Title: Dynamics of the Milky Way Dwarf Satellites

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Abstract:

Dynamics of Milky Way Dwarf Satellites

Louie Strigari
University of California, Irvine

Small-Scale Structure of Dark Matter
Perimeter Institute
June 7, 2008

Collaborators: James Bullock, Manoj Kaplinghat, Marla Geha, Josh Simon, Beth Willman

Overview

- Dark Matter Mass Scale/Mass Function
  - ``Classical'' dwarf satellites
  - New dwarf satellites
- 3D Spatial Motions in Local Group
  - Internal: Core vs. Cusp issue
  - Systematic Motions of satellites

What is the minimum mass dark matter halo?
What is the minimum mass ``galaxy?"

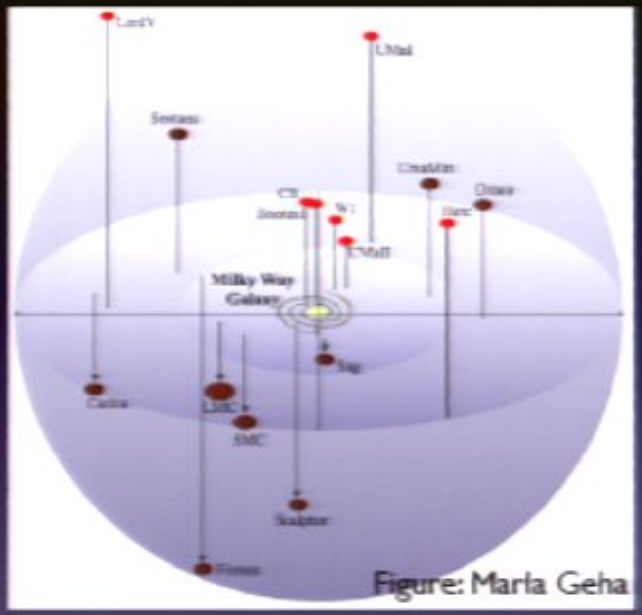
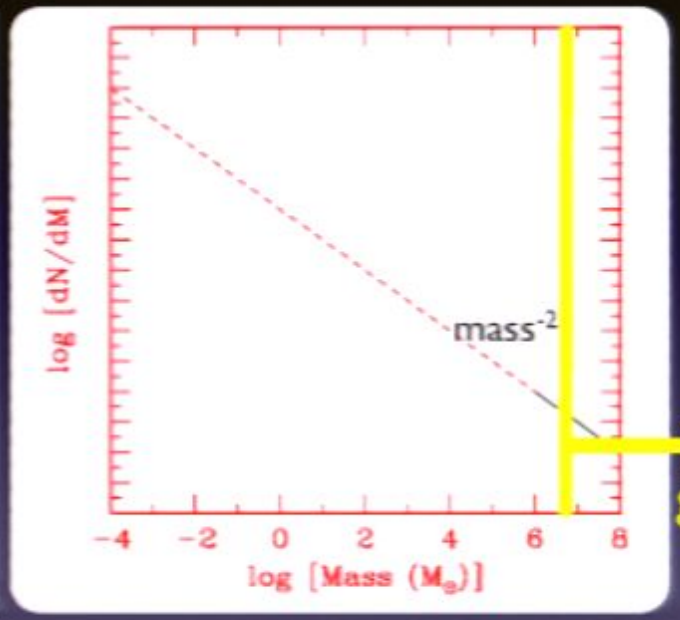


Figure: Maria Geha



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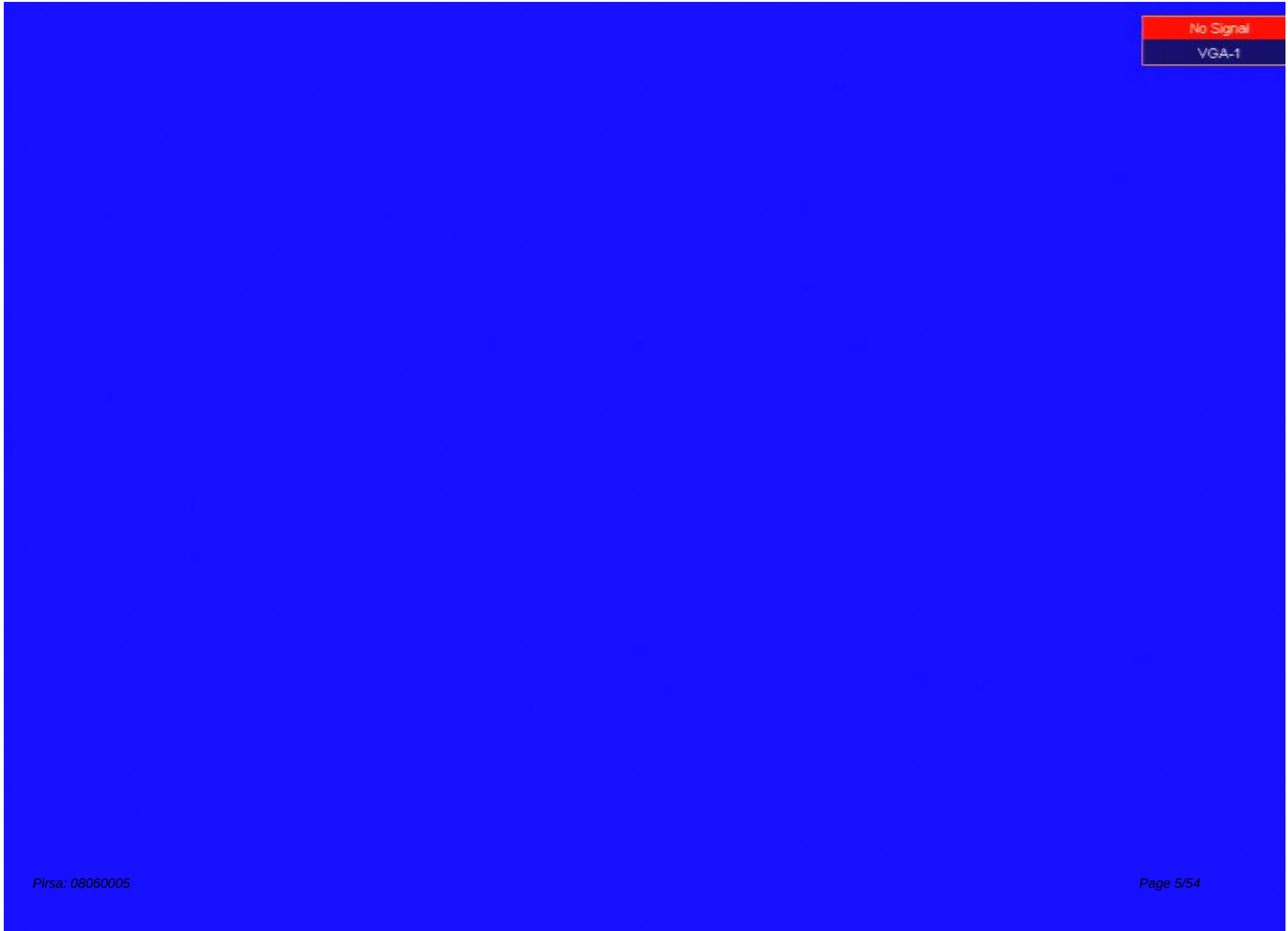
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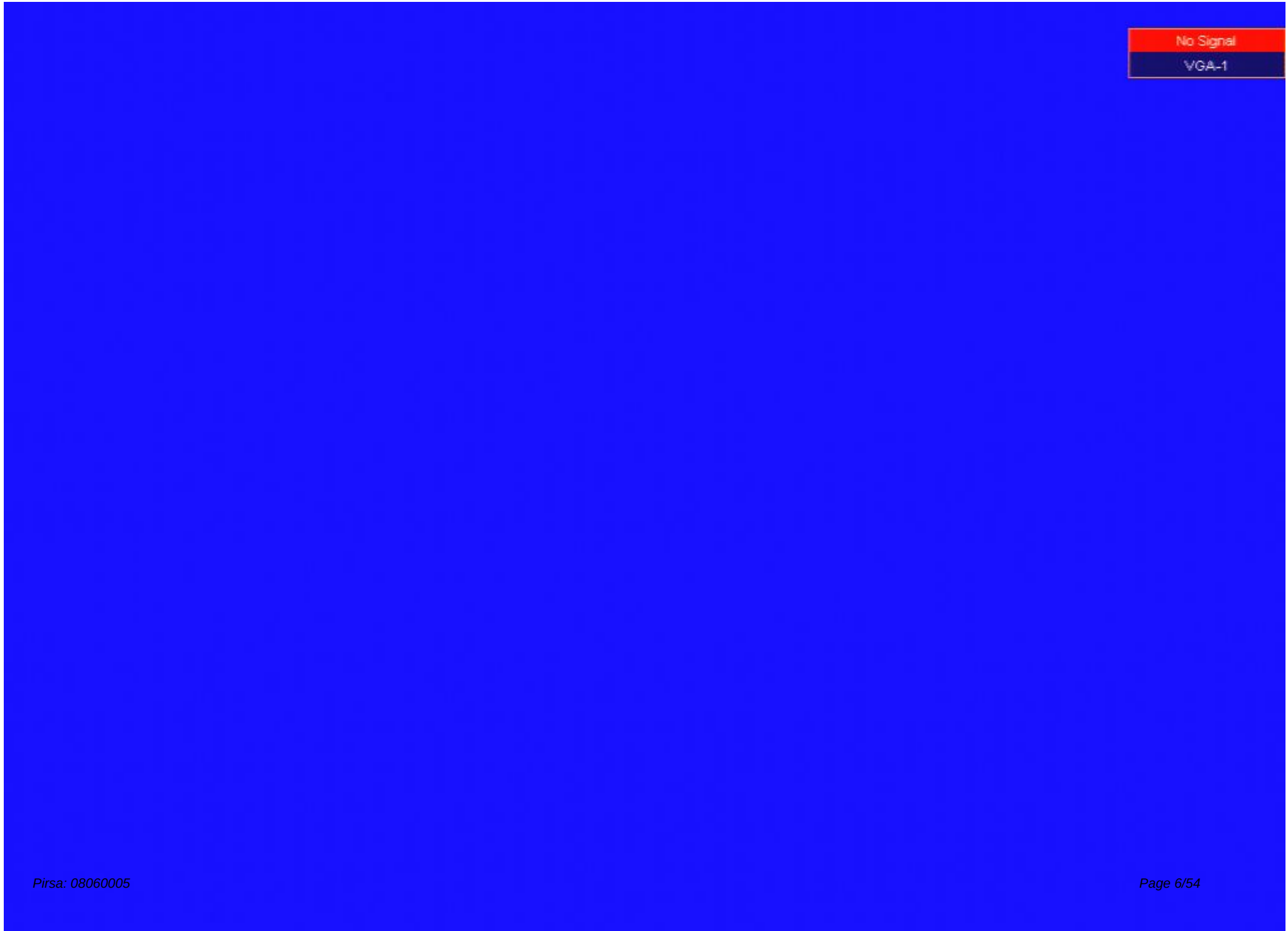
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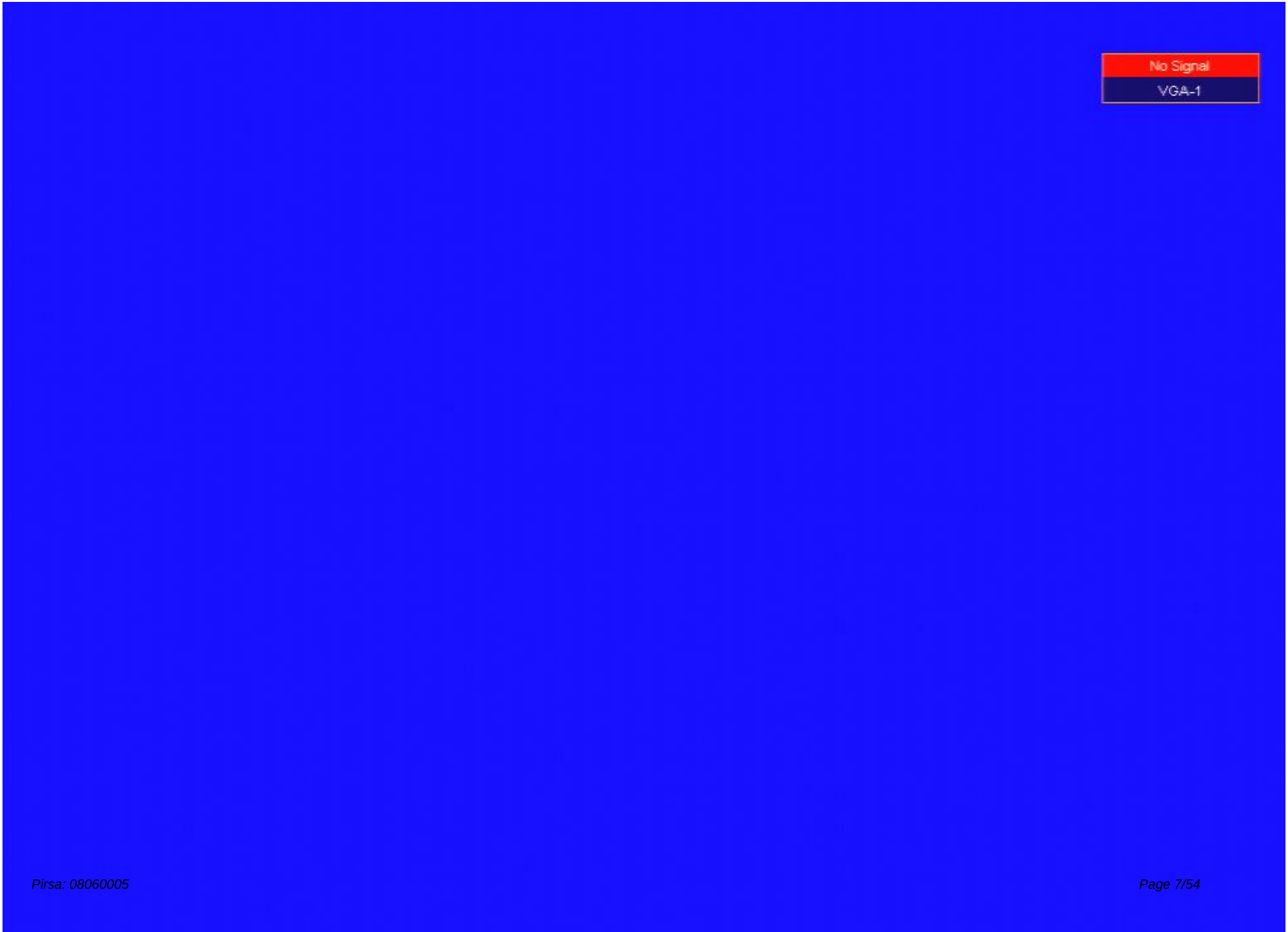
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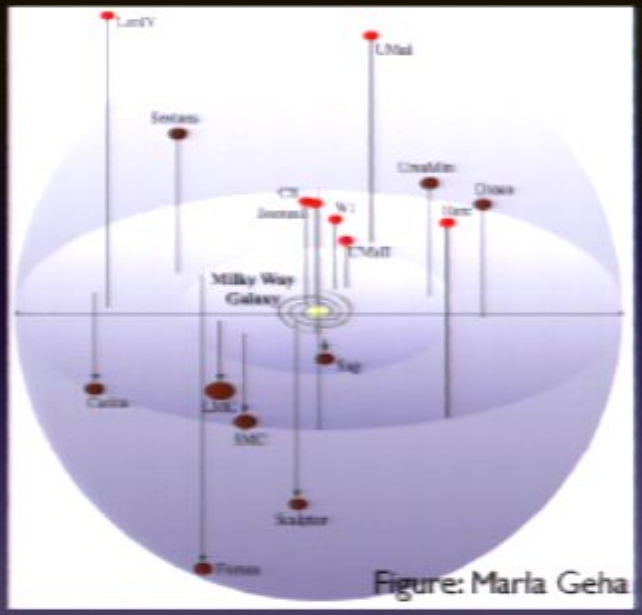

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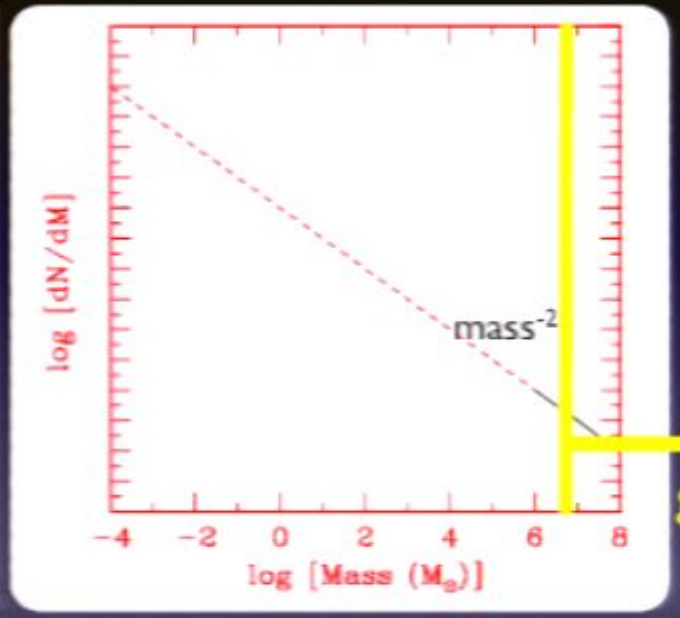

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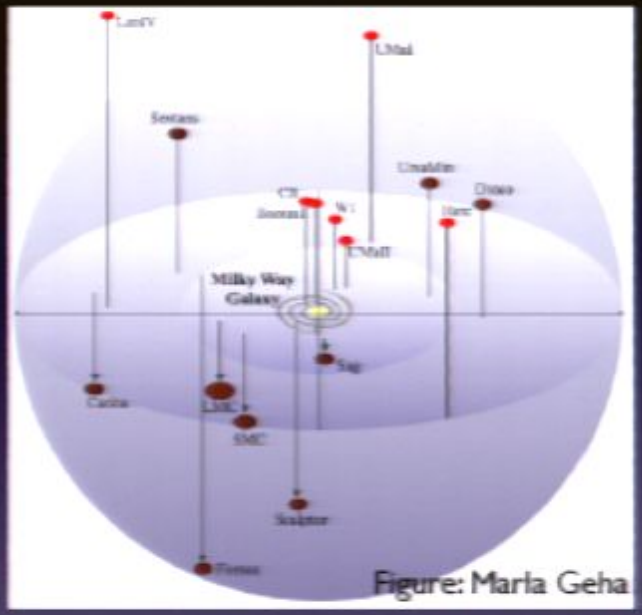

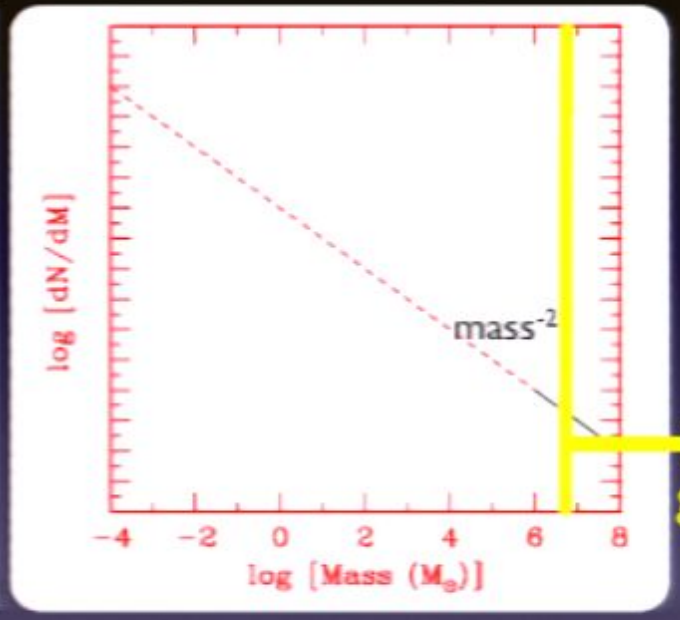

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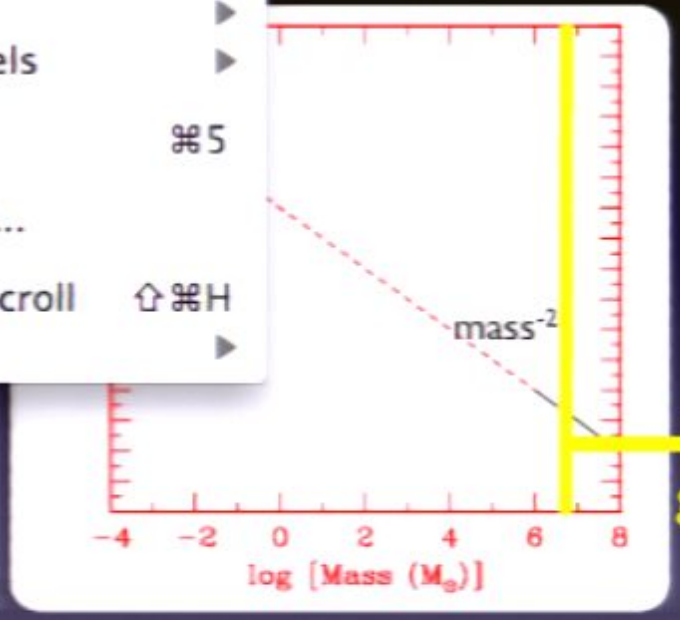

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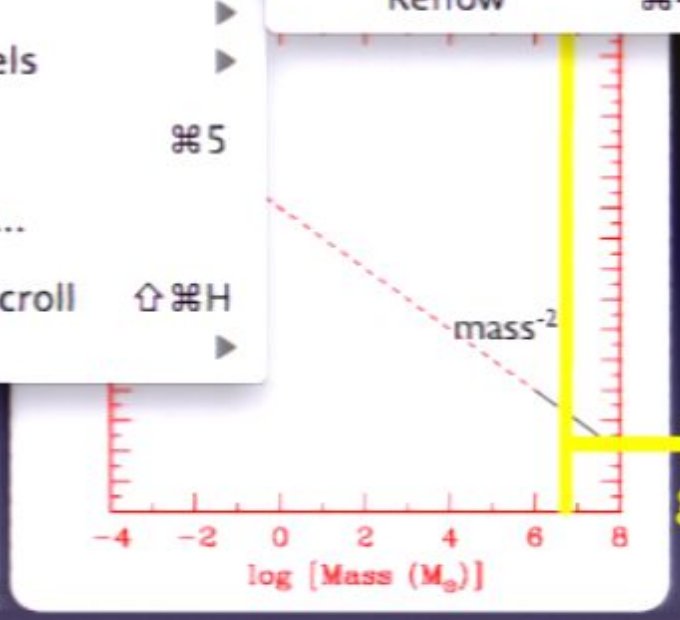

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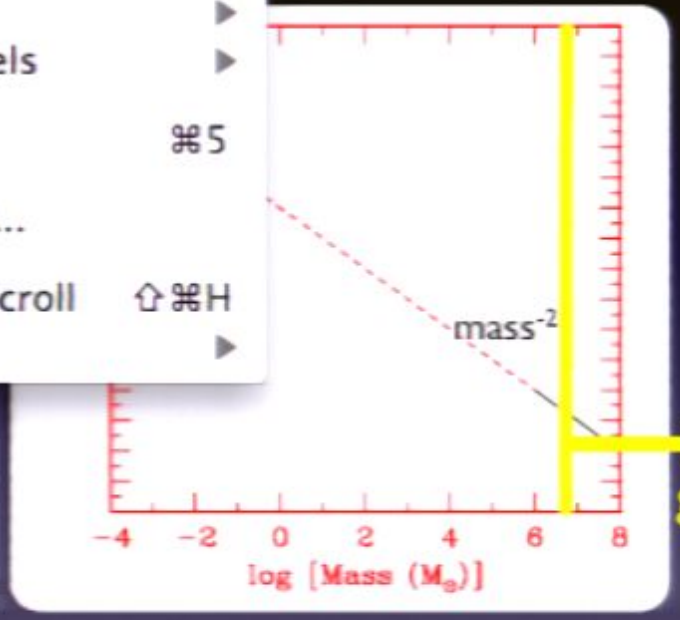

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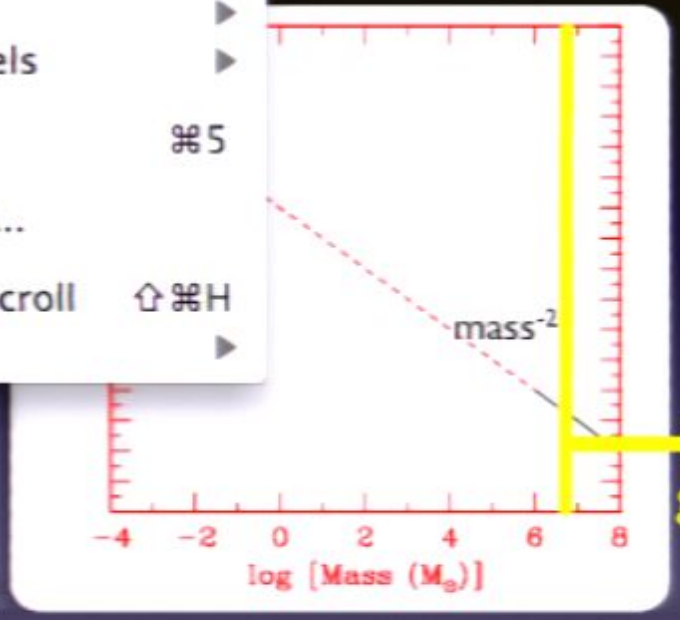

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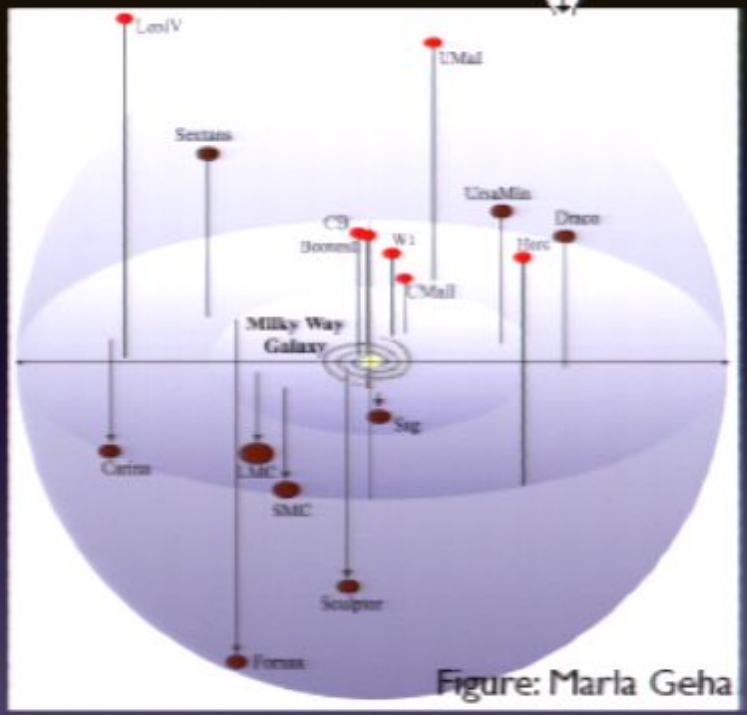

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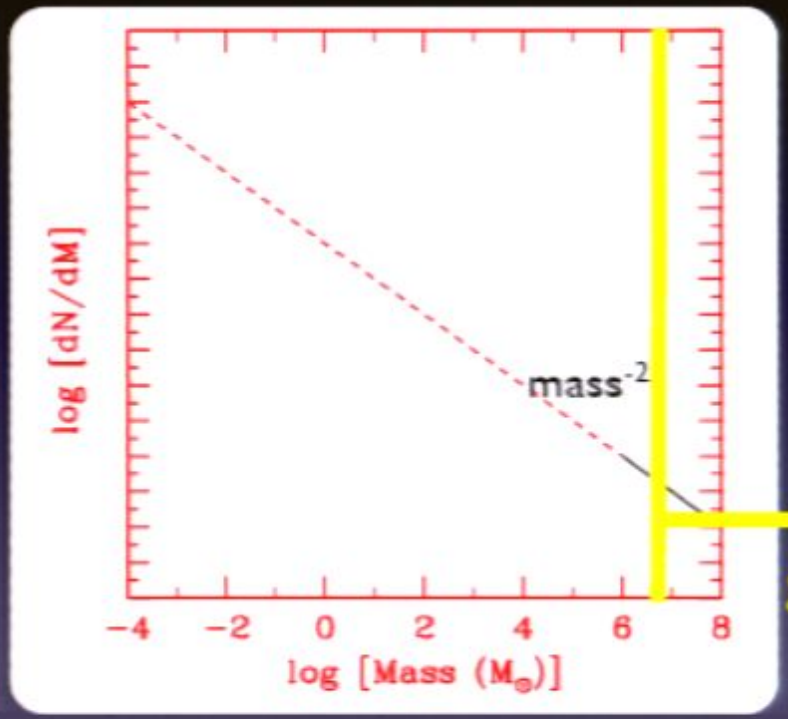

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Low-mass stellar systems

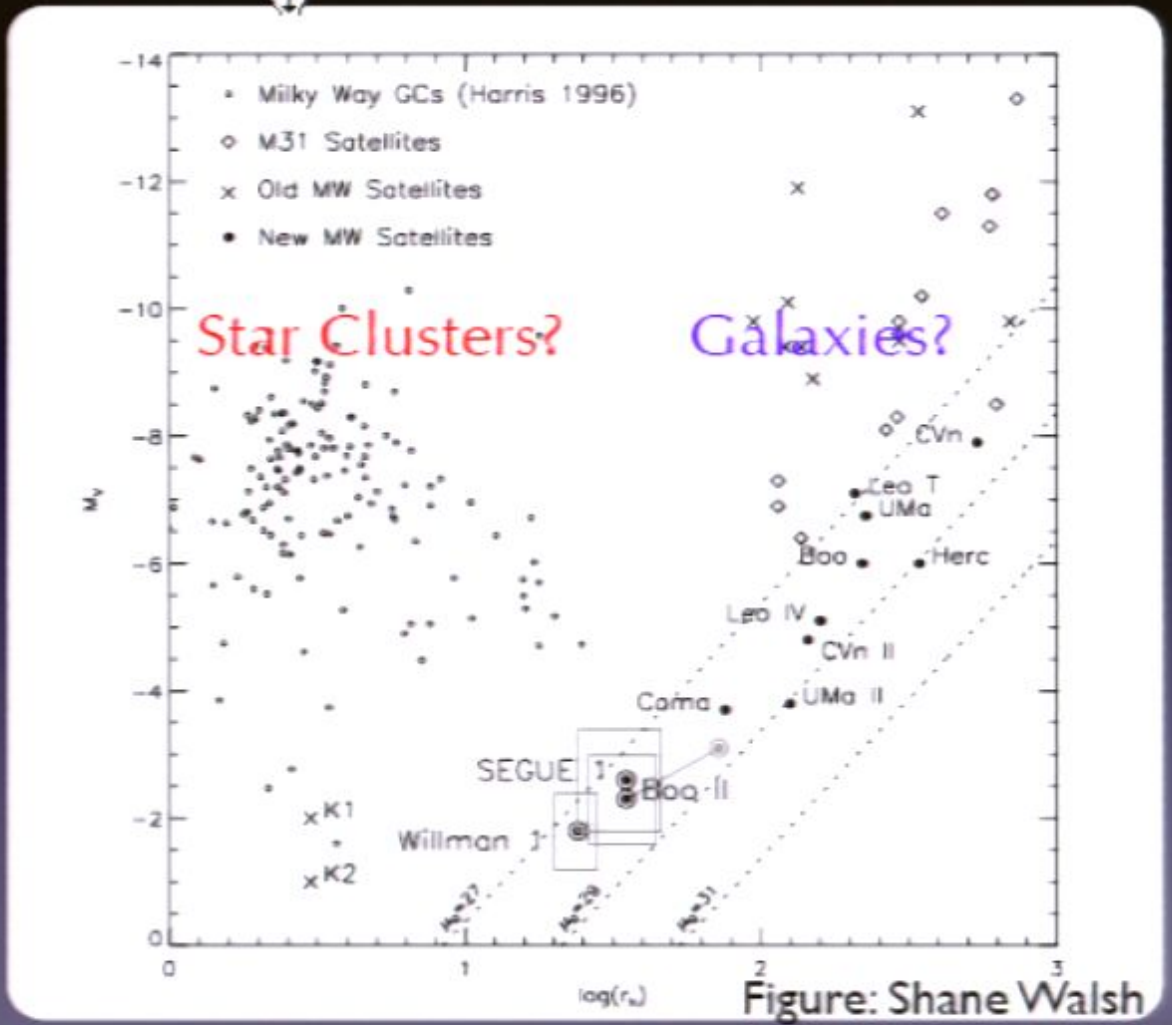

Figure: Shane Walsh

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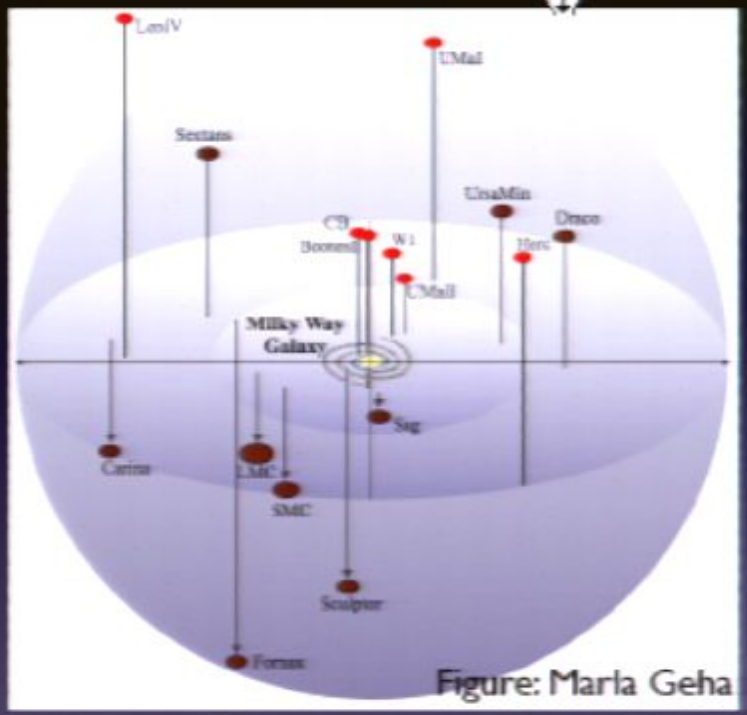

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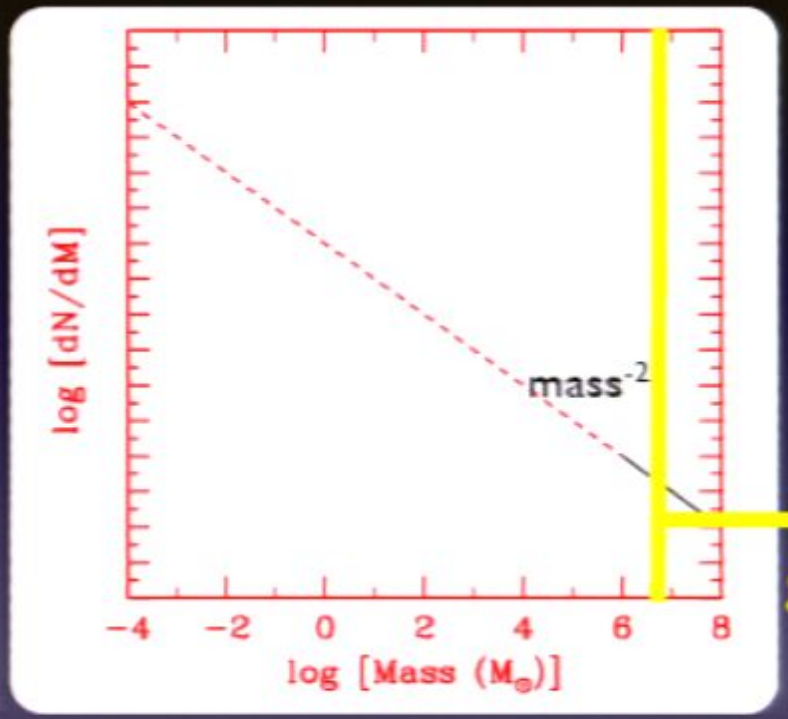

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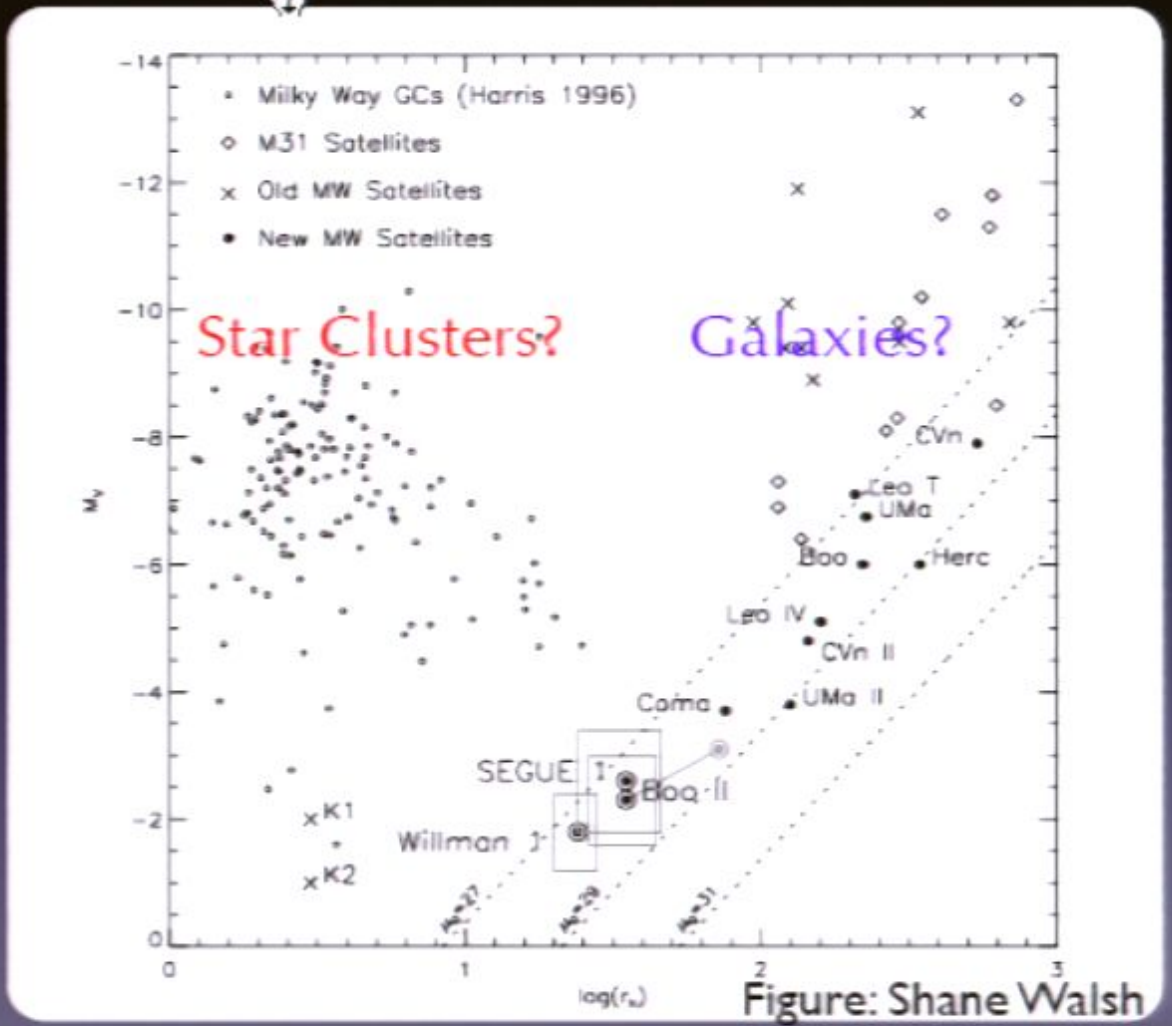

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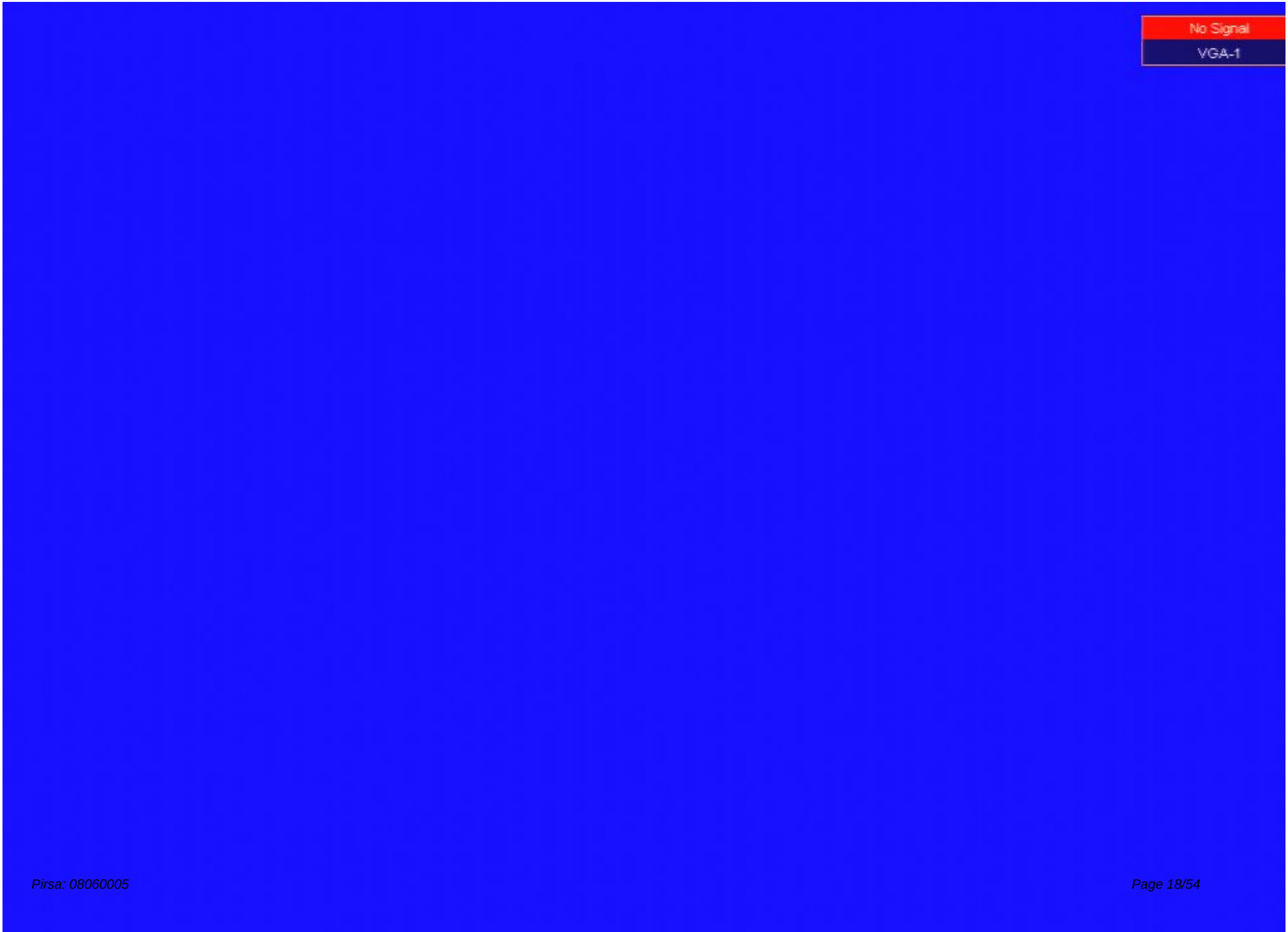
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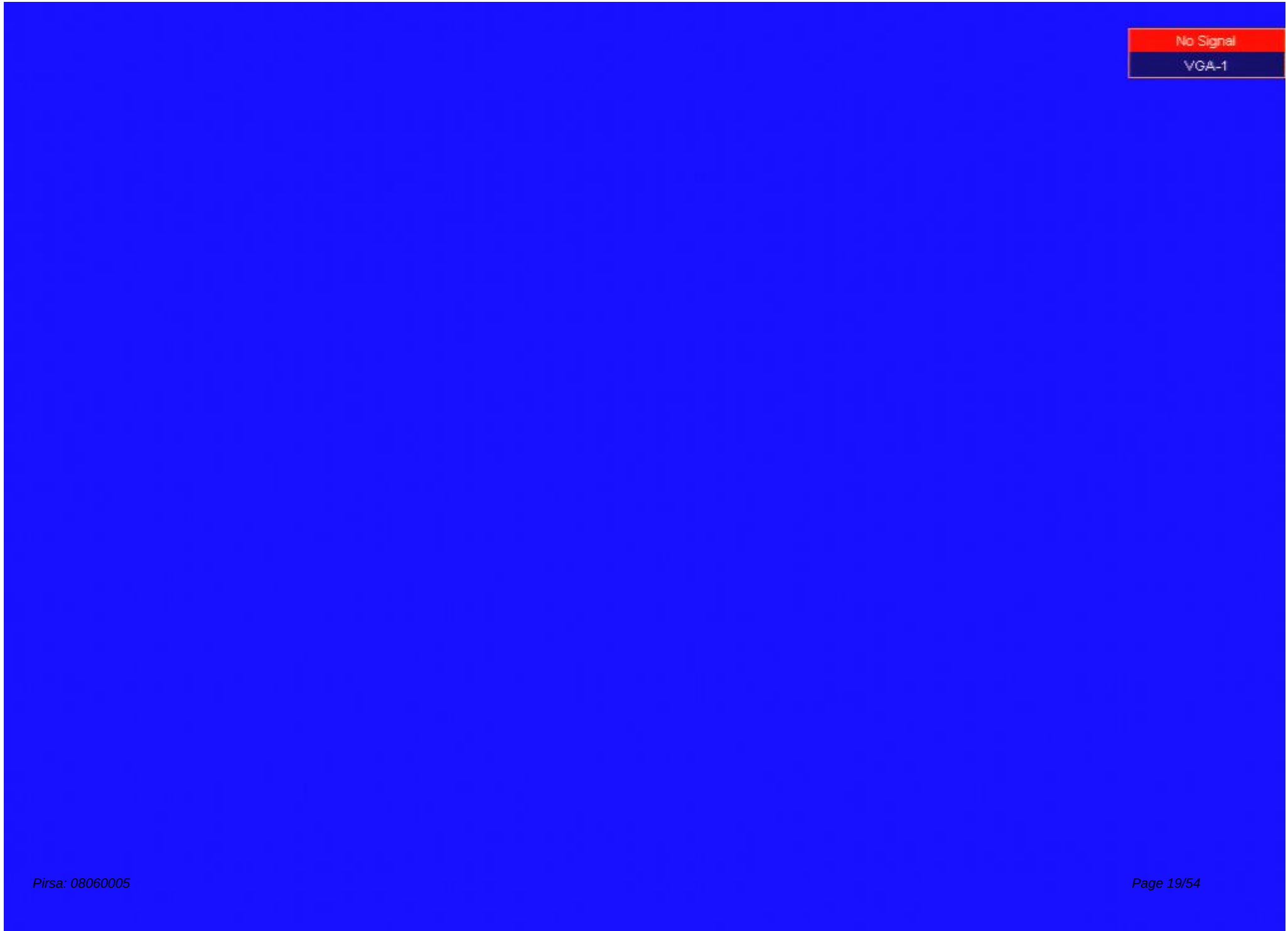
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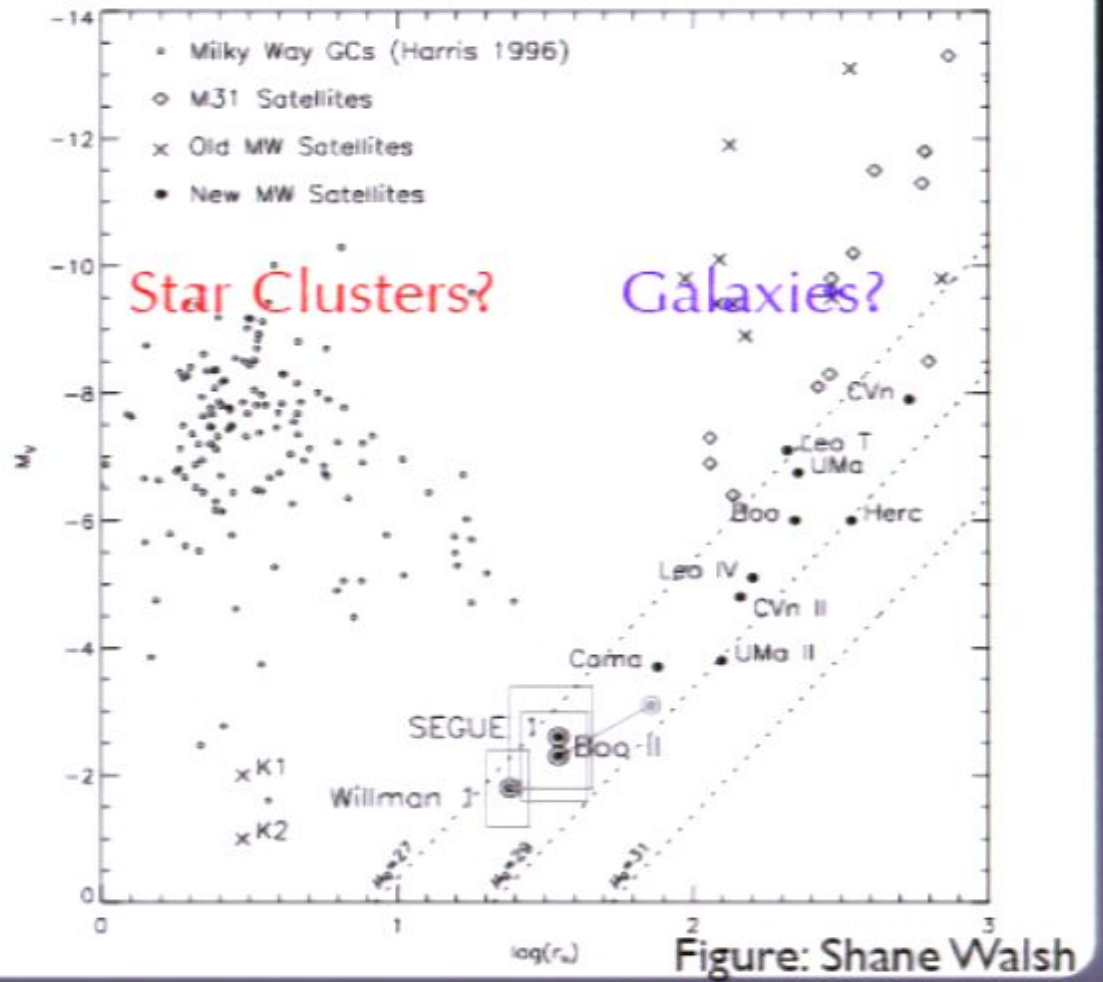

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Kinematics

- Mass within fixed radius is a better constrained observable than the maximum circular velocity
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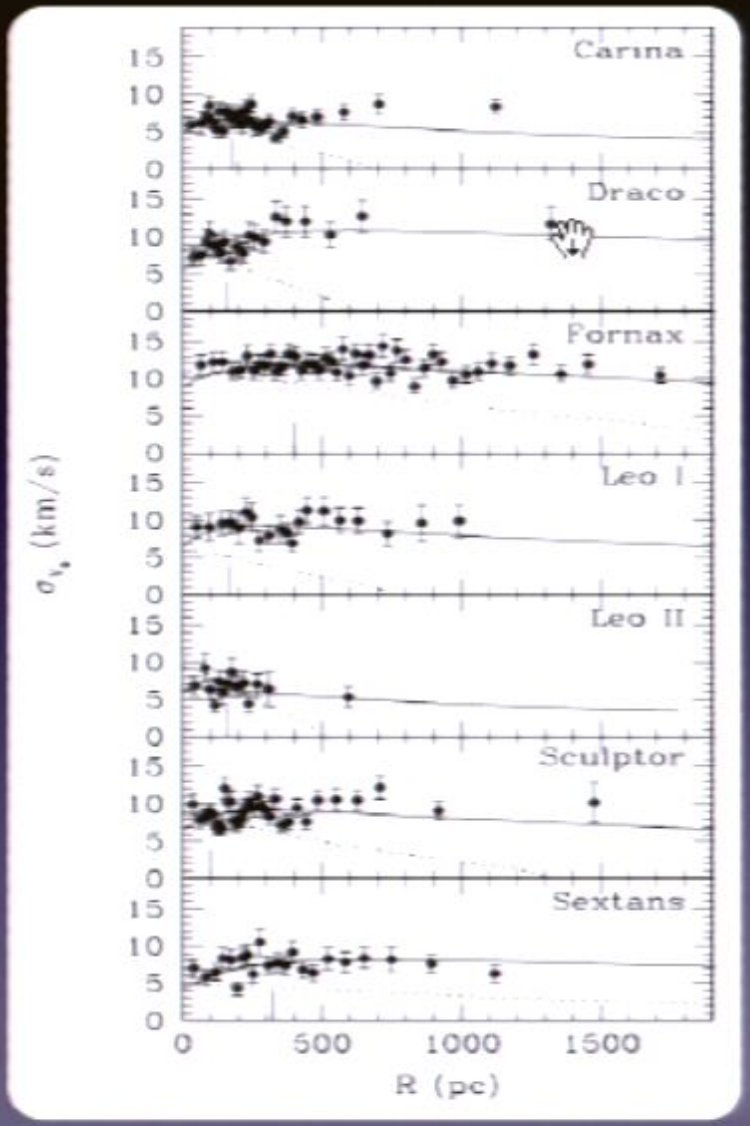
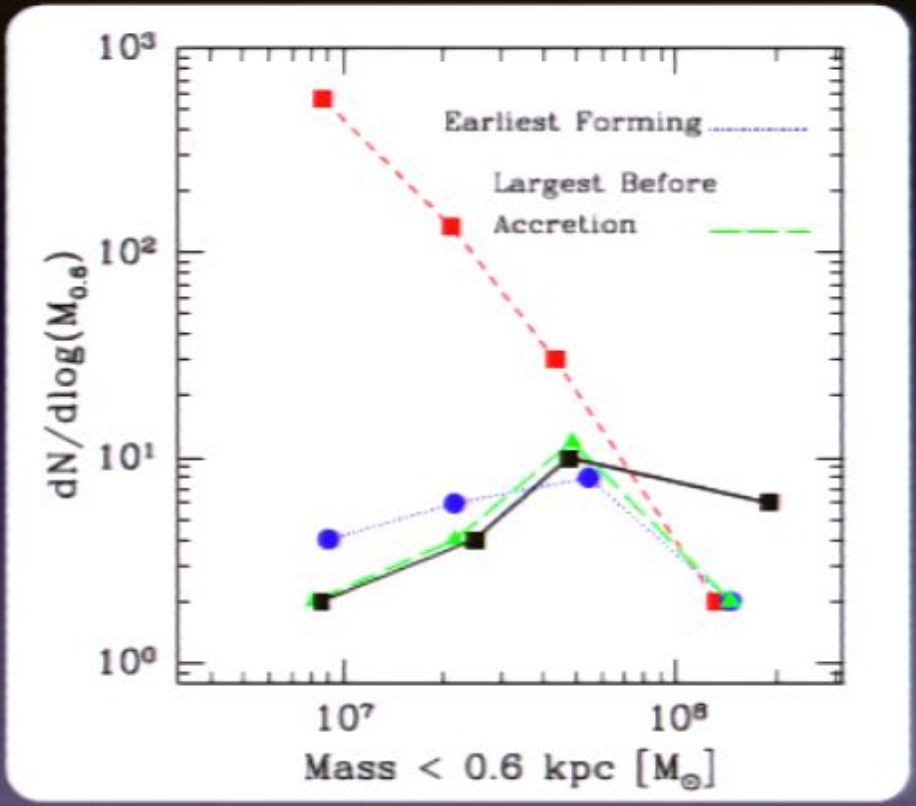


Walker et al, ApJL 2007

Classical Milky Way Satellites

Quantitative comparison to CDM models now possible

Satellites are either the Earliest Forming or Largest Before Accretion
[Strigari et al. 2007; Simon & Geha 2007]



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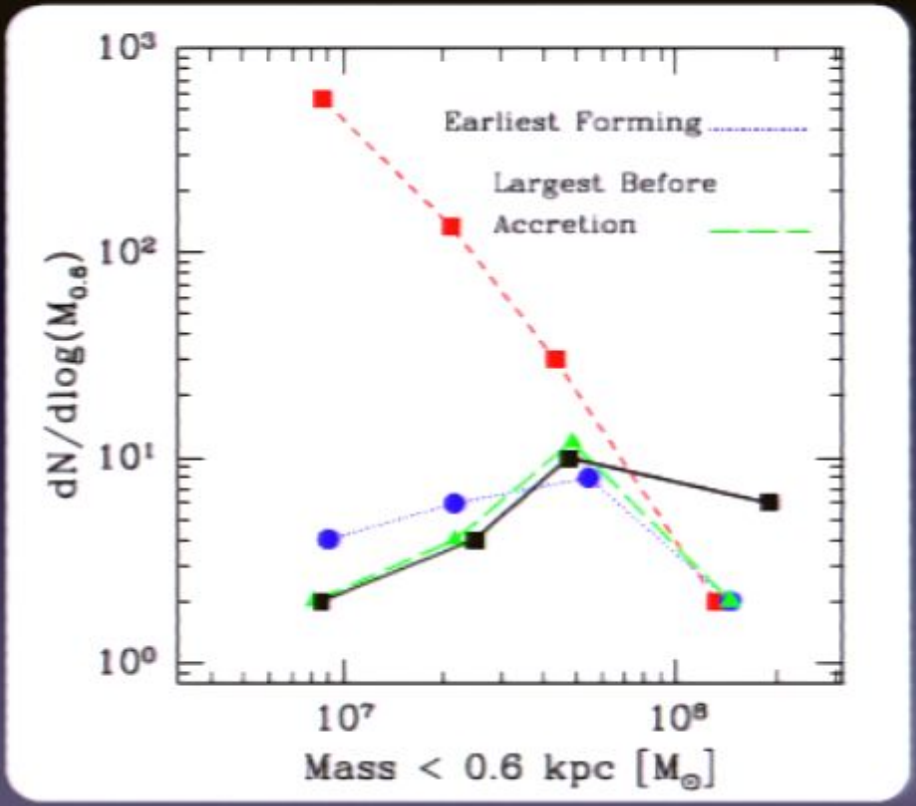

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Mass Modeling

Jeans equation

$$r\frac{d(\rho_\star\sigma_r^2)}{dr} = -\rho_\star(r)V_c^2(r) - 2\beta(r)\rho_\star\sigma_r^2$$

LOS integral

$$\sigma_t^2(R) = \frac{2}{I_\star(R)}\int_R^\infty \left(1 - \beta\frac{R^2}{r^2}\right)\frac{\rho_\star\sigma_r^2 r}{\sqrt{r^2 - R^2}}dr$$

Velocity anisotropy

$$\beta(r) = (\beta_\infty - \beta_0)\frac{r^2}{r_\beta^2 + r^2} + \beta_0$$

$$P(\mathbf{v}|u,\sigma_\mathbf{t}) = \prod_{i=1}^{N}\frac{1}{\sqrt{2\pi\sigma_i^2}}\exp\left[-\frac{1}{2}\frac{(v_i - u)^2}{\sigma_i^2}\right]$$

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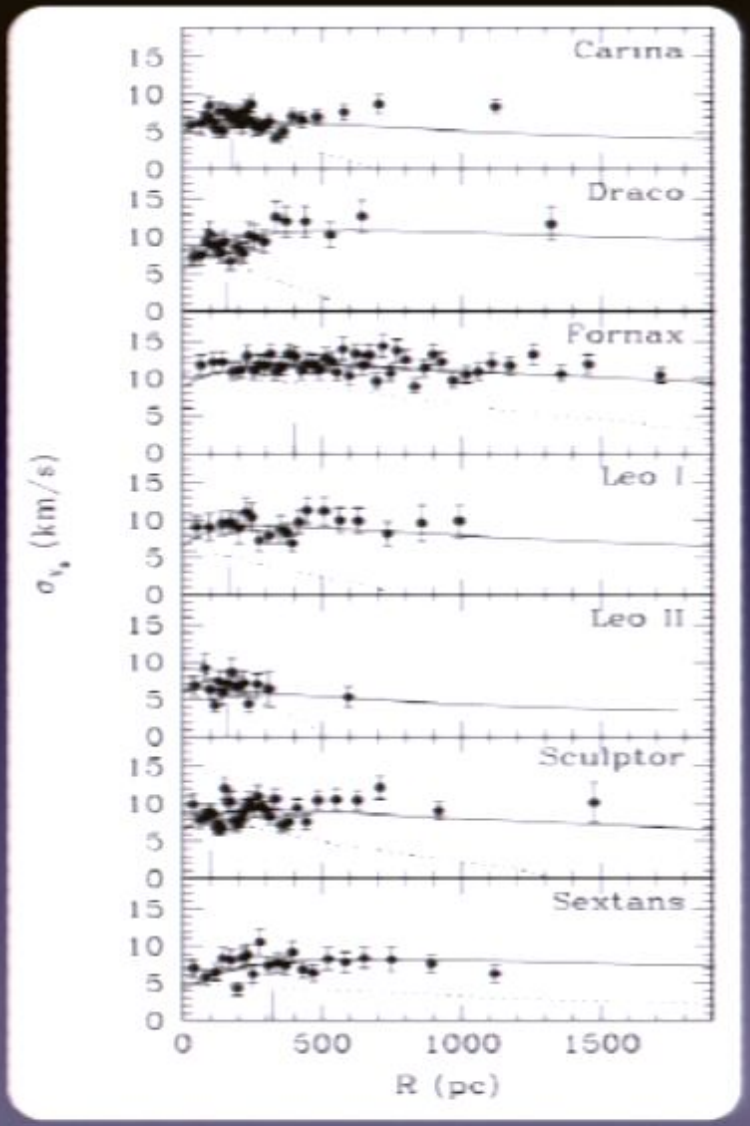

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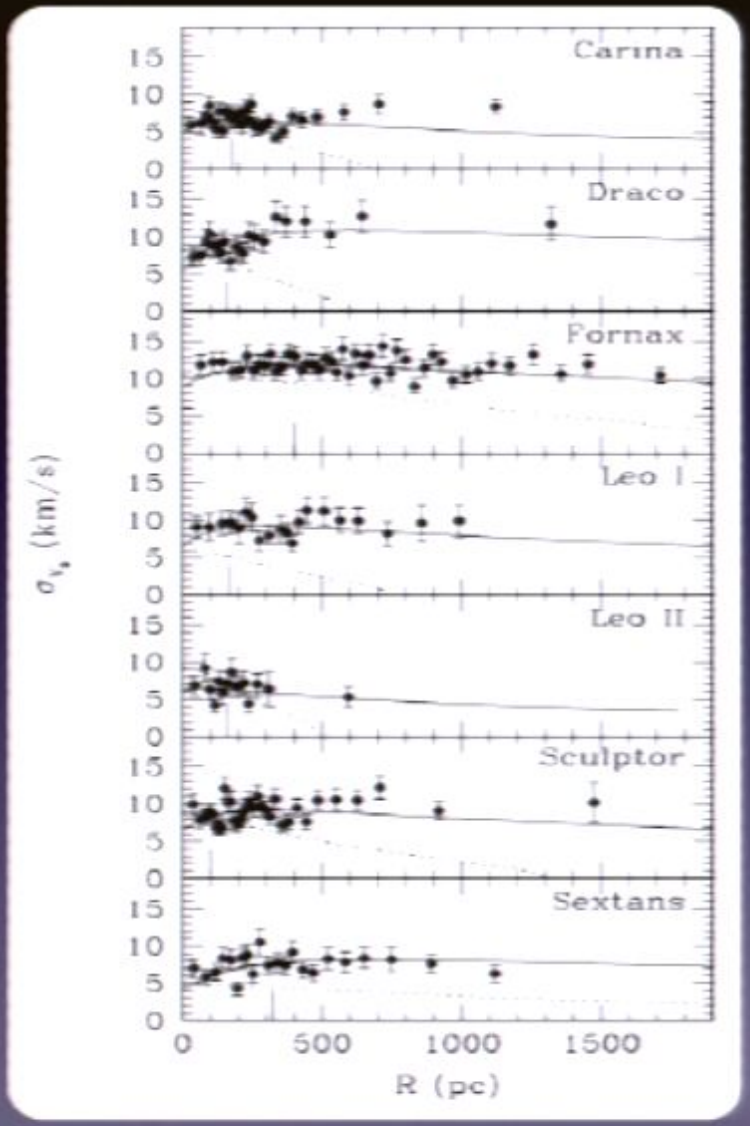

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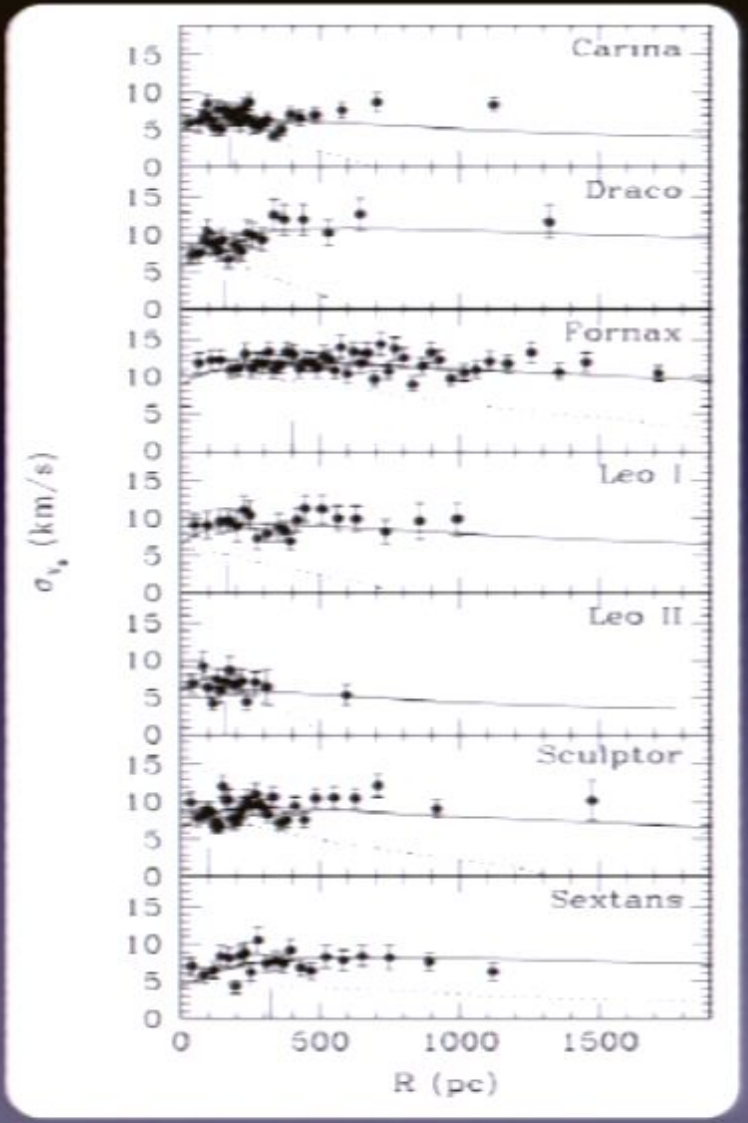

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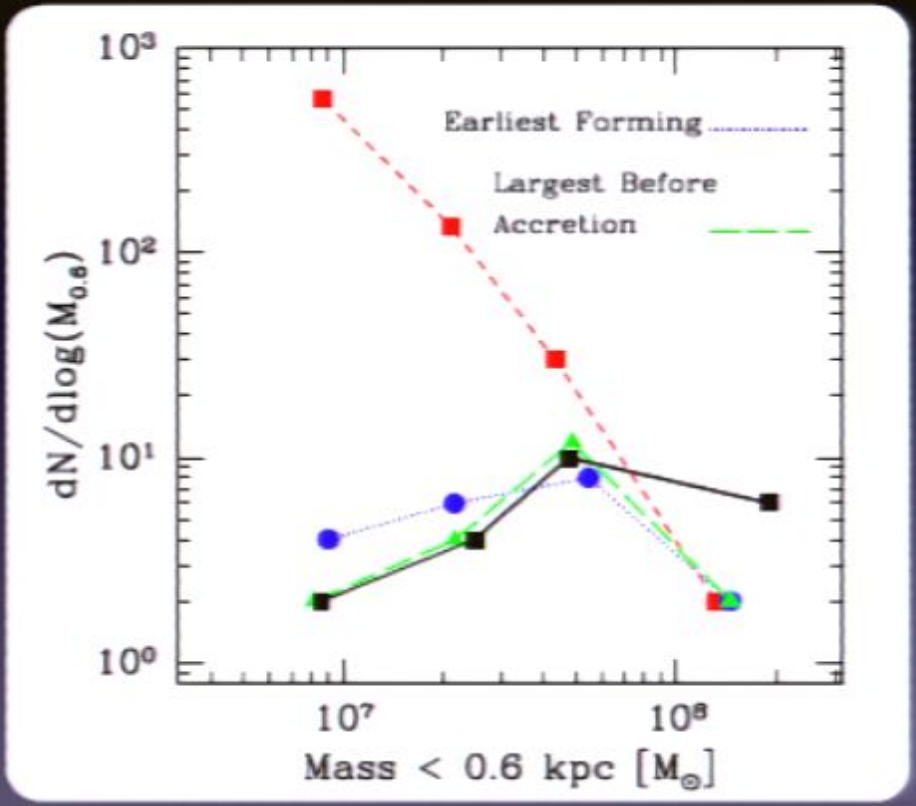

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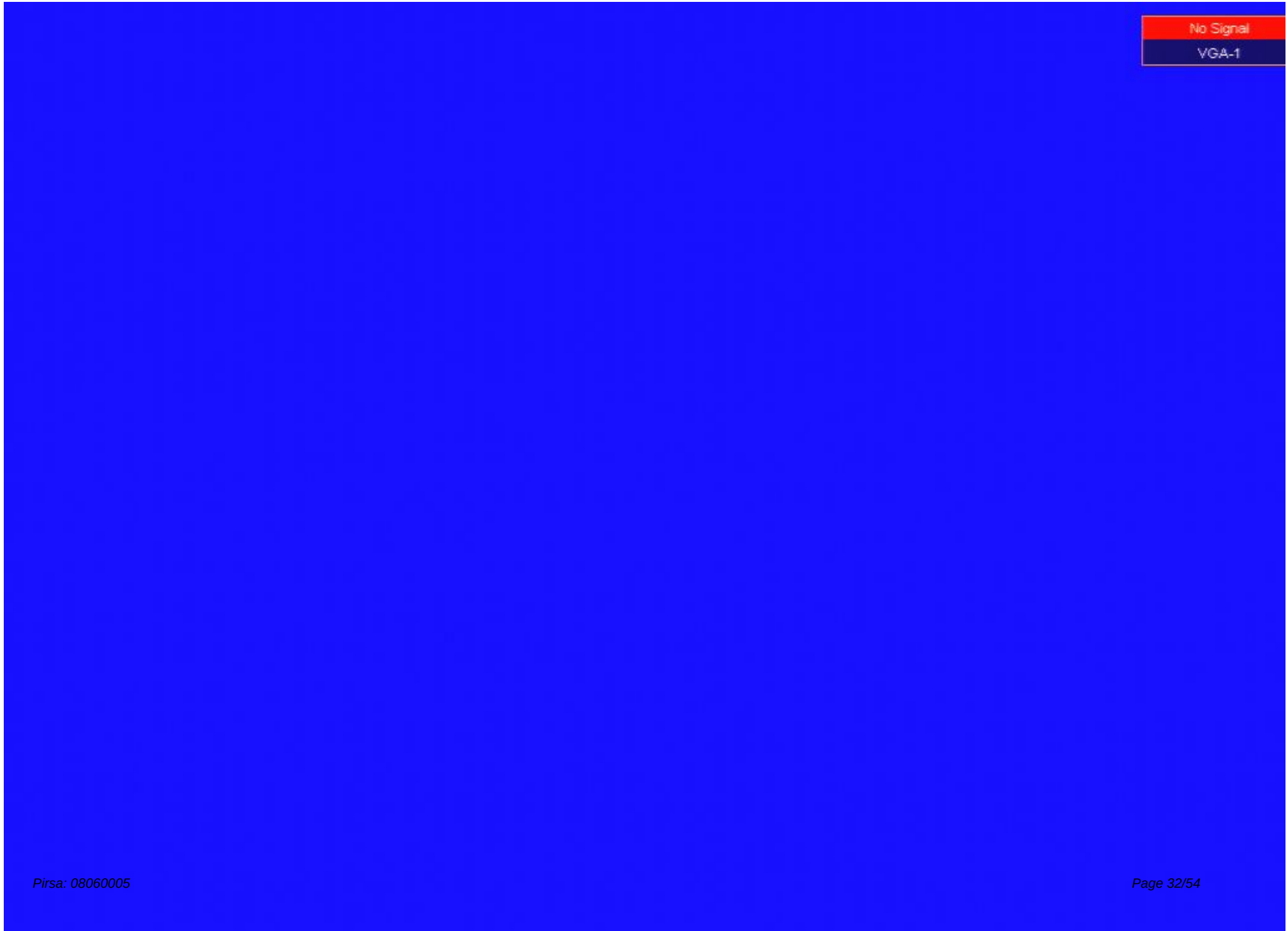
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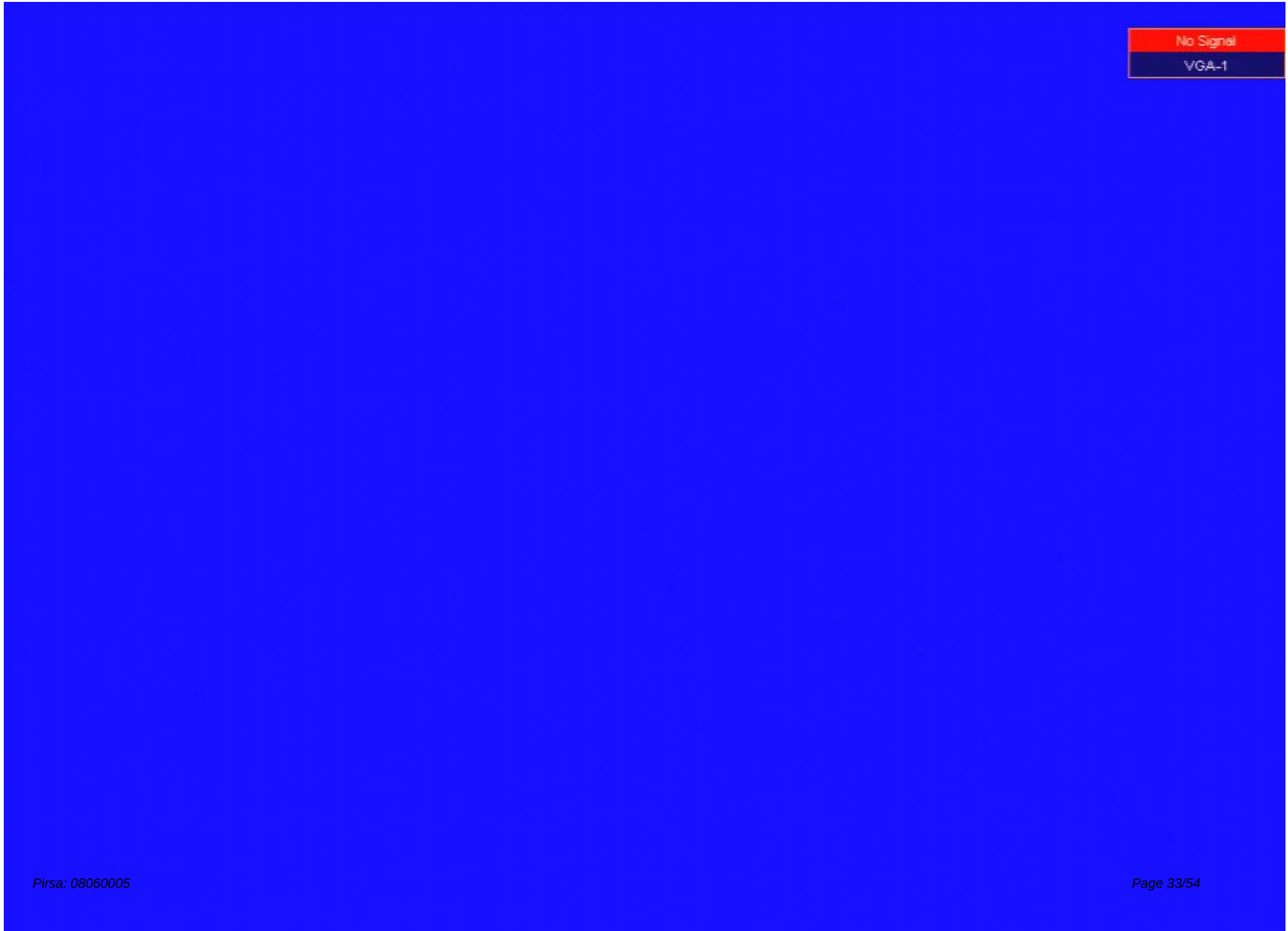
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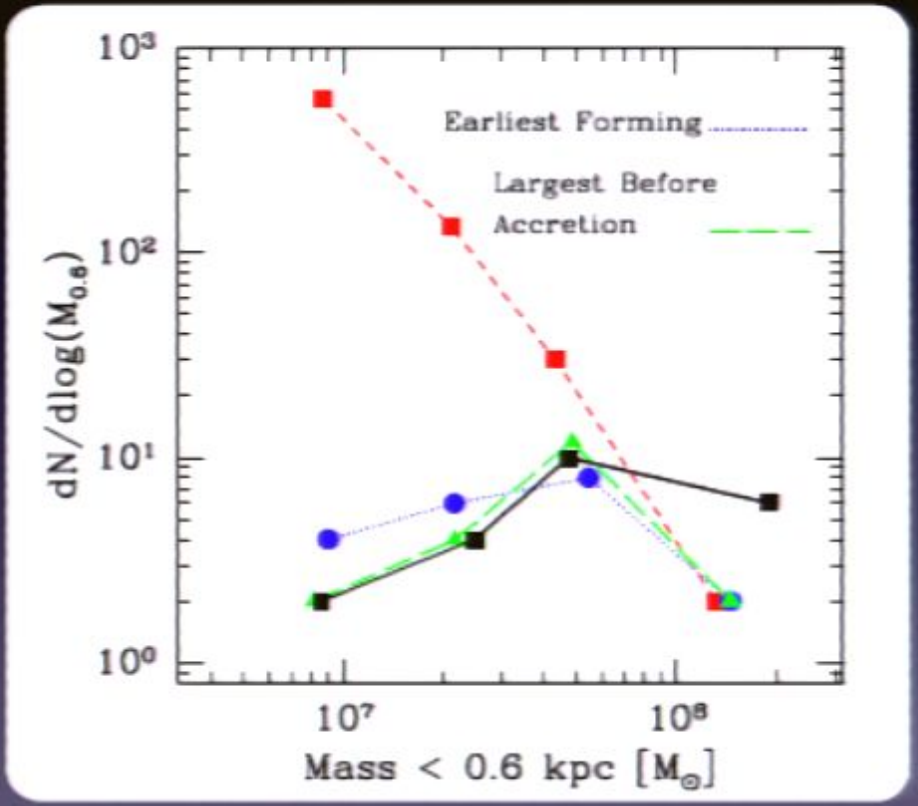

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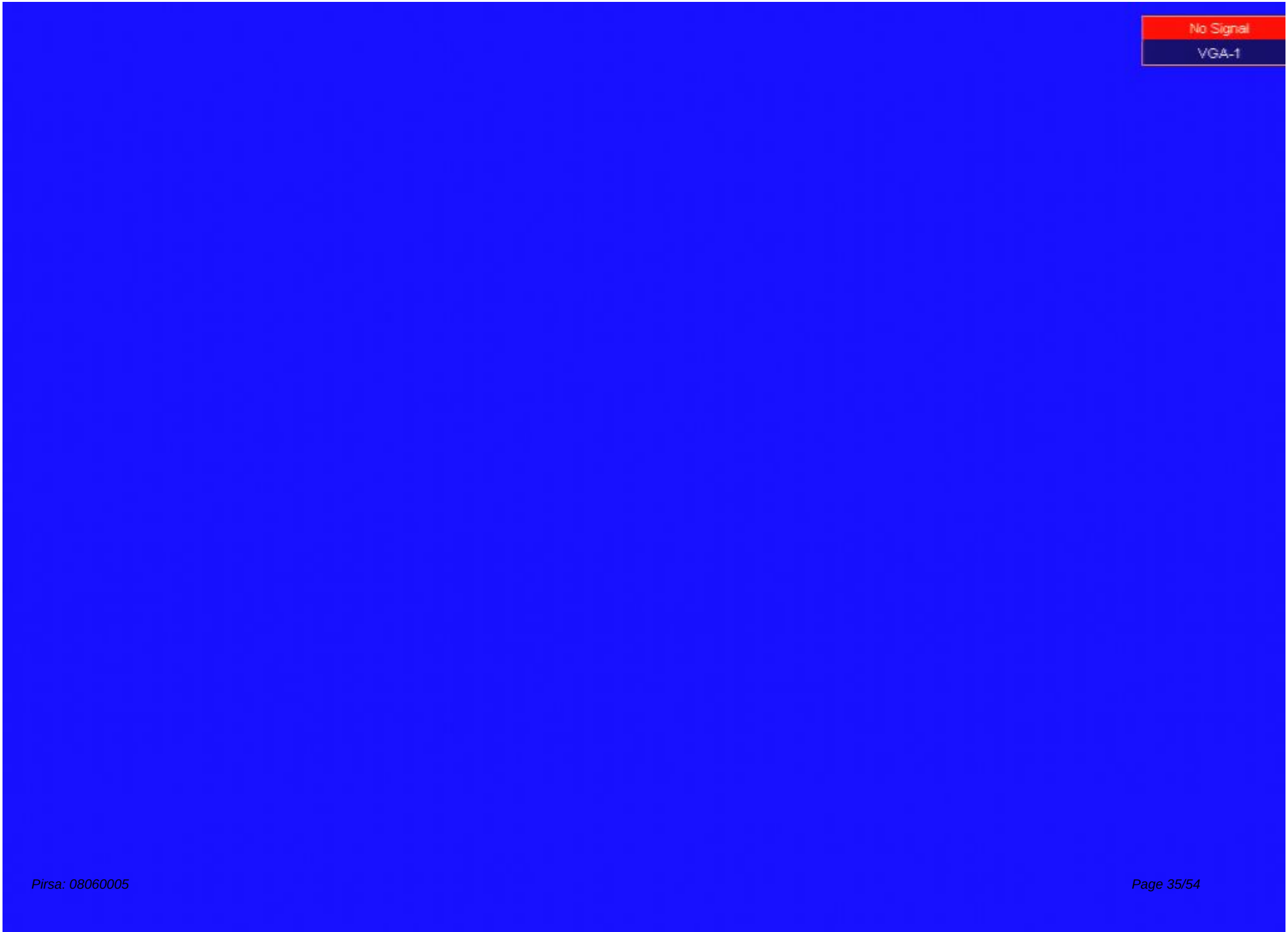
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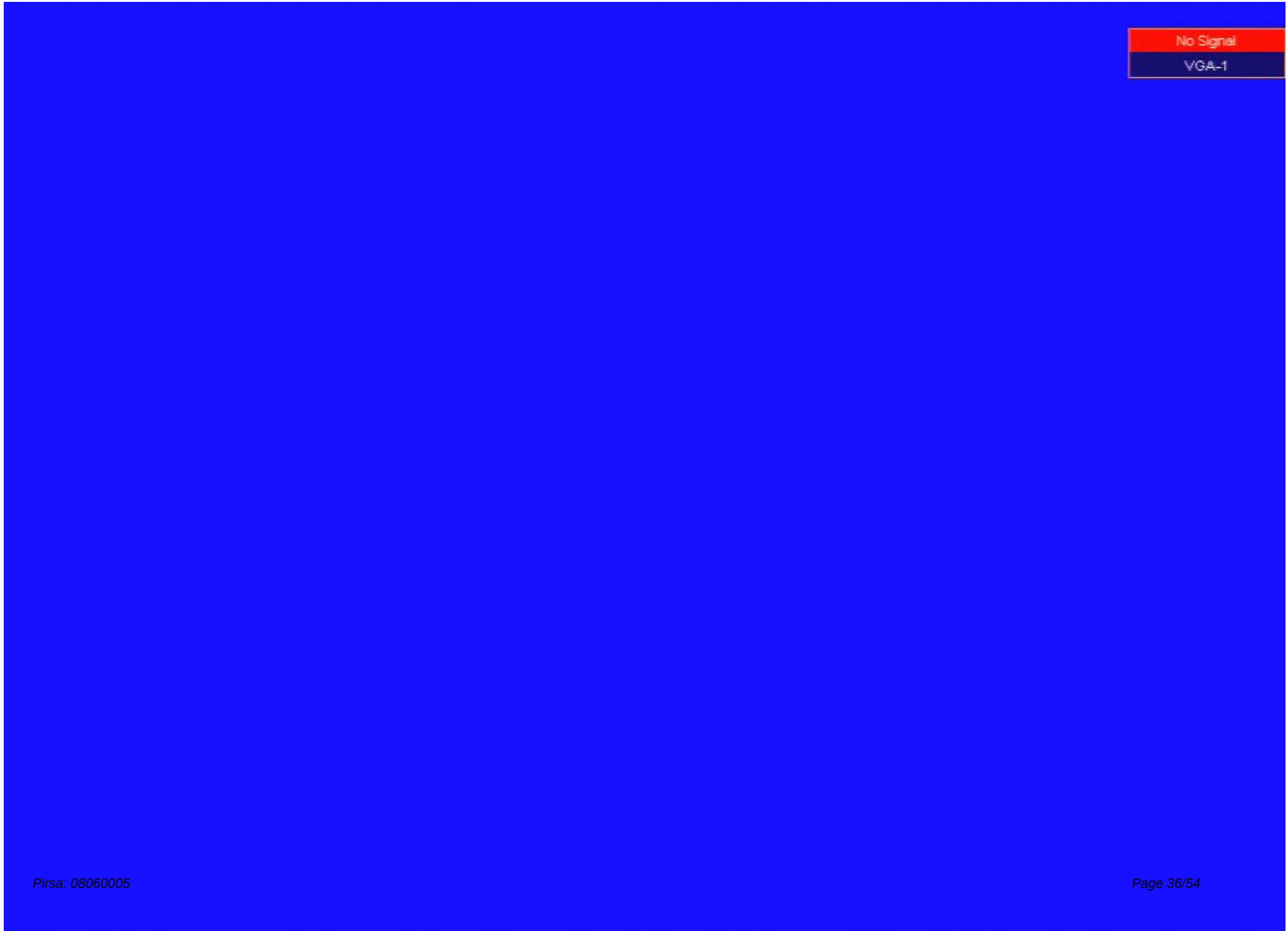
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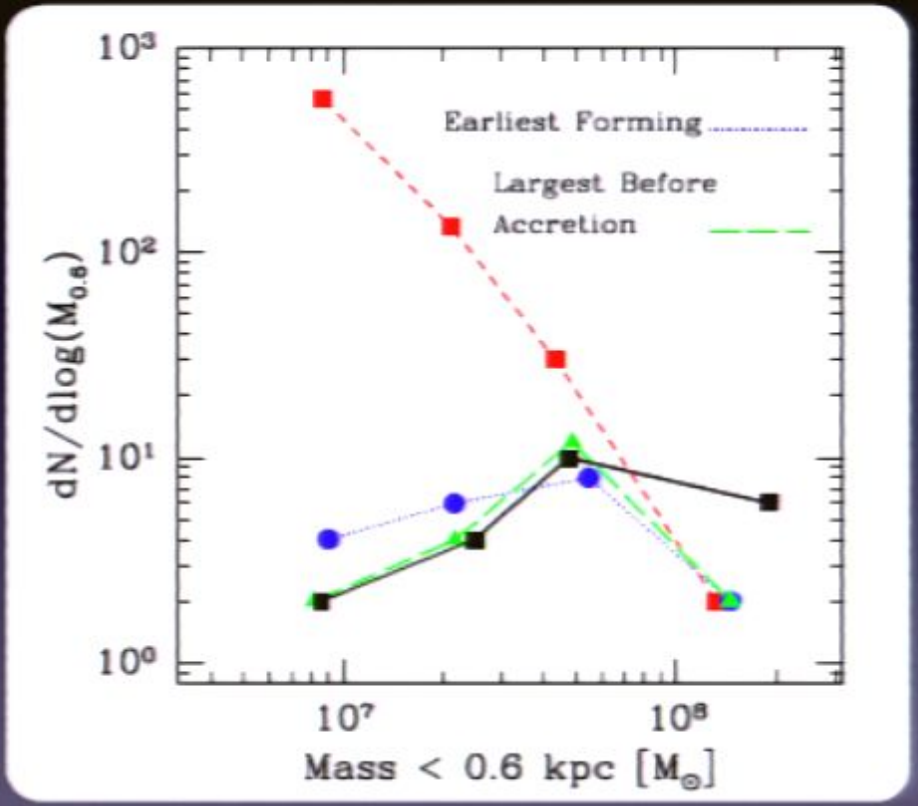
VGA-1

Classical Milky Way Satellites

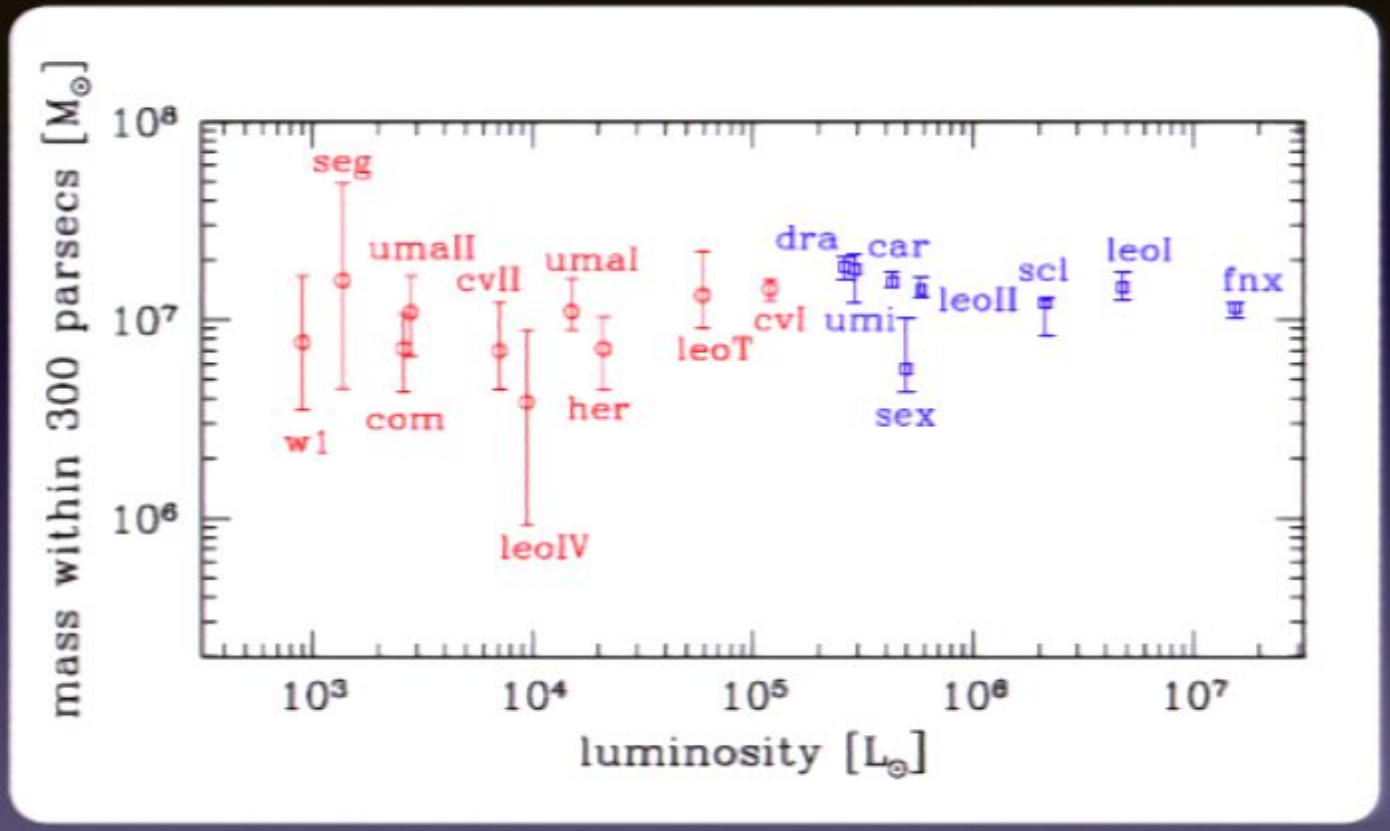
Quantitative comparison to CDM models now possible

Satellites are either the Earliest Forming or Largest Before Accretion
[Strigari et al. 2007; Simon & Geha 2007]



Strigari, Bullock, Kaplinghat, Diemand, Kuhlen, Madau
ApJ 2007

A Common Mass Scale for Milky Way Satellites



Strigari, Bullock, Kaplinghat, Simon, Geha, Willman, Walker [Nature in Press 2008]

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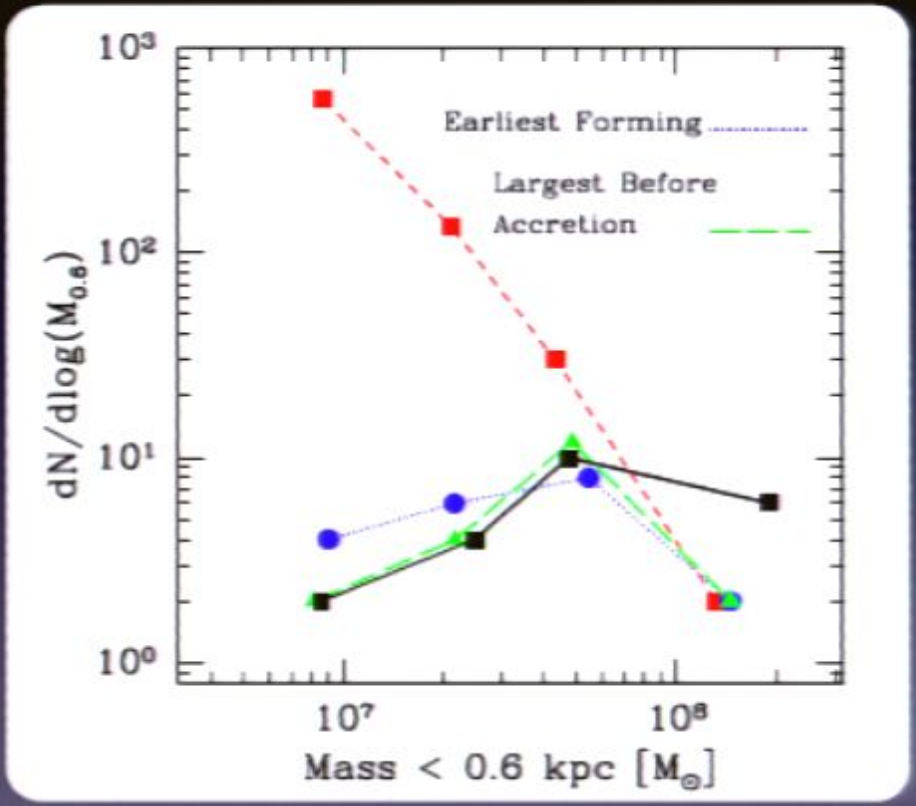

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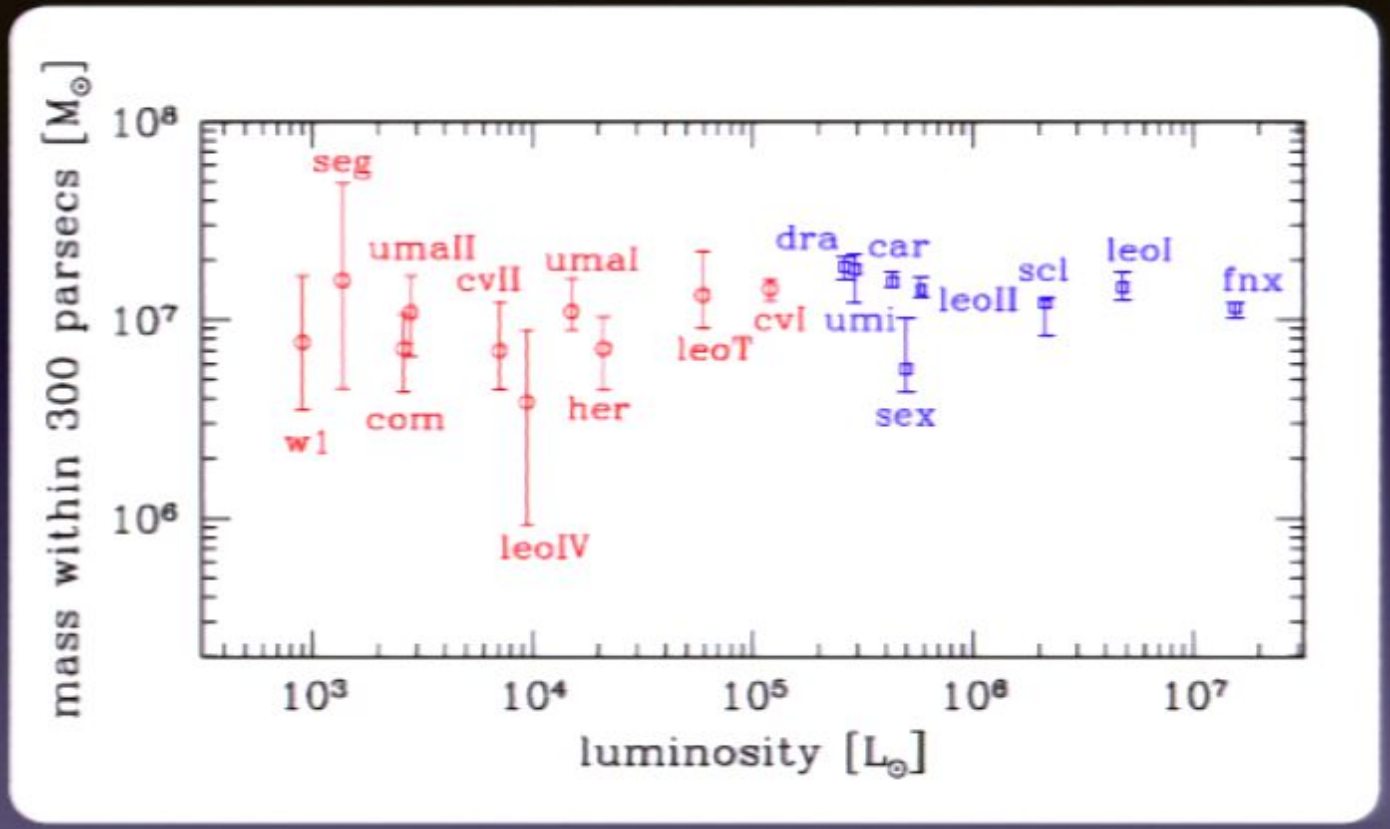

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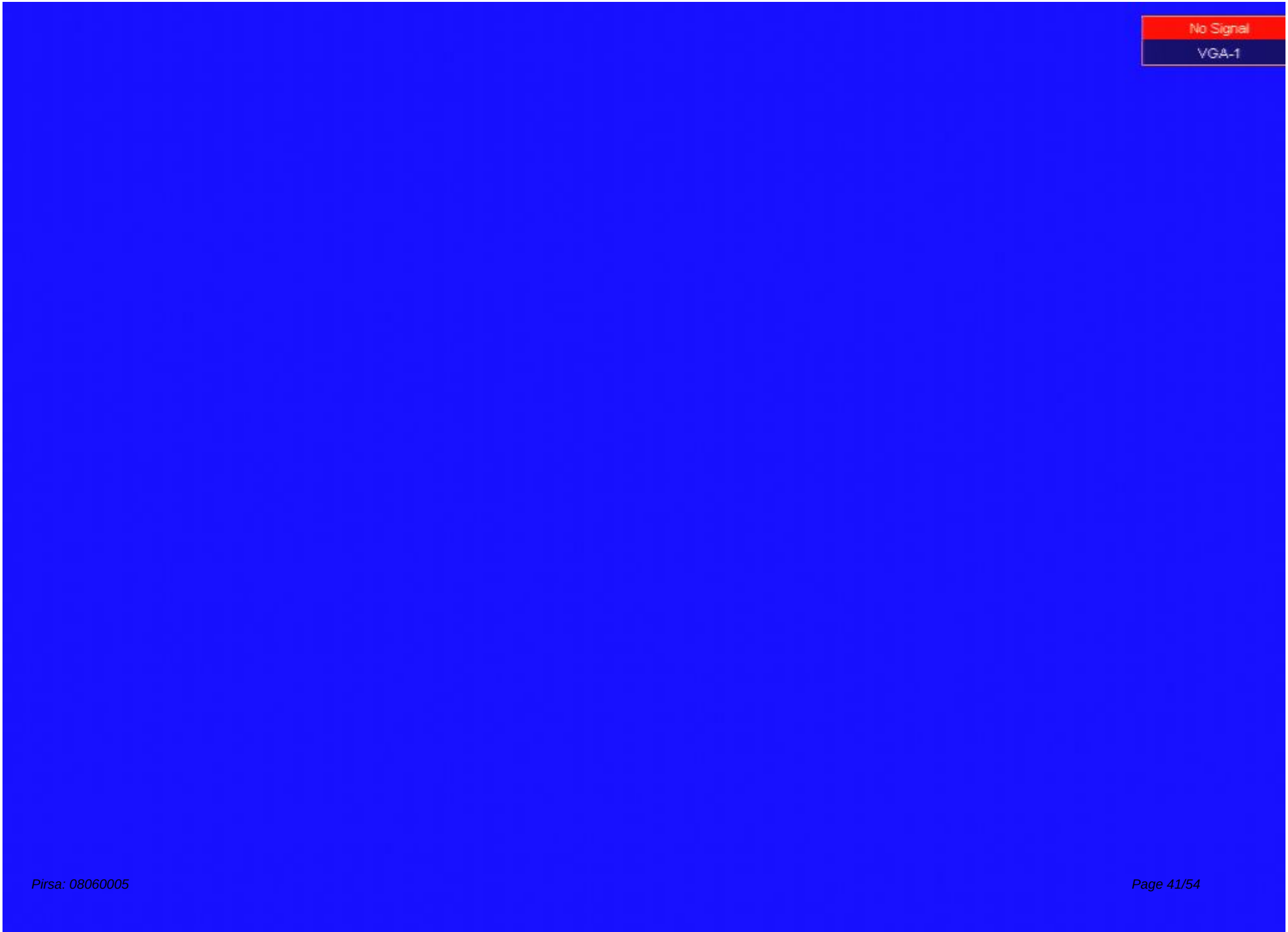
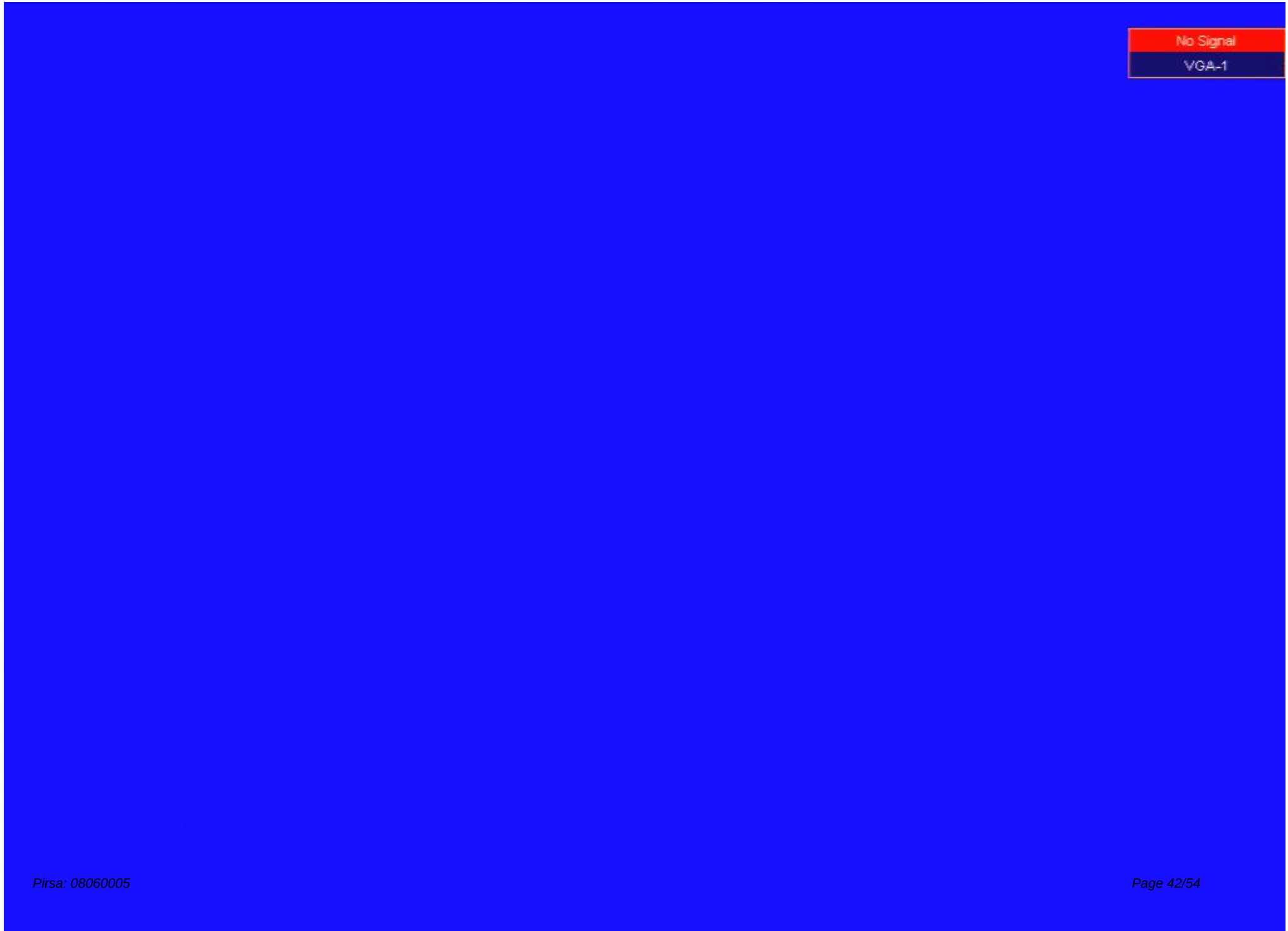

No Signal
VGA-1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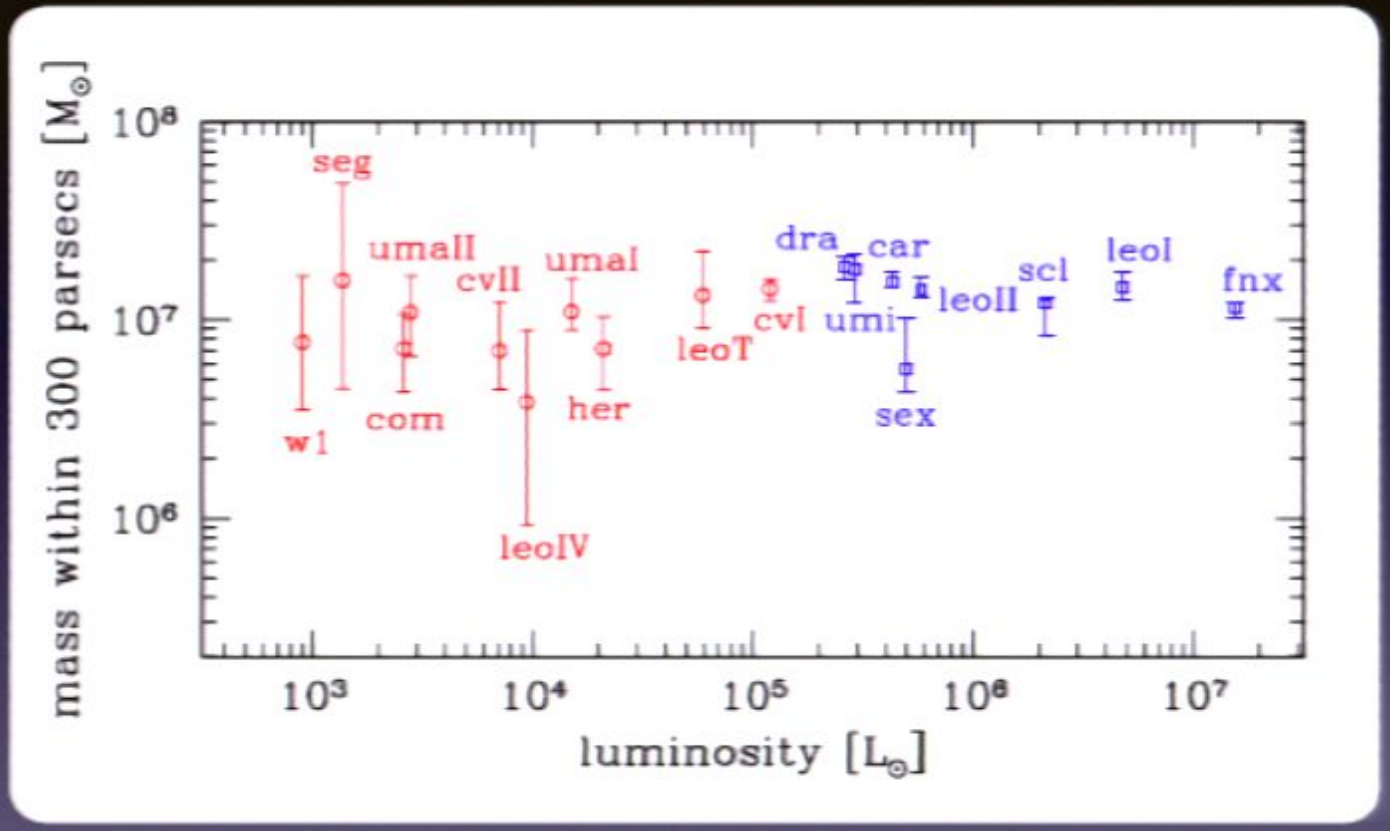
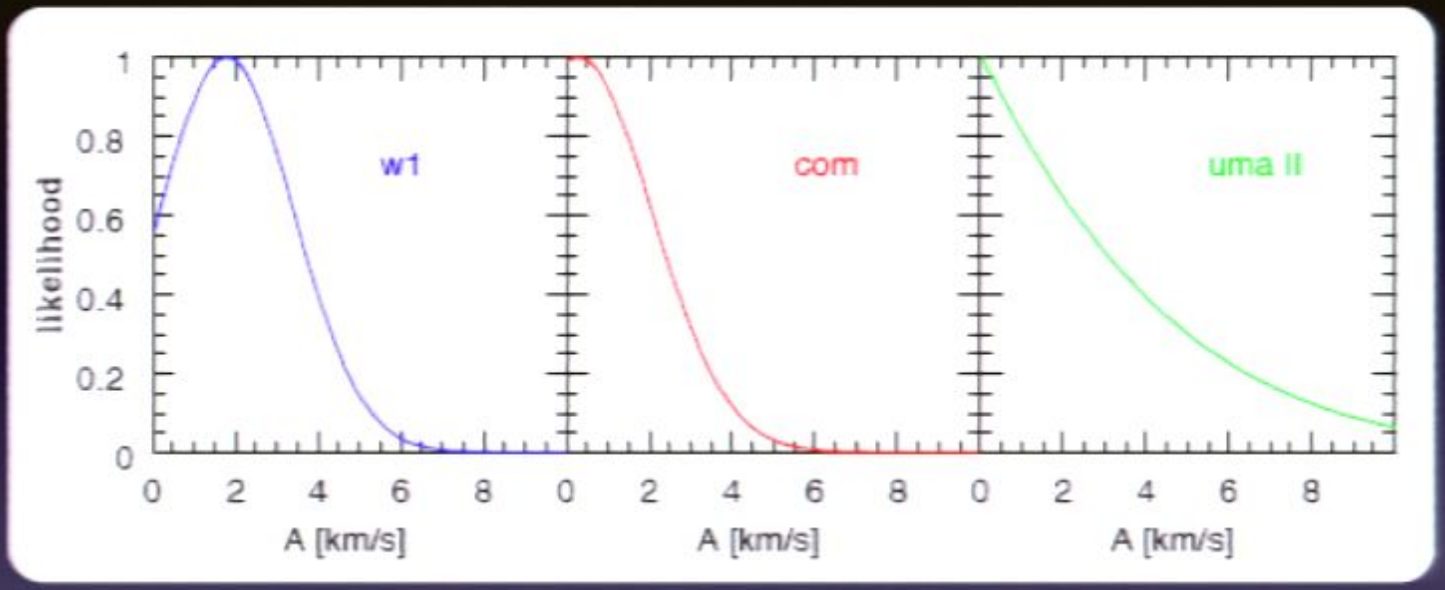
A Common Mass Scale for Milky Way Satellites



Strigari, Bullock, Kaplinghat, Simon, Geha, Willman, Walker [Nature in Press 2008]

Tidal Disruption and Rotation

Systemic velocity: $v \rightarrow v + A \sin(\phi - \phi_0)$

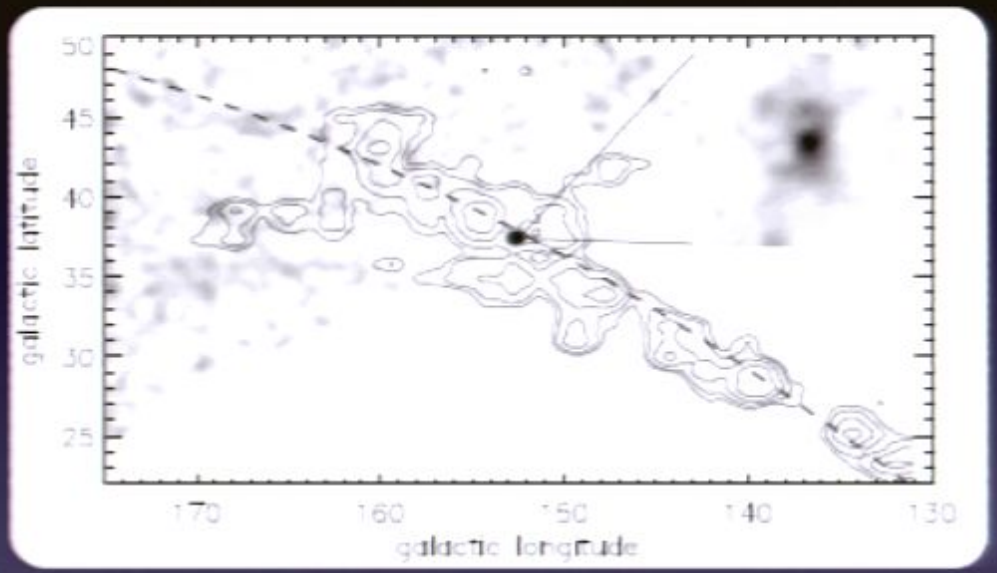


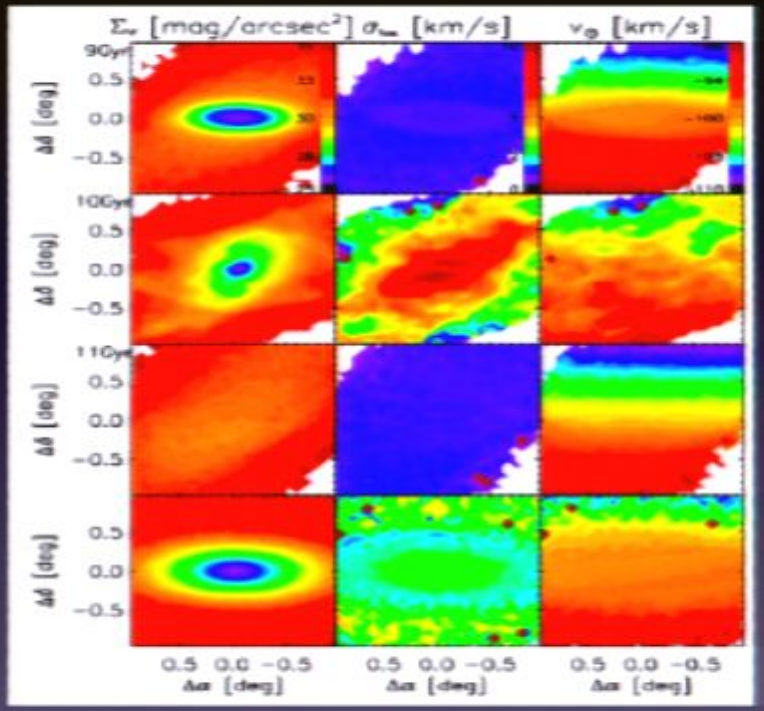
- Low-luminosity dwarfs: R ~100 pc
- Velocity dispersion: sigma ~ 5 km/s
- Distance: D ~ 30-40 kpc [nearest]

Internal gravitational force $F_{int} \sim \text{sigma}^2/R$
External Tidal force $F_{ext} \sim [220 \text{ km/s}]\ R/D^2$

Ratio of these forces is $F_{int}/F_{ext} \sim 100$

Tidal Disruption? Case of Ursa Major II





Zucker et al 2006

Ursa Major II lies on the same great circle as the SDSS-discovered Orphan Stream

However its association with Orphan Stream not clear (Fellhauer et al 2006)

Low-mass stellar systems: Redux

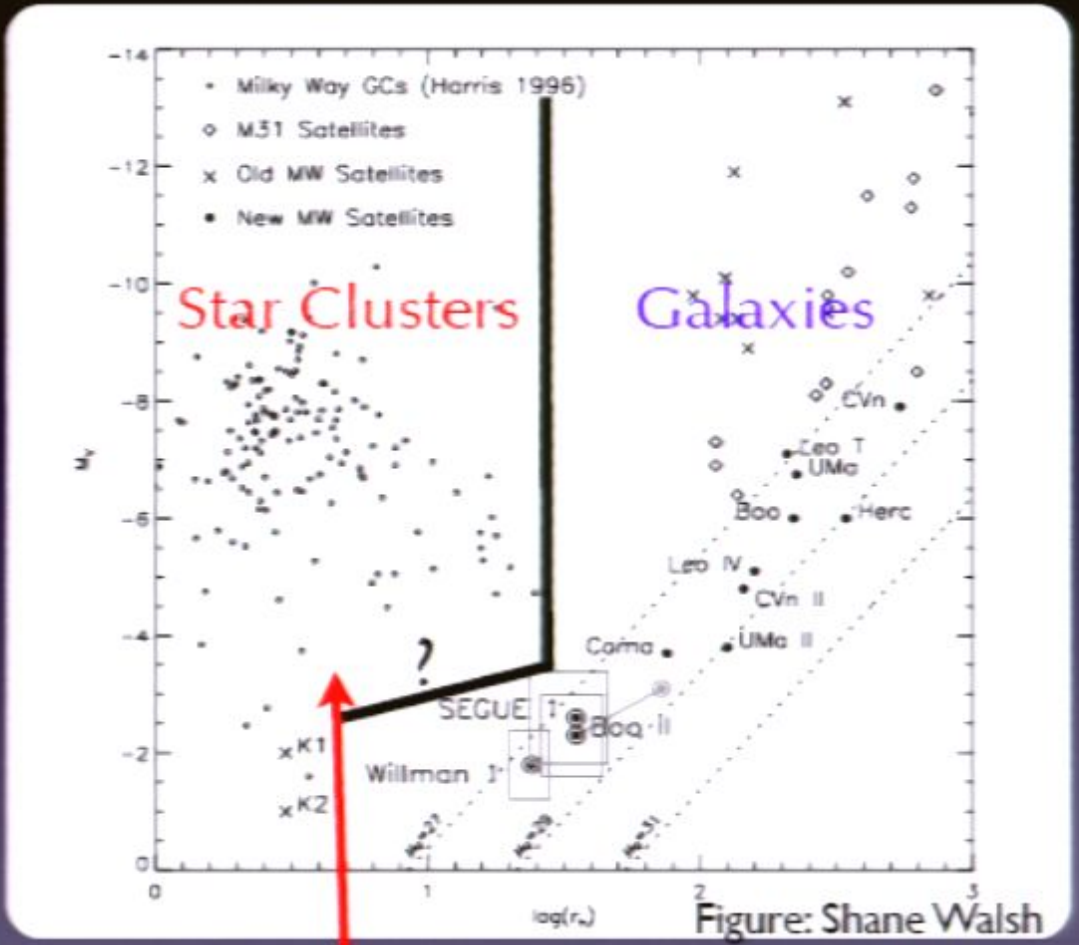


Figure: Shane Walsh

e.g. Palomar 13 Globular Cluster [Cote et al. 2002]

Gamma-ray signals

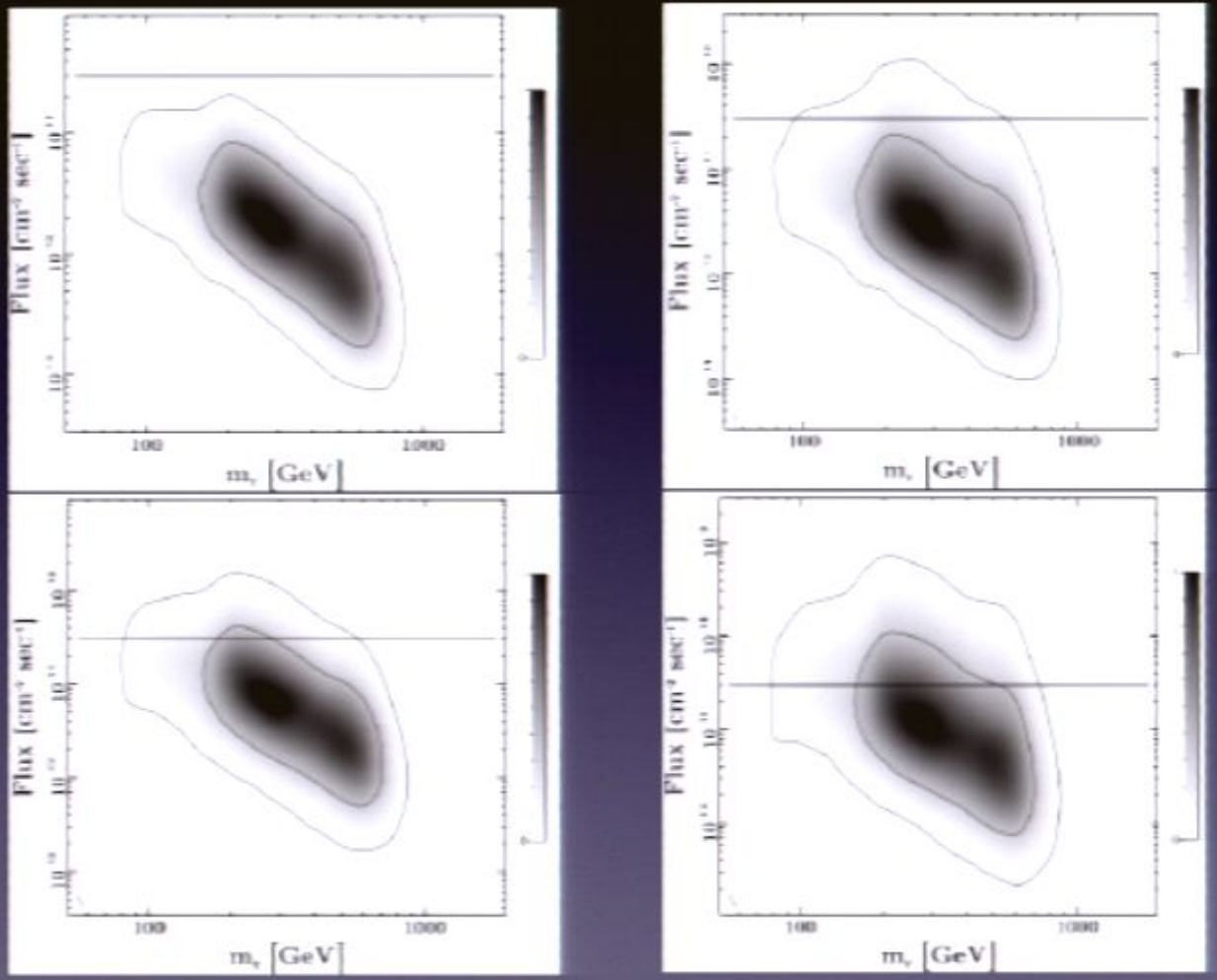
No Boost

With Boost

Preliminary results from G. Martinez et al, 2008

Draco

Willman 1

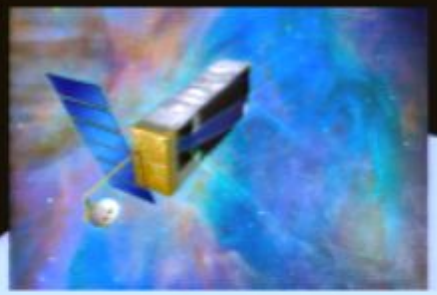


Local Group with micro-to-milli arcsecond astrometry

- Internal stellar proper motions
  - Dark matter density of dwarfs
  - Halo mass, lumpiness from streams and hyper velocity stars
  - Angular momentum distribution of outer halo stars
- Systematic proper motions
  - Orbits of Galactic satellites and star clusters
  - Local Group galaxies [M31, LMC, SMC]

SIM PlanetQuest (Space Interferometry Mission)

Astronomy = "star naming"
Astrometry = "star measuring"



Adapted from: http://planetquest.jpl.nasa.gov/SIM/sim_index.cfm

SIM Positional Error Circle (4μas)

Hipparcos Positional Error Circle (0.64 mas)

HST Positional Error Circle (~1.5 mas)

Reflex Motion of Sun from 100pc (axes 100 μas)

Parallactic Displacement of Galactic Center

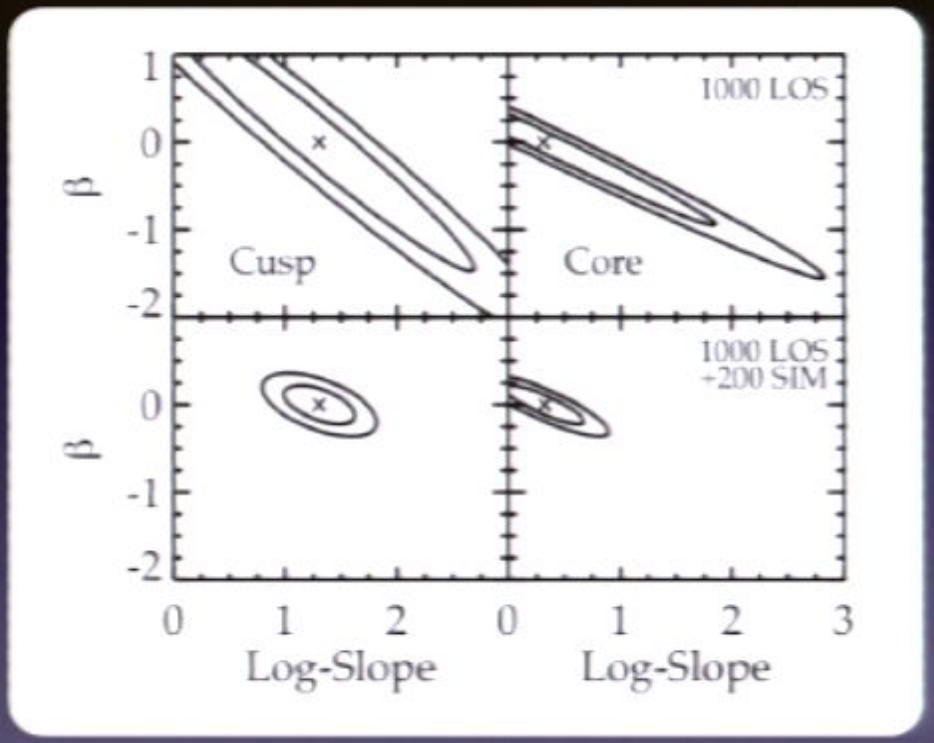
Apparent Gravitational Displacement of a Distant Star due to Jupiter 1 degree away

Louie Strigari, UC Irvine

Internal stellar proper motions

To determine the central slope, must break the degeneracy with the velocity anisotropy
[Wilkinson et al 2001, Strigari, Bullock, Kaplinghat 2007]

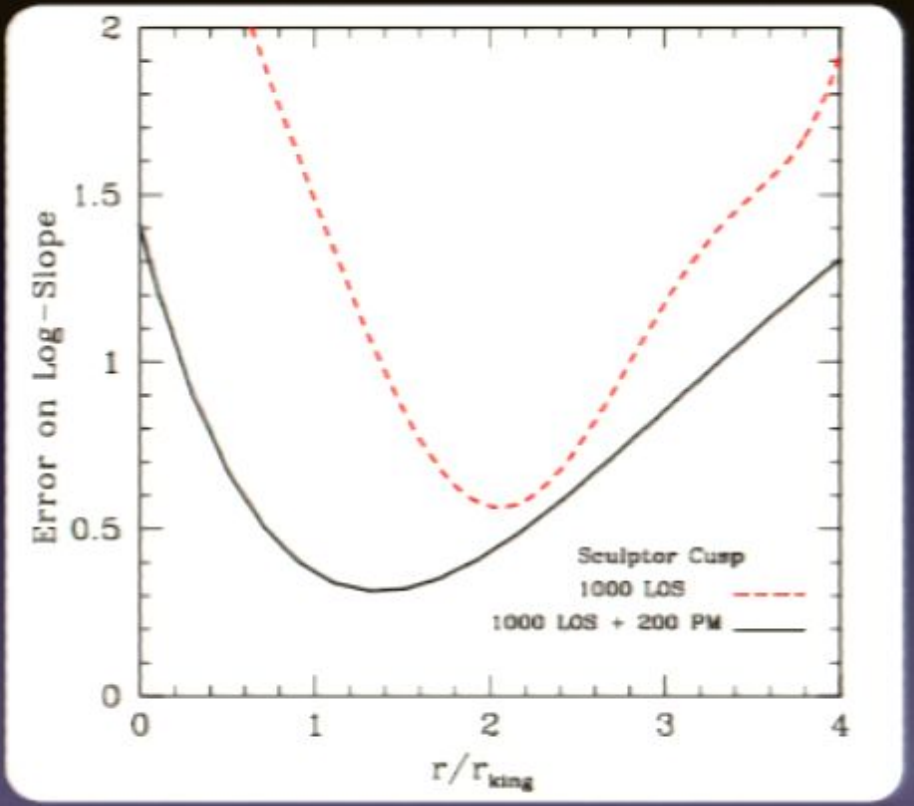
Constrain dark matter models [Kaplinghat talk]



Requirements for SIM

Similar absolute errors are achieved with many LOS velocities

However, proper motions always measure log-slope better in more central regions

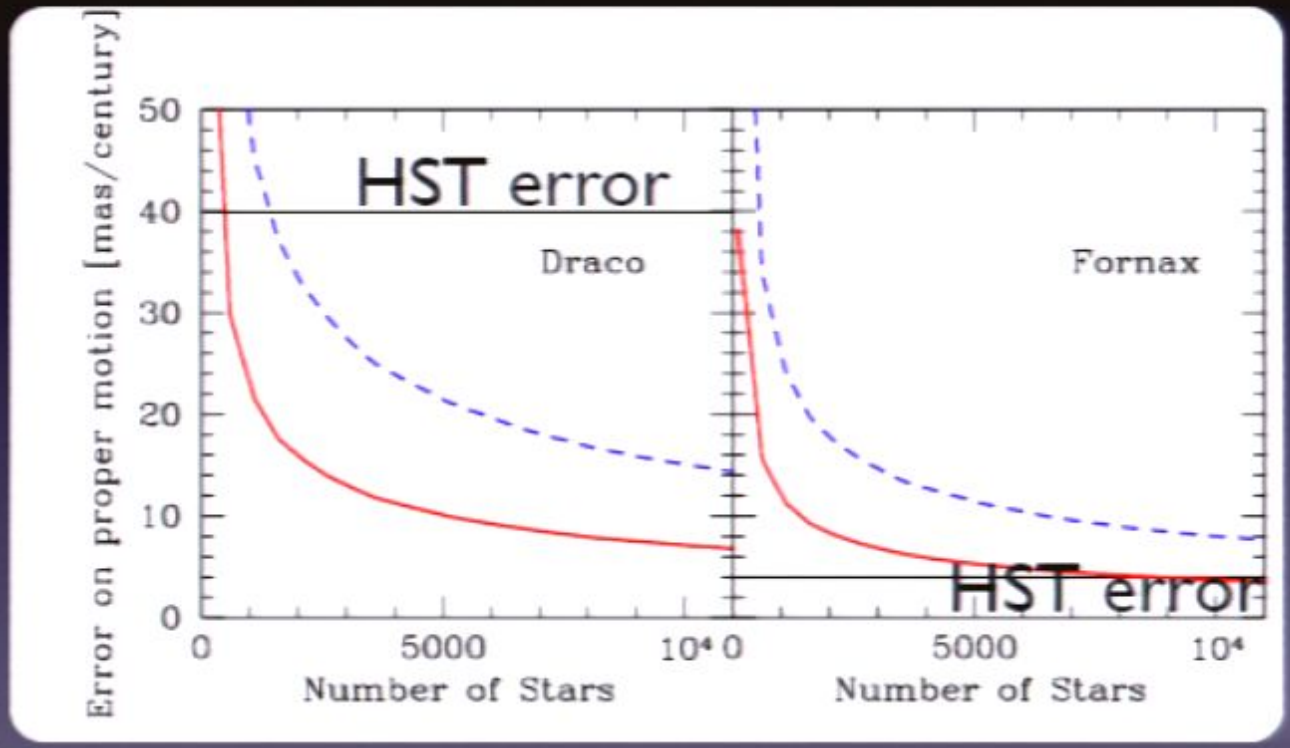


Systematic Proper Motions

- Mass of the Milky Way [Little & Tremaine 1987, Kochanek 1996, Wilkinson & Evans 1999]
- Orbital distribution tests CDM [e.g. Metz & Kroupa 2008, Zentner et al. 2006]
- Satellites on first passage?
  - LMC & SMC [Besla et al 2007]
  - Leo I [Mateo et al 2008]
- Proper motions poorly constrained [Piatek et al. HST measurements]

Proper motions from line-of-sight velocities

Actual LOS velocity: $v_z + v_x x/D + v_y y/D$



[Kaplinghat & Strigari 2008 ApJL in press]

Local Group Dynamics

- Does M31 have measurable tangential motion?
  - Constraints from M33 disk [Loeb et al 2005]
  - M31 Satellite kinematics [van der Marel & Guhathakurka 2008]
  - CMB dipole [Loeb & Narayan 2008]