Particle cosmology

DESY THEORY WORKSHOP
26 - 29 September 2017

Fundamental physics in the cosmos:
The early, the large and the dark Universe

DESY Hamburg, Germany

HELMHOLTZ ASSOCIATION

DESY

1) lessons *from* the Universe *on* fundamental dof's

"The Cosmic Little Prince" by Elspeth McLean

2) implications *of* new fundamental dof's *for* the Universe

LAPTh

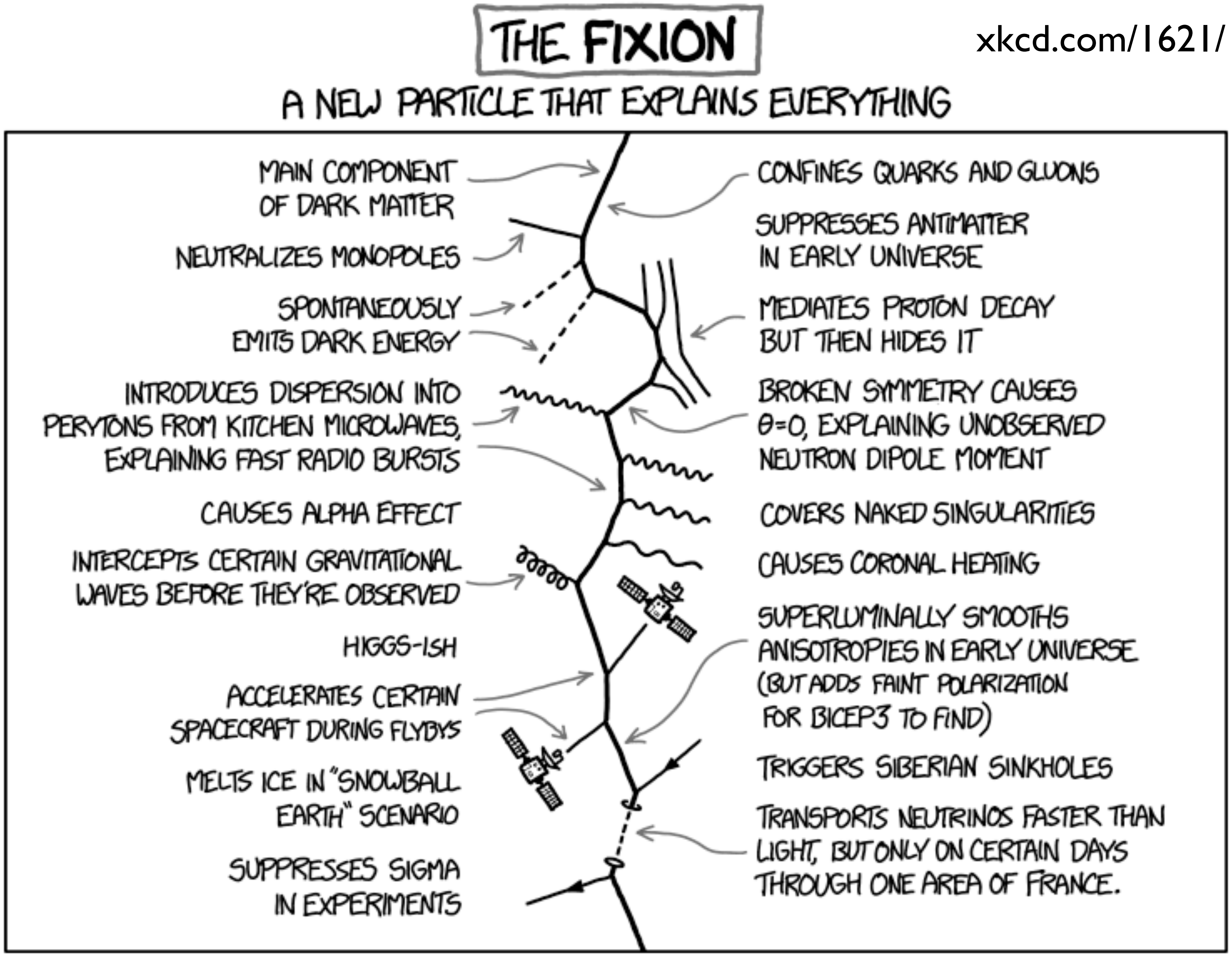
Pasquale Dario Serpico (LAPTh - Annecy, France)

cnrs

Introduction

lessons (?!?) *from* the ~~Universe~~ Theorists *on* fundamental dof’s

xkcd.com/1621/



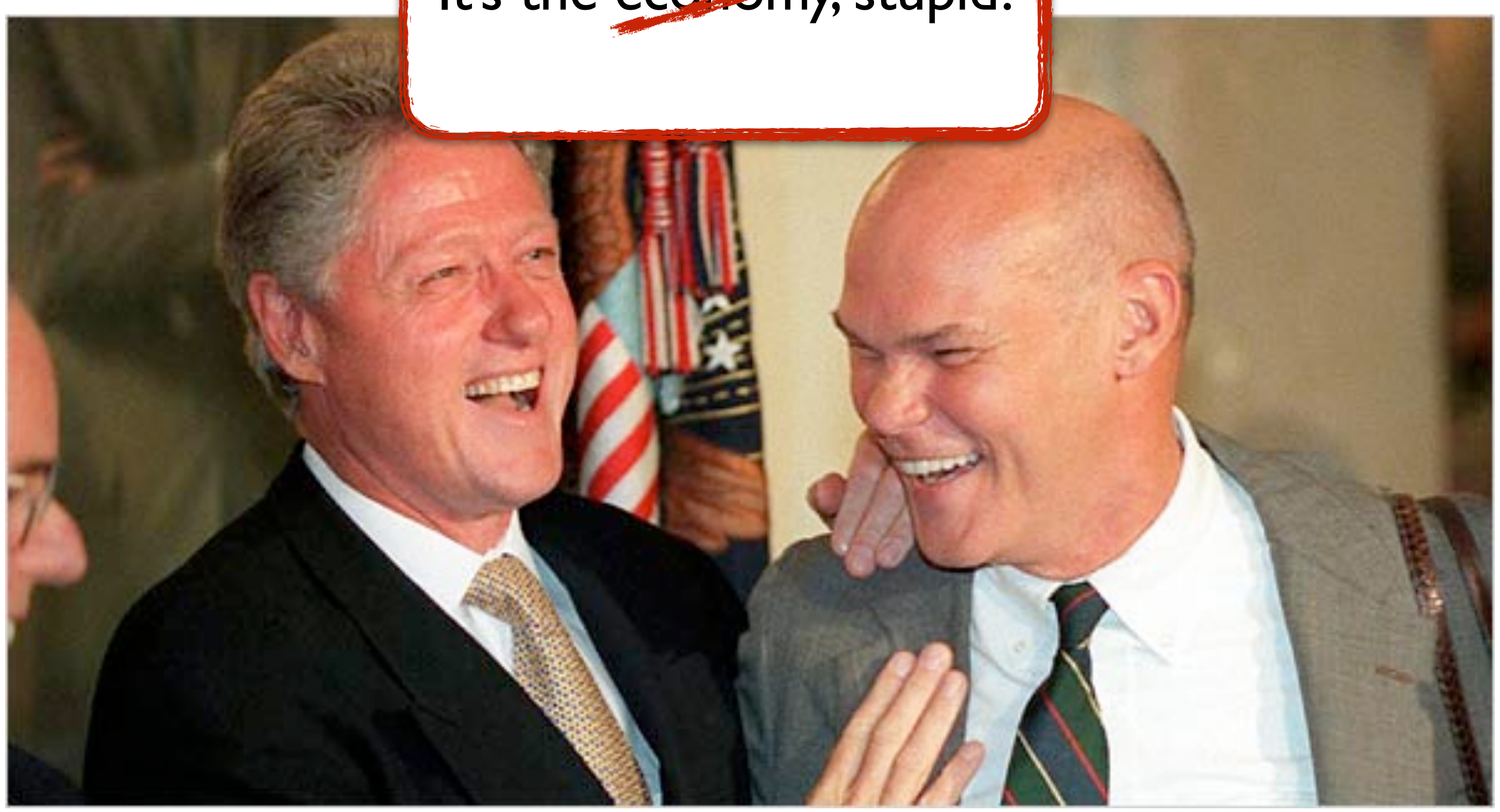
Introduction

lessons *from* the ~~Universe~~ Lab *on* fundamental dof's

Experimentalists' message:

Standard Model

It's the ~~economy~~, stupid!



In the meanwhile…

lessons *from* the Universe *on* fundamental (?!) dof's

- Dark matter
- (Large) baryon asymmetry
- Inflation
- Dark Energy *(at least if not cosmological constant)*

Let's keep an open minded and open attitude, trying to learn from Nature rather than our prejudice.

Let Nature surprise us again, notably via the opening of yet unexplored observational windows (more on this later)

"Who ordered ***that***?"

but also, less well remembered:

"I think physicists are the Peter Pans of the human race. They never grow up…"

But why should cosmology reserve us surprises, given negative results from the Lab searches?

One reason above all: Complementarity!

Cosmology is particularly sensitive to things colliders are not very good at, e.g.

- long-lived particles
- light particles (including mass effects)
- (super)weakly interacting particles

covered by Raphael Flauger

Example of DM: Cosmology tells us *a lot (more than the lab)* about it!

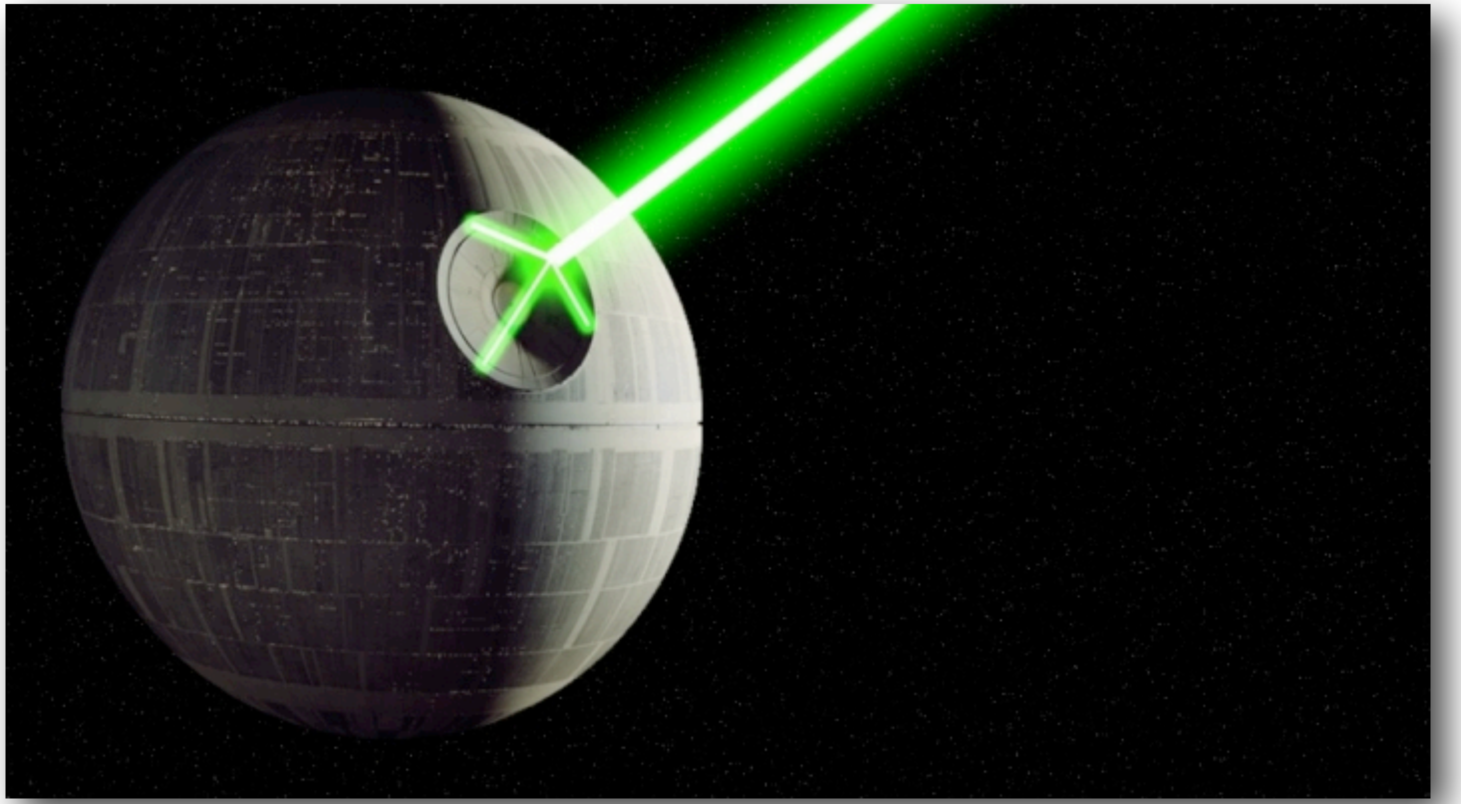
- *How much DM is out there*
- *DM is not "hot" (non-relativistic v-distribution…SM ν's do not work!)*
- *Must be stable or long-lived*
- *DM must be sufficiently heavy*
- *DM is collisionless (or not very collisional, bounds on σ_{el})*
- *DM is dissipationless (bounds on σ_{inel})*
- *DM has small interactions with SM (notably γ and ν)*

No time to discuss them all, let me just focus on examples related to "stability"
(In part I and II… part III is required to match the workshop guidelines)

The Dark

possibly the next-to-closest thing to an "undiscoverable" DM candidate...

"Dark Matter" conversion into "Dark Radiation": Gravitational effects



On a decaying DM fraction

Assume a stable component in DM, plus an unstable relic, whose fraction of the initial total is *f*, decaying into "dark" relativistic species (DR).

$$\begin{aligned}\Omega_{\rm dm} &= \Omega_{\rm sdm} + \Omega_{\rm dcdm} \\ &= (1 - f_{\rm dcdm})\Omega_{\rm dm}^{\rm ini} + f_{\rm dcdm}\exp(-\Gamma_{\rm dcdm} t)\Omega_{\rm dm}^{\rm ini}\end{aligned}$$

To some extent also describes DM' $\rightarrow$ "lighter" DM, which has however additional constraints

The smooth background equations can be easily derived, e.g. from $\nabla_\mu T^{\mu\nu} = 0$

homogeneous equations given by (prime=derivative with respect to conformal time)

$$\rho'_{\rm dcdm} = -3\frac{a'}{a}\rho_{\rm dcdm} - a\Gamma_{\rm dcdm}\rho_{\rm dcdm}$$

$$\rho'_{\rm dr} = -4\frac{a'}{a}\rho_{\rm dr} + a\Gamma_{\rm dcdm}\rho_{\rm dcdm}$$

dilution factors for energy density of

matter

radiation

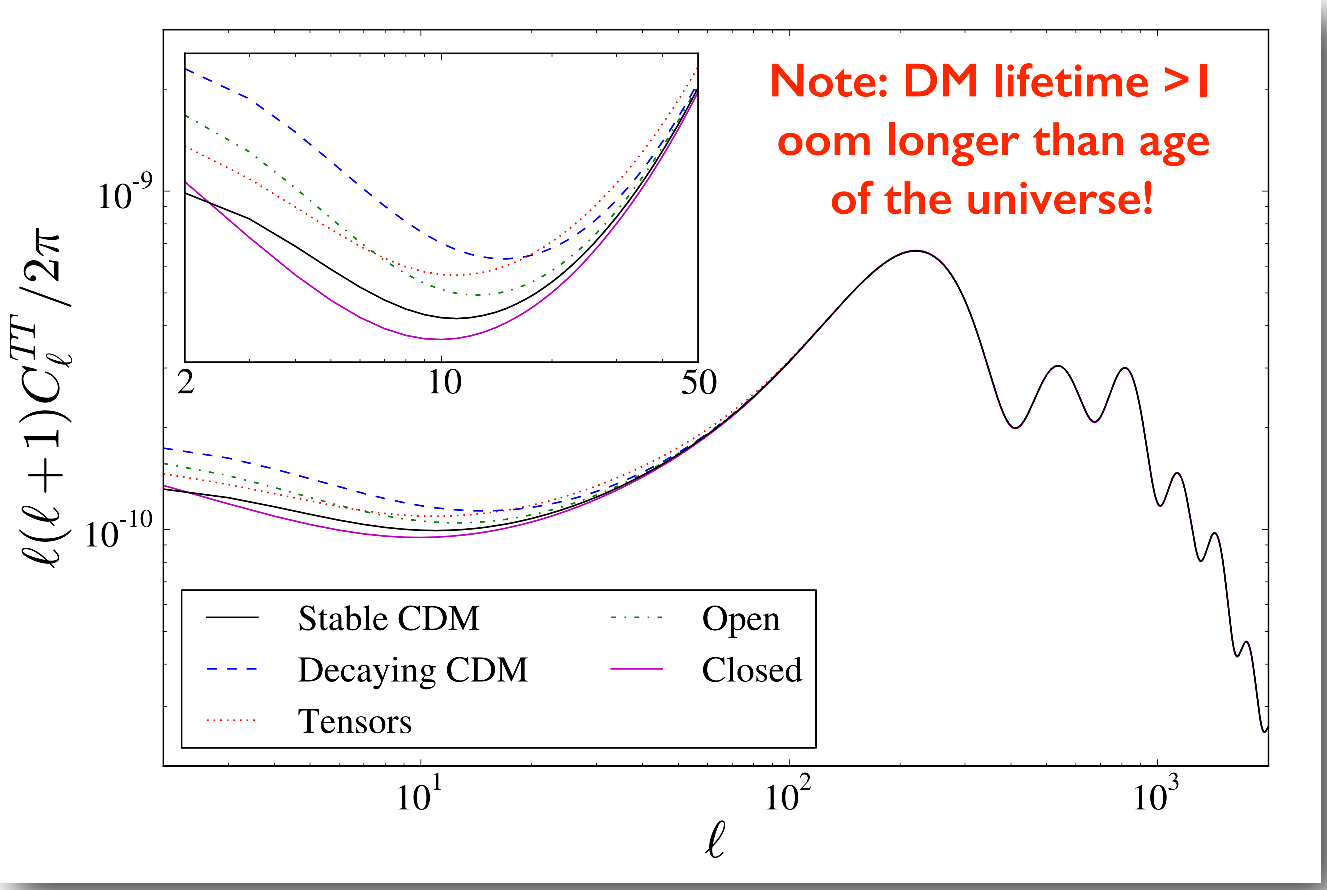
$$\frac{a'}{a} = a\,H = \mathcal{H}$$

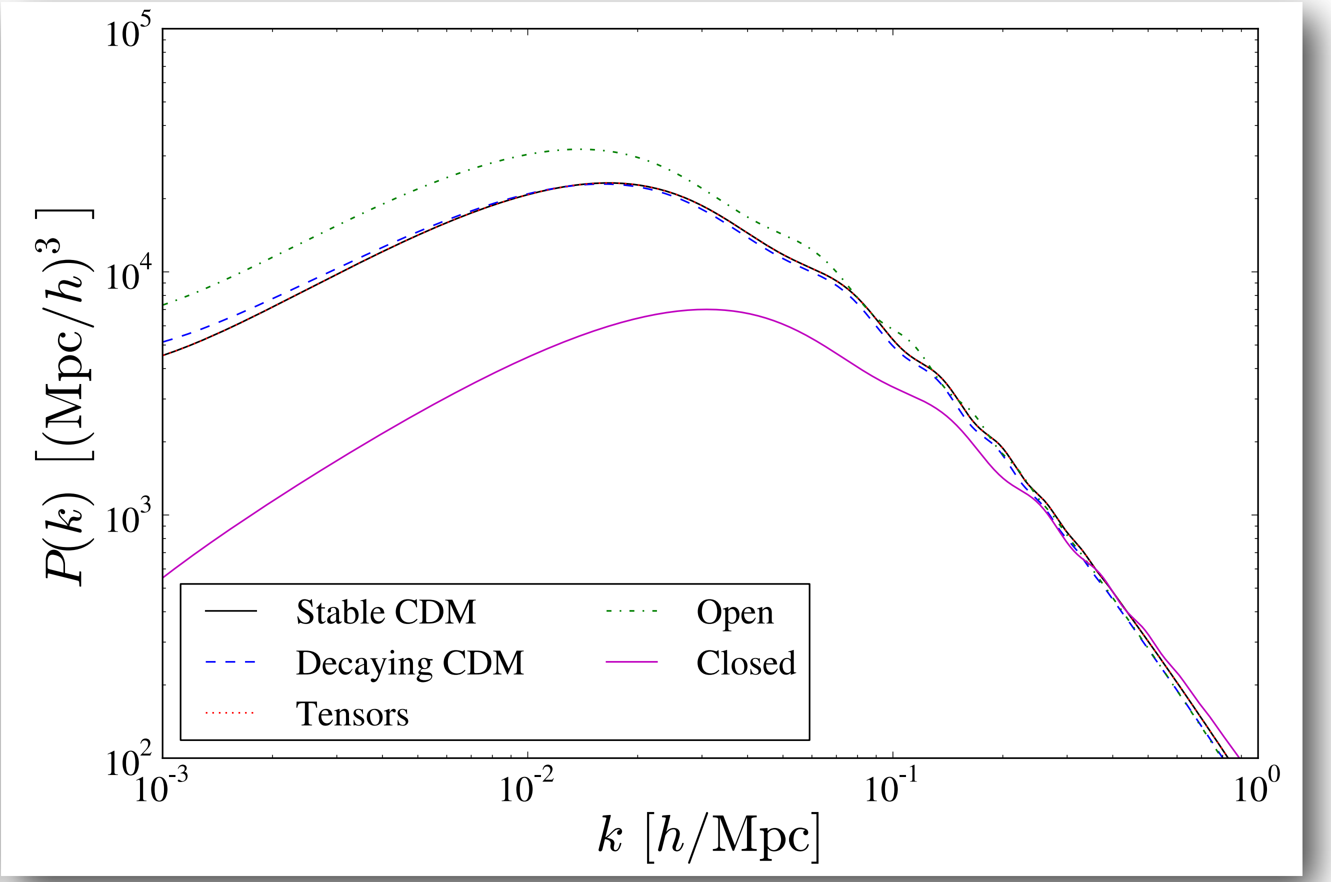
For perturbations, must be careful about gauge choice/fixing… I won't enter in details, if interested see *V. Poulin, P.D.S. and J. Lesgourgues, JCAP 1608, 036 (2016) [1606.02073]*

Effects of a decaying DM fraction

CMB affected (mostly) by late integrated Sachs-Wolfe effect (modification of homogeneous & perturbed DM density at late times affects evolution of metric fluctuation) LSS helps in breaking partial degeneracy with curvature & tensor modes

Model implemented in CLASS, http://class-code.net/





Case for f_{dcdm}=1, from

B. Audren et al. JCAP 1412, 028 (2014) [1407.2418]

Current bounds: τ≳160 Gyr (CMB only)
τ≳170 Gyr (with other consistent data)

V. Poulin, P.D.S. and J. Lesgourgues, JCAP 1608, 036 (2016) [1606.02073]

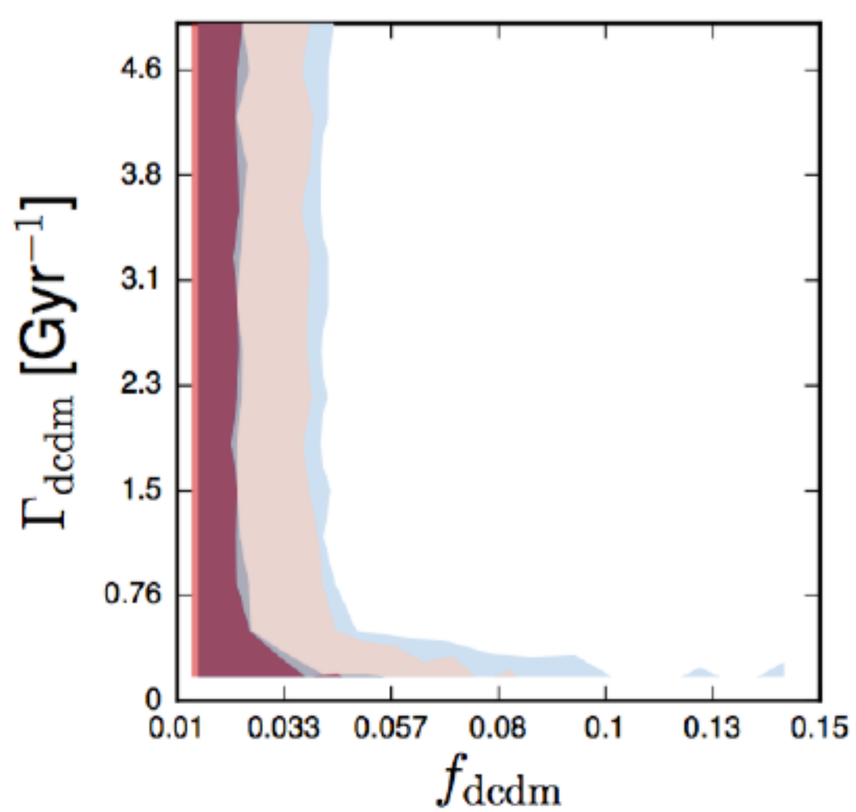
Bounds: 3 timescale regimes

If the lifetime is very long, to first order data are only sensitive to the product Γf

$\Gamma f < 0.0063$ (0.0059) Gyr^{-1} CMB only (+consistent data)

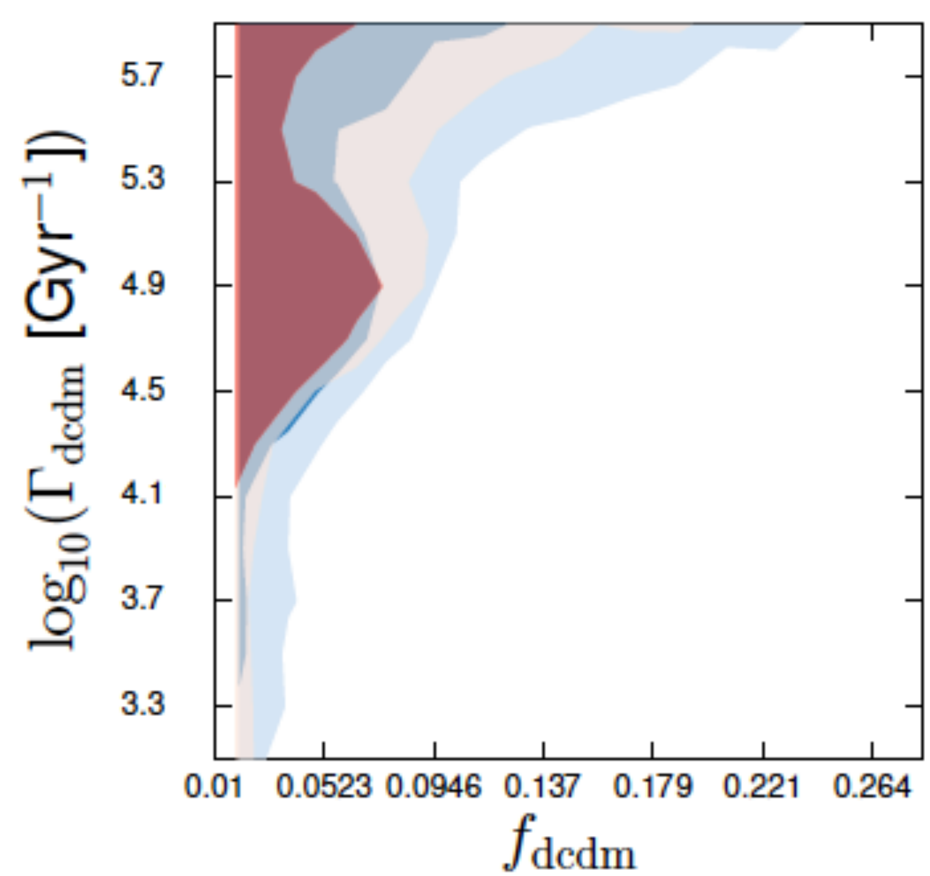
$$
\begin{aligned}
\Omega_{\rm dm} &= \Omega_{\rm sdm} + \Omega_{\rm dcdm} \\
&= (1 - f_{\rm dcdm})\Omega_{\rm dm}^{\rm ini} + f_{\rm dcdm}\exp(-\Gamma_{\rm dcdm}t)\Omega_{\rm dm}^{\rm ini} \\
&= (1 - f_{\rm dcdm})\Omega_{\rm dm}^{\rm ini} + f_{\rm dcdm}[1 - \Gamma_{\rm dcdm}t + \mathcal{O}((\Gamma_{\rm dcdm}t)^2)]\Omega_{\rm dm}^{\rm ini} \\
&= [1 - f_{\rm dcdm}\Gamma_{\rm dcdm}t + \mathcal{O}((\Gamma_{\rm dcdm}t)^2)]\Omega_{\rm dm}^{\rm ini} \ .
\end{aligned}
$$

bounds ~ independent of lifetime between recombination and recent times (bounds apply also to complicated, non-decaying DM)



Less than 3.8% of DM has converted into any invisible radiation from recombination to now!

bounds on *fdcdm* relax for very short lifetimes, accompanied by an increase in the value of $\Omega^{\rm ini}$



…but for a "sweet spot" where "the produced DR" alters N_{eff} appreciably

Numerous applications

Examples in the literature:

within SUSY, if the LSP and NLSP are gravitinos, axions/axinos, RH sneutrinos…

for a recent ex. see e.g. R. Allahverdi et al. "Dark Matter from Late Invisible Decays to/of Gravitinos," Phys. Rev D 91, 055033 (2015)

BSM models (including **string-inspired**) accompanied by dark sectors; generically the lightest particle expected in the dark sector and the **lightest "visible" SUSY partner is metastable**

B. S. Acharya, S. Ellis, G. Kane, B. Nelson & M. Perry, "The lightest visible-sector supersymmetric particle is likely to be unstable," Phys. Rev. Lett.. 117, 181802 (2016)

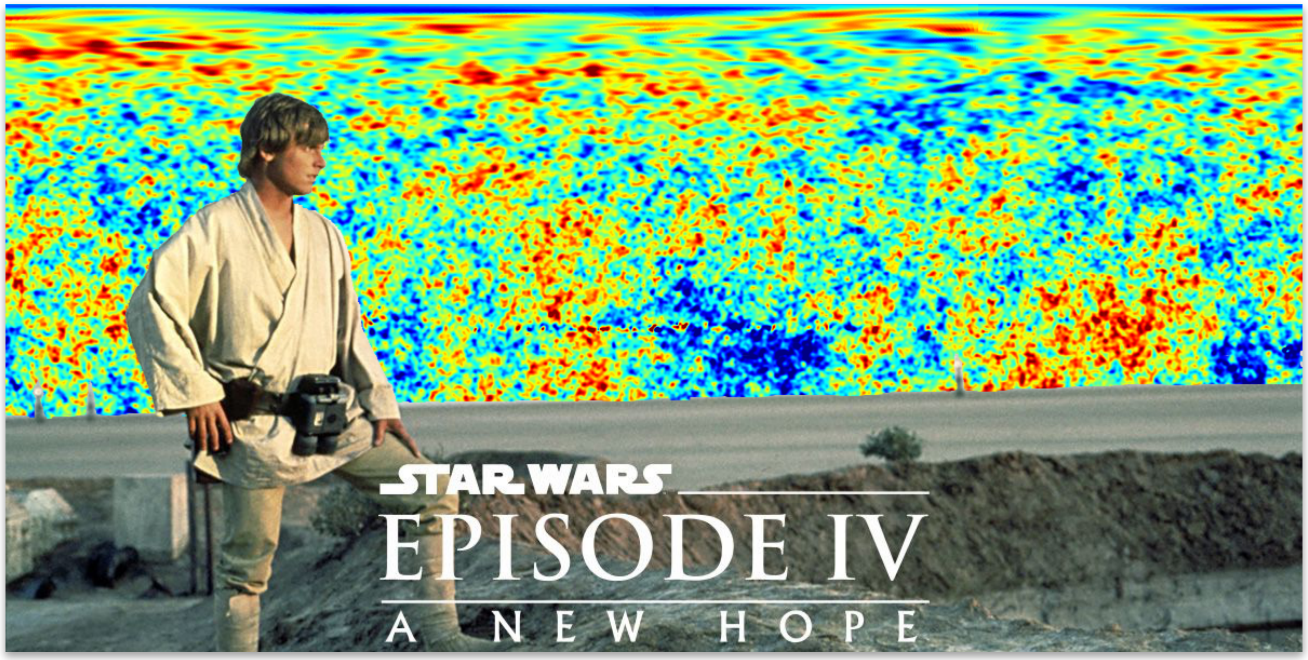
non SUSY examples: keV-scale majoron, decaying into neutrinos

e.g. M. Lattanzi and J. W. F. Valle, "Decaying warm dark matter and neutrino masses," Phys. Rev. Lett., vol. 99, p. 121301, 2007

"non-particle" **example:** Primordial Black Holes (DR = GW due to merging)

reviewed here by Juan Garcia-Bellido, see also S. Clesse

Slightly less invisible Relics:
rays of hope



What if a relic injects interacting SM particles?

associated to a number of processes, like

- Annihilating relics (like WIMP DM)
- Decaying relics such as sterile neutrinos, Super-WIMP progenitors
- Evaporating (hence "light") primordial black holes
- Accreting (hence "stellar mass") primordial black holes *(recently extended accounting for disk formation in V. Poulin et al. arXiv:1707.04206)*

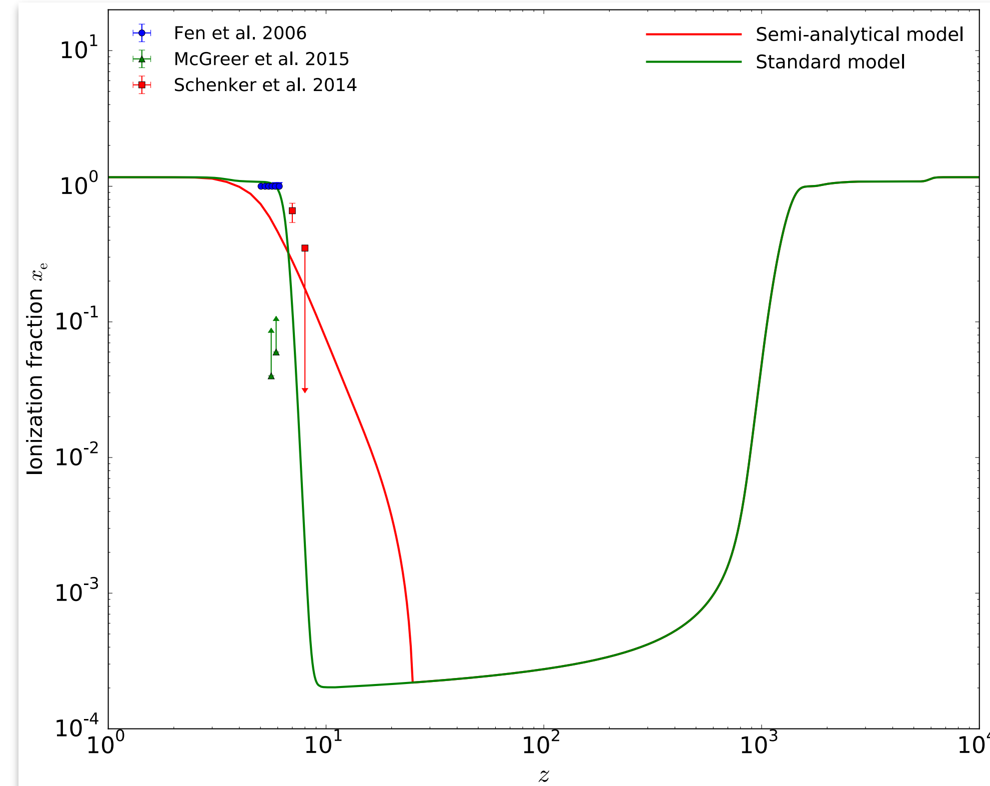
What happens e.g. to CMB observables?

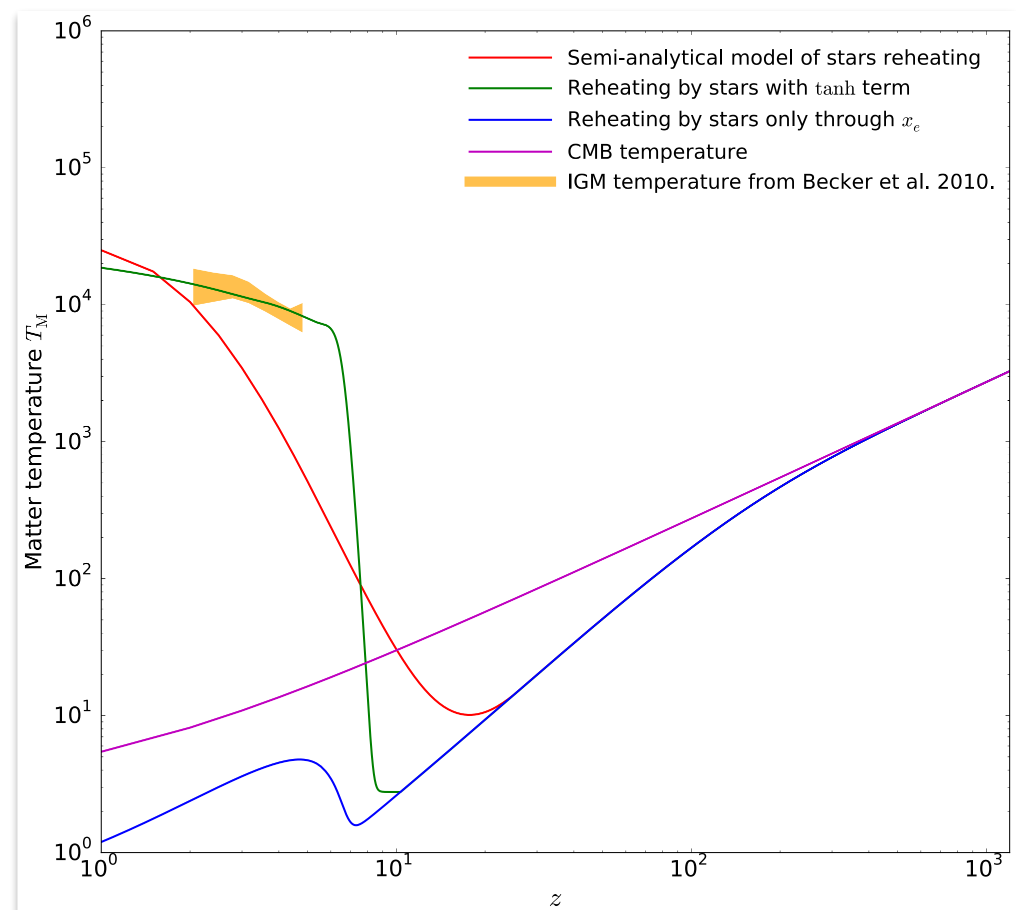
the energy of the injected non-thermal particles is **not negligible wrt the kinetic energy of the baryonic gas.**
They can eventually **heat up** and especially **ionize the gas!** In that case, an alteration in the optical depth experienced by the CMB photons can be induced.

CMB is very sensitive to that! as reviewed by J. Lesgourgues

Basic estimates

Have a look at the standard ionization
and gas temperature evolution





Note:

O(100) eV/baryons more than enough to ionize all atoms!

In the DM, in principle ~5 GeV/baryon "stored"

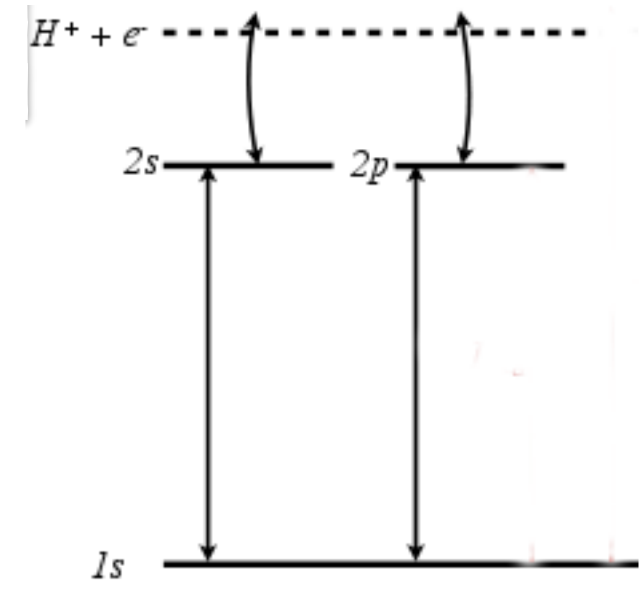
The reionization fraction in the standard expectation drops to ~ 5 10^{-4}

a "visible" b.r. of **O(10^{-11})** may be sufficient to induce major alterations in x_e or T_M!

A quick (& simplified!) introduction to the relevant Eqs.

$$\frac{dx_e(z)}{dz} = \frac{1}{(1+z)H(z)}(R(z) - I(z))$$

ionization fraction Eq.



The « three levels atom »

$$R(z) = C\,\alpha_H x_e^2 n_H \qquad I(z) = C\,\beta_H (1 - x_e) e^{-\frac{h\nu_\alpha}{k_b T_M}}$$

recombination rate

ionization rate

$$\gamma \equiv \frac{8\sigma_T a_r T_{\rm CMB}^4}{3Hm_e c}\frac{x_e}{1 + f_{He} + x_e}$$

Compton "drag" (note that x_e enters into this coefficient)

$$\frac{dT_{\rm M}}{dz} = \frac{1}{1+z}\left[2T_{\rm M} + \gamma(T_{\rm M} - T_{\rm CMB})\right]$$

Eq. for gas temperature

Peebles, P. J. E., "Recombination of the Primeval Plasma", Astrophysical Journal, vol. 153, p. 1, 1968
Zeldovich, Y. B.; Kurt, V. G.; Syunyaev, R. A., "Recombination of Hydrogen in the Hot Model of the Universe", Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, V.55, N. 1, P. 278-286, 1968

Adding exotic terms

$$\frac{dx_e(z)}{dz} = \frac{1}{(1+z)\,H(z)}\left(R(z) - I(z) - I_X(z)\right)$$

$$I_{Xi} = -\frac{1}{n_H(z)E_i}\frac{dE}{dVdt}\bigg|_{\mathrm{dep},i} \qquad I_{X\alpha} = -\frac{(1-C)}{n_H(z)E_\alpha}\frac{dE}{dVdt}\bigg|_{\mathrm{dep},\alpha}$$

These terms encode the model-dependence!

For each channel c, a particle of type/energy P in the cosmological medium with x_e at epoch z only deposits a fraction of the overall energy injected

$$\frac{dE}{dVdt}\bigg|_{\mathrm{dep},c} = f_c^{(P)}(z,x_e)\frac{dE}{dVdt}\bigg|_{\mathrm{inj}}$$

$$K_X = -\frac{2}{H(z)(1+z)3k_b n_H(z)(1+f_{He}+x_e)}\frac{dE}{dVdt}\bigg|_{\mathrm{dep},h}$$

$$\frac{dT_{\mathrm{M}}}{dz} = \frac{1}{1+z}\left[2T_{\mathrm{M}} + \gamma(T_{\mathrm{M}} - T_{\mathrm{CMB}})\right] + K_X(z)$$

The crucial parameters entering the eqs. are the energy deposited by the new source in the plasma

Example of application: relic decay

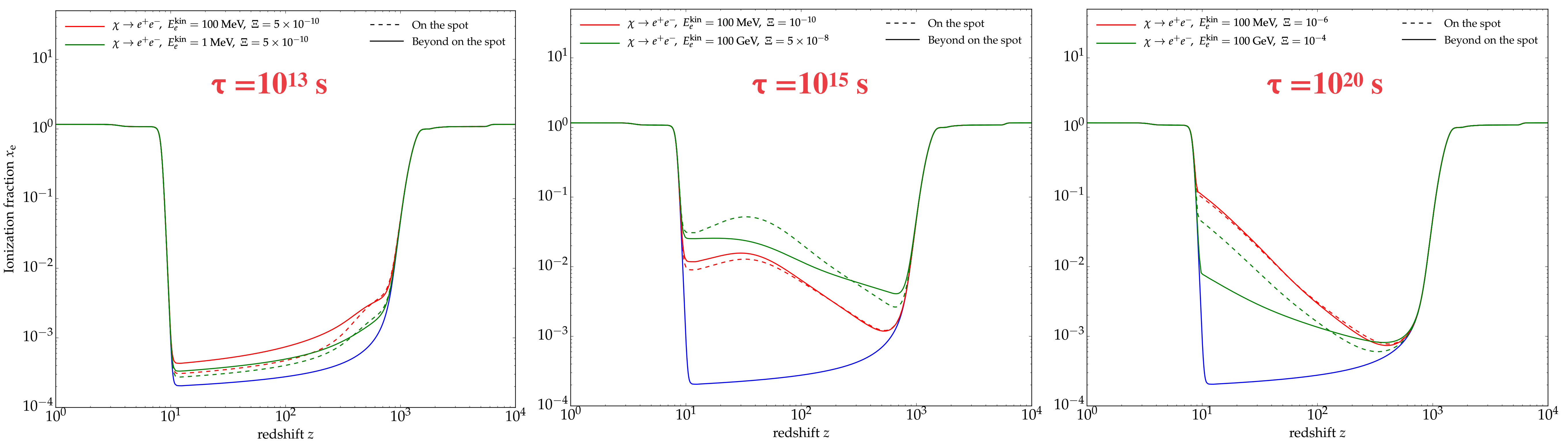
$$\left.\frac{dE}{dV\,dt}\right|_{\rm inj} = (1+z)^3\,\Xi\,\Omega_{\rm DM}\rho_c c^2\Gamma\, e^{-\Gamma\, t}\,,$$

Ξ is the relative amount of energy released into e.m. for a single decay. For instance, a species constituting 1% of the total DM abundance decaying into ν γ corresponds to Ξ=1/200.

We can define the efficiency *f*-functions, and compute the corresponding evolution of x_e and T_M which show a certain variety, notably due to the large range of Γ allowed

CMB effects & bounds similar in spirit-but not in details-to what shown by J. Lesgourgues for DM annihilation

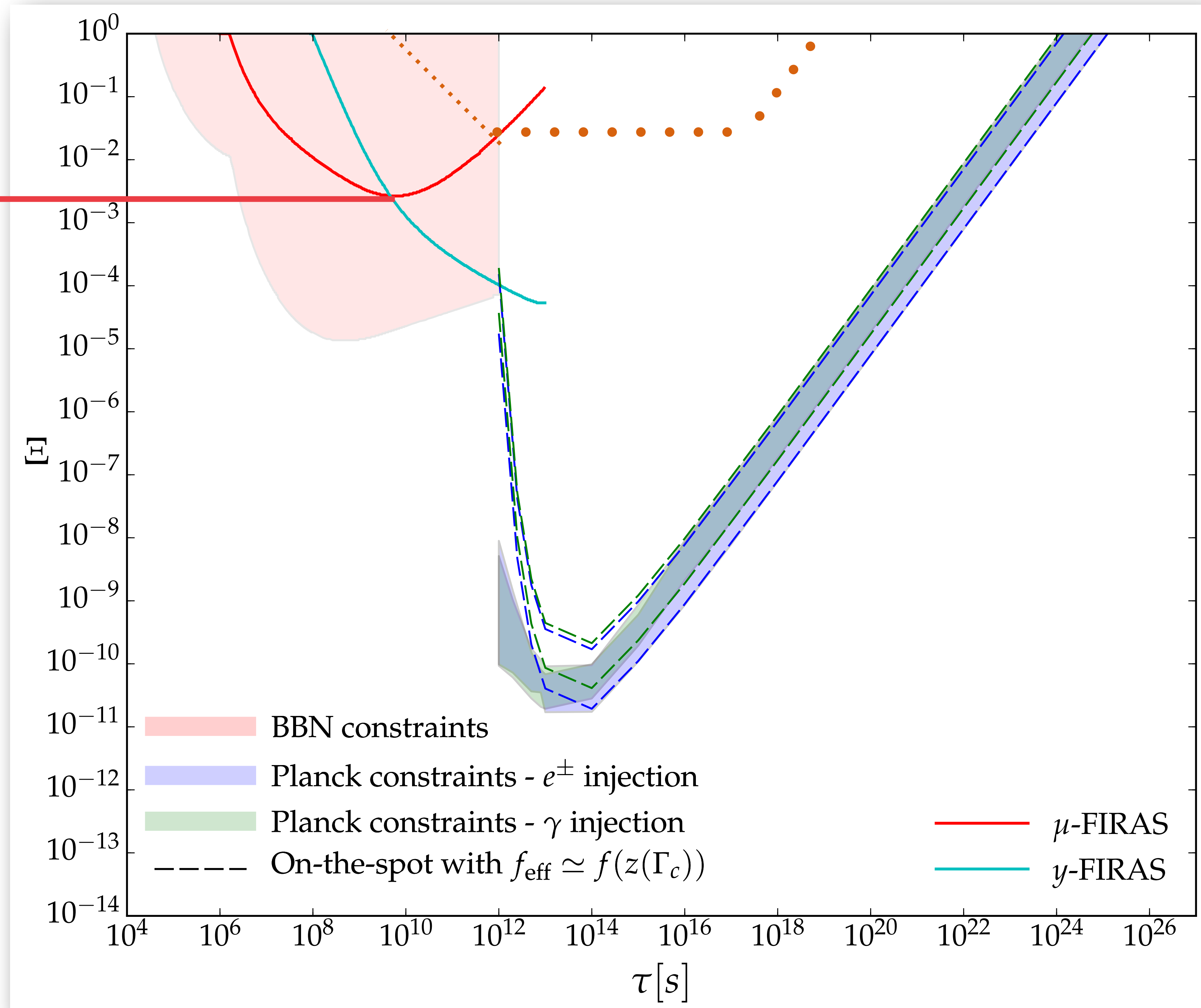
similar to WIMP annihilation | peculiarly bumpy! | similar to early star formation



Results

& Complementarity of different probes

covered in Jens Chluba's talk

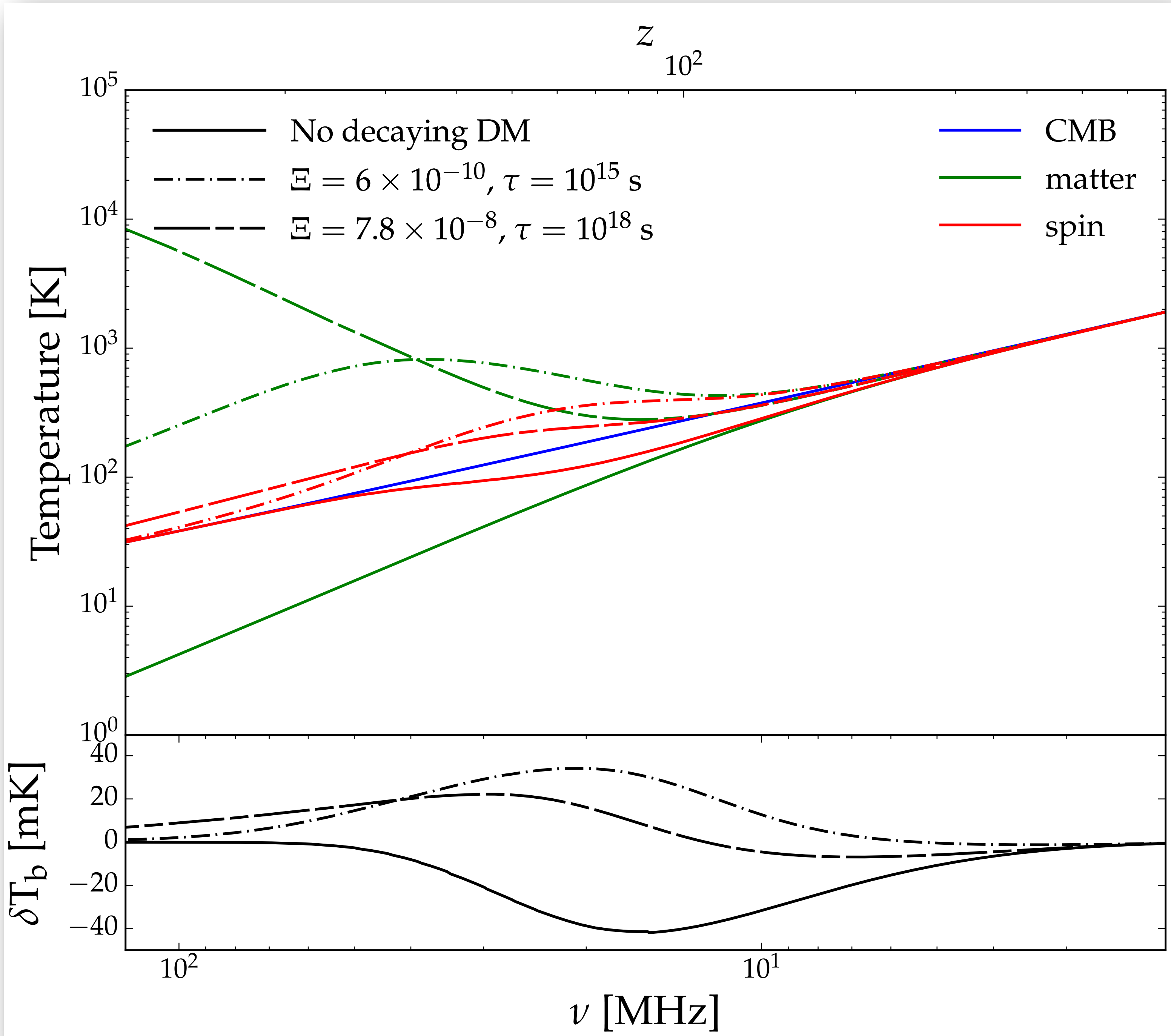


The Large
(sensitivity range)

Notes:

1) we do reach the 10^{-11} level maximal sensitivity estimated at the beginning, for stuff decaying around recombination time
2) Much better than purely gravitational!
3) Complementarity (timescales and actually energies, too!) with other probes

Surprises from the Dark Ages?
21 cm brightness temperature evolution



Allowed values of parameters may lead to a δT-reversal (**gas hotter than CMB**),

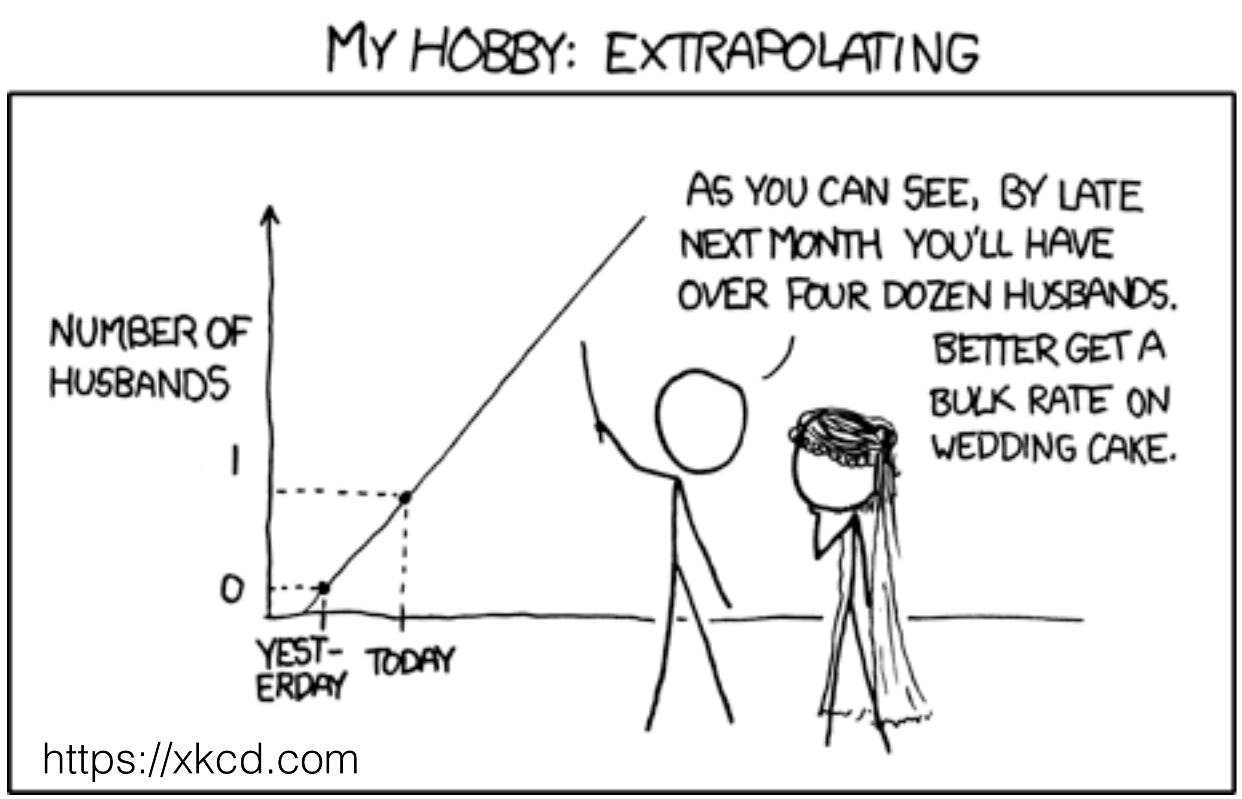
21 cm in emission rather than in absorption expected **at large redshift**!

Part 3

Most of what I said assumes that BSM ingredients essentially bring "perturbative" corrections to standard cosmology. But beware! Most of cosmology relies on:
a few measurements at some epochs + extrapolations (using known physics)

CAVEATS

We know that fundamental physics is incomplete
Extrapolations might break down (actually, they **always** break down at some point!)

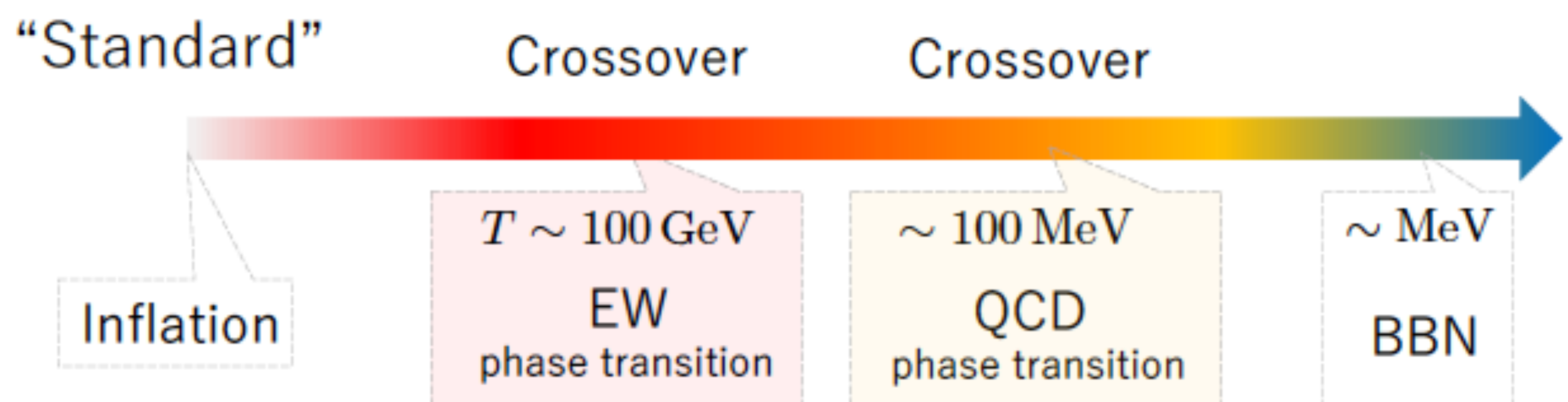


The Early

Is it possible that we are too confident on epochs which we believe are understood & unaltered by BSM?

Seems obvious to push the extrapolation further

most of particle cosmology is based on that assumption, from dark matter computation (be it WIMP, sterile neutrinos…) or baryogengesis, to name but two.



This is often pushed backwards to high temperatures, till the epoch of the end of inflation.

The usual picture is that a radiation-dominated thermal phase continues, with only two mild deviations from this picture expected in the SM, related to the QCD & EW phase transition

Both periods are relatively uneventful, as far as we know

(Both transitions are “crossovers” in the Standard Model)

An intriguing seminal idea

E. Witten, "Cosmological Consequences of a Light Higgs Boson," Nucl. Phys. B 177, 477 (1981)

Explore the consequence of the *Coleman-Weinberg* mechanism for the EW symmetry breaking.

$$V(h) = \frac{\lambda_h}{4} h^4 - \frac{\mu^2}{2} h^2$$

No dimensionful parameter

S. R. Coleman and E. J. Weinberg, "Radiative Corrections as the Origin of Spontaneous Symmetry Breaking," Phys. Rev. D 7, 1888 (1973)

CW: Even if at classical level $(d^2V/dh^2)_{h=0}=0$, the EW breaking happens, due to the quantum corrections (both T=0 and $T\neq0$ should be taken into account).

$$V(\phi) = \frac{3e^4}{512\pi^2}\frac{1}{\sin^4\theta}\left(2+\frac{1}{\cos^4\theta}\right)\left(\phi^4 \ln\frac{\phi}{\langle\phi\rangle} - \frac{1}{4}\phi^4\right)$$

$$V(\phi, T) = \frac{e^2 T^2 \phi^2}{32\sin^2\theta}\left(2+\frac{1}{\cos^2\theta}\right) - \frac{3e^4}{512\pi^2}\frac{1}{\sin^4\theta}\left(2+\frac{1}{\cos^4\theta}\right)\phi^4 \ln\frac{M_W}{T}$$

only W,Z included

Witten realized that this implies a significant "supercooling" of the Universe, before breaking takes place, naively estimated at ~keV scale.

In this limit, a more important phenomenon kicks in, first: scale invariance broken dynamically by the QCD condensate!

$$\Delta V = -\phi(100\,\mathrm{MeV})^3 \frac{\bar{q}q(T)}{\bar{q}q(0)}$$

Does not go without consequences…

exotic QCD phase transition (EW symmetry not broken, yet): one has 6 massless quarks!

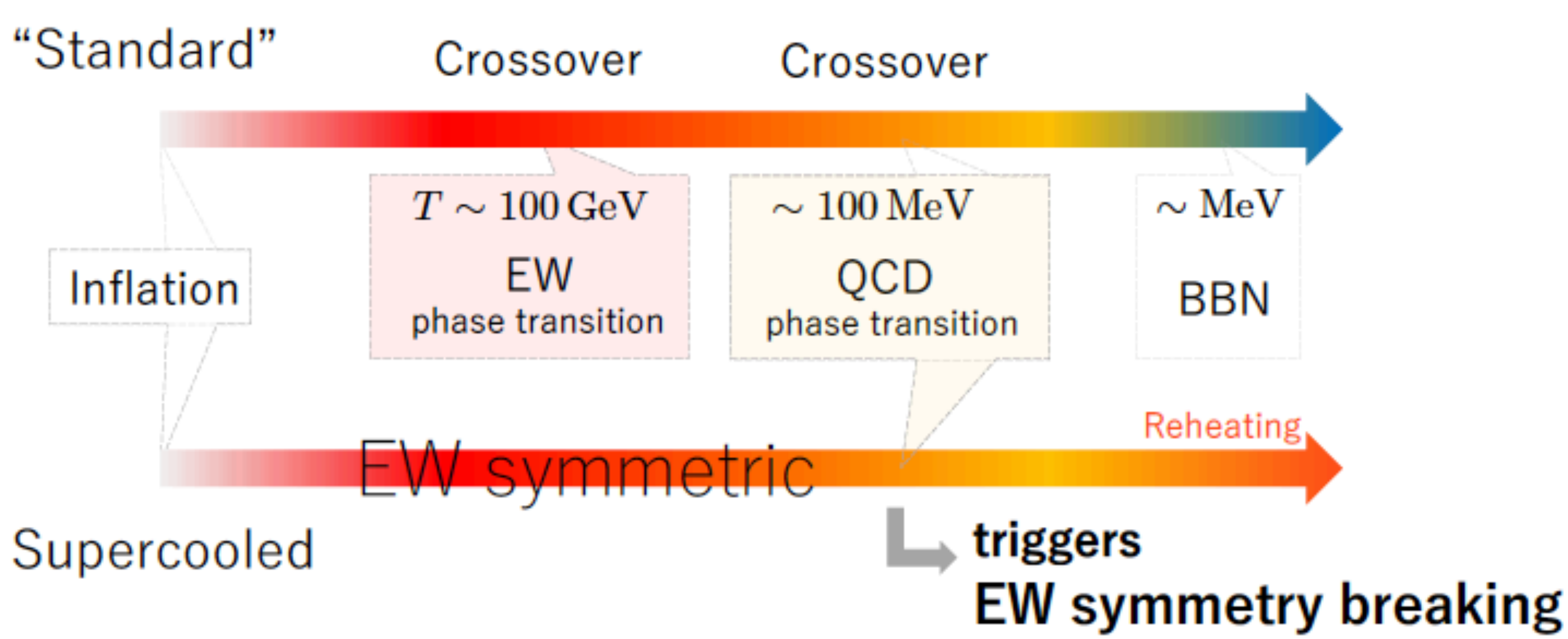
It has been argued already in those years, see in particular

R. D. Pisarski & F. Wilczek, "Remarks on the Chiral Phase Transition in Chromodynamics," PRD 29, 338 (1984)

and later confirmed by lattice, that QCD with N massless flavors undergoes 1st order PT for $N \geq 3$

In Witten's scenario one has chiral symmetry breaking $SU(6) \times SU(6) \to SU(6)$.
The order parameter $\langle \bar{q}q \rangle$ also breaks $SU(2) \times U(1)$: *EW symmetry breaking* takes place, *triggered by the QCD phase transition*…and it is also *1st order* PT.

Alternative picture



Our modest proposal: A revival

The problem is that this can only work for a very light Higgs boson (well below 100 GeV), and is actually incompatible with the currently known values of the Higgs boson and top quark mass (already bounds available more than 20 years ago made this scenario not viable!)

Can it be made to work in BSM extensions? How? What are the implications?

The answer is: **Yes**, in surprisingly minimal BSM extensions!

Highly non trivial & rich possibilities for the history of the Universe

S. Iso, P. D. Serpico and K. Shimada, "QCD-Electroweak first order phase transition in supercooled universe," arXiv:1704.04955 (PRL, in press)

See also W. Buchmuller and D. Wyler, Phys. Lett. B ;249, 281 (1990). V. A. Kuzmin, M. E. Shaposhnikov, and I. I. Tkachev, Phys. Rev. D 45, 466 (1992); G. Servant, Phys. Rev Lett. 113, 171803 (2014) [1407.0030] for early revisitations of this idea, notably (but not exclusively) related to baryogengesis.

Classically scale invariant models, extending the Higgs sector with (at least) one extra scalar, provide the simplest implementation of the "strong supercooling" we seek.

We considered the CW mechanism, now involving the additional scalar ϕ mixed with $\lambda_{mix}<0$

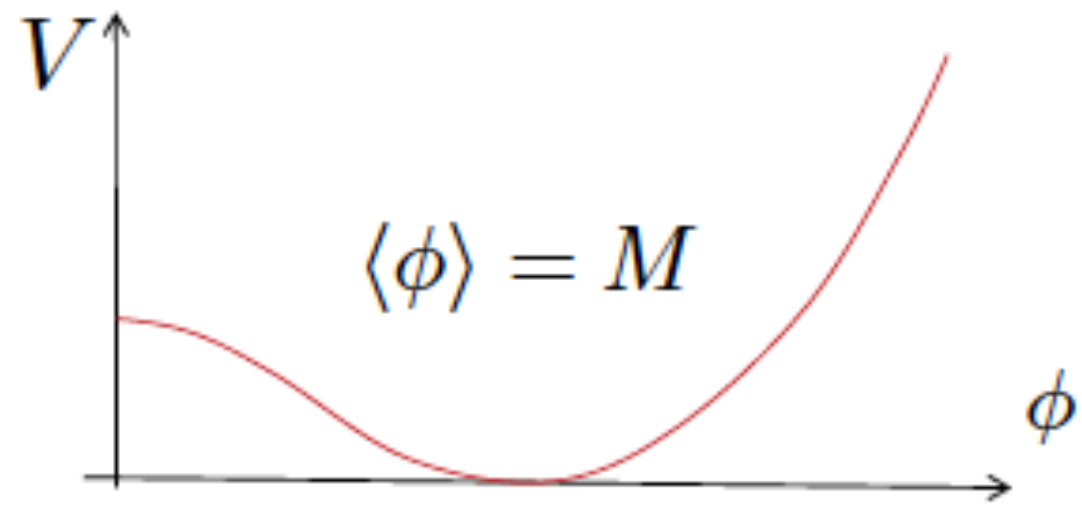
$$V(h,\phi) = \frac{\lambda_h}{4}h^4 + \frac{\lambda_{\rm mix}}{4}\phi^2 h^2 + \frac{\lambda_\phi^{\rm eff}(\phi)}{4}\phi^4$$

The simplest (?) model

In terms of the beta function of the quartic coupling, *B* the one loop CW potential writes

$$V_{\rm CW}(\phi) = V_0 + \frac{B}{4}\phi^4 \left(\ln\frac{\phi}{M} - \frac{1}{4}\right)$$

B depends on the mixing with Higgs as well as possible additional states in the spectrum



For B>0, ϕ has a minimum at *M and CW breaking occurs*

For concrete calculations, we use the minimal, CSI $U(1)_{B\text{-}L}$ model of

S. Iso, N. Okada and Y. Orikasa,
"Classically conformal B-L extended Standard Model," Phys. Lett B 676, 81 (2009) [0902.4050] &
"The minimal B-L model naturally realized at TeV scale," Phys. Rev. D 80, 115007 (2009) [0909.0128]

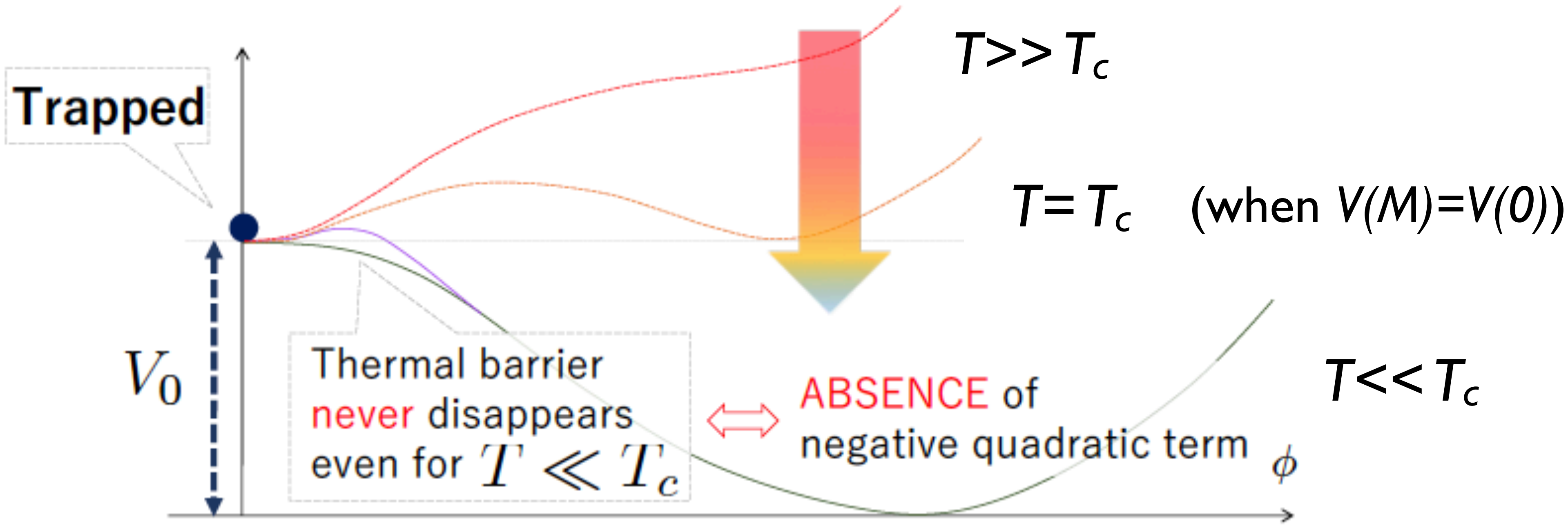
Which has the appealing features of also accounting for ν masses, using the needed scalar ϕ (B-L "Higgs") to this purpose. Also, by gauging B-L it leads to a new interaction mediated by a *Z'*, allowing to incorporate parametrically in our study the effects both of new fermions and new bosons (should capture key aspects of more general models)

Note: *just an example! Similar phenomenology is expected in models with completely different motivations, sharing the key supercooling. E.g. in Randall-Sundrum motivated extra-dimensional models,*

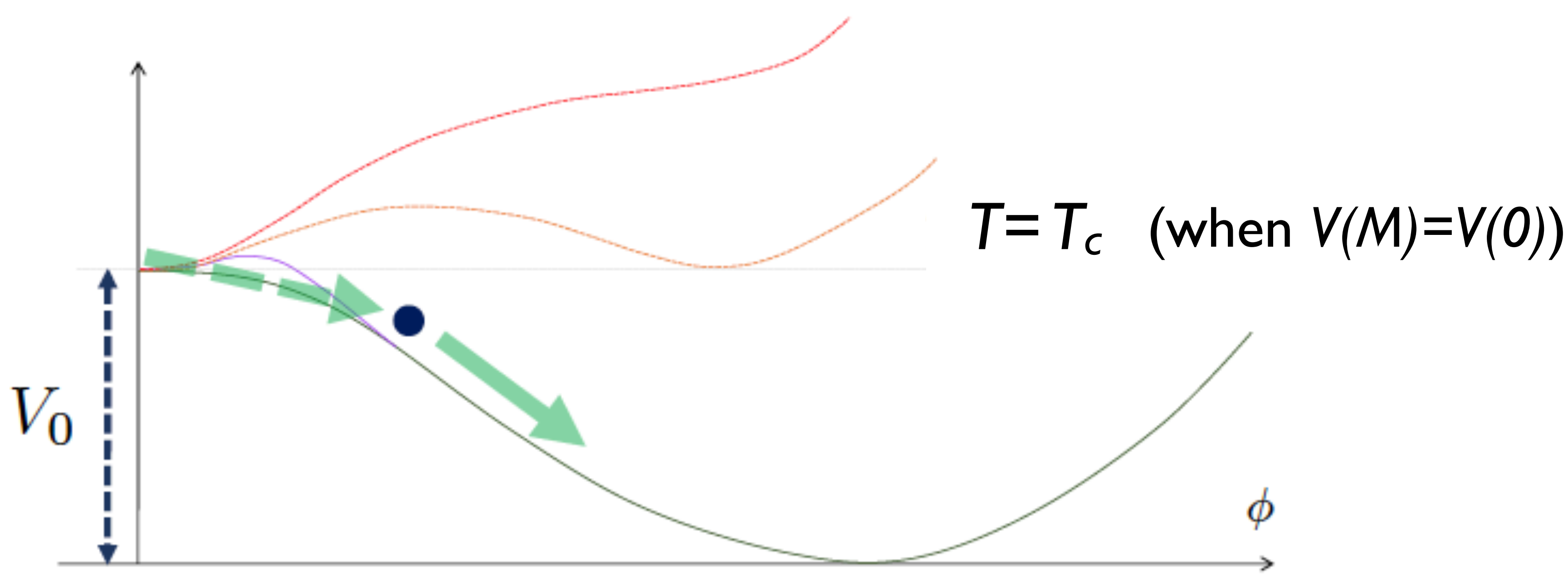
G. Servant and B. von Harling, in preparation

Supercooling in CSI models

The universe remains in the metastable state, with constant expansion rate $H=(V_0/3\ m_{Pl}^2)^{1/2}$ …



…until ϕ **tunnels** through the barrier, i.e. EWSB via $\lambda_{mix}<0$



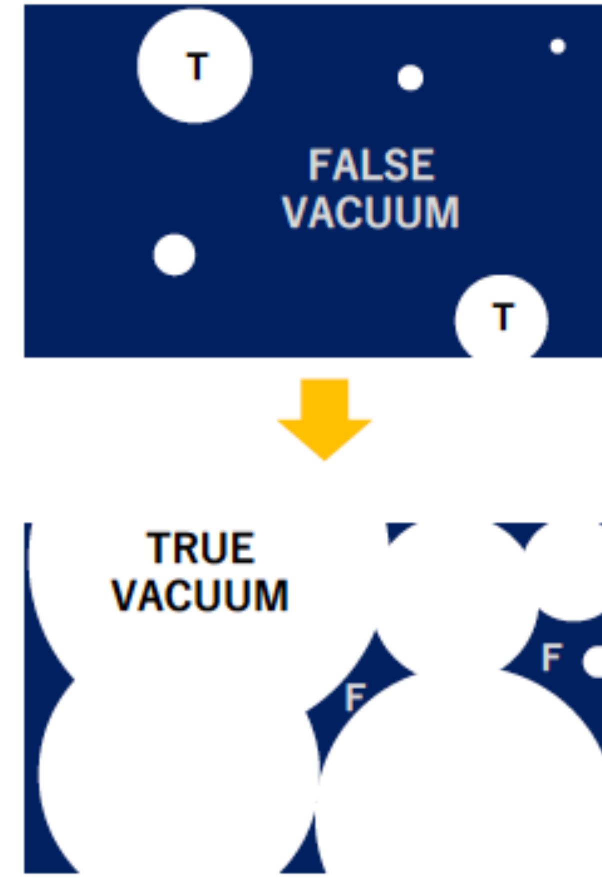
Low percolation temperature T_p

T_c

"true vacuum bubbles *can* form"
(start to be energetically favoured)

T_p

"true vacuum bubbles *do* form"
(i.e. true vacuum bubbles occupying most of the volume of the universe)



In typical 1st order PT, the nucleation process is fast, so that $T_p \lesssim T_c$

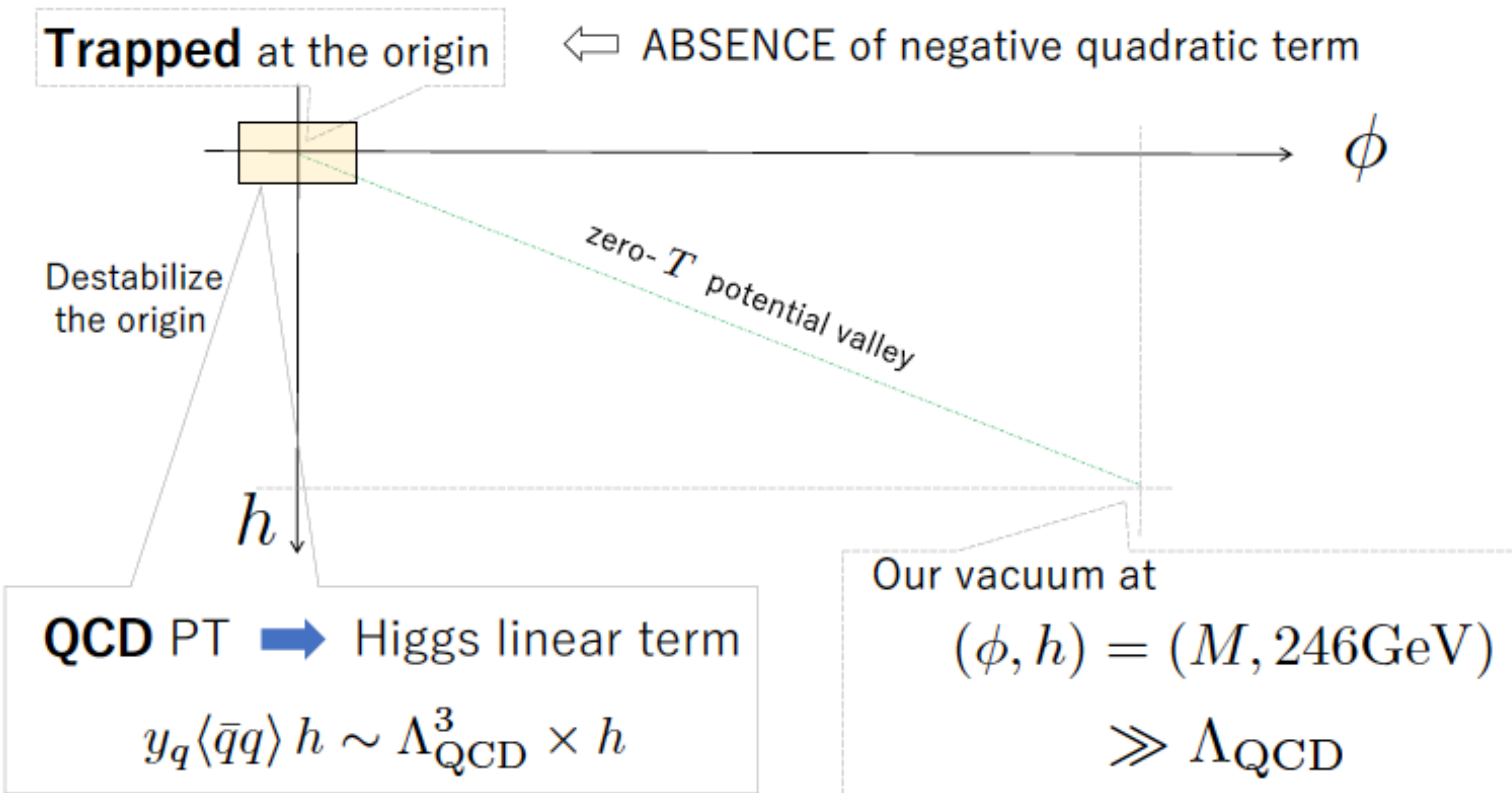
In a supercooled PT, the nucleation process takes time, so that $T_p \ll T_c$

for $g \lesssim 0.2$, EW/B-L phase transition is not completed via tunneling and the *QCD PT happens first* (in most of the Universe volume)

resurrection of Witten's scenario: the dynamics is now dictated by (N=6) QCD PT.

QCD-induced phase transition

Quark condensation induces a tilt in the Higgs potential, destabilizing the origin



A similar "EW symmetry breaking at QCD scale" had been recently considered only as an academic exercise "*What if no Higgs?*"*… of course before the 2012 discovery!*

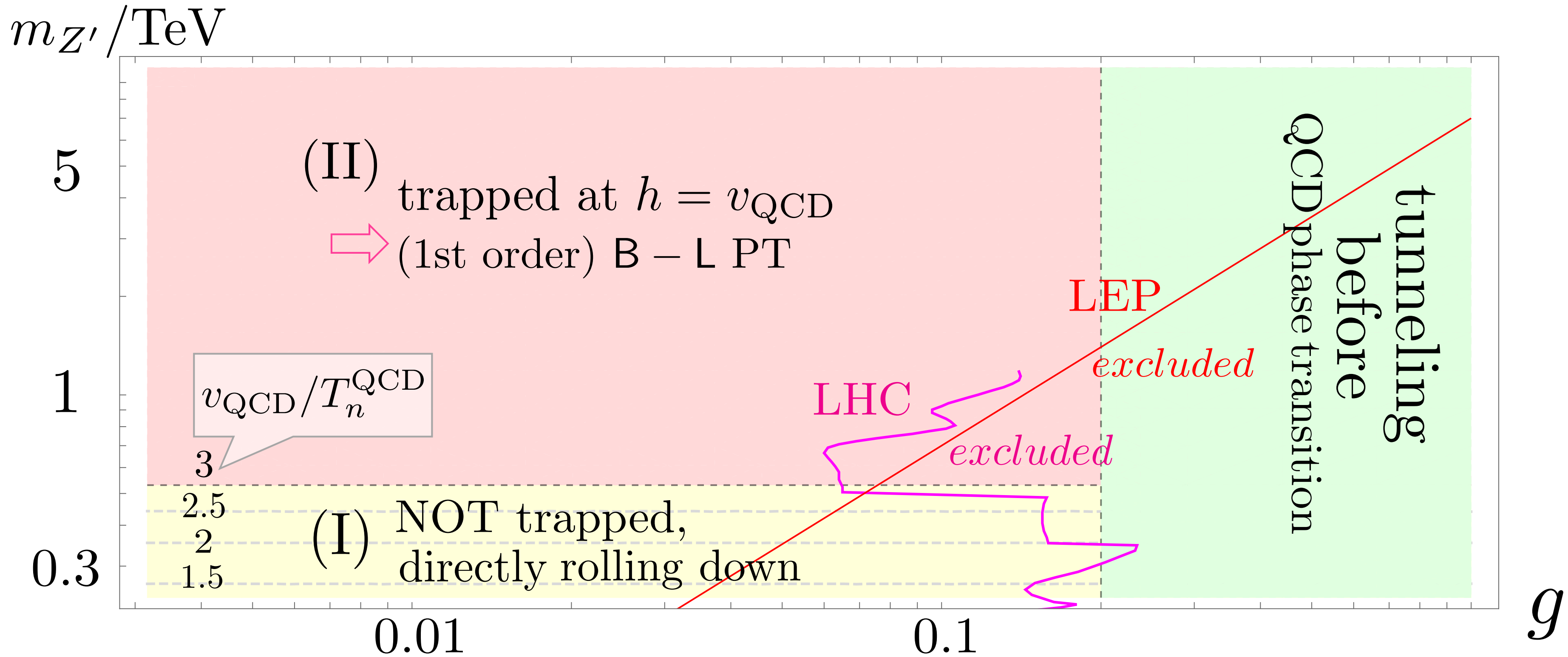
C. Quigg and R. Shrock, "Gedanken Worlds without Higgs: QCD-Induced Electroweak Symmetry Breaking," Phys. Rev. D 79, 096002 (2009) [0901.3958]

Further evolution

Once EW symmetry is broken at the QCD scale, the field will further evolve:

- either by directly rolling down to the true minimum
- or (more easily) a new "mini-inflationary" phase, being trapped at the new minimum

Which one depends on sign of the quadratic term (competition of the Z', RH ν's vs negative QCD scale term)



Most interesting parameters space for this scenario:

$g \ll 0.2$

~ (sub)TeV-scale Z' (*$M_{Z'}$>240 GeV for CW*)

light (at or below EW scale) RH ν's

additional B-L scalar lighter than 20 GeV and a small Higgs mixing, $\lambda_{mix} \sim \lambda_h (v/M)^2 \sim O(g^2 \lambda_h)$

Implications: some cosmological "food for thought"

- We expect dilution factor of ~10^6 due to this "late" reheating (T_R<20 GeV): relics from high-energy physics (e.g. heavy WIMPs, pre-existing baryon-asymmetry) correspondingly diluted. In practice, there cannot be **thermal relics with TeV mass scale**. **Non-thermal DM** *(including sterile neutrinos)* **seem more easily accommodated.**

- Motivates **generating baryon-asymmetry at low scales**, and the mechanism described may help! Cold EW baryogengesis generic opportunity offered by a supercooling stage ending with first order PT, see *T. Konstandin & G. Servant, JCAP 1107, 024 (2011)*

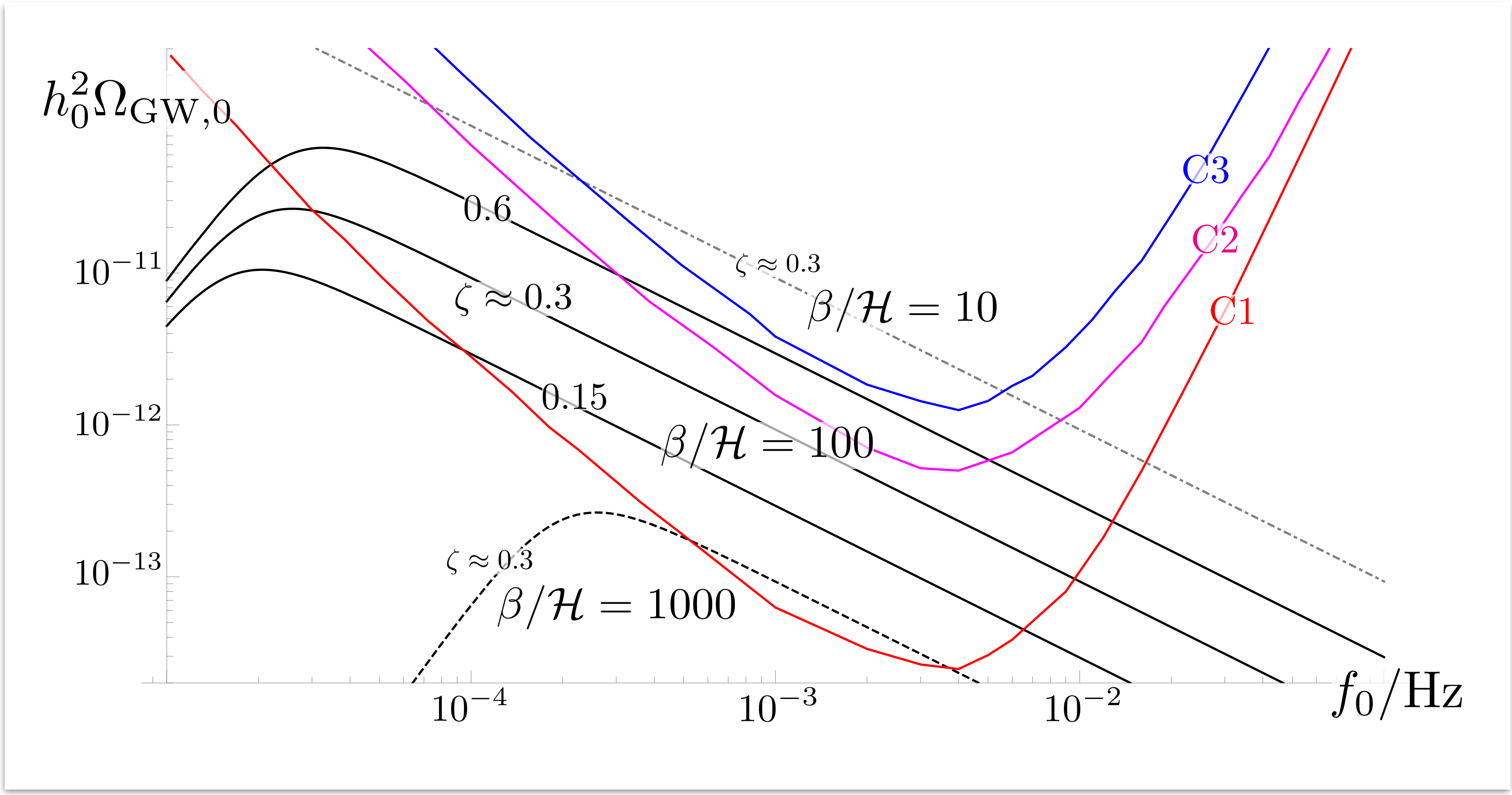
- **Notable scenario where a 1st order QCD PT can be obtained** without invoking large lepton (*D. J. Schwarz & M. Stuke, JCAP 0911, 025 (2009) [0906.3434]*) or baryon asymmetry (*T. Boeckel & J. Schaffner-Bielich, Phys. Rev. Lett. 105, 041301 (2010) [0906.4520]*), thus *conceptually* important. Hard to say if there is any observable remnant, since typically the universe reheats at $T > T_c^{QCD}$, and a second "ordinary" QCD phase transition occurs.

- Possible relics: stellar mass PBH, whose formation could be eased by a 1st order QCD PT (*K. Jedamzik, Phys. Rev. 55, 5871 (1997) [astro-ph/9605152]*) or Ultra-Compact-Mini-Halos (*M. Ricotti and A. Gould, Astrophys. J. 707, 979 (2009)*) with possible lensing signatures

Assessing more specifically and quantitatively (some of) these aspects: Work in Progress!

One intriguing generic expectation

- sizable **background of Gravitational Waves**, whose detectability (and spectrum) depends on parameters, notably the "speed" of PT, β/*H*. Part of it within LISA range, according to configurations considered in *C. Caprini et al. 1512.06239*



generalities on this topic covered in Chiara Caprini's talk

summary and conclusions

- Cosmology provides us with many indications for physics BSM. None of them were "expected".
- In some cases, it also provides us with the best probe of the properties that this physics should have! I illustrated this with a couple of examples.
- If even a tiny fraction of the energy stored in the DM mass is released into "visible" (e.m.) form, CMB constraints can be quite tight (due to gas ionization and heating phenomena)
- CMB can also impose purely gravitational bounds: For instance, it limits to <3.8% the conversion of DM mass into "dark" radiation (like GW)
- Future CMB anisotropy missions (ground…& space-based?), CMB spectral distortions (PIXIE-like) or 21 cm tomography (e.g. SKA) will further improve sensitivity to "particle physics".
- The power of the cosmological probe should not make us forget that we are *ignorant* about what was really going on, even at *T* naively "under SM control". Relatively minimal new physics can dramatically alter cosmology even at *T~O(GeV)*, with implications for DM (or other relics from the early universe, like PBH), Baryogenesis, or GW.
- *Generic Lesson:* Do not take unexplored cosmological epochs for granted, surprises may hide: we must *probe* them!

THANK YOU FOR YOUR ATTENTION!

ORATIO PRO COSMOLOGIA PARTICULARUM

i.e.:

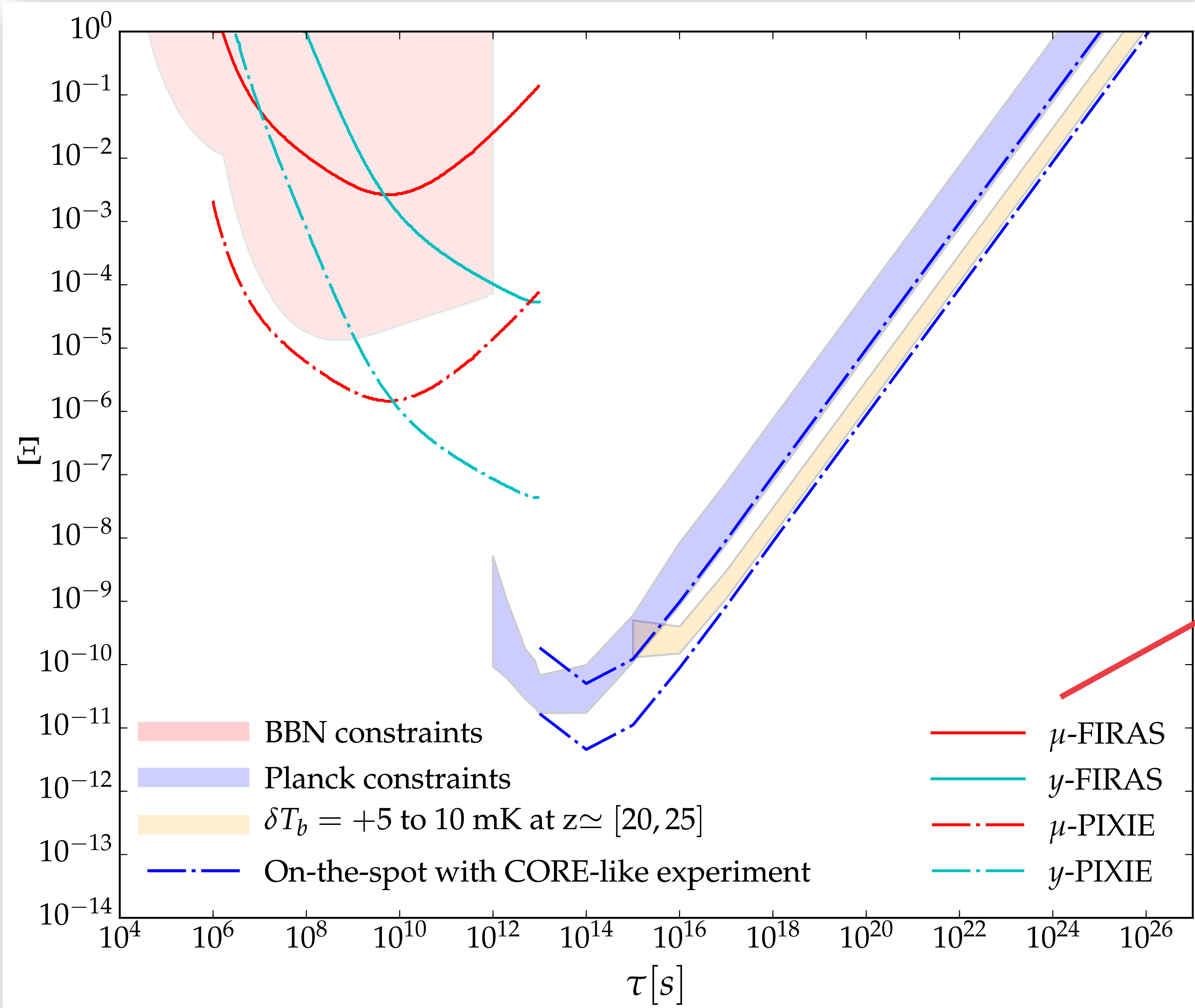
1) lessons *from* the Universe *on* fundamental dof's

2) implications *of* new fundamental dof's *on* the Universe

"The Cosmic Little Prince" by Elspeth McLean

Pasquale Dario Serpico (LAPTh - Annecy, France)

Forecasts



covered in Jens Chluba's talk

No information on 21 cm *power spectrum* folded in!