Big Bang Nucleosynthesis

. . . and Insights into Neutrino Physics and Dark Matter

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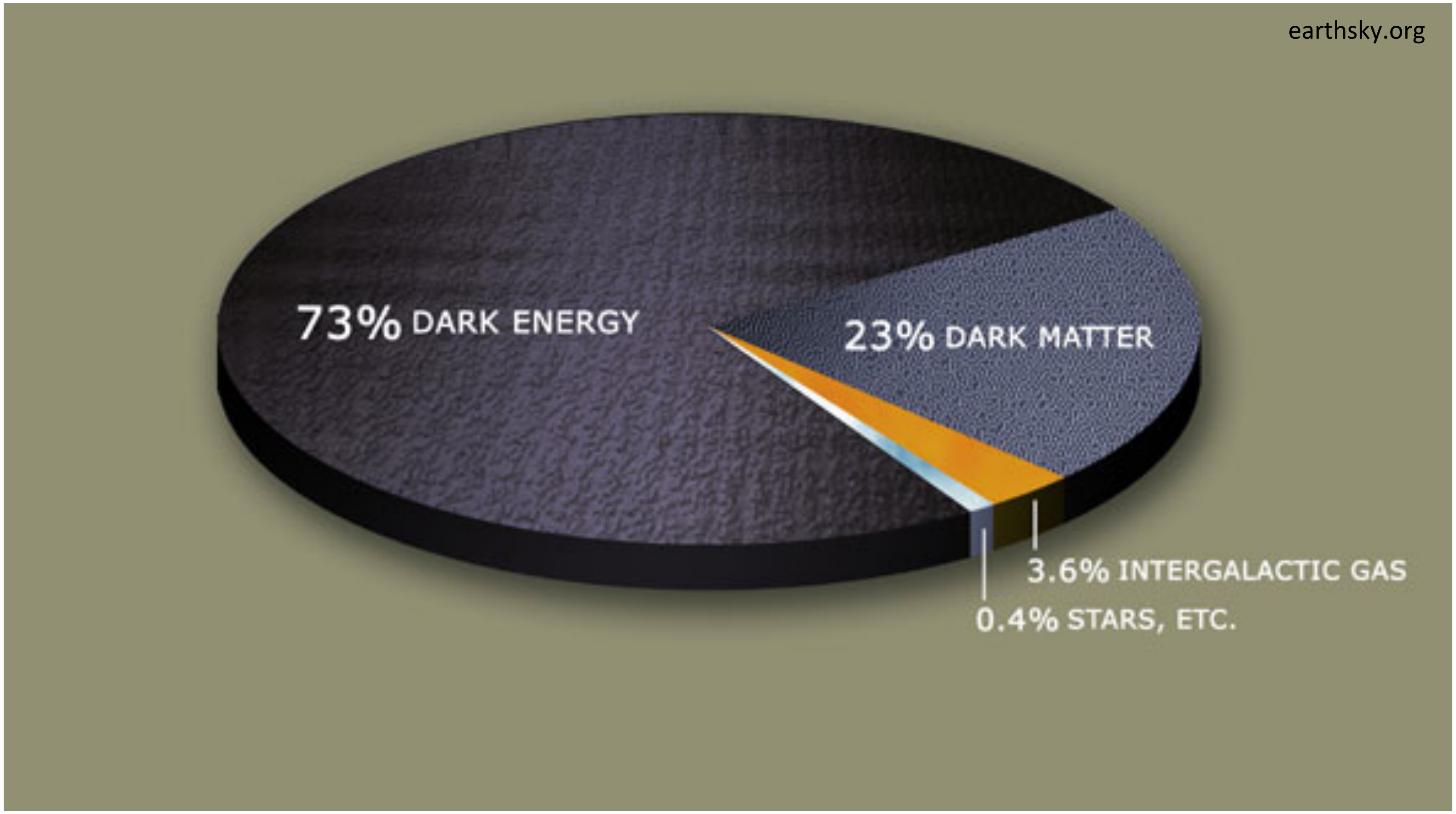
Nucleosynthesis and cosmic elemental abundances
give insights into *neutrino physics*,
the history of the baryonic component and structure formation,
and the composition and spatial distribution of ***Dark Matter***

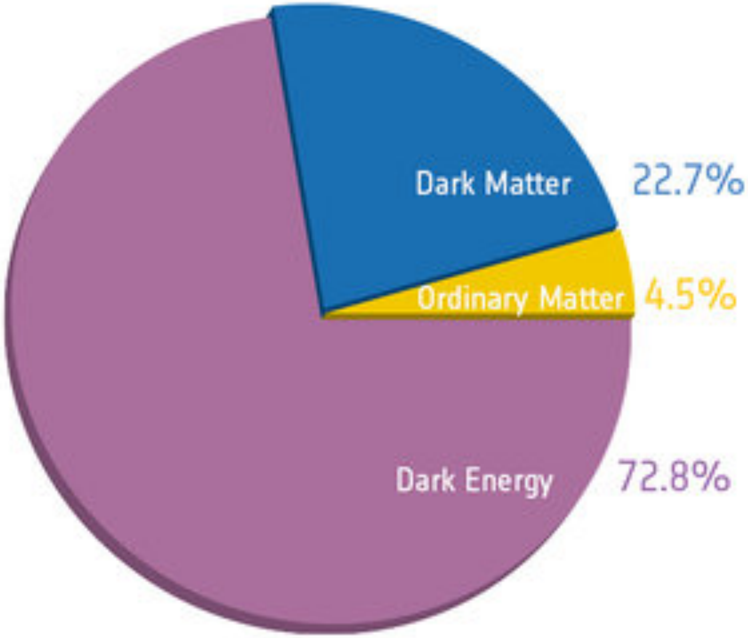
closing in on constraining the neutrino relic energy spectra . . .

this probes dark sector physics . . .

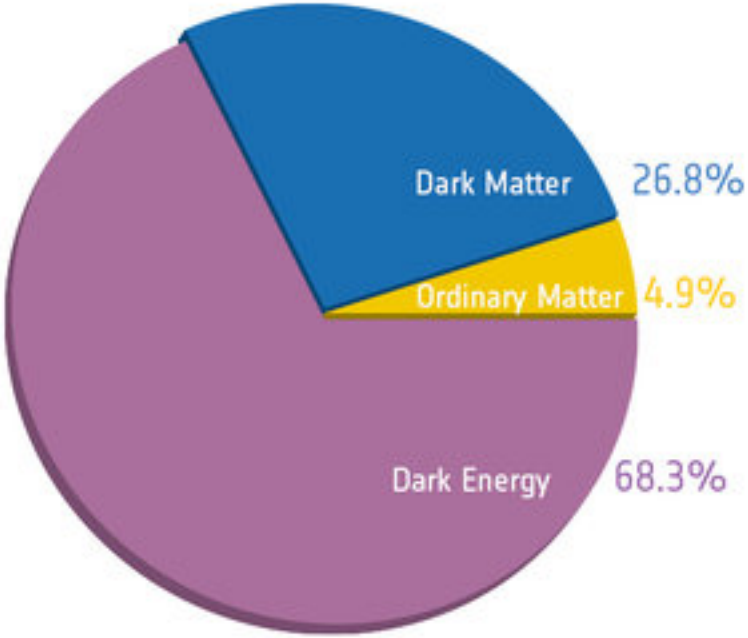
We live in a homogeneous and isotropic, critically closed (Ω=1), “flat”, spacetime



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.



Before Planck



After Planck

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 Possible *Indirect* Detections

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!

The underlying premise of my talk . . .

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?

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

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

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

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

⇒ 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:
⇒ measured hierarchy (LBNE?; Reactor Expt.s?; SN?);
⇒ 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 $\longrightarrow \eta \equiv \frac{n_{\mathrm{b}} - n_{\bar{\mathrm{b}}}}{n_\gamma}$

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

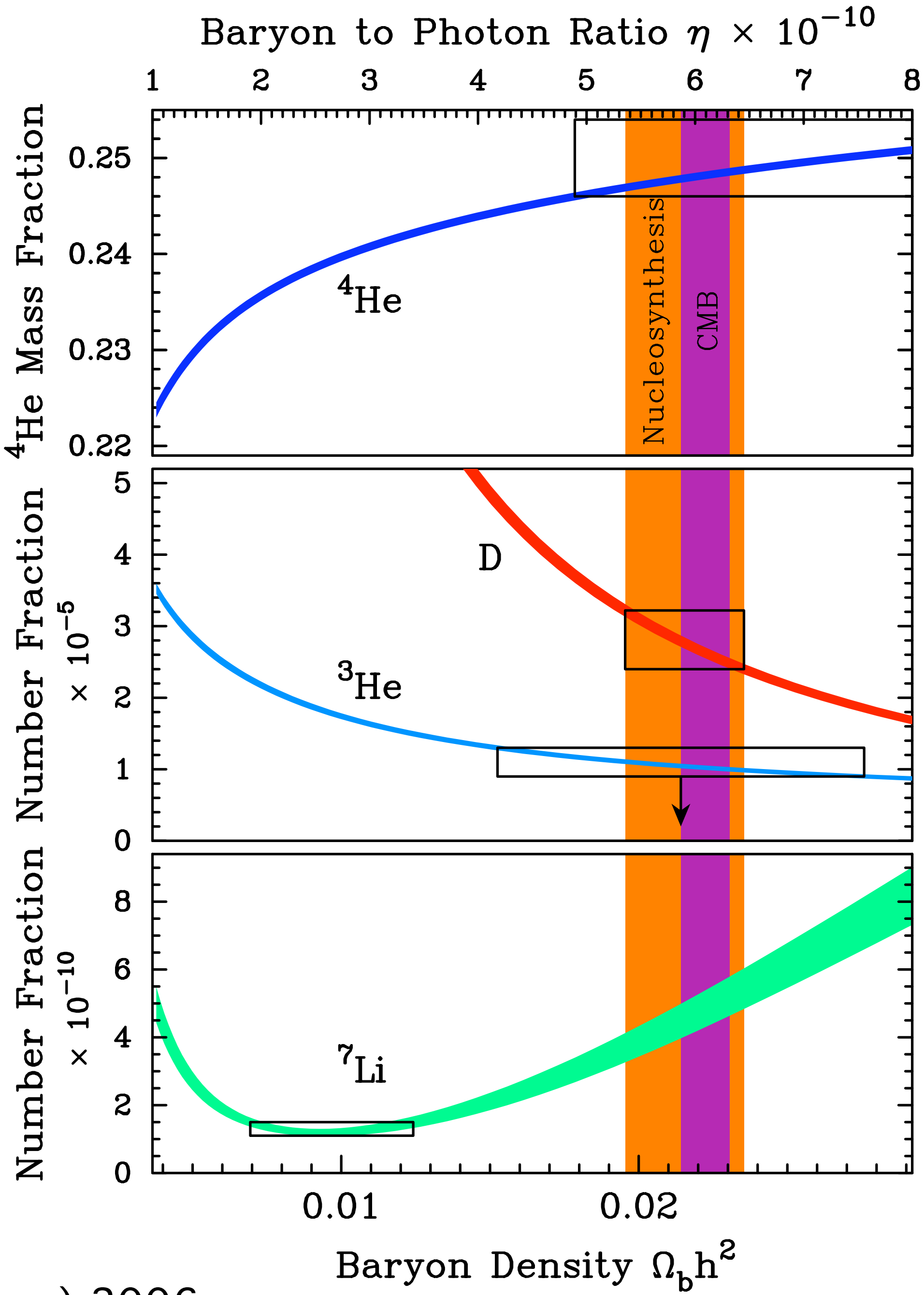
$$\eta = 6.11 \times 10^{-10}$$

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):

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

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

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

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

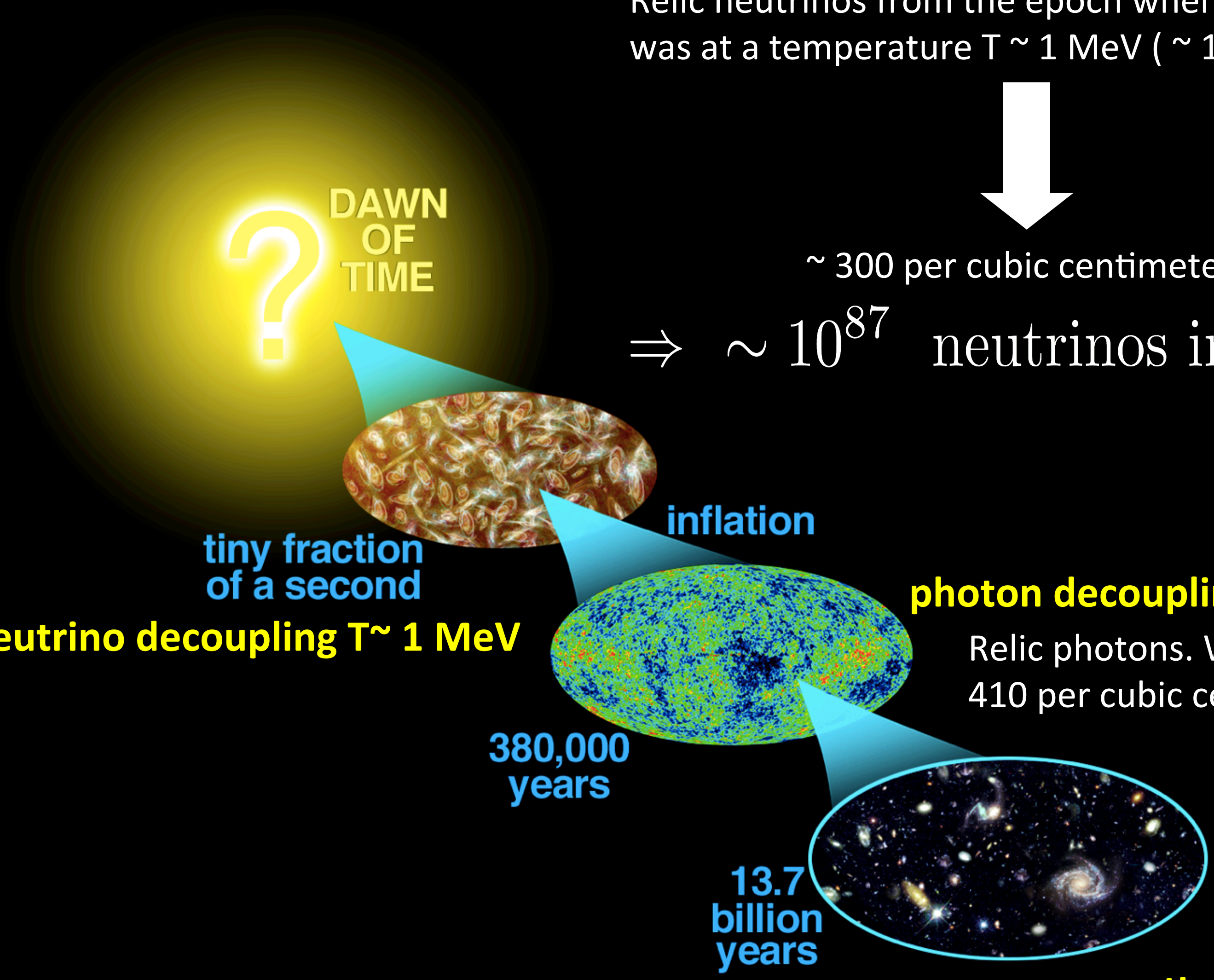
(3) Lithium is a mess:

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

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

~ 300 per cubic centimeter

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



neutrino decoupling T~ 1 MeV

photon decoupling T~ 0. 2 eV

Relic photons. We measure
410 per cubic centimeter

vacuum+matter dominated at current epoch

Matter-Radiation Equality

$$\rho_{\mathrm{matter}} \propto a^{-3}$$

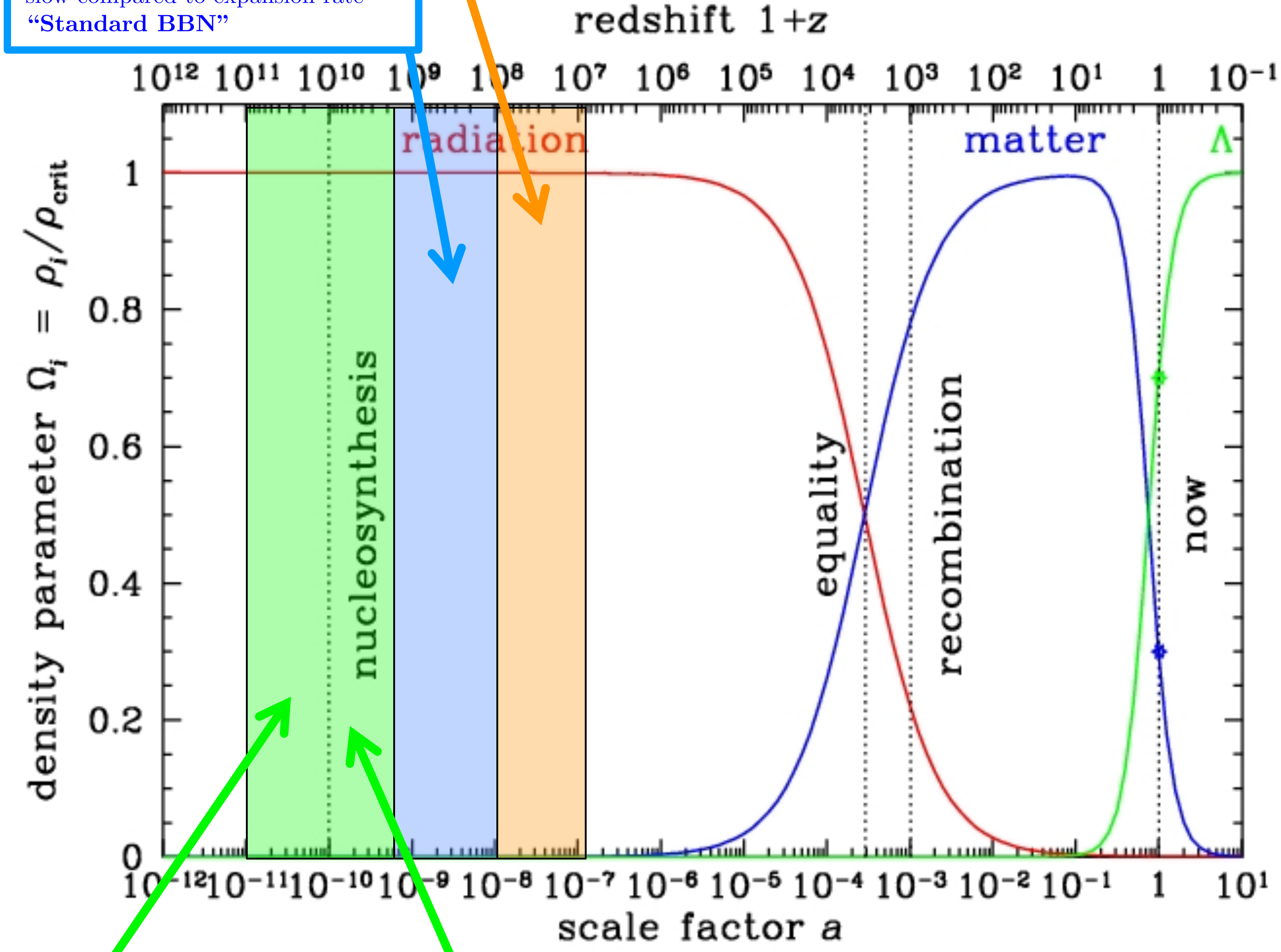
$$\rho_{\mathrm{radiation}} \propto a^{-4}$$

These are equal at an epoch where

$$1 + z_{\mathrm{eq}} = \frac{\rho_{\mathrm{CDM}} + \rho_{\mathrm{b}}}{\rho_{\mathrm{rad}}} \approx 40500\, \frac{\Omega_{\mathrm{CDM}}\, h^2 + \Omega_{\mathrm{b}}\, h^2}{1 + 0.23\, N_{\mathrm{eff}}}$$

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

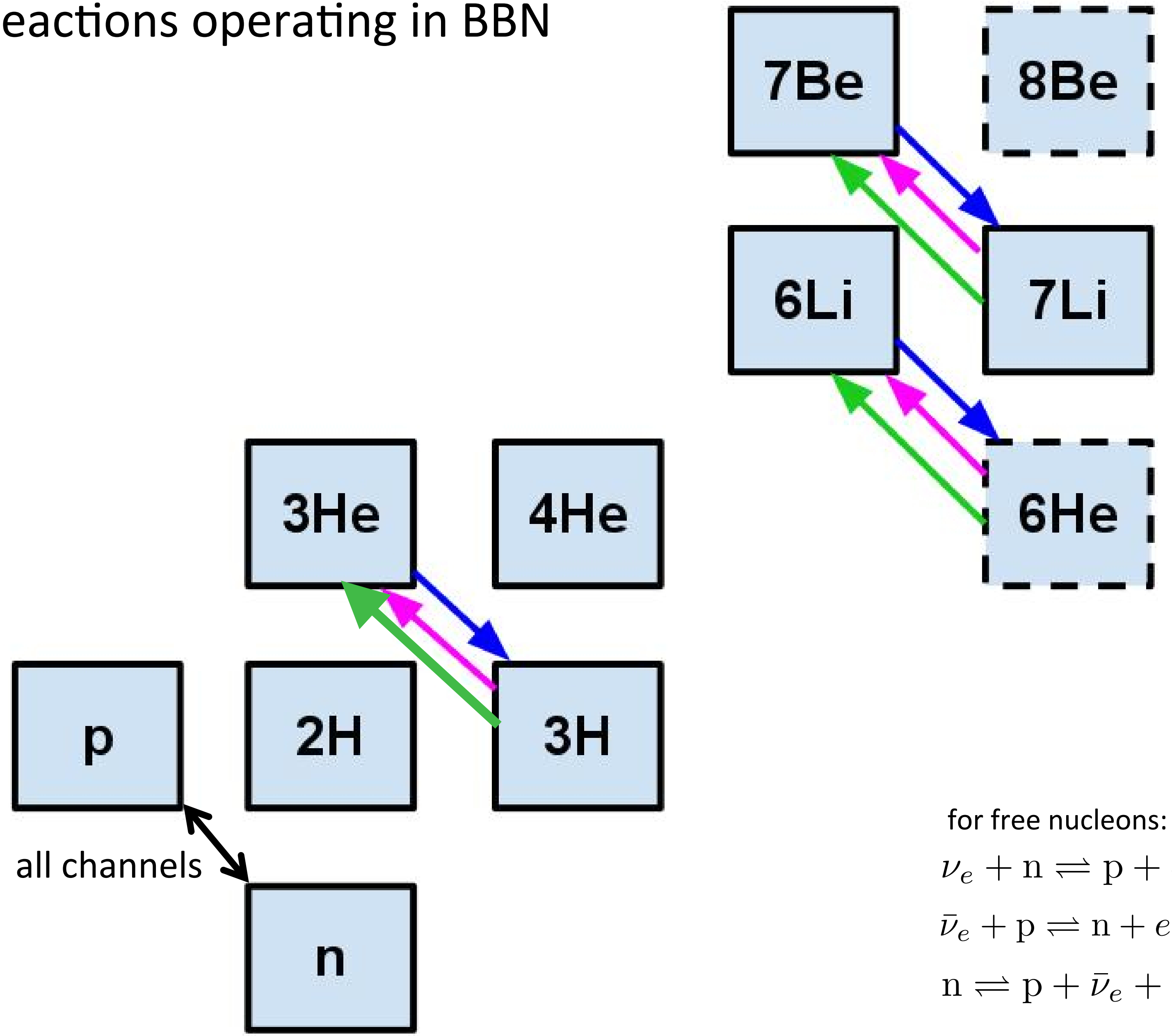
$T < 10\,\mathrm{keV}$ **particle decay-induced cascade nucleosynthesis?**



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.

weak reactions operating in BBN



for free nucleons:

$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$$

$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$

$$\mathrm{n} \rightleftharpoons \mathrm{p} + \bar{\nu}_e + e^-$$

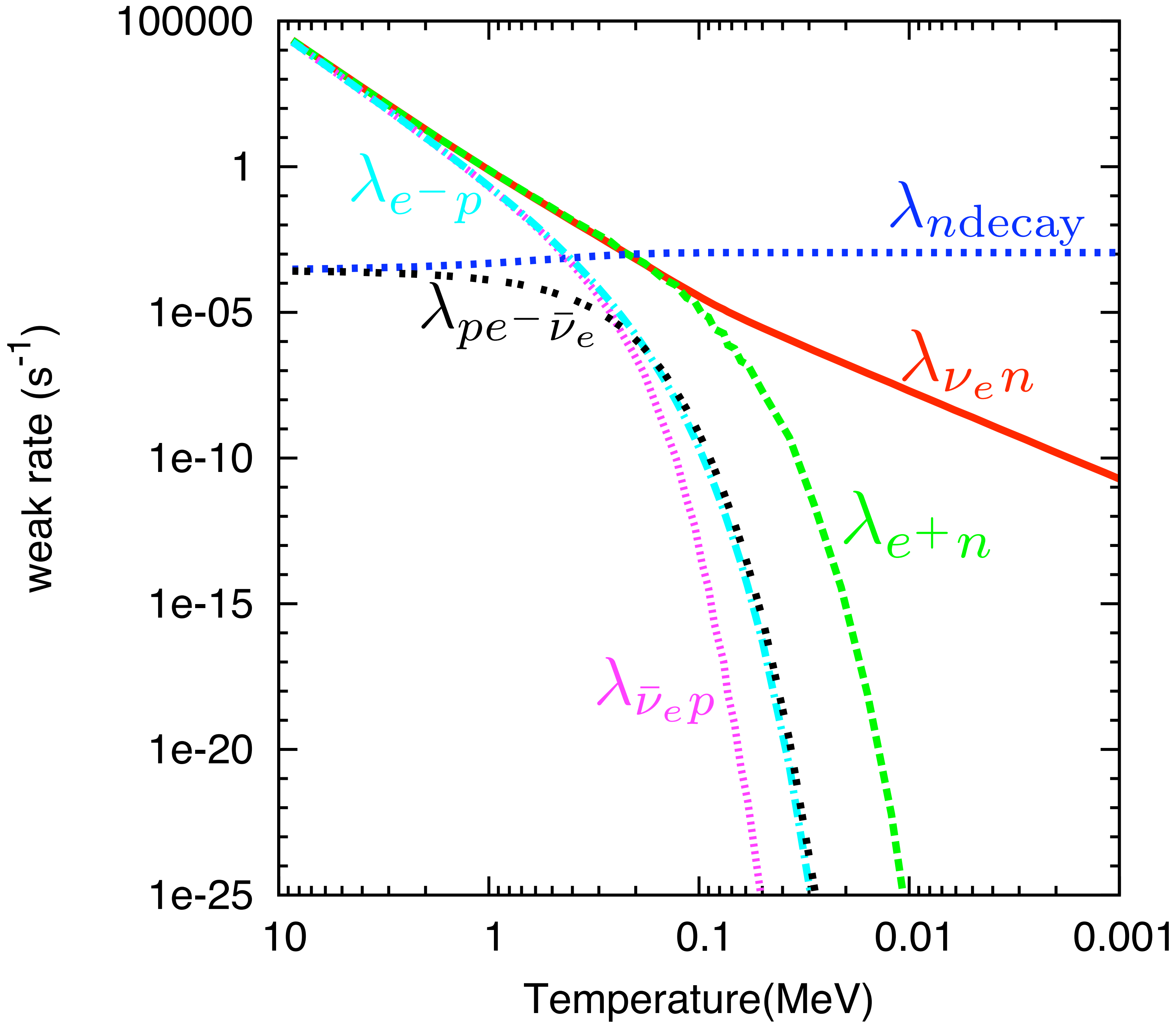
Neutron-to-proton ratio n/p is set by the competition between the rates of these processes:

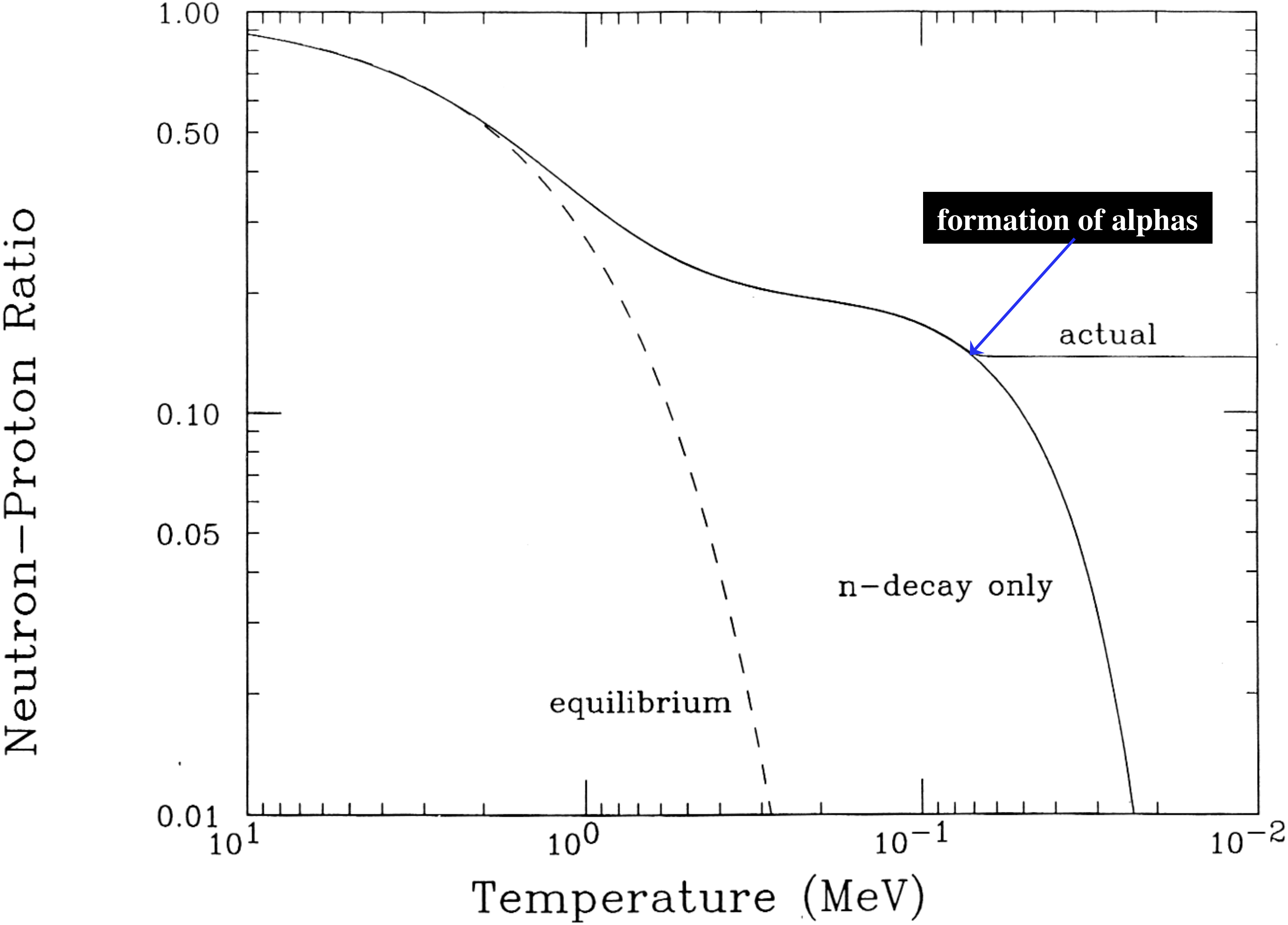
$$\nu_e + n \rightleftharpoons p + e^- \quad \begin{cases} \text{forward rate } \lambda_{\nu_e n} & \\ \text{reverse rate } \lambda_{e^- p} & \textbf{threshold} \end{cases}$$

$$\bar{\nu}_e + p \rightleftharpoons n + e^+ \quad \begin{cases} \text{forward rate } \lambda_{\bar{\nu}_e p} & \textbf{threshold} \\ \text{reverse rate } \lambda_{e^+ n} & \end{cases}$$

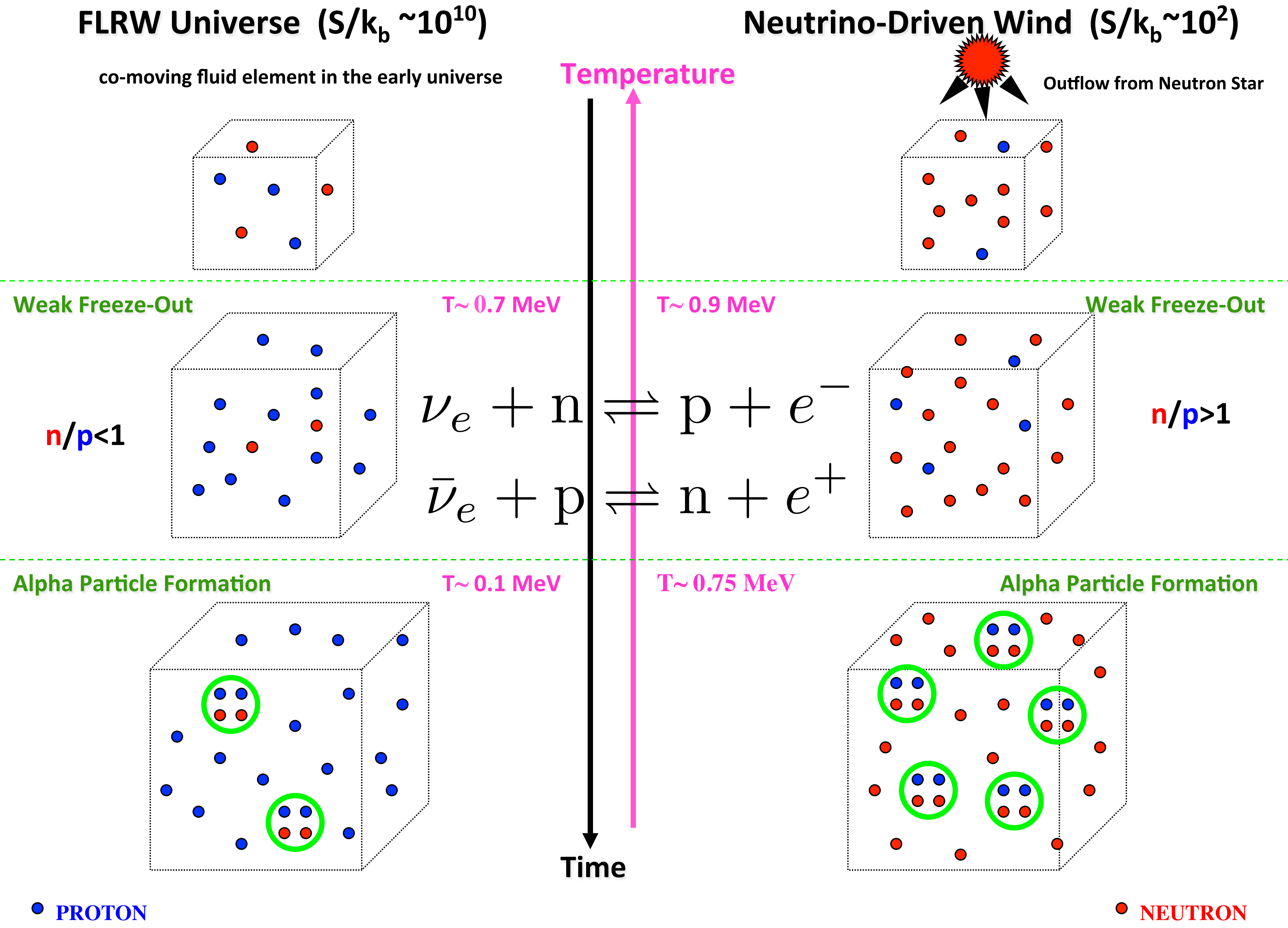
$$n \rightleftharpoons p + e^- + \bar{\nu}_e \quad \begin{cases} \text{forward rate } \lambda_{n\mathrm{decay}} & \\ \text{reverse rate } \lambda_{pe^- \bar{\nu}_e} & \textbf{threshold} \end{cases}$$

neutron-proton mass difference $\delta m_{np} \equiv m_n - m_p \approx 1.293\,\mathrm{MeV}$


100000
1
1e-05
1e-10
1e-15
1e-20
1e-25
10
1
0.1
0.01
0.001
weak rate (s^{-1})
Temperature(MeV)
λ_{e^-p}
$\lambda_{n\,decay}$
$\lambda_{pe^-\bar{\nu}_e}$
$\lambda_{\nu_e n}$
λ_{e^+n}
$\lambda_{\bar{\nu}_e p}$



formation of alphas



FLRW Universe ($S/k_b \sim 10^{10}$)

Neutrino-Driven Wind ($S/k_b \sim 10^2$)

co-moving fluid element in the early universe

Temperature

Outflow from Neutron Star

Weak Freeze-Out

T~ 0.7 MeV

T~ 0.9 MeV

Weak Freeze-Out

n/p<1

$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$$

$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$

n/p>1

Alpha Particle Formation

T~ 0.1 MeV

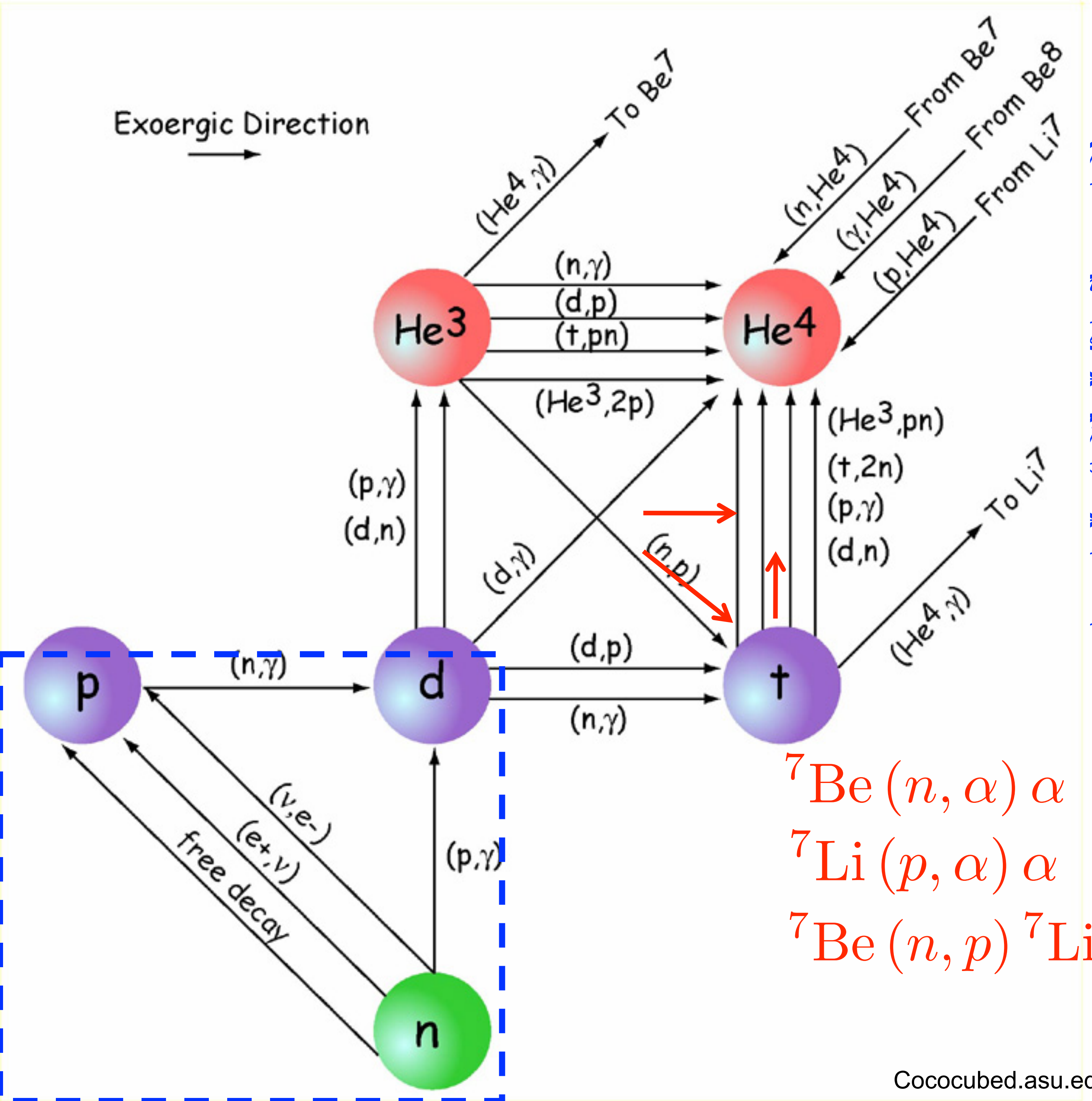
T~ 0.75 MeV

Alpha Particle Formation

Time

● PROTON

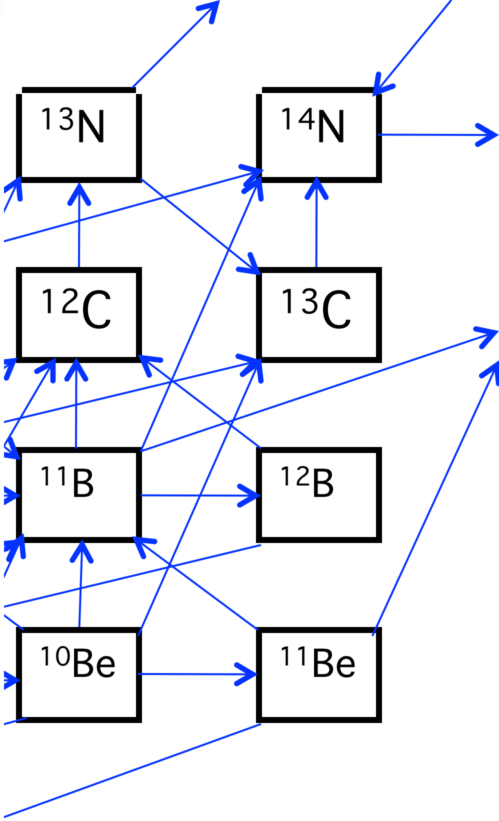
● NEUTRON



$^{7}\mathrm{Be}\,(n,\alpha)\,\alpha$

$^{7}\mathrm{Li}\,(p,\alpha)\,\alpha$

$^{7}\mathrm{Be}\,(n,p)\,^{7}\mathrm{Li}$



$$^{8}\mathrm{Be} \to 2\alpha$$

Cococubed.asu.edu/code-pages/net_bigbang.shtml

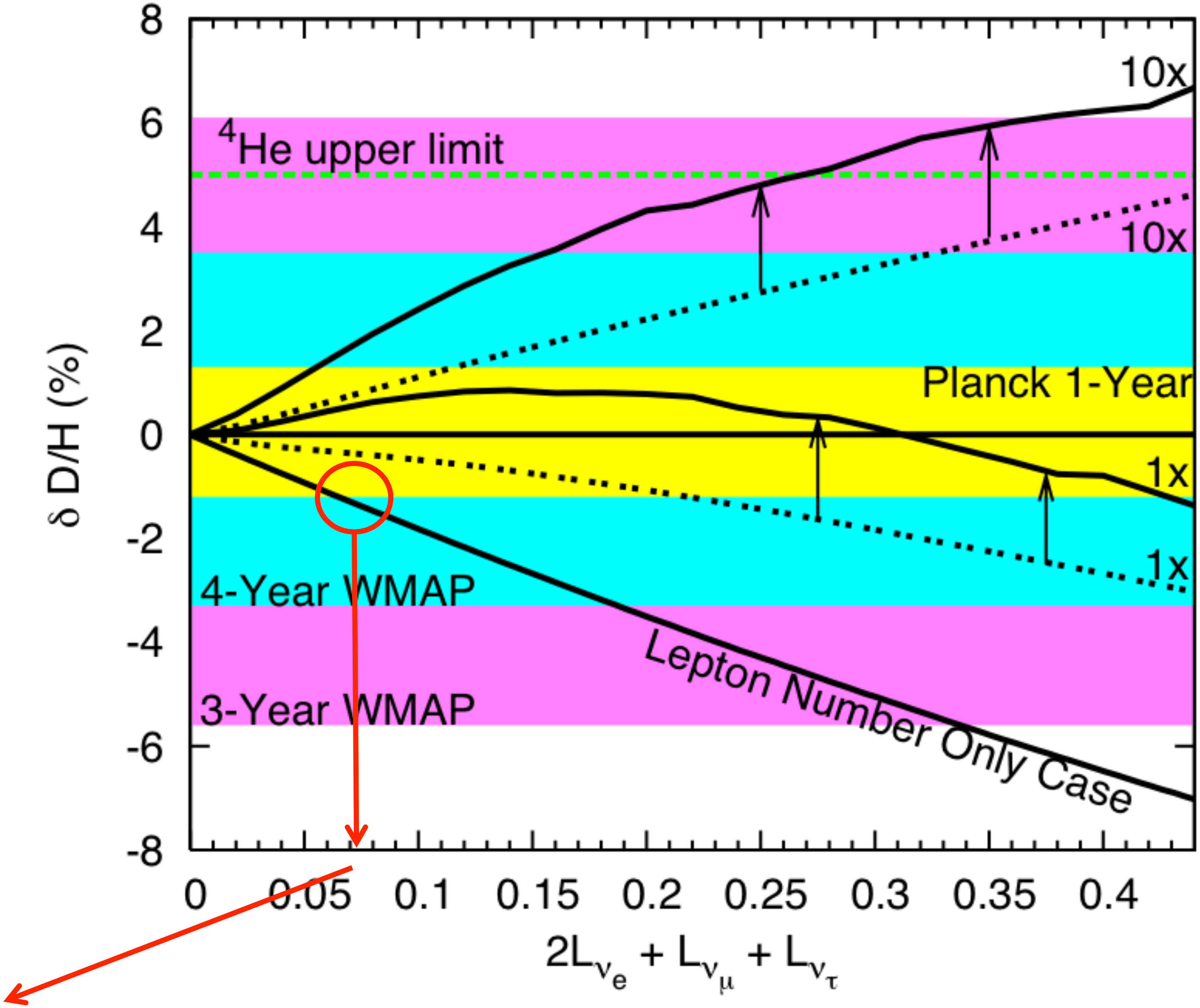
very crudely:

^{4}He yield sensitive to neutron/proton ratio

^{2}H sensitive to baryon density

Actually, helium *does* depend on baryon density, and deuterium *does* depend on the n/p ratio and the expansion rate.

C. Smith, G. Fuller, C. Kishimoto, K. Abazajian, PRD **74,** 085008 (2006)


$\delta m^2 = 1\ \mathrm{eV}^2$

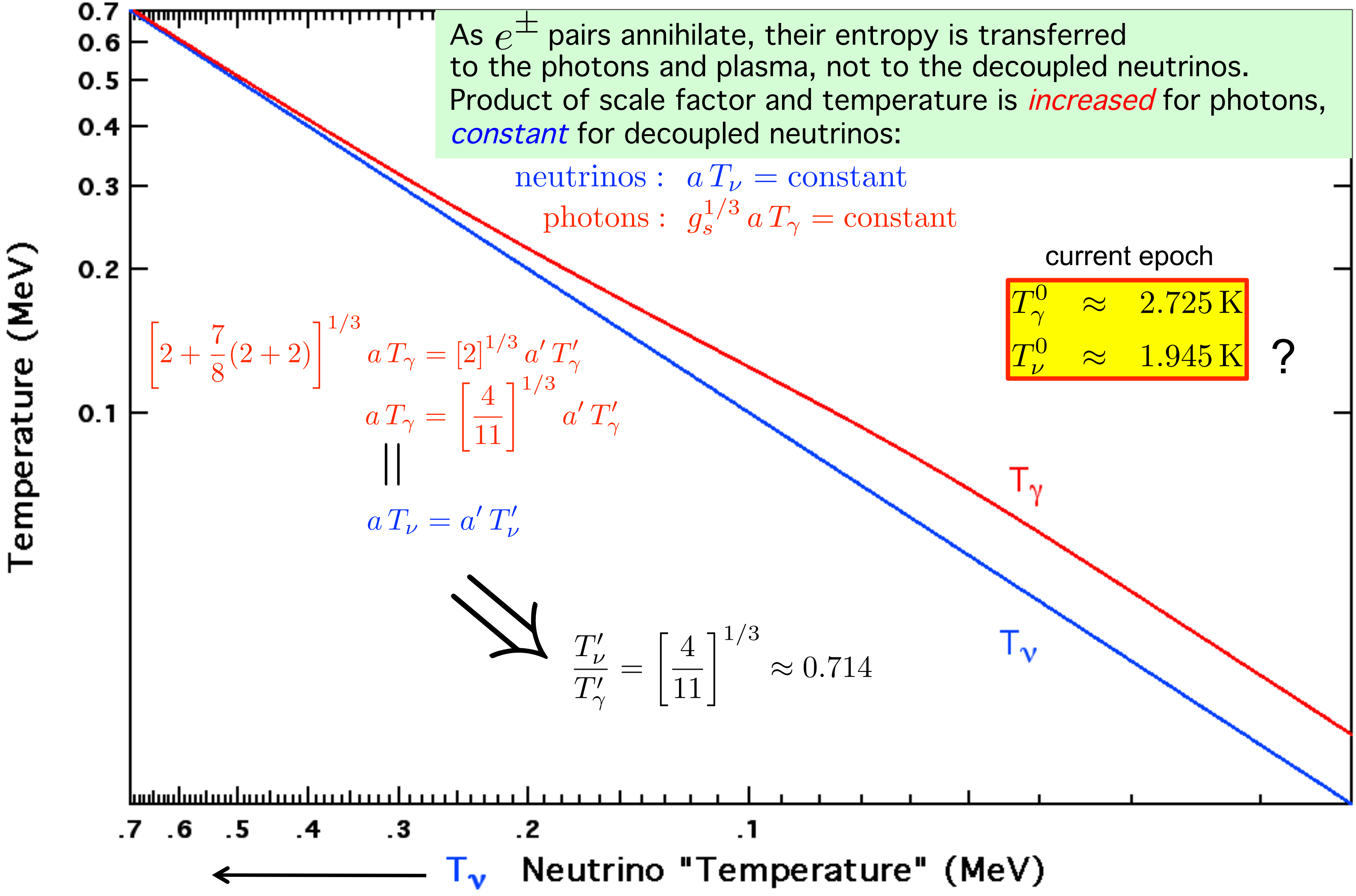
$0.07 = 2L_{\nu_e} + L_{\nu_\mu} + L_{\nu_\tau} \approx 4L_{\nu_e} \quad \Rightarrow L_{\nu_e} < 0.02$ versus current limit < 0.15

Symmetry is everything in GR

Homogeneity and isotropy of the universe dictates that there be no heat flow or non-uniform heat sources: evolution is adiabatic

entropy in a co-moving volume is conserved

For relativistic particles contributing statistical weight g, the entropy per unit proper volume is
$S = \frac{2\,\pi^2}{45}\, g\, T^3$,
so in a co-moving volume a^3 (cube of scale factor),
the product $S \cdot a^3$ is conserved $\rightarrow g^{1/3}\, a\, T =$ constant.



As $e^{\pm}$ pairs annihilate, their entropy is transferred to the photons and plasma, not to the decoupled neutrinos. Product of scale factor and temperature is *increased* for photons, *constant* for decoupled neutrinos:

$$\text{neutrinos}: \quad a\,T_\nu = \text{constant}$$

$$\text{photons}: \quad g_s^{1/3}\,a\,T_\gamma = \text{constant}$$

current epoch

$$\boxed{\begin{array}{lcl} T_\gamma^0 & \approx & 2.725\,\mathrm{K} \\ T_\nu^0 & \approx & 1.945\,\mathrm{K} \end{array}}$$

?

$$\left[2 + \frac{7}{8}(2+2)\right]^{1/3} a\,T_\gamma = [2]^{1/3}\,a'\,T'_\gamma$$

$$a\,T_\gamma = \left[\frac{4}{11}\right]^{1/3} a'\,T'_\gamma$$

$$||$$

$$a\,T_\nu = a'\,T'_\nu$$

$$\Rightarrow \quad \frac{T'_\nu}{T'_\gamma} = \left[\frac{4}{11}\right]^{1/3} \approx 0.714$$

← scale factor $a \propto 1/T_\nu$ →

Dark Radiation

N_{eff} as a probe of neutrino sector
and high energy-scale physics

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)

$$\mathrm{Nine-year\ WMAP} \quad \mathrm{N_{eff}} = 3.26 \pm 0.35$$
$$\mathrm{ACT} \quad \mathrm{N_{eff}} = 2.78 \pm 0.55$$
$$\mathrm{SPT-SZ\ Survey} \quad \mathrm{N_{eff}} = 3.71 \pm 0.35 \quad (\mathrm{H_0\ and\ BAO\ priors})$$

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

analysis with BAO &
sterile mass < 10 eV,
thermal spectrum

$$\mathrm{N_{eff}} < 3.80 \quad \& \quad m_\nu^{\mathrm{sterile}} < 0.42\,\mathrm{eV}, \ \mathrm{at}\ 95\%\ \mathrm{conf.}$$

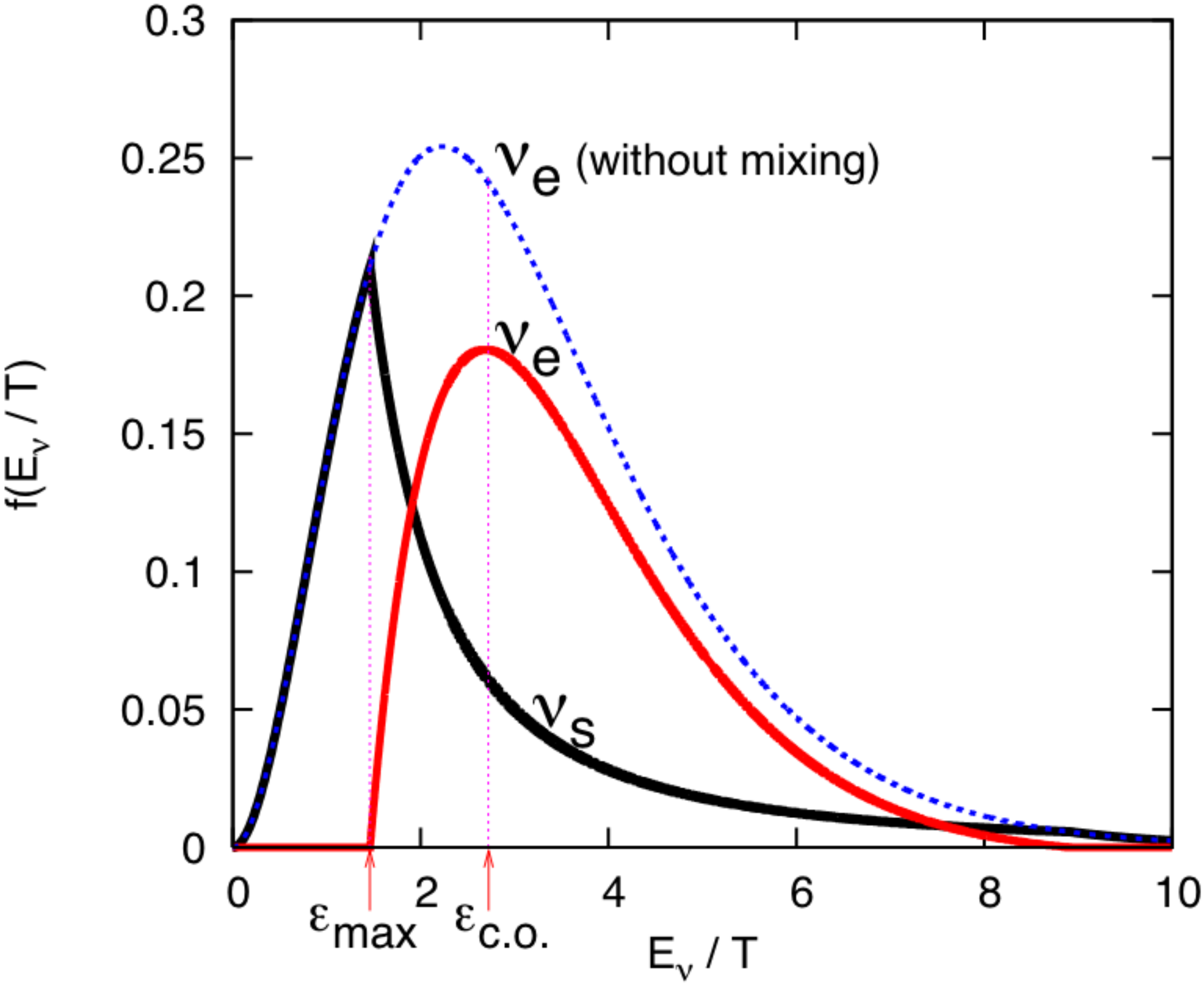
Caveats on CMB as a probe of sterile neutrinos

. . . 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

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

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



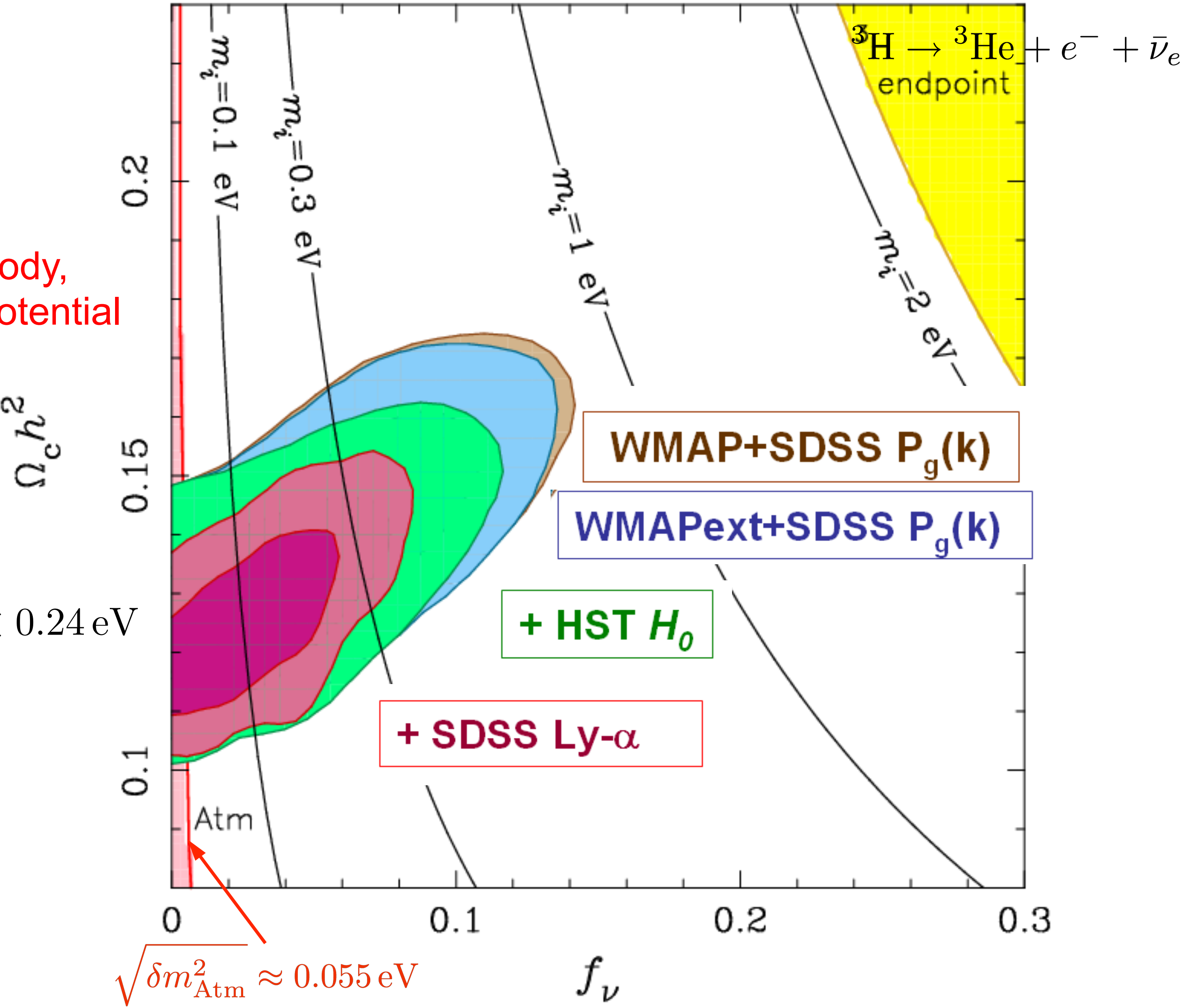
C. Kishimoto, G. M. Fuller, C. Smith, PRL **97,** 141301 (2006)

cosmological constraints on neutrino rest mass

WMAP$_{\text{+ACBAR+CBI}}$ + SDSS + HST: ν Dark Matter

assumes that neutrinos have thermal, black body, zero chemical potential energy spectra

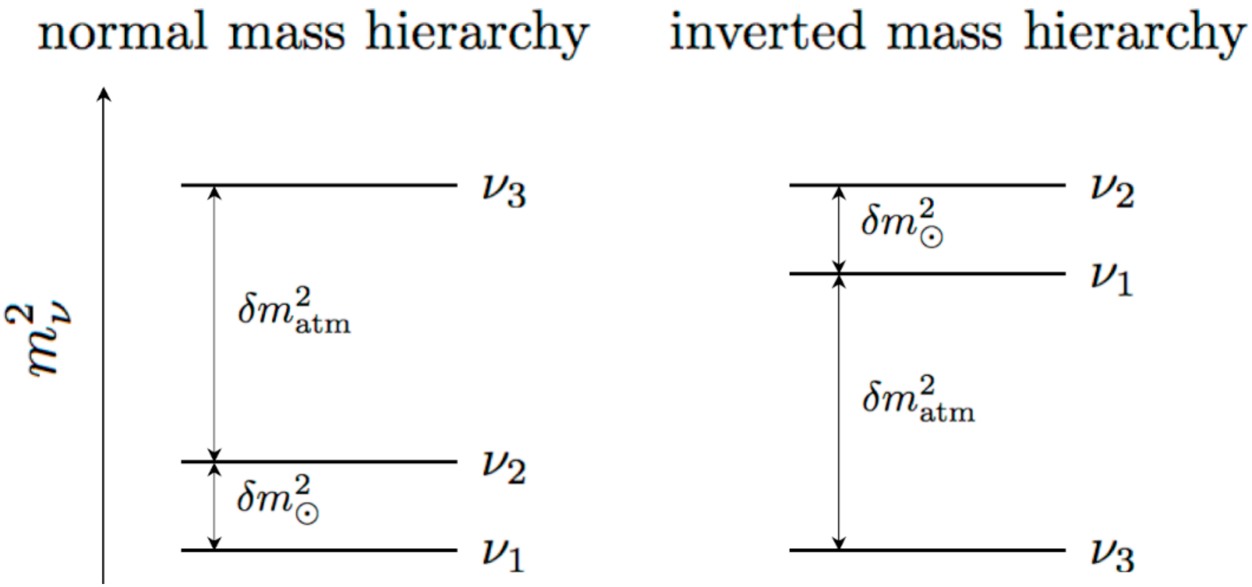
Planck $\sum m_\nu < 0.24\,\mathrm{eV}$



$\sqrt{\delta m^2_{\mathrm{Atm}}} \approx 0.055\,\mathrm{eV}$

K. Abazajian

at least one of the vacuum neutrino mass eigenvalues satisfies $m_3 \ (\text{or } m_2) \geq \sqrt{\delta m^2_{\text{atm}}} \approx 0.05\,\text{eV}$



normal mass hierarchy

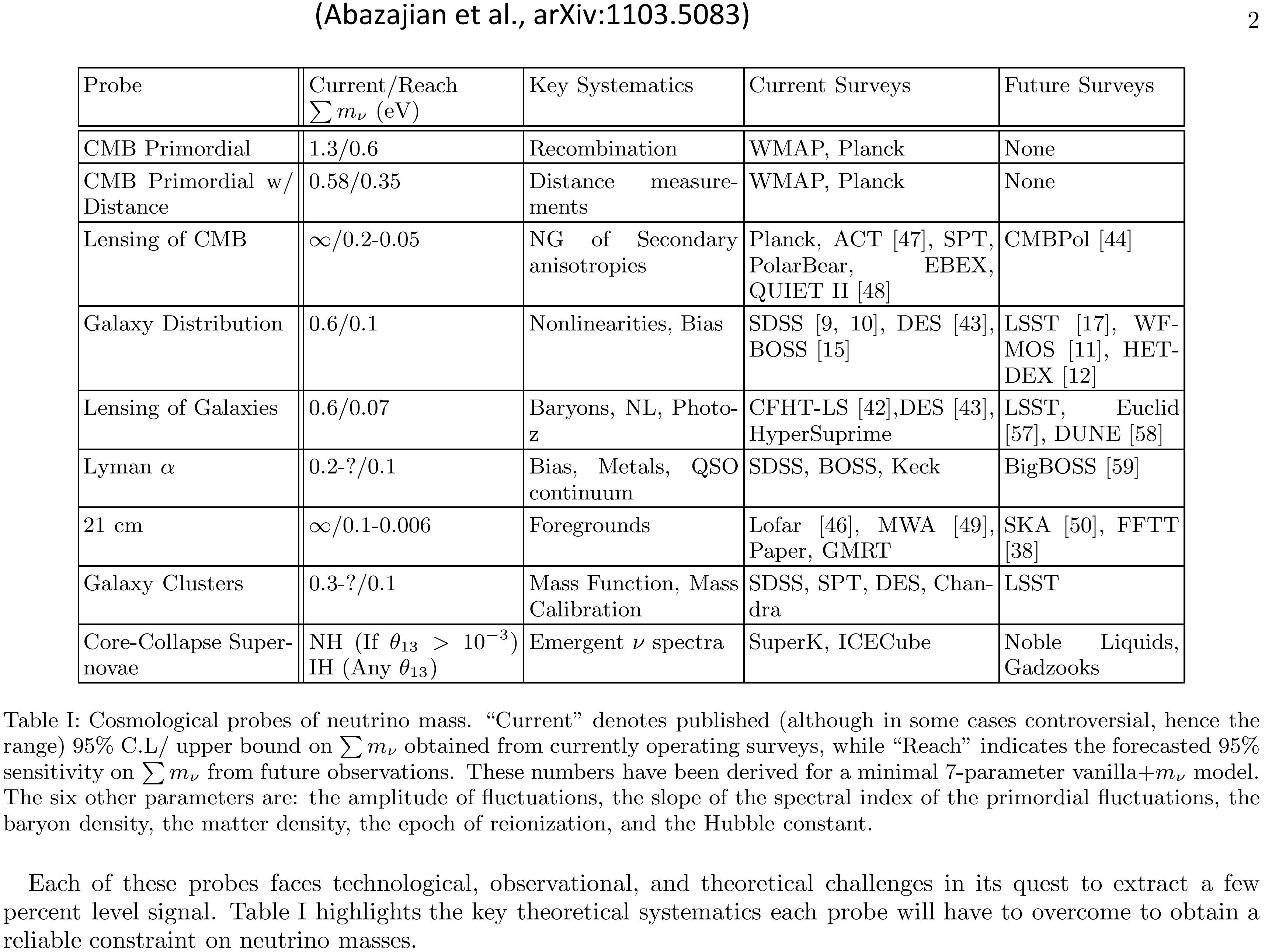
inverted mass hierarchy

$\Sigma m_\nu \geq 0.05\,\text{eV}$ $\Sigma m_\nu \geq 0.1\,\text{eV}$

$$\sum m_\nu < 0.23\,\text{eV} \ \ (95\,\text{percent conf.; Planck + WP + highL + BAO})$$

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.

CMB + large-scale structure observations *do not* actually measure
the neutrino rest mass, but rather a convolution of this
with the relic neutrino energy spectrum.

It is likely, in my opinion, that we already know the relevant neutrino rest mass,
so that a signal for the "sum of the light neutrino masses" is tantamount to
a *detection of the relic neutrino background*.

This therefore would give a constraint on the relic neutrino energy spectrum.

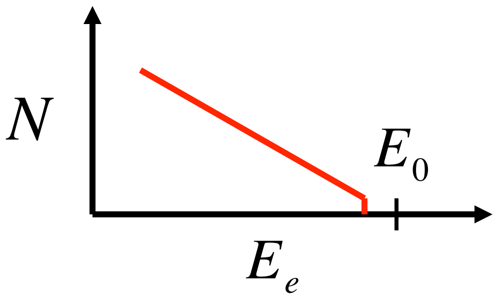
Direct Laboratory Limits on Neutrino Rest Masses

"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)

$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e \qquad \frac{dN}{dE_e} \propto \sqrt{\left(E_e - E_0\right)^2 - "m^2_{\nu_e}"}$$



$$"m^2_{\nu_e}" \approx +0.6 \pm 2.8 \pm 2.1 \ \text{eV}^2$$
$$\approx -1.6 \pm 2.5 \pm 2.1 \ \text{eV}^2$$

< 4 eV² with high confidence

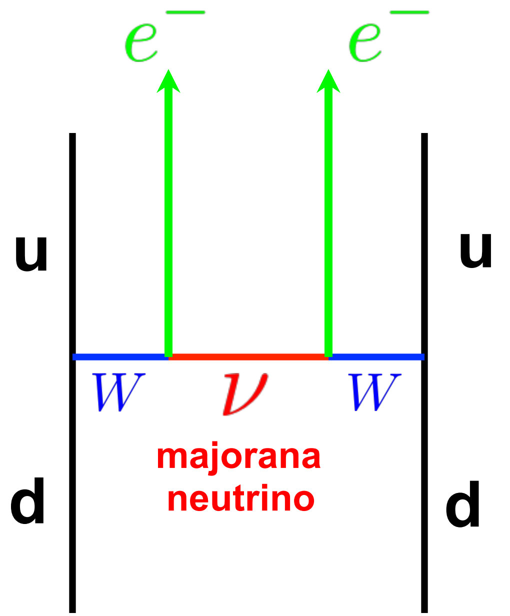
- J. Bonn *et al.,* Nucl. Phys. B 91, 273, 2001.

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

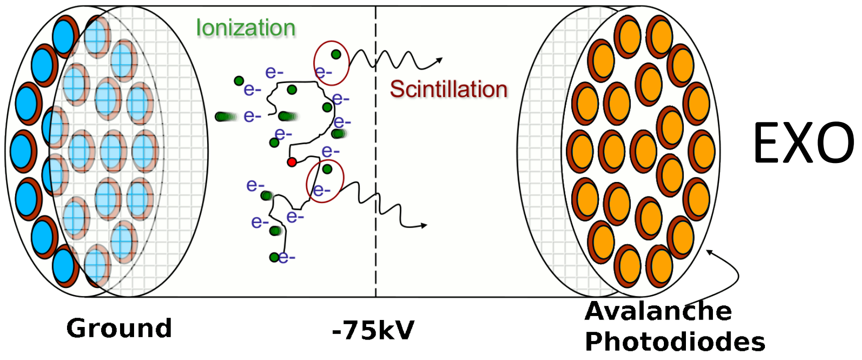
Majorana Neutrinos: Neutrinoless Double Beta Decay



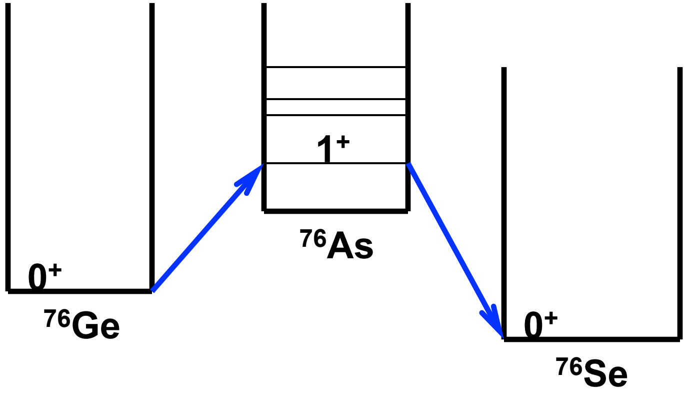
$$\Gamma_{0\nu} = \frac{1}{\tau_{\beta\beta}} = G_{0\nu} |M_{\text{nuc}}|^2 m_{\beta\beta}^2$$

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

two neutrons change into two protons



Second order weak process:
coherent sum over intermediate nuclear states



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

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

contrary to what you may have heard . . .

Sterile Neutrinos can be
Hot, Warm, or *COLD*
Dark Matter

. . . depending on how their relic densities are produced !!

Bruno Pontecorvo

recognized that the handedness of the weak interaction meant that non-zero neutrino rest mass could enable neutrino spin flip from active, left-handed states, to **sterile**, right-handed states.

Soviet Physics – JETP **26**, 984 (1968)

A take-away message from the experiments is that neutrinos have ***non-zero rest masses***

This fact begs the question: Are there sterile neutrino states?

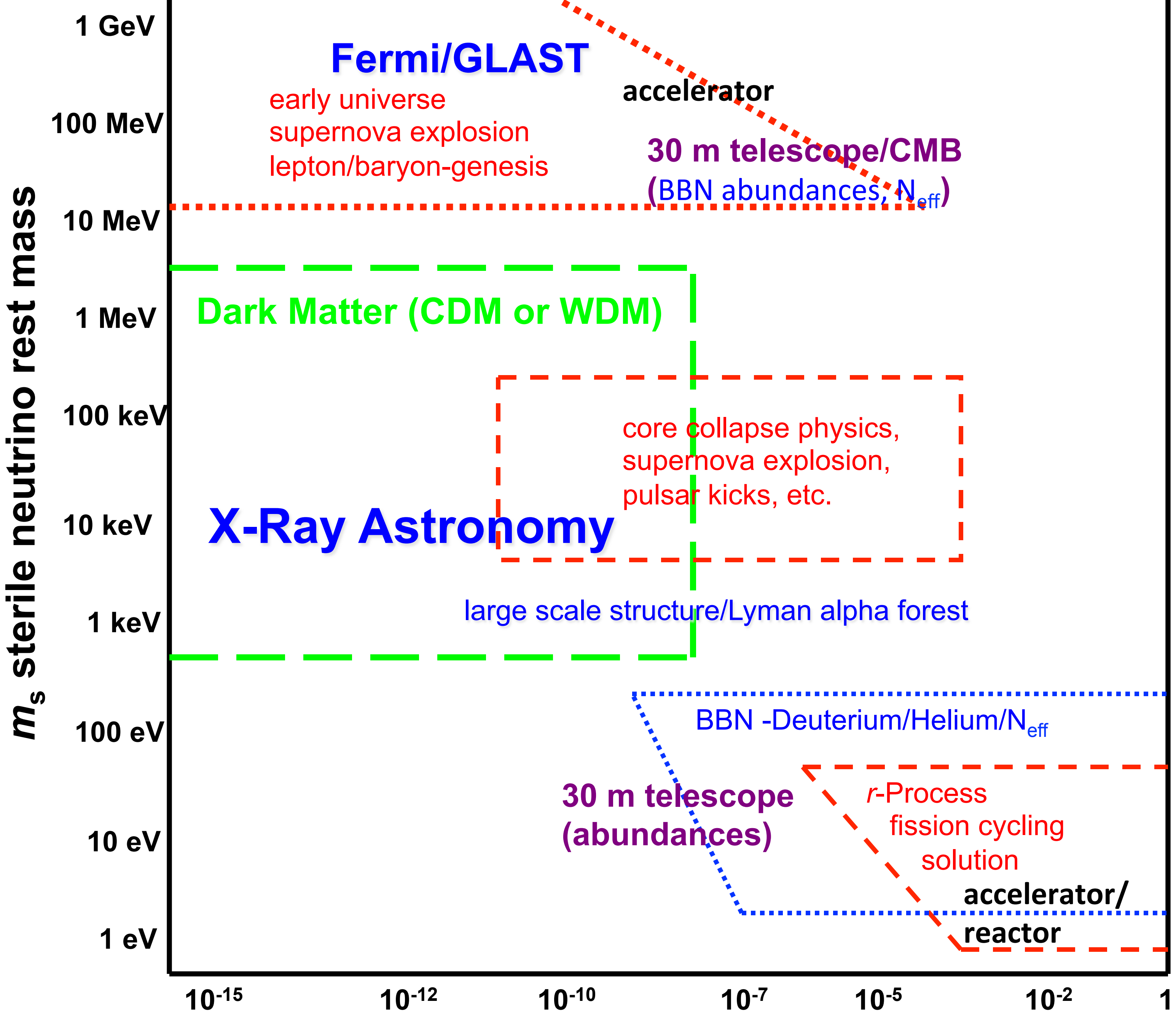
$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$|\nu_s\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

If sterile neutrinos mix with active neutrinos in vacuum like this, then they are not really ***sterile*** !!

active neutrino cross section $\sigma \sim G_{\rm F}^2\, E_\nu^2$

"sterile" neutrino cross section $\sigma \sim (G_{\rm F}^2\, \sin^2\theta)\, E_\nu^2$



Fermi/GLAST

early universe
supernova explosion
lepton/baryon-genesis

accelerator

30 m telescope/CMB
(BBN abundances; N_{eff})

Dark Matter (CDM or WDM)

core collapse physics,
supernova explosion,
pulsar kicks, etc.

X-Ray Astronomy

large scale structure/Lyman alpha forest

BBN -Deuterium/Helium/N_{eff}

30 m telescope
(abundances)

r-Process
fission cycling
solution

accelerator/
reactor

$\nu_s \rightarrow \pi^0 + \nu_{e,\mu,\tau}$

$\gamma + \gamma$

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

electromagnetic
decay channels

(decay processes
positioned at
energy thresholds)

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

ν_s interaction strength relative to normal weak interaction

$|U_{e4}|^2$ active-sterile vacuum mixing

Sterile Neutrino Dark Matter production models

see review by Alex Kusenko: *Physics Reports* **481**, 1 (2009)

active-active neutrino scattering-induced decoherence

S. Dodelson & L. M. Widrow, Phys. Rev. Lett. **72**, 17 (1994)

A. D. Dolgov & S. H. Hansen, Astropart. Phys. **16**, 339 (2002)

→ Largely eliminated by the X-ray observations

But Many Models Are Still Viable . . .

low temperature inflation

M. Shaposhnikov & I. Tkachev, Phys. Lett. B **639**, 414 (2006)

Higgs decay and dilution/late-entropy addition

A. Kusenko, Phys. Rev. Lett. **97**, 241301 (2006)
K. Petraki & A. Kusenko (2007), arXiv:0711.4646
K. Petraki (20008), arXiv:0801.3470
T. Asaka, S. Blanchet, M. Shaposhnikov, Phys. Lett. B **631**, 151 (2005)
G. Fuller, C. Kishimoto, A. Kusenko, A. Patwardhan 2014

lepton number-enhanced decoherence

X. Shi & G. M. Fuller, Phys. Rev. Lett. **83**, 3120 (1999)

K. Abazajian, G.M. Fuller, M. Patel, Phys. Rev. D **64**, 023501 (2001)

C. Kishimoto & G.M. Fuller, Phys. Rev. D **78**, 023524 (2008) arXiv:0802.3377

M. Shaposhnikov, Nucl. Phys. B **763**, 49 (2007)

~~**(1) Quantum Mechanical Limit:** Dodelson & Widrow 1994~~

~~active neutrino scattering-induced de-cohere [illegible] produces~~
~~a relic density of ster [illegible] utrinos -- *picks out keV scale rest masses, small vacuum mixing angles*~~

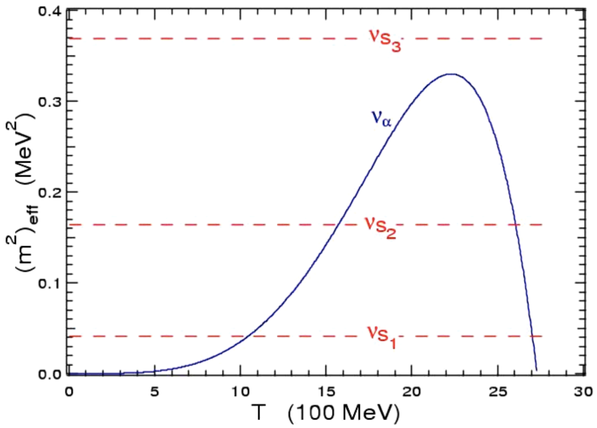
(2) Lepton number-driven resonant production: Shi & Fuller 1998; Abazajian, Fuller, Patel 2001; Abazajian ‘14

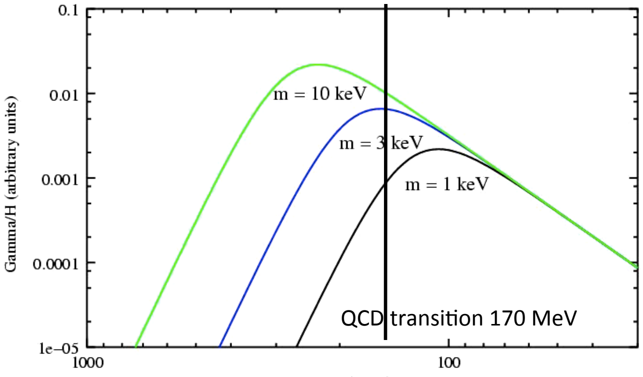
Like MSW, initial lepton number partially converted to a relic sterile neutrino population

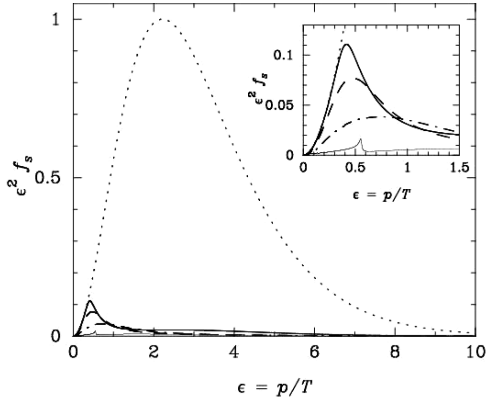
-- *can work for smaller mixing angles, colder sterile neutrino relic energy spectrum*

-- *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)*





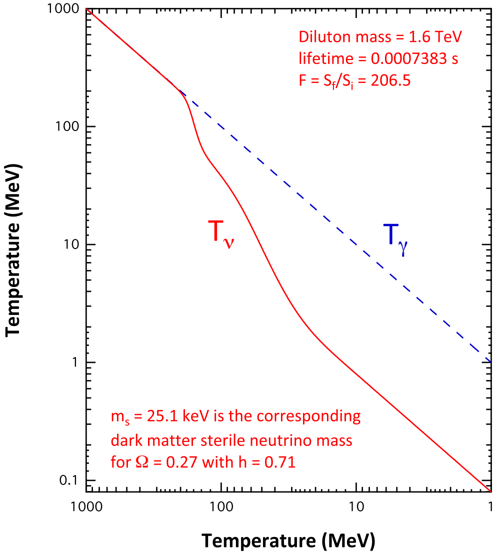


(3) Higgs decay; Dilution:

e.g., Asaka, Shaposhnikov, Kusenko (2006);
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*



Crude QKE's - Evolution of the neutrino distribution functions given by a Boltzmann-like equation:

$\alpha = e,\mu,\tau$

$$\frac{\partial}{\partial t} f_s(p,t) - Hp\frac{\partial}{\partial p} f_s(p,t) \approx \Gamma(\nu_\alpha \to \nu_s; p,t)\left[f_\alpha(p,t) - f_s(p,t)\right]$$

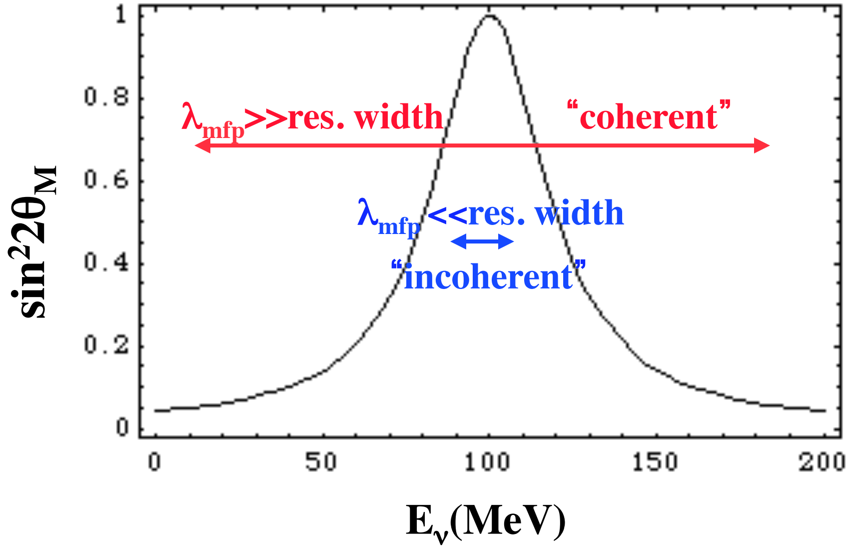
neutrino inelastic scattering rate

neutrino flavor conversion rate

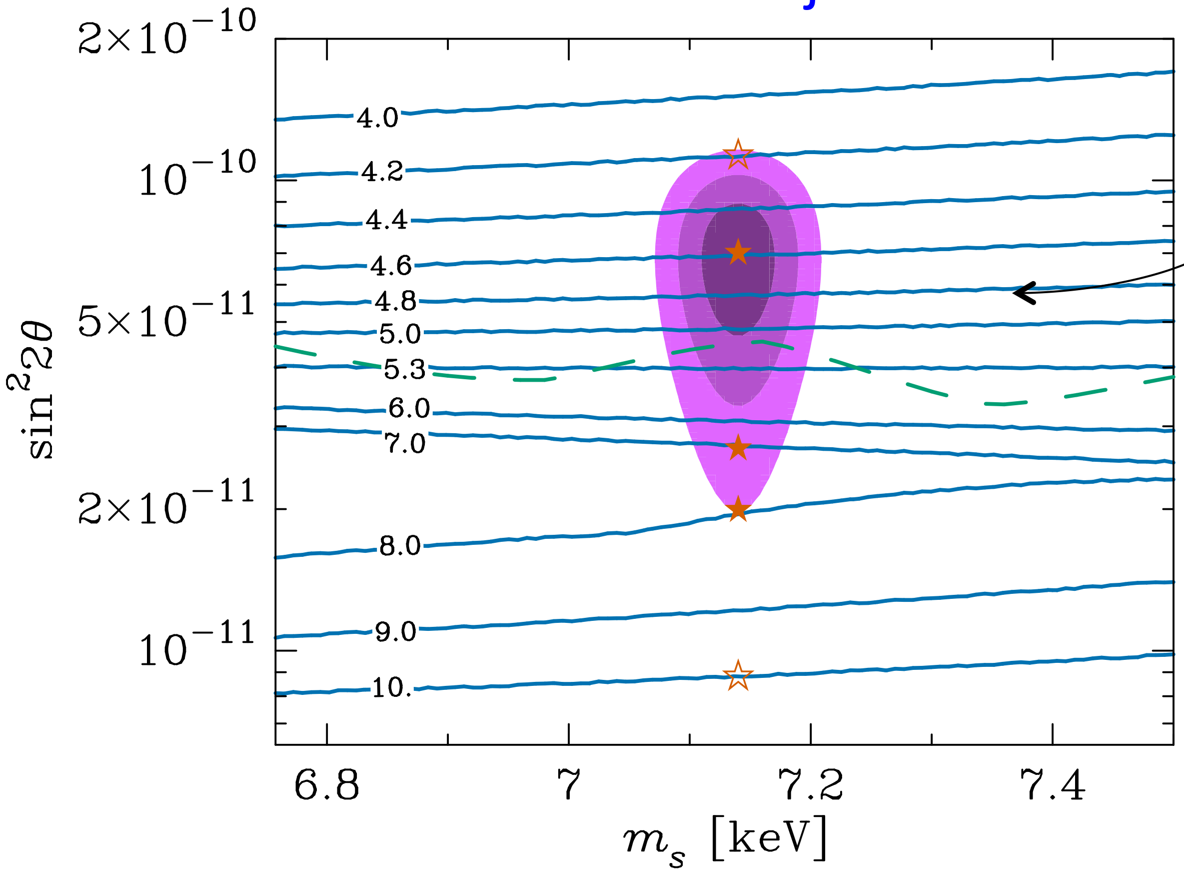
$$\approx \tfrac{1}{2}\Gamma_\alpha(p)\sin^2 2\theta_M \left[1 + \left(\tfrac{1}{2}\Gamma_\alpha(p)\, l_M\right)^2\right]^{-1}$$

$$|\nu_\alpha\rangle = \cos\theta_M |\nu_1\rangle + \sin\theta_M |\nu_2\rangle$$

$$|\nu_s\rangle = -\sin\theta_M |\nu_1\rangle + \cos\theta_M |\nu_2\rangle$$



Abazajian 2014



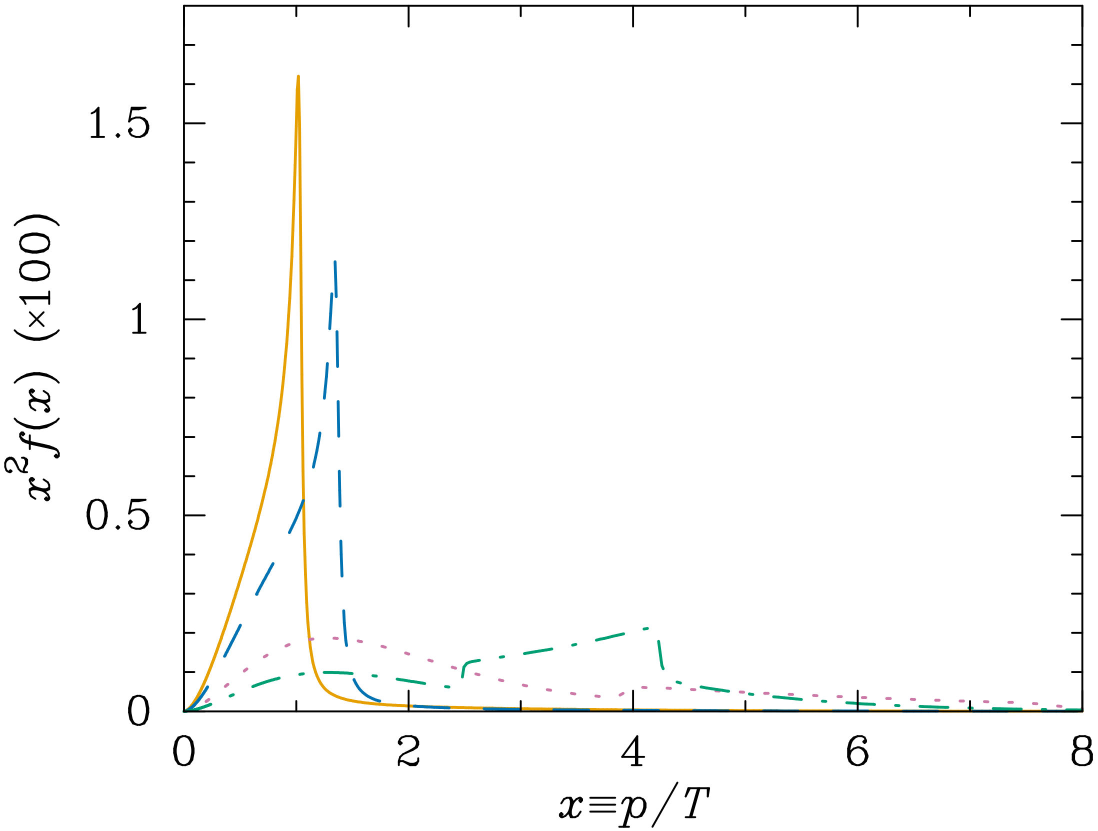
contours of
initial lepton number
in units of 10^{-4}

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

Abazajian 2014 – use $m_s = 7\,\mathrm{keV},\ \sin^2\theta \sim 5\times10^{-11}$, lepton number 5×10^{-4}



Dilution-Generated Sterile Neutrino Dark Matter

Fuller, Kusenko, Kishimoto,
Patwardhan
2014

Use *two* particles - one is a sterile neutrino; the other may be

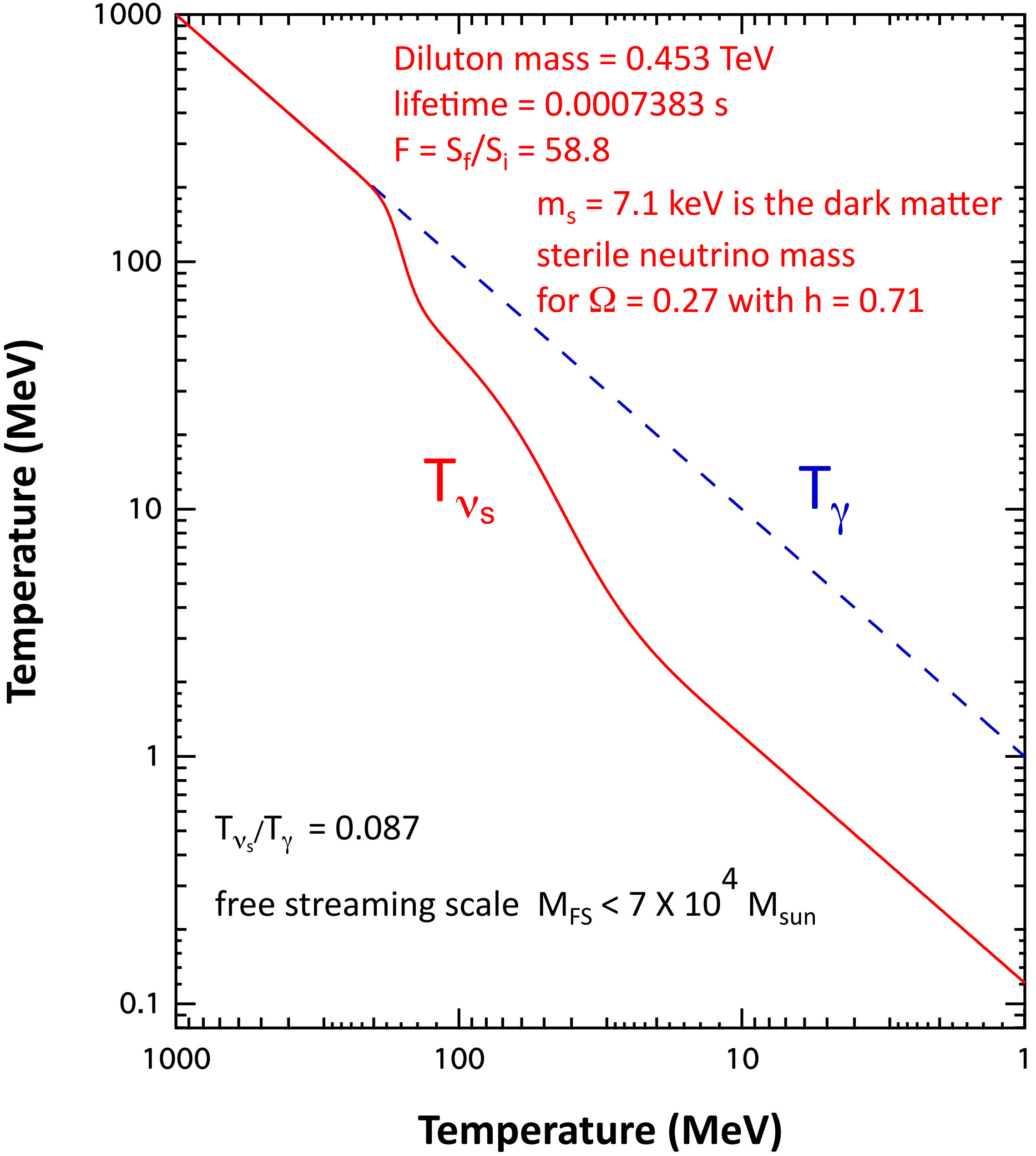
-both in thermal/chemical equilibrium at very high temperature

-both decouple at very high temperature (T >> 100 GeV)

-the heavier particle, the **DILUTON** (dilution generator), decays prior to weak decoupling

-the lighter particle has its relic density diluted down to a range where it can be dark matter

(The dilution event "cools" the particle's energy spectrum, making it **COLDER** than its rest mass might lead you to believe!)



Diluton mass = 0.453 TeV
lifetime = 0.0007383 s
$F = S_f/S_i = 58.8$

m_s = 7.1 keV is the dark matter sterile neutrino mass for $\Omega = 0.27$ with $h = 0.71$

$T_{\nu_s}/T_\gamma = 0.087$

free streaming scale $M_{FS} < 7 \times 10^4\ M_{sun}$

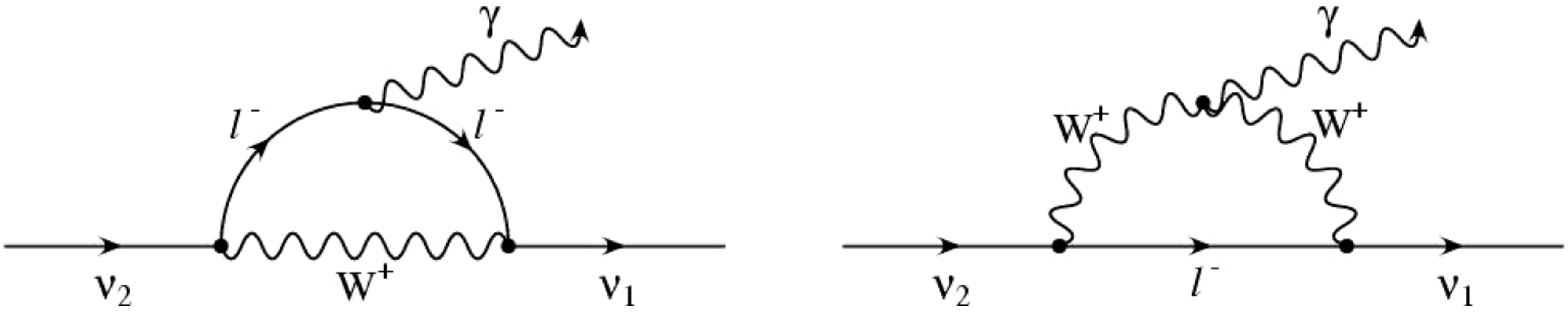
Fuller, Kishimoto, Kusenko, Patwardhan

7.1 keV sterile neutrino dark matter
two extreme limits for production compared/contrasted

dark matter relic density produced	**Resonantly** **(medium-enhanced de-coherent oscillations)** at $T \gg 1\,\mathrm{TeV}$ initial density $n_{\nu_s} = 0$	**by Dilution** **from thermal equilibrium** at $T \gg 1\,\mathrm{TeV}$ initial density $n_{\nu_s} \sim T^3$
dark matter character	Cool (warm to cold)	Cold
Tooth Fairies	initial lepton number $(L_\nu \sim 10^{-3})$	*two* sterile neutrinos
Warts	assumptions about (absence of) new high energy scale physics	assumptions about high energy scale physics (need thermalization) **baryogenesis requirements**
Predictions/ handles?	left over lepton number? ⇒ BBN, CMB ?	high energy scale physics ⇒ inflation, Higgs?

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.



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

photon line $E_\gamma = m_\mathrm{s}/2$

Singlet Neutrino Radiative Decay Rate

$$\Gamma_\gamma \approx \frac{\alpha G_F^2}{64\pi^4} m_2^5 \left[\sum_\beta U_{1\beta} U_{2\beta} F(r_\beta) \right]^2$$

$$\approx 6.8 \times 10^{-33}\,\mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-10}} \right) \left(\frac{m_s}{\mathrm{keV}} \right)^5$$

no GIM suppression for sterile neutrinos

$$F(r_\beta) \approx -\tfrac{3}{2} + \tfrac{3}{4} r_\beta$$

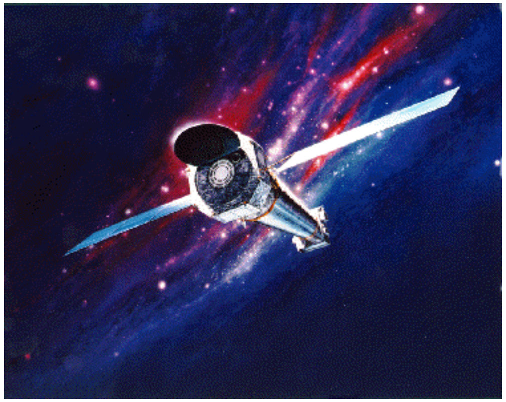
$$r_\beta = \left(M_\beta^{lep} / M_W \right)^2$$

A serendipitous coincidence: K. Abazajian, G. M. Fuller, W. H. Tucker, *Astrophys. J.* **562**, 593 (2001)

X-ray observatories (e.g., XMM-Newton and Chandra have greatest sensitivity for photons with energies between about 1 keV to 10 keV, serendipitously coincident with the expected photon energies from decaying Dark Matter "sterile" neutrinos.

Typical lifetimes against radiative decay are some ~10^{16} times the age of the universe! However, if steriles are the Dark Matter, then in a typical cluster of galaxies there could be ~10^{78} of these particles.

This could allow x-ray observatories to probe physics at interaction strengths some 10-14 orders of magnitude smaller than the Weak Interaction.



Chandra X-Ray Observatory

XMM-Newton X-Ray Observatory

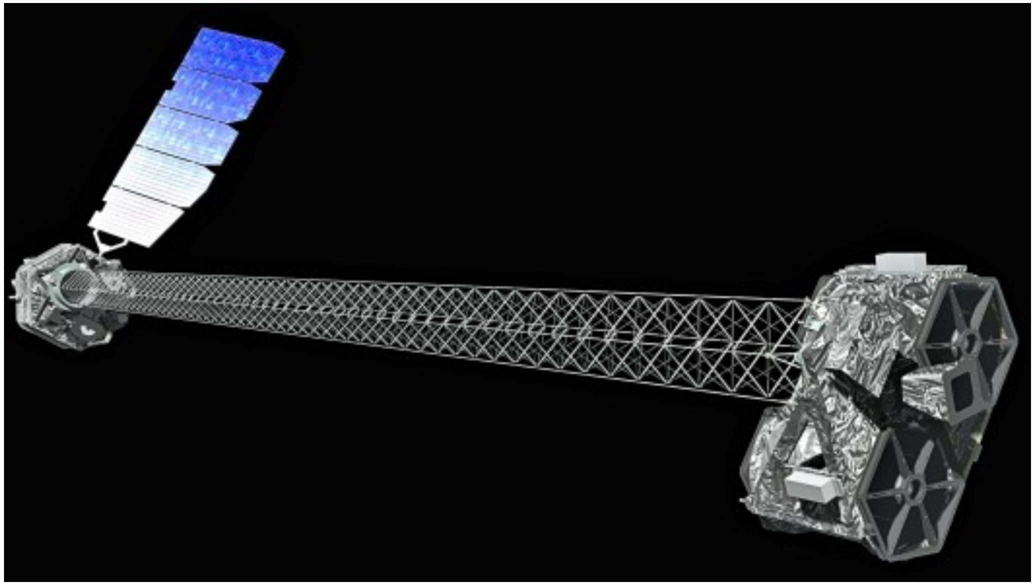
Heavy diluton-generated sterile neutrino dark matter:

rest masses m_s = ~ 10 keV to ~ 300 keV (*maybe higher*)

$$E_\gamma = \frac{m_s}{2}$$

Produce X-ray lines in a perfect range for **NuStar** (6 keV to 79 keV)

at higher X-ray energy, galaxy clusters become good targets for searching for sterile neutrino dark matter decay X-ray lines:
lots of dark matter in field of view; no expected higher energy atomic lines.

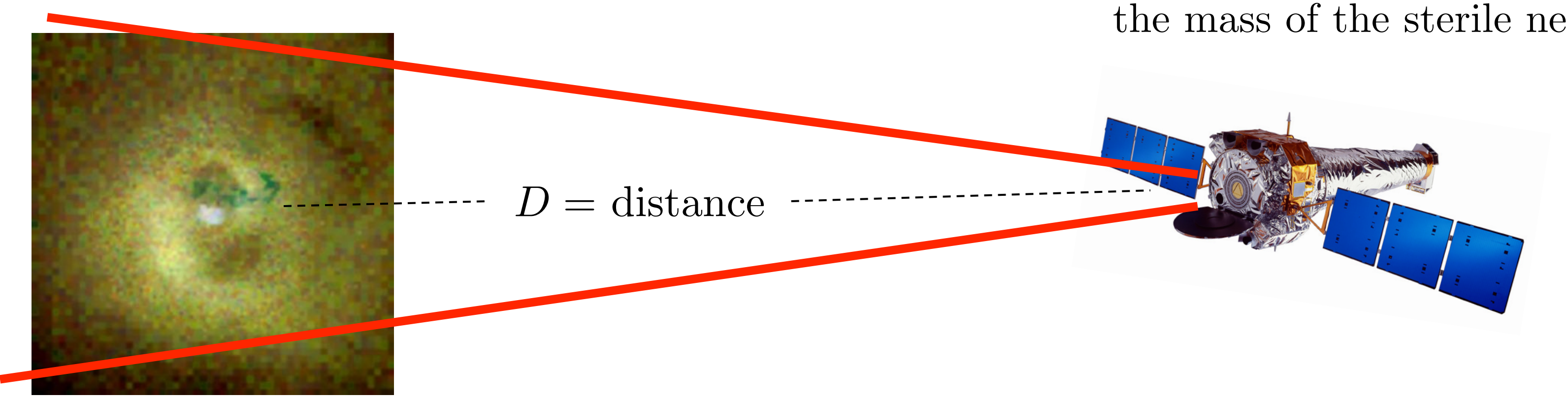


The Perseus Cluster of Galaxies - NOAO http://www.noao.edu/outreach/aop/

$\sim$ 1000 galaxies in an extended cluster $\Rightarrow \sim 10^{15}\,\mathrm{M}_\odot$ of dark matter!

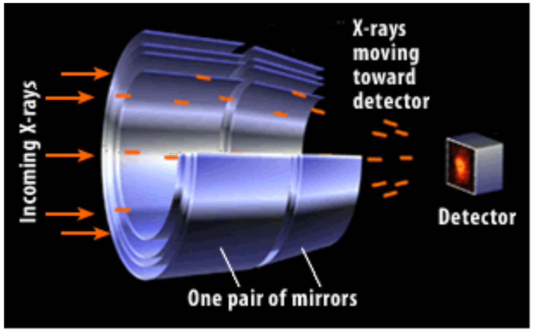
M = mass of dark matter
in field of view of X-ray telescope

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

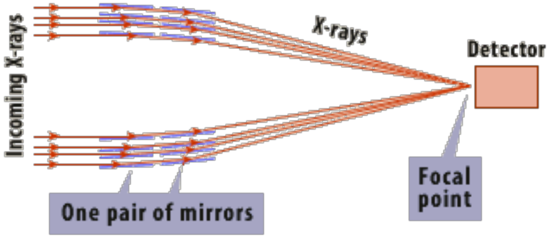


D = distance

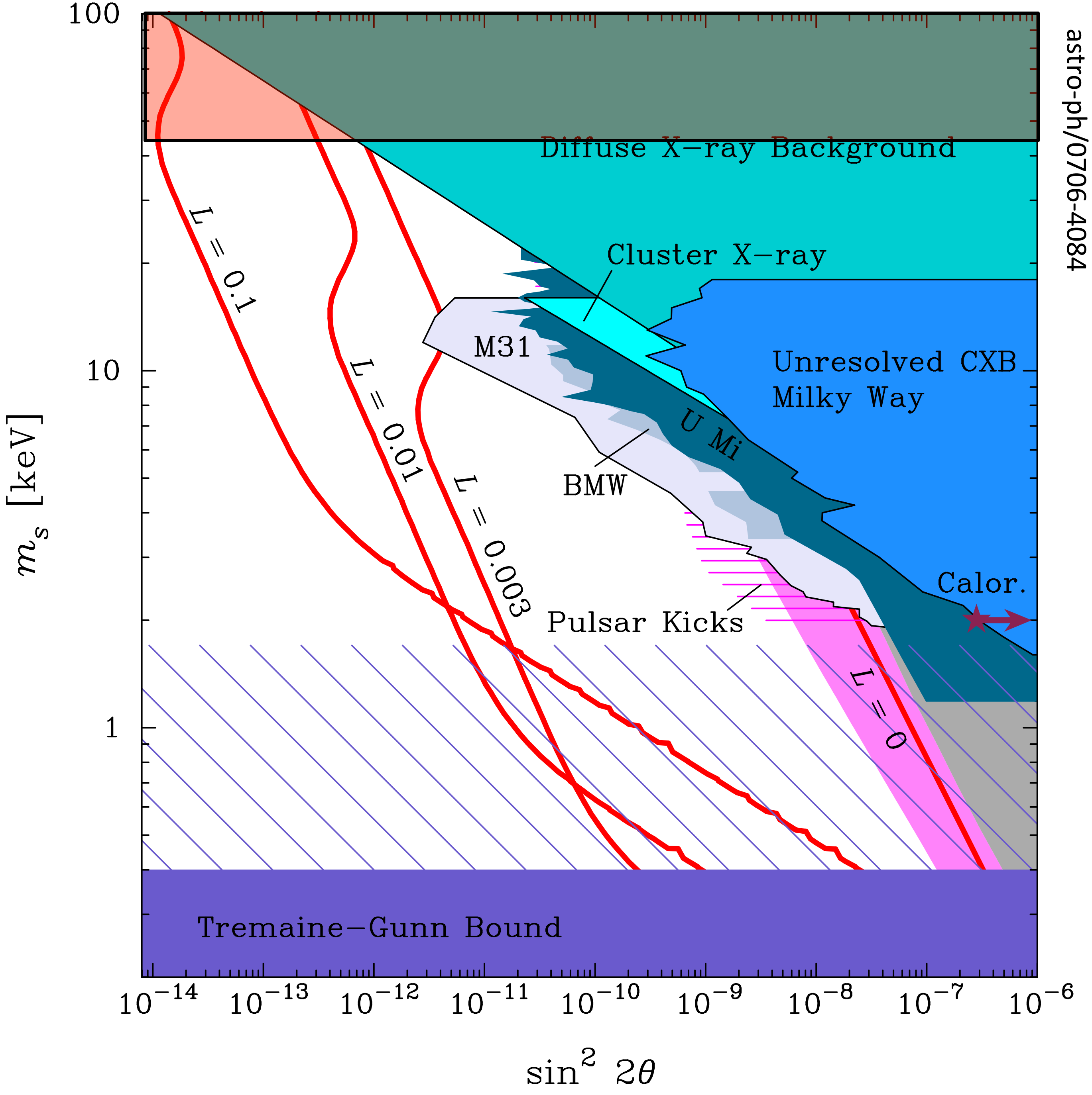
measured X-ray flux in line
$\propto M \cdot D^{-2} \cdot m_{\mathrm{s}}^5 \cdot \sin^2\theta$



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.



H. Yuksel, J. Beacom, C. Watson
astro-ph/0706-4084

K. Abazajian 2012

Possible Detections ??

two different X-ray astronomy groups see a **3.55 keV** line in **clusters of galaxies** and in M31,
and this line is ***consistent with a dark matter decay origin***,
corresponding to a **7.1 keV rest mass sterile neutrino**
with vacuum mixing with active neutrinos $\sin^2 2\theta = (2 - 20) \times 10^{-11}$

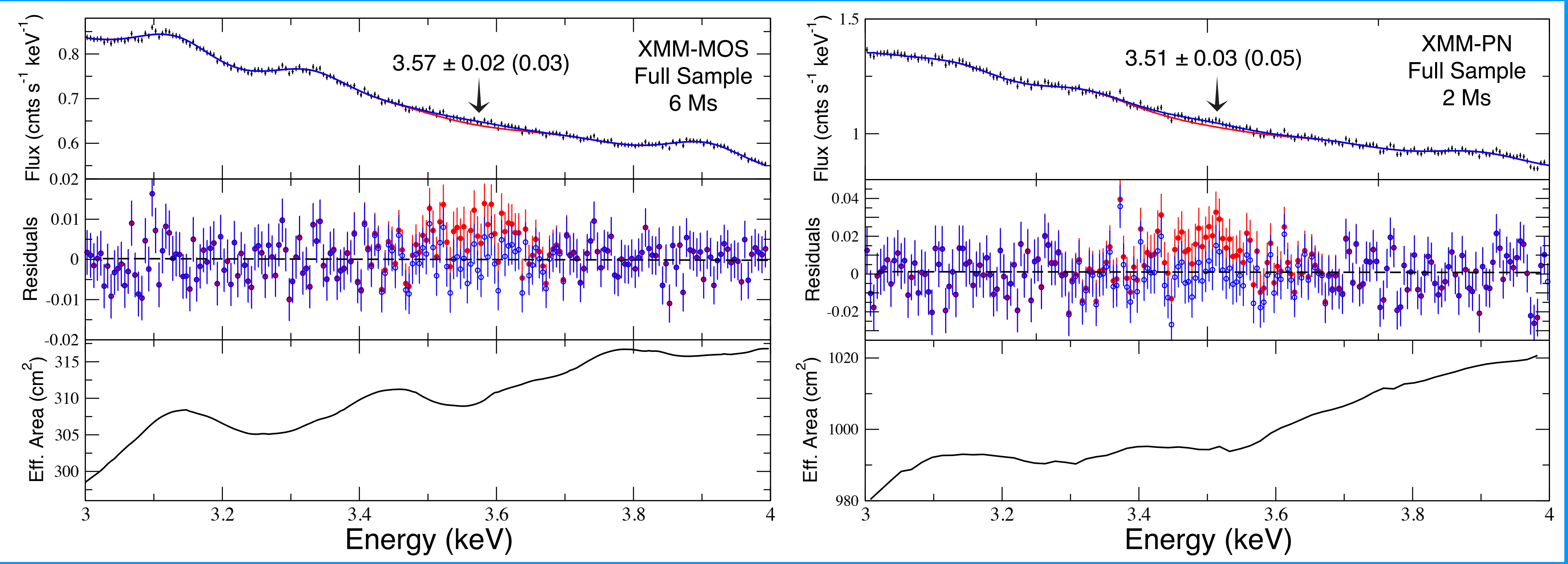
E. Bulbul, M. Markevitch, A. Foster, R. Smith, M. Lowenstein, S. Randall
"*Detection of an unidentified emission line in the stacked X-ray spectrum of Galaxy Clusters*" arXiv:1402.2301

line seen for Perseus, and stacked spectra of 73 clusters,
with *XMM* in *two different* detectors (MOS, PN);
and in Perseus with the ACIS-S and ACIS-I detectors on *CHANDRA*

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

Observatory: XMM-Newton
Target: M31 Galaxy and Perseus Cluster
Detection: Line at 3.518 + 0.019 – 0.022 keV
Perseus flux of (8.6 + 2.2 – 2.3) × 10^{-6} photons/cm^2/sec
M31 flux of (4.6 ± 1.4) × 10^{-6} photons/cm^2/s

Full Cluster Sample



$$\Delta\chi^2 = 22.8$$

$$\Delta\chi^2 = 13.9$$

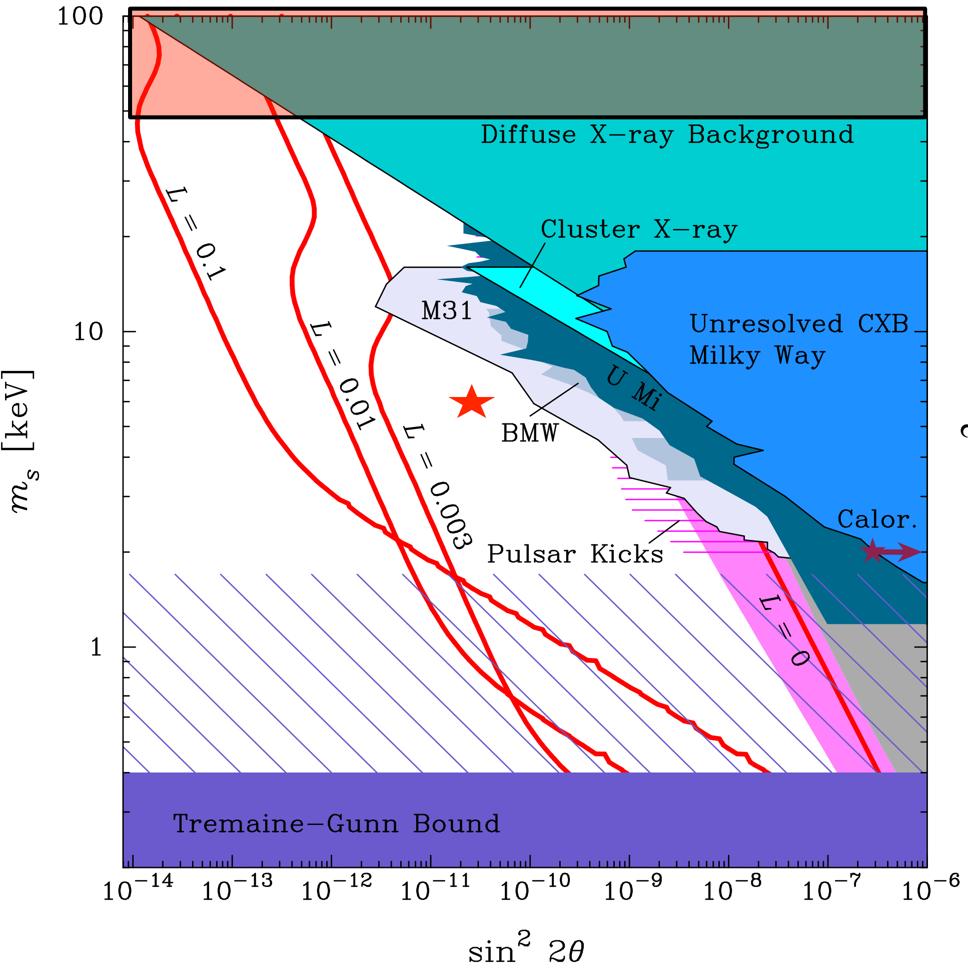
$$F_{\rm DM} = 4.0^{+0.8}_{-0.8}(^{+1.8}_{-1.2}) \times 10^{-6}$$

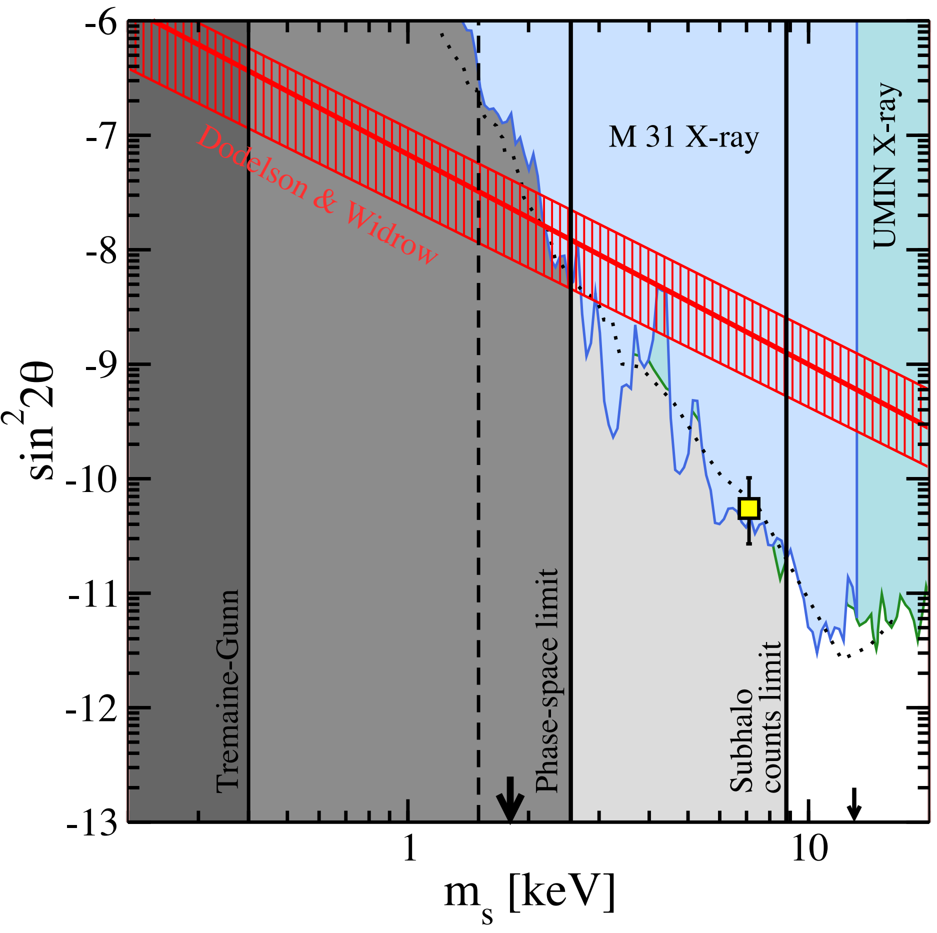
$$F_{\rm DM} = 3.9^{+0.6}_{-1.0}(^{+1.0}_{-1.6}) \times 10^{-6}$$

$$\frac{\sin^2 2\theta}{10^{-11}} = 6.8^{+1.4}_{-1.4}(^{+2.0}_{-3.0})$$

$$\frac{\sin^2 2\theta}{10^{-11}} = 6.7^{+1.7}_{-1.0}(^{+2.7}_{-1.7})$$

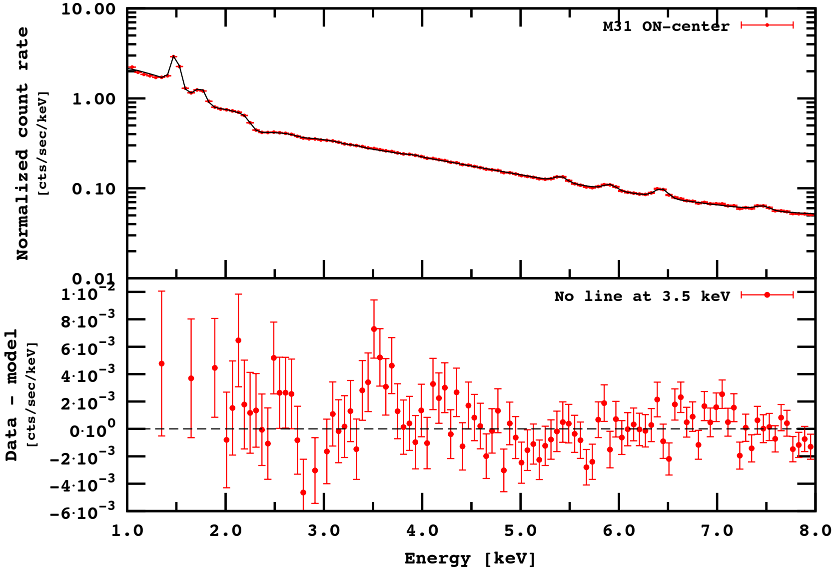
Sterile Nu decay line

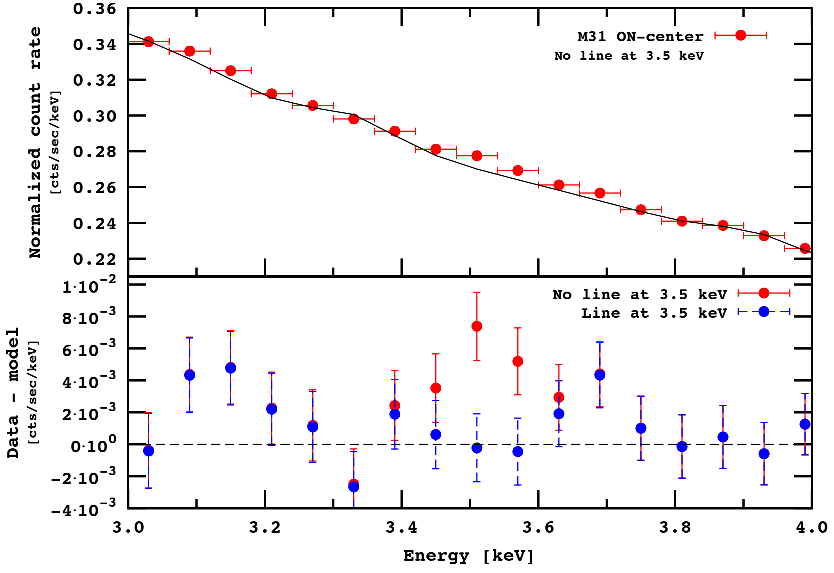


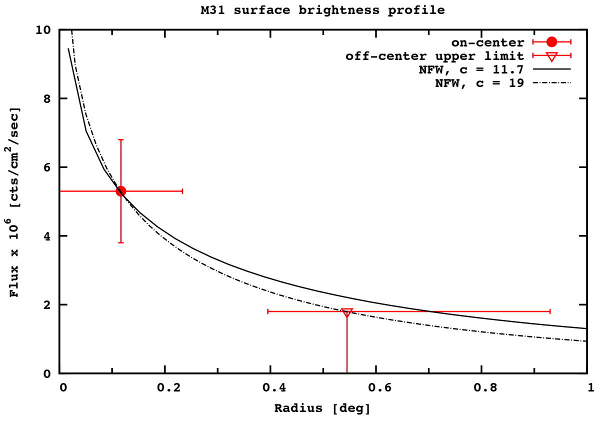


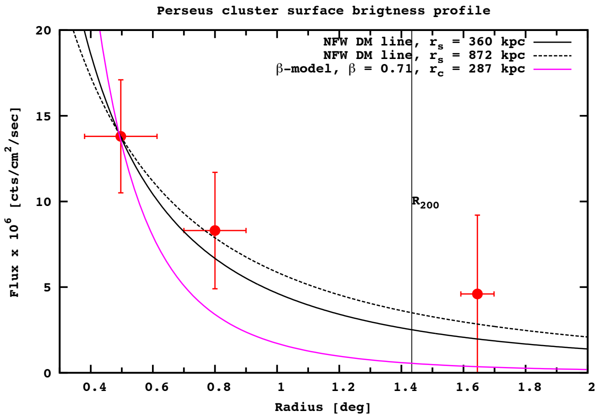
Abazajian, K. (2012)
Yüskel, H., Beacom, J. F., Watson, C.

Horiuchi, Abazajian, K., S., Kaplighat, M. (2014)


M31 ON-center
No line at 3.5 keV
Normalized count rate
[cts/sec/keV]
Data - model
[cts/sec/keV]
10.00
1.00
0.10
0.01
1·10^-2
8·10^-3
6·10^-3
4·10^-3
2·10^-3
0·10^0
-2·10^-3
-4·10^-3
-6·10^-3
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Energy [keV]

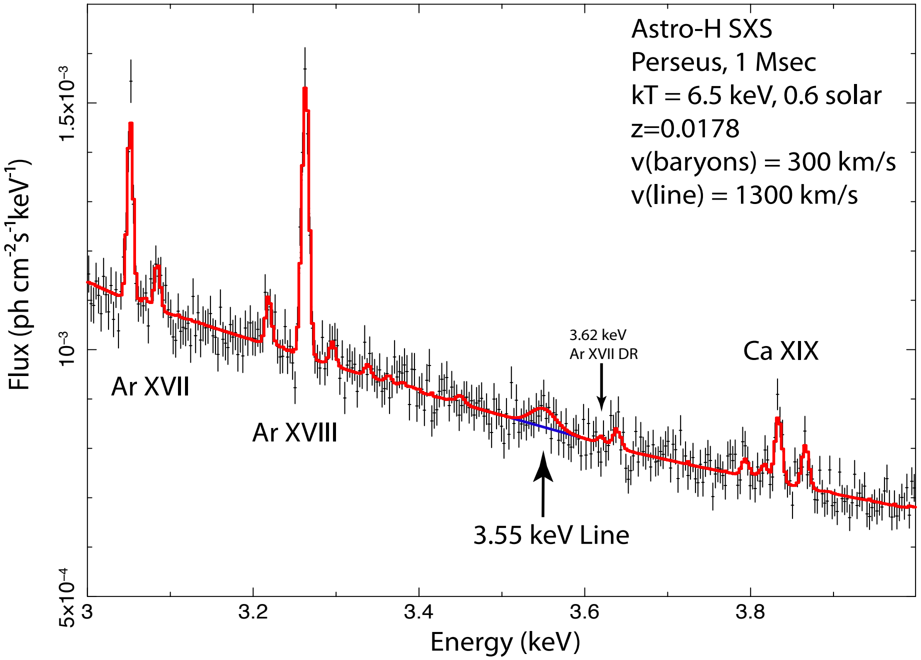

M31 ON-center
No line at 3.5 keV
No line at 3.5 keV
Line at 3.5 keV
Normalized count rate
[cts/sec/keV]
Data - model
[cts/sec/keV]
0.36
0.34
0.32
0.30
0.28
0.26
0.24
0.22
1·10^-2
8·10^-3
6·10^-3
4·10^-3
2·10^-3
0·10^0
-2·10^-3
-4·10^-3
3.0
3.2
3.4
3.6
3.8
4.0
Energy [keV]


M31 surface brightness profile
on-center
off-center upper limit
NFW, c = 11.7
NFW, c = 19
Flux x 10^6 [cts/cm^2/sec]
10
8
6
4
2
0
0
0.2
0.4
0.6
0.8
1
Radius [deg]


Perseus cluster surface brigtness profile
NFW DM line, r_s = 360 kpc
NFW DM line, r_s = 872 kpc
β-model, β = 0.71, r_c = 287 kpc
R_200
Flux x 10^6 [cts/cm^2/sec]
20
15
10
5
0
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Radius [deg]

Future smoking gun? -- **Astro-H** will have ~ few eV energy resolution

Bulbul et al.



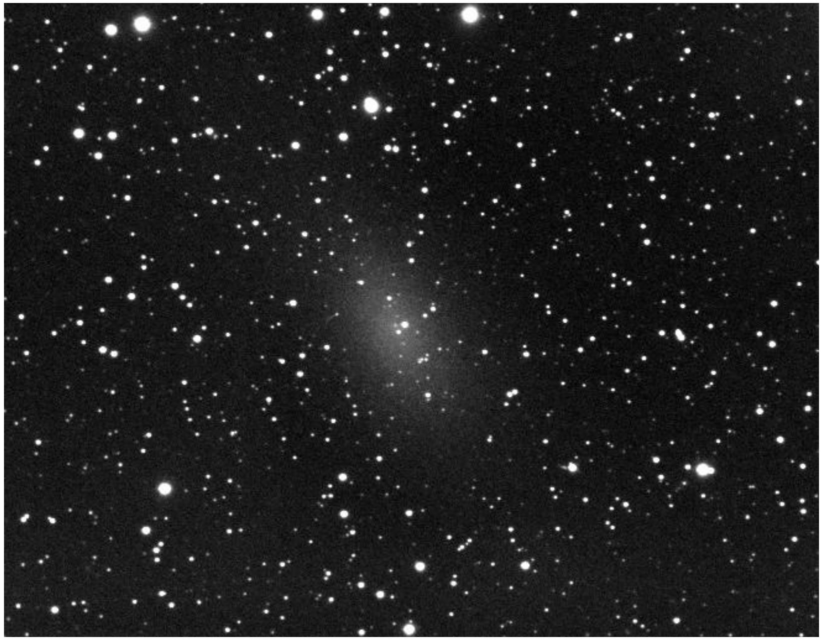
resolve the Virial width?

see Lowenstein & Kusenko

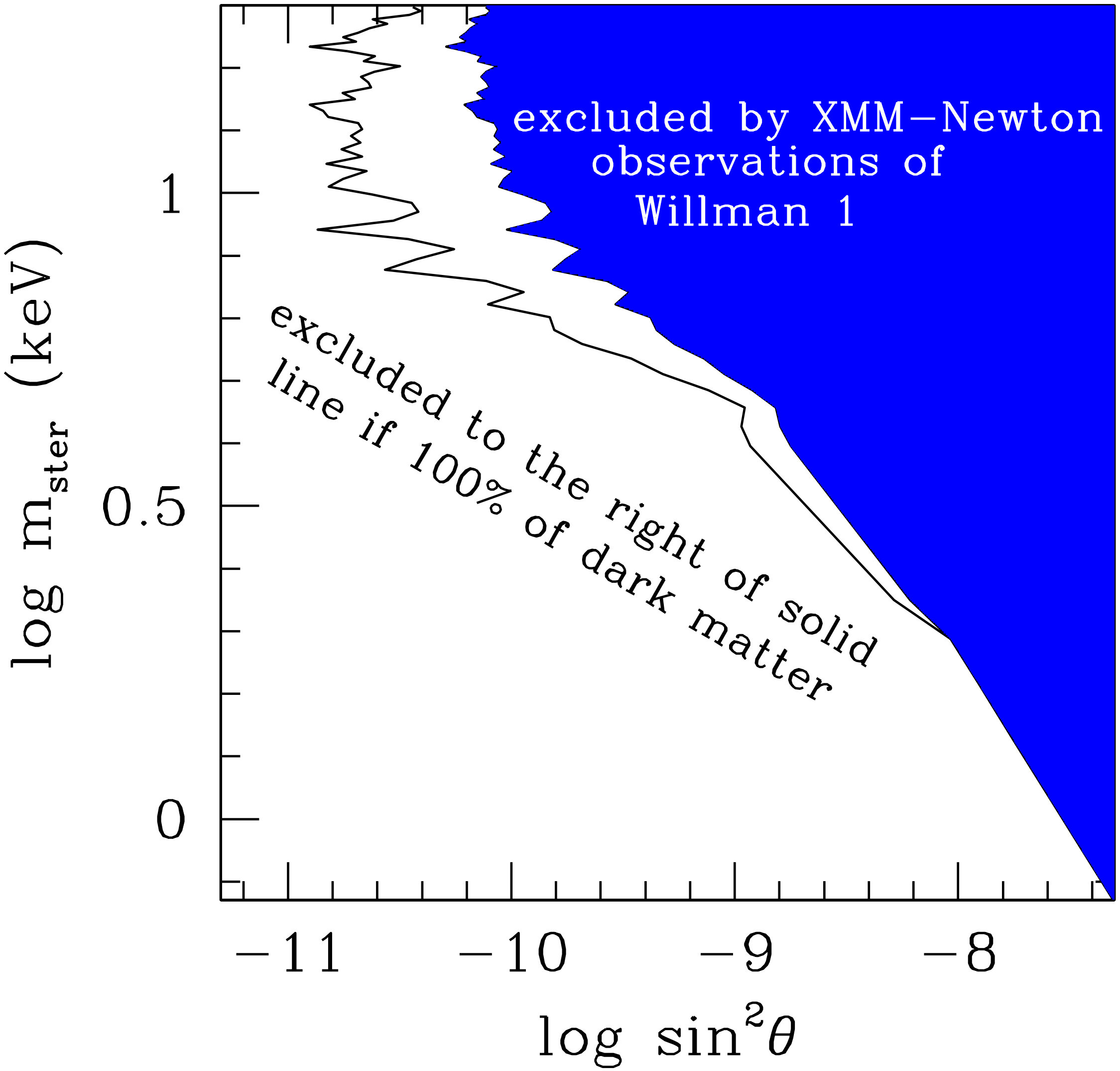
Dwarf Spheroidal Galaxies

M. Lowenstein & A. Kusenko

-not much gas, not many stars,
mostly dark matter! – low X-ray background



Loewenstein & Kusenko (2012)



Dwarf galaxies are the *supreme court* for indirect dark matter searches

(both for sterile neutrinos and WIMP-annihilation)

BUT . . .

--We need the dark matter ***content*** and ***spatial distribution*** in dwarf spheroidal galaxies

-- These depend on "baryonic feedback" processes and the mass assembly history of these systems

-- ***Nucleosynthesis/chemical evolution*** may provide best insights into these issues