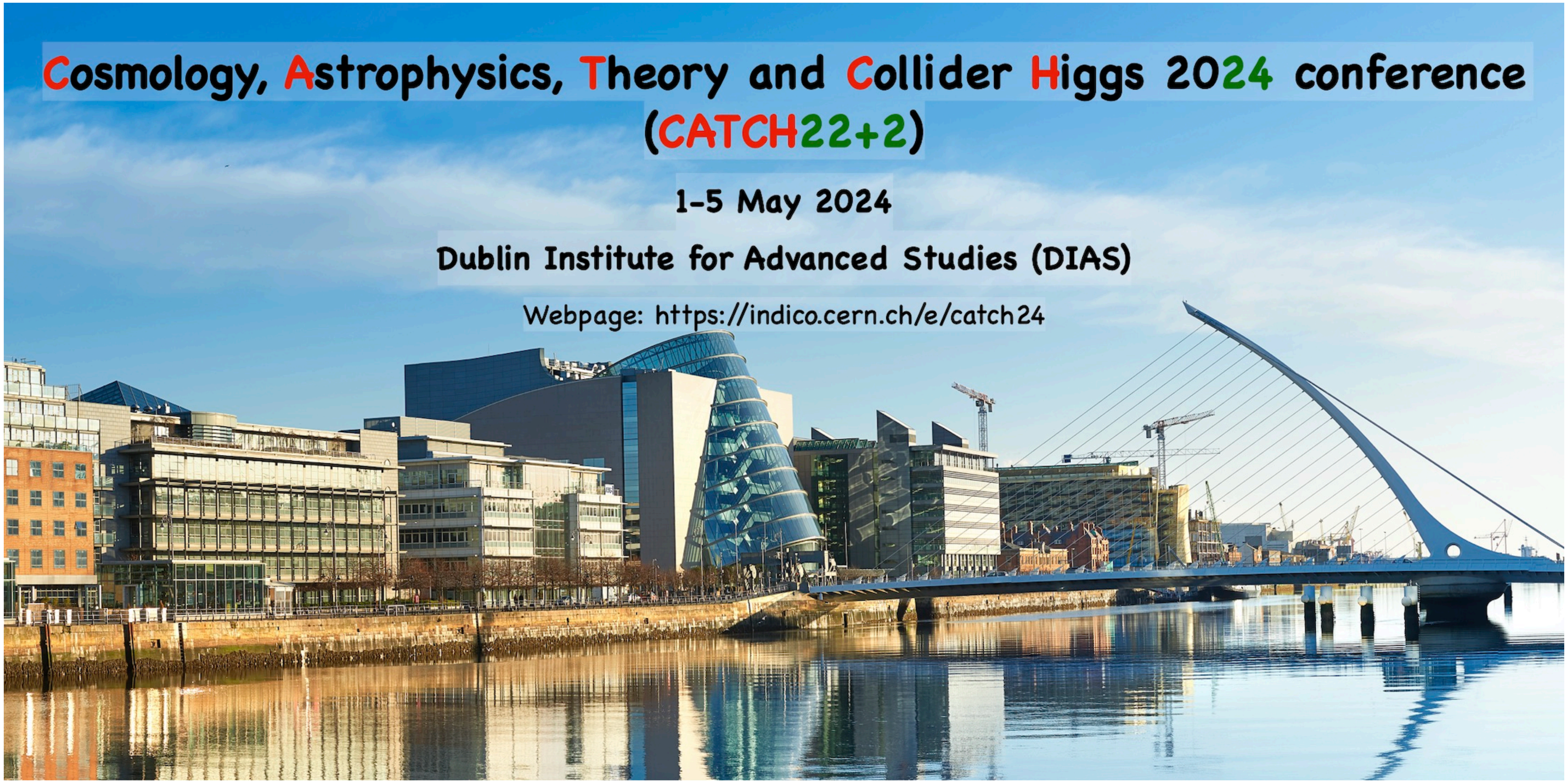
Cosmic Matter-Antimatter Separation and Sterile Neutrino Dark Matter

Mikhail Shaposhnikov

Based on work with Alexey Smirnov



Cosmology, Astrophysics, Theory and Collider Higgs 2024 conference
(CATCH22+2)

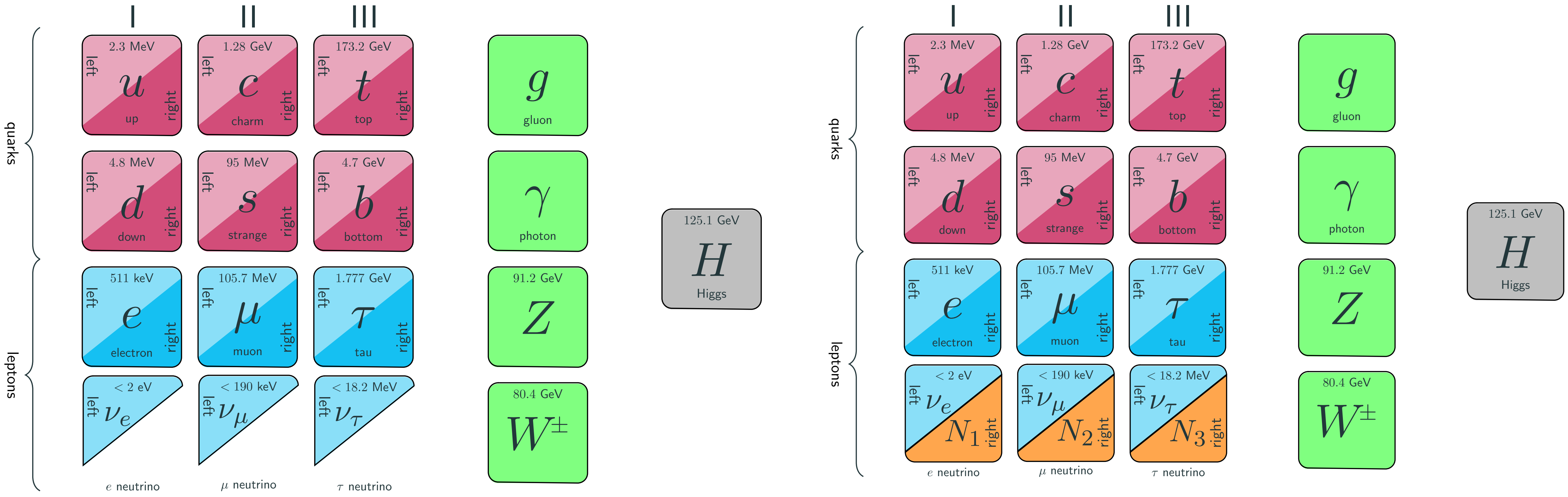
1-5 May 2024

Dublin Institute for Advanced Studies (DIAS)

Webpage: https://indico.cern.ch/e/catch24

νMSM as a minimal model of new physics

The simplest theory of new physics which can explain all experimental drawbacks of the Standard Model (neutrino masses and oscillations, dark matter, baryon asymmetry of the Universe, incorporating cosmological Higgs inflation leading to the observable universe) is at extension of the SM by 3 right-handed neutrinos (or heavy neutral leptons - HNLs) : the minimal type I see-saw model or νMSM.



HNL roles in the νMSM

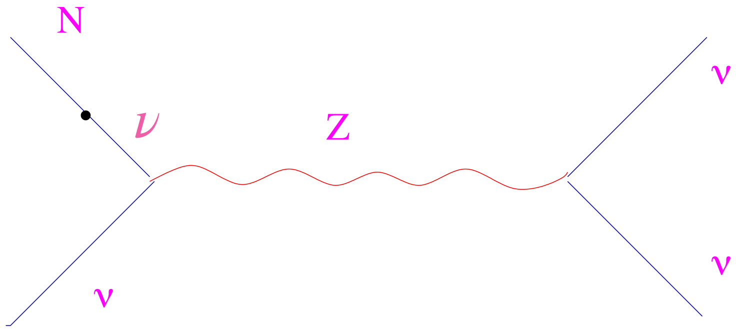
N_1- Dark Matter particle (Dodelson, Widrow; Shi, Fuller; Dolgov, Hansen;….)

$N_{2,3}$ - responsible for neutrino masses and baryogenesis (See-saw team - Minkowski and others; Fukugita, Yanagida, …; Akhmedov, Rubakov, Smirnov; Asaka, MS,…)

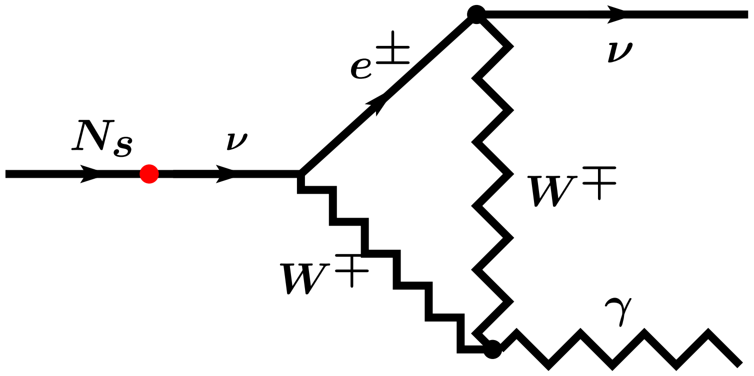
Constraints on DM sterile neutrino N₁

$$\theta = m_D / M_M$$

- **Stability.** N₁ must have a lifetime larger than that of the Universe. Main decay mode $N_1 \to 3\nu$ is not observable.

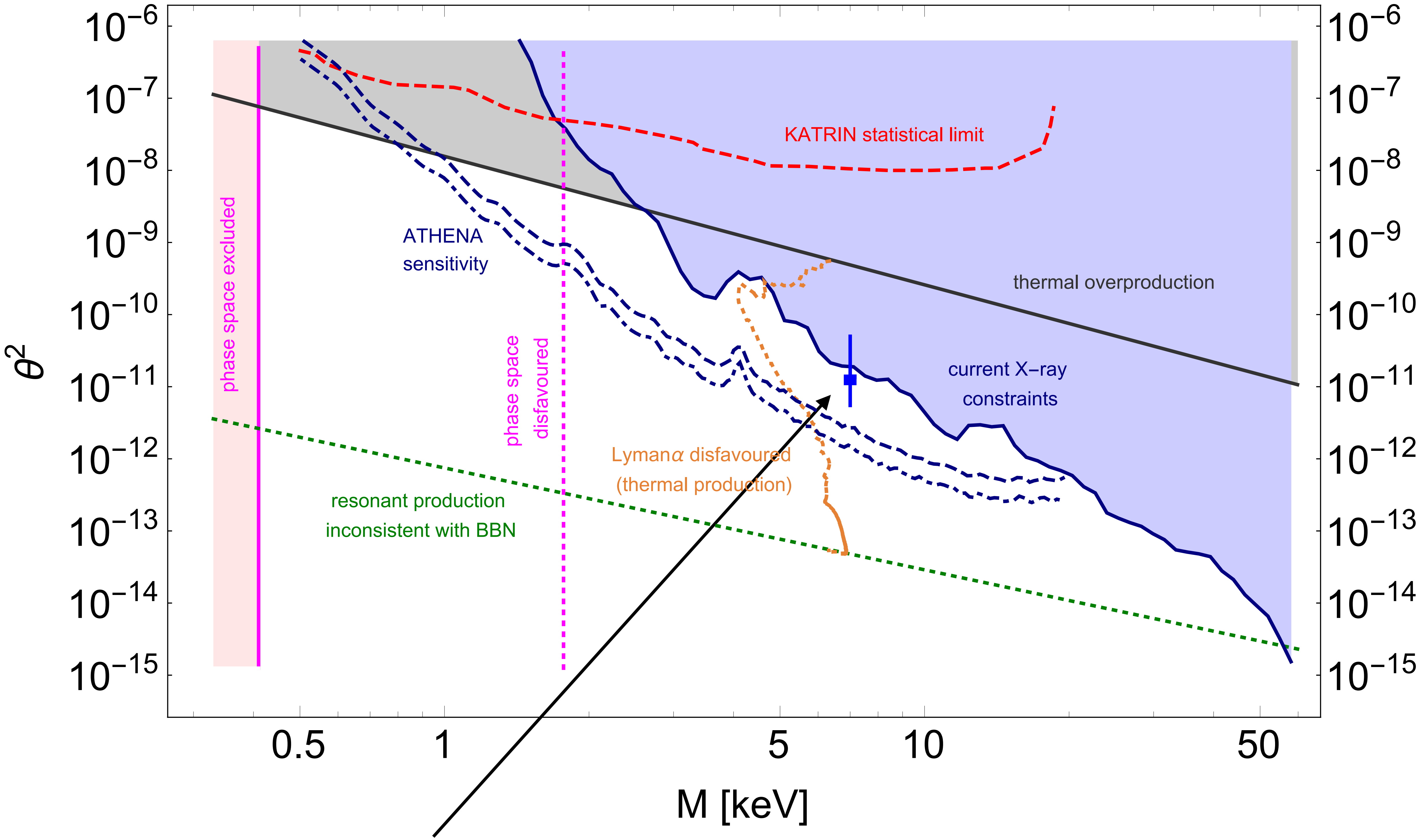


- **X-rays.** N₁ decays radiatively, $N_1 \to \gamma\nu$, producing a narrow line $E_\gamma = M_1/2$ which can be detected by X-ray telescopes (such as Chandra or XMM-Newton).



$$\Gamma_{\text{rad}} = \frac{9\alpha G_F^2}{256 \cdot 4\pi^4} \sin^2(2\theta) M_s^5$$

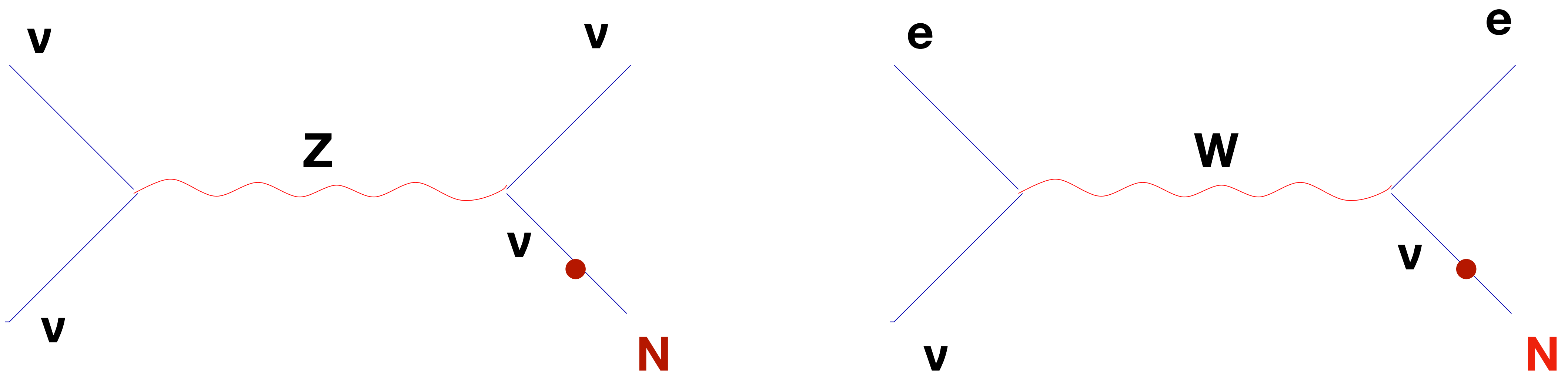
X-ray and structure formation constraints



Possible detection (?), still controversial, to be resolved in 2023-2024

Bulbul et al; Boyarsky et al

DM sterile neutrino production at low temperatures

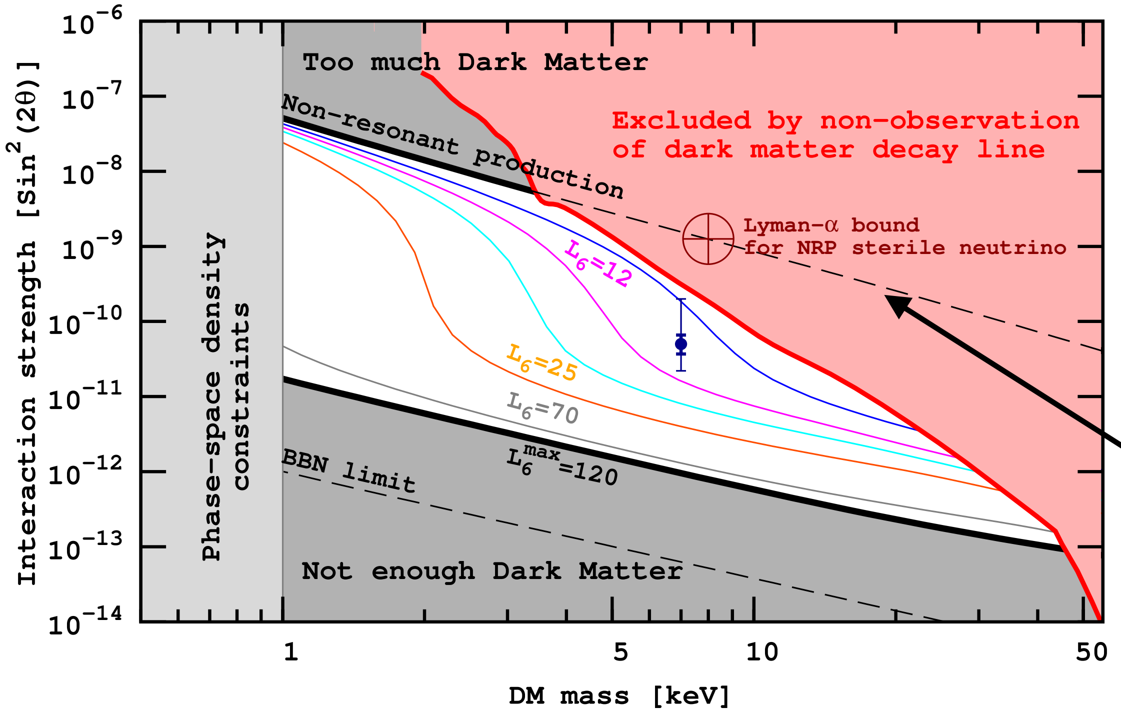


The temperature of production of DM sterile neutrinos: the QCD epoch

$$T \simeq 250 \left(\frac{M_1}{7 \text{ keV}} \right)^{1/3} \text{ MeV}$$

Dodelson, Widrow; Shi, Fuller; Dolgov, Hansen; Abazajian, Fuller, Patel; … Asaka, Laine, MS;..

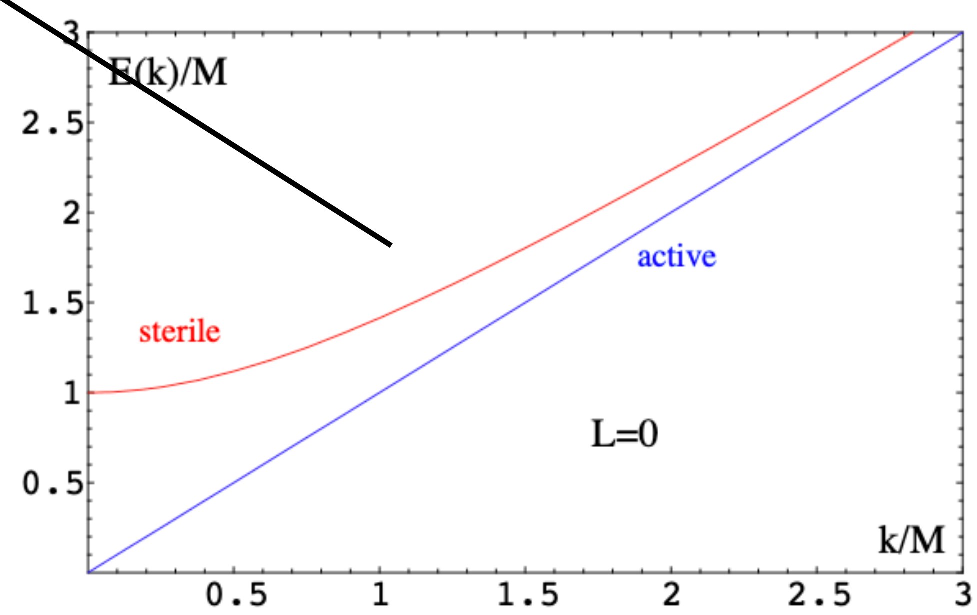
Non-resonant production



Relation between the lifetime and abundance.

Momentum of sterile neutrino $\simeq 0.85 p_T$

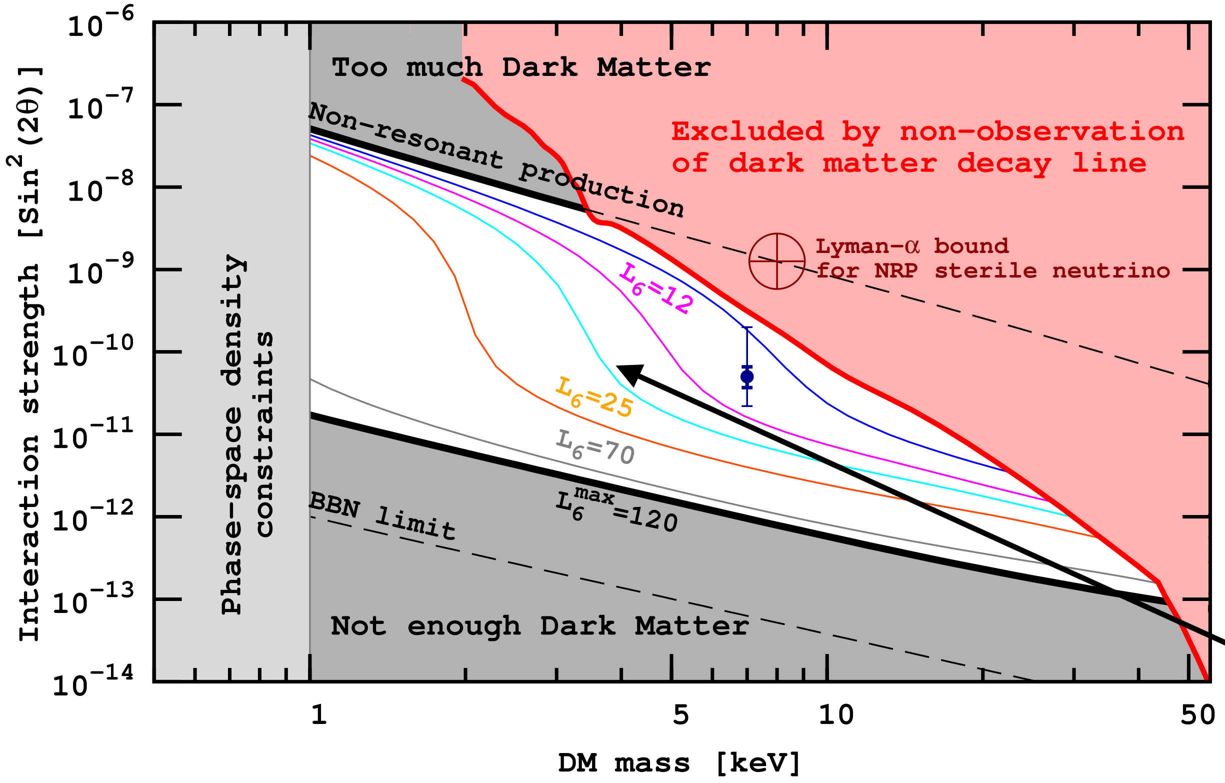
DW mechanism



Transitions $\nu \rightarrow N_1$

Dodelson-Widrow

Resonant production

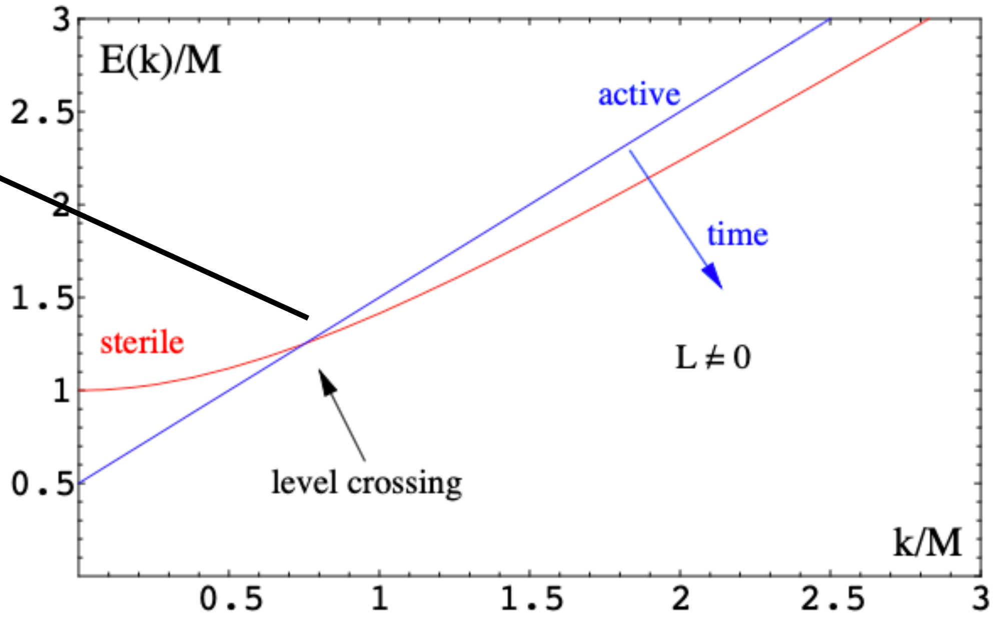


Relation between the lifetime abundance, and lepton asymmetry.

Momentum of sterile neutrino $\simeq 0.3 p_T$

L_6 - lepton asymmetry in units 10^{-6}

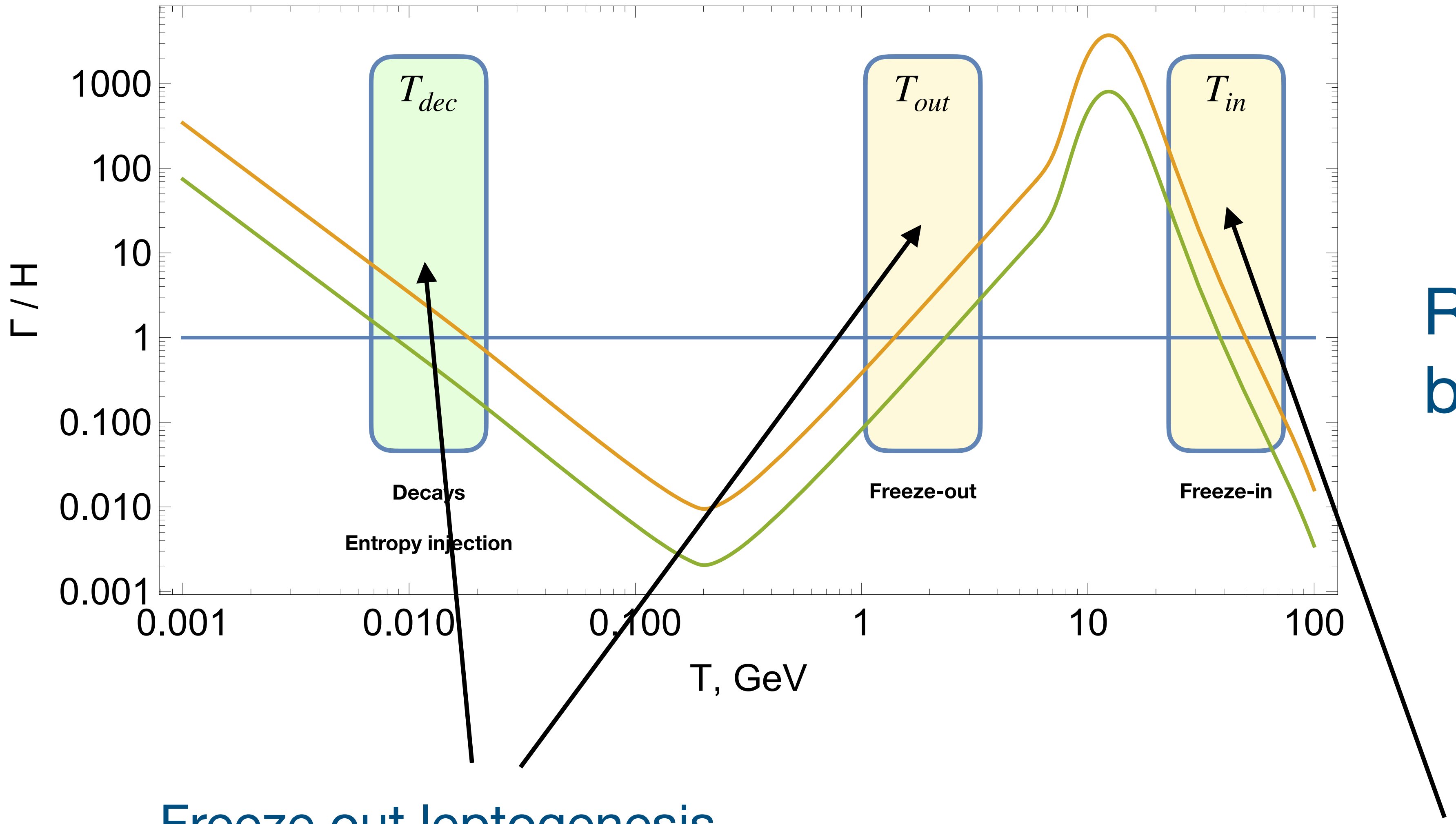
SF mechanism



Resonant transitions

Shi-Fuller

Leptogenesis at few GeV



Relation between baryogenesis and DM

Freeze out leptogenesis
can ensure 100% of DM,
but very strong degeneracy
between N2,3 is required

Freeze in leptogenesis
can ensure ~50% of DM

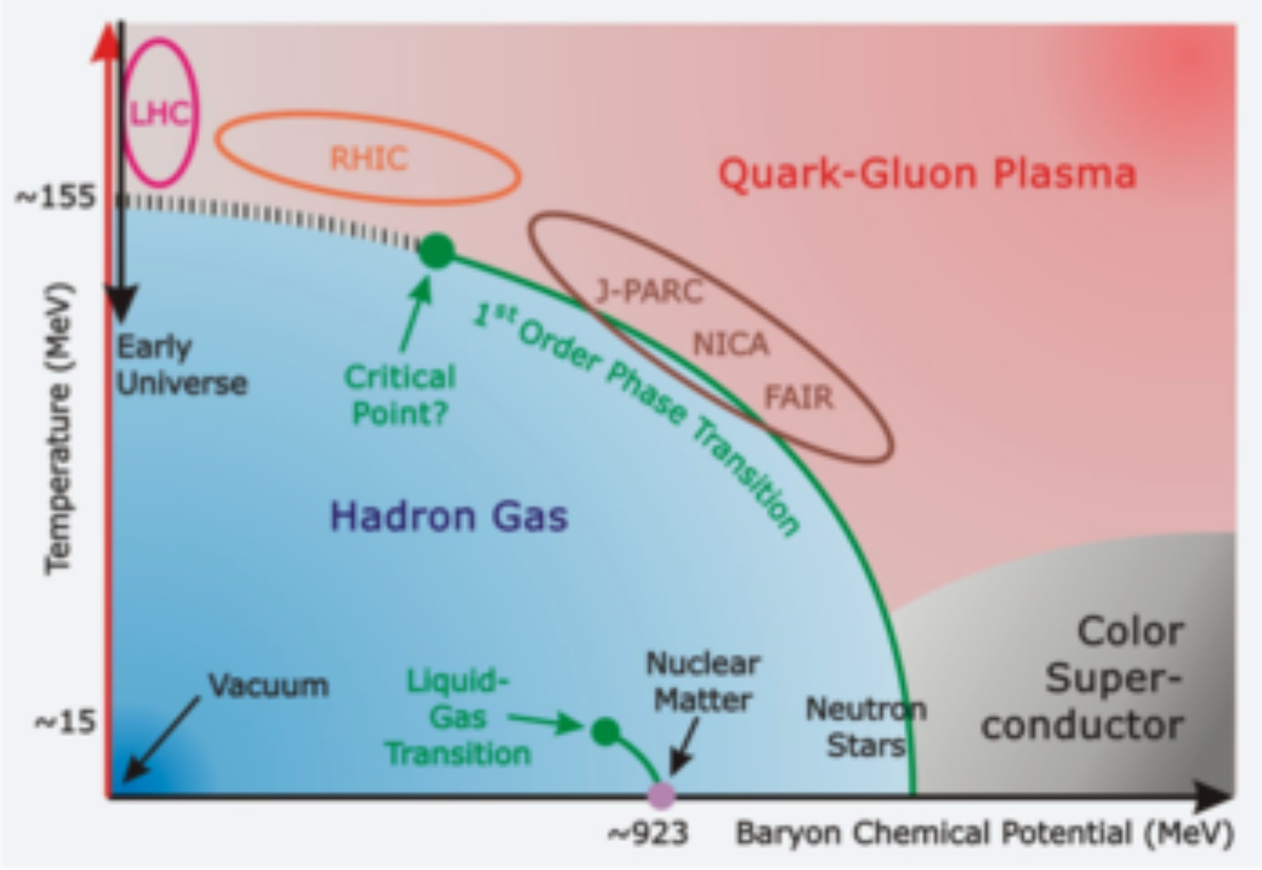
MS; Canetti, Drewes, Frossard, MS; Eijima, Timiryasov, MS; Laine, Ghiglieri

QCD phase transition?

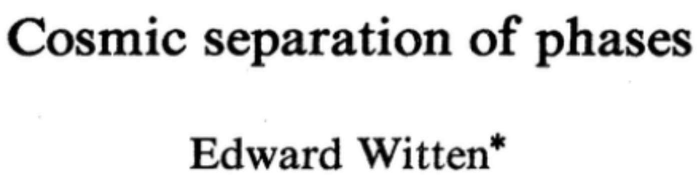
All the studies of sterile neutrino DM production were done assuming that the Universe was homogeneous at $T \sim \Lambda_{\mathrm{QCD}}$. Possible source of inhomogeneities - the QCD phase transition.

- Lattice evidence - smooth crossover

- “Evidence” is not a proof yet - let’s assume that the transition did happen in the early Universe

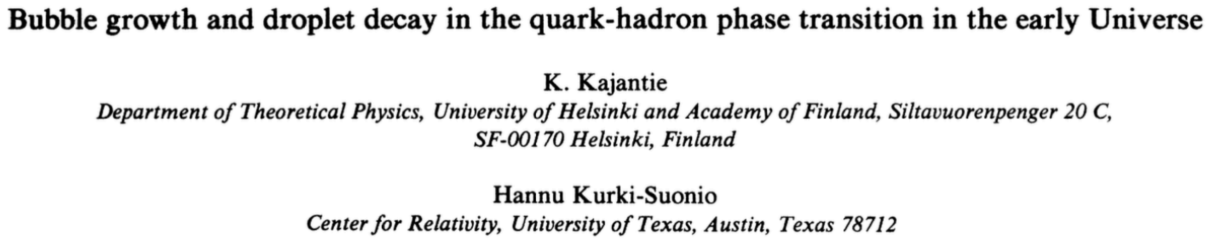


Cosmic separation of phases



Cosmic separation of phases

Edward Witten*



Bubble growth and droplet decay in the quark-hadron phase transition in the early Universe

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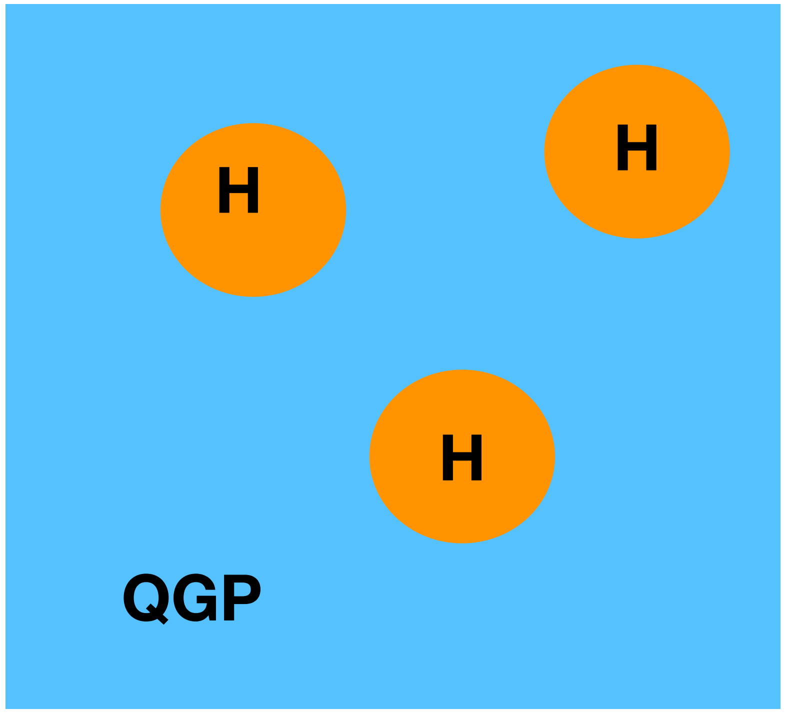
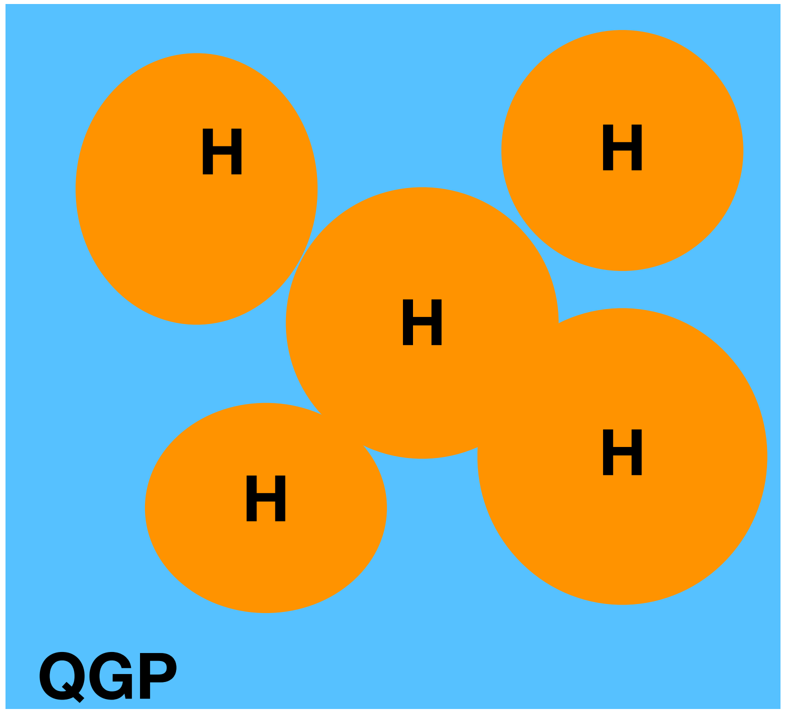
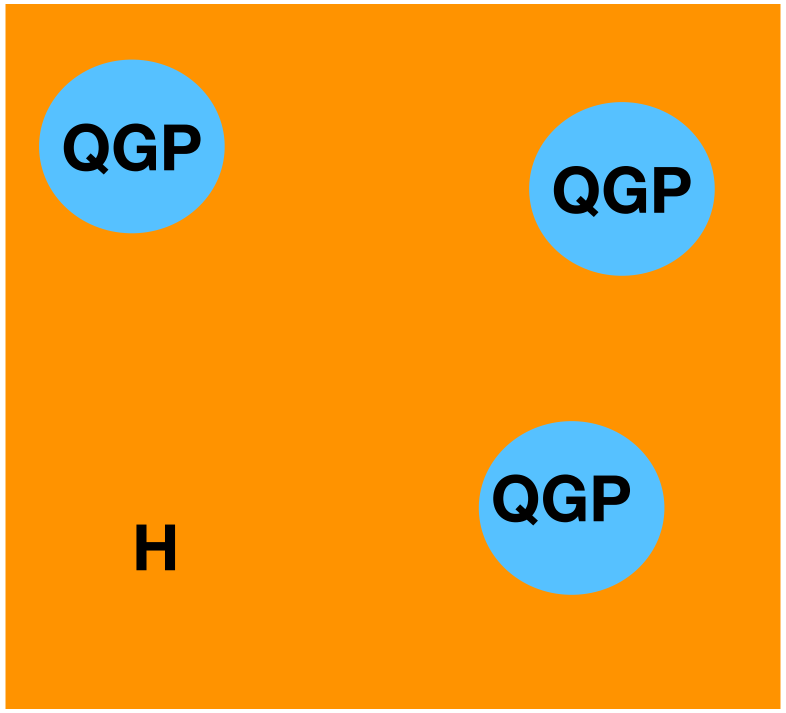


hadronic
bubbles



percolation

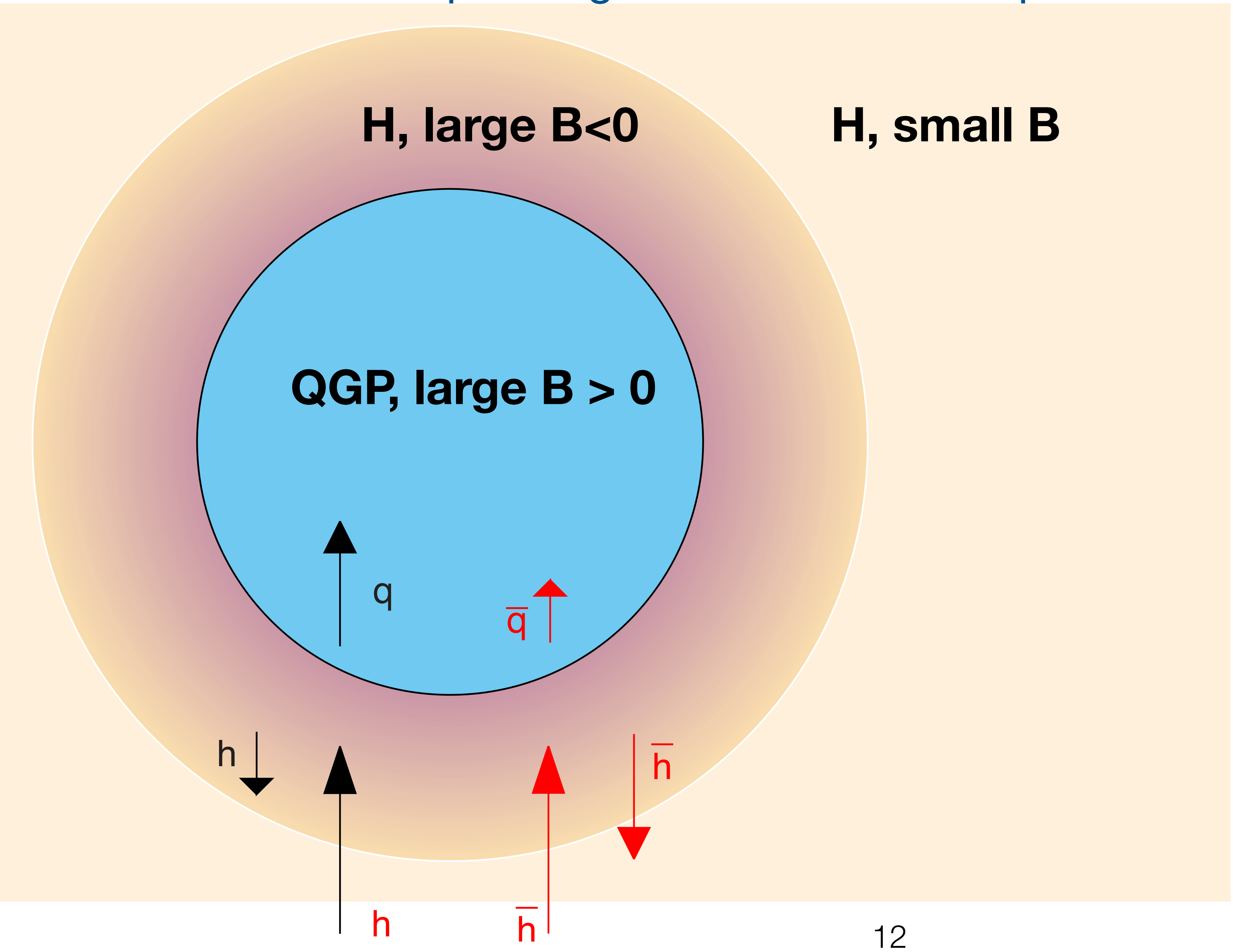


QGP droplets

Constant temperature ~ 160 MeV, horizon size ~ 10 km, distance between bubbles ~ 1cm - 1m, PT duration ~ 10^{-5} seconds. Baryon number is confined in QGP droplets and can reach nuclear density. BBN is not spoiled, as the inhomogeneities have sizes smaller than the neutron diffusion scale.

Matter-antimatter separation

The Universe may contain lepton asymmetry $\Delta_L = L/s \gg B/s = \Delta_B \simeq 9 \times 10^{-11}$, coming from HNLs or from other sources. It creates asymmetries in quark flavours ~ Δ_L, to make the plasma electrically neutral. This leads to C, CP and CPT breaking. This may result in difference of reflection coefficients of quarks and antiquarks from the domain walls separating QGP and hadronic phases.



Matter-antimatter domains with ~ nuclear density and sizes a factor of few (depending on lepton asymmetry) smaller than the distance between bubbles

$$n_B^d \propto \left(\frac{1}{V_d}\right)^{\kappa}$$

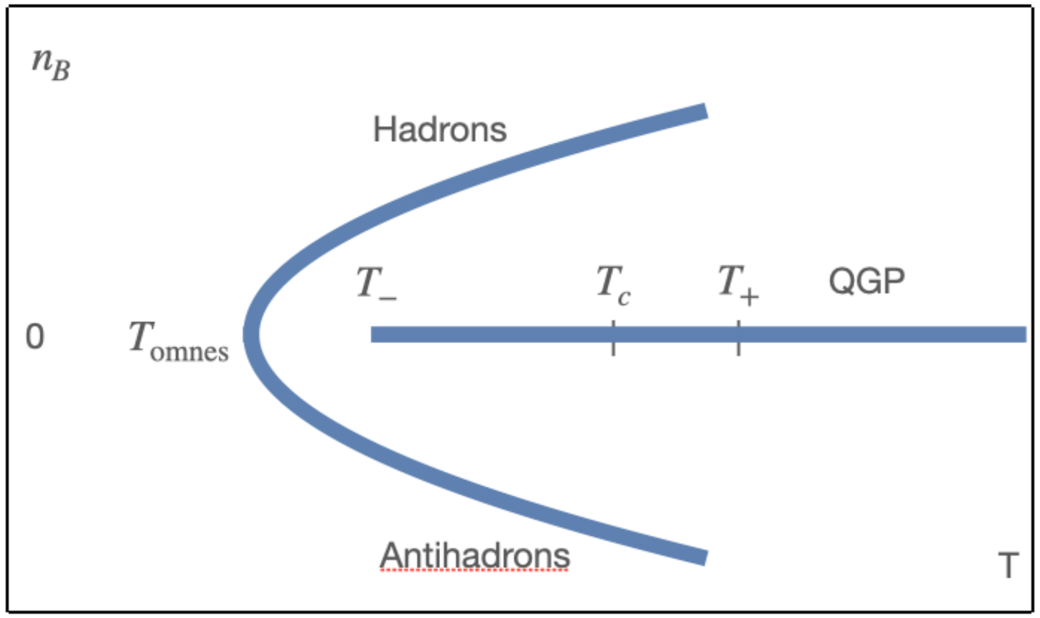
depends on reflection amplitude

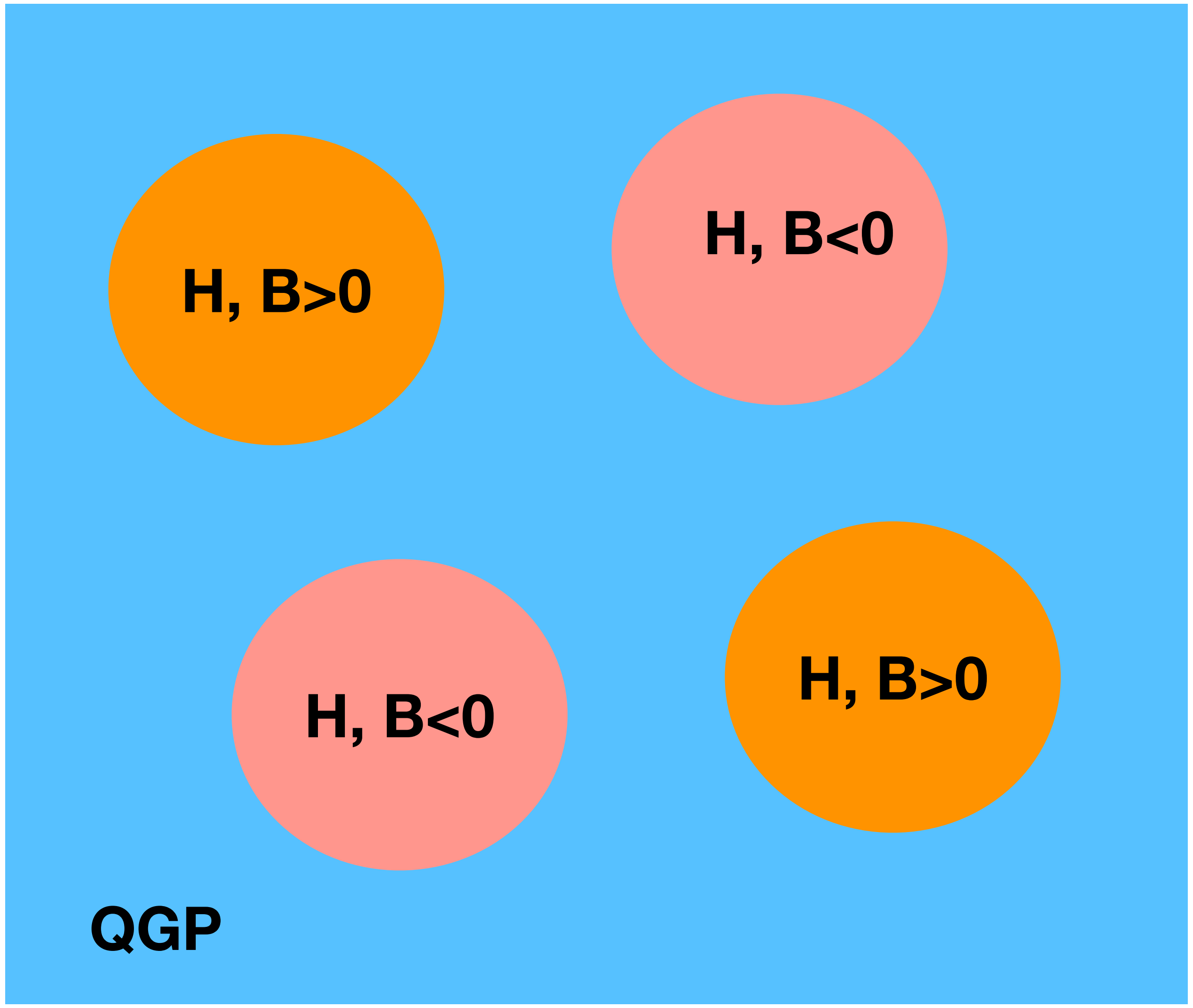
baryon density

droplet volume

Omnes phase transition

Very exotic possibility: Omnes, 1969 - temporary spontaneous breaking of CP symmetry, leading to ~ nuclear density matter-antimatter domains





Sterile neutrino Dark Matter at QCD phase transition

Resonant transitions in matter-antimatter domains with high density similar to Mikheev-Smirnov-Wolfenstein effect

Two cases to be considered:

- Droplet sizes are larger than the active neutrino mean free path, $\lambda_\nu \simeq 0.4\ \mathrm{cm}$: resonant transitions $\nu \to N_1$ inside the droplets
- Droplet sizes are smaller than the active neutrino mean free path, $\lambda_\nu \simeq 0.4\ \mathrm{cm}$: scattering of neutrino on droplets, $\nu + \mathrm{droplet} \to N_1 + \mathrm{droplet}$

Large droplets

Number of resonantly produced sterile neutrinos:

$$n_N = \frac{\theta^2 M^2 T^2}{4\pi} \int dt\, x_{\mathrm{res}}^2\, n_F(x_{\mathrm{res}}) \frac{V_{\mathrm{QGP}}(t)}{V_{\mathrm{QGP}}(t_0)},$$

where the resonant energy is given by

$$x_{\mathrm{res}}(t) = \frac{M^2}{\sqrt{2} G_F n_B^d(t) T}$$

Small droplets

Number of produced sterile neutrinos:

$$n_N = \pi n_\nu \int dt \langle P_N \rangle r_d^2(t) \frac{1}{(2r_d(t_0))^3},$$

where $\langle P_N \rangle$ is the probability of the process $\nu + \mathrm{droplet} \to N_1 + \mathrm{droplet}$,

$$\langle P_N \rangle \approx \frac{2\pi}{3\zeta(3)} \frac{\theta^2 M^2 \bar{r}_d}{T} \left(\frac{\omega_{\mathrm{res}}}{T} \right)^2 n_F(\omega_{\mathrm{res}})$$

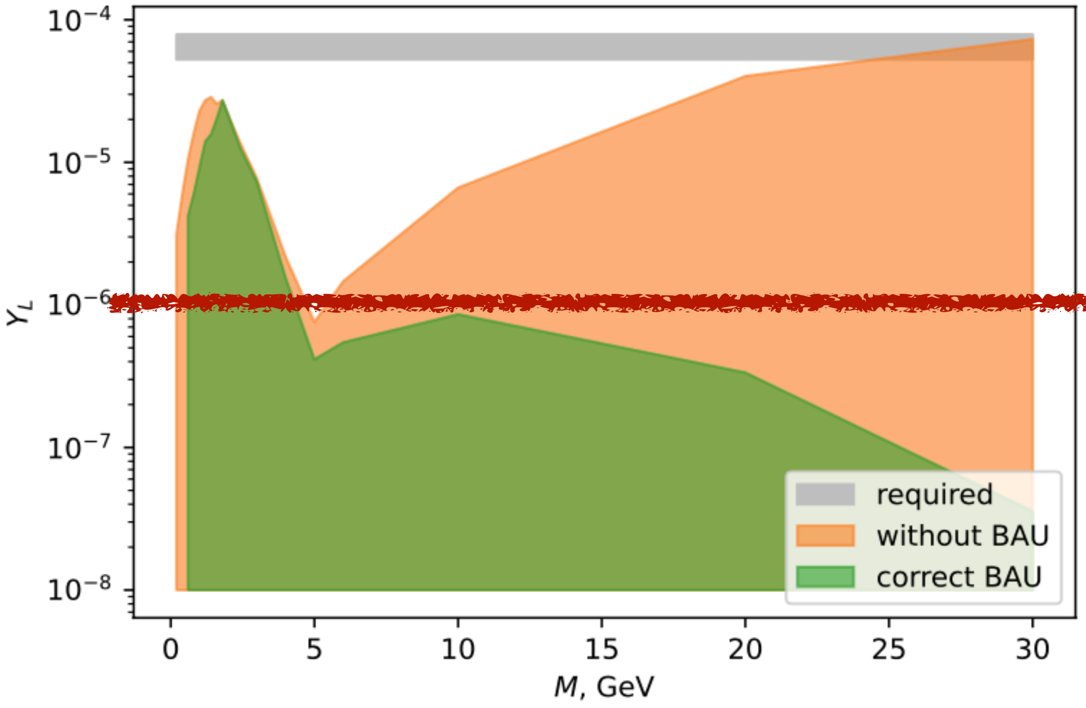
Sterile neutrino Dark Matter at QCD phase transition

Precise computation is hardly possible because of many uncertainties. Reasonable assumptions about the dynamics of PT allow to make rough estimates:

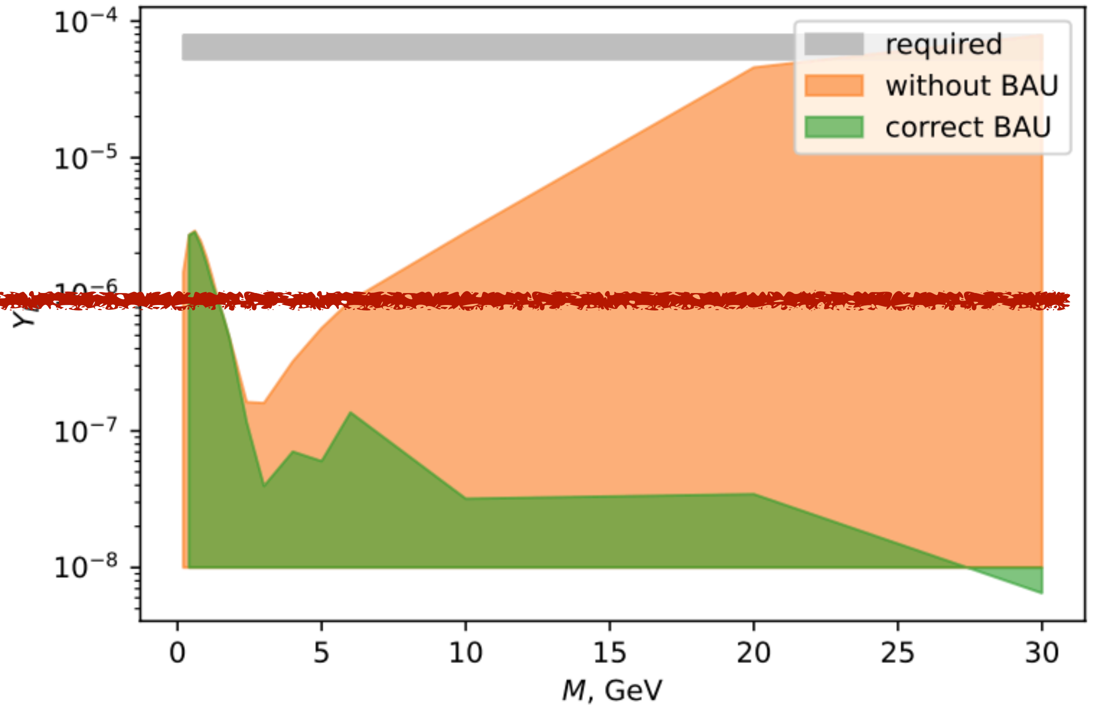
- Omnes PT - efficient production of DM even for DM sterile neutrino with mixing angles θ^2 below 5×10^{-11} (indicated by X-rays).
- Spectrum of produced sterile neutrinos may be considerably cooler than that in DW or SF mechanisms, making N_1 essentially cold DM candidate with momentum $\simeq 0.1 p_T$.
- Lepton asymmetry driven matter-antimatter separation: efficient production of DM even for lepton asymmetries factor ~ 100 below the value needed in the homogeneous case $\Delta_L \simeq 6.6 \times 10^{-5}$ (for 7 keV sterile neutrino and $\theta^2 \simeq 5 \times 10^{-11}$).

Connection with heavier HNLs

Eijima, MS, Timiryasov



Normal ordering of neutrino masses



Inverted ordering of neutrino masses

Lepton asymmetries so large can only be generated in the *ν*MSM if the NHL masses are small enough.

This is the first indication of their mass scale.

Conclusions

- If the first order QCD phase transition took place, the sterile neutrino DM production can be enhanced due to temporal matter-antimatter separation.

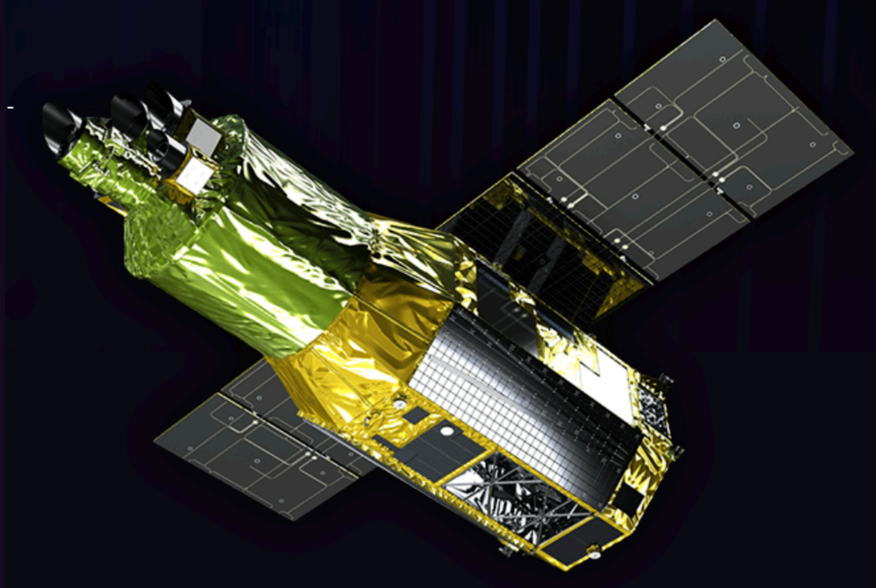
- Depending on the nature of the transition, the required lepton asymmetries can be smaller than in the homogeneous situation.

- These asymmetries can be produced at the freeze in of heavier HNLs, without fine-tunings, if their mass is below few GeV.

- New future experiments and observations which can find HNLs: XRISM in space, launched in September 2023 (DM) and SHiP at CERN, accepted in March 2024

XRiSM

X-Ray Imaging and Spectroscopy Mission



The XRISM payload consists of two instruments:

- Resolve, a soft X-ray spectrometer, which combines a lightweight X-ray Mirror Assembly (XMA) paired with an X-ray calorimeter spectrometer, and provides non-dispersive 5-7 eV energy resolution in the 0.3-12 keV bandpass with a field of view of about 3 arcmin.
- Xtend, a soft X-ray imager, is an array of four CCD detectors that extend the field of the observatory to 38 arcmin on a side over the energy range 0.4-13 keV, using an identical lightweight X-ray Mirror Assembly.

Spectral resolution is more than 10 times better than in XMM-Newton!

XRISM was launched by the H-IIA rocket from the Tanegashima Space Center at 8:42 a.m on September 7, 2023 JST, (23:42 on September 6, 2023 UT). Photo Credit: L. Hartz

SHiP

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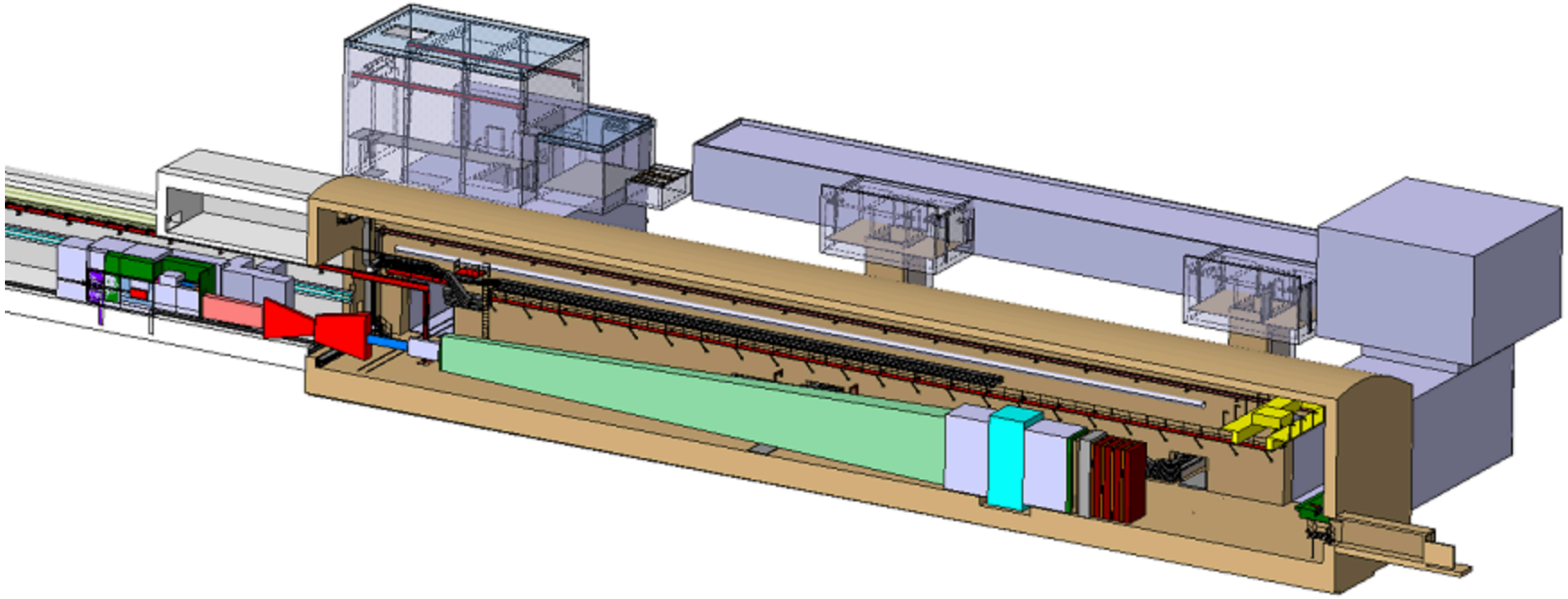
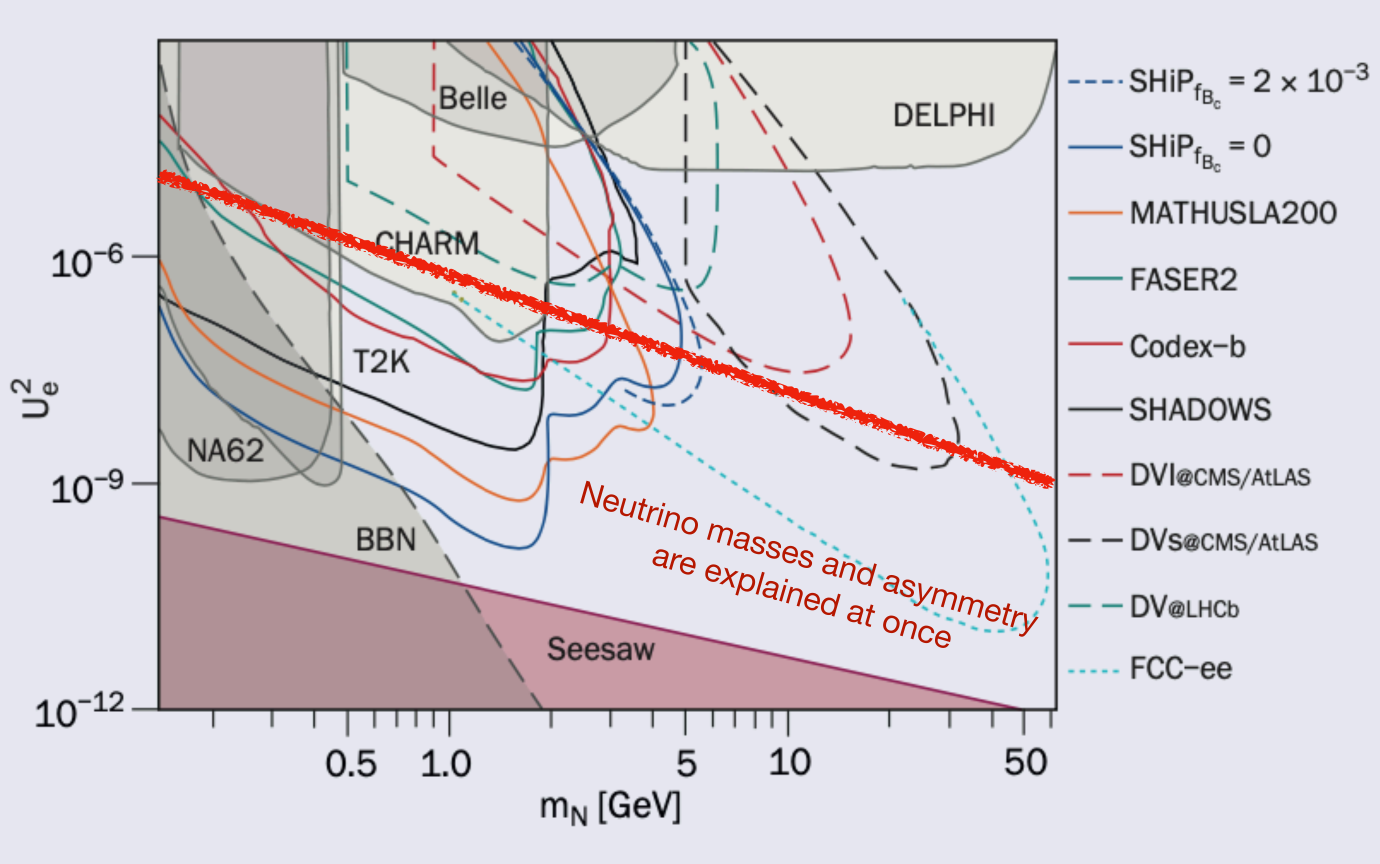


Projection of bounds on HNLs



Sensitivity in number of events is 10’000 times better than in previous experiments!

Experiment selected at CERN in March this year