Neutrino mass and neutrino dark matter

Do non-relativistic neutrinos constitute the dark matter ?

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Outline

Introduction: What is dark matter DM

A modeling in virial equilibrium

Comparison to a galaxy cluster

Mass, properties, name of DM particle

Nucleosynthesis

About virial equilibrium

Dark matter condensation on cluster; reionization

Conclusion

The two types of dark matter

- Galactic dark mater:
  MACHOs: Massive Astrophysical Compact Halo Objects: H-He planets

- Cluster dark matter
  WIMPs Weakly Interacting Massive Particles: this talk
- The dark matter of galaxy clusters is non-baryonic.
- Detected from rotation curves, by lensing
- About 20% of total mass of the Universe.

- Not MACHOs or WIMPs but MACHOs and WIMPs !!

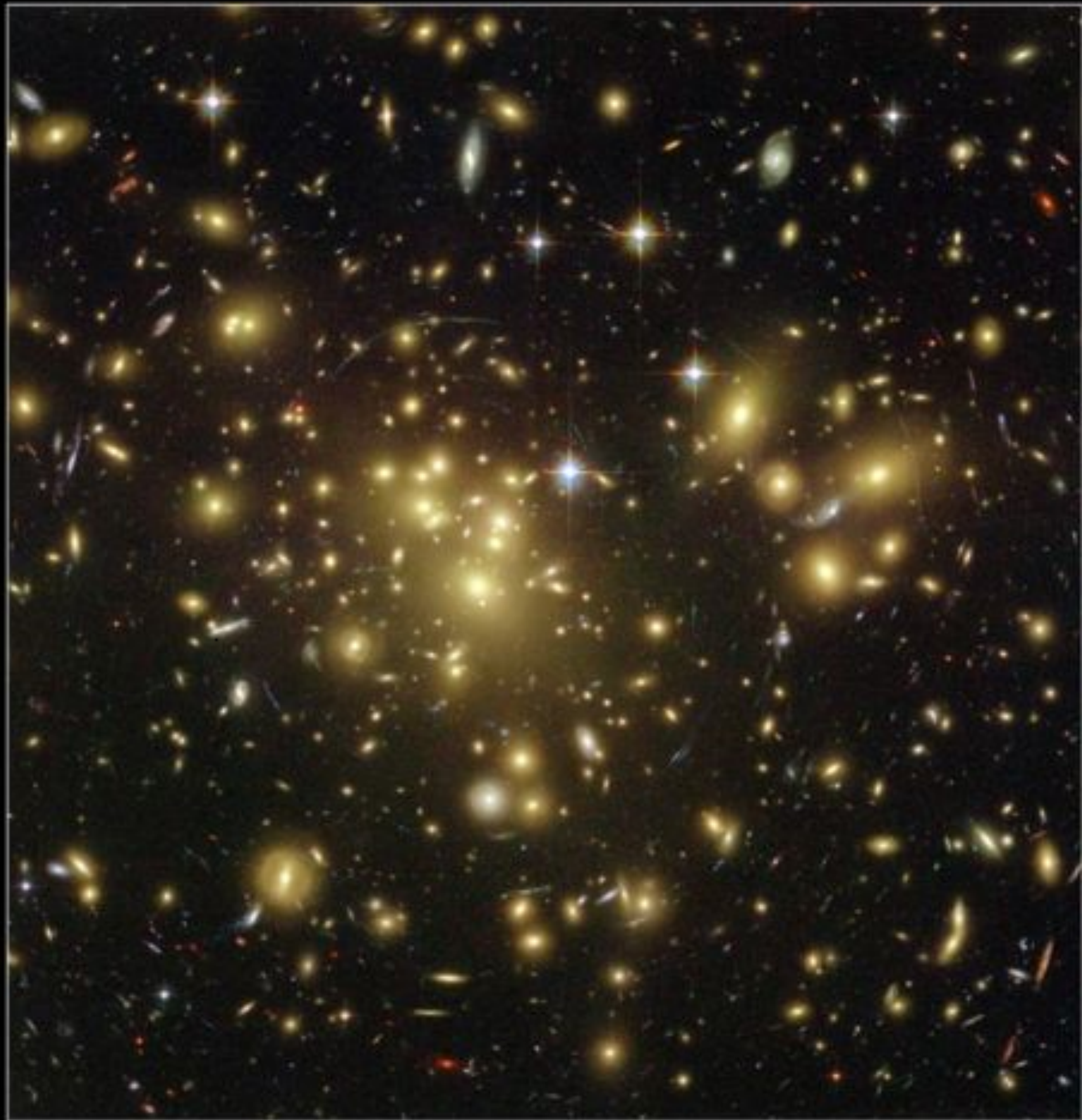
- # Abell 1689 galaxy cluster
- Nearby z = 0.184

- Total mass
  $1-3 \ \ 10^{15} \ \ M_{\Theta}$

- Luminous mass
  $4.4 \ \ 10^{11} \ \ M_{\Theta}$

- Baryon poor

- Einstein ring



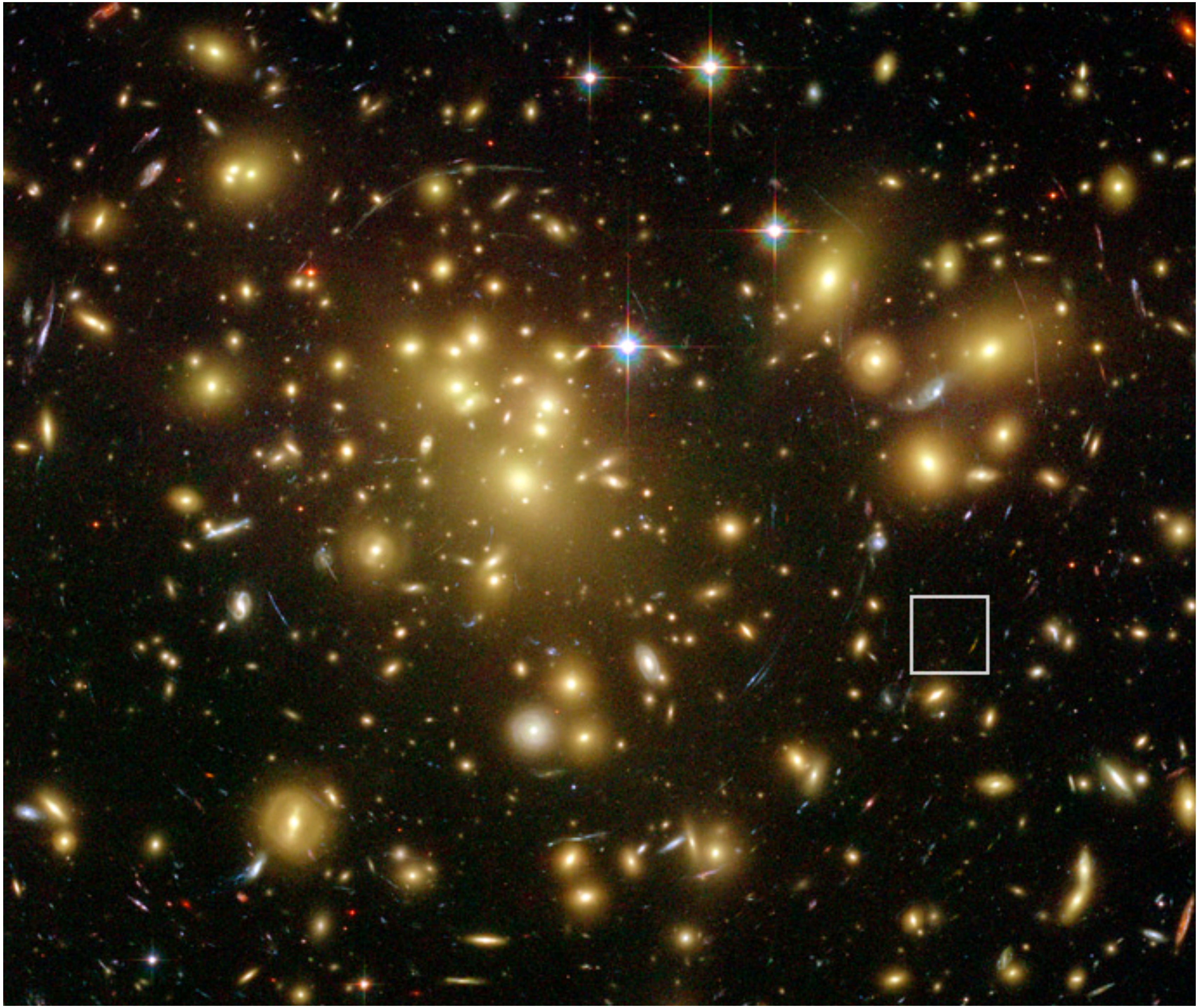
Galaxy Cluster Abell 1689
Hubble Space Telescope • Advanced Camera for Surveys

NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA
STScI-PRC03-01a

Incomplete
Einstein ring
at 100/h kpc

Abell 1689
Center

Dark matter
acts as
crystal ball



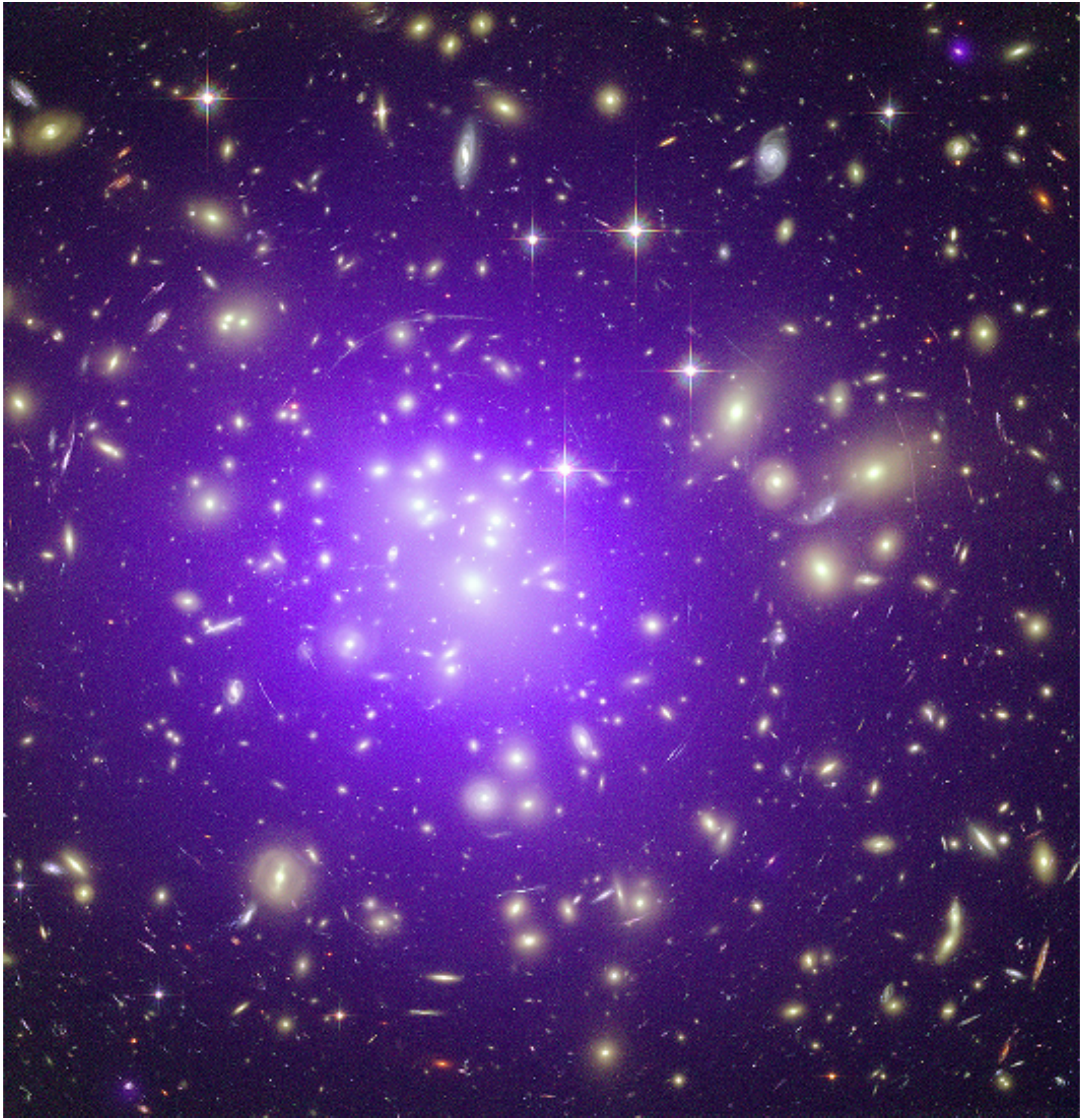
Abell 1689

X-ray emitting gas

T=10 keV = 1.16 10^8 K

Three components:

Dark matter
Galaxies
Gas

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Theory

- Assume that DM comes from fermions
  in their common gravitational potential U(r)
- Mass m, degeneracy g; g = 2 (2s+1) #families
- Mass density for equilibrium at T

$$\rho_D = \int \frac{d^3 p}{(2\pi\hbar)^3} \frac{\bar{g}m}{\exp[(p^2/2m + mU(r) - \mu)/k_B T] + 1}$$

- Gravitational potential $U(r) = G\int d^3r' \rho(r')(\frac{1}{r'} - \frac{1}{|\mathbf{r}-\mathbf{r}'|})$
  U(0)=0

- Poisson eqn (spherical symmetry) $U'' + \frac{2}{r}U' = 4\pi G\rho$

- Together they give closed problem for U(r)

Dark matter (x), Galaxies (G) and gas (g)

- Hydrostatic equilibrium $\frac{p_i'(r)}{\rho_i(r)} = -\frac{GM(r)}{r^2} \qquad i = x, G, g$

  M(r) total mass inside r

- Ideal gas laws $p_i = \frac{\rho_i}{\overline{m}_i} k_B T_i \qquad i = G, g$

- Result $\rho_i = A_i \, e^{-\overline{m}_i U / k_B T_i}$

- Virial equilibrium:
  equal velocity dispersions $(\sigma_v^G)^2 \equiv \frac{T_G}{\overline{m}_G} = \frac{T_x}{m_x} = \frac{T_\alpha}{m_\alpha} = (\sigma_v^g)^2$

Dimensionless shape

radius, potential $x = r/R_*,\ \phi = U/k_BT,$

thermal length, scale $\lambda_T = \left(\frac{2\pi\hbar^2}{mk_BT}\right)^{1/2}, \qquad R_* = \left(\frac{\lambda_T^3 k_BT}{4\pi g G m^2}\right)^{1/2}$

Dark density $\rho_D(r) = -\frac{\bar{g}m}{\lambda_T^3}\mathrm{Li}_{3/2}\left(-e^{\alpha-\phi(x)}\right)$ polylogarithm $\mathrm{Li}_\gamma(z) = \sum_{k=1}^{\infty}\frac{z^k}{k^\gamma}$

Poisson eqn $\phi'' + \frac{2}{x}\phi' = -\mathrm{Li}_{3/2}\left(-e^{\alpha-\phi}\right) + e^{\alpha_G - \bar{\beta}_G\phi} + e^{\alpha_g - \bar{\beta}_g\phi}$

dark matter + Galaxies + gas

Virial equilibrium: Galaxies $\bar{\beta}_G = 1$

gas (ionized H, He, 30% solar metallicity) $\bar{\beta}_g = 0.153$

Observed quantity in strong and weak lensing

Integrated mass along line-of-sight

$$\Sigma(r_\perp) = \int_{-\infty}^{\infty} \mathrm{d}z \rho \left(\sqrt{r_\perp^2 + z^2}\right)$$

Average in (0, r)

$$\overline{\Sigma}(r) = \frac{1}{\pi r^2} \int_0^r \mathrm{d}r_\perp 2\pi r_\perp \, \Sigma(r_\perp)$$

Average in (r, r_m)

$$\overline{\Sigma}(r \to r_m) = [r_m^2 \overline{\Sigma}(r_m) - r^2 \overline{\Sigma}(r)]/(r_m^2 - r^2)$$

Contrast function

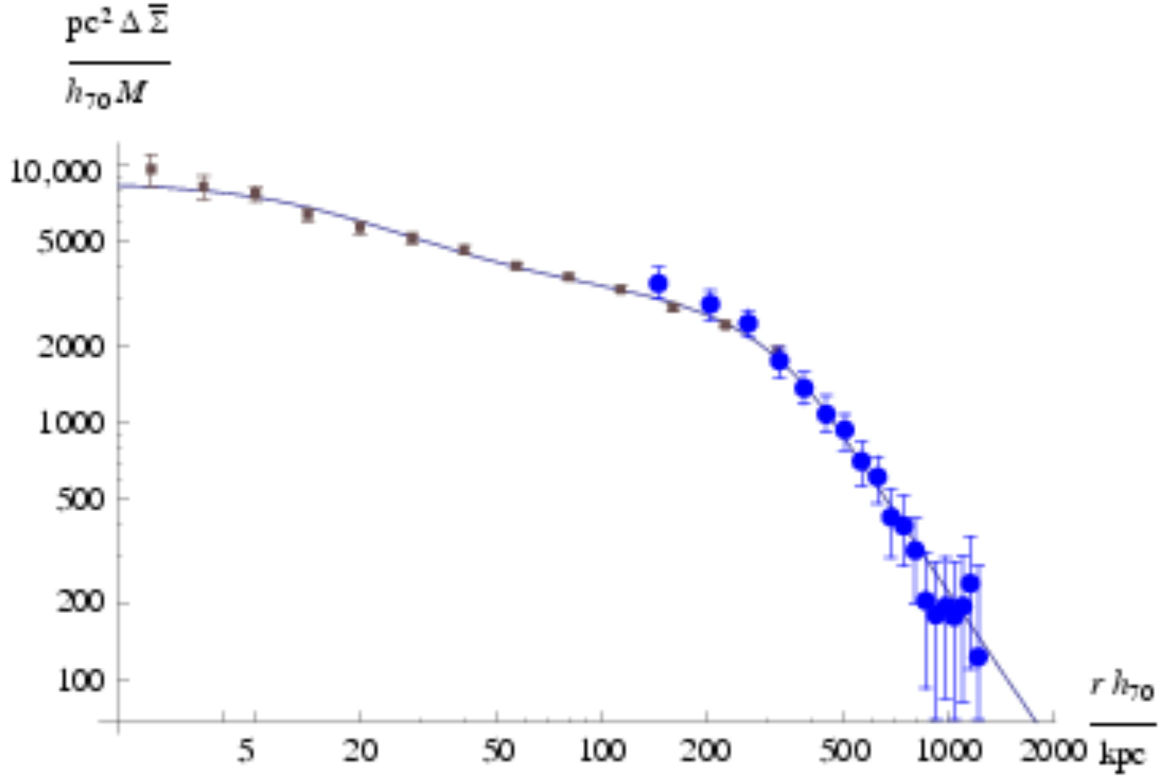
$$\Delta\overline{\Sigma}(r) \equiv \overline{\Sigma}(r) - \overline{\Sigma}(r \to r_m) = \frac{\overline{\Sigma}(r) - \overline{\Sigma}(r_m)}{1 - r^2/r_m^2}.$$

From the model

$$\overline{\Sigma}(r) = A\,\Phi\left(\frac{r}{R_*}\right), \quad \Phi(x) = \int_0^\infty \mathrm{d}s\, \phi'(x \cosh s)$$

Fit to A1689 lensing data of Tyson and Fischer ApJ 1995

Limousin et al, ApJ 2007



$A = 59.4 \pm 9.6\, h_{70} M_{\odot} \mathrm{pc}^{-2}$, $\alpha = 38.4 \pm 3.1$, $\alpha_g = 2.36$

$R_* = 297 \pm 10\, h_{70}^{-1} \mathrm{kpc}$, $\alpha_G = 8.26 \pm 0.32$. $\bar{\beta}_G = 1$ $\bar{\beta}_g = 0.153$

The mass of the dark matter particle

$$m = \frac{1}{2^{1/8}\bar{g}^{1/4}} \frac{\hbar^{3/4}}{A^{1/8}G^{3/8}R_*^{5/8}}$$

$\bar{g}$ = number of *available* modes in cluster

reduced Hubble parameter $h_{70} = \frac{H_0}{70\,\mathrm{km/s\ Mpc}}$

$$m = h_{70}^{1/2}\left(\frac{12}{\bar{g}}\right)^{1/4} 1.455 \pm 0.030\ \mathrm{eV}$$

small error, 2.0%

Previous estimates and searches: keV, MeV, GeV, TeV: excluded

Cosmic density of g *occupied* modes that once were thermal

$$n_F = g\frac{3}{4}\frac{4}{11}\frac{\zeta(3)}{\pi^2}\left(\frac{k_B T_\gamma}{\hbar c}\right)^3 = g\,55.977\,\mathrm{cc}^{-1}$$

Cosmic matter fraction

$$\Omega_x = \frac{n_F m}{\rho_c} = \frac{g}{12}\left(\frac{12}{\bar{g}}\right)^{1/4} h_{70}^{-3/2} 0.1893 \pm 0.0039$$

What is the dark matter particle?

The dark matter fraction $\Omega_x = \frac{n_F m}{\rho_c} = \frac{g}{12}\left(\frac{12}{\bar{g}}\right)^{1/4} h_{70}^{-3/2} 0.1893 \pm 0.0039$

Early decouplers have small occupation g: Not axions, gravitinos, neutralinos, X-inos

Match possible to WMAP5 $\Omega_D = 0.214 \pm 0.027$ for $\bar{g}$ =12

(anti) neutrinos, left+right-handed, 3 families 2*2*3=12 mass = 1.455 eV

Neutrino oscillations cause small mass differences, 0.001 eV or less

Thermal length visible to the eye $\lambda_{T\nu} = \frac{\hbar\sqrt{2}}{m_\nu\sqrt{GAR_*}} = 0.20 \text{ mm}$

Temperature is low $T_\nu^A = \pi G m_\nu A R_*/k_B = 0.0447\,\text{K}$

Typical speed is non-relativistic, v = 490 km/s

Local density can be enormous: in Abell center: one billion in a few cc

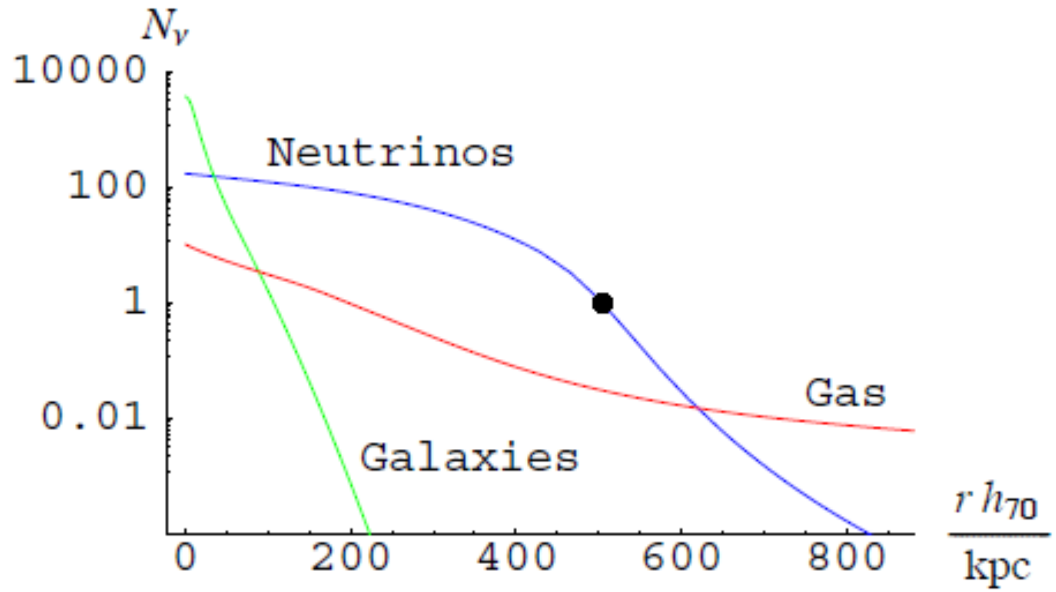
The biggest quantum structure in the Universe

normalized density:

neutrinos

per cubic thermal wavelength

per degree of freedom



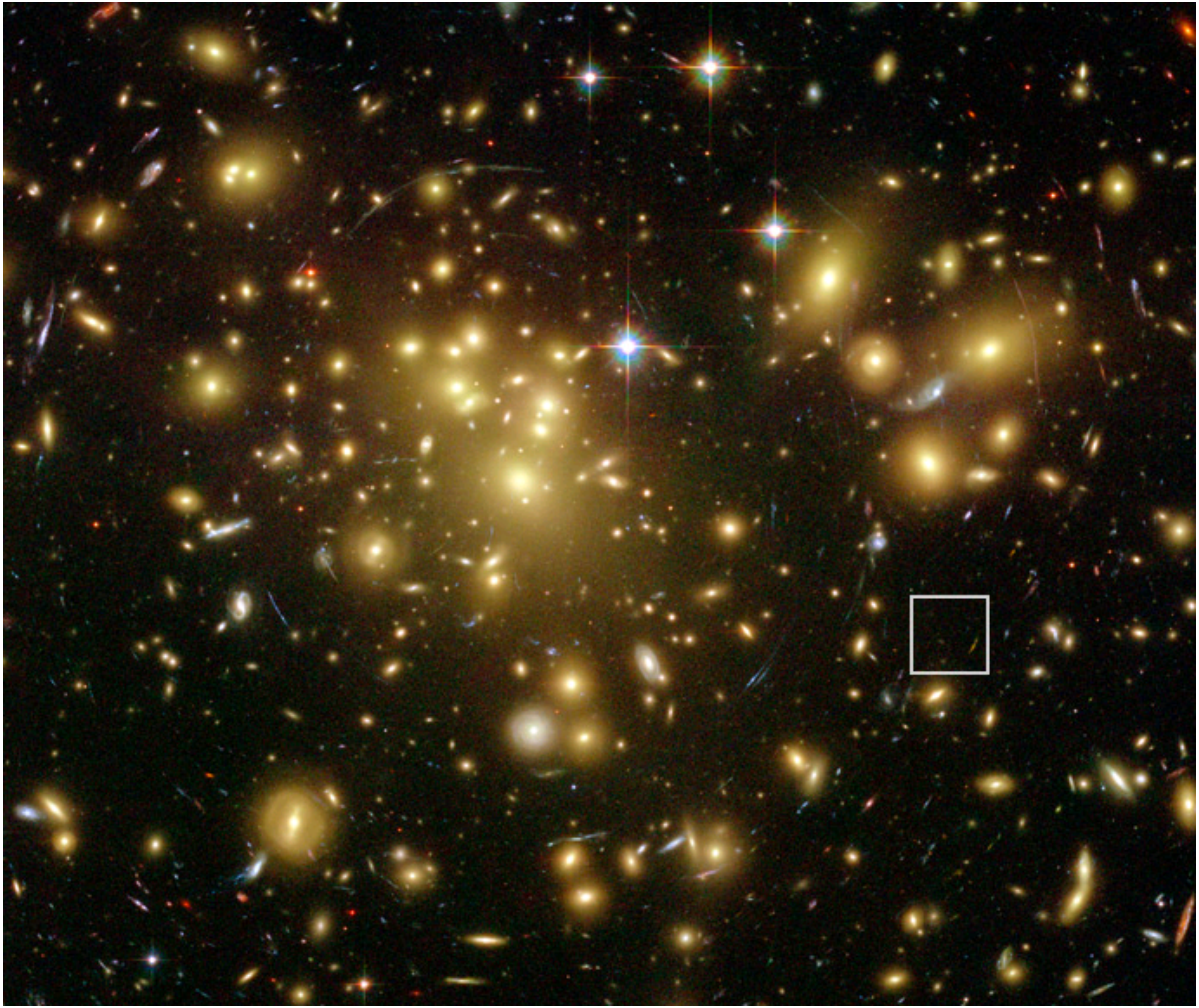
Galaxies, gas:
Baryons are poor tracers of dark matter *density*, even though they do trace the *enclosed mass*

N>1: quantum degenerate nu's
N=1: quantum-to-classical crossover

at r = 505 kpc = 1.6 million light year
d = 2r = 3.2 million light year
That is pretty big …

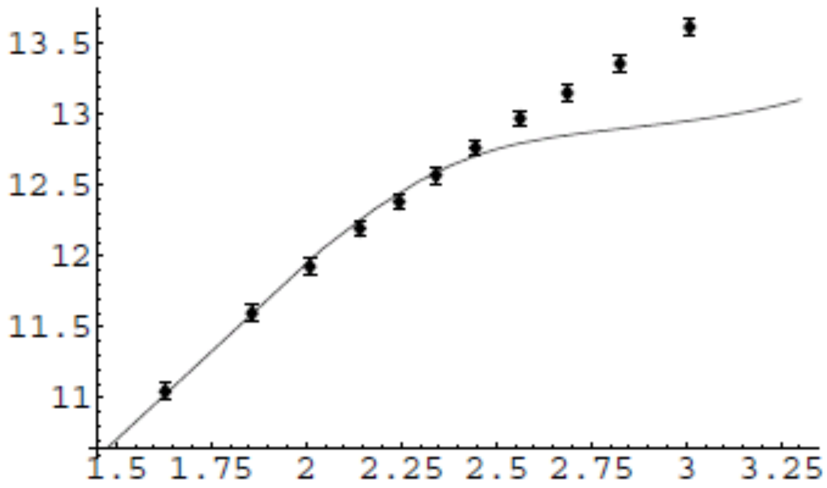
Incomplete
Einstein ring
at 100/h kpc

Abell 1689
Center



Temperature of gas: 10 keV=10^8 K

Virial T of alpha-particles $T_\alpha = \frac{m_\alpha}{m_\nu} T_\nu = 9.9 \pm 1.0 \text{ eV}$ overlaps with it.



Virial equilibrium assumed;
only amplitude adjusted

Cluster radiates in X-rays like a star in light.
Radiated energy supplied by contraction, as for stars.
Radiation helps to maintain virial equilibrium.

Dirac and Majorana masses (3*3 matrices)

- Dirac mass 1.45 eV, ideally $m_{\nu_1} = Y_e m_e = 2^{3/4} G_F^{1/2} m_e^2 = 1.4998\ \mathrm{eV}$
  iff h=0.744: good Hubble value

- Majorana: neutrino + neutrino annihilation
  Lepton number not conserved
- Majorana mass > 0.0001 eV creates right-handed (sterile) neutrinos in period when 200 MeV < T < 1 MeV
- Majorana mass causes neutrinoless double beta-decay.
  Experimental upperbound: < 0.2-0.7 eV

Sterile neutrinos and nucleosynthesis

- Sterile neutrinos cause enhanced expansion

$$H' = SH, \quad \rho' = S^2 \rho \qquad S = \left(\frac{16 + 7g(4/11)^{4/3}}{16 + 42(4/11)^{4/3}} \right)^{1/2} = 1.1854$$

- Faster expansion: too few neutron decays, too much He-4
- If neutrino asymmetry: more neutrinos than anti-neutrinos

$$L \equiv \frac{n_\nu - n_{\bar{\nu}}}{n_\gamma} = \frac{\pi^2}{12\zeta(3)} (\xi + \frac{\xi^3}{\pi^2}) \qquad \xi = \mu / kT$$

- Thus more reactions for neutron decay
- These effects can compensate each other $n + \nu_e \to p + e$
- So nucleosynthesis can accommodate right-handed neutrinos

Effect nu-asymmetry on data Steigman IJMP E, 2005

$$S = \left(\frac{16 + 7g(4/11)^{4/3}}{16 + 42(4/11)^{4/3}} \right)^{1/2} = 1.1854$$

$$\eta_{\rm He} = \eta_{10} + 100(S-1) - \frac{575}{4}\xi$$

$$\eta_{\rm D} = \eta_{10} - 6(S-1) + \frac{5}{4}\xi$$

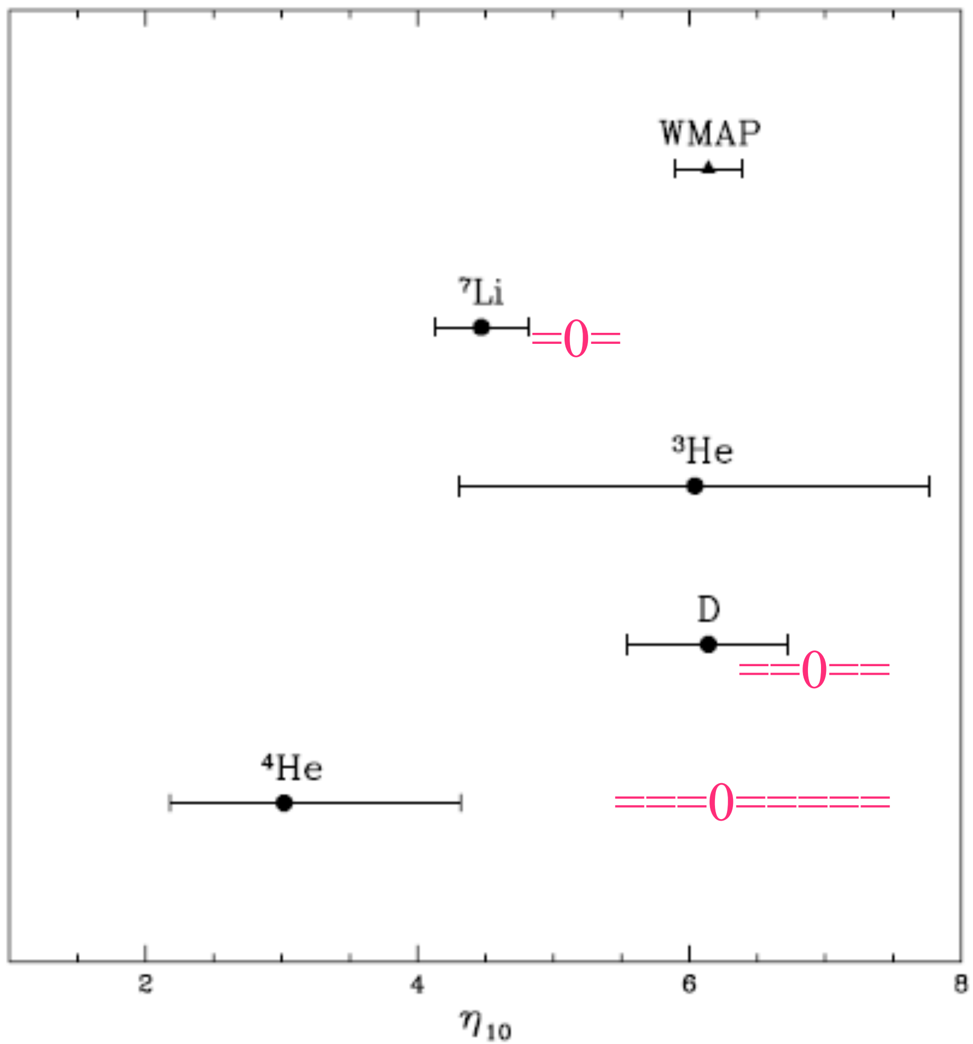
$$\eta_{\rm Li} = \eta_{10} - 3(S-1) - \frac{7}{4}\xi$$

$\Delta N = 3$

$S = 1.184$

$\xi = 0.152$ Adjusting He-4 to WMAP

$L = 0.106$



Why virial equilibrium?

- Lynden Bell: violent relaxation, faster than collisional
- Relaxation in time-dependent potential:
  every object (individual particle, galaxy) exchanges energy with the whole cluster
- Iff phase space density becomes uniform, then Fermi-Dirac distribution
- X-ray radiation helps to maintain the virial state, as in the sun

CDM or HDM?

- Cold Dark Matter: heavy particles already clumped at decoupling z=1100
- But light neutrinos are free streaming until trapped by galaxy cluster

$$\partial_t f_\nu + \frac{\mathbf{p}\cdot\partial_\mathbf{r} f_\nu}{m_\nu} - \left(\mathbf{p}H + \hat{\mathbf{r}}\frac{Gm_\nu M(r,t)}{r^2}\right)\cdot\partial_\mathbf{p} f_\nu = 0$$

- Free streaming $f_\nu = \frac{1}{e^{\beta pc} + 1}$
- Crossover when Newton force matches Hubble force: z = 6 - 7
- Then cosmic voids loose neutrinos and become empty
- This heats the intracluster gas up to 10 keV, so it *reionizes,* without heavy stars
- Hot Dark Matter paradigm agrees with gravito-hydrodynamics

Gravitational hydrodynamics

- Structure formation starts in plasma: proto-voids & galaxy clusters
- Explains CMB T-fluctuations of micro-Kelvins

- At decoupling: galaxies; proto-globular clusters 40,000 solar mass
- Some PGCs developed into globular star clusters
- Other PGCs act as ideal gas "particles" around galaxies.
- Explains isothermal model for galactic dark matter: rotation curves, Tully Fisher relation
- (Dwarf) galactic DM does *NOT* exclude neutrinos.

- Final fragmentation in H-He planets of earth weight.
- Thousands of frozen planets observed in microlensing thousands of heated planets in planetary nebulae

N,Gibson,Schild, arXiv 0906.5801

Summary

- Observed DM of Abell 1689 cluster explained by thermal fermions of eV mass.
  keV, MeV, GeV, TeV, PeV excluded. Thermal bosons (axions) excluded.

- Fitting with global dark matter fraction: 6 active + 6 sterile (anti-)neutrinos
  Mass about 1.45 eV, depends on h. Ideal case: m=1.4998 eV, h=0.744

- Gas temperature 10^8 K = alpha-particle temp., gas profile matches automatically

- Baryons are poor tracers of dark matter *density*.

- Free flow into potential well occurs at z = 6 - 7. Causes reionization,
  without heavy stars

- Neutrino Hot Dark Matter challenges Cold Dark Matter (CDM).

- Dark matter particle was not (and should not) be observed in searches

  ADMX, ANAIS, ArDM, ATIC, BPRS, CAST, CDMS, CLEAN, CRESST, CUORE, CYGNUS, DAMA, DEEP, DRIFT, EDELWEISS, ELEGANTS, EURECA, GENIUS, GERDA, GEDEON, GLAST, HDMS, IGEX, KIMS, LEP, LHC, LIBRA, LUX, NAIAD, ORPHEUS, PAMELA, PICASSO, ROSEBUD, SIGN, SIMPLE, UKDM, XENON, XMASS, ZEPLIN. DAMIC, FERMI, ICECUBE, VERITAS.

- Neutrino mass tested in Katrin search between 0.2 eV – 2 eV (2012).

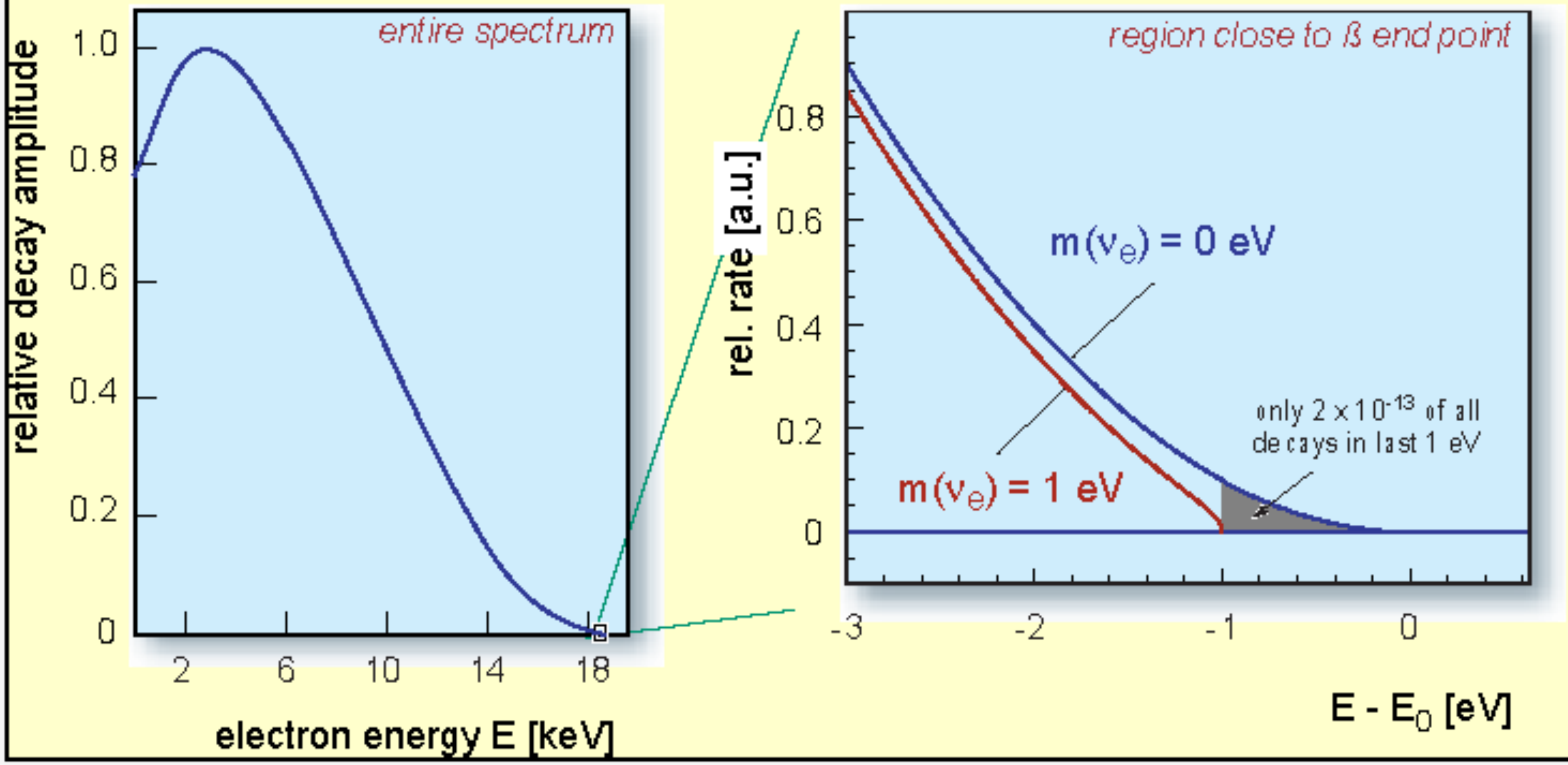
tritium ß-decay and the neutrino rest mass

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

superallowed

half life : $t_{1/2}$ = 12.32 a

ß end point energy : E_0 = 18.57 keV



KArlsruhe **TRI**tium **N**eutrino Experiments