Gravitational clustering of relic neutrinos and implications for their detection

Yvonne Y. Y. Wong

DESY Hamburg

in collaboration with Andreas Ringwald, arXiv:hep-ph/0408241

DESY Theory Workshop 2004

Cosmic neutrino background (CνB)

- CνB: neutrino decoupling at $t \sim 1$ s [cf. CMB, $t \sim 10^5$ yr]
- Properties today:

$$T_{\mathrm{C}\nu\mathrm{B},0} = \left(\frac{4}{11}\right)^{1/3} T_{\mathrm{CMB},0} \sim 2 \text{ K} \sim 10^{-4} \text{ eV}, \quad \text{rel. FermiDirac} \tag{1}$$

$$\bar{n}_{\mathrm{C}\nu\mathrm{B},0} = \frac{3}{22} n_{\mathrm{CMB},0} \simeq 56 \text{ cm}^{-3} \quad \text{per helicity per flavour} \tag{2}$$

$$\Omega_{\mathrm{C}\nu\mathrm{B},0} = \frac{2\sum_{i=1}^{3} m_{\nu_i} \bar{n}_{\mathrm{C}\nu\mathrm{B},0}}{\rho_c} = \frac{1 \times 10^{-2}}{h^2} \sum_{i=1}^{3} \frac{m_{\nu_i}}{\text{eV}} \tag{3}$$

- Consistent with BBN and CMB/LSS data
- Never been directly detected via scattering type experiments

Neutrino mass and clustering

- ν oscillation experiments $\Rightarrow m_{\nu,3} \gtrsim \sqrt{\Delta m^2_{\rm atm}} \sim 0.04$ eV
- Kinematic effects of m_ν on LSS $\Rightarrow \Omega_\nu \lesssim 5$ % in ΛCDM $\Rightarrow m_{\nu,i} \lesssim 0.6$ eV
- Late time, small scale ($\lesssim 10$ Mpc) ν clustering:

$$\bar{v}_{\rm C\nu B} \simeq 1.6 \times 10^2 \; (1+z) \left(\frac{\rm eV}{m_\nu} \right) \; {\rm km \ s^{-1}}$$

  - cf. velocity dispersion of galaxy, 2×10^2 km s^{-1}; galaxy cluster, 10^3 km s^{-1}
  - clustering at $z \lesssim 2$

- Local "hot spots"
  - clustering in Milky Way $\Leftrightarrow$ fully earthbound CνB direct searches
  - clustering in galaxy clusters $\Leftrightarrow$ searches using cosmic rays

Gravitational clustering of relic neutrinos

- Nonrelativistic Vlasov (4) and Poisson (5) equations,

$$\frac{Df_i}{D\tau} \equiv \frac{\partial f_i}{\partial \tau} + \dot{\boldsymbol{x}} \cdot \frac{\partial f_i}{\partial \boldsymbol{x}} - a m_i \nabla \phi \cdot \frac{\partial f_i}{\partial \boldsymbol{p}} = 0 \quad (4)$$

$$\nabla^2 \phi = 4\pi G a^2 \sum_i \left[\underbrace{\frac{m_i}{a^3} \int d^3p \; f_i(\boldsymbol{x}, \boldsymbol{p}, \tau)}_{\rho_i(\boldsymbol{x},\tau)} - \bar{\rho}_i(\tau) \right] \quad (5)$$

m_i = mass of the ith component, e.g., CDM, neutrino, etc.
$f_i(\boldsymbol{x}, \boldsymbol{p}, \tau)$ = phase space density
$\rho_i(\boldsymbol{x}, \tau)$ = physical (mass) density
$\phi(\boldsymbol{x}, \tau)$ = total peculiar potential
$a(\tau)$ = scale factor
$\boldsymbol{x}, \boldsymbol{p}, \tau$ = comoving phase space coordinates and conformal time

Solution method	N-body simulation [CHDM: Kofman *et al.* '96]	Linear approximation [e.g., Singh, Ma '03]	N-one-body simulation [Ringwald, Y^3W '04]
Description	Particle-based: $\frac{d\boldsymbol{x}}{d\tau} = \frac{\boldsymbol{p}}{am_i}$ $\frac{d\boldsymbol{p}}{d\tau} = -am_i \nabla \phi$	Fourier methods: $f(\boldsymbol{x}) \rightarrow \hat{f}(\boldsymbol{k})$	Particle-based, cf. N-body simulation
Assumptions	"None"	$f(\boldsymbol{x}, \boldsymbol{p}, \tau) \sim f_0(p)$, $f_0 =$ unperturbed phase space density, limited validity	1. Only $\rho_{\rm cdm}$ contrib. to ϕ [$\Omega_\nu/\Omega_{\rm cdm} < 0.2$ in ΛCDM; free-streaming $\Rightarrow \frac{\rho_\nu}{\rho_{\rm cdm}} < \frac{\Omega_\nu}{\Omega_{\rm cdm}}$] 2. $\rho_{\rm cdm}$ is known, e.g., halo density profiles from pure ΛCDM simulations
Resources	Supercomputer	Semi-analytical	My laptop (in principle!!)
Resolution	Limited $\sim$100 kpc, incl. ν	Unlimited	Excellent ~ 1 kpc

- Parameteric CDM halo density profiles based on simulations:
  - Navarro Frenk White profile:

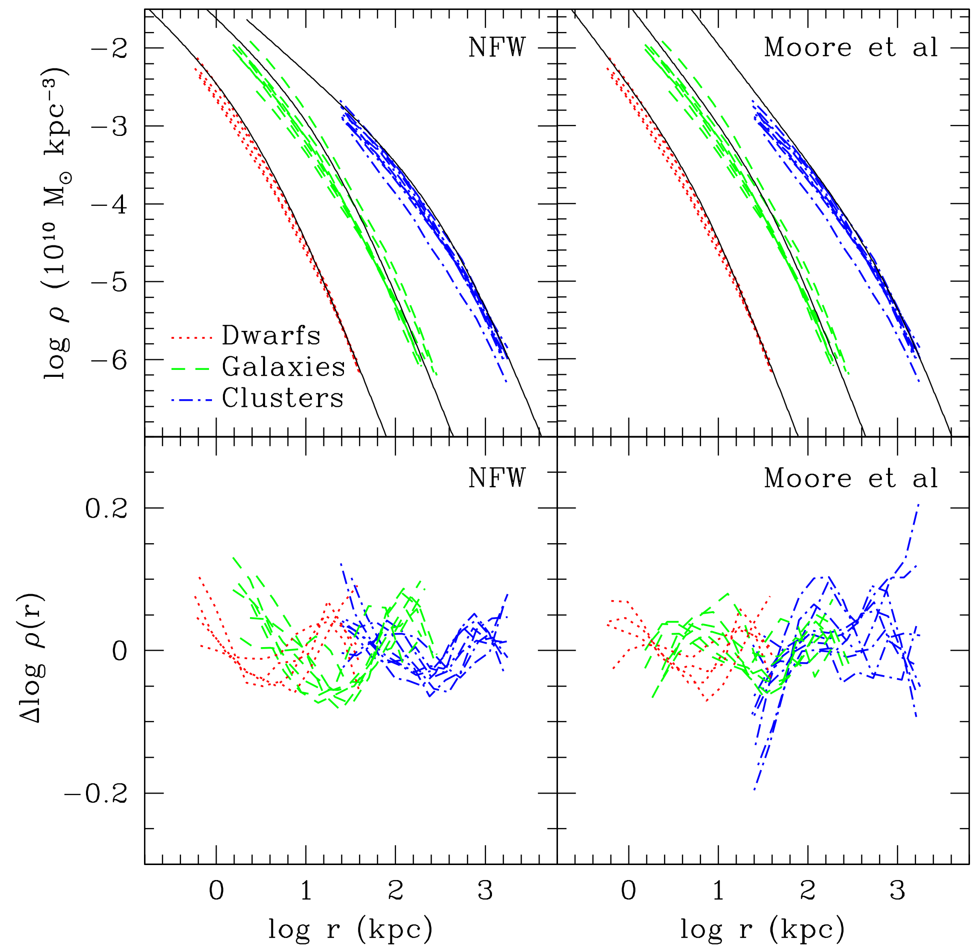
$$\rho_{\rm cdm}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

  - Moore 99 profile:

$$\rho_{\rm cdm}(r) = \frac{\rho_0}{(r/r_0)^{1.5}(1+r/r_0)^{1.5}}$$

- Applicable for

— dwarfs, $\sim 10^{11} M_\odot$
— galaxies, $\sim 10^{12} M_\odot$
— galaxy clusters, $\gtrsim 10^{14} M_\odot$



[Navarro *et al.* '04]

Clustering in NFW halos

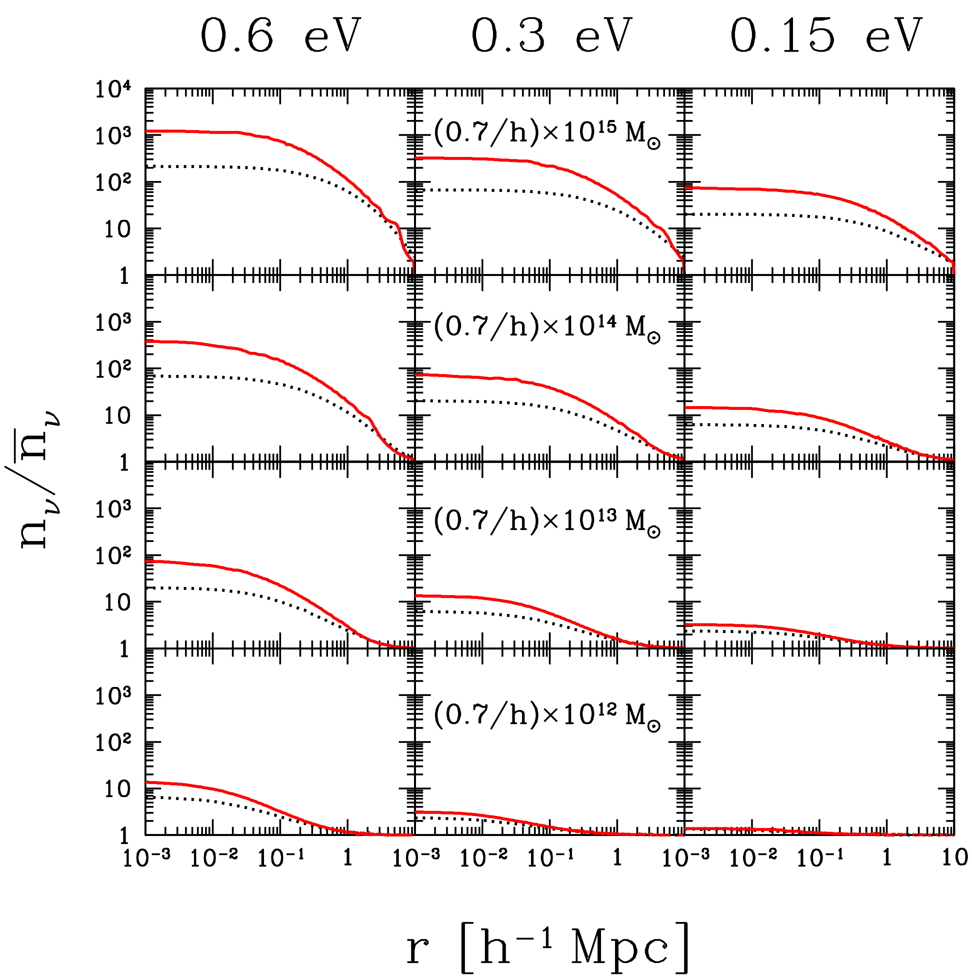
- $\{\Omega_\Lambda, \Omega_m, h\} = \{0.7, 0.3, 0.7\}$
- Neutrino free-streaming

  $\Rightarrow$ $n_\nu/\bar{n}_\nu$ flattens at small r

  $\Rightarrow$ $\rho_\nu/\rho_{\rm cdm} < \bar{\rho}_\nu/\bar{\rho}_{\rm cdm}$
- Overdensity [—]

  $\propto$ $M_{\rm halo}$ for fixed r, m_ν

  $\propto$ $m_\nu^{(1\div 3)}$ for fixed r, $M_{\rm halo}$
- Linear theory [$\cdots$] under-estimates $n_\nu/\bar{n}_\nu$

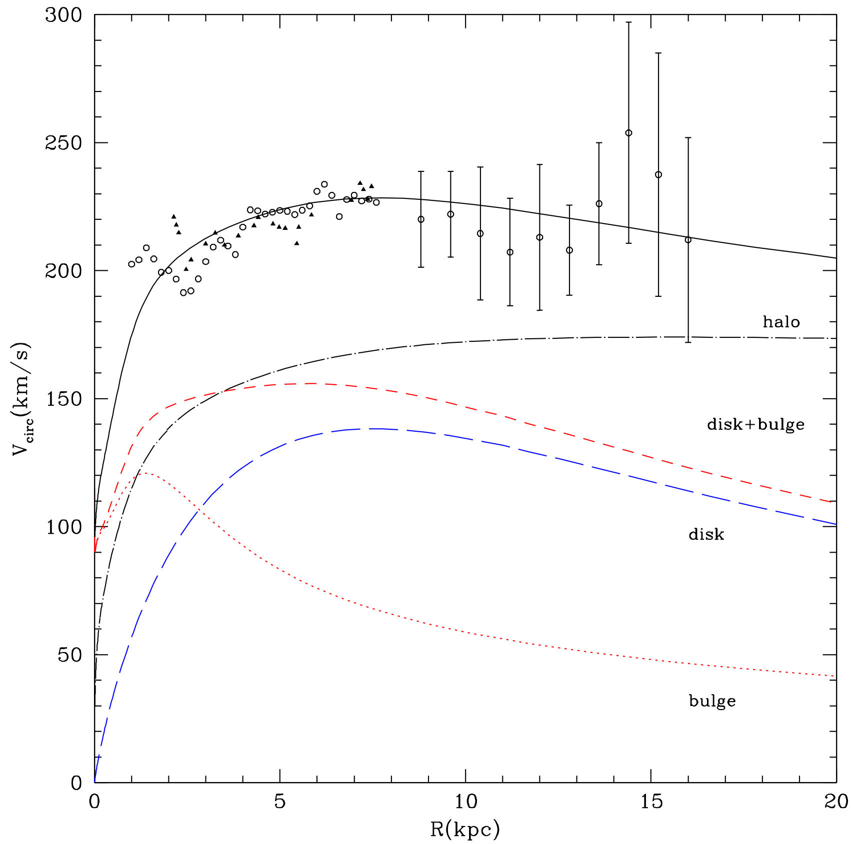


[Ringwald, Y^{3}W '04]

Clustering in the Milky Way

- $r_{\rm earth} \approx 8$ kpc from Galactic Centre
- Baryons dominate central 10 kpc [disk+bulge+bar(?)]
  - use mass distribution inferred from observations; MW mass models
- ν overdensity at $r_{\rm earth}$:

	$n_\nu/\bar{n}_\nu$
$m_\nu = 0.6$ eV	20
$m_\nu = 0.45$ eV	10
$m_\nu = 0.3$ eV	4.4
$m_\nu = 0.15$ eV	1.6



[Klypin, Zhao, Somerville '02]

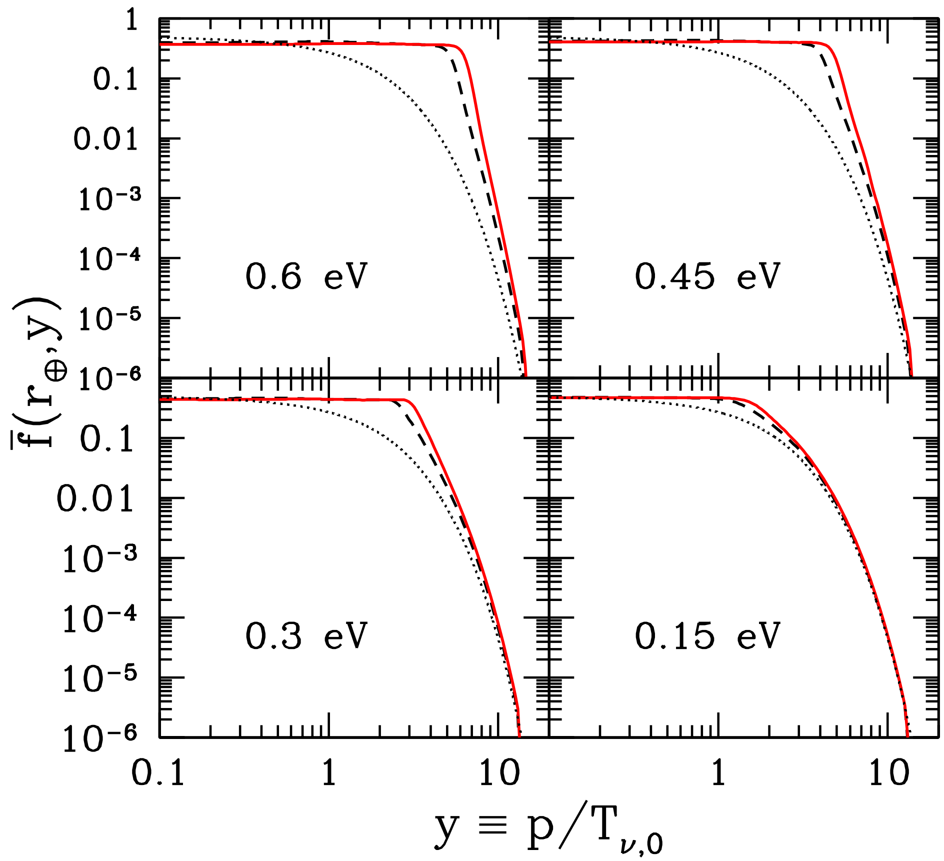
- Momentum distribution at $r_{\rm earth}$ almost isotropic:
  $\langle p_r \rangle \simeq 0, \quad 2\langle p_r^2 \rangle \simeq \langle p_T^2 \rangle$

- Semi-degenerate $\bar{f}$ [—] at low momenta; turning point at $p_{\rm esc} \equiv m_\nu v_{\rm esc} = m_\nu \sqrt{2|\phi(r_{\rm earth})|}$

- Matches Fermi–Dirac [$\cdots$] at high momenta

- Tremaine–Gunn bound:
  $\bar{f} \leq \max(f_{\rm initial}) = 1/2$ (FD)

$\Rightarrow$ highest overdensity possible given m_ν



[Ringwald, Y^3W '04]

Implications for direct detection: fully earthbound

- Flux detection: de Broglie $\lambda_\nu \sim 0.1$ cm $\Rightarrow$ coherent scattering over $V \sim \lambda_\nu^3$ $\Rightarrow$ mechanical force [e.g., Shvartsman *et al.* '82, Smith, Lewin '83]

$$\text{acceleration}, a_t \simeq \overbrace{\frac{N_{AV}}{A}}^{\text{coherent}} \rho_t V \sum_{\nu,\bar{\nu}} \underbrace{n_\nu v_\nu}_{\text{flux}} N_{AV} A \overbrace{\sigma_{\nu N}}^{G_F^2 m_\nu^2/\pi} \underbrace{m_\nu v_\nu}_{\text{mom.transfer}}$$

  - most optimistic $[m_\nu \simeq 0.6 \text{ eV}, \; n_\nu/\bar{n}_\nu \simeq 20]$, $a_t \sim 10^{-26}$ cm s^{-2} [measurable now: $\gtrsim 10^{-13}$ cm s^{-2}; next decade (?): $\gtrsim 10^{-23}$ cm s^{-2}]
  - outlook: 30 to 40 years [P.F.Smith '03] [Hagmann '99]

- Fine print
  - Dirac vs Majorana, extra factor $v_\nu/c \sim 10^{-3}$ for ν_M
  - solar ν, $a_t \sim 10^{-27}$ cm s^{-2}; directionality?
  - WIMPs, $\sigma_{\chi N} \lesssim 10^{-45}$ cm^2 [Duda, Gelmini, Nussinov '01]

Implications for direct detection: with cosmic rays

- Resonant annihilation of Extremely Energetic ($\gtrsim 10^{21}$ eV) Cosmic ν on CνB:

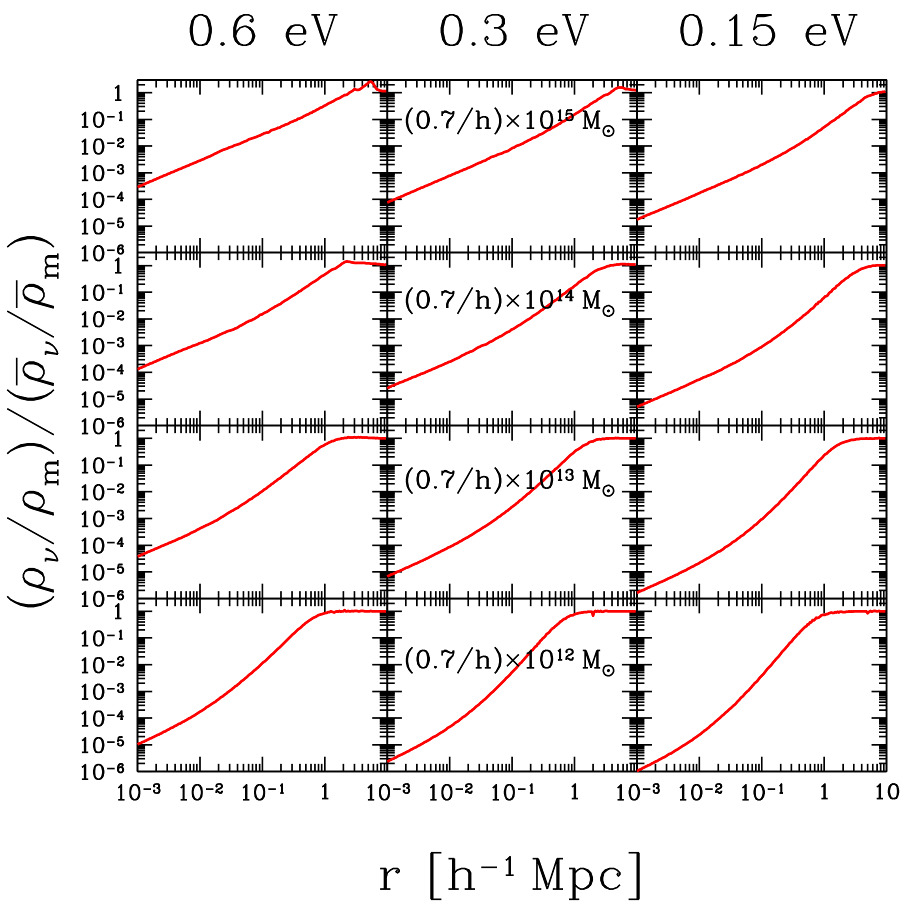
$$\nu_{\rm EEC\nu} + \bar{\nu}_{\rm C\nu B} \rightarrow Z^0 \rightarrow \text{hadrons}$$

1. absorption dips in EECν flux $\Rightarrow$ B. Eberle's talk [V.7, 16:30, Rm 3a]
2. emission features, Z decay products [cf. "Z-burst" for UHECR]

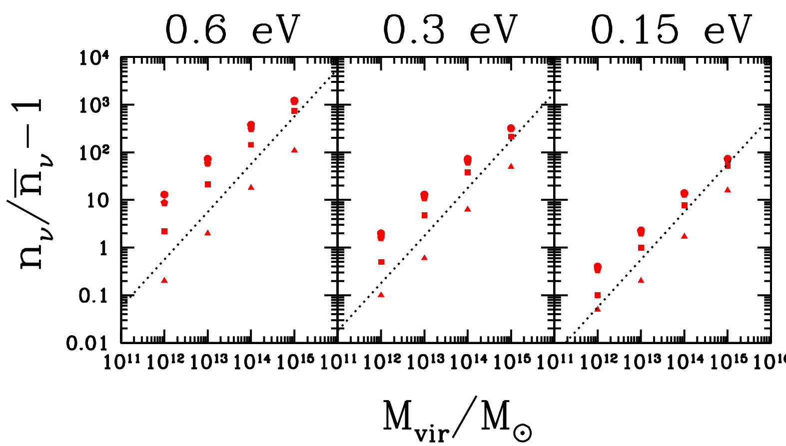
- Emission spectroscopy
  - galaxy clusters in local universe ($\lesssim 50$ Mpc) $\Rightarrow$ directional dependence in $E \gtrsim E_{\rm GZK} \sim 4 \times 10^{19}$ eV events
  - e.g., Virgo cluster, distance ~ 15 Mpc, mass $\sim 10^{15}\ M_\odot$:
    * $m_\nu = 0.6$ eV, $n_\nu/\bar{n}_\nu \sim 1000 \Rightarrow \sim 55$ times the unclustered rate
    * $m_\nu = 0.15$ eV, $n_\nu/\bar{n}_\nu \sim 60 \Rightarrow \sim 8$ times the unclustered rate
  - Auger, EUSO, OWL??

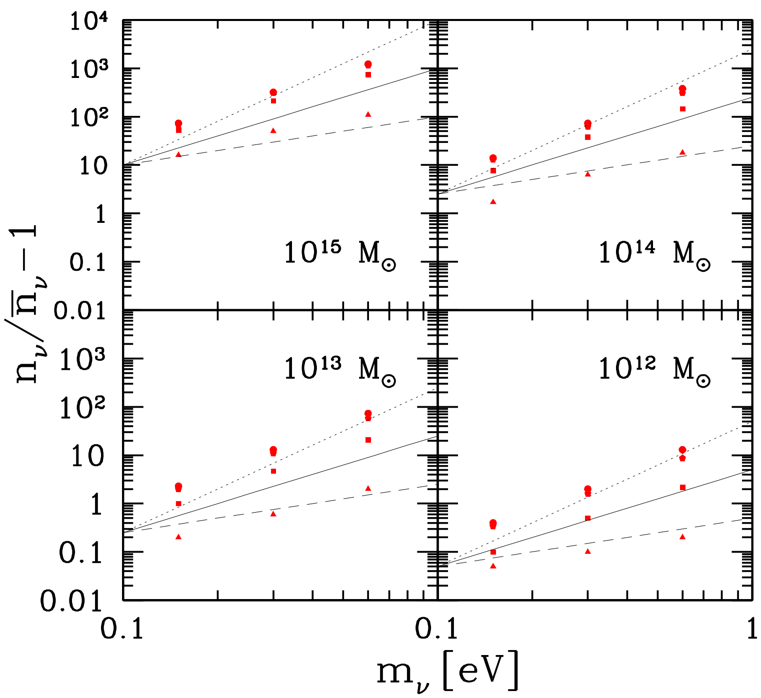
Summary

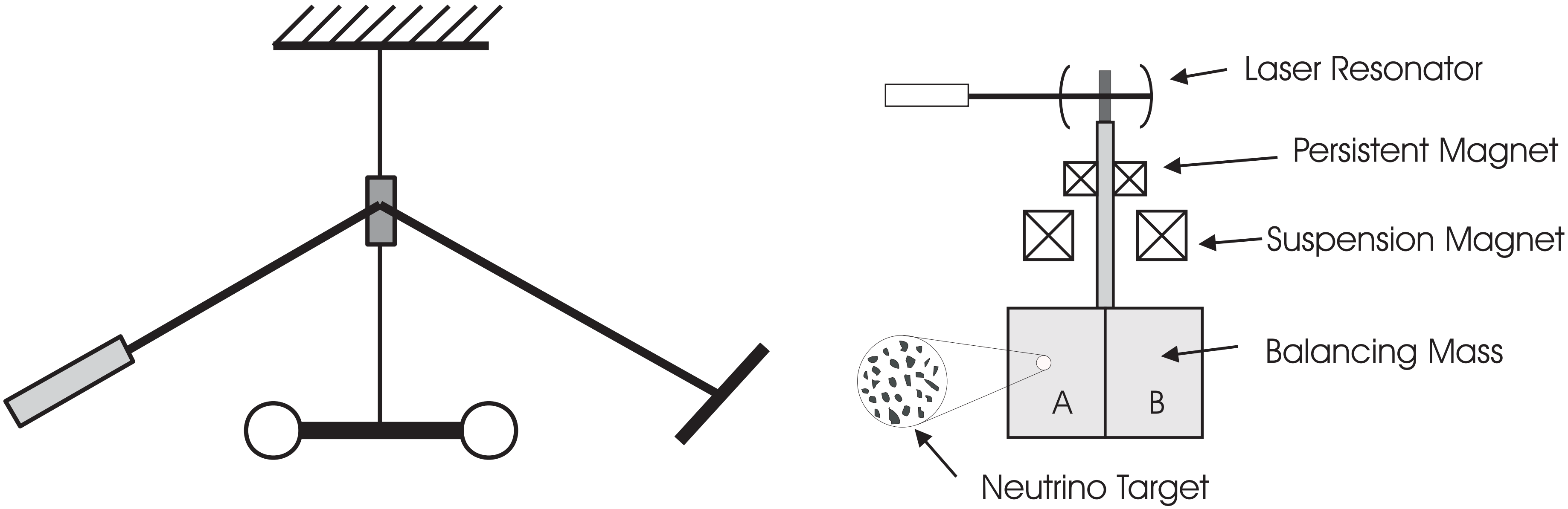
- Neutrino mass $\Rightarrow$ gravitational clustering on existing structures
- Direct detection of CνB: not for another 30 to 40 years
- Detection with cosmic rays
  - absorption spectroscopy: possibly next decade, if conditions are right
  - emission spectroscopy: ??



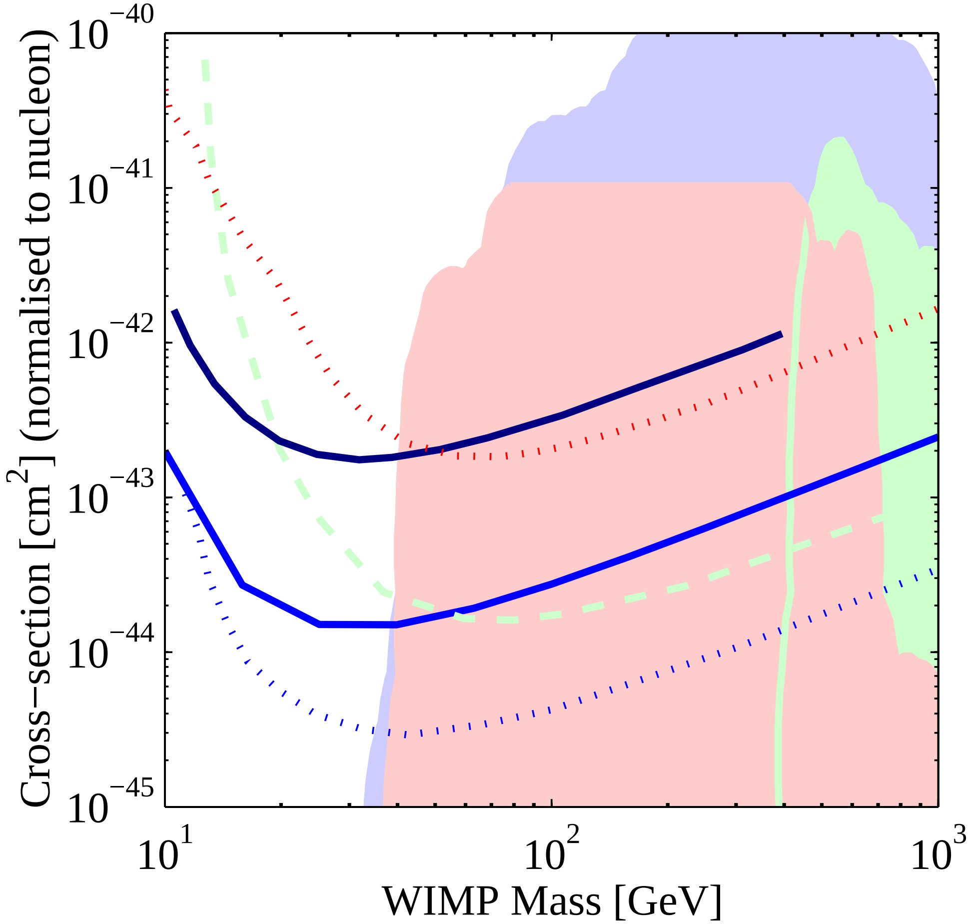
[Ringwald, Y^3W '04]






Laser Resonator
Persistent Magnet
Suspension Magnet
Balancing Mass
A
B
Neutrino Target

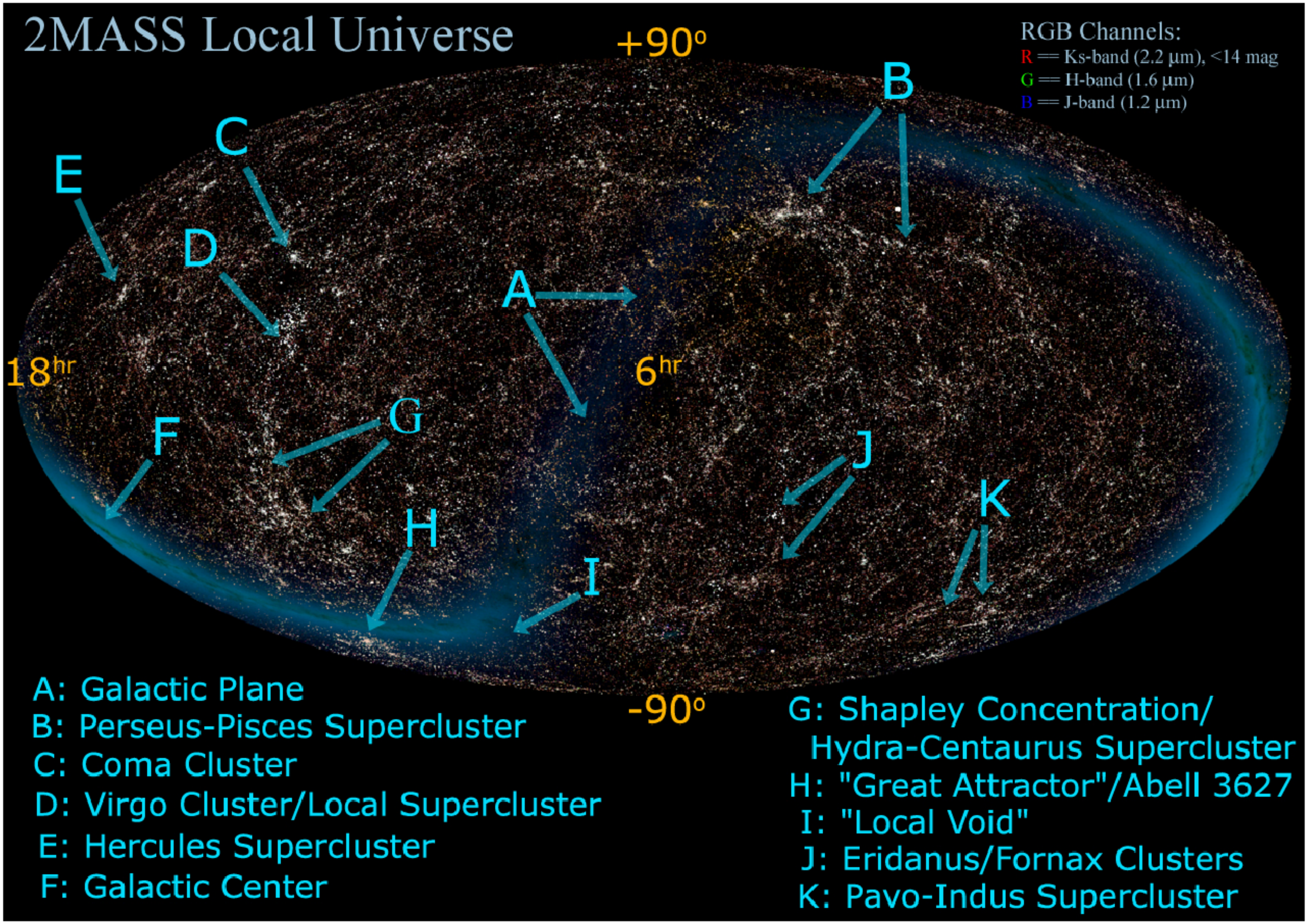
[Hagmann ‘99]



Future DM direct searches

- GENIUS
- CRESST-II
- CDMS-Soudan
- Edelweiss-II
- ZEPLIN-MAX

[Bertone, Hooper, Silk '04]


2MASS Local Universe
+90°
RGB Channels:
R == Ks-band (2.2 μm), <14 mag
G == H-band (1.6 μm)
B == J-band (1.2 μm)
B
C
E
D
A
18hr
6hr
G
F
J
K
H
I
-90°
A: Galactic Plane
B: Perseus-Pisces Supercluster
C: Coma Cluster
D: Virgo Cluster/Local Supercluster
E: Hercules Supercluster
F: Galactic Center
G: Shapley Concentration/
Hydra-Centaurus Supercluster
H: "Great Attractor"/Abell 3627
I: "Local Void"
J: Eridanus/Fornax Clusters
K: Pavo-Indus Supercluster