Weinberg: "I never had any idea you would assemble the stars listed below"

3x2x1 50!

SM@50

The Standard Model at 50 Years: a celebratory symposium

will take place in the

Physics Department
Case Western Reserve University

Cleveland, Ohio, June 1-4, 2018.

For more information, email SMat50@case.edu

Speakers

Steven Adler	Michael Peskin
James "BJ" Bjorken	Hellen Quinn
Alain Blondel	Carlo Rubbia
Norman Christ	Jurgen Schukraft
Savas Dimopoulos	Glenn Starkman
Henriette Elvang	Robin Stuart
Mary K. Gaillard	Cyrus Taylor
David Gross	Samuel Ting
Gerard 't Hooft	Steven Weinberg
Takaaki Kajita	Mark Wise
Bryan W. Lynn	Sau Lan Wu
Pavel Fileviez Perez	Benjamin F.L. Ward

DM discussion

My qualifications:

Marc Kamionkoski: “you’re the only person at the meeting who’s never written a paper about spectral distortions

In the process of becoming even less qualified, as Ema told us.

Mark Kamionkoski's Outline

- Preliminaries
- Dissipation of acoustic modes ("Standard-Model" predictions
  - Tests of inflation
  - Tests of small-scale-suppression mechanisms
  - Non-gaussianity
- Decaying particles / **PBHs**
- Late-time contributions
- **Grab bag**
- Shopping list

Courtesy of Marc Kamionkowski

Exotic mechanisms to suppress small-scale power

(Nakama, Chluba, MK 2017; also Diacoumis&Wong 2017; Sarkar, Sethi, Das 2017)

- Only mechanisms (e.g., BSI from inflation (e.g., MK-Liddle 2000)) that eliminate *radiation*-density perturbations have effect on mu distortion
- Mechanisms (e.g., DM from charged-particle decay at tau~3.5 yr (e.g., Sigurdson-MK 2004)) that reduce matter fluctuations without smoothing radiation fluctuations do not alter standard mu prediction

Courtesy of Marc Kamionkowski

Early energy injection from exotic sources

- Chluba-Sunyaev thermalization
  - Primordial isocurvature
  - Detailed frequency spectrum (Katri-Sunyaev)
  - **DM annihilation**
  - **DM decays**
  - PBHs
  - Magnetic fields
  - Superconducting cosmic strings
  - Axions
  - Damping of tensor perturbations (Chluba, Dai, Grin, Amin, MK 2014)

Courtesy of M. Kamionkowski

PBHs

- Ricotti, Ostriker, Mack (2008) infer strong constraints to ~30-Msun PBH DM from FIRAS
- We find distortion detectable with PIXIE only if $L \sim L_{edd}$ for accreting PBHs (YAH,MK 2016; also Aloni, Blum, Flauger 2017; Horowitz 2017; Poulin))
- (30-Msun PBH DM scenario faces stiff pressure from early-U binaries; YAH, Kovetz, MK 2017)

Courtesy of M. Kamionkowski

Shopping List / To Do

- Foregrounds (e.g., Abitbol, Chluba, Hill, Johnson 2017; Remazeilles&Chluba 2018; Remazeilles, Delabrouille, Cardoso 2010; Sathyanarayana Rao, Subrahmanyan,Udaya Shankar, Chluba 2017)?
- **More sophisticated frequency-space characterization (beyond mu and y) ? (Chluba & Jeong 2014; Mukherjee, Silk, Wandelt 2018)**
- **Complementarity with fluctuations? (e.g., Poulin, Lesgourgues, Serpico 2017)**
- **Build the science case**
  - **What *essential* science results?**
  - **What is the elevator pitch?**

Courtesy of M. Kamionkowski

Degeneracies

Probing inflation with spectral distortions: need to characterize & quantify other possible sources of distortions … including those from "exotic" physics! E.g. :

- **dark matter effects**: Ali-Haimoud - Chluba - Kamionkowski 2015, Nakama - Chluba - Kamionkowski 2017, Diacoumis - Wong 2017; Pasquale Serpico's talk on Wed., Yacine Ali-Haimoud's talk on Thur., Suvodip Mukherjee's & James Diacoumis' talks on Friday
- **decays/annihilations of relics** (see Subir Sarkar's talk on Wed.)
- **primordial black holes** (see Juan Garcia-Bellido's talk on Wed.)

Courtesy of Ema Dimastrogiovanni

What do WIMPs do on CMB?

Via annihilation byproducts, they inject energy in the medium

$$\frac{dE}{dV\,dt} = \rho_c^2 (1+z)^6 \Omega_{DM}^2 \, p_{ann}$$

key-parameter linked to particle physics

$$p_{ann} = \frac{\hbar\sigma v i}{8\pi m_X^2}[4\pi][2m_X] f(z) = f(z)\frac{\hbar\sigma v i}{m_X}$$

To *some extent* injected energy can be used to heat the medium (& excite/ionize it, after recombination)

$$\left.\frac{dE}{dV\,dt}\right|_{dep,c} = f_c^{(P)}(z, x_e) \left.\frac{dE}{dV\,dt}\right|_{inj}$$

CMB is sensitive to:

$x_e(z)$ & notably the overall optical depth experienced by photons: WIMPs can alter recombination & reionization

T_M & the heating: at early times via spectral distortions, at late times subleading (via feedback on $x_e(z)$, to which it is coupled)

Qualitatively, decaying or annihilating particles can have similar effects, but:

CMB **spectral distortions & CMB anisotropies** expected for WIMP DM annihilation are **linked**, since recombination & reionization effects directly related to heating & no "tunable" timescales available

Courtesy of Pasquale Serpico

Some seminal papers on this subject (pre-2008)

J.A. Adams, S. Sarkar, D.W. Sciama,
"CMB anisotropy in the decaying neutrino cosmology" MNRAS 301, 210 (1998) [astro-ph/9805108]

X. L. Chen and M. Kamionkowski,
"Particle decays during the cosmic dark ages," Phys. Rev. D 70, 043502 (2004) [astro-ph/0310473].

L. Zhang, X. Chen, M. Kamionkowski, Z. G. Si and Z. Zheng,
"Constraints on radiative dark-matter decay from the cosmic microwave background," Phys. Rev. D 76, 061301 (2007) [0704.2444]

P. J. E. Peebles, S. Seager and W. Hu, "Delayed recombination," Astrophys. J. 539, L1 (2000)

R. Bean, A. Melchiorri and J. Silk,
"Recombining WMAP: Constraints on ionizing and resonance radiation at recombination," Phys. Rev. D 68, 083501 (2003) [astro-ph/0306357] "Cosmological constraints in the presence of ionizing and resonance radiation at recombination," Phys. Rev. D 75, 063505 (2007) [astro-ph/0701224]

N. Padmanabhan and D. P. Finkbeiner,
"Detecting dark matter annihilation with CMB polarization: Signatures and experimental prospects," Phys. Rev. D 72, 023508 (2005) [astro-ph/0503486].

M. Mapelli, A. Ferrara and E. Pierpaoli,
"Impact of dark matter decays and annihilations on reionzation," MNRAS 369, 1719 (2006) [astro-ph/0603237]

L. Zhang, X. L. Chen, Y. A. Lei and Z. G. Si,
"The impacts of dark matter particle annihilation on recombination and the anisotropies of the cosmic microwave background," Phys. Rev. D 74, 103519 (2006) [astro-ph/0603425].

Dozens of relevant papers, in the last decade…

Courtesy of Pasquale Serpico

Why are CMB anisotropies such a sensitive probe?

Have a look at the standard ionization and gas temperature evolution

Note:

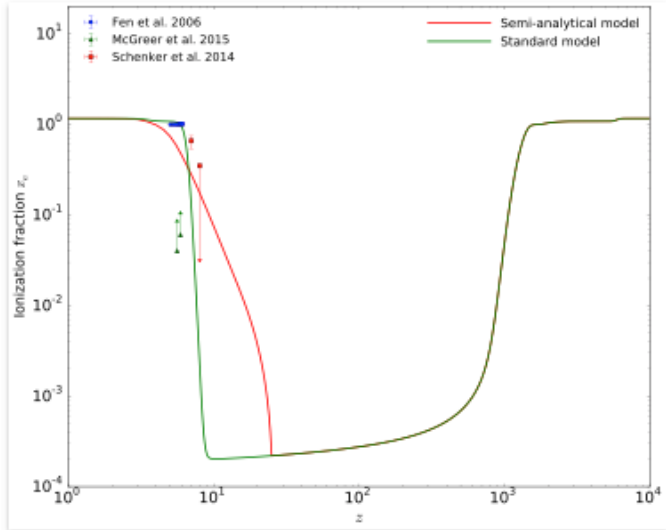
few tens of eV/baryons are in principle sufficient to ionize all atoms!

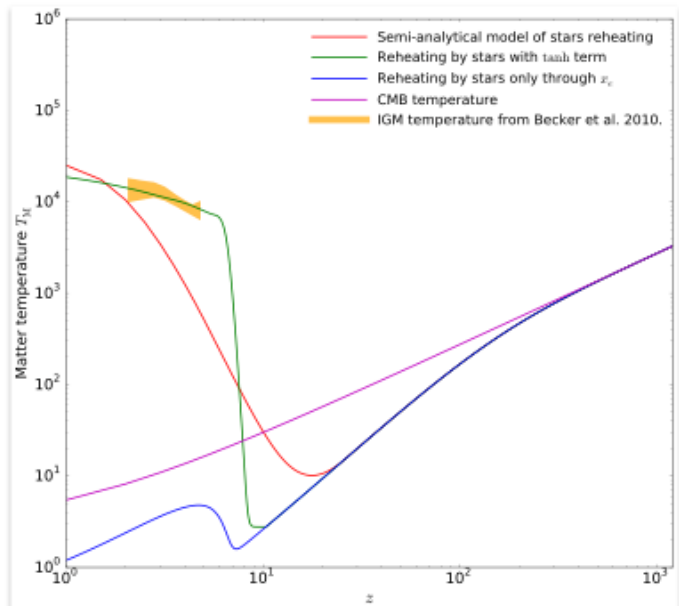
In the DM, in principle ~5 GeV/baryon "stored"

The reionization fraction in the standard expectation drops to ~ 5 10^{-3}

converting O(10^{-11}) of the energy stored into DM mass into visible form may be sufficient to induce major alterations in x_e or T_M!

this maximal sensitivity is actually achieved, if energy is injected at/just after recombination





Courtesy of Pasquale Serpico

Spectral distortions: how do they compare?

In principle, both "μ-y" and "recombination" epochs are affected

These effects appear to be small

Primordial distortions of the order $\mu \approx 3 \times 10^{-10} f_{\mathrm{d,lim}} \left[\frac{M_\chi c^2}{100\,\mathrm{GeV}}\right]^{-1} \left[\frac{\Omega_\chi h^2}{0.13}\right]^2 \left[\frac{\langle \sigma v \rangle}{3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}}\right]$

P. McDonald, R. J. Scherrer and T. P. Walker, "Cosmic microwave background constraint on residual annihilations of relic particles," Phys. Rev. D 63, 023001 (2001) [astro-ph/0008134]

So, *naively* one can only hope to improve over *current* bounds if sensitivity to distortions attains at least the 10^{-10} level *(two generations of detectors away?)*

Alterations to the (yet undetected) recombination spectrum @ (sub)percent level

J. Chluba, "Could the Cosmological Recombination Spectrum Help Us Understand Annihilating Dark Matter?," MNRAS 402, 1195 (2010) [0910.3663]

As you might guess, there are loopholes to this conclusion, otherwise my talk is over

Courtesy of Pasquale Serpico

Loopholes al Serpico:

- First loophole: z-dependence of annihilation rate:
    - $\langle\sigma v\rangle(z)$ e.g. p-wave annihilations pick up extra $v^2 \sim (1+z)^2$ allows them to cause SD but be benign for anisotropies
- Second loophole: freeze-out via "coscattering"
- Third loophole: Late Kinetic Decoupling via DM-baryon scattering
    - "The best you can do": thermalize all of the DM, $\rightarrow$SD $\propto n\chi/n\gamma$, so $-\mu \sim O(10^{-9})$ $m\chi/mb$; hence FIRAS bounds only apply below ~180 keV, but PIXIE could reach GeV's
- Fourth loophole: LKD via DM-photon scattering

- SD Effects of DM-standard model scattering
  - More details in James Diacoumis’ talk on Friday!

Summary & Conclusions

CMB SD do not appear a promising channel to constrain/detect vanilla WIMPs, notably due to competing constraints from CMB anisotropies (& to some extent BBN)

But:

1) There is no indication for vanilla WIMPs *(obvious, but worth reminding…)*
2) There are a few off-the-beaten-path cases (relatively light particles annihilating via p-wave, coscattering, LKD scenarios) where the SD is known to be much more promising.
3) Some of the features promising for SD also found in models attempting to address the "small-scale tensions" in the CDM paradigm (& maybe recently anomalous EoR observations?)

Then, SD provides one of the few (the only?) "perturbative" channels for diagnostics.

And I did not even enlarge too much the DM theory space, other interesting consequences e.g. for axion models, PBH, macroscopic DM, etc.

Courtesy of Pasquale Serpico

Degeneracies

Probing inflation with spectral distortions:

need to characterize&quantify other possible sources of distortions

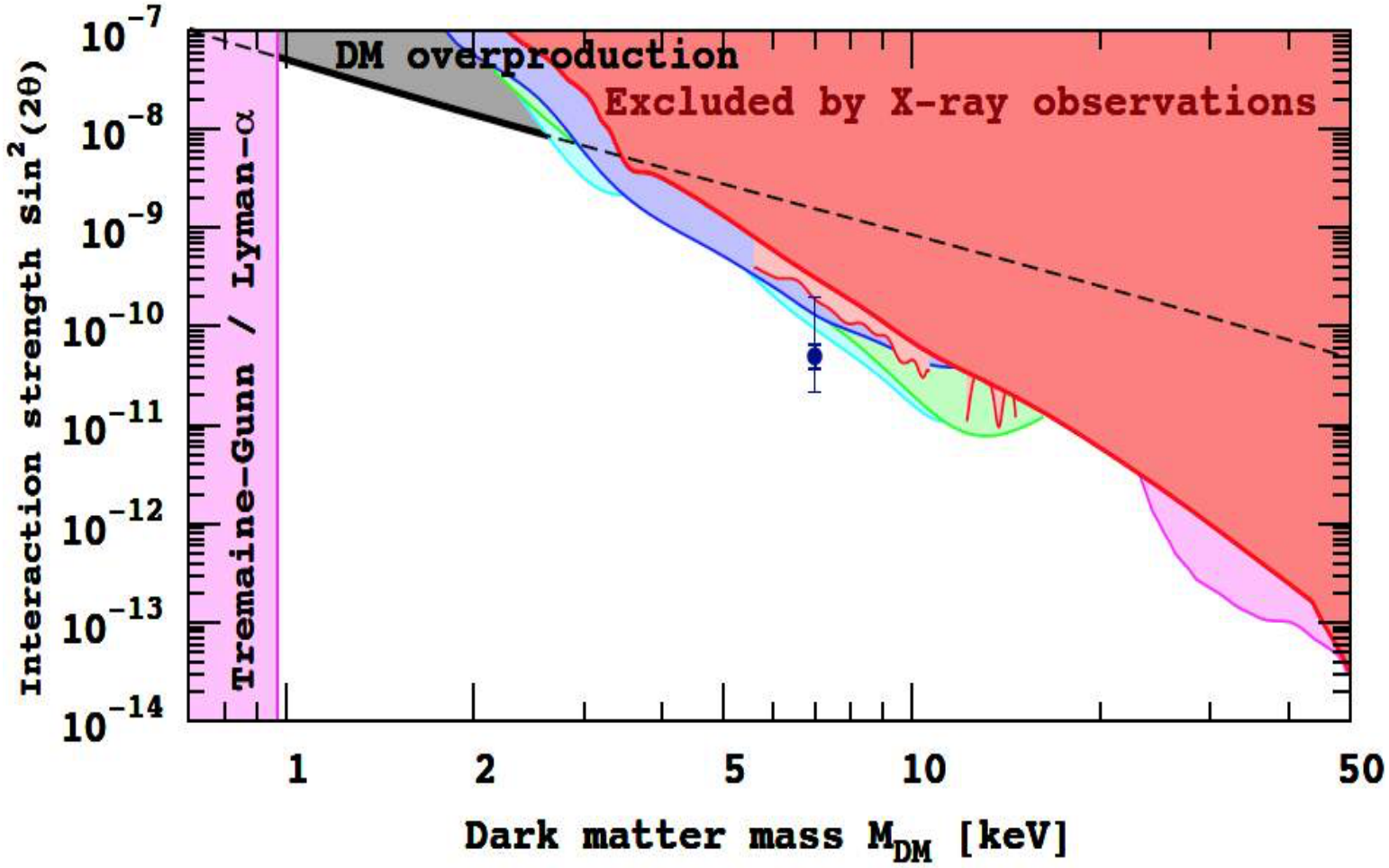
… including those from “exotic” physics! E.g. :

- dark matter effects

  Ali-Haimoud - Chluba - Kamionkowski 2015, Nakama - Chluba - Kamionkowski 2017, Diacoumis - Wong 2017, …, see Pasquale Serpico’s talk on Wed., Yacine Ali-Haimoud’s talk & discussion session on Thur., Suvodip Mukherjee’s & James Diacoumis’ talks on Friday

- decays/annihilations of relics (see Subir Sarkar’s talk on Wed.)
- primordial magnetic fields (see Kerstin Kunze’s talk)
- primordial black holes (see Juan Garcia-Bellido’s talk on Wed.)
- topological defects
- …

Much excitement about detection of possible decay line at ~3.5 keV!



Boyarsky & Shaposhnikov, ARNPS **59**:191,2009
Ruchayskiy *et al*, JCAP 01:025,2018

7 keV 'warm dark matter', even if it exists, has too long a lifetime to create CMB distortions, however there may be *other* sterile neutrinos with MeV masses ⇒ shorter lifetimes which can e.g. solve the "Li problem" and be probed via their μ distortions (Salvati *et al*, JCAP 08:022,2016)

Courtesy of Subir Sarkar

Degeneracies

Probing inflation with spectral

need to characterize&quantify

… including those from "exo

- dark matter effects

  Ali-Haimoud - Chluba - Ka
  Kamionkowski 2017, Diaco
  talk on Wed., Yacine **Ali-Ha**
  Suvodip Mukherjee's & **Jan**

- decays/annihilations of re
- primordial magnetic field
- primordial black holes (se
- topological defects
- …

Spectral distortions from macroscopic dark matter

dark matter formed in the early Universe (QCD phase transition) in the form of composite baryonic objects of approximate nuclear density and macroscopic size ("macros")

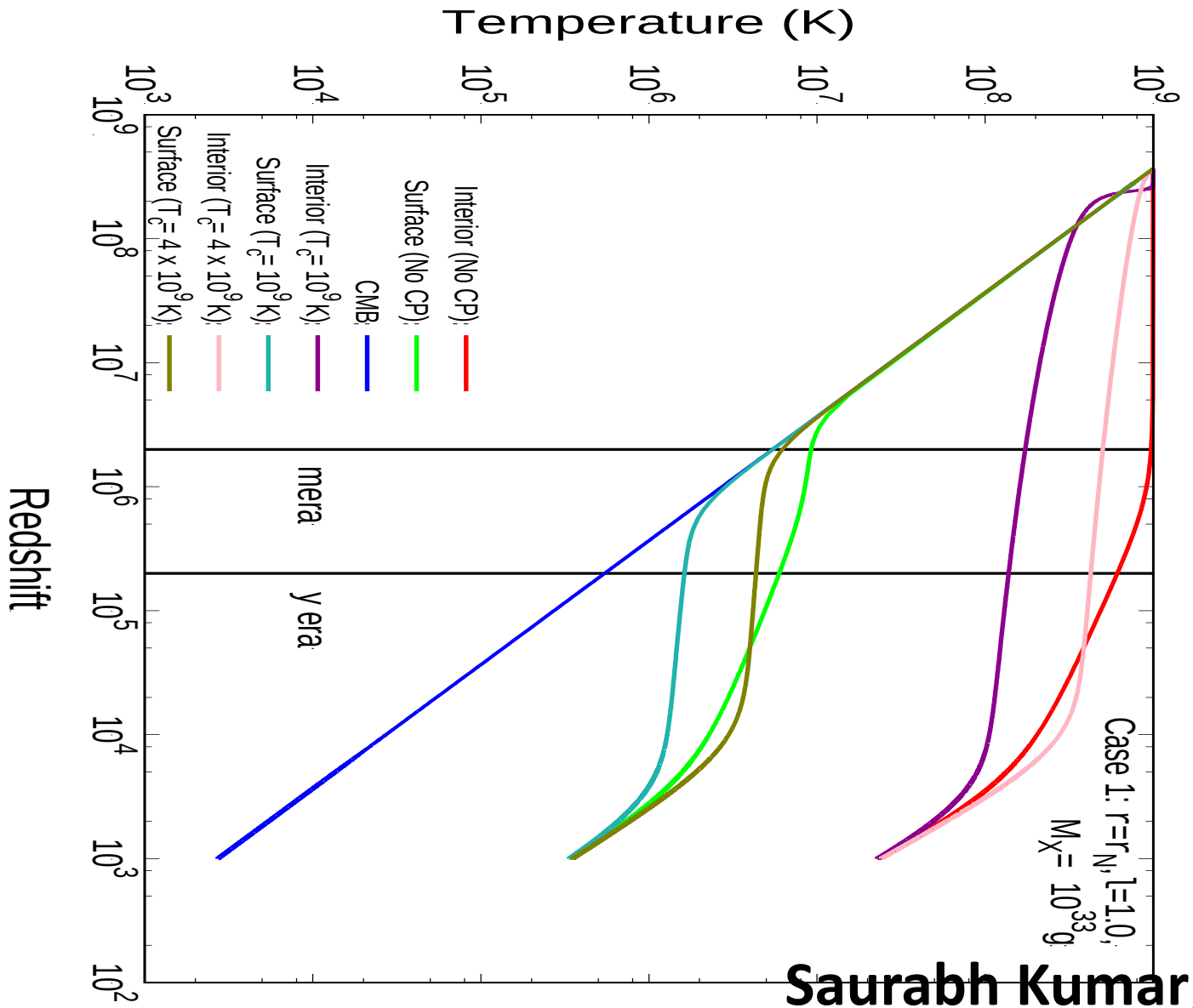
macros cool slowly (by emission of neutrinos and photons) distorting the CMB (as well as affecting the cosmic neutrino background)

y distortion from these objects would be detectable by a PIXIE-like experiment

(with Saurabh Kumar, Glenn Starkman, Craig Copi, Bryan Lynn)

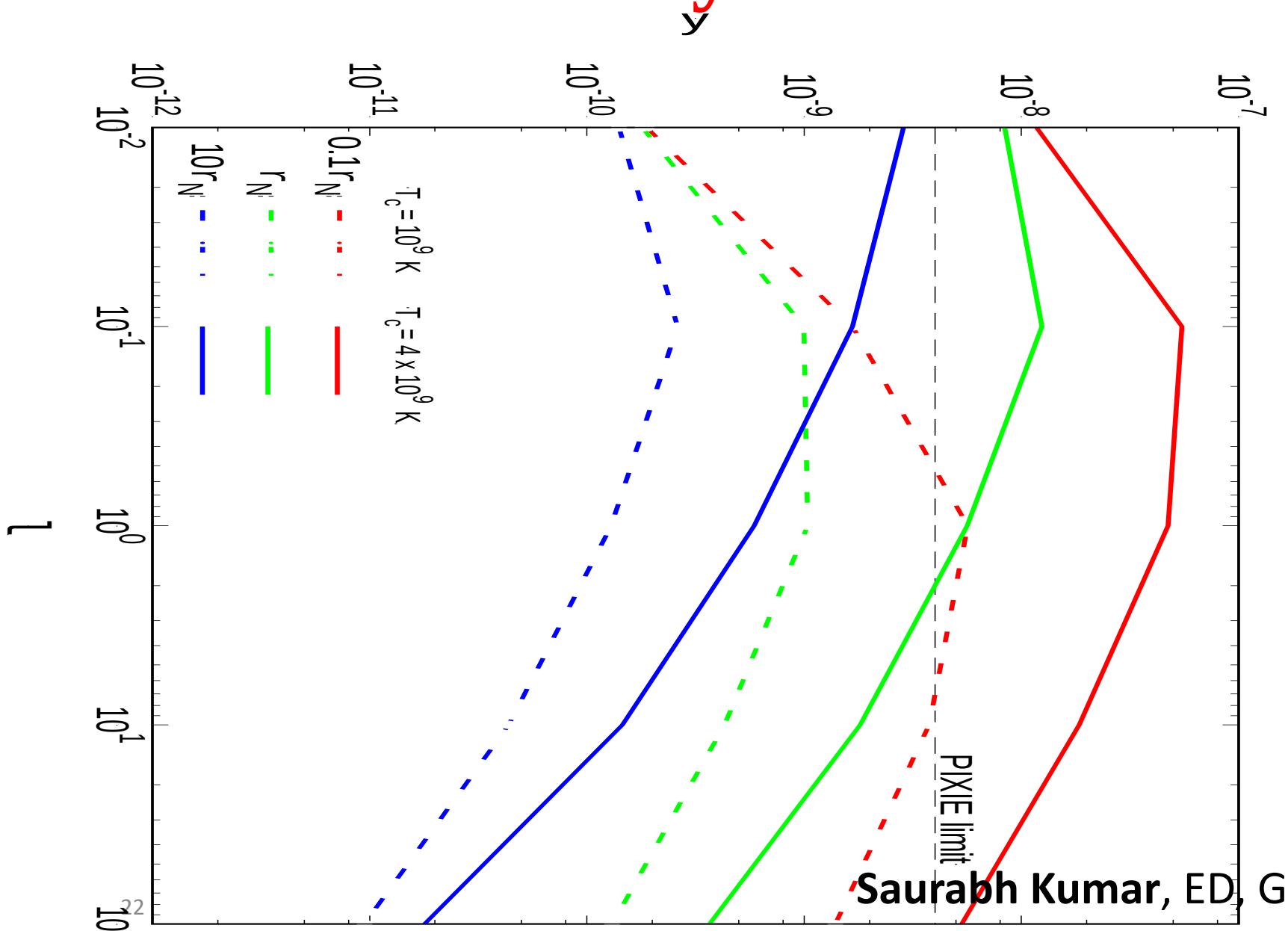
Courtesy of Ema Dimastrogiovanni

RESULTS: T vs. z



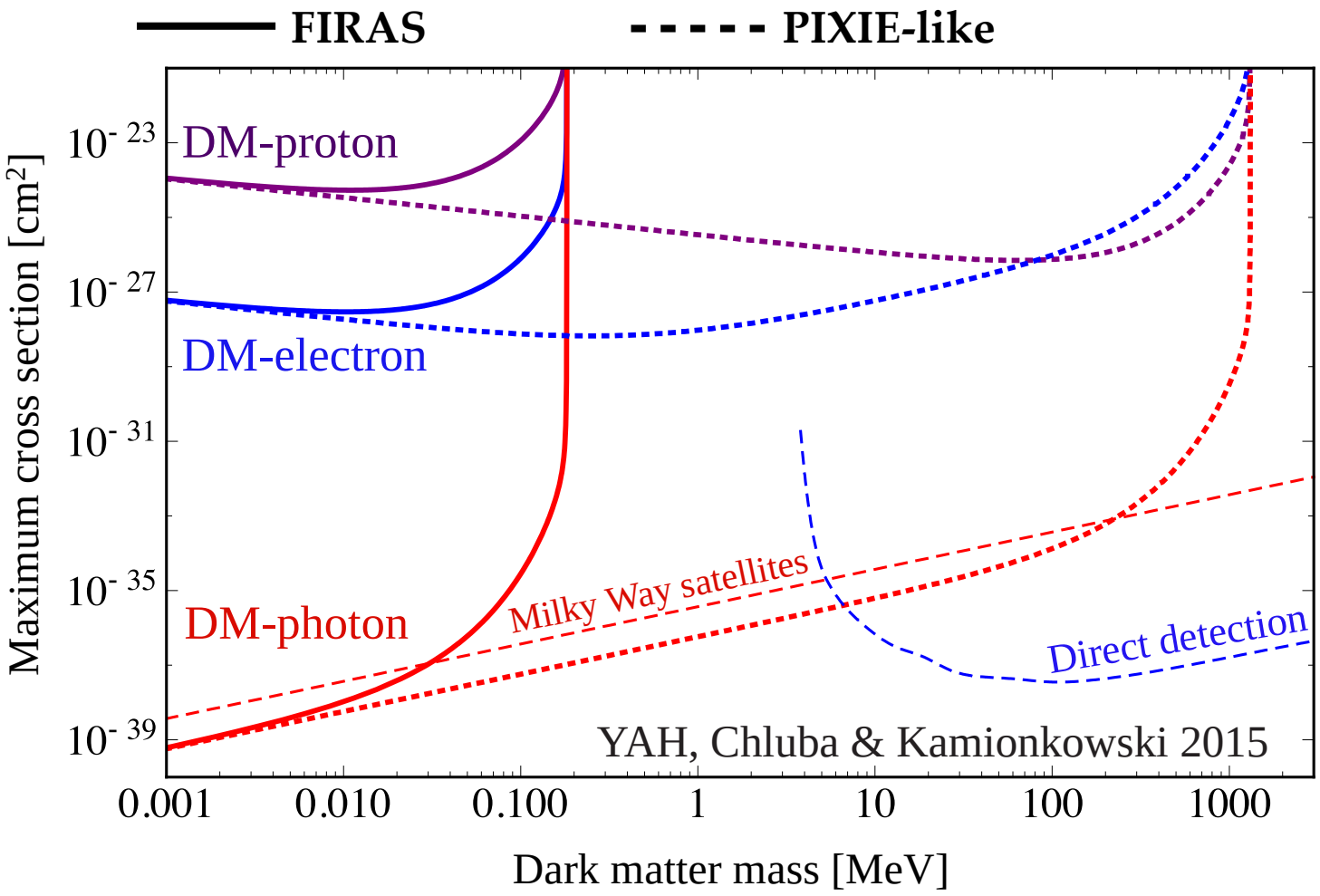
Saurabh Kumar, ED, GDS, Copi, Lynn.

RESULTS: y distortion



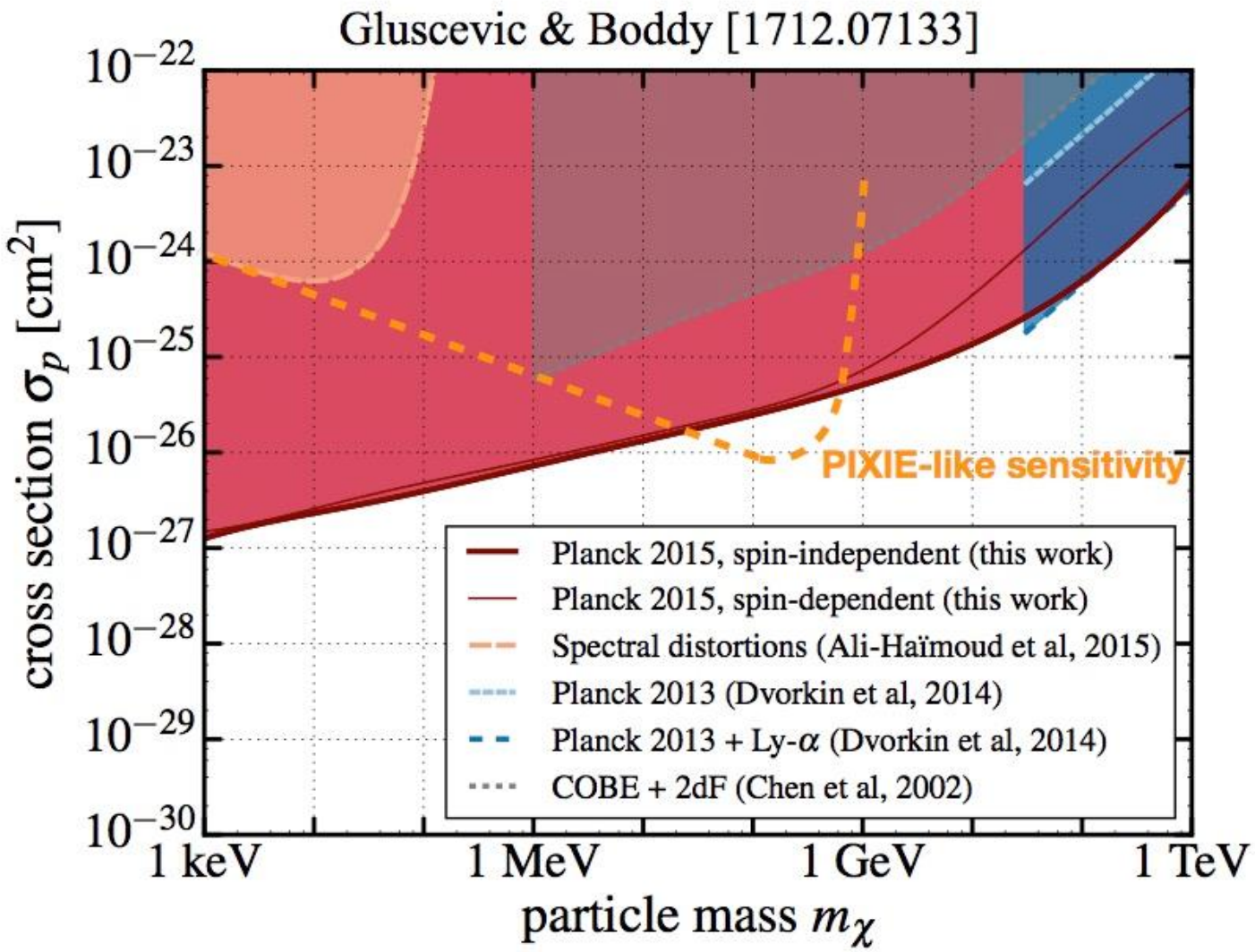
Saurabh Kumar, ED, GDS, Copi, Lynn.

Interacting dark matter as a heat sink: spectral distortions



Courtesy of Yacine Ali-Haimoud

For constant cross section with protons, CMB anisotropy do better



Courtesy of Yacine Ali-Haimoud

Priomordial Black Holes

Underlying physics for CMB bounds

Carr 1981, Ricotti et al. 2008, YAH & Kamionkowski 2017

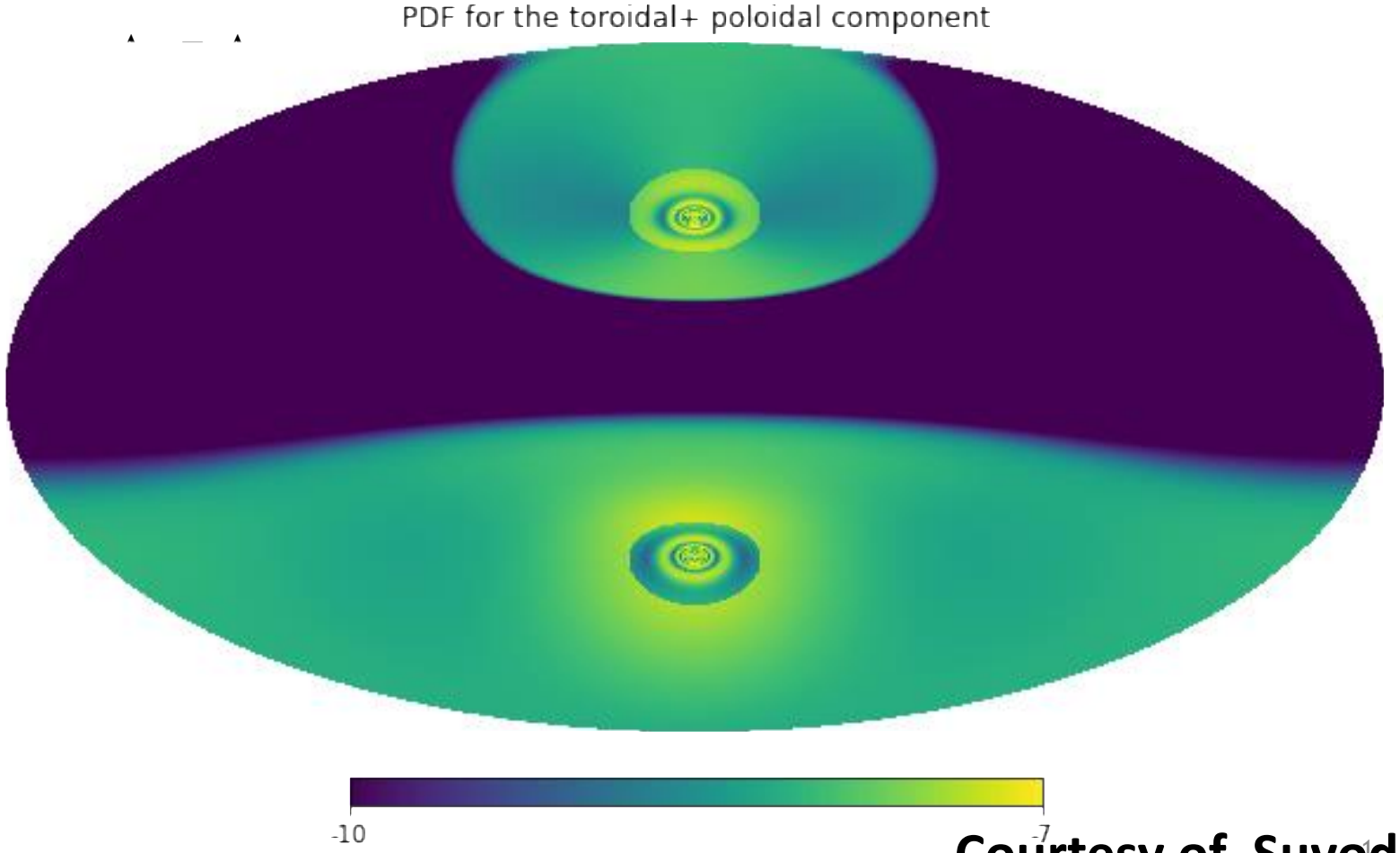
1. PBHs accrete baryons
2. a fraction of the accreted mass is re-radiated
3. a fraction of this luminosity is deposited into the plasma
4. some is deposited as heat => CMB spectral distortions
5. some leads to extra ionizations
   => change the recombination history and visibility function
   => affects CMB temperature and polarization anisotropies

Our philosophy: (i) first-principles, low-fudge-number calculation (ii) estimate the minimal physically plausible effect in order to set conservative upper limits

Courtesy of Yacine Ali-Haimoud

Resonant Conversion from axions

axion mass: 5*10^-13 eV



Courtesy of Suvodip Mukherjee

MK's Shopping List / To Do

- Foregrounds (e.g., Abitbol, Chluba, Hill, Johnson 2017; Remazeilles&Chluba 2018; Remazeilles, Delabrouille, Cardoso 2010; Sathyanarayana Rao, Subrahmanyan,Udaya Shankar, Chluba 2017)?
- More sophisticated frequency-space characterization (beyond mu and y) ? (Chluba & Jeong 2014; Mukherjee, Silk, Wandelt 2018)
- Complementarity with fluctuations? (e.g., Poulin, Lesgourgues, Serpico 2017)
- **Build the science case**
  - **What *essential* science results?**
  - ~~What is theelevator pitch?~~ **Is DM part of the elevator pitch?**

Courtesy of M. Kamionkowski

DM as essential SD science