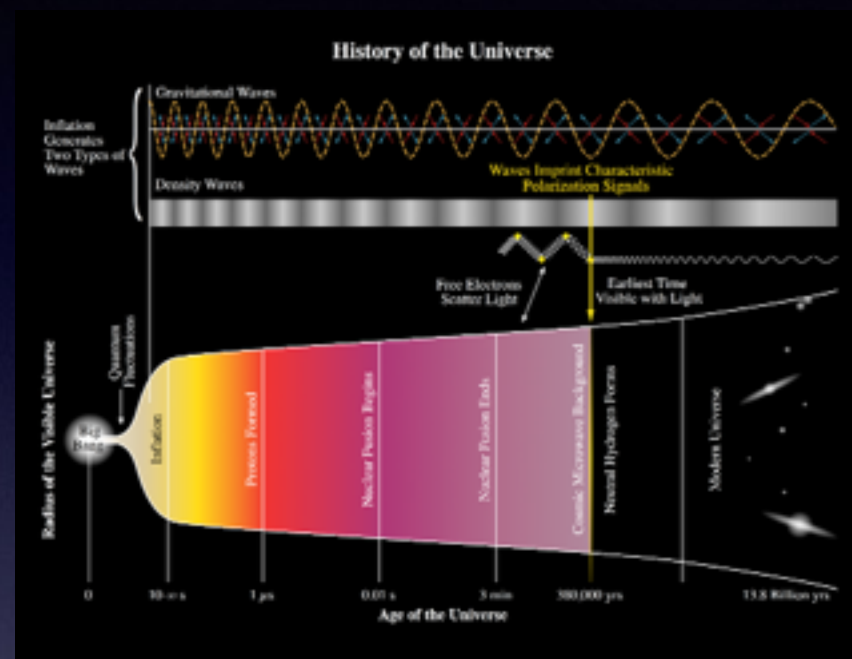
Histories of dark matter



Yann Mambrini

http://www.ymambrini.com/My_World/Physics.html

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Chapter one: the primordial Universe

INTRODUCTION

Searches of dark matter in direct/indirect detection strategies or in accelerators detectors depends on two fundamental parameters: the mass of the dark matter and its coupling to the visible/Standard Model world. These two parameters are also the ones that will determine the thermal (or non-thermal) history of the dark matter in the Universe. Both are connected.

In the first part of the lecture, I will concentrate on the dependance of the thermal history on these two parameters depending on the nature of its couplings whereas in the second part I will see what are the perspective of detection/signal/constraints from the experimental data already available.

Plan/menu

The Universe reheats (waking up)

[WIMPZILLA]

Some dark matter particles leave the table early (breakfast)

[FIMP/E-WIMP]

Some are more talkative and stay until the (lunchtime)

[WIMP]

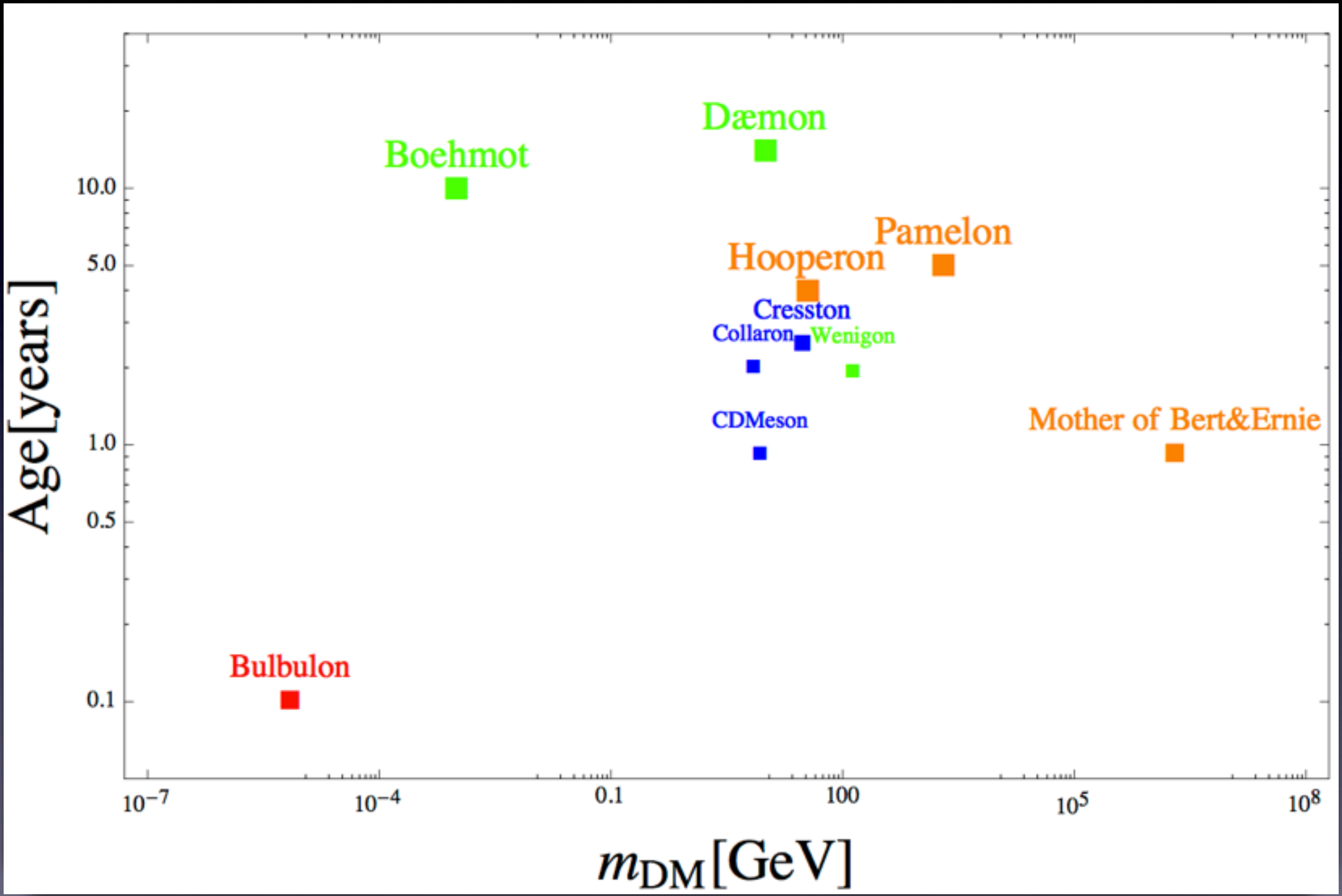
Some stay for the teatime snack

[Warm dark matter]

In any case, they should be present for the dinner

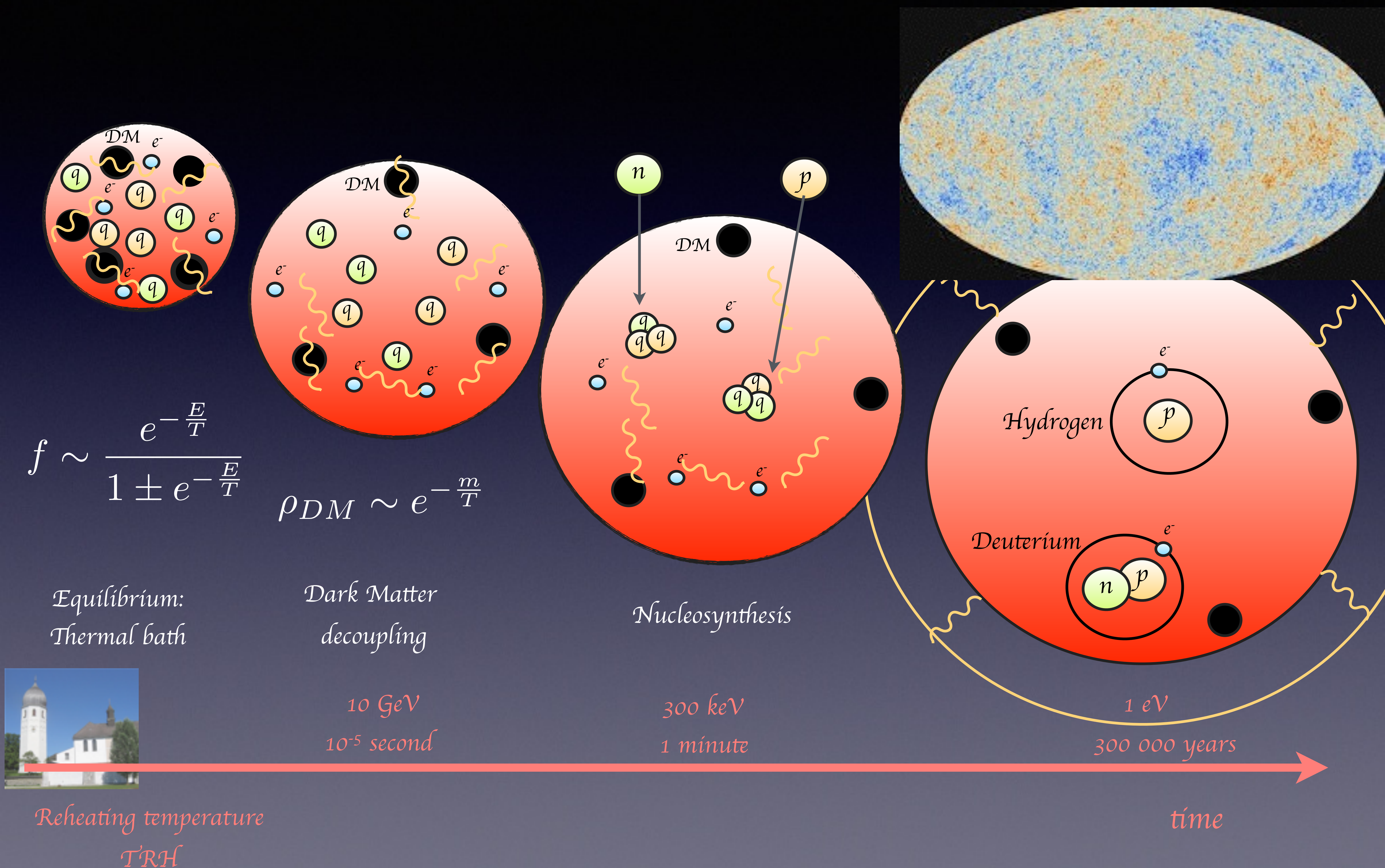
[Galactic detection]

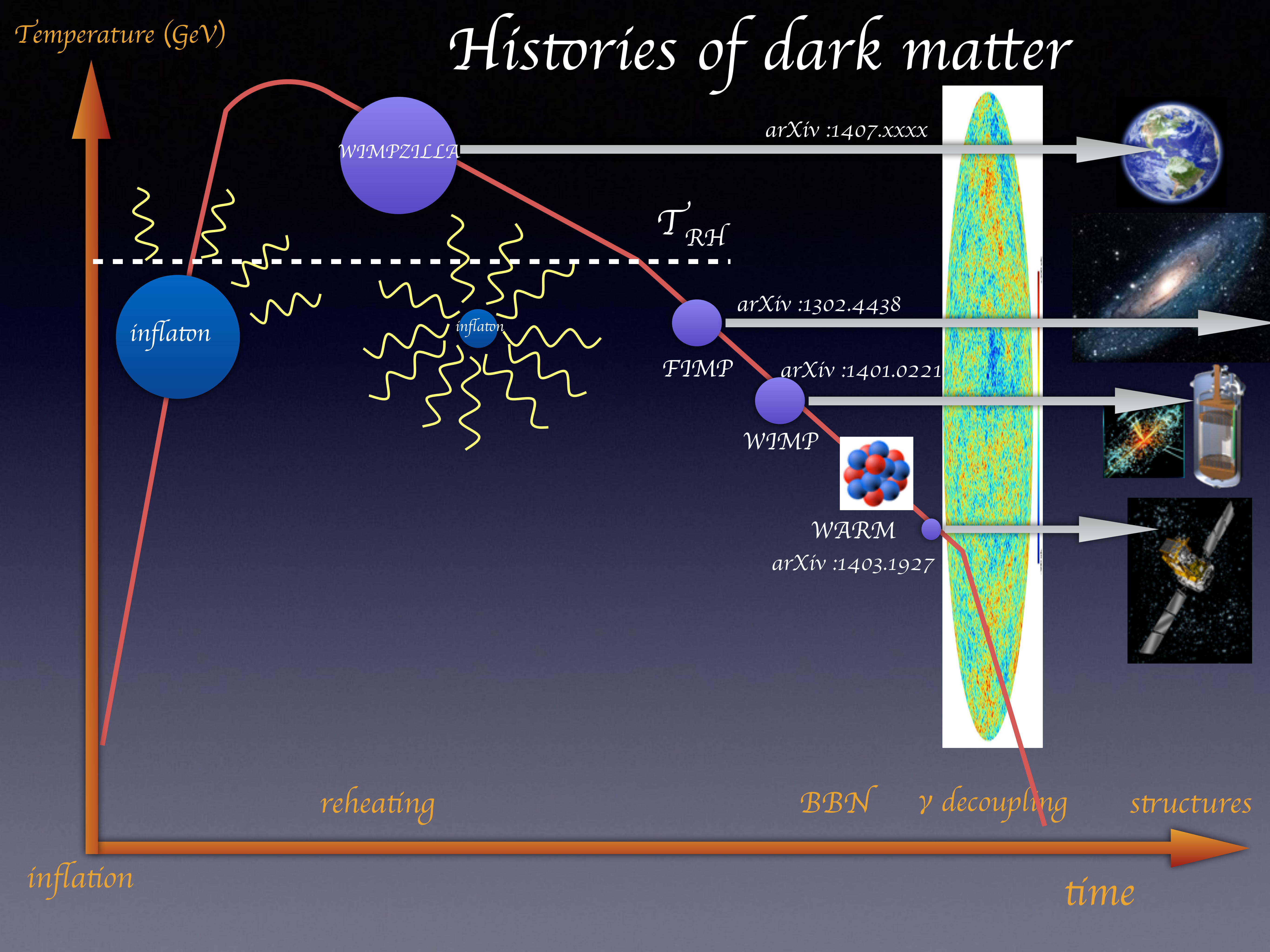
Which candidates for the job?



Plot extracted from http://resonaances.blogspot.com/

A little thermal history of the Universe



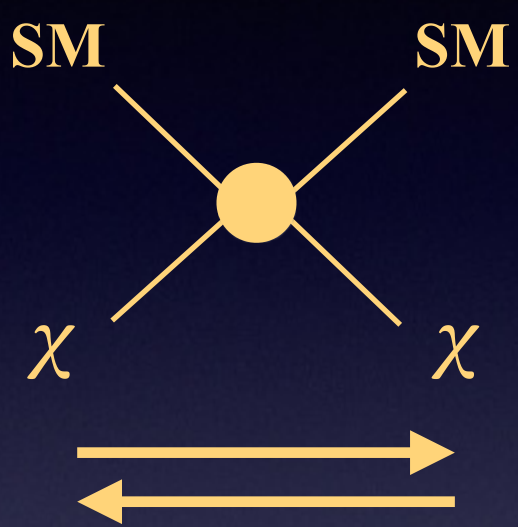


Histories of dark matter
Temperature (GeV)
WIMPZILLA
arXiv :1407.xxxx
T_{RH}
inflaton
inflaton
FIMP
arXiv :1302.4438
arXiv :1401.0221
WIMP
WARM
arXiv :1403.1927
reheating
BBN
γ decoupling
structures
inflation
time

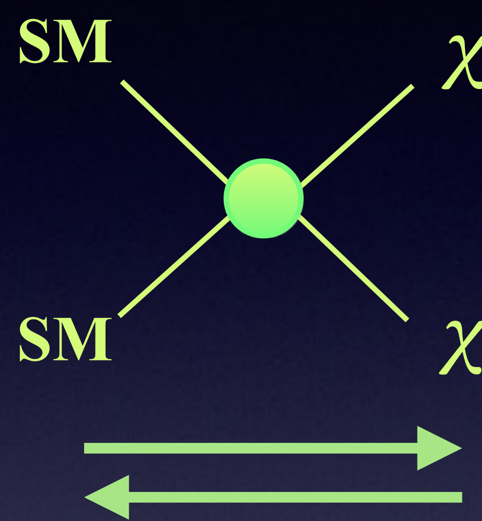
The meaning of thermal equilibrium

A system of particles (χ + SM) is in thermal equilibrium

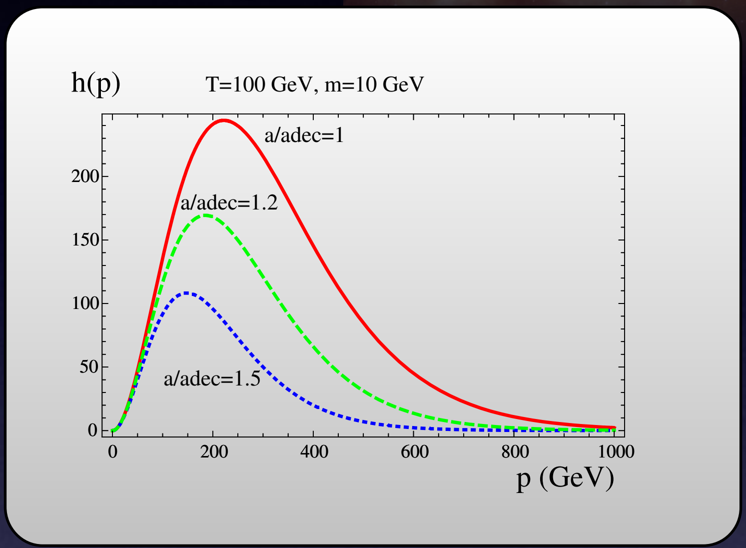
when both kinetic and chemical equilibrium is achieved :



kinetic equilibrium



chemical equilibrium



This is the only way to define a temperature of the Universe, which is in fact the temperature of the photons : $n(T) \propto T^3$.

Usually, (except some exception/transition) both are realized simultaneously.

$$\Gamma_{\chi\chi\to SM\ SM}(T) < H(T) = \frac{\dot{a}(T)}{a(T)}, \quad \text{a being the scale factor}$$

1/H, (H being the Hubble parameter) is also called the « doubling time »: Universe is twice bigger after the time 1/H. The previous expression just means that the chemical equilibrium dominates over the expansion rate.

The meaning of decoupling

The decoupling happens when the expansion rate dominates over the interaction rate:

$$\Gamma_{SM\ SM\rightarrow\chi\chi}(T_d) = n(T_d)\times\langle\sigma v\rangle_{T_d} = H(T_d)$$

In one second, the Universe has doubled is sized, but the thermal bath has produced less than 2 particles χ : the χ are diluted. T_d is called the decoupling temperature

$$T_d^3\times\frac{|\mathcal{M}_{SM\rightarrow\chi}(T_d)|^2}{s}\simeq T_d^3\times\frac{|\mathcal{M}_{SM\rightarrow\chi}(T_d)|^2}{T_d^2} = H(T_d) = \frac{T_d^2}{M_{\rm Pl}}$$

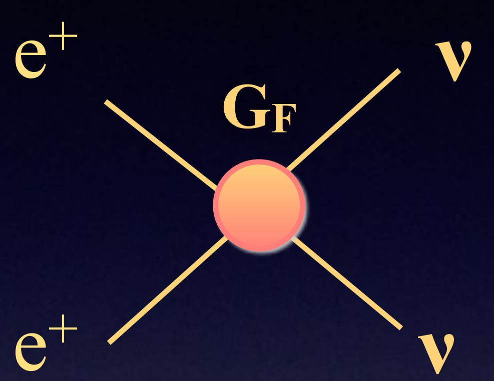
Decoupling of the inflaton : T_d=T_{RH} (reheating)

Decoupling of the dark matter: T_d=T_{FO} (freeze-out)

Decoupling of the atoms: T_d = T_{rec} (recombination/CMB)

Two ways of decoupling

$n \times \langle \sigma v \rangle < H$ means n is small <u>OR</u> σ v is small.



$G_F = 10^{-5}$ GeV^{-2}

The massless case (neutrino)

The decoupling condition

$$n \times \langle \sigma v \rangle \simeq T_\nu^3 \times G_F^2 T_\nu^2 = H(T_\nu) = \frac{T_\nu^2}{M_{\rm Pl}} \Rightarrow T_\nu \simeq \left(G_F^2 M_{\rm Pl}\right)^{-1/3} \simeq 3 \text{ MeV}$$

At 3 MeV, the neutrinos decouple from the thermal bath, but being still relativistic

The massive case (dark matter)

The decoupling condition

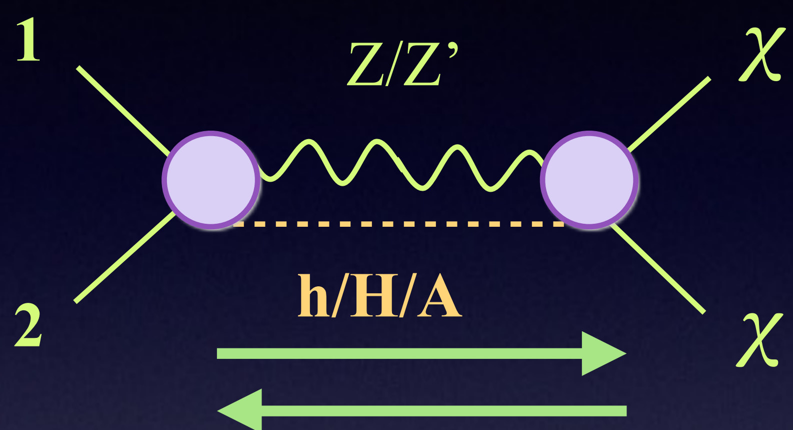
$$n \times \langle \sigma v \rangle \simeq (T_\chi m_\chi)^{3/2} e^{-m_\chi/T_\chi} \times \frac{1}{T_\chi^2} = H(T_\chi) = \frac{T_\chi^2}{M_{\rm Pl}} \Rightarrow \frac{m_\chi}{T_\chi} \simeq 25$$

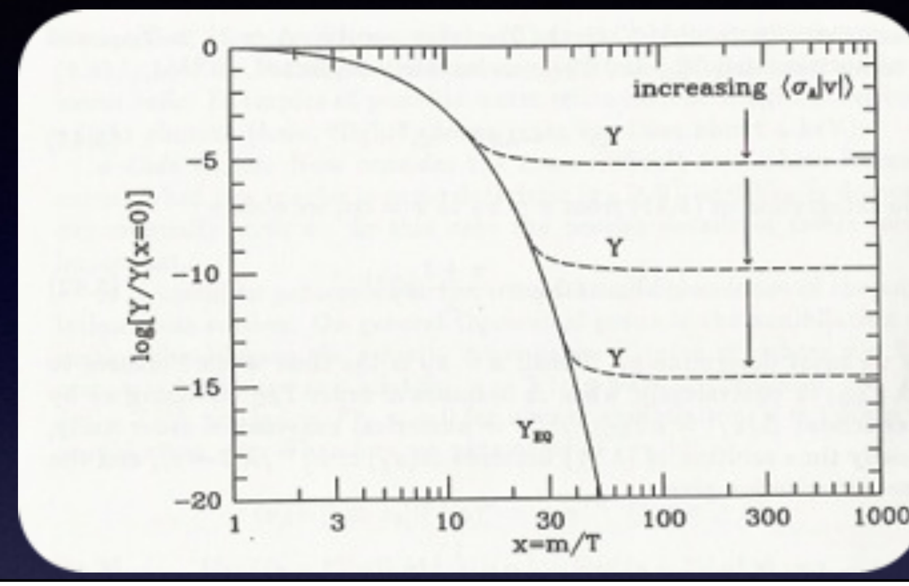
T_χ corresponds physically to the temperature under which the thermal bath does not have sufficient energy to produce a dark matter particle.

The Boltzman equation

The exact way to solve precisely the problem

(even if the proceedings approximations give in 90% of the case relatively good results)





$$\frac{dn}{dt} = -3Hn - \langle\sigma v\rangle\left(n^2 - n_{eq}^2\right) \quad \Rightarrow \quad \frac{dn}{dT} = 3\frac{n}{T} - \frac{\langle\sigma v\rangle}{HT}\left(n_{eq}^2 - n^2\right)$$

$$\left(\frac{d}{dt} = \frac{dT}{dt}\frac{d}{dT} = -T\frac{da/dt}{a}\frac{d}{dT} = -HT\frac{d}{dT} \quad \rightarrow \quad t \propto \frac{M_{\rm Pl}}{T^2}\right)$$

defining the yield $Y = \frac{n}{S}$, with the entropy $S = \frac{2\pi^2}{45} g_s T^3$

$$\boxed{\frac{dY_\chi}{dT} = T^2\frac{\langle\sigma v\rangle_{1,2\to\chi\chi}}{H(T)}\left(Y_\chi^2 - Y_{eq}^2\right)}$$ with $\langle\sigma v\rangle = \int_{T_{RH}}^{T} \Pi_i \frac{d^3p_i}{(2\pi)^{3i}}|\mathcal{M}_{1,2\to\chi\chi}|^2 e^{-E_1/T}e^{-E_2/T}$ and $H(T) = \frac{T^2}{M_{\rm Pl}}$

This is the so-called Boltzmann equation

$$\Omega h^2 \simeq \frac{3\times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma v\rangle}, \quad \Omega h^2_{\rm PLANCK} \simeq 0.1 \quad \Rightarrow \quad \langle\sigma v\rangle_{\rm decoupling} \simeq 3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1} \sim 10^{-9}\ \mathrm{GeV}^{-2}$$

$<\sigma v> \sim G_F^2$: « WIMP miracle »

A (too?) simple application

The Lee-Weinberg bound (1977)

PHYSICAL REVIEW LETTERS

VOLUME 39 — 25 JULY 1977 — NUMBER 4

Cosmological Lower Bound on Heavy-Neutrino Masses

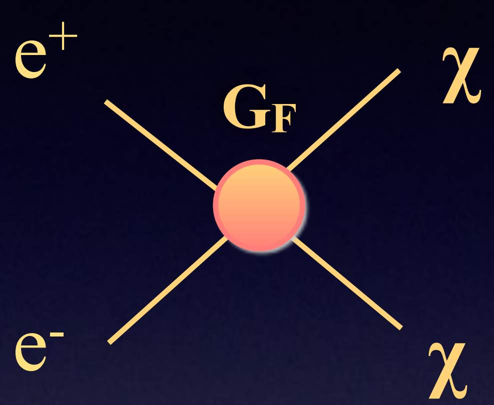
Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] *Batavia, Illinois 60510*

and

Steven Weinberg[c]
Stanford University, Physics Department, Stanford, California 94305

(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

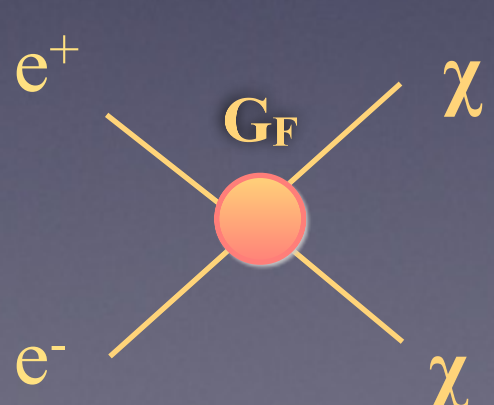


$G_F = 10^{-5}$ GeV^{-2}

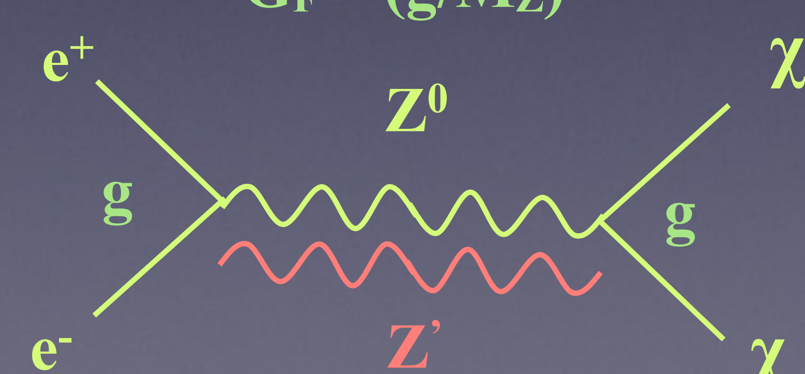
$$\langle \sigma v \rangle = G_F^2 m_\chi^2 > 10^{-9}\ \mathrm{GeV}^{-2} \quad \Rightarrow \quad m_\chi > 2\ \mathrm{GeV}$$

Bound no valid in a microscopic approach:

$G_F \sim (g/M_Z)^2$



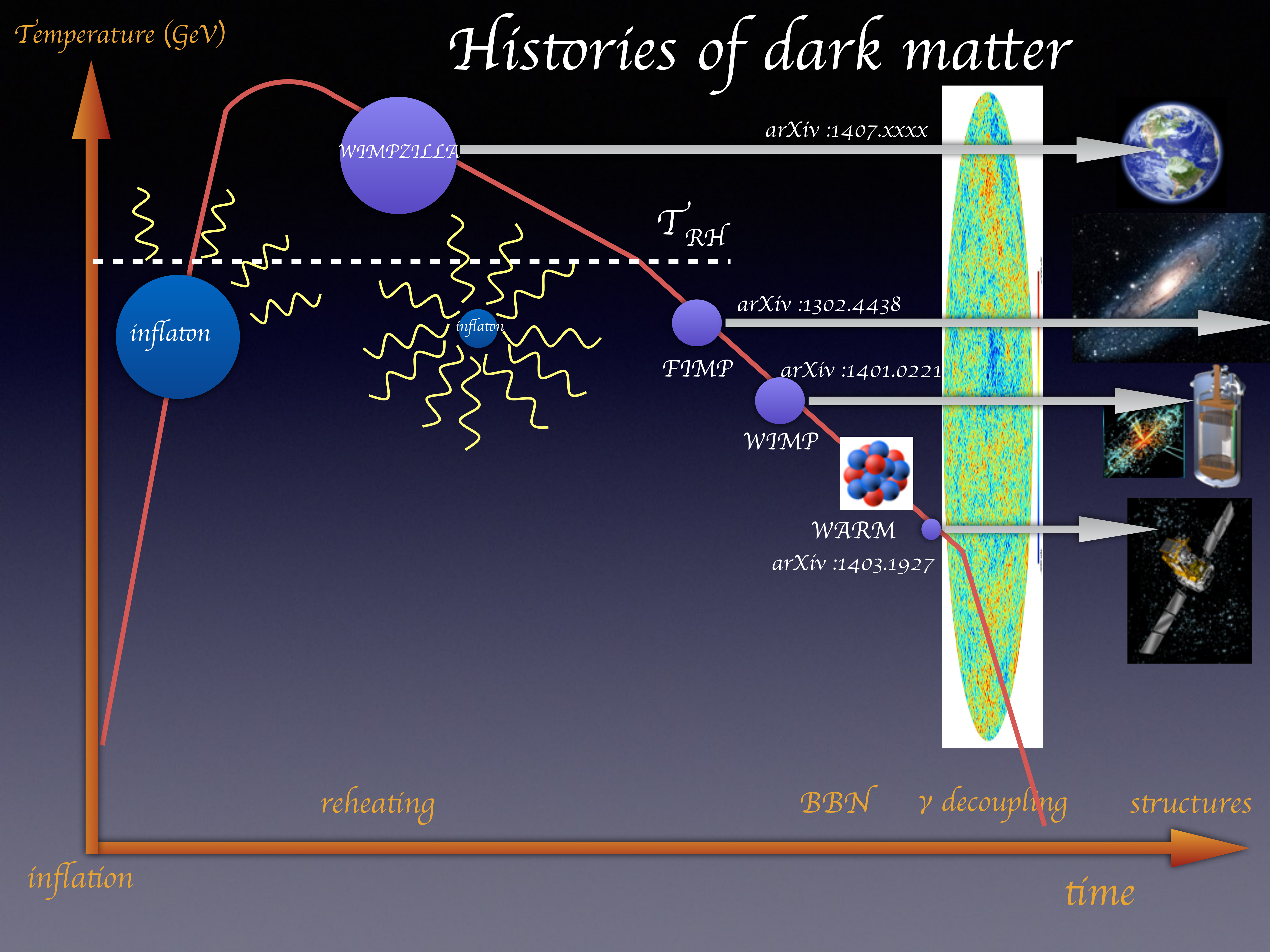
microscopic → **approach**



« 5^{th} forth (P. Fayet, 1978)»

Lee-Weinberg bound not valid anymore (possibility for light dark matter)

Histories of dark matter



Part I

The WIMPZILLA case

Wake up, the Universe reheats!

Based on work in progress

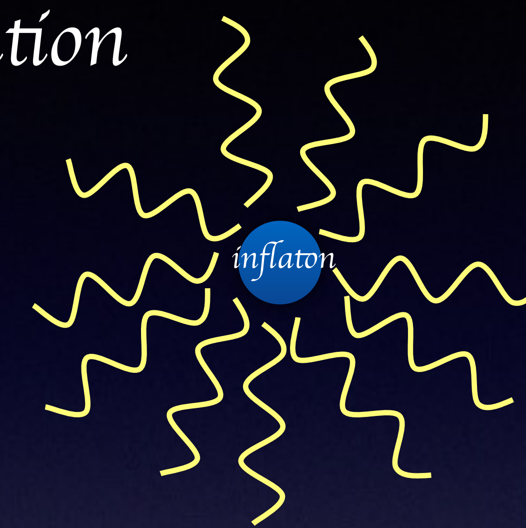
Looking for the maximum temperature of the Universe

$$\dot{\rho}_I + 3H\rho_I + \Gamma_I \rho_I = 0$$

Boltzmann equation for the decaying Inflaton

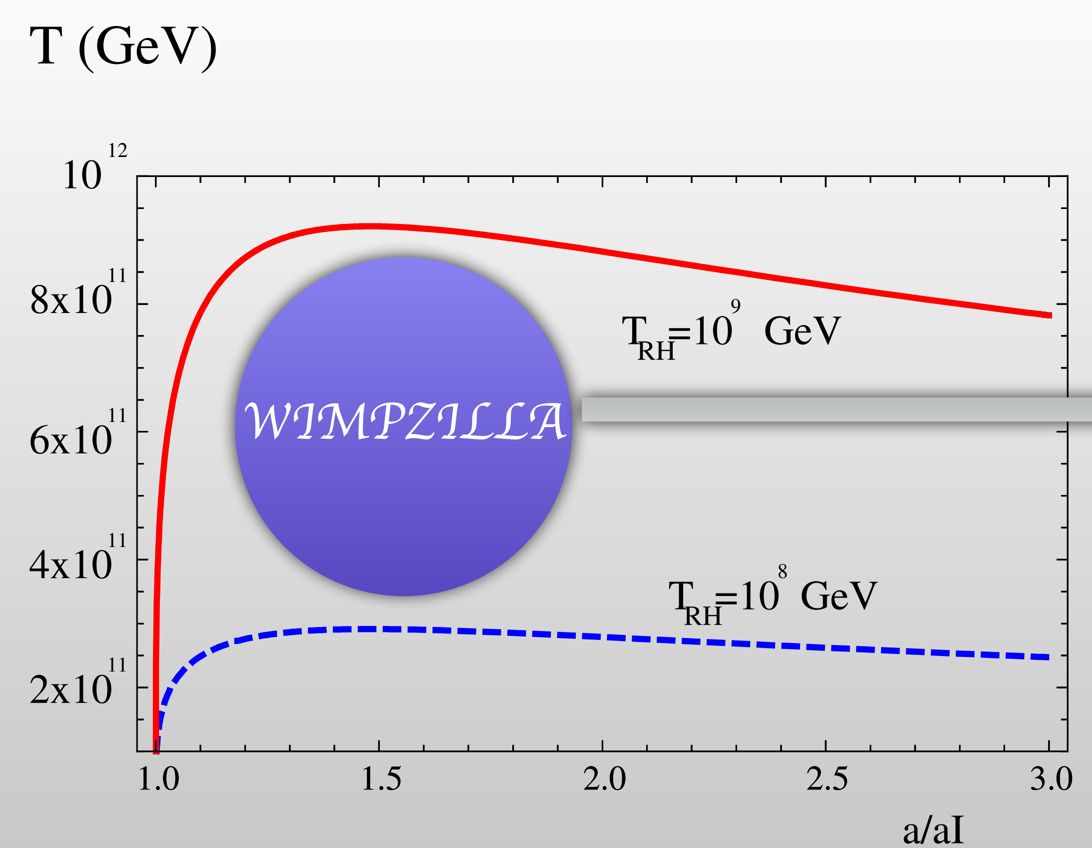
$$\dot{\rho}_R + 4H\rho_R - \Gamma_I \rho_I = 0$$

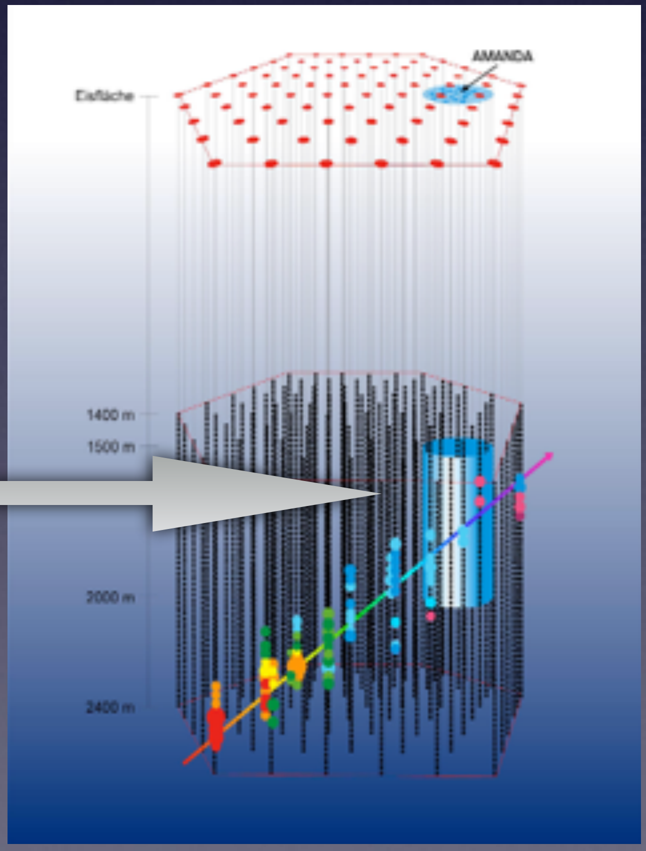
Boltzmann equation for the Radiation



$$T = \left(\frac{9}{5g_*\pi^3}\right)^{1/8} \sqrt{T_{RH}}\,(H_I M_p)^{1/4} \left[\left(\frac{a}{a_I}\right)^{-3/2} - \left(\frac{a}{a_I}\right)^{-4}\right]^{1/4}$$

$$(\rho \ \alpha \ T^4)$$



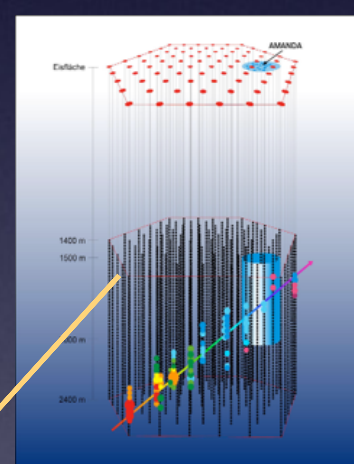


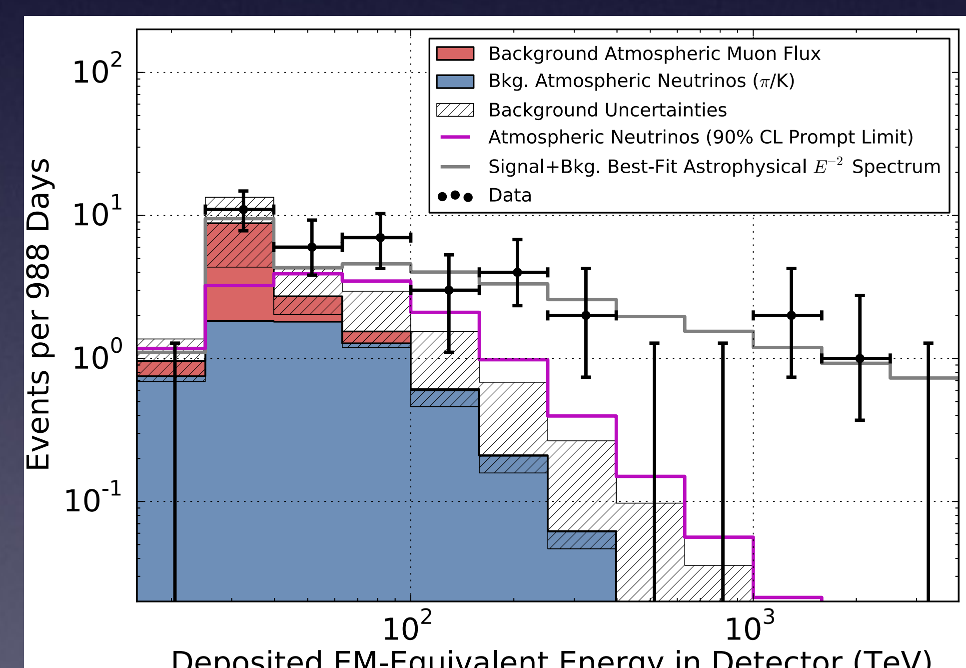
ICECUBE (South Pole)

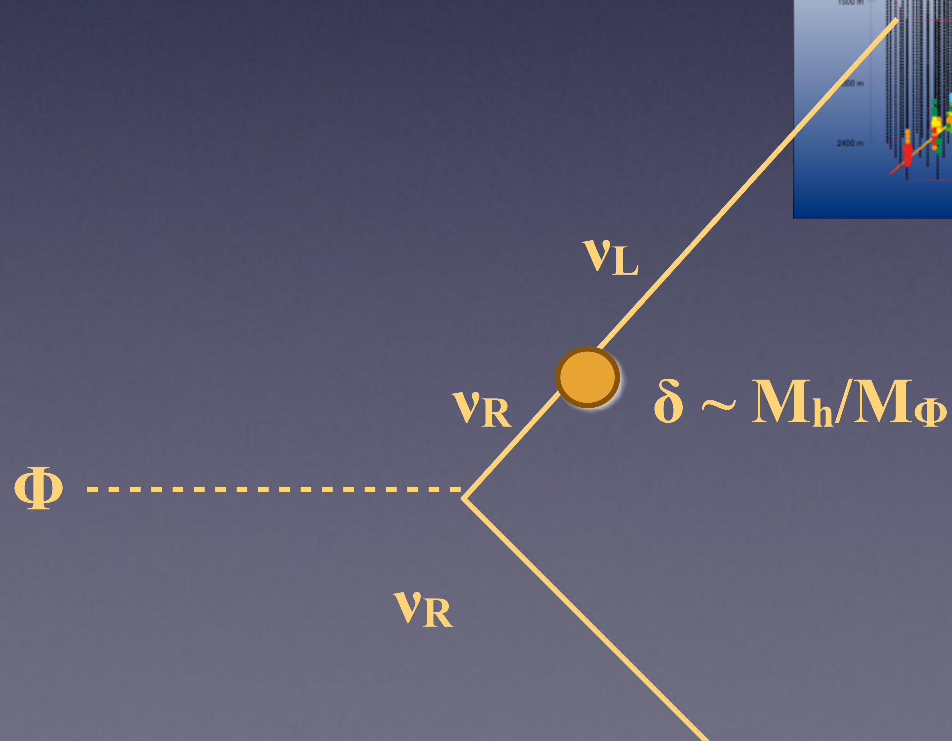
A concrete example: the PeV events (3) measured by ICECUBE

$$\mathcal{L} = -\lambda_{RR}\Phi\ \nu_R\nu_R - \lambda_{LR}\ \bar{\nu}_L H \nu_R$$

$$M_\Phi = \frac{1}{\sqrt{2}}\lambda_{RR}\langle\Phi\rangle$$







$$\tau = 10^{28}\ \text{seconds}$$

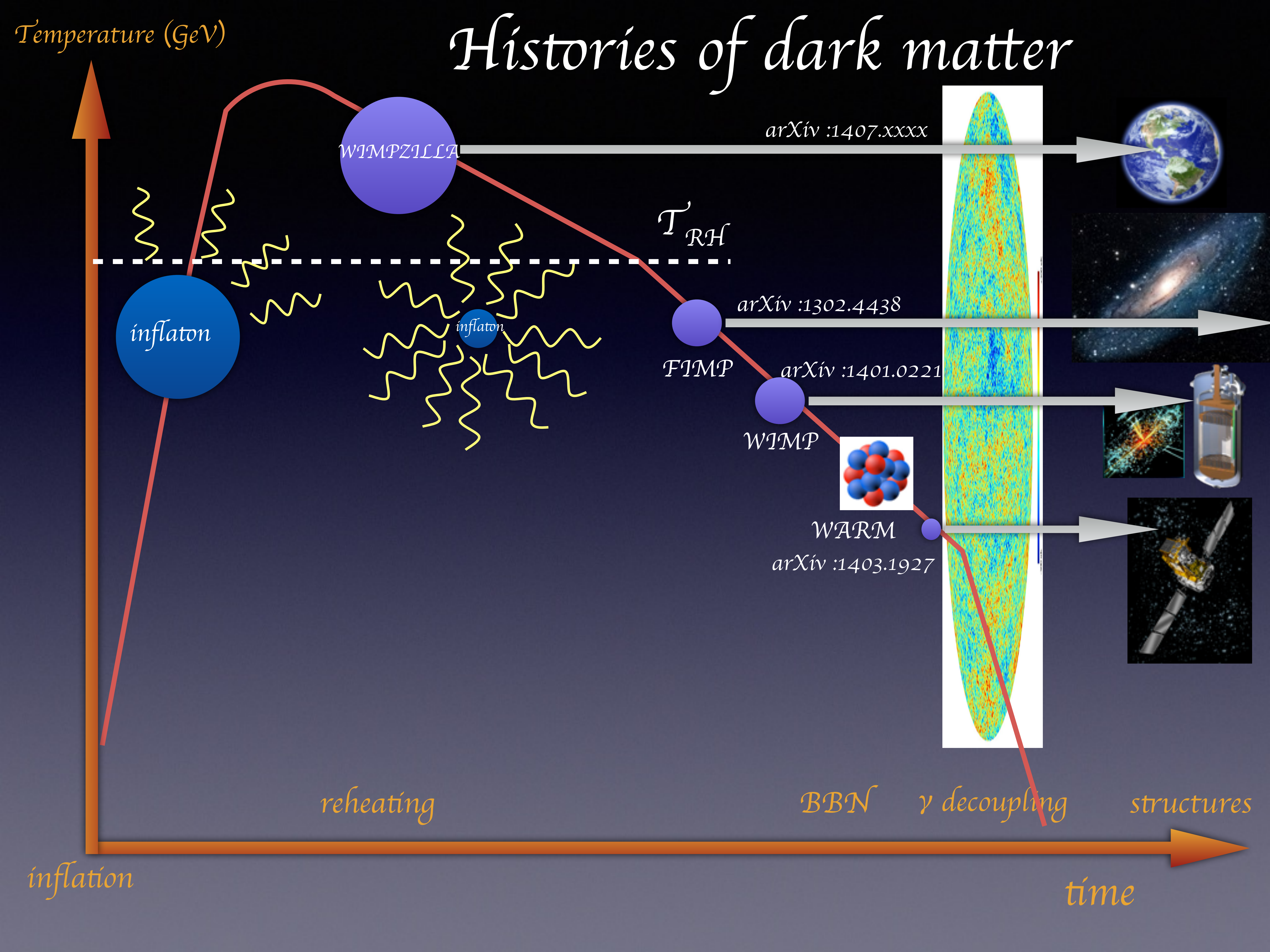
work in progress..

Part II

The FIMP case

Shy dark matter..

Based on work with K. Olive, J. Quevillon and B. Zaldivar (2013) / PRL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Temperature (GeV)
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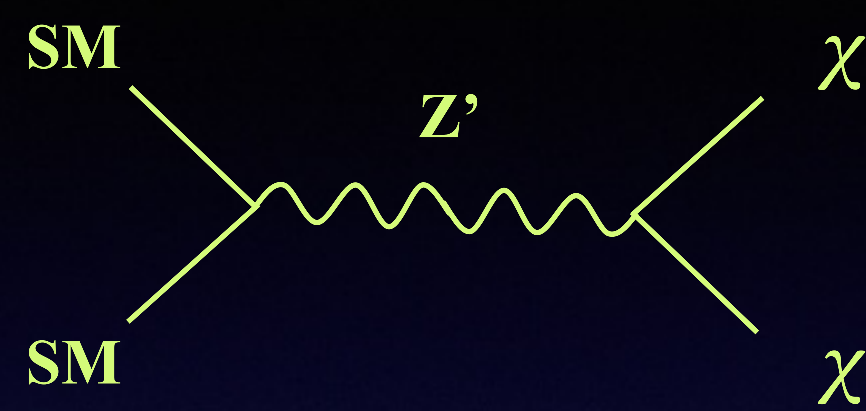
arXiv :1302.4438
FIMP
arXiv :1401.0221
WIMP
WARM
arXiv :1403.1927
reheating
BBN
γ decoupling
structures
inflation
time

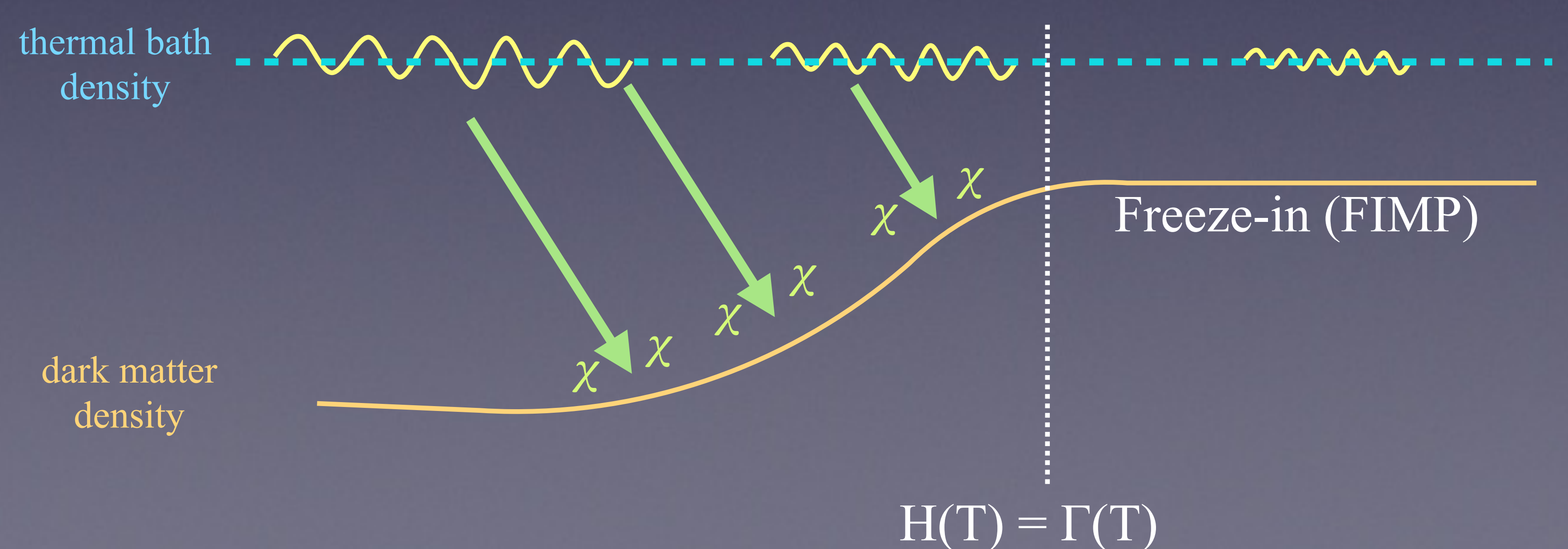
Very feebly interacting dark matter (freeze-in mechanism, FIMP)

Scattering process is too weak to reach kinetic equilibrium with the thermal bath



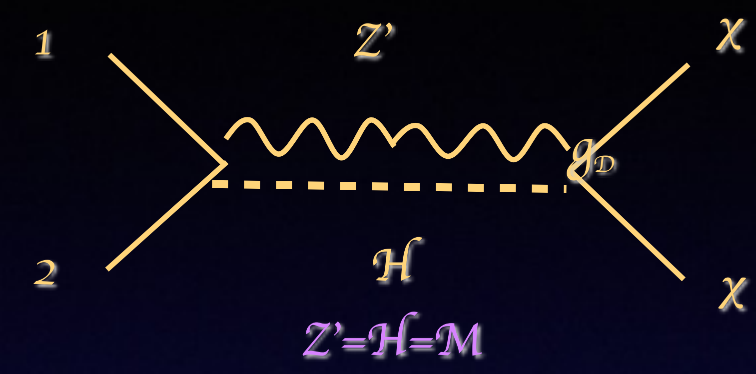
Annihilation is too weak to reach the thermal equilibrium

The dark matter is produced from the thermal bath but at a very slow rate, until the expansion rate dominates the annihilation (H > Γ)



A deeper insight on the Boltzmann equation

$$\frac{dY}{dT} \simeq -\frac{M_{\rm Pl}|\mathcal{M}_{1,2\to\chi\chi}|^2}{s} \times Y_{eq}^2$$



$$\Omega h^2 = 0.1 \quad \Rightarrow \quad Y^{\chi}_{now} \simeq 10^{-12}, \quad Y^{1,2}_{eq} \simeq 10^{-2}, \quad Y^{\chi}_{T_{RH}} = 0$$

- $g_D \sim T/MPl$

Planck/gravitational induced coupling

$$\langle \sigma v \rangle \propto \frac{1}{M_{Pl}^2}$$

$$\Rightarrow \frac{dY}{dT} \propto \frac{1}{M_{Pl}}$$

$$\Rightarrow Y(T) \propto \frac{T_{RH}-T}{M_{Pl}}$$

$$\simeq \frac{T_{RH}}{M_{Pl}}$$

Gravitino DM problem : $T_{RH} \sim 10^7$ GeV

- $M_M < T_{RH}$

$$|\mathcal{M}|^2 \propto g_D^2$$

$$\Rightarrow \frac{dY}{dT} \propto g_D^2 \frac{M_{Pl}}{T^2}$$

$$\Rightarrow Y(T) \propto g_D^2 \frac{M_{Pl}}{T}$$

$g_D \simeq g_{EW}$: WIMP

$g_D \simeq 10^{-10}$: FIMP

- $M_M > T_{RH}$

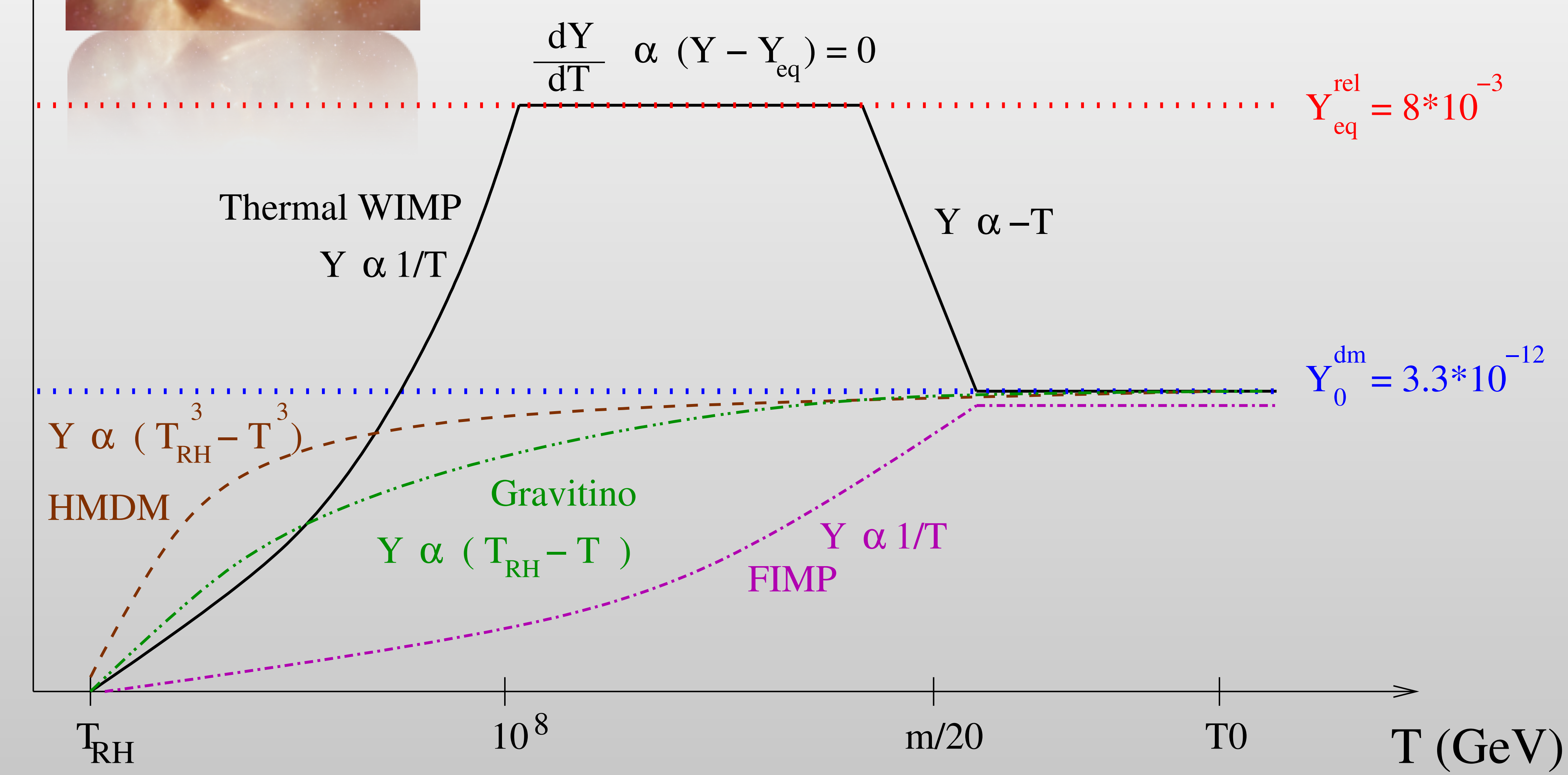
$$|\mathcal{M}|^2 \propto g_D^2 \left(\frac{T^2}{M_M^2}\right)^2$$

$$\Rightarrow \frac{dY}{dT} \propto g_D^2 \frac{M_{Pl} T^2}{M_M^4}$$

$$\Rightarrow Y(T) \propto g_D^2 \frac{M_{Pl}}{M_M^4}\, T_{RH}^3$$

Non-equilibrium thermal dark matter, Intermediate state

Summary for FIMP dark matter

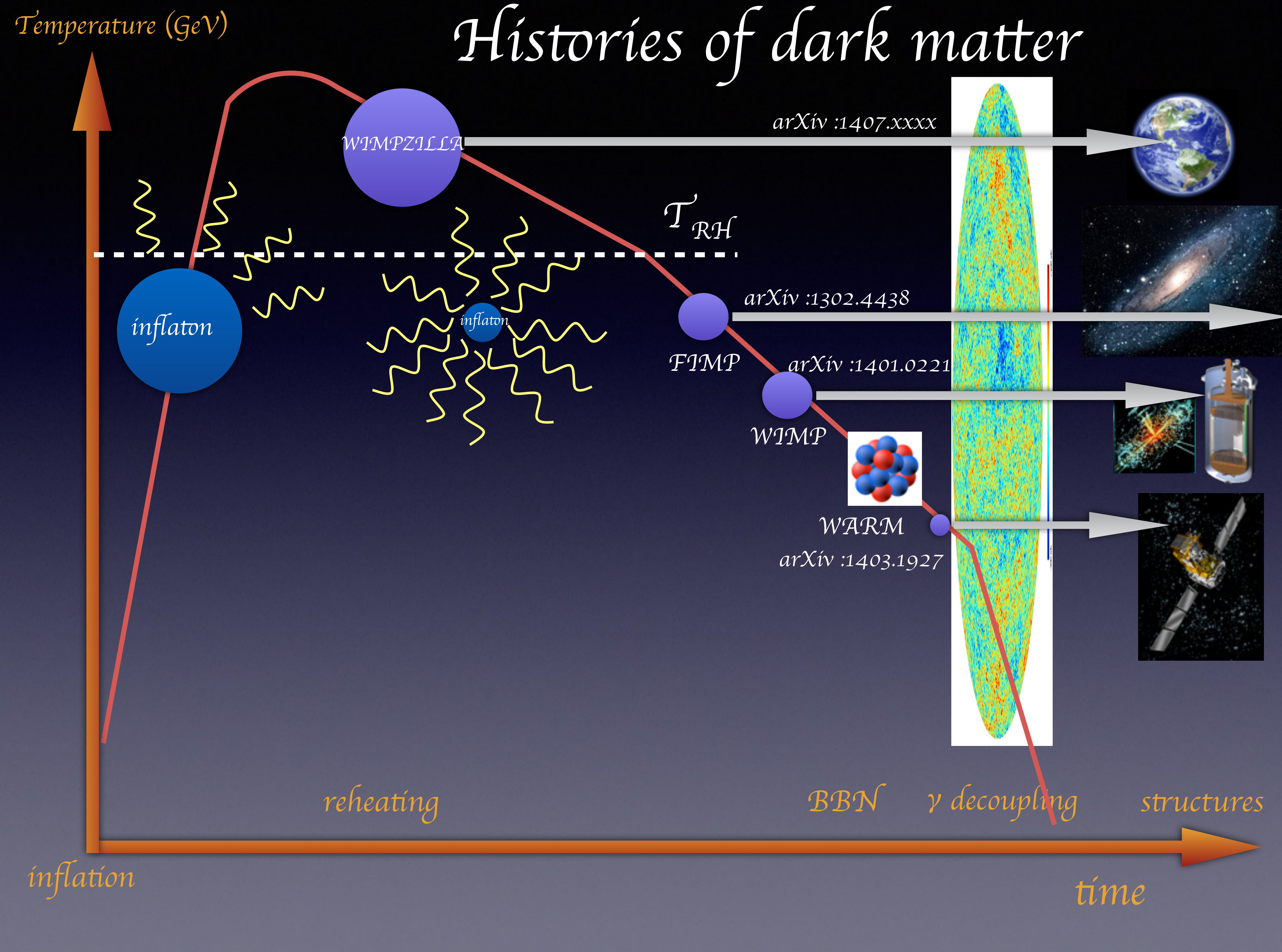


Part III

The WIMP case

Combining detection modes:
the limit of effective approach

Histories of dark matter



From the effective approach to the microscopic one

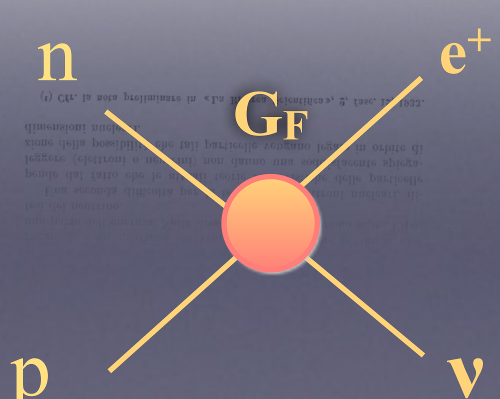
TENTATIVO DI UNA TEORIA DEI RAGGI β

Ipotesi fondamentali della teoria.

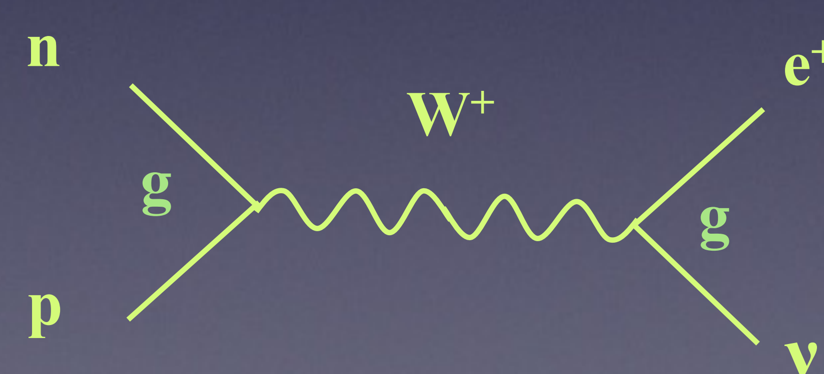
Enrico Fermi

"Tentativo di una teoria dei raggi β", Ricerca Scientifica, 1933

Renormalizable theory! and specific signatures (discovery of charge/ neutral current at CERN)



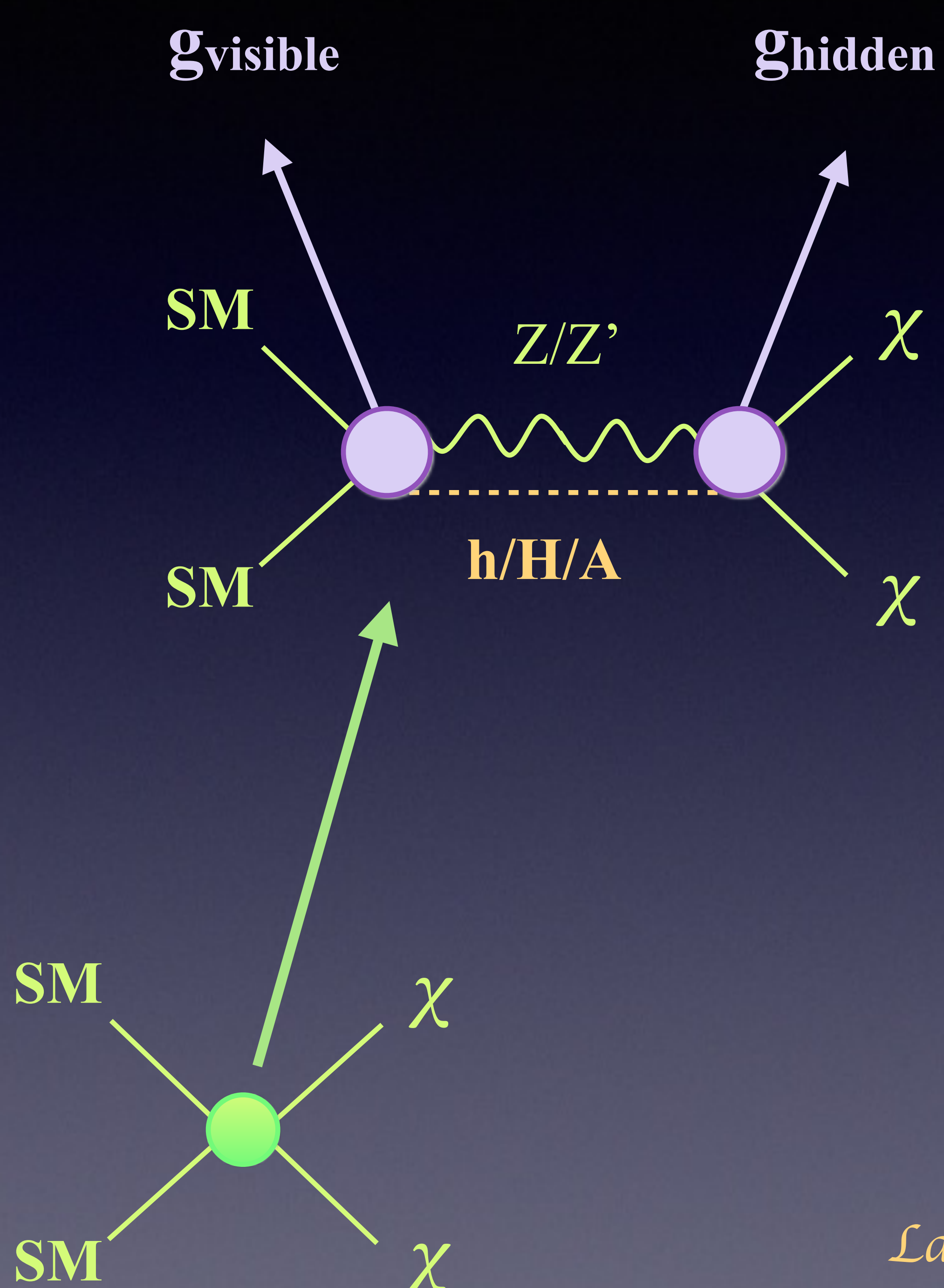
microscopic → **approach**



$G_F = 10^{-5}\ \mathrm{GeV}^{-2}$

$G_F \sim (g/M_W)^2$

The effective approach applied to dark matter interaction



$g_{visible}$	g_{hidden}	DD	WMAP	LHC
1	1	✗	✓	✗
ε	1	✓	✓	✓
1	ε	✓	✓	✗
ε	ε	✓	✗	✓

$\varepsilon \ll 1$

Tendencies:

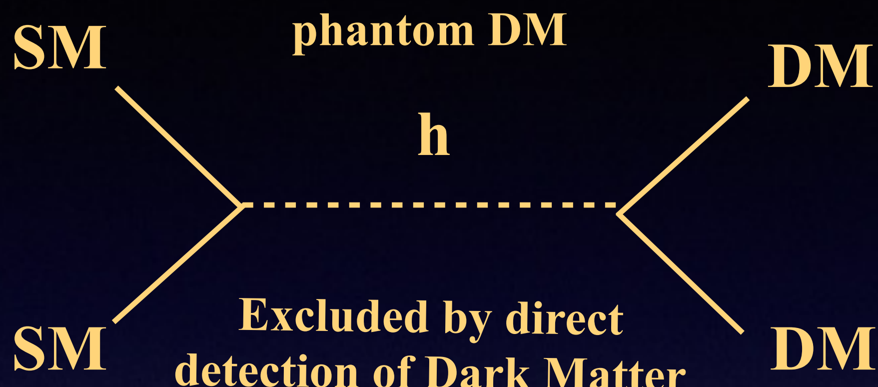
Large $g_{visible}$ is strongly constrained by LHC

Large g_{hidden} is strongly constrained by DD experiments

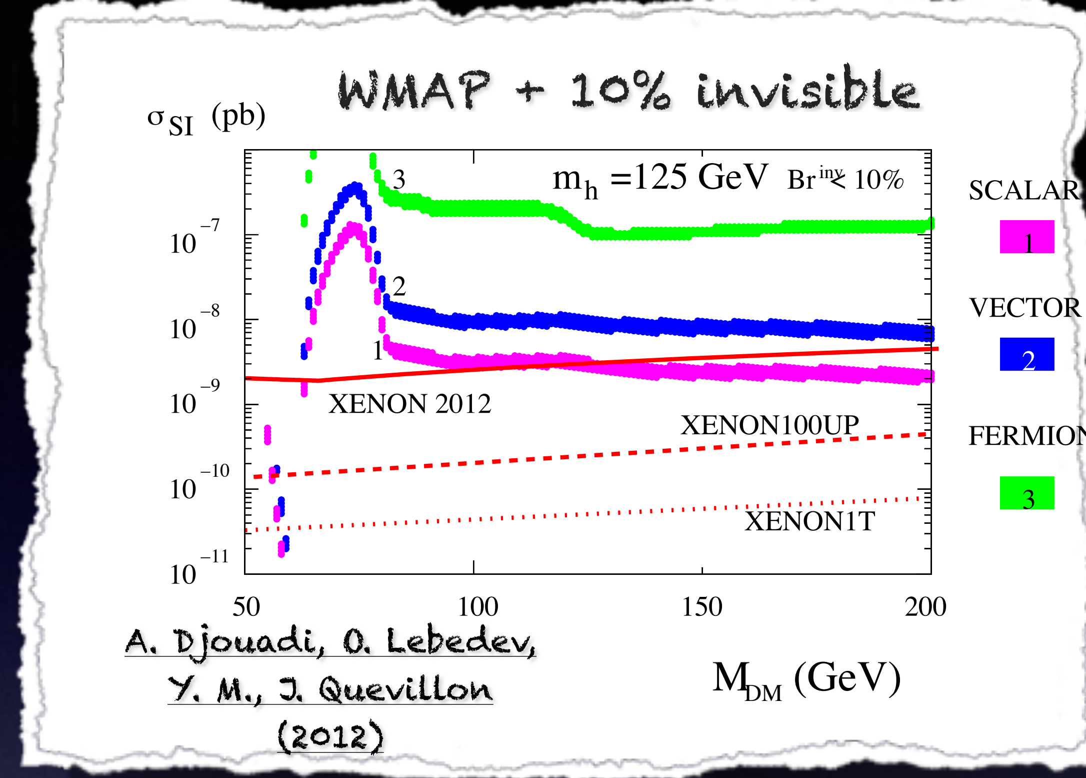
Small $g_{visible}$ and g_{hidden} are strongly constrained by WMAP (overabundance)

What are the possible mediators?

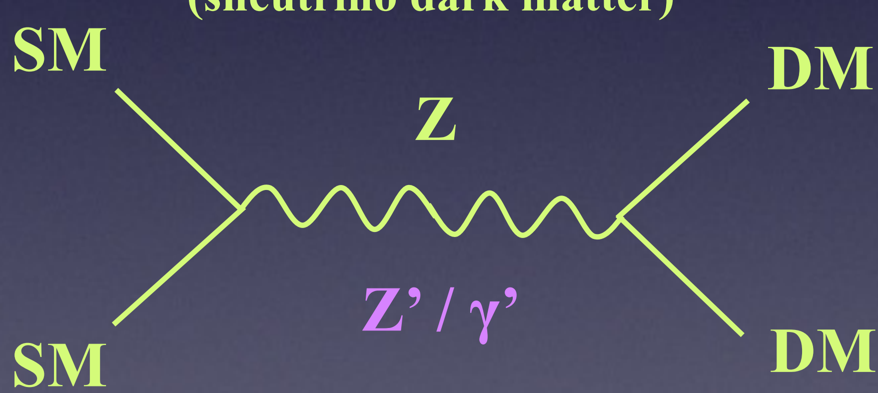
Higgs portal
darkons
phantom DM



Excluded by direct detection of Dark Matter

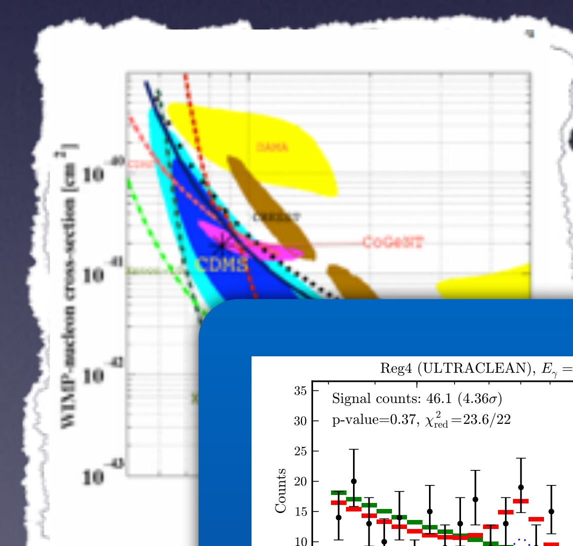


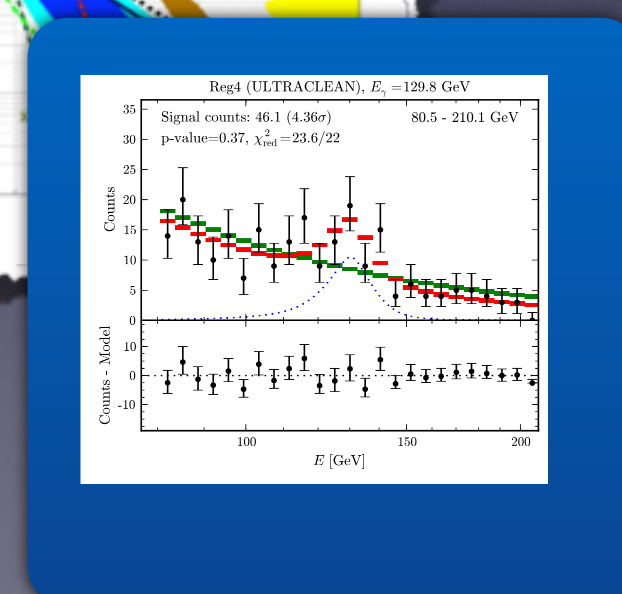
Z portal
(sneutrino dark matter)



Excluded by direct detection of Dark Matter

Falk, Olive, Srednicki
(1994)

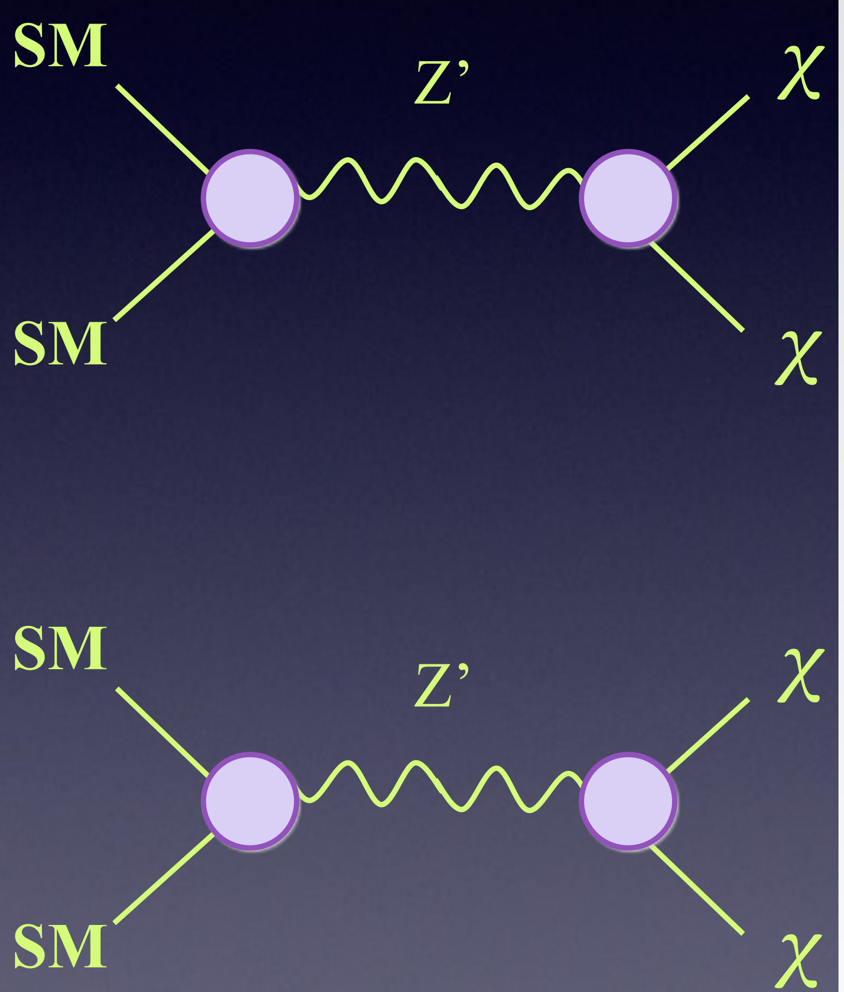




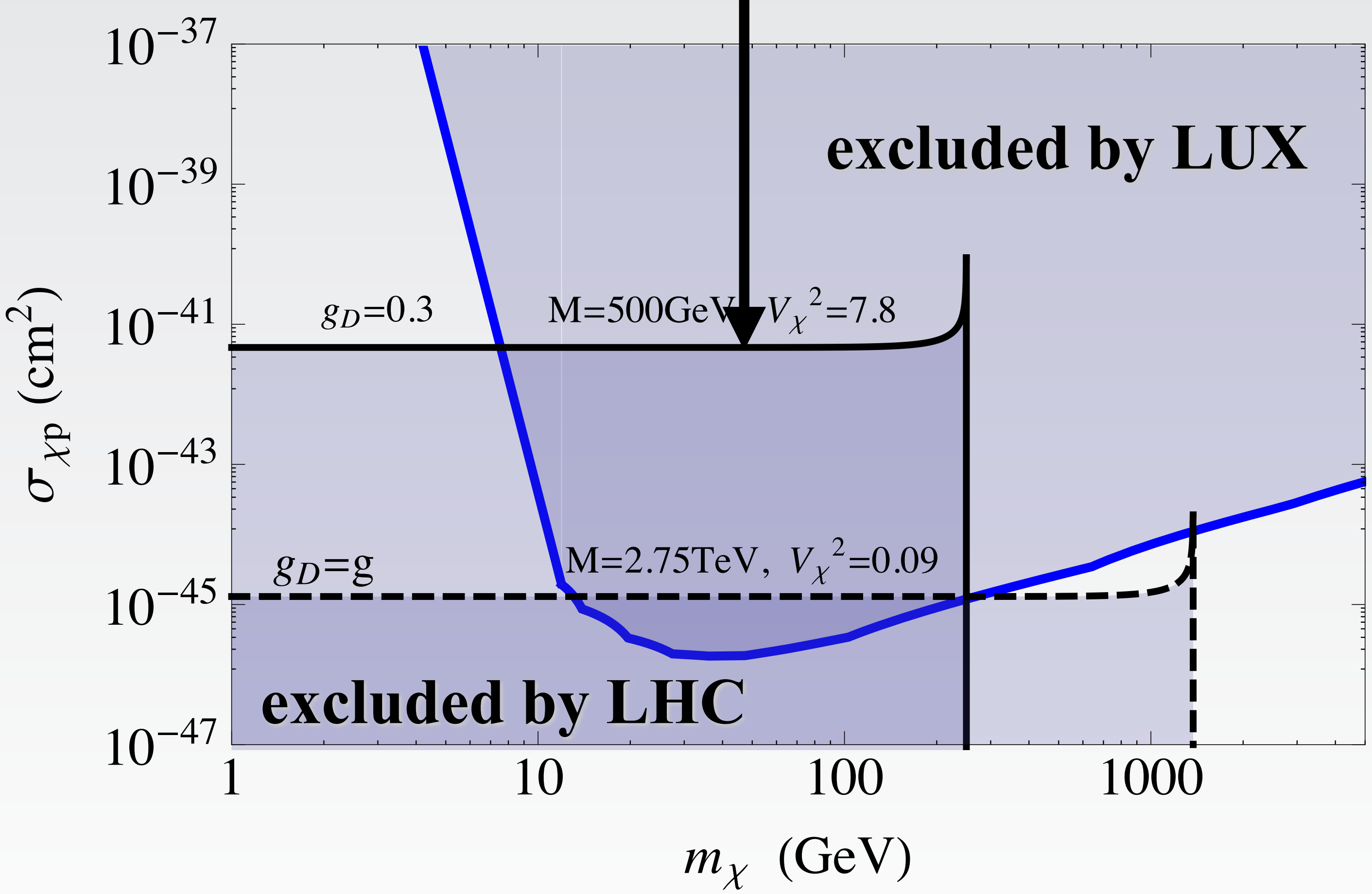
Z' portal
Hidden photon
(mirror dark matter)

Not excluded
Can explain excess observed by CRESST/
CoGENT/DAMA
or FERMI monochormatic line

The Z' case



Excluded because small dark coupling g_D => Z' produced abundantly at LHC: this gives a LOWER bound on DD cross section

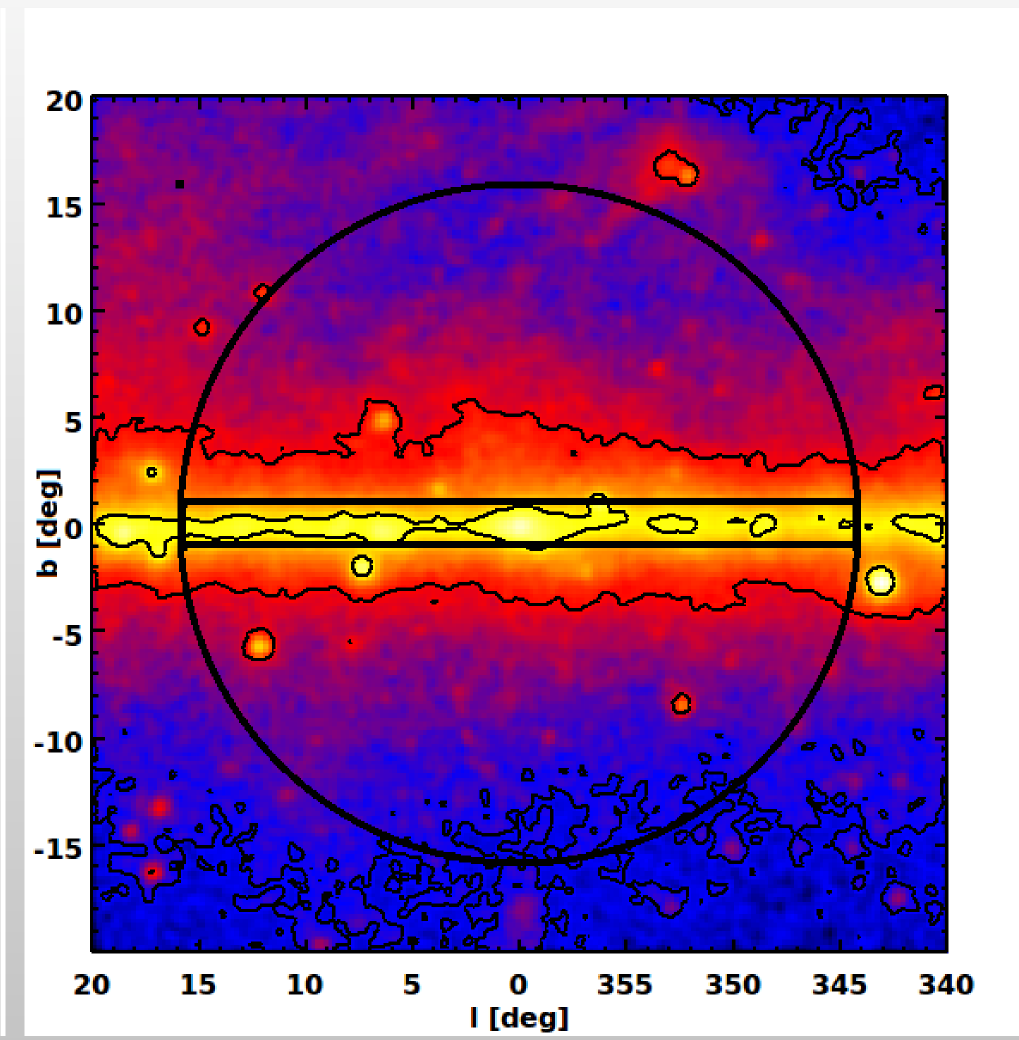


LHC + LUX limits

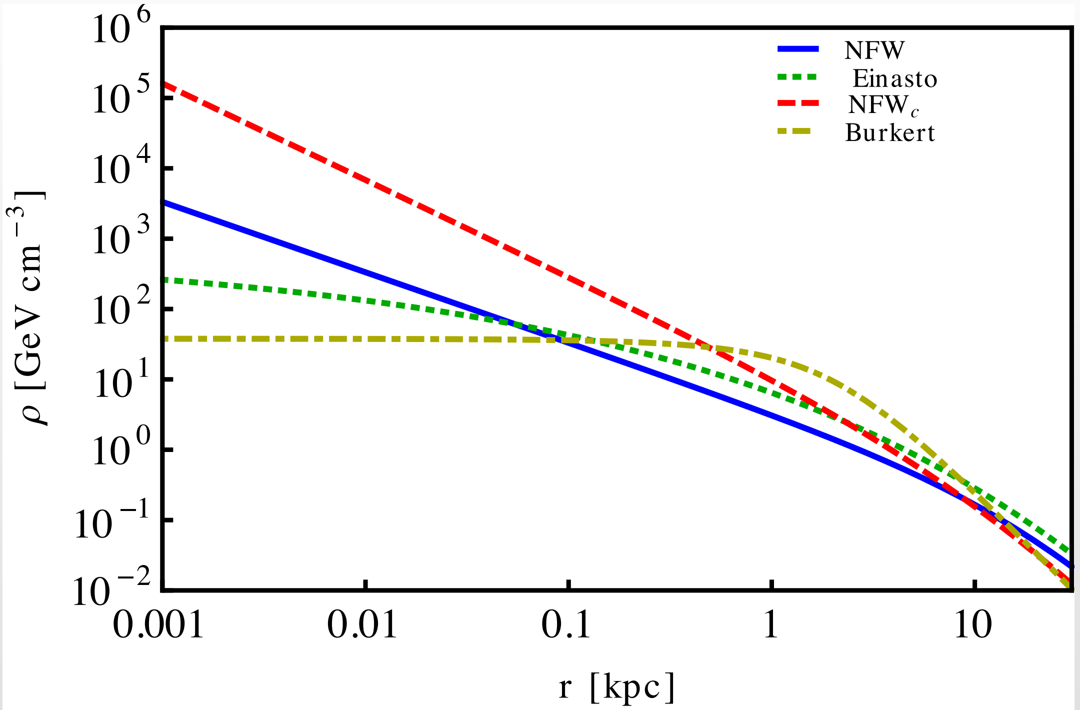
Based on work with G. Arcadi, M. Tytgat and B. Zaldivar (2014) / JHEP

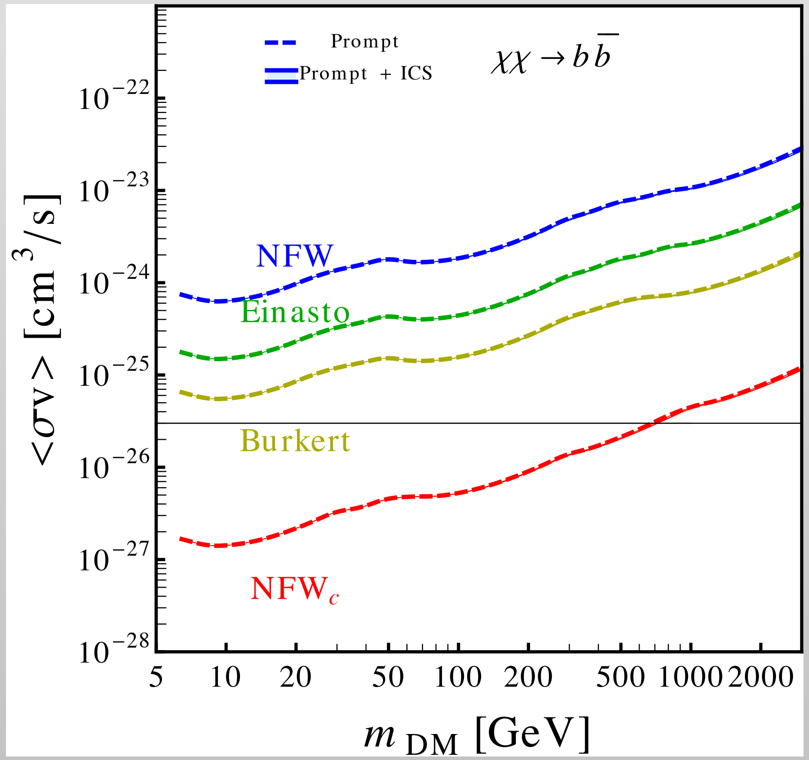
Looking for photons around the galactic center

Milky way



Galactic profiles





G. A. Gómez-Vargas, M. A. Sánchez-Conde, Y. Mambrini, C. Muñoz

JCAP 1310 (2013) 029

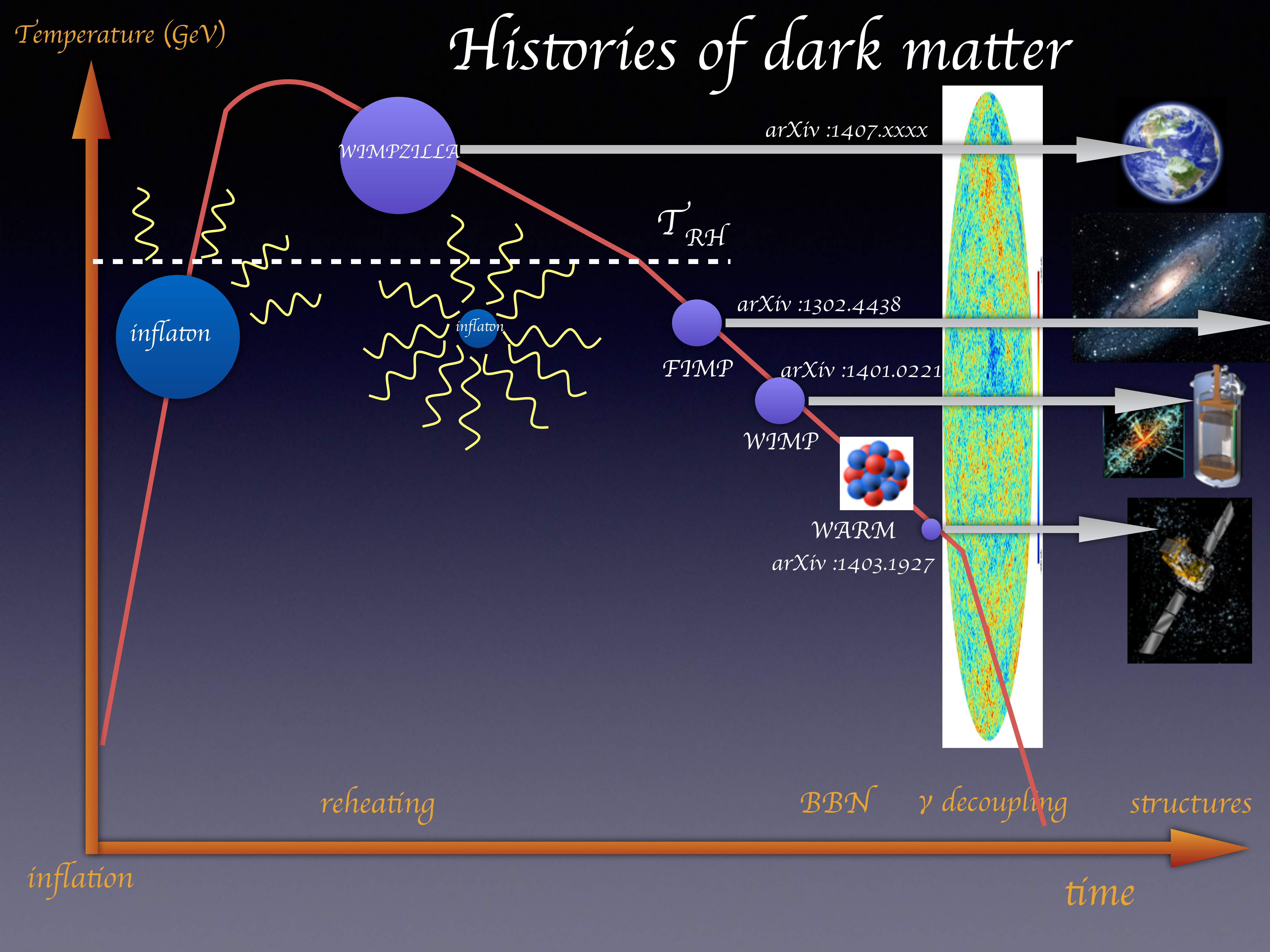
Part IV

The warm dark matter case

A signal?

Based on work with E. Dudas and L. Heurtier (2014) / PRD

Histories of dark matter



Hot/warm/cold dark matter

Relic density of hot dark matter.

The exemple of the neutrino: the Cowsik-Mac Clelland bound (1972)

VOLUME 29, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 1972

An Upper Limit on the Neutrino Rest Mass*

R. Cowsik† and J. McClelland

Department of Physics, University of California, Berkeley, California 94720

(Received 17 July 1972)

In order that the effect of graviation of the thermal background neutrinos on the expansion of the universe not be too severe, their mass should be less than 8 eV/c^2.

When a neutrino (or any relativistic particle) decouple, its distribution follows the one of the thermal bath (by energy conservation) even if not being in thermal equilibrium with the bath. Its momentum is just redshifted by the expansion rate: $n_\nu(T) = T_\nu^{\,3} = 109\ \mathrm{cm}^{-3}$

$$\Omega_\nu h^2 = \frac{\rho_\nu}{\rho_0^c} h^2 = \frac{n_\nu\ m_\nu}{10^{-5}\ \mathrm{GeV\ cm}^3} \simeq \frac{m_\nu}{92\ \mathrm{eV}} \quad \Rightarrow \quad m_\nu \lesssim 9\ \mathrm{eV}$$

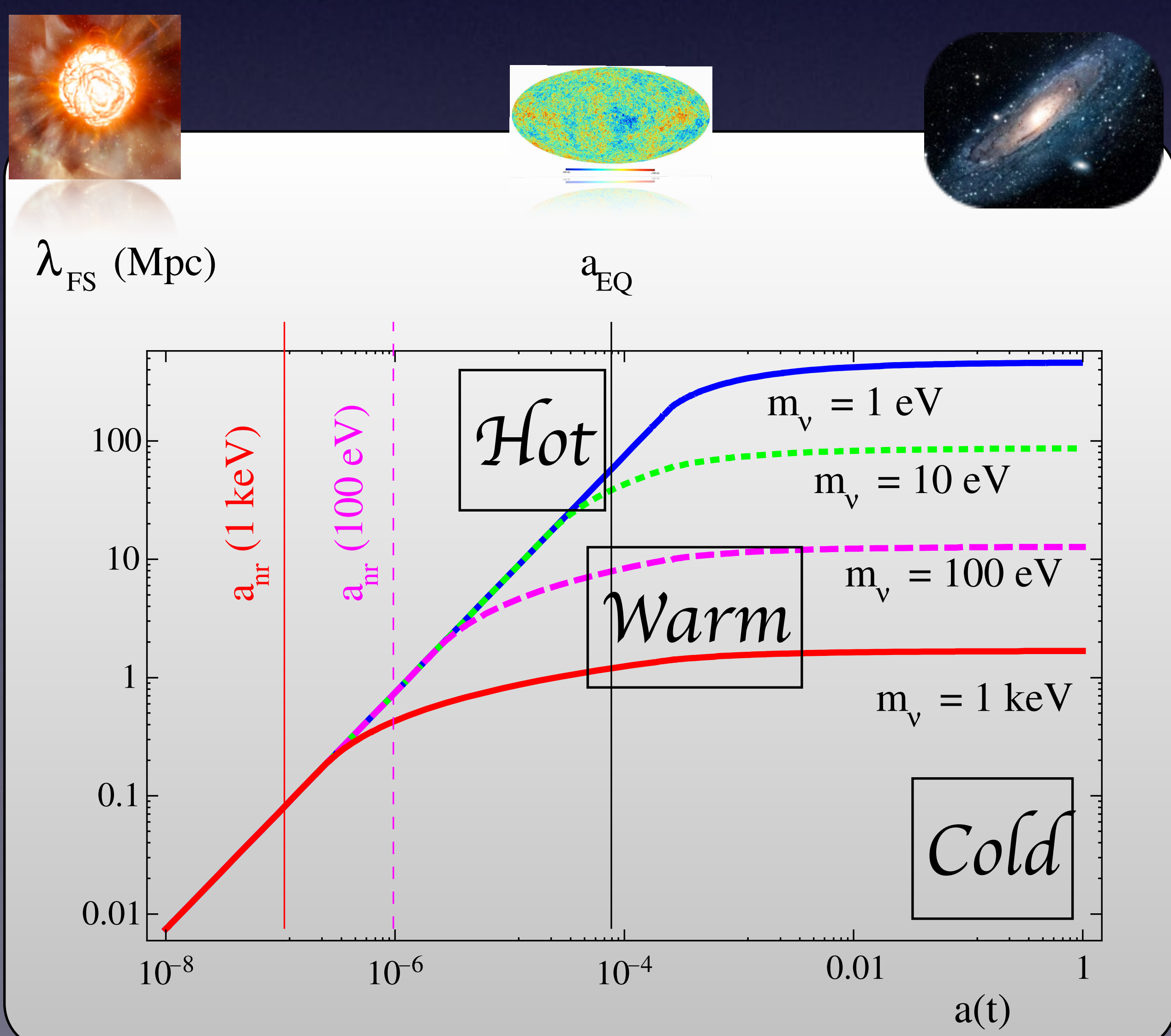
This bounds is valid for ANY dark matter candidate that decouples while being relativistic. Maximum value ~ keV (playing on E6 degrees of freedom/ Yanagida 2014)

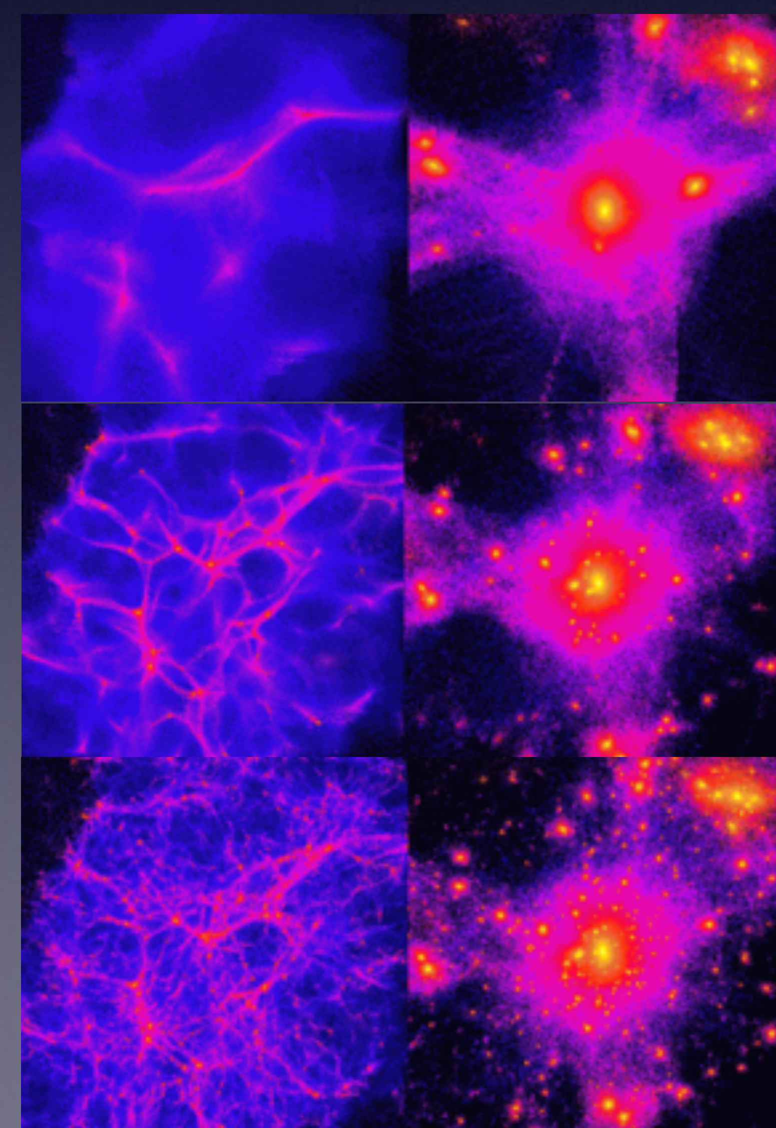
Problem of hot dark matter: formation structure

A particle when decoupled relativistic (« hot ») collisionless will have tendency to stream out from overdense region into underdense region, smoothing out in the process inhomogenities. One should then compute its free-streaming path, and check that it is lower than the size of proto-galaxies (~Megaparsec)

$$\lambda_{FS}(t) = \int_0^t dr = \int_0^t \frac{v(t')}{a(t')} dt'$$

$$\lambda_{FS}^{\infty} = \frac{M_P}{T_0 T_{nr}} \sqrt{\frac{45}{4\pi^3 g_\rho}} \left[\frac{5}{2} + \ln\left(\frac{\rho_0^R T_{nr}}{\rho_0^M T_0} \right) \right] \approx 70 \text{ Mpc} \frac{1 \text{ eV}}{T_{nr}} \approx 210 \text{ Mpc} \frac{1 \text{ eV}}{m_\nu}$$





Hot dark matter (ν)

Warm dark matter (ν_R)

Cold dark matter (neutralino)

credit ITP, University of Zurich

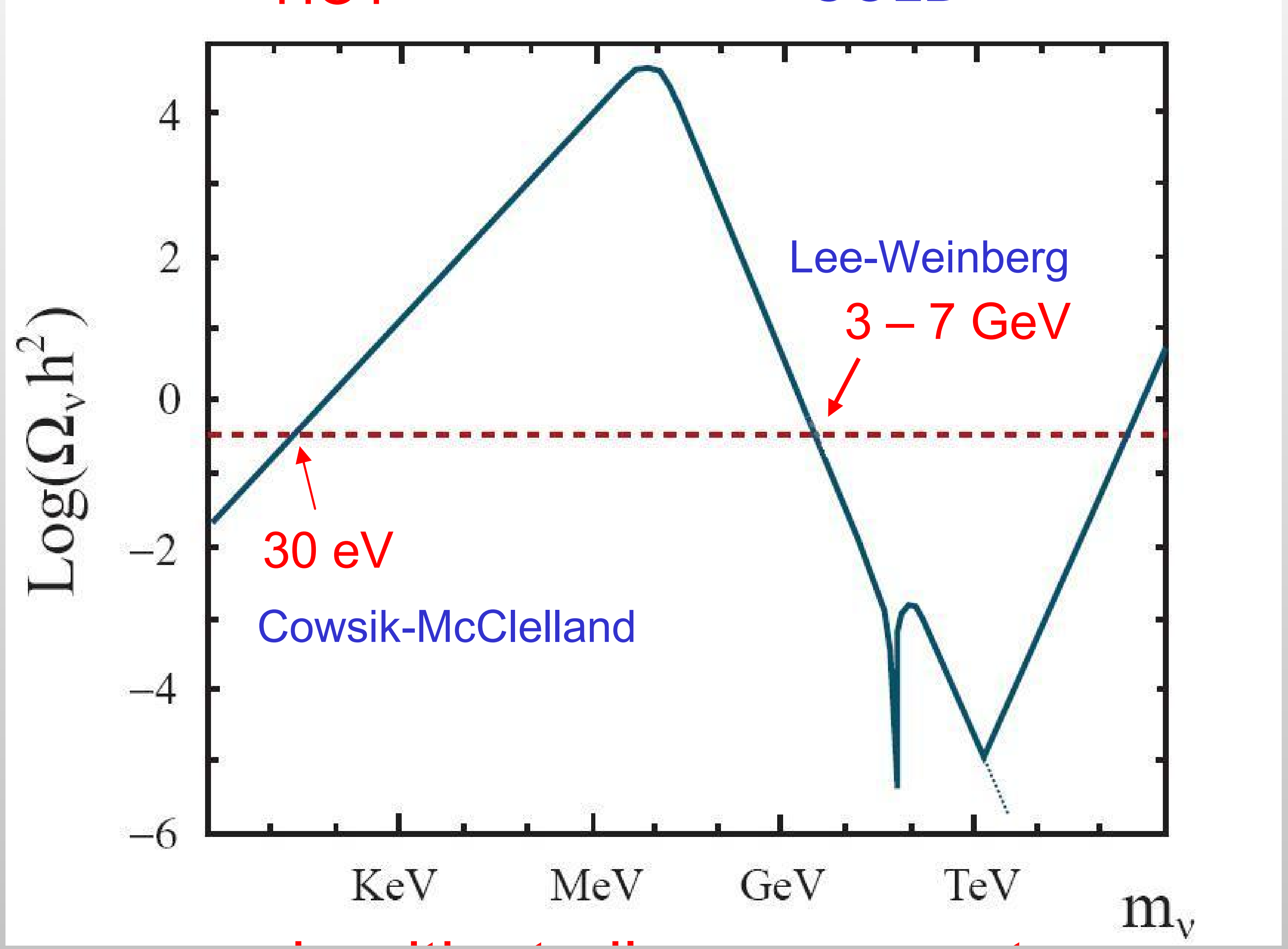
Summary, hot versus cold dark matter

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{91.5\,\mathrm{eV}}$$

HOT

$$\Omega_\nu h^2 \propto <\sigma_{ann} v>^{-1}$$

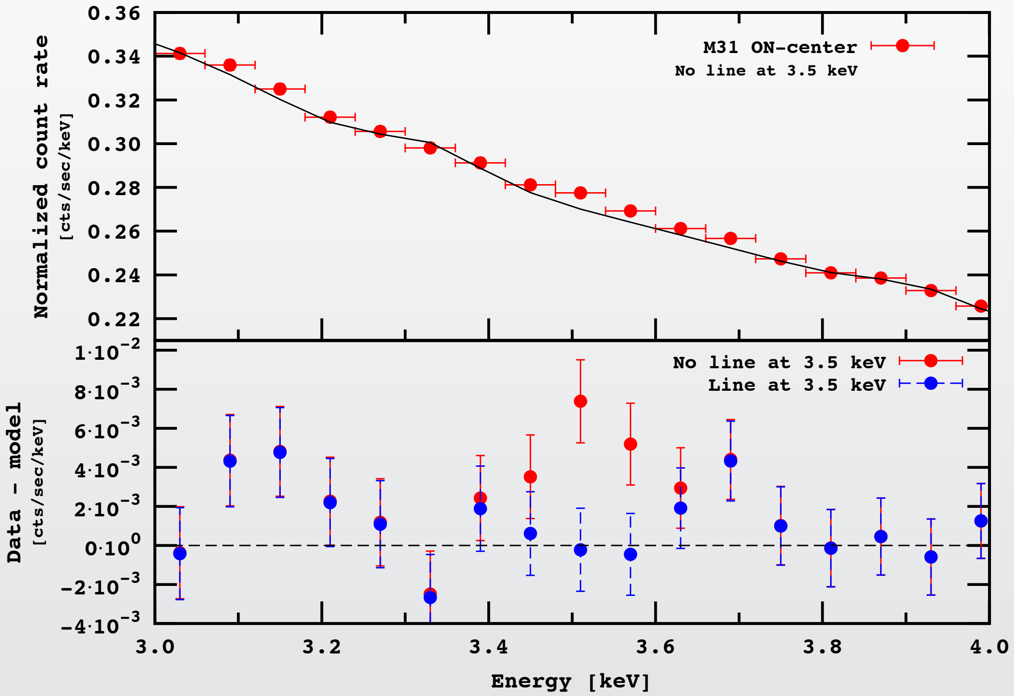
COLD



Signal: XMM NEWTON and 3.5 keV line?

XMM Newton

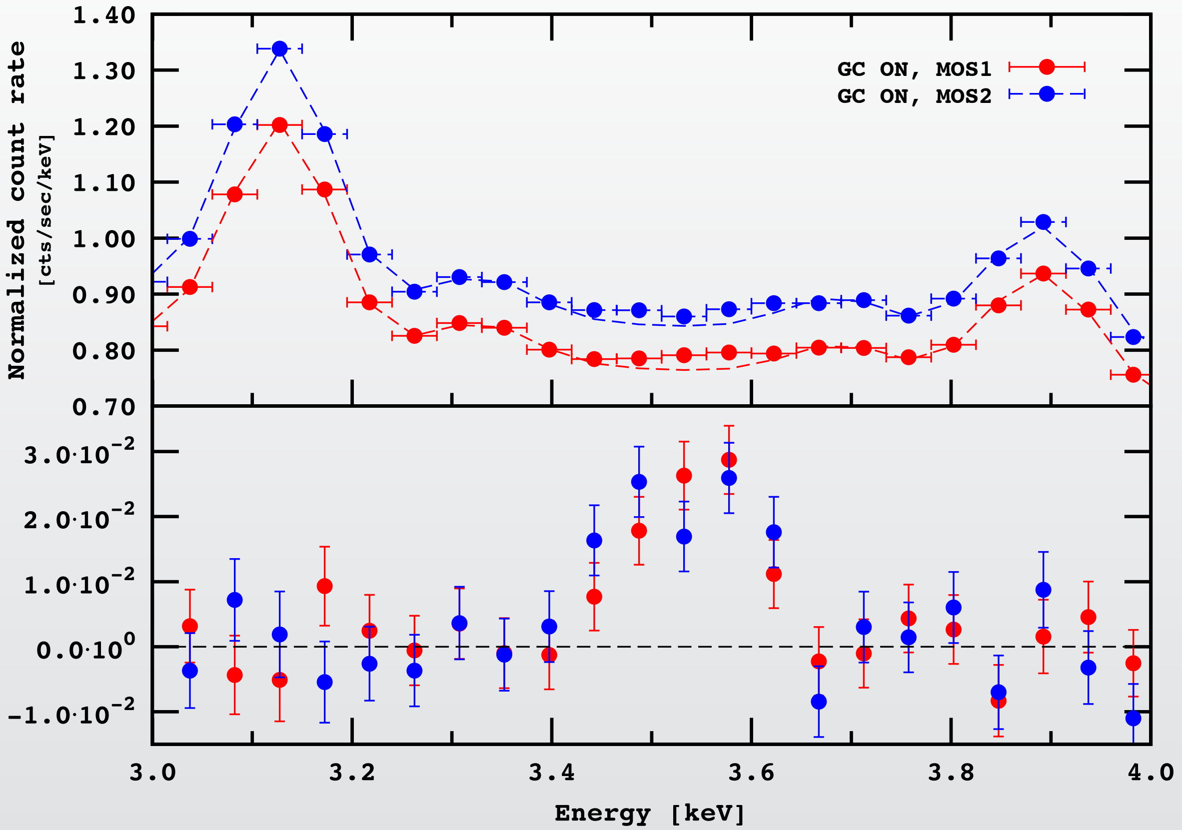
Clusters of galaxies (02/14)



A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, J. Franse; http://arxiv.org/abs/1402.4119

E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, S. W. Randall; http://arxiv.org/abs/1402.2301

Galactic center (08/14)



A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, J. Franse arXiv:1408.2503

$$\phi^{obs}_{\gamma\gamma} \simeq 5.2 \times 10^{-5} \text{ photons cm}^{-2}\text{ s}^{-1} \quad \text{at} \quad 3.55 \text{ keV}$$

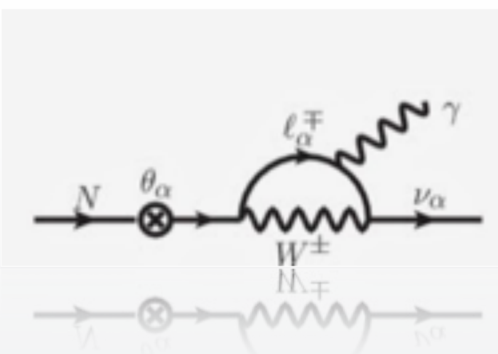
(Perseus, 78 Mpc)

$$\Phi_{\gamma\gamma} = \frac{L}{4\pi D_{pe}^2} = \frac{\rho_{Pe}}{m_{dm}} \times \Gamma(DM \to \gamma\gamma) \times \frac{(R_{Pe})^3}{3(D_{Pe})^2}$$

$$\Gamma(DM \to \gamma\gamma) \simeq 10^{-23} \left(\frac{m_{dm}}{\text{keV}}\right) \Phi_{\gamma\gamma} \quad \text{cm}^{-2}\text{s}^{-1}$$

Some decaying/exciting interpretation

Sterile neutrino



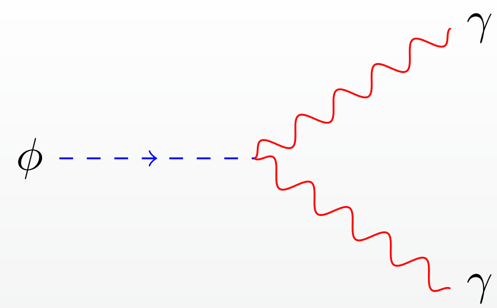
$$\Gamma(N \to \gamma\nu) = 5 \times 10^{-32}\ \mathrm{s}^{-1} \left(\frac{\sin\theta}{10^{-10}}\right)\left(\frac{m_N}{\mathrm{keV}}\right)^5$$

keV γγ observation

$$\Gamma \simeq \frac{1}{(2-20)\times 10^{27}\mathrm{s}}$$

arXiv:1403.5837

Axion-like particle



$$\mathcal{L} = \frac{\phi}{\Lambda} F_{\mu\nu}F^{\mu\nu}, \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

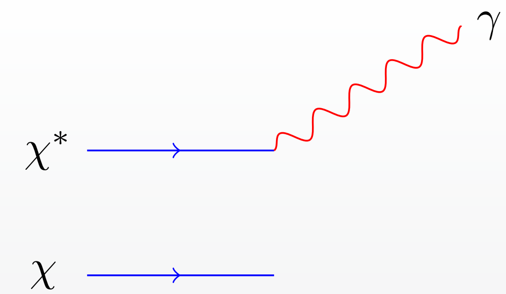
$$\Gamma(\phi \to \gamma\gamma) = \frac{m_\phi^3}{8\pi\Lambda^2}$$

keV γγ observation

$$\Lambda \simeq 5 \times 10^{17}\mathrm{GeV}$$

arXiv:1403.0865

Exciting DM



$$\mathcal{L} = \frac{1}{\Lambda}\chi^*\sigma_{\mu\nu}\chi F^{\mu\nu}, \quad \sigma_{\mu\nu} = [\gamma_\mu\gamma_\nu]$$

$$m_{\chi^*} - m_\chi = 3.5\ \mathrm{keV}$$

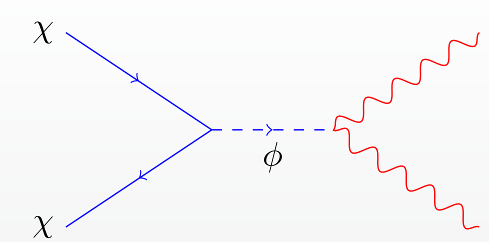
$$m_\chi \sim 100\ \mathrm{GeV}$$

keV γγ observation

$$\Lambda \simeq 10^{11}\ \mathrm{GeV}$$

arXiv:1404.5446

Annihilating DM



$$\mathcal{L}_{eff} \supset -\frac{m_s^2}{2}S^2 - \frac{m_\phi^2}{2}\phi^2 - \tilde{m}\phi S^2 + \frac{\phi}{\Lambda}F_{\mu\nu}F^{\mu\nu}$$

$$\langle\sigma v\rangle_{\gamma\gamma}^{micro} = \frac{4m_s^2\tilde{m}^2}{\pi\Lambda^2(4m_s^2 - m_\phi^2)^2}\ .$$

keV γγ observation

$$300\ \mathrm{keV} \lesssim m_\phi \lesssim 50\ \mathrm{MeV}\,.$$

$$\Lambda \gtrsim 3\ \mathrm{TeV} \quad [m_\phi \lesssim 50\ \mathrm{MeV}]\,.$$

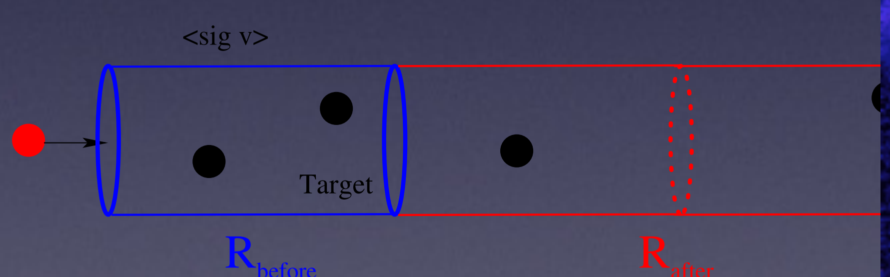
arXiv:1404.1927

Conclusions

A huge possibilities in the dark sector (even not talking about axions!!) especially when opening the box of a non-standard thermal history of the Universe

In the last 20-30 years a lot of theoretical frameworks/technology detectors has been focused on the electroweak scale (~100 GeV) mainly based on (maybe?) too simple arguments (« WIMP miracle », Lee Weinberg bounds..). Since 5-10 years, the box is open, looking from the milli-eV dark matter (« dark photon »), to sterile neutrino (warm dark matter) or PeV signatures (WIMPZILLA)

The second chapter will cover the discovery status, its prospects and issues



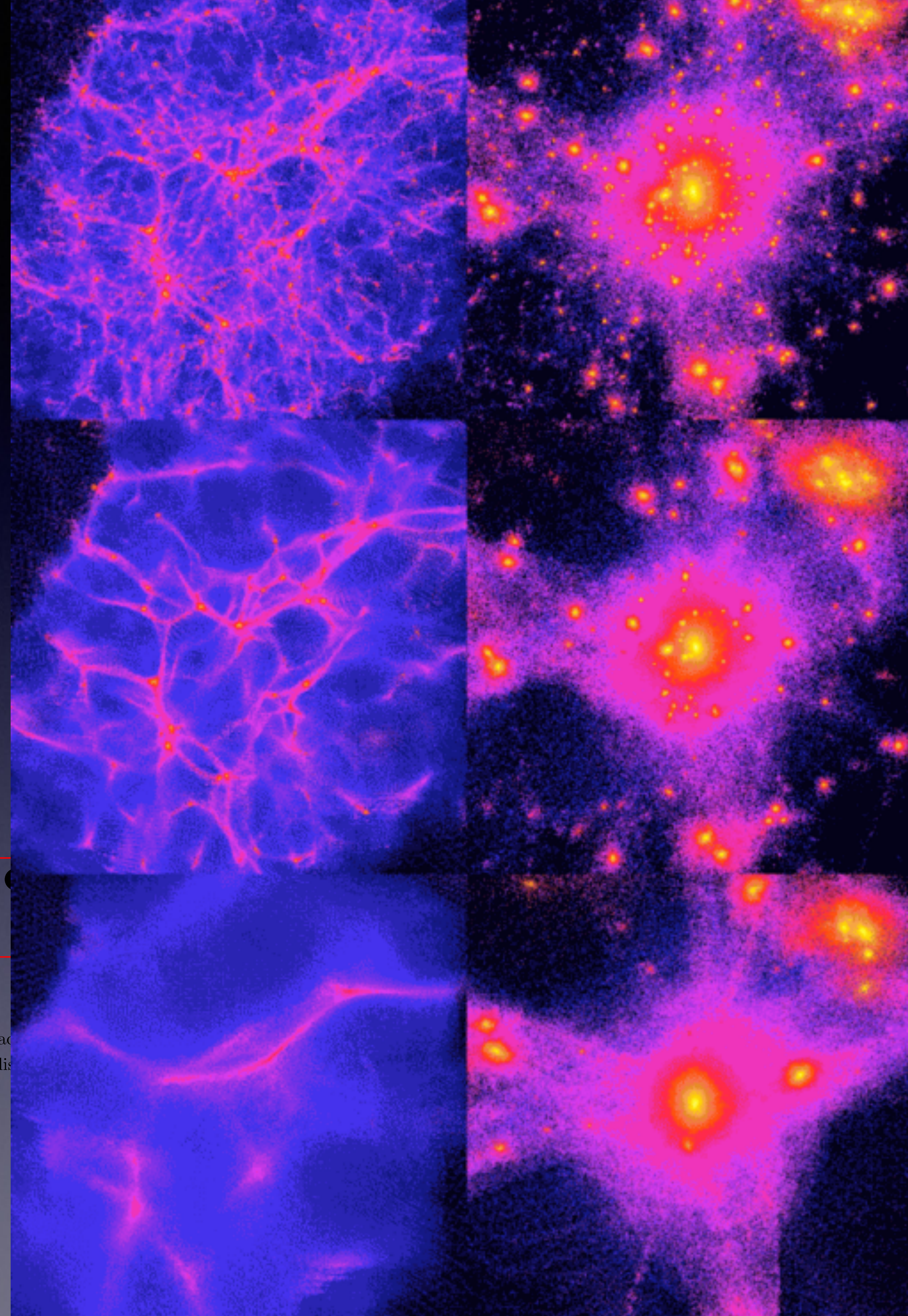


Figure 2.7: Illustrative example of the decoupling epoch when the number of interac
during a time Δt due to the dilution of the target. The volume necessary to have 2 collis
just sufficient to give one collision (R_{after})

.