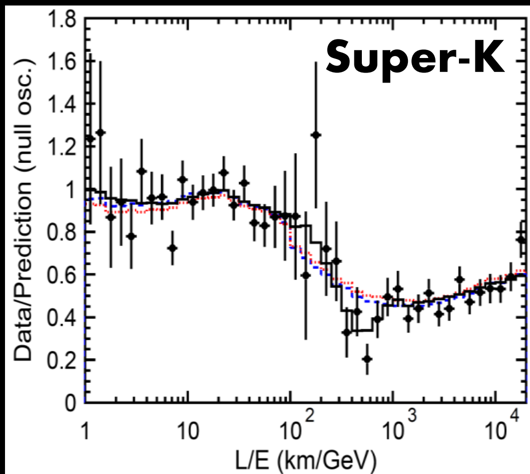
Astrophysical Bounds on Secret Neutrino Interactions

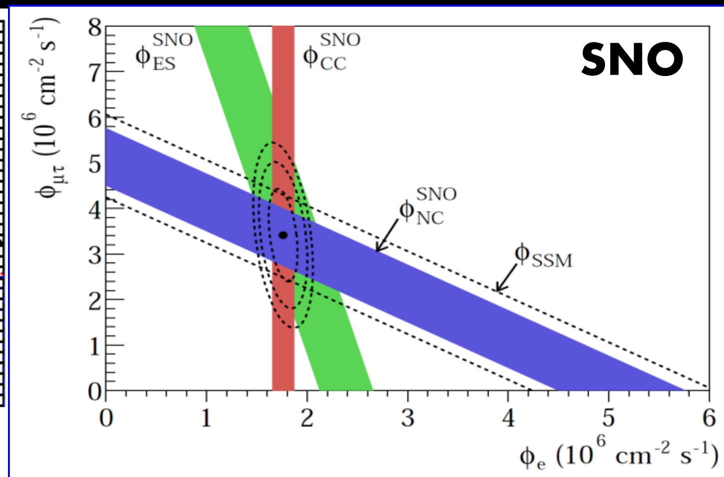
Shun Zhou
(IHEP, Beijing)

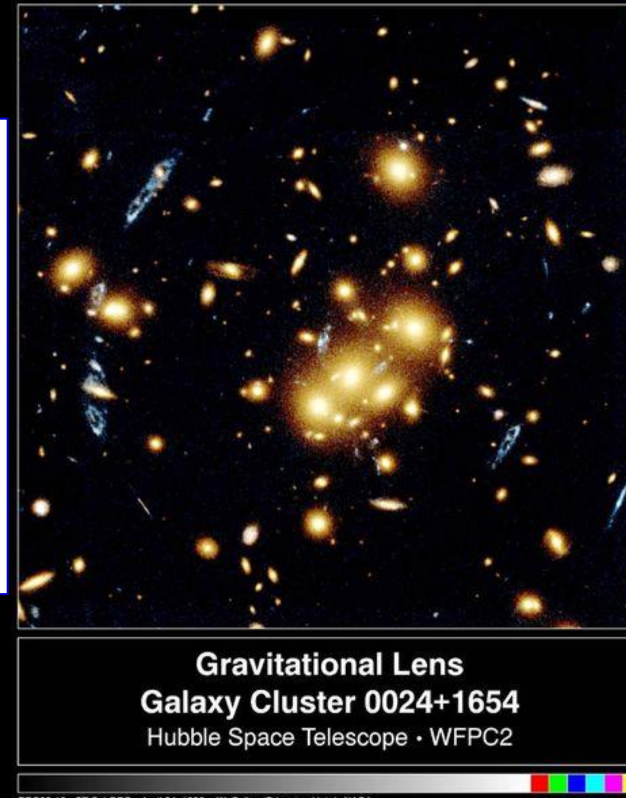
APEC Seminar @ Kavli IPMU, The University of Tokyo, Tokyo
June 27, 2019

New Physics beyond the Standard Model

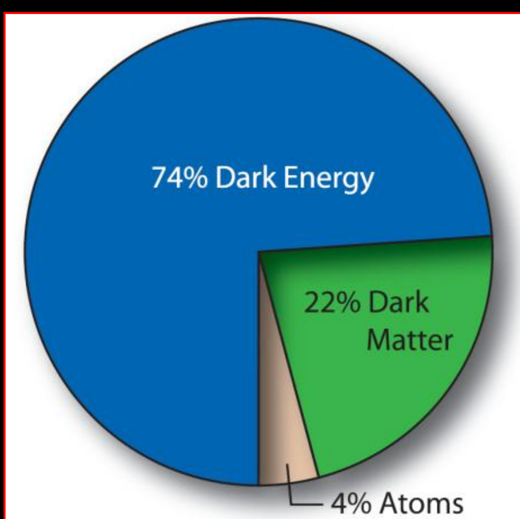
- **Neutrinos are Massive!**

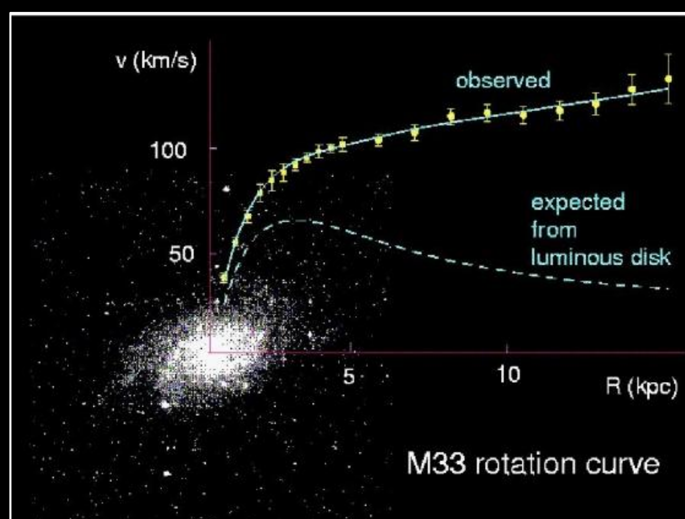


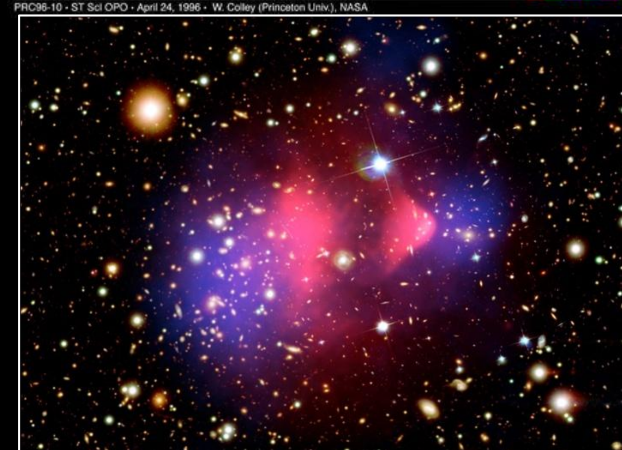




- **Most of the Matter is Dark!!**







Why Secret Neutrino Interactions?

- In the SM, neutrinos participate only in CC and NC weak interactions
- The neutrino-neutrino interactions have **NEVER** been directly tested
- Secret interactions among neutrinos appear in a number of NP models

PHYSICAL REVIEW D
PARTICLES AND FIELDS

THIRD SERIES, VOLUME 36, NUMBER 10 — 15 NOVEMBER 1987

Supernova 1987A and the secret interactions of neutrinos

Edward W. Kolb
Osservatorio Astronomico di Roma, via del Parco Mellini 84, 00136 Rome, Italy
and NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510
and Department of Astronomy and Astrophysics, The University of Chicago, Chicago, Illinois 60637

Michael S. Turner
NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510
and Department of Astronomy and Astrophysics, The University of Chicago, Chicago, Illinois 60637
and Department of Physics and the Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637
(Received 13 July 1987)

By using SN1987A as a "source" of neutrinos with energy ~ 10 MeV we place limits on the couplings of neutrinos with cosmic background particles. Specifically, we find that the Majoron–electron-neutrino coupling must be less than about 10^{-3}; if neutrinos couple to a massless vector particle, its dimensionless coupling must be less than about 10^{-3}; and if neutrinos couple with strength g to a massive boson of mass M, then g/M must be less than 12 MeV^{-1}.

Why Secret Neutrino Interactions?

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Example 1: Neutrinophilic Two-Higgs-Doublet Models (ν2HDM)

- Introduce a Higgs doublet Φ exclusively for tiny Dirac neutrino masses
- Keep the ν Yukawa couplings of order one through a small VEV of Φ

$$-\mathcal{L} = \overline{\ell_{\rm L}} Y_l H E_{\rm R} + \overline{\ell_{\rm L}} Y_\nu \Phi \nu_{\rm R} + {\rm h.c.}$$

$Z_2: +1$ **SM particles** $Z_2: -1$ **Others**

$$M_\nu = Y_\nu \langle \Phi \rangle$$

- Exists an eV-mass scalar particle η
- Excluded by SN energy-loss arguments

$$-\mathcal{L}_{\rm Y} = \sum_{\alpha,\beta=e}^{\tau} (Y_\nu)_{\alpha\beta} \overline{\nu_\alpha} \nu_\beta \eta = \sum_{i=1}^{3} y_i \overline{\nu_i} \nu_i \eta$$

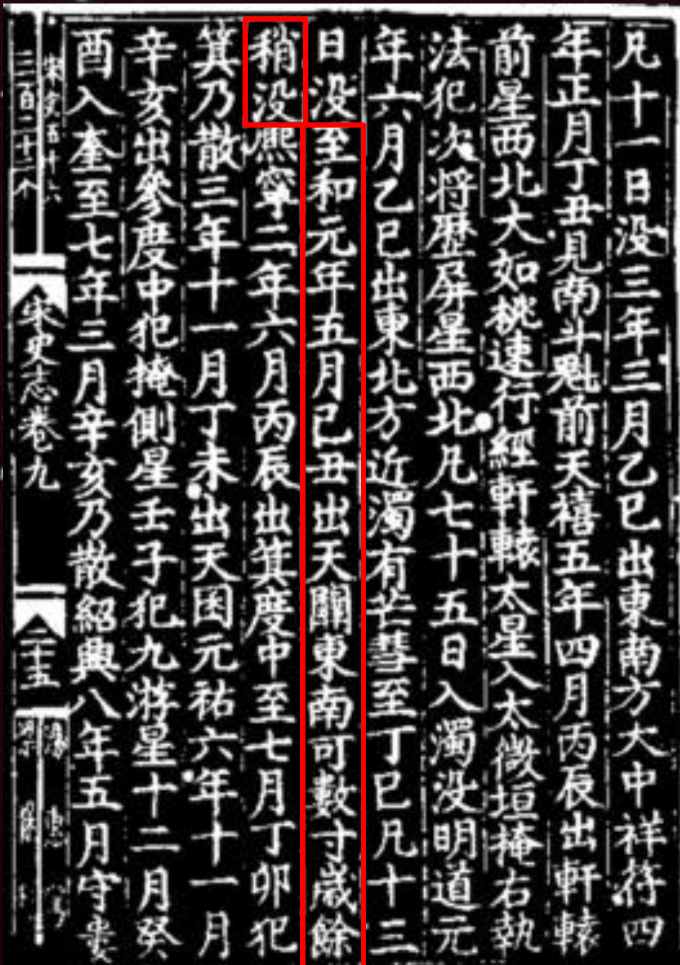
Wang, Wang & Yang, EPL, 06
Gariel & Nandi, PLB, 07
Sher & Triola, PRD, 2011

$$y_i \lesssim 3.5 \times 10^{-5}$$

Zhou, PRD, 2011

Galactic SN 1054

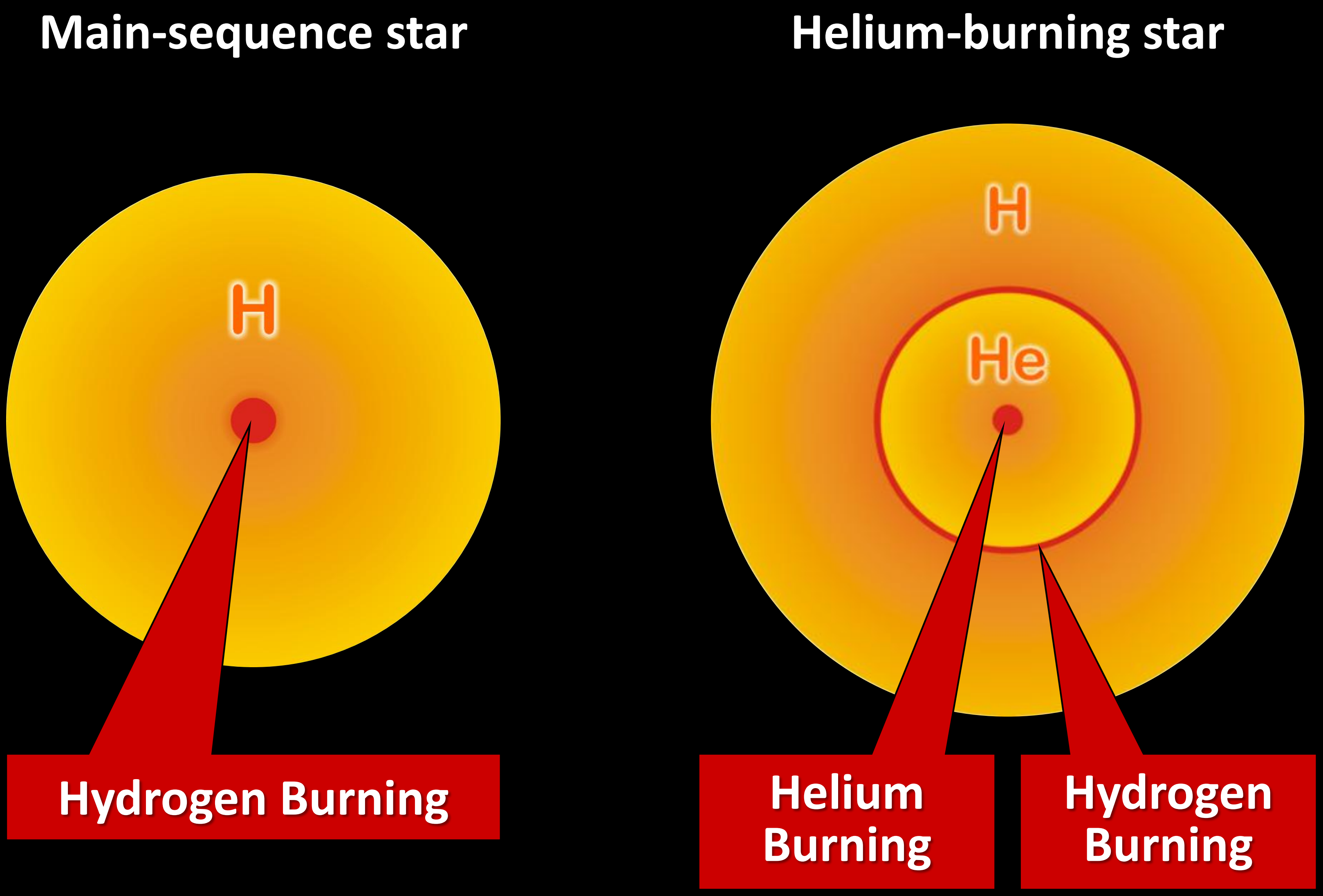
Distance: 6500 light years (2 kpc)
Center: Neutron Star (R~30 km)
Progenitor : M ~ 10 solar masses



凡十一日沒三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃速行經軒轅太星入太微垣掩右執法犯次將歷屛星西北凡七十五日入濁沒明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十三日沒至和元年五月己丑出天關東南可數寸歲餘稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天囷元祐六年十一月辛亥出參度中犯掩側星壬子犯九游星十二月癸酉入奎至七年三月辛亥乃散紹興八年五月守婁

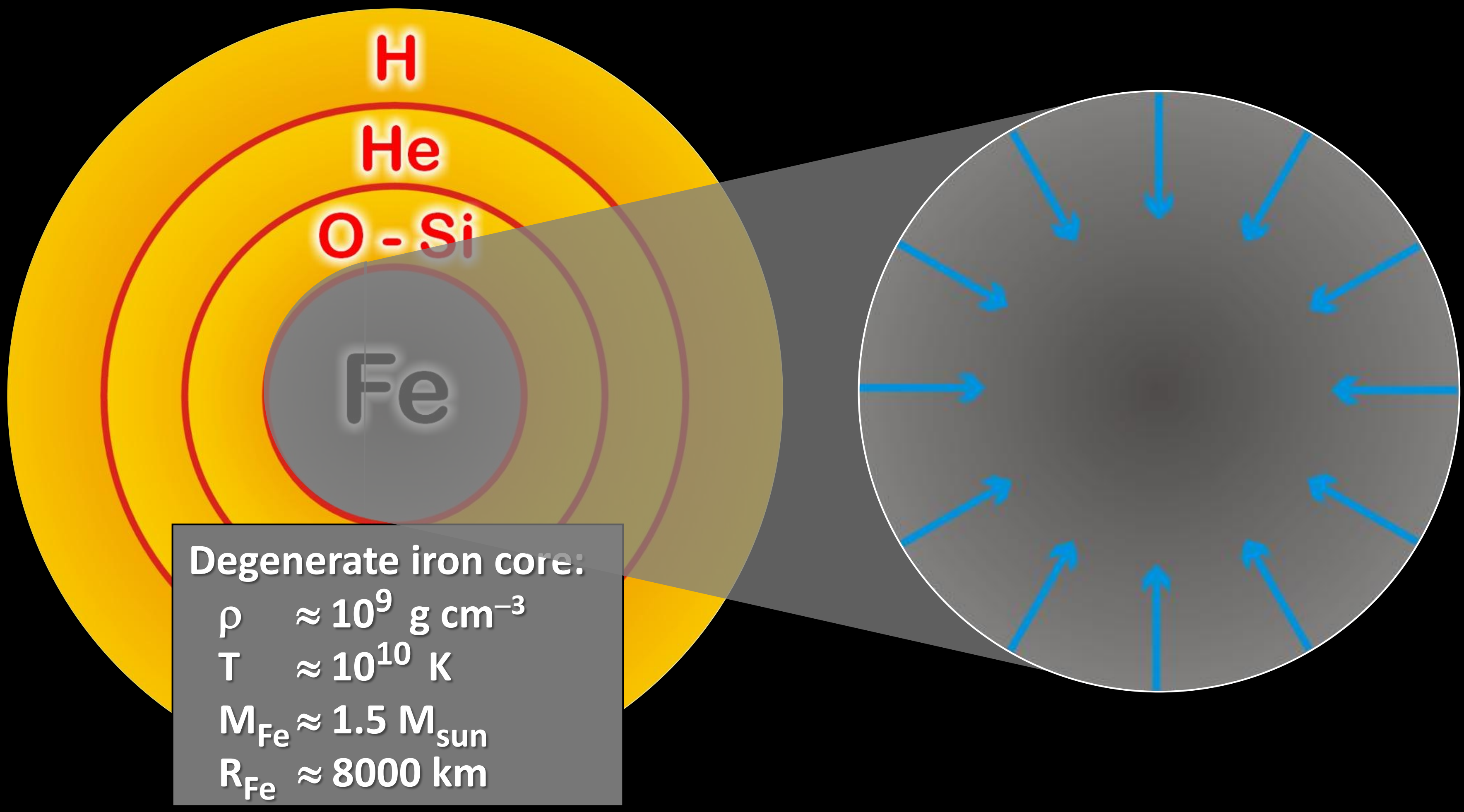
Red: Optical (Hubble)
Blue: X-Ray (Chandra)

Stellar Collapse and SN Explosion



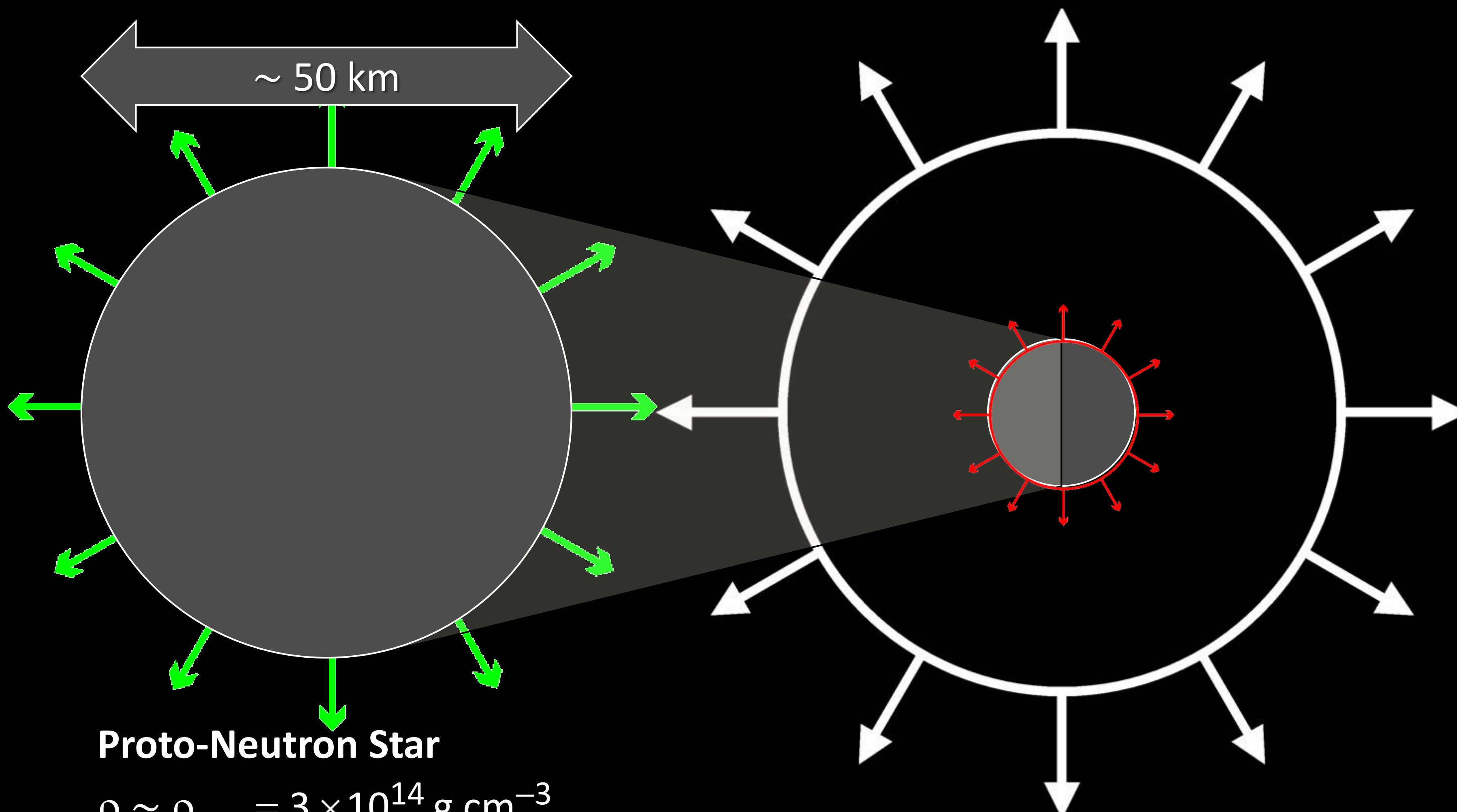
Stellar Collapse and SN Explosion

Onion structure | **Collapse (implosion)**



Stellar Collapse and SN Explosion

Newborn Neutron Star **Neutrino-driven Explosion**



Proto-Neutron Star

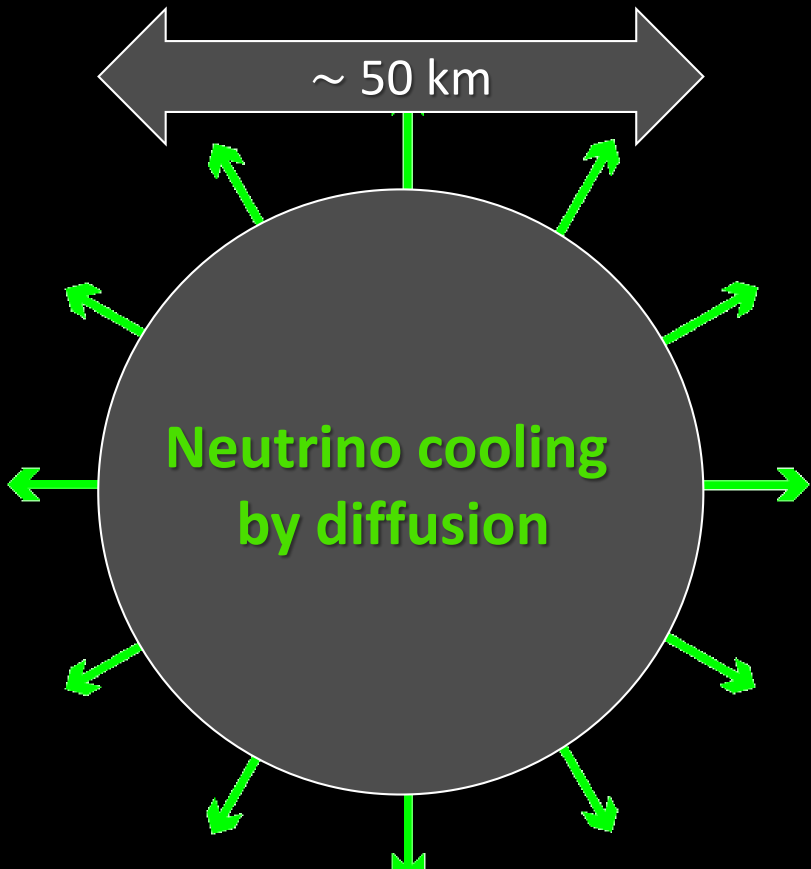
$\rho \sim \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \sim 30\ \mathrm{MeV}$

Stellar Collapse and SN Explosion

© Raffelt

Newborn Neutron Star



Proto-Neutron Star

$\rho \sim \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \sim 30$ MeV

Gravitational binding energy

$E_b \approx 3 \times 10^{53}$ erg $\approx$ 17% $M_{SUN}\, c^2$

This shows up as

99% Neutrinos

1% Kinetic energy of explosion

(1% of this into cosmic rays)

0.01% Photons, outshine host galaxy

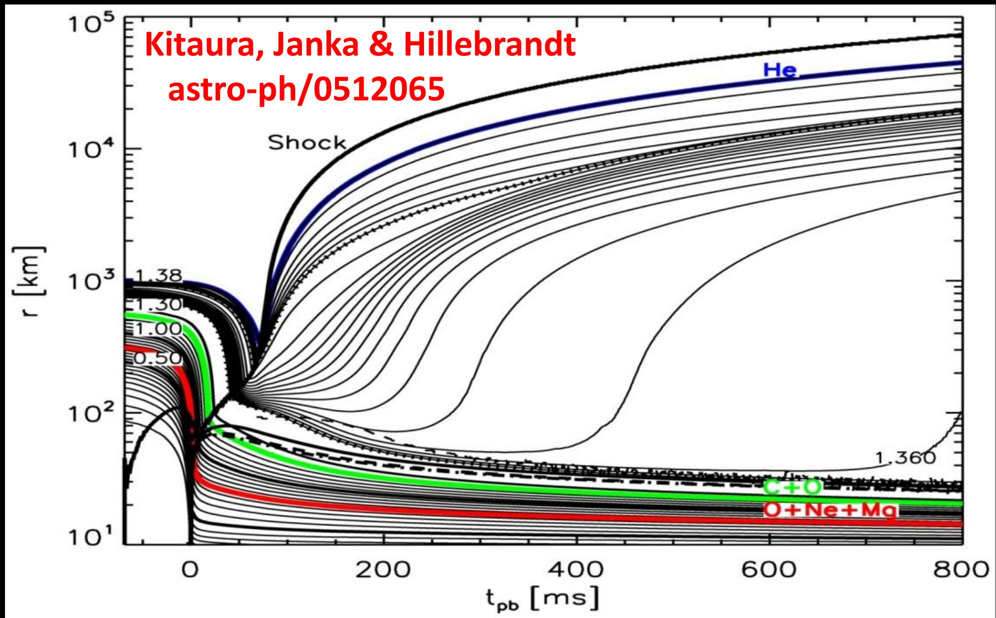
Neutrino luminosity

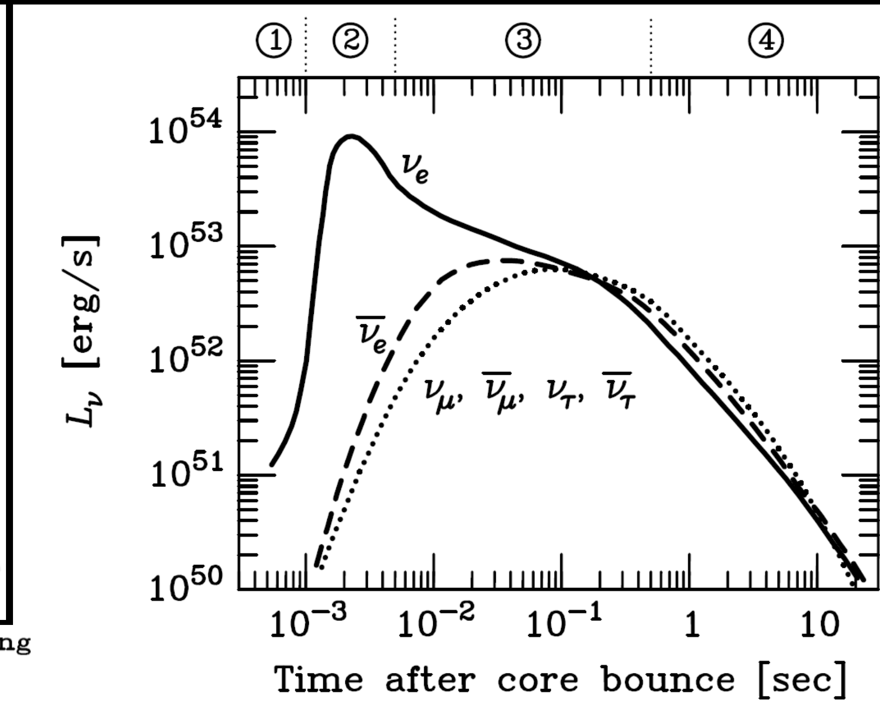
$L_\nu \approx 3 \times 10^{53}$ erg / 3 sec

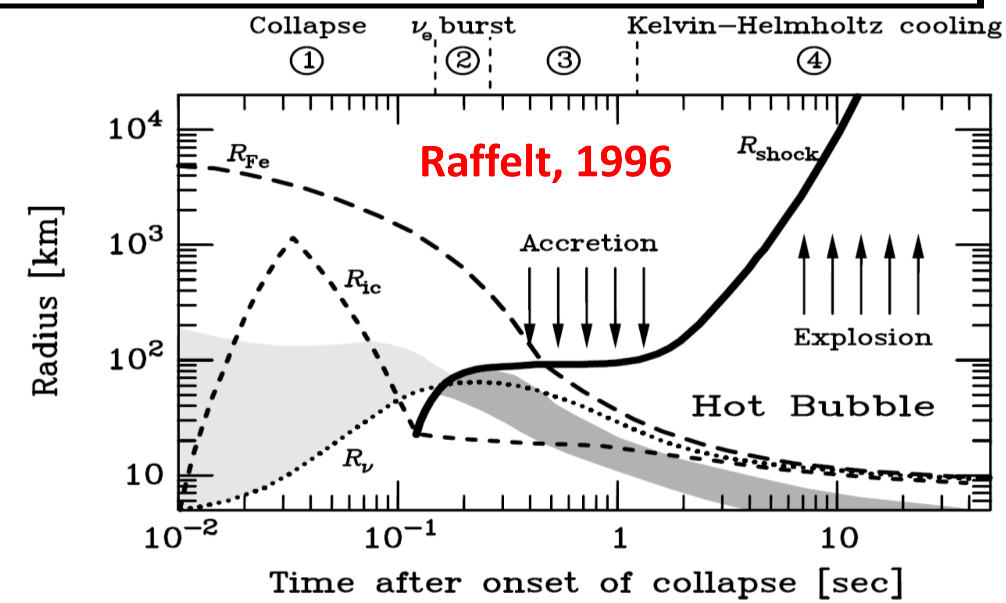
$\approx 3 \times 10^{19}\ L_{SUN}$

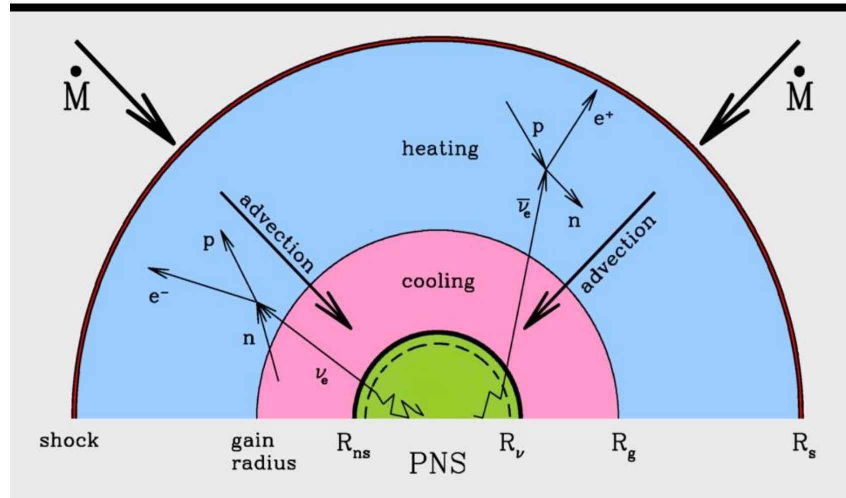
While it lasts, outshines the entire visible universe

Supernova Neutrinos: Theoretical Predictions





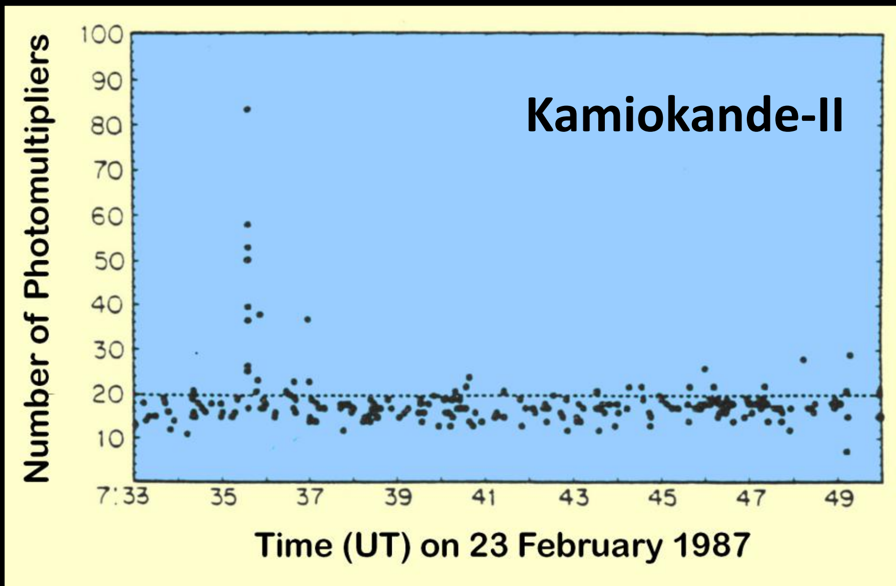


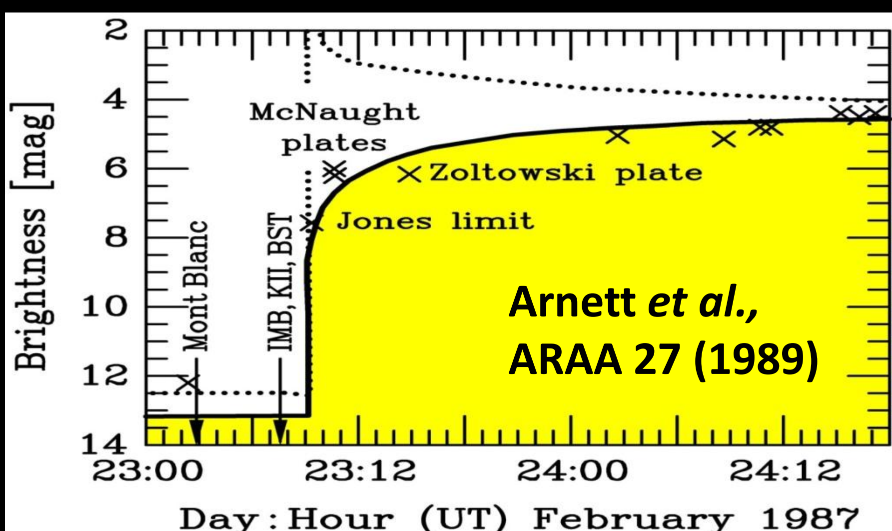



Sanduleak - 69 202

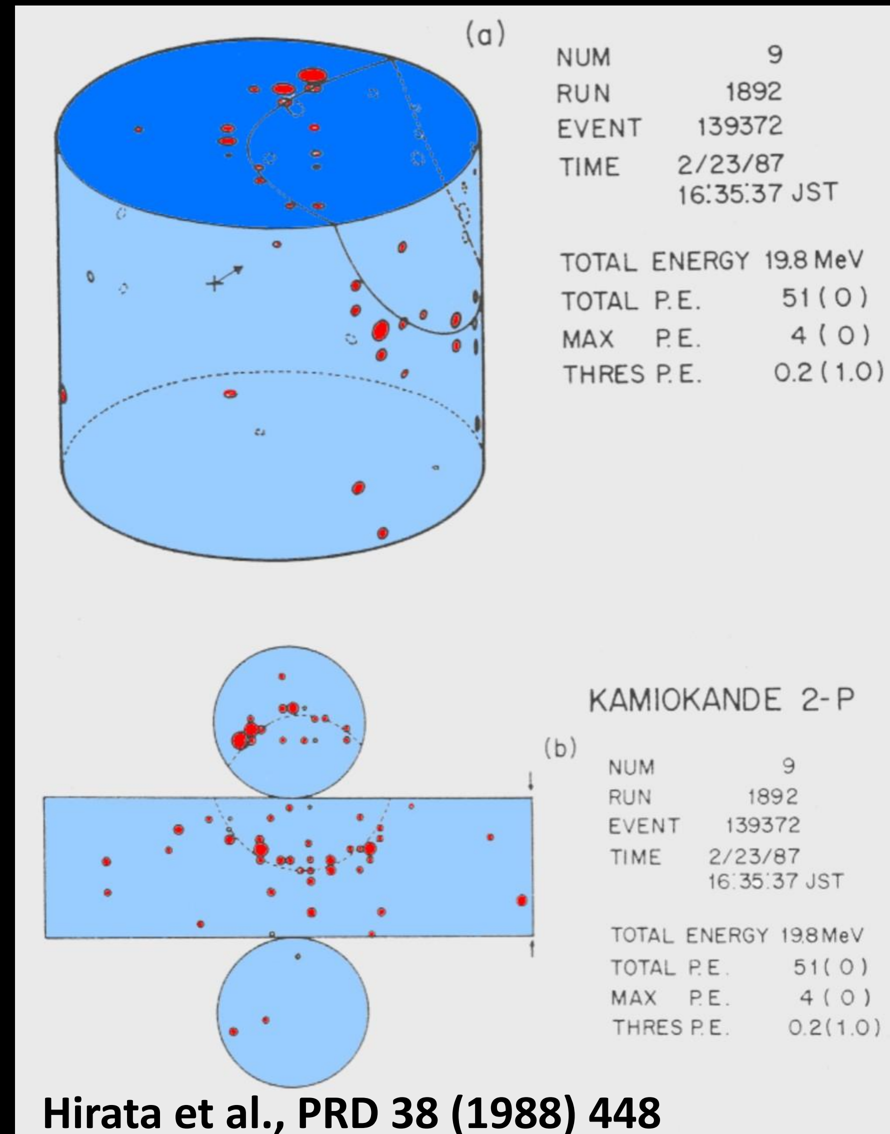

Supernova 1987A
23 February 1987
Large Magellanic Cloud SN 1987A
Distance：165 000 light yrs (50 kpc)
Center：Neutron Star
(expected, but not found)
Progenitor： M ~ 18 solar masses

Supernova Neutrinos: SN 1987A





Arnett *et al.*, ARAA 27 (1989)



Hirata et al., PRD 38 (1988) 448

Supernova Neutrinos: SN 1987A

Kamiokande-II (Japan):

- Water Cherenkov (2,140 ton)
- Clock Uncertainty ± 1 min

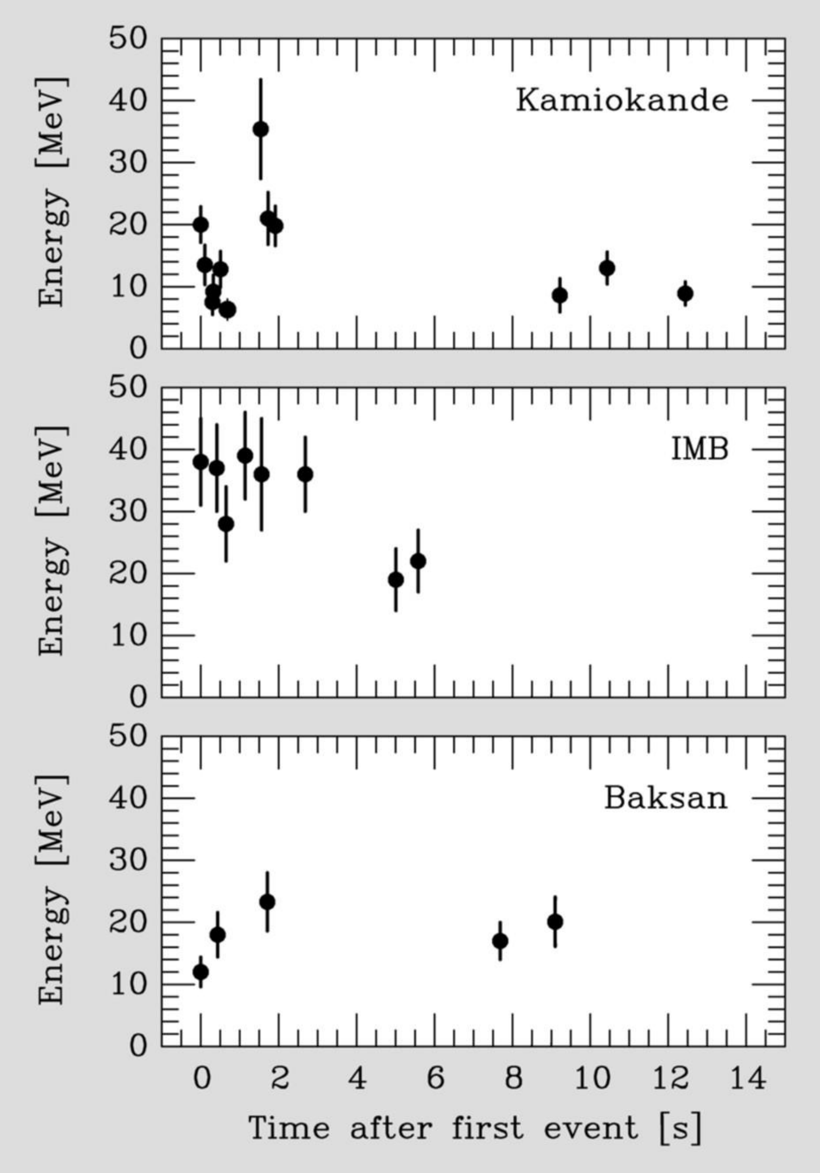
Irvine-Michigan-Brookhaven (US):

- Water Cherenkov (6,800 ton)
- Clock Uncertainty ±50 ms

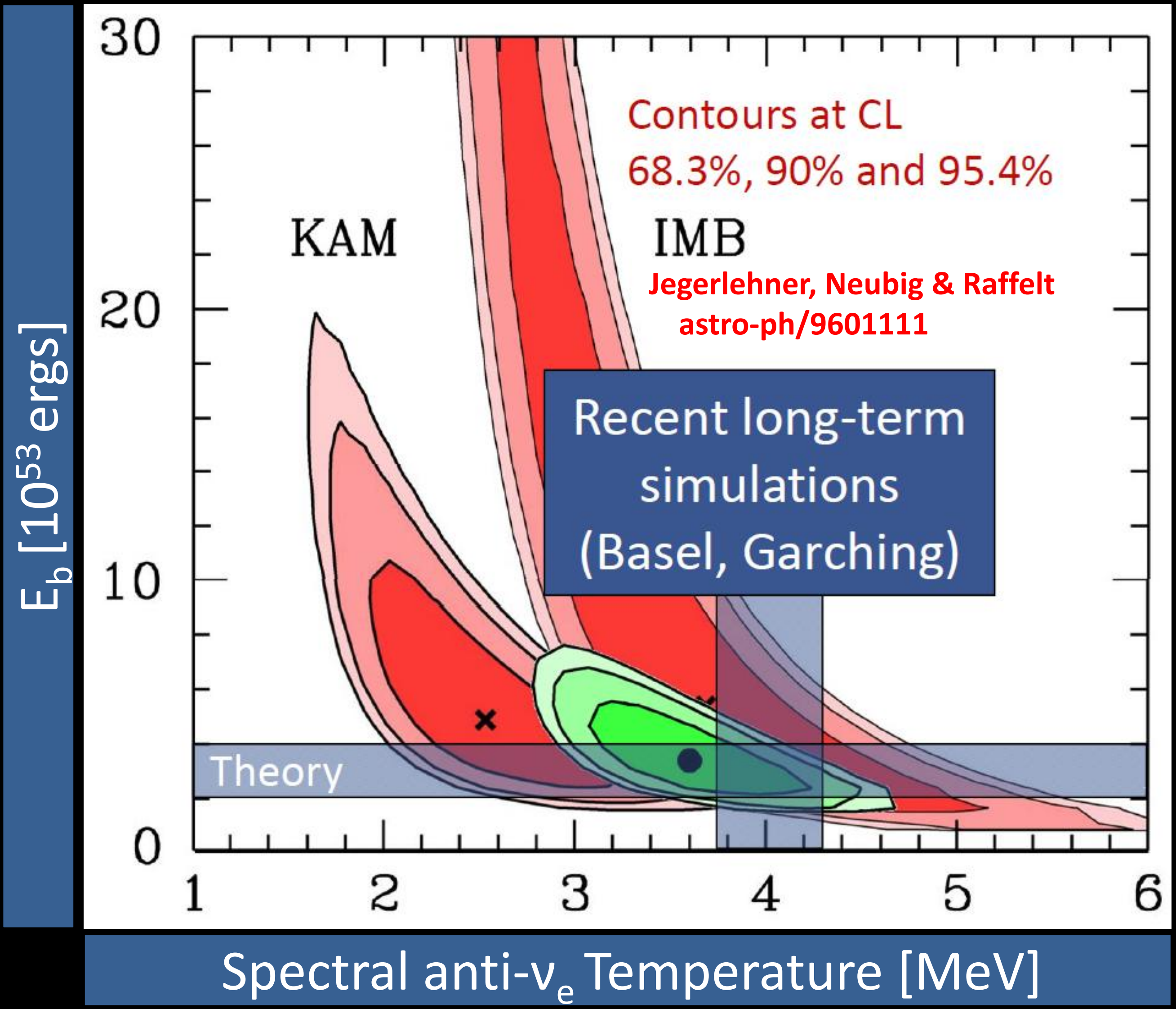
Baksan LST (Soviet Union):

- Liquid Scintillator (200 ton)
- Clock Uncertainty +2/-54 s

Mont Blanc: 5 events, 5 h earlier



Supernova Neutrinos: SN 1987A



Assumptions:
- ☐ Thermal
- ☐ Equipart.

Conclusions:
- ■ Collapse
- ■ Ave.Ener.
- ■ Duration

Problems:
- ☐ 24 events
- ☐ by chance

Core-collapse Supernova Explosions: Status

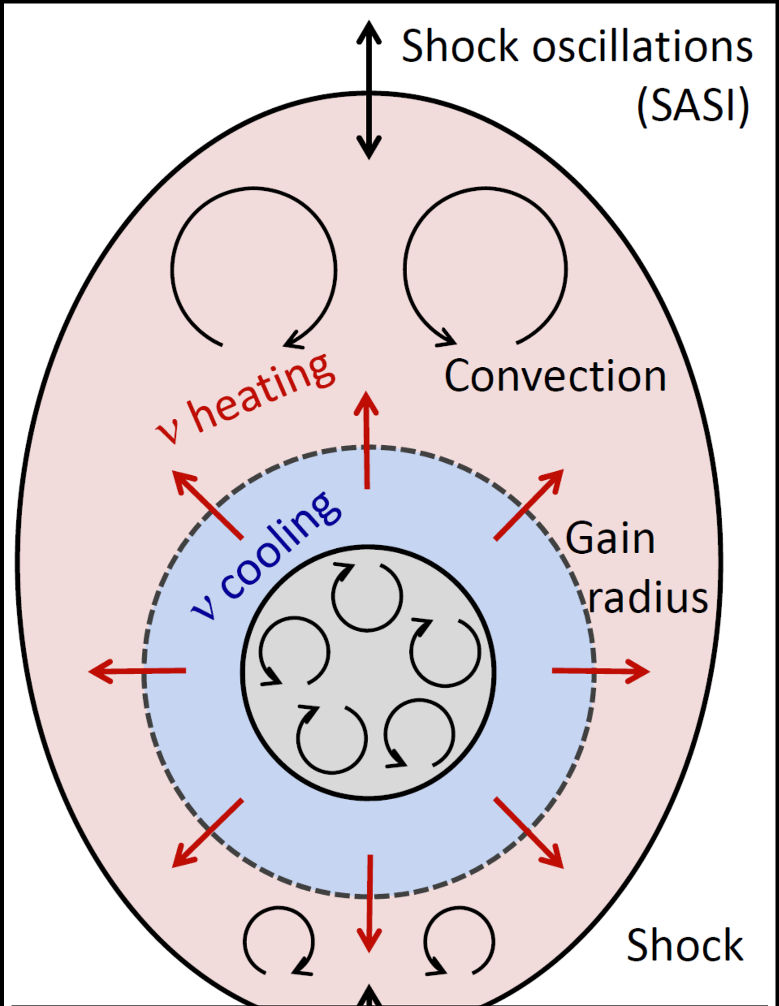
■ Explosion Mechanism：Neutrino-driven Explosion

- The prompt shock halted at 150 km, by disintegrating heavy nuclei

- Neutrinos deposit their energies via interaction with matter; 1 % neutrino energy leads to successful explosion

- Simulations in 1D & 2D for different progenitor masses observe explosions

- 3D simulation has just begun; but no clear picture (resolution, progenitors)

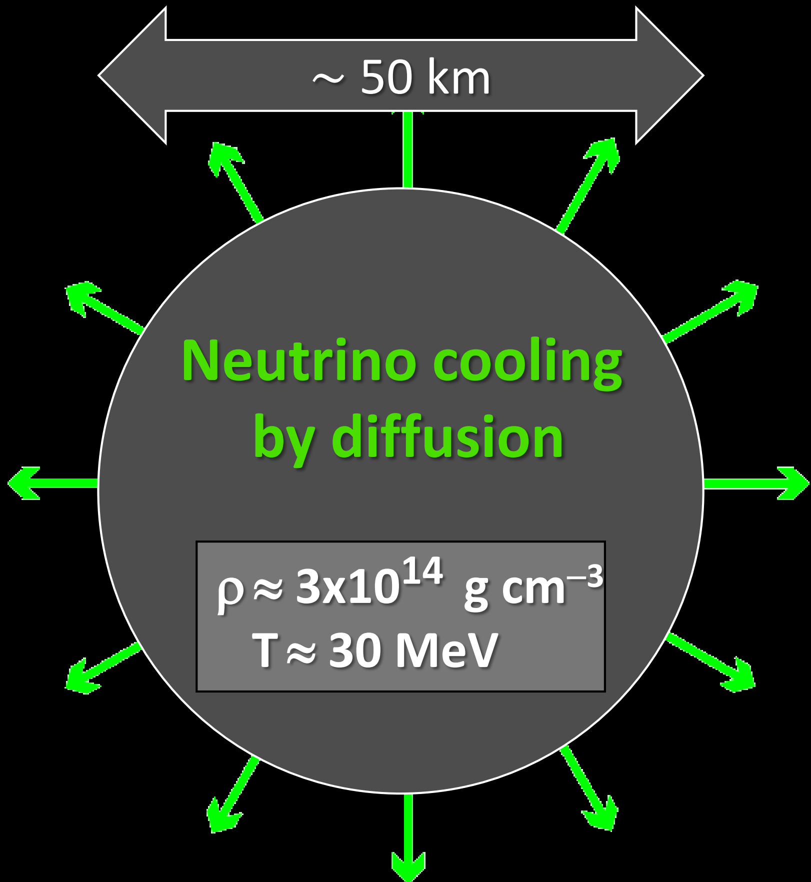


for a review, Janka, 1702.08825

Constraining Secret Neutrino Interactions

- How to test secret neutrino interactions: **Astrophysics** and **Cosmology**
- Core-collapse Supernovae: 10 sec neutrino signals from **SN 1987A**
- Successful theory of Cosmology: **BBN**, CMB and Structure Formation

Newborn Neutron Star



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© G. Raffelt

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SN Bounds on ν2HDM

Zhou, PRD, 2011

$$-\mathcal{L}_Y = \sum_{\alpha,\beta=e}^{\tau} (Y_\nu)_{\alpha\beta} \overline{\nu_\alpha} \nu_\beta \eta = \sum_{i=1}^{3} y_i \overline{\nu_i} \nu_i \eta$$

$$M_\nu = Y_\nu \langle \Phi \rangle$$

Ideal parameters

$$m_i = 0.1 \text{ eV}$$
$$\langle \Phi \rangle = 0.1 \text{ eV}$$
$$y_i = O(1)$$

Kolb-Turner Bound: The mean free path of neutrinos in the background of *η* should be larger than the distance between the SN and the earth so that the observation of SN neutrinos in Kamiokande-II and IMB is not affected

$y_i < 10^{-3}$ → $\langle \Phi \rangle = 100 \text{ eV}$ $m_\eta = 100 \text{ eV}$

Free-streaming Bound: The CMB observation shows that neutrinos must be freely streaming during the decoupling era of photons, indicating the rate of *η-mediated* neutrino self-interactions should be smaller than the Hubble expansion rate

$y_i < 10^{-4}$ → $\langle \Phi \rangle = 1 \text{ keV}$ $m_\eta = 1 \text{ keV}$

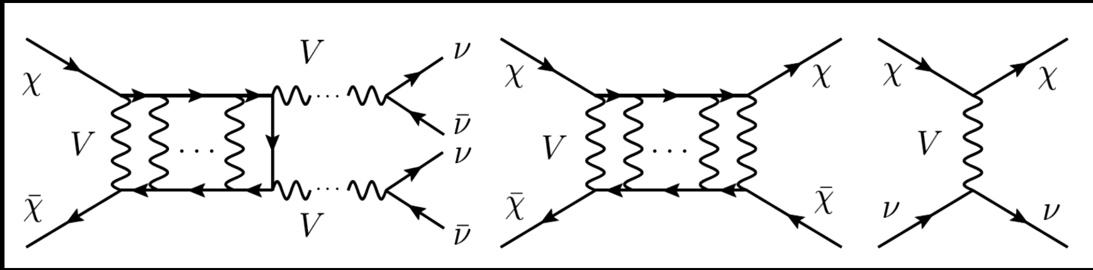
Energy-loss SN Bound: The *η* particles copiously produced in the SN core escape from the core, carrying away a large amount of energies, which should not exceed the total neutrino energy (volume emission rate $Q_\eta < 3 \times 10^{33} \text{ erg} \cdot \text{cm}^{-3} \cdot \text{s}^{-1}$)

$y_i < 10^{-5}$ → No longer natural as expected

Why Secret Neutrino Interactions?

Example 2: Solving the Small-Scale Structure Problems of Cold DM

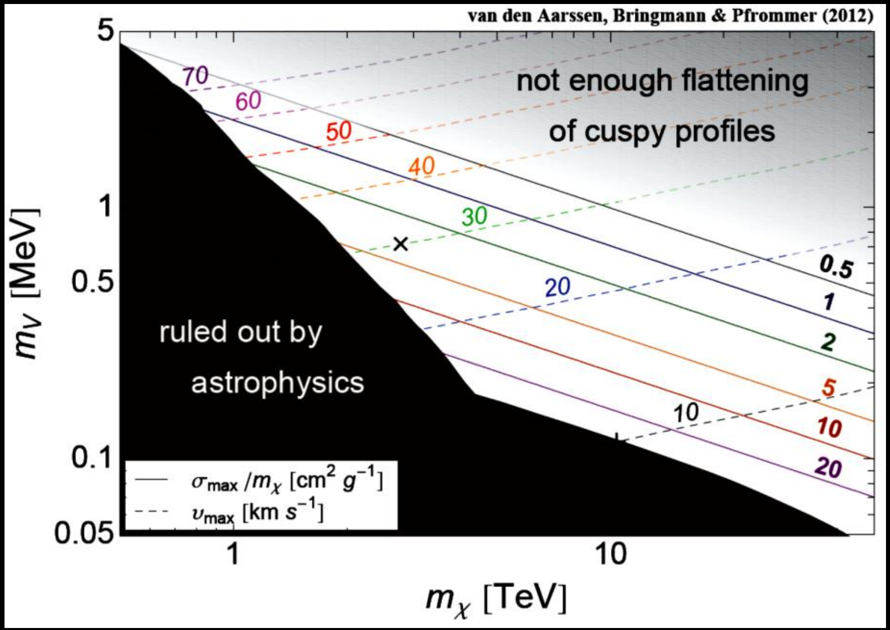
- Introduce a vector boson V of MeV mass, mediating the ν-χ interaction
- Self-interacting CDM and retain the kinetic equilibrium between ν and χ

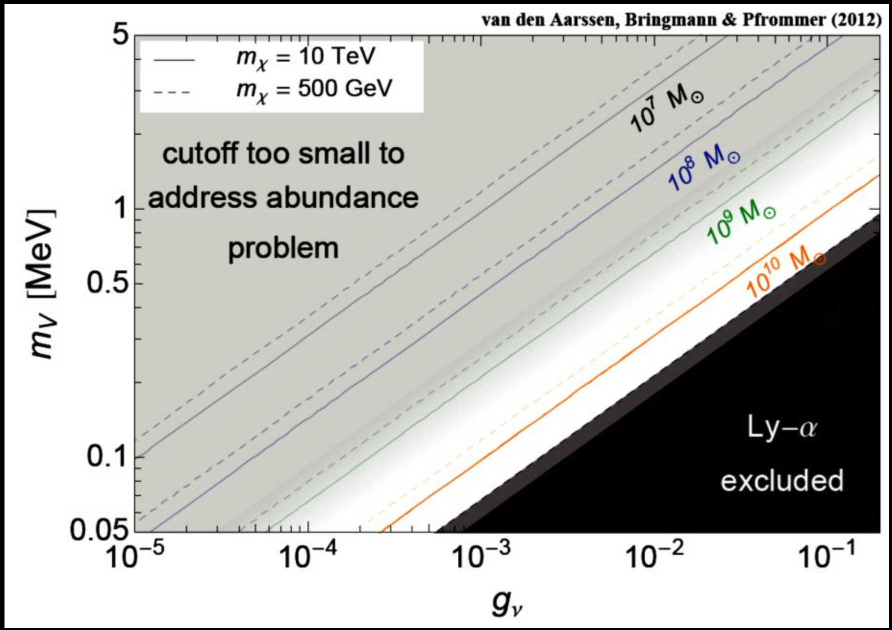


$$\mathcal{L}_{\rm int} \supset -g_\chi \bar{\chi} \not{V} \chi - g_\nu \bar{\nu} \not{V} \nu$$

van den Aarssen et al., PRL, 2012

Ahlgren, Ohlsson, Zhou, PRL, 2013





Evidence for an Expanding Universe

Edwin P. Hubble
(1889 – 1953, USA)

E.P. Hubble, Proc. Natl Acad. Sci. USA 15, 168–173 (1929)

A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

BY EDWIN HUBBLE

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON

Communicated January 17, 1929

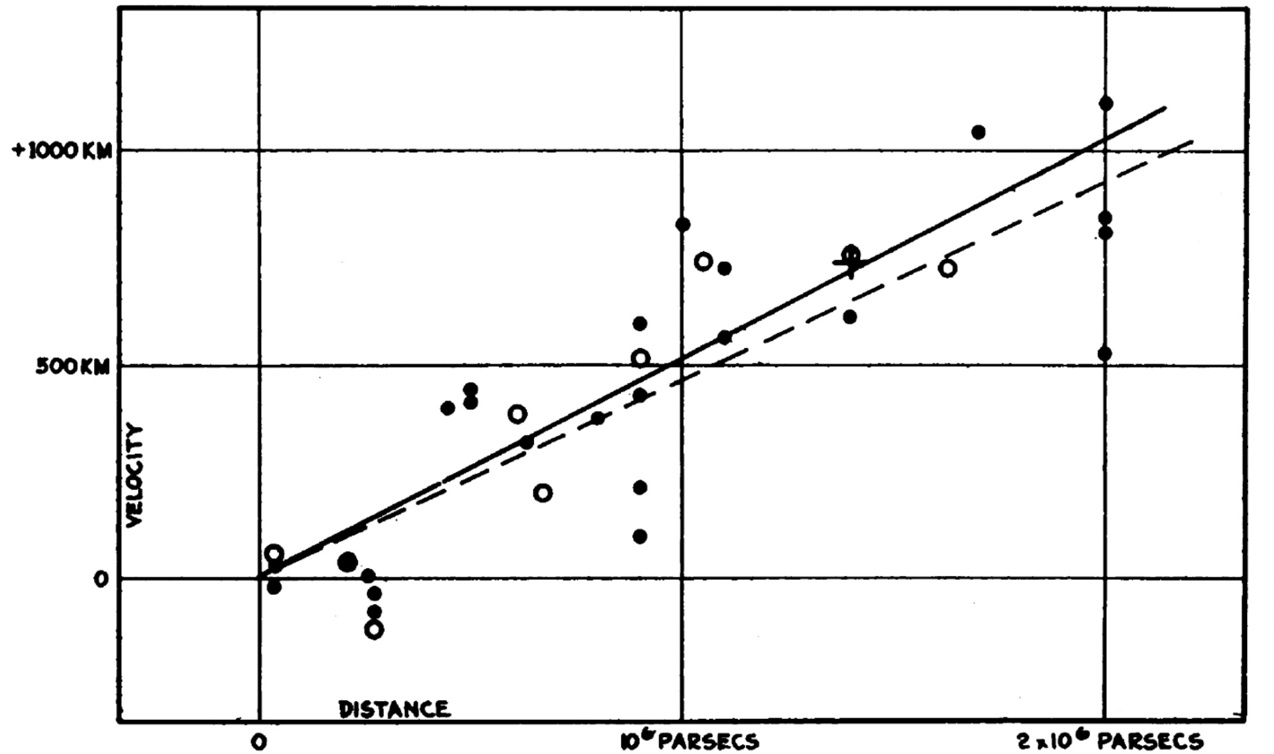
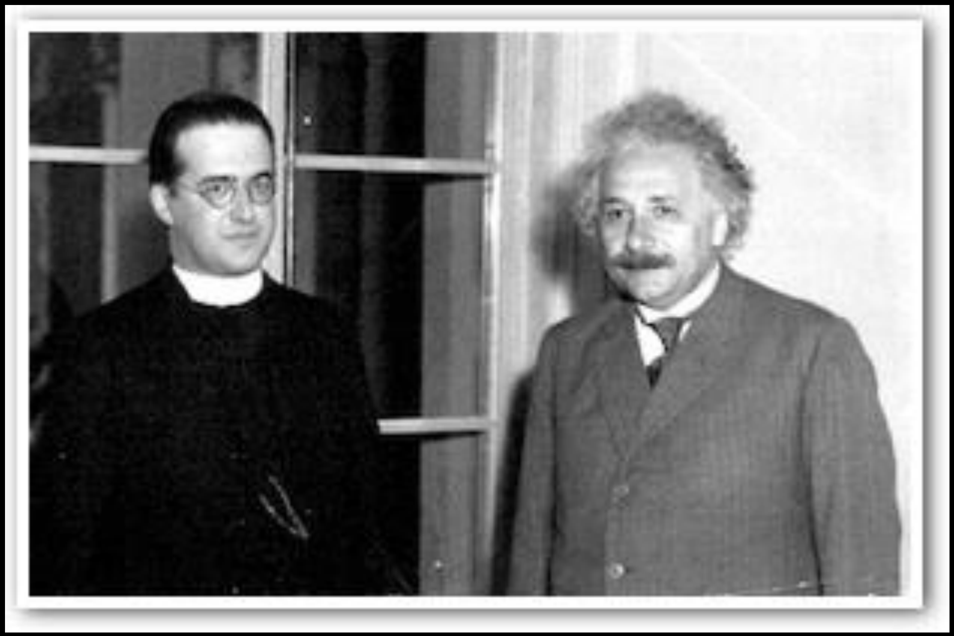


FIGURE 1

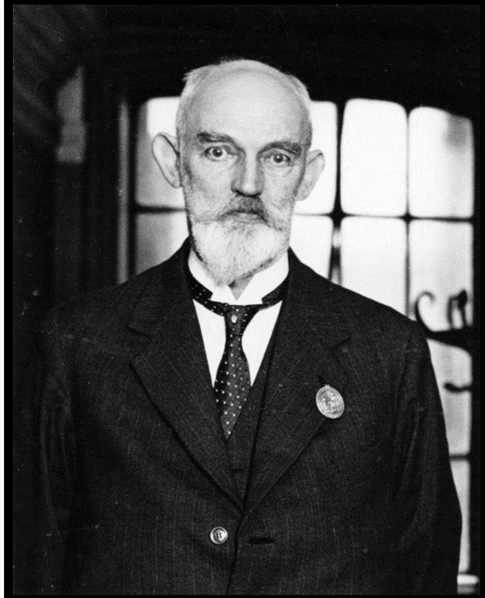
Velocity-Distance Relation among Extra-Galactic Nebulae.

Origin of Modern Cosmology



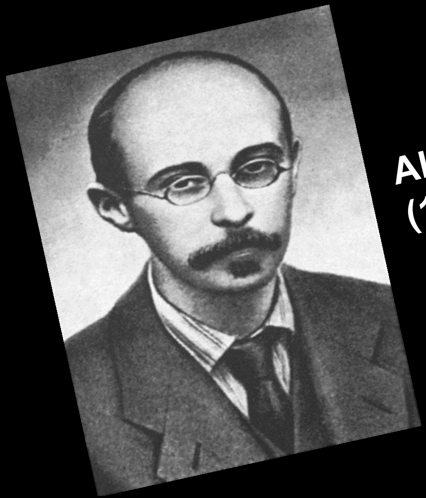
Georges Lemaître
(1894 – 1966, Belgium)

Albert Einstein
(1879 – 1955, Germany)



Willen de Sitter
(1872 – 1934, Holland)

Arthur Eddington
(1882 – 1944, England)

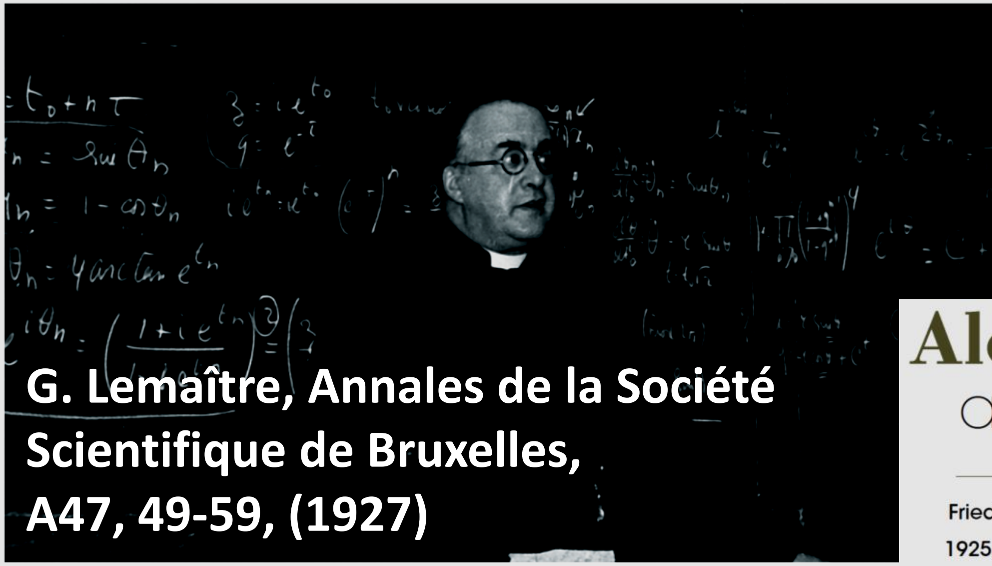


Alexander Friedmann
(1888 – 1925, Russia)

Howard Robertson
(1903 – 1961, USA)

Arthur Walker
(1909 – 2001, England)

Origin of Modern Cosmology



G. Lemaître, Annales de la Société Scientifique de Bruxelles, A47, 49-59, (1927)

GEORGES LEMAÎTRE/CATHOLIC UNIV. LOUVAIN/TECLIM

Georges Lemaître giving a lecture at the Catholic University of Louvain in Belgium.

Mystery of the missing text solved

A discovered letter explains the loss of key paragraphs during the transl
of Georges Lemaître's papers about the expanding Universe, shows M

Nature 479 (2011) 171

Lemaître 1927: based on rough data, first estimated the expansion rate

Physics Today 65 (2012) 38

Friedmann 1922/24: non-static solutions, including an expanding Universe

Alexander Friedmann and the origins of modern cosmology

Ari Belenkiy

Friedmann, who died young in 1925, deserves to be called the father of Big Bang cosmology. But his seminal contributions have been widely misrepresented and undervalued.

Ninety years ago, Russian physicist Alexander Friedmann (1888–1925) demonstrated for the first time that Albert Einstein's general theory of relativity (GR) admits nonstatic solutions. It can, he found, describe a cosmos that expands, contracts, collapses, and might even have been born in a singularity.

Friedmann's fundamental equations describing those possible scenarios of cosmic evolution provide the basis for our current view of the Big Bang and the accelerating universe. But his achievement initially met with strong resistance, and it has since then been widely misrepresented. In this article, I hope to clarify some persistent confusions regarding Friedmann's cosmological theory in the context of related work by contemporaries such as Einstein, Willem de Sitter, Arthur Eddington, and Georges Lemaître.

Last year's Nobel Prize in Physics was shared by three cosmological observers who discovered

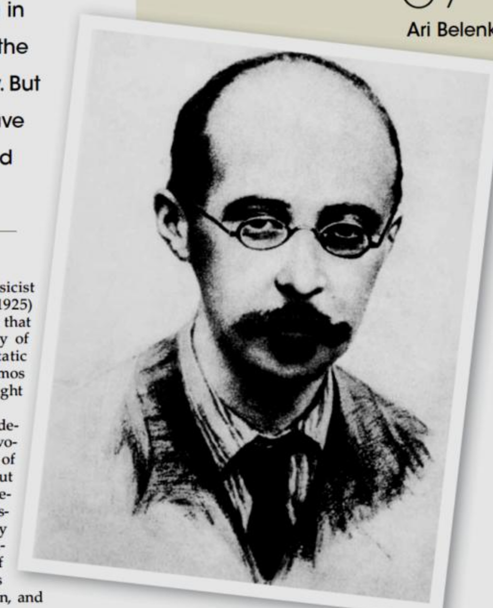


Figure 1. Alexander Friedmann in Petrograd, Soviet Union, in the early 1920s.

iau1812 — Press Release

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29 October 2018

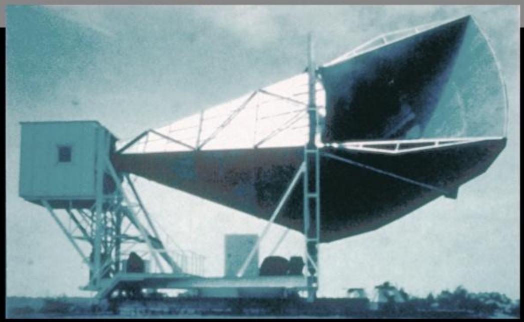
IAU members vote to recommend renaming the Hubble law as the Hubble–Lemaître law

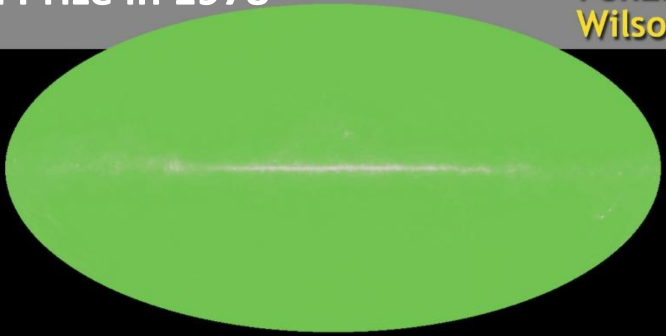
Following a period of consultation with the astronomical community, the resolution to suggest renaming the Hubble law was presented and discussed at the XXX General Assembly of the IAU, held in Vienna (Austria) in August 2018. All Individual and Junior Members of the IAU (11072 individuals) were invited to participate in an electronic vote, which concluded at midnight UT on 26 October 2018. 4060 cast a vote by the deadline (37%).

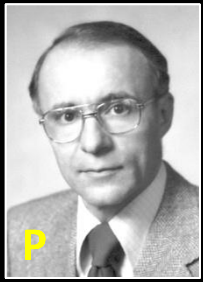
The proposed resolution has been accepted with 78% of the votes in favour and 20% against (and 2% abstaining).

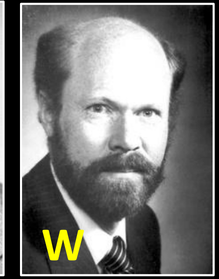
Progress in Observational Cosmology

1965 **Discovery of CMB, Nobel Prize in 1978** Penzias and Wilson

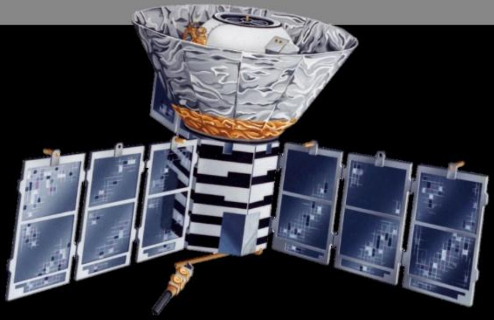


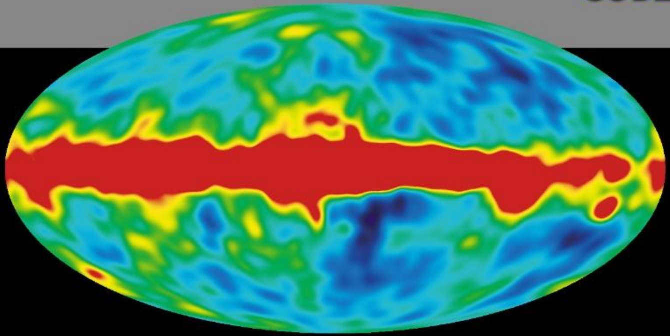


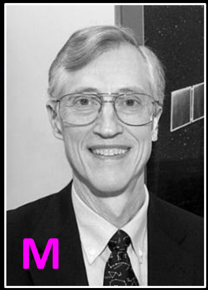


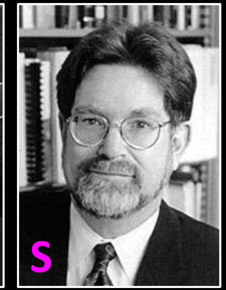


1992 **Anisotropy in CMB, Nobel Prize in 2006** COBE

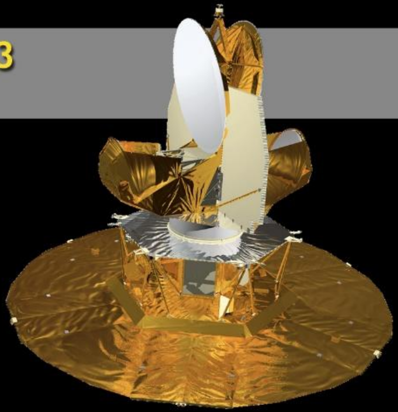


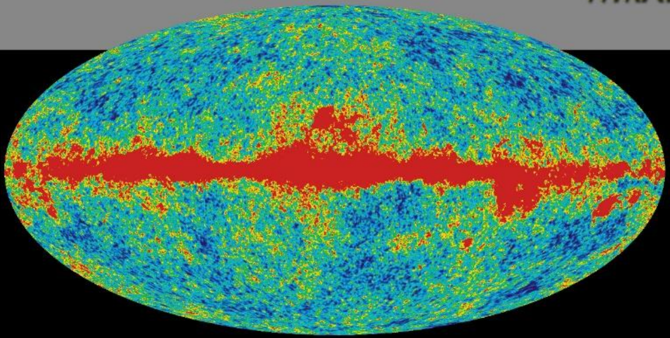






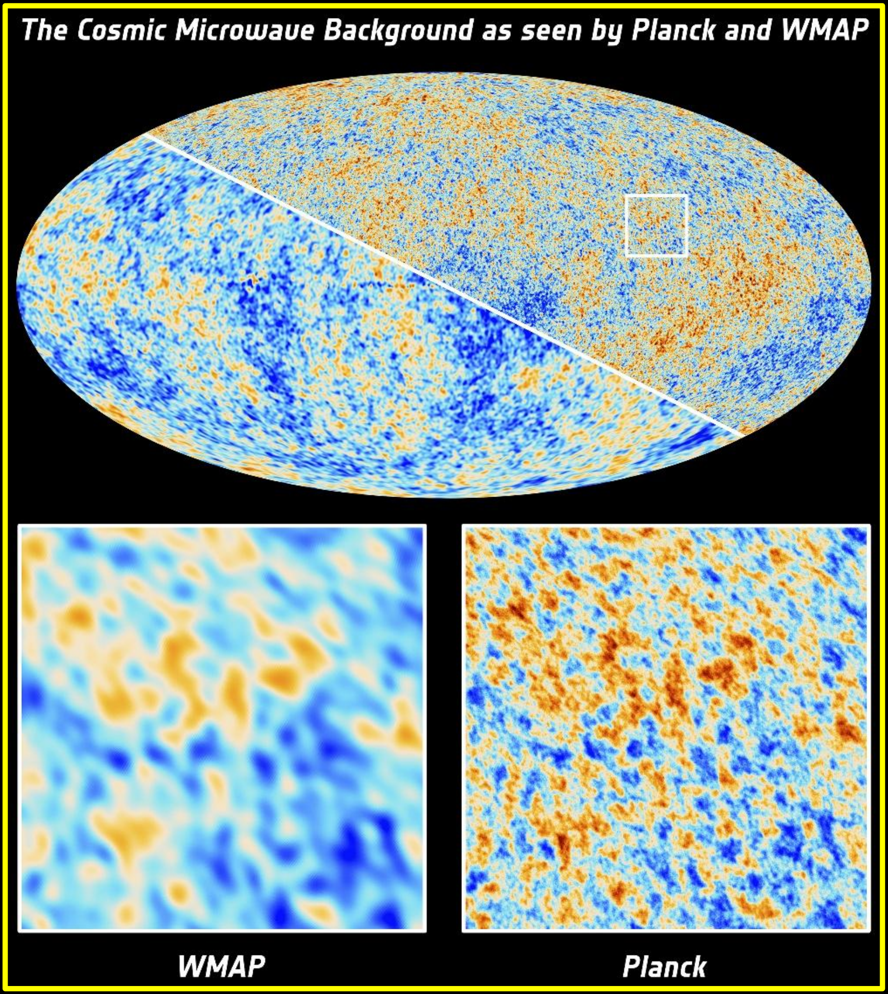
2003 WMAP





Cosmic Microwave Background (CMB)

Progress in Observational Cosmology



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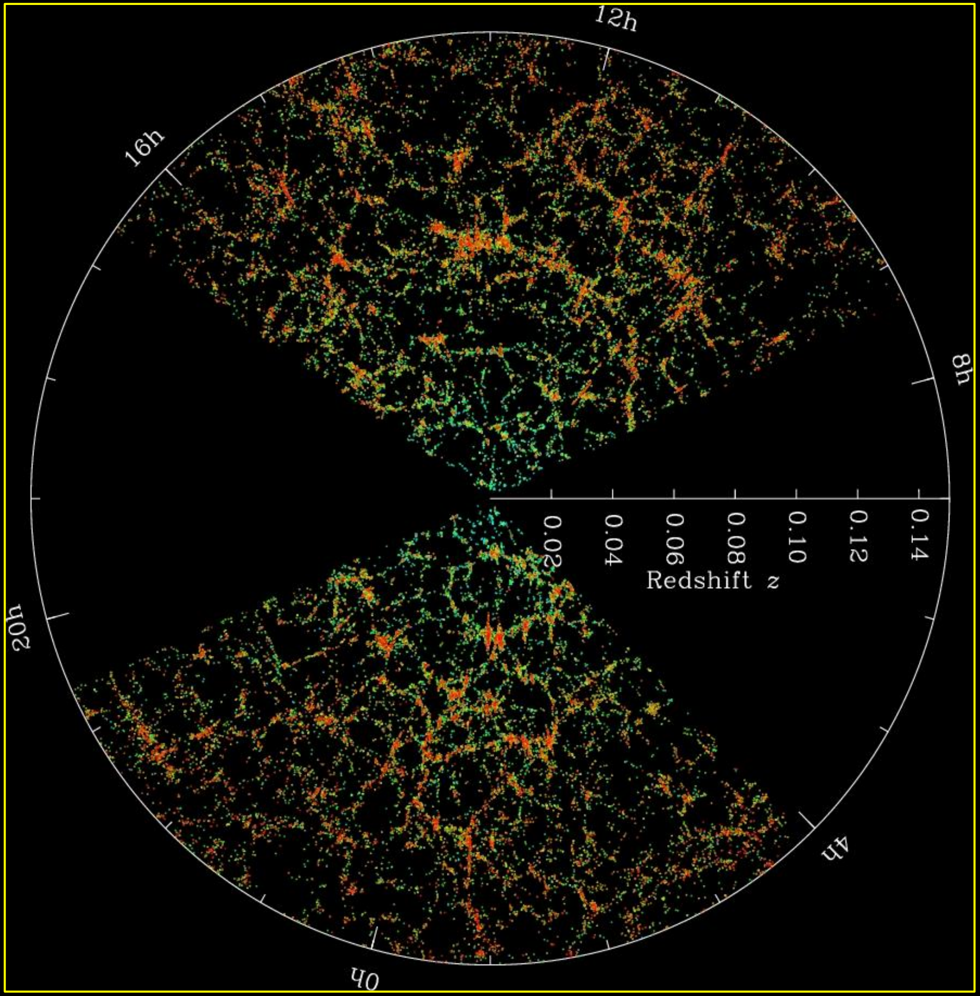
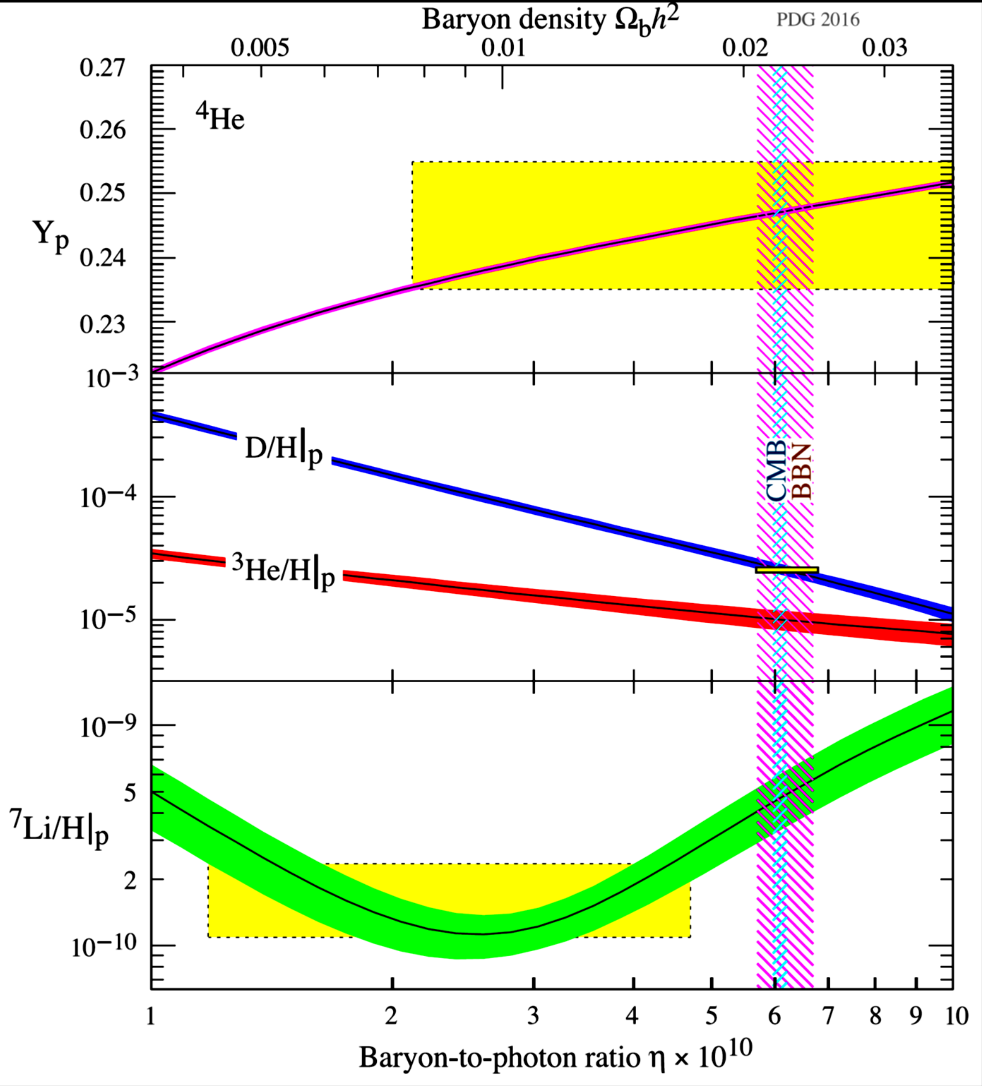
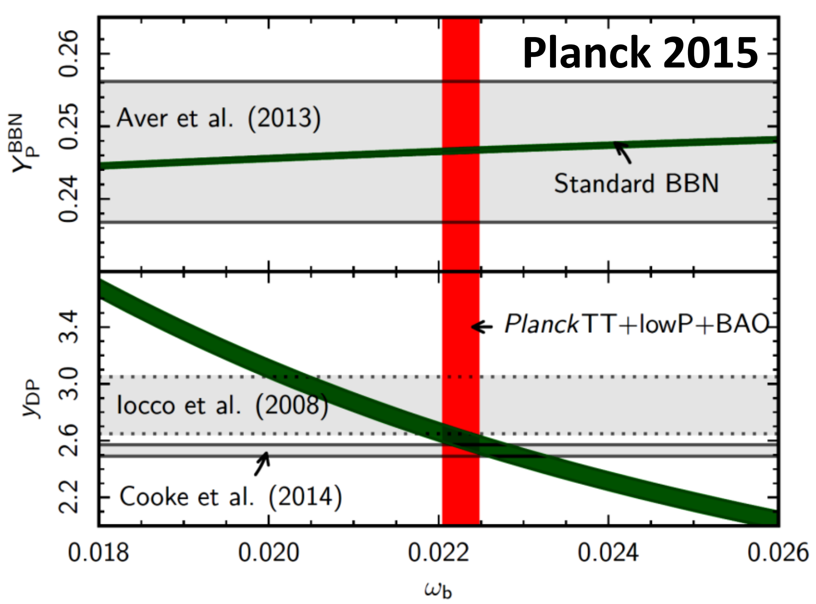
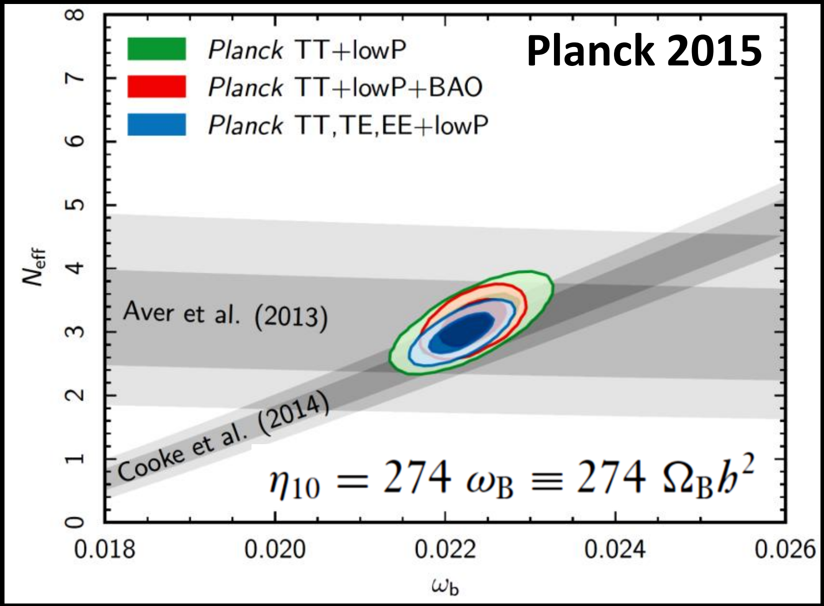


Large Scale Structure (LSS) from Sloan Digital Sky Survey (SDSS)

Progress in Observational Cosmology

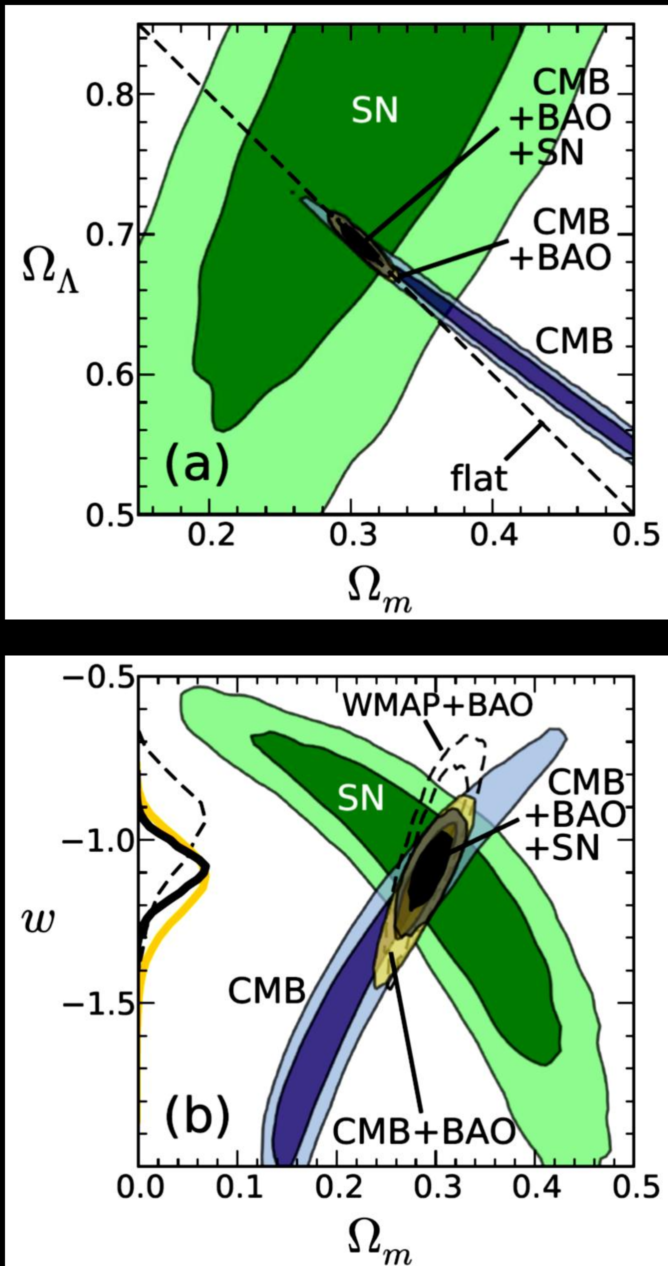






Big Bang Nucleosynthesis (BBN) and CMB

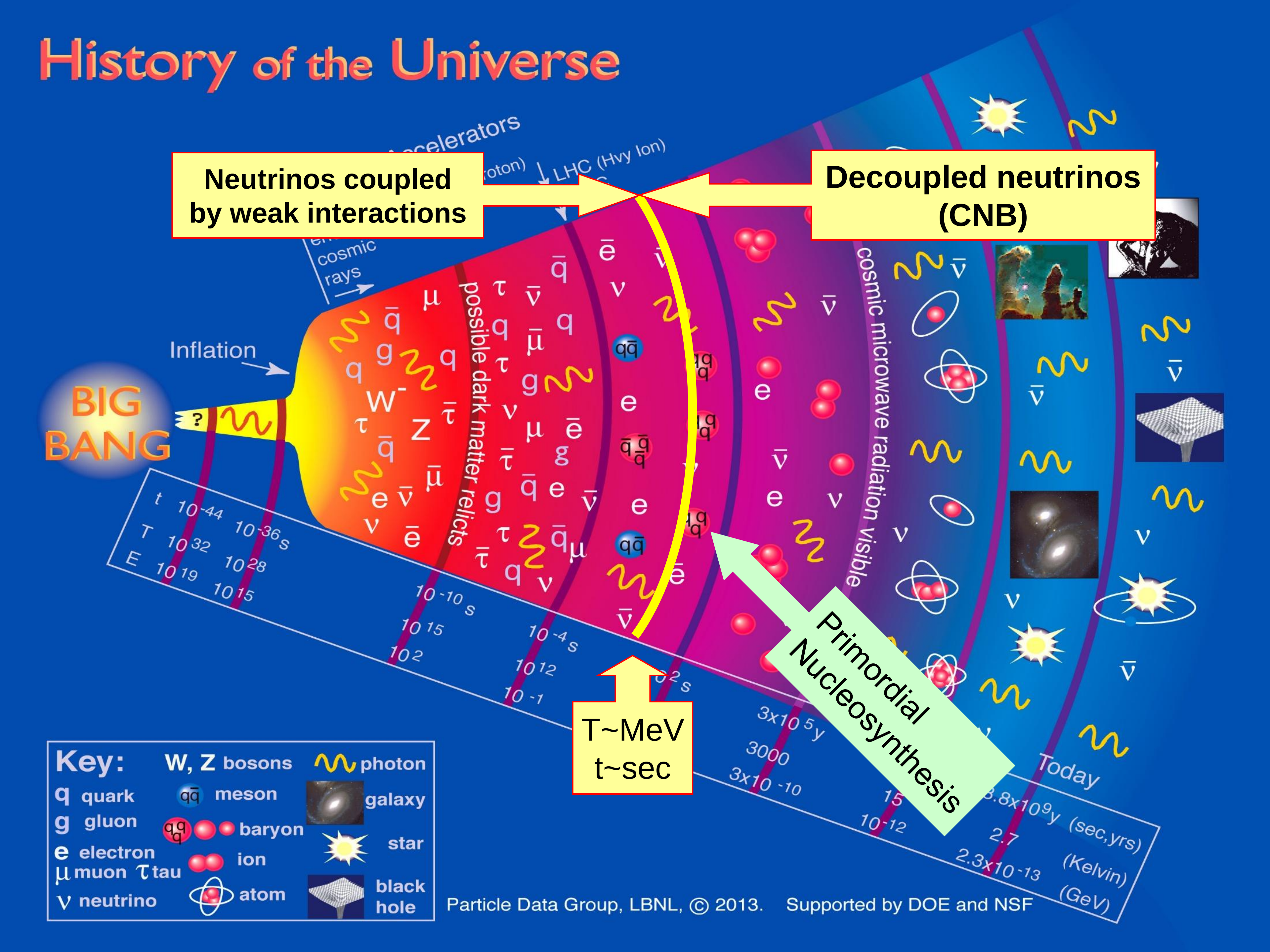
Standard Model of Cosmology



PDG 2016	*Planck*+WP +highL	*Planck*+WP +highL+BAO	*WMAP*9+eCMB +BAO
$\Omega_b h^2$	0.02207 ± 0.00027	0.02214 ± 0.00024	0.02211 ± 0.00034
$\Omega_c h^2$	0.1198 ± 0.0026	0.1187 ± 0.0017	0.1162 ± 0.0020
$100\,\theta_{MC}$	1.0413 ± 0.0006	1.0415 ± 0.0006	–
n_s	0.958 ± 0.007	0.961 ± 0.005	0.958 ± 0.008
τ	$0.091^{+0.013}_{-0.014}$	0.092 ± 0.013	$0.079^{+0.011}_{-0.012}$
$\ln(10^{10}\Delta^2_{\mathcal{R}})$	3.090 ± 0.025	3.091 ± 0.025	3.212 ± 0.029
h	0.673 ± 0.012	0.678 ± 0.008	0.688 ± 0.008
σ_8	0.828 ± 0.012	0.826 ± 0.012	$0.822^{+0.013}_{-0.014}$
Ω_m	$0.315^{+0.016}_{-0.017}$	0.308 ± 0.010	0.293 ± 0.010
Ω_Λ	$0.685^{+0.017}_{-0.016}$	0.692 ± 0.010	0.707 ± 0.010

Cosmic Neutrino Background (CNB)

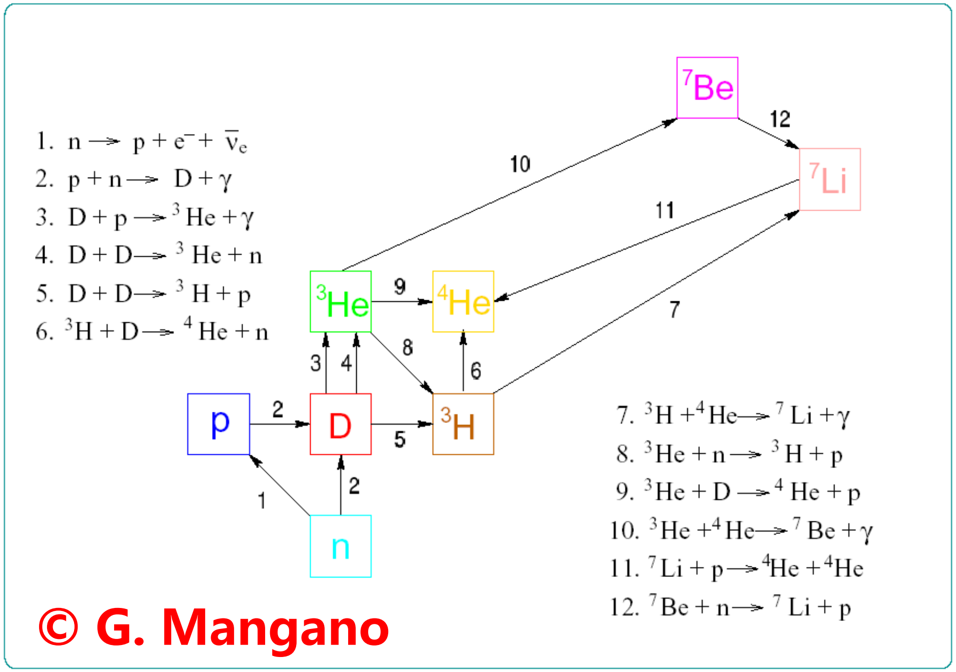
- Indirect evidence from BBN, CMB and LSS
- How to detect CNB in terrestrial experiments?
- PTOLEMY: ν capture on beta-decaying nuclei



History of the Universe
Neutrinos coupled by weak interactions
Decoupled neutrinos (CNB)
Accelerators
LHC (Hvy Ion)
cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
T~MeV
t~sec
Primordial Nucleosynthesis
t 10^-44 10^-36 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-4 s
10^12
10^-1
10^2 s
3x10^5 y
3000
3x10^-10
15
10^-12
Today
13.8x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
e electron
star
μ muon τ tau
ion
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2013. Supported by DOE and NSF

Standard Theory of BBN

See Cyburt et al., RMP, 16, for a review



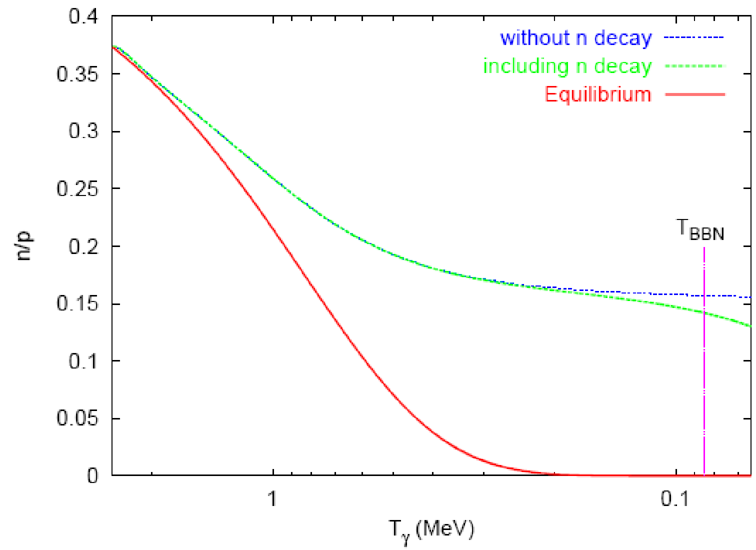
Phase I: 0.8-0.1 MeV n-p reactions

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

n/p freezing and neutron decay

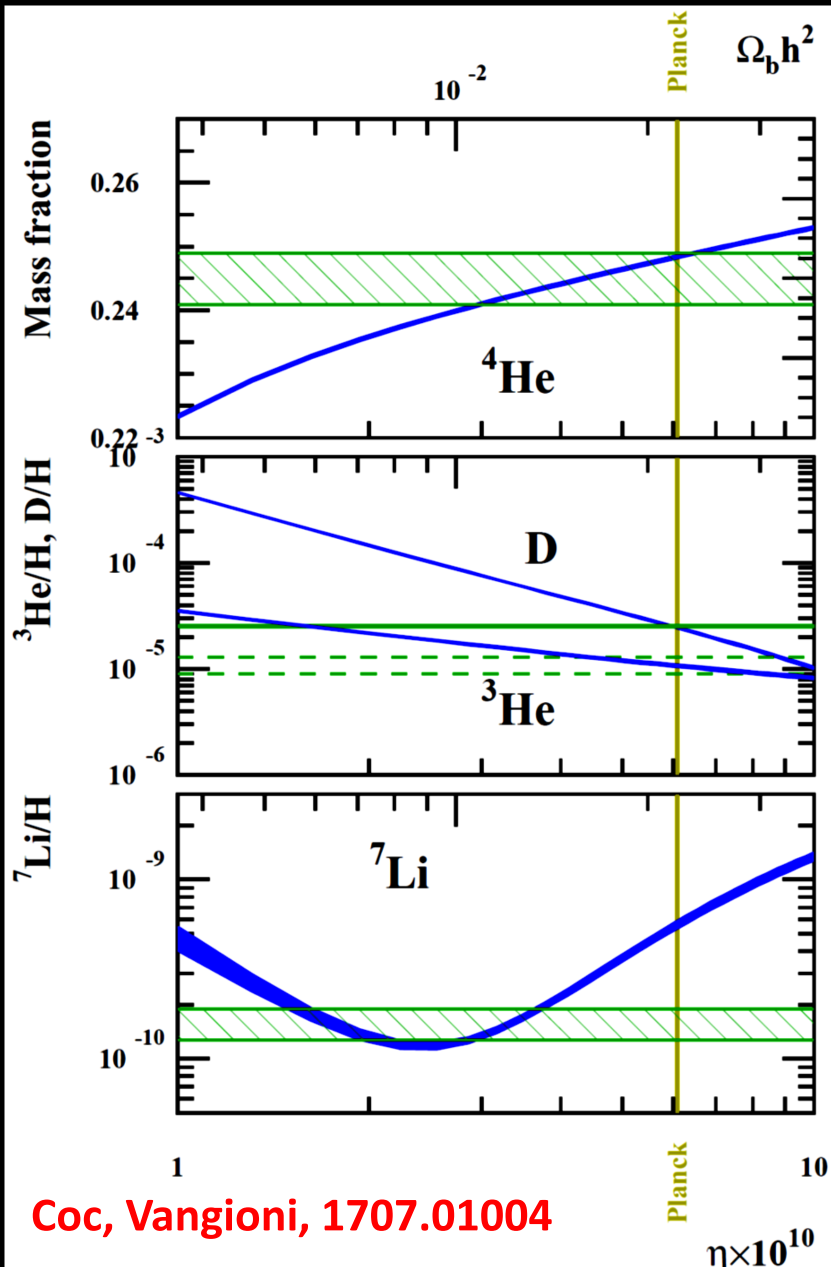
$$n \longleftrightarrow p + e^- + \bar{\nu}_e$$

1. Weak interactions freeze out at T ~1 MeV
2. Deuterium forms via p n → D γ at T ~ 0.1 MeV
3. Nuclear chain



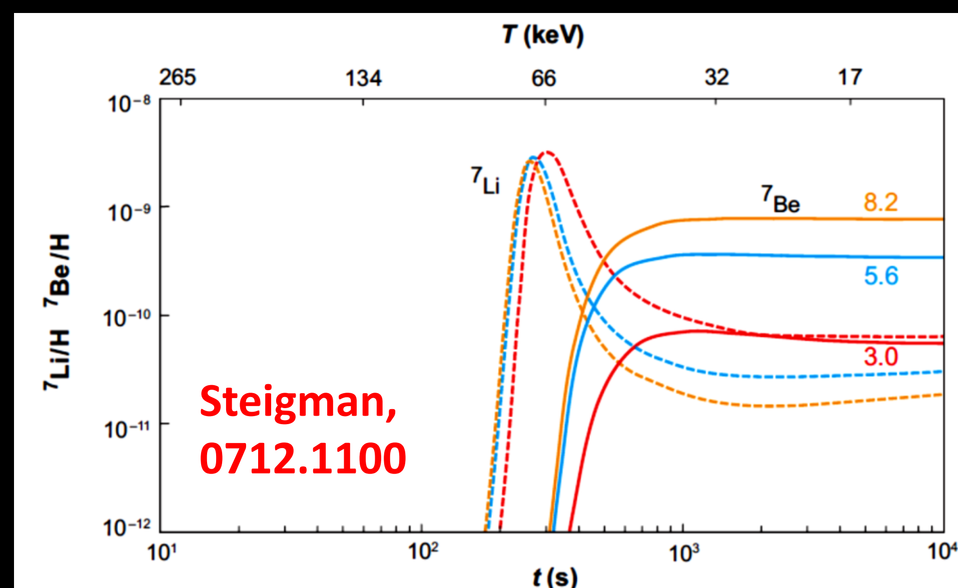
$$\left(\frac{n}{p}\right)_{eq} \simeq \exp\left(-\frac{m_n - m_p}{T_\gamma}\right) = \exp\left(-\frac{1{,}293\ \text{MeV}}{T_\gamma}\right)$$

BBN: Theory vs. Observations



Coc, Vangioni, 1707.01004

- Y_p mass fraction of ^{4}He: emission lines from the low-metallicity extragalactic H II (ionized H) regions
- Abundance ratio D/H: absorption lines by high-z and low-Z neutral gases from distant quasars
- Abundance ratio Li/H: emission lines from the metal-poor halo stars in our Galaxy

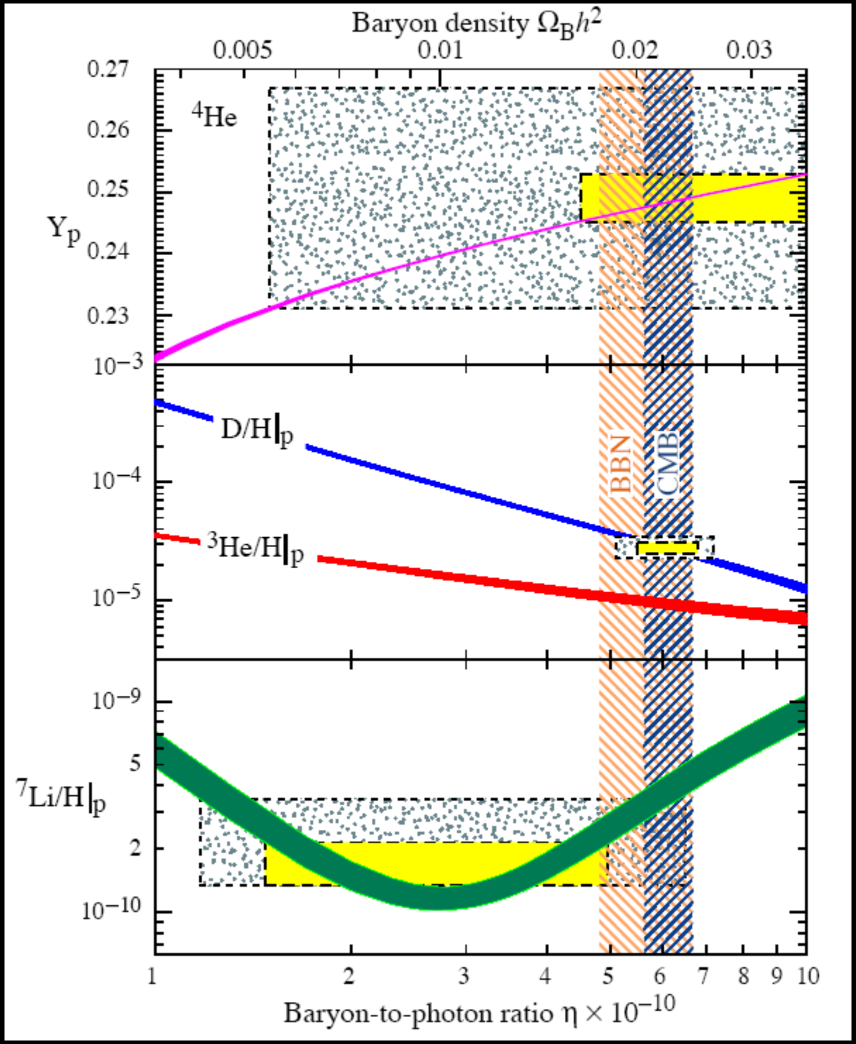


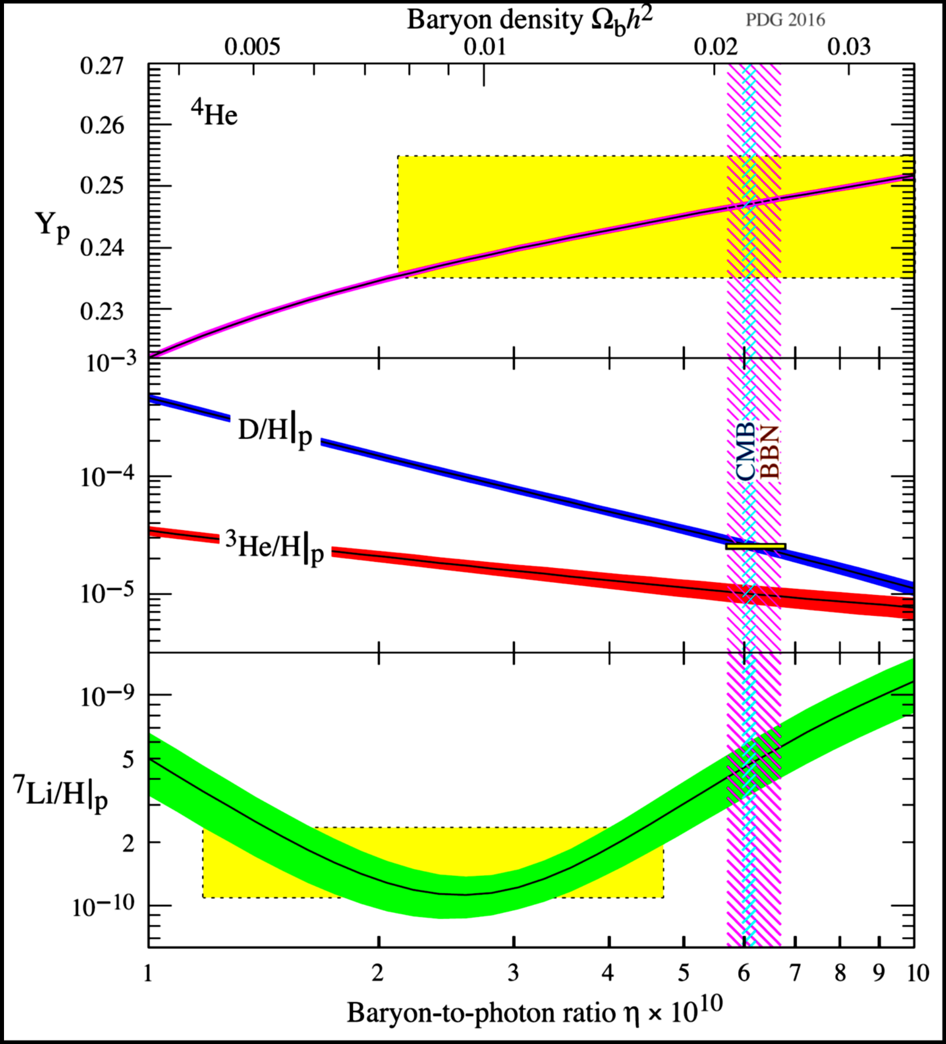
Steigman, 0712.1100

The Lithium Problem

Fields, 1203.3551

Solutions: (a) Astrophysics; (b) Nuclear Physics; (c) Particle Physics (NP)





PDG 2006 → PDG 2016

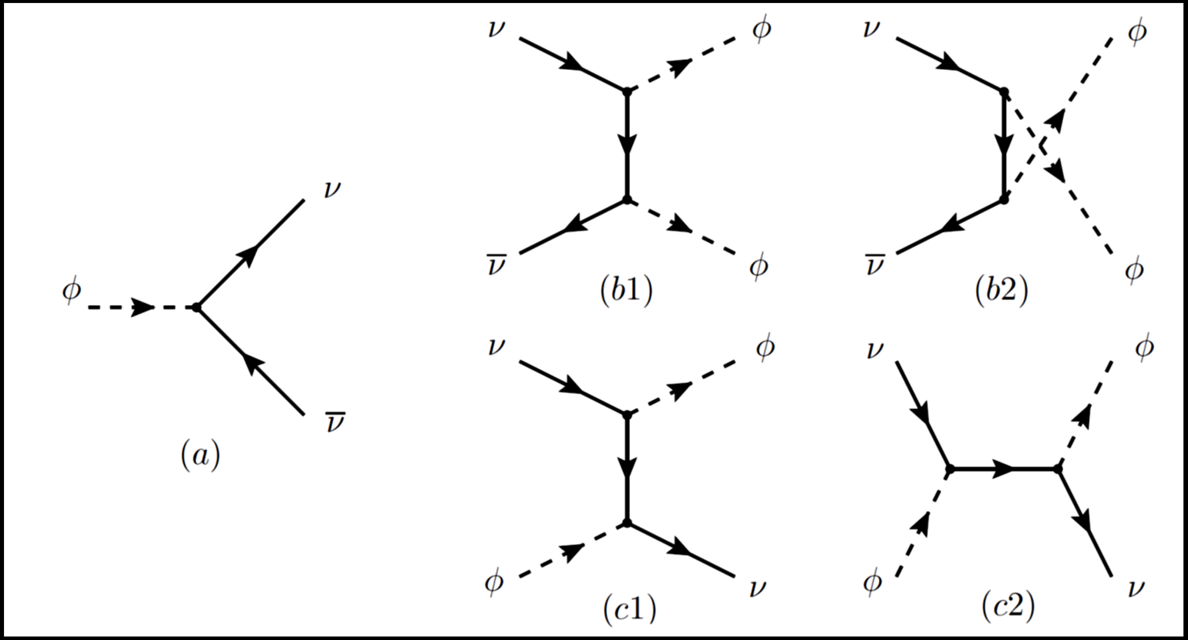
Simple BBN Constraints

Huang, Ohlsson, Zhou, 1712.04792

Working Example:

$$\mathcal{L}_{\rm SNI} = g_\phi^{\alpha\beta}\overline{\nu_{\alpha \rm L}}\nu^{\rm C}_{\beta \rm L}\phi + g_V^{\alpha\beta}\overline{\nu_{\alpha \rm L}}\gamma^\mu\nu_{\beta \rm L}V_\mu + {\rm h.c.}$$

- Either scalar or vector boson & flavor-diagonal and universal couplings
- Assume no right-handed neutrinos, otherwise more severely constrained
- **Require $\Delta N_{\rm eff} < 1$ on the extra radiation at the temperature T = 1 MeV**



- Decays and inverse decays dominate for a relatively large mass
- For small masses, the annihilation of neutrino pairs is more efficient
- For m < 1 MeV, one can just count the relativistic degrees of freedom

$N_{\rm eff} \equiv (\rho_{\rm r} - \rho_\gamma)/(\rho_\nu/3)$

	Scalar Boson	**Vector Boson**
Extra Radiation	$\Delta N_{\rm eff} = 1/2 \cdot 8/7 \approx 0.57$	$\Delta N_{\rm eff} = 3/2 \cdot 8/7 \approx 1.71$

Simple BBN Constraints

Huang, Ohlsson, Zhou, 1712.04792

Boltzman Equations

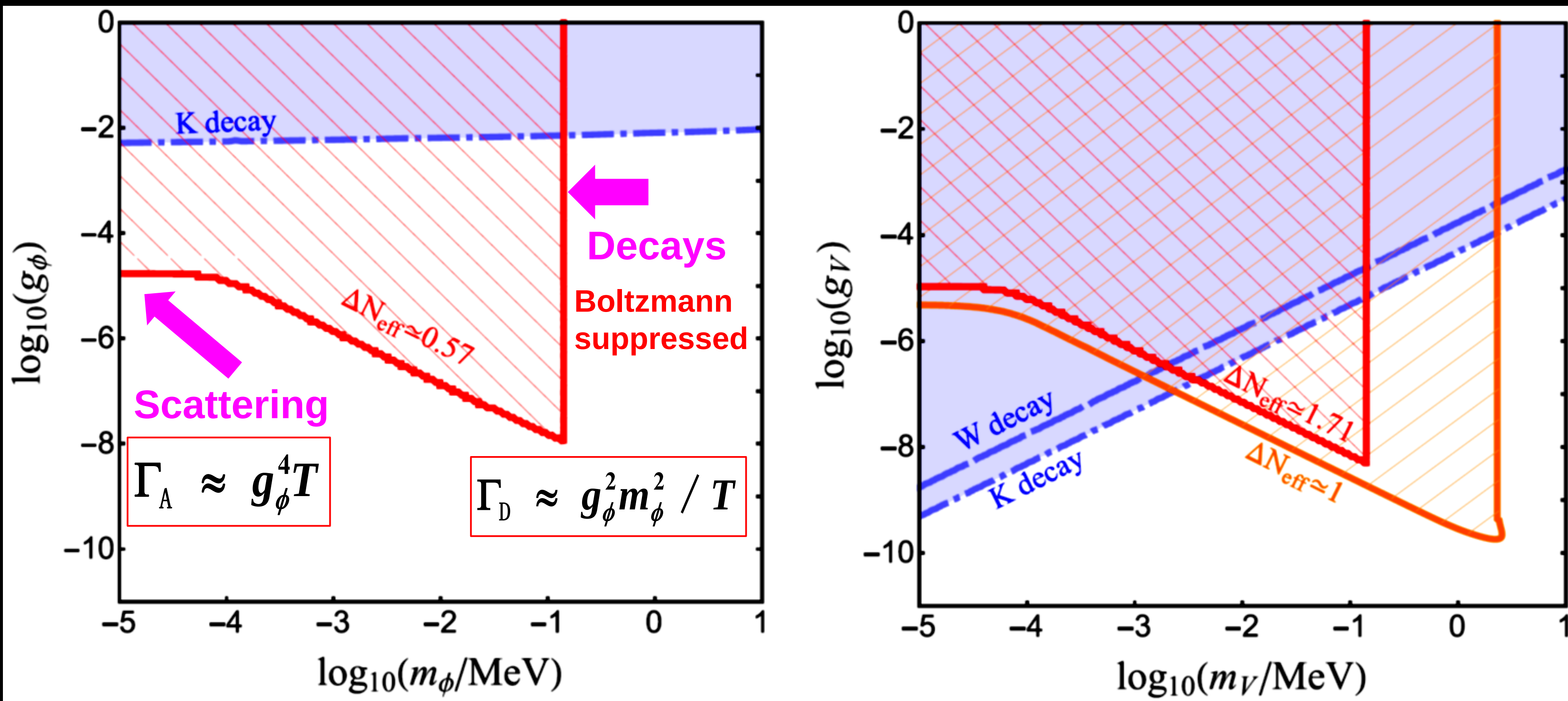
$$\frac{\partial f_i(|\mathbf{p}_i|,t)}{\partial t} - H|\mathbf{p}_i|\frac{\partial f_i(|\mathbf{p}_i|,t)}{\partial|\mathbf{p}_i|} = C^i_{\rm D}(f_\nu, f_{\phi/V}) + C^i_{\rm A}(f_\nu, f_{\phi/V}) + C^i_{\rm E}(f_\nu, f_{\phi/V})$$

with collision terms

$$C^\phi_{\rm D} = \frac{1}{2E_\phi}\int {\rm d}\tilde{p}_\nu {\rm d}\tilde{p}_{\overline{\nu}}\tilde{\delta}^4(p)\left[f_\nu f_{\overline{\nu}}(1+f_\phi) - f_\phi(1-f_\nu)(1-f_{\overline{\nu}})\right]|\overline{\mathcal{M}}_{\rm D}|^2\,,$$

$$C^\phi_{\rm A} = \frac{1}{2E_\phi}\int {\rm d}\tilde{p}_\nu {\rm d}\tilde{p}_{\overline{\nu}}{\rm d}\tilde{p}'_\phi\tilde{\delta}^4(p)\left[f_\nu f_{\overline{\nu}}(1+f'_\phi)(1+f_\phi) - f_\phi f'_\phi(1-f_\nu)(1-f_{\overline{\nu}})\right]|\overline{\mathcal{M}}_{\rm A}|^2$$

$$C^\phi_{\rm E} = \frac{1}{2E_\phi}\int {\rm d}\tilde{p}_\nu {\rm d}\tilde{p}'_\nu{\rm d}\tilde{p}'_\phi\tilde{\delta}^4(p)\left[f_\nu f'_\phi(1+f_\phi)(1-f'_\nu) - f'_\nu f_\phi(1+f'_\phi)(1-f_\nu)\right]|\overline{\mathcal{M}}_{\rm E}|^2$$



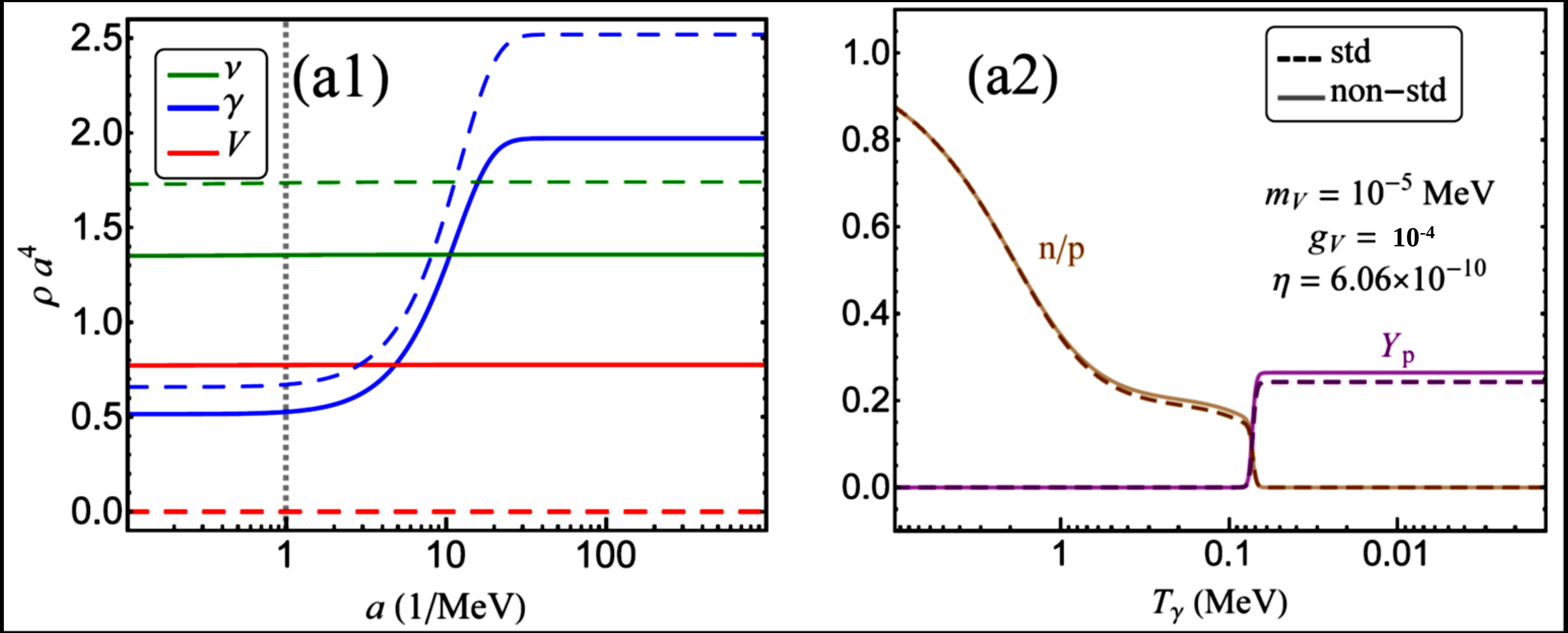
Light Element Abundances

Huang, Ohlsson, Zhou, 1712.04792

- Note: expansion rate dominated by radiation during the whole BBN era
- Calculate the energy density of extra radiation by using Boltzmann Eqs
- Compute the light element abundances via the public code **AlterBBN**

Case I: reaches thermal equilibrium above T = 10 MeV

Arbey, 1106.1363



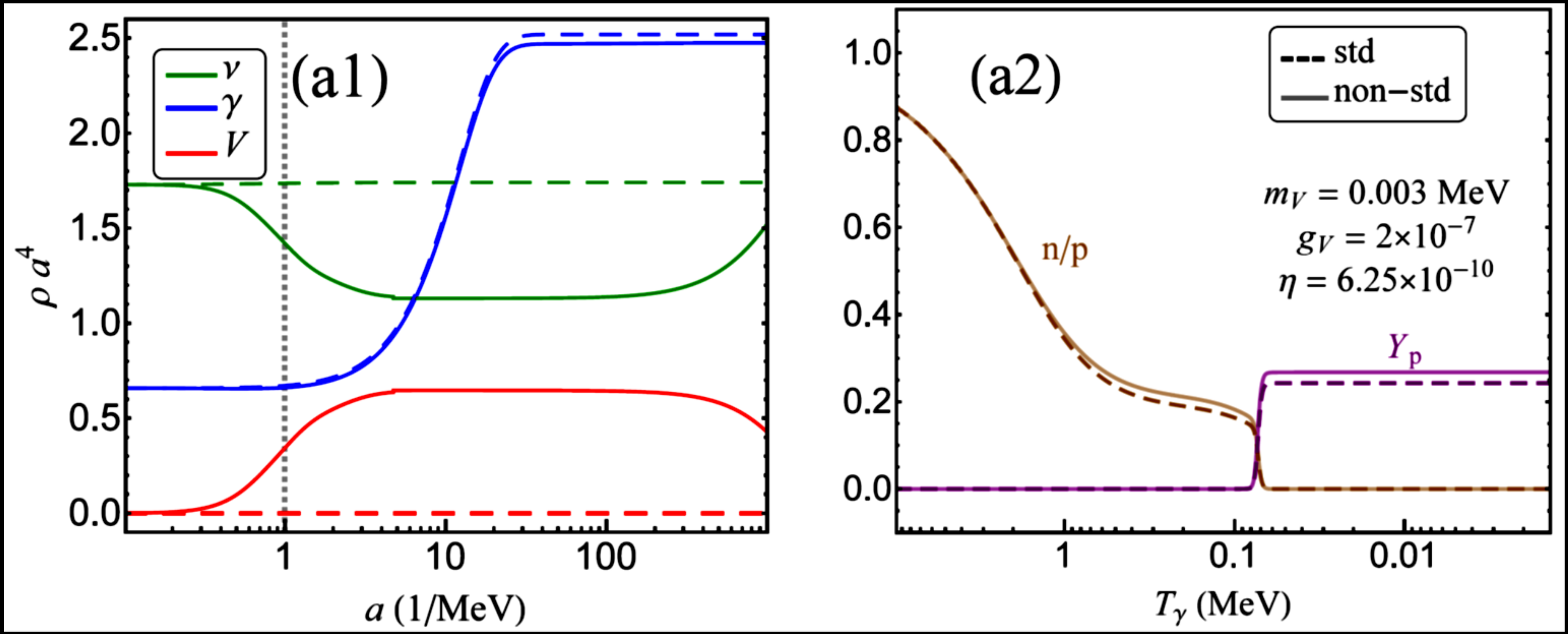
- The vector boson V thermalized far above T = 10 MeV or a = 0.1 MeV^{-1}
- Weak interactions for n-p freeze out earlier, so a larger n/p & Y_p by 8.5%

Light Element Abundances

Huang, Ohlsson, Zhou, 1712.04792

- Note: expansion rate dominated by radiation during the whole BBN era
- Calculate the energy density of extra radiation by using Boltzmann Eqs
- Compute the light element abundances via the public code **AlterBBN**

Case III: not in thermal equilibrium at T = 1 MeV



- The vector boson V not be fully thermalized at T = 1 MeV ($\Delta N_{eff} = 0.5$)
- But neutrino temperature is greatly reduced, so a larger n/p & Y_p by 10%

Final Constraints

Huang, Ohlsson, Zhou, 1712.04792

- Constructing the chi-square function (i, j = D, ^{4}He):

Fiorentini, PRD, 98

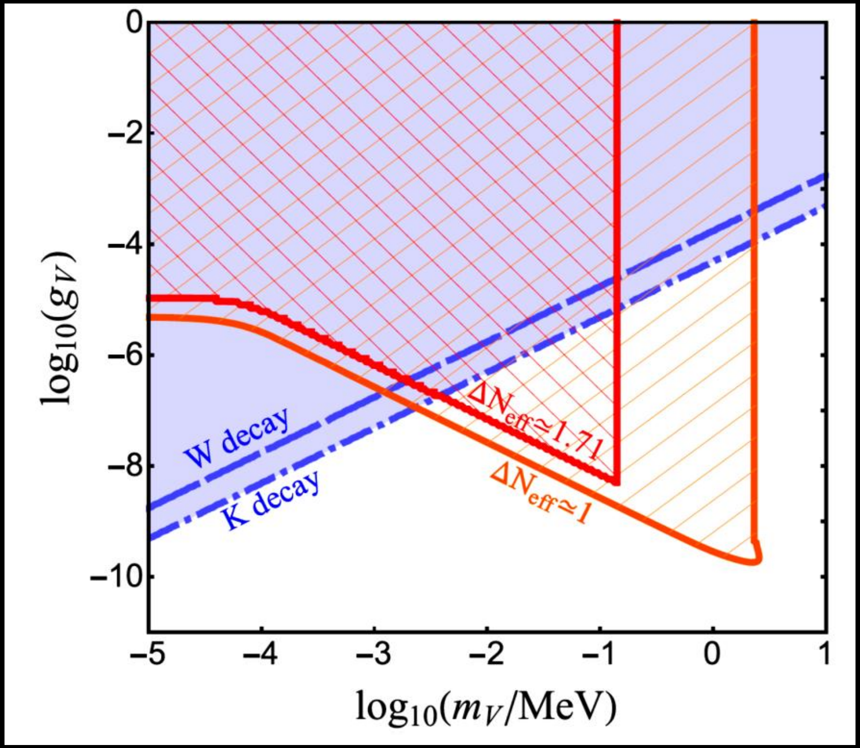
$$\chi^2 = \sum_{i,j} (Y_i^{\rm th} - Y_i^{\rm ex})[S_{ij}]^{-1}(Y_j^{\rm th} - Y_j^{\rm ex})$$

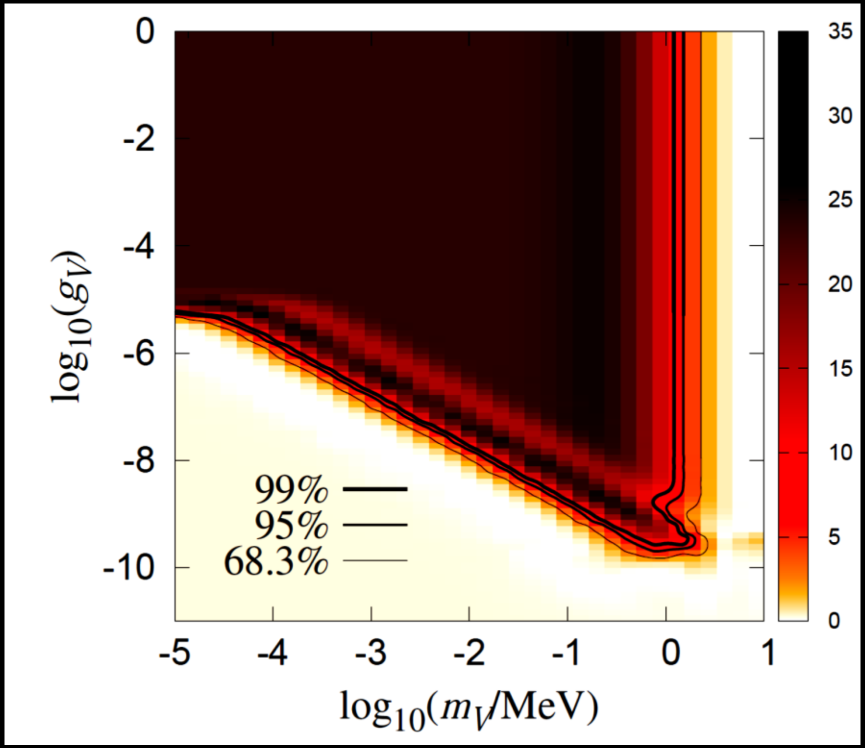
Theoretical errors from reaction rates included

$$Y_{\rm p} = 0.2449 \pm 0.0040$$ → 1.60%

$$\mathrm{D/H}|_{\rm p} = (2.53 \pm 0.04) \times 10^{-5}$$

- Scan over the parameters (η, m_V, g_V) to minimize the chi-square function





◆ Almost understood, only a different region along the slant contours (right)

Summary & Outlook

Important messages

Constraints from CCSNe and the Early Universe

NOT always safe to interact with neutrinos

Standard Cosmology

- Expansion
- BBN
- CMB/Struct. Formation

Neutrinos/ Dark Matter

Particle Physics

+

Astrophysics

+

Cosmology

Thanks for your attention!