DEPARTAMENTO DE ASTRONOMIA
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A MATÉRIA ESCURA NO CENTRO DOS AGLOMERADOS DE GALÁXIAS: MOND E NEUTRINOS

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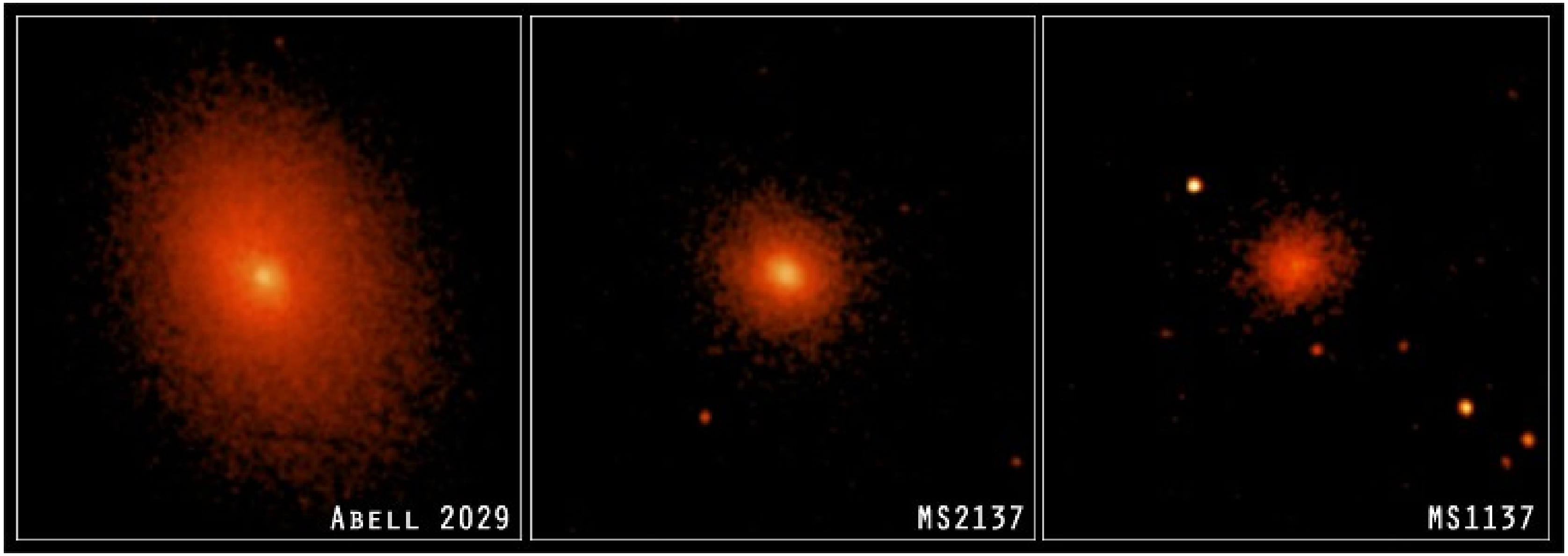
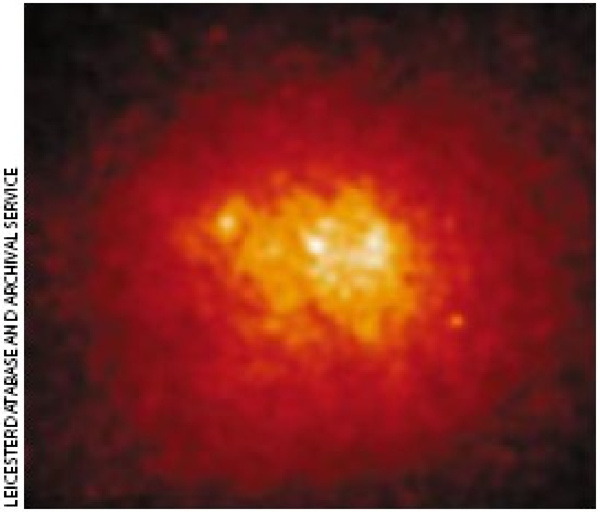
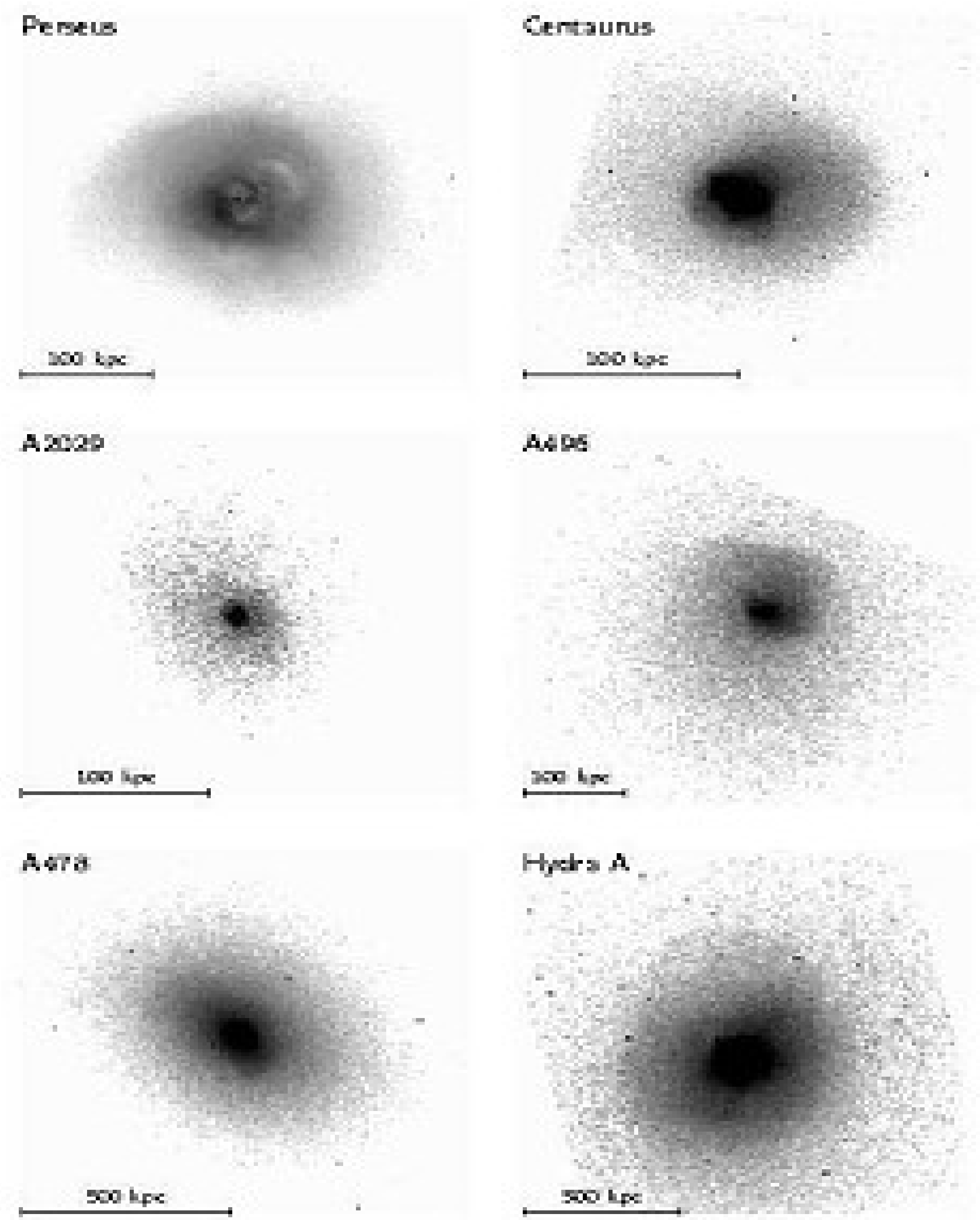
Plano

- **Aglomerados de galáxias – motivação**
- **Perfil radial de massa**
  - Descrições alternativas
- **MOND** (Gravitação Newtoniana Modificada)
  - Aglomerados: problemas
- **Neutrinos massivos**
- **MOND + neutrinos**
  - Aglomerados
- **Conclusões**

Aglomerados de Galáxias







Desde Zwicky .....

Situação em 1988 ....☹

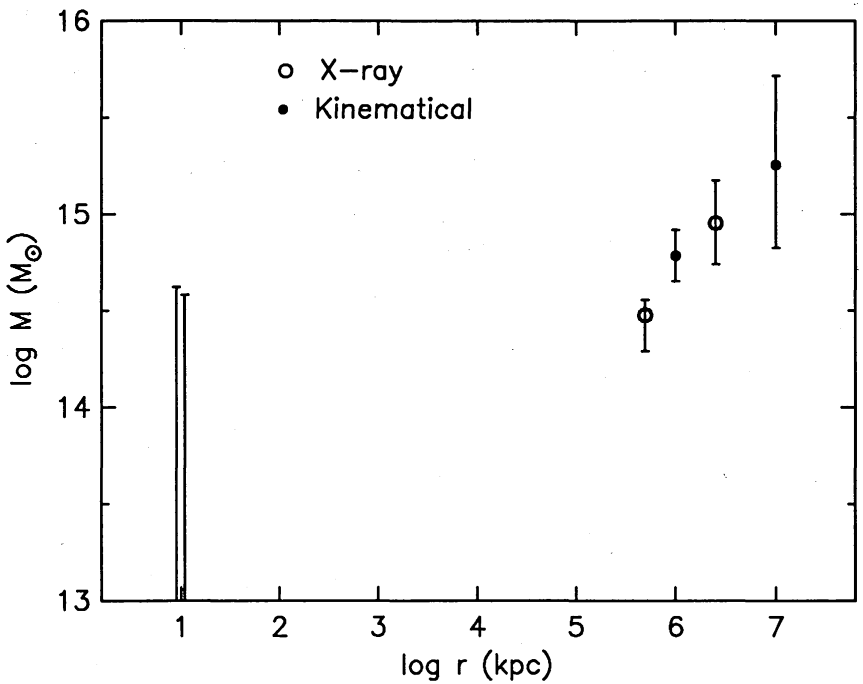


Fig. 3 Constraints on the mass distribution in Coma derived from kinematical and X–ray techniques ($h = 1$).

z = 0.0232

DARK MATTER: BOUND TO GALAXIES OR SMOOTHLY DISTRIBUTED?

Given that the total masses of clusters like Coma greatly exceed their luminous masses—although by amounts that are still fairly uncertain—it is natural to wonder whether the dark matter is bound to the bright galaxies (in the

Fonte: Merrit, ASPC (1988)

Hoje

Fonte: Lewis et al (2003)

A2029, z=0.0767

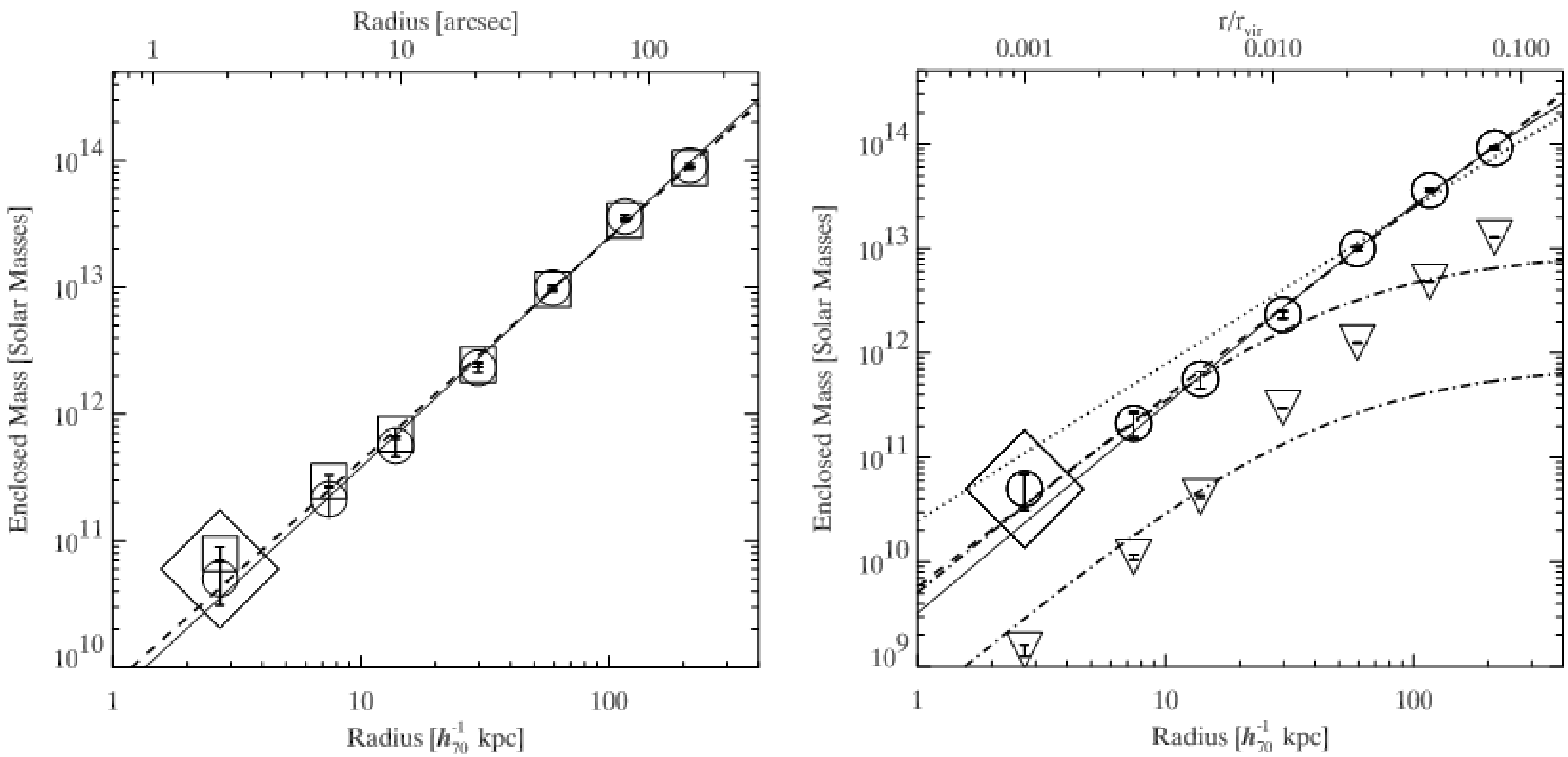
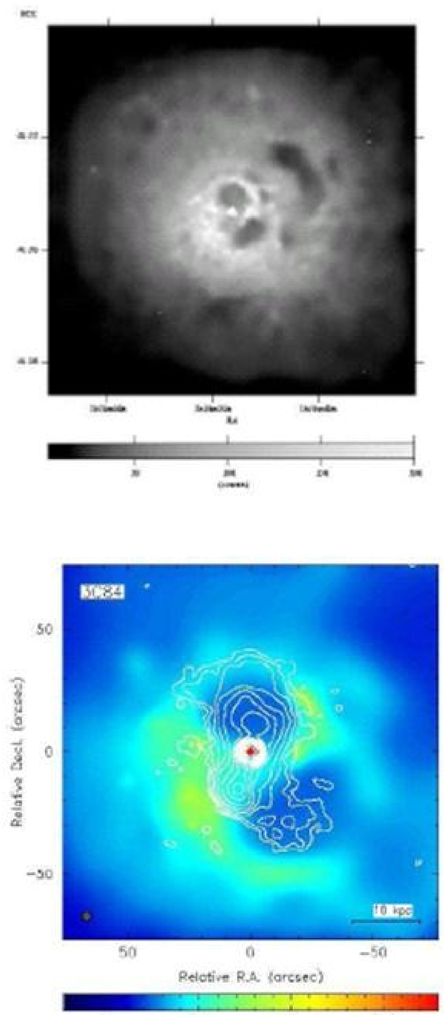
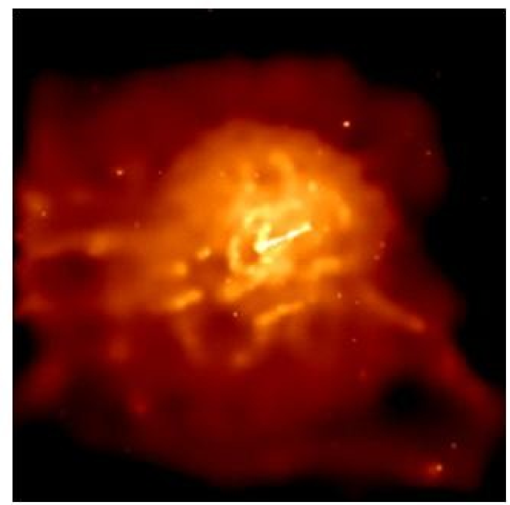


FIG. 2.—*Left*: Total enclosed cluster mass, obtained from the BM86 fit (*open circles*) and the power-law fit (*open squares*) to the temperature data. The cusp model for ρ_g was used in both cases. Power-law fits to the mass points are overlaid on both data sets (*solid line*: BM86 T_g model; *dashed line*: power-law T_g model). We have used large open symbols to identify the data points, as some of the error bars are barely visible in this logarithmic plot. The first data points are also enclosed with a large open diamond to emphasize the large additional systematic uncertainty at this radius (see §§ 3.2 and 3.4). *Right*: Total enclosed cluster mass (data points enclosed with open circles), overlaid with three different mass models: NFW97 (*solid curve*), power-law (*dashed line*), and M99 (*dotted curve*). The total enclosed gas mass is plotted as data points enclosed with open triangles. We have also overlaid an estimate of the stellar mass (*dot-dashed curves*; see § 5.1). The bottom curve assumes a M_*/L_V of 1; the top curve assumes a M_*/L_V of 12. [*See the electronic edition of the Journal for a color version of this figure.*]

\+ Simulações: Fausti Neto et al., MNRAS (2007)

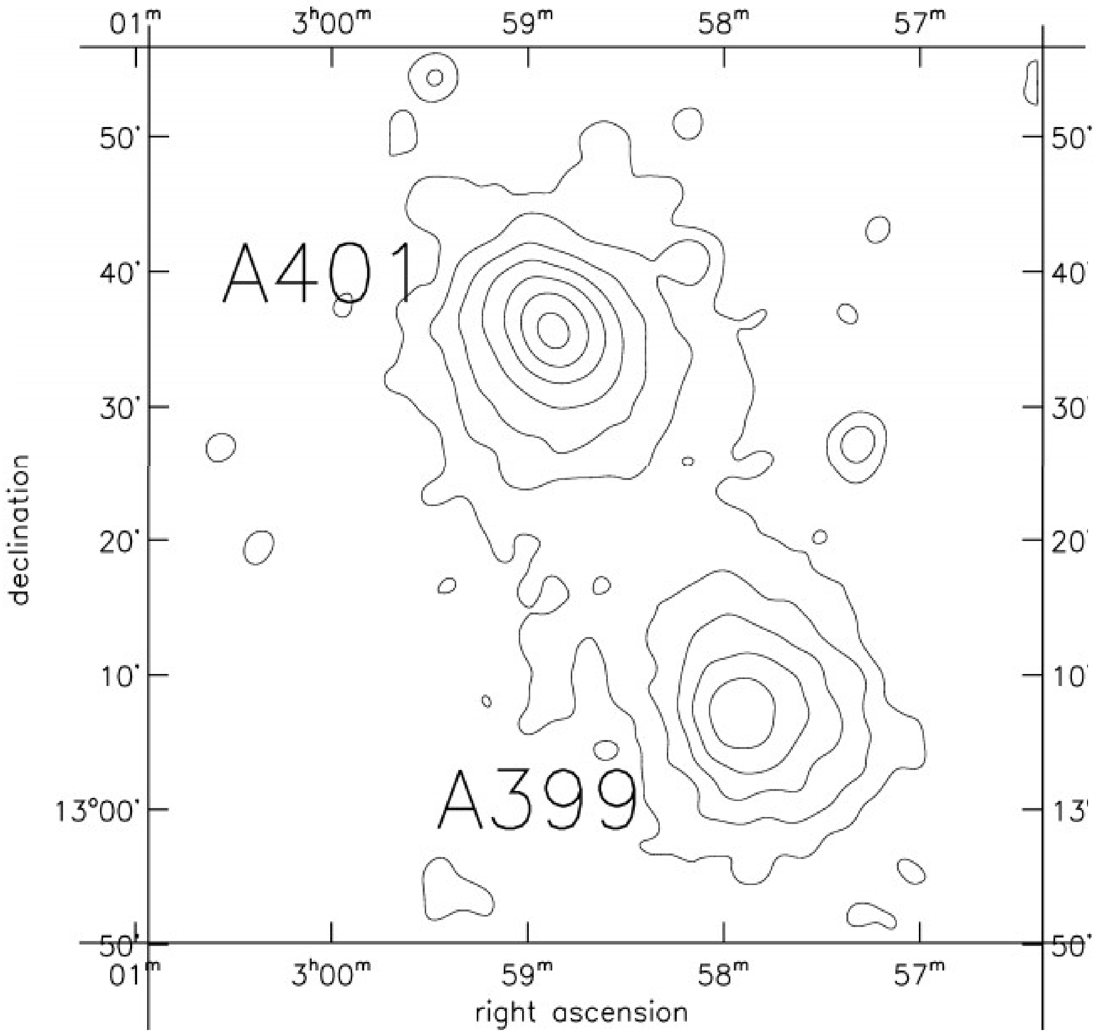
Complexidade central ...

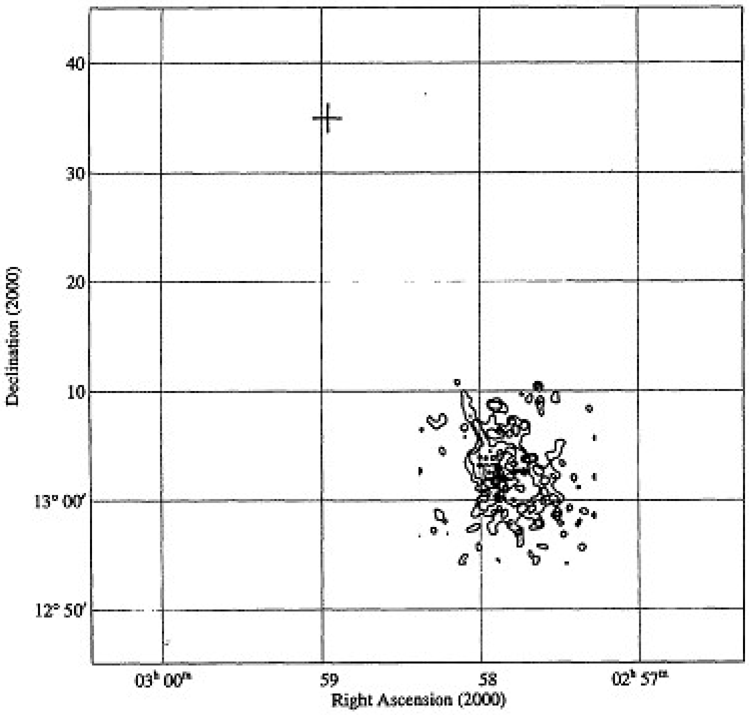




Virgo

A426

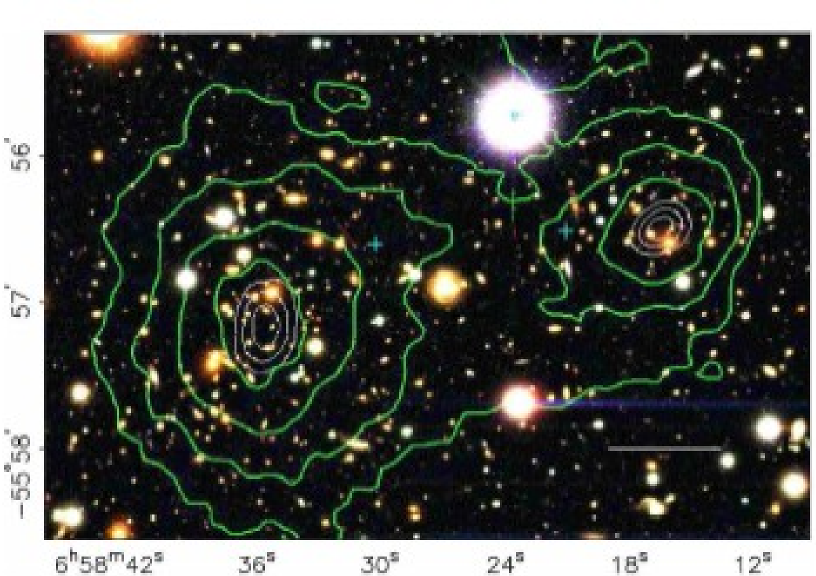


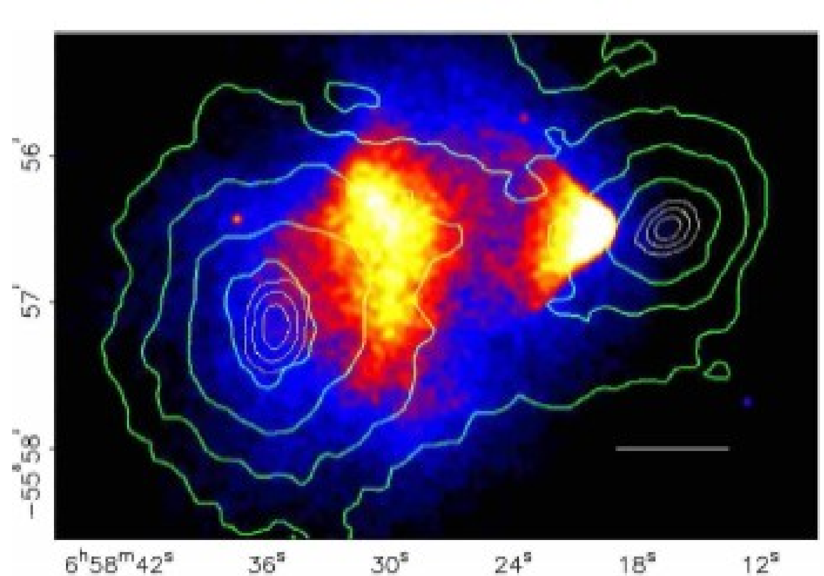


A399 e A401

Nevalainen et al, ApJ 1999
Fabian, Peres e White, MNRAS 1997

The Bullet Cluster





1E0657−58

Weak lensing + Raio-X

Fonte: Clowe et al., ApJ (2007)

Exotica x Não-exótica

Avanços (Nova Física...) em muitas frentes

1. Espectroscopia Multifibra
2. Telescópios Raio-X
3. Simulações: *Hierarchical Clustering*
4. Estudos Semi-analíticos
5. Lentes Gravitacionais

Perfil radial de DM: M(<r)

Distribuição radial de massa

Distribuição Radial de DM

- Via Raio-X: Equilíbrio Hidrostático

$$M(r) = -\frac{k_B T_g}{\mu m_p G} . r . \left(\frac{d \ln \rho_g}{d \ln r} + \frac{d \ln T_g}{d \ln r} \right)$$

- Ajuste de modelo pré-definido (*Fitting*)

- Deprojeção (espacial+espectral)

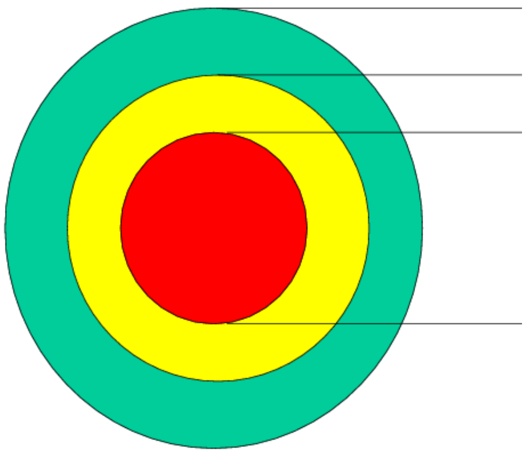
Modelos paramétricos

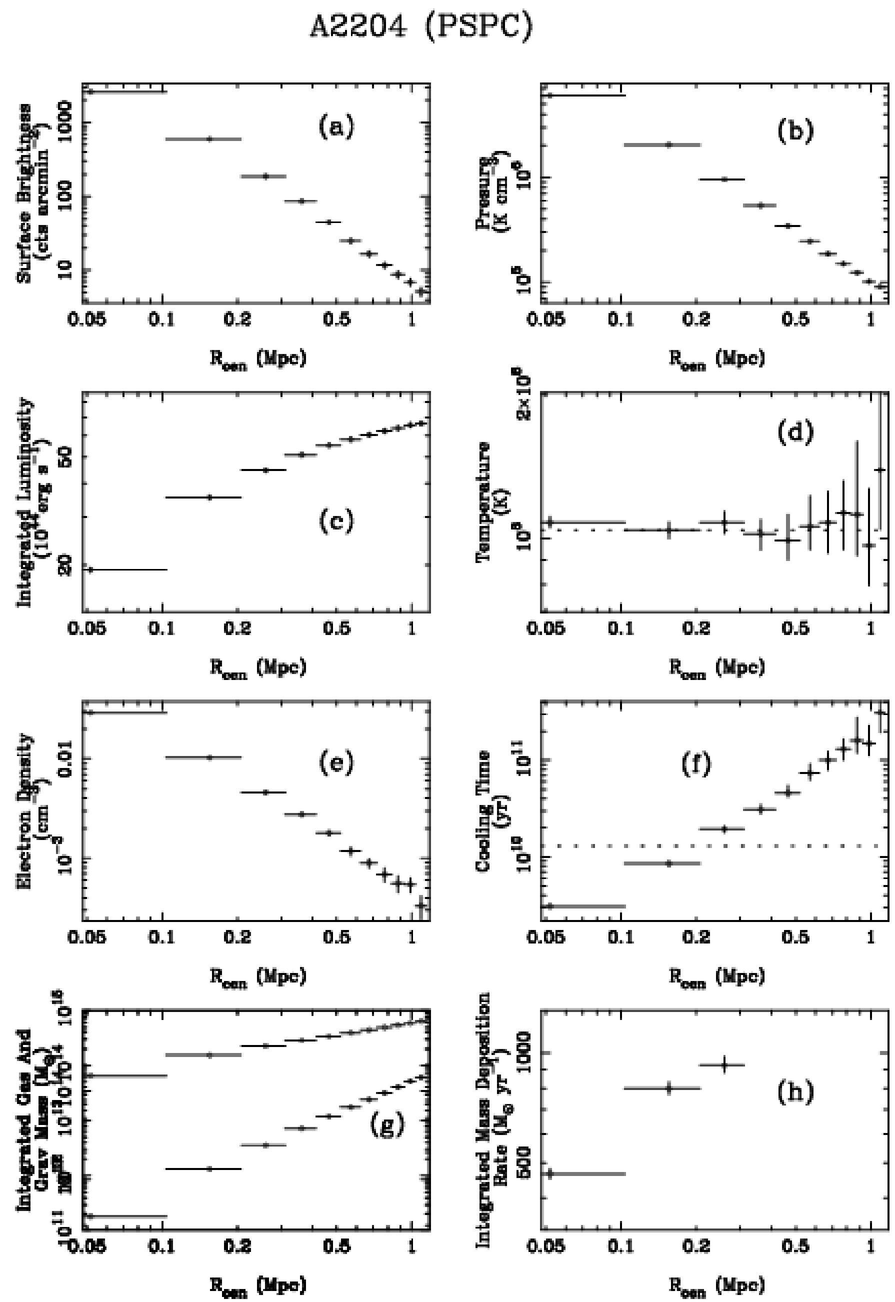
NFW

$$\rho = \rho_0 \cdot \frac{1}{x.(1+x)^2}$$

$$M(r) = 4\pi\rho_0.r_s.\left[\ln(1+x) - \frac{x}{1+x}\right]$$

Deprojeção





Fonte: Peres et al., MNRAS (1998)

Paradigma da Matéria Escura (DM)

The great majority of astronomers now believe that the universe is dominated by cold, collisionless, non-baryonic dark matter. But despite more than 20 years of intense effort, no non-gravitational evidence for dark matter has ever been found:

no direct detection of dark matter, **no annihilation radiation** from it, **no evidence from reactor experiments** supporting the physics (beyond the standard model) upon which dark matter candidates are based.

We know nothing about dark matter, except for the properties that we have attributed to it, and also that it is not enough: we need to postulate an even more mysterious "dark energy" to supplement it.

Aguirre, Julho 2004

MOND

Equação de Poisson

$$\vec{\nabla}\left(\mu\vec{\nabla}\phi\right) = 4\pi G\rho$$

Para problemas com simetria esférica:

$$g.\mu\left(\frac{g}{a_0}\right) = g_N$$

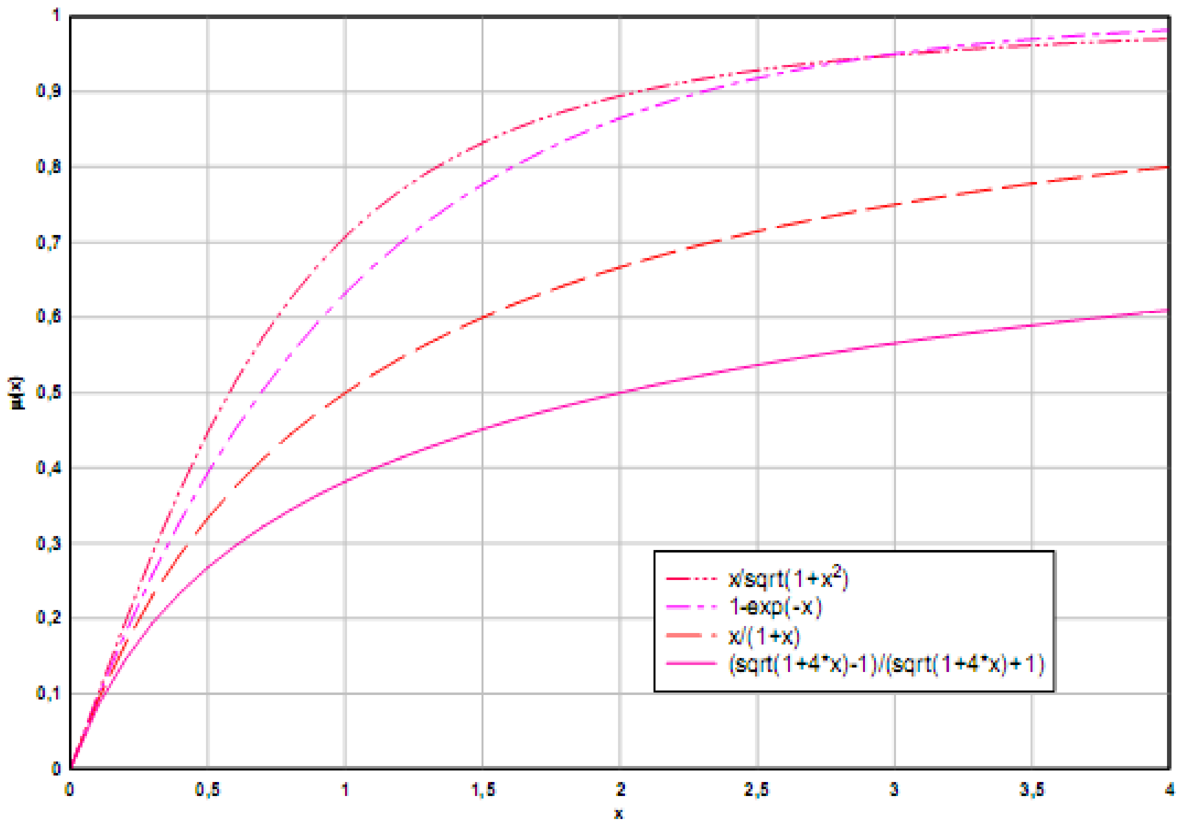
μ(x)

$$\mu(x) = \frac{x}{1+x}$$

$$\mu(x) = \frac{x}{\sqrt{1+x^2}}$$

$$\mu(x) = \frac{\sqrt{1+4x}-1}{\sqrt{1+4x}+1}$$

$$\mu(x) = 1 - exp(-x)$$



Extremos ...

$$\mu\left(\frac{a}{a_0}\right) \approx \begin{cases} 1 & \text{se } a \gg a_0, \\ a/a_0 & \text{se } a \ll a_0. \end{cases}$$

$$\boxed{g = \sqrt{g_N . a_0}}$$

Medindo a massa: Newton e MOND

$$g = \frac{GM_N}{r^2}$$

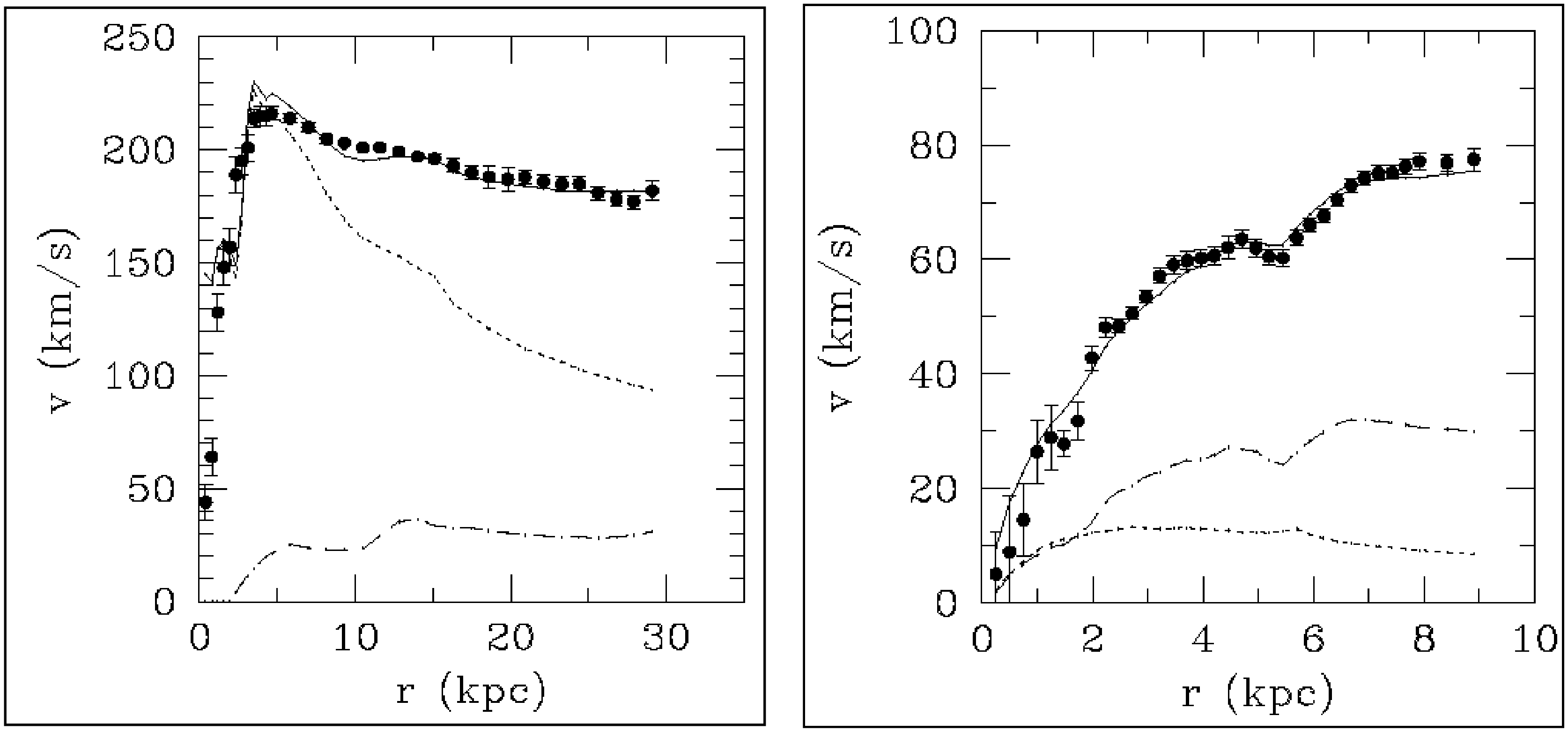
$$g.\mu\left(\frac{g}{a_0}\right) = \frac{GM_M}{r^2}$$

$$\mu = \frac{M_M}{M_N}$$

OBS: $g_N \equiv GM/r^2$ $$g = \frac{GM_N}{r^2}$$

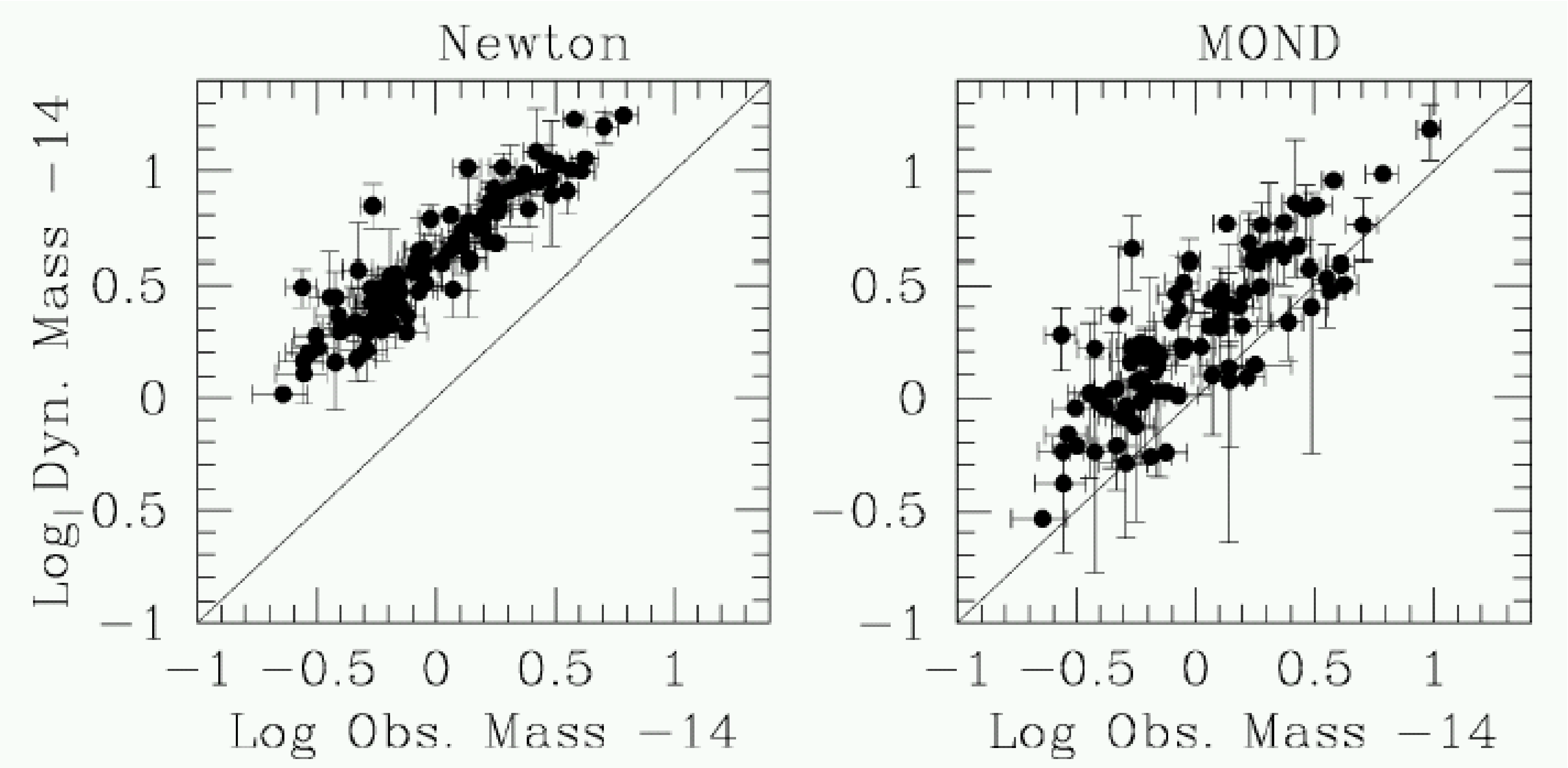
Galáxias - MOND

$a_0 \approx 1.2 \times 10^{-8}$ cm.s^{-2} Begeman (1992)



Fonte: Merrit, ASPC (1988)

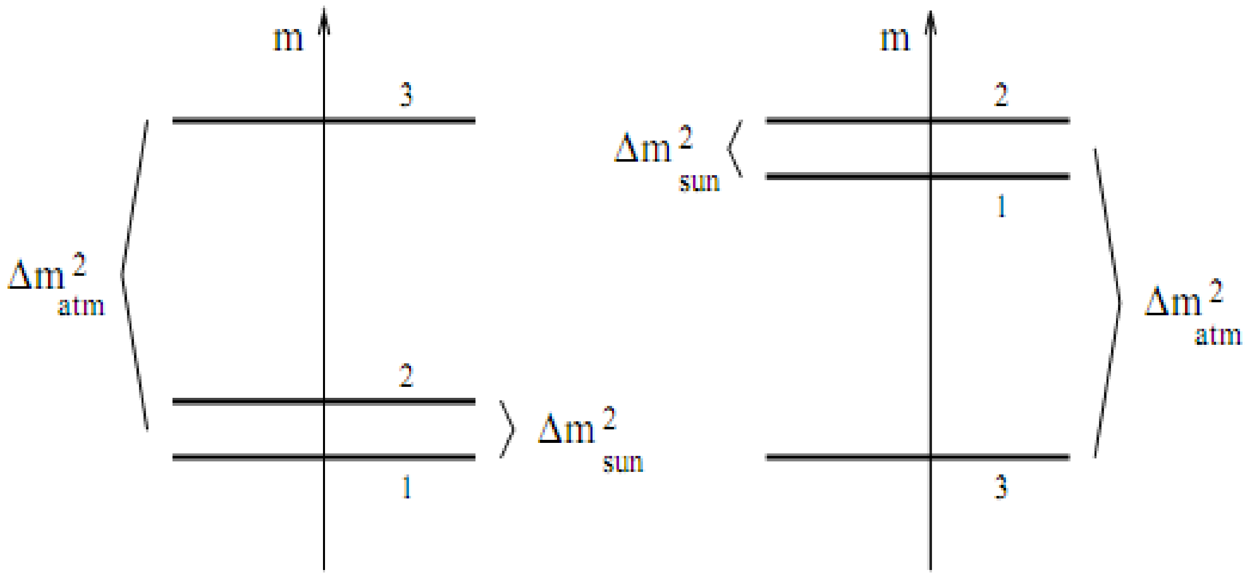
MOND em Aglomerados



Fonte: Sanders, 2003

Neutrinos massivos

Hierarquia de massas



NORMAL INVERTIDA

$$L_{osc} \sim 2\pi \frac{2 < E >}{|m_1^2 - m_2^2|}$$

Limites: CMB + LSS

Limite ($M_\nu <$)	Origem dos Dados
10.6	WMAP1
2.0	WMAP1
2.0	WMAP3
2.1	WMAP1, VSA, ACBAR & CBI
1.6	WMAP1, VSA, ACBAR & CBI
3.1	WMAP1, BOOMERANG03, VSA, ACBAR, CBI, DASI & MAXIMA

Limite	Dados (além do WMAP-1)
1.2	CMB (pre-WMAP), 2dF-gal
1.0	+ HST, SNIa
1.74	SDSS-gal
0.75	CMB (pre-WMAP), 2dF-gal, SDSS-gal, HST
1.0	ACBAR, 2dF-gal, SDSS-gal
0.6	+ HST, SNIa
0.96	VSA, 2dF-gal
1.54	SDSS-gal, SNIa
1.4	CMB, 2dF-gal, HST, SNIa
1.2	CMB, 2dF-gal, SDSS-gal
1.27	CMB, SDSS-gal
1.16	CMB, 2dF-gal
0.87	WMAP3, 2dF-gal

Limites cosmológicos

- Pioneiros – Cowsik e McClelland (1972 e 73)
- Clássico: Tremaine e Gunn (1979)
- Limites atuais e futuros:
  - Radiação cósmica de fundo (CMB)
  - Estrutura em larga escala (LSS)

<u>Aglomerados de galáxias</u>

- Cowsik e Mclelland
- Tremaine e Gunn
- Treumann, Kull, etc..

Limite de Gunn e Tremaine

$$f(r,p) = (2\pi m_\nu^2 \sigma^2)^{-(3/2)} n(r) exp\left[\frac{-p^2}{2m_\nu^2\sigma^2}\right]$$

$$f(r,p)_{max} = (2\pi)^{-(3/2)} m_\nu^{-4} \sigma^{-3} \rho_\nu$$

$$\rho_{max} = 1\text{x}10^{-28}\left(\frac{m_\nu}{1eV}\right)^4 \left(\frac{T}{\text{k}eV}\right)^{(3/2)} \text{g.cm}^{-3}$$

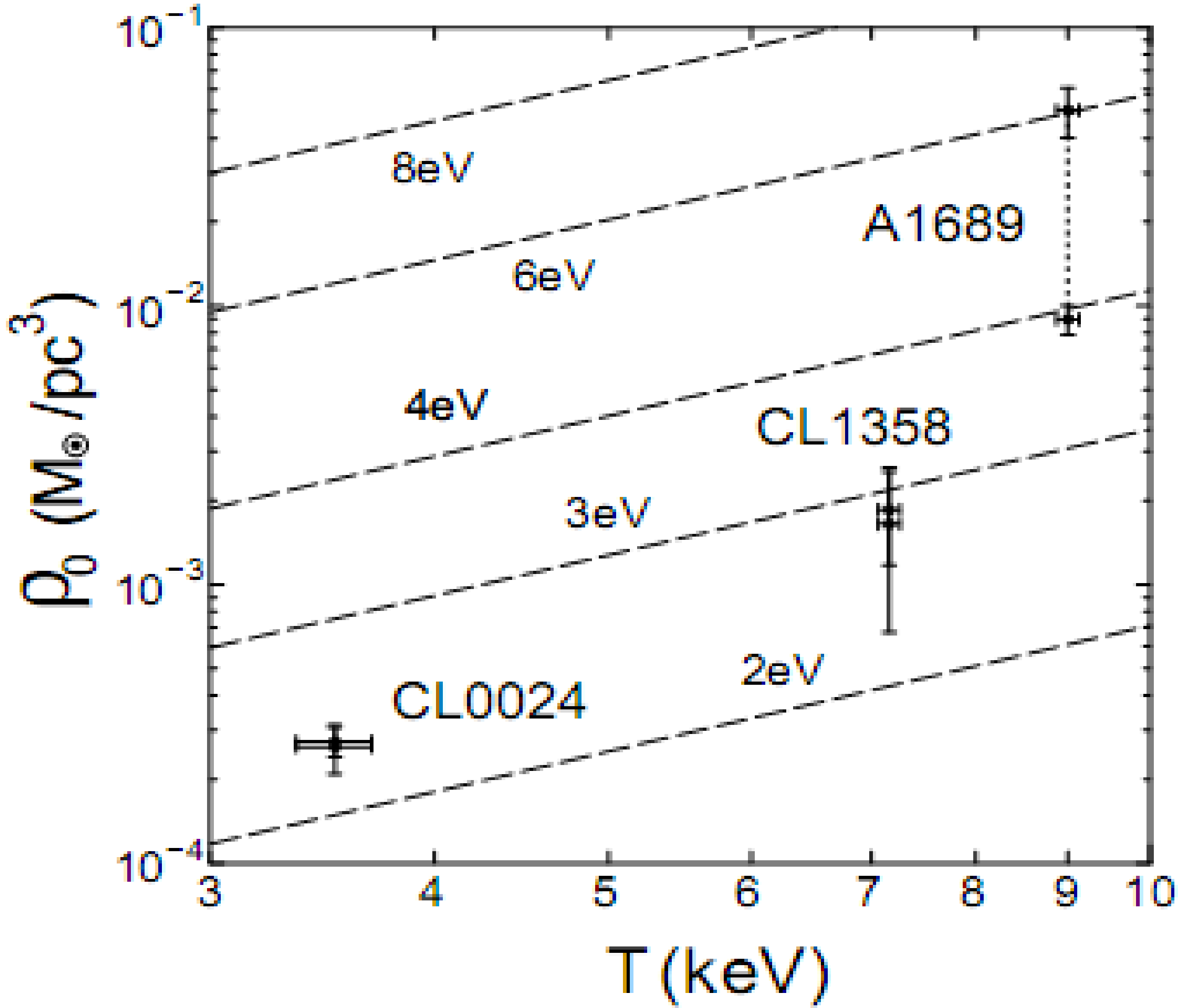
Aglomerados

MOND + neutrinos

MOND + neutrinos

- Proposta de Sanders (2003, 2007)
- “Modelo”:
  - Virialização – Gás e neutrinos
  - Relação de Tremaine e Gunn
  - m ≈ 2 eV
  - Obtenção das relações observáveis: L-T, etc..
  - Disposição em um diagrama: densid. vs temp.:

$$\rho_\nu \leq 2.3 \times 10^{-5} M_\odot \mathrm{pc}^{-3} \left(\frac{m_\nu}{2eV}\right)^4 \left(\frac{T}{keV}\right)^{3/2}$$



Fonte: Takahashi e Chiba 2007

Diagramas DT

- Problemas
  - Amostras? ...Poucos aglomerados
  - Ajustes: Utilização de modelo-beta
  - Lentes: Região muito central (< 100kpc)
  - Virialização incompleta?
  - Fluxos de resfriamento ?

Amostra no Raio-X: B55

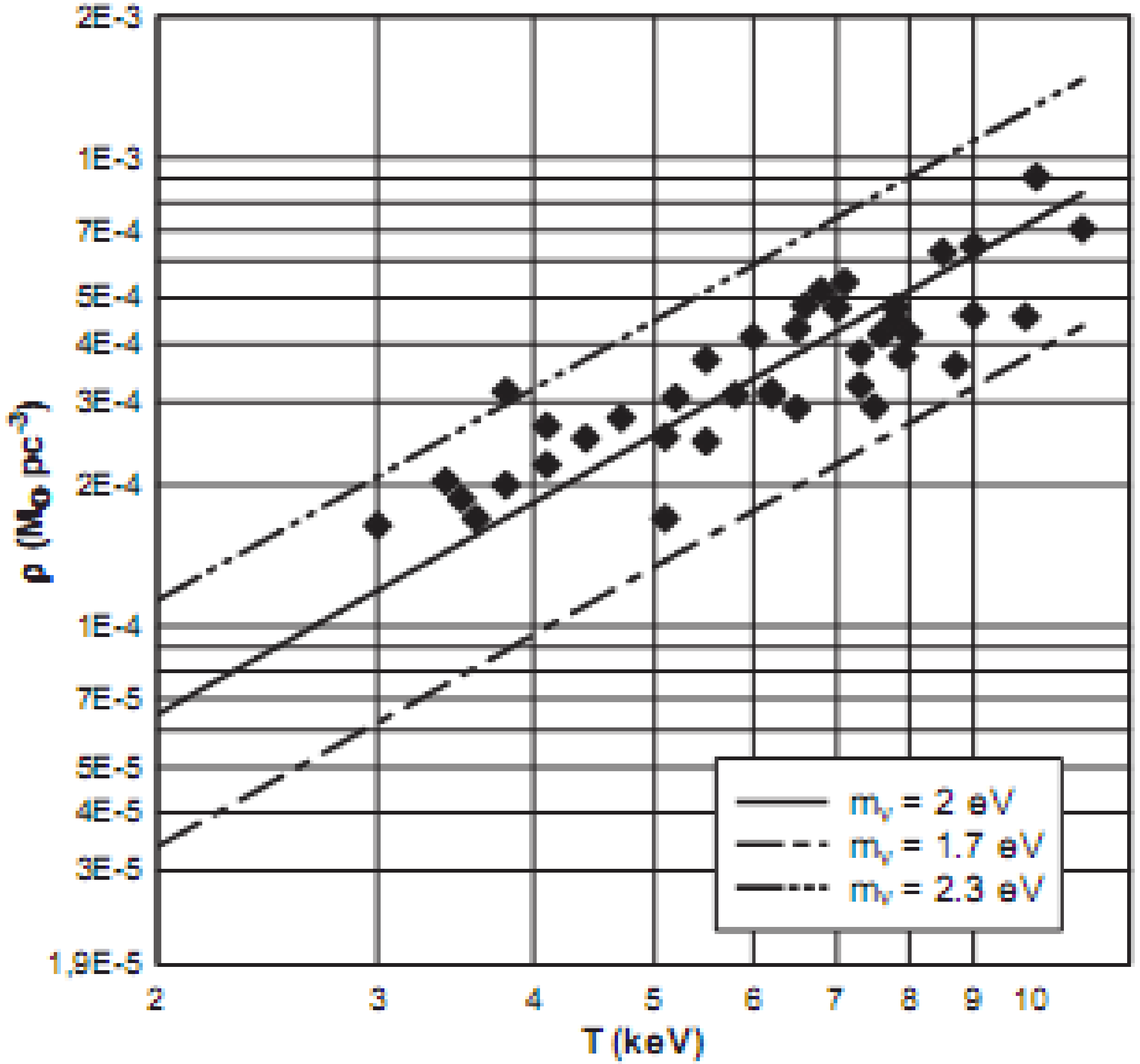
- Os mais brilhantes aglomerados (brightest 55)
- Flux-limited
- Homogênea: ROSAT + análise
- Objetos próximos e bem conhecidos
  - Resolução espacial: 10”
  - Raio pode ser fixado em 500 kpc
- Perfil de massa via deprojeção

Diagrama DT x B55

$$M_\nu = M_{tot} - M_{gas}$$

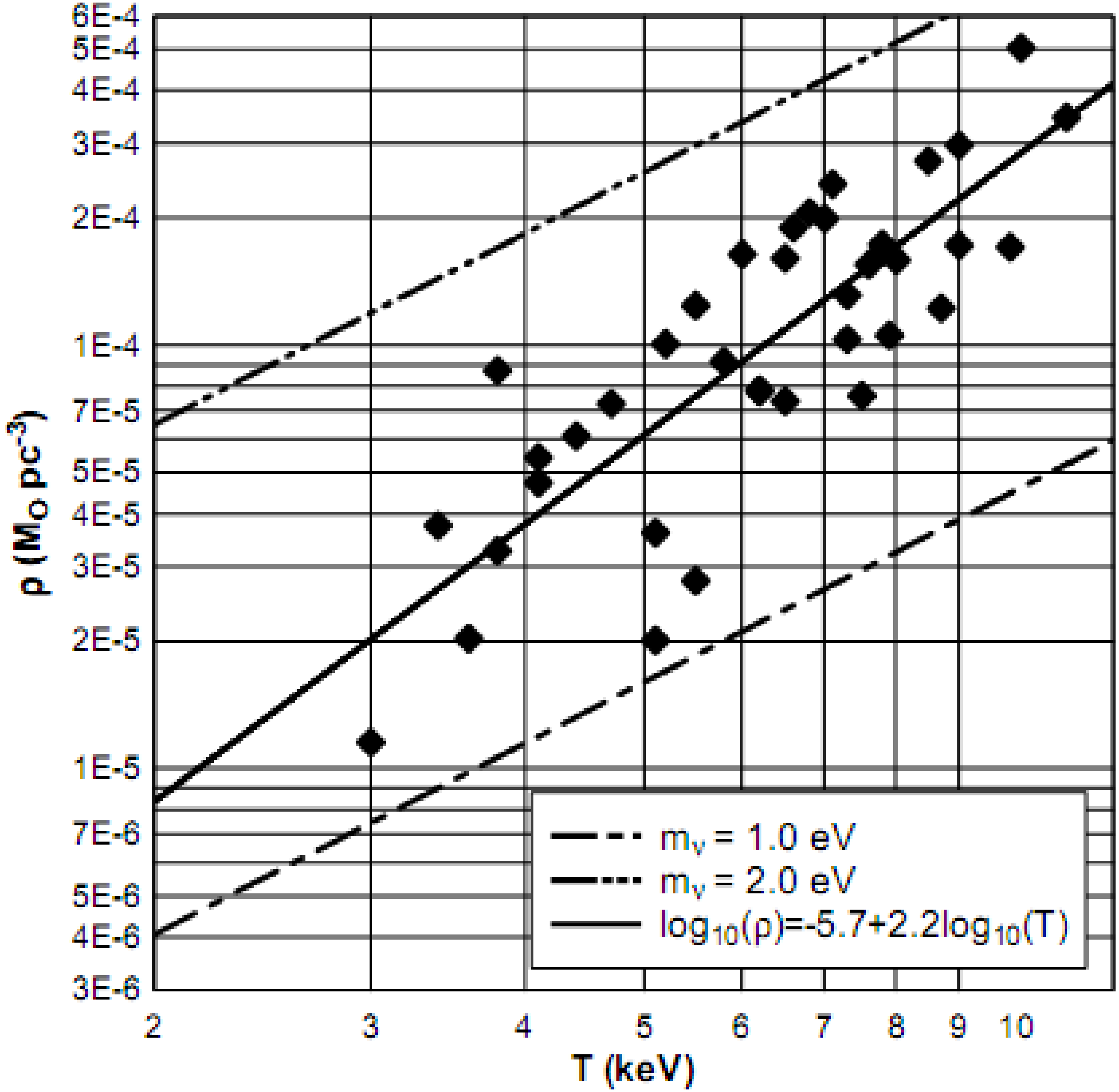
- Raio fixo: 500 kpc
  - Contaminação estelar desprezível
  - Virialização elevada
- Tratamento homogêneo
- Sem ajuste de modelos pré-definidos
- Ampla variação em T
- Sem exceções!
- Newton e MOND

Newton



2E-3
1E-3
7E-4
5E-4
4E-4
3E-4
2E-4
1E-4
7E-5
5E-5
4E-5
3E-5
1,9E-5
2
3
4
5
6
7
8
9
10
T (keV)
ρ ($M_\odot$ pc^{-3})
m_ν = 2 eV
m_ν = 1.7 eV
m_ν = 2.3 eV

MOND



6E-4
5E-4
4E-4
3E-4
2E-4
1E-4
7E-5
5E-5
4E-5
3E-5
2E-5
1E-5
7E-6
5E-6
4E-6
3E-6
ρ (M_O pc^-3)
2
3
4
5
6
7
8
9
10
T (keV)
m_ν = 1.0 eV
m_ν = 2.0 eV
log10(ρ)=-5.7+2.2log10(T)

Raios-X vs Lensing

- Centro: 50 kpc vs 500 kpc

- Amostras Lensing
  - Poucos objetos
  - Objetos distantes: projeção + comp estelar
  - Determinação da temperatura
  - Bias: Aglomerados massivos
  - Complexidade central

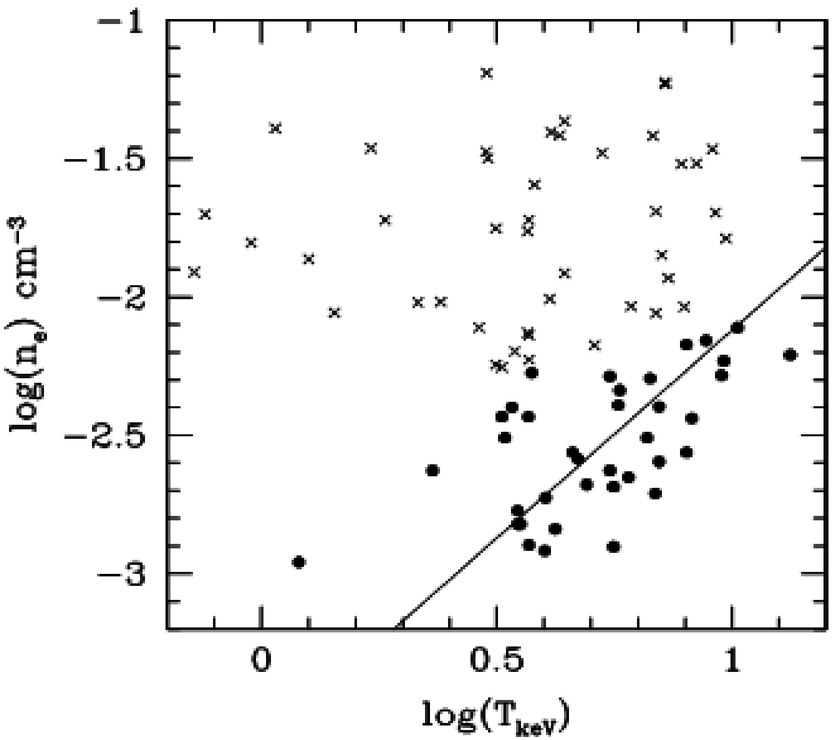
Grupos e aglomerados menores

- Angus et al 2007
  - Amostra pequena
  - Inclusão de grupos ($T \approx 2$ keV)
  - Relação: M-T ? :

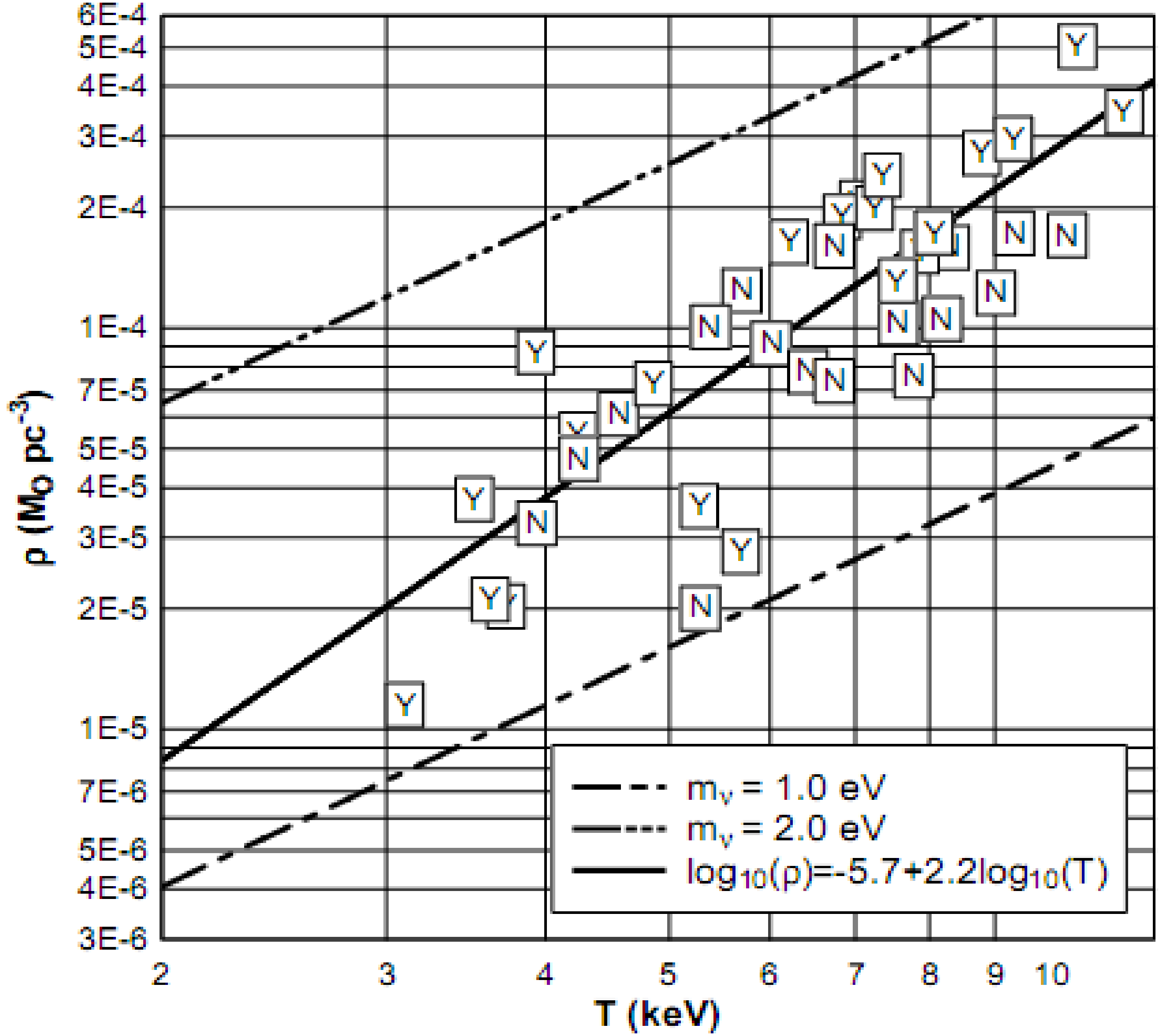
> In Table 1 we list the masses of the different mass components in the sample of clusters, and in Fig. 4 we plot the MOND dynamical mass of the clusters against temperature, which unearths an intriguing correlation of the form $M_m \propto T^{2.3\pm0.1}$, whereas Sanders (2007) predicts a relation of the form $M_m \propto T^2$.
>
> Equally significant, we show in Fig. 6 the total resid-

Cooling Cores?

- Diferença entre Cooling Cores e Non-cooling cores?
- Segregação no diagrama DT?



Fonte: Sanders, MNRAS 2007

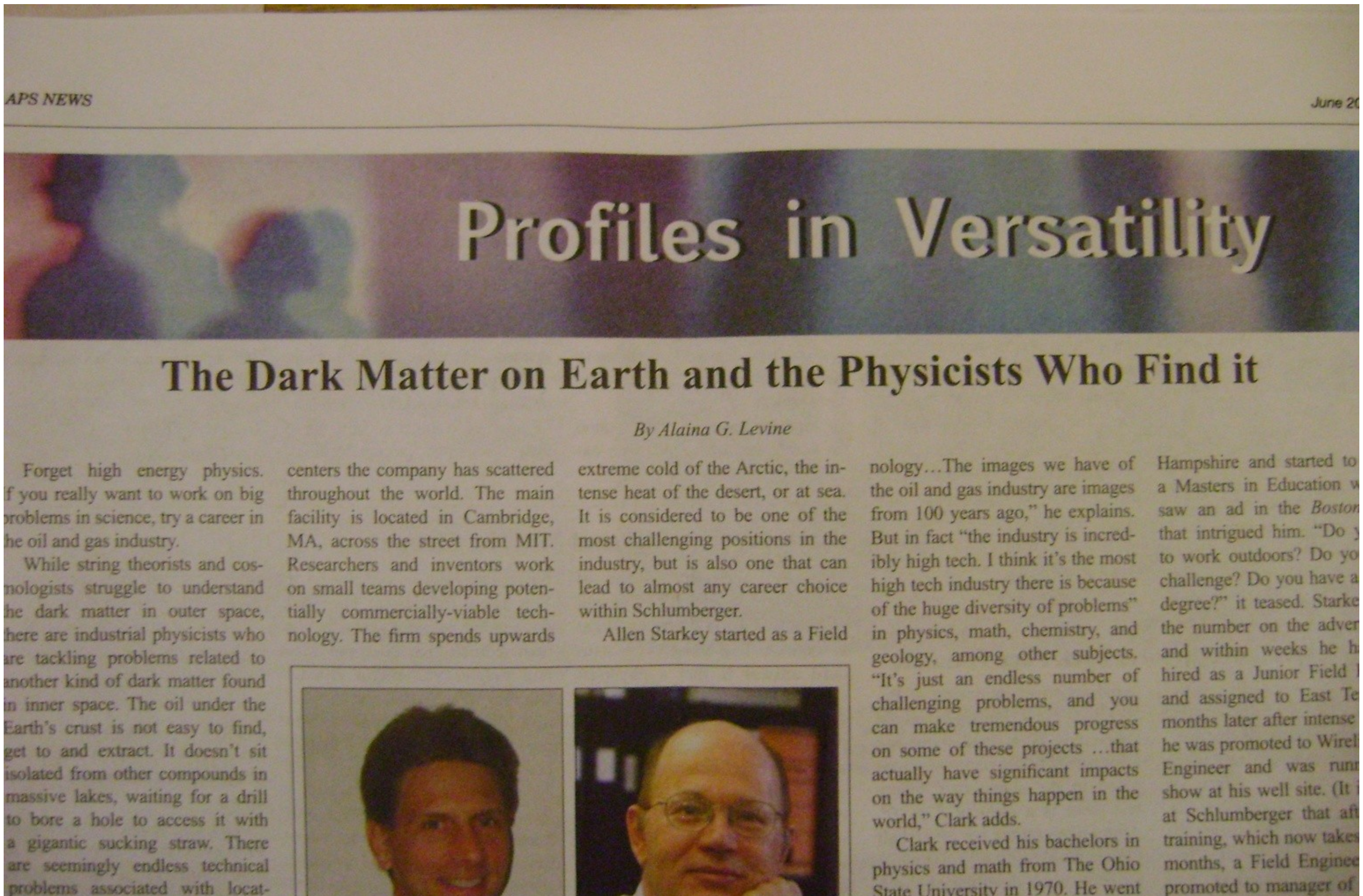


6E-4
5E-4
4E-4
3E-4
2E-4
1E-4
7E-5
5E-5
4E-5
3E-5
2E-5
1E-5
7E-6
5E-6
4E-6
3E-6
ρ (M☉ pc⁻³)
2
3
4
5
6
7
8
9
10
T (keV)
mν = 1.0 eV
mν = 2.0 eV
log10(ρ)=-5.7+2.2log10(T)

Conclusões

- MOND + neutrinos 2 eV – OK.
- Revisão utilização do Diagrama DT
- Não há diferenciação entre Aglomerados – Cooling Core e Non-Cooling Core
- Futuro:
  - amostras via Chandra e XMM x Lensing
  - Relaxação violenta em MOND ?

Descoberta a DM ?



Profiles in Versatility

The Dark Matter on Earth and the Physicists Who Find it

By Alaina G. Levine

Forget high energy physics. f you really want to work on big roblems in science, try a career in he oil and gas industry.

While string theorists and cosnologists struggle to understand he dark matter in outer space, here are industrial physicists who re tackling problems related to nother kind of dark matter found n inner space. The oil under the Earth's crust is not easy to find, get to and extract. It doesn't sit isolated from other compounds in massive lakes, waiting for a drill to bore a hole to access it with a gigantic sucking straw. There are seemingly endless technical problems associated with locat-

centers the company has scattered throughout the world. The main facility is located in Cambridge, MA, across the street from MIT. Researchers and inventors work on small teams developing potentially commercially-viable technology. The firm spends upwards

extreme cold of the Arctic, the intense heat of the desert, or at sea. It is considered to be one of the most challenging positions in the industry, but is also one that can lead to almost any career choice within Schlumberger.

Allen Starkey started as a Field

nology…The images we have of the oil and gas industry are images from 100 years ago," he explains. But in fact "the industry is incredibly high tech. I think it's the most high tech industry there is because of the huge diversity of problems" in physics, math, chemistry, and geology, among other subjects. "It's just an endless number of challenging problems, and you can make tremendous progress on some of these projects …that actually have significant impacts on the way things happen in the world," Clark adds.

Clark received his bachelors in physics and math from The Ohio State University in 1970. He went

Hampshire and started to
a Masters in Education w
saw an ad in the *Boston*
that intrigued him. "Do y
to work outdoors? Do yo
challenge? Do you have a
degree?" it teased. Starke
the number on the adver
and within weeks he h
hired as a Junior Field
and assigned to East Te
months later after intense
he was promoted to Wirel
Engineer and was runn
show at his well site. (It i
at Schlumberger that aft
training, which now takes
months, a Field Enginee
promoted to manager of