Nonthermal dark matter and its observational implications

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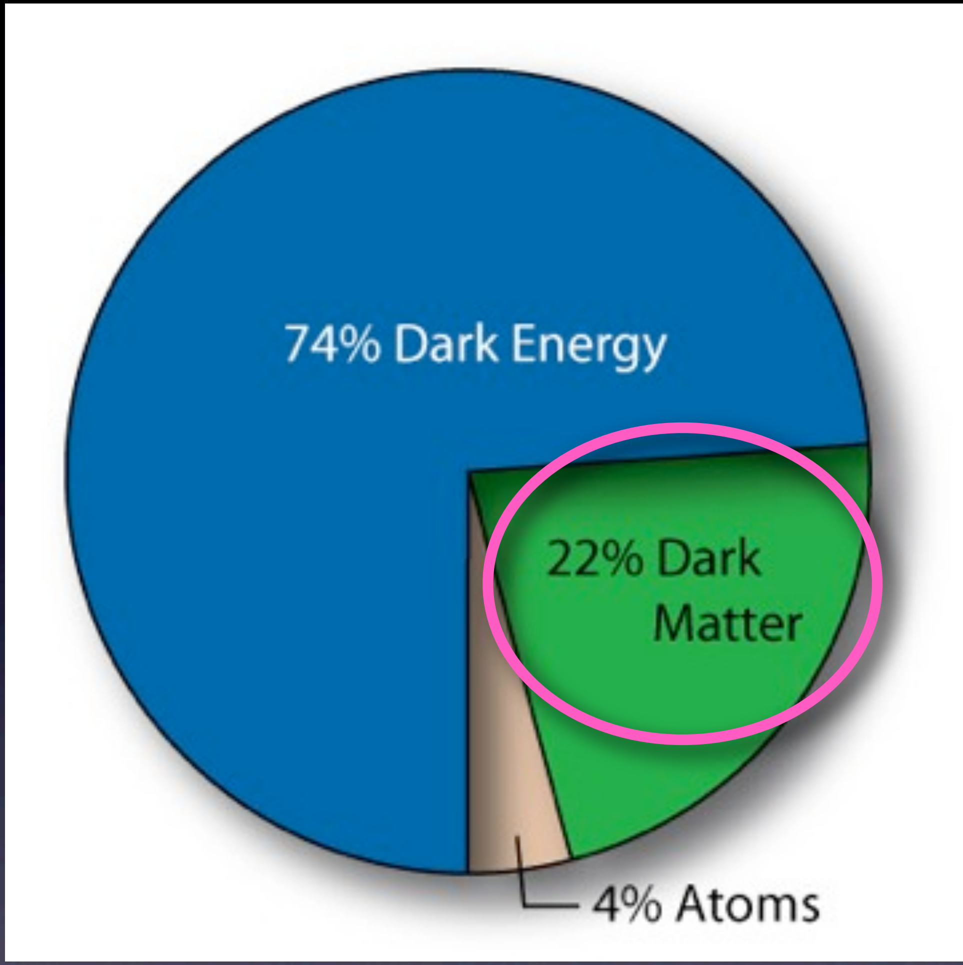
Nonthermal Cosmological Histories of the Universe
Workshop@Michigan Univ. (2010/10/18)

Contents

- PAMELA/Fermi from DM annihilation
- CMB constraints on DM annihilation
- Inflationary gravitational waves as a probe of non-thermal history of the Universe

Energy content of the Universe after WMAP



- What is dark matter ?

  SUSY Neutralino? Gravitino?

  Axion? KK particle? or ...

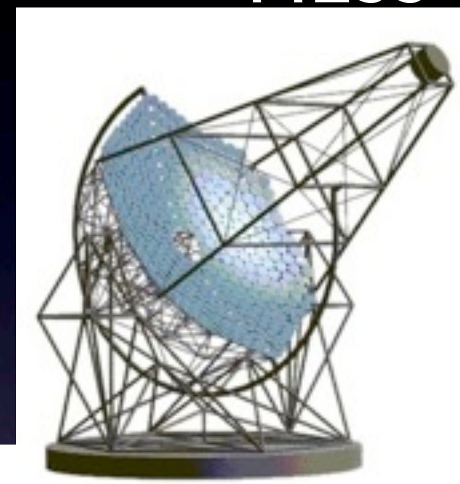
Evidence of DM?

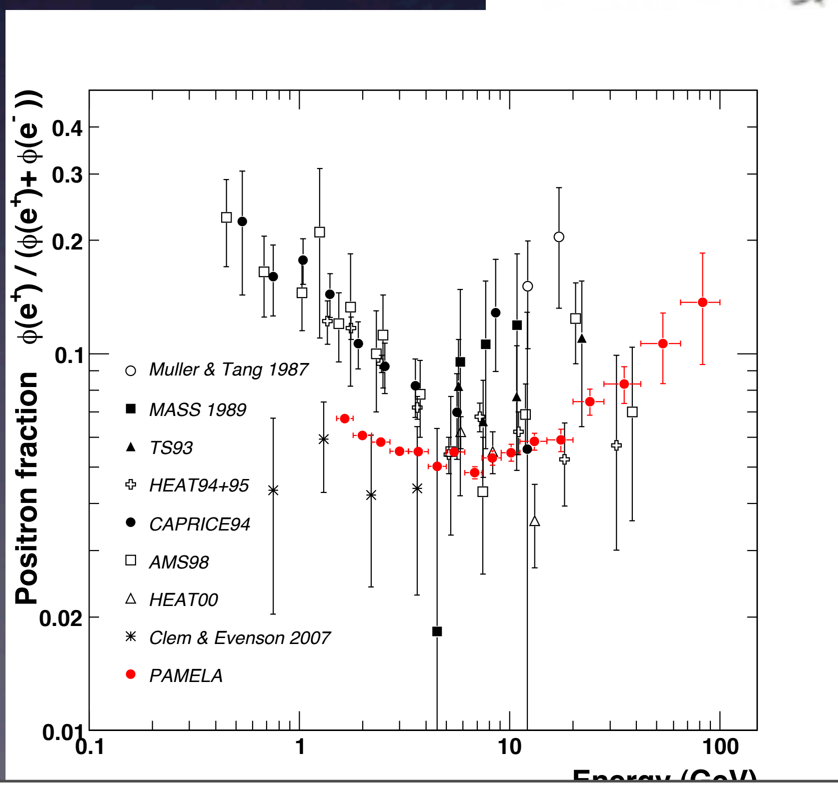
Excess in cosmic-ray positron & electron flux

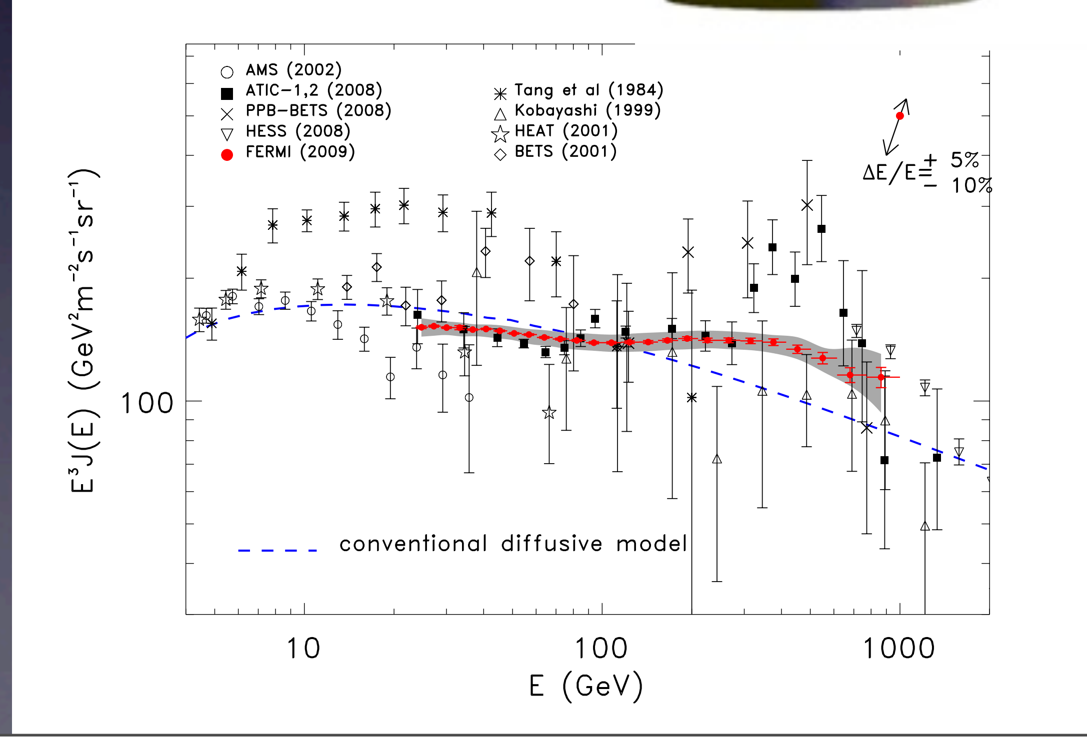
PAMELA

Fermi

HESS

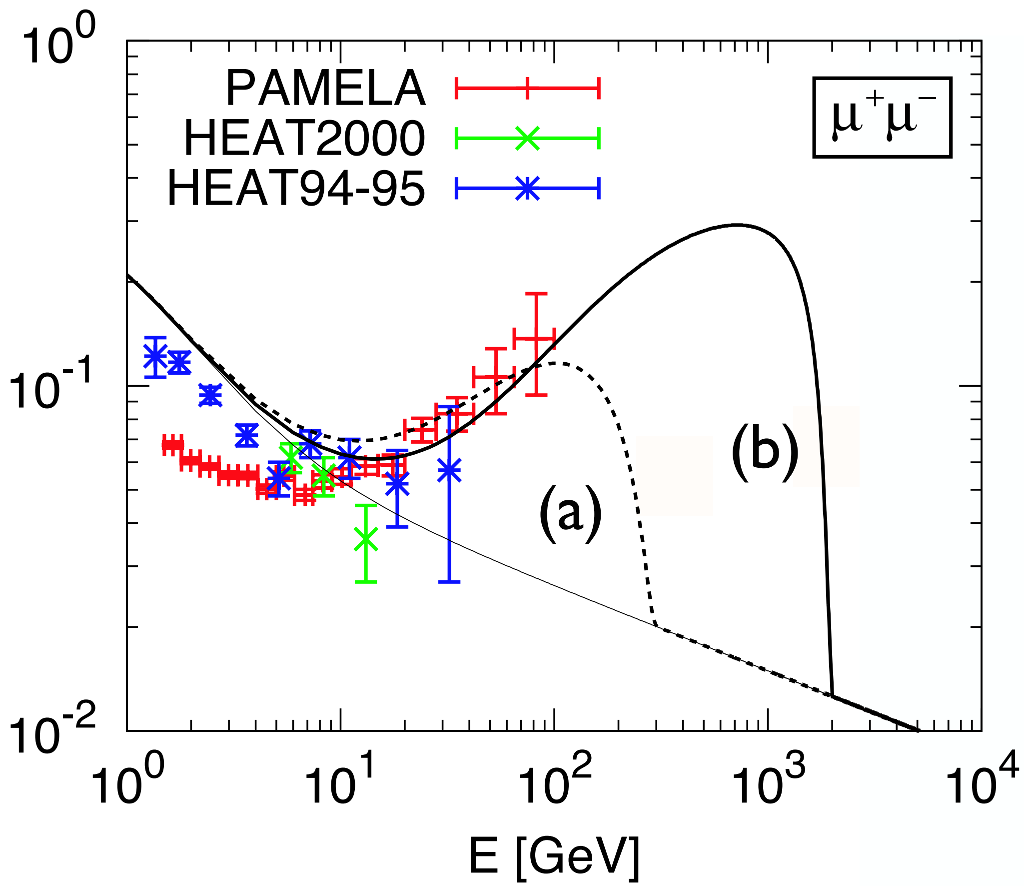




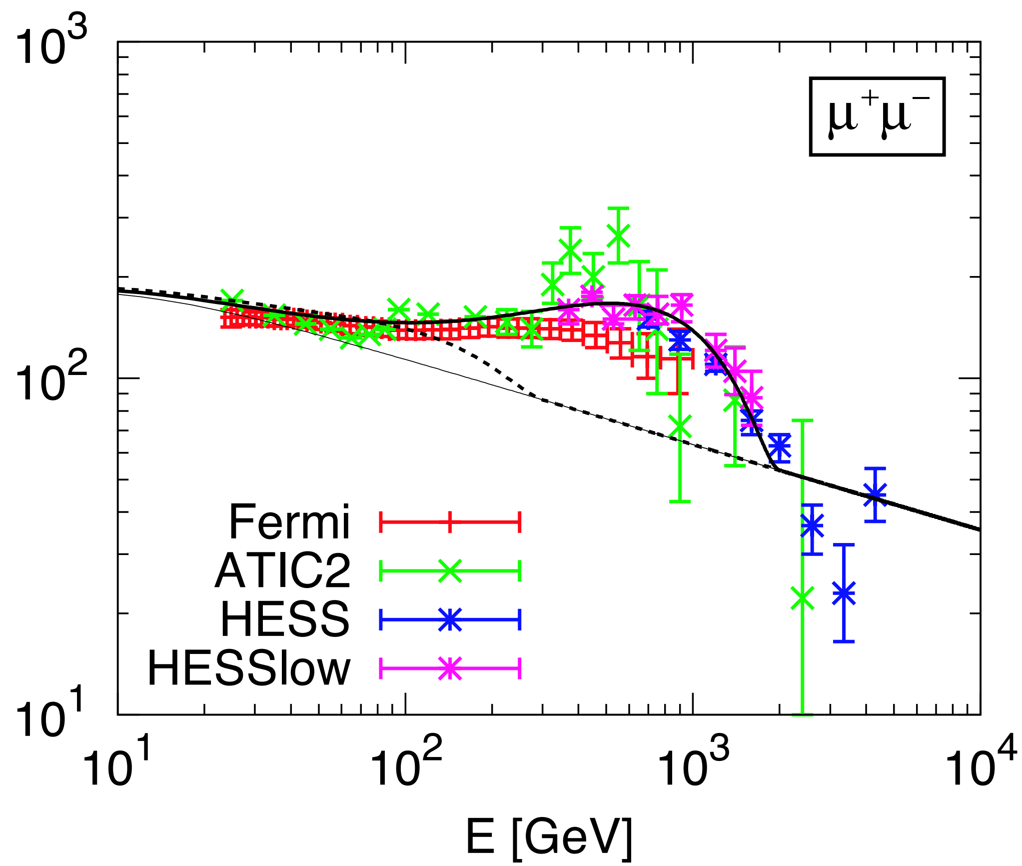


Cosmic-rays from DM annihilation

Positron fraction



Total flux $[\mathrm{GeV^2 m^{-2} s^{-1} sr^{-1}}]$



$$\chi\chi \to \mu^+\mu^- : (a)\ m_\chi = 300\mathrm{GeV}, \langle \sigma v \rangle = 2.0 \times 10^{-24}\mathrm{cm^3 s^{-1}}$$

$$(b)\ m_\chi = 2\mathrm{TeV}, \langle \sigma v \rangle = 5.0 \times 10^{-23}\mathrm{cm^3 s^{-1}}$$

J.Hisano, M.Kawasaki, K.Kohri, T.Moroi and KN (2009)

PAMELA & Fermi $\longrightarrow$ $\langle \sigma v \rangle \sim 10^{-23} \mathrm{cm}^3 \mathrm{s}^{-1}$

Thermal relic DM $\longrightarrow$ $\langle \sigma v \rangle \sim 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$

- **Velocity-dependent cross section**

  Sommerfeld enhancement [J.Hisano, S.Matsumoto, M.Nojiri (2003), N.Arkani-Hamed et al. (2008)]

- **Nonthermal dark matter**

  Decay of long-lived particle

  Moduli [T.Moroi, L.Randall (1999), G.Gelmini, P.Gondolo (2006), M.Nagai, KN (2008) B.Acharya, P.Kumar, K.Bobkov, G.Kane, J.Shao, S.Watson (2008)]

  See also [M.Endo, K.Hamaguchi, F.Takahashi (2006), S.Nakamura, M.Yamaguchi (2006) M.Dine, R.Kitano, A.Morisse, Y.Shirman(2006)]

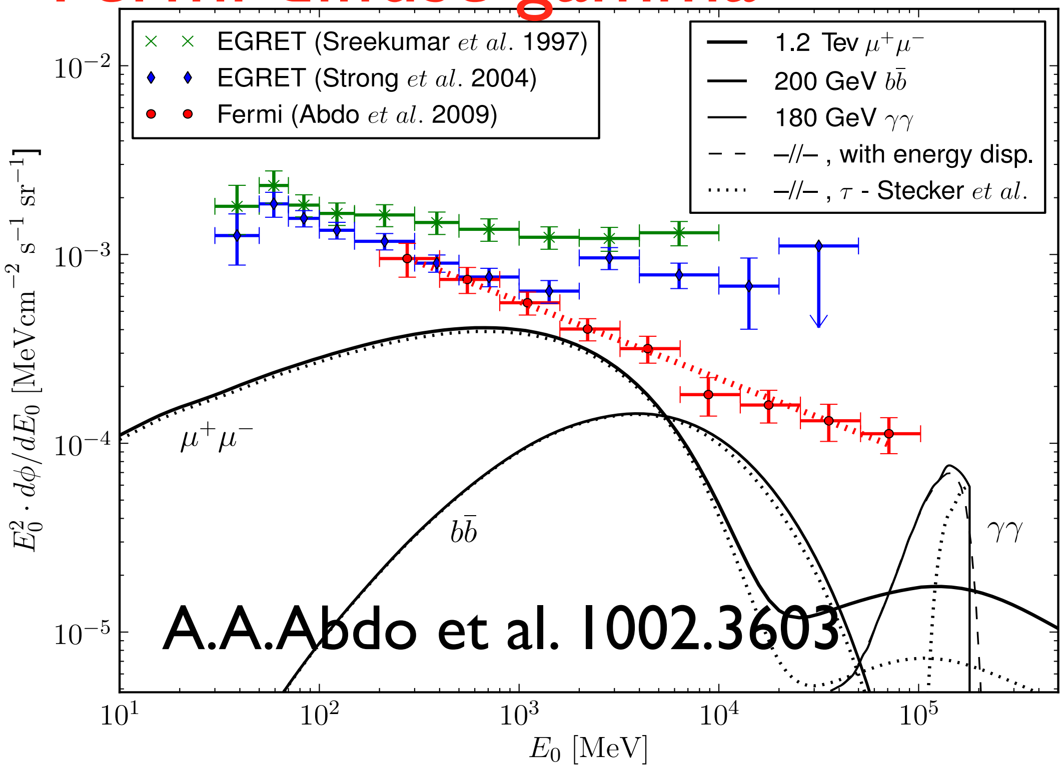
  Q-ball [M.Fujii, K.Hamaguchi (2002)]

  Saxion [M.Endo, F.Takahashi (2006), M.Kawasaki, KN (2008)]

  etc...

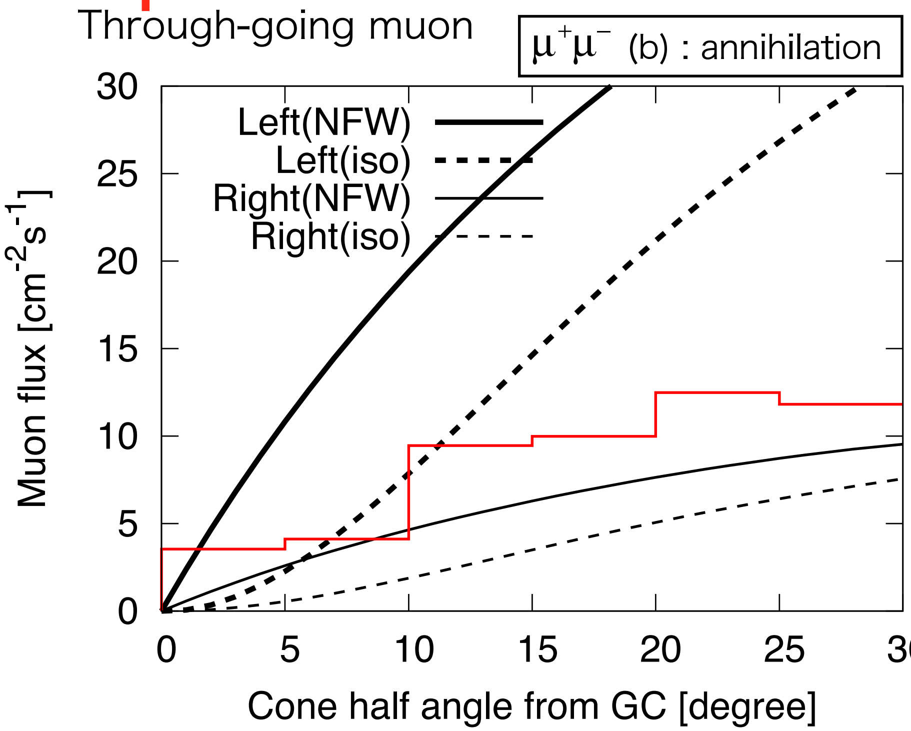
→ Constraints from gamma, neutrino, etc.

Fermi diffuse gamma

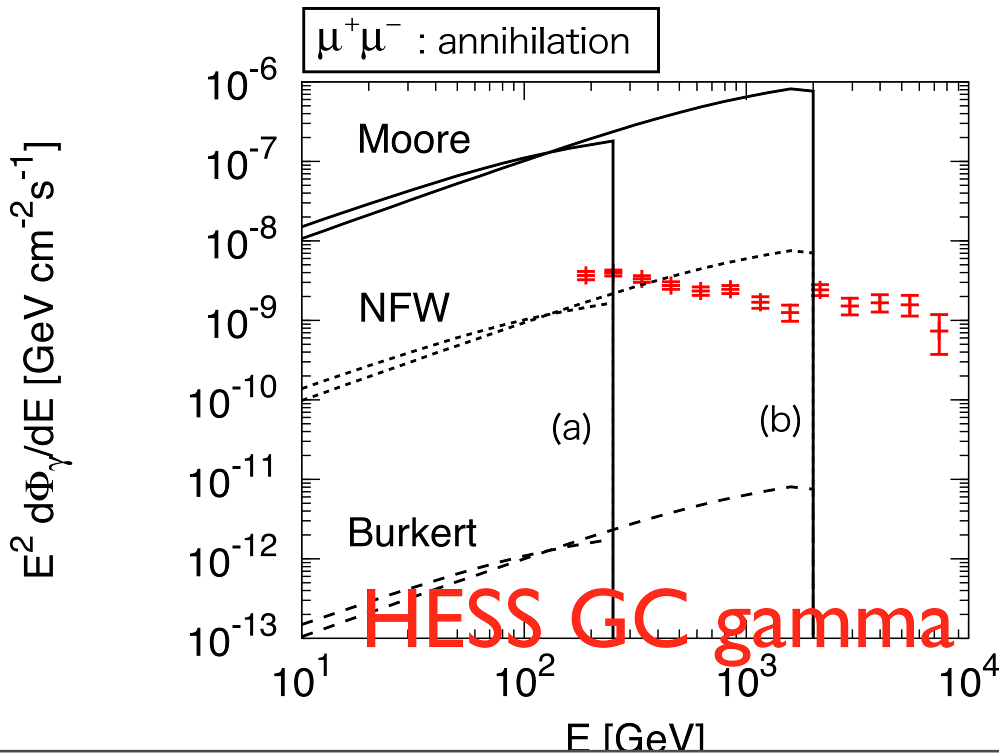


A.A.Abdo et al. 1002.3603

SK upward muon



Hisano, Kawasaki, Kohri, KN (08)

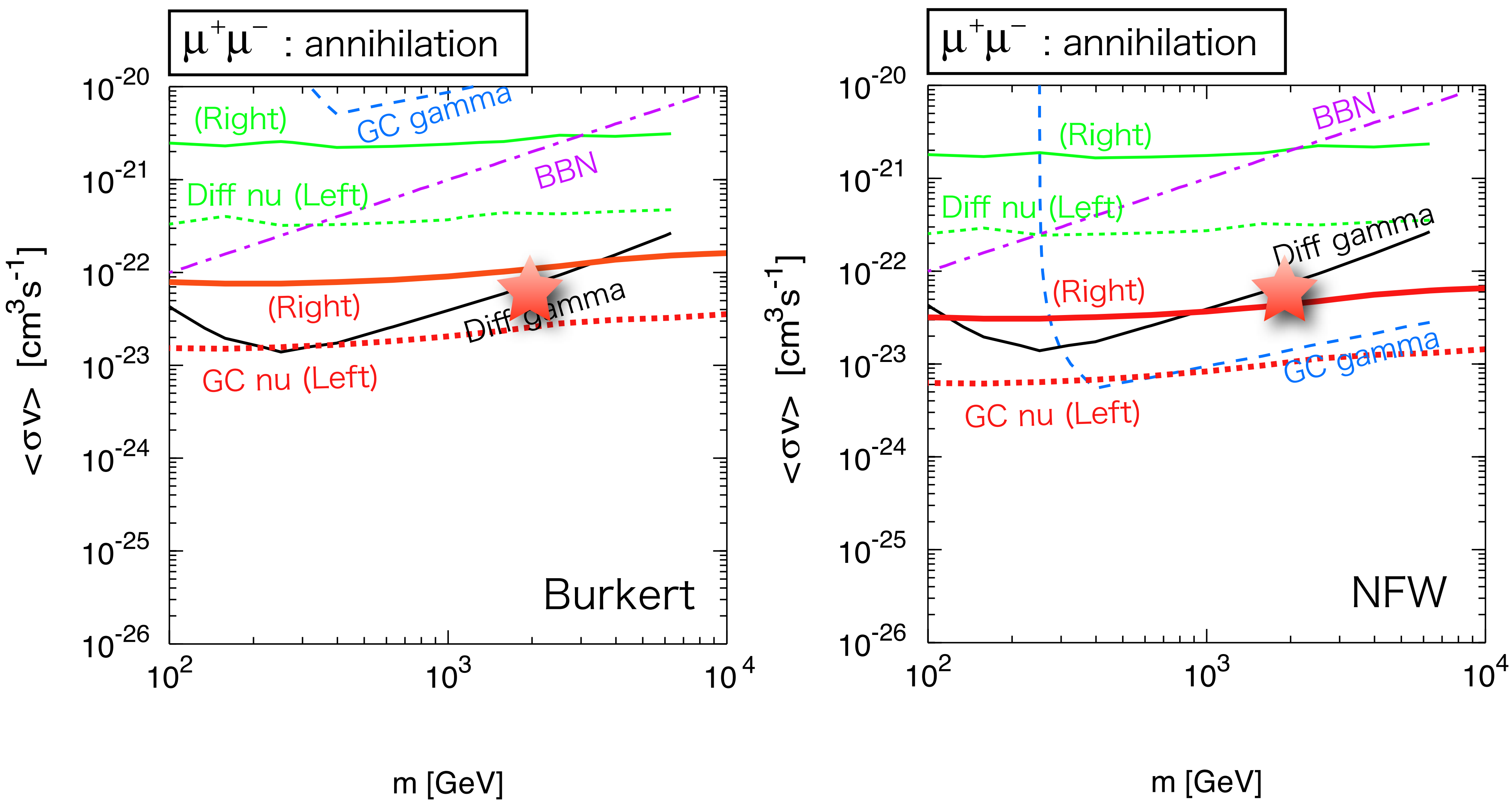


HESS GC gamma

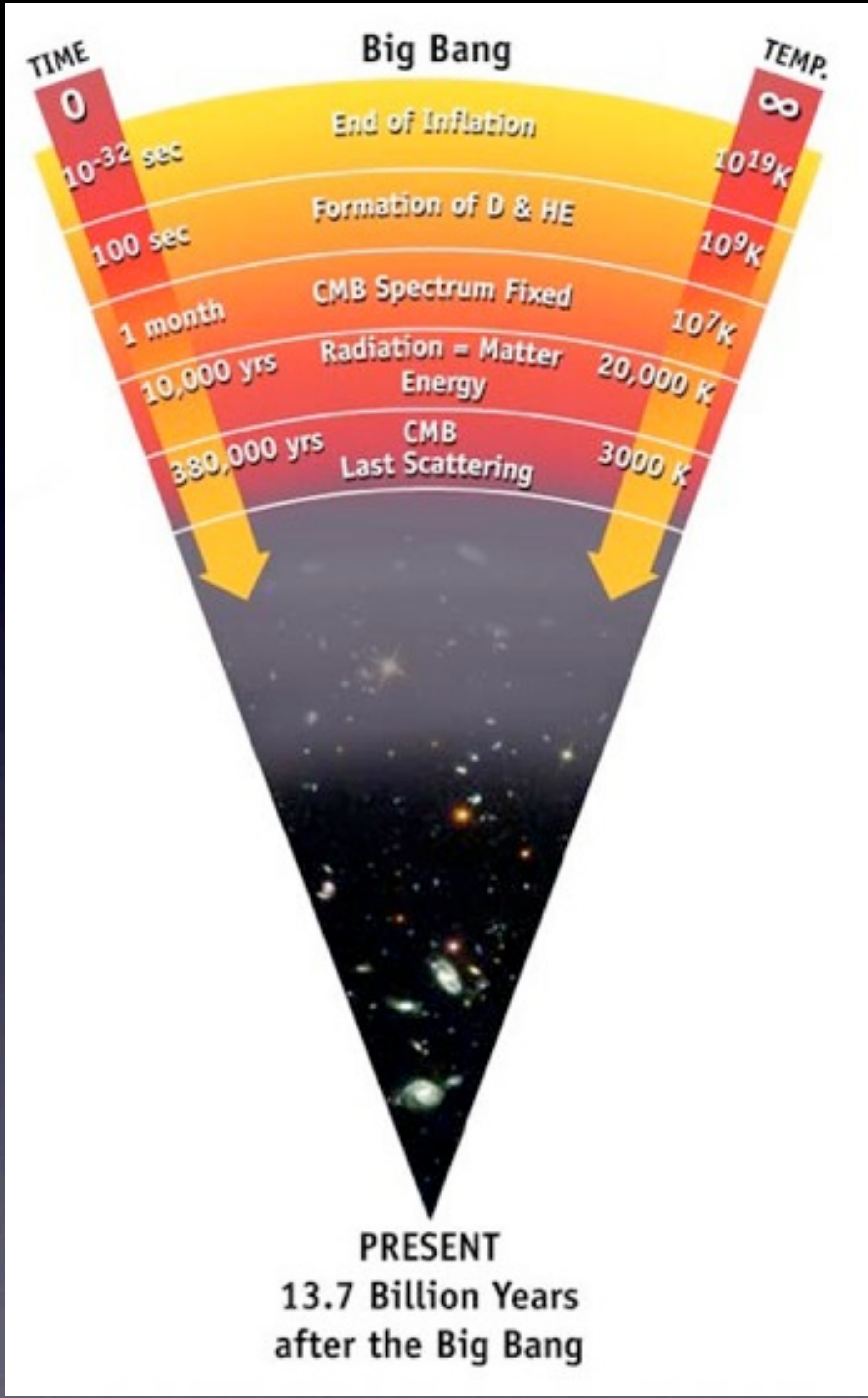
Others

- Anti protons
- Gamma from dwarf galaxy
- Diffuse neutrino
- Synchrotron radiation

Constraints on DM annihilation cross section

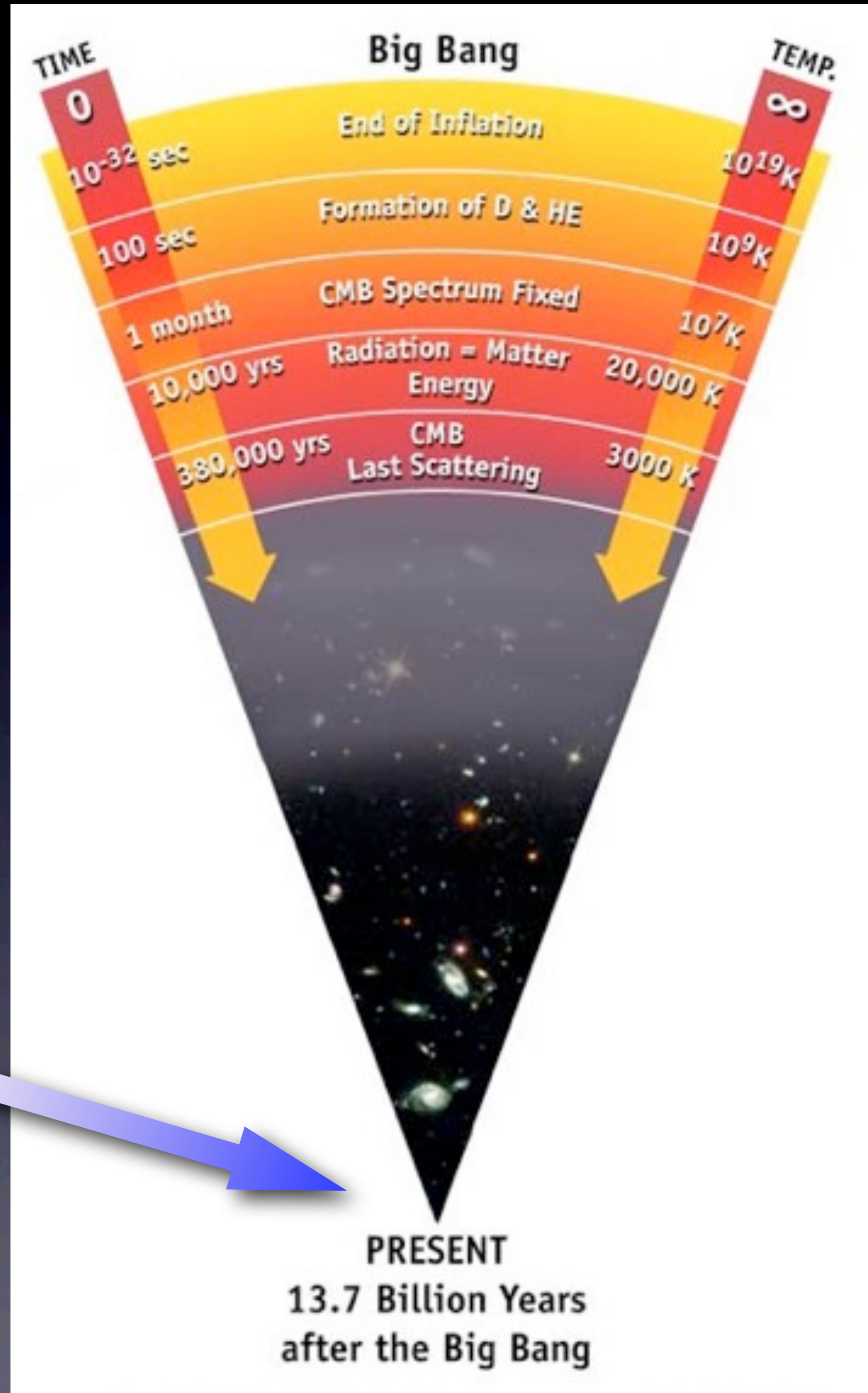


KN, Ph.D Thesis



2010年10月17日日曜日


Dark matter annihilation
in the Galaxy now
Positron,
Gamma-ray,
Neutrinos,...

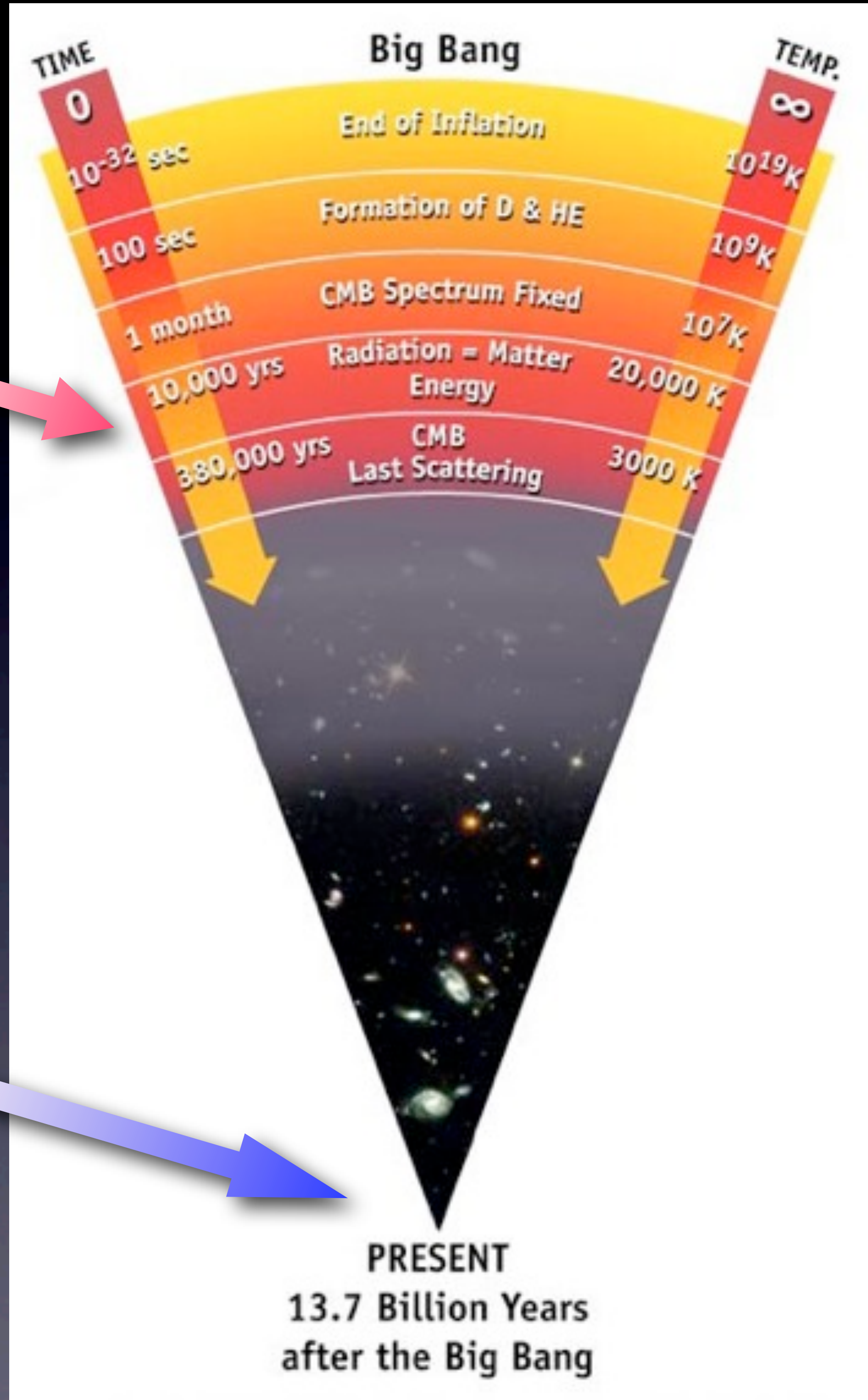

Big Bang
TIME
TEMP.
0
∞
End of Inflation
10-32 sec
1019K
Formation of D & HE
100 sec
109K
CMB Spectrum Fixed
1 month
107K
Radiation = Matter Energy
10,000 yrs
20,000 K
CMB Last Scattering
380,000 yrs
3000 K
PRESENT
13.7 Billion Years
after the Big Bang

Dark matter annihilation
in the early Universe

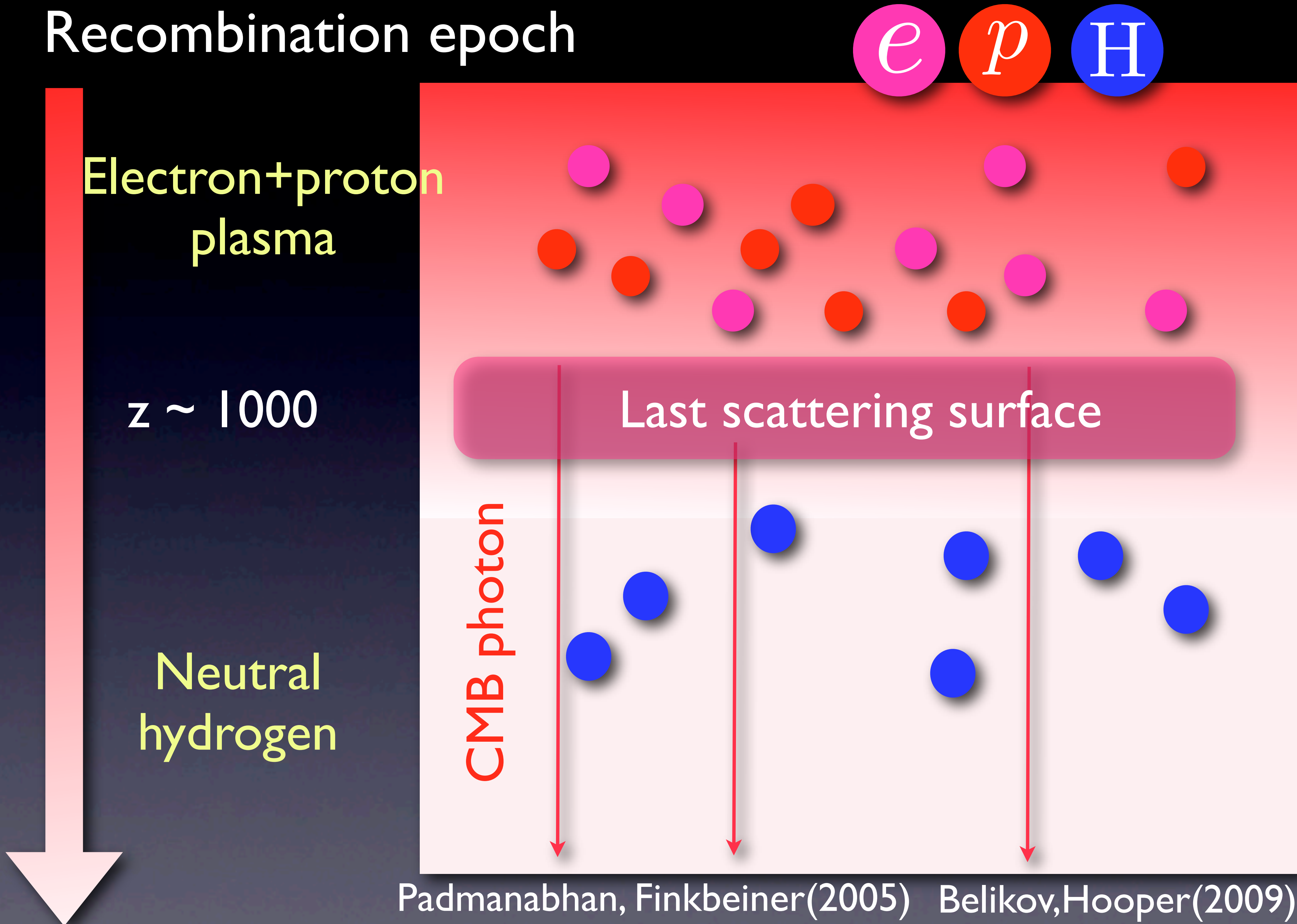
Effects on
Big-Bang Nucleosynthesis
& CMB anisotropy

Dark matter annihilation
in the Galaxy now

Positron,
Gamma-ray,
Neutrinos,...

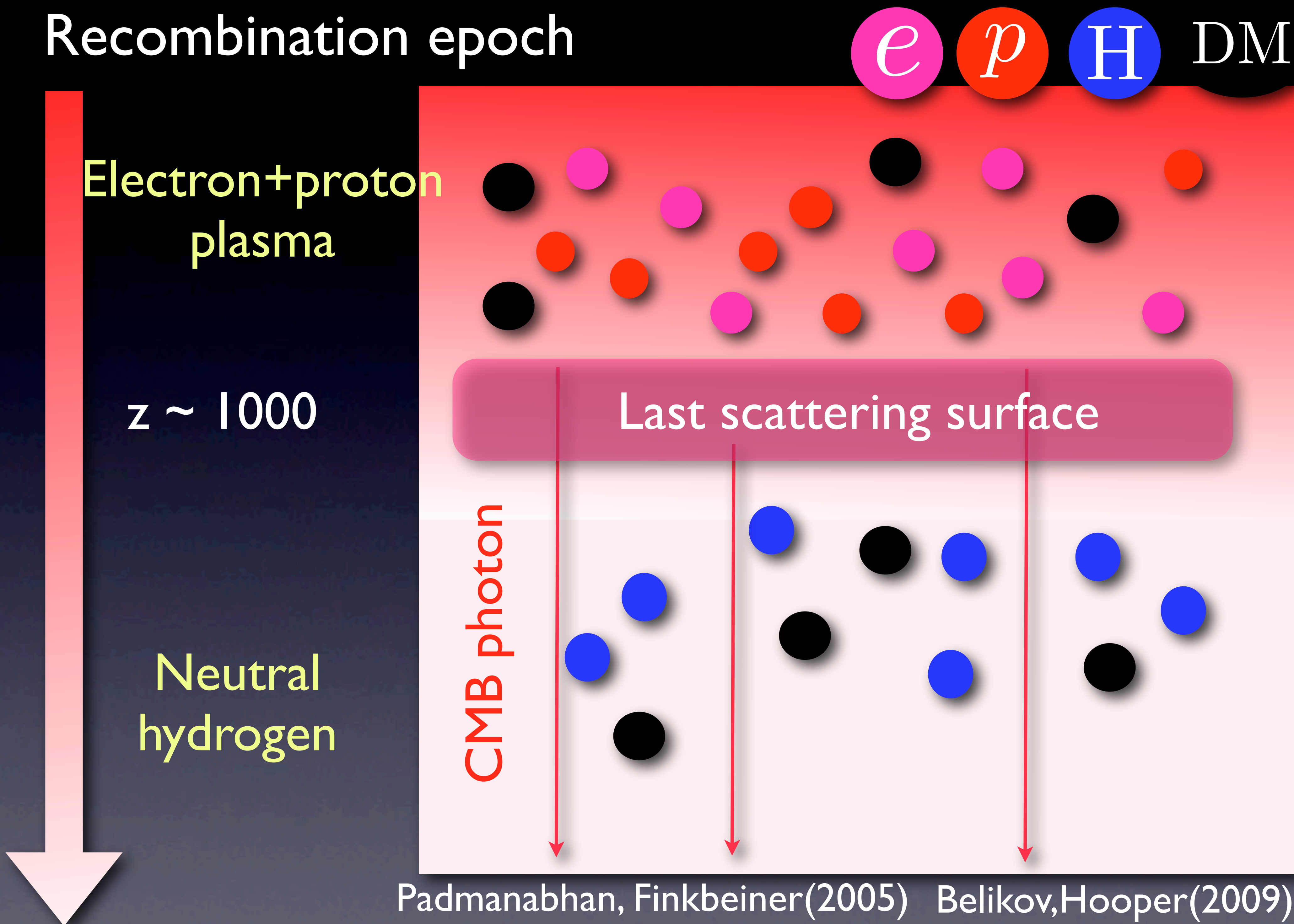


Recombination epoch



Padmanabhan, Finkbeiner(2005) Belikov,Hooper(2009)
S.Galli et al.,(2009), G.Huesti et al.(2009) T.Slatyer et al.(2009)

Recombination epoch



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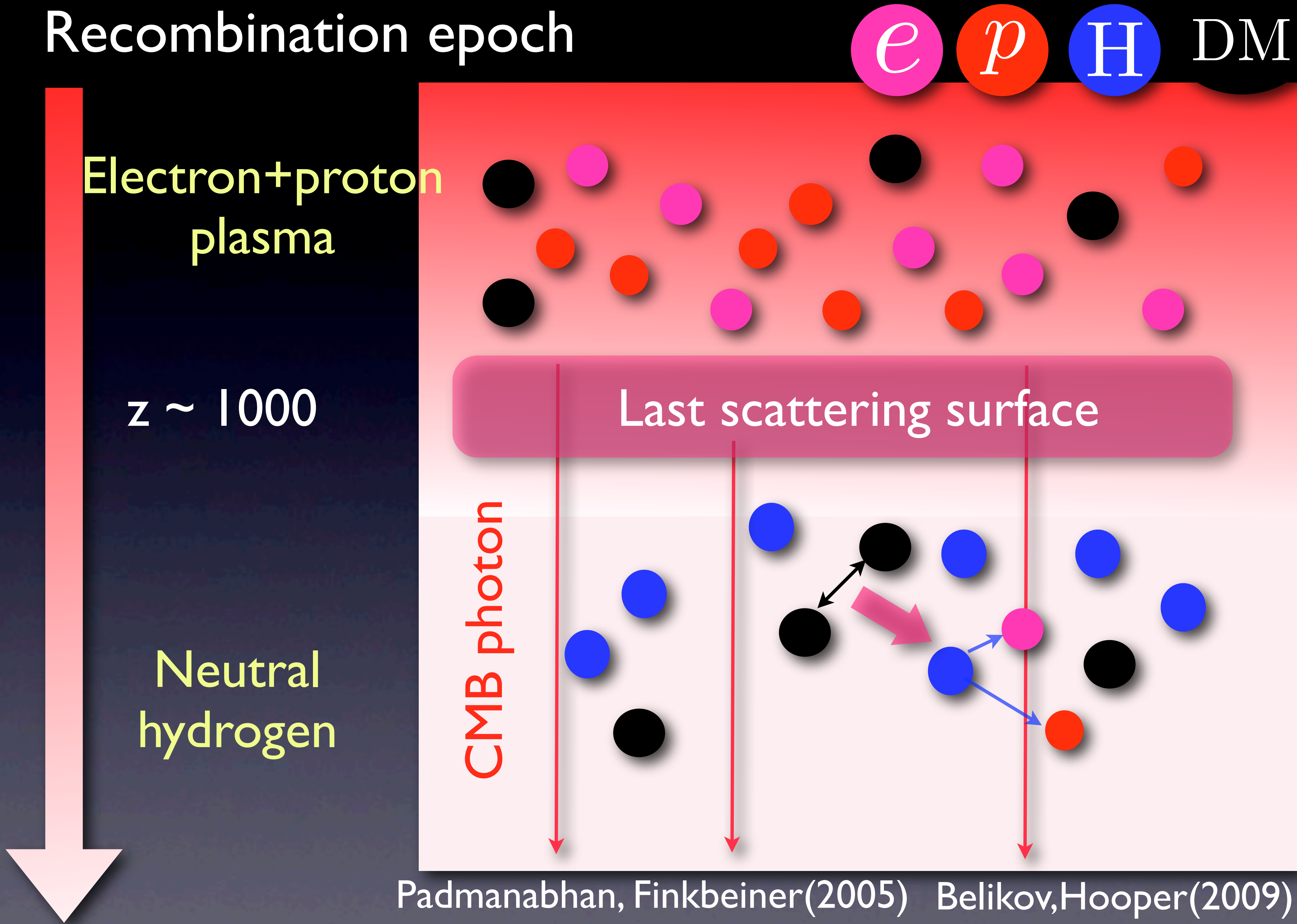

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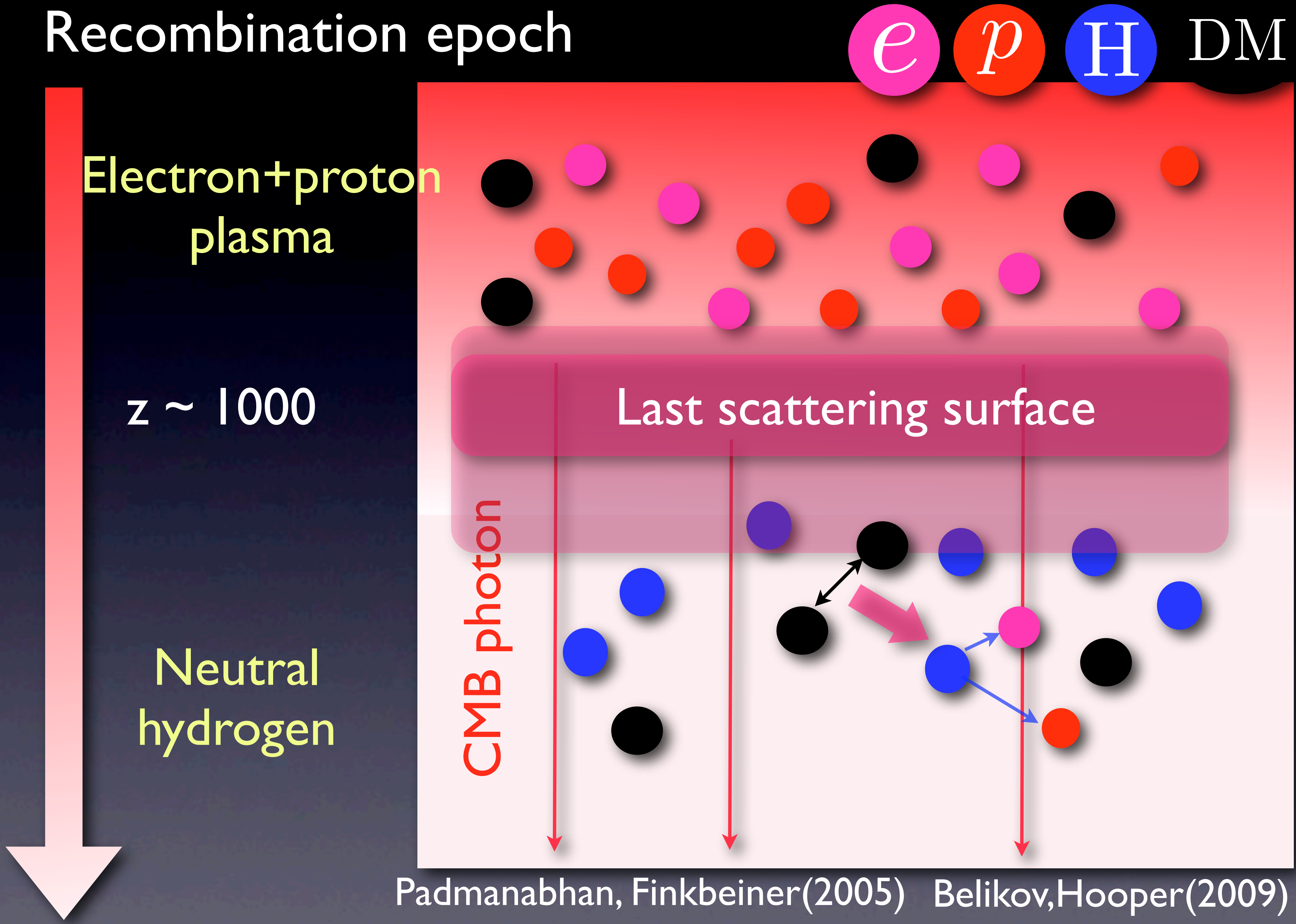


Padmanabhan, Finkbeiner(2005) Belikov,Hooper(2009)
S.Galli et al.,(2009), G.Huesti et al.(2009) T.Slatyer et al.(2009)

Energy deposition from DM in the early universe

T.Kanzaki, M.Kawasaki, KN (2009)

(a) Photon injection

- Pair creation

  $$\gamma + \gamma_{\rm BG} \to e^+ e^-$$

- Compton scatter

  $$\gamma + e_{\rm BG} \to \gamma + e^-$$

- Photon-photon scatter

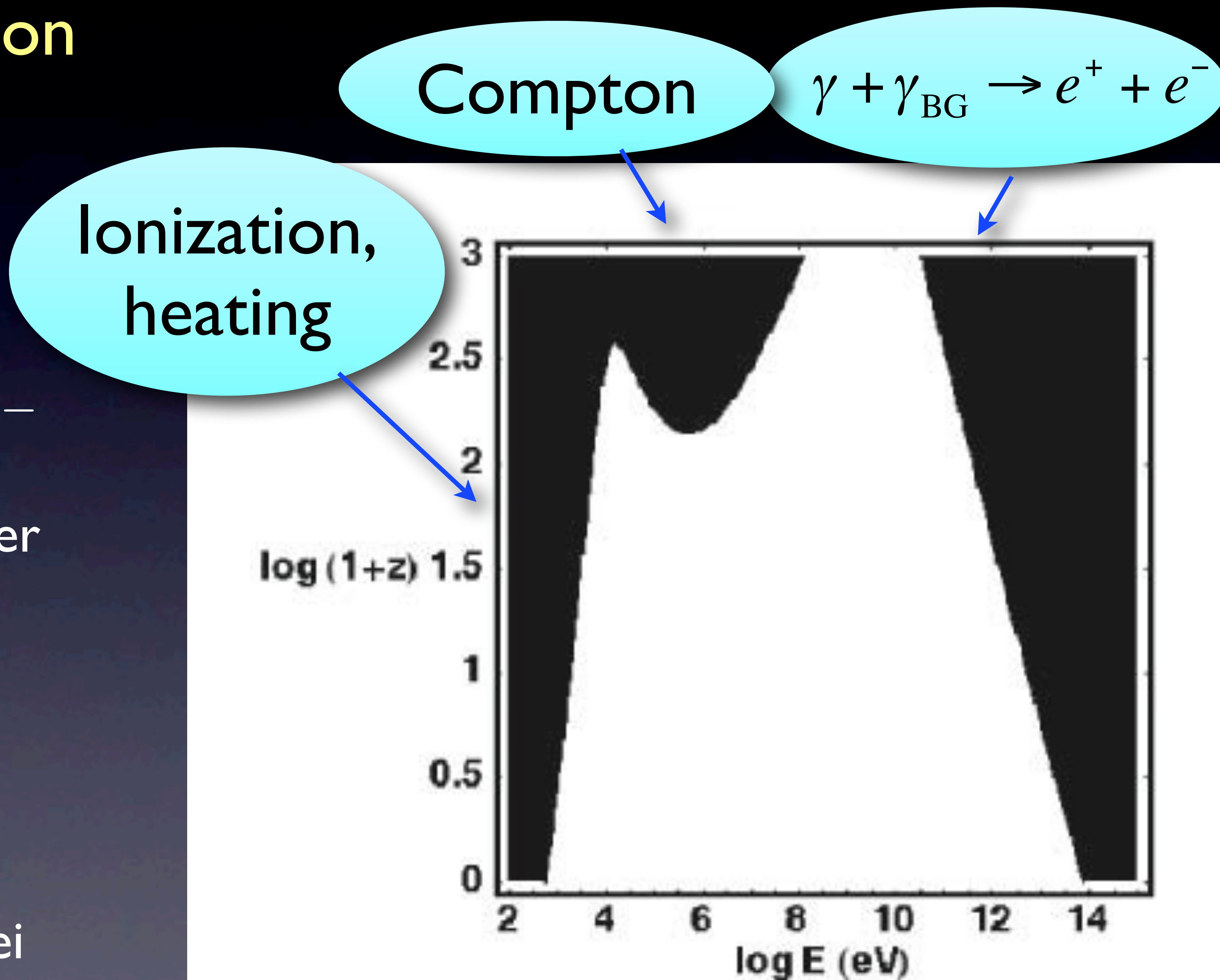
  $$\gamma + \gamma_{\rm BG} \to \gamma\gamma$$

- Ionization of H

  $$\gamma + {\rm H} \to p + e^-$$

- Pair creation in nuclei

  $$\gamma + {\rm H} \to e^- e^+ + {\rm H}$$



Chen, Kamionkowski (2004)

(b) Electron injection

- Inverse Compton scatter $e^- + \gamma_{\rm BG} \rightarrow e^- + \gamma$
- Coulomb collision $e^- + e^-_{\rm BG} \rightarrow e^- + e^-$
- Collision with H $e^- + {\rm H} \rightarrow e^- + {\rm H}$
- Ionization of H $e^- + {\rm H} \rightarrow 2e^- + p$
- Excitation of H $e^- + {\rm H} \rightarrow e^- + {\rm H}^*$

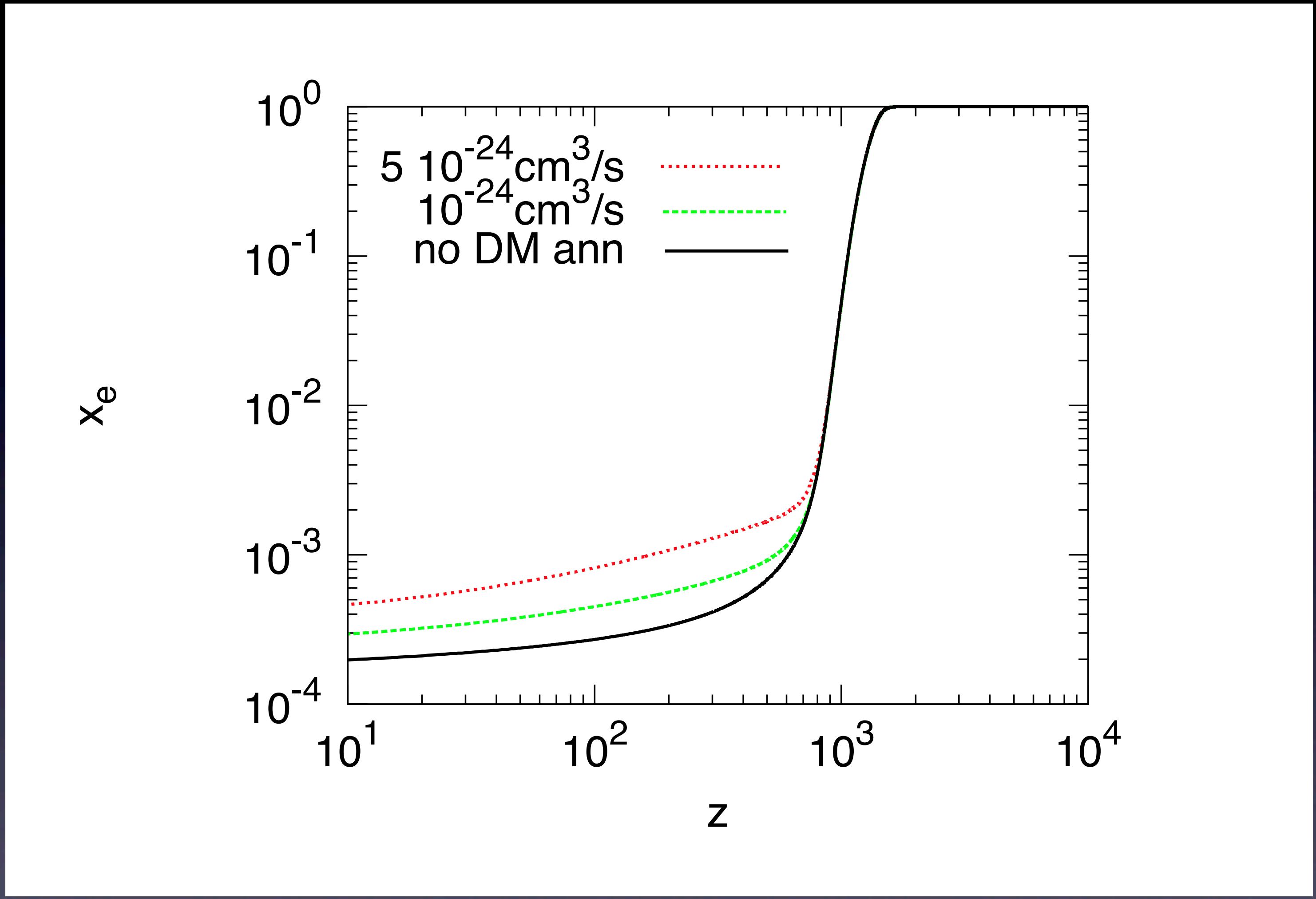
Dominant energy loss process of high energy electron is Inverse-Compton scattering

→ Up-scattered CMB has energy $E \sim \gamma_e^2 E_{\rm CMB}$

→ Ionization, heating, etc...

Modify RECFAST code to include these effects

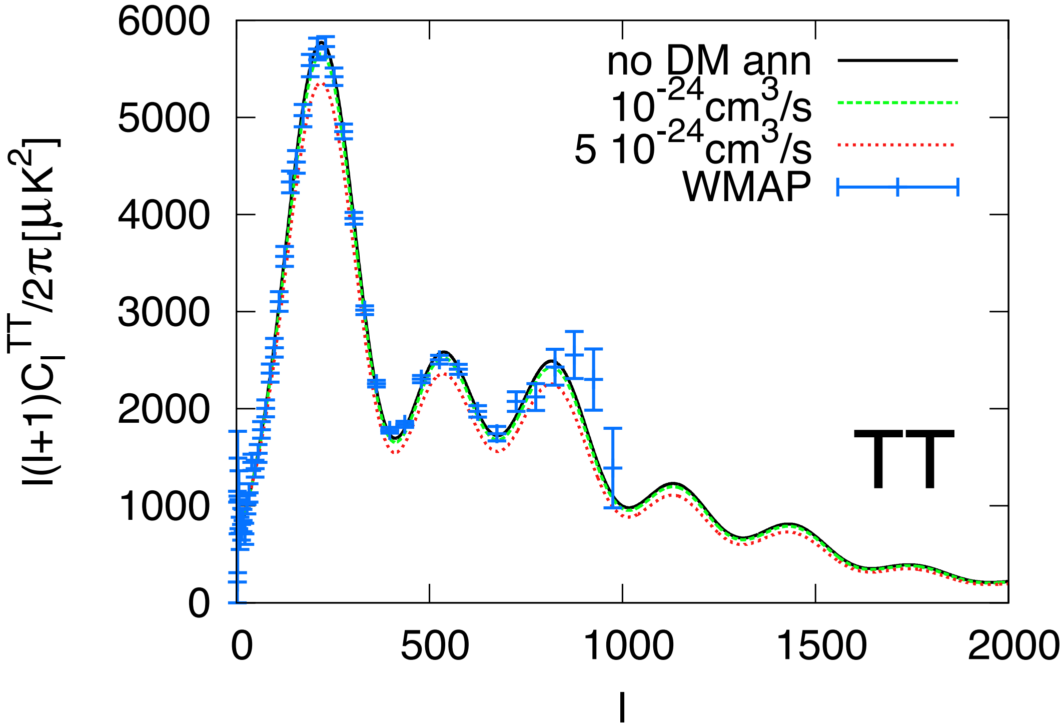
Ionization fraction of H



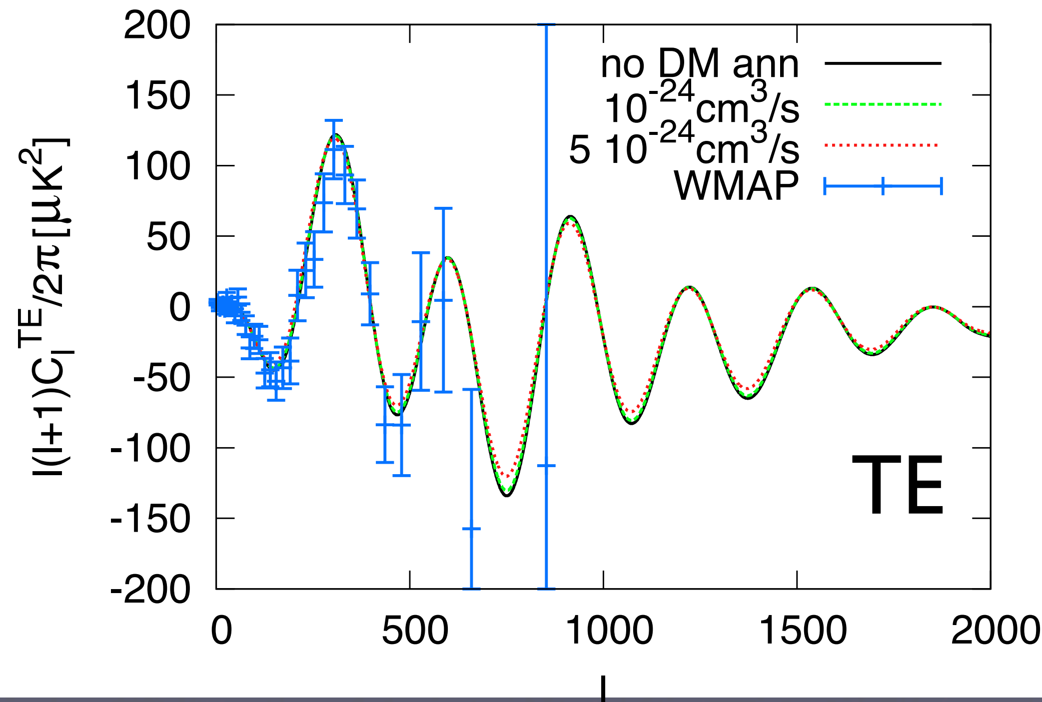
DM annihilation effect increases ionization fraction

→ Large optical depth

CMB anisotropy with effect of DM annihilation



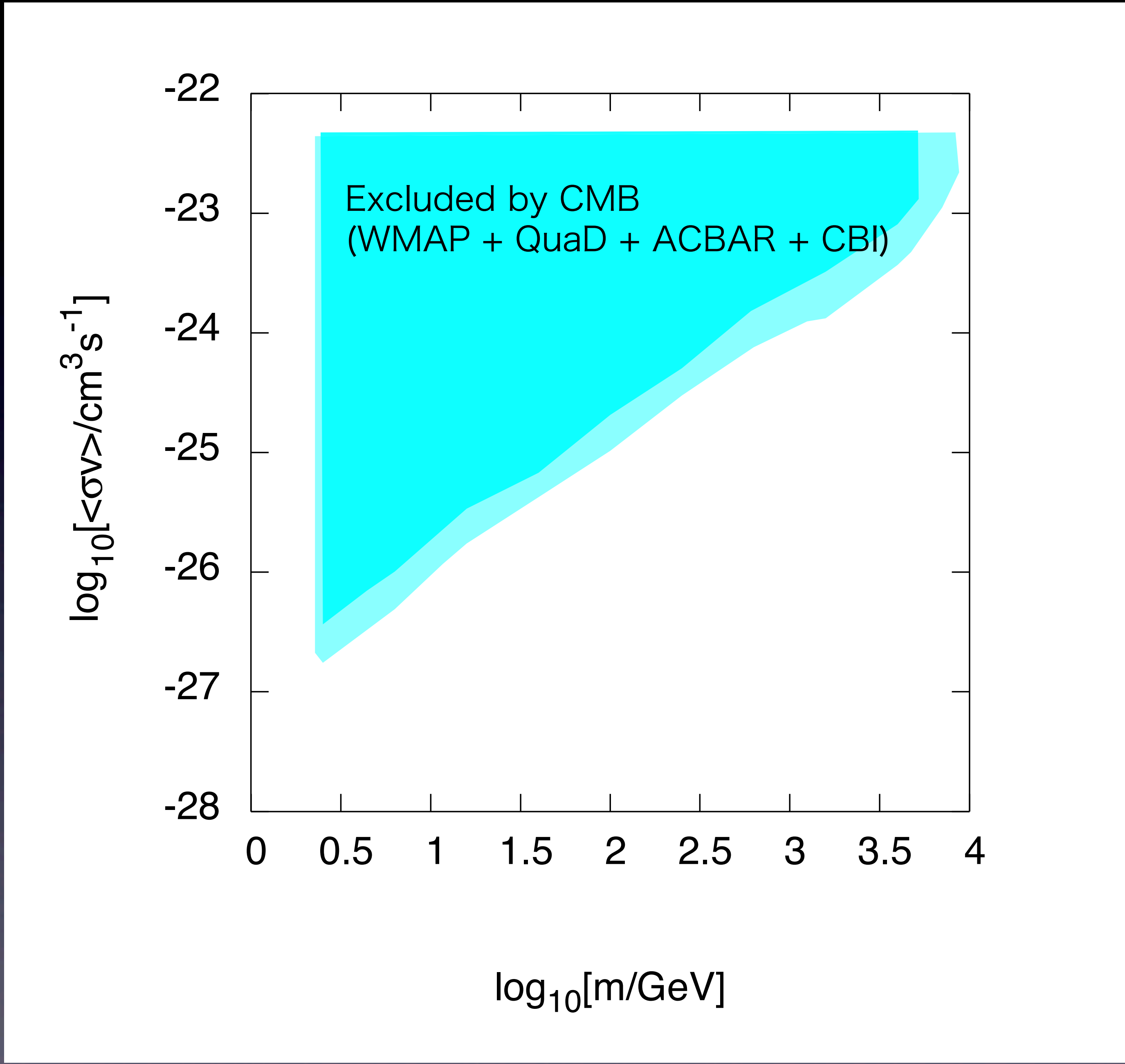
$$\chi\chi \to e^+e^-$$



$$\langle\sigma v\rangle = 10^{-24}\mathrm{cm}^3\mathrm{s}^{-1}$$
$$\langle\sigma v\rangle = 5\times 10^{-24}\mathrm{cm}^3\mathrm{s}^{-1}$$

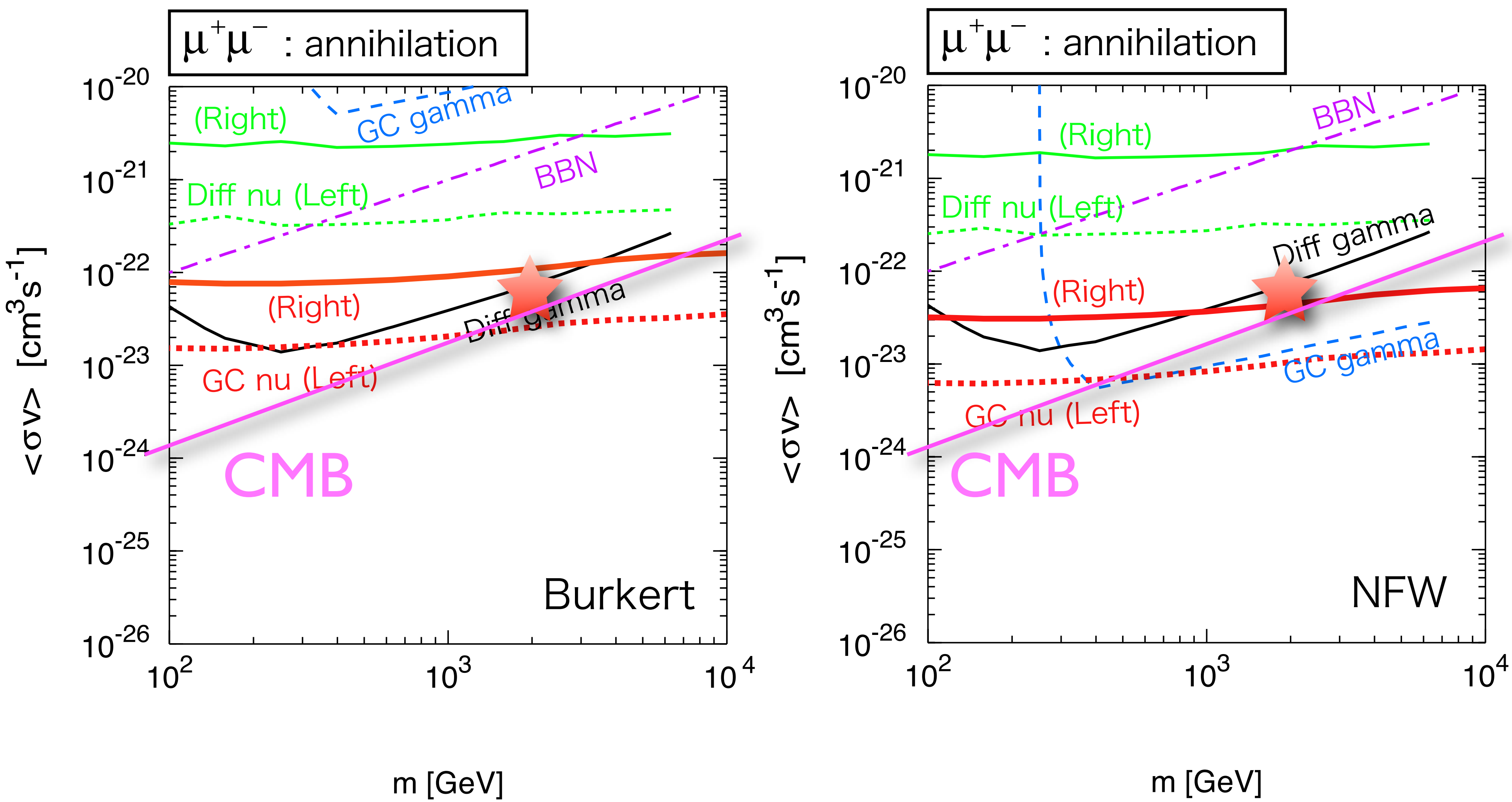
T.Kanzaki, M.Kawasaki and KN, arXiv:0907.3985

$$\chi\chi \rightarrow e^+e^-$$



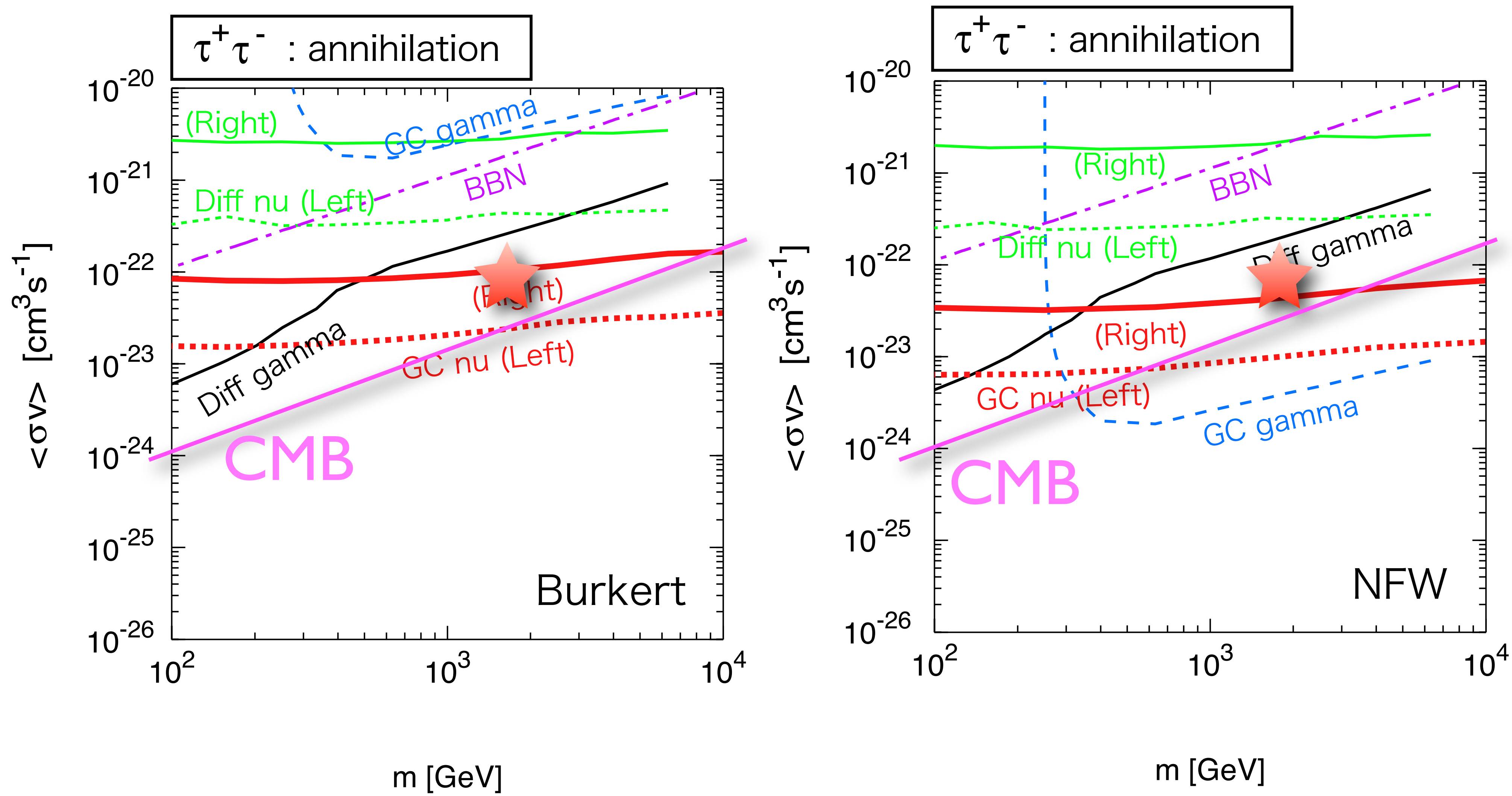
M.Kawasaki, KN and T.Sekiguchi, in prep.

Summary of constraints on DM annihilation cross section



KN, Ph.D Thesis

Summary of constraints on DM annihilation cross section

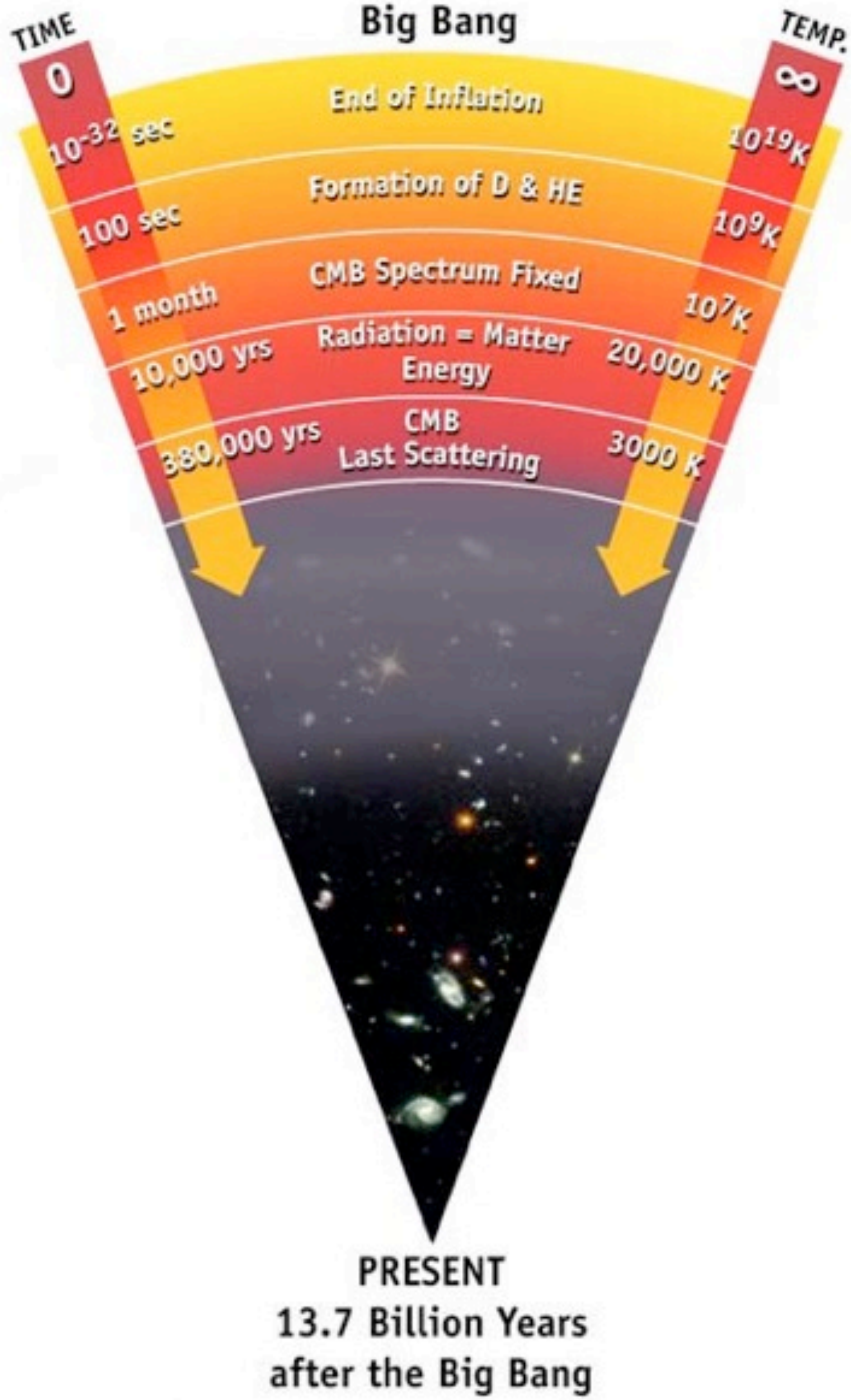


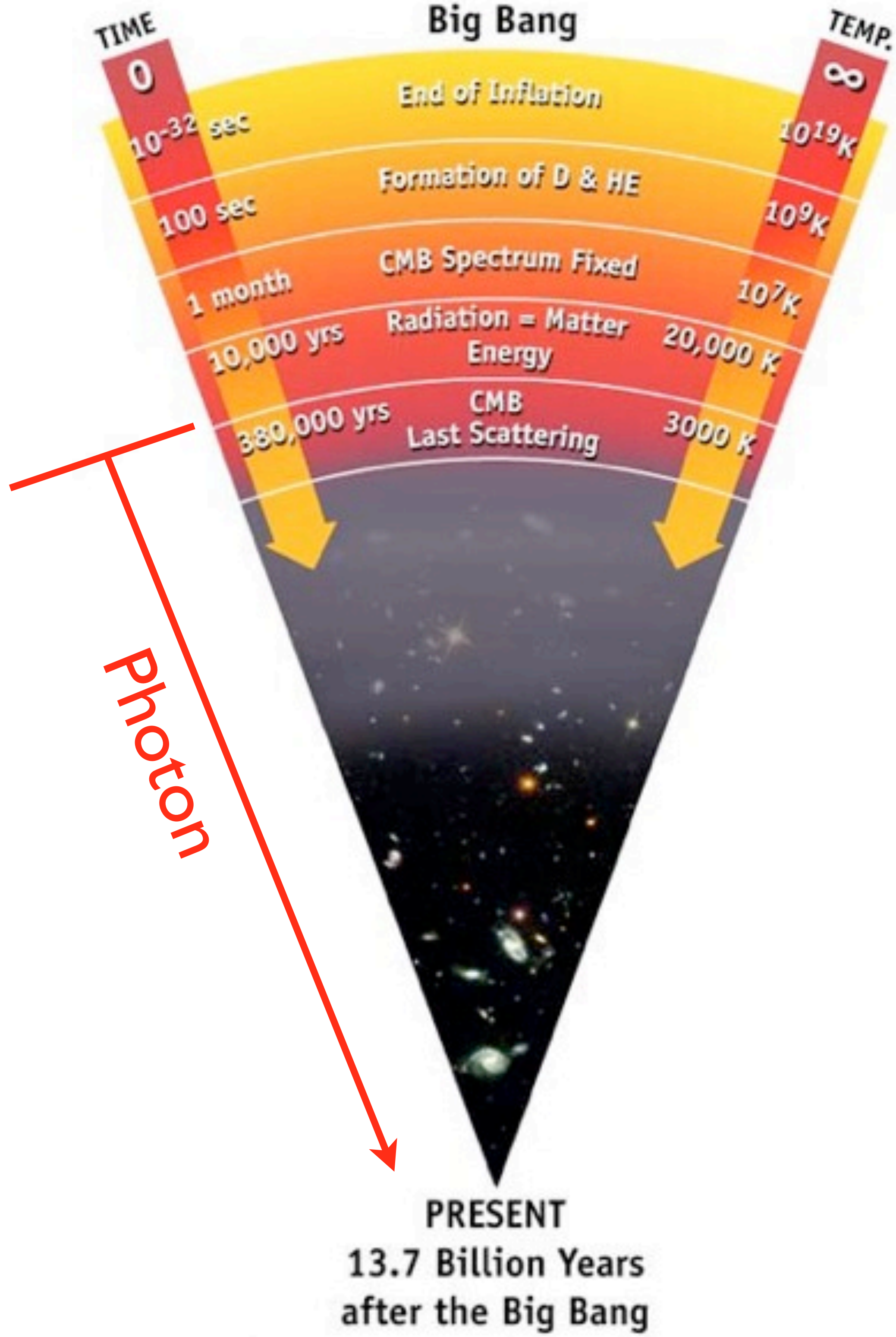
KN, Ph.D Thesis

Probing (non)thermal history of the Universe

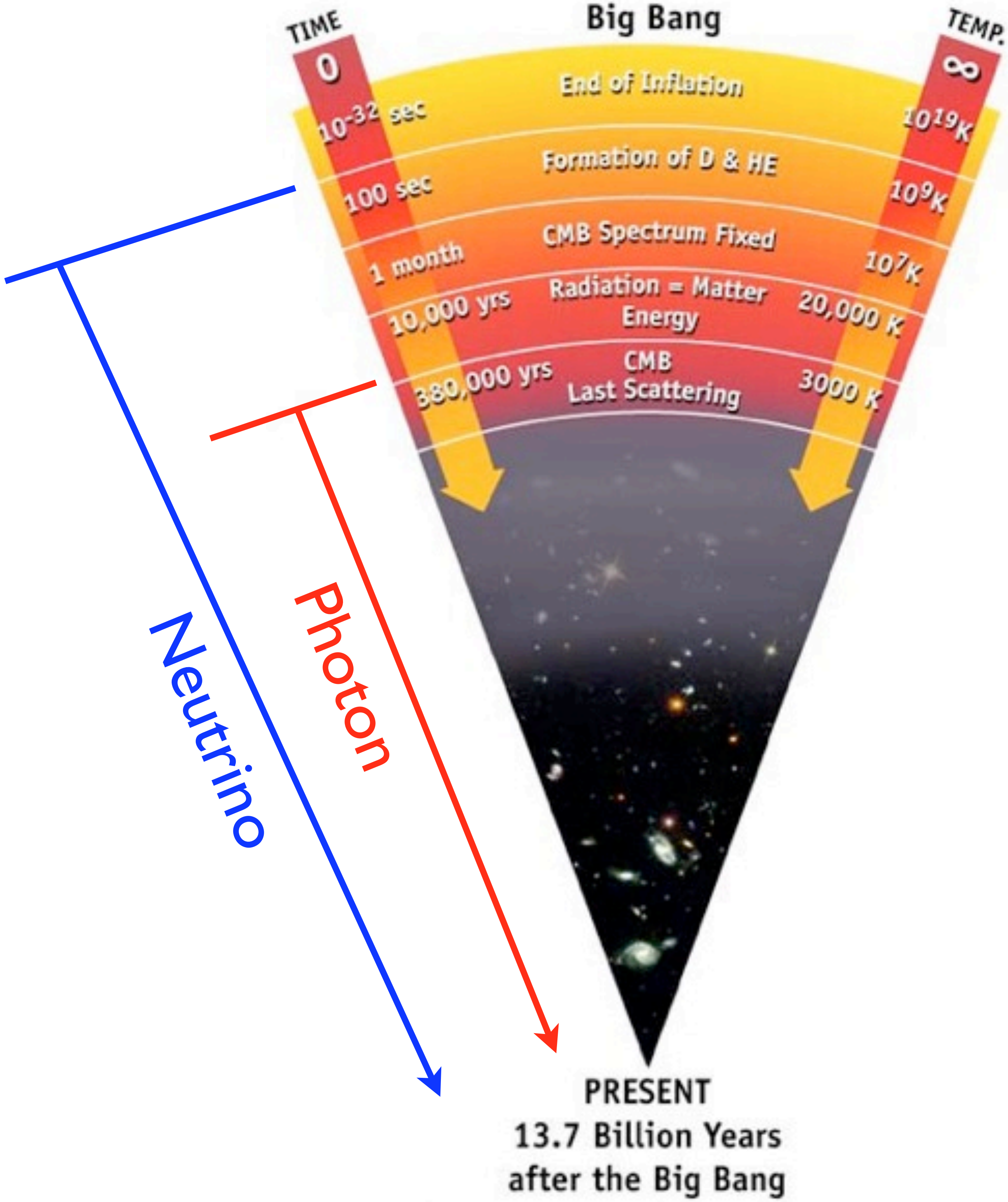
↓

Gravitational Wave


Big Bang
TIME
0
End of Inflation
10-32 sec
10¹⁹K
Formation of D & HE
100 sec
10⁹K
CMB Spectrum Fixed
1 month
10⁷K
Radiation = Matter Energy
10,000 yrs
20,000 K
CMB Last Scattering
380,000 yrs
3000 K
TEMP.
∞
PRESENT
13.7 Billion Years after the Big Bang



TIME
Big Bang
TEMP.
0
∞
End of Inflation
10-32 sec
1019K
Formation of D & HE
100 sec
109K
CMB Spectrum Fixed
1 month
107K
Radiation = Matter Energy
10,000 yrs
20,000 K
CMB Last Scattering
380,000 yrs
3000 K
Photon
PRESENT
13.7 Billion Years after the Big Bang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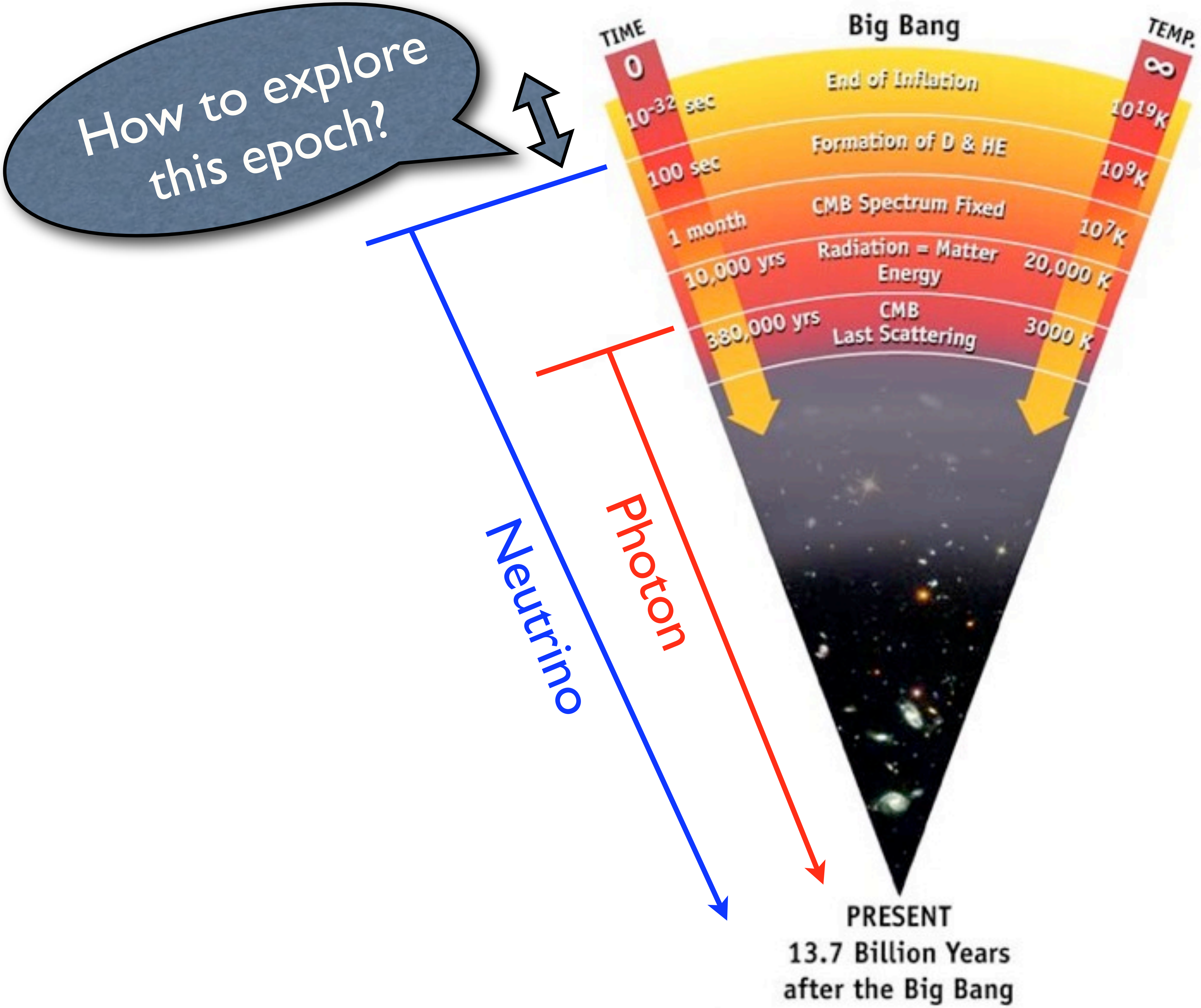
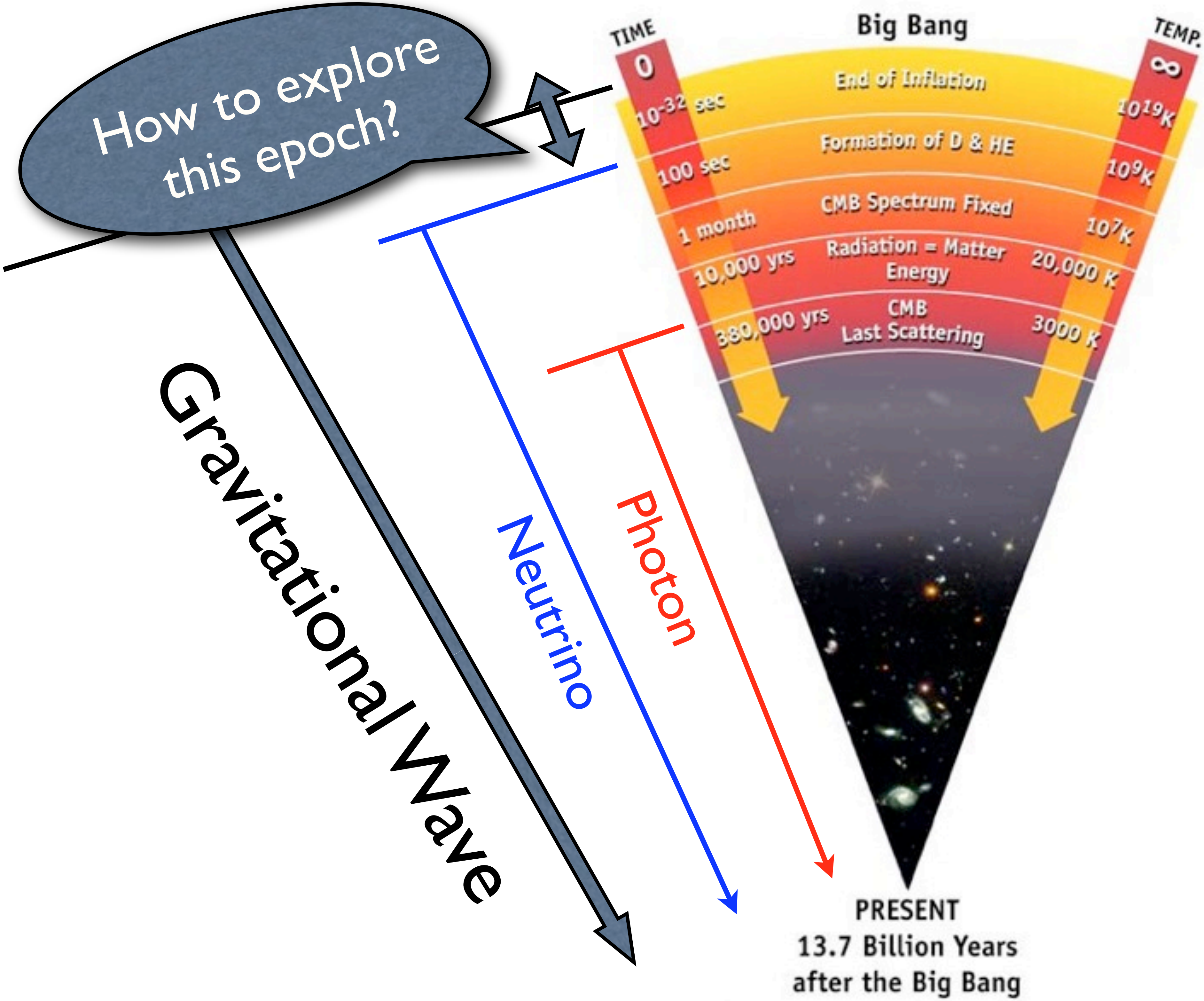
20,000 K
CMB Last Scattering
380,000 yrs
3000 K
Neutrino
Photon
PRESENT
13.7 Billion Years after the Big Bang


How to explore this epoch?
Big Bang
TIME
TEMP.
0
∞
End of Inflation
10^{-32} sec
10^{19}K
Formation of D & HE
100 sec
10^{9}K
CMB Spectrum Fixed
1 month
10^{7}K
Radiation = Matter Energy
10,000 yrs
20,000 K
CMB Last Scattering
380,000 yrs
3000 K
Photon
Neutrino
PRESENT
13.7 Billion Years after the Big Bang



How to explore this epoch?
Gravitational Wave
Neutrino
Photon
TIME
Big Bang
TEMP.
0
∞
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10-32 sec
10^19 K
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Gravitational waves from inflation

Metric perturbation (tensor part)

$$ds^2 = a^2(t)[-d\tau^2 + (\delta_{ij} + 2h_{ij})dx^i dx^j]$$

$$h_{ij} = \frac{1}{M_P} \sum_{\lambda=+,-} \int \frac{d^3k}{(2\pi)^{3/2}} h_k^\lambda(t) e^{i\mathbf{kx}} e_{ij}^\lambda$$

Same as massless field

Quantization

$$\langle h_k^\lambda h_{k'}^{\lambda'} \rangle = \frac{H_{\rm inf}^2}{2k^3} \delta^3(k-k')\delta^{\lambda\lambda'}$$

Dimensionless power spectrum

$$\Delta_h^2(k) = 64\pi G \left(\frac{H_{\rm inf}}{2\pi} \right)^2$$

Evolution of GW

$$\ddot{h}_k^\lambda + 3H\dot{h}_k^\lambda + \frac{k^2}{a^2}h_k^\lambda = 0$$

→ Outside the horizon : $h_k^\lambda = \text{const.}$

In the horizon : $h_k^\lambda \propto a^{-1}$

$$\frac{d\rho_{\rm gw}}{d\ln k} = \sum_\lambda \frac{1}{32\pi G} k^2 |h_k^\lambda|^2 \left(\frac{a_{\rm in}(k)}{a_0}\right)^2$$

$\propto k^{-4}$ for $k < k_{\rm eq}$

$\propto k^{-2}$ for $k > k_{\rm eq}$

$$\Omega_{\rm gw}(k) = \frac{1}{\rho_c}\frac{d\rho_{\rm gw}}{d\ln k}$$

$\propto k^{-2}$ for $k < k_{\rm eq}$

$\propto \text{const}$ for $k > k_{\rm eq}$

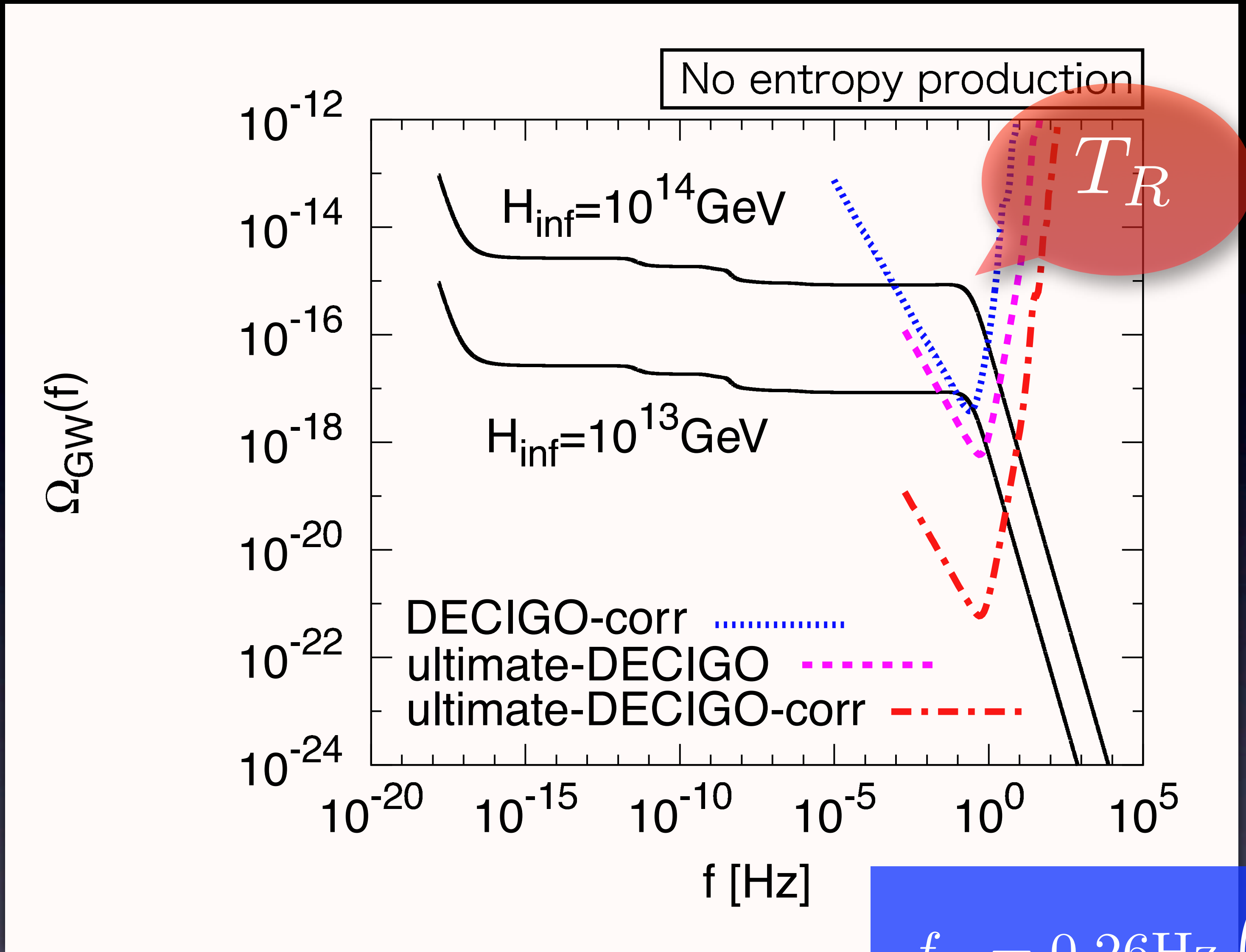
Rule :

$\Omega_{\rm gw}(k) \propto k^{-2}$ for horizon entry in MD era

$\Omega_{\rm gw}(k) \propto \text{const}$ for horizon entry in RD era

Spectrum of GWB

$T_\mathrm{R} = 10^7$ GeV

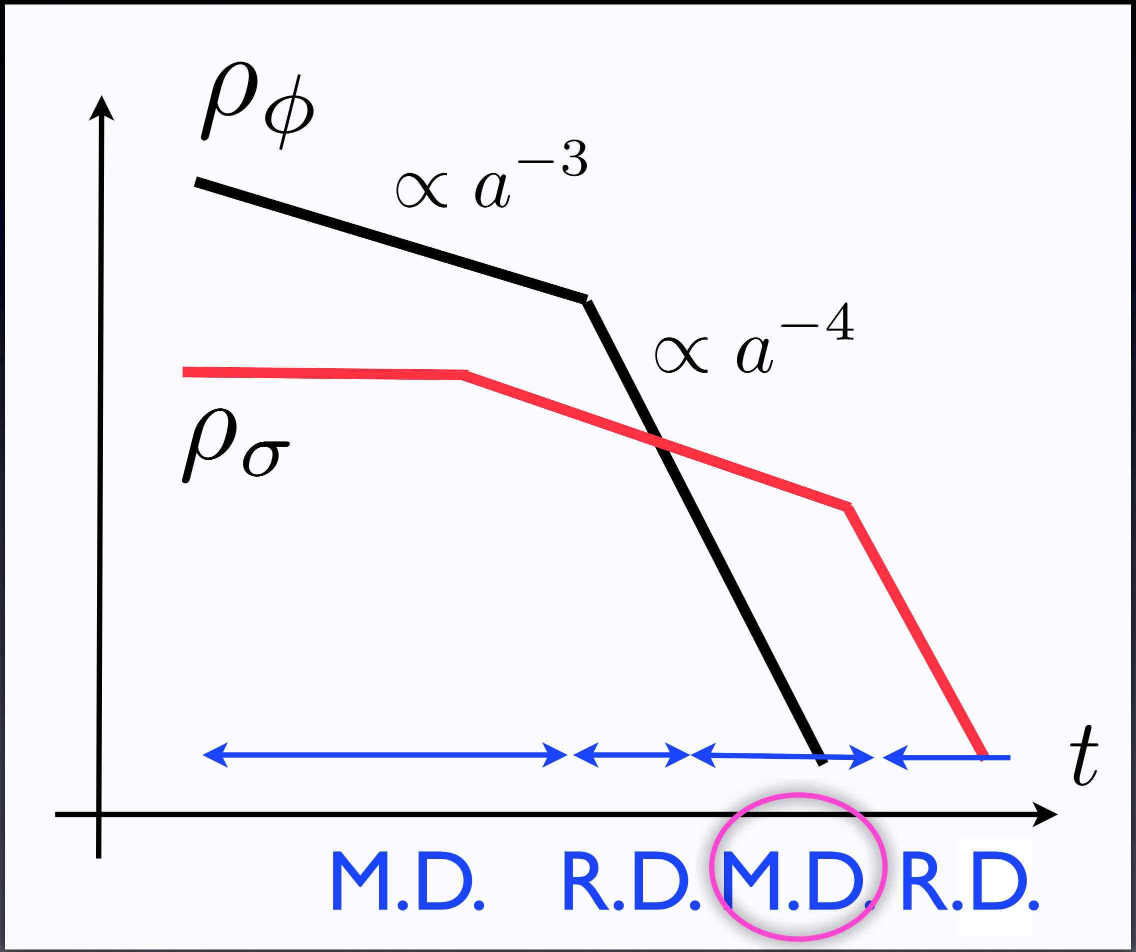


$$f_R = 0.26\mathrm{Hz}\left(\frac{T_R}{10^7\mathrm{GeV}}\right)$$

GWB spectrum＝Thermal history of the Universe

N.Seto, J.Yokoyama(2003), Boyle, Steinhardt (2005) KN, Saito, Suwa, Yokoyama(2008)

Thermal history may be modified due to the moduli field.



ϕ : inflaton

σ : moduli

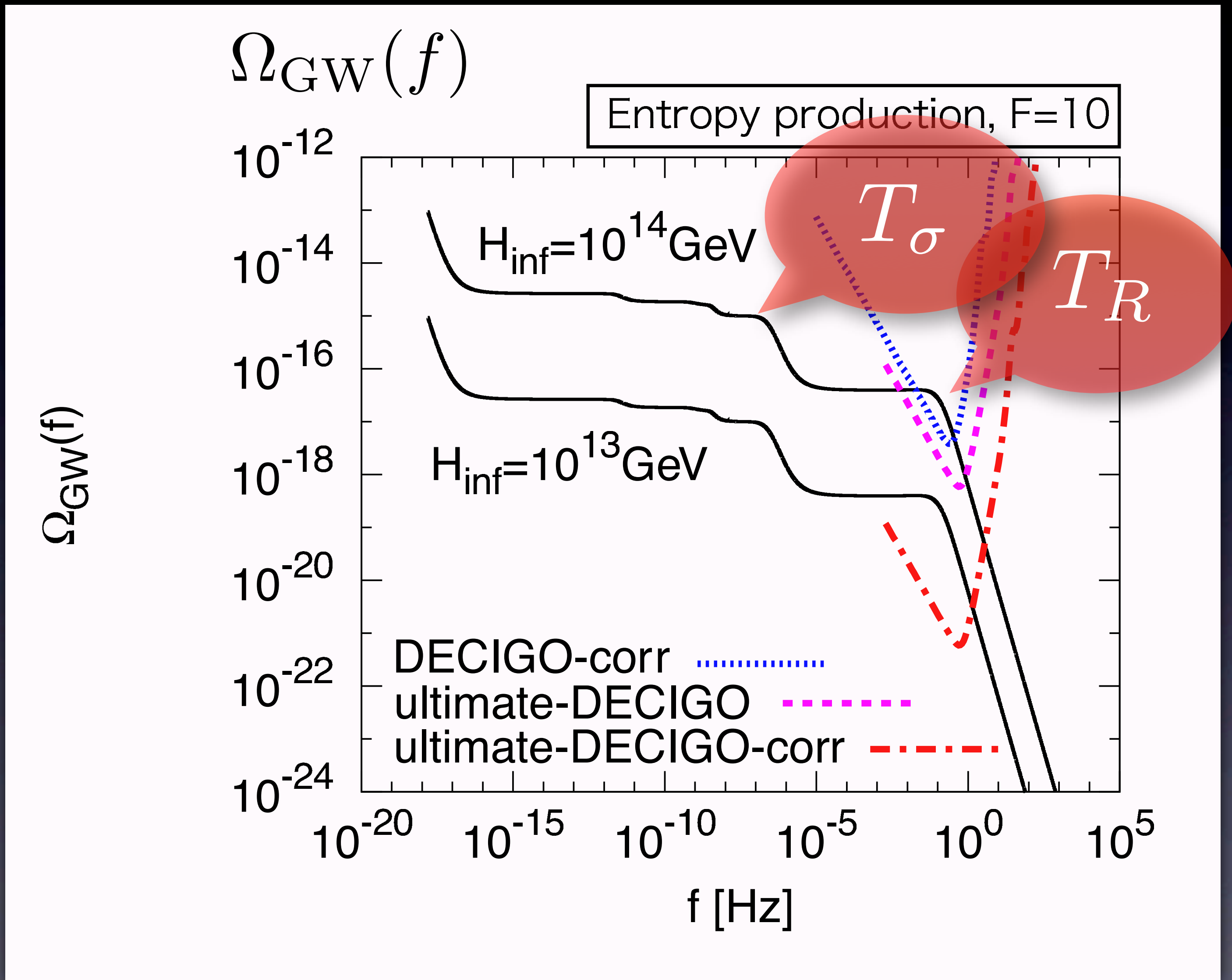
(Source of nonthermal DM)

intermediate M.D. epoch due to moduli domination

→ Imprints on the GWB spectrum

Moduli-dominant case

modulation on the GW spectrum



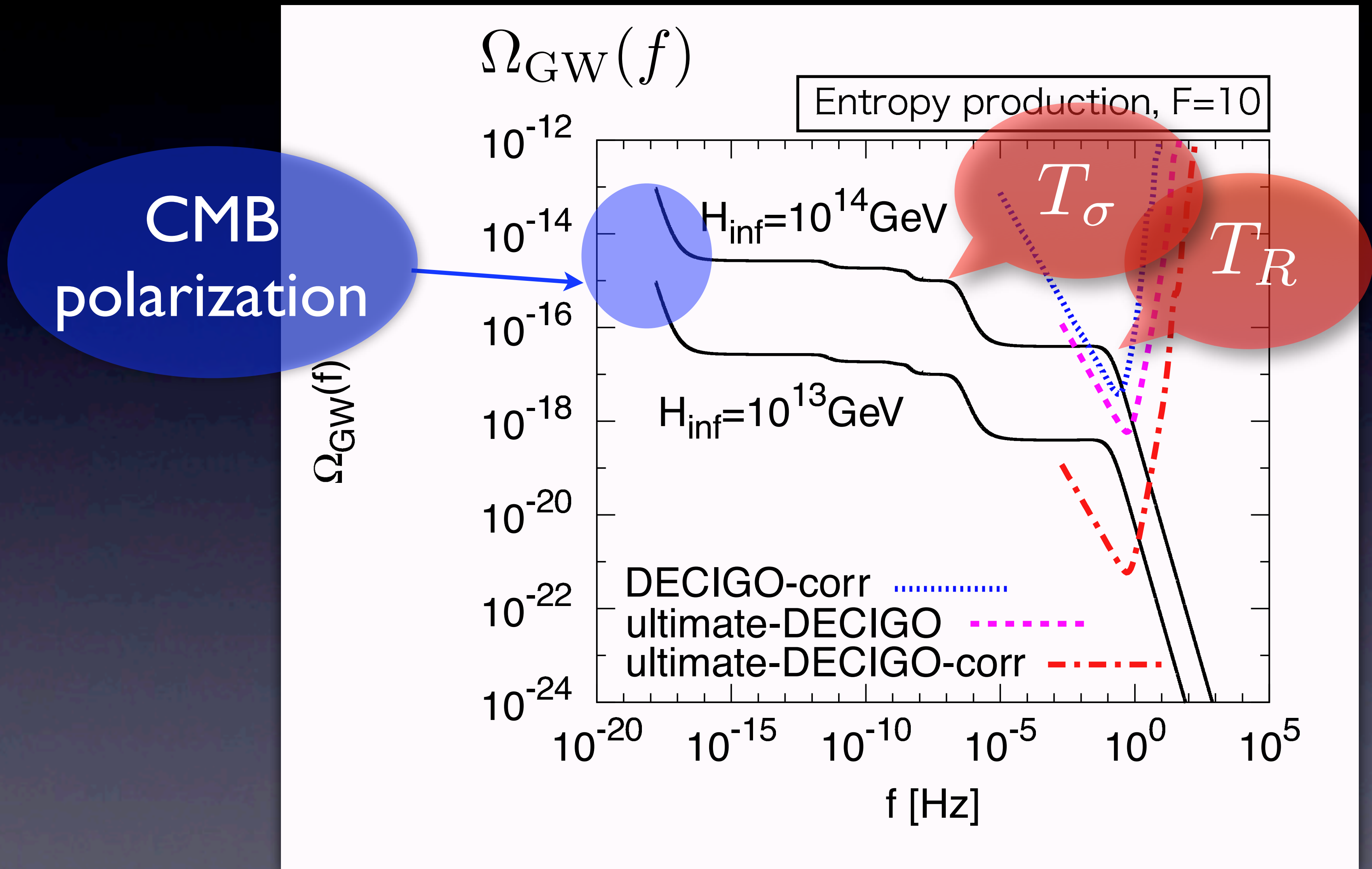
DECIGO
~2027 ?

$T_\sigma = 10\text{GeV}$ $\quad T_R = 10^7\text{GeV}$

KN, J.Yokoyama (2009)

Moduli-dominant case

modulation on the GW spectrum



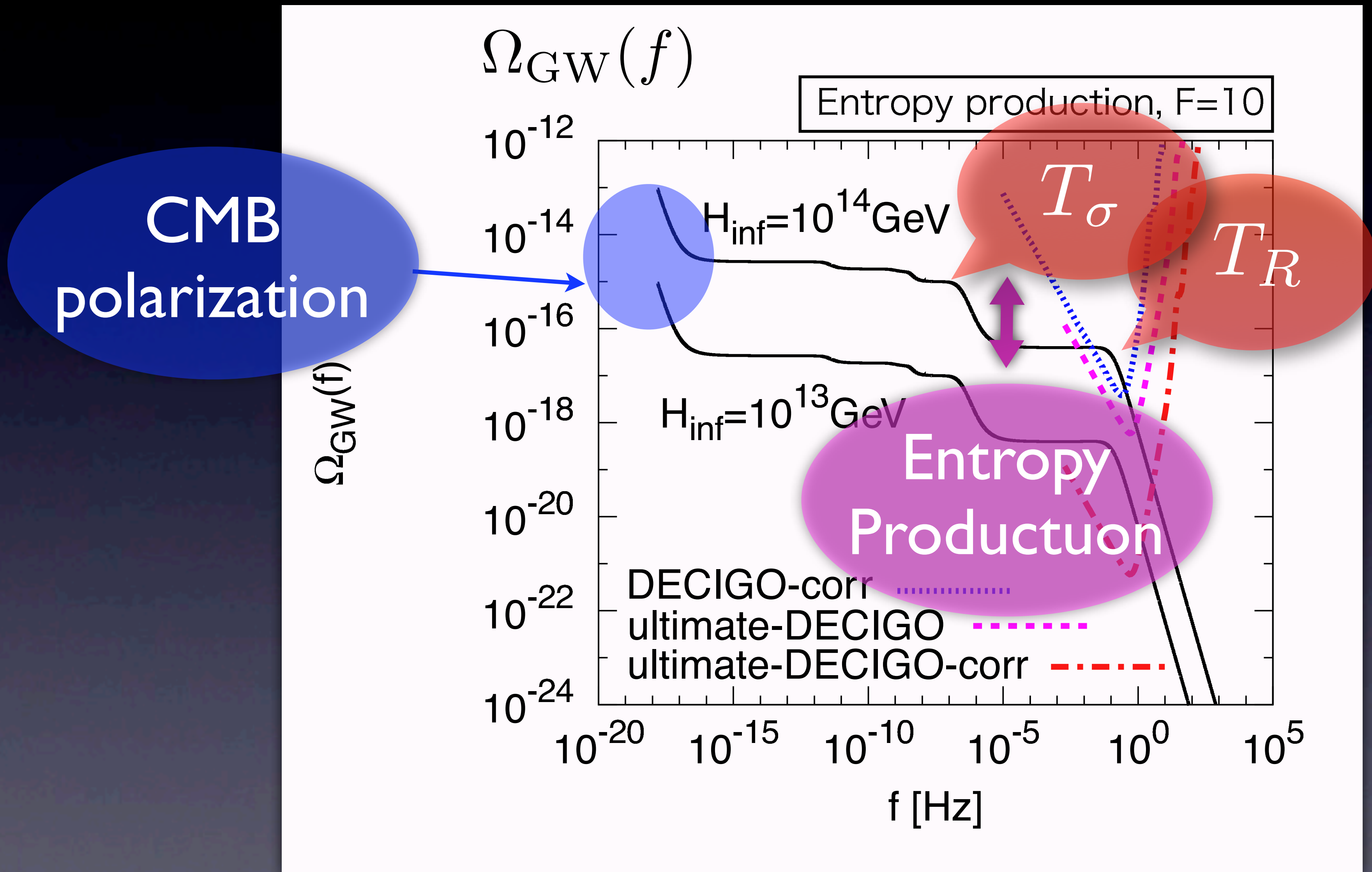
DECIGO
~2027 ?

KN, J.Yokoyama (2009)

$T_\sigma = 10\mathrm{GeV}$ $\quad T_R = 10^7\mathrm{GeV}$

■ Moduli-dominant case

modulation on the GW spectrum



DECIGO
~2027 ?

KN, J.Yokoyama (2009)

$T_\sigma = 10\mathrm{GeV} \quad T_R = 10^7\mathrm{GeV}$

Summary

- PAMELA/Fermi may indicate (nonthermal) DM with large cross section.
- Stringent constraint on the annihilation cross section from WMAP.
- (Non)thermal history of the Universe may be confirmed at future space laser interferometers.

Back-up Slides

GW spectrum at present

$$\rho_{\rm GW}(k) \sim \frac{1}{G} h_k^2 (k/a)^2$$

$k/a \sim H$ at horizon entry

$$\rho_{\rm tot} \sim \frac{1}{G} H^2$$

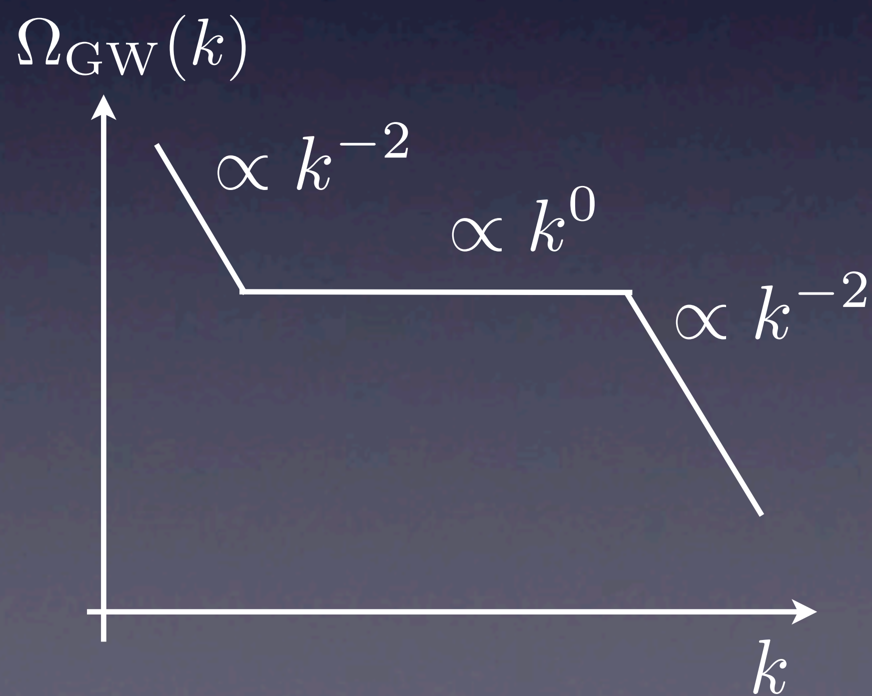
$$\Omega_{\rm GW}(k) = \frac{\rho_{\rm GW}(k)}{\rho_{\rm tot}} \sim \text{const. at horizon entry}$$

After horizon entry,

$$\Omega_{\rm GW}(k) \propto \text{const. in RD}$$

$$\Omega_{\rm GW}(k) \propto a^{-1} \text{ in MD}$$

$$(\; a(k)/a_0 \propto k^{-2} \;)$$



Astrophysical foreground

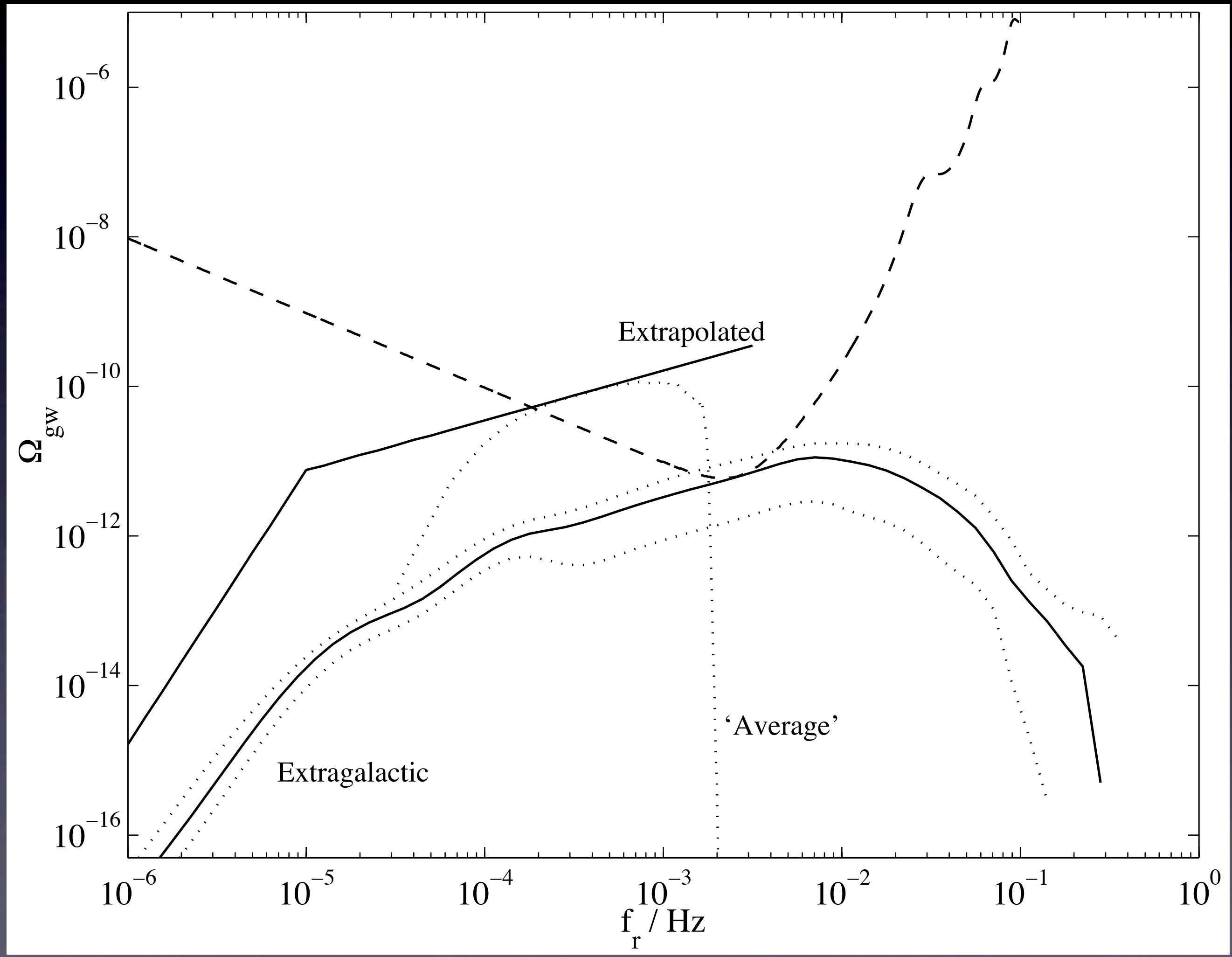
(1) White Dwarf binary

Merger of WD binary

→ Gravitational Waves

Completely stochastic

→ Cannot be removed.

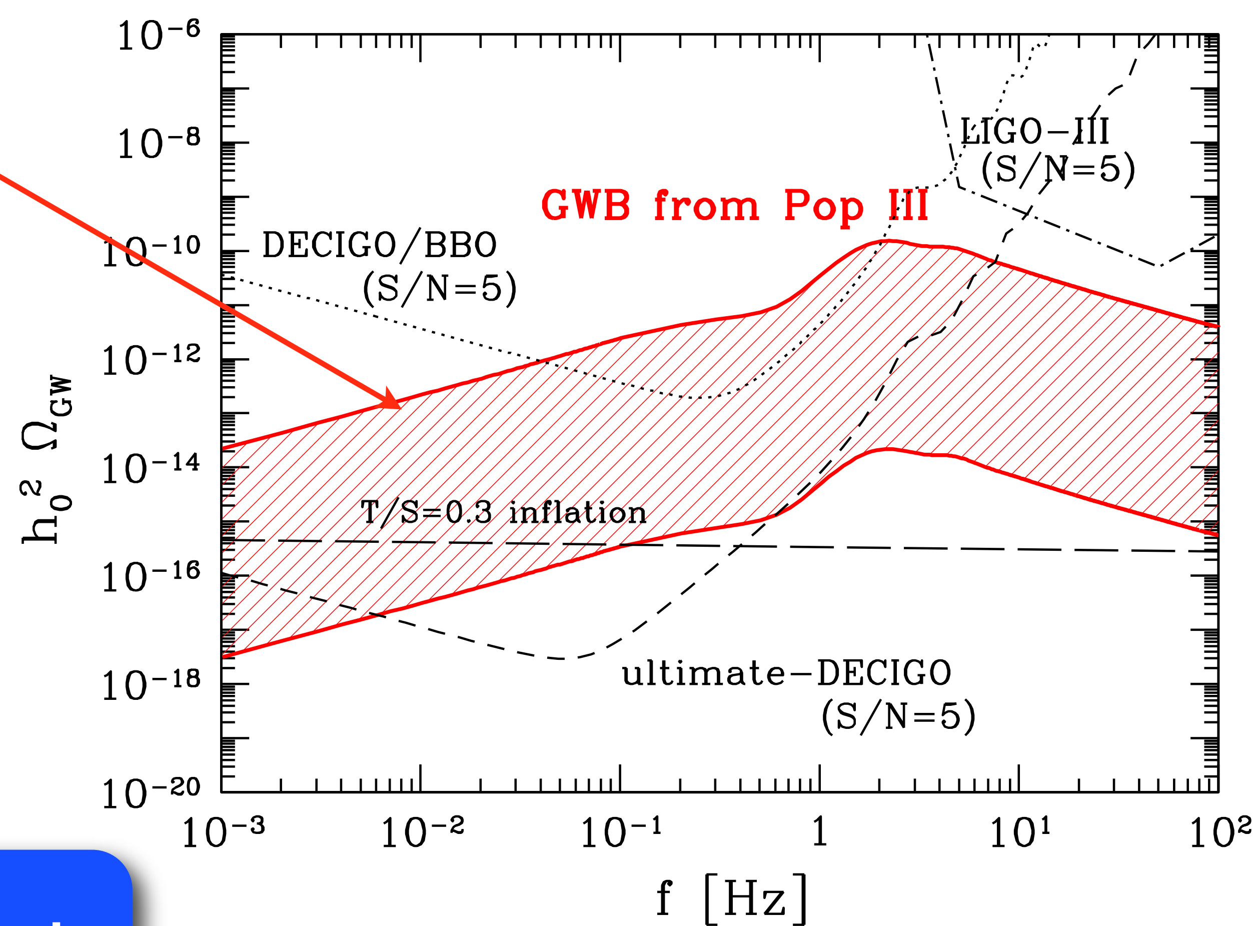


Farmer and Phinney (03)

(2) Population III Stars

Collapse of first stars → Gravitational Waves

May hide inflationary GW

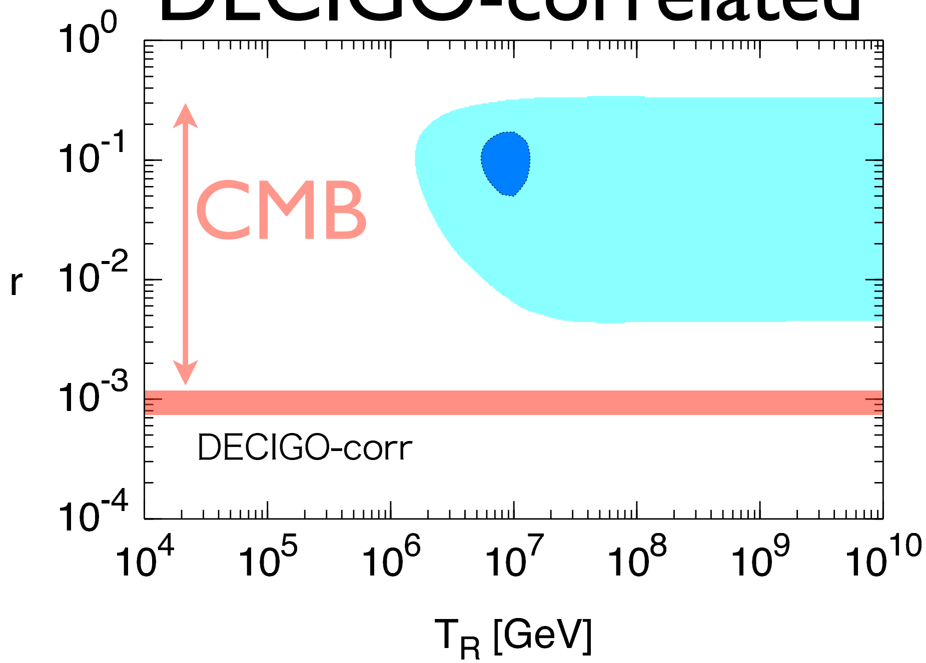


- But SFR at early epoch is uncertain
- Duty cycle may not be so large

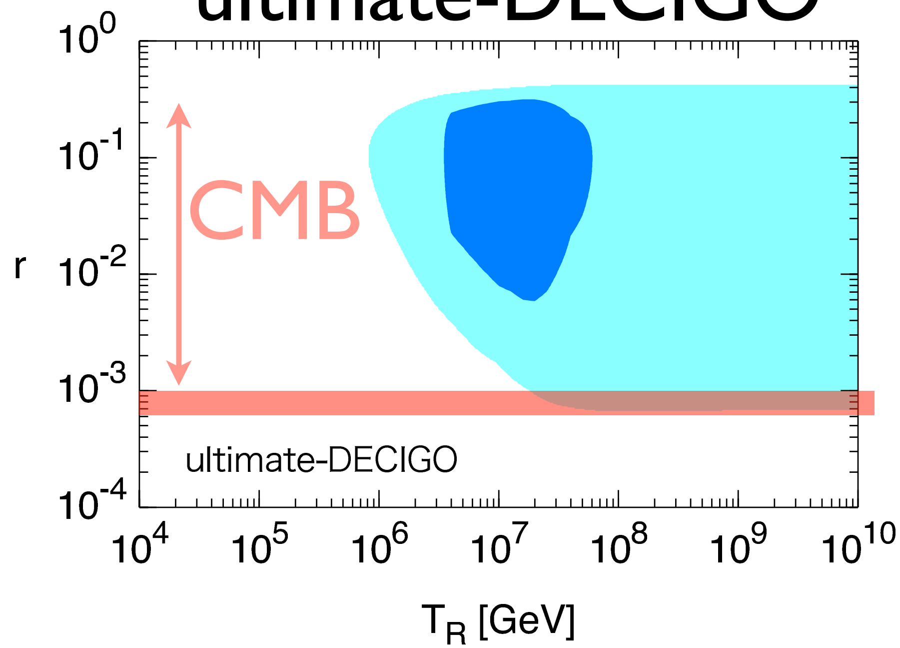
→ Can be removed.

Suwa, Takiwaki, Kotake, Sato (06)

DECIGO-correlated



ultimate-DECIGO

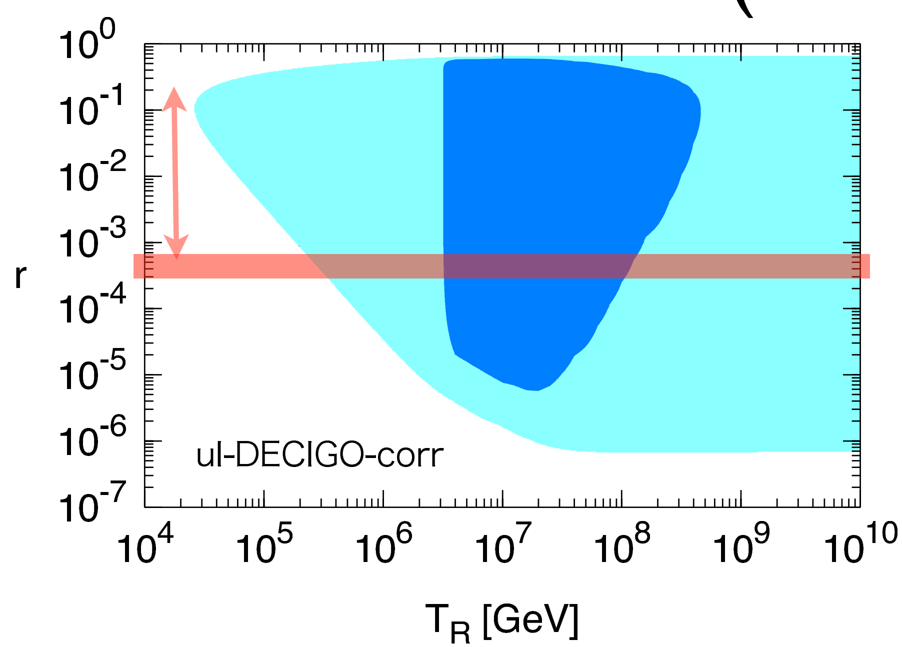


GW can be detected

TR can be determined

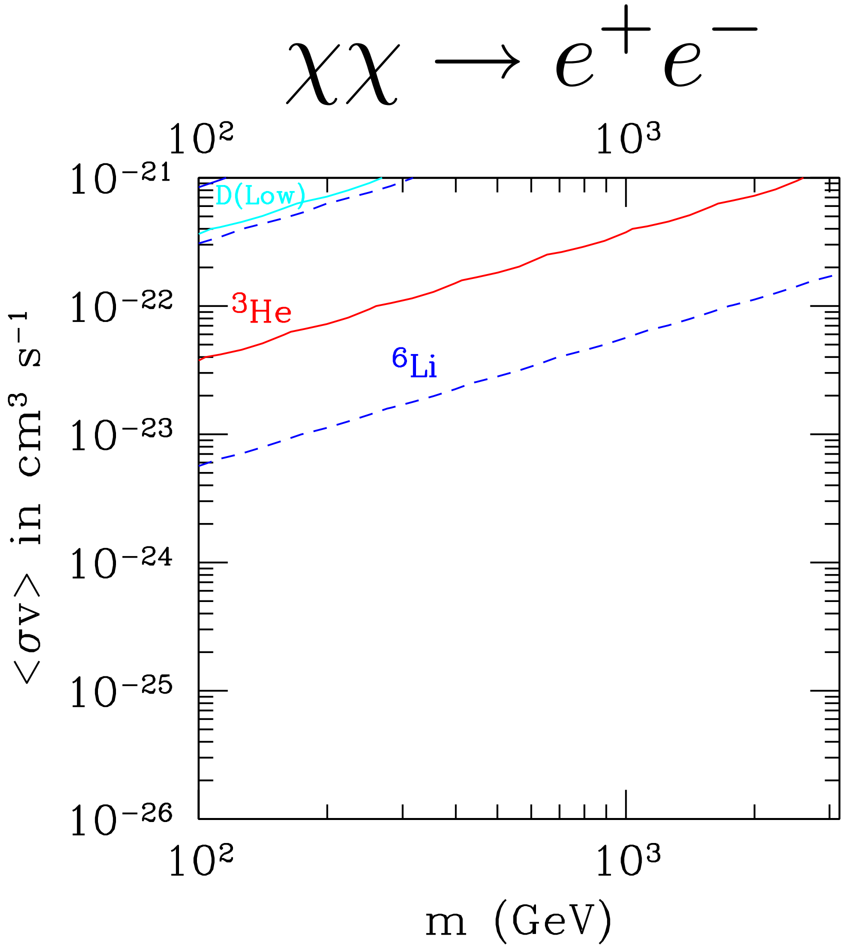
Future observations can determine or constrain TR

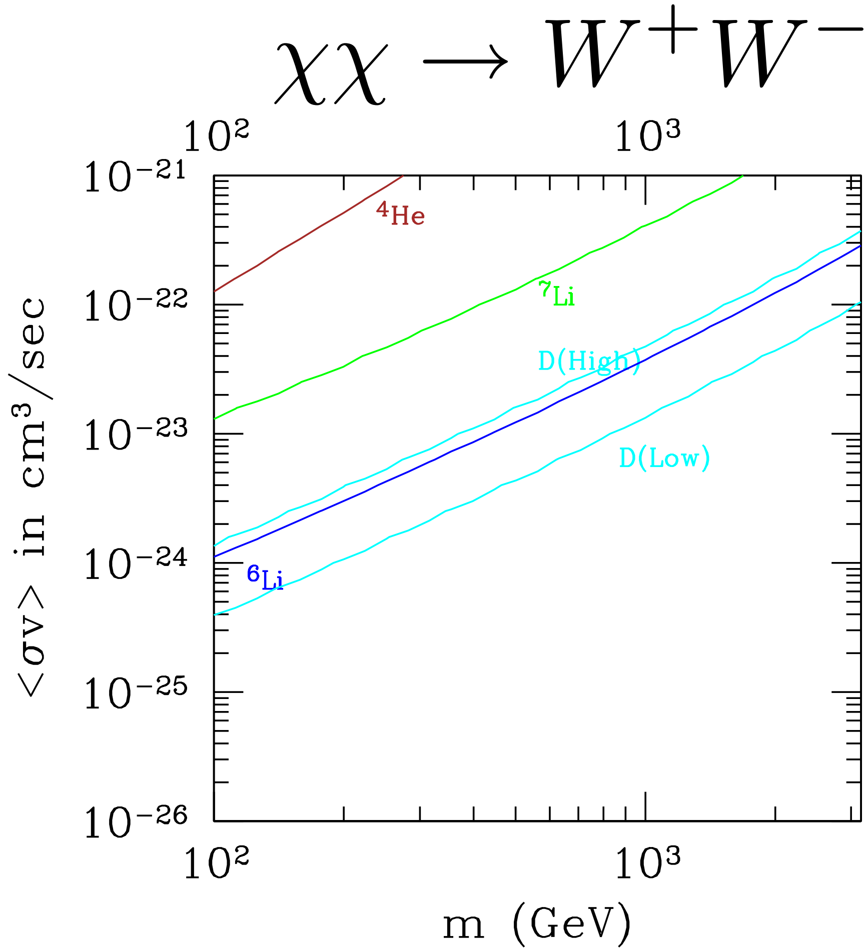
ultimate-DECIGO (corr)



KN, Saito, Suwa, Yokoyama(2008)

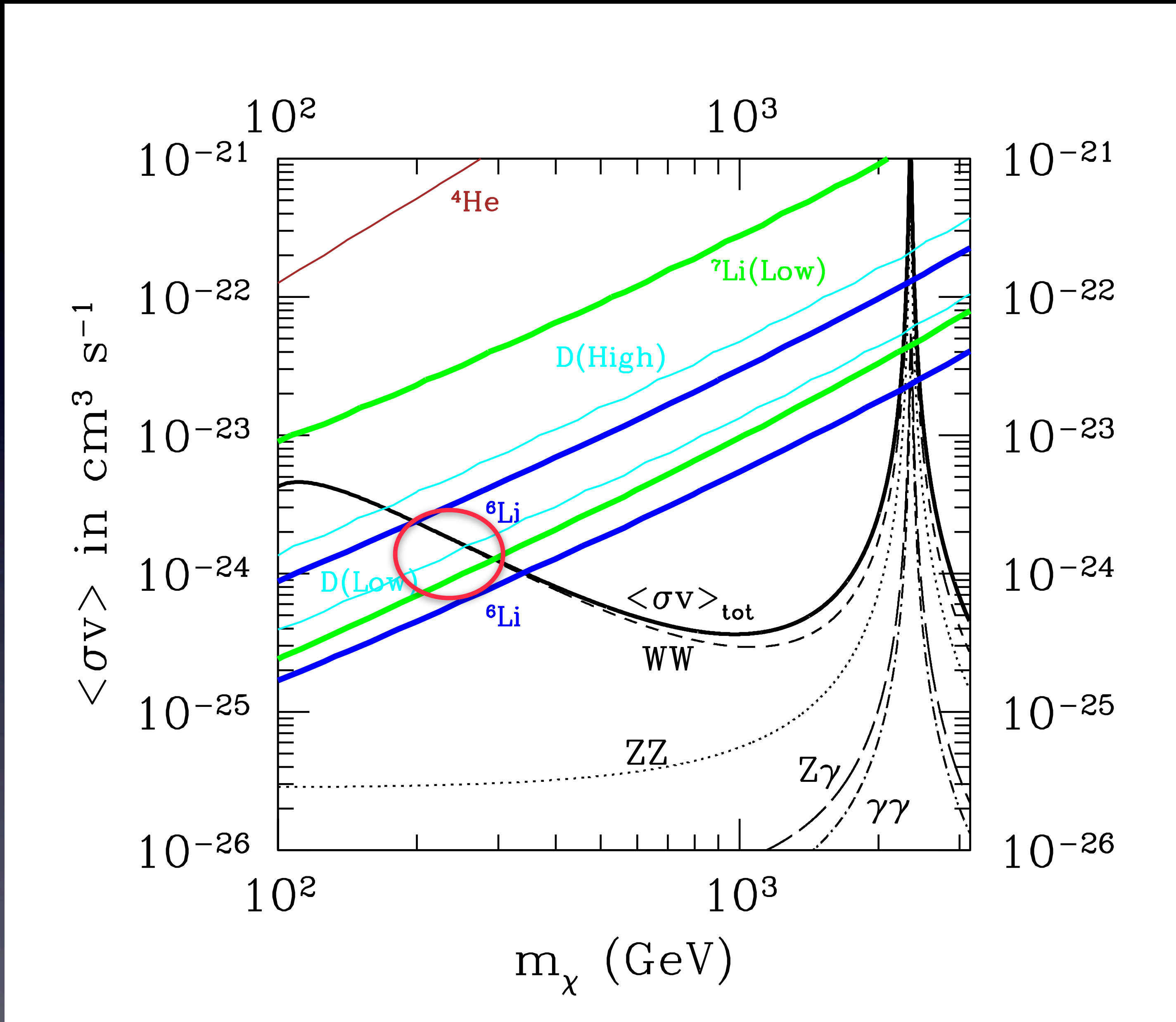
BBN constraints on DM annihilation cross section





J.Hisano, M.Kawasaki, K.Kohri, T.Moroi and KN (2009)

The case of Wino DM

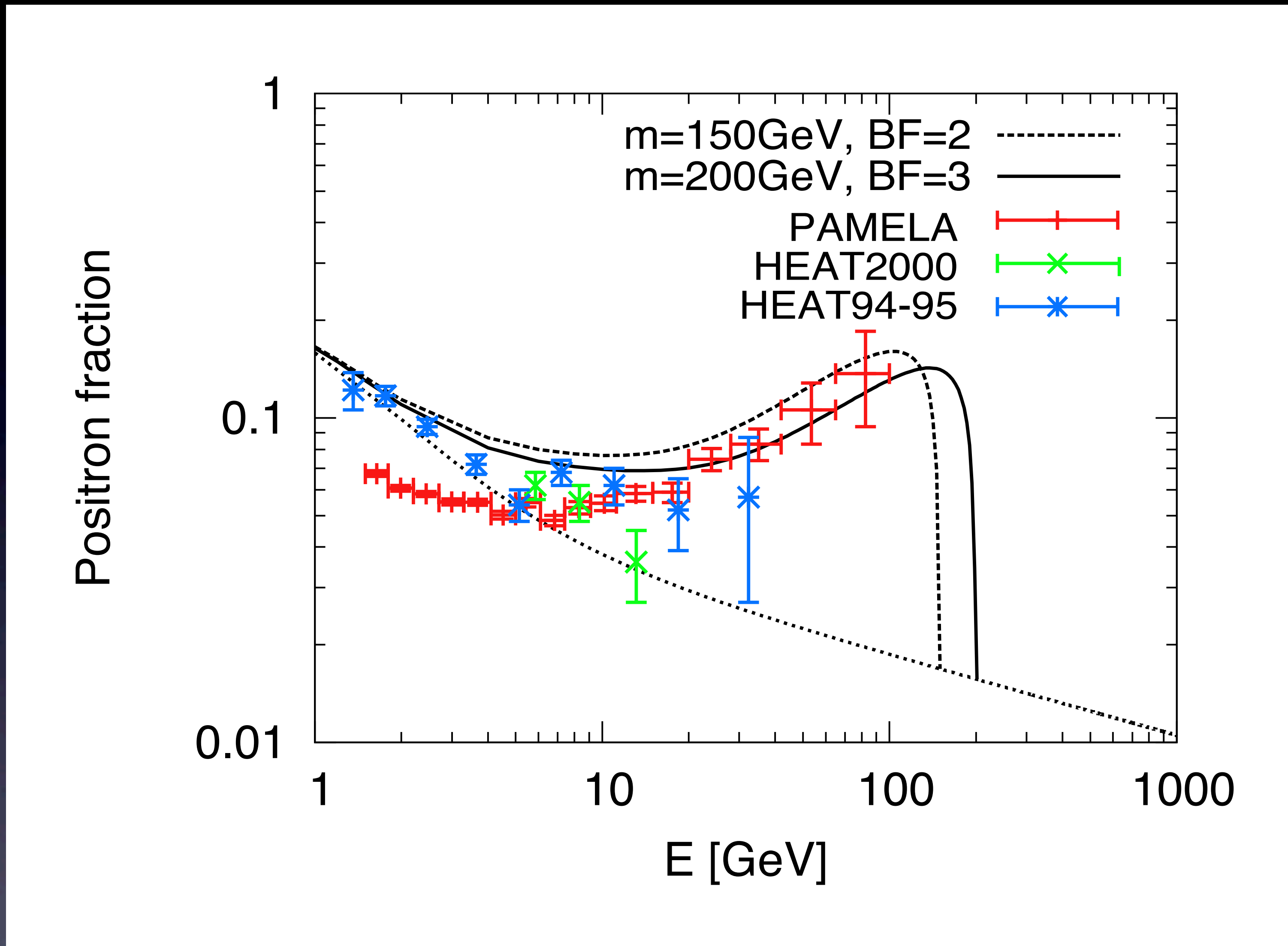


200GeV Wino

Solve Lithium Problem?

J.Hisano, M.Kawasaki, K.Kohri and KN (2008)

~200GeV Wino fits the PAMELA data (not Fermi)



J.Hisano, M.Kawasaki, K.Kohri and KN (2008)

Anti-Protons may be safe : Grajek,Kane,Phalen,Pierce,Watson(2008)
G.Kane, R.Lu, S.Watson (2009)