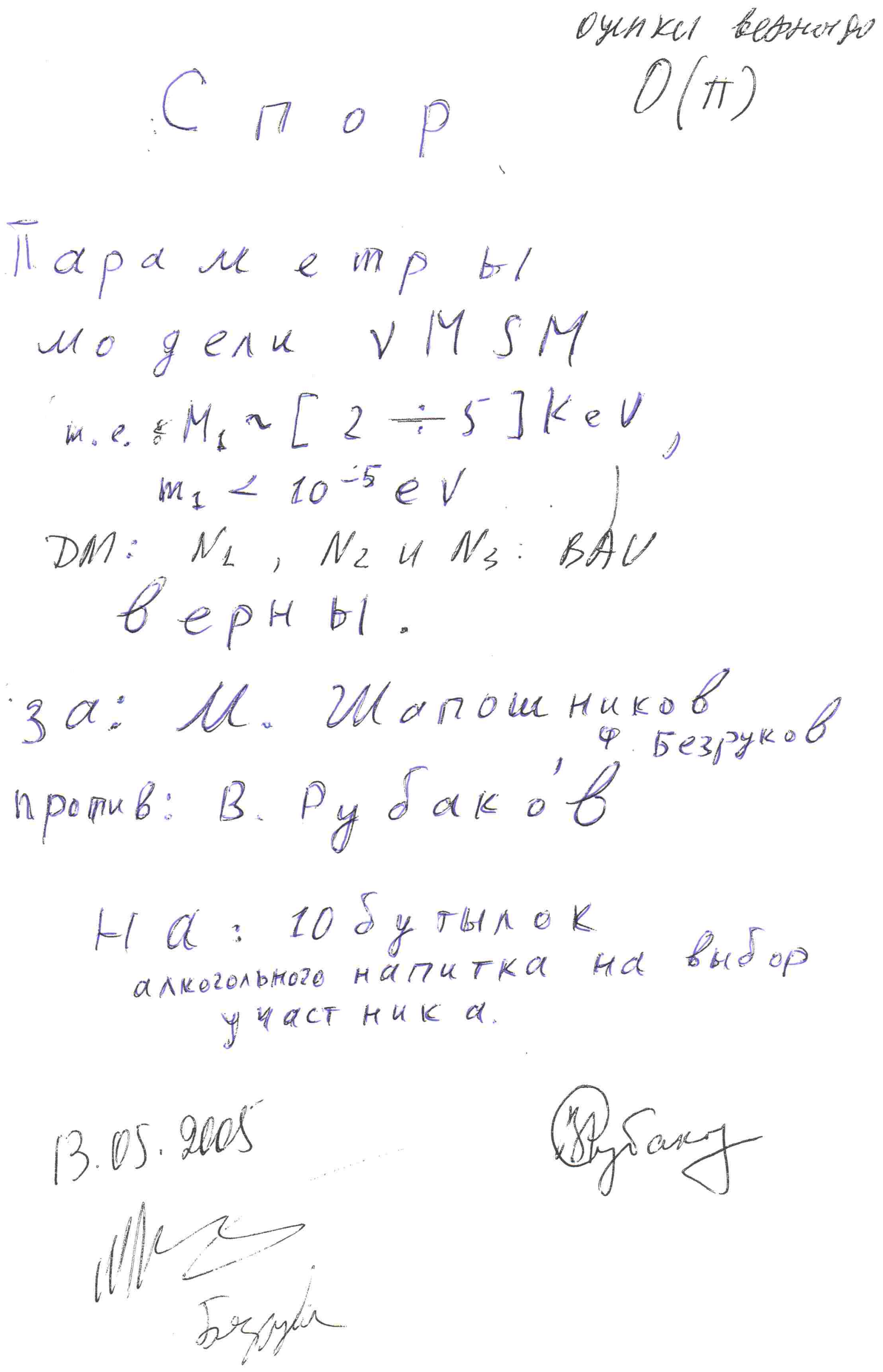
Sterile Neutrino Dark Matter, Matter-Antimatter Separation, and the QCD Phase Transition

Mikhail Shaposhnikov

Dedicated to memory of Valery

This work was done in collaboration with Alexey Smirnov, it is relevant for the bet Fedor Bezrukov and I had with Valery in 2005, and with the articles Valery written 25 and 15 years ago…



оценки вероятности
$O(\pi)$

Спор

Параметры
модели νMSM
т.е.: $M_1 \sim [2 \div 5]$ KeV,
$m_1 < 10^{-5}$ eV
DM: N_1, N_2 и N_3: BAU
верны.

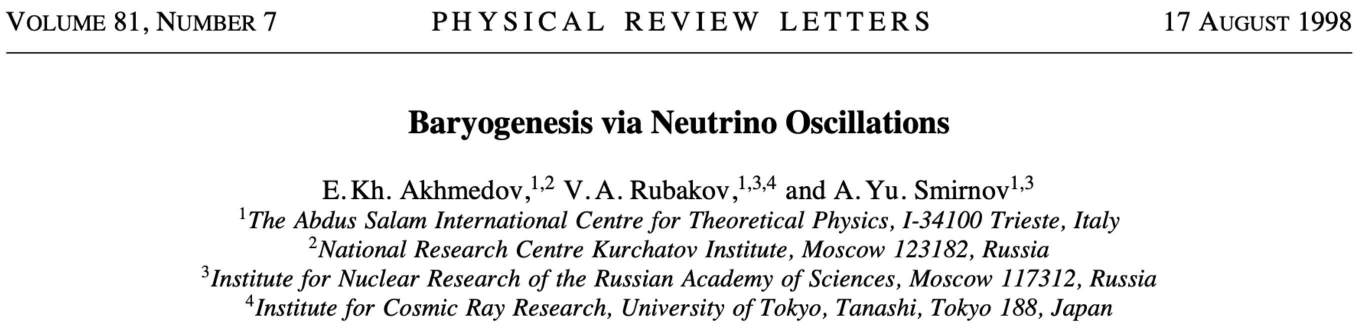
за: М. Шапошников, Ф. Безруков
против: В. Рубаков

На: 10 бутылок алкогольного напитка на выбор участника.

13.05.2005

Рубаков

Безруков



VOLUME 81, NUMBER 7 PHYSICAL REVIEW LETTERS 17 AUGUST 1998

Baryogenesis via Neutrino Oscillations

E. Kh. Akhmedov,[1,2] V. A. Rubakov,[1,3,4] and A. Yu. Smirnov[1,3]
[1]*The Abdus Salam International Centre for Theoretical Physics, I-34100 Trieste, Italy*
[2]*National Research Centre Kurchatov Institute, Moscow 123182, Russia*
[3]*Institute for Nuclear Research of the Russian Academy of Sciences, Moscow 117312, Russia*
[4]*Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo 188, Japan*

Constraining sterile neutrino dark matter with phase space density observations

D Gorbunov[1], A Khmelnitsky[1] and V Rubakov[1]

Published 24 October 2008 • IOP Publishing Ltd
Journal of Cosmology and Astroparticle Physics, Volume 2008, October 2008

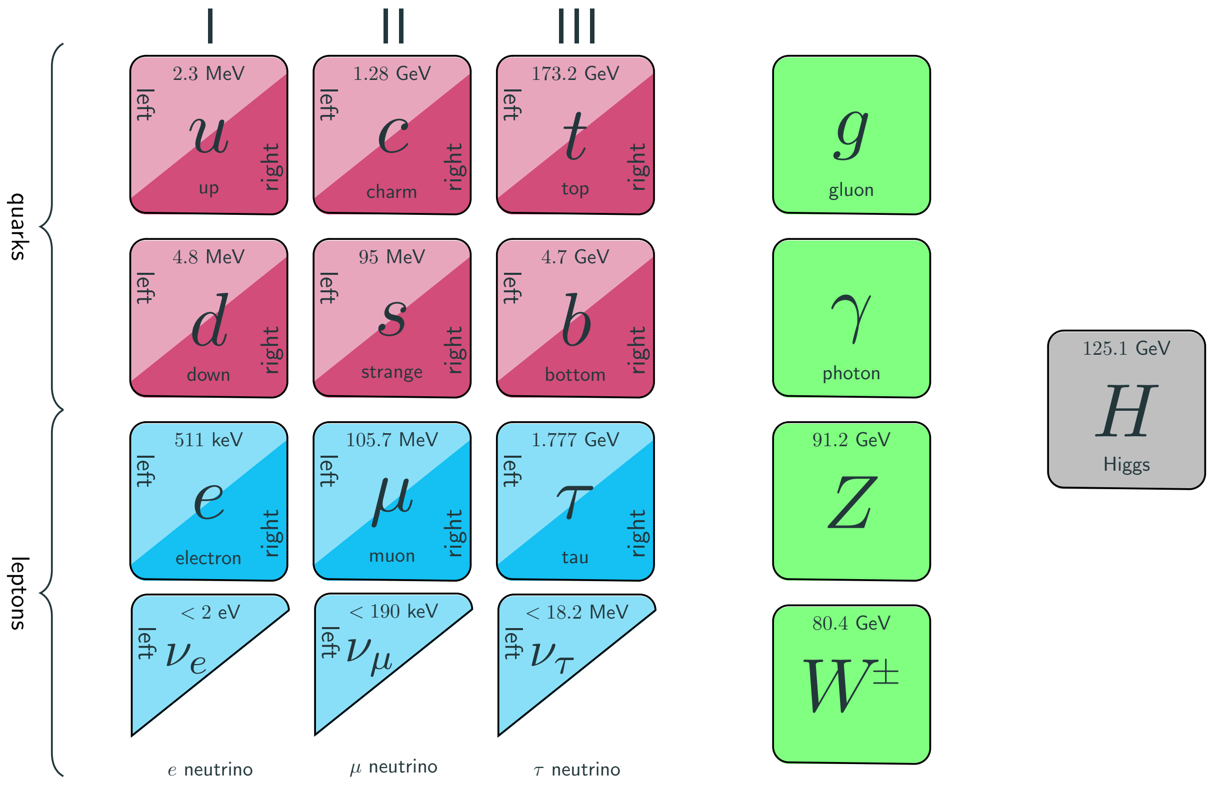
Yerevan 1982

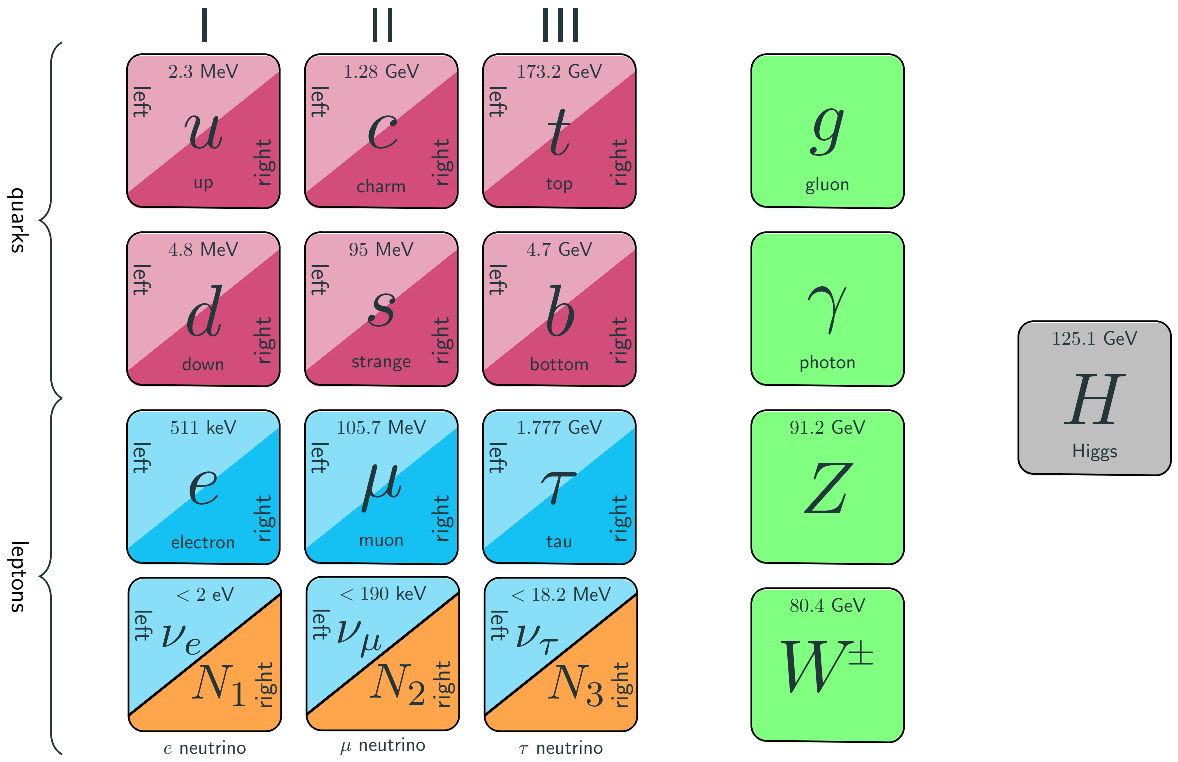
Outline

- νMSM as the minimal model of new physics
- Sterile neutrino Dark Matter
- QCD phase transition?
- Matter-antimatter separation
- Sterile neutrino Dark Matter at QCD phase transition
- Conclusions

νMSM as the 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

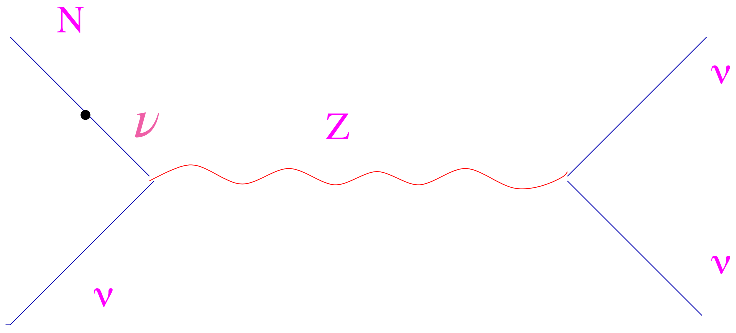
N_1- Dark Matter particle (Dodelson, Widrow; Shi, Fuller; Dolgov, Hansen;….)

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

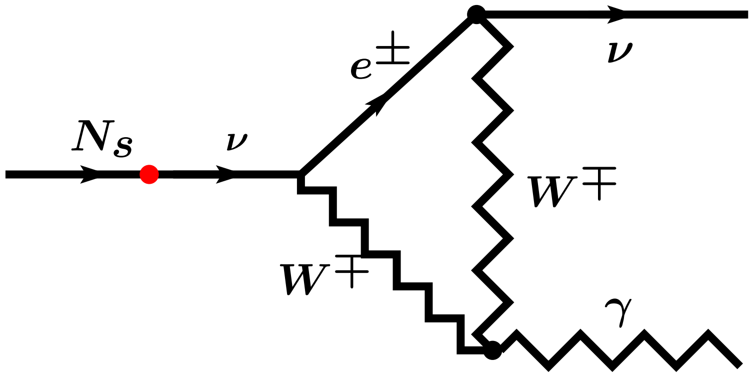
Constraints on DM sterile neutrino N₁

$$\theta = m_D/M_M$$

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

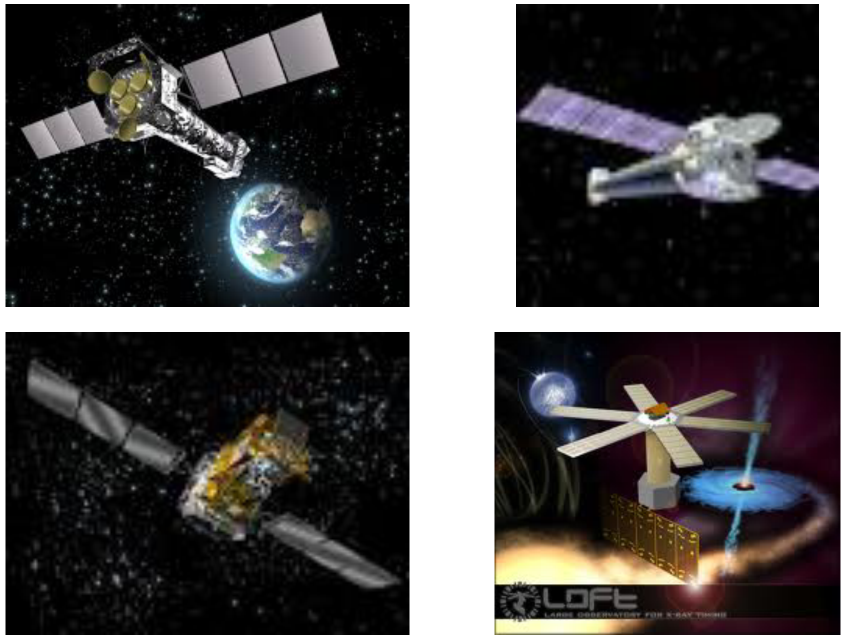


- **X-rays.** N₁ decays radiatively, $N_1 \to \gamma\nu$, producing a narrow line $E_\gamma = M_1/2$ which can be detected by X-ray telescopes (such as Chandra or XMM-Newton).

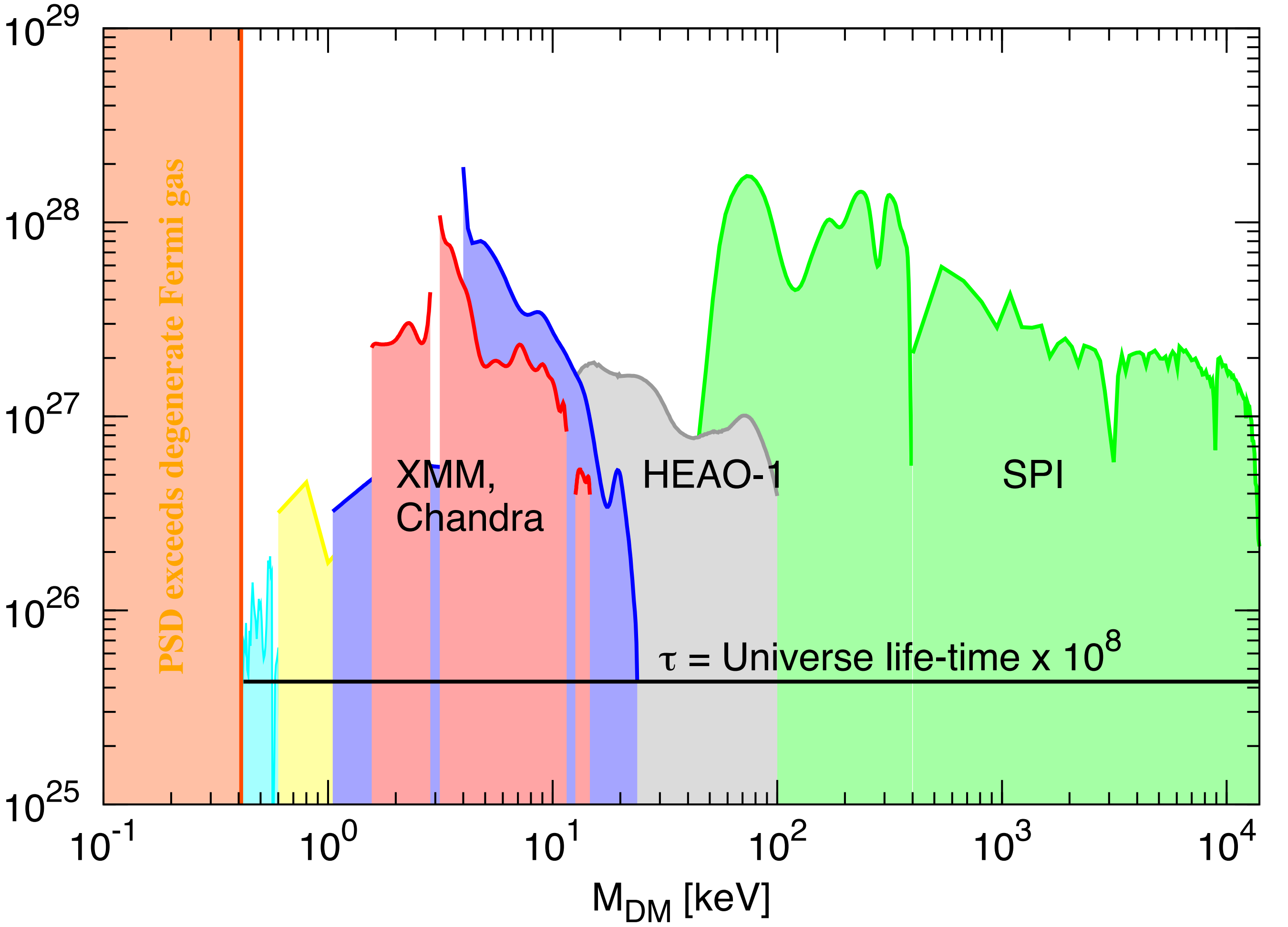


$$\Gamma_{\rm rad} = \frac{9\alpha G_F^2}{256 \cdot 4\pi^4}\ \sin^2(2\theta) M_s^5$$

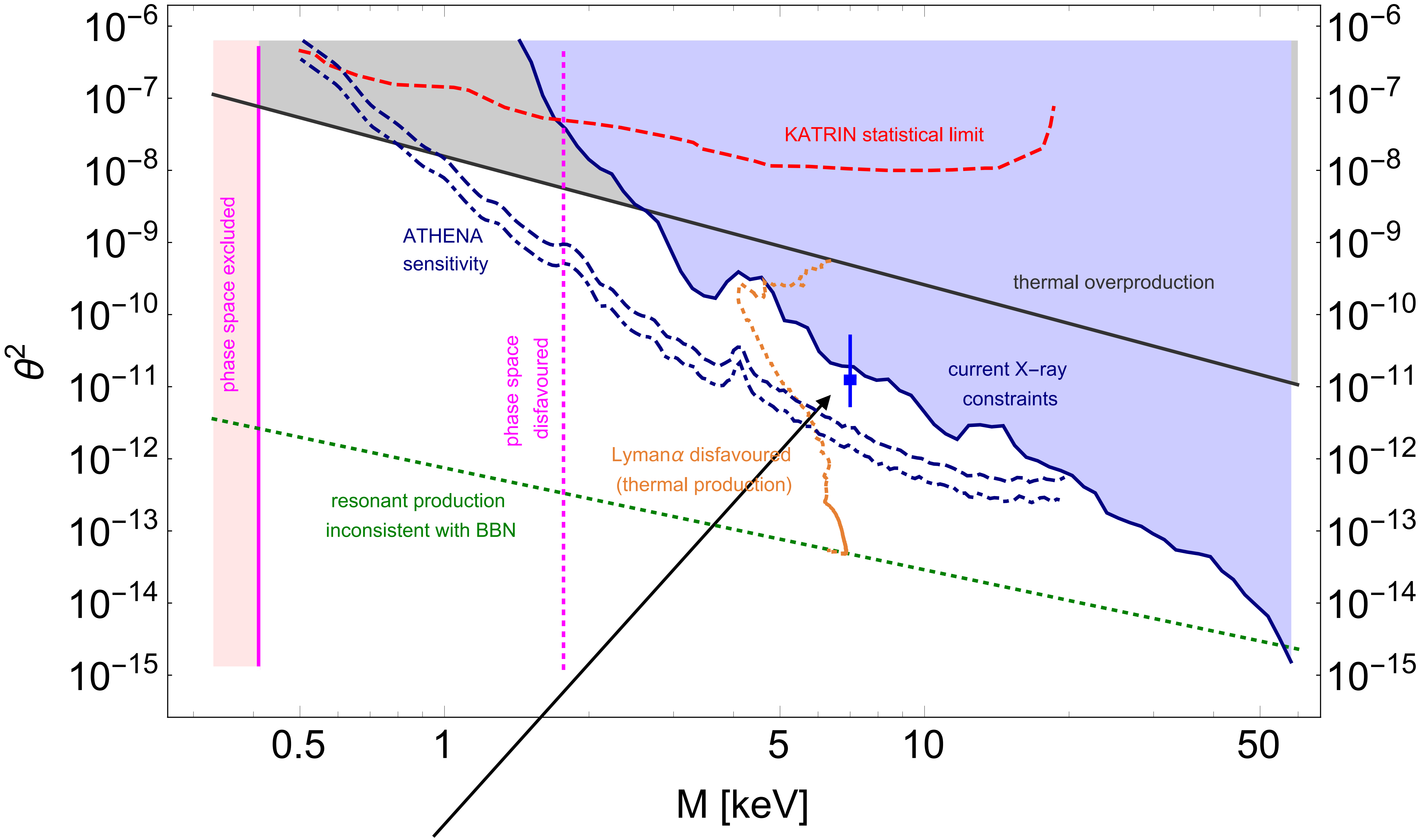
Lifetime constraints



Available X-ray satellites:
Suzaku, XMM-Newton, Chandra,
INTEGRAL, NuStar

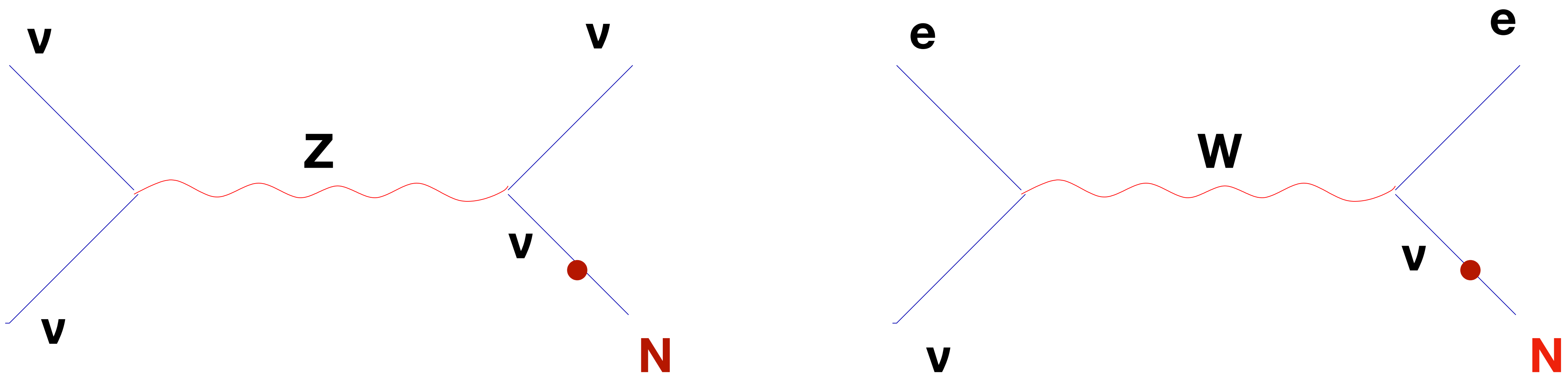


X-ray and structure formation constraints



Possible detection (?), still controversial, to be resolved in 2023-2024
Bulbul et al; Boyarsky et al

DM sterile neutrino production at low temperatures

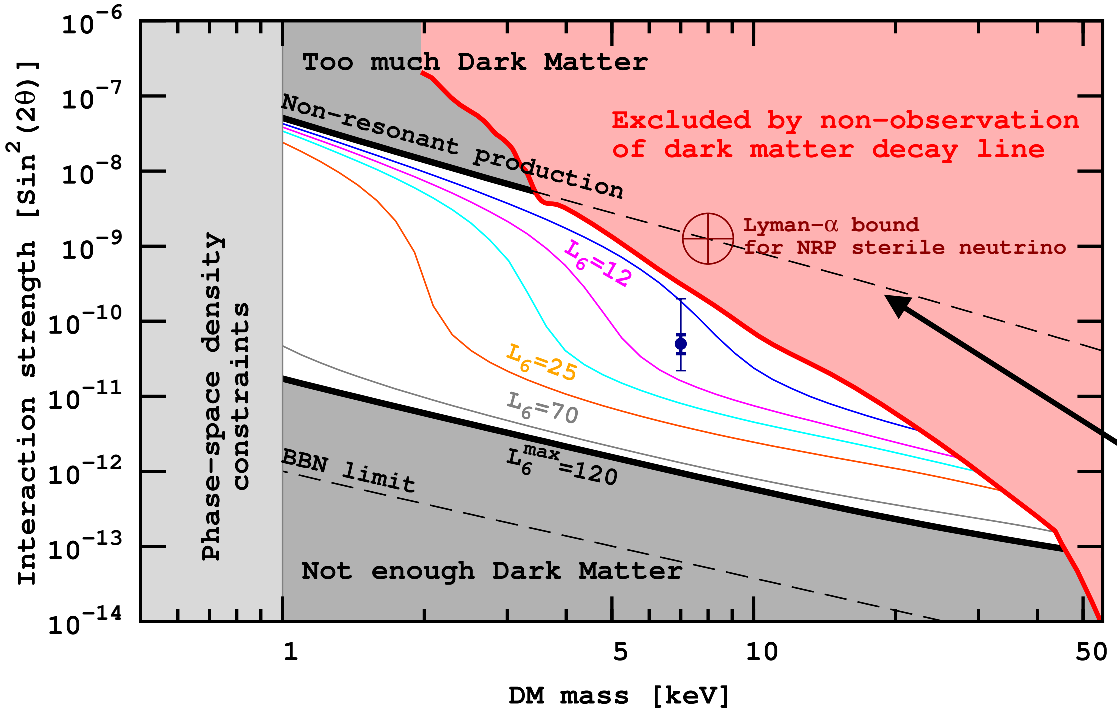


The temperature of production of DM sterile neutrinos: the QCD epoch

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

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

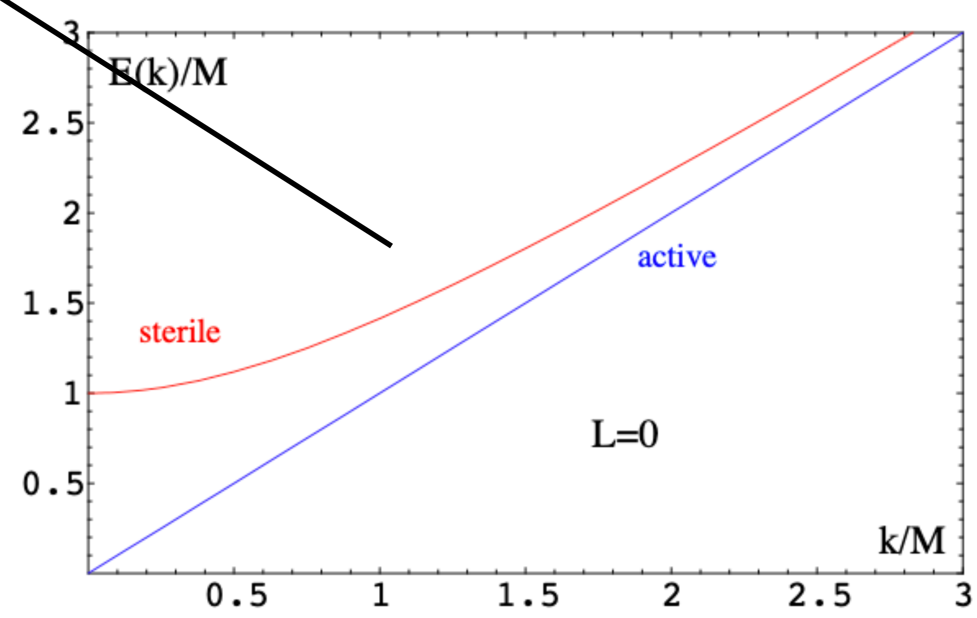
Non-resonant production



Relation between the lifetime and abundance.

Momentum of sterile neutrino $\simeq 0.85 p_T$

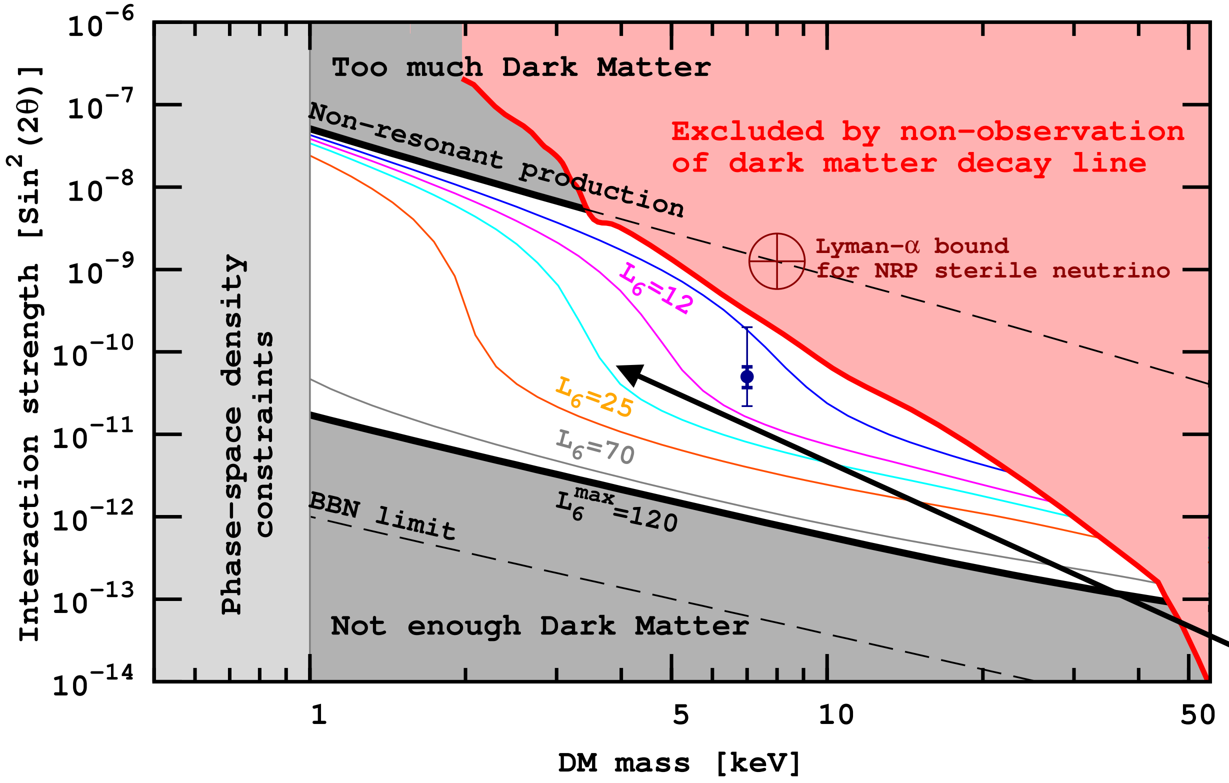
DW mechanism



Transitions $\nu \longrightarrow N_1$

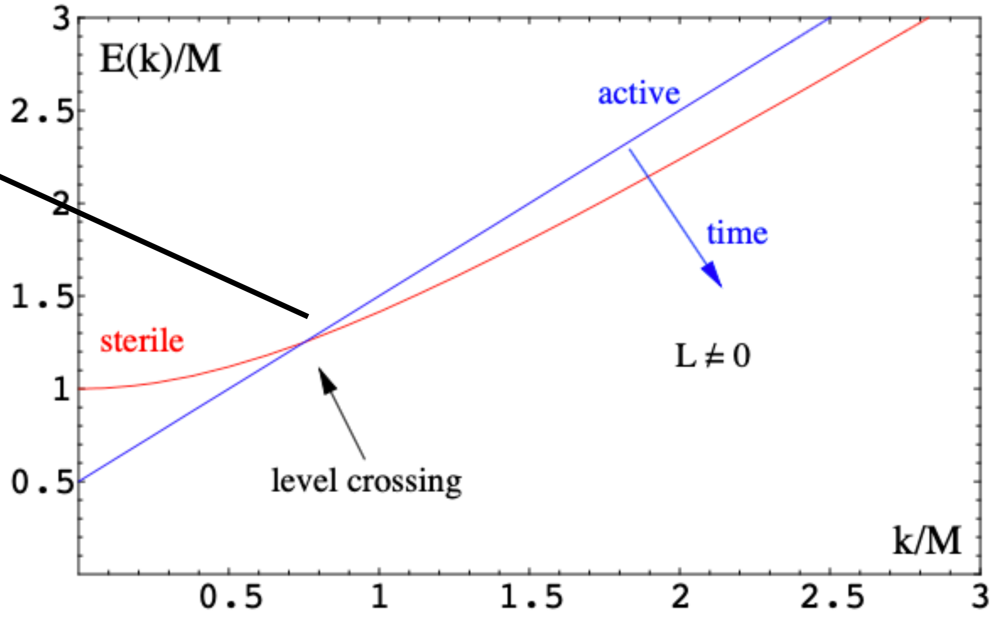
Dodelson-Widrow

Resonant production



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

SF mechanism



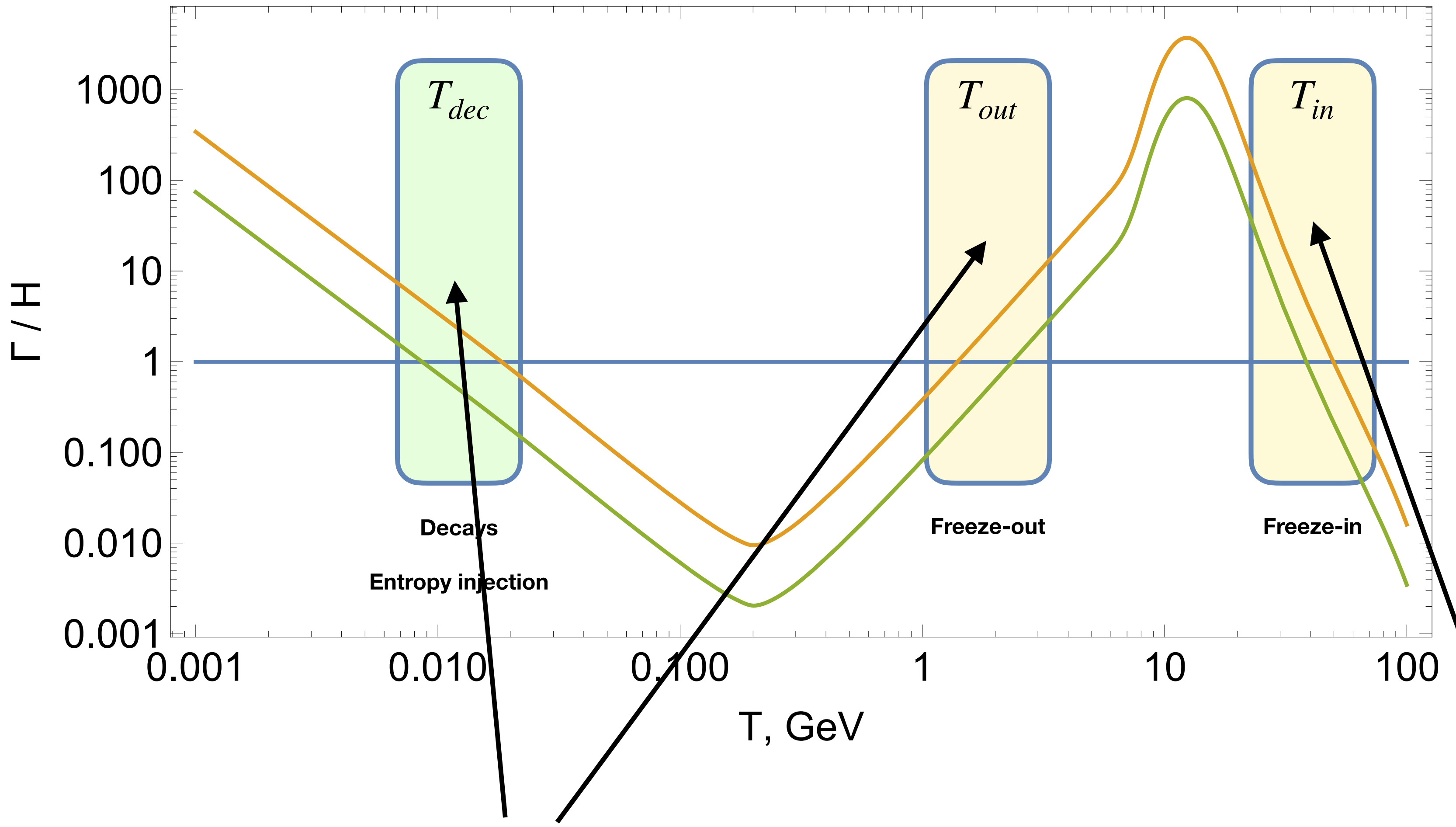
Relation between the lifetime abundance, and lepton asymmetry.

Momentum of sterile neutrino $\simeq 0.3p_T$

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

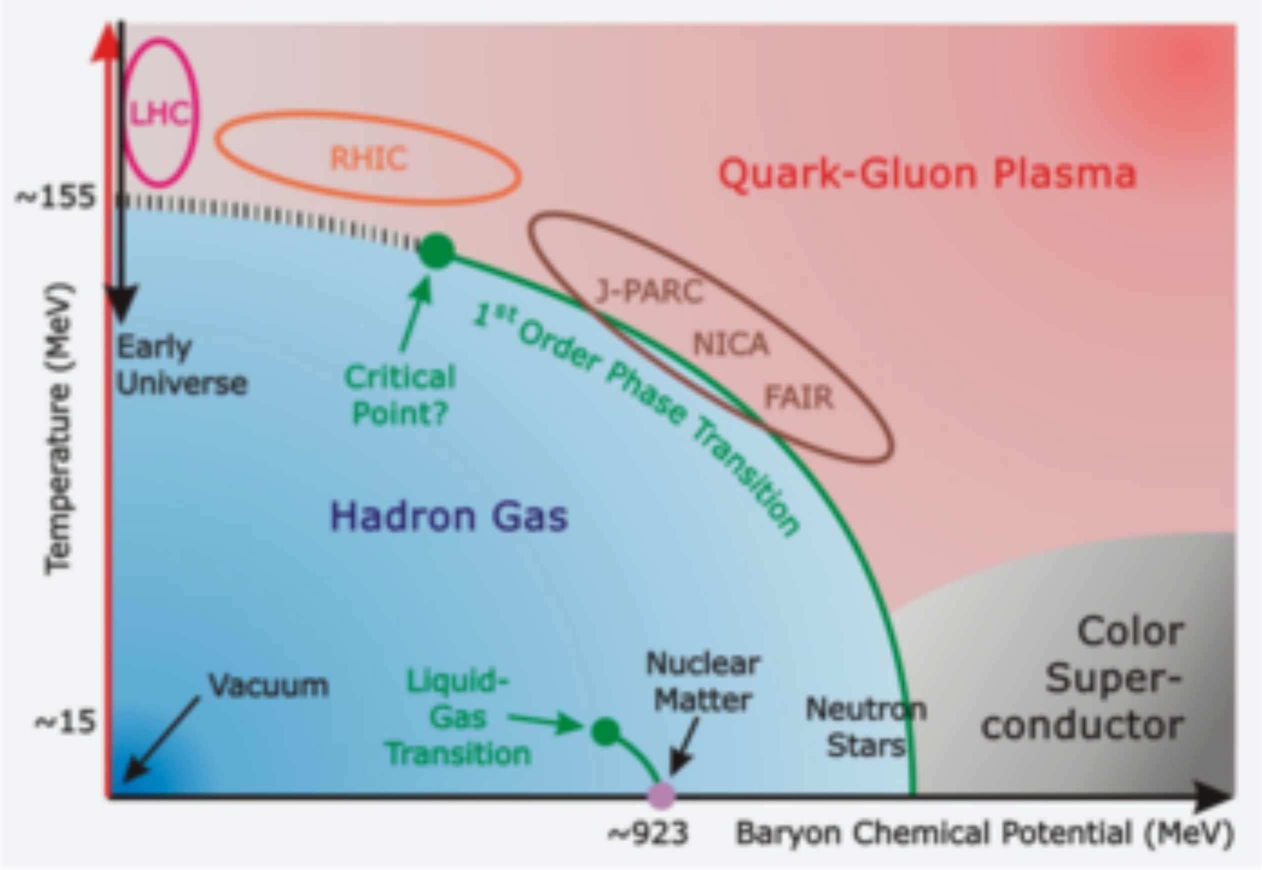
QCD phase transition?

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

No order parameter which can distinguish the hadron and quark gluon plasma states

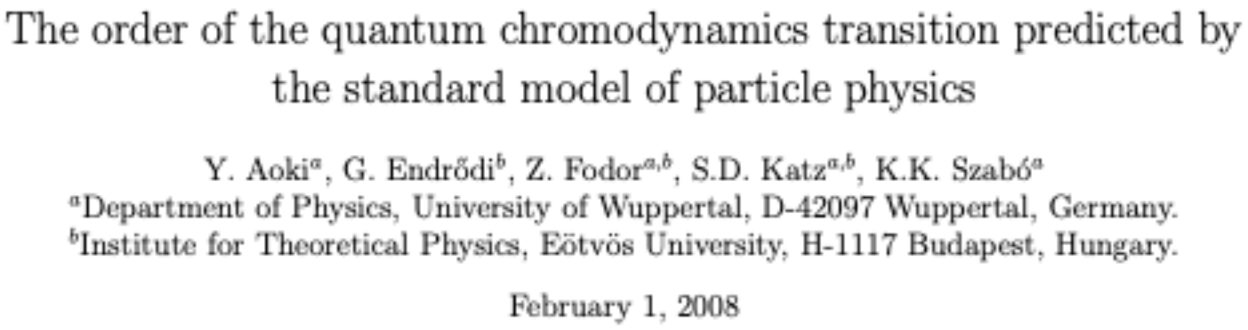
Possibilities:

- First order phase transition
- Second order phase transition
- No phase transition



Lattice evidence

QCD is a strongly coupled theory: the evidence for the absence of the QCD PT comes from lattice simulations, which are extremely challenging because of light quarks u, d and s. Large volumes and small lattice spacings are very demanding.

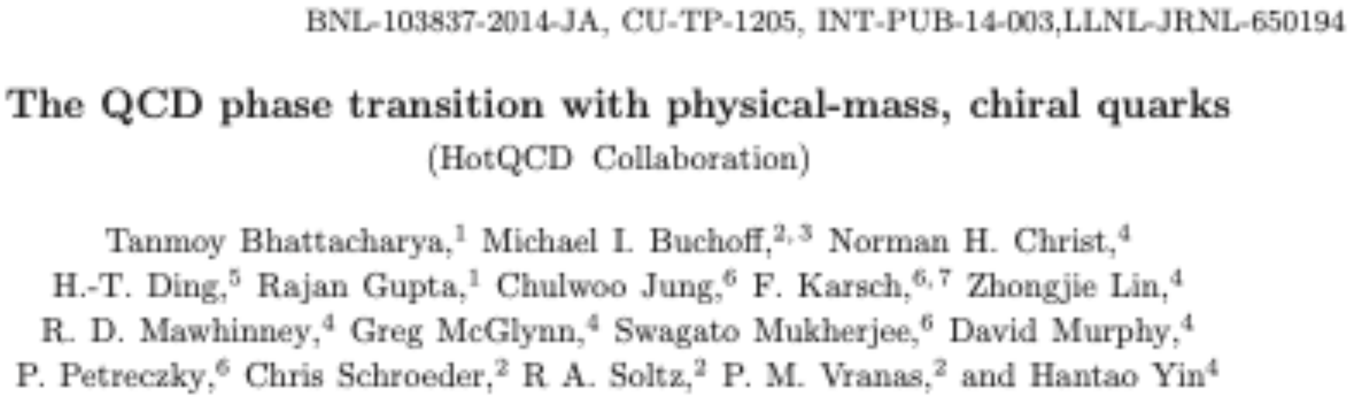


The order of the quantum chromodynamics transition predicted by the standard model of particle physics

Y. Aoki[a], G. Endrődi[b], Z. Fodor[a,b], S.D. Katz[a,b], K.K. Szabó[a]
[a]Department of Physics, University of Wuppertal, D-42097 Wuppertal, Germany.
[b]Institute for Theoretical Physics, Eötvös University, H-1117 Budapest, Hungary.

February 1, 2008

Staggered fermions,
$LT_c = 3,4,5; N_t = 4,6,8,10$



BNL-103837-2014-JA, CU-TP-1205, INT-PUB-14-003,LLNL-JRNL-650194

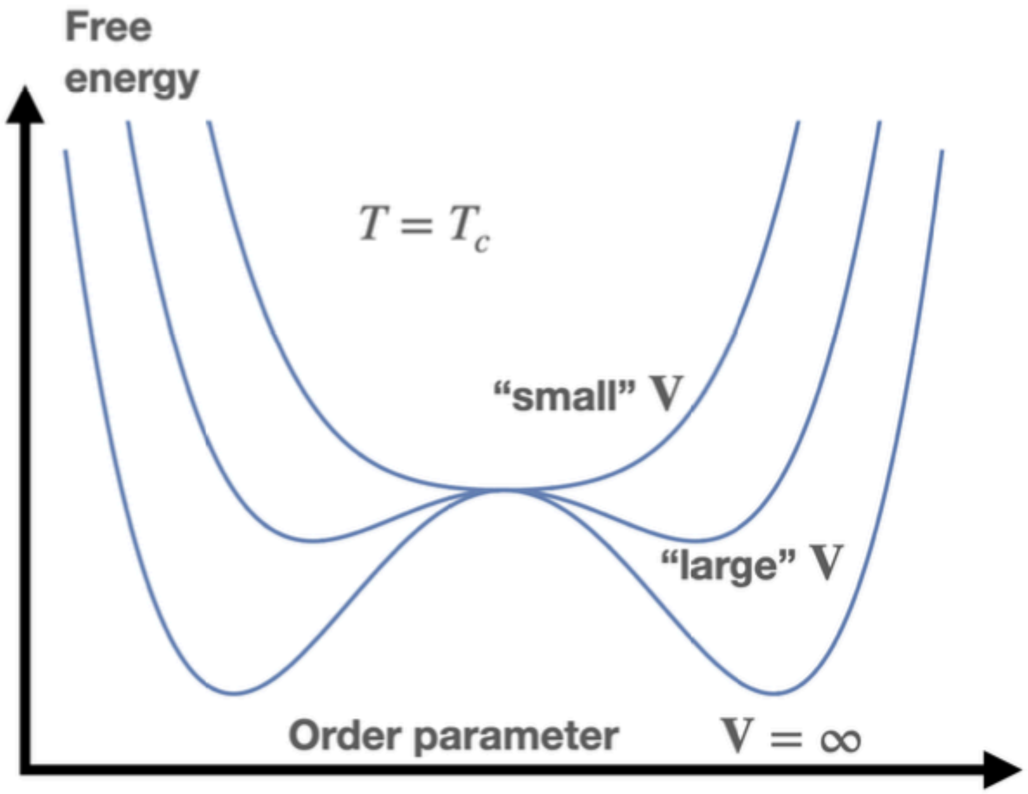
The QCD phase transition with physical-mass, chiral quarks
(HotQCD Collaboration)

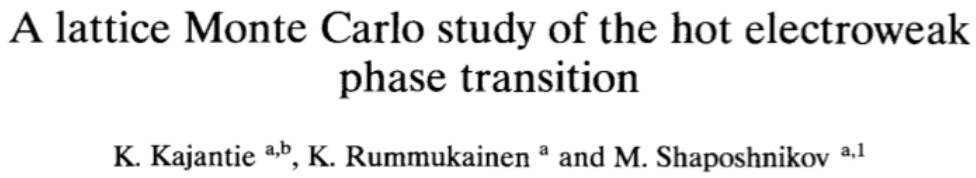
Tanmoy Bhattacharya,[1] Michael I. Buchoff,[2,3] Norman H. Christ,[4]
H.-T. Ding,[5] Rajan Gupta,[1] Chulwoo Jung,[6] F. Karsch,[6,7] Zhongjie Lin,[4]
R. D. Mawhinney,[4] Greg McGlynn,[4] Swagato Mukherjee,[6] David Murphy,[4]
P. Petreczky,[6] Chris Schroeder,[2] R A. Soltz,[2] P. M. Vranas,[2] and Hantao Yin[4]

Domain wall fermions,
$L = 4,\ 11\ \text{fm}; N_t = 8$

Finite volume and spacing effects

First order phase transition may disappear if the volume of the system is too small. $LT_c = 5$ - is it a large number?




A lattice Monte Carlo study of the hot electroweak phase transition

K. Kajantie [a,b], K. Rummukainen [a] and M. Shaposhnikov [a,1]

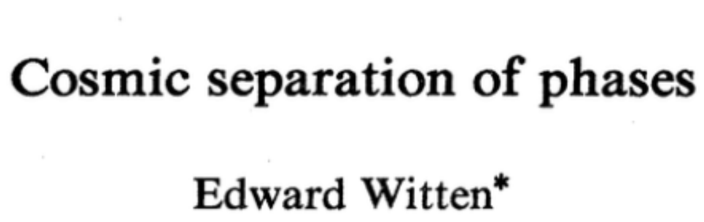
Our experience with the electroweak phase transition: we need $Lm_W > 5$ to see first order EW PT.

It is alarming that most of simulations of the QCD phase transition were done with $Lm_\pi < 5$. Number of protons in volume $Lm_\pi = 5$: 0.36, number of Λ hyperons: 0.14

To get 2 Λ in the lattice volume we need $LT_c = 12$, and lattices with $N \simeq 128$.

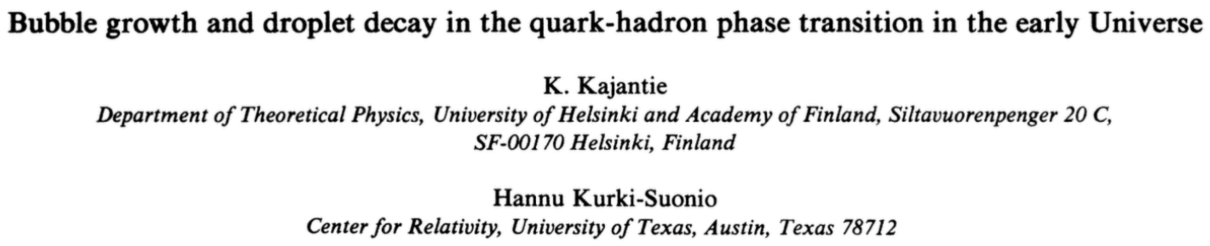
Perhaps, the conclusion that there is no QCD PT is premature.
I will assume that this is indeed the case.

Cosmic separation of phases



Cosmic separation of phases

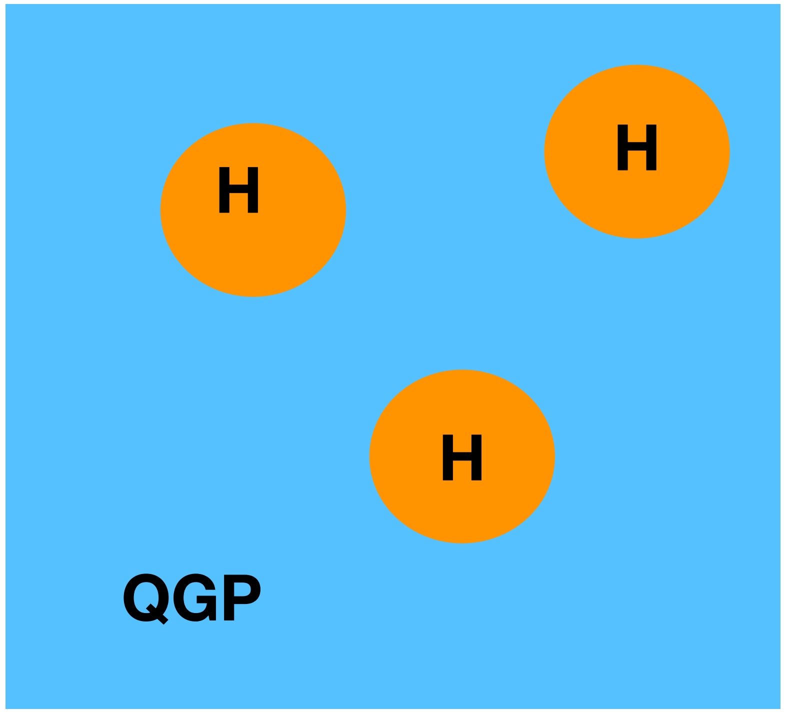
Edward Witten*



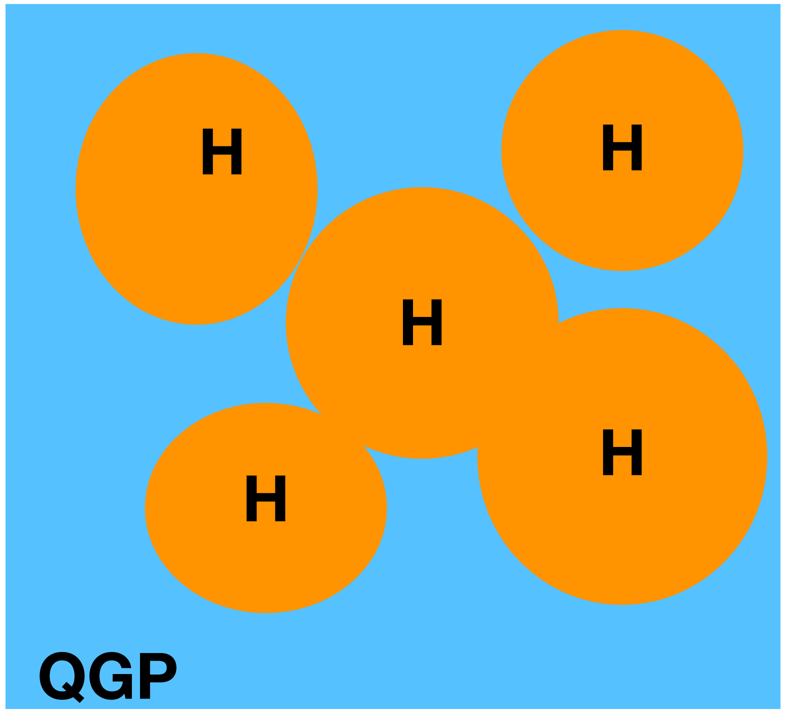
Bubble growth and droplet decay in the quark-hadron phase transition in the early Universe

K. Kajantie
Department of Theoretical Physics, University of Helsinki and Academy of Finland, Siltavuorenpenger 20 C, SF-00170 Helsinki, Finland

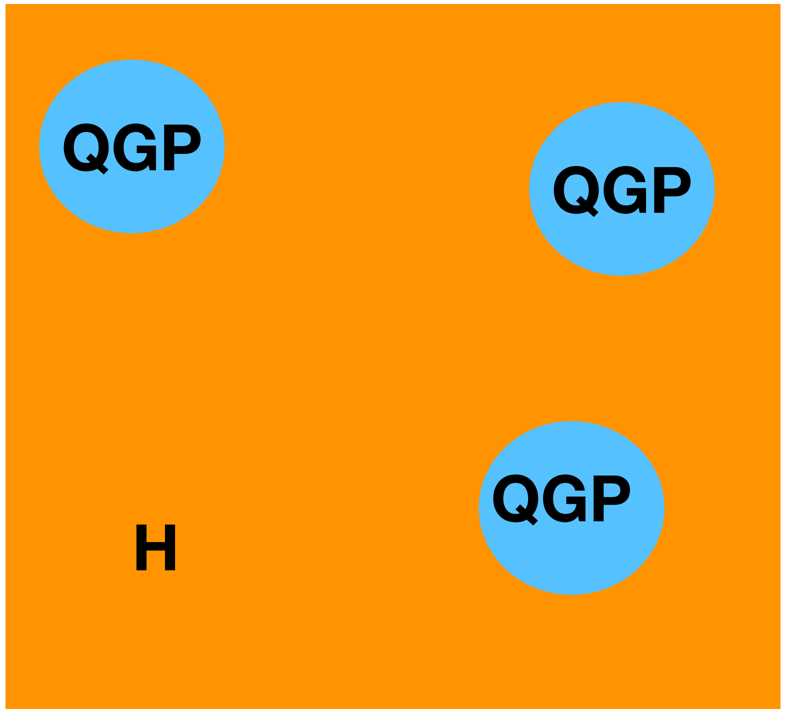
Hannu Kurki-Suonio
Center for Relativity, University of Texas, Austin, Texas 78712



hadronic
bubbles



percolation

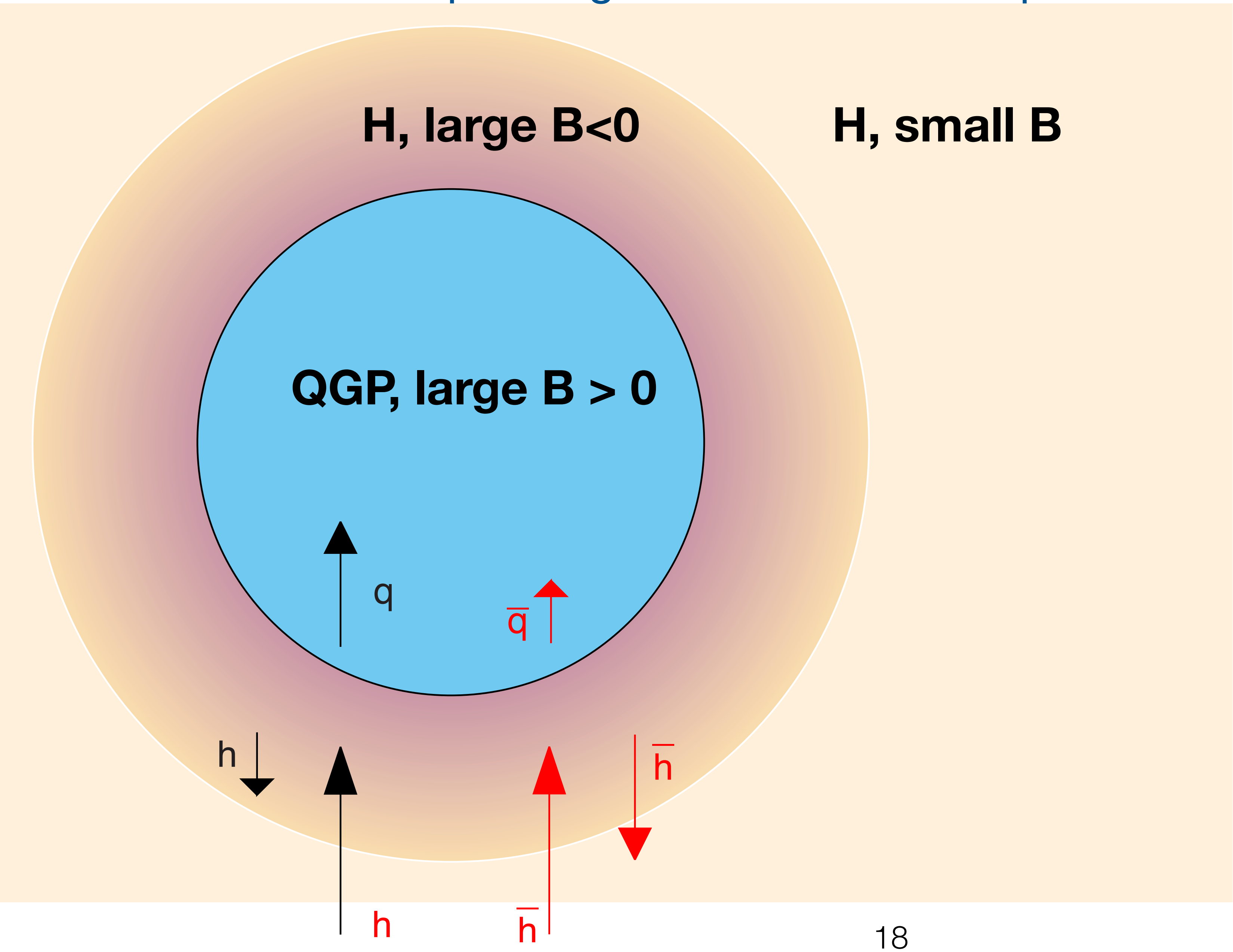


QGP droplets

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

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

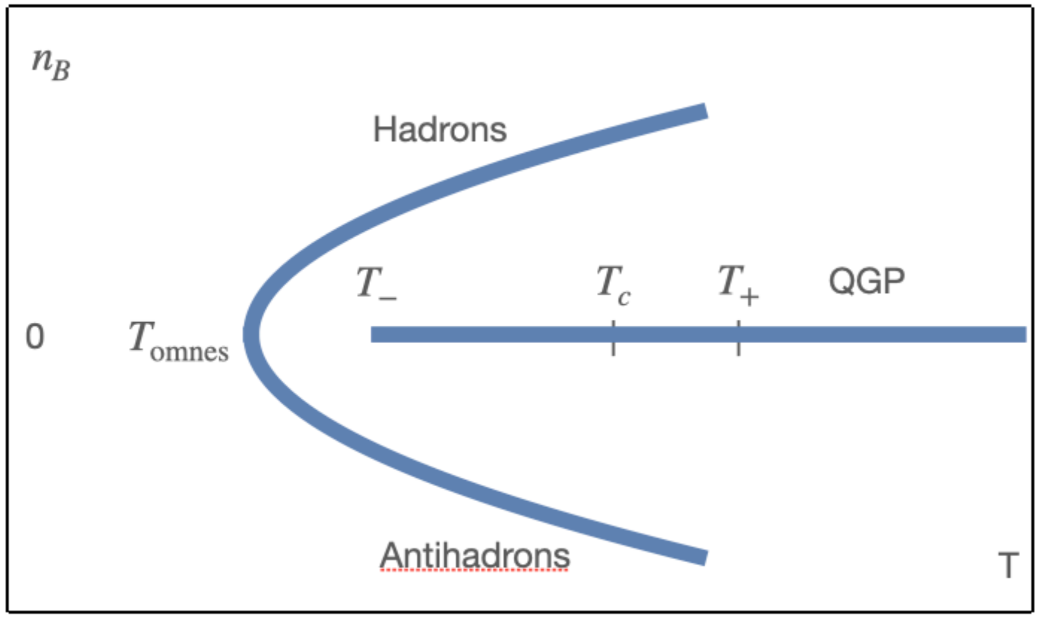
depends on reflection amplitude

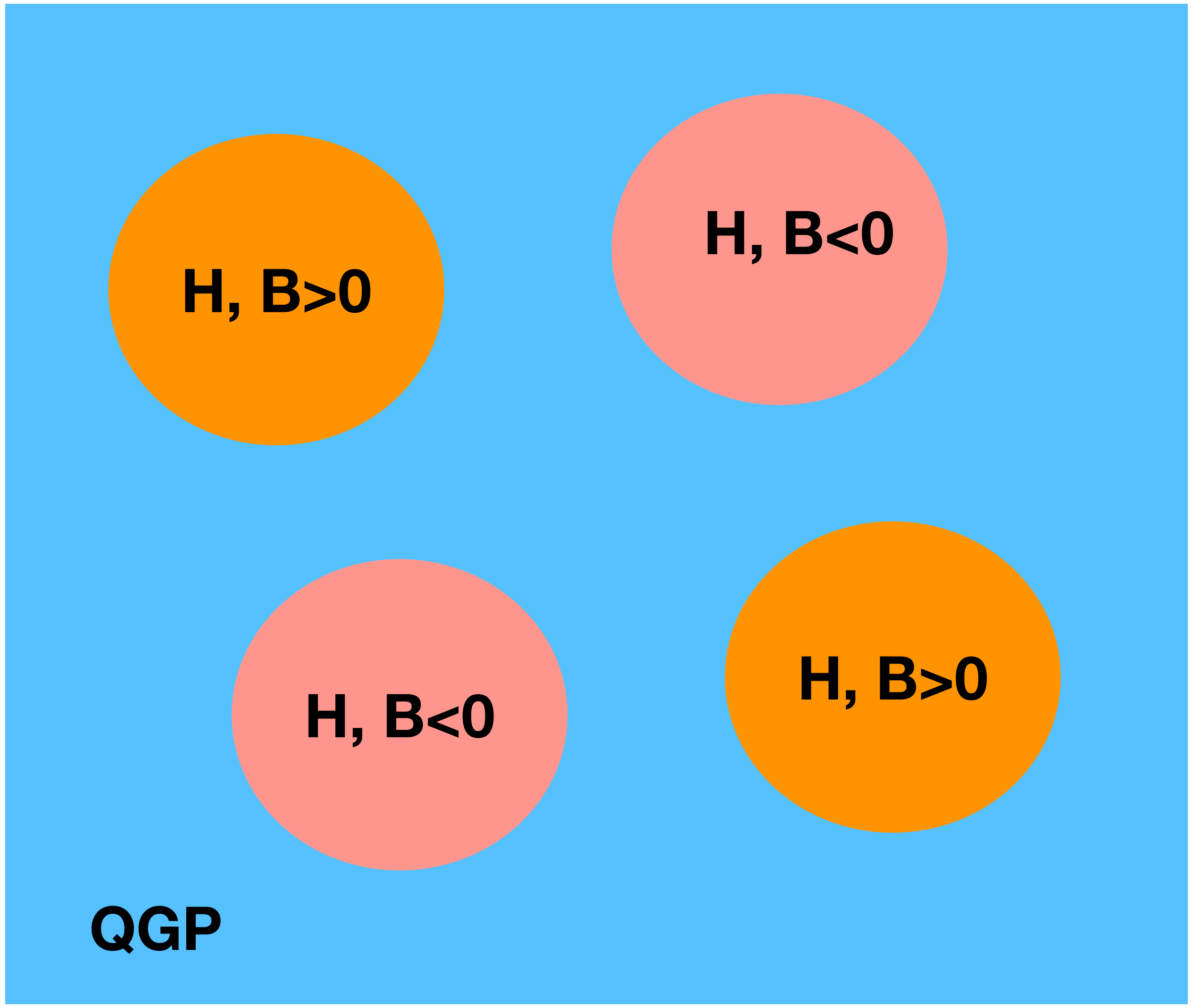
baryon density

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:

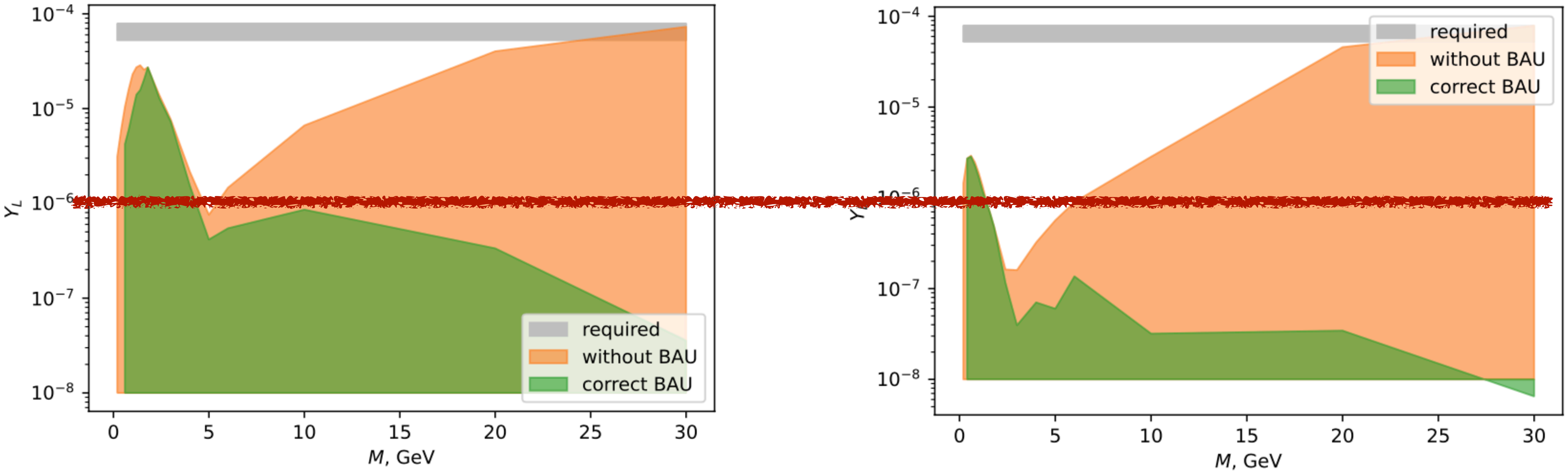
- Omnes PT - efficient production of DM even for DM sterile neutrino with mixing angles θ^2 below 5×10^{-11} (indicated by X-rays).
- Spectrum of produced sterile neutrinos may be considerably cooler than that in DW or SF mechanisms, making N_1 essentially cold DM candidate with momentum $\simeq 0.1 p_T$.
- 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 νMSM 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.

How much time it will take to resolve our bet with Valery?

Historical development of the SM: gradual adaptation of electroweak theory to experimental data during the past 50 years.

- Bosonic sector of the electroweak model remains intact from 1967, with the discoveries of the W and Z bosons in 1983 and the Higgs boson in 2012.
- The fermionic sector evolved from one to two and finally to three generations, revealing the remarkable symmetry between quarks and leptons.
- It took about 20 years to find all the quarks and leptons of the third generation.

Optimistic answer:

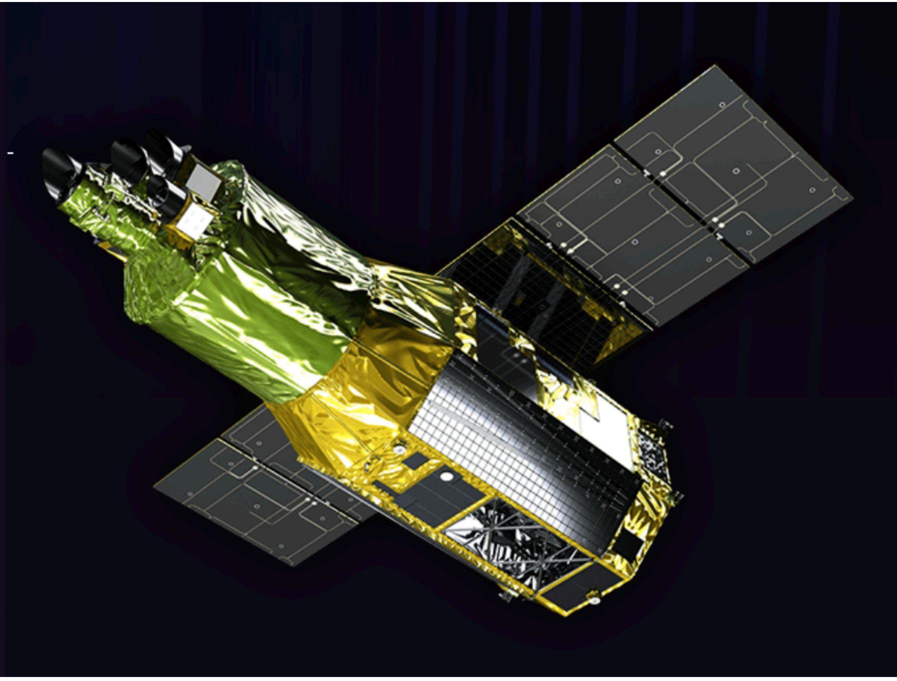
N_1 at XRISM in 2023 (?)

$N_{2,3}$ at SHiP @ CERN in 2031 (?)

XRISM X-Ray Imaging and Spectroscopy Mission

SHiP Search for Hidden Particles

XRISM X-Ray Imaging and Spectroscopy Mission



The XRISM payload consists of two instruments:

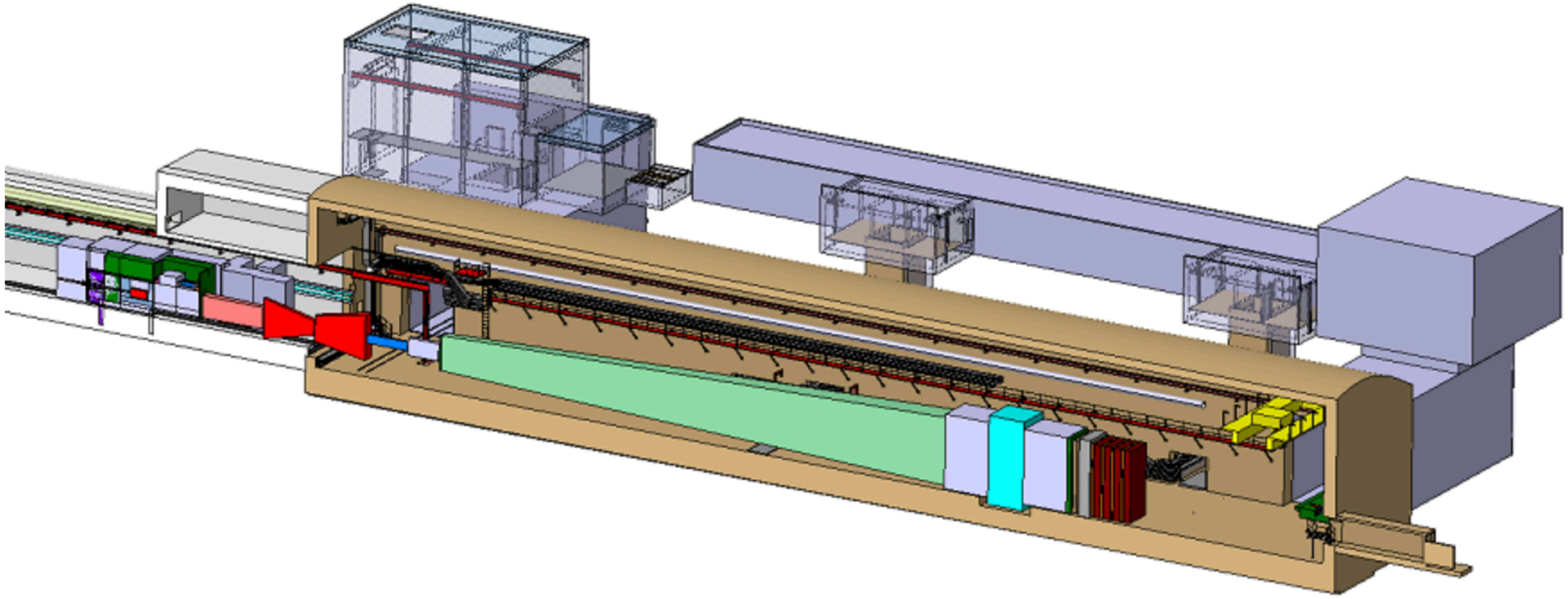
- Resolve, a soft X-ray spectrometer, which combines a lightweight X-ray Mirror Assembly (XMA) paired with an X-ray calorimeter spectrometer, and provides non-dispersive 5-7 eV energy resolution in the 0.3-12 keV bandpass with a field of view of about 3 arcmin.
- Xtend, a soft X-ray imager, is an array 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!

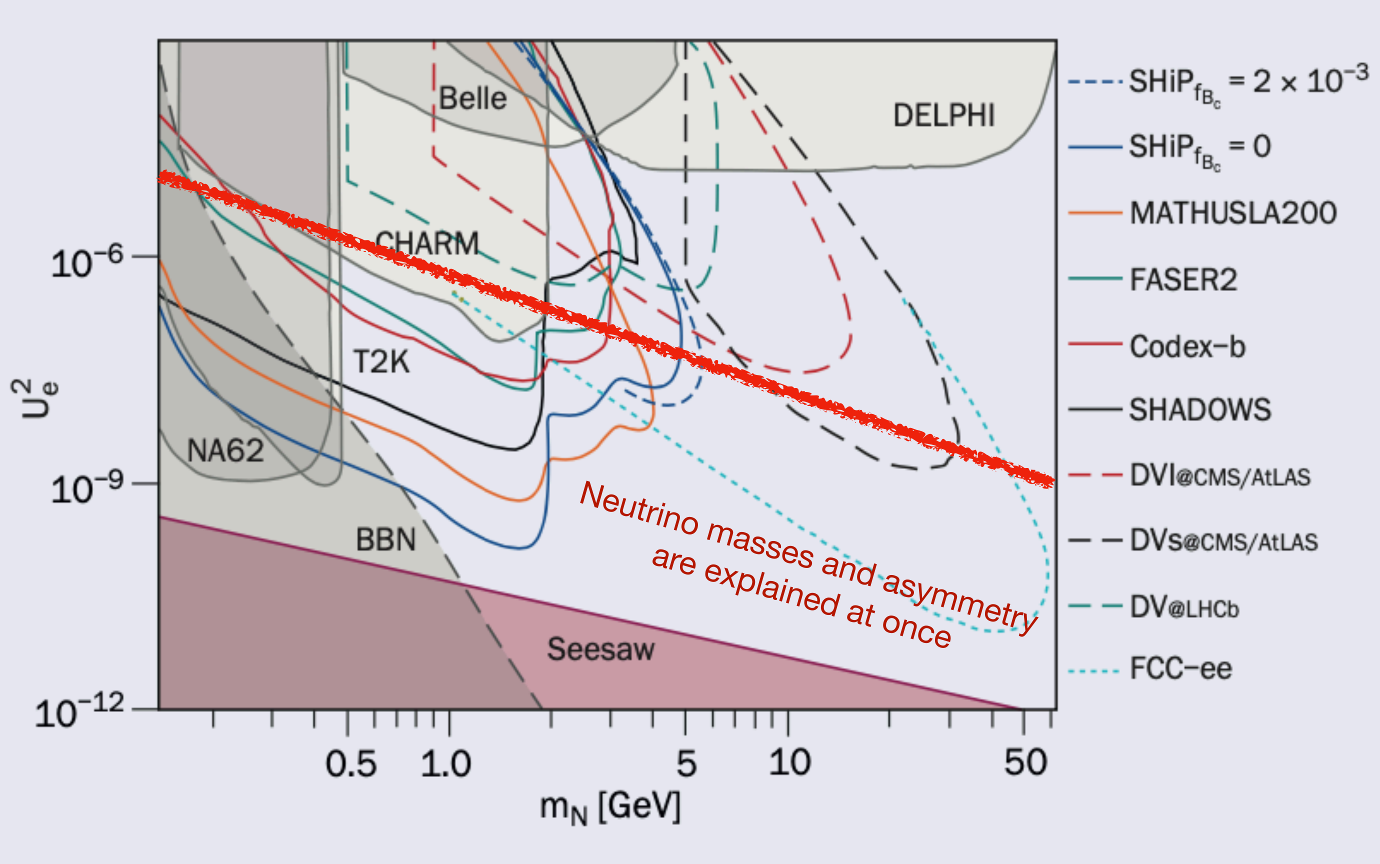
XRISM was launched by the H-IIA rocket from the Tanegashima Space Center at 8:42 a.m on September 7, 2023 JST, (23:42 on September 6, 2023 UT). Photo Credit: L. Hartz

SHiP

Search for Hidden Particles



Projection of bounds on HNLs



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

A decision at CERN is expected to be taken before the end of 2023

Back up slides

Most general renormalisable see-saw Lagrangian with Majorana neutrinos:

Standard Model

Higgs field

HNL Majorana mass

$$\mathscr{L} = \mathscr{L}_{SM} + i\,\bar{N}_I \gamma^\mu \partial_\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I \tilde{H} - \frac{M_{IJ}}{2} \bar{N}_I^c N_J + h.c.$$

HNL kinetic term

HNL Yukawa couplings,
leading to Dirac mass

Neutrino masses and Yukawa couplings from Neutrino physics

$$Y^2 = Trace[F^\dagger F]$$

Scale F as x, and M as x^2, low energy neutrino physics is not changed!

$$m_\nu \propto \frac{F^2 v^2}{M}$$