Weinberg: “I never had any idea you would assemble the stars listed below.”

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 SM@50@case.edu

Speakers

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

24th International Symposium on
PArticles, Strings & COSmology

June 4-8, 2018, Cleveland, USA
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
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 $L \sim L_{\text{edd}}$ 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)
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 μ and γ)? (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. :


• **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

\[
\frac{dE}{dV \, dt} = \cdots \xi^2 (1 + z)^6 \mathcal{R}_D^2 \ p_{\text{ann}}
\]

key-parameter linked to particle physics

\[
p_{\text{ann}} = \frac{\hbar \nu_i}{8 \pi m_X^2} [4 \pi] [2m_X] \ f (z) = f (z) \frac{\hbar \nu_i}{m_X}
\]

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

\[
\left. \frac{dE}{dV \, dt} \right|_{\text{dep},c} = \left. \frac{dE}{dV \, dt} \right|_{\text{inj}}
\]

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,

X. L. Chen and M. Kamionkowski,

L. Zhang, X. Chen, M. Kamionkowski, Z. G. Si and Z. Zheng,


R. Bean, A. Melchiorri and J. Silk,

N. Padmanabhan and D. P. Finkbeiner,

M. Mapelli, A. Ferrara and E. Pierpaoli,

L. Zhang, X. L. Chen, Y. A. Lei and Z. G. Si,

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 $\sim5 \text{ GeV/baryon}$ "stored"

The reionization fraction in the standard expectation drops to $\sim5 \times 10^{-3}$

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-γ” and “recombination” epochs are affected

These effects appear to be small

Primordial distortions of the order

\[ \mu \approx 3 \times 10^{-10} f_{\text{lim}} \left( \frac{M_1 \sigma^2}{100 \text{ GeV}} \right)^{-1} \left( \frac{\Omega_2 H^2}{0.13} \right)^{2} \left( \frac{\langle \sigma v \rangle}{3 \times 10^{-25} \text{ cm}^3/\text{s}} \right) \]


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


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:
  • \(<\sigma v>(z)\) 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, co-scattering, 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

- 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 \( \sim 3.5 \) keV!

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 \( \Rightarrow \) shorter lifetimes which can e.g. solve the “Li problem” and be probed via their \( \mu \) distortions (Salvati et al, JCAP 08:022, 2016)
Degeneracies

Probing inflation with spectral distortions: need to characterize & quantify other possible sources of distortion... including those from “exotic” effects:

- dark matter effects

  Ali-Haımoud - Chluba - Kamionkowski 2017, Diacoumis - Wong 2017, ... see Pasquale Serpico’s talk on Wed.

- decays/annihilations of relics

  Suvodip Mukherjee’s & James Diacoumis’ talk’s on Fri.

- primordial magnetic fields

- primordial black holes (see Kerstin Kunze’s talk)

- topological defects

- ...
RESULTS: T vs. z

$T$ vs. $z$

Temperature (K)

Redshift

$10^2$ $10^3$ $10^4$ $10^5$ $10^6$ $10^7$ $10^8$ $10^9$

Case 1: $r = r_N$, $l = 1.0$, $M_X = 10^{33}$ g

CMB

Interior ($T_c = 10^9$ K)

Surface ($T_c = 10^9$ K)

Interior ($T_c = 4 \times 10^9$ K)

Surface ($T_c = 4 \times 10^9$ K)

Saurabh Kumar, ED, GDS, Copi, Lynn.
RESULTS: $y$ distortion

$T_c = 10^9$ K
$T_c = 4 \times 10^9$ K

Saurabh Kumar, ED, GDS, Copi, Lynn.
Interacting dark matter as a heat sink: spectral distortions

![Graph showing dark matter cross sections](image)

**FIRAS**

**PIXIE-like**

- **DM-proton**
- **DM-electron**
- **DM-photon**

**Milky Way satellites**

**Direct detection**

YAH, Chluba & Kamionkowski 2015

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Courtesy of Yacine Ali-Haimoud
For constant cross section with protons, CMB anisotropy do better

Gluscevic & Boddy [1712.07133]

Cross section $\sigma_p$ [cm$^2$]

- Planck 2015, spin-independent (this work)
- Planck 2015, spin-dependent (this work)
- Planck 2013 (Dvorkin et al, 2014)
- Planck 2013 + Ly-$\alpha$ (Dvorkin et al, 2014)
- COBE + 2dF (Chen et al, 2002)

PIXIE-like sensitivity

Particle mass $m_\chi$
PROMORIAL 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

3/18/2018

Courtesy of Yacine Ali-Haimoud
Resonant Conversion from axions

axion mass: $5 \times 10^{-13}$ eV

PDF for the toroidal+ poloidal component

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 γ)? (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? Is DM part of the elevator pitch?

Courtesy of M. Kamionkowski
DM as essential SD science