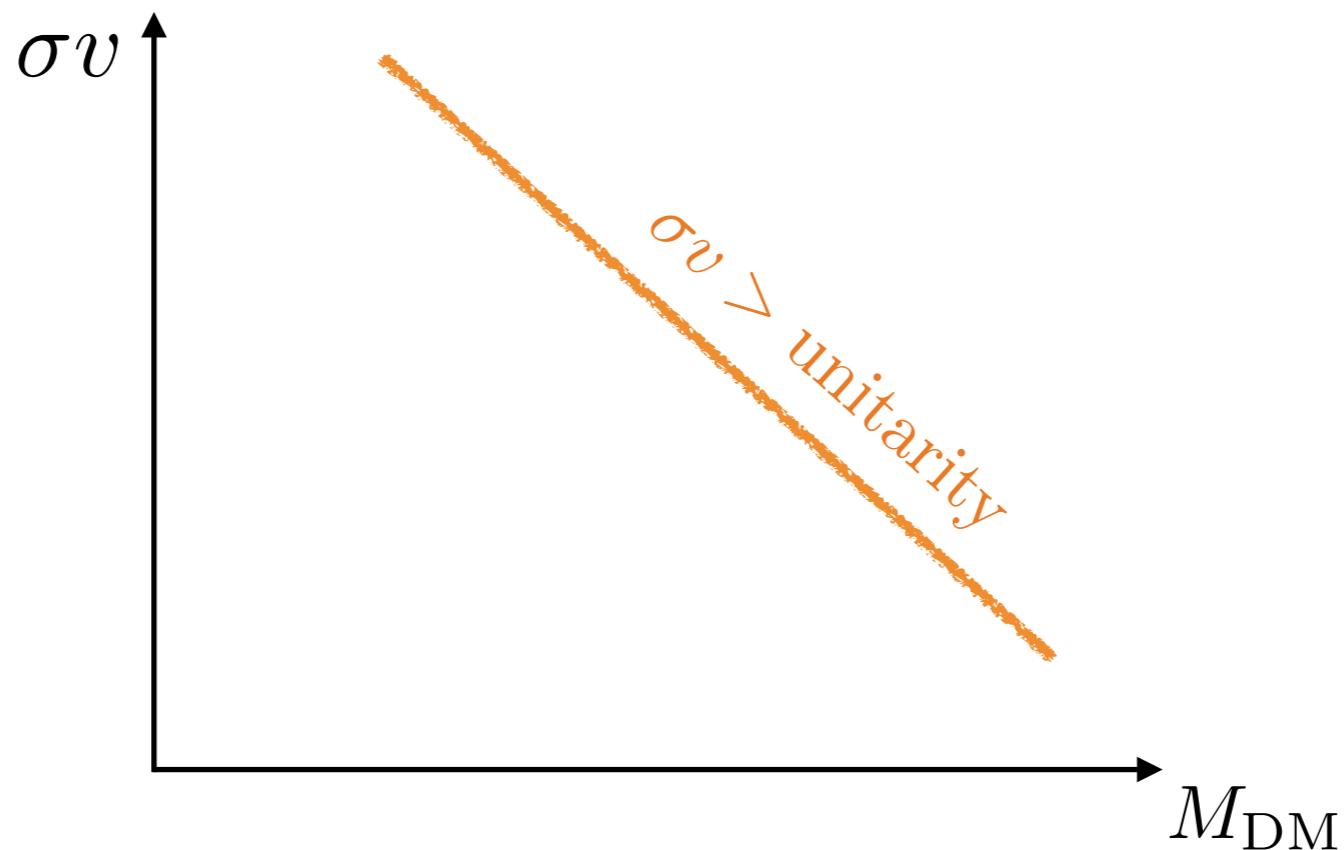
Some theories need it to dilute dangerous relics

Topological defects

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

Early Matter and DM Unitarity Bound

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

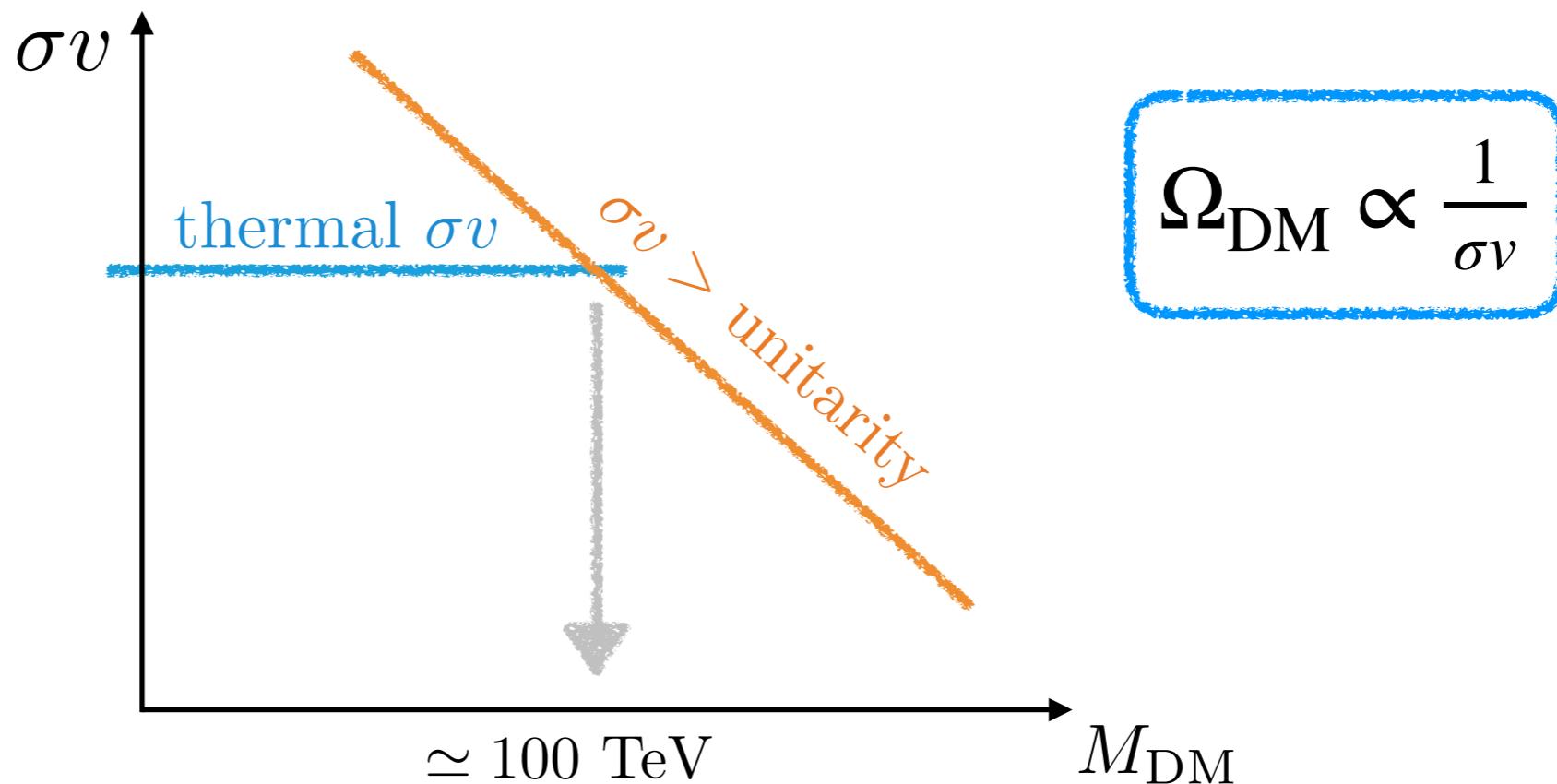


Early Matter and DM Unitarity Bound

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\Rightarrow

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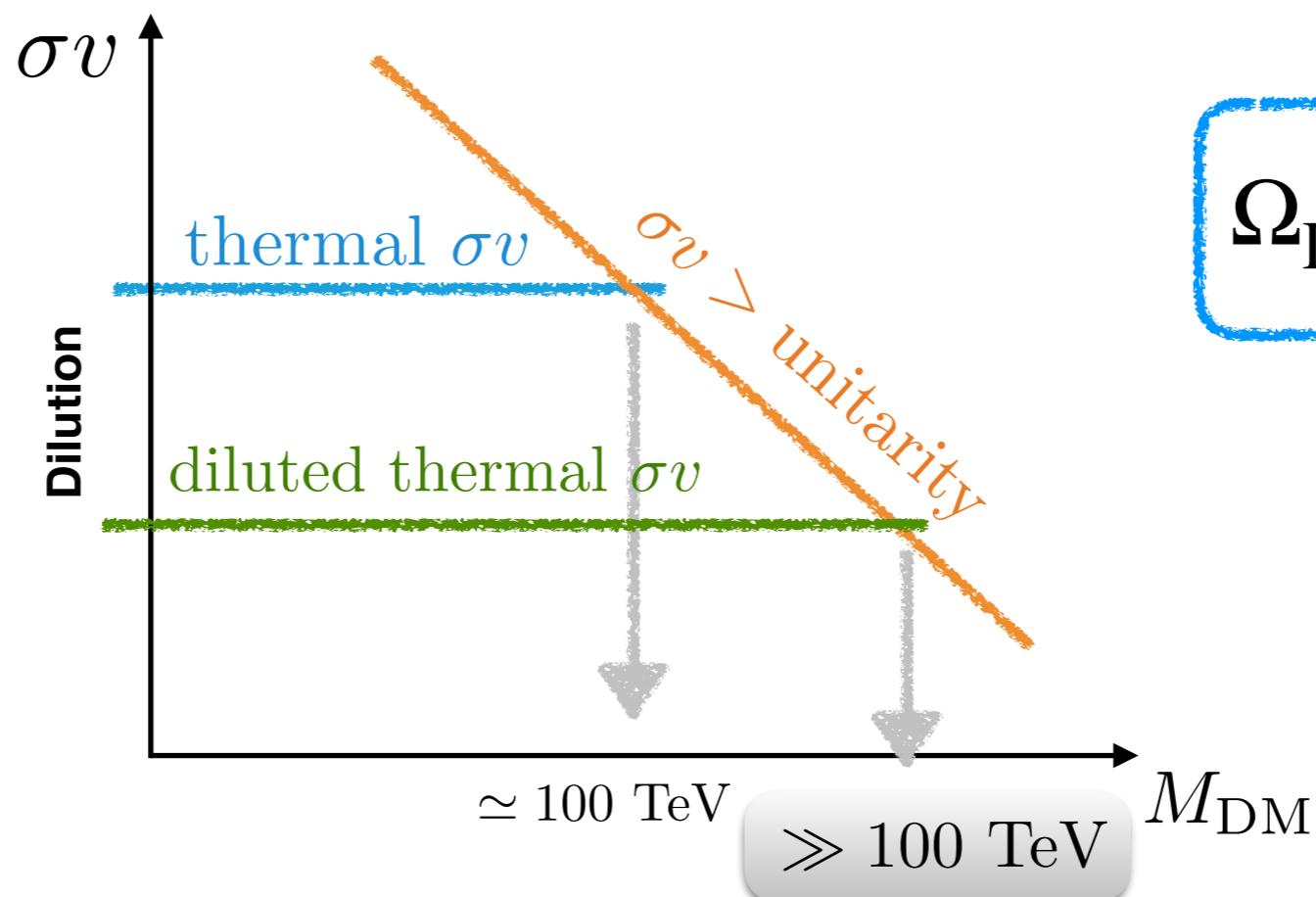


Early Matter and DM Unitarity Bound

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

Concrete Examples

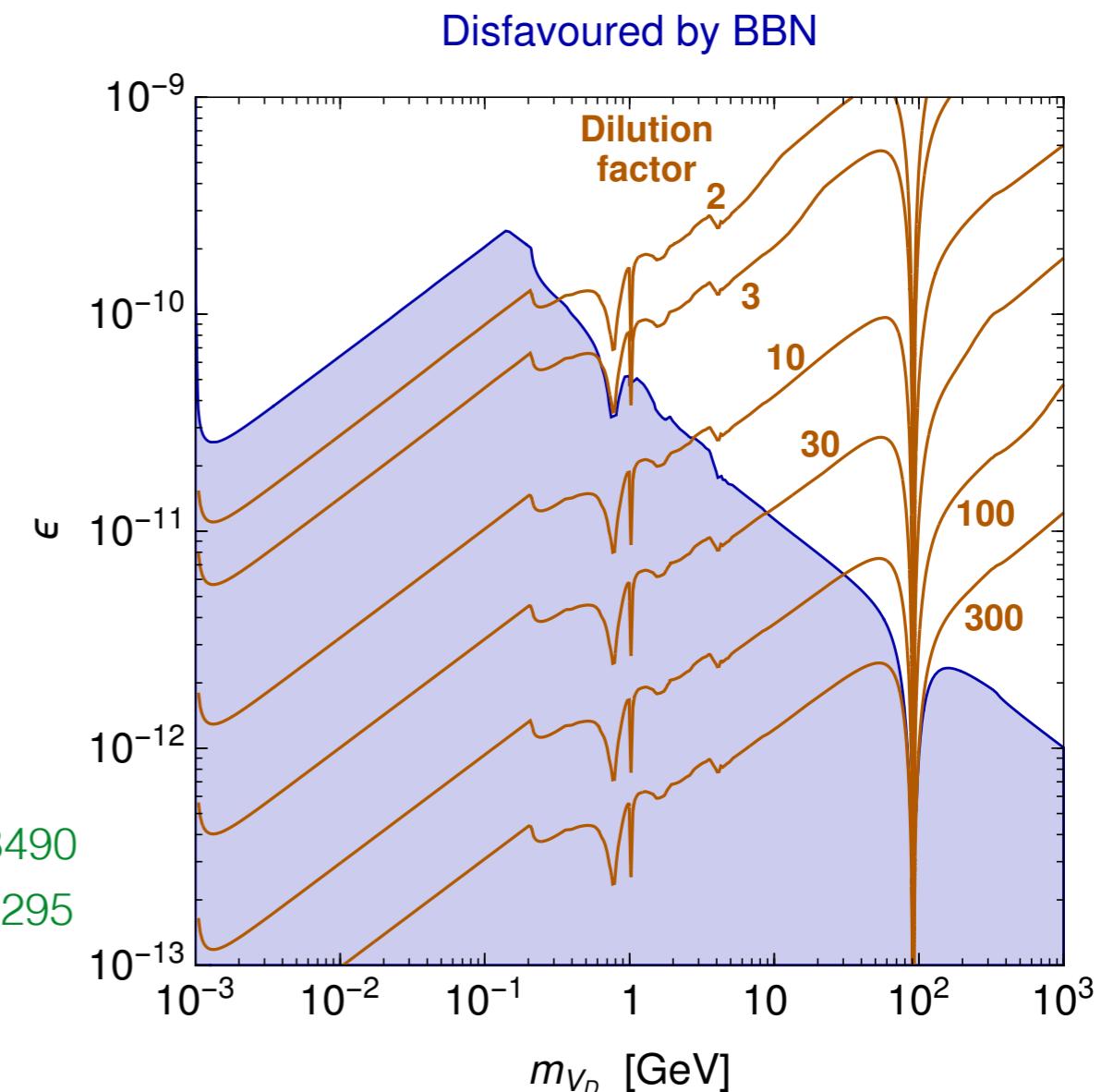
Dark Photon

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

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

Berlin+1602.08490

Cirelli+1612.07295



BSM scalar

fundamental, or 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

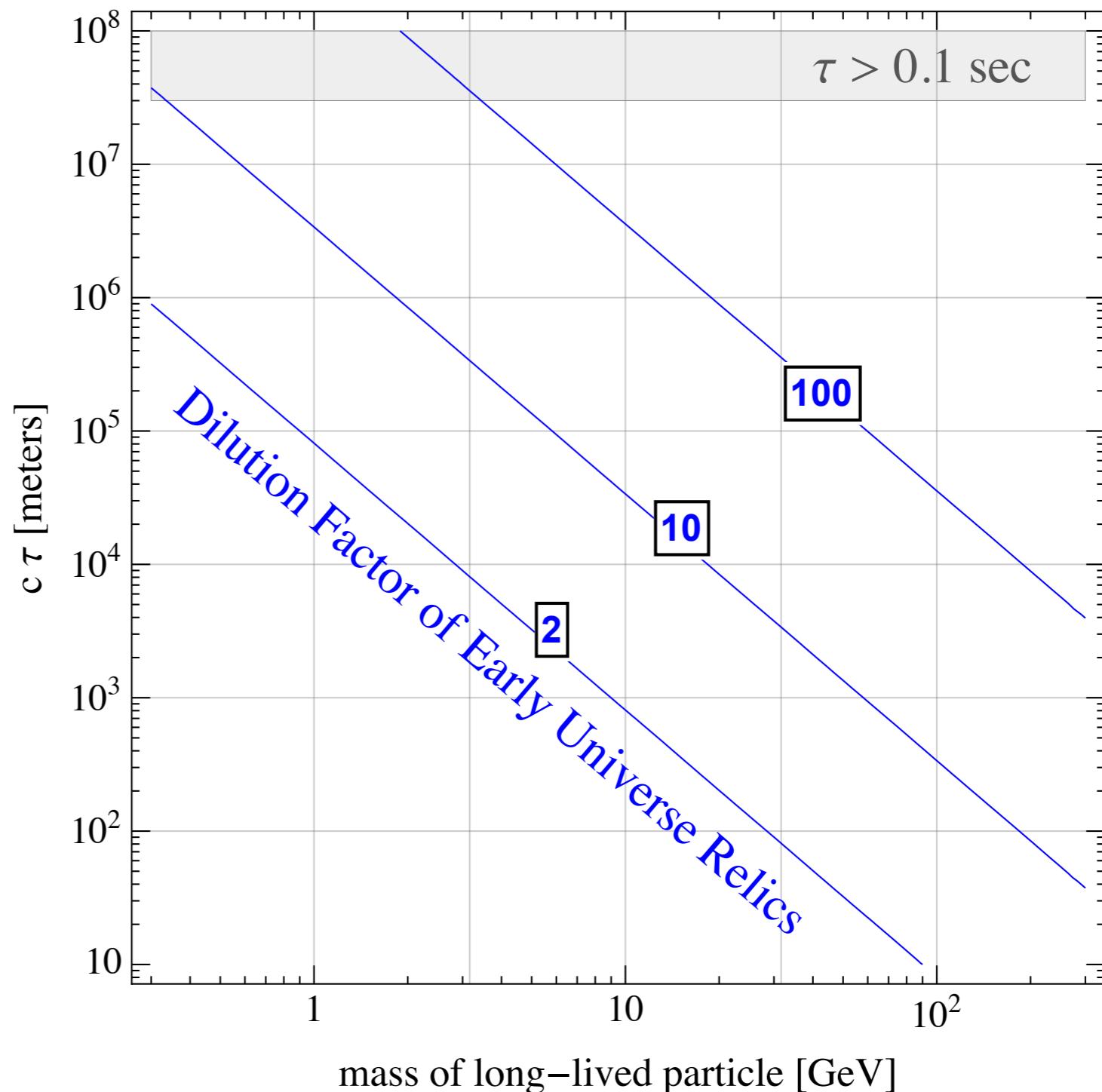
...

Can we test in the Lab?

FS + Kai Schmidt-Hoberg & Fady Bishara

Early Matter \approx Long Lived Particles!

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



Example Experiment: Mathusla

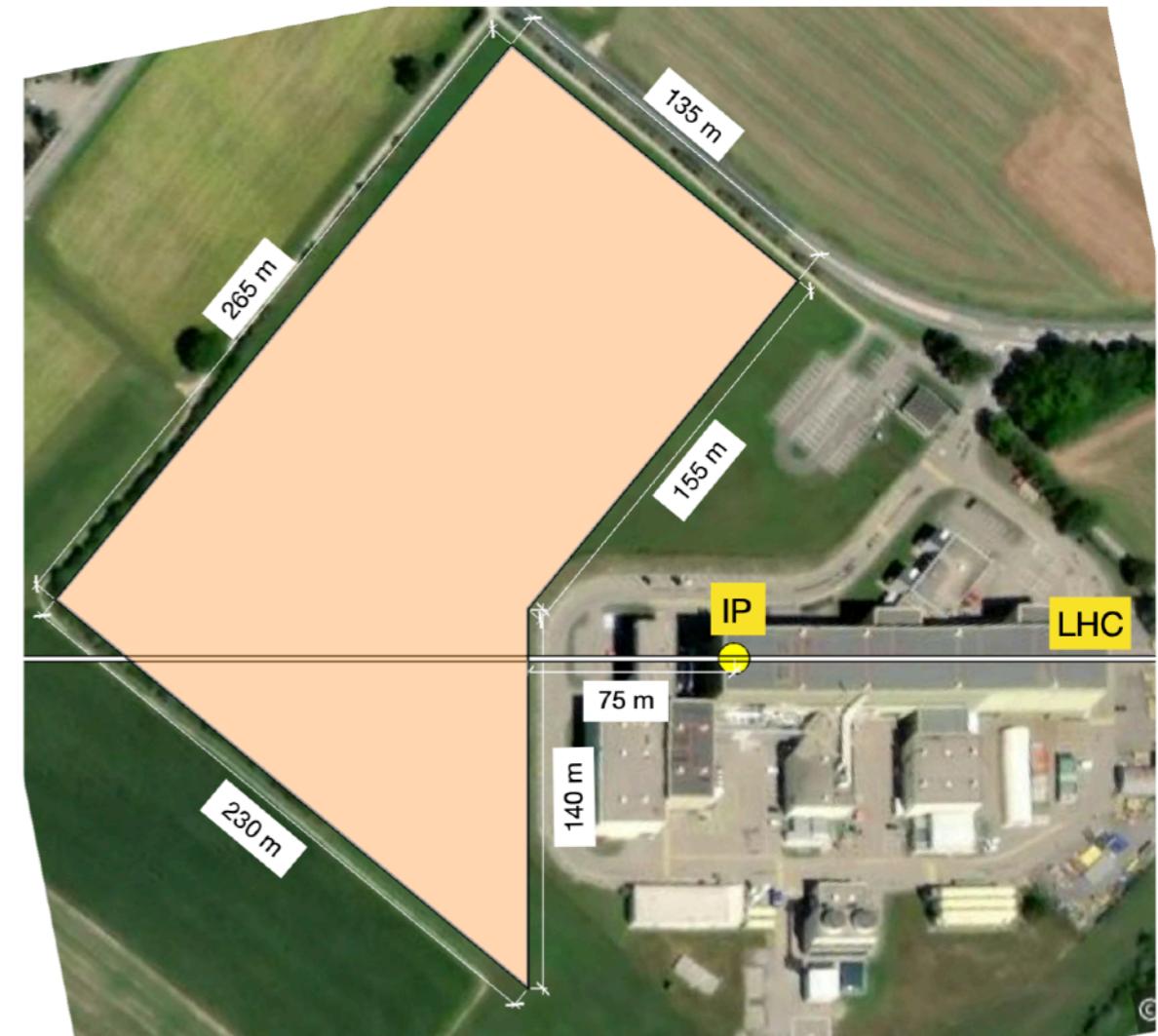
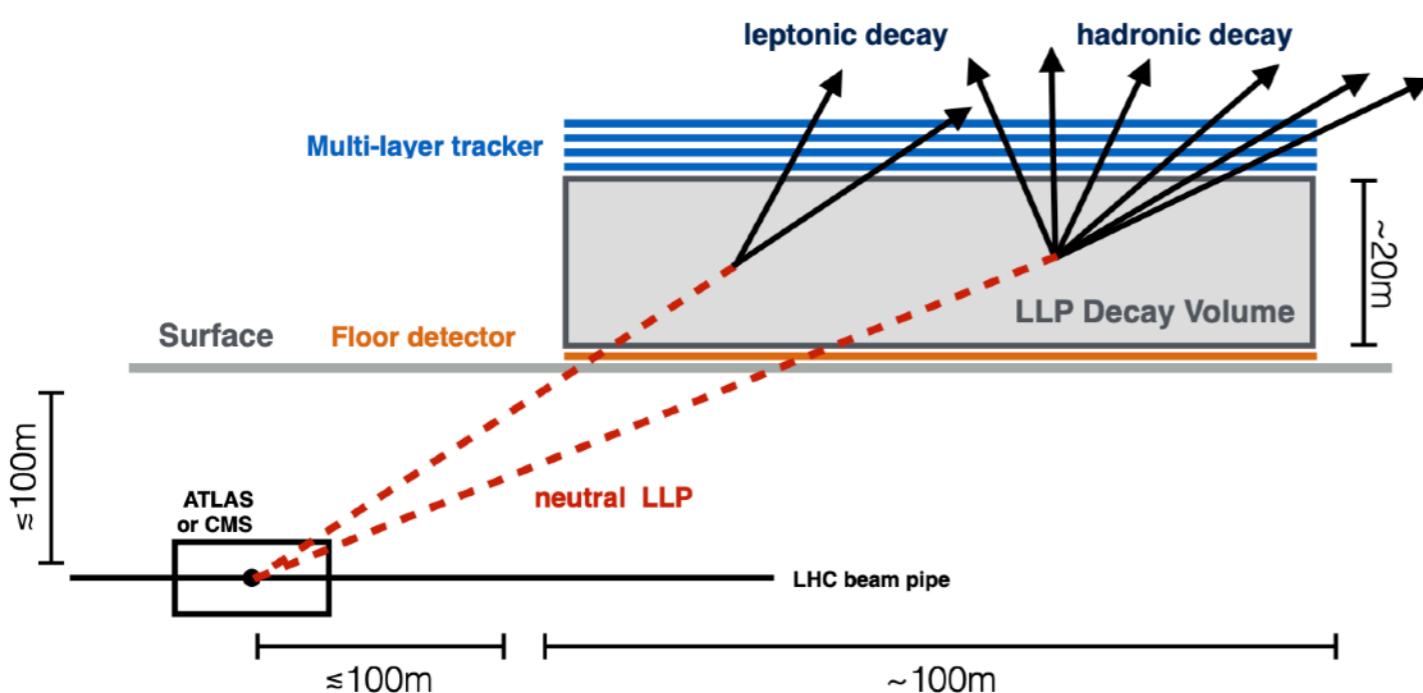
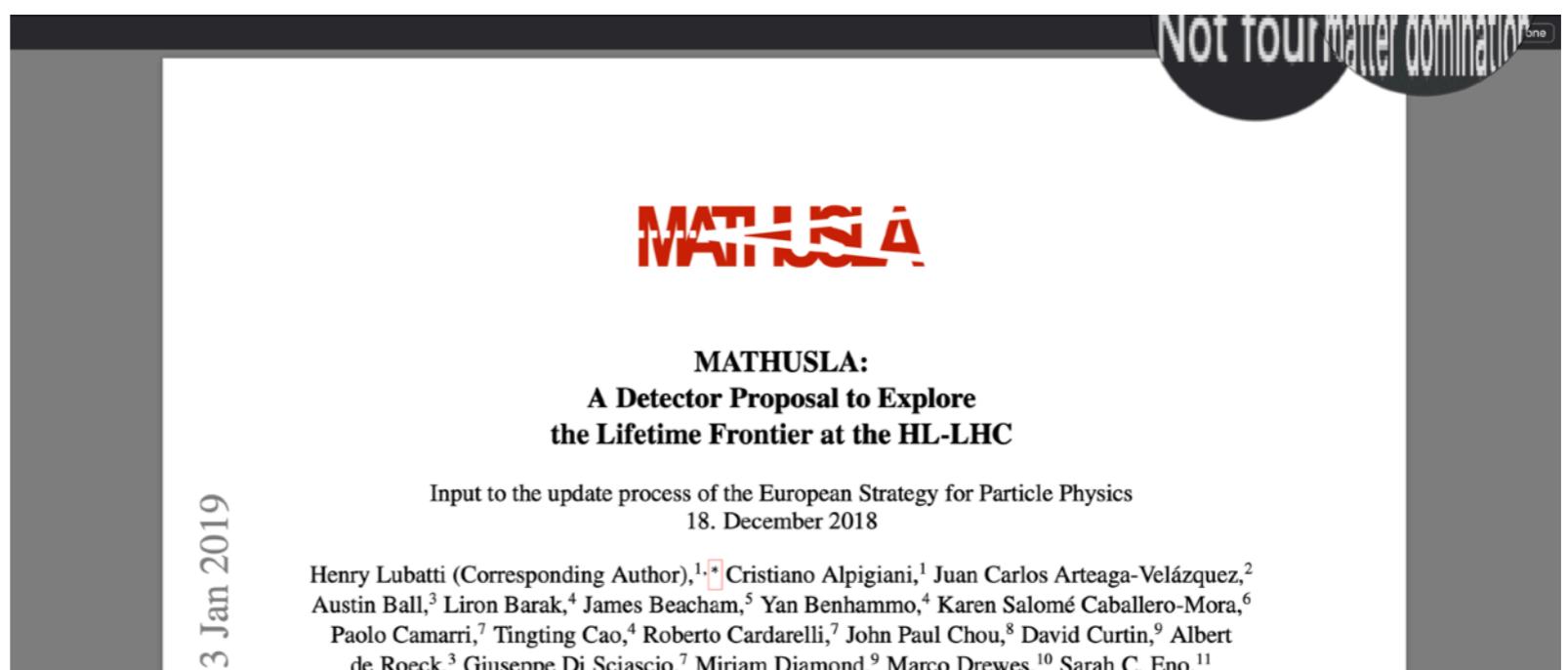
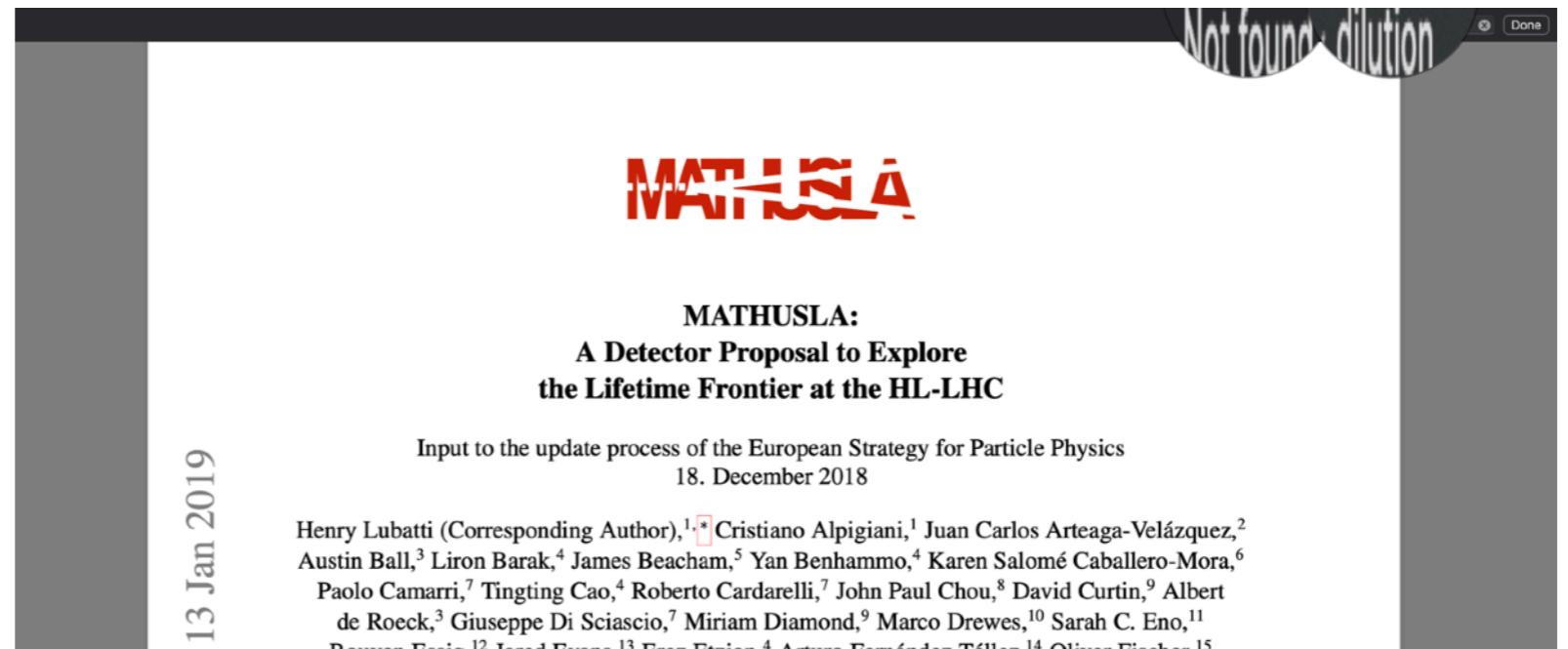


Figure from 1901.04040

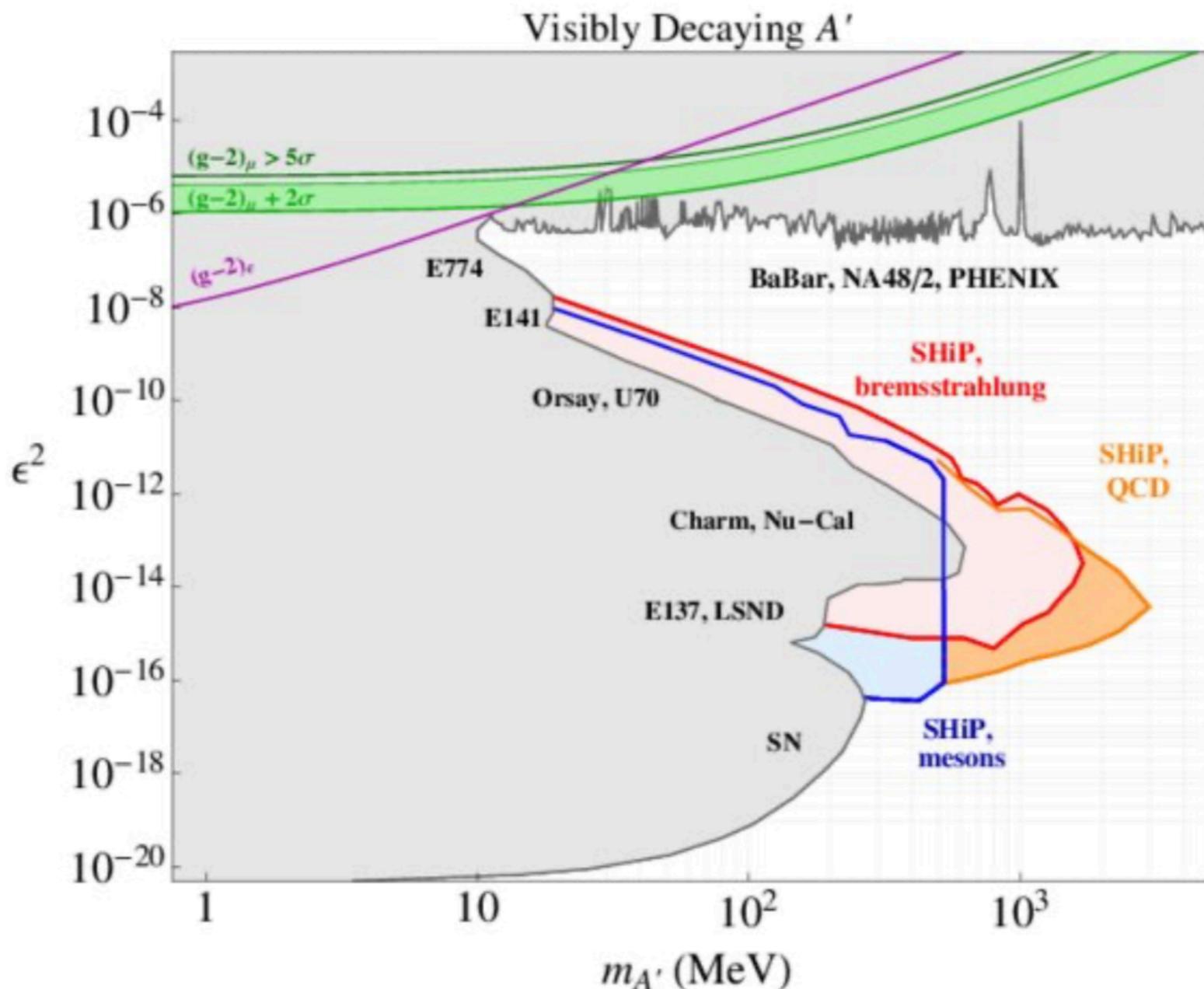
Can LLP searches test Dilution from Early Matter?

ctrl+f

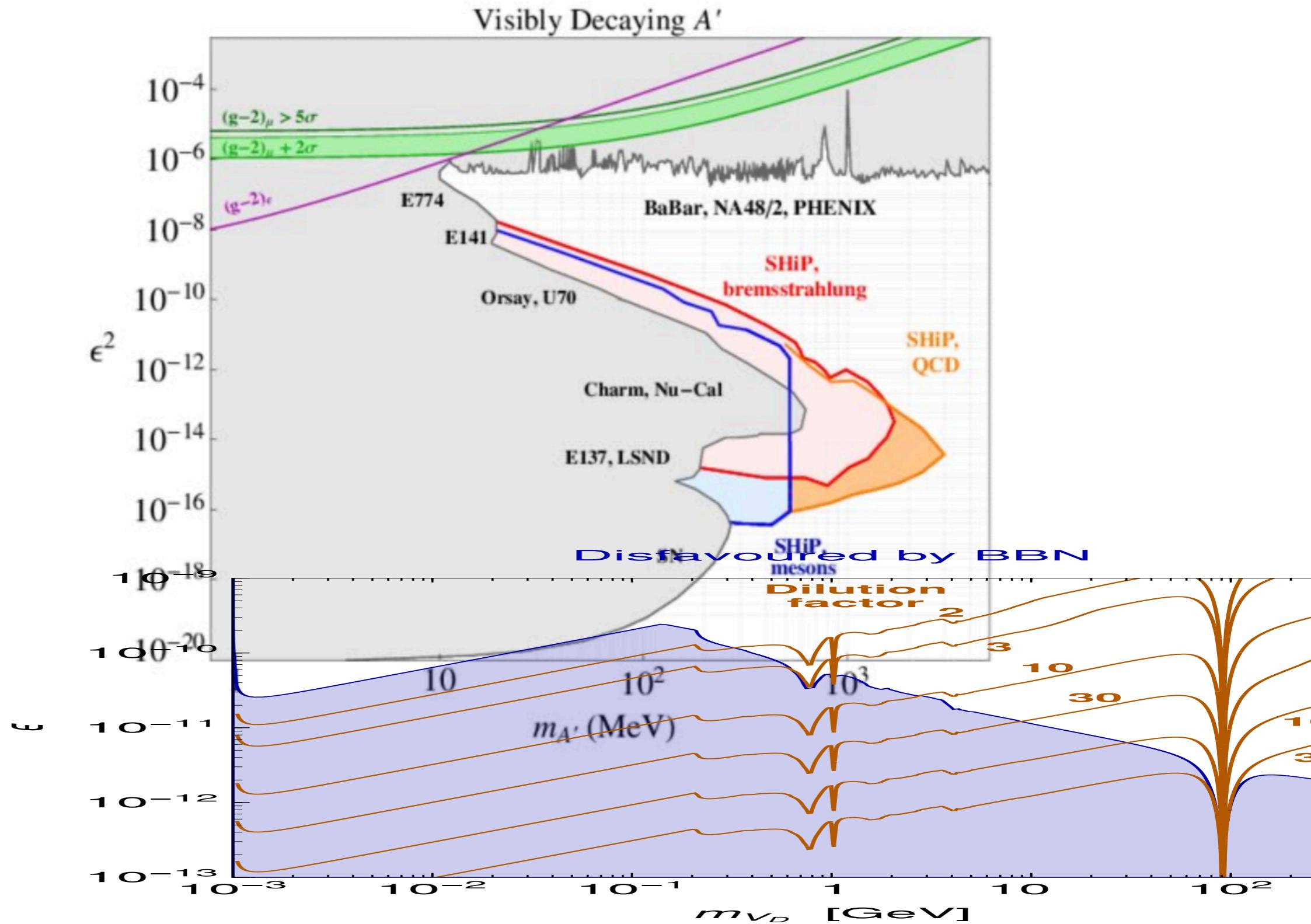


Similarly for other LLP experiments...

Dark Photon Domination



Dark Photon Domination: NO



How to probe larger dilutions @ colliders

Smart combination of collider production vs decay



Obstacle to Large coupling in production:

2)

$$T_{\text{dec}} \gtrsim m$$

Matter should thermally decouple early
otherwise $\rho_{\text{matter}} \propto \exp(-m/T) \ll \rho_{\text{rad}} \propto T^4$

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Decouple at a phase transition!

A successful example: (dark) Glueballs

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

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

Glueball $S =$ gluon bound state

A successful example: (dark) Glueballs

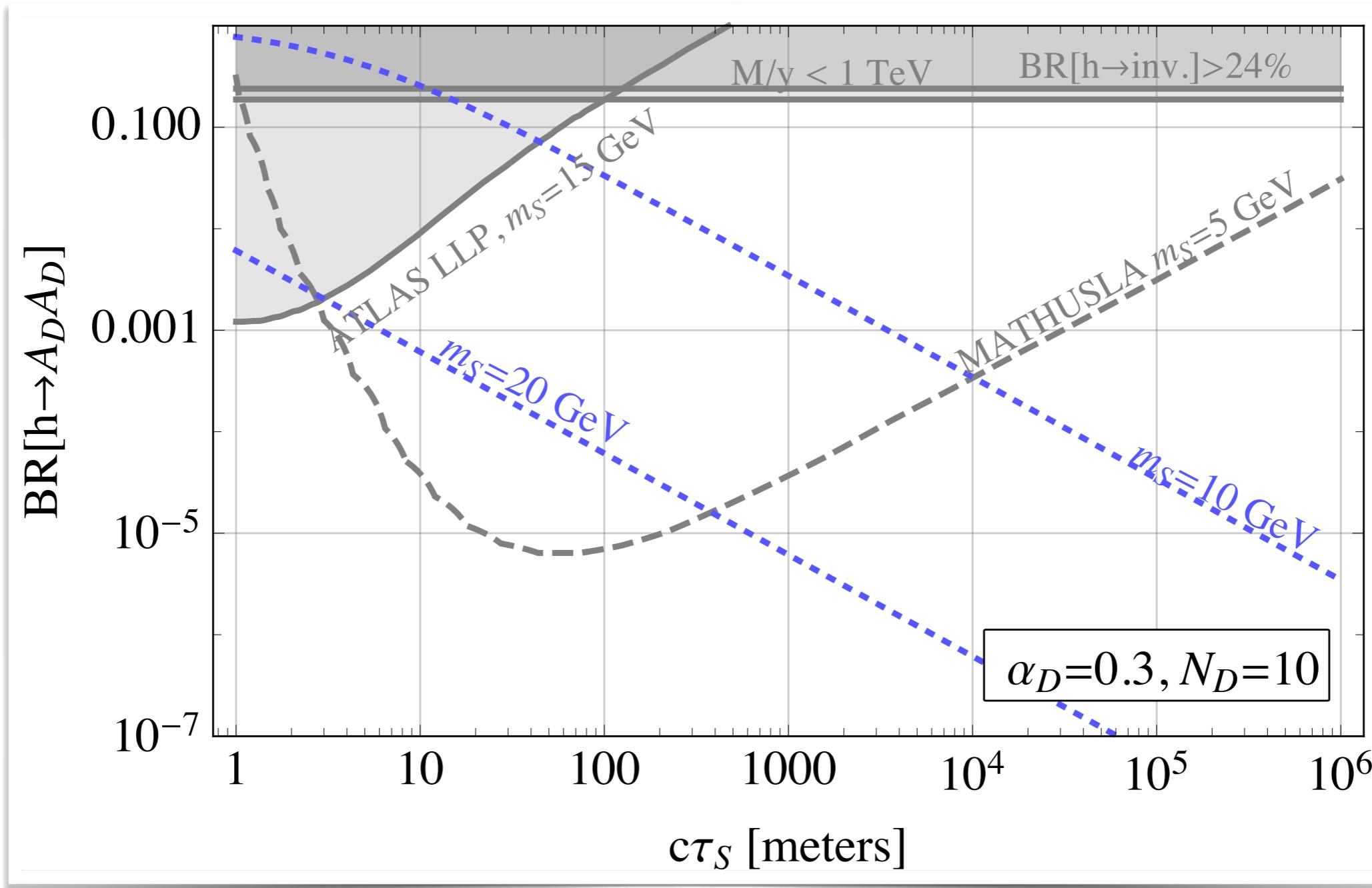
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Glueball S = gluon bound state

- 1) $\tau \lesssim \text{sec}$ Via large enough y
- 2) $T_{\text{dec}} \gtrsim m$ Decouple at confining phase transition of $SU(N_D)$
- 3) Production @ colliders via Higgs decays

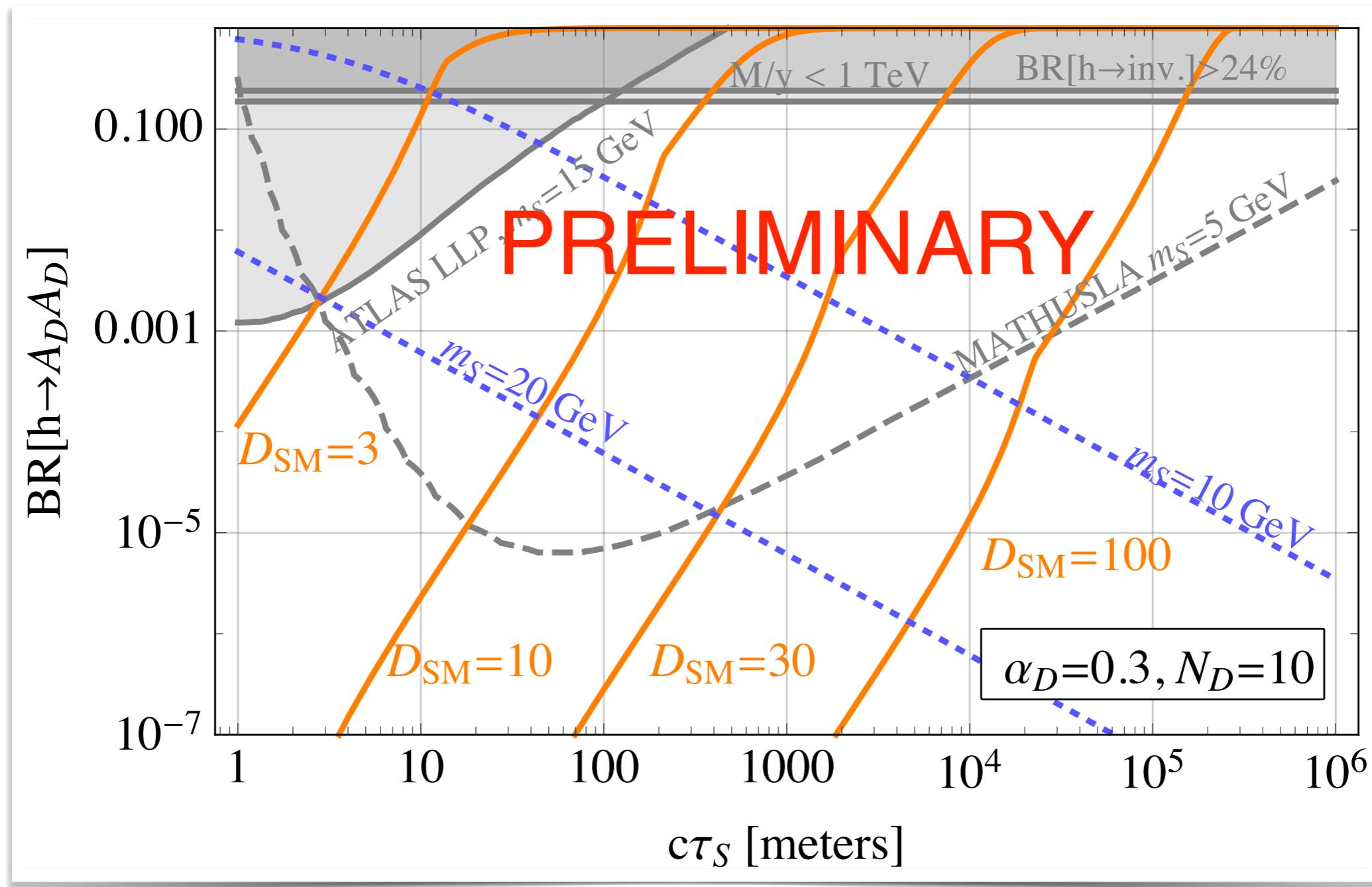
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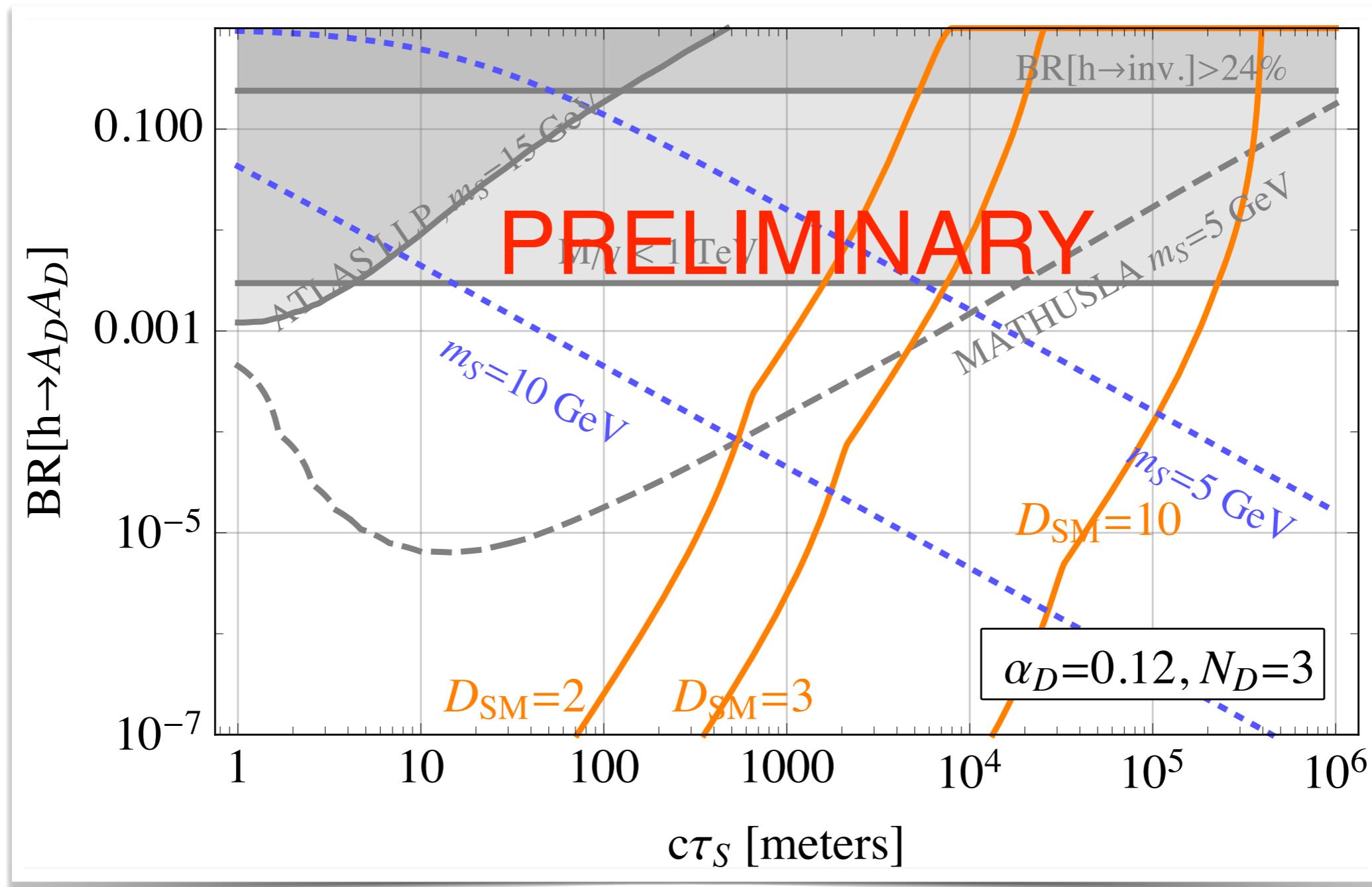
D_{SM} = Dilution of early relics (DM, GWs,...) * cannibalism still to be taken into account



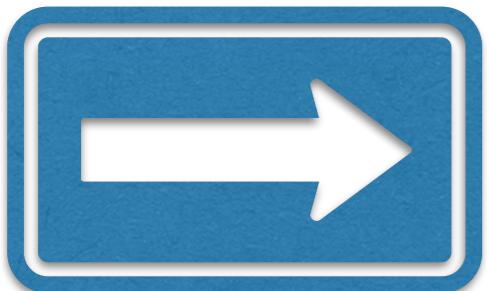
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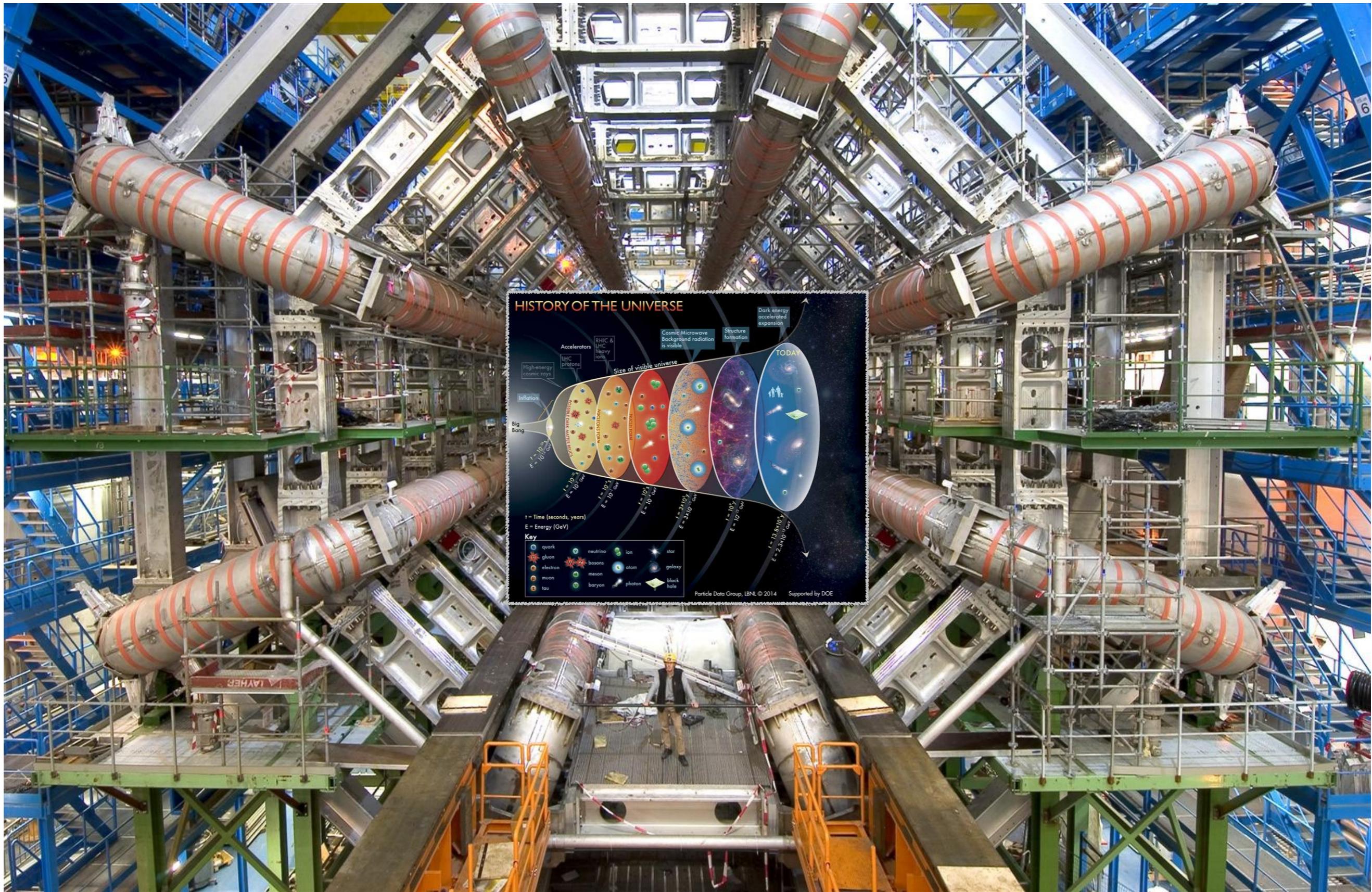


To do/ outlook

- > Quantify Impact of cannibalism of glueballs
- > Glueballs from VBF
- > Production from SUSY cascades
- >



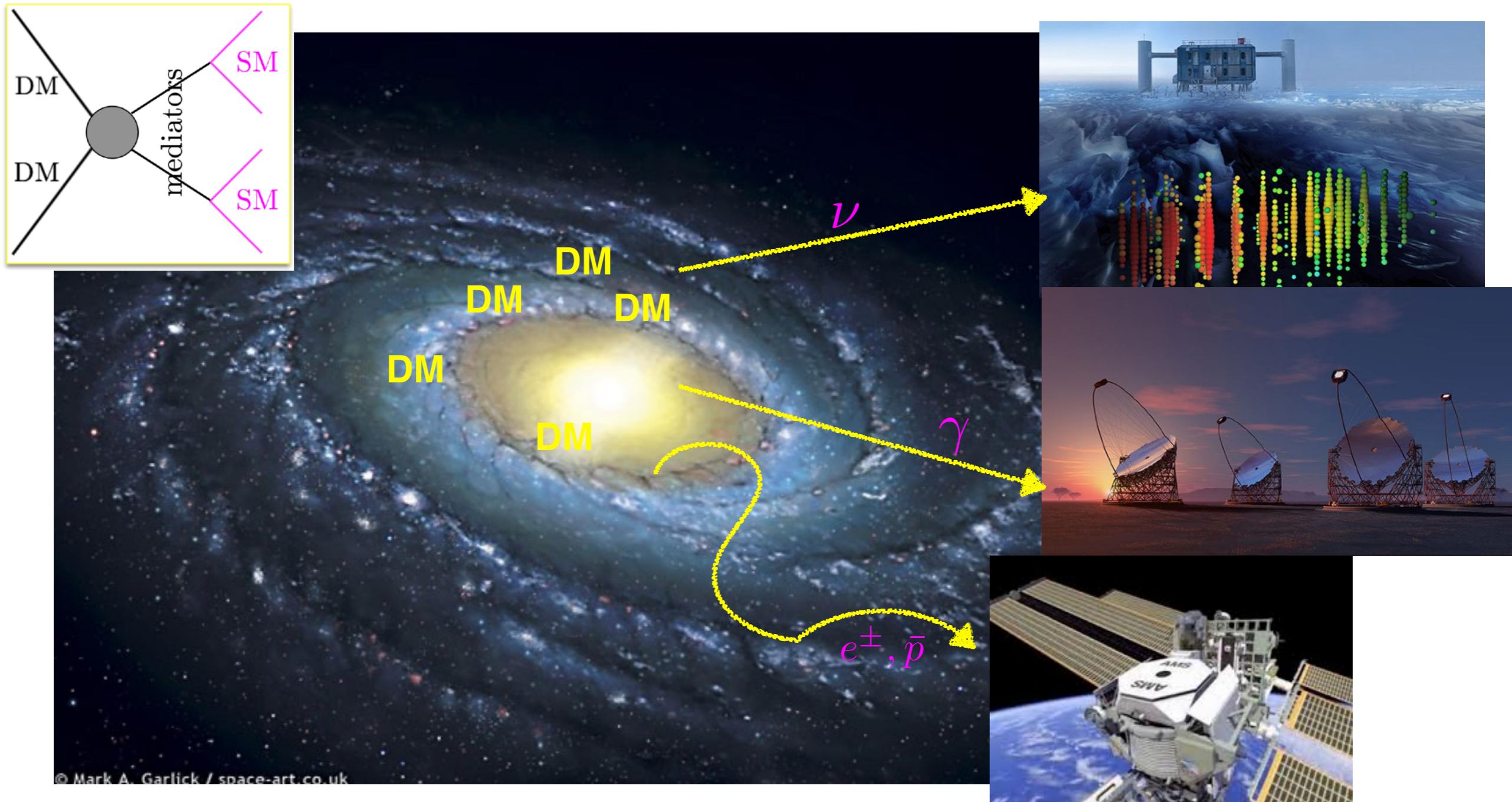
Inputs Welcome!



Back up

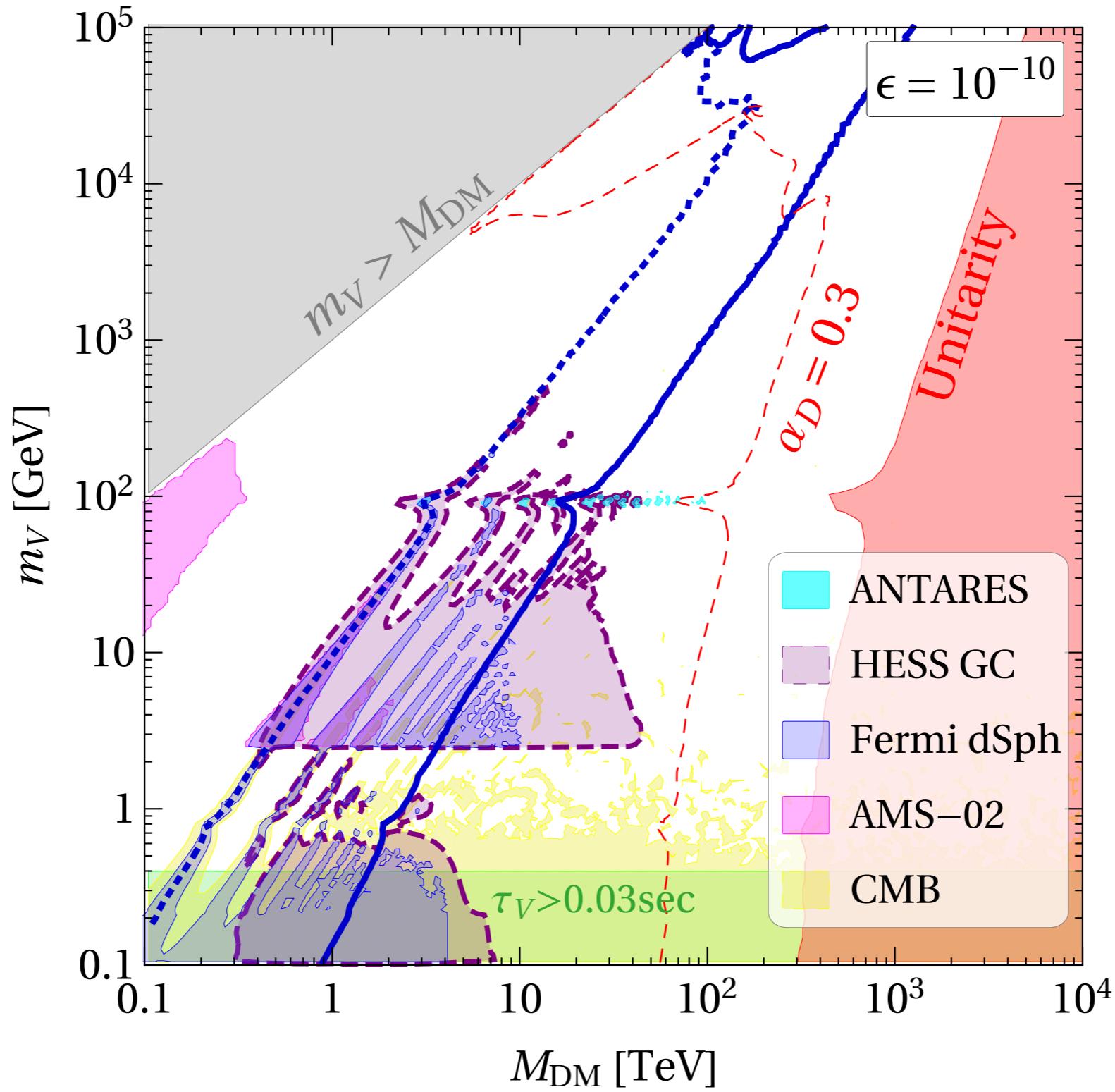
Experimental Tests

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



Tests of Diluted Dark Matter

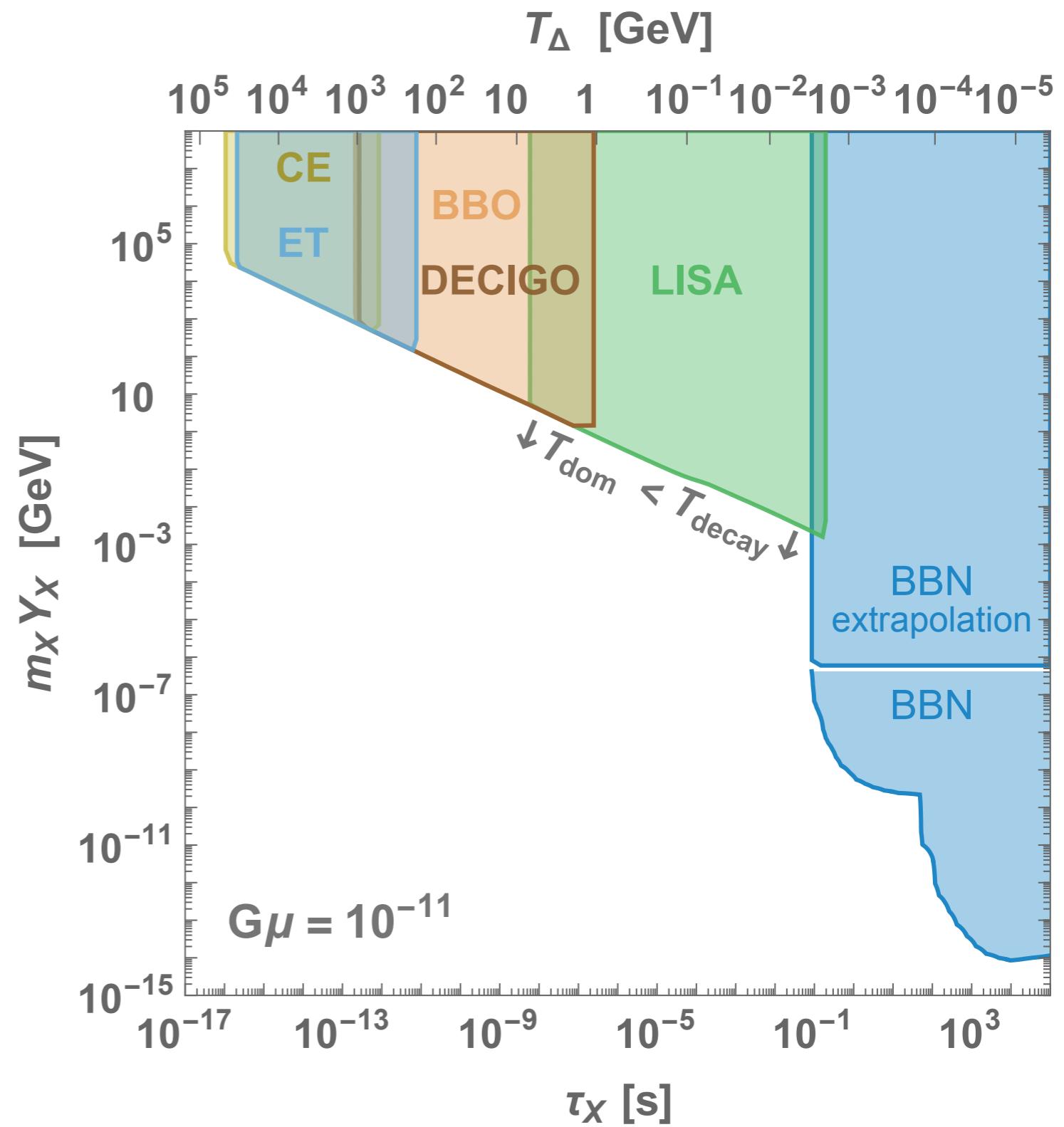
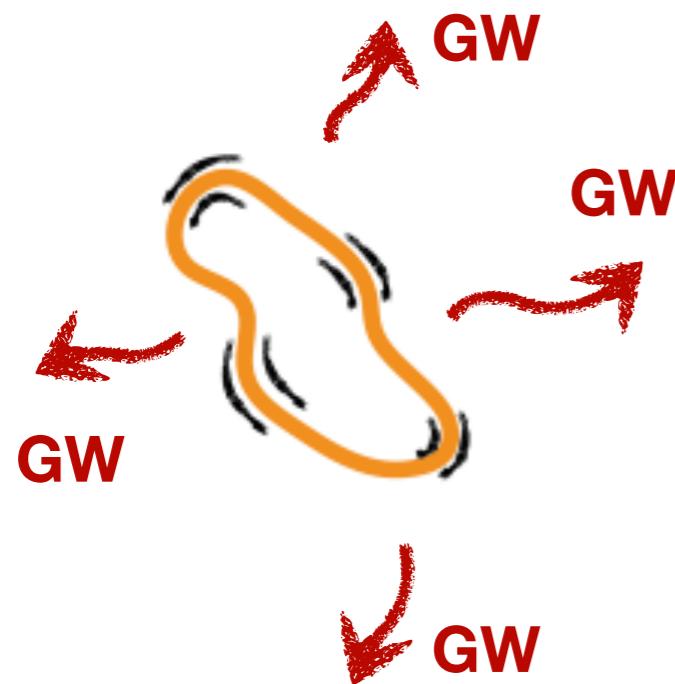
Cirelli+1811.03608
Blanco+1906.00010



Early Matter dilutes Gravitational Waves

e.g. from cosmic strings

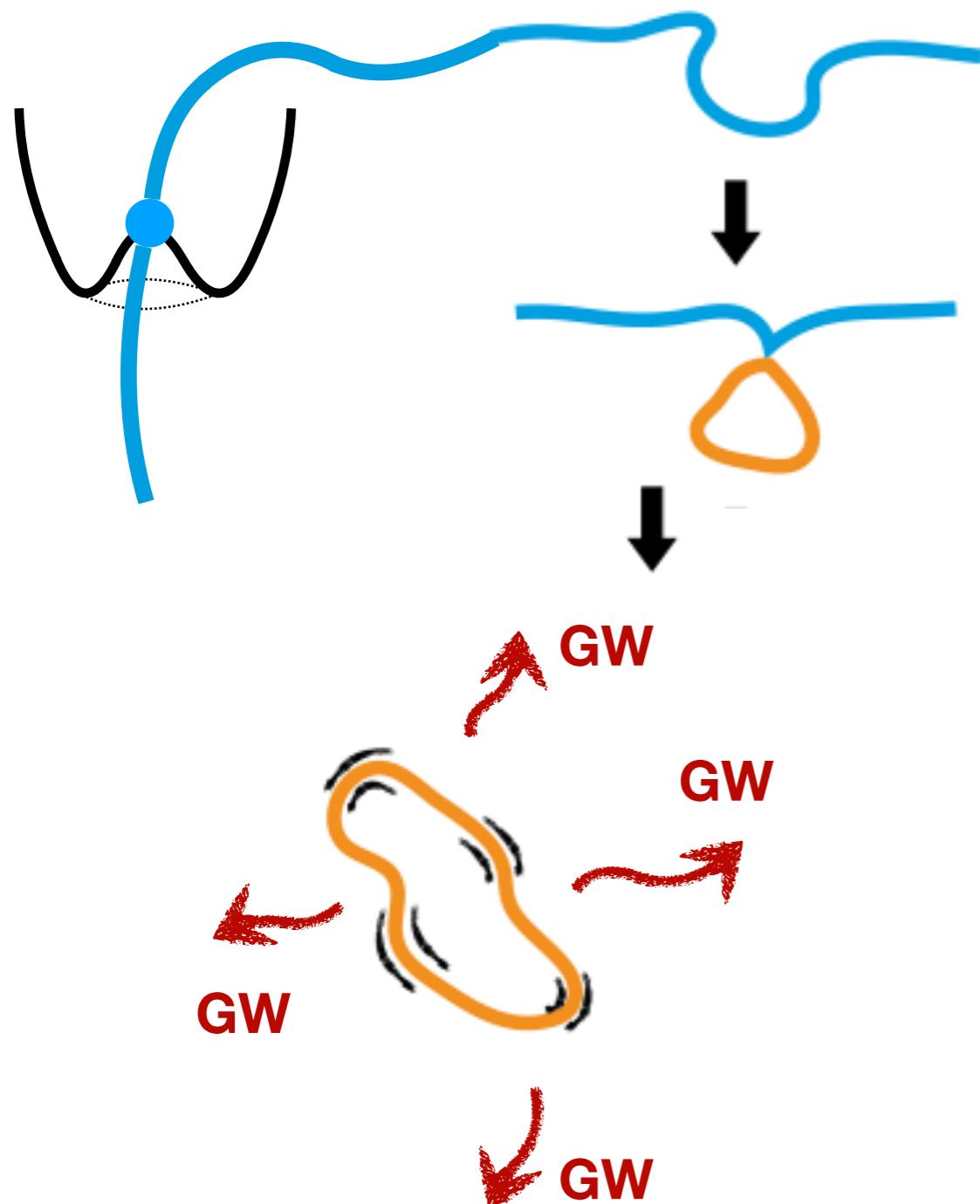
Gouttenoire+1912.03245



Gravitational Waves from Cosmic Strings

Gouttenoire+1912.03245

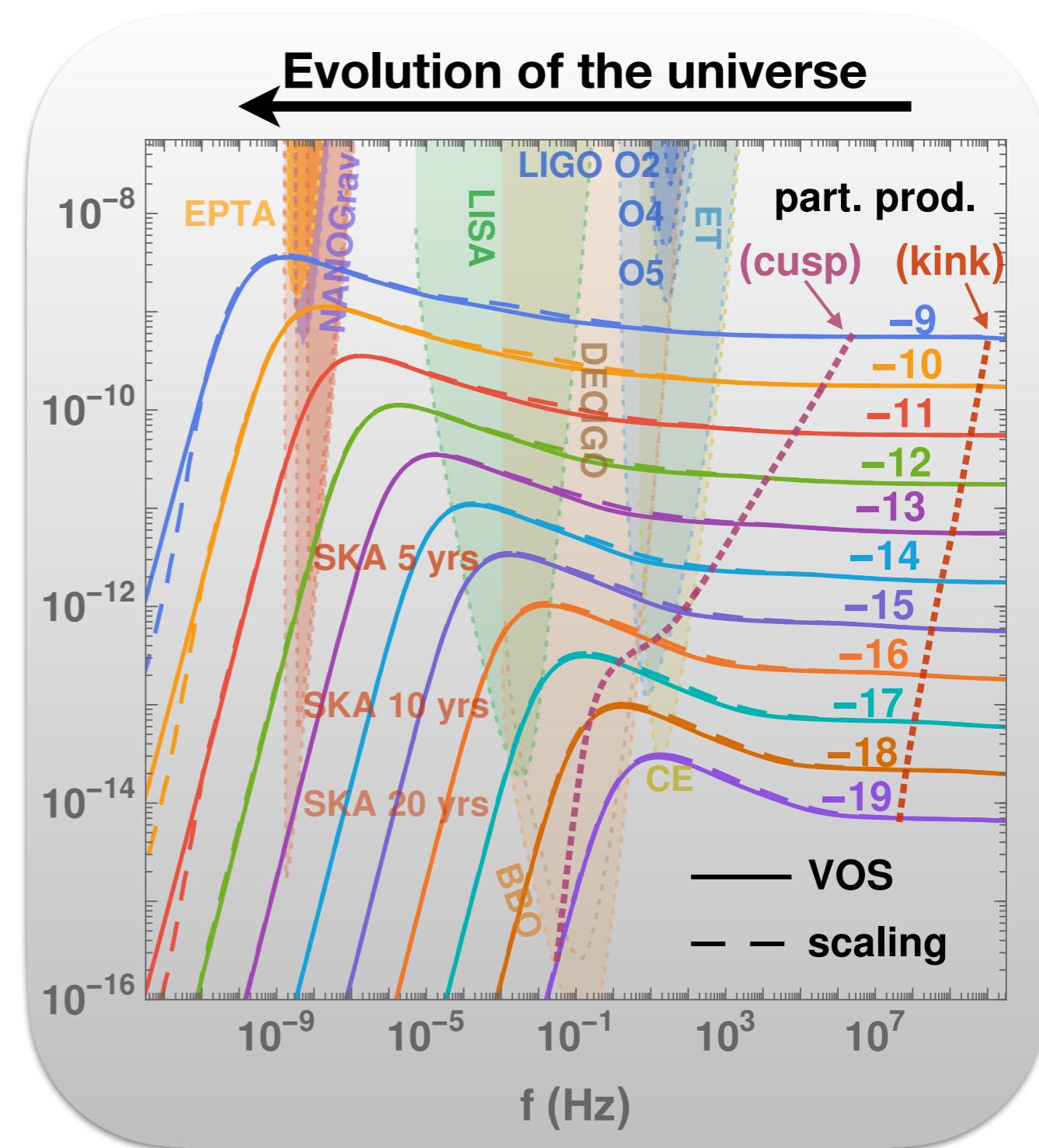
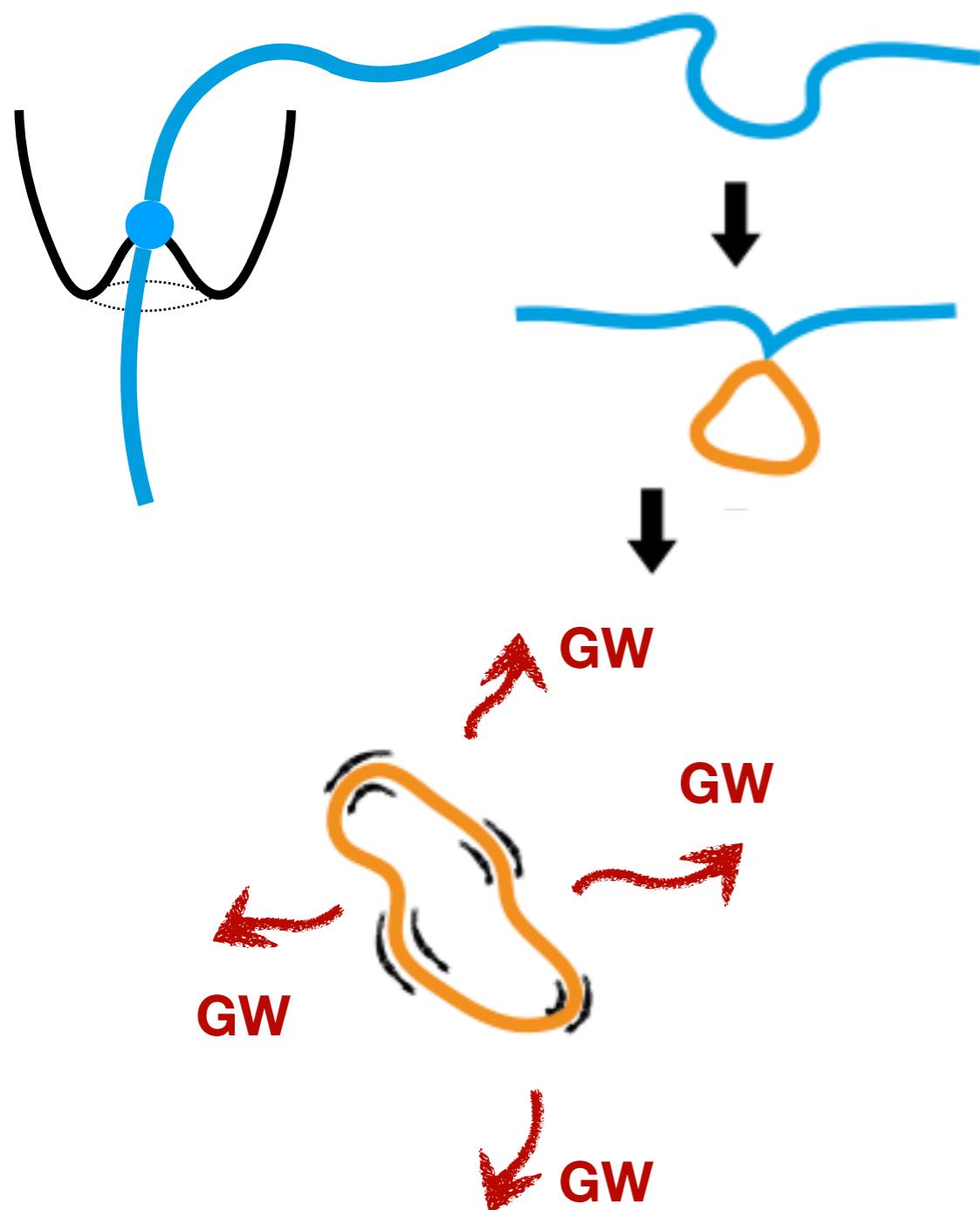
Spontaneous symmetry breaking of $U(1)$ in Early Uni.



Gravitational Waves from Cosmic Strings

Gouttenoire+1912.03245

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



Simple Scalar Domination

Mixing with Higgs Boson

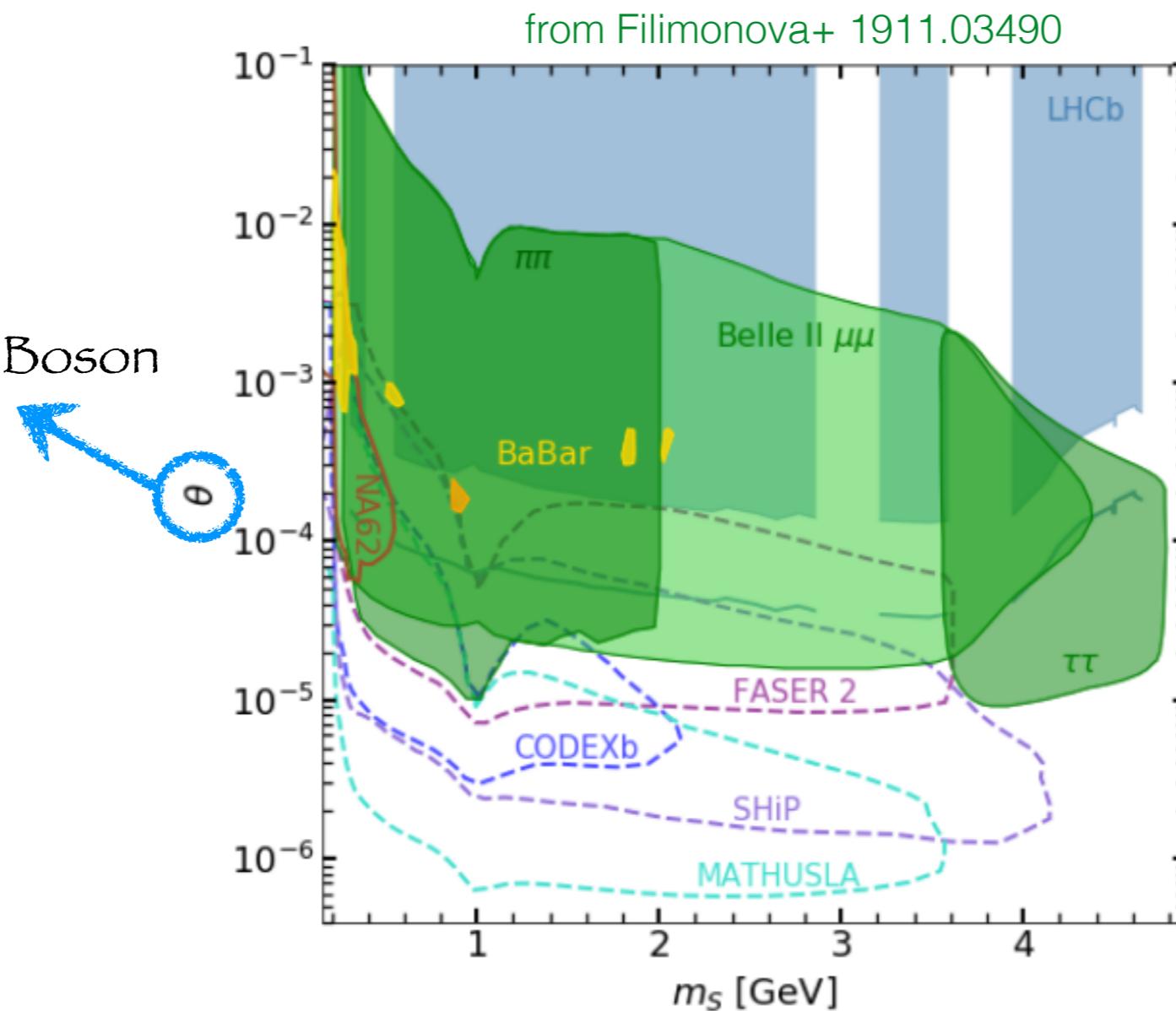
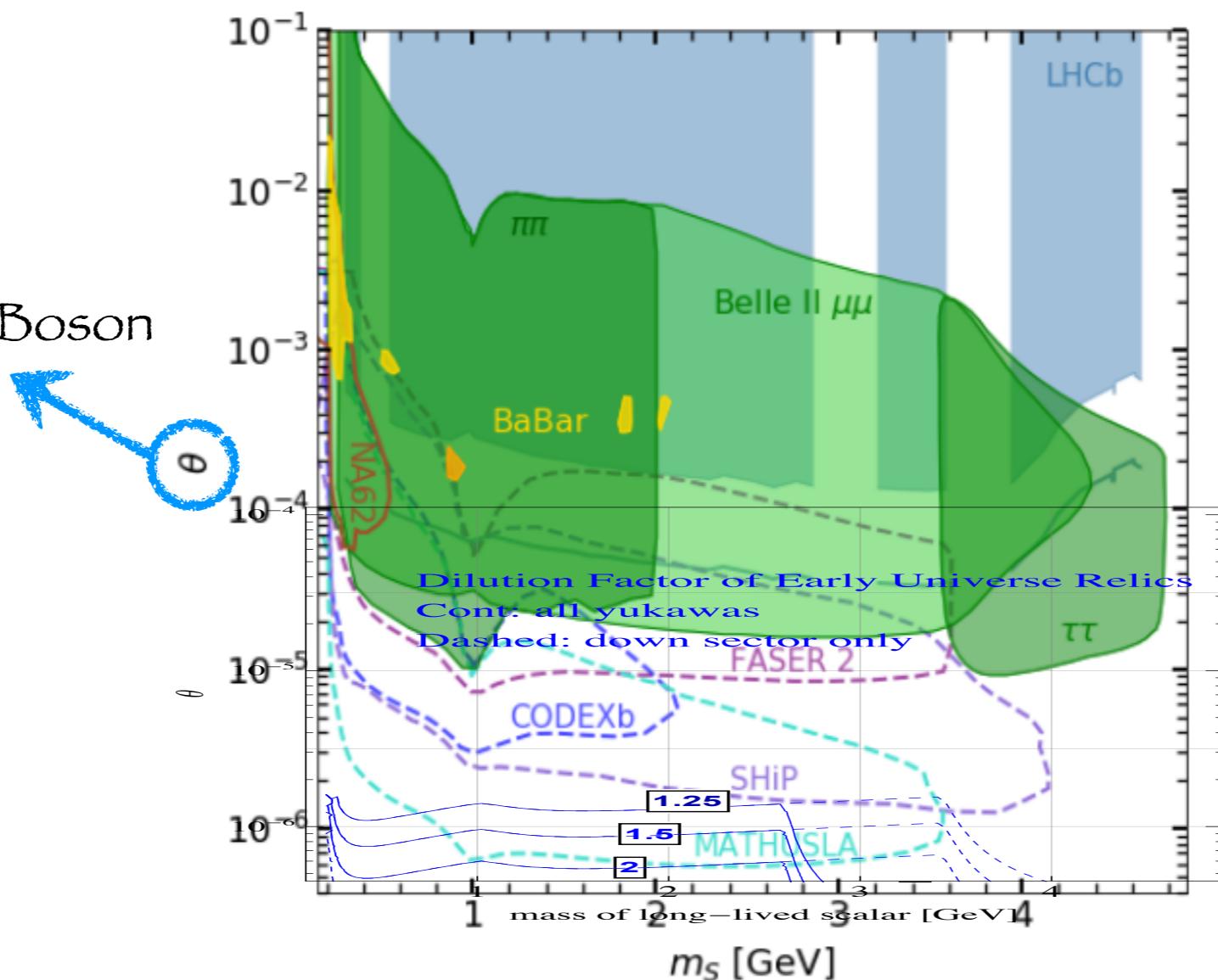


FIG. 2: Searches for dark scalars with displaced vertices. Shown are 95% CL bounds from $B^+ \rightarrow K^+ S(\rightarrow \mu\bar{\mu})$ searches at LHCb [51] (blue) and 90% CL bounds on $\mathcal{B}(B \rightarrow X_s S)\mathcal{B}(S \rightarrow f)$ with $f = \mu^+\mu^-$ (yellow) and $\pi^+\pi^-$ (orange)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

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

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

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

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

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

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

3) Production @ colliders via Higgs decays

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