Neutrinos and cosmology
a secret liaison

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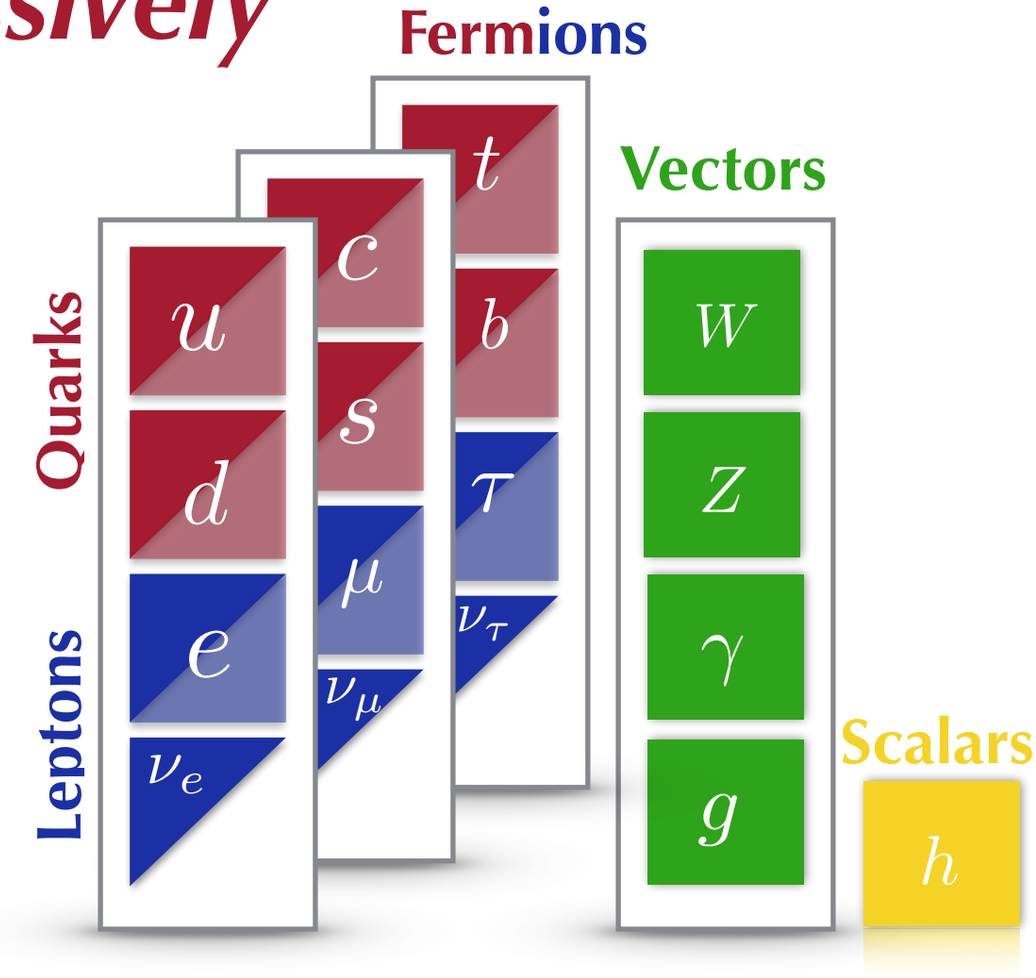
The Standard Model is *excessively* successful …

Almost everything is explained by only 19 parameters.

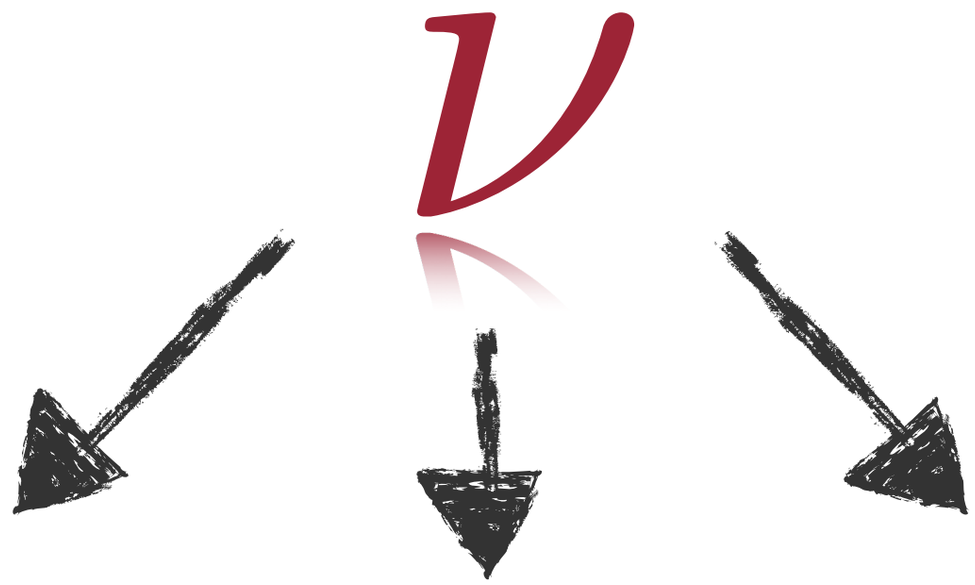


Fortunately, it is <u>incomplete</u>.

New physics is needed for 3 robust empirical facts:

- The masses of the “neutrinos”,
- The existence of dark matter, and
- The matter-antimatter asymmetry of the Universe

Neutrinos are omnipresent and many of their parameters are known to great precision. Let’s take them as a guide to construct new theories.



Astro	HEP	Cosmo
Nucleosynthesis Supernovae, …	Flavor physics Unification, …	BAU Radiation, …

Neutrinos are indeed so important that they lead to 4 Nobel prizes!

2015: Kajita & McDonald, "*for the discovery of neutrino oscillations, which shows that neutrinos have mass*"

2002: Davis & Koshiba, "*for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos*"

1995: Reines, "*for the detection of the neutrino*"

1988: Lederman, Schwartz, & Steinberger, "*for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino*"

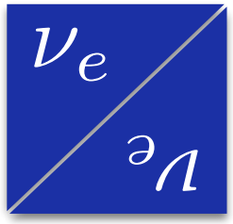
Why are neutrinos massless in the SM?

There are two types of masses for elementary fermions:

Dirac masses. Require 2 fundamental fields, glued by the mass term

$$m_e e_L^\dagger e_R$$

Majorana masses. Neutral fermions need only one building block



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But .. only the "Left" neutrinos appear in the SM!

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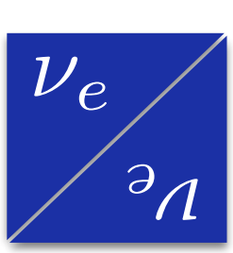


$$\nu_R = -i\sigma_2 \nu_L^\star$$

But .. gauge invariance forbids such a mass!

$$\begin{pmatrix} e_L \\ \nu_L \end{pmatrix} \rightarrow \nu_L^\dagger(-i\sigma_2\nu_L^\star) + e_L^\dagger(-i\sigma_2 e_L^\star)$$

Quick fix: add 3 "Right" neutrinos

Now, we can finally have Dirac type masses $m_D \nu_L^\dagger \nu_R$

And since the new fields are neutral, they can also have Majorana type masses $m_M \, \nu_R^\dagger (i\sigma_2 \nu_R^\star)$

So we end up with a matrix $\begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix}$

In the limit of large Majorana mass, the diagonalisation leads to naturally tiny masses. This is the seesaw mechanism.

$$m_{light} = \frac{m_D^2}{m_M}$$

$$1\,\mathrm{eV} = \frac{(100\,\mathrm{GeV})^2}{10^{13}\,\mathrm{GeV}}$$

The Dirac mass comes from the Higgs mechanism,

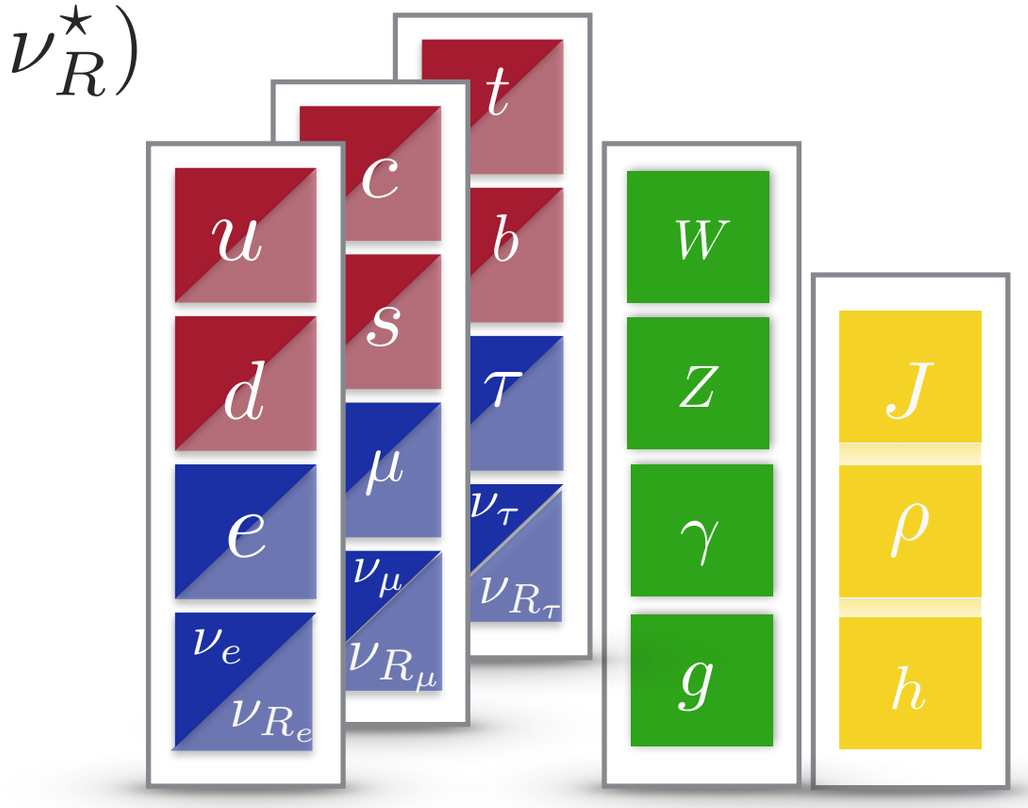
$$y_\nu \langle H \rangle \nu_L^\dagger \nu_R \rightarrow \ m_D \nu_L^\dagger \nu_R$$

But the Majorana term is completely free and appears ad-hoc. Let's 'Higgs' it.

$$m_M \nu_R^\dagger (i\sigma_2 \nu_R^\star) \rightarrow y_N \langle S \rangle \nu_R^\dagger (i\sigma_2 \nu_R^\star)$$

The new Higgs can be written as

$$S = \langle S \rangle + \rho + iJ$$



The Majoron as DM

An acceptable candidate should satisfy many criteria. It has to be …

- dark (neutral to a large extent),
- collisionless,
- quasi-stable,
- OK with search limits
- cold or warm,
- and last but not least, account for DM abundance.

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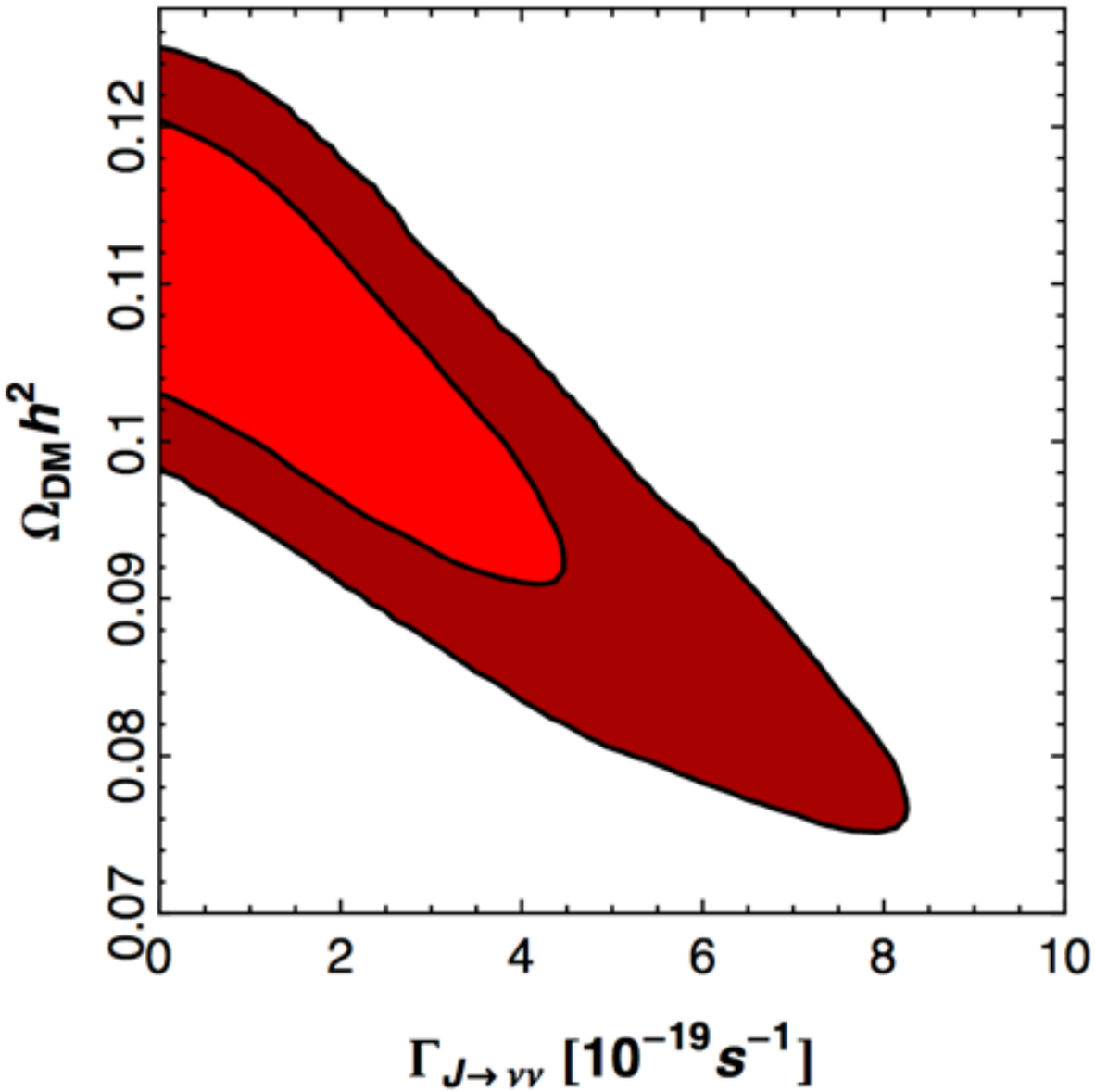
The majoron decays very slowly

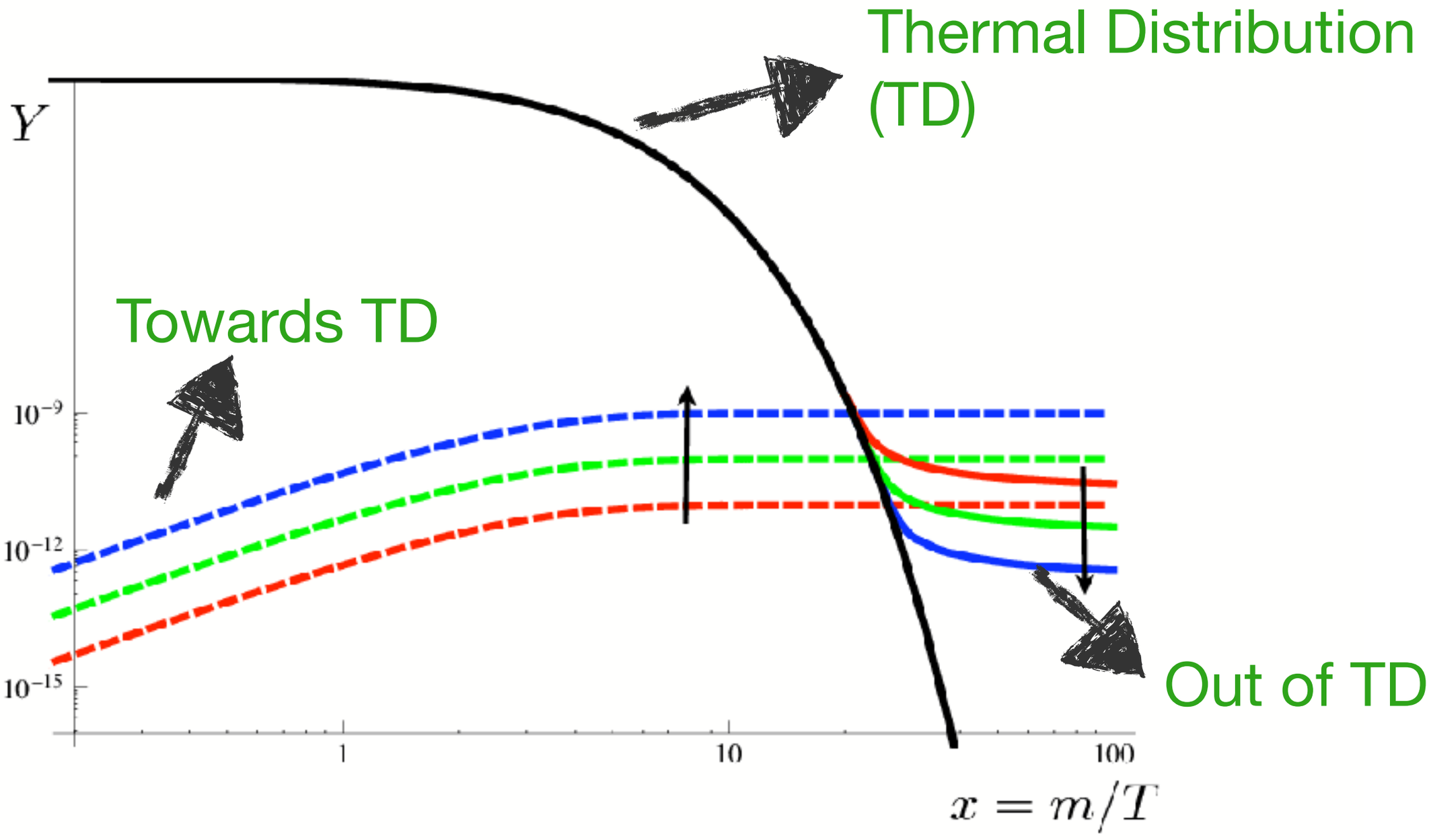
The majoron couples dominantly to neutrinos. Its lifetime is therefore greatly suppressed,

$$\tau_J \propto \frac{1}{m_J} \frac{< S >^2}{m_\nu^2} \gg 14 \text{ Gyr}$$

Nevertheless, it can leave imprints on the CMB (decays to invisible light particle change the late evolution of gravitational potentials) and a lower bound can be derived. **Indirect test!**



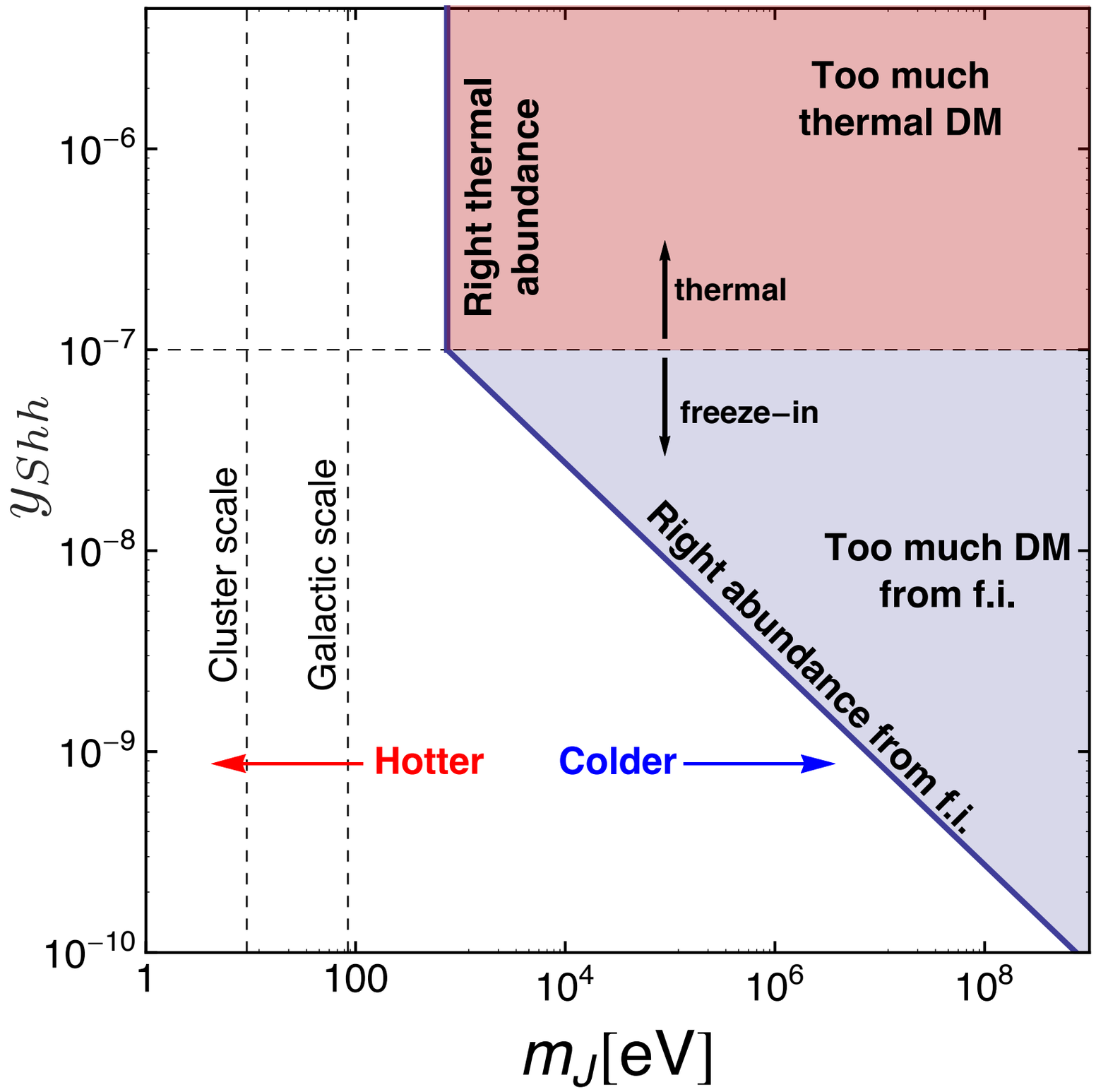
Dark Matter production in an expanding Universe



Production of Majorons

Majorons are Warm if produced thermally, with mass of O(keV).

Or Cold if produced via freeze-in, with larger masses.



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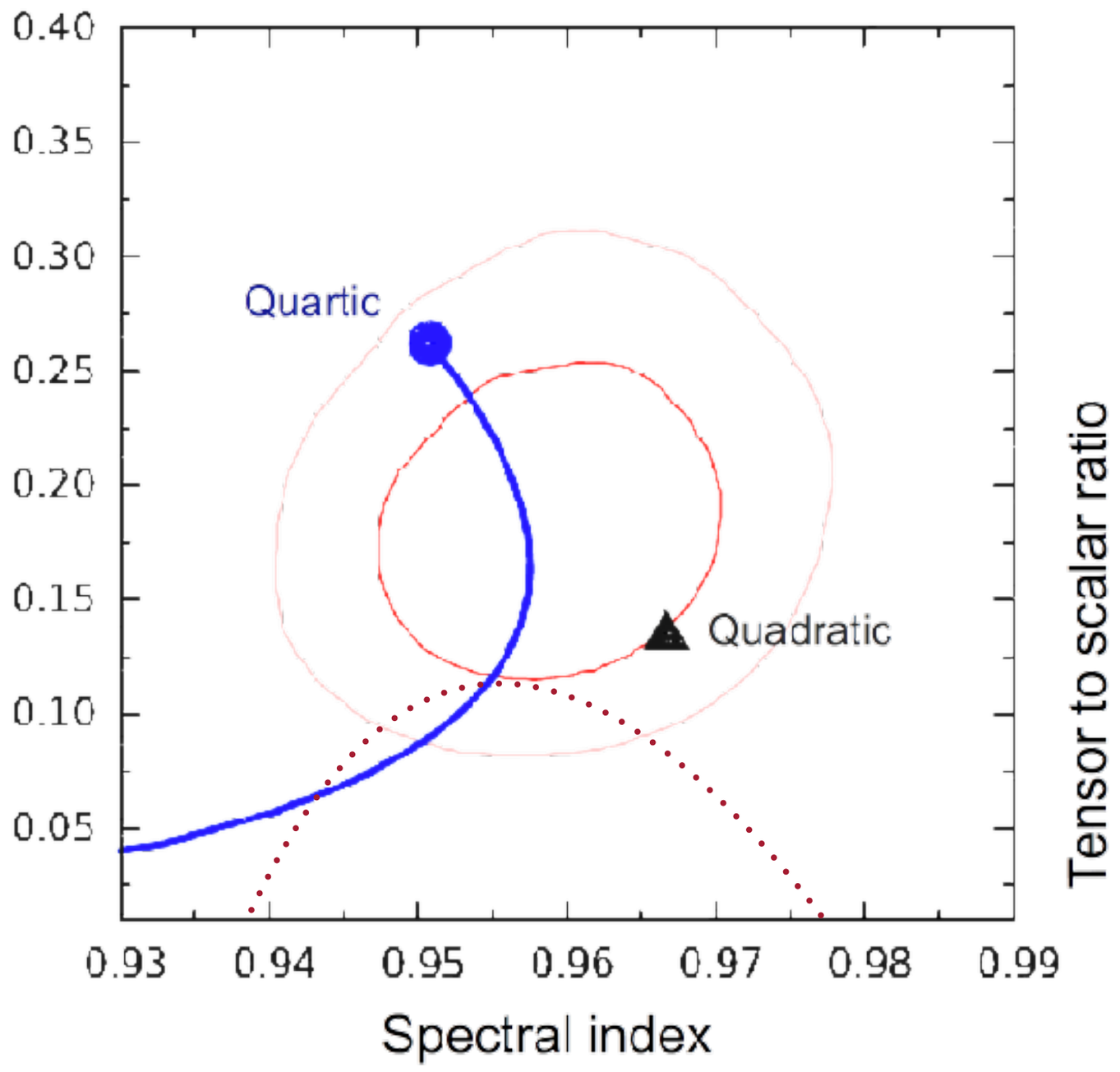
What about the real part of S?

Inflation solves observational cosmology conundrums (flatness, horizon, isotropy, etc.), seeds cosmological perturbations, & recovers hot Big Bang cosmology.

S-inflation change the prediction of standard quartic inflation thanks to interactions with *N*.



Majoron DM

Baryogenesis via Leptogenesis

$\mathrm{SM} + S + 3\nu_R$

Neutrino masses via Seesaw

Quartic Inflation (CW corrected)

Majoron DM

$\mathrm{SM} + S + 3\nu_R$

Neutrino masses via Seesaw

Credits

Seesaw mechanism

Minkowski 1977; Gell-Mann, Ramond, Slansky 1979; Yanagida 1980; Mohapatra, Senjanovic 1980; Schechter, Valle 1980.

Majoron

Chikashige, Mohapatra, Peccei, 1981

Majoron mass

Akhmedov et al. 1992; Babu, Rothstein, Seckel 1993

Majoron as Warm DM

Berezinsky, Valle 1993

Majoron cosmology

Lattanzi, Valle, 2007; Bazzocchi, Lattanzi, Riemer-Sørensen, Valle, 2008

Inflation in seesaw

Boucenna, Morisi, Shafi, Valle, 2014

Majoron as Cold DM from freeze-in

Boucenna, Lattanzi, Valle, *in prep.*

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