Cosmological Connections

Fundamental Symmetries, Neutrinos, Neutrons, and related Nuclear Astrophysics

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Fundamental issues in ***Neutrino Physics*** and ***BSM Physics***

Neutrino-less Double Beta Decay - *lepton number violation, "neutrino mass"*

EDM – *beyond standard model physics / early universe leptogenesis/baryogenesis*

Sterile neutrino searches

Precision neutron lifetime/neutron physics (see paper for this meeting)

Etc.

Complementary to core issues
and objectives in cosmology/astrophysics

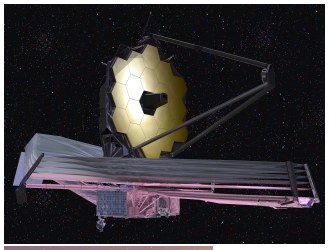
Neutrino Mass, Lepton Number Violation, Weak Interactions, BSM-Physics, and the Nature of Dark Matter

Compact Object Physics:
Supernovae, NS-NS/BH mergers,
Origin of the Elements with A > 7

Early Universe & Cosmology:
Origin of baryon/lepton numbers,
Origin and Evolution of Structure,
Big Bang Nucleosynthesis/chemical evolution

Huge World-Wide Investment in Observational Infrastructure:

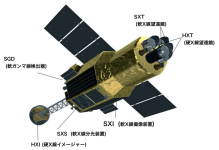
thirty meter class **optical/IR telescopes**:
TMT, GMT, ELT, etc. Plus spaced-based: **JWST**



Cosmic Microwave Background (CMB):
Future polarization experiments:
PolarBear; SPT; ACT; etc.
Space-based: "CMB-Pol"
Radio: *ALMA;* **21-cm arrays** *e.g.,* **SKA**

Gravitational Radiation astronomy:
LIGO, VIRGO, GEO600, etc.
CMB

X-Ray/Gamma-Ray
Astro-H; Fermi, etc.



VERY EXCITING FUTURE . . .

. . . because of the advent of . . .

(1) comprehensive cosmic microwave background (CMB) observations (*e.g.*, Planck, PolarBear, ACT, SPT, CMBPol) (e.g., high precision baryon number and cosmological parameter measurements, N_{eff}, ^{4}He, ν mass limits)

(2) 10/30-meter class telescopes, adaptive optics, and orbiting observatories (e.g., precision determinations of deuterium abundance, dark energy/matter content, structure history etc.)

(3) Laboratory neutrino mass/mixing measurements

is setting up a nearly over-determined situation where ***new*** Beyond Standard Model **neutrino physics** likely ***must*** show itself!

My main point about the exciting developments . . .

Five developments which will set up sensitivity to new (dark sector) sector physics:

Currently degeneracy between these; broken by phasing of acoustic peaks, E-mode polarization?

$\Rightarrow$ CMB-derived precision baryon-to-photon ratio (uncertainty $\leq 1\%$)

$\Rightarrow$ CMB-inferred primordial helium abundance (uncertainty $\sim 2\,\%$)

$\Rightarrow$ Precision primordial deuterium determination (uncertainty $\leq 2\%$) → 30-m class telescopes Cooke *et al.* (2013)

$\Rightarrow$ CMB "precision" $N_{\rm eff}$ measurement (uncertainty $\sim 2\%$)

$\Rightarrow$ Measurement/tight constraints on the "sum of the light neutrino masses"

push limits on $\sum m_\nu$ down *below* known masses;
aided by experimental developments:
$\Rightarrow$ measured hierarchy (LBNE?; Reactor Expt.s?; SN?);
$\Rightarrow$ measured mass.

This allows CMB observatories to become CνB observatories!

Moreover, the CνB **number density/energy spectrum** encodes the physics of the early universe, and is especially sensitive to issues of entropy generation/dilution, particle decay, sterile neutrinos, low re-heat inflation, *etc.*

baryon number of universe $\longrightarrow$ $$\eta \equiv \frac{n_{\rm b} - n_{\bar{\rm b}}}{n_\gamma}$$

From CMB acoustic peaks, and/or observationally-inferred primordial D/H:

$$\eta = 6.11 \times 10^{-10}$$

three lepton numbers $\longrightarrow$

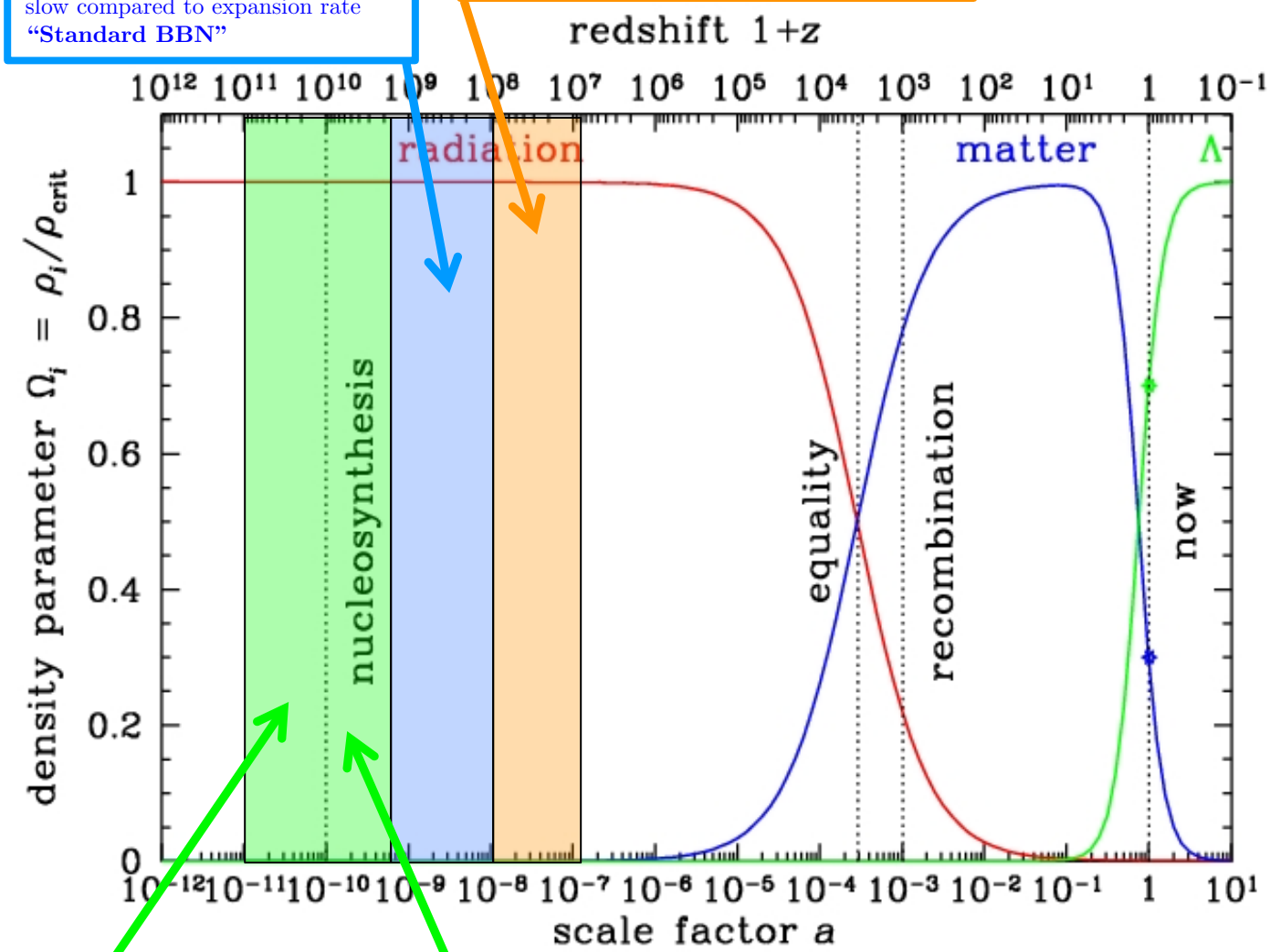
$$\begin{cases} L_{\nu_e} \approx \dfrac{n_{\nu_e} - n_{\bar{\nu}_e}}{n_\gamma} \\ L_{\nu_\mu} = \dfrac{n_{\nu_\mu} - n_{\bar{\nu}_\mu}}{n_\gamma} \\ L_{\nu_\tau} = \dfrac{n_{\nu_\tau} - n_{\bar{\nu}_\tau}}{n_\gamma} \end{cases}$$

From observationally-inferred ^{4}He and large scale structure and using *collective (synchronized) active-active neutrino oscillations* (Abazajian, Beacom, Bell 03; Dolgov et al. 03):

$$|L_{\nu_{\mu,\tau}}| \sim L_{\nu_e} < 0.15$$

Freeze-Out from
Nuclear Statistical Equilibrium:
thermonuclear reactions become
slow compared to expansion rate
"Standard BBN"

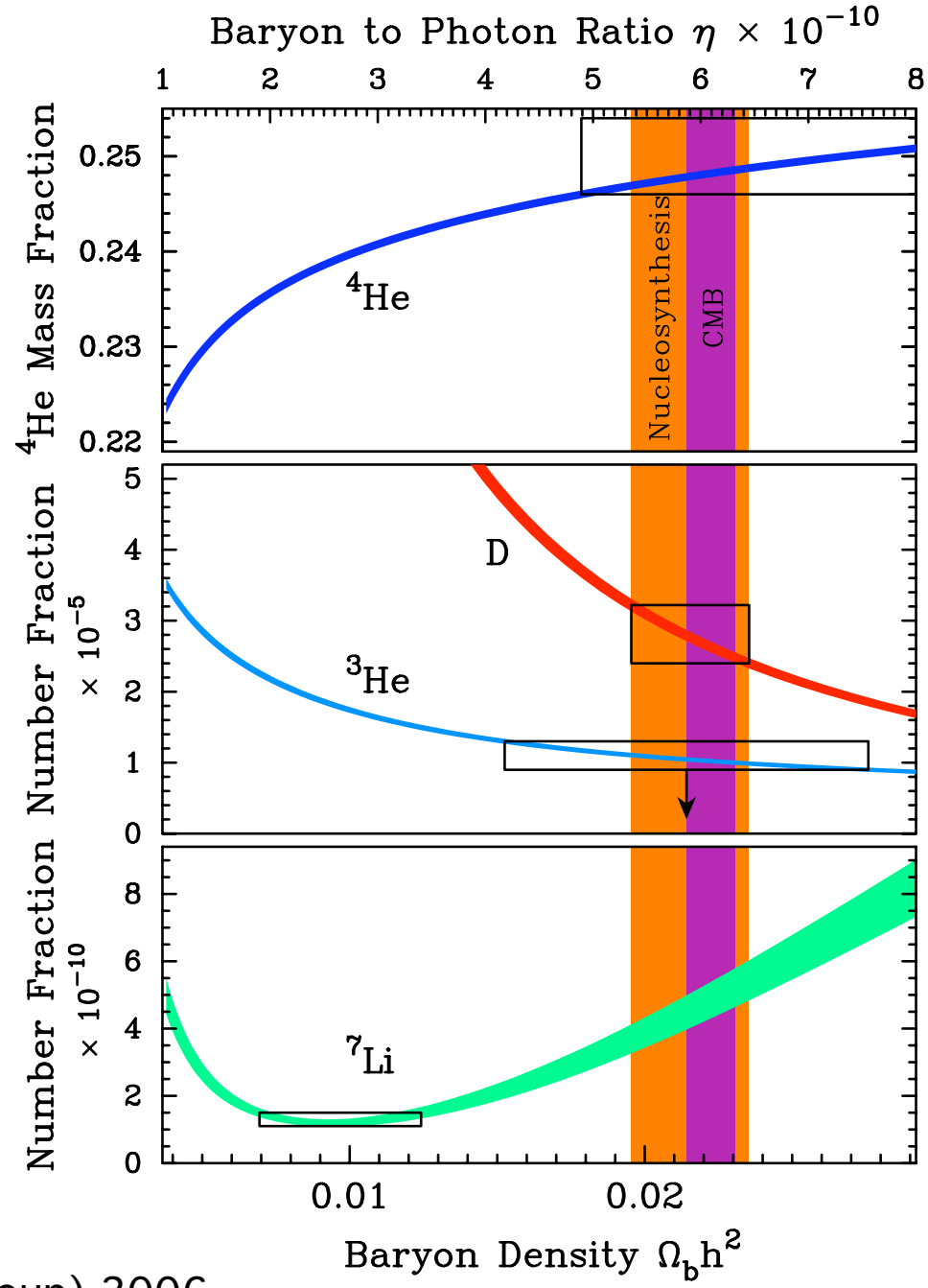
$T < 10\,\mathrm{keV}$ **particle decay-induced cascade nucleosynthesis?**



Weak Decoupling
neutrinos drop out of thermal equilibrium,
e.g., $\nu + e \rightleftarrows e + \nu$
becomes slow compared to expansion rate.

Weak Freeze-Out $T \sim 0.7\,\mathrm{Mev}$ to $\sim 0.2\,\mathrm{MeV}$
(neutron/proton) ratio drops out of equilibrium,
$\nu_e + \mathrm{n} \rightleftarrows \mathrm{p} + e^-$
$\bar{\nu}_e + \mathrm{p} \rightleftarrows \mathrm{n} + e^+$
$\mathrm{n} \rightleftarrows \mathrm{p} + \bar{\nu}_e + e^-$
become slow compared to the expansion rate.

Standard BBN



Nao Suzuki (Tytler group) 2006

So, where do we stand in comparing the observationally-determined light element abundances with BBN predictions ??

(1) only really complete success is deuterium

– and this is very good! (see Ryan Cook's recent work!)

(2) Helium is historically problematic, but promising with CMB

From compact blue galaxy linear regression, extrapolation to zero metallicity

Izotov & Thuan (2010) get helium mass fraction $\mathrm{Y_P} = 0.2565 \pm 0.0010\ (\mathrm{stat.}) \pm 0.0050\ (\mathrm{sys.})$

Using the CMB-determined baryon-to-photon ratio the standard BBN prediction is

$\mathrm{Y_P} = 0.2482 \pm 0.0007$ Steigman 1008.476

Best bet may be future CMB determinations via the Silk damping tail,

$\mathrm{Y_p} = 0.266 \pm 0.021\ \ (68\ \mathrm{percent\ conf.\ Planck + WP + highL})$

very tricky – N_{eff} and ^{4}He almost degenerate

(3) Lithium is a mess:

observed ^{7}Li low relative to BBN prediction by factor of 3

So what is unique about the
cosmic neutrino background (CνB)
as a lab for studying neutrinos?

In a nutshell:

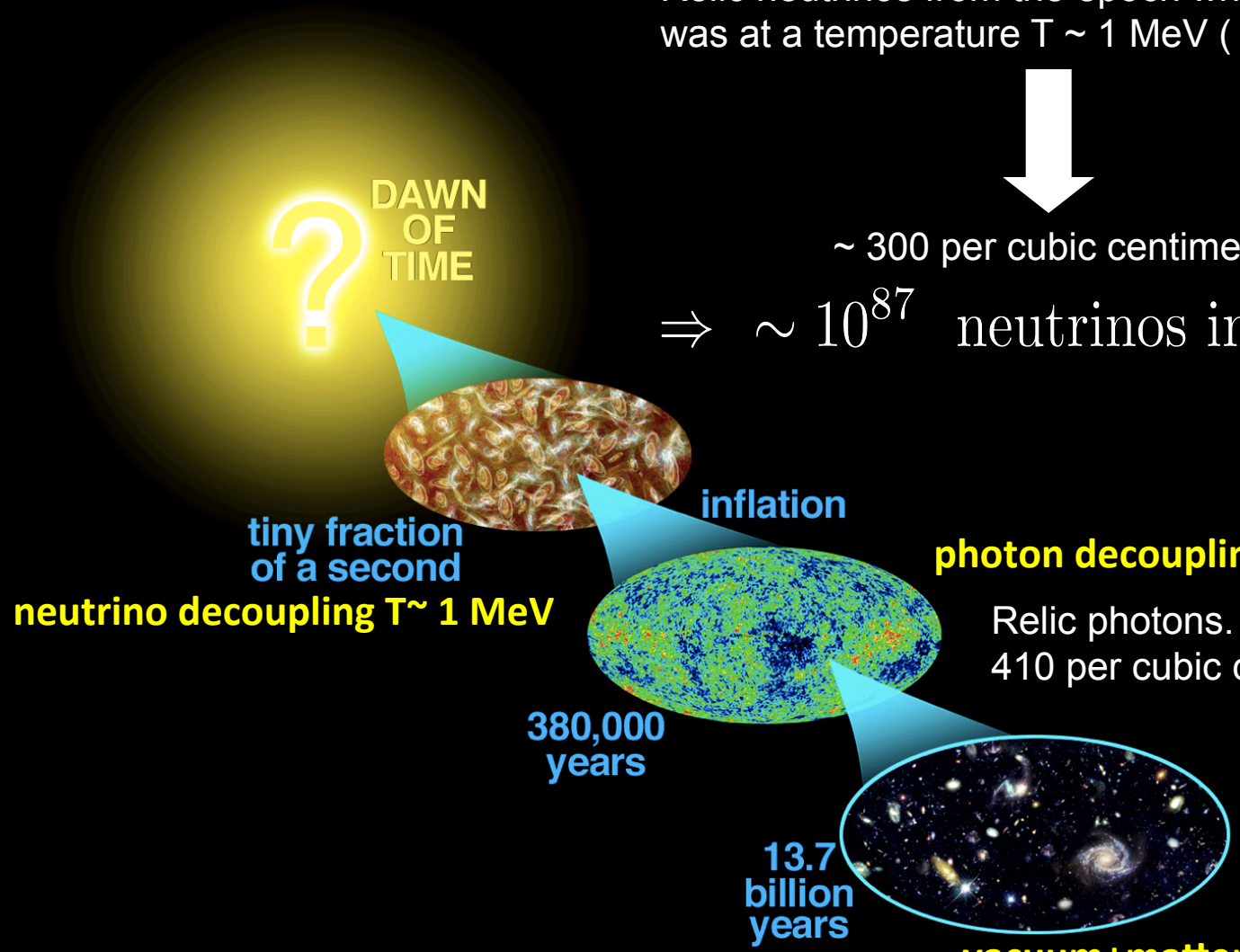
There are a ***huge*** number of these neutrinos.
They make themselves felt in Big Bang Nucleosynthesis
and by their gravitational effects.

Moreover, the relic density of these neutrinos
and their energy spectra could give unique insights
into the physics of the very early universe

Relic neutrinos from the epoch when the universe was at a temperature T ~ 1 MeV (~ 10^{10} K)

~ 300 per cubic centimeter

$$\Rightarrow \sim 10^{87} \text{ neutrinos in universe}$$



photon decoupling T~ 0. 2 eV

Relic photons. We measure 410 per cubic centimeter

vacuum+matter dominated at current epoch

Astrophysical Probes of Neutrino Rest Mass

(Abazajian et al., arXiv:1103.5083)

Probe	Current/Reach $\sum m_\nu$ (eV)	Key Systematics	Current Surveys	Future Surveys
CMB Primordial	1.3/0.6	Recombination	WMAP, Planck	None
CMB Primordial w/ Distance	0.58/0.35	Distance measurements	WMAP, Planck	None
Lensing of CMB	∞/0.2-0.05	NG of Secondary anisotropies	Planck, ACT [47], SPT, PolarBear, EBEX, QUIET II [48]	CMBPol [44]
Galaxy Distribution	0.6/0.1	Nonlinearities, Bias	SDSS [9, 10], DES [43], BOSS [15]	LSST [17], WFMOS [11], HETDEX [12]
Lensing of Galaxies	0.6/0.07	Baryons, NL, Photo-z	CFHT-LS [42],DES [43], HyperSuprime	LSST, Euclid [57], DUNE [58]
Lyman α	0.2-?/0.1	Bias, Metals, QSO continuum	SDSS, BOSS, Keck	BigBOSS [59]
21 cm	∞/0.1-0.006	Foregrounds	Lofar [46], MWA [49], Paper, GMRT	SKA [50], FFTT [38]
Galaxy Clusters	0.3-?/0.1	Mass Function, Mass Calibration	SDSS, SPT, DES, Chandra	LSST
Core-Collapse Supernovae	NH (If $\theta_{13} > 10^{-3}$) IH (Any θ_{13})	Emergent ν spectra	SuperK, ICECube	Noble Liquids, Gadzooks

Table I: Cosmological probes of neutrino mass. "Current" denotes published (although in some cases controversial, hence the range) 95% C.L/ upper bound on $\sum m_\nu$ obtained from currently operating surveys, while "Reach" indicates the forecasted 95% sensitivity on $\sum m_\nu$ from future observations. These numbers have been derived for a minimal 7-parameter vanilla+m_ν model. The six other parameters are: the amplitude of fluctuations, the slope of the spectral index of the primordial fluctuations, the baryon density, the matter density, the epoch of reionization, and the Hubble constant.

Each of these probes faces technological, observational, and theoretical challenges in its quest to extract a few percent level signal. Table I highlights the key theoretical systematics each probe will have to overcome to obtain a reliable constraint on neutrino masses.

Direct Laboratory Limits on Neutrino Rest Masses

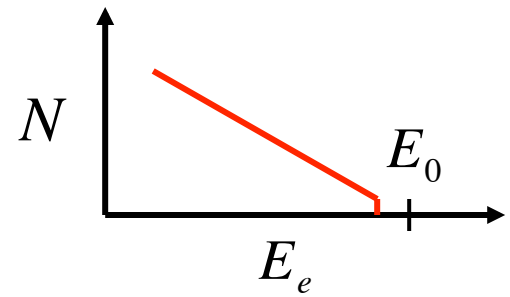
"m_{ν_τ}" < 18.2 MeV (τ - decay; Groom *et al.*, Eur. J. Phys., C15, 1, 2000.)

"m_{ν_μ}" <190 keV (π - decay)

"m_{ν_e}" < 2 eV (Tritium endpoint; KATRIN eventually down to 200 meV =.2 eV)

$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

$$\frac{dN}{dE_e} \propto \sqrt{\left(E_e - E_0\right)^2 - "m_{\nu_e}^2"}$$



"$m^2_{\nu_e}$" $\approx +0.6 \pm 2.8 \pm 2.1$ eV²

$\approx -1.6 \pm 2.5 \pm 2.1$ eV²

< 4 eV² with high confidence

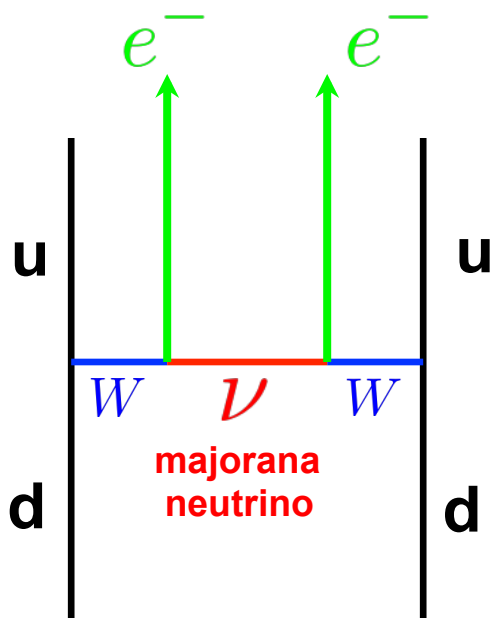
- J. Bonn *et al.*, Nucl. Phys. B 91, 273, 2001.

In terms of matrix elements of the Unitary Transformation:

"$m^2_{\nu_e}$" $= m_1^2|U_{e1}|^2 + m_2^2|U_{e2}|^2 + m_3^2|U_{e3}|^2 + \ldots + m_n^2|U_{en}|^2$

but since "$m^2_{\nu_\alpha}$" $\equiv \sum_i m_i^2 \, |U_{\alpha i}|^2 \Rightarrow$ this limit applies to all neutrinos

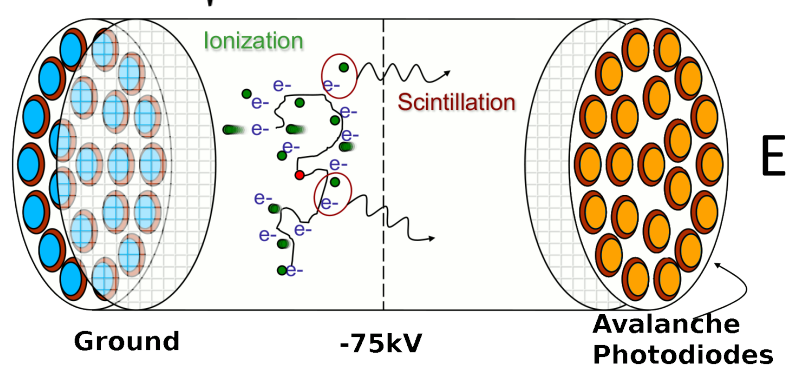
Majorana Neutrinos: Neutrinoless Double Beta Decay



two neutrons change into two protons

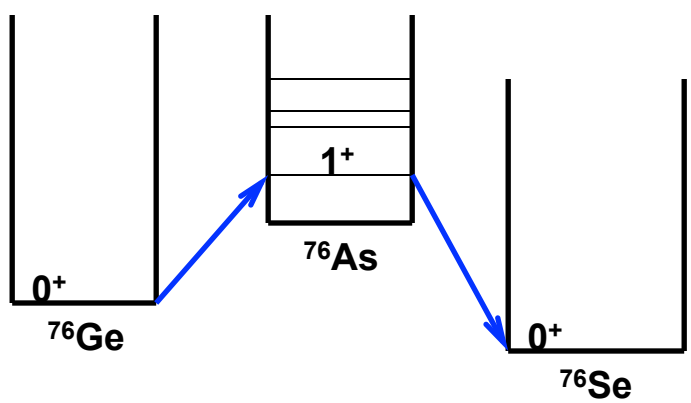
$$\Gamma_{0\nu} = \frac{1}{\tau_{\beta\beta}} = G_{0\nu}|M_{\rm nuc}|^2 m_{\beta\beta}^2$$

$$\langle m_{\beta\beta}\rangle = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$



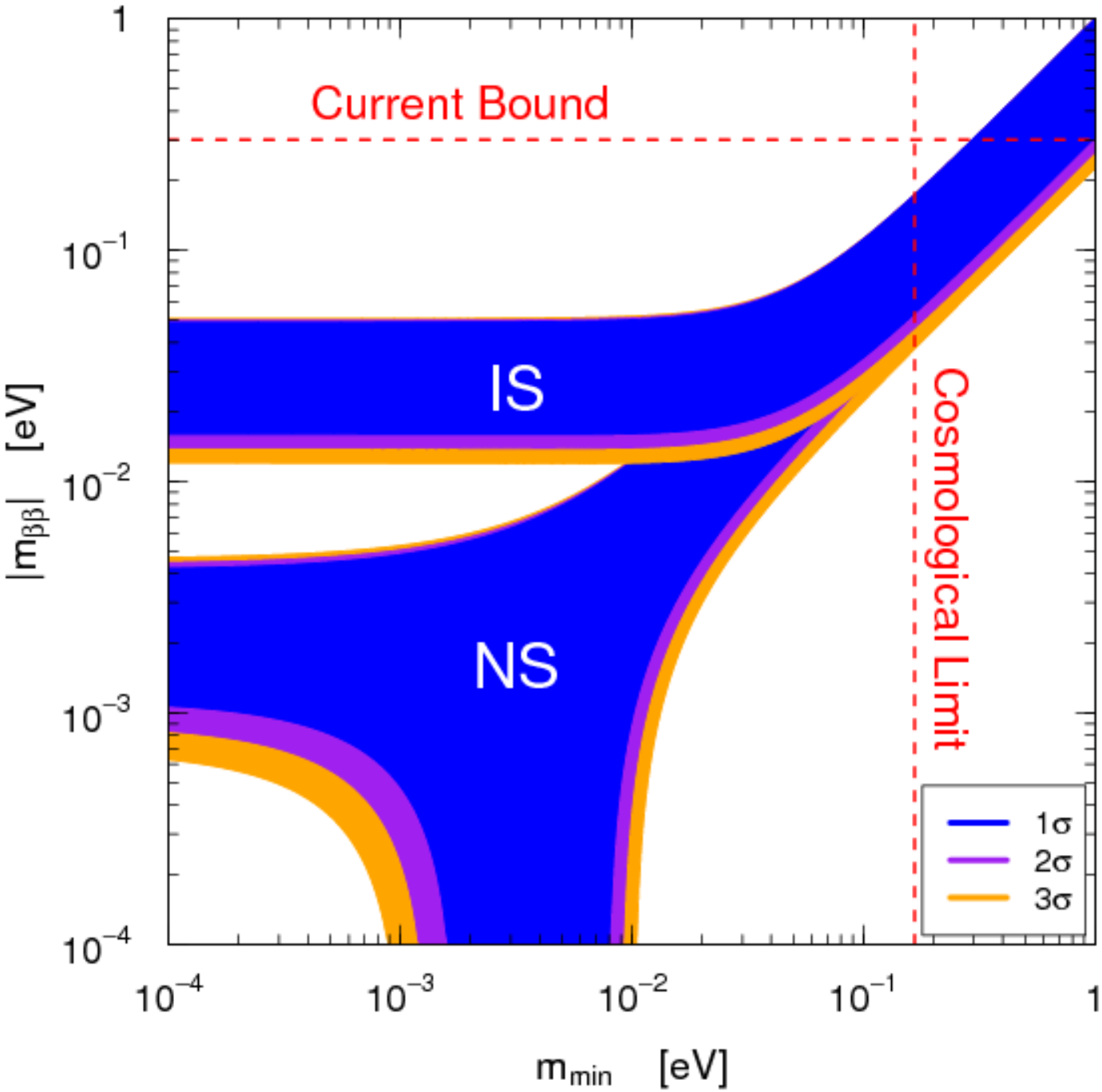
EXO

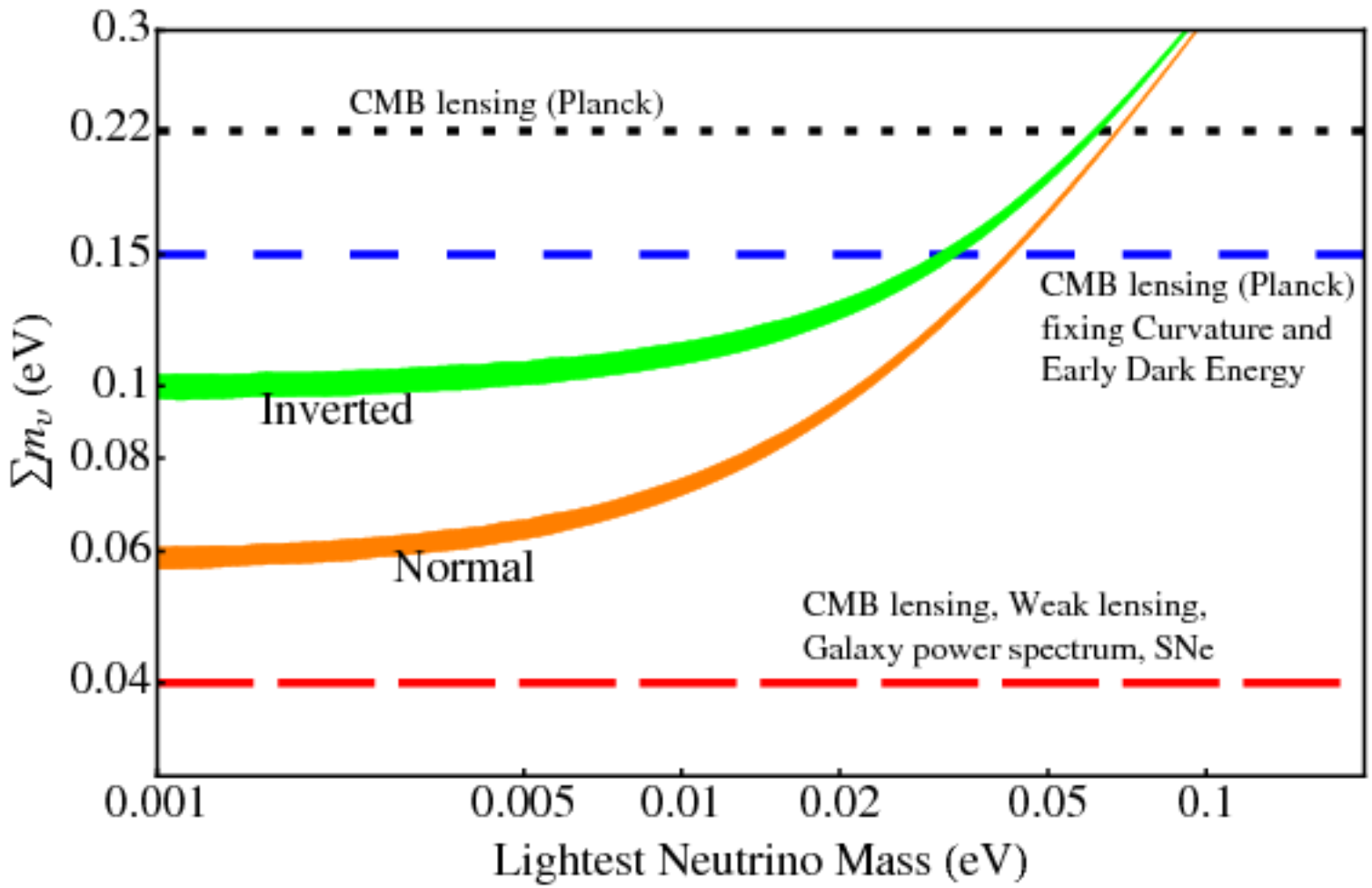
Second order weak process:
coherent sum over intermediate nuclear states



experiments should get to > 10^{27} year lifetime, or

$$m_{\beta\beta} < 100\,\mathrm{meV}$$


Current Bound
IS
NS
Cosmological Limit
1σ
2σ
3σ
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$|m_{\beta\beta}|$ [eV]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
m_{min} [eV]


0.3
0.22
0.15
0.1
0.08
0.06
0.04
$\sum m_\nu$ (eV)
CMB lensing (Planck)
CMB lensing (Planck)
fixing Curvature and
Early Dark Energy
Inverted
Normal
CMB lensing, Weak lensing,
Galaxy power spectrum, SNe
0.001
0.005
0.01
0.02
0.05
0.1
Lightest Neutrino Mass (eV)

None of these actually *measure* neutrino rest mass

All measure something different – are complementary

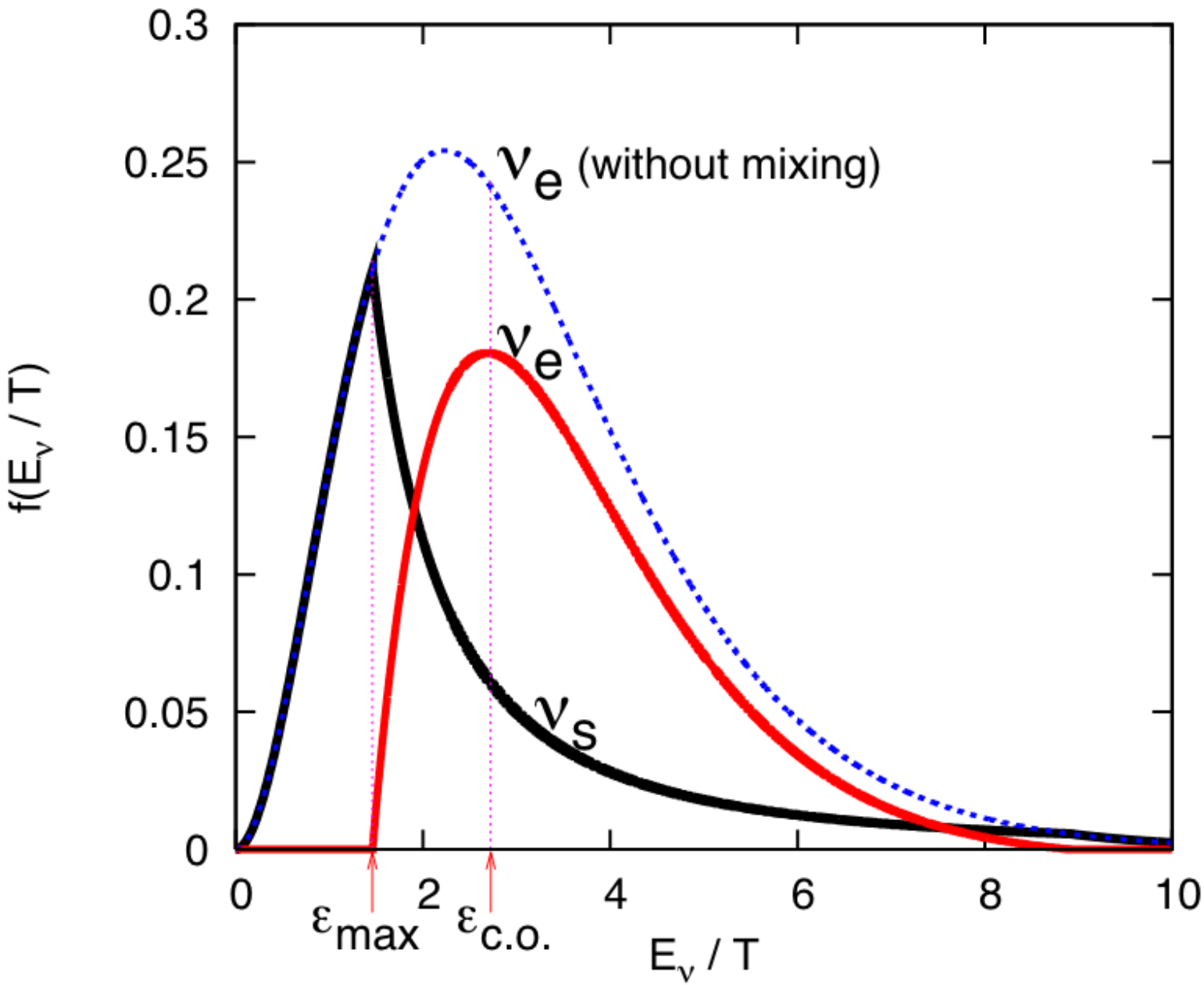
Caveats on CMB as a probe of sterile neutrinos

. . . there are scenarios where *sterile neutrinos* would **not** have thermal energy spectra/number densities (sterile neutrinos are sub-weakly interacting!)

. . . be careful with BBN + CMB, especially for ^{4}He. What we call N_{eff} is **not** what determines the *expansion rate* and *neutron/proton ratio* at T ~ 1 MeV BBN epoch

$$\left.\begin{aligned} \nu_e + \mathrm{n} &\rightleftharpoons \mathrm{p} + e^- \\ \bar{\nu}_e + \mathrm{p} &\rightleftharpoons \mathrm{n} + e^+ \\ \mathrm{n} &\rightleftharpoons \mathrm{p} + e^- + \bar{\nu}_e \end{aligned}\right\}$$

Rates of these competing processes set ^{4}He and they are *very* sensitive to neutrino energy spectra – active-sterile oscillations can affect these



C. Kishimoto, G. M. Fuller, C. Smith, PRL **97,** 141301 (2006)

Dark Radiation

N_{eff} as a probe of neutrino sector and BSM physics

There are three N_{eff}'s:
(1) The old particle physicists' version (number of kinds of neutrinos!);
(2) The modern "theorist" version (parameterization of radiation energy density);
(3) What gets measured! The observer's version

Radiation energy density at γ-decoupling $(T_\gamma \approx 0.2\,\mathrm{eV})$
is parameterized by the
so called "*effective number of neutrino degrees of freedom*".

This is a misnomer as it refers to energy density
from ***any and all*** relativistic particles at that epoch.

$$\rho_{\mathrm{radiation}} = \left[2 + \frac{7}{4} \left(\frac{4}{11} \right)^{4/3} \mathrm{N_{eff}} \right] \frac{\pi^2}{30} T_\gamma^4$$

The standard model predicts $N_{\mathrm{eff}} = 3.046$ Calabrese *et al.* PRD **83**, 123504 (2011)

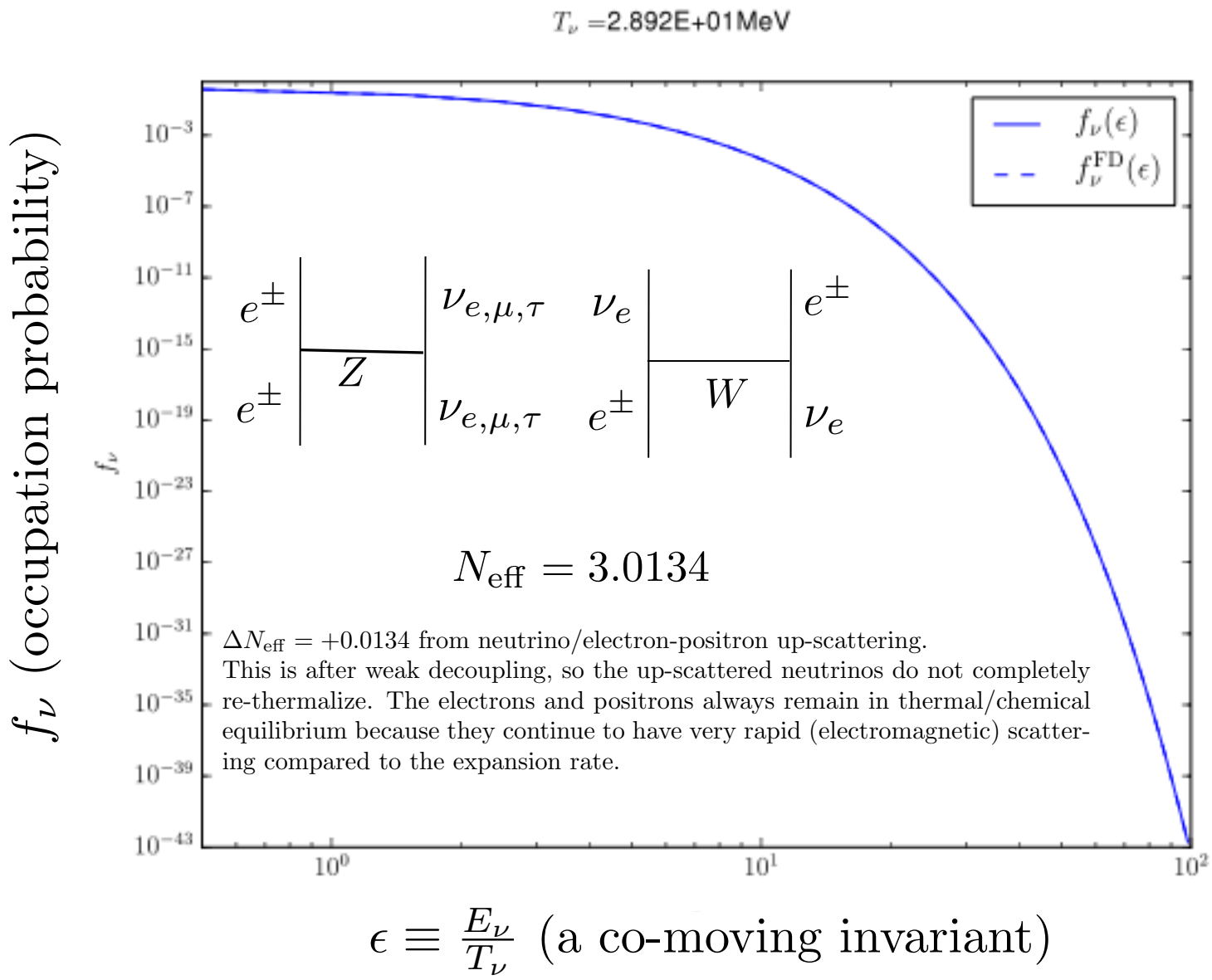
$\mathrm{Nine-year\ WMAP}\ \ \mathrm{N_{eff}} = 3.26 \pm 0.35$

$\mathrm{ACT}\ \ \mathrm{N_{eff}} = 2.78 \pm 0.55$

$\mathrm{SPT-SZ\ Survey}\ \ \mathrm{N_{eff}} = 3.71 \pm 0.35\ \ (\mathrm{H_0\ and\ BAO\ priors})$

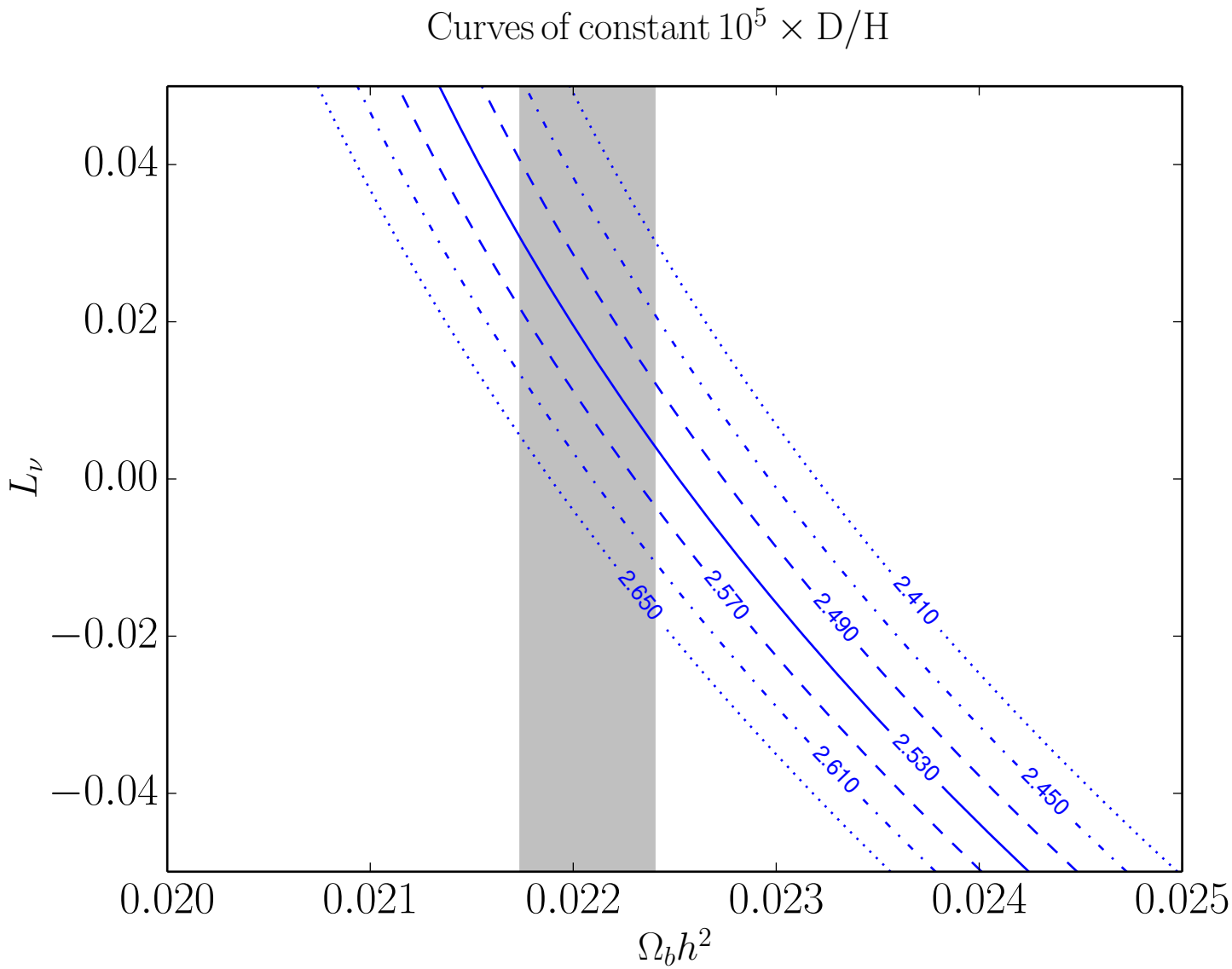
Planck $\mathrm{N_{eff}} = 3.30^{+0.54}_{-0.51},\ 95\%\ \mathrm{conf.},\ \mathrm{WMAP\ pol.},\ \mathrm{high}\ l,\ \mathrm{BAO}$

analysis with BAO & sterile mass < 10 eV, thermal spectrum $\mathrm{N_{eff}} < 3.80\ \ \&\ \ m_\nu^{\mathrm{sterile}} < 0.42\,\mathrm{eV},\ \mathrm{at}\ 95\%\ \mathrm{conf.}$

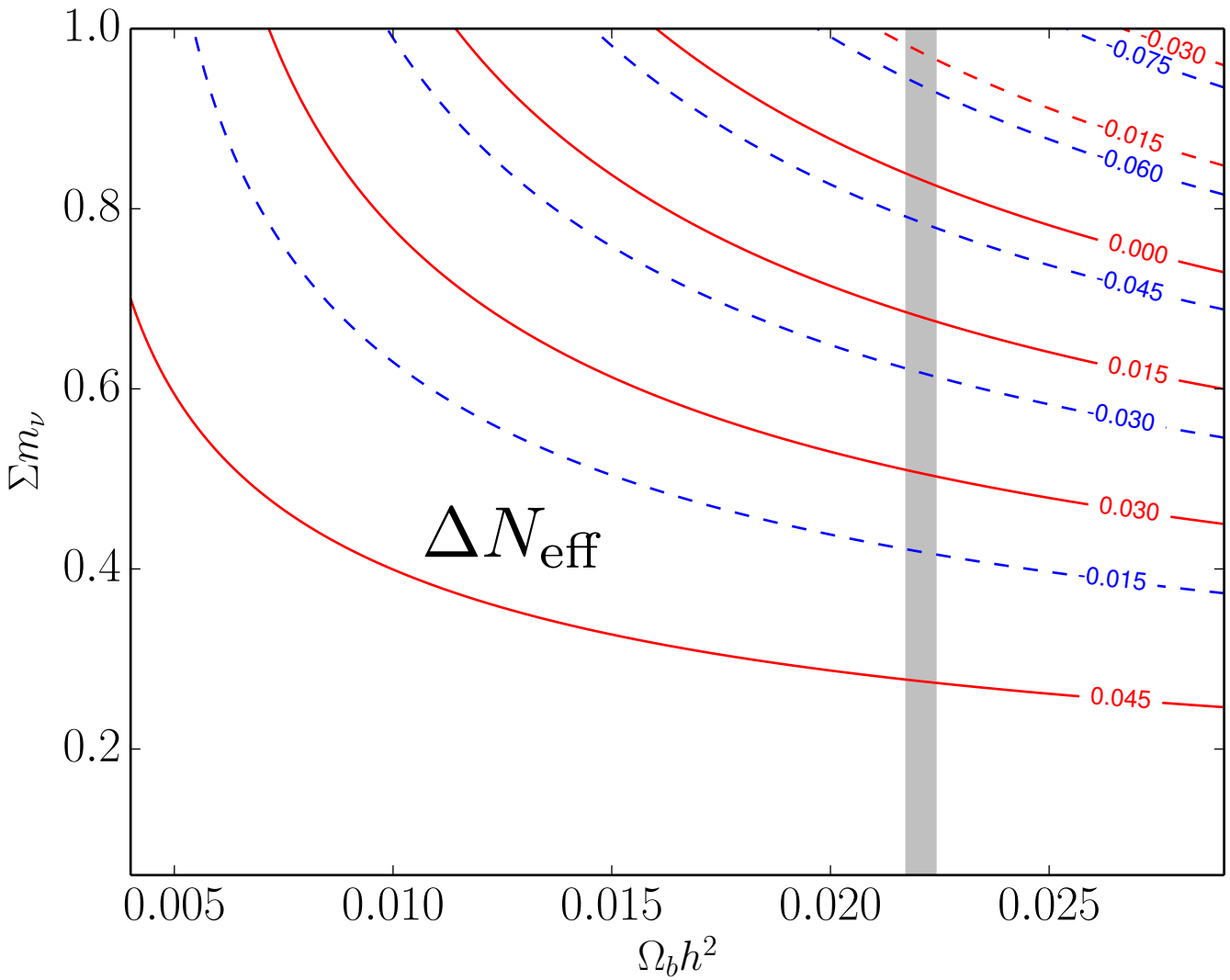


E. Grohs, M. Paris, GMF *"BURST" code* 2014

How Deuterium abundance changes in the lepton number/baryon number parameter space

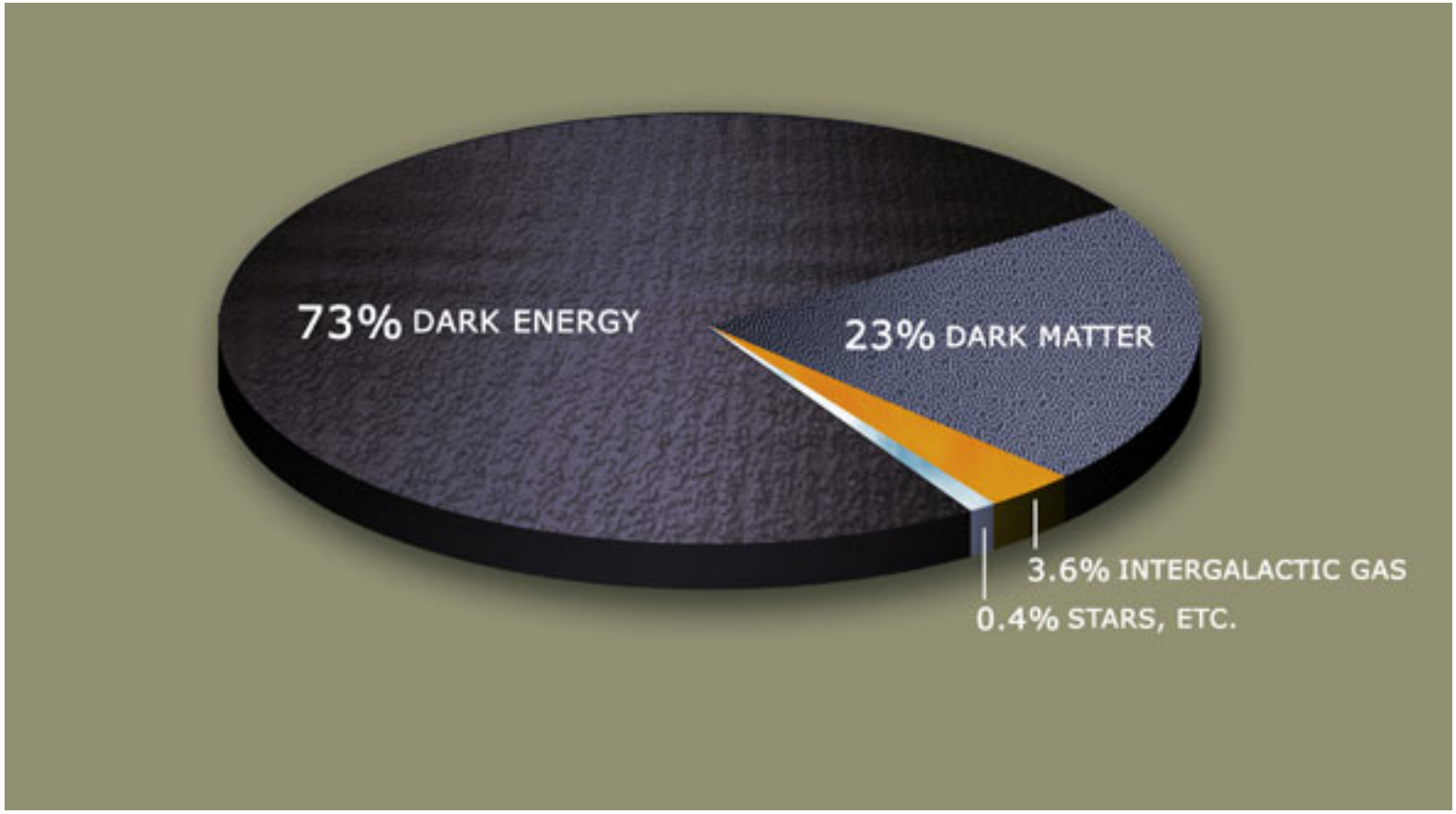


E. Grohs, GMF, M. Paris 2014



E. Grohs, M. Paris, GMF 2014

We live in a homogeneous and isotropic, critically closed (Ω=1), "flat", spacetime



earthsky.org

If $\Omega = 1$ it is always $\Omega = 1$, and this spacetime symmetry is preserved regardless of what microphysics operates and the changing relative mix of different sources of the closure energy density.

popular (and *not so popular*) Dark Matter Candidates

★-Weakly Interacting Massive Particles (WIMPS) CDM, mass ~ 100 GeV ??
30 to 70 GeV rest mass WIMP -- T. Daylan *et al.* arXiv:1402.6703

-Asymmetric Dark Matter CDM, mass ~ several GeV ??

- Primordial Black Holes CDM, mass ~ moon mass ??

- Axions (scalars) CDM, mass ~ 10^{-5} eV ??

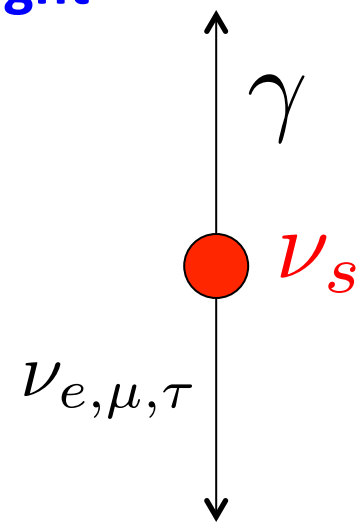
★- "Sterile" Neutrinos CDM or WDM, rest mass ~ 1 keV to ~ 100 keV ??
7.1 keV rest mass sterile neutrino – E. Bulbul *et al.* arXiv:1402.2301
and Boyarsky *et al.* arXiv:1402.4119

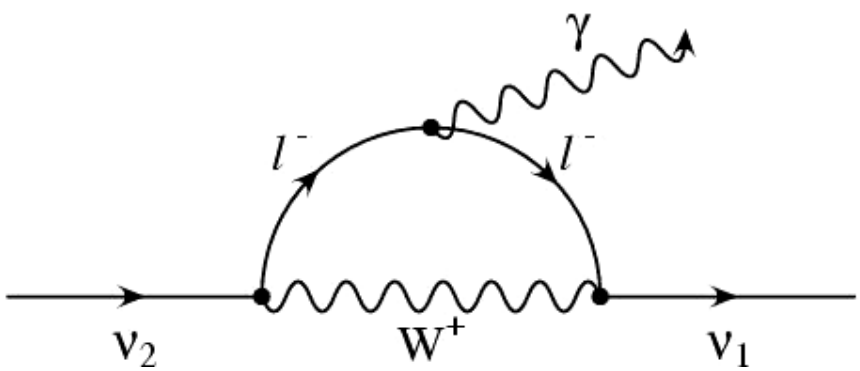
$\Omega = 1$ ("flat"/homogeneous/isotropic) is a *spacetime* symmetry.
Spacetime is agnostic as to what makes up the closure density, so all of these dark matter sources may contribute!

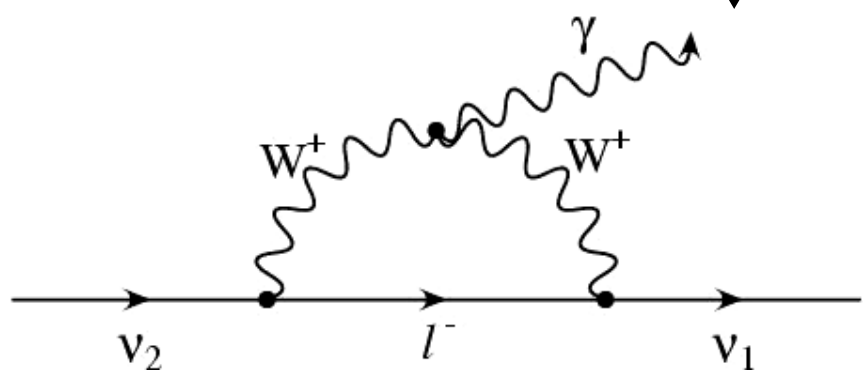
★Recent Claimed *Indirect* Detections

A heavy "sterile" neutrino can decay into a light "active" neutrino and a photon.

The final state light neutrino and photon *equally share* the rest mass energy of the initial heavy neutrino.





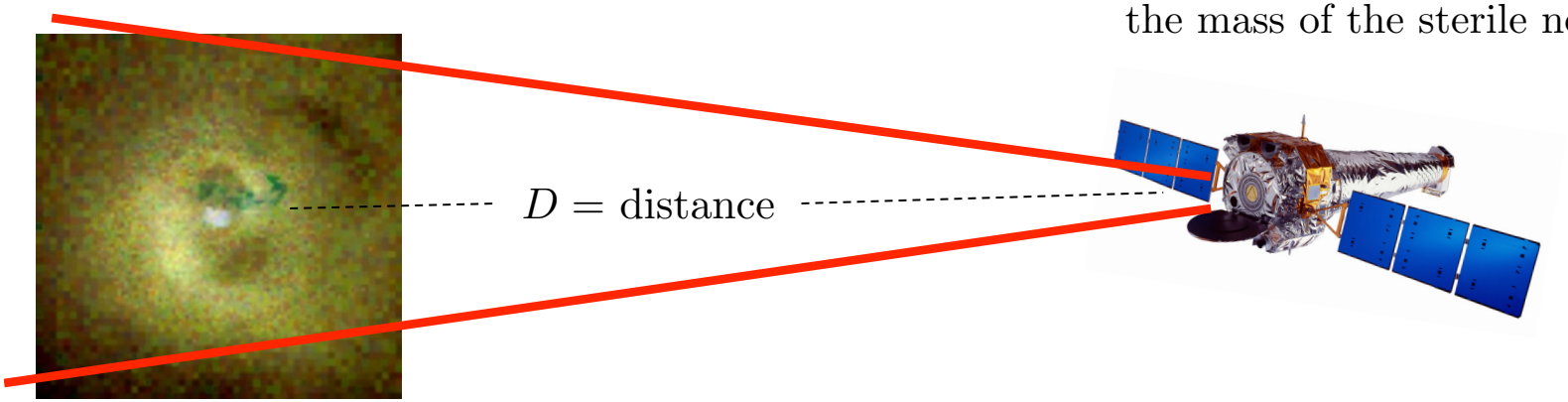


$$\nu_s \rightarrow \nu_{e,\mu,\tau} + \gamma$$

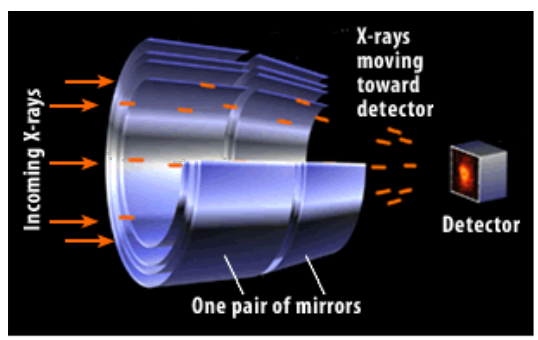
photon line $E_\gamma = m_s/2$

M = mass of dark matter
in field of view of X-ray telescope

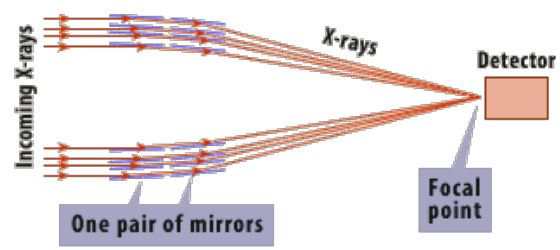
energy of X-ray line:
$E_\gamma = \frac{1}{2}\, m_{\rm s}$,
measuring this gives
the mass of the sterile neutrino $m_{\rm s}$



measured X-ray flux in line
$\propto M \cdot D^{-2} \cdot m_{\rm s}^5 \cdot \sin^2\theta$



Courtesy Chandra mission website:
http://chandra.harvard.edu



Chandra's mirrors are positioned so they're almost parallel to the entering X-rays. The mirrors look like open cylinders, or barrels. The X-rays skip across the mirrors much like stones skip across the surface of a pond.

Possible Detections ??

two different X-ray astronomy groups see a **3.5 keV** line in **clusters of galaxies** and in M31,
and this line is ***consistent with a dark matter decay origin***,
corresponding to a **7 keV rest mass sterile neutrino**
with vacuum mixing with active neutrinos $\sin^2 2\theta = (2 - 20) \times 10^{-11}$

E. Bulbul, M. Markevitch, A. Foster, R. Smith, M. Lowenstein, S. Randall
"*Detection of an unidentified emission line in the stacked X-ray spectrum of Galaxy Clusters*" arXiv:1402.2301

A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, J. Franse
"An unidentified line in the X-ray spectrum of the Andromeda galaxy and Perseus galaxy cluster" arXiv:1402.4119

(1) Quantum Mechanical Limit: Dodelson & Widrow 1994

active neutrino scattering-induced de-coherence produces
a relic density of sterile neutrinos -- *picks out keV scale rest masses, small vacuum mixing angles*

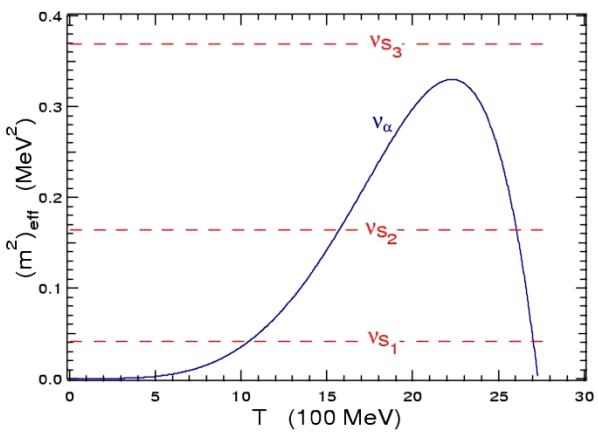
(2) Lepton number-driven resonant production: Shi & Fuller 1998; Abazajian, Fuller, Patel 2001; Abazajian '14

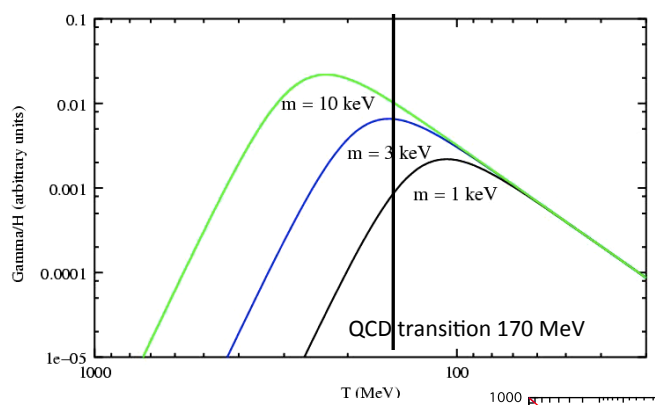
Like MSW, initial lepton number partially converted to a relic sterile neutrino population

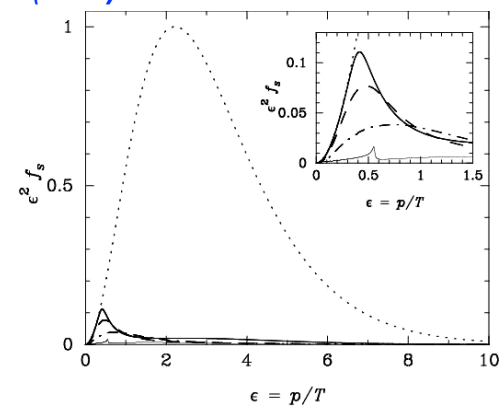
-- *can work for smaller mixing angles, colder sterile neutrino relic energy spectrum*

-- *sterile neutrinos may allow you to make the lepton number*

*e.g., Asaka & Shaposhnikov , "The nuMSM, dark matter, and baryon asymmetry", PLB **620**, 17 (2005)*





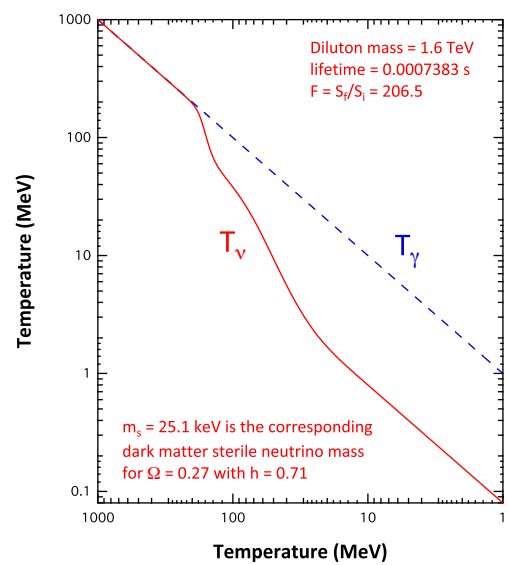


(3) Higgs decay; Dilution:

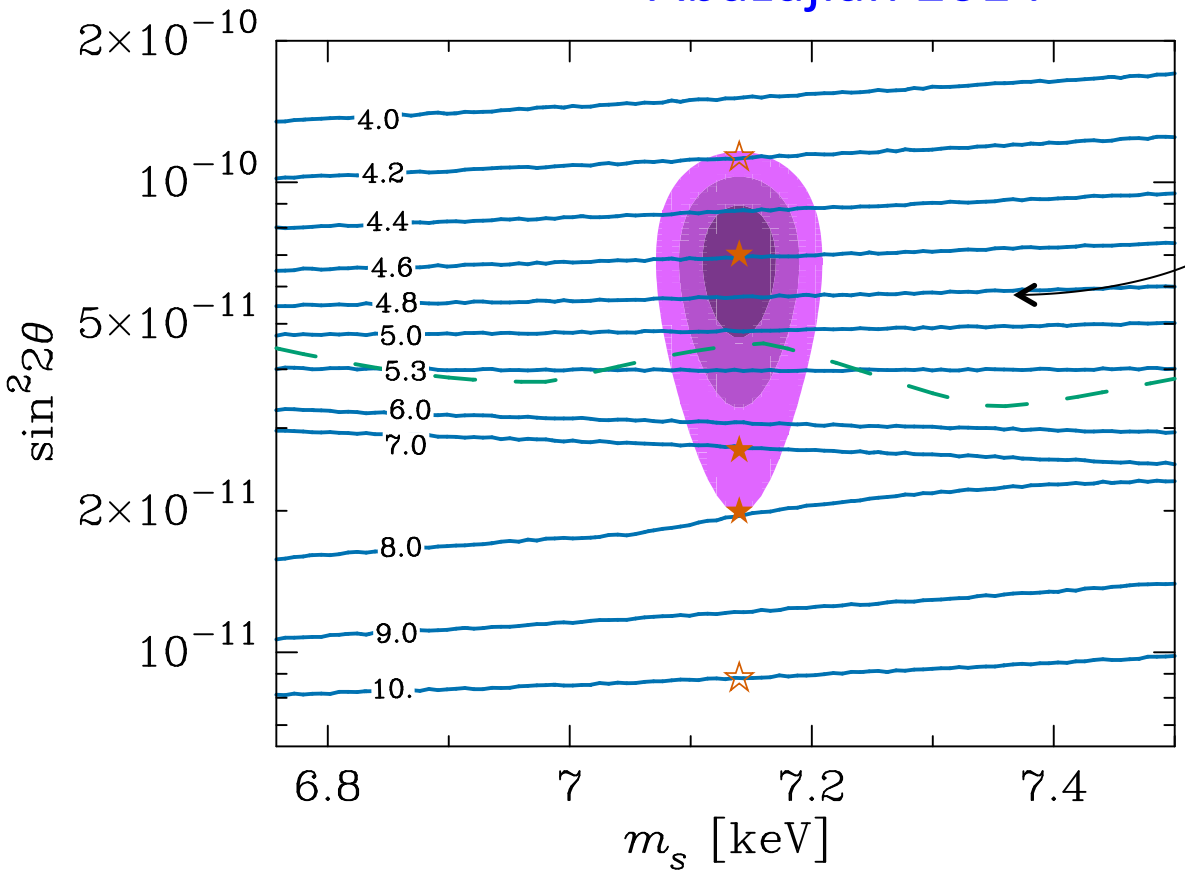
e.g., Asaka, Shaposhnikov, Kusenko (2006);
F. Bezrukov, D. Gorbunov arXiv:1403.4638
Fuller, Kishimoto, Kusenko, Patwardhan (2014)

thermalize or partially thermalize steriles very early,
then dilute them down to a DM relic density

-- *can produce relic sterile neutrino populations which are CDM for rest masses ~ 1 keV to ~ 10 MeV, with extremely small vacuum mixing angles*



Abazajian 2014



contours of
initial lepton number
in units of 10^{-4}

Lepton number is
$\mathcal{L} = 2\,L_{\nu_\alpha} + \sum_{\beta\neq\alpha} L_{\nu_\beta}$, where $\alpha, \beta = \mathrm{e}, \mu, \tau$

where individual lepton numbers are, *e.g.*,
$L_{\nu_\alpha} = (n_{\nu_\alpha} - n_{\bar{\nu}_\alpha})/n_\gamma$

and the baryon number is
$\eta = (n_{\mathrm{baryon}} - n_{\mathrm{anti-baryon}})/n_\gamma = 6.11 \times 10^{-10}$

So what is unique about core collapse supernovae as a "lab" for studying neutrinos?

In a nutshell:

Core collapse supernovae are cold,
highly electron lepton number degenerate systems.

They are ***exquisitely sensitive*** to lepton number violating processes.

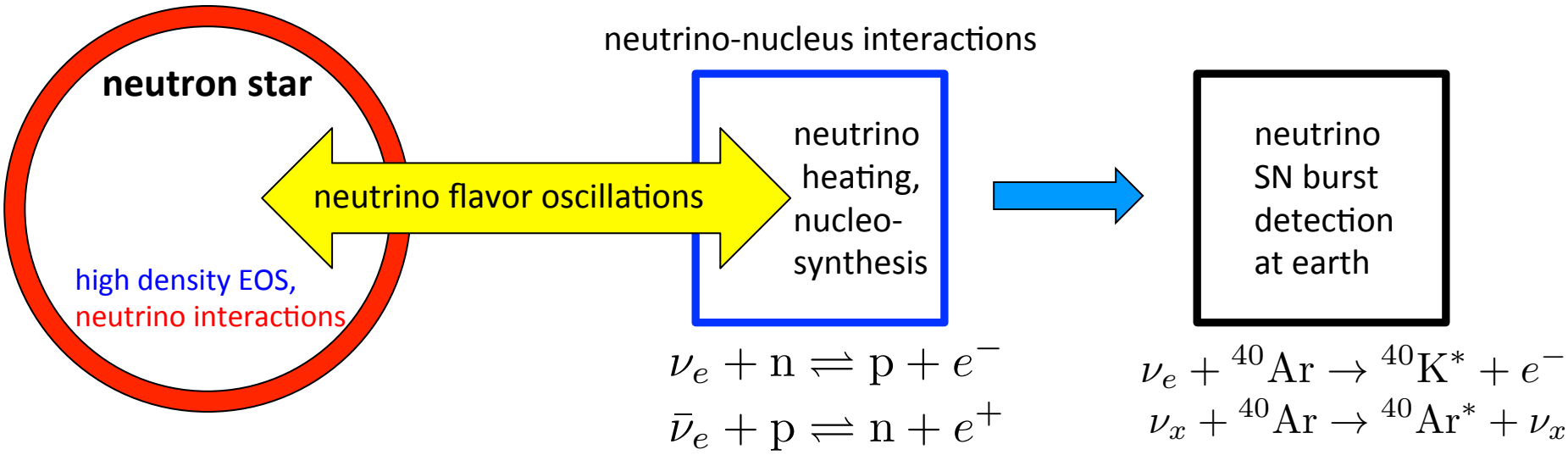
Macroscopic effects in SN physics or signal from:
flavor oscillations: very sensitive to neutrino mass hierarchy;
spin coherence: sensitive to Majorana/Dirac nature of neutrinos
& absolute neutrino masses

Simulations of core collapse supernovae are very sophisticated:
multi-dimensional radiation hydrodynamics;
Boltzmann neutrino transport, and *detailed microphysics/EOS* . . .

Our understanding of the effects of nonzero neutrino mass (flavor oscillations; spin flip), though numerically sophisticated, is crude, and difficult to incorporate into the SN simulations.

There are *unsettled issues* in the story of supernova neutrinos.

Calculating neutrino flavor transformation in the core collapse supernova environment is a vexing problem,
but one whose solution may lie at the heart of many aspects of the physics of stellar collapse, nucleosynthesis, and the ν signal.



We need the fluxes and energy spectra of each flavor/type of neutrino at all epochs and at all radii.

Quantum Kinetic Equations

$$i\,D\hat{f} - \left[\hat{\mathcal{H}}, \hat{f}\right] - \hat{U}\left[\hat{\phi}\right] = \text{collision terms}\left(\hat{f}, \hat{\bar{f}}\right)$$

where $\hat{f}$ and $\hat{\bar{f}}$ are 3×3 Hermitian density operators for neutrinos and antineutrinos, respectively, and $\hat{\phi}$ is a 3×3 complex matrix encoding spin coherence.

and where $\hat{\mathcal{H}}$ & $\hat{U}$ give neutrino interactions with matter and other neutrinos

separation of scales ??

Schroedinger-like:

$$i\frac{\partial|\psi\rangle}{\partial t} = \hat{H}|\psi\rangle \text{ with } |\psi\rangle = (\psi_{\rm e}, \psi_\mu, \psi_\tau)$$

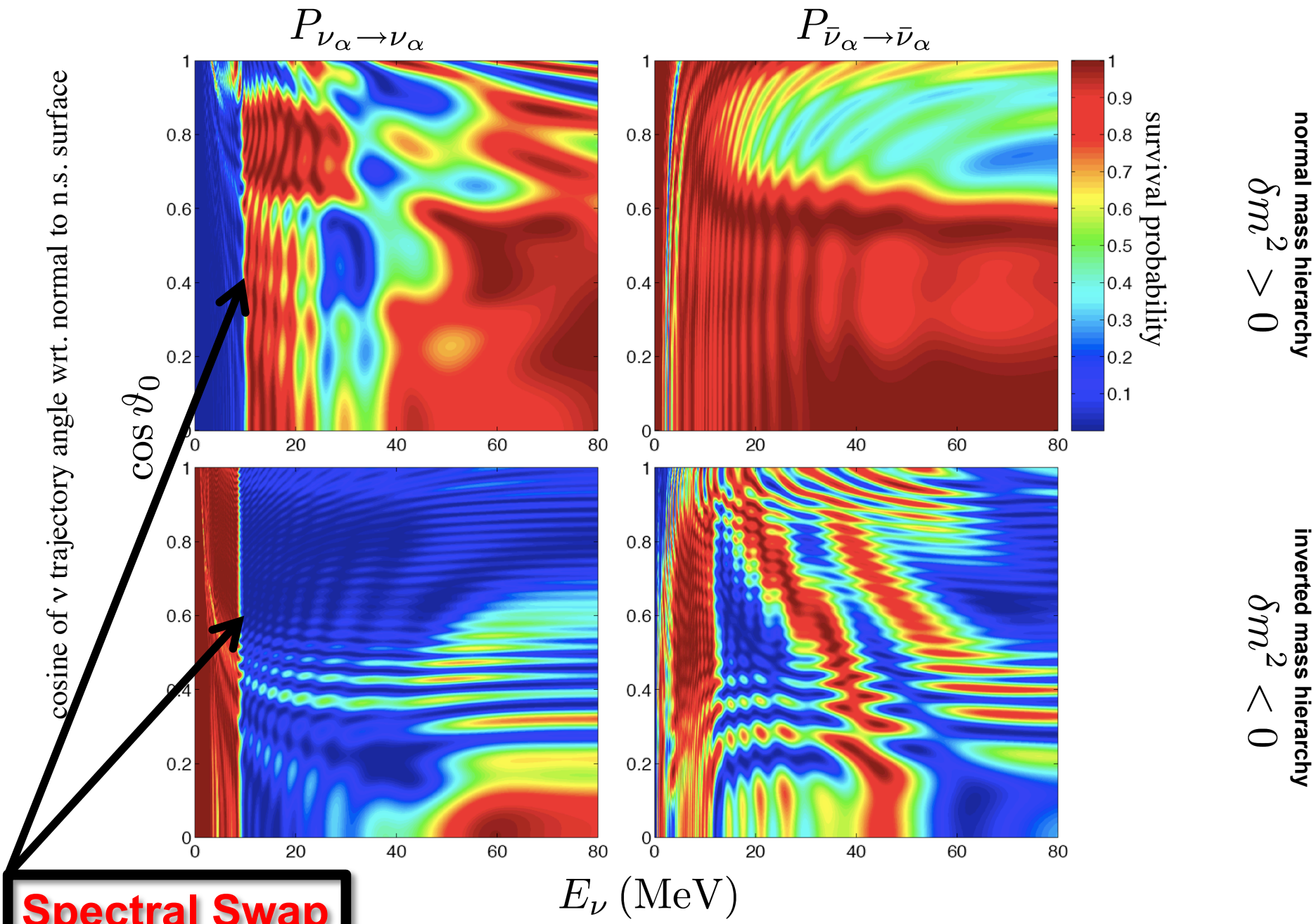
$$\hat{H} = \frac{m^2}{2E} + \hat{H}_{{\rm e}\nu} + \hat{H}_{\nu\nu}$$

@ "low" density where neutrinos propagate coherently

Boltzmann equation

@ "high" density where inelastic scattering dominates

A. Vlasenko, G.M.F., V. Cirigliano (2013), arXiv:1309.2628



Spectral Swap

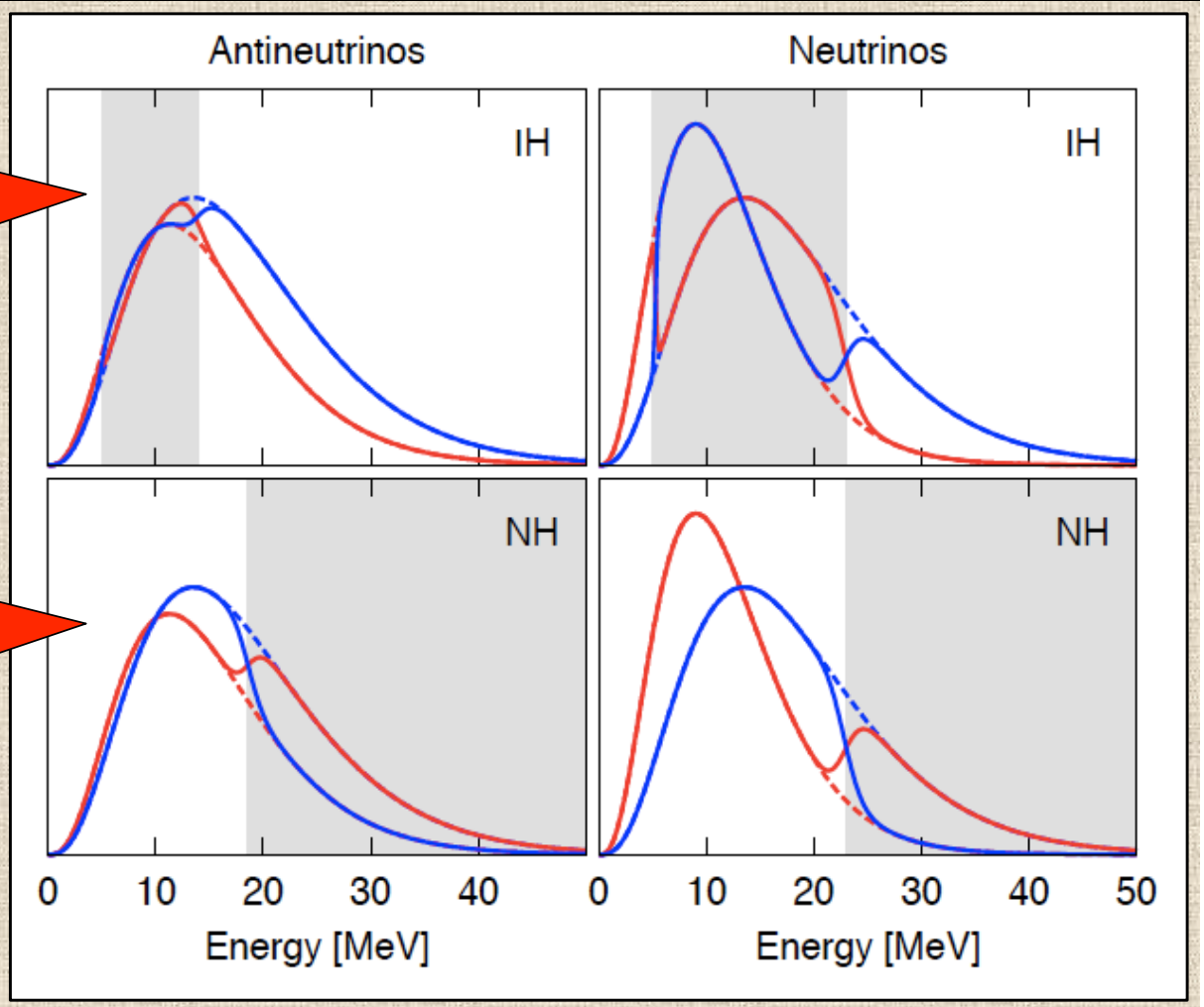
consequences of neutrino mass and quantum coherence in supernovae

H. Duan, G. M. Fuller, J. Carlson, Y.-Z. Qian, Phys. Rev. Lett. **97**, 241101 (2006) **astro-ph/0606616**

Multiple Spectral Splits

Spectral Splits in Inverted Hierarchy

Spectral Splits in Normal Hierarchy



Dasgupta, Dighe, Raffelt and Smirnov, arXiv: 0904.3542 (PRL)

Azimuthal asymmetry develops in neutrino flavor field above neutron star

enhanced instability
in the neutrino flavor field
– not easily matter-suppressed

nonlinearity:
neutrino flavor field may not retain the symmetry of the neutrino sphere initial conditions

G. Raffelt, S. Sarikas, and D. de Sousa; ArXiv:1308.142

A. Mirrizi; ArXiv:1308.5255

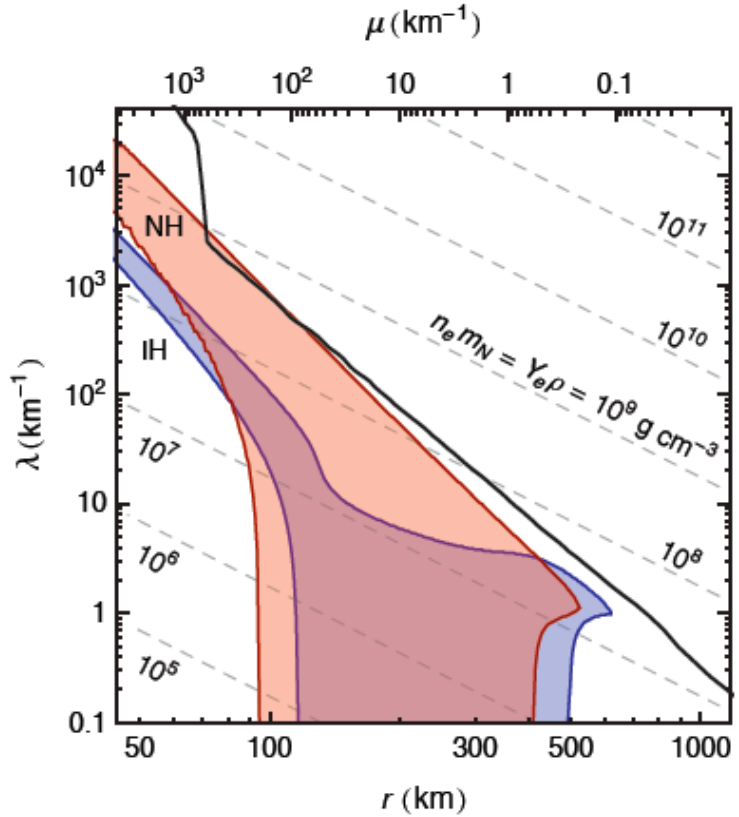


FIG. 2: Region where $\kappa r > 1$ for IH (blue) and NH (red), depending on radius r and multi-angle matter potential λ for our simplified SN model. *Thick black line:* SN density profile. *Thin dashed lines:* Contours of constant electron density, where Y_e is the electron abundance per baryon. (The IH case corresponds to Fig. 4 of Ref. [18], except for the simplified spectrum used here.)

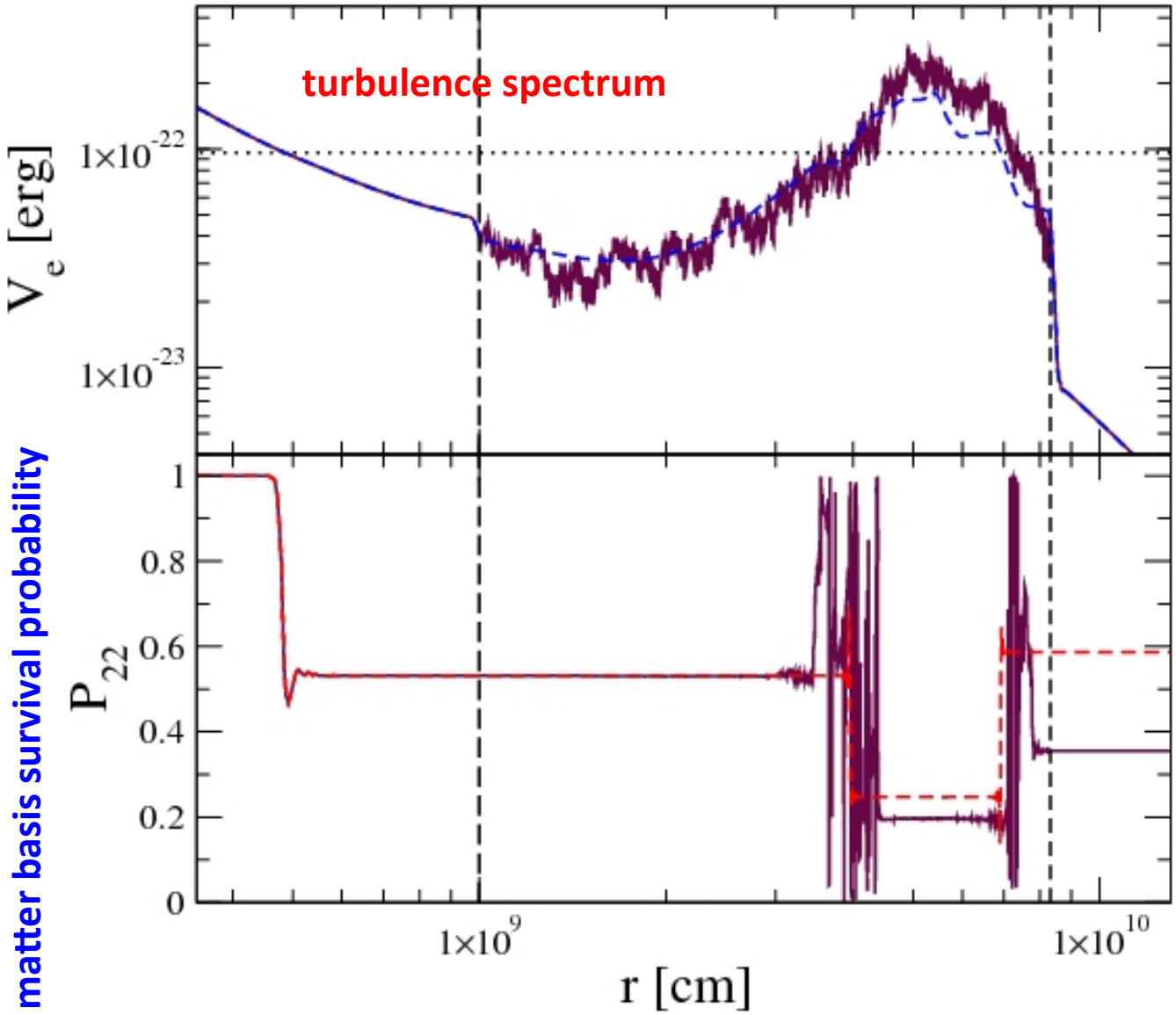
Effects that can modify or even wash-out the swap signal

-the supernova shock

-turbulence & density fluctuations

-neutrino direction-changing scattering
(quantum kinetic effects)

"Turbulence effects on supernova neutrinos",
J.P. Kneller & C. Volpe, Phys. Rev. D **82**, 123004 (2010)



Toward Quantum Kinetics

G. Sigl & G. Raffelt, Nucl. Phys. B **406**, 423 (1993)
B.H.J. McKellar and M.J. Thomson, Phys. Rev. D **49**, 2710 (1994)
K. Enqvist, K. Kainulainen, J. Maalami, Nucl. Phys. B **349**, 743 (1991)
C. Volpe, D. Vaanaen, C. Espinoza, ArXiv:1302.2374
A. Vlasenko, G. M. Fuller, V. Cirigliano,
Phys. Rev. D **89**, 105004 (2014), ArXiv:1309.2628
V. Cirigliano, G. M. Fuller, A. Vlasenko arXiv:1406.5558

(a) Effects of a small amount of direction-changing scattering on the neutrino flavor transformation? – The Halo

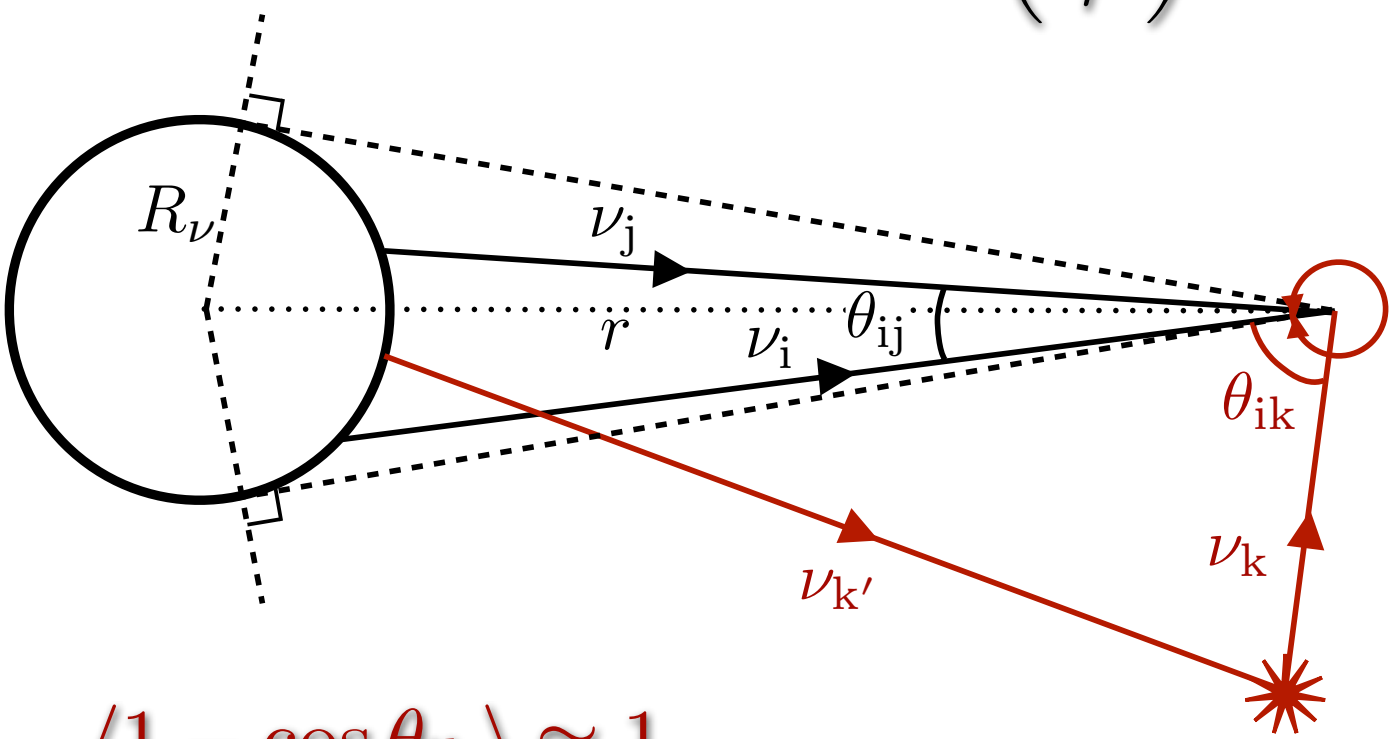
(b) *Spin Coherence*: neutrino-antineutrino inter-conversion

A. Vlasenko, G. M. Fuller, V. Cirigliano, Phys. Rev. D **89**, 105004 (2014), ArXiv:1309.2628

J. Cherry, A. Friedland, G. Fuller, J. Carlson, A. Vlasenko, Phys. Rev. Lett. **108**, 261104 (2012) 1203.1607

The Neutrino Halo

$$r \gg R_\nu \Rightarrow \langle 1 - \cos\theta_{\rm ij} \rangle \propto \left(\frac{R_\nu}{r}\right)^2$$

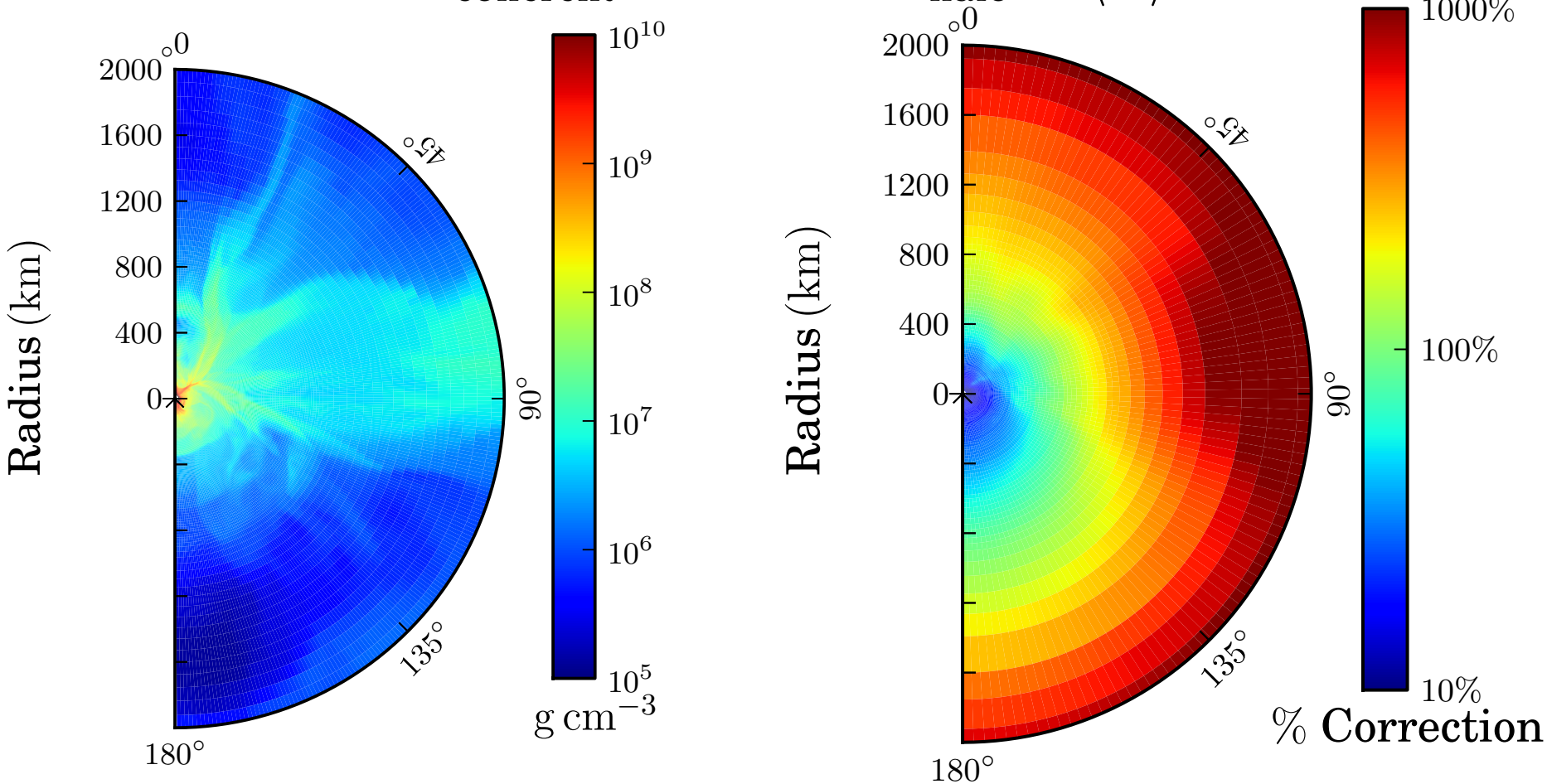


$$\langle 1 - \cos\theta_{\rm ik} \rangle \approx 1$$

$\sim 10^{-3}$ of all ν's

How large is the Halo effect for free nucleons?

$$\sigma_{\text{coherent}} \propto A^2 \;\Rightarrow\; \mathcal{H}_{\text{halo}} \propto \langle A \rangle$$



J. F. Cherry, A. Friedland, G. M. Fuller, J. Carlson, and A. Vlasenko, Phys. Rev. Lett. **108**, 261104 (2012), 1203.1607.

Spin Coherence –feedback crucial

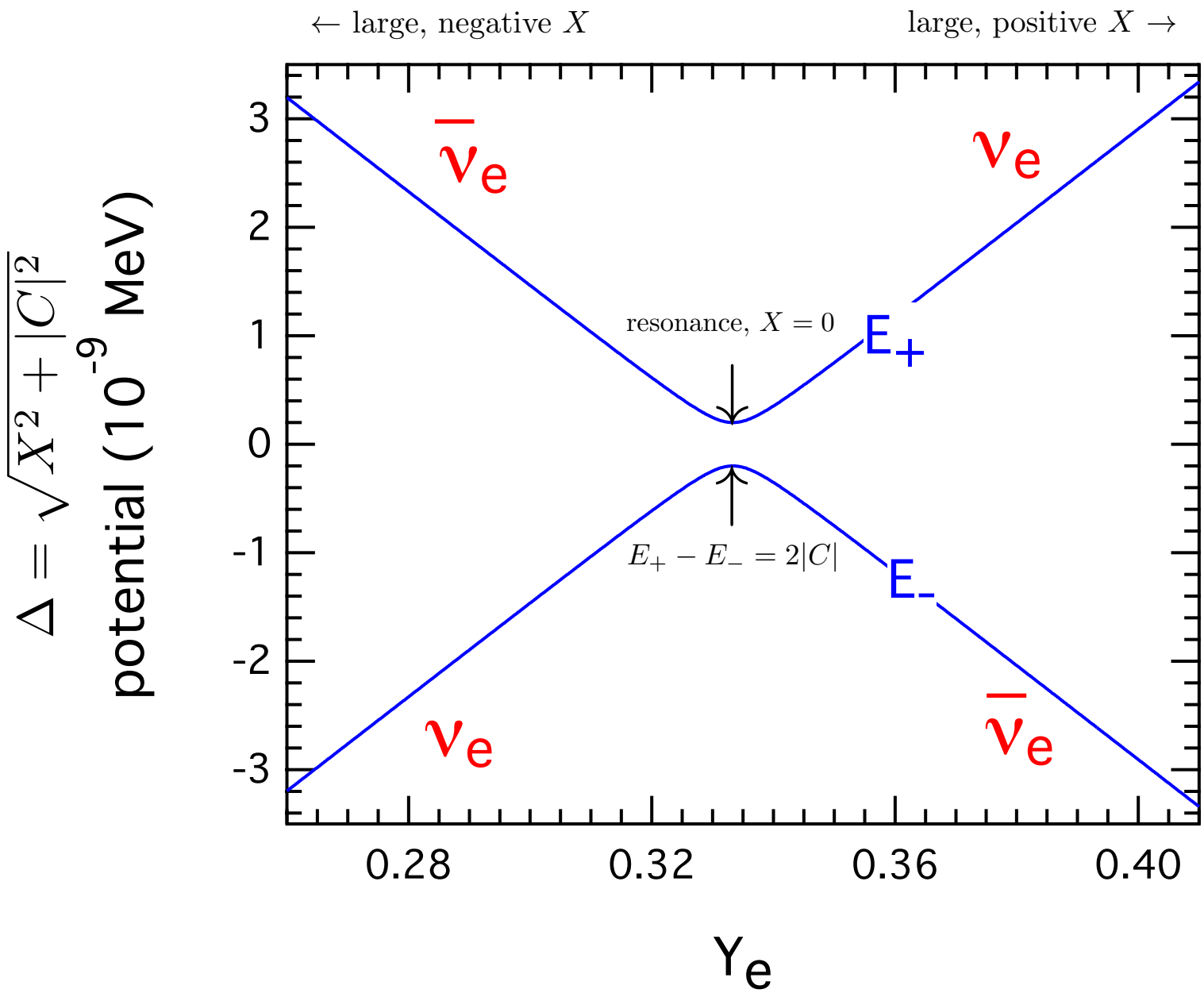
neutrino-antineutrino inter-conversion?

Not adiabatic in linear approximation,
but nonlinear feedback could be important

Alexey Vlasenko, G. M. Fuller, V. Cirigliano ArXiv:1406.6724
Alexey Vlasenko, GMF, V. Cirigliano, PRD **89**, 105004 (2014) ArXiv:1309.2628
V. Cirigliano, GMF, A. Vlasenko ArXiv: 1406.5558
C. Volpe, D. Vaananen, C. Espinoza, ArXiv: 1302.2374
B. Surreau & C. Volpe ArXiv: 1409.3591

Need: Neutrino mass; Majorana neutrinos; anisotopy in environment

Potentially significant implications for: *nucleosynthesis, neutrino signal, dynamics*



at relatively high matter (baryon) density

Neutrino-Antineutrino inter-conversion

interesting analogy to Majorana neutrino spin precession in a ***real magnetic field***

A. de Gouvea & S. Shalgar arXiv:1301.5637 showed that
standard model neutrino transition magnetic moment (~ 10^{-22} Bohr magnetons)
could engender *collective* neutrino-antineutrino oscillations – require ~ 10^{12} Gauss fields

similar process with QKE spin coherence, but no magnetic field required
--- sensitive to Majorana/Dirac nature of neutrinos, absolute mass, Majorana phases

neutrino-antineutrino conversion
potentially very important for nucleosynthesis
because the relative mix of neutrinos and antineutrinos
determines neutron-to-proton ratio

CONCLUSIONS for SN neutrinos

- Experimental neutrino physics has given us *some* of the mass/mixing properties of the neutrinos.
  Neutrino flavor evolution is sensitive to these, but may be sensitive to other BSM issues e.g., *hierarchy*, *magnetic moments*, *absolute mass*, *Majorana/Dirac* nature.

- Neutrino self coupling-induced ***nonlinearity*** has led to surprises and may lead to more
  -- very difficult to incorporate into existing SN simulations
  -- existing neutrino flavor simulations in SN are crude – but some phenomena are generic

- Despite uncertainties in calculations, it is imperative that we build and maintain an underground detector to capture a Galactic core collapse event

  – swaps/splits are generic and will likely form at *late times (where neutrino fluxes are low!)*

  -- will learn a great deal about supernovae, *e.g., if experiment gives us the hierarchy*

  -- heavy element nucleosynthesis, *e.g., r-Process models can be sensitive to neutrino/antineutrino ratio, which can influence the neutron/proton ratio*