Title: Neutrino and Dark Radiation Properties from Cosmic Datasets

Speakers: Marilena LoVerde

Series: Cosmology & Gravitation

Date: March 12, 2024 - 11:00 AM

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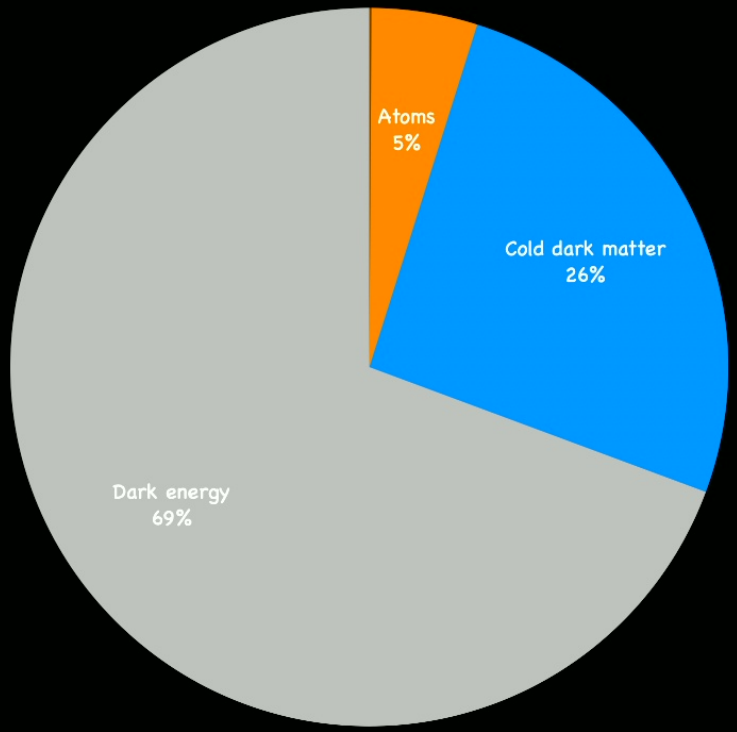
Abstract: Neutrinos and other light relic particles leave a number of imprints in the cosmic microwave background anisotropies and on maps of the large-scale structure of our Universe. These imprints can not only demonstrate the presence of these particles and constrain their masses, but can provide insight into their nature via signatures of interactions or other behavior that changes during the history of the Universe. I will describe this physics, present constraints on non-standard neutrino self-interactions and other forms of dark radiation from cosmic datasets. I will also discuss prospects for detecting neutrino mass and highlight how relic neutrinos force us to adopt new technology when modeling structures in the Universe today.

Zoom link

Neutrinos and Dark Radiation from Cosmic Datasets

Marilena Loverde
University of Washington

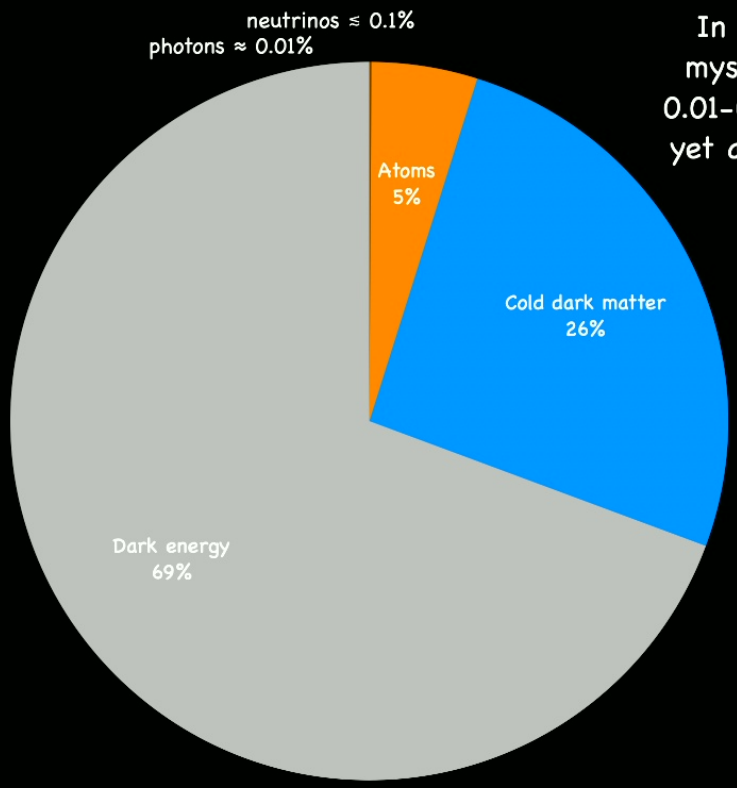
Matter budget



today

Matter budget

Is it really so simple?

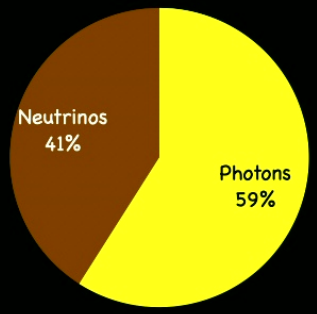


In particular, other mystery stuff at the 0.01-0.1% is detectable yet allowed by current data!

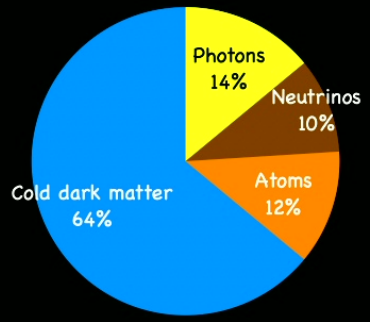
today

Matter budget

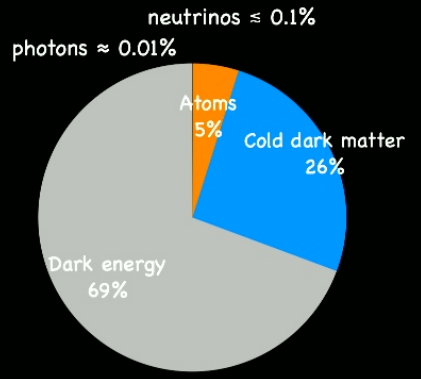
What we expect



radiation dom (T<<MeV)

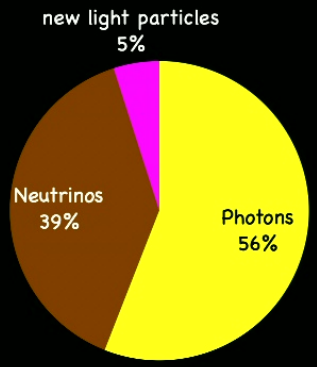


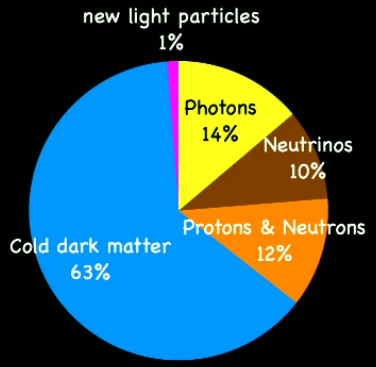
CMB decoupling

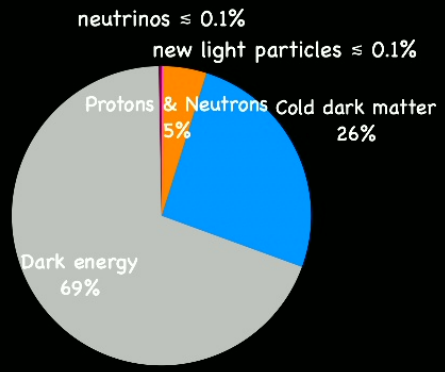


today

What could be







Neutrinos still have unknowns

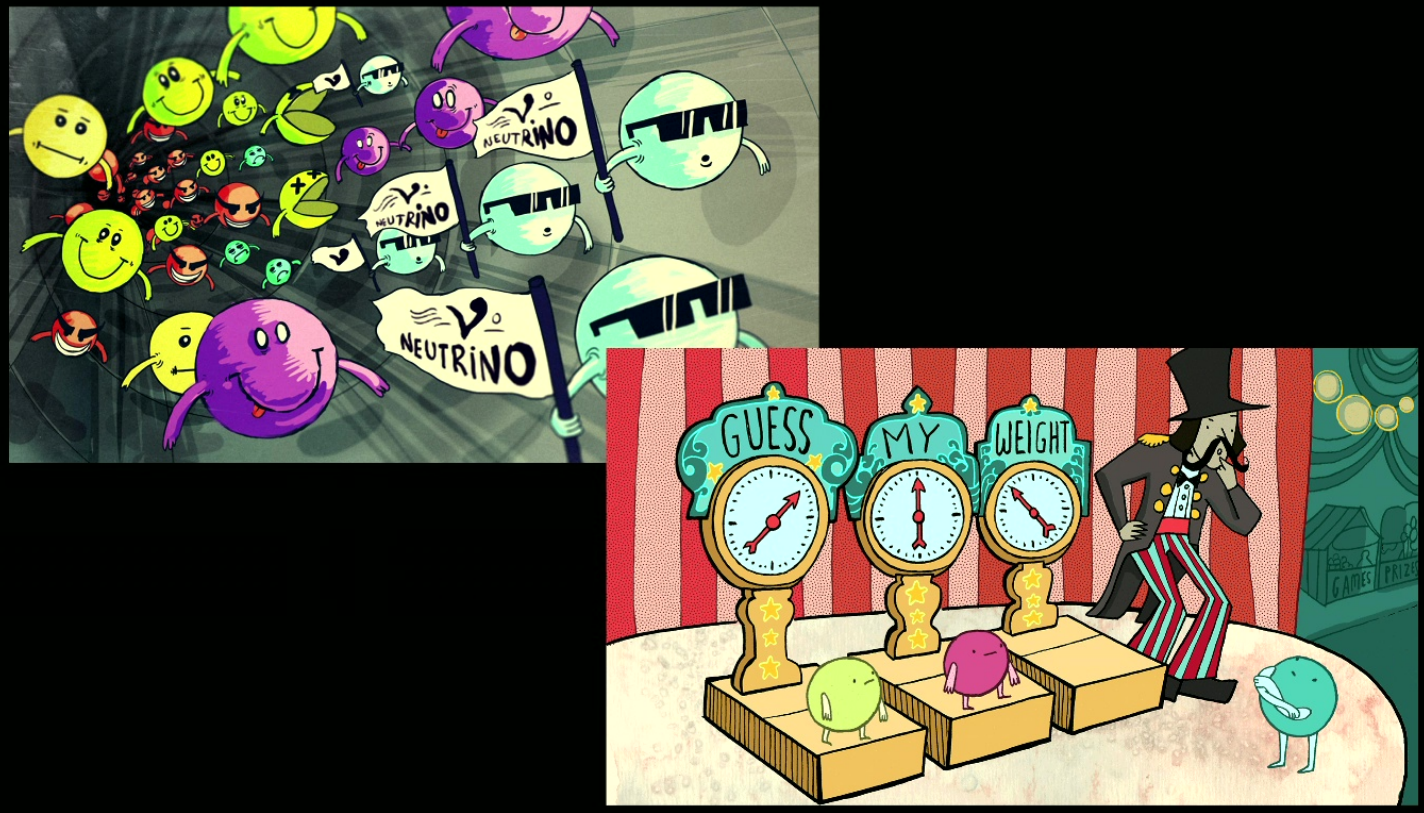
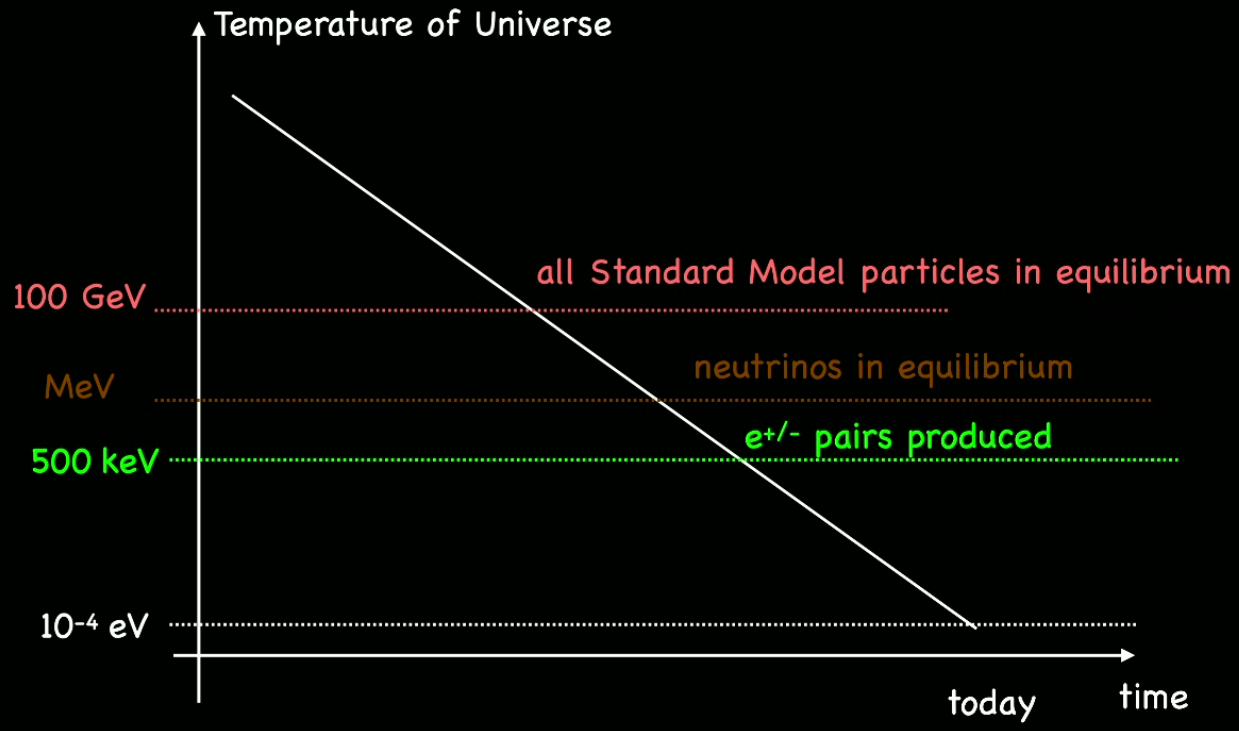


image credit: Sandbox Studio via Symmetry Magazine

Outline

- Light relics, what are they and what do we know?
- Impact of interactions
- Observables
  - *Cosmic Microwave Background*
  - *Large-scale structure*
  - *Gravitational Waves*
- Outlook

Relics of the Hot Big Bang



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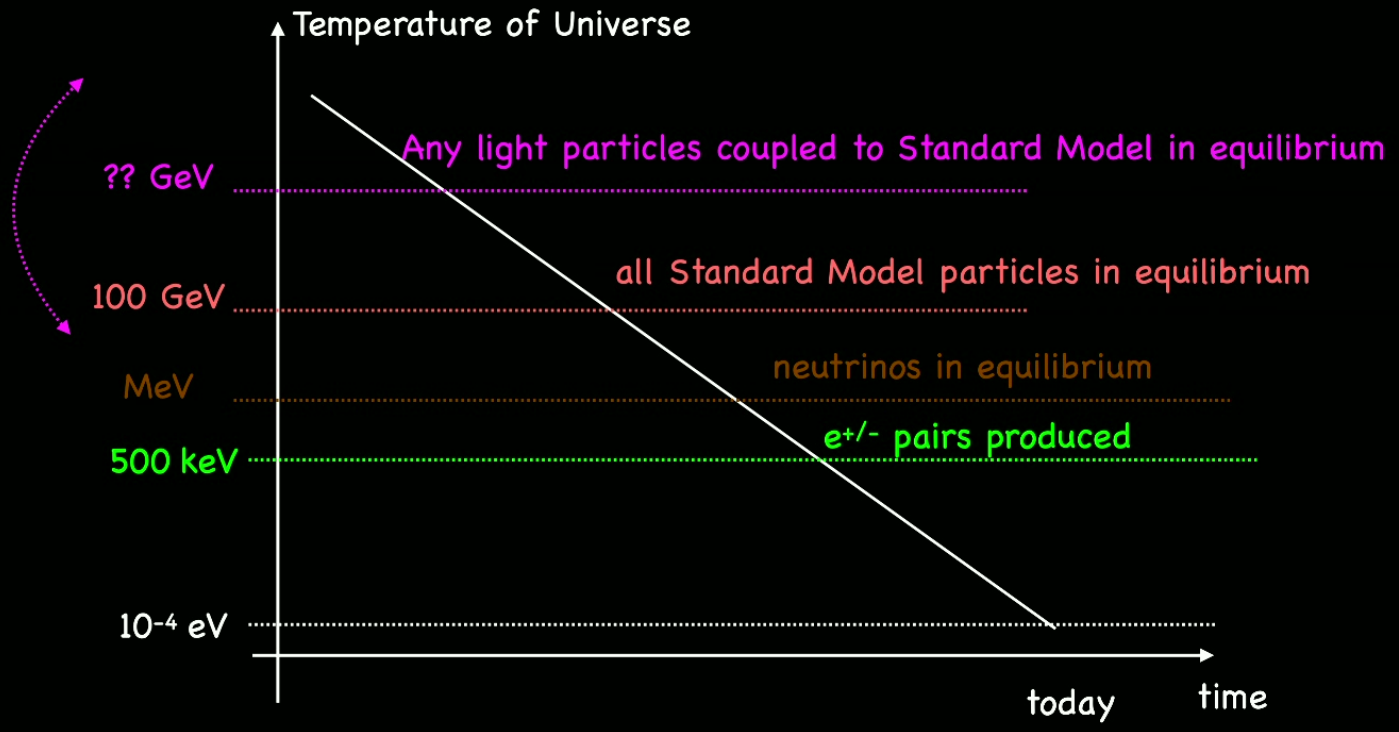

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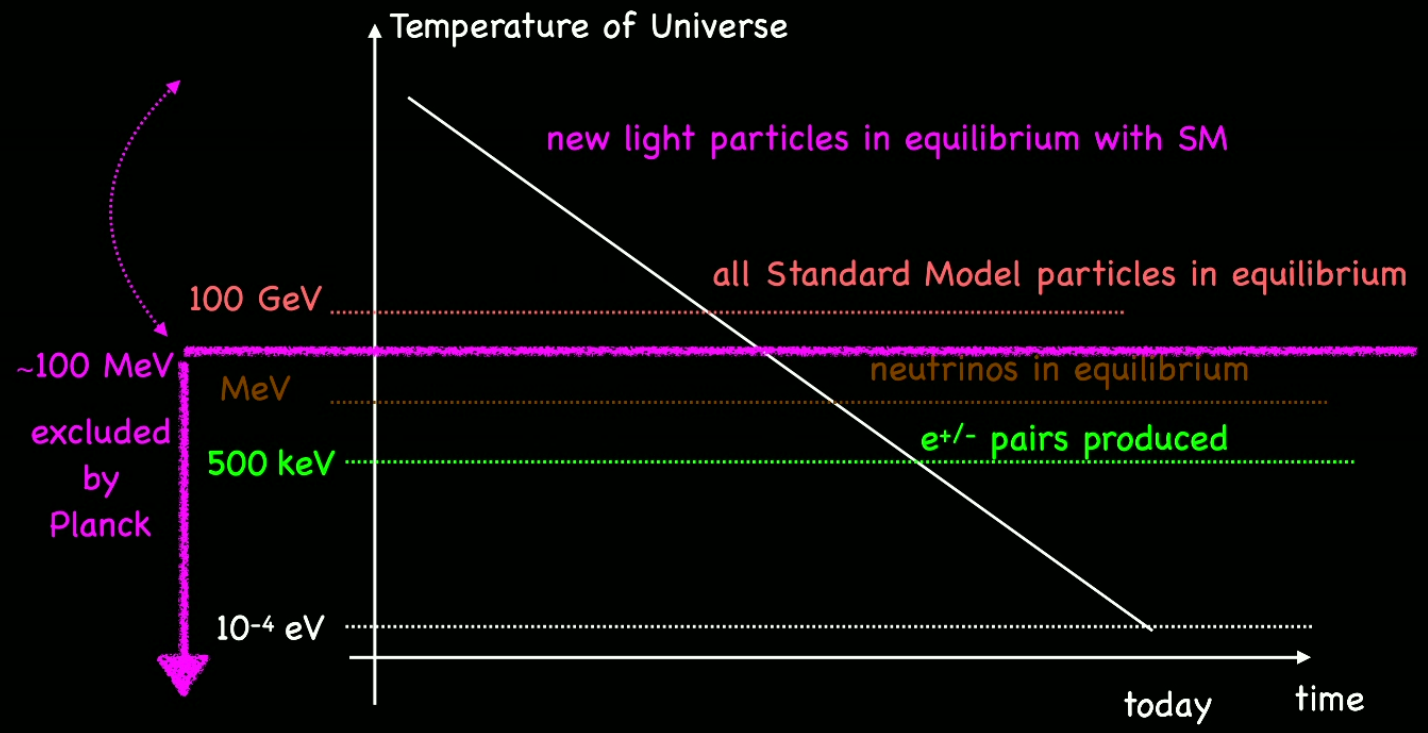
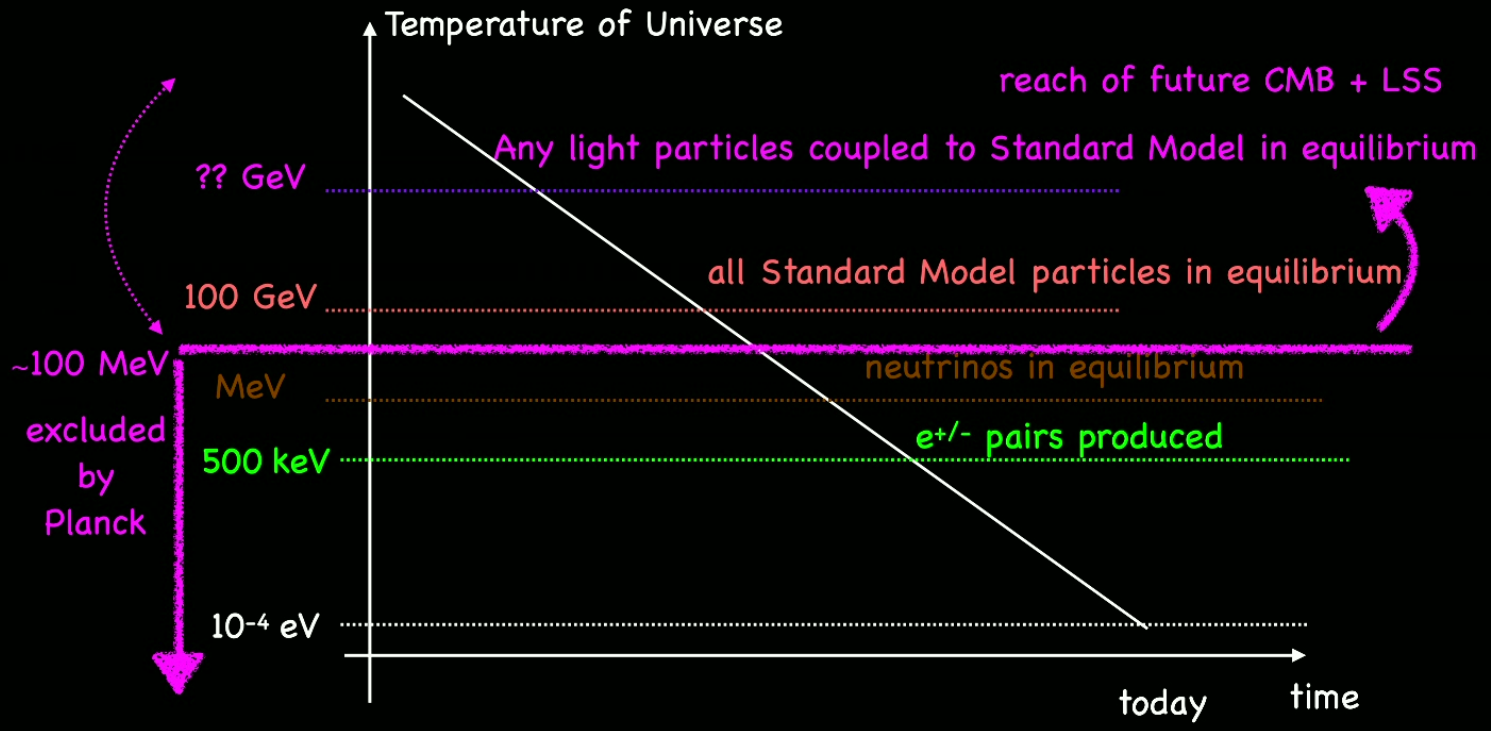
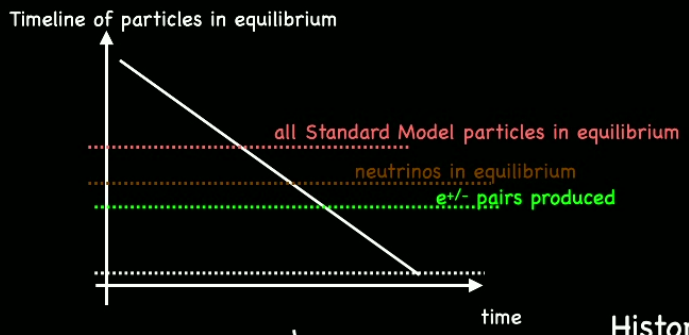


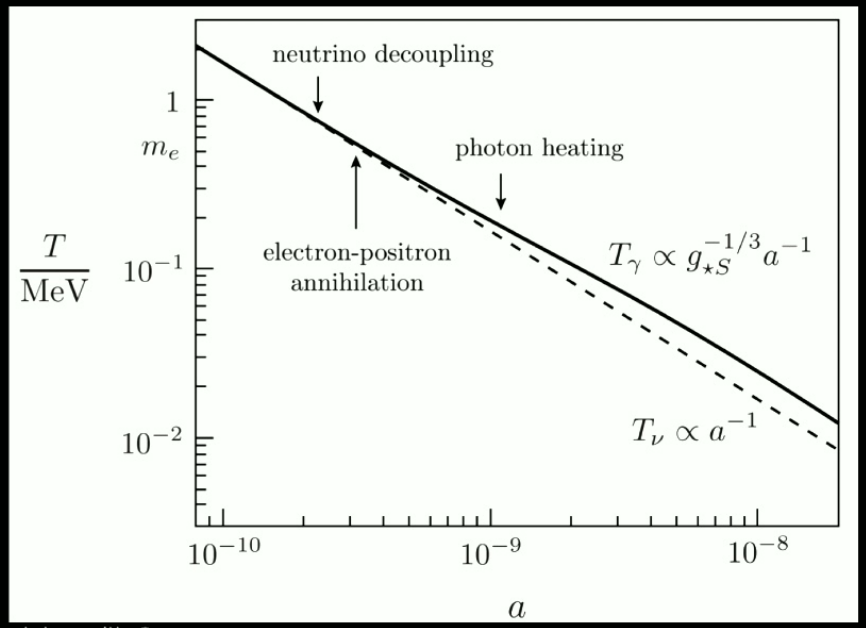
Relics of the Hot Big Bang



Relics of the Hot Big Bang



History of photon and neutrino temperatures

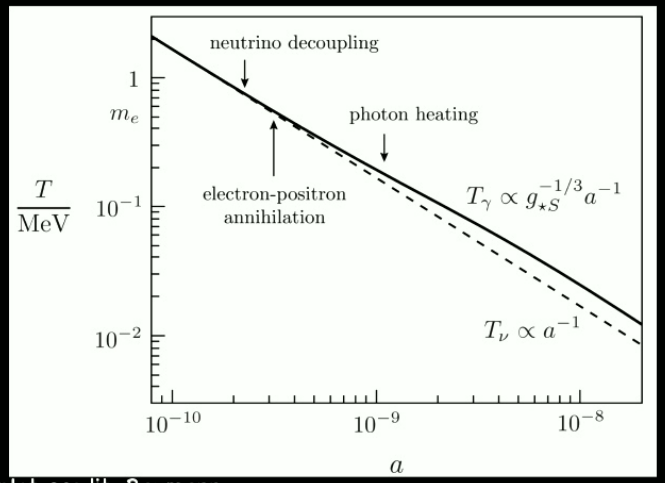


plot credit: Baumann

predict $\rho_\nu = \frac{7}{8} \frac{\pi^2 g_* T_\nu^4}{30}$

Relics of the Hot Big Bang

History of photon and neutrino temperatures

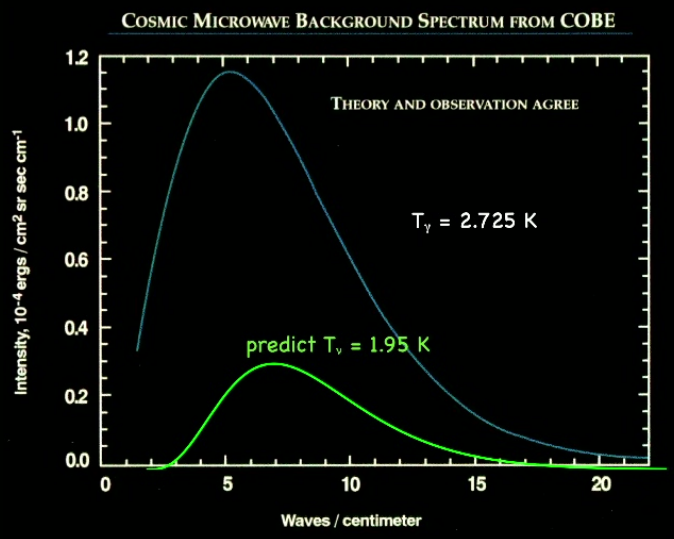


plot credit: Baumann

predictions for relic abundance

$$\rho_\nu = \frac{7\pi^2 N_\nu}{120} T^4$$

$$n_\nu = \frac{3\zeta(3) N_\nu}{2\pi^2} T^3$$



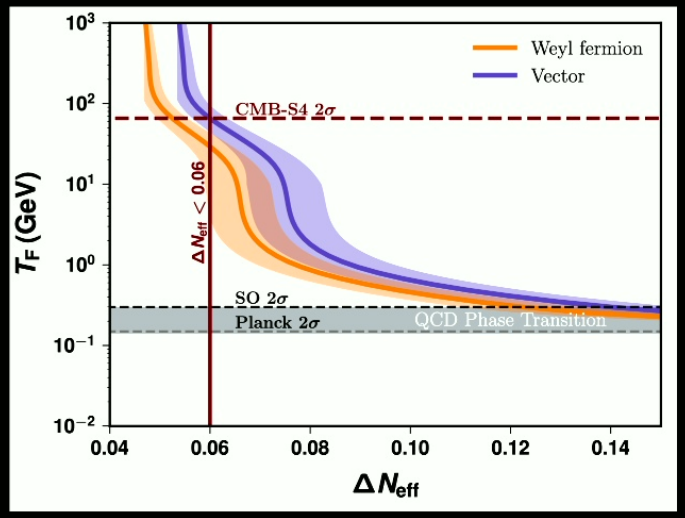
Relics of the Hot Big Bang

$$N_{eff} = \left(\frac{11}{4}\right)^{4/3} \frac{8}{7} \frac{\rho_{radiation,\ total} - \rho_\gamma}{\rho_\gamma}$$

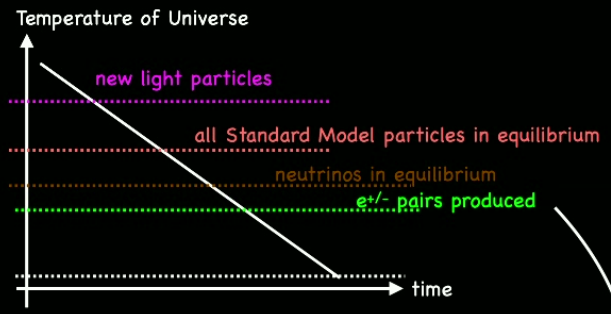
$$\Delta N_{eff} = N_{eff} - 3.044$$

3.044 = standard model prediction for 3 neutrinos

ΔN_{eff} doesn't have to be thermal, but if it is, firm prediction for value from $T_{freeze\text{-}out}$

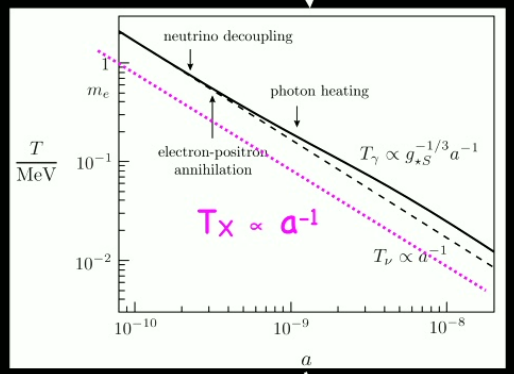


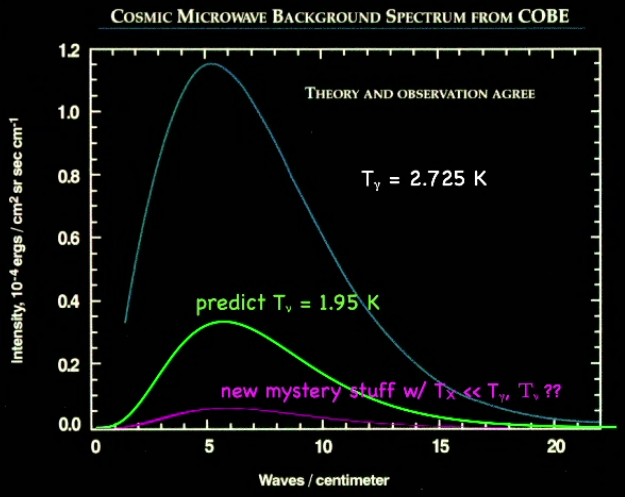
Relics of the Hot Big Bang



$\rho_X \propto g\, T^4$

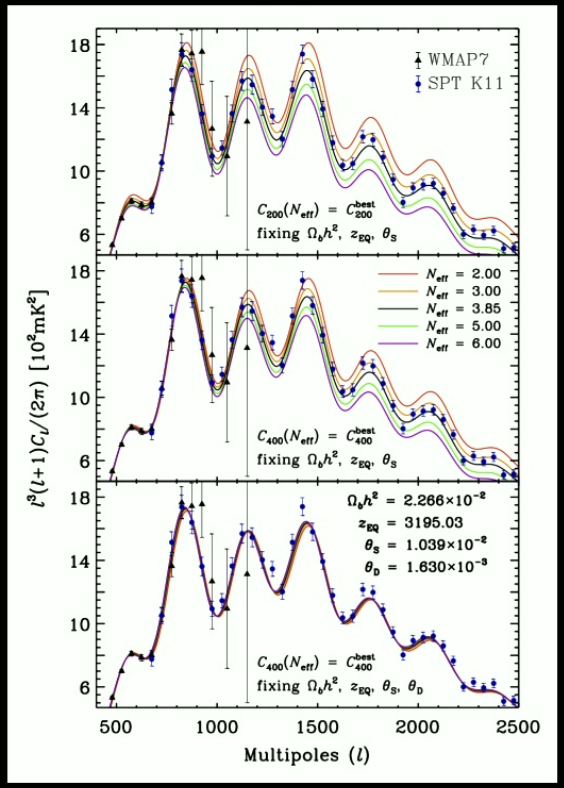
$n_X \propto g\, T^3$





Probes of light relics

CMB Damping scale



Hou, Keisler, Knox, Millea, Reichardt 2011

$$r_d^2 = \pi^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H} \left[\frac{R^2 + \frac{16}{15}(1+R)}{6(1+R^2)} \right]$$

N_{eff}

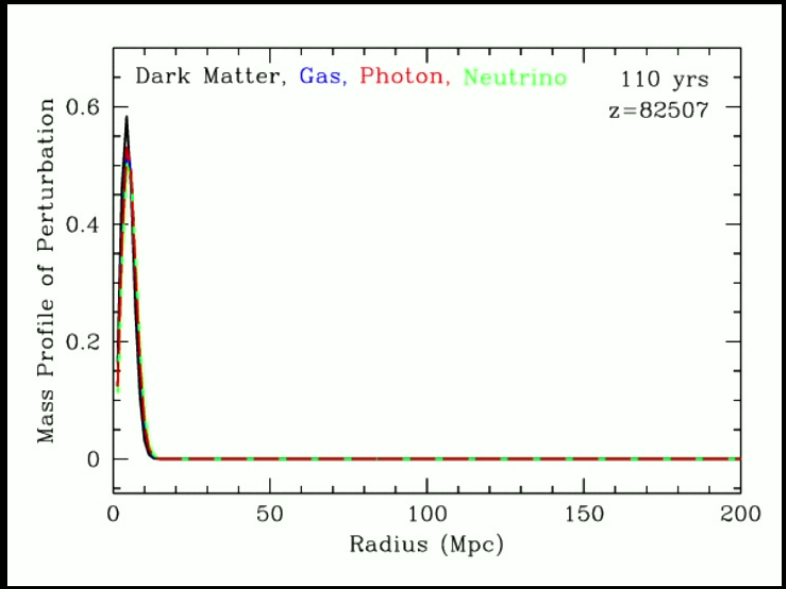
Planck: N_{eff} = 2.99 +/- 0.17

CMB-S4: $\sigma(N_{eff})$ = 0.03

Seljak and Bashinsky 2004

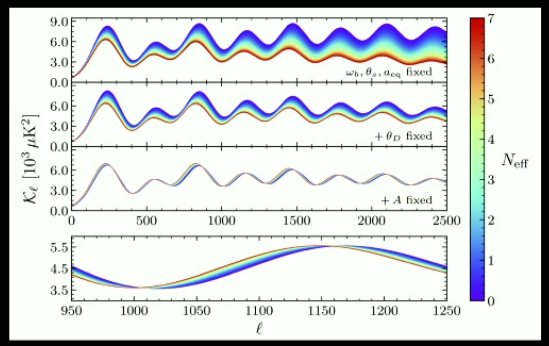
Probes of **free-streaming** neutrinos and dark radiation

Free streaming radiation introduces a phase shift in acoustic oscillations

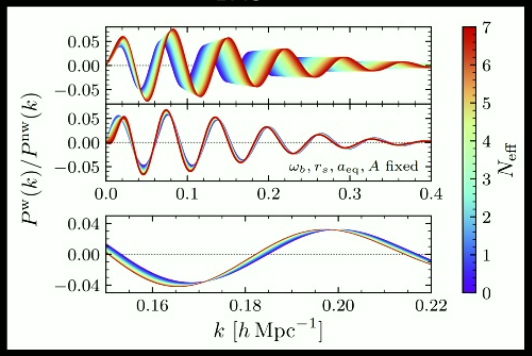


Eisenstein, Seo, White 2007

CMB



BAO



Wallisch 2018

Seljak and Bashinsky 2004 Baumann, Green, Meyers, Wallisch 2016

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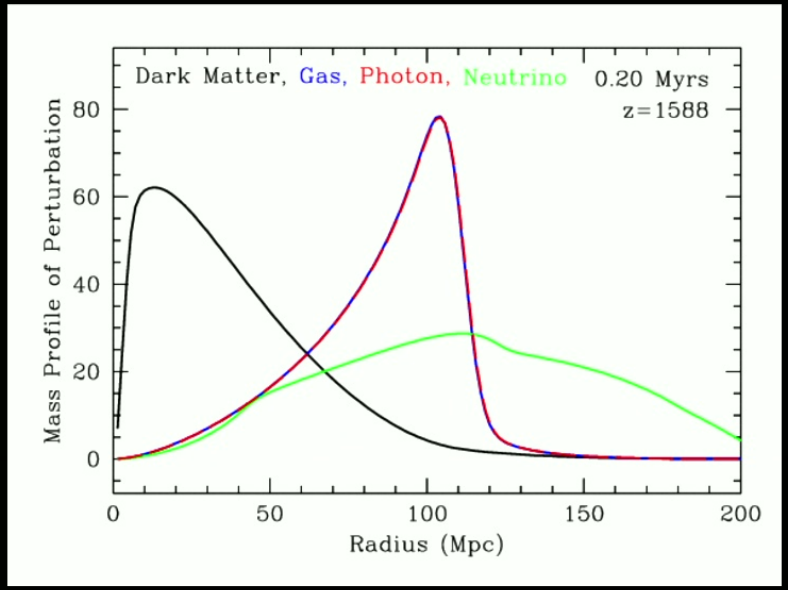
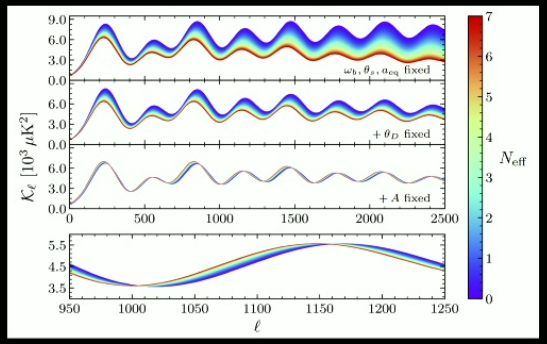
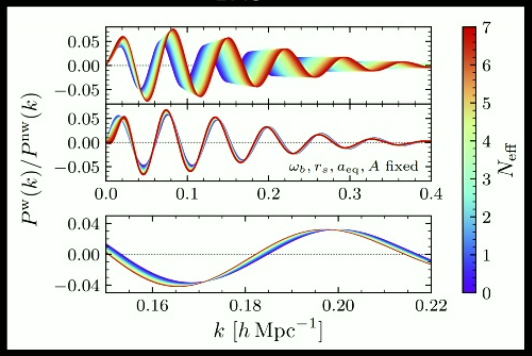


Eisenstein, Seo, White 2007

CMB



BAO



Wallisch 2018

Seljak and Bashinsky 2004 Baumann, Green, Meyers, Wallisch 2016

Probes of **free-streaming** neutrinos and dark radiation

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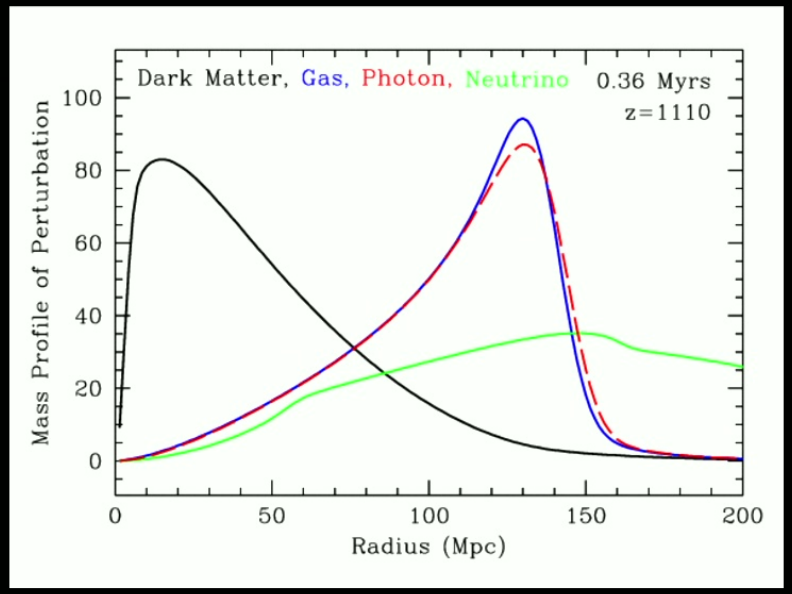

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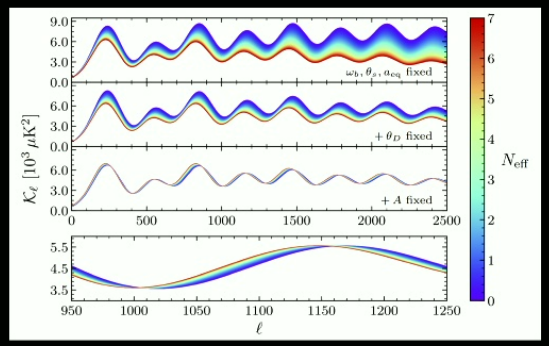
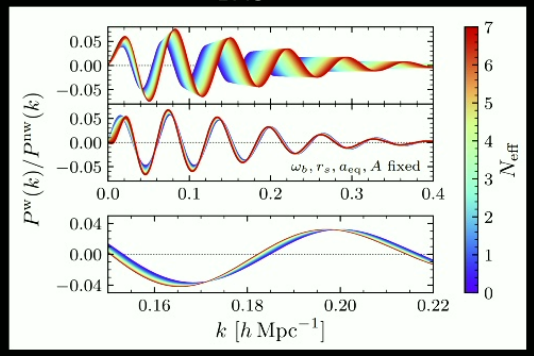


BAO



Wallisch 2018

Seljak and Bashinsky 2004 Baumann, Green, Meyers, Wallisch 2016

If we detect extra radiation in the early universe, how can we learn more about what it is?

Signatures of Interactions

Peizhi Du
(Rutgers)

Thejs Brinckmann
(University of Ferrara)

Jae-Hyeok Chang
(Maryland)

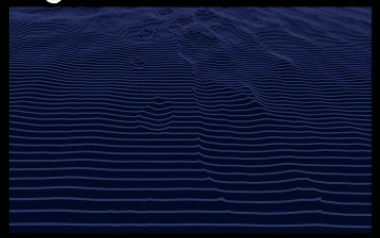
Signatures of Interactions

If we detect $\Delta N_{eff} > 0$, how do we know what it is?

axions

sterile neutrinos?

gravitational waves?



majorans?

dark gauge bosons?

new light fermions?

Signatures of Interactions

We can learn about more than just the energy density in neutrinos by studying the gravitational dynamics of perturbations in neutrinos

neutrinos don't interact but free-stream after $z \sim 10^9$, or $t \sim 1s$

$\rightarrow$ perturbations propagate at $c \simeq 1$

Signatures of Interactions

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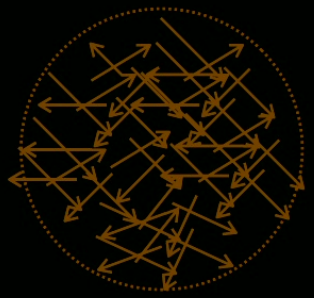
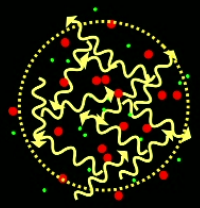


neutrinos don't interact but free-stream after $z \sim 10^9$, or $t \sim 1s$

→ perturbations propagate at $c \simeq 1$



photons tightly coupled to baryons, behave as a single relativistic "photon-baryon" fluid

→ perturbations propagate at $c_s \simeq 1/\sqrt{3}$

In fact, c_s for neutrinos is also $1/\sqrt{3}$, but the distribution of particles is broader

Signatures of Interactions

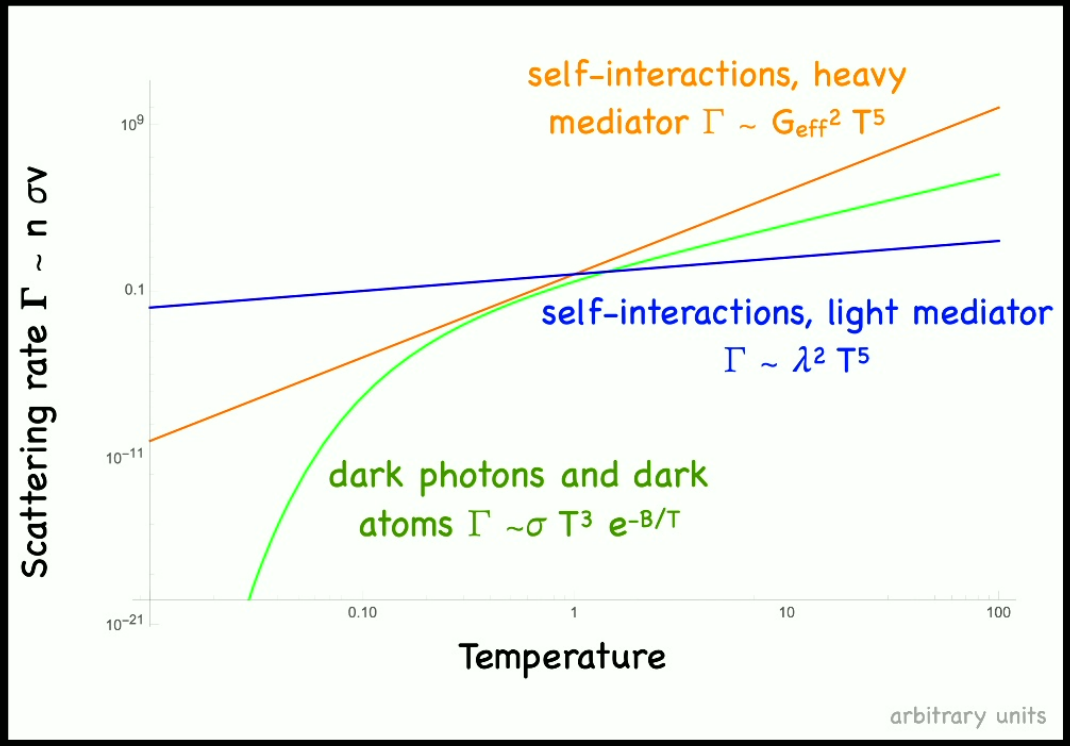
Interactions (or lack thereof!) important for observables

Yet, interactions depend on time (temperature)

Need to know interaction history to fully model observables

Signatures of Interactions

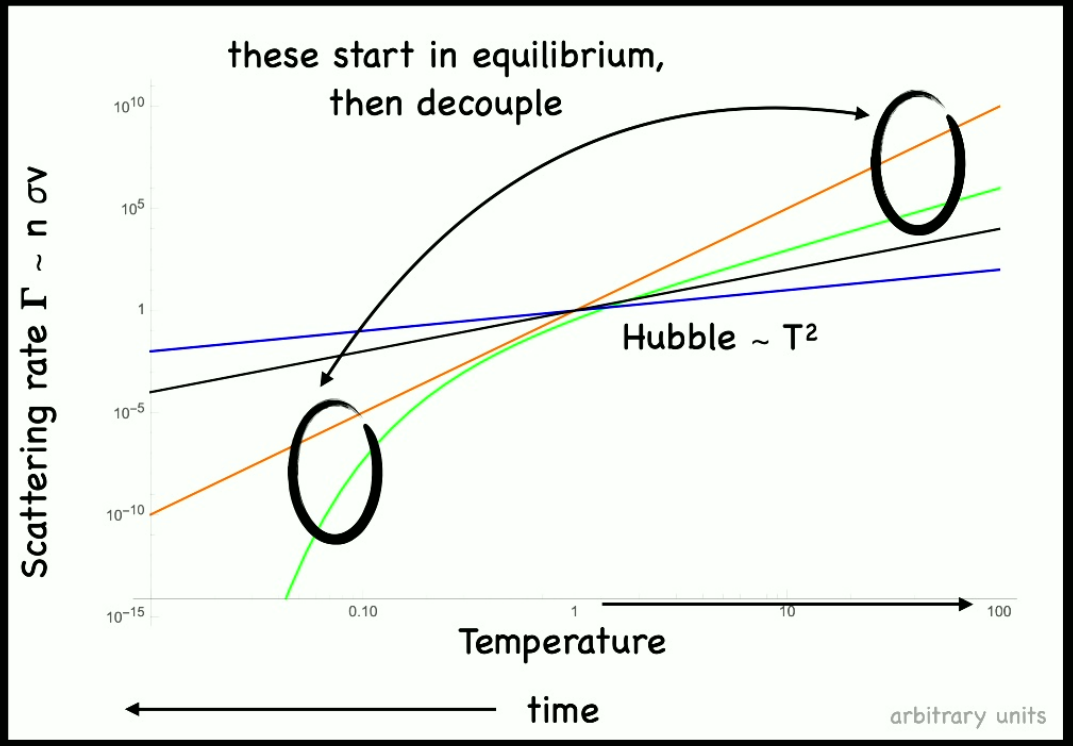
Interaction history can vary



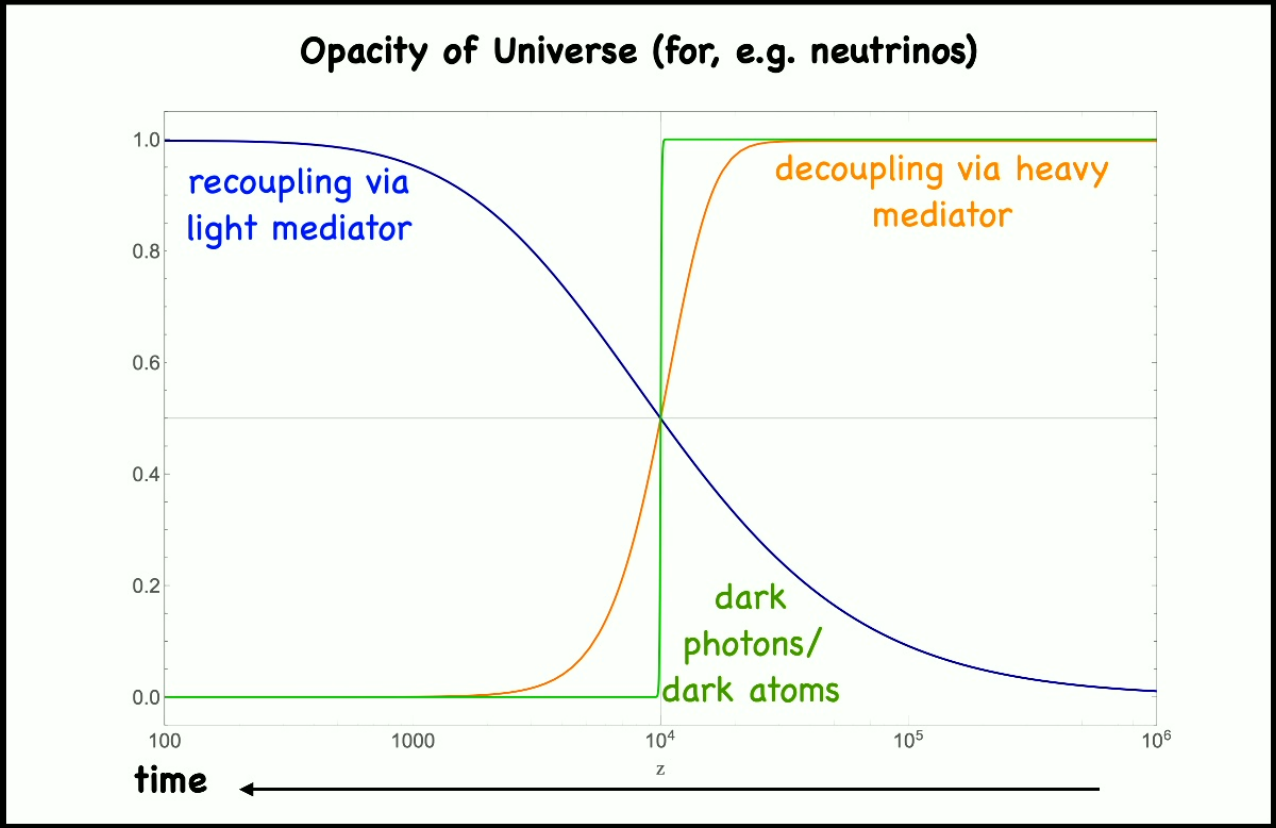
Signatures of Interactions

Interaction history can vary

light mediator
heavy mediator
dark decoupling

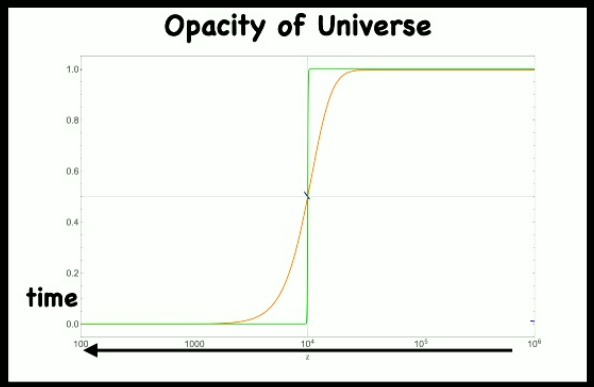


Signatures of Interactions



Signatures of Interactions

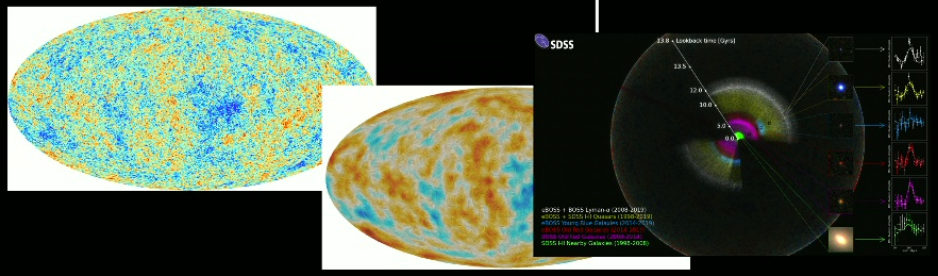
time-dependent changes to evolution of neutrinos/ radiation



time-dependent changes to evolution of metric perturbations

Φ, Ψ

scale-dependent changes to observables



Signatures of Interactions

$$N_{eff} = N_{free\text{-}streaming} + N_{fluid} + N_{interacting}$$

- standard model neutrinos since $z \sim 10^9$
- gravitational waves
- . . . .

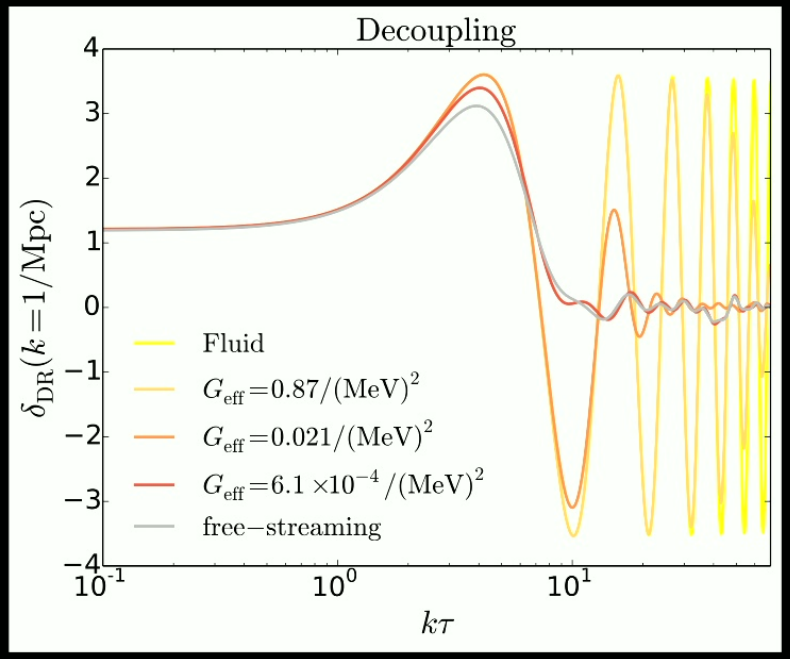
- dark photons scattering off dark atoms
- anything that continues to scatter off itself until z~2000
- . . . .

- dark photons that decouple at $z \gtrsim 2000$
- neutrino with new self-interactions
- dark gauge bosons
- majorans that recouple
- . . . .

Each looks different in data

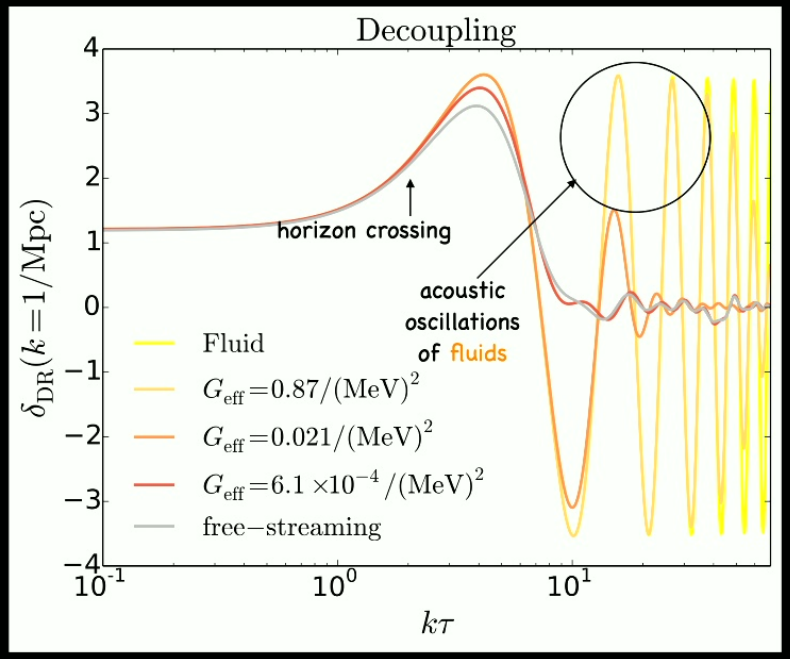
Signatures of Interactions - CMB

time-dependent changes to evolution of neutrinos/ radiation



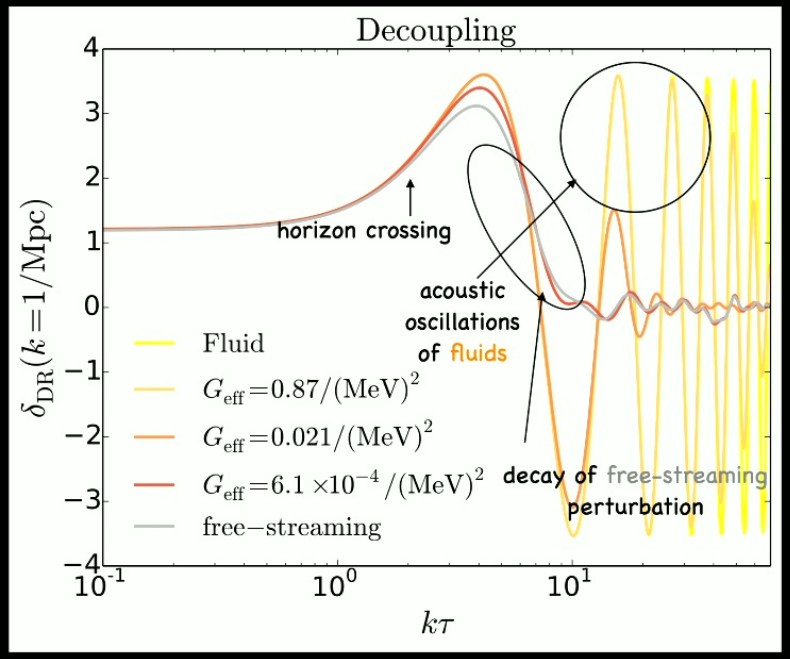
Signatures of Interactions - CMB

time-dependent changes to evolution of neutrinos/ radiation



Signatures of Interactions - CMB

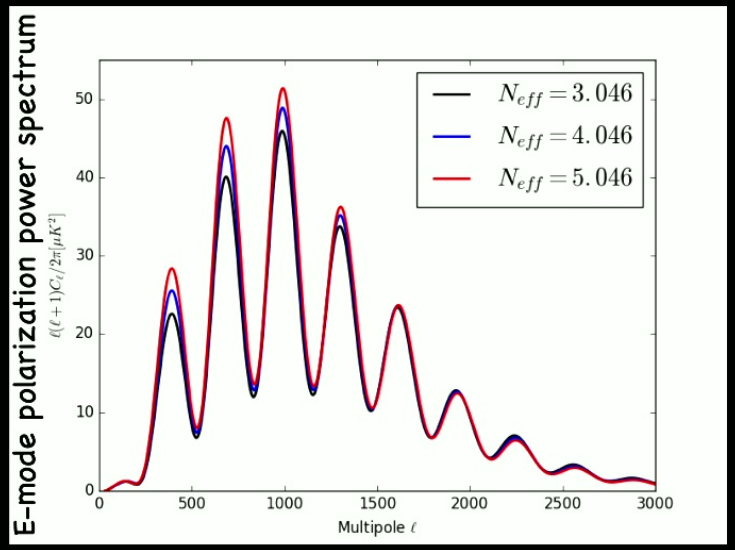
time-dependent changes to evolution of neutrinos/ radiation



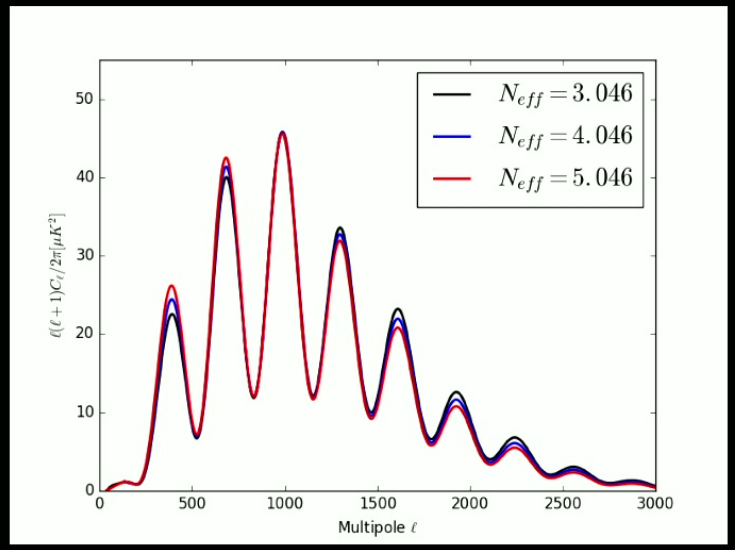
Signatures of Interactions - CMB

This difference in composition is visible in CMB data !

New particles that are fluid-like



New particles that are free-streaming



(i.e. same extra $\rho_{radiation}$, different composition)

Bashinsky & Seljak 2003

Cyr-Racine and Sigurdson 2014

Baumann, Green, Meyers, Wallisch 2015

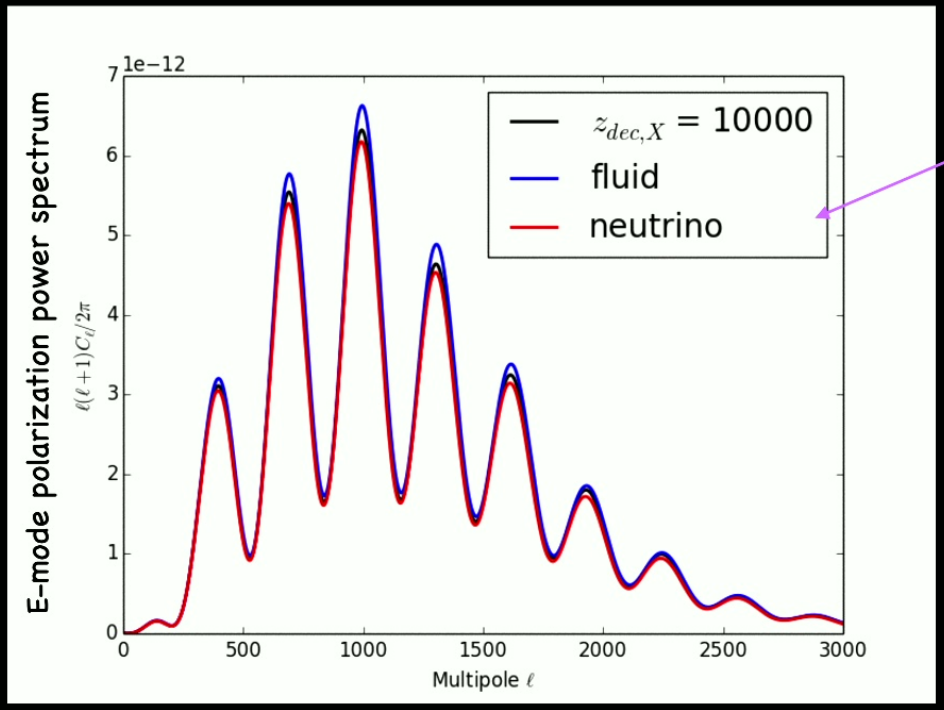
Blinov, Marques-Tavares 2020

Choi, Chiang, ML 2018

Signatures of Interactions - CMB

This difference in composition is visible in CMB data !

The data can tell if neutrinos or new particles decoupled during epochs probed by the CMB



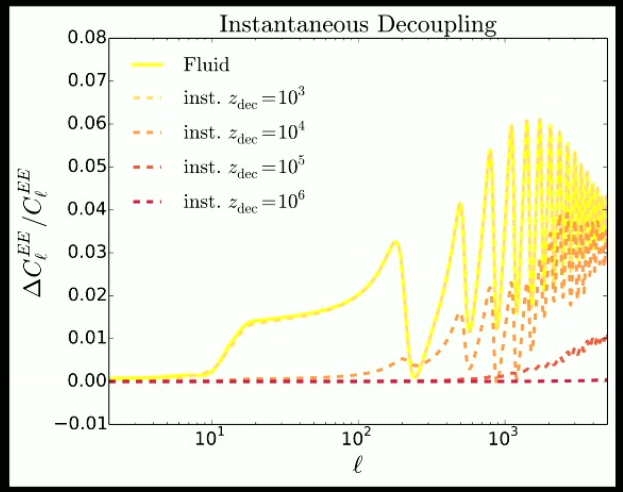
(standard!)

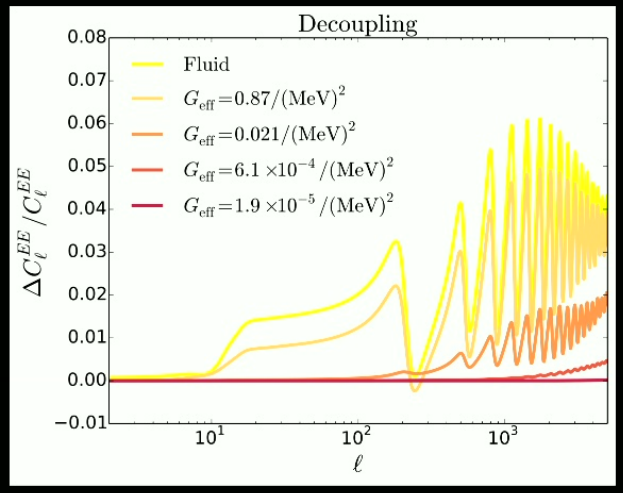
Cyr-Racine & Sigurdson 2014; Lancaster, Cyr-Racine, Knox, Pan 2017; Choi, Chiang, ML 2018; Kreisch, Cyr-Racine, Dore 2020; Brinckmann, Chang, ML 2020

Signatures of Interactions - CMB

This difference in composition is visible in CMB data !

The duration of the decoupling/recoupling transition is also visible

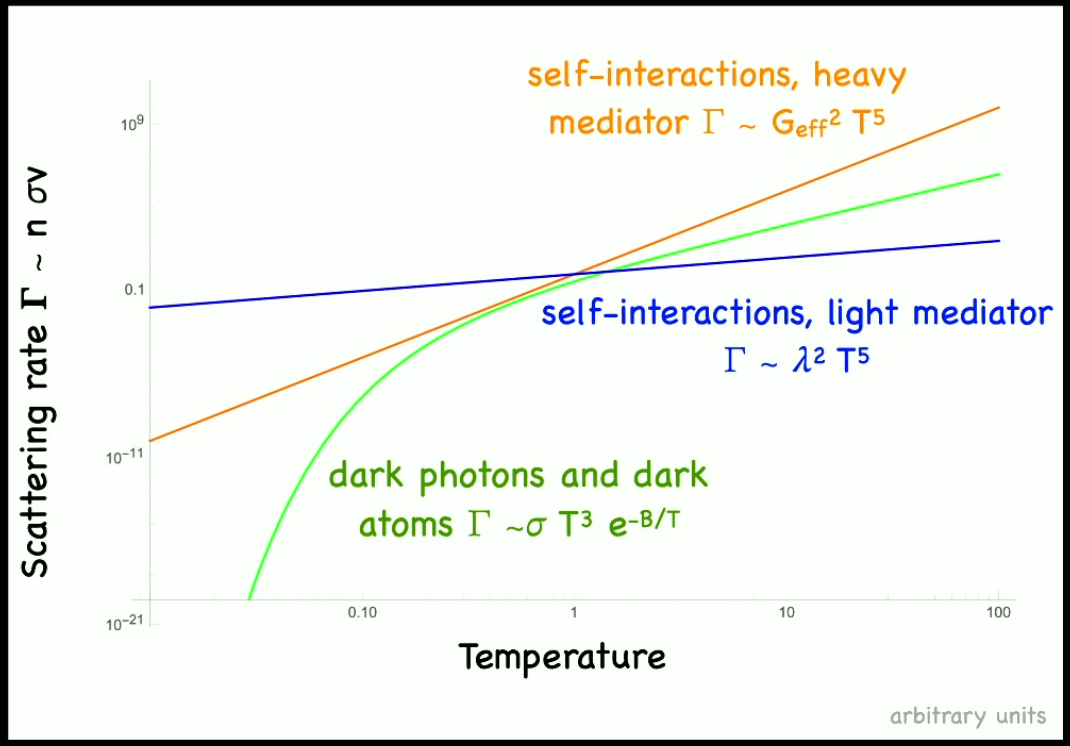




duration changes overall amplitude *and* scale-dependence

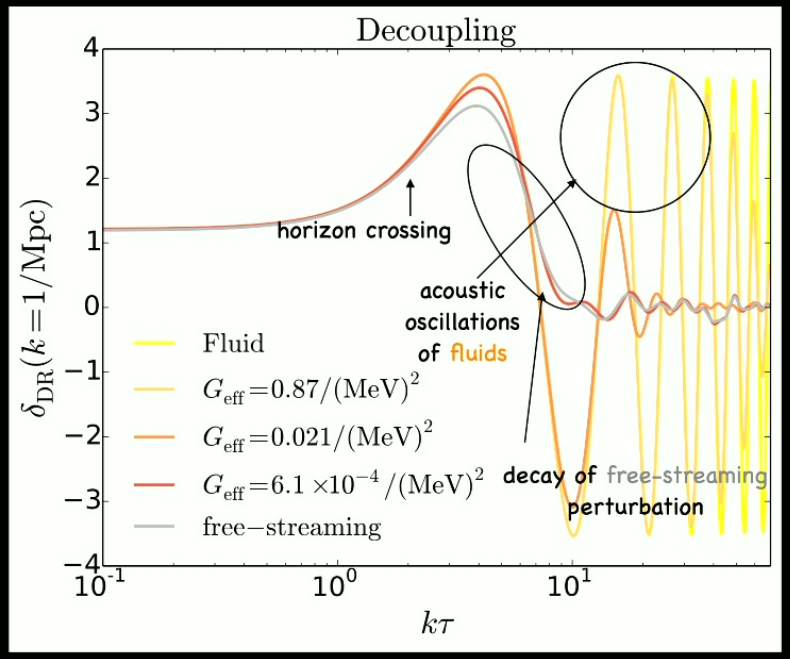
Signatures of Interactions

Interaction history can vary



Signatures of Interactions - CMB

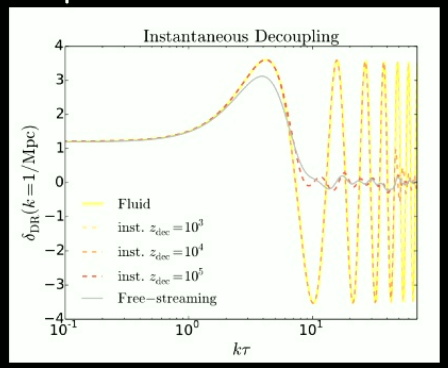
time-dependent changes to evolution of neutrinos/ radiation



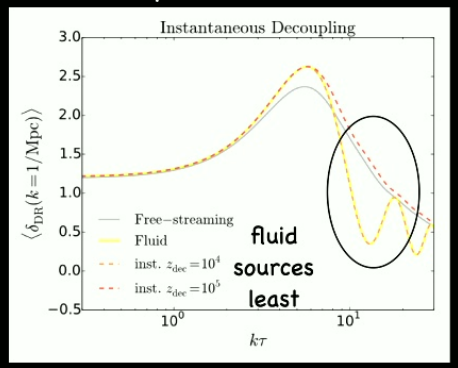
Signatures of Interactions - LSS

$\delta_{\text{dark radiation}} \xleftrightarrow{\text{gravity}} \delta_{\text{cdm}}$

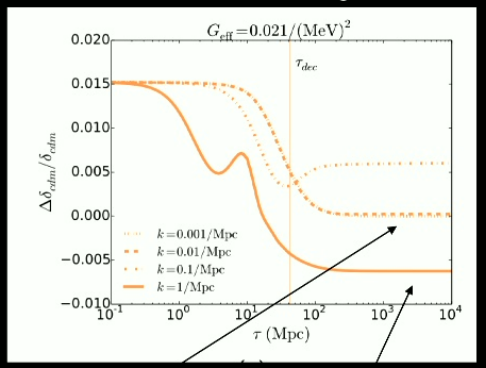
perturbations in DR



time average of δ_{DR}
better captures source to $\nabla^2\Phi$



change in δ_{cdm} relative to free-streaming



slight bump for mode that decouples just after horizon crossing

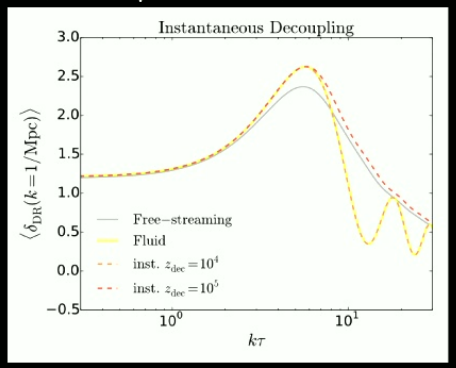
CDM perturbations suppressed in fluid-limit

Brinckmann, Chang, Du, Loverde 2022

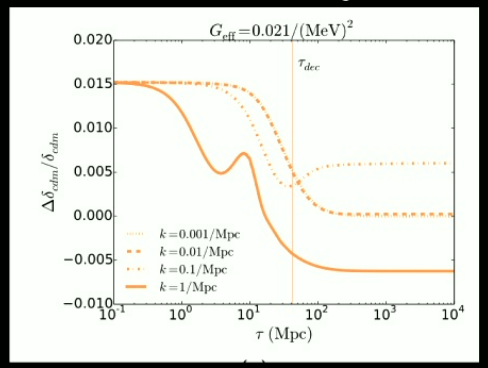
Signatures of Interactions - LSS

$\delta_{\text{dark radiation}}$ ⟷ (gravity) δ_{cdm}

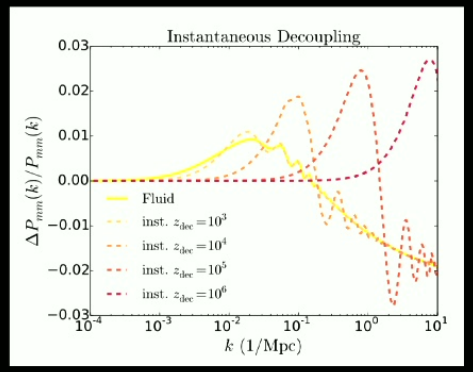
time average of δ_{DR}
better captures source to $\nabla^2 \Phi$



change in δ_{cdm} relative to free-streaming



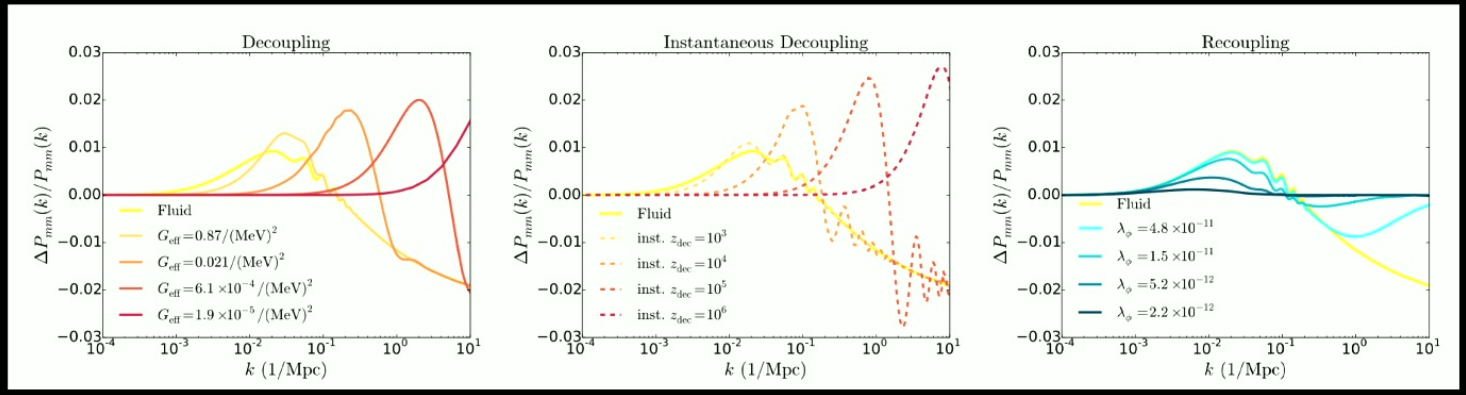
change in P(k) relative to free-streaming



Brinckmann, Chang, Du, Loverde 2022 Kreisch, Cyr-Racine, Dore 2019

Signatures of Interactions - LSS

change in P(k) relative to free-streaming varies with decoupling/recoupling process

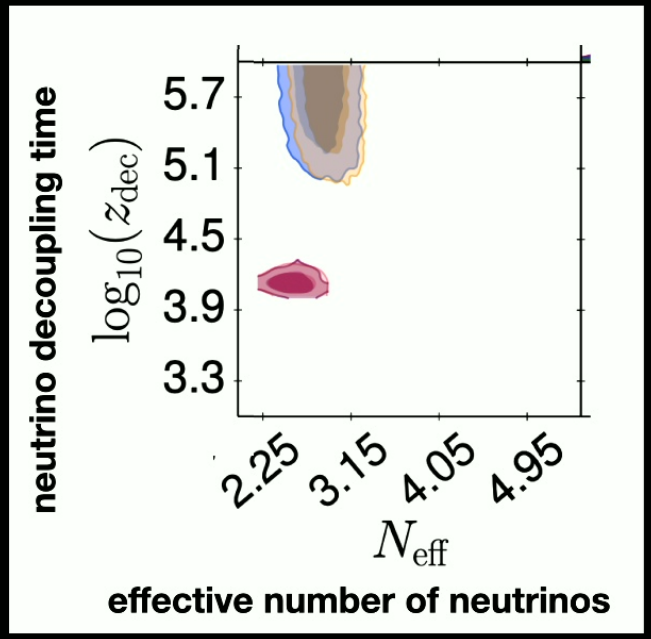


each plot above assumes $N_{\text{free-streaming}} = 3.044$, $N_{\text{interacting}} = 0.5$

Brinckmann, Chang, Du, Loverde 2022 Kreisch, Cyr-Racine, Dore 2019

Constraints on new neutrino interactions

Planck 2018 TT, TE, EE, low -E, lensing + BAO



(this second mode disappears when H0 data added)

(standard neutrinos decouple at z ~10^9, t ~ 1s)

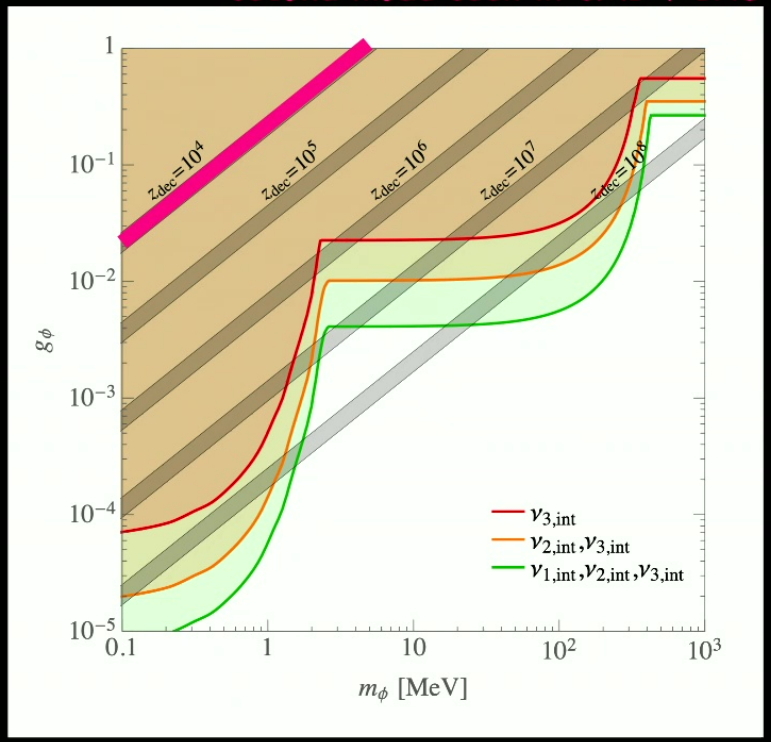
Brinckmann, Chang, ML 2020

Constraints on new neutrino interactions

Second mode incompatible with particle physics data

second mode seen in CMB + BAO data

Constraints from Kaon, tau & double beta decay on interactions among mass states mediated by a majoron

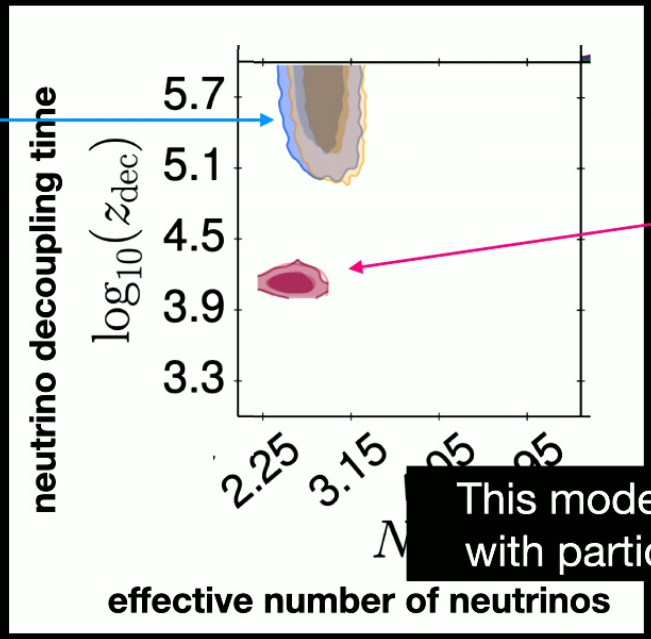


Blinov, Kelly, Krnjaic, McDermott 2019
Lyu, Stamou, Wang 2020
Brinckmann, Chang, ML 2020

Constraints on new neutrino interactions

Planck 2018 TT, TE, EE, low -E, lensing + BAO

Allows neutrino interactions as late as $z\sim10^5$, $t\sim$ 50 years, w/ no change in values of other cosmological parameters



Also permits a second mode w/neutrinos interacting until $z\sim10^4$, $t\sim$ 4000 years and different values of other cosmological parameters!

This mode is incompatible with particle physics data

(this second mode disappears when H0 data added)

Yet, the second mode also appears in matter power spectrum?

Full shape P(k) analyses: He, An, Ivanov, Gluscevic 2023; Camarena, Cyr-Racine, Houghteling 2023

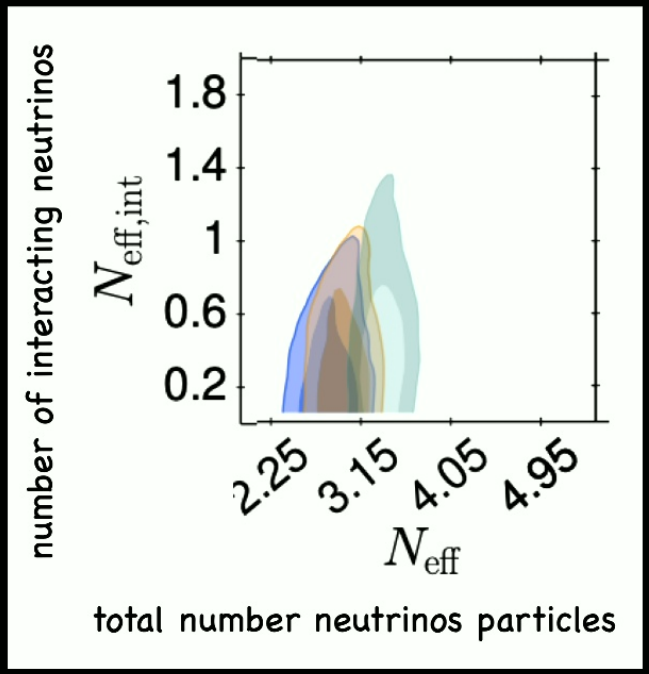
(standard neutrinos decouple at $z\sim10^9$, $t\sim$ 1s)

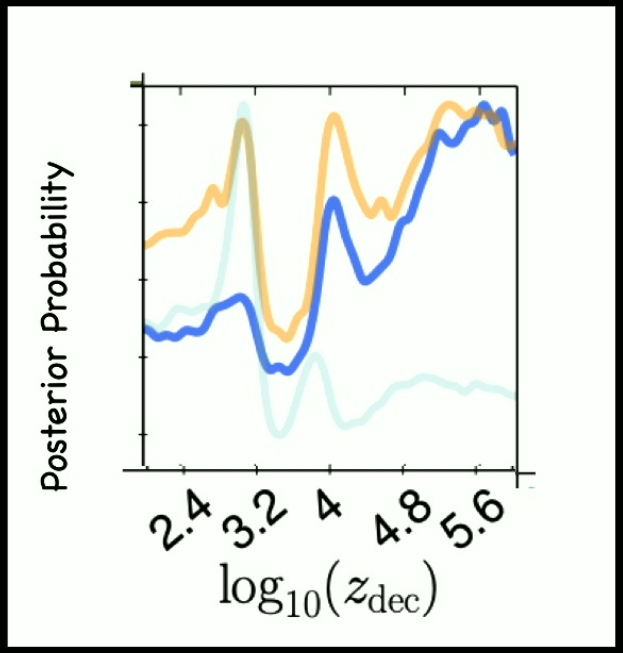
Brinckmann, Chang, ML 2020

Constraints on new neutrino interactions

Does current CMB data allow for neutrinos (or other new particles?) with non-standard self-interactions?

Planck 2018 TT, TE, EE, low -E, lensing + BAO



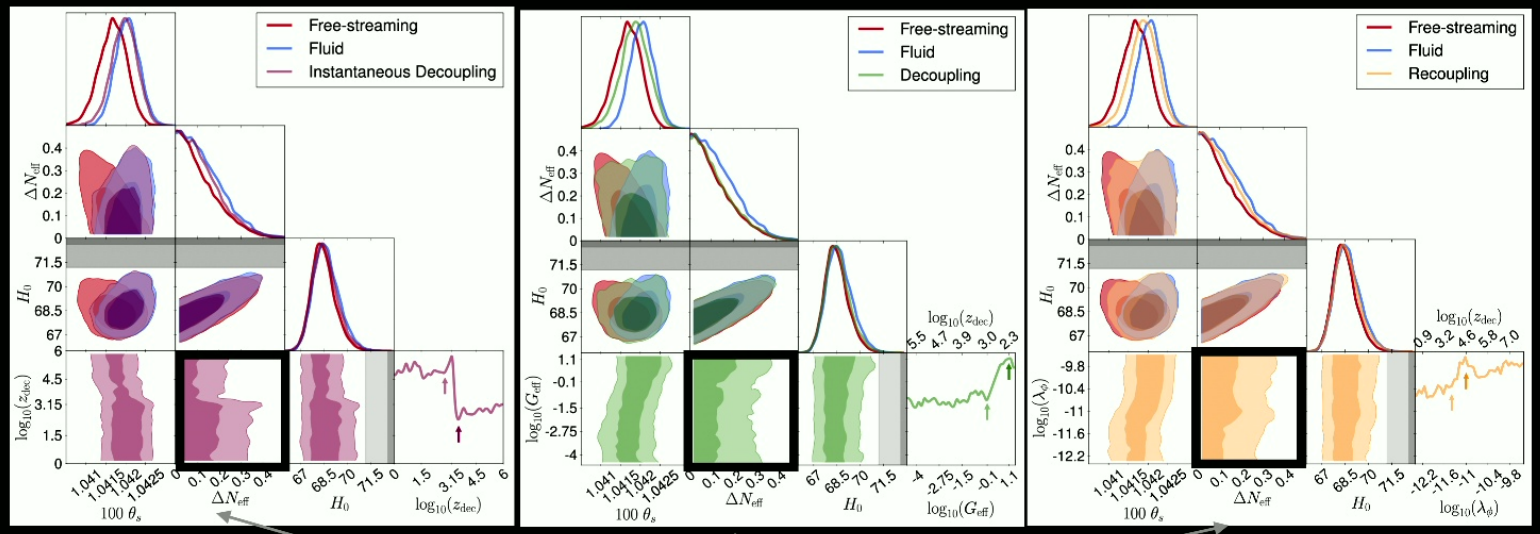


primary CMB+ lensing
+ BAO
+ BAO & H0

Brinckmann, Chang, ML 2020

Constraints on new dark radiation

Idea: keep neutrinos fixed to Standard Model, search for additional (possibly self-interacting) radiation



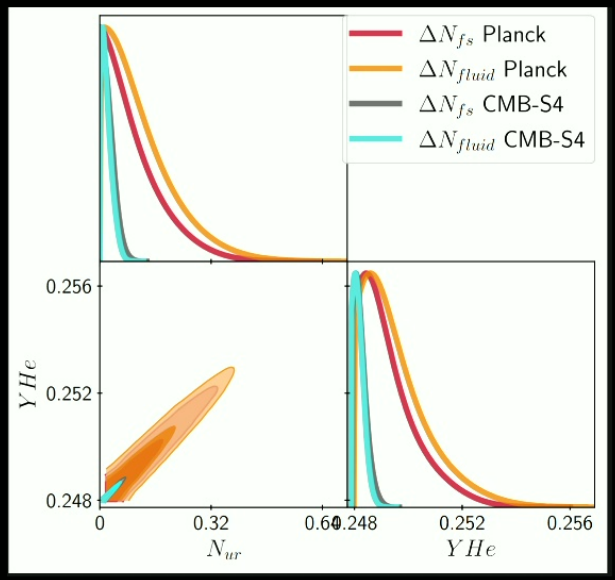
No detections, but data allows more dark radiation if that radiation is interacting

Brinckmann, Chang, Du, ML 2023

Constraints on Interactions

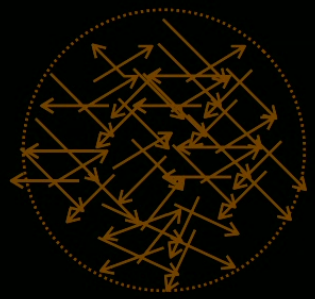
What can we do with future CMB-S4 data?

Murali Saravanan
(here this week too!)

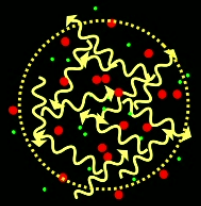


Constraints on Interactions - GW

Free-streaming particles affect (long-wavelength) gravitational wave propagation



the stress-energy tensor of free-streaming radiation can acquire a tensor piece



the stress-energy of fluid-like radiation cannot

Weinberg 2004

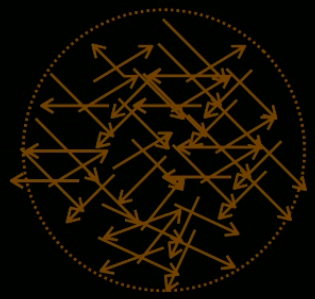
Constraints on Interactions

CMB data probes Universe after $z \sim 10^6$ ($t \sim 1$ year)

How can we probe interactions at earlier epochs?

Constraints on Interactions - GW

Free-streaming particles affect (long-wavelength) gravitational wave propagation



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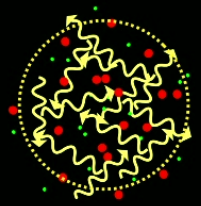
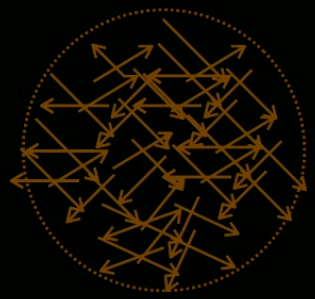


the stress-energy of fluid-like radiation cannot

Weinberg 2004

Constraints on Interactions - GW

Free-streaming particles affect (long-wavelength) gravitational wave propagation



the stress-energy tensor of free-streaming radiation can acquire a tensor piece

⟶ couples to gravitational waves

Free-streaming particles add a source term to gravitational wave e.o.m.

$$\partial_x^2 h_\lambda + 2\frac{\partial_x a}{a}\partial_x h_\lambda + h_\lambda = -24\Omega_\nu(\tau)\left(\frac{\partial_x a}{a}\right)^2 \int_{x_i}^{x} \mathrm{d}u\, \left[1 - \mathcal{O}_\nu(u,x)\right] K(x-u)\partial_u h_\lambda,$$

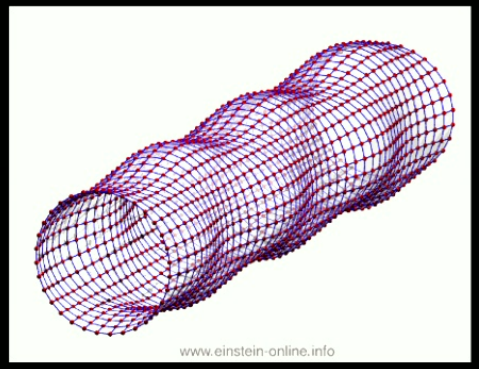
net effect is qualitatively different for primordial (inflationary) GWs versus causal GWs

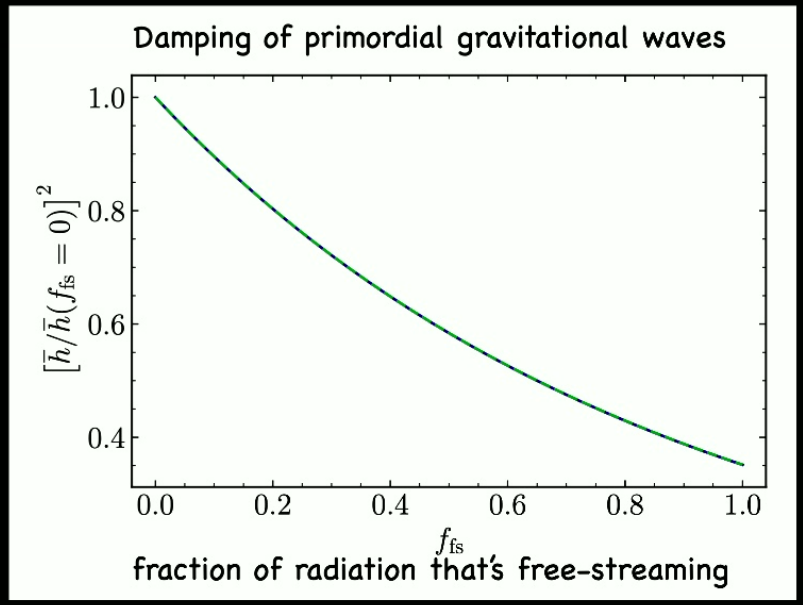
Weinberg 2004

$x = c_\gamma k \tau$

Constraints on Interactions - GW

Free-streaming particles change evolution of inflationary gravitational waves





Weinberg 2004

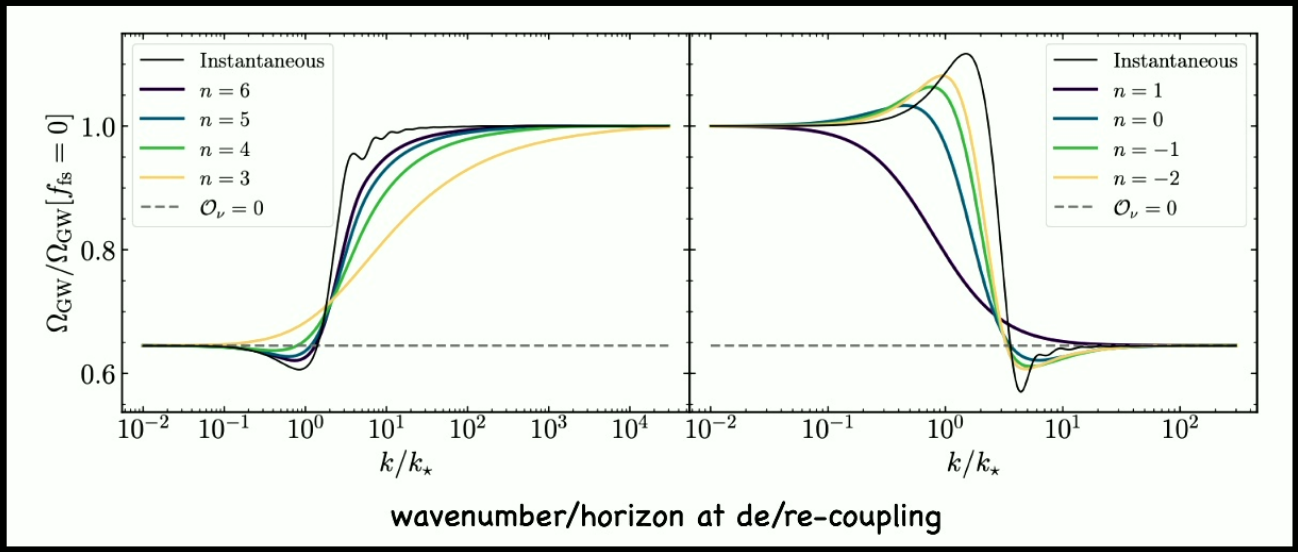
Boyle & Steinhardt 2008

ML, Weiner 2022

Constraints on Interactions - GW

Free-streaming particles change evolution of inflationary gravitational waves

Damping of primordial gravitational waves depends on interactions among relativistic particles

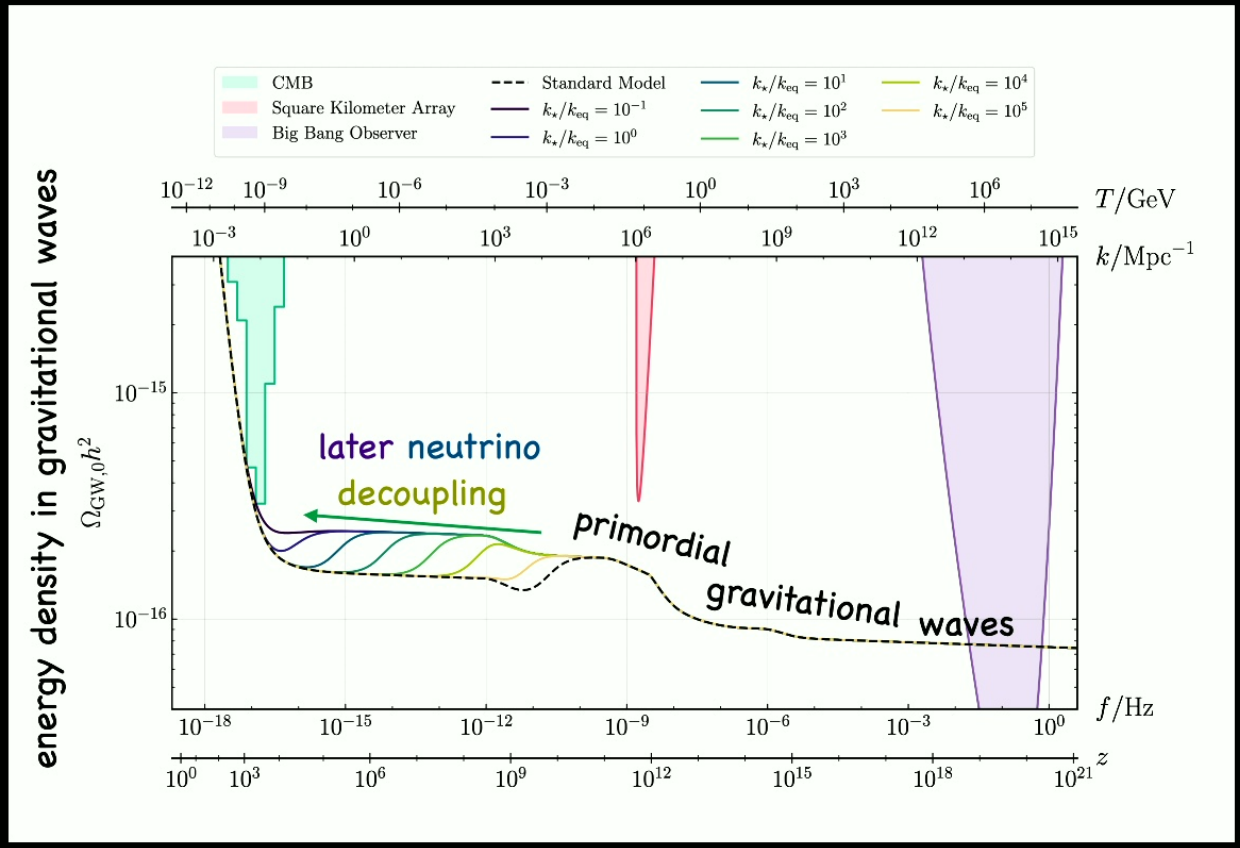


Weinberg 2004

ML, Weiner 2022

Constraints on Interactions - GW

Free-streaming particles change evolution of inflationary gravitational waves



Ghosh, Khatri, Roy 2017

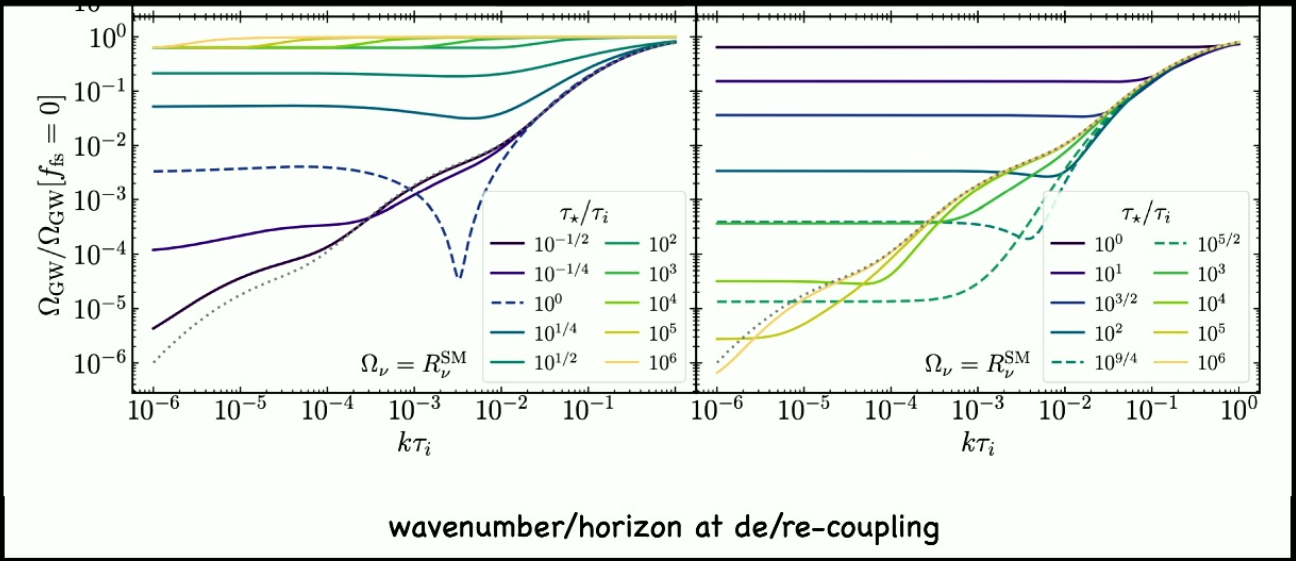
ML, Weiner 2022

Constraints on Interactions - GW

Free-streaming particles change evolution of causally produced gravitational waves

$$\partial_x^2 h_\lambda + 2\frac{\partial_x a}{a}\partial_x h_\lambda + h_\lambda = -\frac{8}{5} f_{\rm fs} \left(\frac{\partial_x a}{a}\right)^2 [h_\lambda(x) - h_\lambda(x_i)]$$

Damping of gravitational waves depends on interactions among relativistic particles



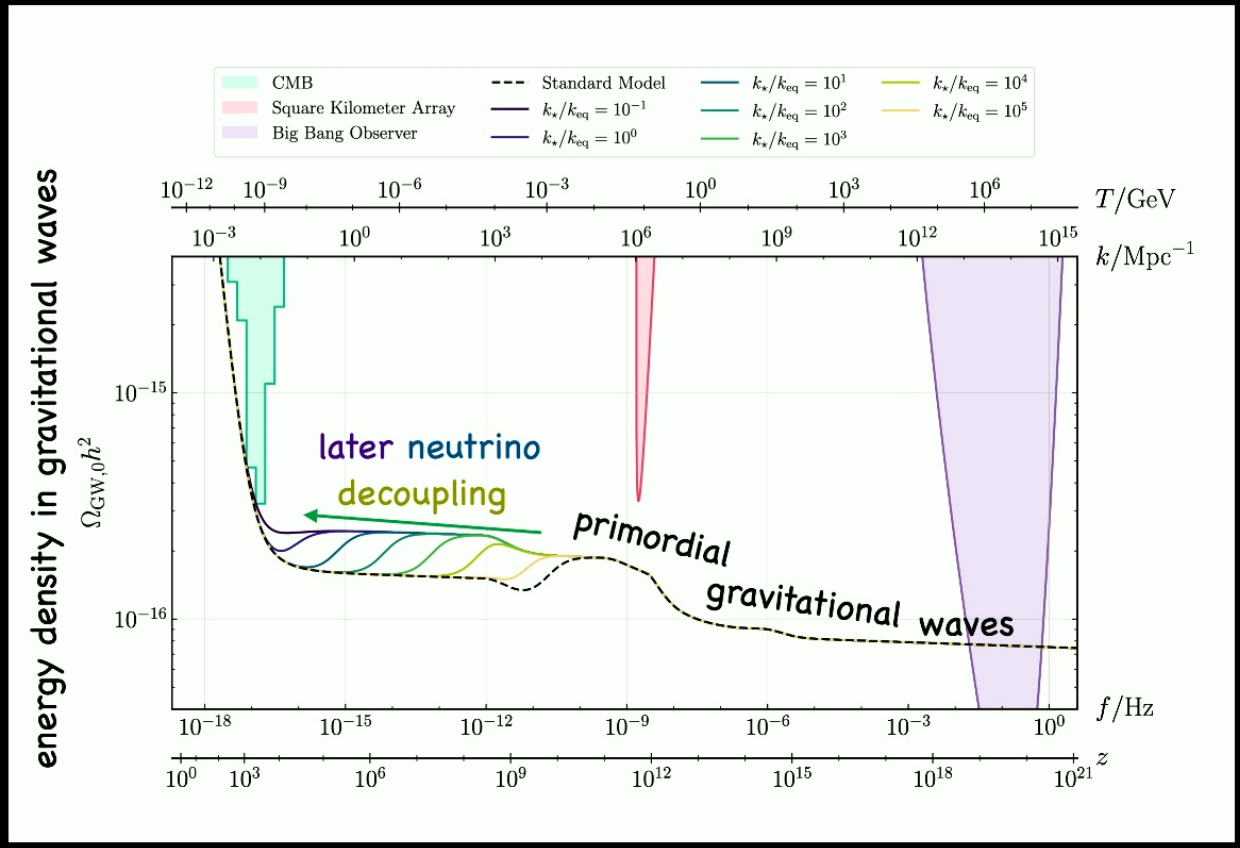
wavenumber/horizon at de/re-coupling

Hook, Marques-Tavares, Racco 2020

ML, Weiner 2022

Constraints on Interactions - GW

Free-streaming particles change evolution of inflationary gravitational waves



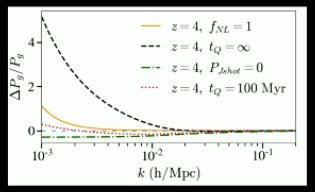
Ghosh, Khatri, Roy 2017

ML, Weiner 2022

Lots more on neutrinos, light relics, and beyond!

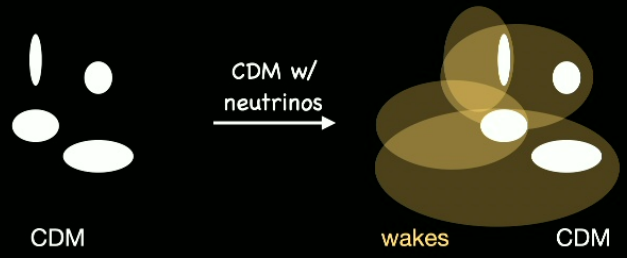
Cosmology Group Meeting Thursday

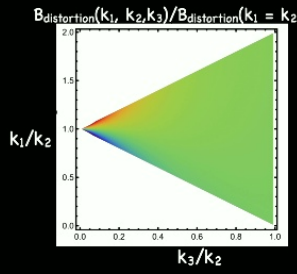
Scale-dependent bias from neutrinos and UV background fluctuations, interaction with fNL constraints + pNG beyond fNL

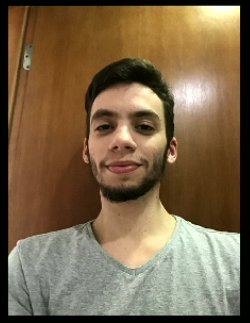


Charuhas Shiveshwarkar

new approaches to massive neutrinos: wakes, improved fluid approx, . . .







Caio Nascimento

Conclusions

- Cosmology provides lots of interesting information about neutrinos, and other light relic particles!
- A variety of cosmological datasets are sensitive to both the energy density and nature of relics, *whether they are fluid-like, free-streaming, or decouple at late times*
- At present no preference for new neutrino interactions, or additional dark radiation, but data allows some of both
- Opportunities exist for future detection!