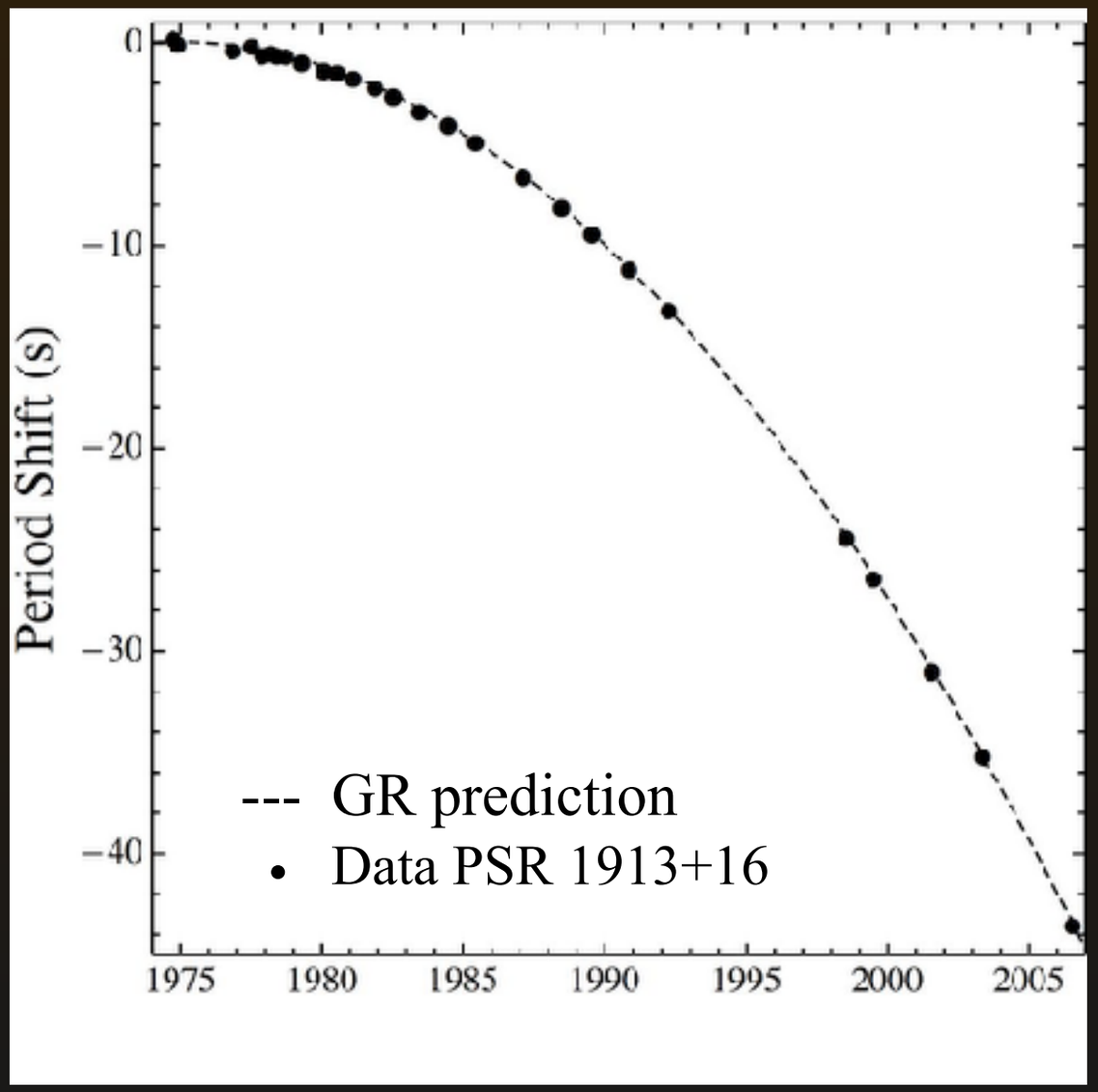
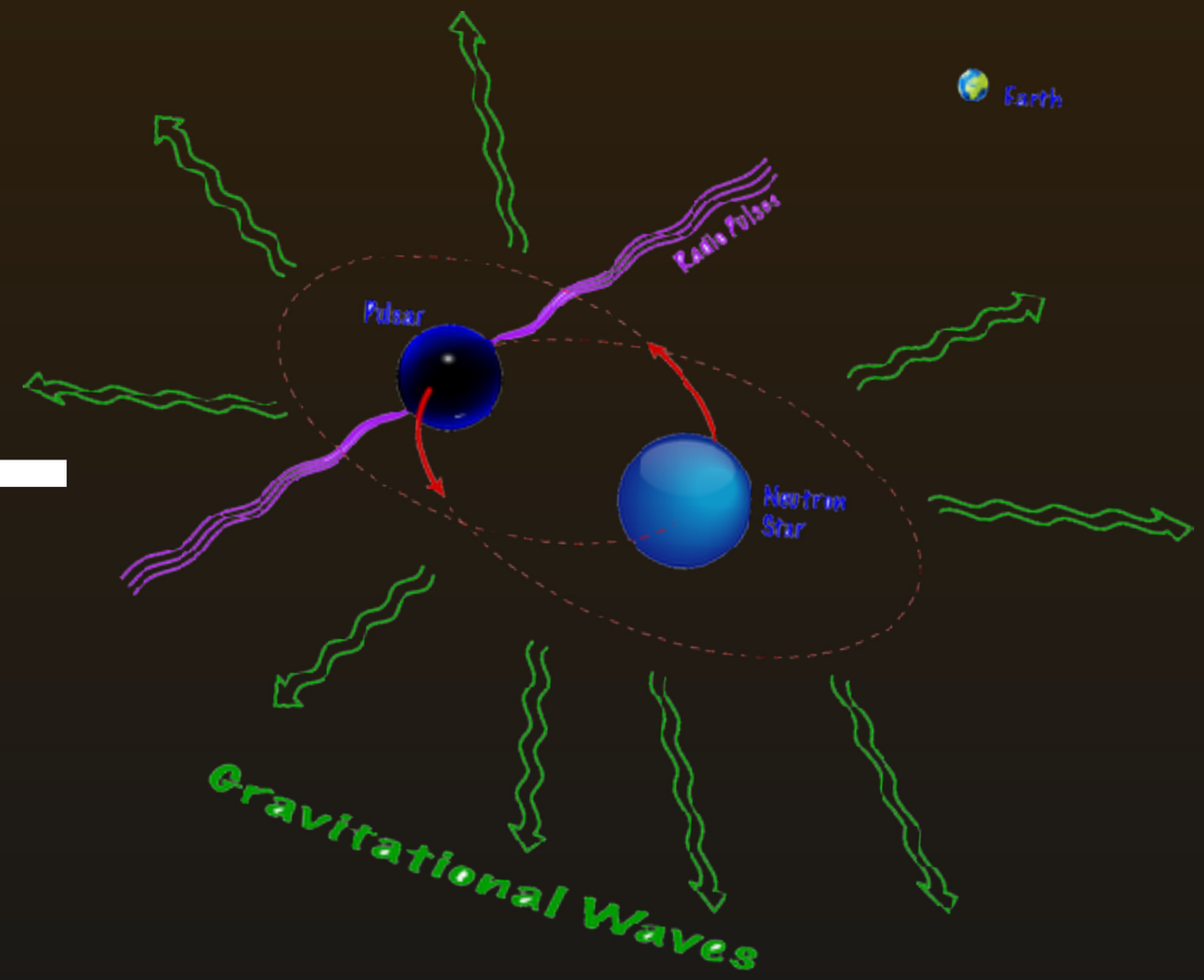
Wroclaw Supernova Project

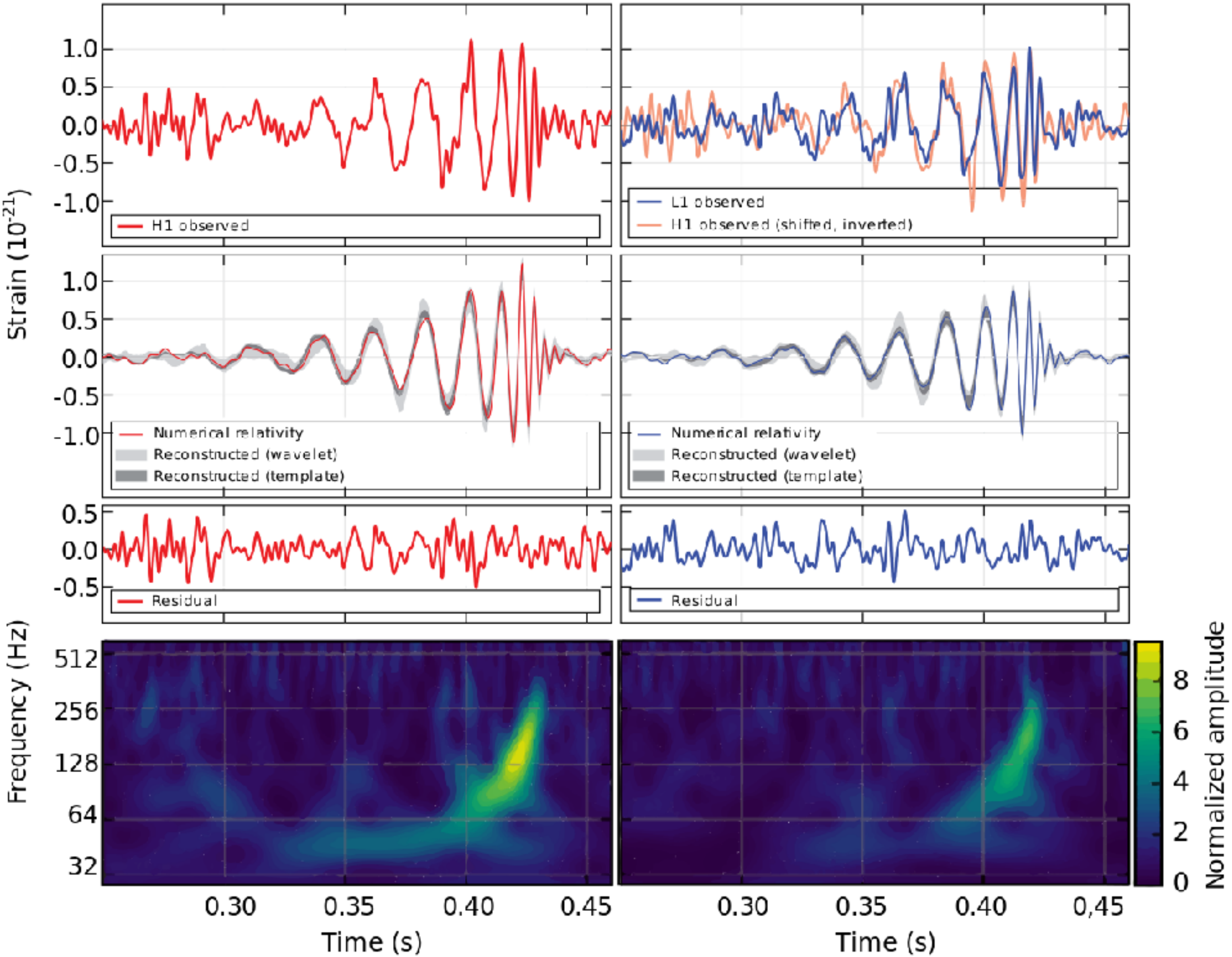
The Nobel Prize in Physics 1993

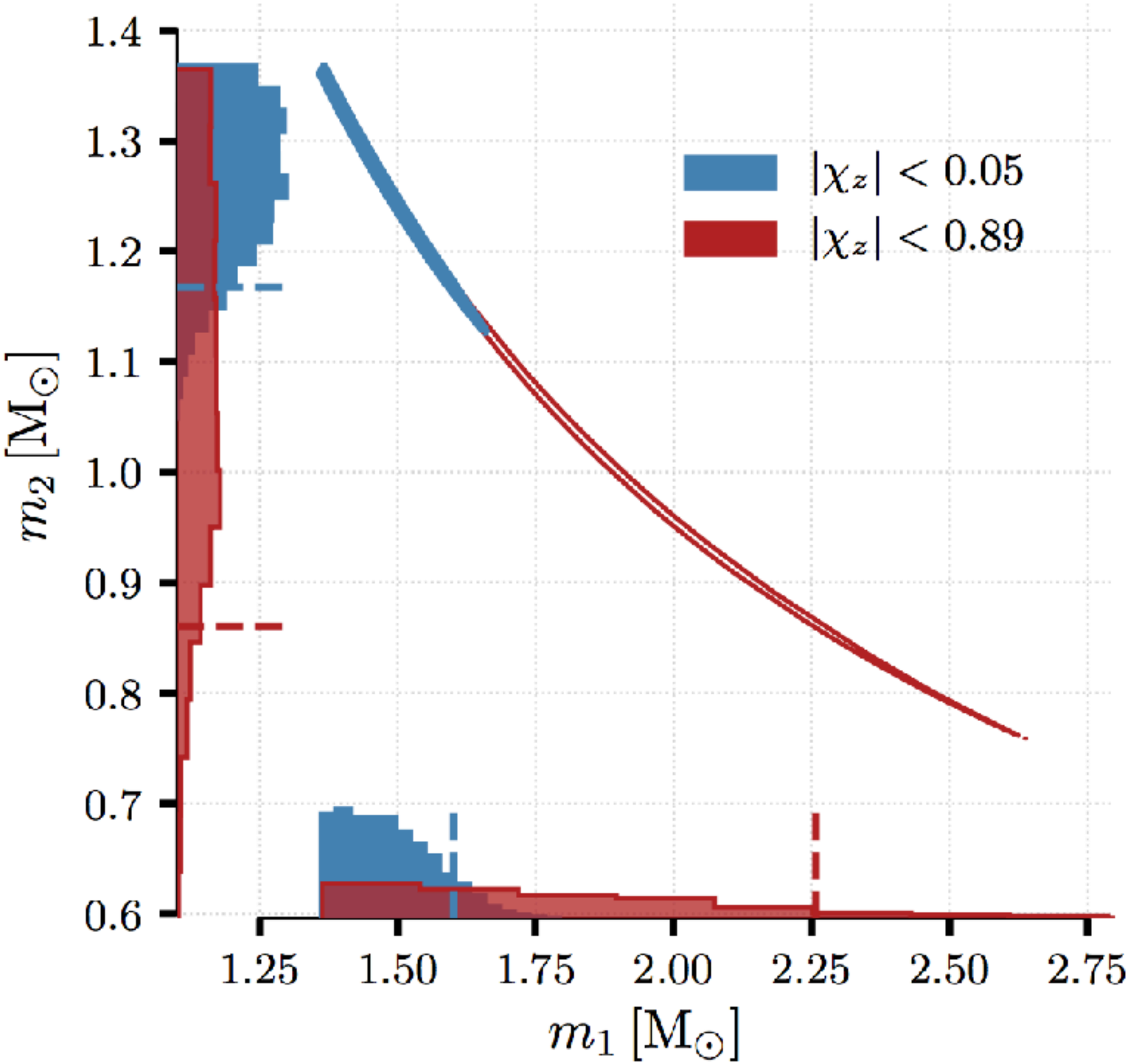
Russell A. Hulse, Joseph H. Taylor Jr.

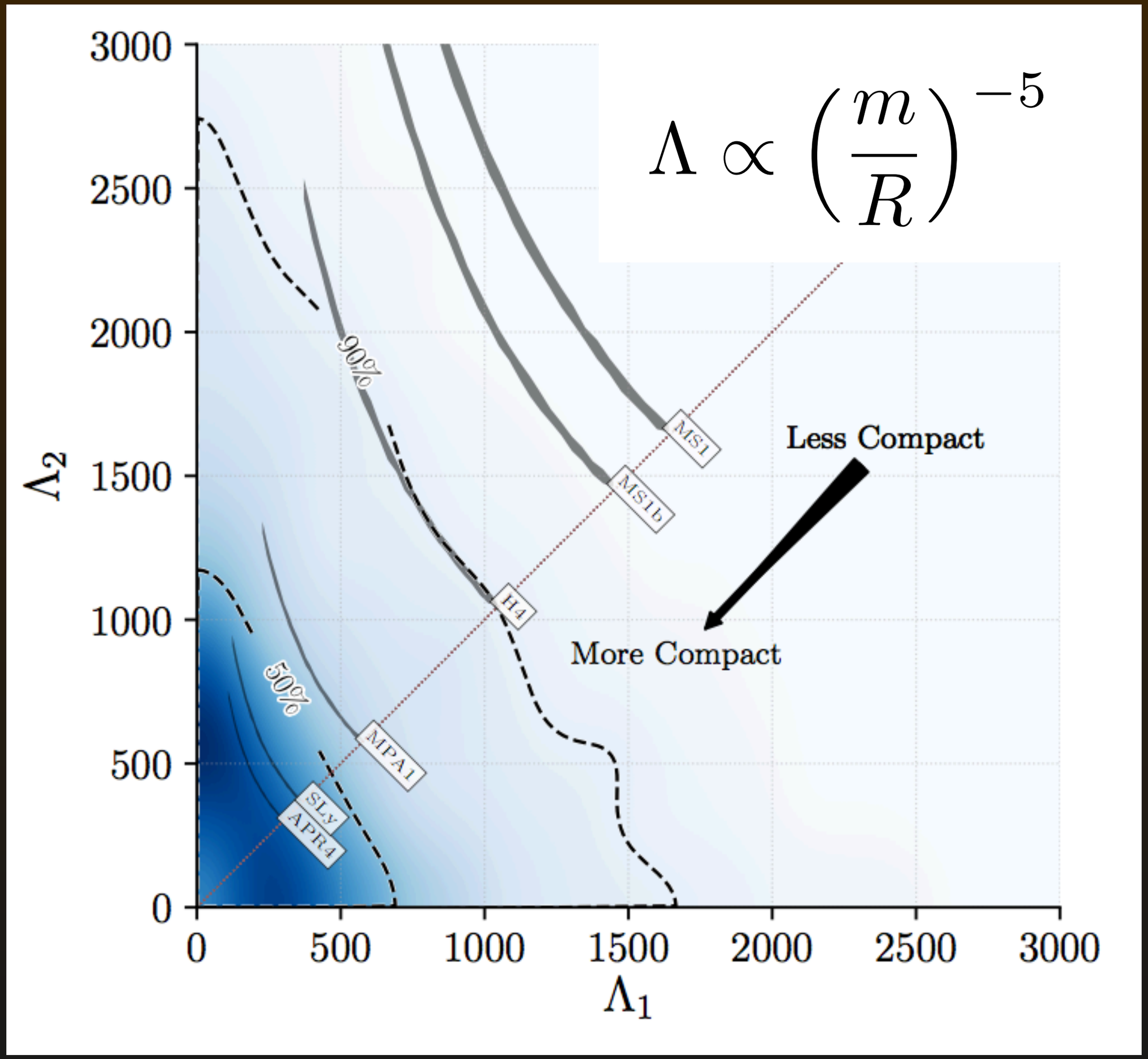
"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"

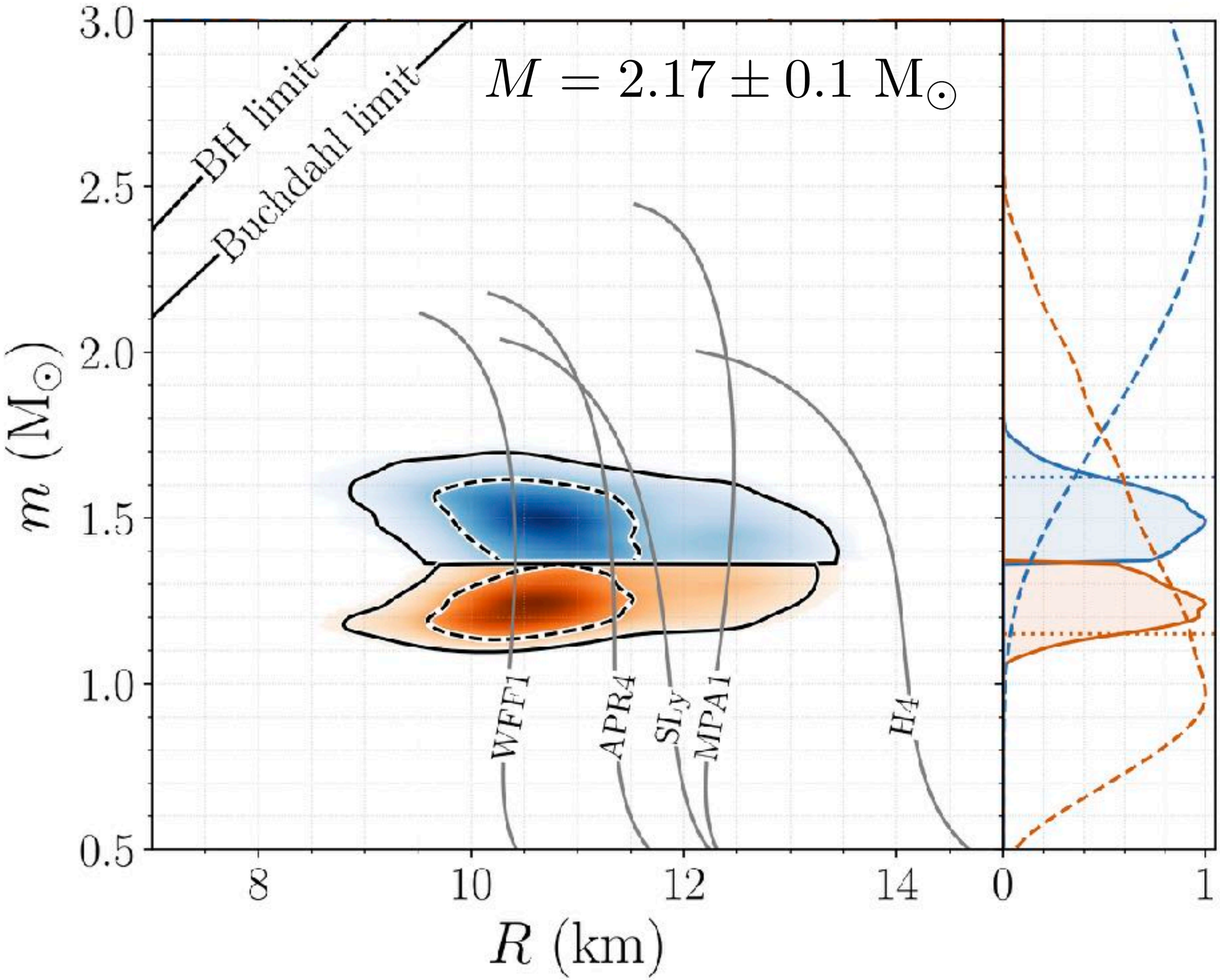


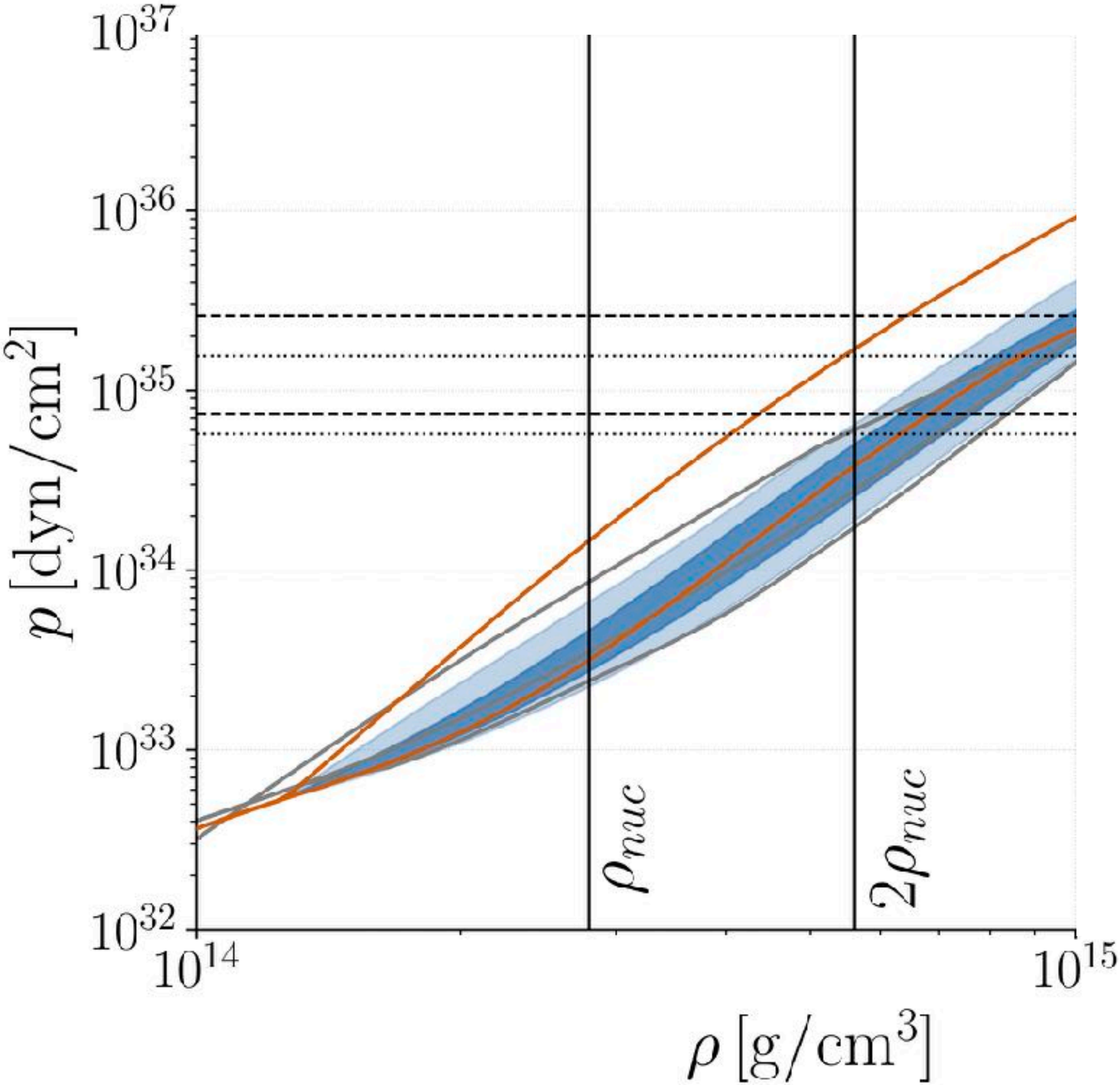


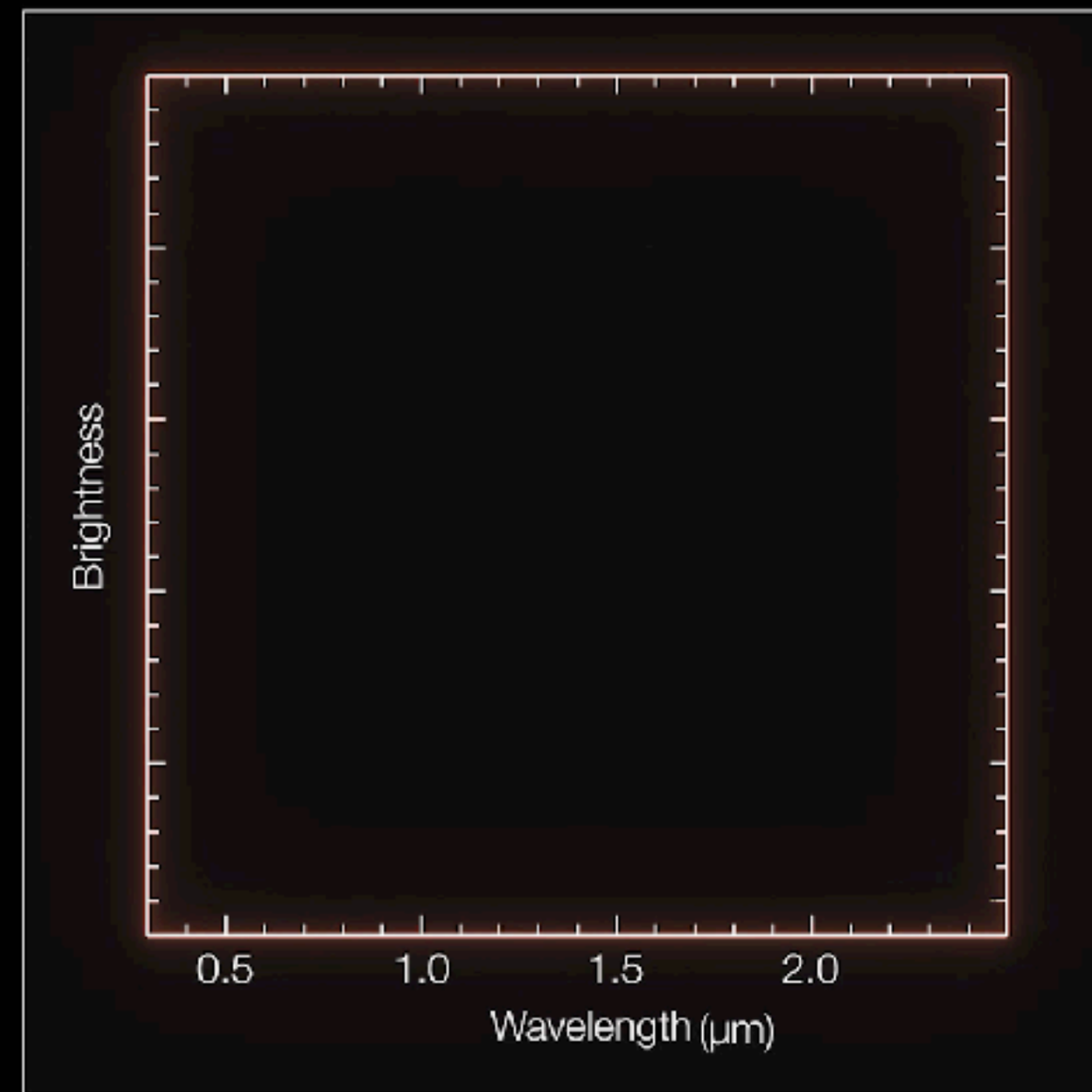

Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude
8
6
4
2
0


$|\chi_z| < 0.05$
$|\chi_z| < 0.89$
m_2 [M$_\odot$]
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
1.25
1.50
1.75
2.00
2.25
2.50
2.75
m_1 [M$_\odot$]

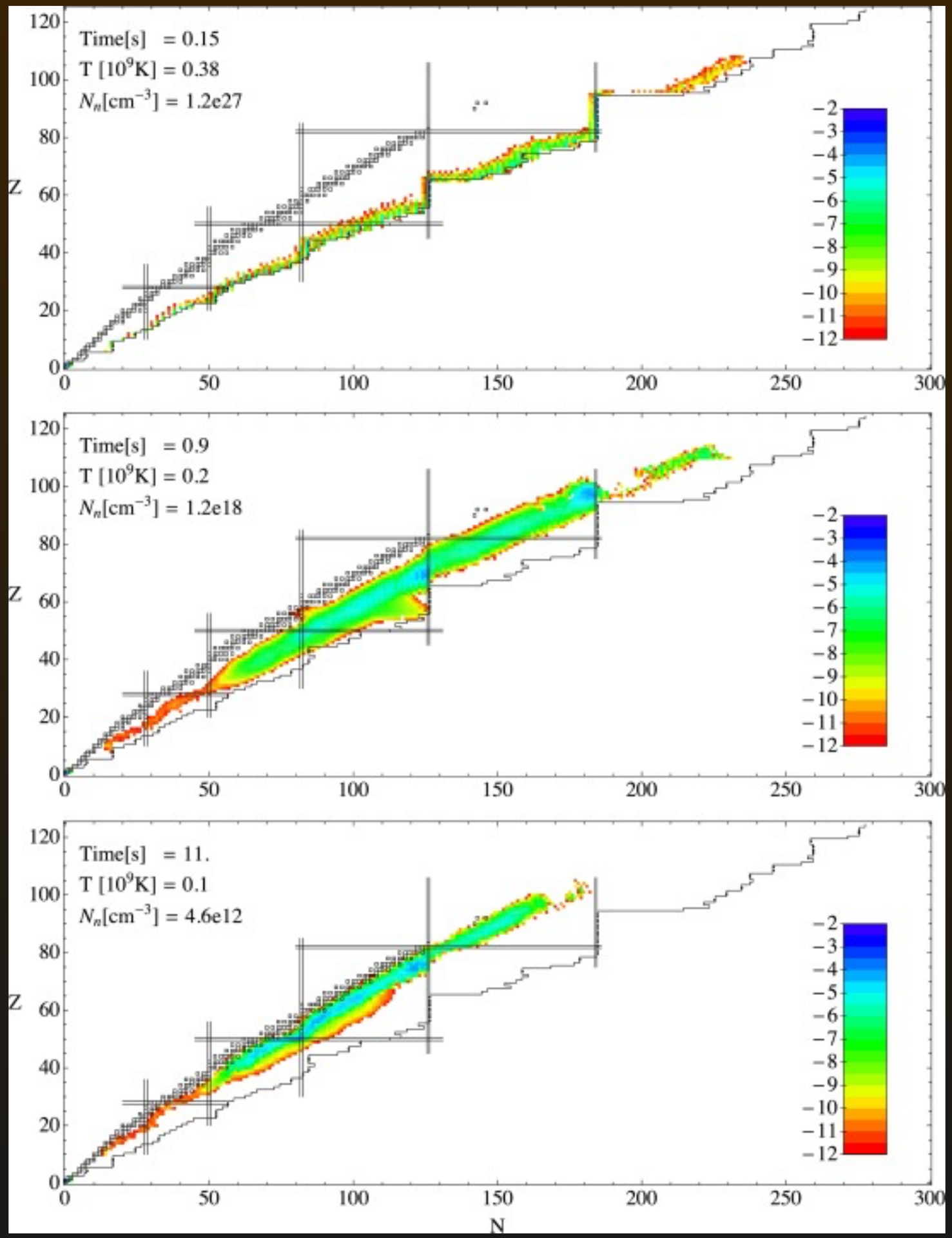

$\Lambda \propto \left(\frac{m}{R}\right)^{-5}$
Less Compact
More Compact
90%
50%
MS1
MS1b
H4
MPA1
SLy
APR4
Λ_2
Λ_1
0
500
1000
1500
2000
2500
3000


$M = 2.17 \pm 0.1\ \mathrm{M}_\odot$
BH limit
Buchdahl limit
WFF1
APR4
SLy
MPA1
H4
m ($\mathrm{M}_\odot$)
R (km)
3.0
2.5
2.0
1.5
1.0
0.5
8
10
12
14
0
1


10^{37}
10^{36}
10^{35}
10^{34}
10^{33}
10^{32}
p [dyn/cm^2]
ρ_{nuc}
$2\rho_{nuc}$
10^{14}
10^{15}
ρ [g/cm^3]



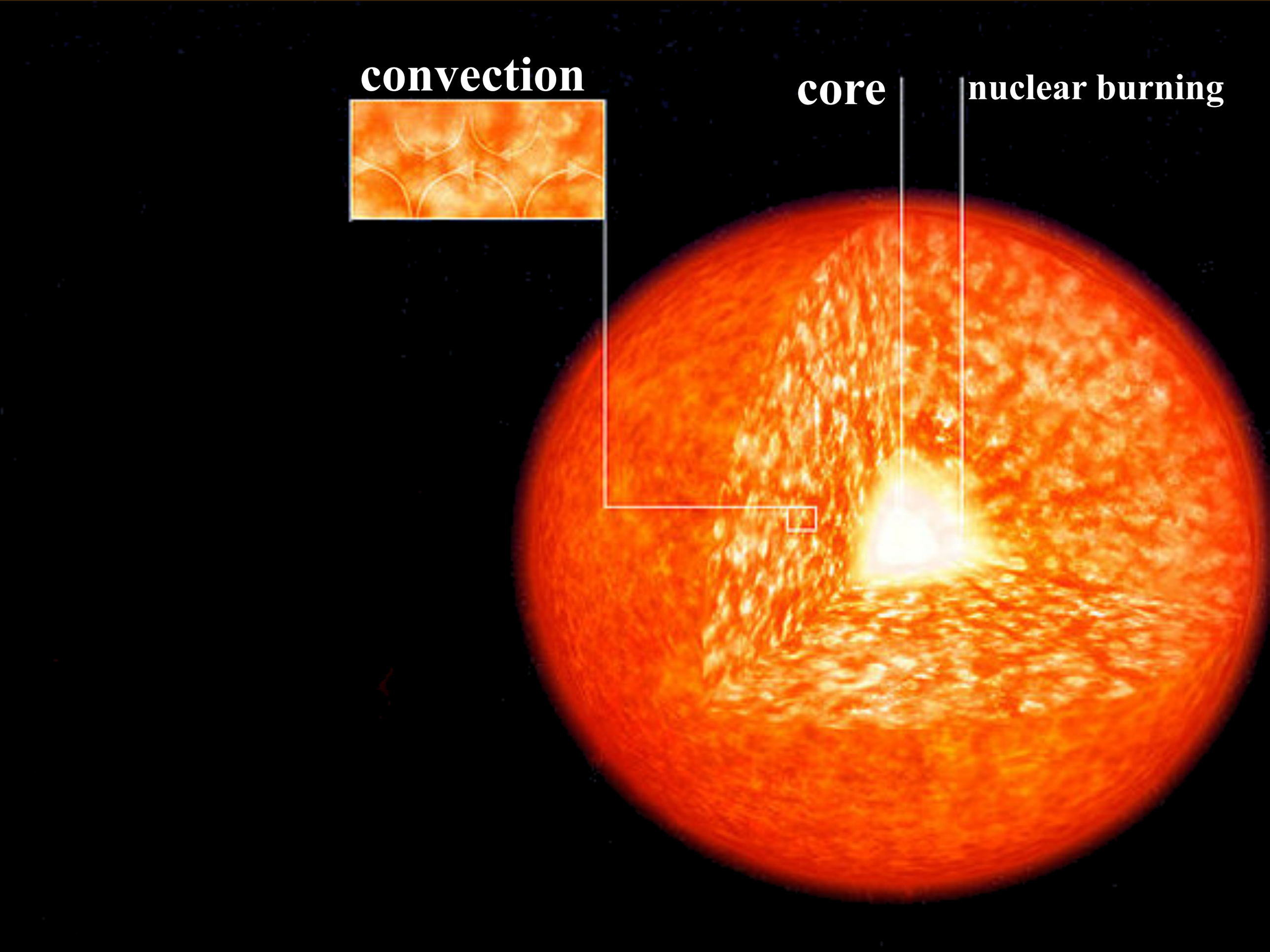
Time: -1225 days

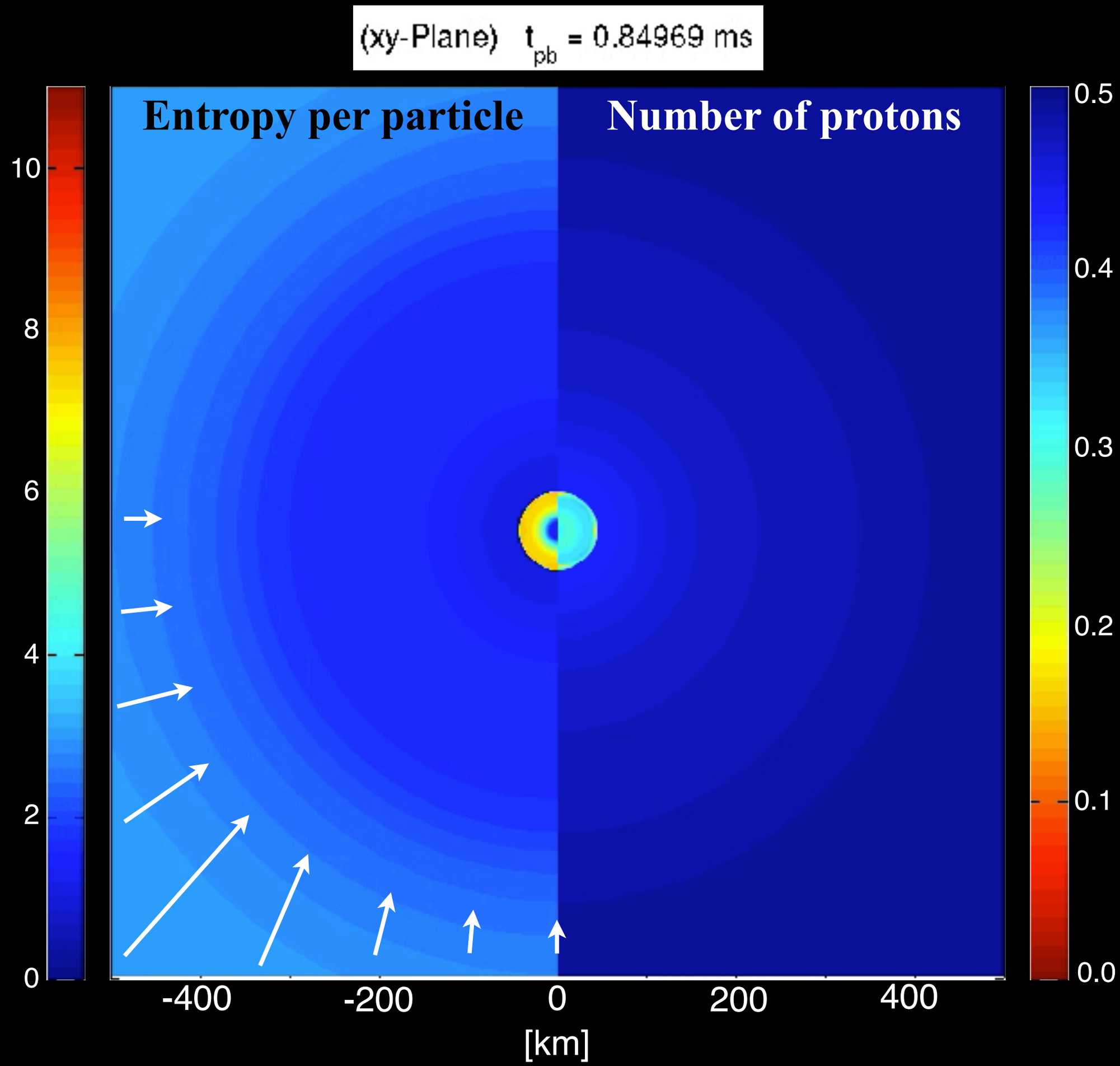

Time[s] = 0.15
T [10^9K] = 0.38
N_n[cm^-3] = 1.2e27
Time[s] = 0.9
T [10^9K] = 0.2
N_n[cm^-3] = 1.2e18
Time[s] = 11.
T [10^9K] = 0.1
N_n[cm^-3] = 4.6e12
Z
N
0
20
40
60
80
100
120
0
50
100
150
200
250
300
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12

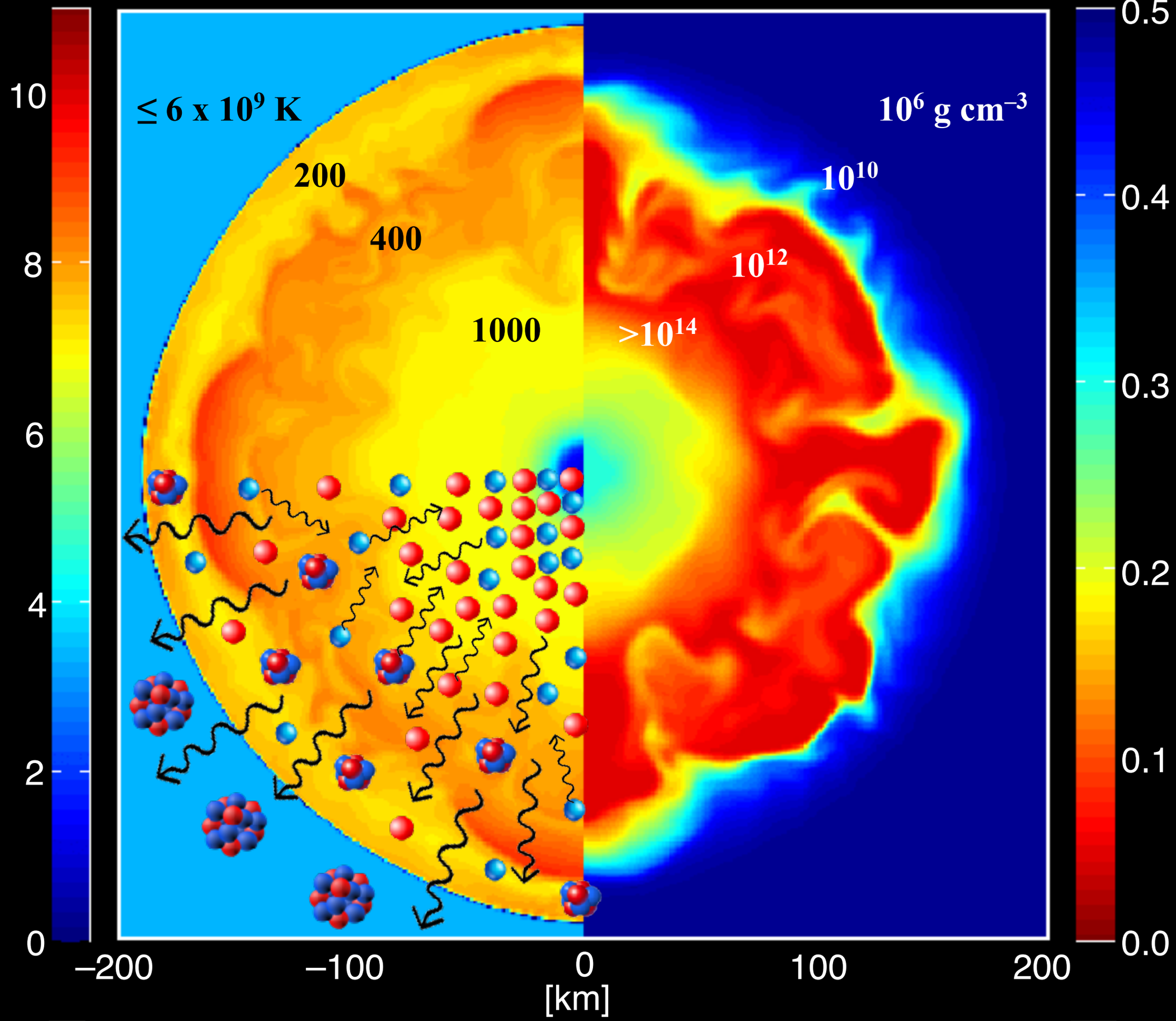
galaxy ~ 100’000’000’000 = 10^{11} stars

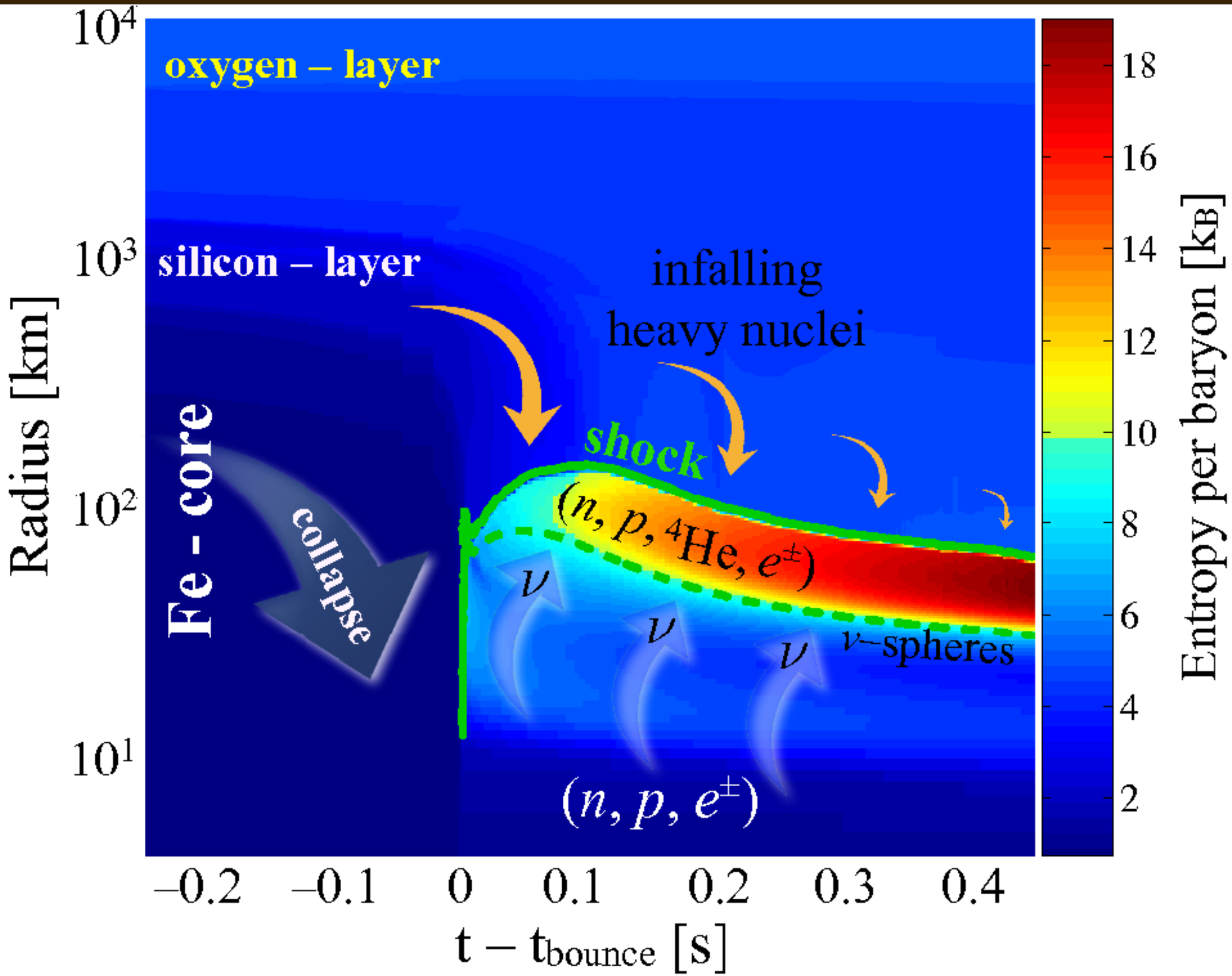
$$M_{\rm star} \sim 10 - 60\ {\rm M}_\odot$$

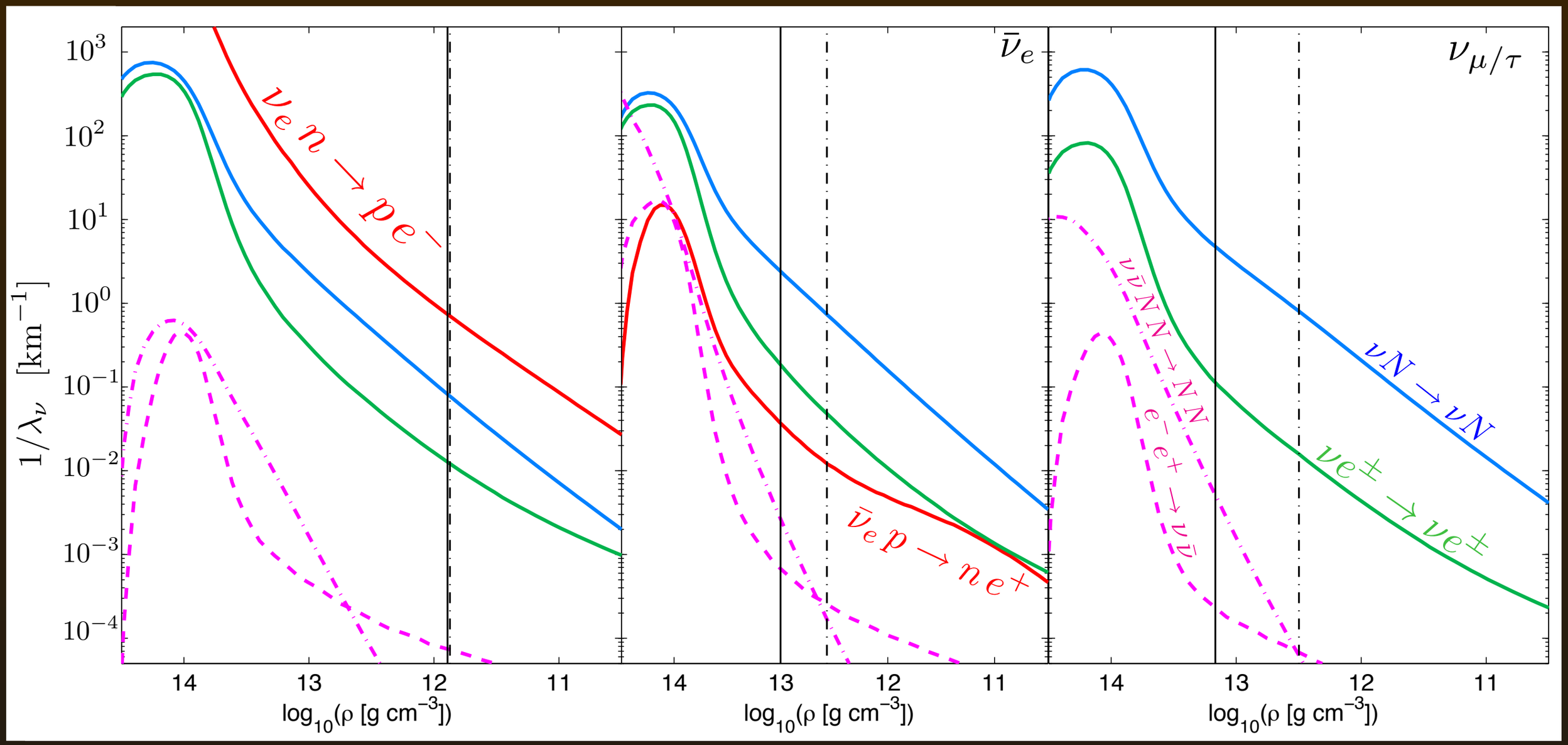
$$\left(1\ {\rm M}_\odot = 2 \times 10^{33}\ {\rm g}\right)$$


convection
core
nuclear burning


(xy-Plane) t_{pb} = 0.84969 ms
Entropy per particle
Number of protons
10
8
6
4
2
0
-400
-200
0
200
400
[km]
0.5
0.4
0.3
0.2
0.1
0.0


≤ 6 x 10⁹ K
200
400
1000
10⁶ g cm⁻³
10¹⁰
10¹²
>10¹⁴
10
8
6
4
2
0
–200
–100
0
100
200
[km]
0.5
0.4
0.3
0.2
0.1
0.0

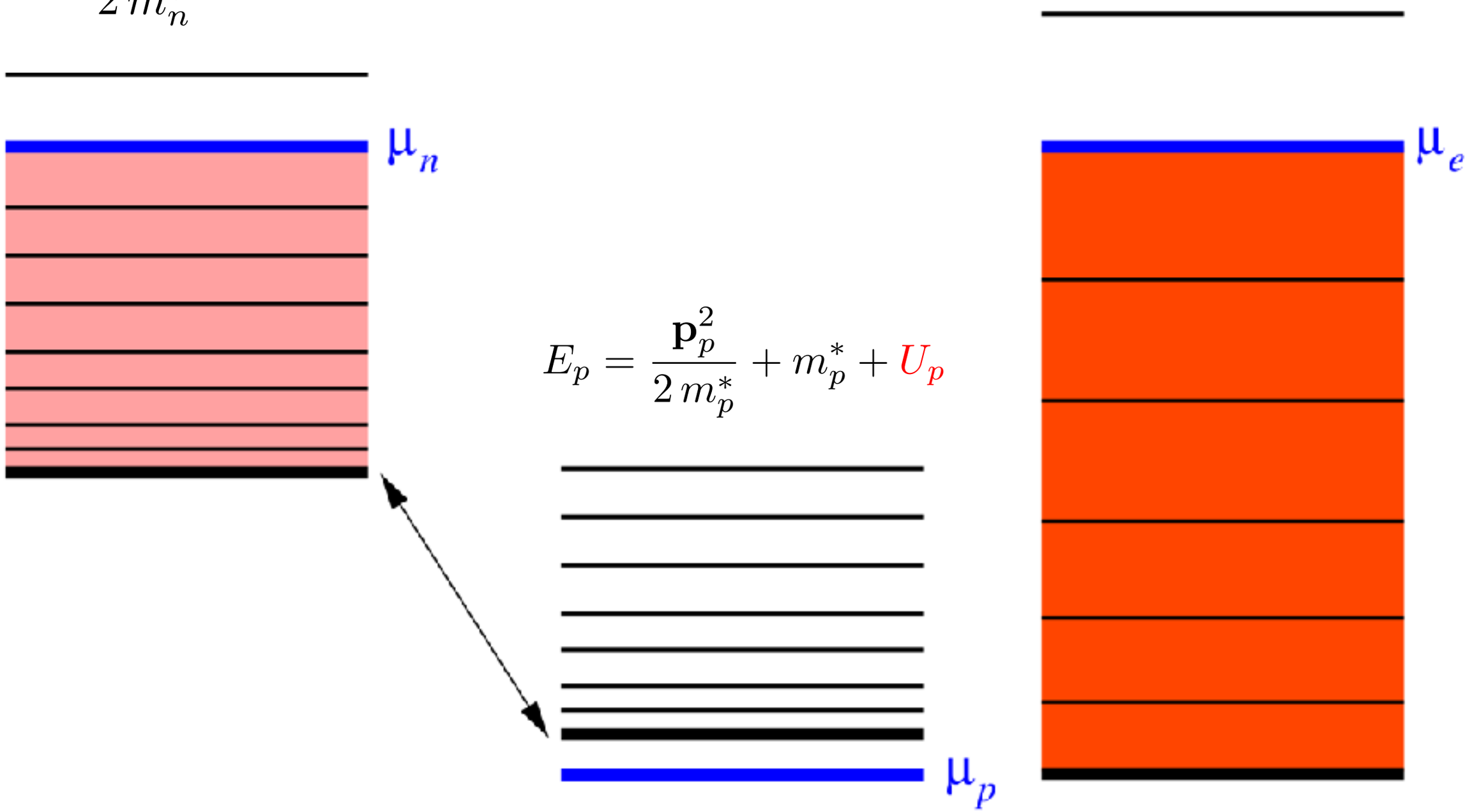

oxygen – layer
silicon – layer
infalling
heavy nuclei
shock
Fe - core
collapse
$(n, p, {}^4\mathrm{He}, e^{\pm})$
ν
ν
ν
ν–spheres
$(n, p, e^{\pm})$
Radius [km]
10^4
10^3
10^2
10^1
–0.2
–0.1
0
0.1
0.2
0.3
0.4
$t - t_{\mathrm{bounce}}$ [s]
Entropy per baryon [k_B]
18
16
14
12
10
8
6
4
2



Fischer et al., Phys. Rev. D85, 083003 (2012)

$$\nu_e\, n \rightarrow p\, e^-$$

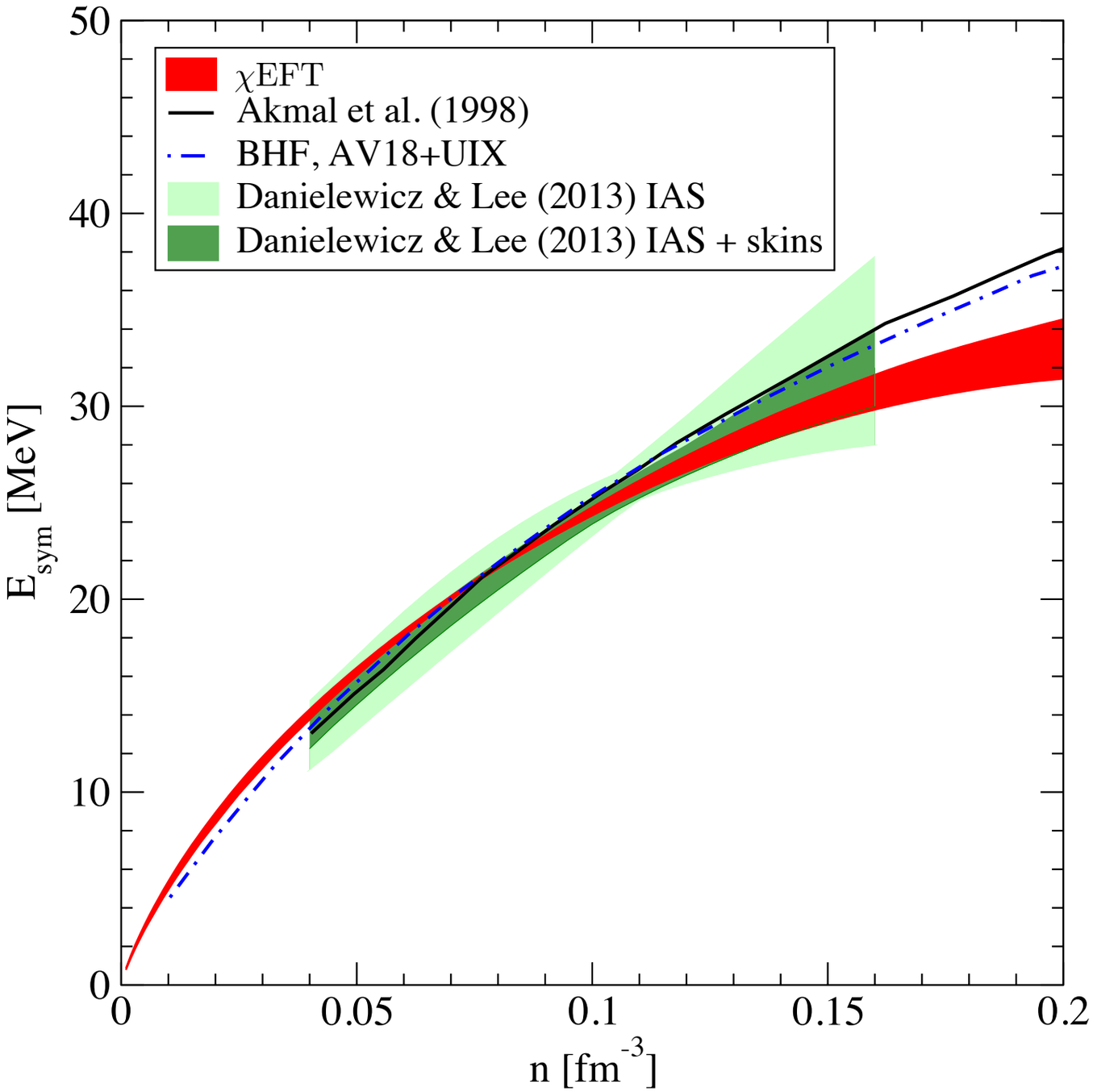
$$E_n = \frac{\mathbf{p}_n^2}{2\, m_n^*} + m_n^* + U_n$$

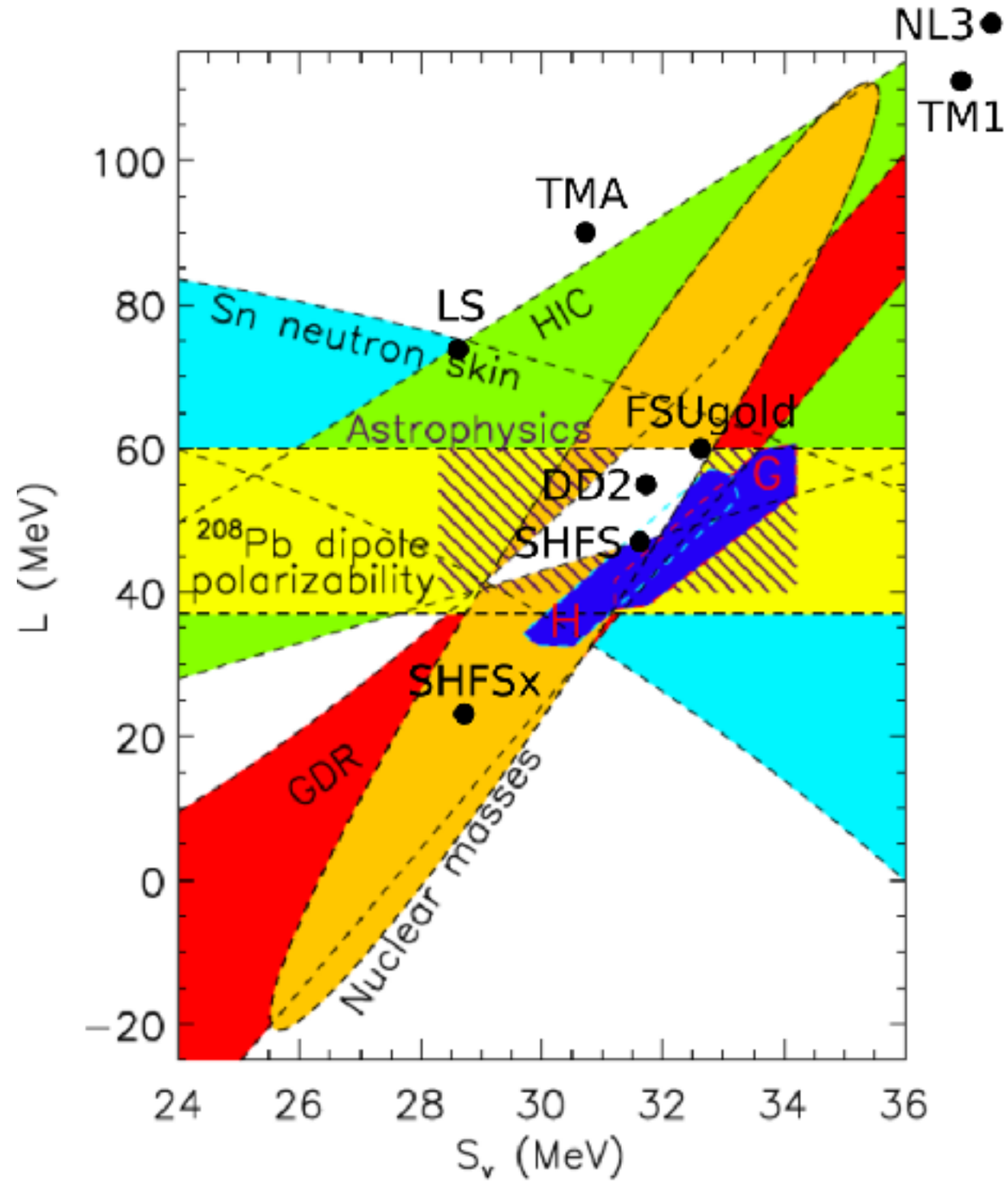


$$E_p = \frac{\mathbf{p}_p^2}{2\, m_p^*} + m_p^* + U_p$$

$$U_n - U_p \propto S^F(T, \rho)$$

Martinez-Pinedo et al., Phys. Rev. Lett. 109, 251104 (2012)





Lattimer & Lim, Eur. Phys. J. A50, 11 (2014)

$$e^- + p \leftrightarrows n + \nu_e$$
$$e^+ + n \leftrightarrows p + \bar{\nu}_e$$
$$n \leftrightarrows p + e^- + \bar{\nu}_e$$

$U_n - U_p \propto S(\rho)$

inelastic contributions
weak magnetism
$g_A \longrightarrow g_A - g_s\,;\;\; g_s \sim 0.15$

$$\nu_\alpha(\bar{\nu}_\alpha) + N^* \leftrightarrows N^* + \nu_\alpha(\bar{\nu}_\alpha)$$

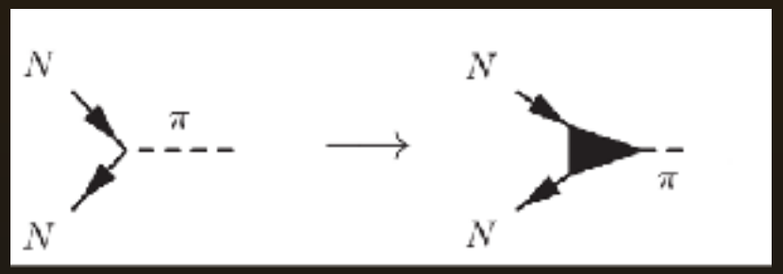
+ nuclear correlations, $S_A < 1$

$$e^- + (A,Z) \leftrightarrows (A,Z-1) + \nu_e$$
$$\nu_\alpha + (A,Z) \leftrightarrows (A,Z) + \nu_\alpha$$
$$(A,Z)^* \leftrightarrows (A,Z) + \nu_\alpha + \bar{\nu}_\alpha$$

nuclear structure

$$\nu_\alpha(\bar{\nu}_\alpha) + e^\pm \leftrightarrows e^\pm + \nu_\alpha(\bar{\nu}_\alpha)$$
$$\nu_\alpha + \nu_\beta \leftrightarrows \nu_\beta + \nu_\alpha$$

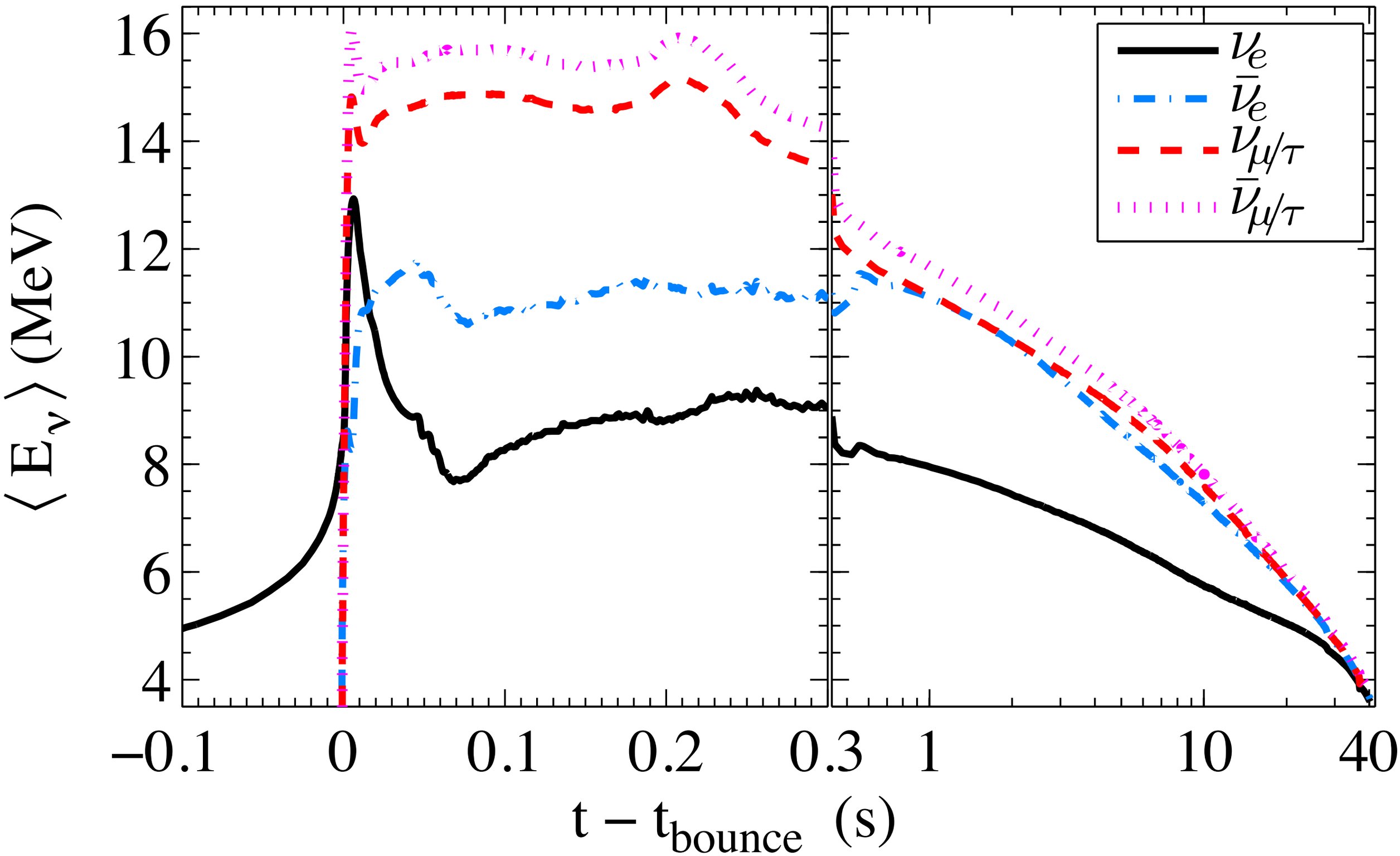
$$e^- + e^+ \leftrightarrows \nu_\alpha + \bar{\nu}_\alpha$$
$$NN \leftrightarrows NN + \nu_\alpha + \bar{\nu}_\alpha$$
$$\nu_\alpha + \bar{\nu}_\alpha \leftrightarrows \nu_\beta + \bar{\nu}_\beta$$

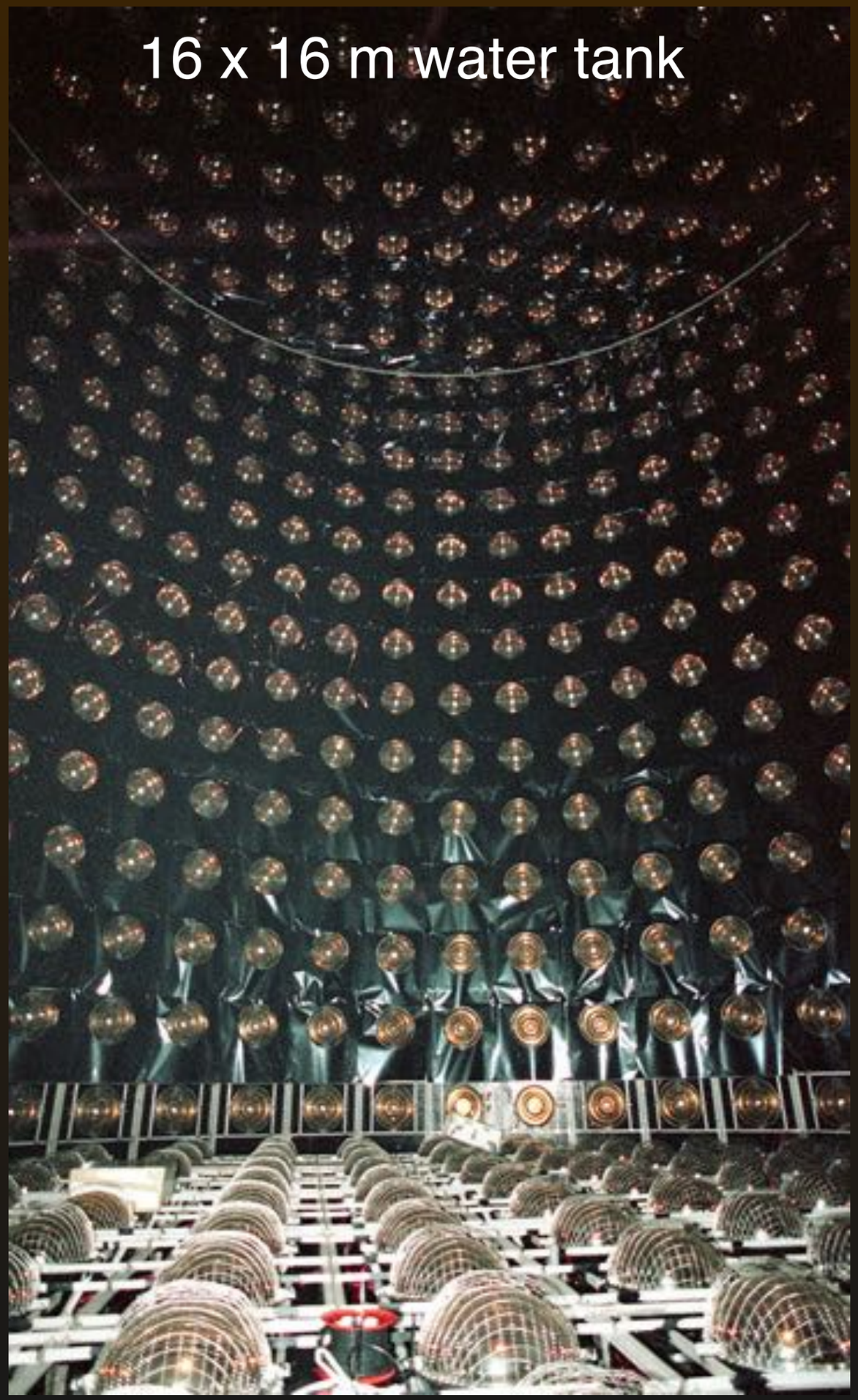


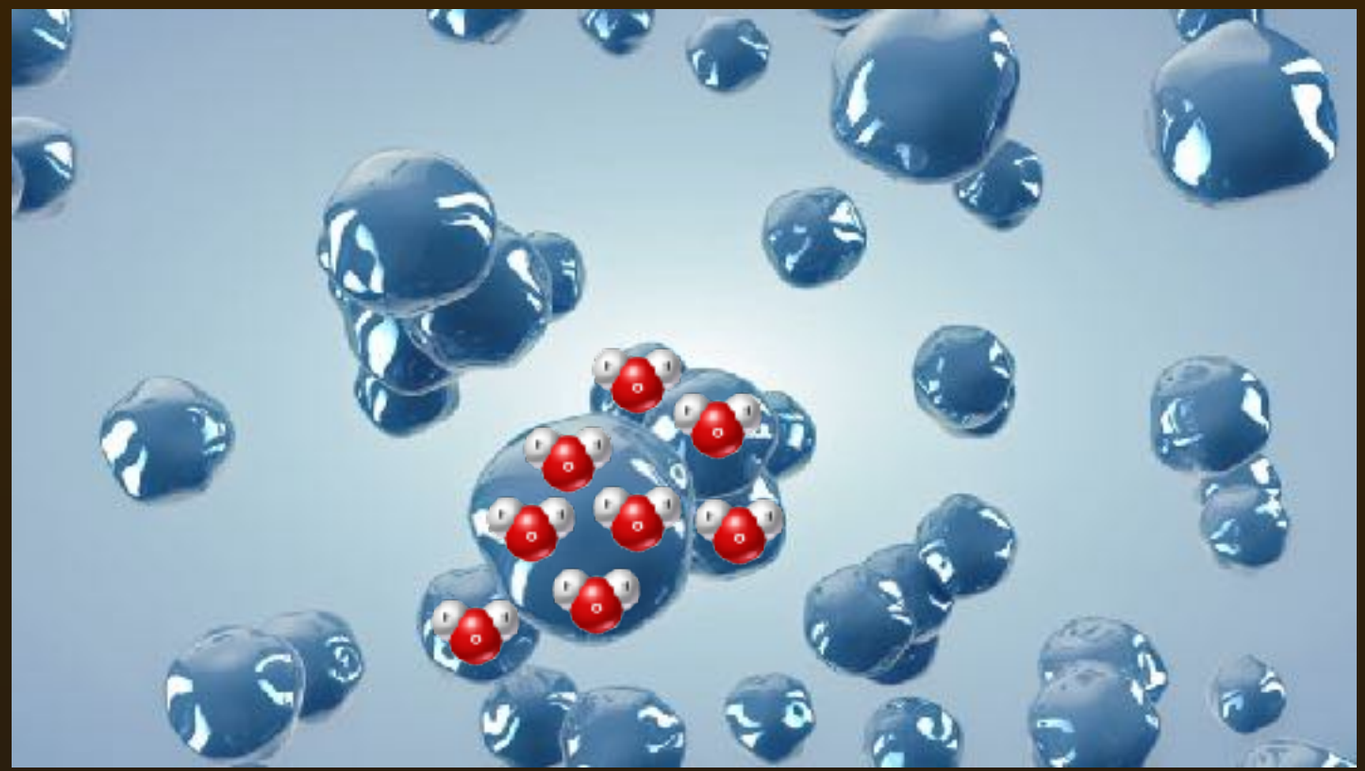
$g_A^*(\rho)$

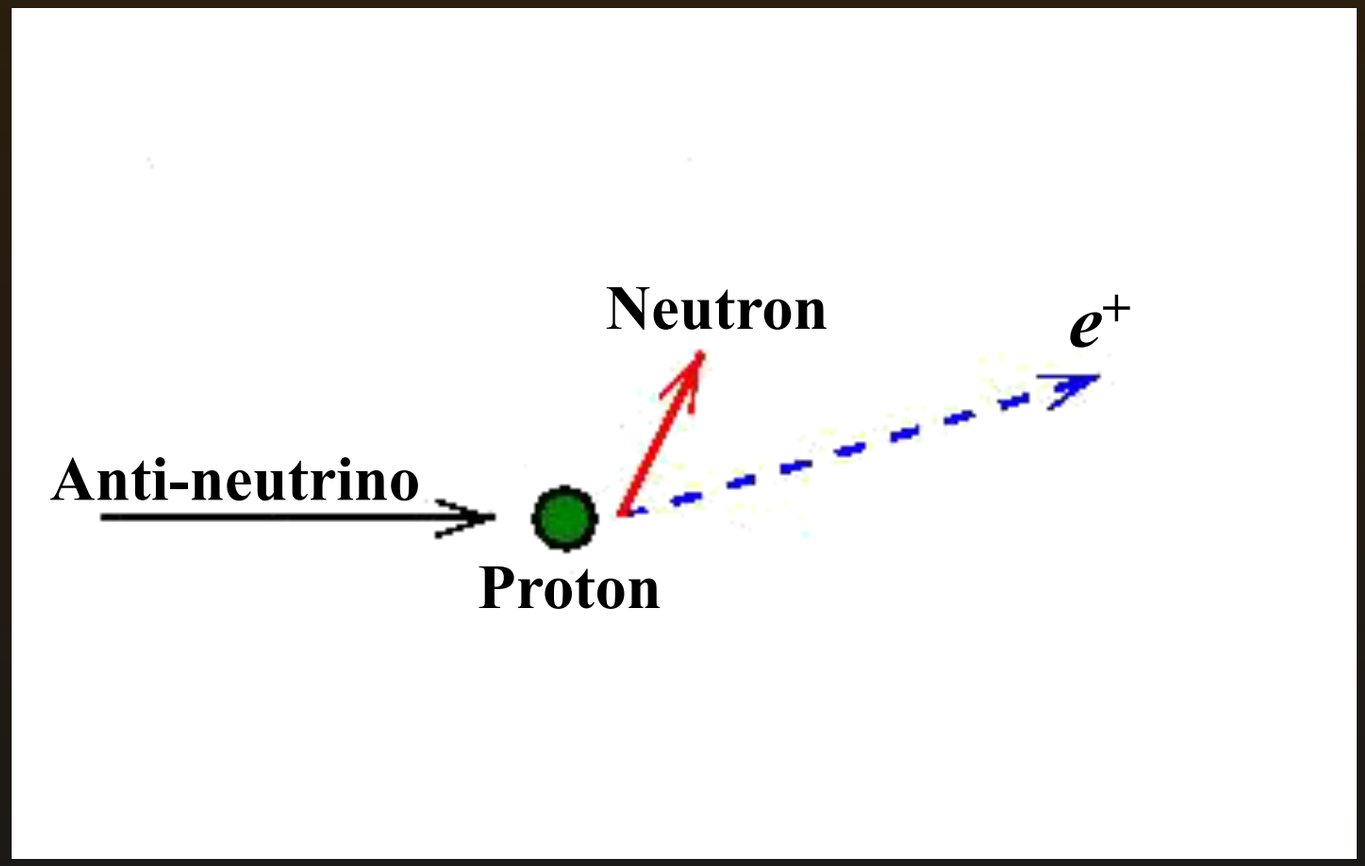
$$\mu^- + p \leftrightarrows n + \nu_\mu$$
$$\mu^- \leftrightarrows e^- + \nu_\mu + \bar{\nu}_e$$
$$\nu_e + \mu^- \leftrightarrows e^- \nu_e$$

Bollig et al.,(2017) PRL 119, 242702


16
14
12
10
8
6
4
$\langle E_\nu \rangle$ (MeV)
–0.1
0
0.1
0.2
0.3
1
10
40
$t - t_{bounce}$ (s)
ν_e
$\bar{\nu}_e$
$\nu_{\mu/\tau}$
$\bar{\nu}_{\mu/\tau}$

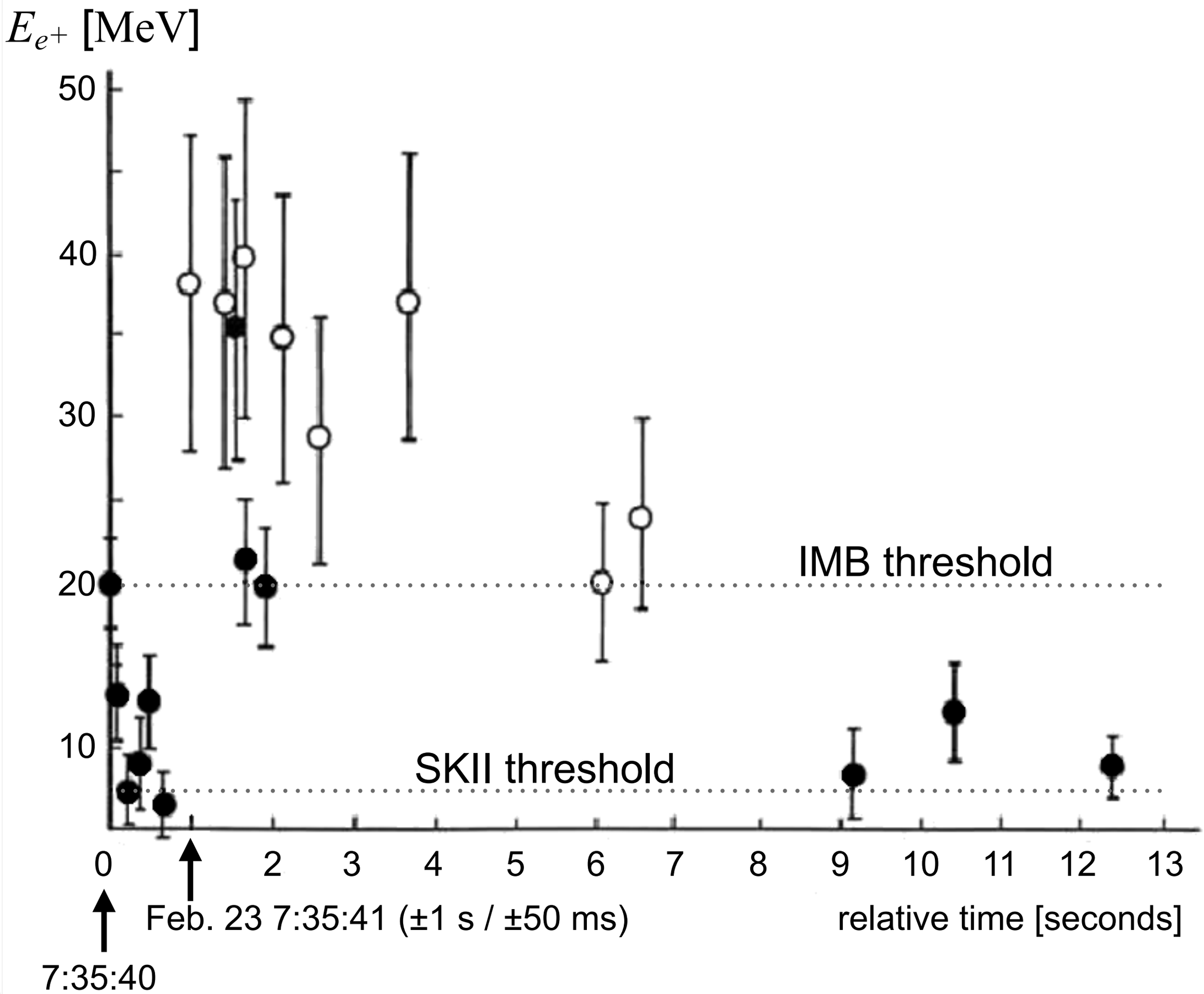

16 x 16 m water tank



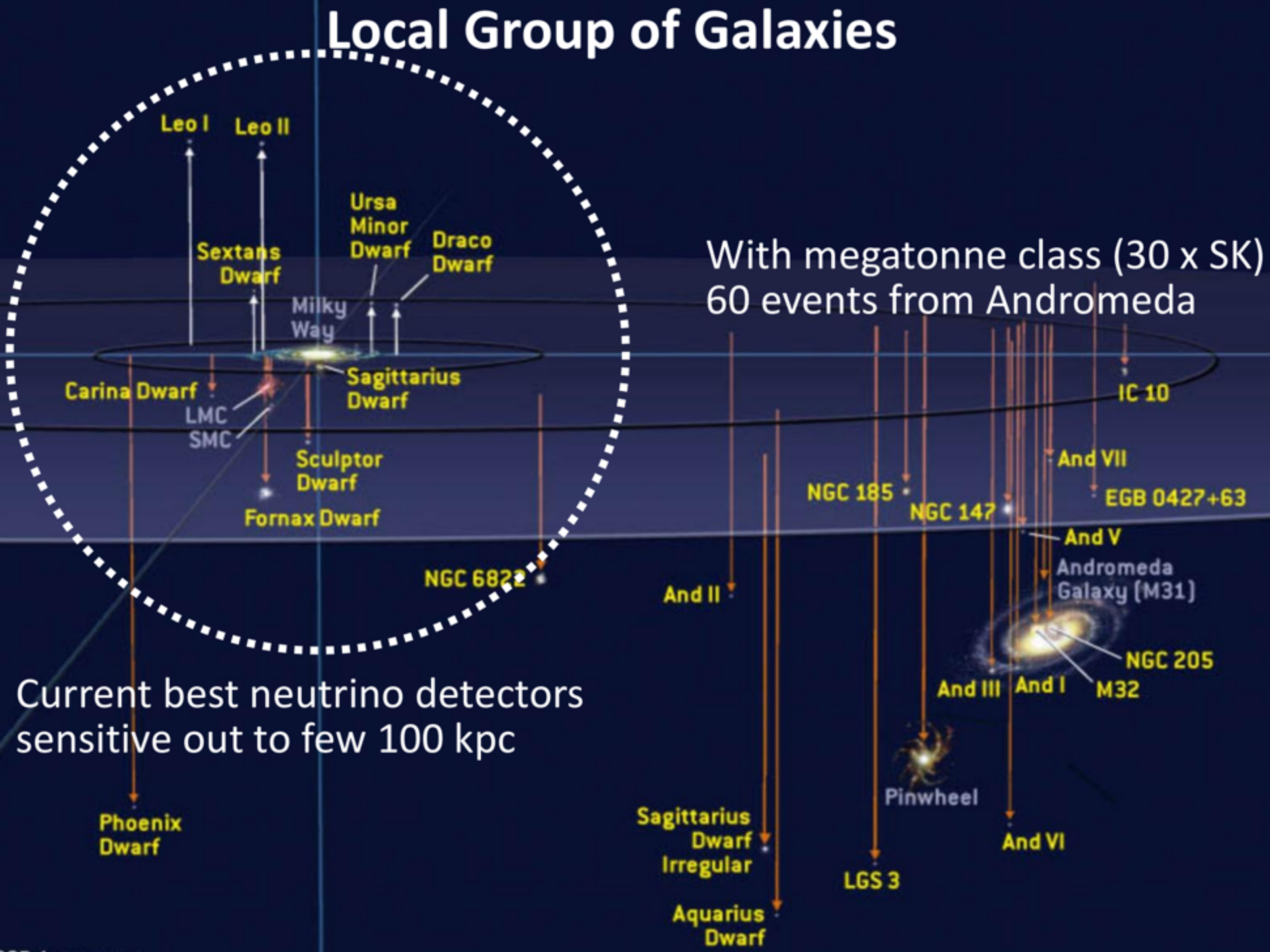

Neutron
e^+
Anti-neutrino
Proton

```
1751.011  *                                                                                                                  *7516
1750.911  *         + +                                                                                                      *7515
1750.811  *      +          +                                                                                                *7514
1750.711  *                                                                                                                  *7513
1750.611  *    + +                                                                                                           *7512
1750.511  *    ++    +                                                                                                       *7511
1750.411  *       ++ +                                                                                                       *7510
1750.311  *      +     +                                                                                                     *7509
1750.211  *         + 2+                                                                                                     *7508
1750.111  *       +  2                                                                                                       *7507
1750.01   *       2 +                                                                                                        *7506
1749.91   *                                                                                                                  *7505
1749.81   *      +   +                                                                                                       *7504
1749.71   *      + 2+ +                                                                                                      *7503
1749.61   *   +   ++ +   +                                                                                                   *7502
1749.51   *       + +                                                                                                        *7501
1749.41   *         +2                                                                                                       *7500
1749.31   *     +   +                                                                                                        *7499
1749.21   *     +      2                                                                                                     *7498
1749.11   *          +                                                                                                       *7497
1749.01   *           +                                                                                                      *7496
1748.909  *        +                                                                                                         *7495
1748.809  *         ++                                                                                                       *7494
1748.709  *      + +  +                                                                                                      *7493
1748.609  *      +    +                                                                                                      *7492
1748.509  *                                                                                                                  *7491
1748.409  *          +  +                                                                                                    *7490
1748.309  *                                                                                                                  *7489
1748.209  *      + ++                                                                                                        *7488
1748.109  *        + +                                                                                                       *7487
1748.009  *      + + ++                                                                                                      *7486
1747.908  *         ++                                                                                                       *7485
1747.808  *     +                                                                                                            *7484
1747.708  *        2 +                                                                                                       *7483
1747.608  *                                                                                                                  *7482
1747.508  * +     +                                                                                                          *7481
1747.408  *           +                                                                                                      *7480
1747.308  *      2                                                                                                           *7479
1747.208  *     +   +                                                                                                        *7478
1747.108  *        ++                                                                                                        *7477
1747.008  *       +   +                                                                                                      *7476
1746.907  *     +     +                                                                                                      *7475
1746.807  *                                                                                                                  *7474
1746.707  *      +       +                                                                                                   *7473
1746.607  *     + ++                                                                                                         *7472
1746.507  *                                                                                                                  *7471
1746.407  *   +                                                                                                              *7470
1746.307  *     + +                                                                                                          *7469
1746.207  *     +   +     2                                                                                                  *7468
1746.107  *        ++      +                                                                                                 *7467
1746.007  *   +    ++   +                                                                                                    *7466
1745.906  *       + ++                                                                                                       *7465
1745.806  *   +                                                                                                              *7464
1745.706  *        ++                                                                                                        *7463
1745.606  *      + ++                                                                                                        *7462
1745.506  *          2                                                                                                       *7461
1745.406  *       +                                                                                                          *7460
1745.306  *   +     +                                                                                                        *7459
1745.206  *       +                                                                                                          *7458
1745.106  *         +                                                                                                        *7457
1745.006  *       ++                                                                                                         *7456
1744.906  *   +  +  2 +                                                                                                      *7455

1744.805  *      +2                                                                                                          *7454
1744.705  *           +                                                                                                      *7453
1744.605  *        +3                                                                                                        *7452
1744.505  *      +   +                                                                                                       *7451
1744.405  *       +  +                                                                                                       *7450
1744.305  *                                                                                                                  *7449
1744.205  *      +                                                                                                           *7448
1744.105  *     + ++                                                                                                         *7447
1744.005  *       2  +   +                                                                                                   *7446
1743.905  *                                                                                                                  *7445
1743.804  *       2+ 2    +                                                                                                  *7444
1743.704  *            +                                                                                                     *7443
1743.604  *                                                                                                                  *7442
1743.504  *  +       +                                                                                                       *7441
1743.404  *         3 +                                                                                                      *7440
1743.304  *             +  +                +                                                                                *7439
1743.204  *        +       ++              +  +             +   +   +                          +                             *7438
1743.104  *                                                                                                                  *7437
1743.004  *      2  +                                                                                                        *7436
1742.904  *                                                                                                                  *7435
1742.803  *        + +                                                                                                       *7434
1742.703  *        +                                                                                                         *7433
1742.603  *       + +                                                                                                        *7432
1742.503  *       + +                                                                                                        *7431
1742.403  *     +   2 +                                                                                                      *7430
1742.303  *    +                                                                                                             *7429
1742.203  *      + +                                                                                                         *7428
1742.103  *      +++                                                                                                         *7427
1742.003  *          + +                                                                                                     *7426
1741.903  *  +                                                                                                               *7425
1741.803  *     3                                                                                                            *7424
1741.703  *                                                                                                                  *7423
1741.602  *    +  + +    +                                                                                                   *7422
1741.502  *       +                                                                                                          *7421
1741.402  *                                                                                                                  *7420
1741.302  *                                                                                                                  *7419
1741.202  *                                                                                                                  *7418
1741.102  *                                                                                                                  *7417
1741.002  *                                                                                                                  *7416
1740.902  *                                                                                                                  *7415
1740.802  *                                                                                                                  *7414
1740.701  *                                                                                                                  *7413
1740.601  *                                                                                                                  *7412
1740.501  *                                                                                                                  *7411
1740.401  *                                                                                                                  *7410
1740.301  *                                                                                                                  *7409
1740.201  *                 +                                                                                                *7408
1740.101  *       +                                                                                                          *7407
1740.001  *       2                                                                                                          *7406
1739.901  *        ++                                                                                                        *7405
1739.801  *          +                                                                                                       *7404
1739.7    *     +++ +                                                                                                        *7403
1739.6    *       2+++                                                                                                       *7402
1739.5    *      +  ++    +                                                                                                  *7401
1739.4    *          +                                                                                                       *7400
1739.3    *      2                                                                                                           *7399
1739.2    *    + +                                                                                                           *7398
1739.1    *                                                                                                                  *7397
1739      *       3++                                                                                                        *7396
1738.9    *        ++                                                                                                        *7395
1738.8    *    +   2                                                                                                         *7394
1738.699  *                                                                                                                  *7393
1738.599  *       +                                                                                                          *7392
1738.499  *          +                                                                                                       *7391
```

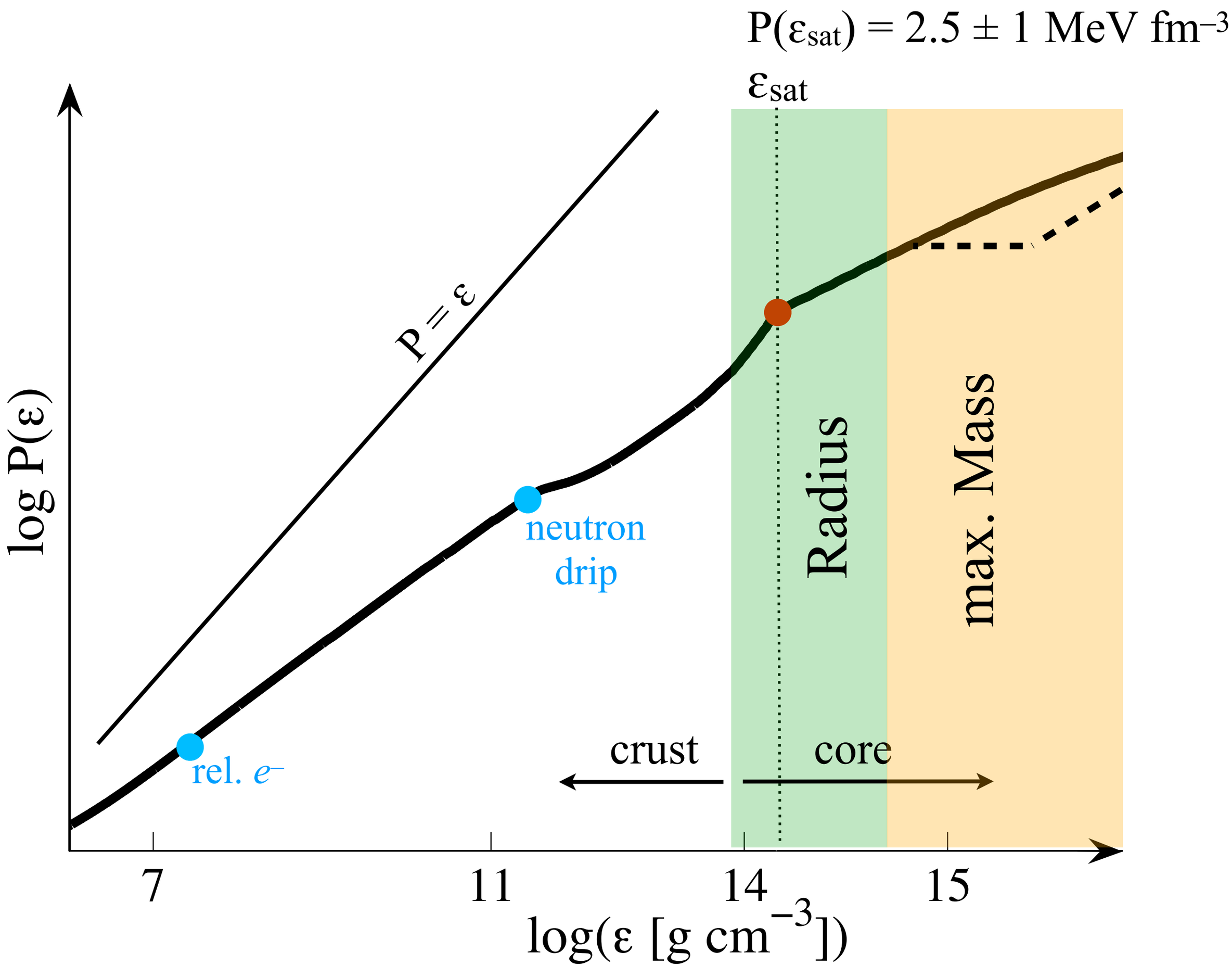

E_{e^+} [MeV]
50
40
30
20
10
IMB threshold
SKII threshold
0
2
3
4
5
6
7
8
9
10
11
12
13
Feb. 23 7:35:41 (±1 s / ±50 ms)
relative time [seconds]
7:35:40

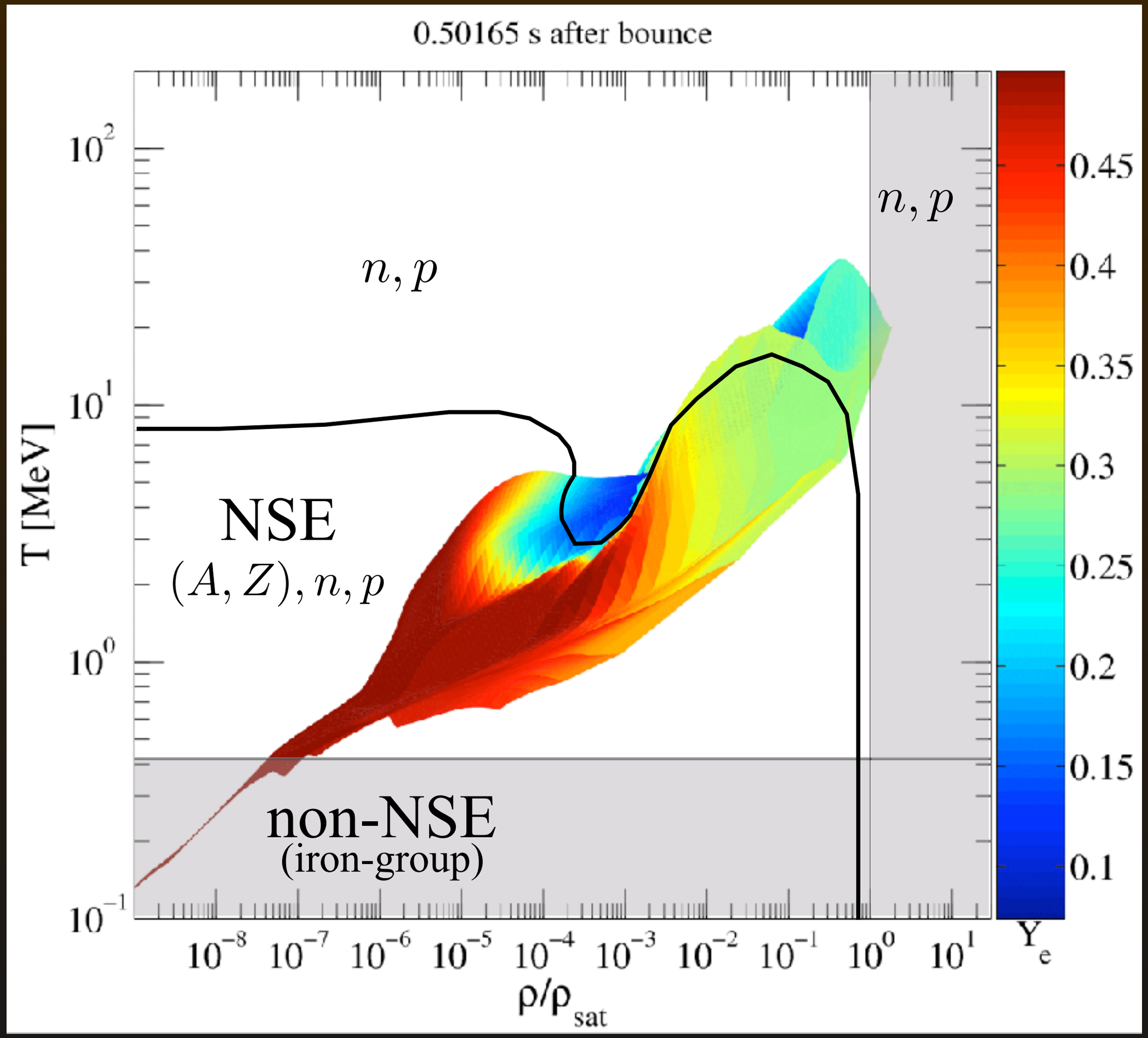
Local Group of Galaxies

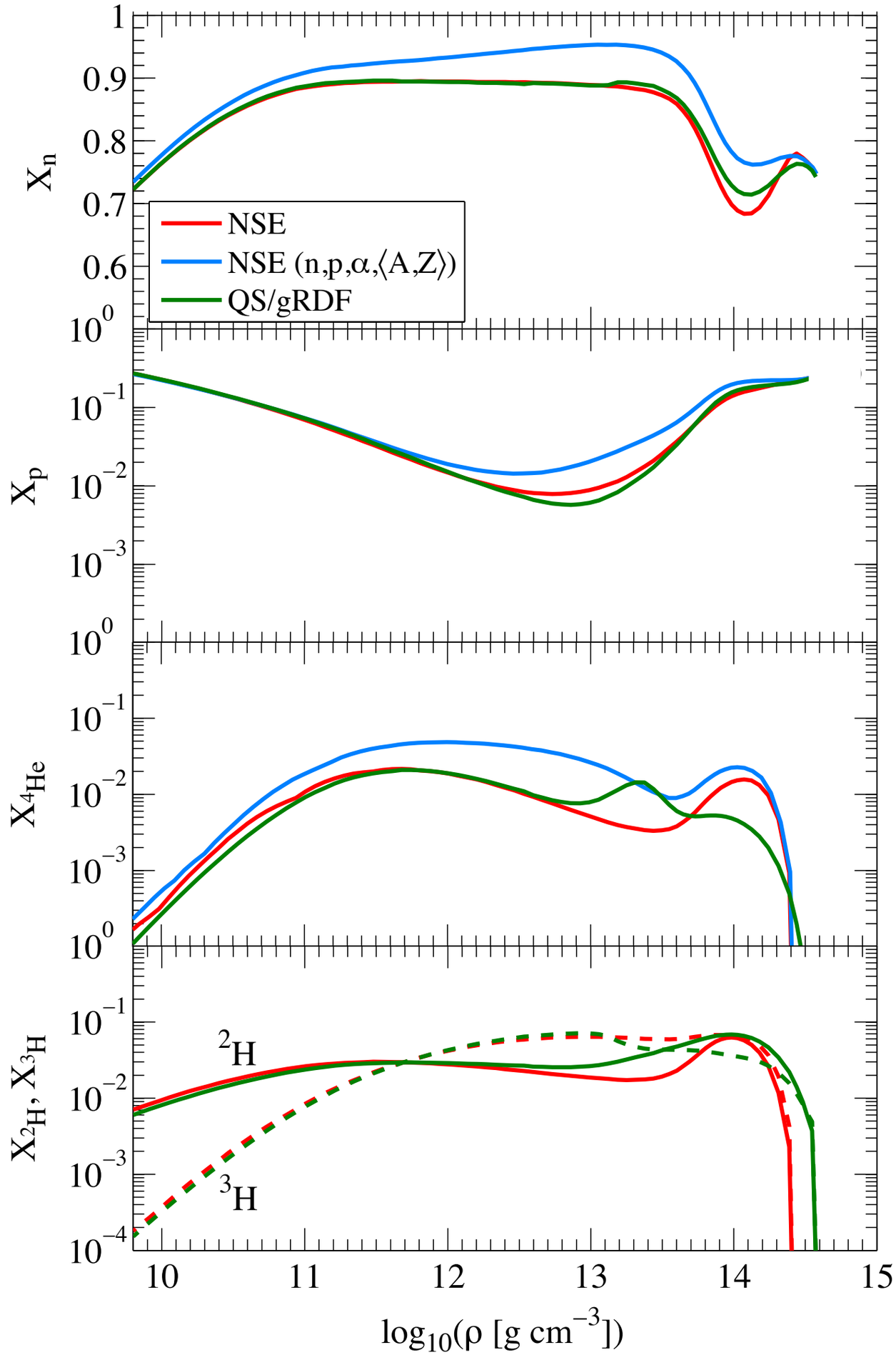


With megatonne class (30 x SK)
60 events from Andromeda

Current best neutrino detectors
sensitive out to few 100 kpc


P(εsat) = 2.5 ± 1 MeV fm−3
εsat
log P(ε)
P = ε
neutron
drip
rel. e−
crust
core
Radius
max. Mass
7
11
14
15
log(ε [g cm−3])

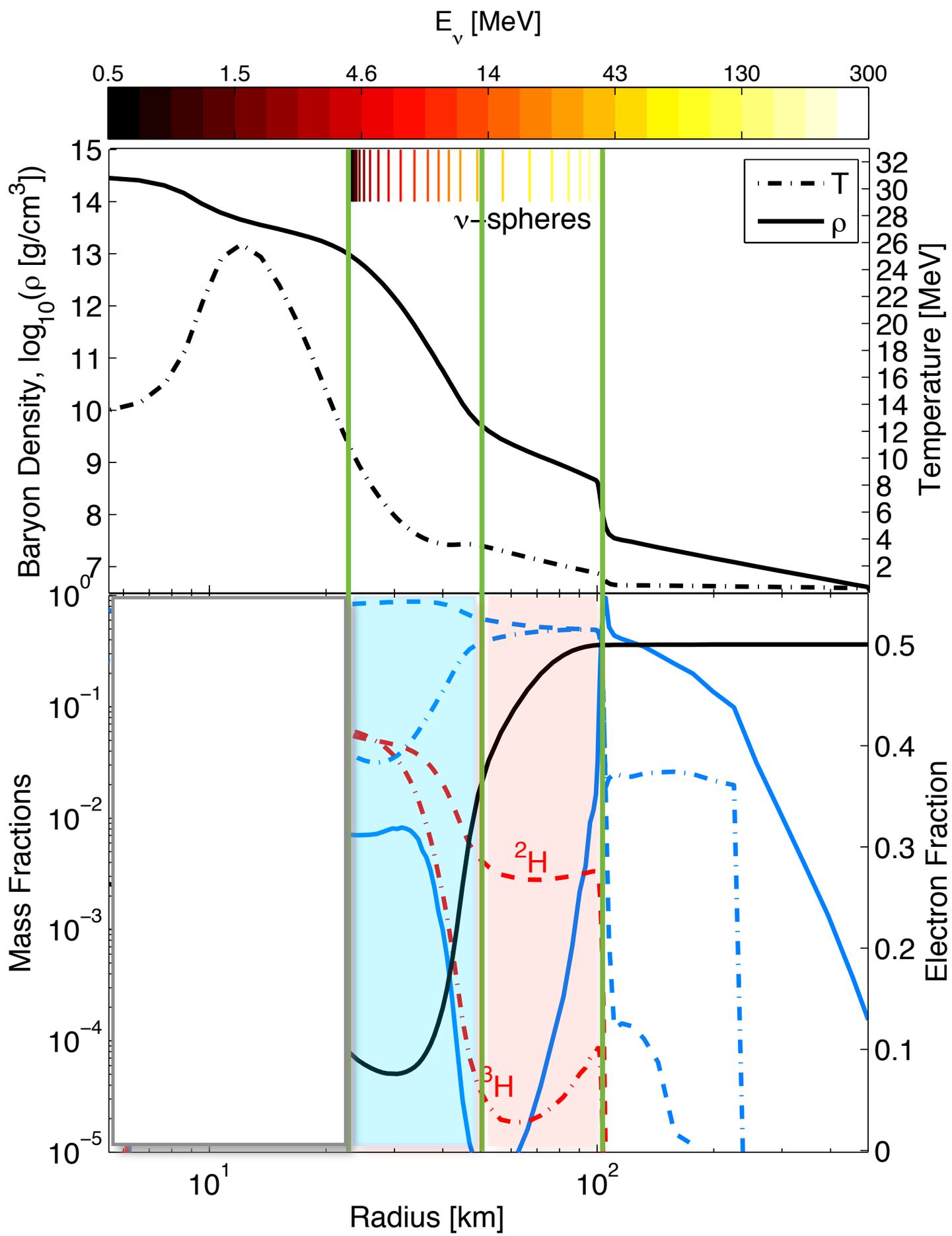

0.50165 s after bounce
n, p
n, p
NSE
$(A, Z), n, p$
non-NSE
(iron-group)
T [MeV]
10^2
10^1
10^0
10^{-1}
10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1
ρ/ρ_{sat}
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
Y_e



NSE: "all" clusters

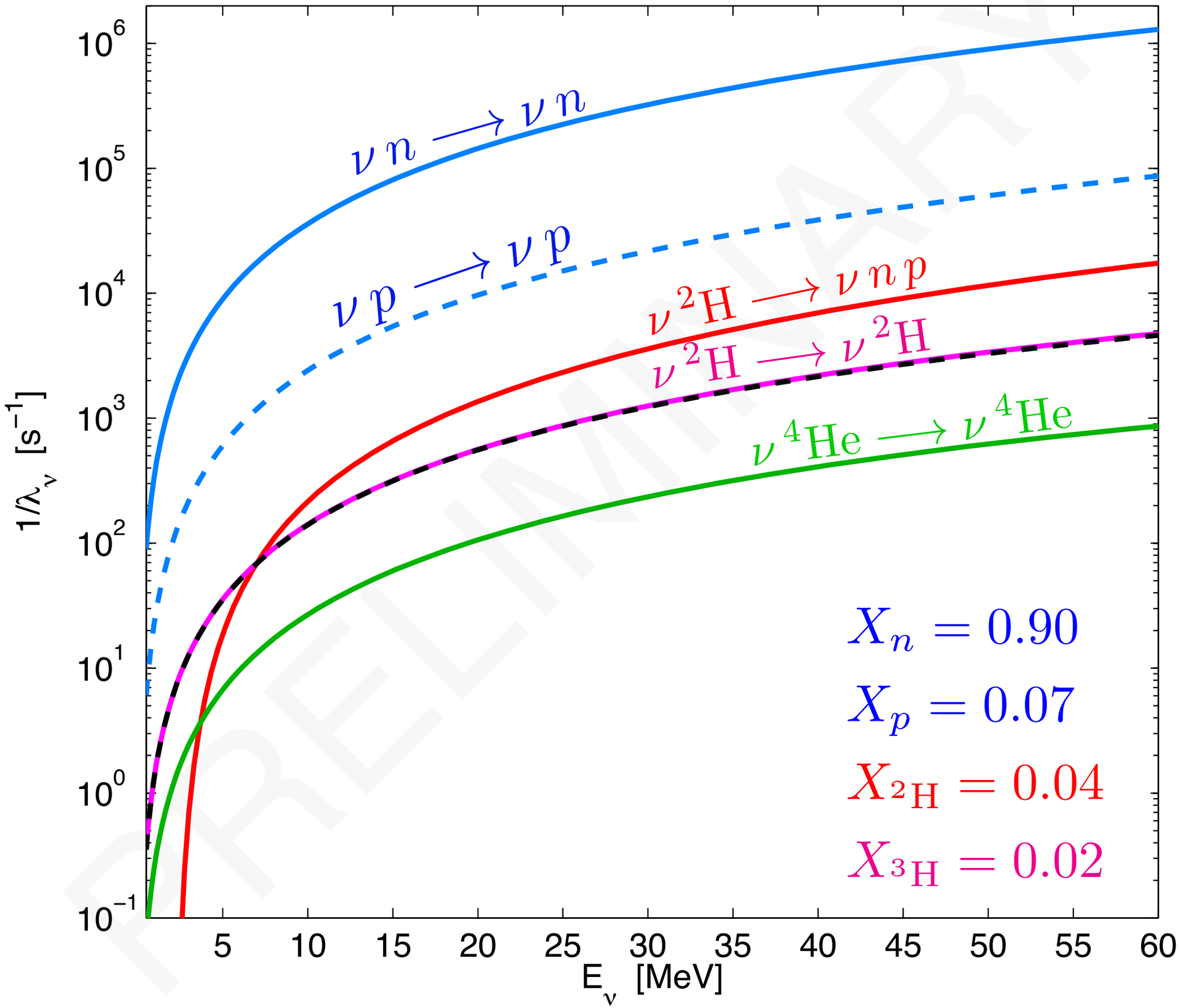
NSE: {*n*, *p*, ^{4}He, (A,Z)}

QS/gRDF



Sumiyoshi & Röpke (2008) PRC 77, 055804
Arcones et al.,(2008) PRC 77, 055804
Hempel & TF et al.,(2012) ApJ 748, 70
Furusawa et al.,(2013) ApJ 774, 13

$$\nu_\alpha + {}^2\mathrm{H} \leftrightarrows p + n + \nu_\alpha$$
$$\nu_\alpha + {}^2\mathrm{H} \leftrightarrows {}^2\mathrm{H} + \nu_\alpha$$
$$\nu_\alpha + {}^3\mathrm{H} \leftrightarrows {}^3\mathrm{H} + \nu_\alpha$$
$$\nu_\alpha + {}^3\mathrm{He} \leftrightarrows {}^3\mathrm{He} + \nu_\alpha$$



PRELIMINARY

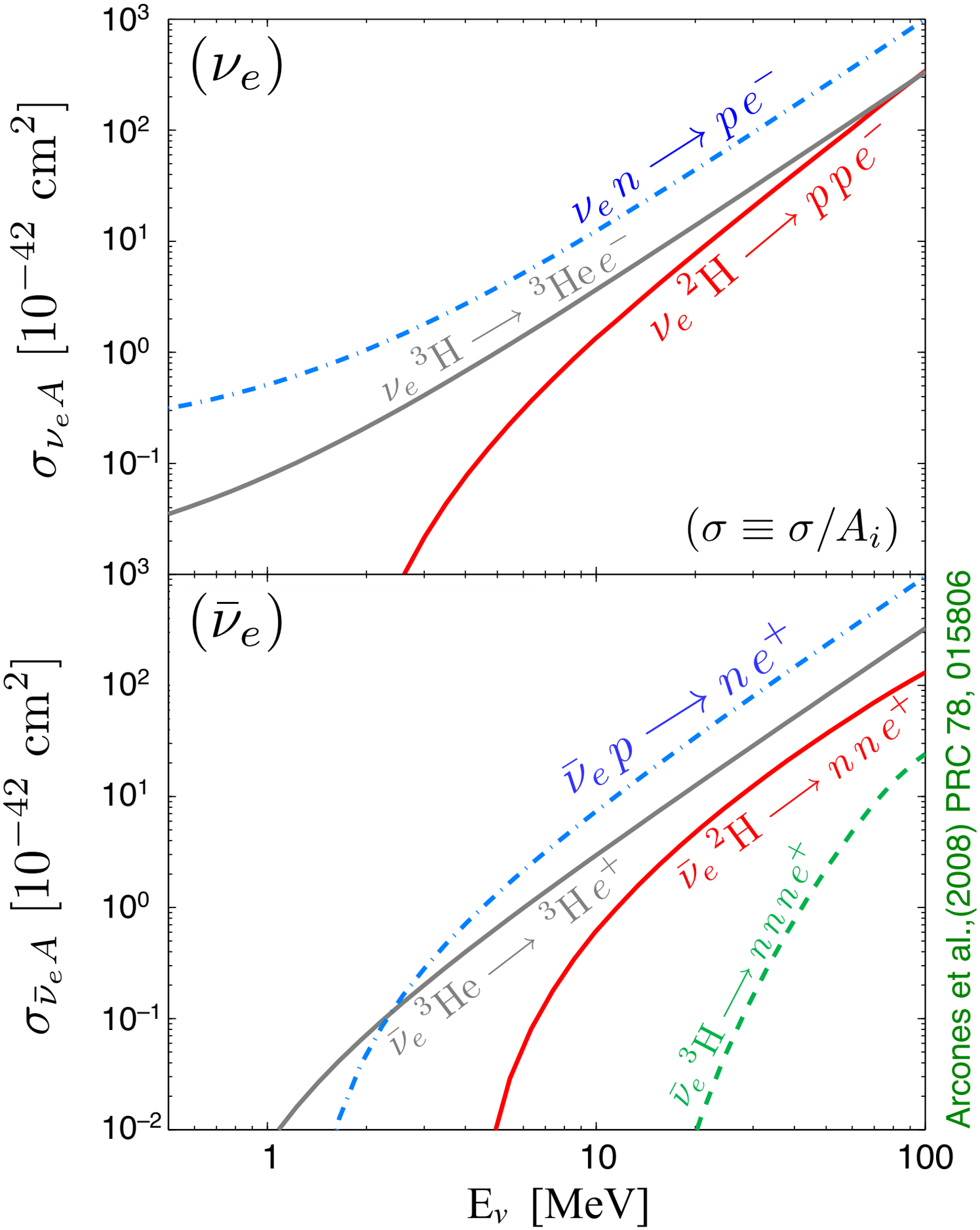
$$\nu_e + {}^2\mathrm{H} \leftrightarrows p + p + e^-$$
$$\bar{\nu}_e + {}^2\mathrm{H} \leftrightarrows n + n + e^+$$

$$e^- + {}^2\mathrm{H} \leftrightarrows n + n + \nu_e$$
$$e^+ + {}^2\mathrm{H} \leftrightarrows p + p + \bar{\nu}_e$$

$$\bar{\nu}_e + e^- + {}^2\mathrm{H} \leftrightarrows n + n$$
$$\nu_e + e^+ + {}^2\mathrm{H} \leftrightarrows p + p$$

$$\nu_e + {}^3\mathrm{H} \leftrightarrows n + p + p + e^-$$
$$\bar{\nu}_e + {}^3\mathrm{H} \leftrightarrows n + n + n + e^+$$

$$\nu_e + {}^3\mathrm{H} \leftrightarrows {}^3\mathrm{He} + e^-$$
$$\bar{\nu}_e + {}^3\mathrm{He} \leftrightarrows {}^3\mathrm{H} + e^+$$



Arcones et al.,(2008) PRC 78, 015806

$$\nu_e + {}^2\mathrm{H} \longrightarrow p_1 + p_1 + e^- , \qquad \bar{\nu}_e + {}^2\mathrm{H} \longrightarrow n_1 + n_1 + e^+$$

Nakamura et al.,(2001) PRC63, 034617

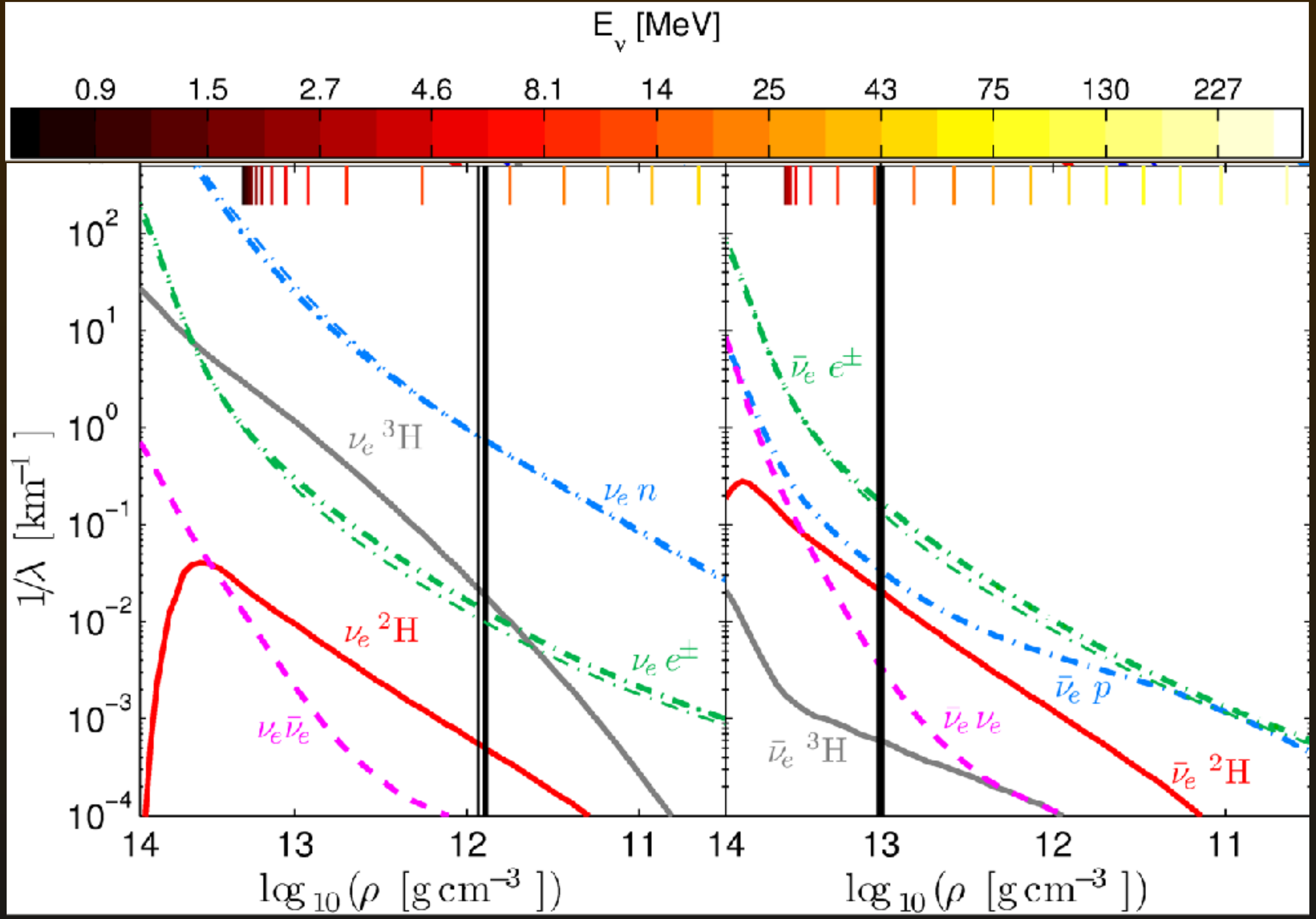
$$\chi(E_\nu) = \frac{g_{\,{}^2\mathrm{H}}}{2} \int \frac{d^3 p_{\,{}^2\mathrm{H}}}{(2\pi^3)} d\Omega_e \, dp_e \, d(\cos\theta) \boxed{\left(\frac{d\sigma_{\nu\,{}^2\mathrm{H}}}{dp_e}(E^*_\nu) \right)}$$

$$\times \boxed{\tilde{f}_{\,{}^2\mathrm{H}}\left(p_{\,{}^2\mathrm{H}}\right)} \boxed{\left(1 - f_e(E_e)\right)\left(1 - f_1(E_1)\right)\left(1 - f_2(E_2)\right)}$$

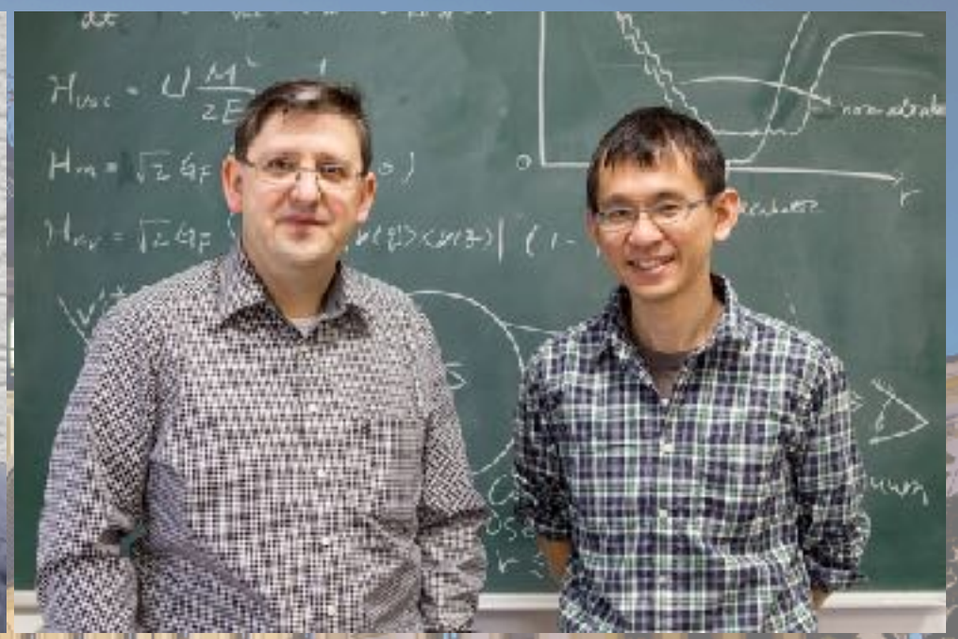
$$E^*_{\nu_e} = E_{\nu_e} + \left(m^*_{\,{}^2\mathrm{H}} - m_{\,{}^2\mathrm{H}}\right) + \left(U_{\,{}^2\mathrm{H}} - 2U_p\right) - 2\left(m^*_p - m_p\right)$$

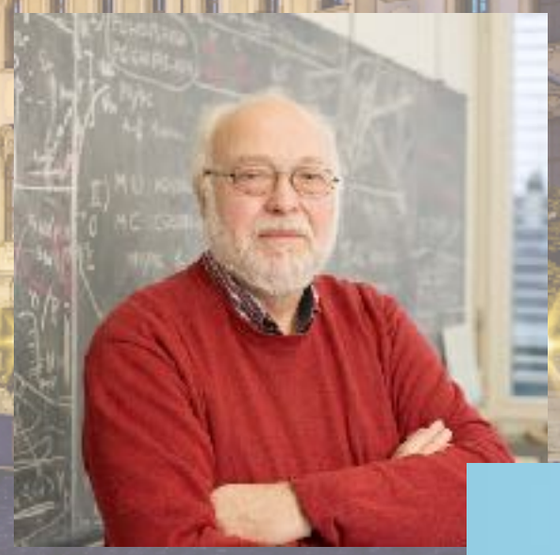
$$E^*_{\bar{\nu}_e} = E_{\bar{\nu}_e} + \left(m^*_{\,{}^2\mathrm{H}} - m_{\,{}^2\mathrm{H}}\right) + \left(U_{\,{}^2\mathrm{H}} - 2U_n\right) - 2\left(m^*_n - m_n\right)$$

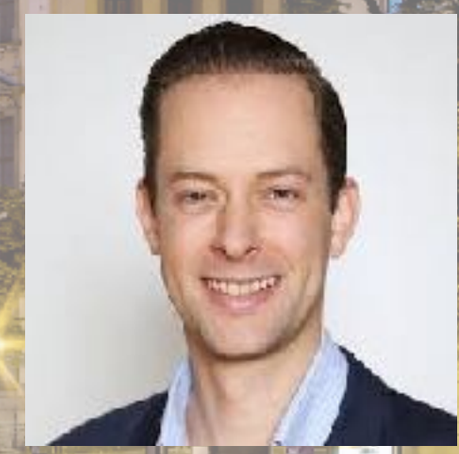
$$U_{\,{}^2\mathrm{H}} \simeq \mu_{\,{}^2\mathrm{H}} - \phi_{\,{}^2\mathrm{H}}$$


E_ν [MeV]
0.9
1.5
2.7
4.6
8.1
14
25
43
75
130
227
1/λ [km^-1]
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
ν_e ³H
ν_e ²H
ν_e ν̄_e
ν_e n
ν_e e^±
ν̄_e e^±
ν̄_e ³H
ν̄_e ν_e
ν̄_e p
ν̄_e ²H
14
13
12
11
log_10(ρ [g cm^-3])

Wroclaw Supernova Project







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