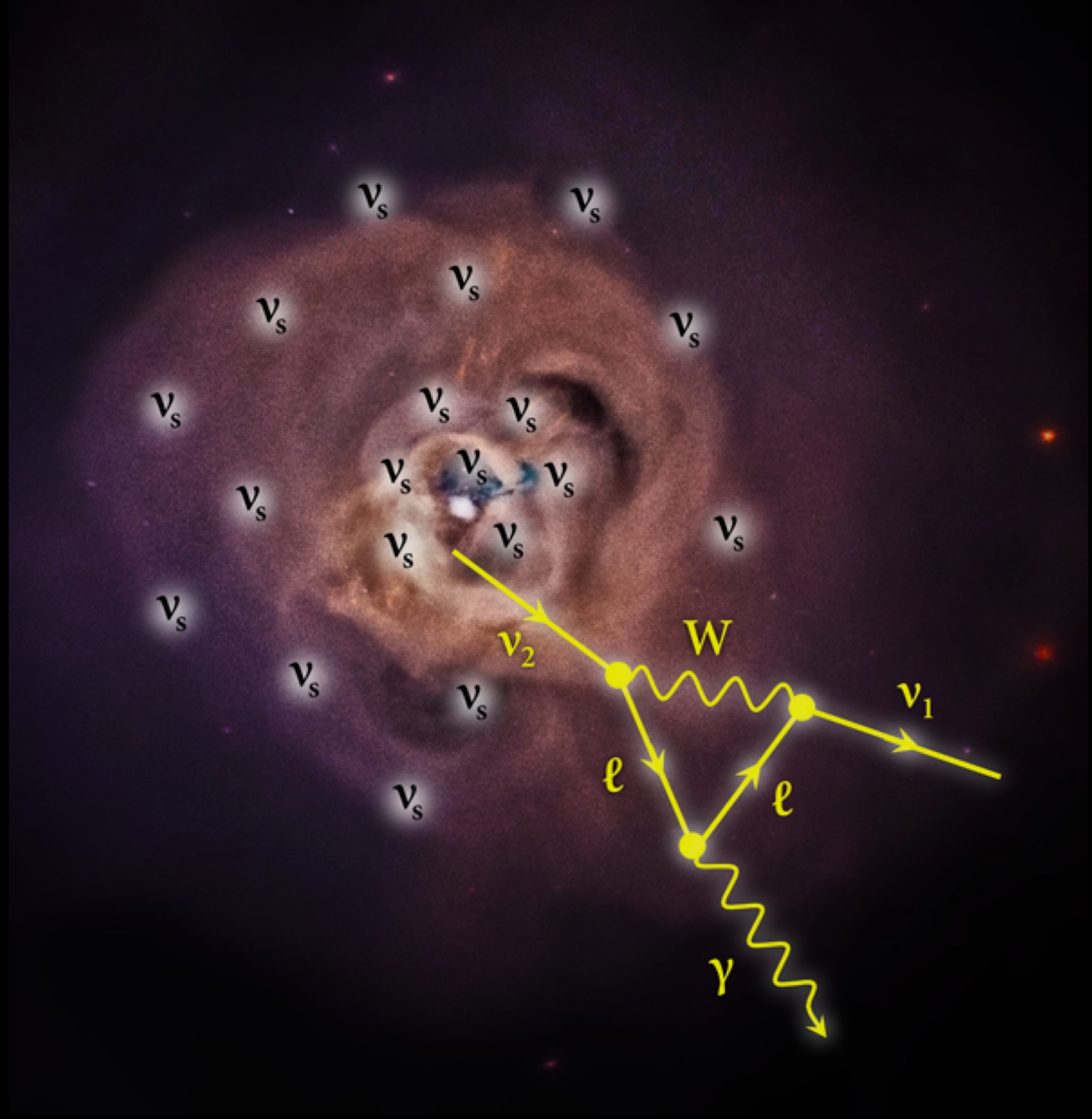
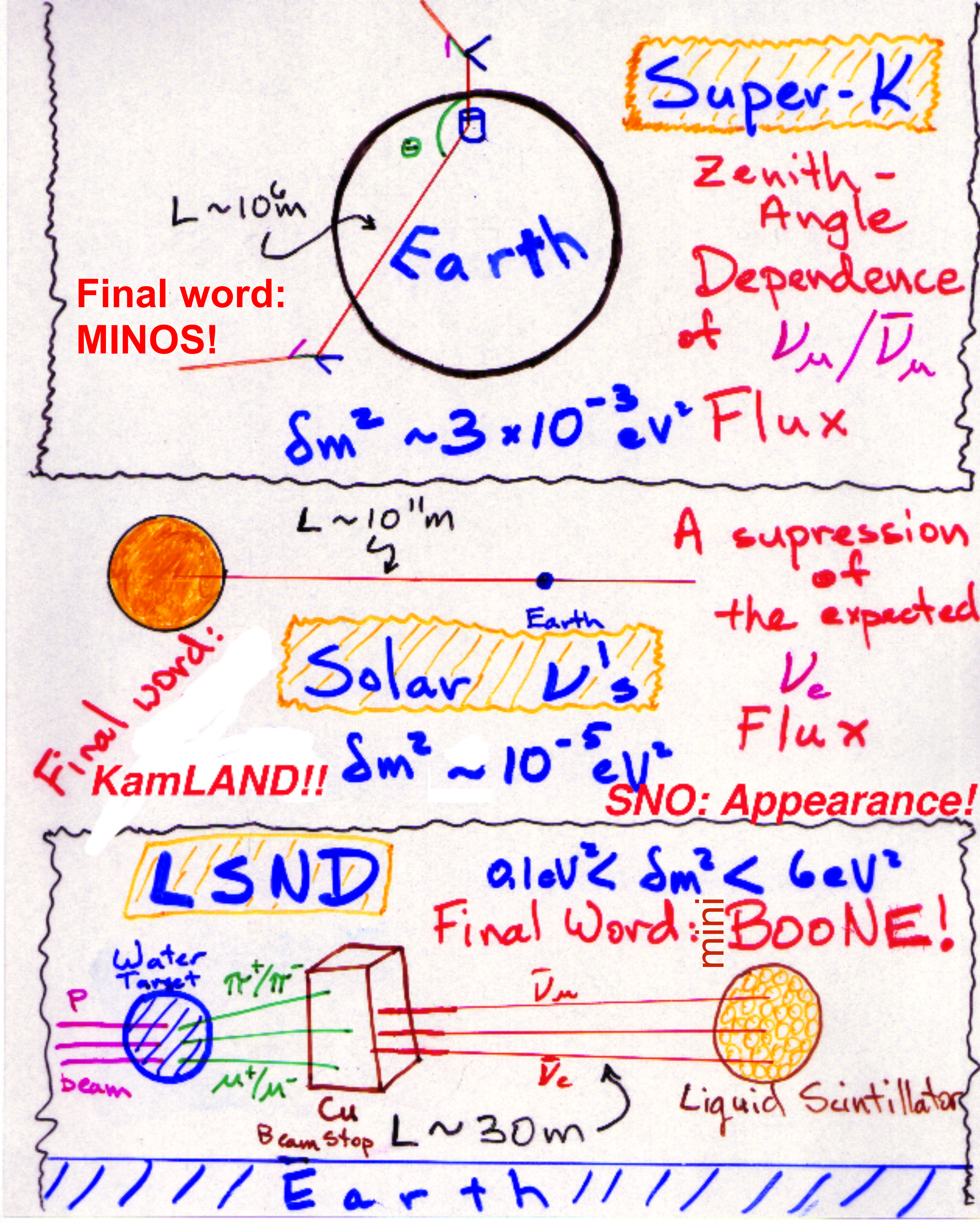



# Sterile Neutrino Dark Matter Interpretations of the 3.5 keV Line

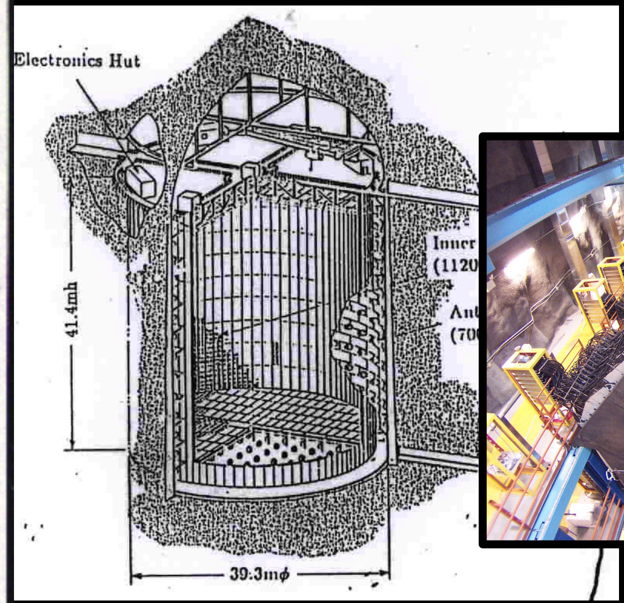
Kevork Abazajian
University of California, Irvine

June 6, 2016

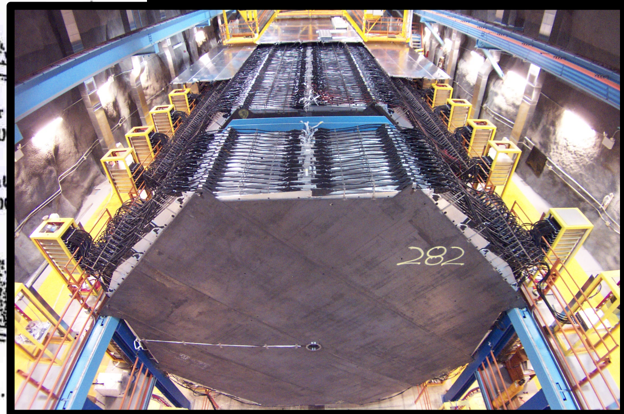
MPI Heidelberg

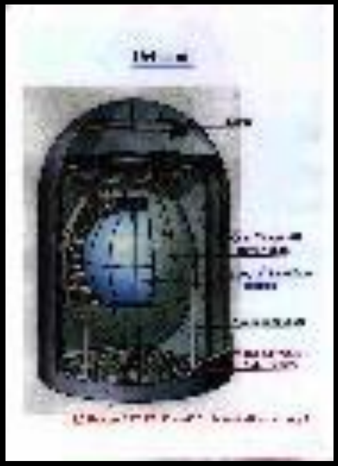
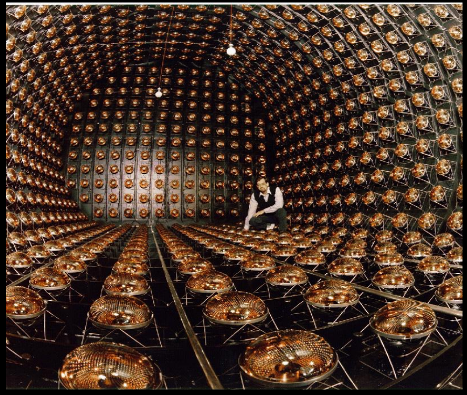
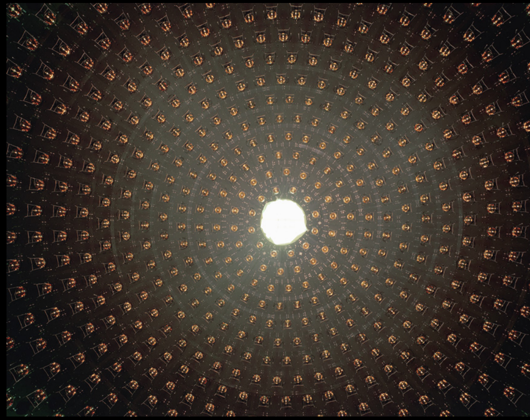


Super-K
Zenith-Angle Dependence of $\nu_\mu/\bar{\nu}_\mu$ Flux
$L \sim 10^6$ m
Earth
Final word: MINOS!
$\delta m^2 \sim 3 \times 10^{-3}$ eV$^2$
$L \sim 10^{11}$ m
Earth
Solar $\nu$'s
A supression of the expected $\nu_e$ Flux
Final word: KamLAND!!
$\delta m^2 \sim 10^{-5}$ eV$^2$
SNO: Appearance!
LSND
$0.1$ eV$^2 < \delta m^2 < 6$ eV$^2$
Final Word: miniBOONE!
Water Target
p beam
$\pi^+/\pi^-$
$\mu^+/\mu^-$
Cu Beam Stop
$\bar{\nu}_\mu$
$\nu_e$
$L \sim 30$ m
Liquid Scintillator
Earth



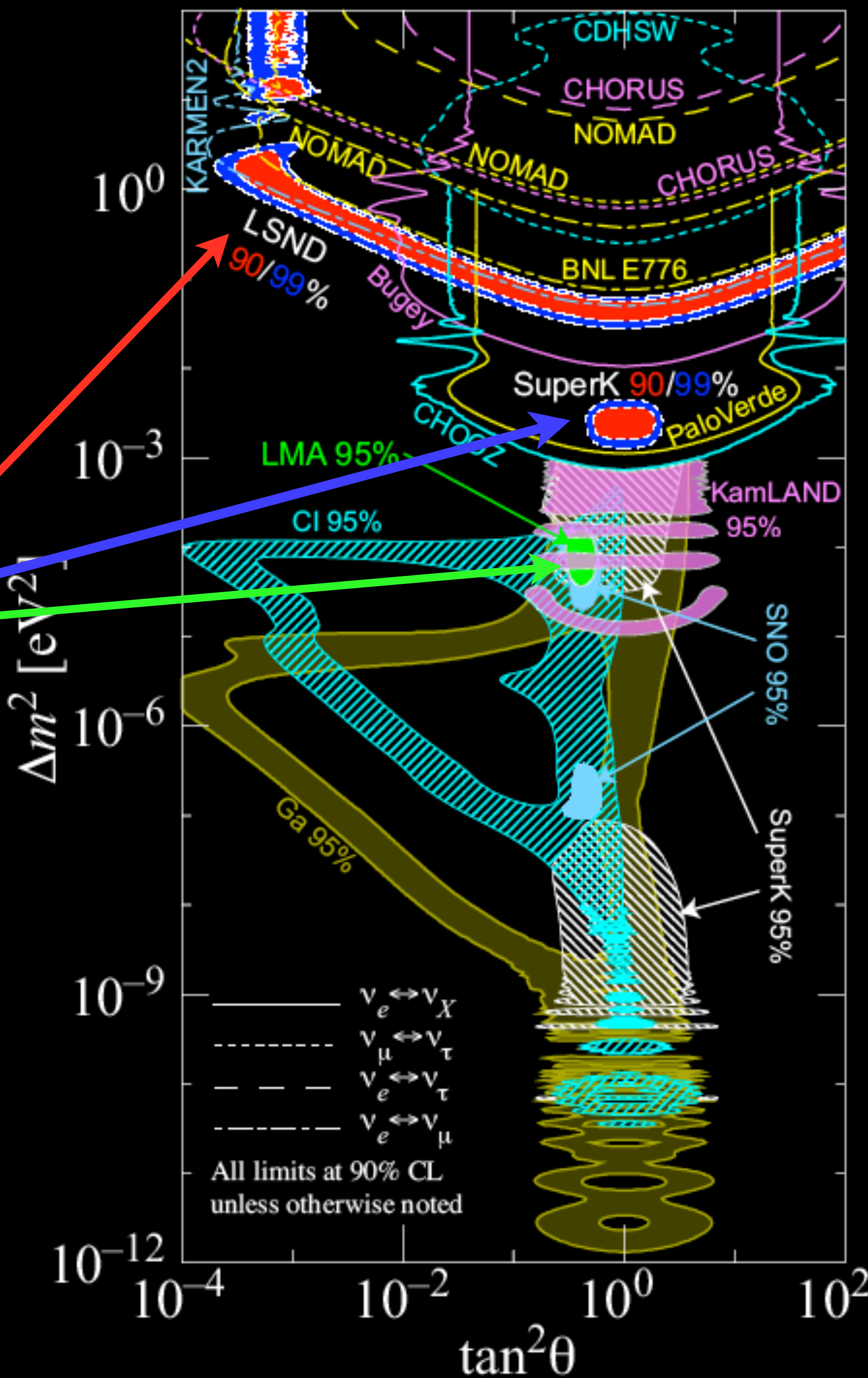
Electronics Hut
41.4m
39.3m

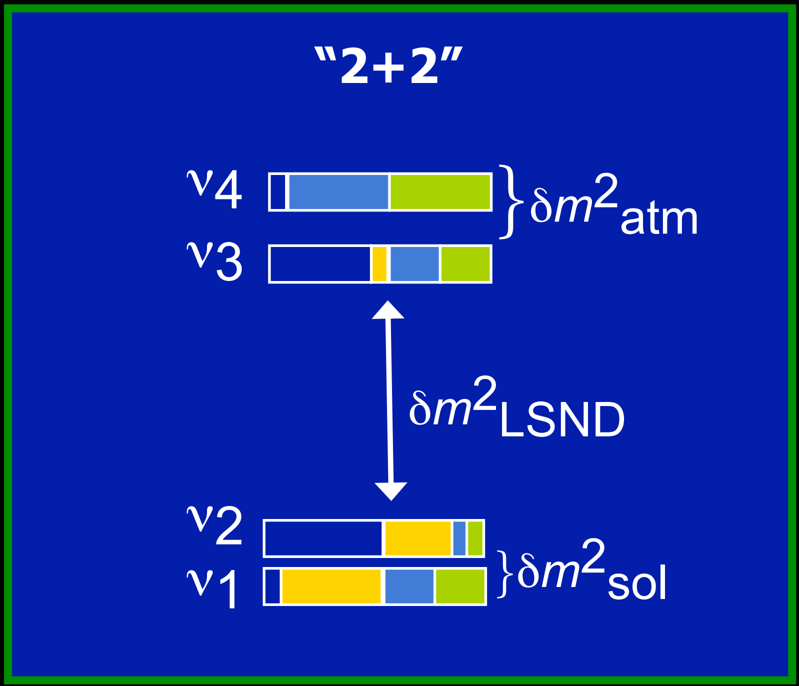


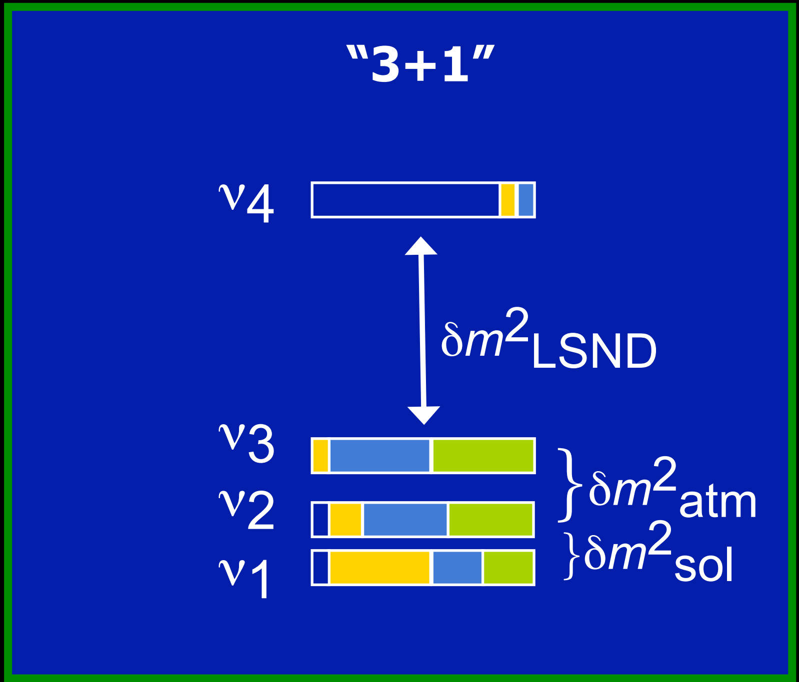




# Experimental Motivation: Too Much of a Good Thing?

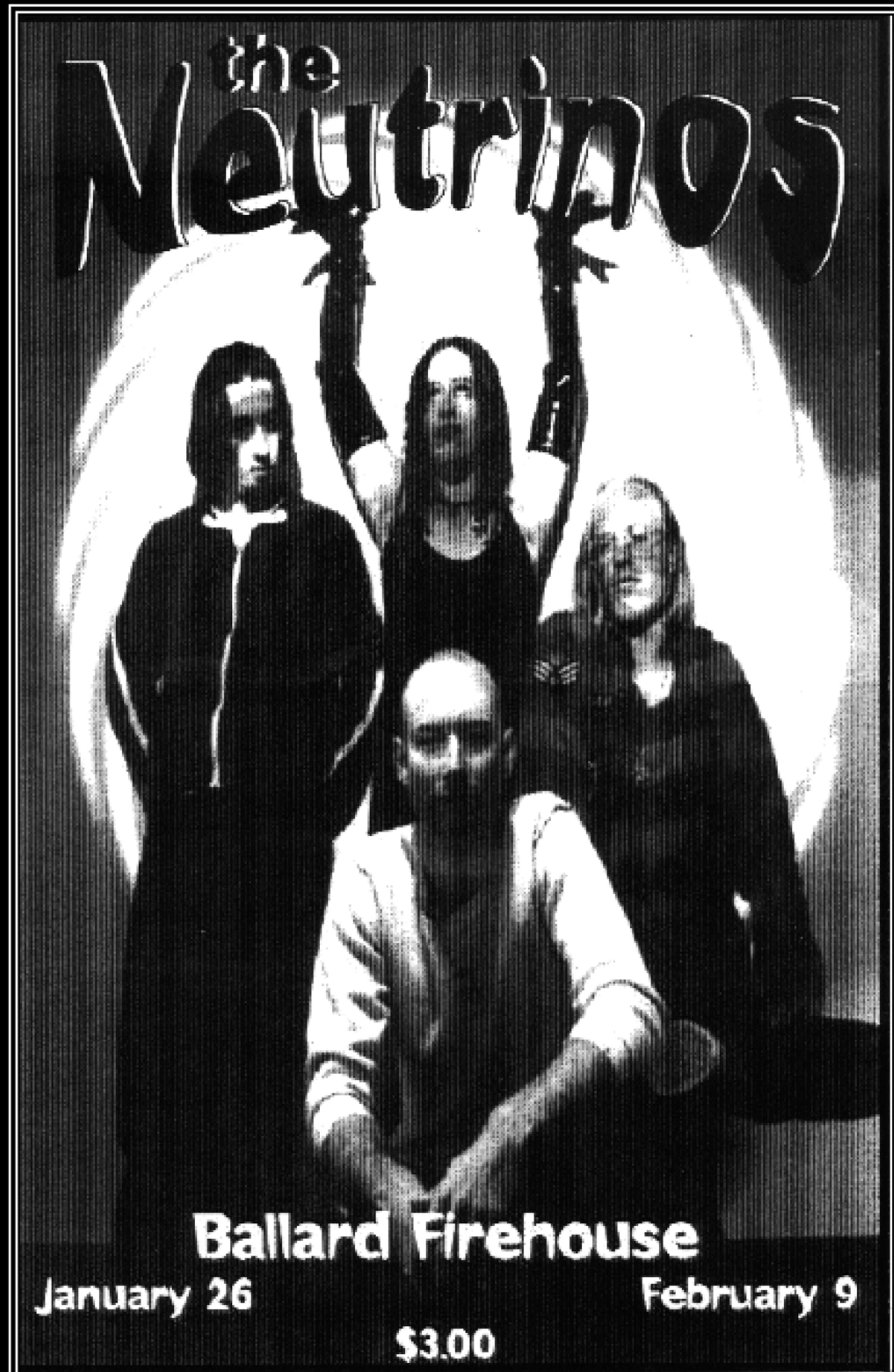
Three Mass Differences




PDG, RPP 2004


the
Neutrinos
Ballard Firehouse
January 26
February 9
$3.00

# Note:
# keV ≠ eV

$\boldsymbol{N_{\mathrm{eff}} = 3.15 \pm 0.23}$ (Planck Collab. 2015)

$\Rightarrow$ constrains *dark radiation*, not *dark matter*

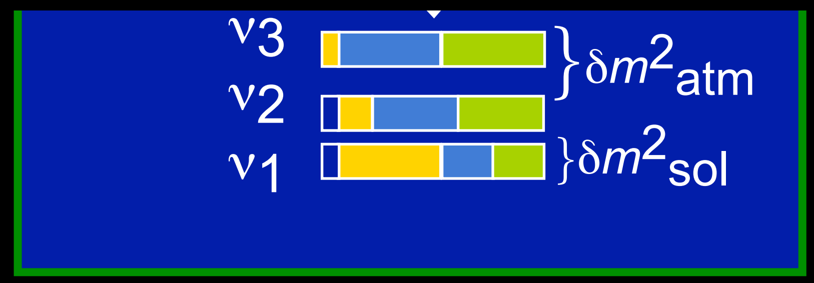
# Dark Matter Neutrinos

Sterile Neutrino Dark Matter $\nu_4$

$$
\begin{aligned}
|\nu_\alpha\rangle &= \cos\theta|\nu_a\rangle + \sin\theta|\nu_b\rangle \\
|\nu_s\rangle &= -\sin\theta|\nu_a\rangle + \cos\theta|\nu_b\rangle
\end{aligned}
$$

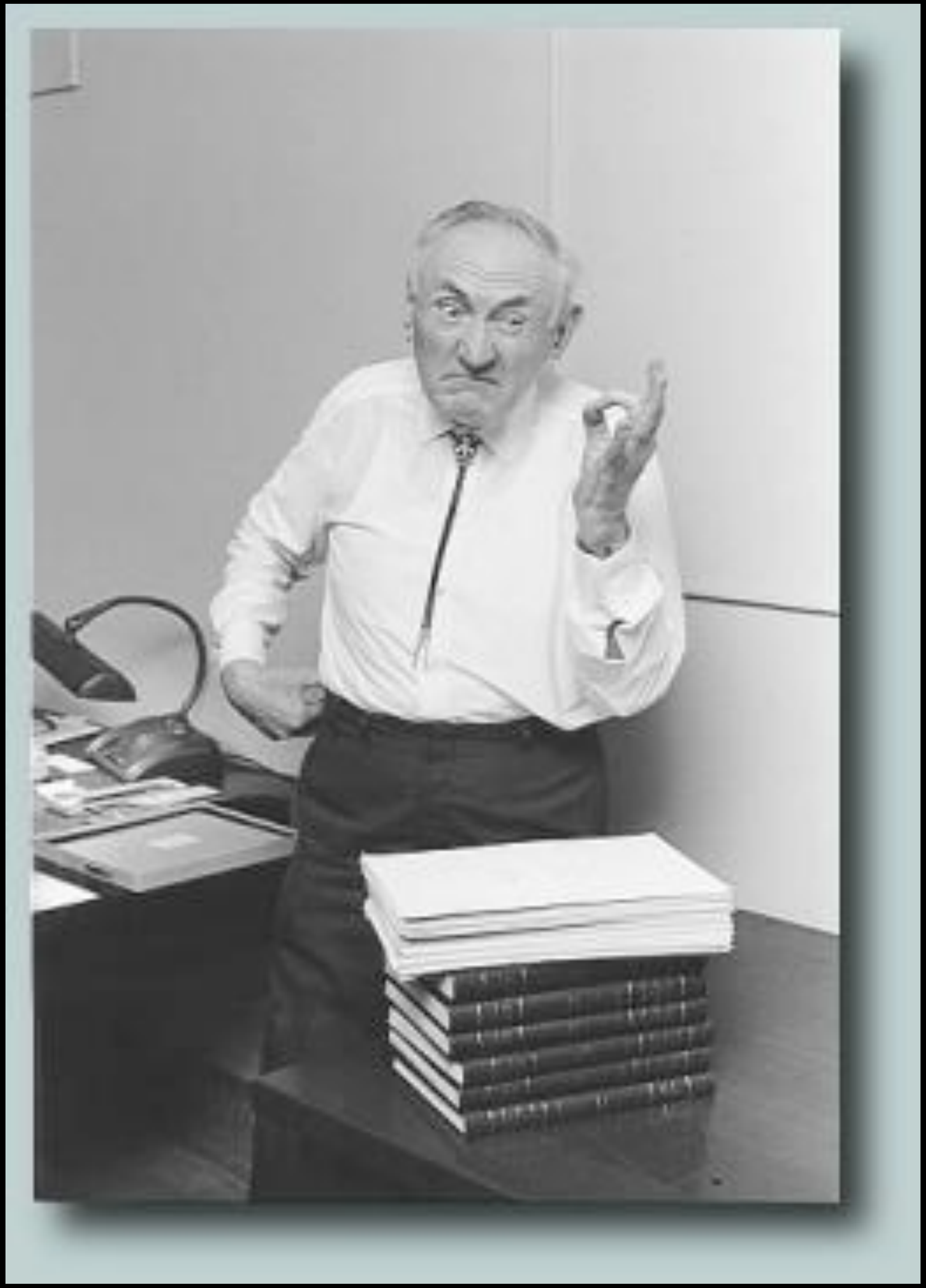
$\sim 1\ \mathrm{keV}$

$\sin^2 2\theta \lesssim 10^{-7}$




$\sim 0.01\ \mathrm{eV}$

# The Cosmological Dark Matter Problem

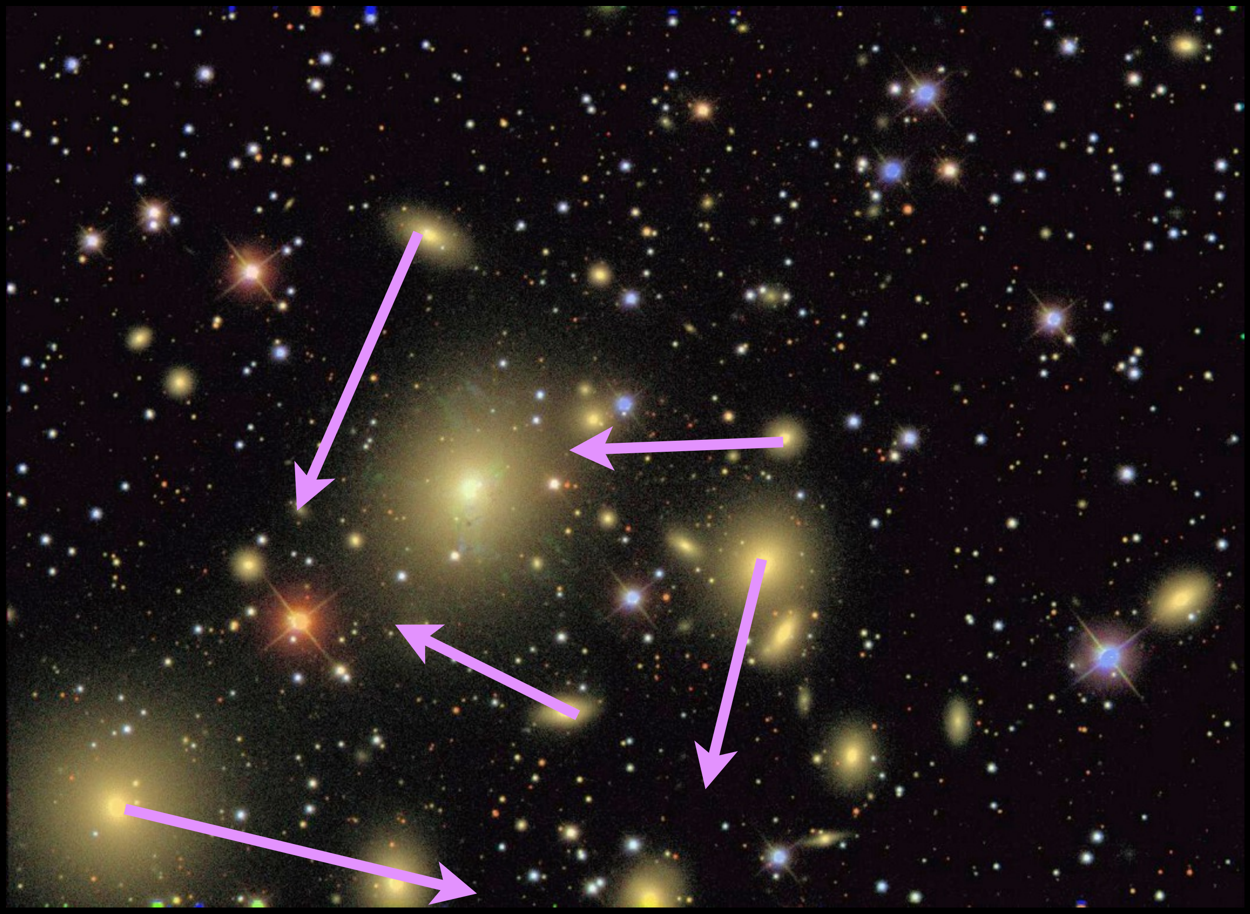


First indications: velocity of galaxies in a cluster

$$GM = \langle v^2 \rangle r_{1/2} \alpha^{-1}$$

$$\Rightarrow M \gg M_{\rm stars} + M_{\rm gas}$$

Zwicky (1933):
the "dunkel-materiel"/ the "dark matter"



# Sterile Neutrinos as Dark Matter: History

- "Super-weak" neutrinos ($G < G_F$) [Olive & Turner, 1982]: Earlier Decoupling, abundance set by standard dark matter production mechanism of decoupling temperature and degrees of freedom disappearance

- "Sterile" neutrinos [Dodelson & Widrow, 1993]: No SM interactions beyond mass terms, inclusion of finite-temperature modifications to self-energy, lack of thermalization. WDM.

- "Resonant" sterile neutrinos [Shi & Fuller, 1999]: Finite temperature production with non-zero lepton number resonant enhanced production. WDM to CDM. "Cool" Dark Matter.

- "Precision" Sterile Neutrino Dark Matter & **Proposal for X-ray Detection** [Abazajian, Fuller & Patel 2001; KA 2005]: Full momentum-space production description with QCD transition corrections, resonant to non-resonant solutions as a continuum in lepton number.

# Sterile Neutrinos

## Beyond the Standard Model of Particle Physics

- $\nu_s$ Phenomenological Insertion of Majorana & Dirac Mass Terms of Comparable Magnitude (atmos. & solar) (e.g. $\nu$MSM Asaka et al 2006)

- $\nu_s$ Left-Right Symmetric Models (Pati & Salam 1974; Mohapatra & Pati 1975)

- $\nu_s$ Higher Dimensional Operators in String-Inspired models (Langacker 1998)

- $\nu_s$ Bulk Fermions in Large Extra Dimensions (ADD; Dvali & Smirnov 2000)

- $\nu_s$ Axino in R-parity Violating Minimal Supersymmetric Models (Chun & Kim 1999)

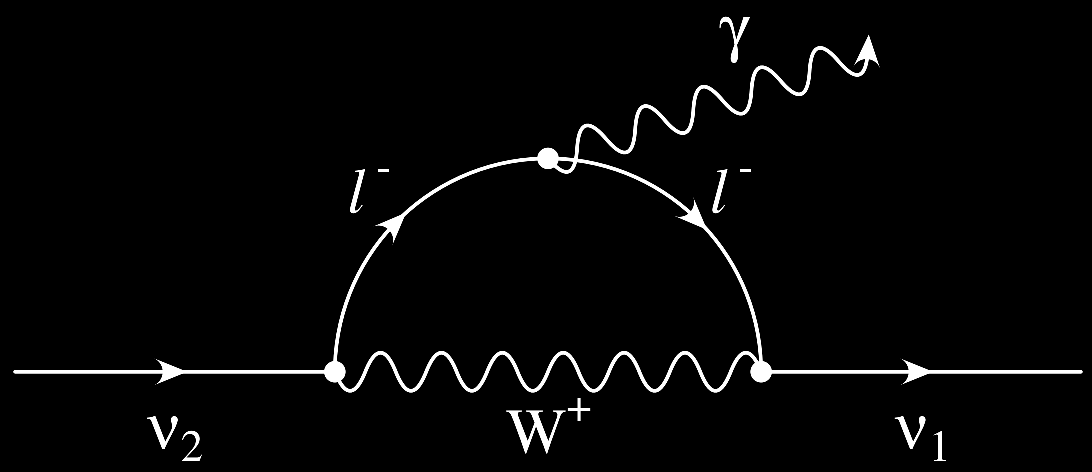
# The $\nu$MSM : a minimalist model

- "Neutrino Minimal Standard Model of Particle Physics"
- Model stipulates that short-baseline anomalies have nothing to do with neutrino oscillations
- Basically the minimal "mini see-saw" mechanism

$$\delta\mathcal{L} = \bar{N}_I i\partial_\mu\gamma^\mu N_I - f^\nu_{I\alpha}\Phi\bar{N}_I L_\alpha - \frac{M_I}{2}\bar{N}^c_I N_I + h.c.$$

- Two heavy ≳ 100 GeV sterile neutrinos provide atmospheric & solar mass scales, leptogenesis; **no room for LSND**
- Light sterile neutrino is the Dark Matter [Asaka, Blanchet & Shaposhnikov 2005]
- More involved models generally involve similar insertions for neutrino mass generation

# Sterile ν WDM Radiative Decay in the X-ray

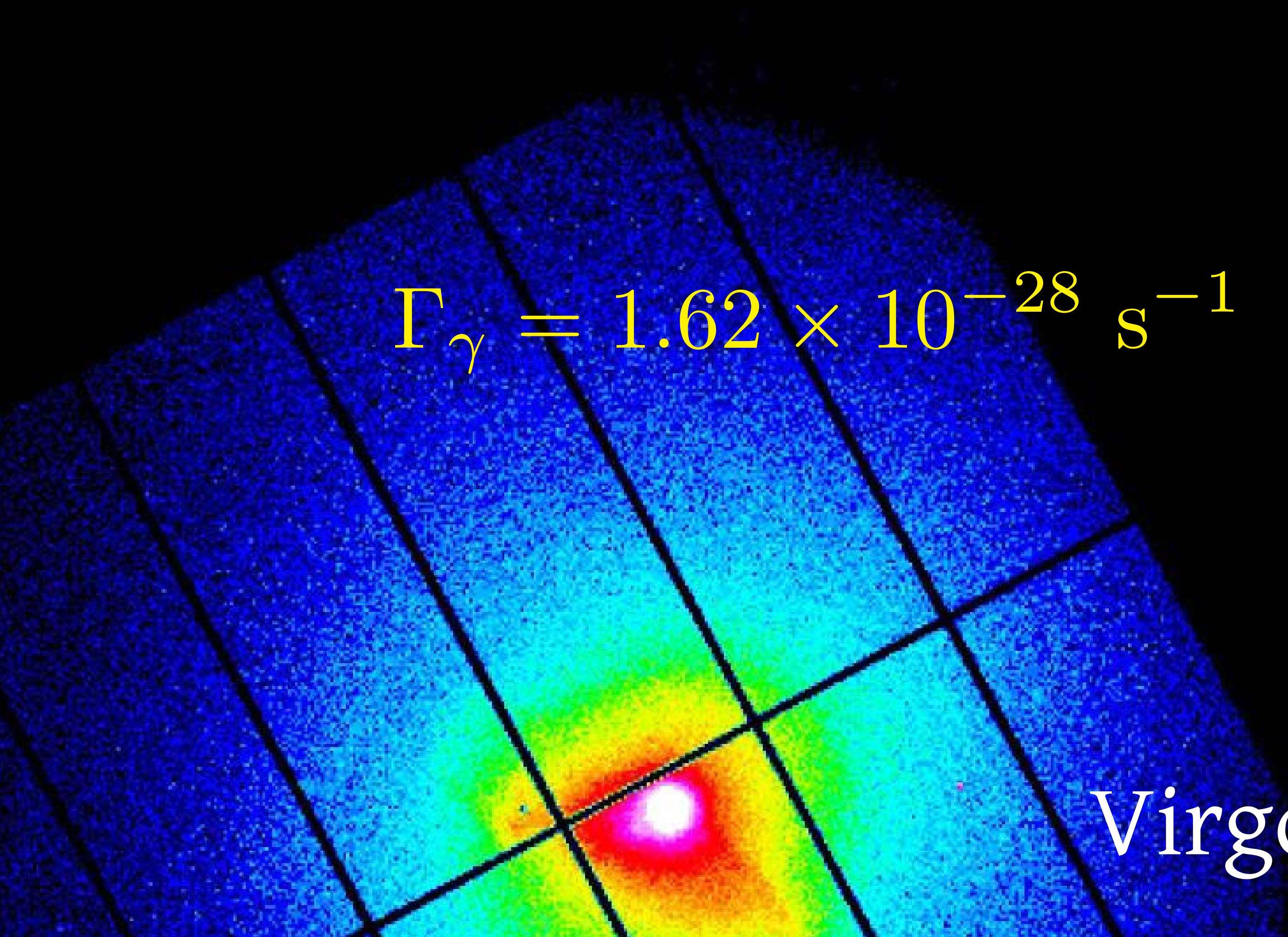



**Decay**: Shrock 1974; Pal & Wolfenstein 1981
**X-ray**: Abazajian, Fuller & Tucker 2001

$$``\nu_s" \rightarrow ``\nu_\alpha" + \gamma$$

$$E_\gamma = \frac{m_s}{2} \sim 1 \text{ keV}$$

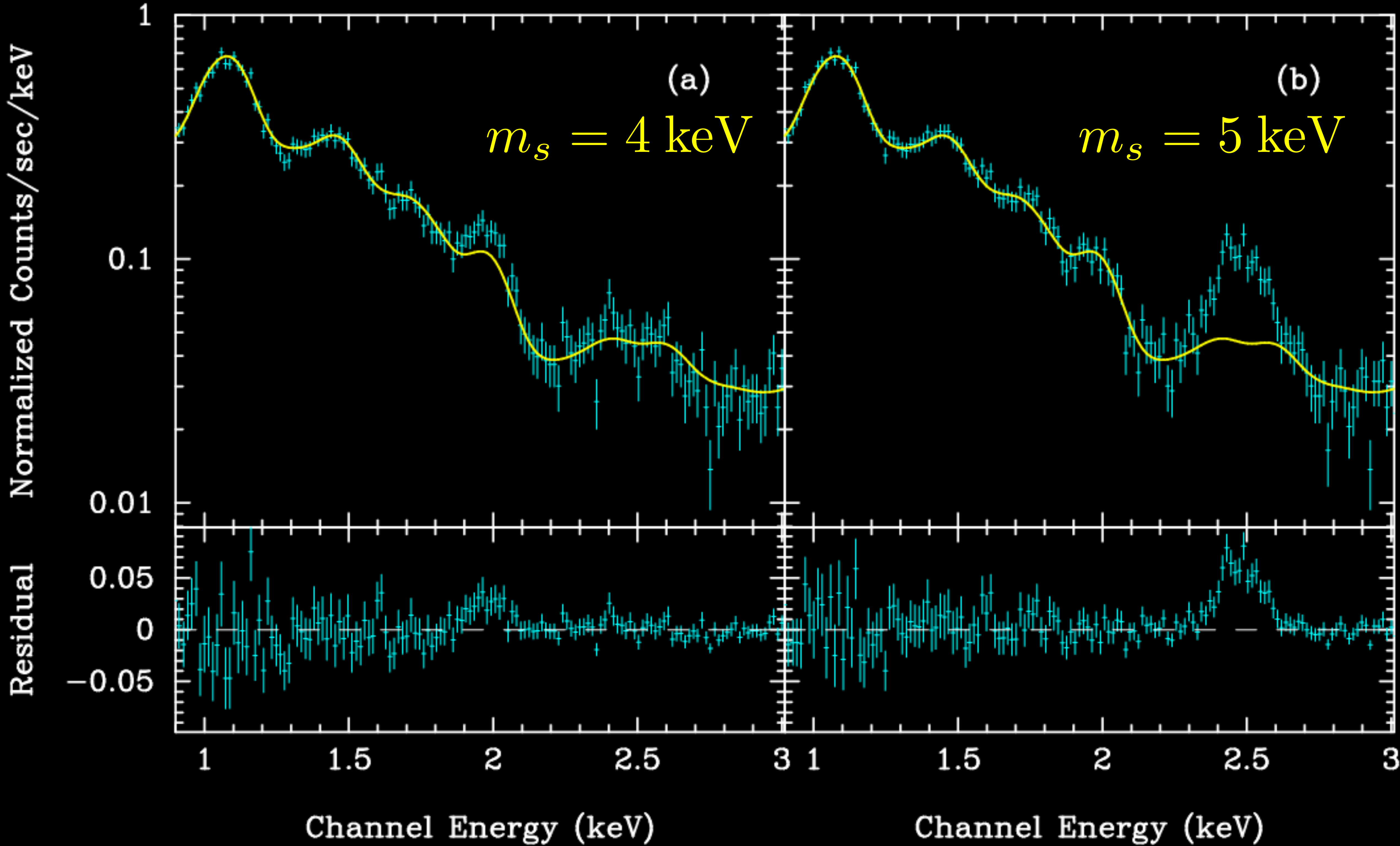
$$\Gamma_\gamma = 1.62 \times 10^{-28} \text{ s}^{-1} \left(\frac{\sin^2 2\theta}{7 \times 10^{-11}}\right)\left(\frac{m_s}{7 \text{ keV}}\right)^5$$



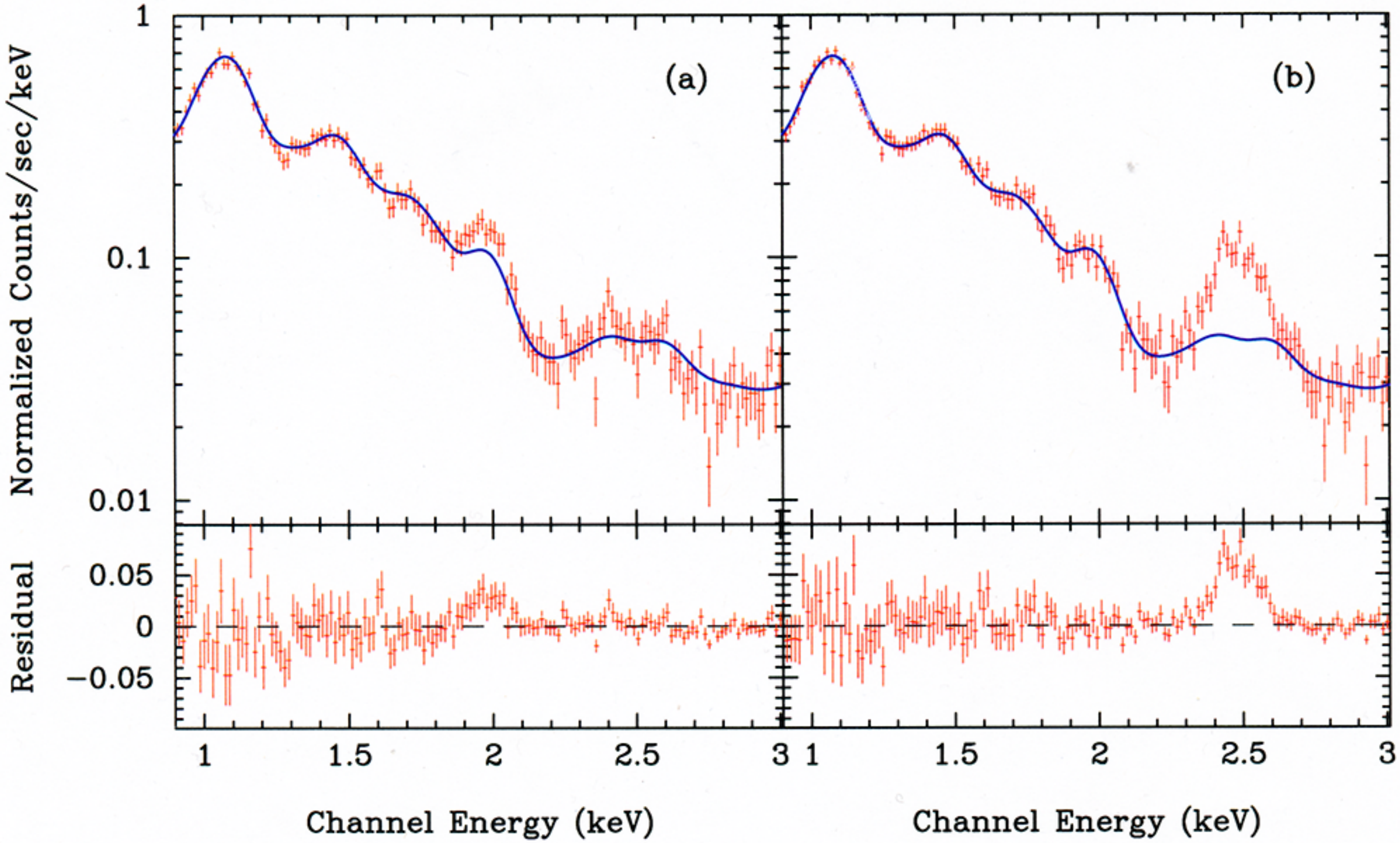
Virgo Cluster: $10^{78}$ DM particles

# Upper Mass Limit on $\nu_s$ DM: X-ray observations of Virgo

Abazajian, Fuller & Tucker 2001



Slide from 2001

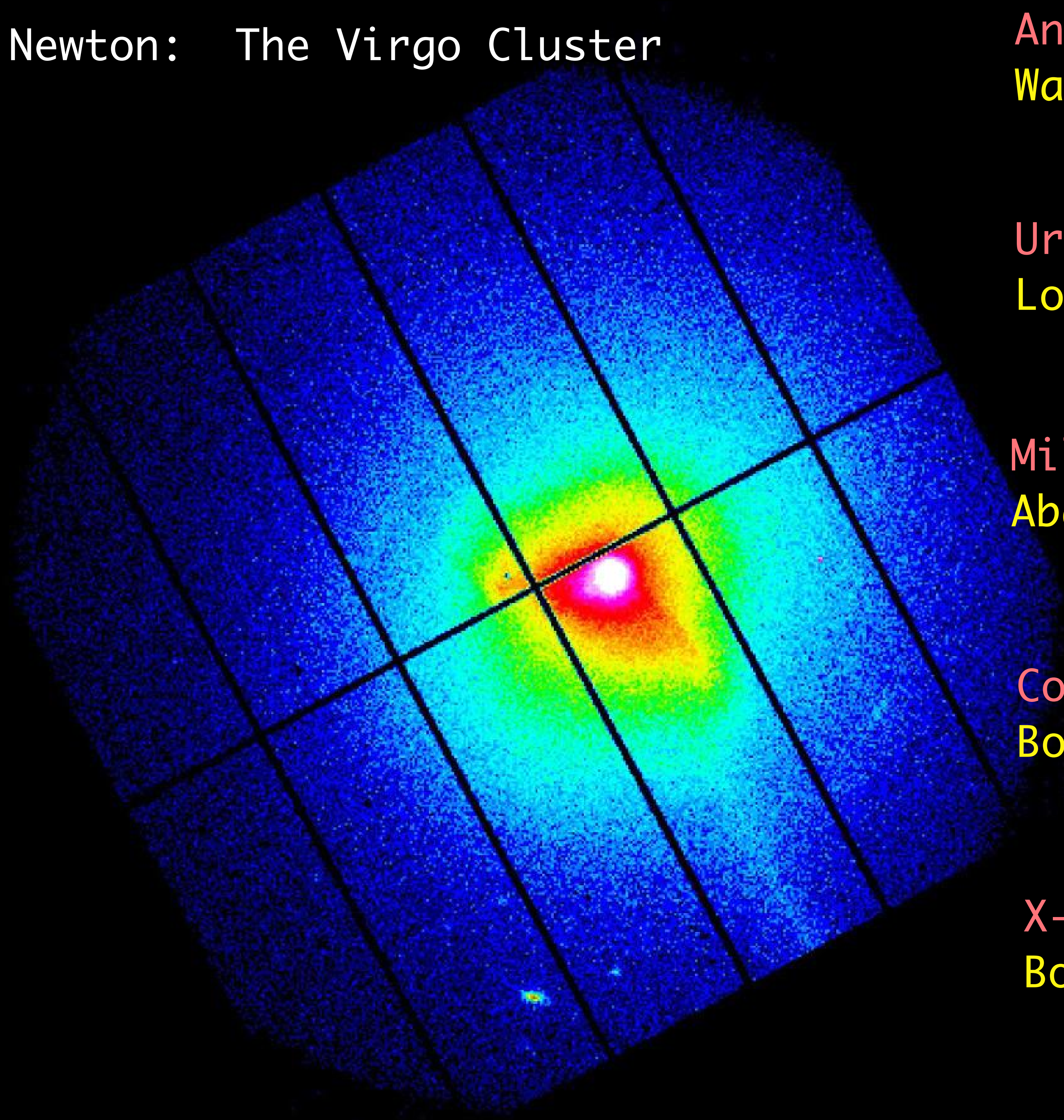



Current Limits

+

Future Detection?

# X-ray Constraint Summary




Andromeda Galaxy:
Watson et al. 2011

$$m_s < 2.2 \text{ keV}$$

Ursa Minor:
Lowenstein et al. 2008

$$m_s < 3.1 \text{ keV}$$

Milky Way in CXB:
Abazajian et al. 2006

$$m_s < 5.7 \text{ keV}$$

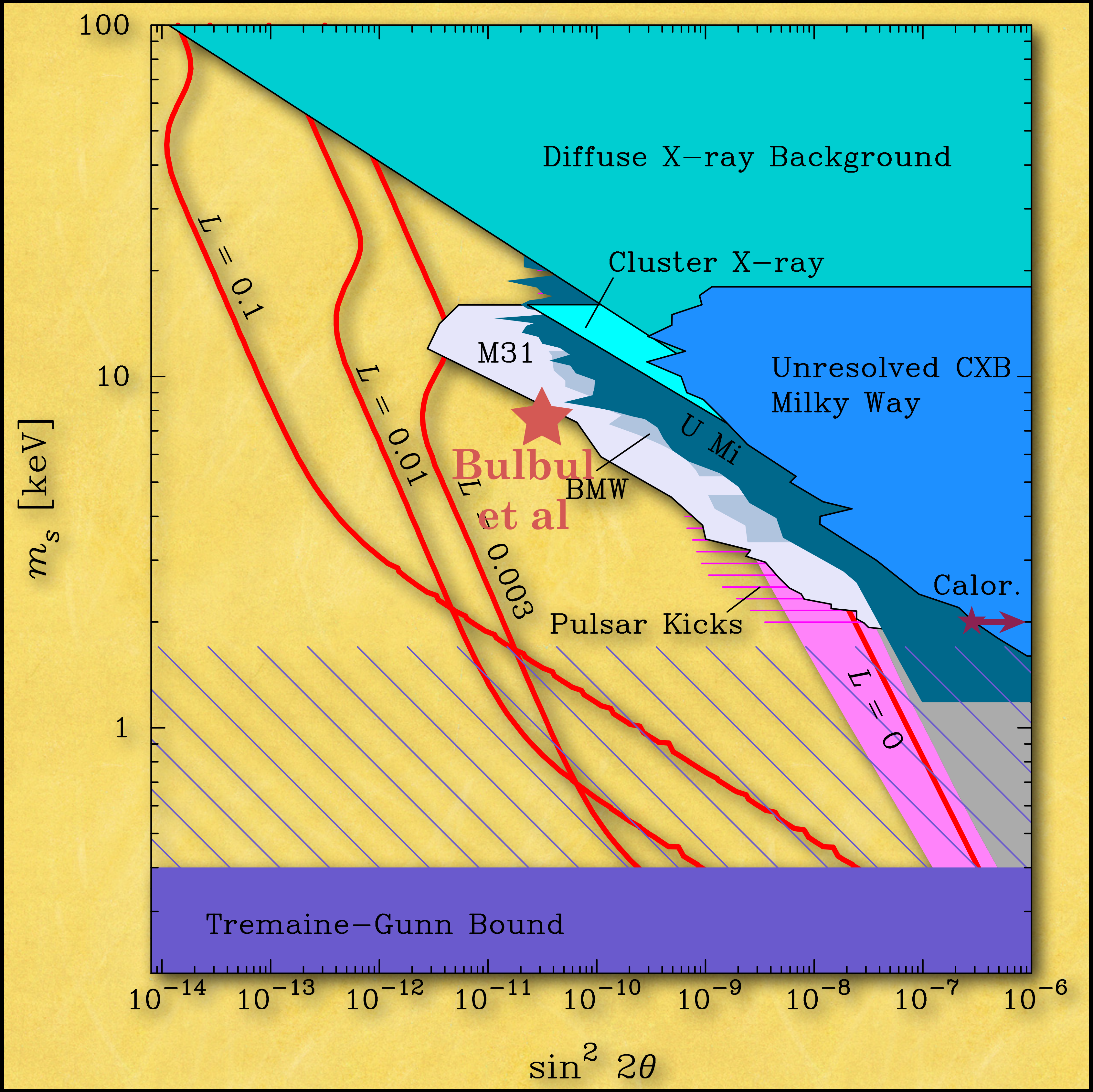
Coma + Virgo Clusters:
Boyarsky et al. 2006

$$m_s < 6.3 \text{ keV}$$

X-Ray Background:
Boyarsky et al. 2006

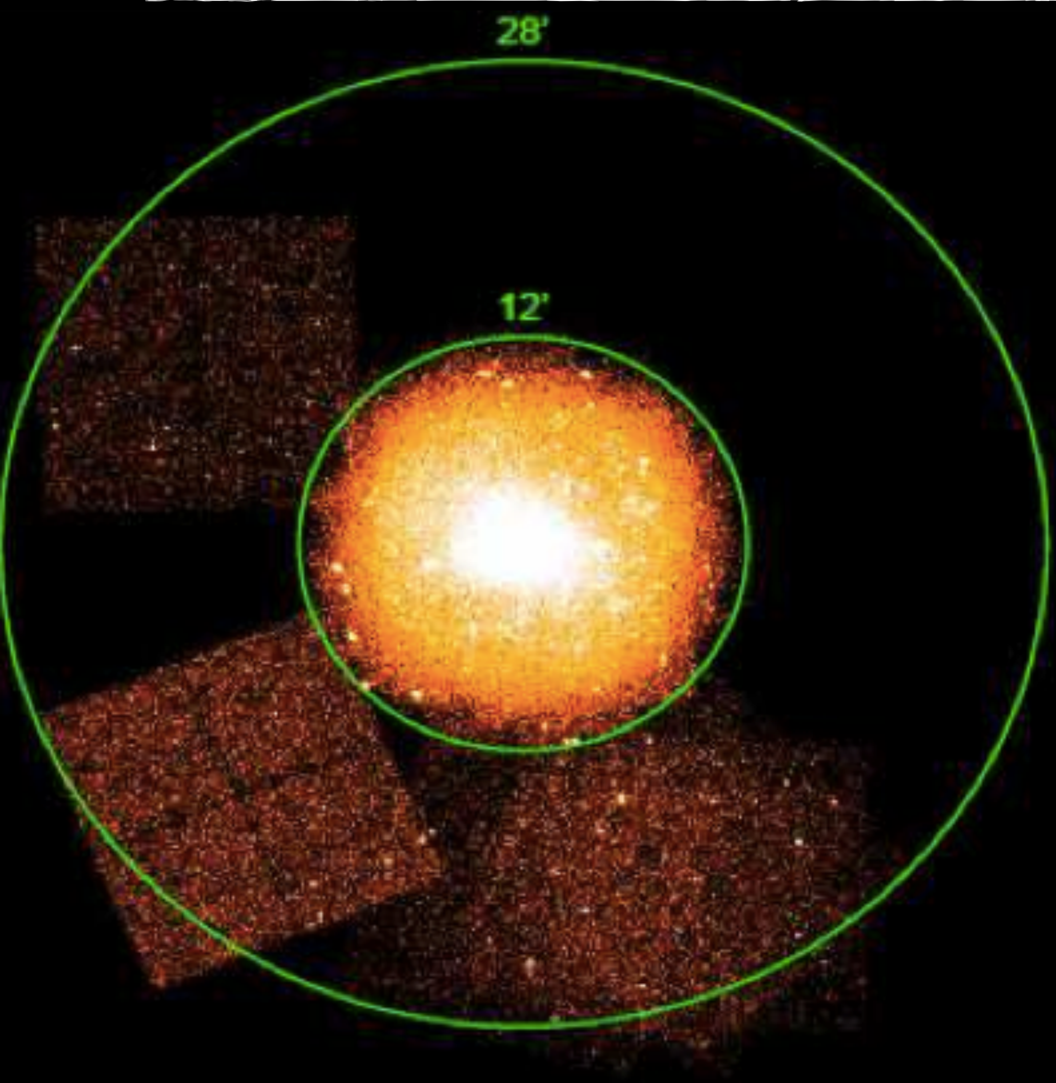
$$m_s < 8.9 \text{ keV}$$

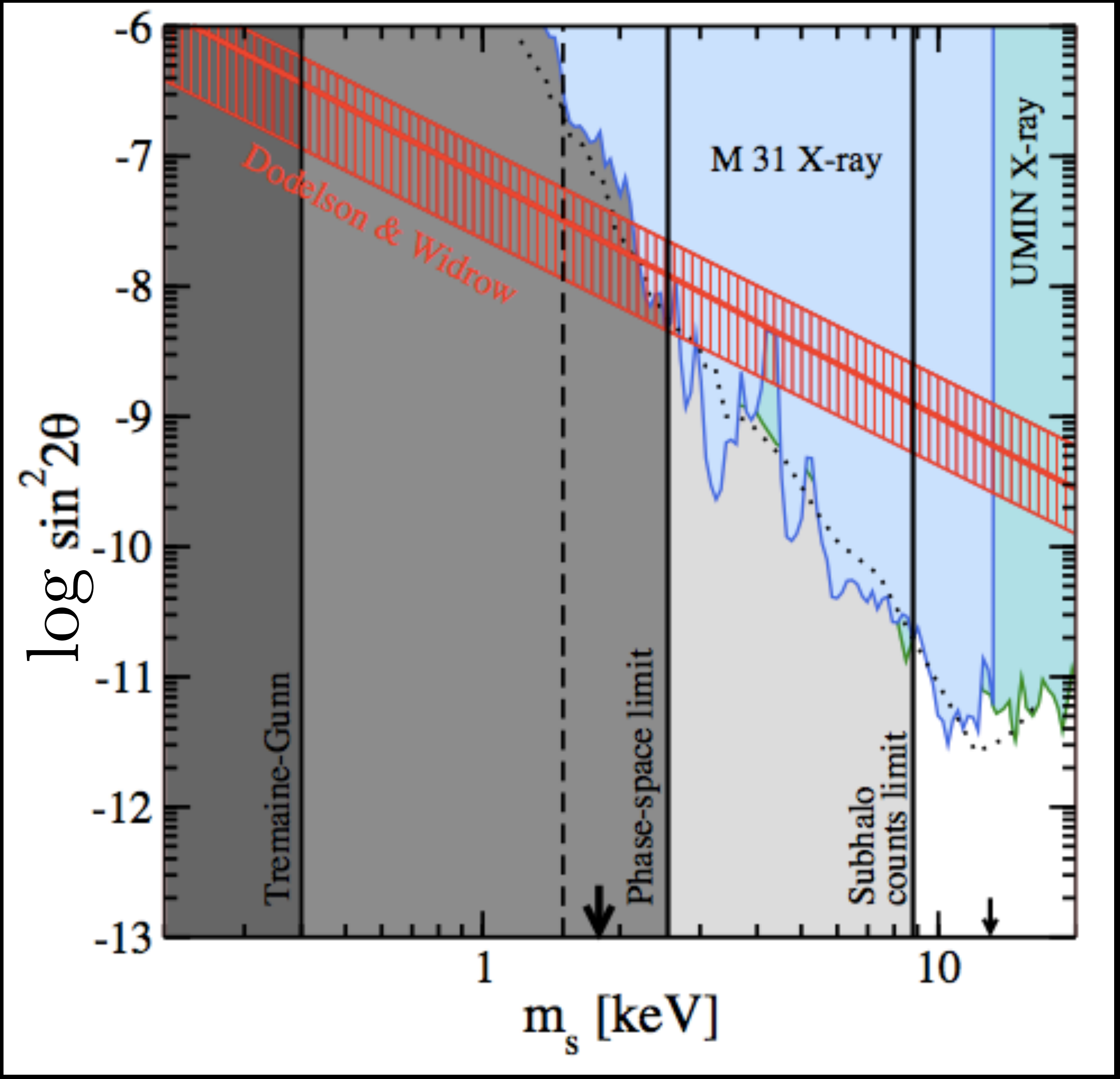
# Sterile Neutrino Dark Matter Parameter Space Summary




Abazajian 2011

# *Best constraints are from Horiuchi+ 2013*



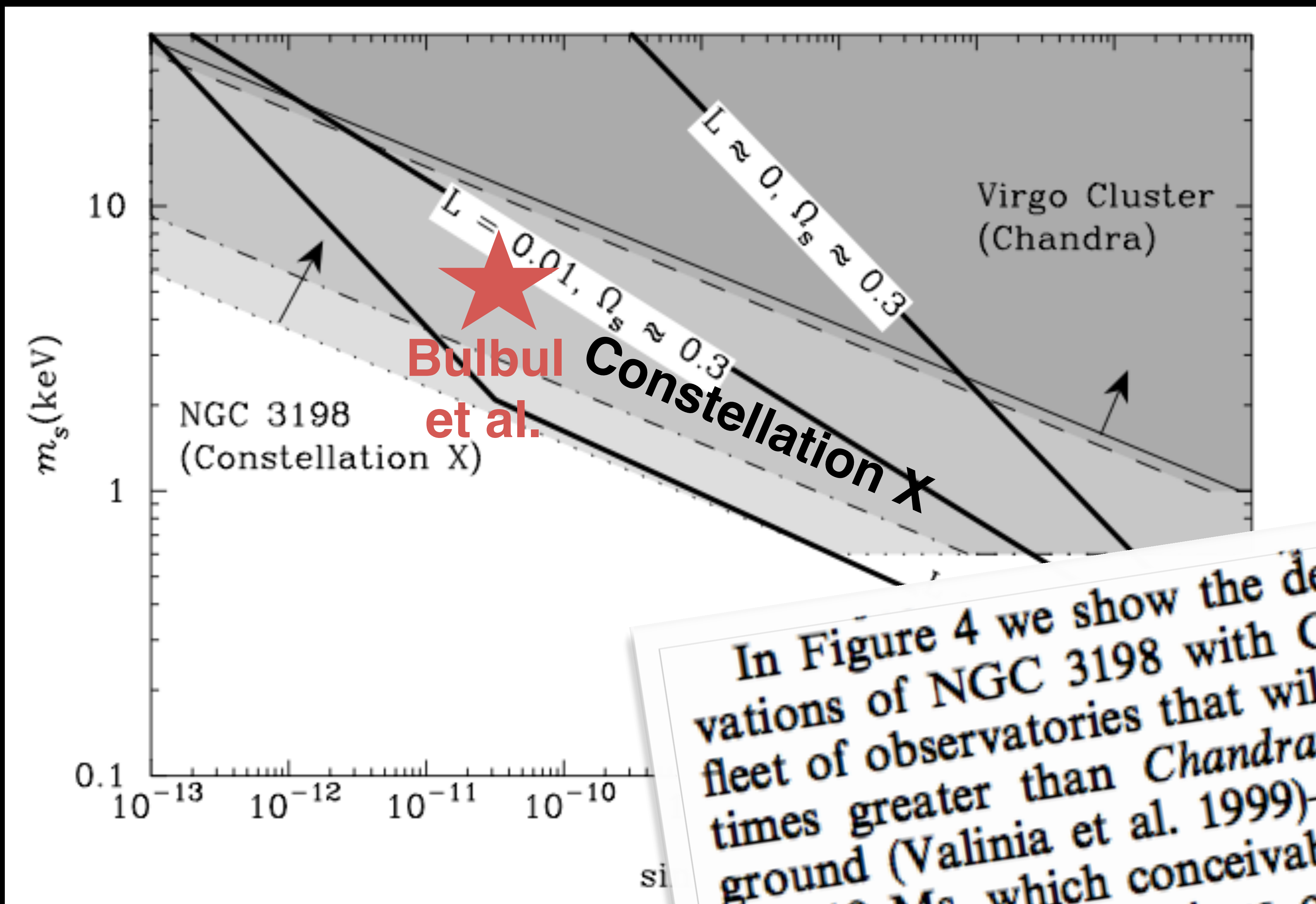



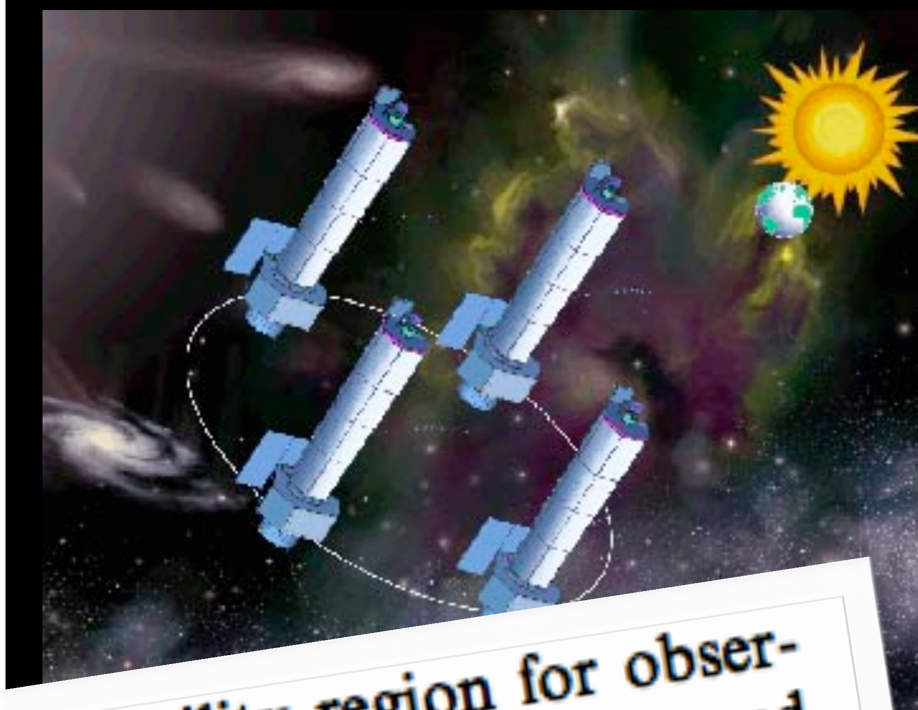

Combined subhalo and X-ray constraints: exclude standard DW dark matter $\nu_s$

Horiuchi, Humphrey, Abazajian & Kaplinghat, PRD arXiv:1311.0282

# Forecast X-ray Observation Sensitivity for *Constellation-X*

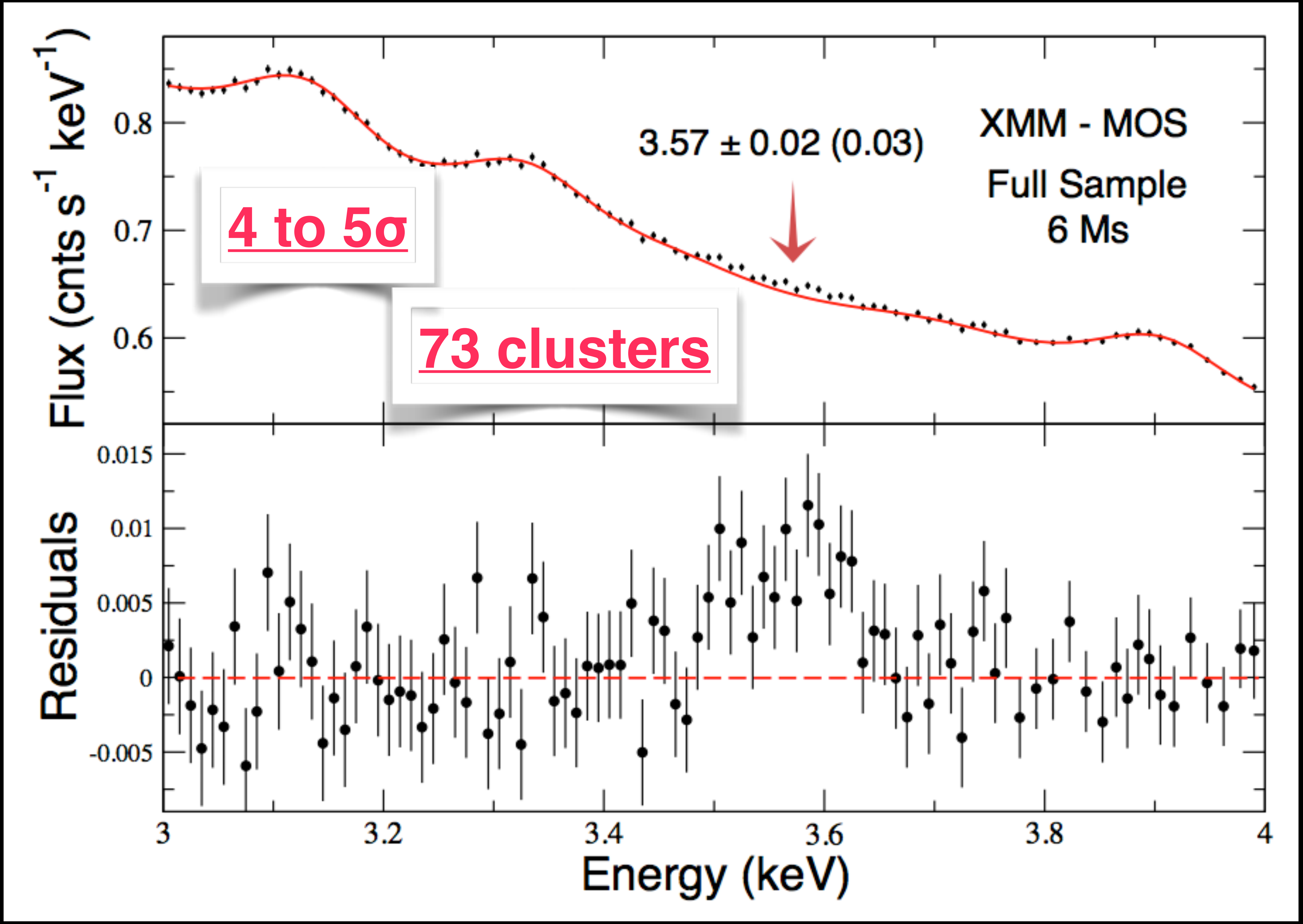
**Abazajian, Fuller & Tucker 2001**



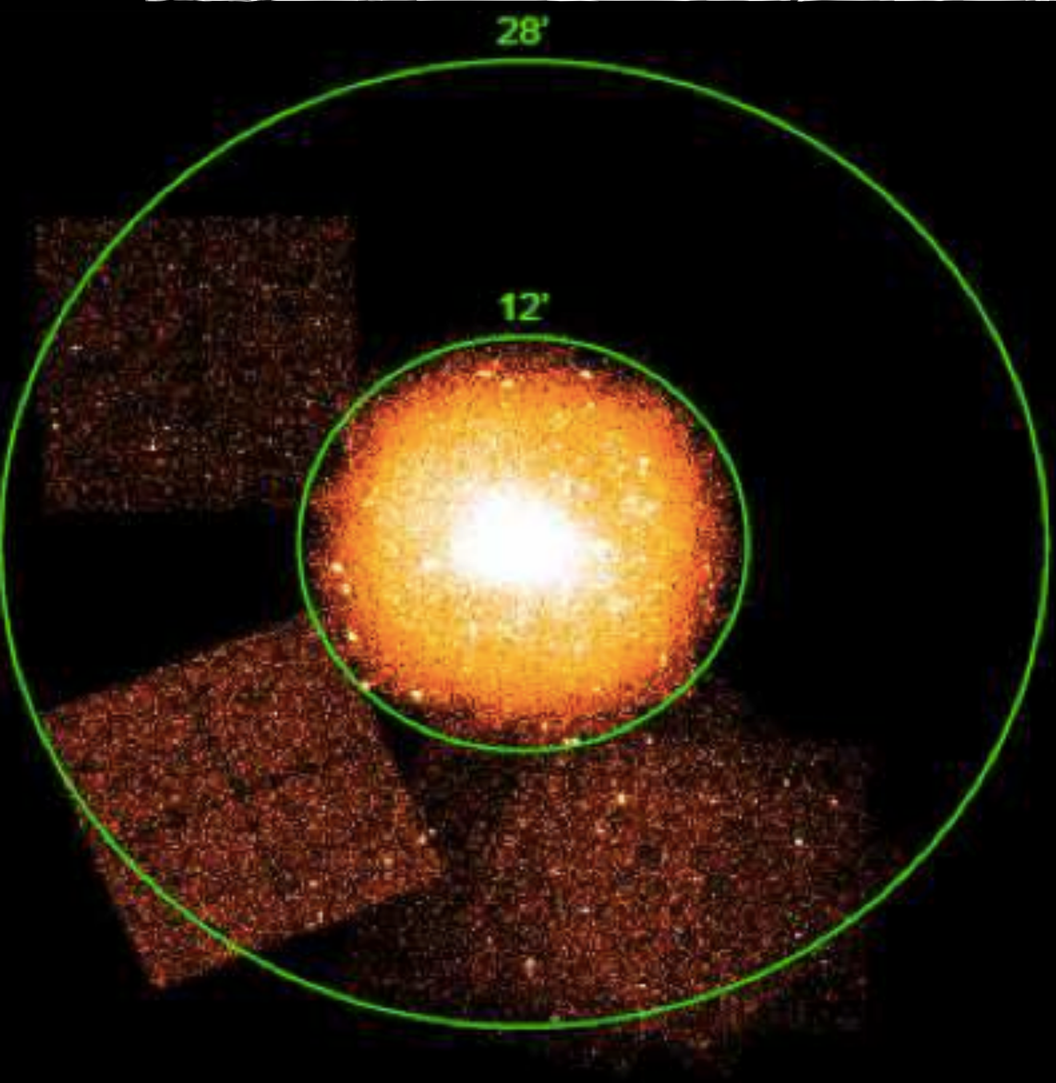
In Figure 4 we show the detectability region for observations of NGC 3198 with Constellation X—a proposed fleet of observatories that will have an effective area ~10 times greater than *Chandra* and no instrumental background (Valinia et al. 1999)—for two integration times, 1 and 10 Ms, which conceivably could be achieved through several long observations over a few years. An exposure equivalent to this could be obtained by a stacking analysis of the spectra of a number of similar clusters (see, e.g., Brandt et al. 2001; Tozzi et al. 2001). Constellation X, with very long integration times, holds out the prospect of covering nearly the entire WDM parameter space of interest for

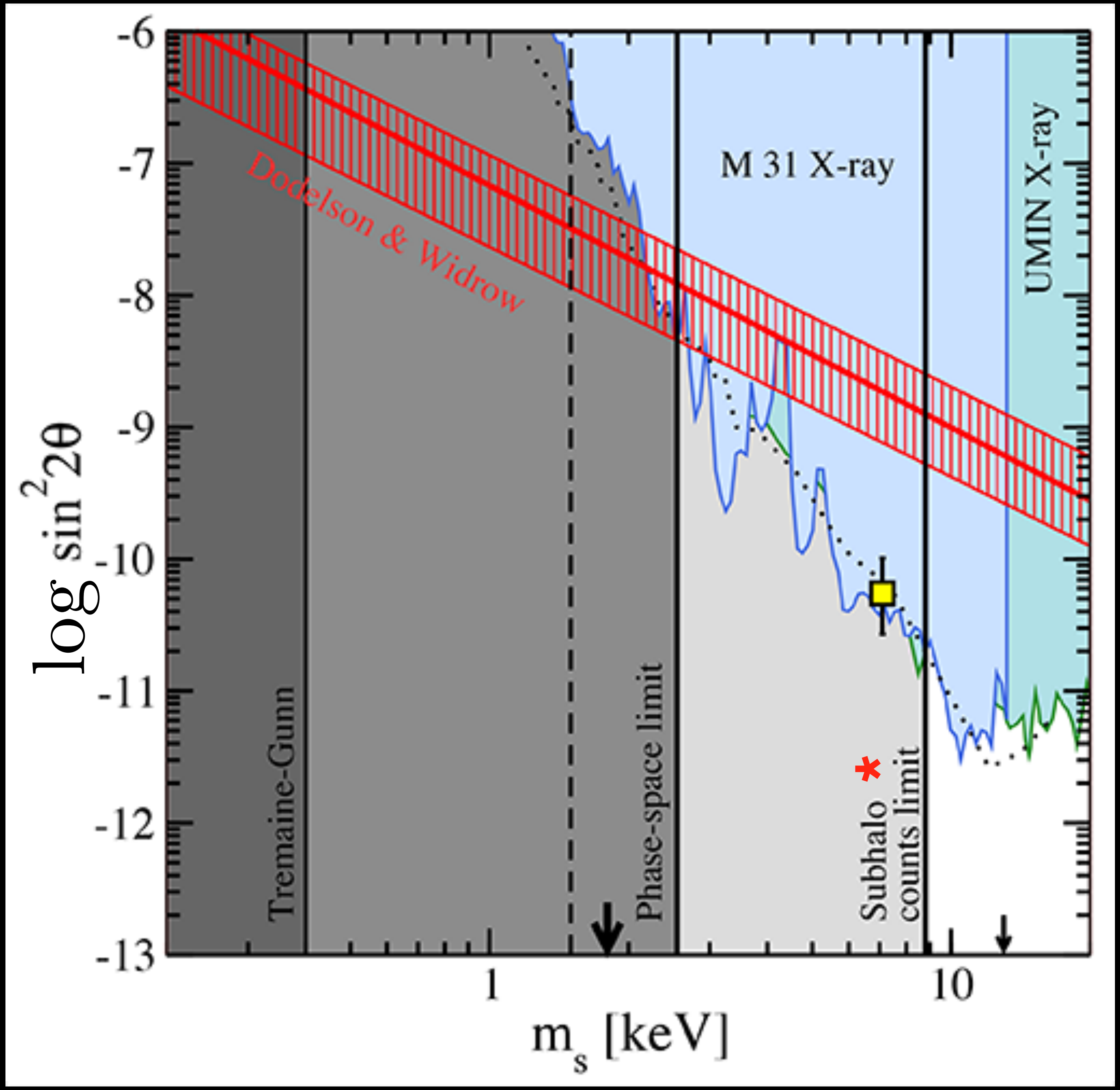
# The Detection of an Unidentified Line




Bulbul et al. ApJ arXiv:1402.2301

# *Chandra* X-ray M31 plus substructure constraints

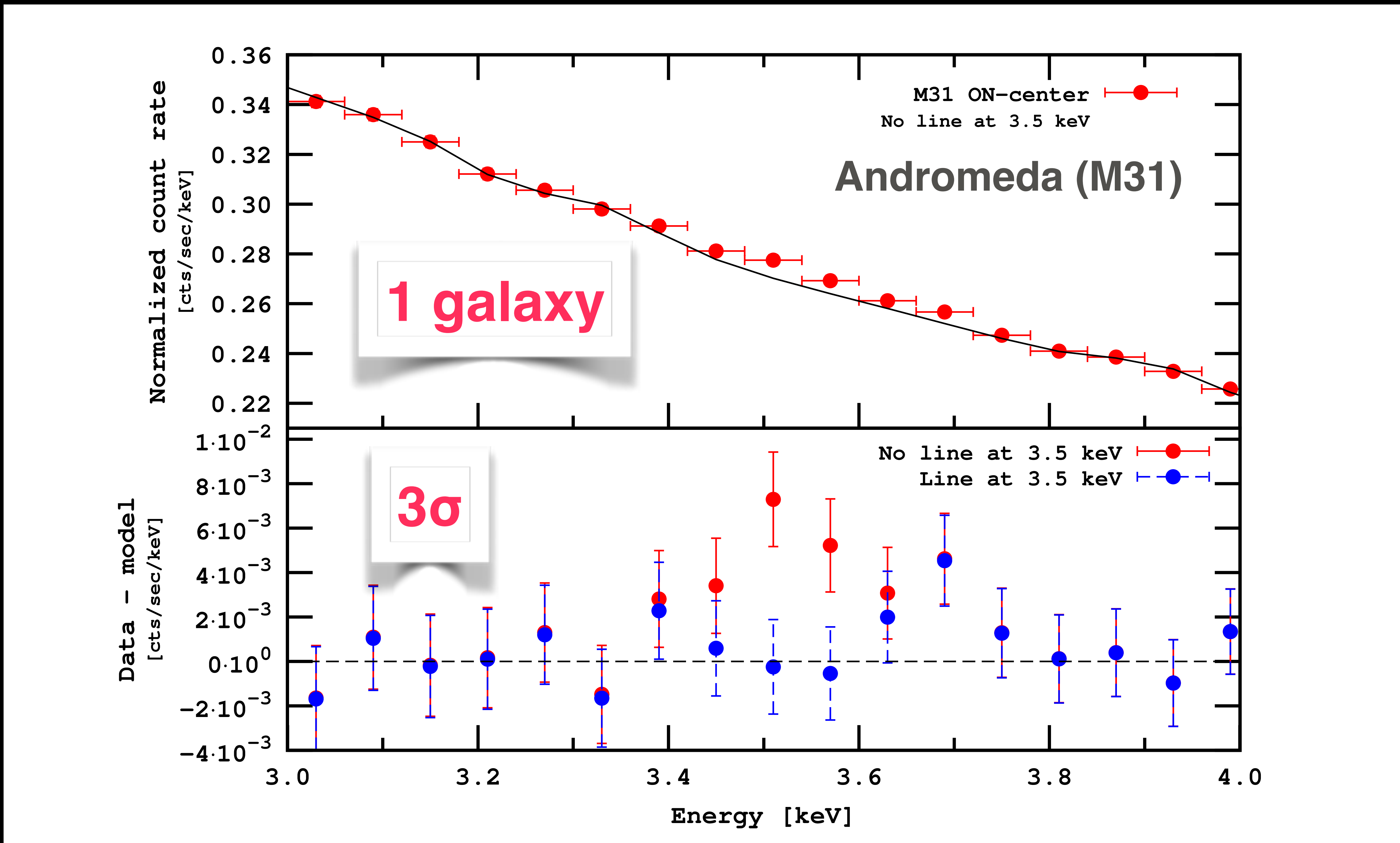



Combined subhalo and X-ray constraints: exclude standard $\nu_s$

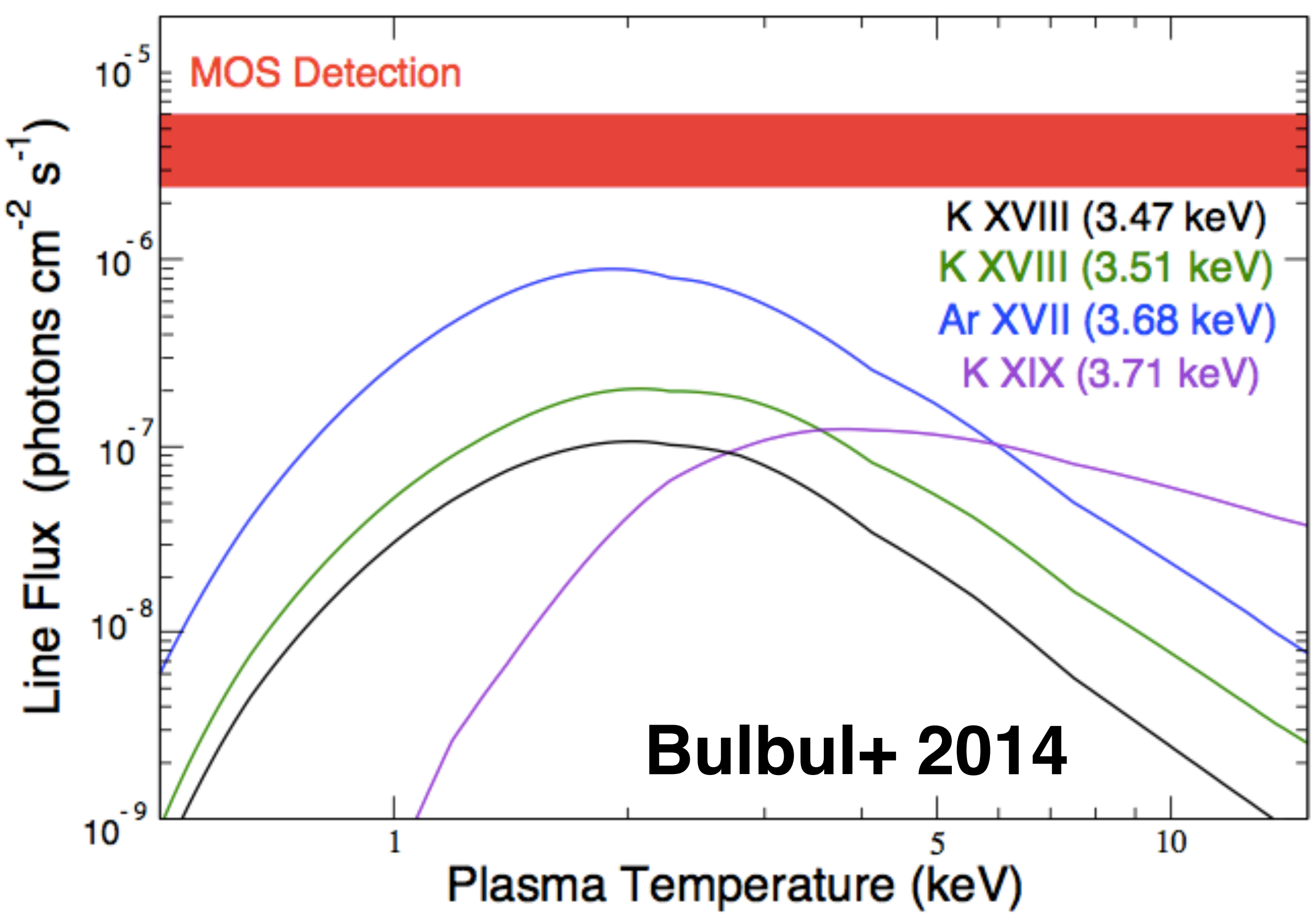
Horiuchi, Humphrey, Abazajian & Kaplinghat, PRD arXiv:1311.0282

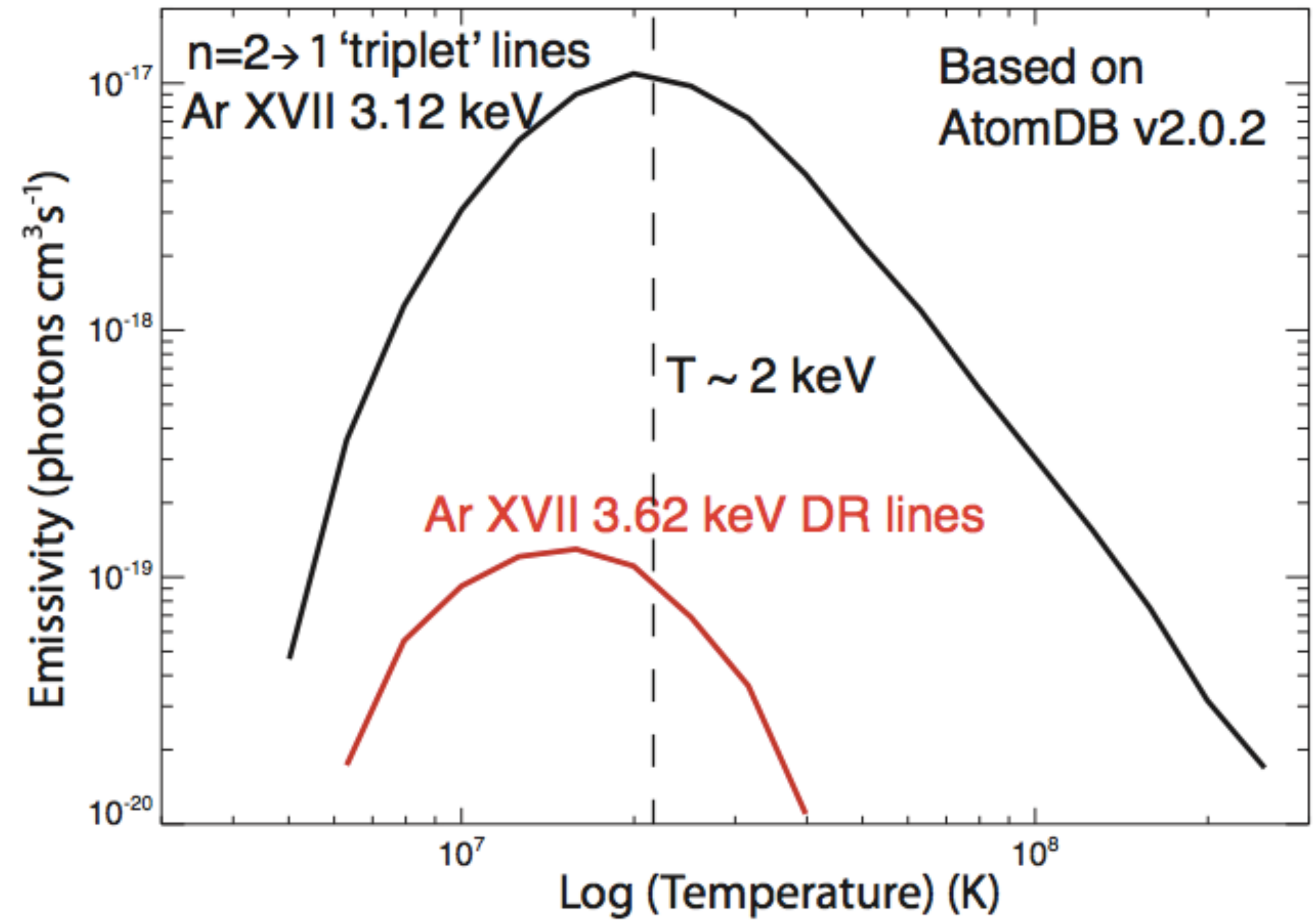
# The Detection of an Unidentified Line II




Boyarsky et al. PRL arXiv:1402.4119

# Metal Lines in Clusters at 3.5 keV? *unlikely*




- Most lines at this energy are too low in flux for the typical plasma temperatures
- Those that could be close, Ar XVII DR, would have accompanying lines that make its flux a factor of 30 too low

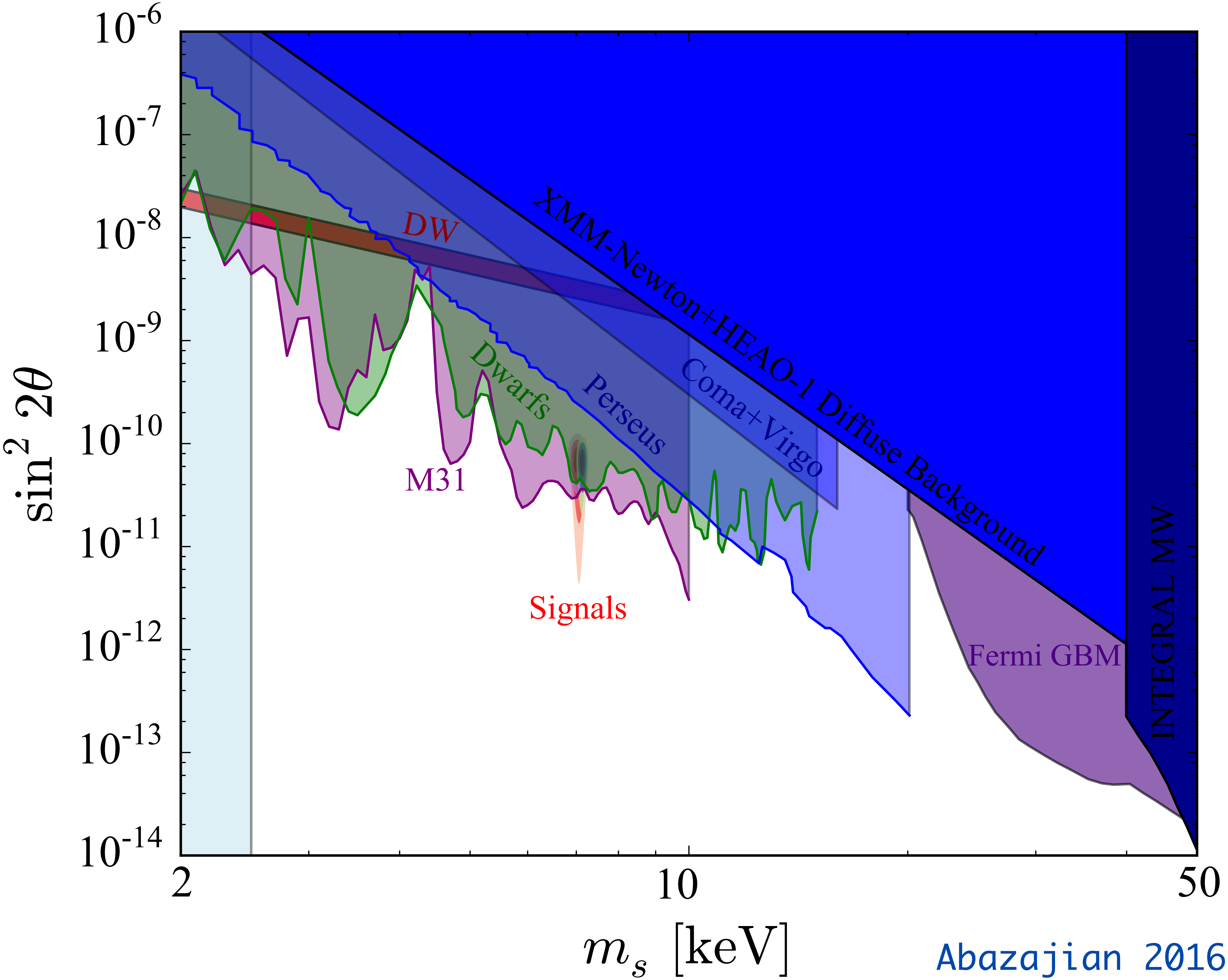
# 3.5 keV X-ray Line Observations

- **Bulbul et al. (ApJ arXiv:1402.2301)**
  - **73 clusters** with *XMM-Newton*, **MOS** + **PN** CCDs
    - stacking $z$ = 0.01 to 0.35 clusters blends features in the instrument response function
    - **4 - 5σ in full MOS data set**
    - found in several subsets of observations → ***Trials factor unnecessary***
  - **Indications at 2.2σ Perseus** with *Chandra*
  - Not seen in Virgo, but consistent upper limit
- **Boyarsky et al. (PRL arXiv:1402.4119)**
  - **Andromeda indication** at 3σ - *XMM-Newton*
  - **Perseus indication** at 2.3σ - *XMM-Newton*
  - Combined detection at **4.4σ**
- **Boyarsky et al. (PRL 1408.2503)**
  - **Milky Way Galactic Center 3.5 keV line at 5.7σ** - *XMM-Newton*
  - Consistent with dark matter in field of view
  - Due to complexity of this region, atomic lines could be responsible (*here alone*)

# 3.5 keV X-ray Line Observations

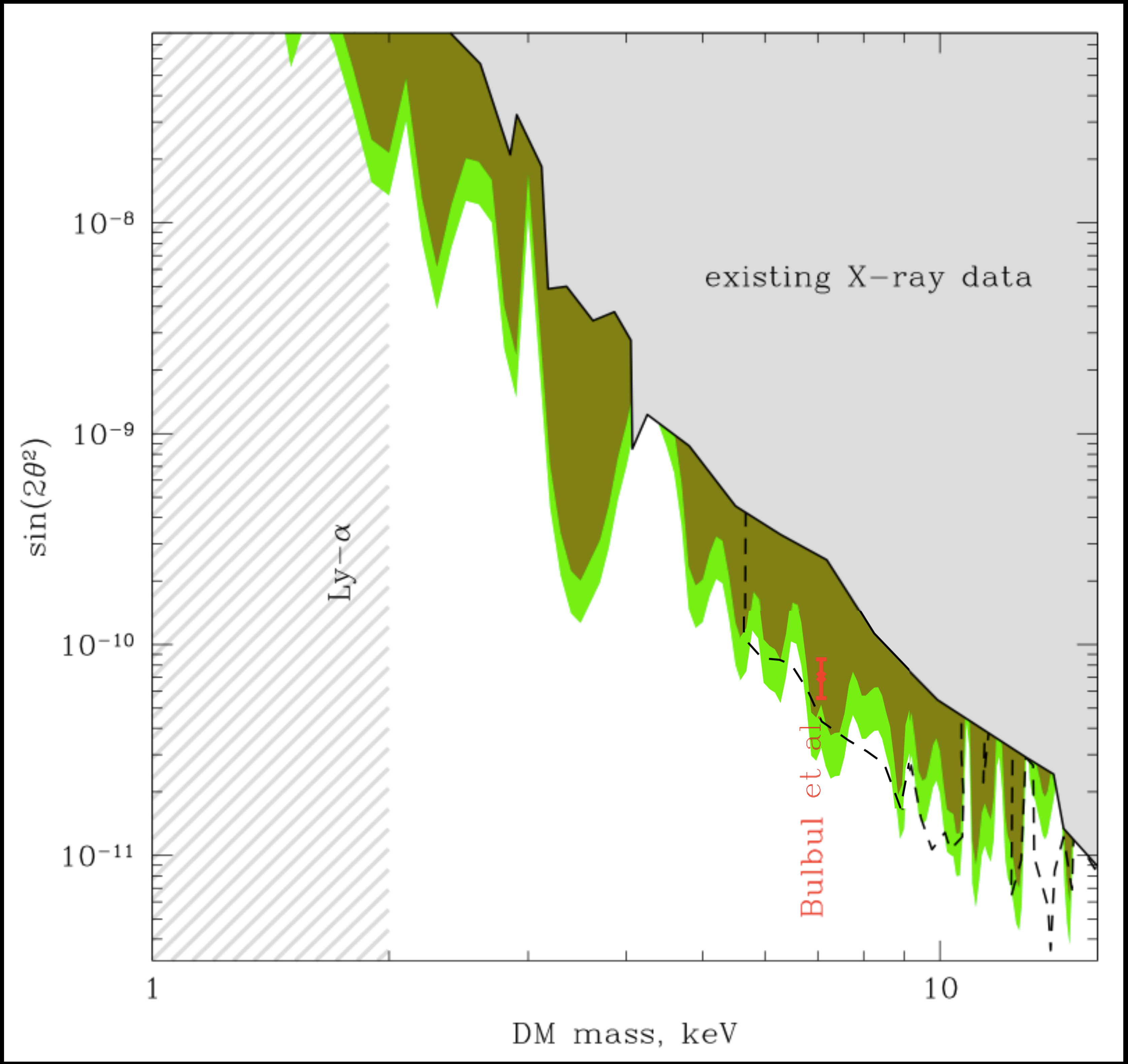
- **Jeltema & Profumo (MNRAS arXiv:1408.1699)**
  - subtract an unconstrained KXVIII line from *XMM-Newton* Galactic Center data
  - use new data to constrain presence of dark matter line, concluding to room for line (*methodology!*)
- **Andersen et al. (MNRAS arXiv:1408.4115)**
  - Stack ~80 galaxies with *XMM-Newton* & *Chandra*
  - Have systematic residuals in continuum of order signal
  - Claim high statistical significance exclusion regardless
- **Urban et al. (MNRAS arXiv:1411.0050)**
  - **Detected at 7.4σ** with *Suzaku* in Perseus,
  - Claim that the flux profile appears inconsistent with dark matter (**Franse+ arXiv:1604.01759** reanalysis shows consistency the line profile)
- **Iakubovskyi et al. (arXiv:1508.05186)**
  - **Detected in 8 new clusters** at >2σ in *XMM-Newton* and *Chandra* observations
  - Redshifting of line is consistent with it being at the source (i.e., not instrumental)

# Sterile Neutrino Dark Matter: Parameter Space Summary




Abazajian 2016

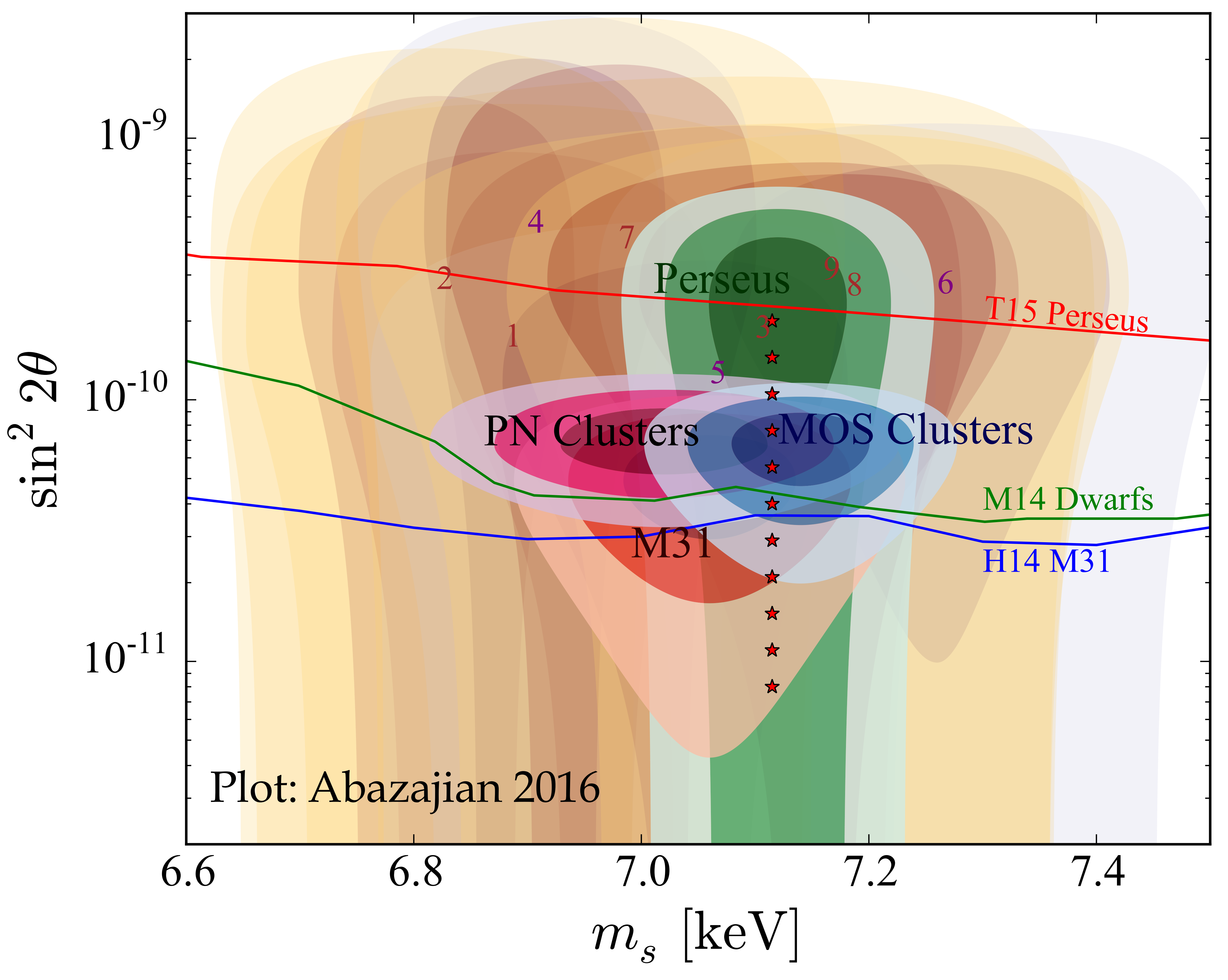
# Stacked Observations II: Dwarf Galaxies




sample of 8 dwarf galaxies observed with XMM-Newton, total of ~408 ksec of observations

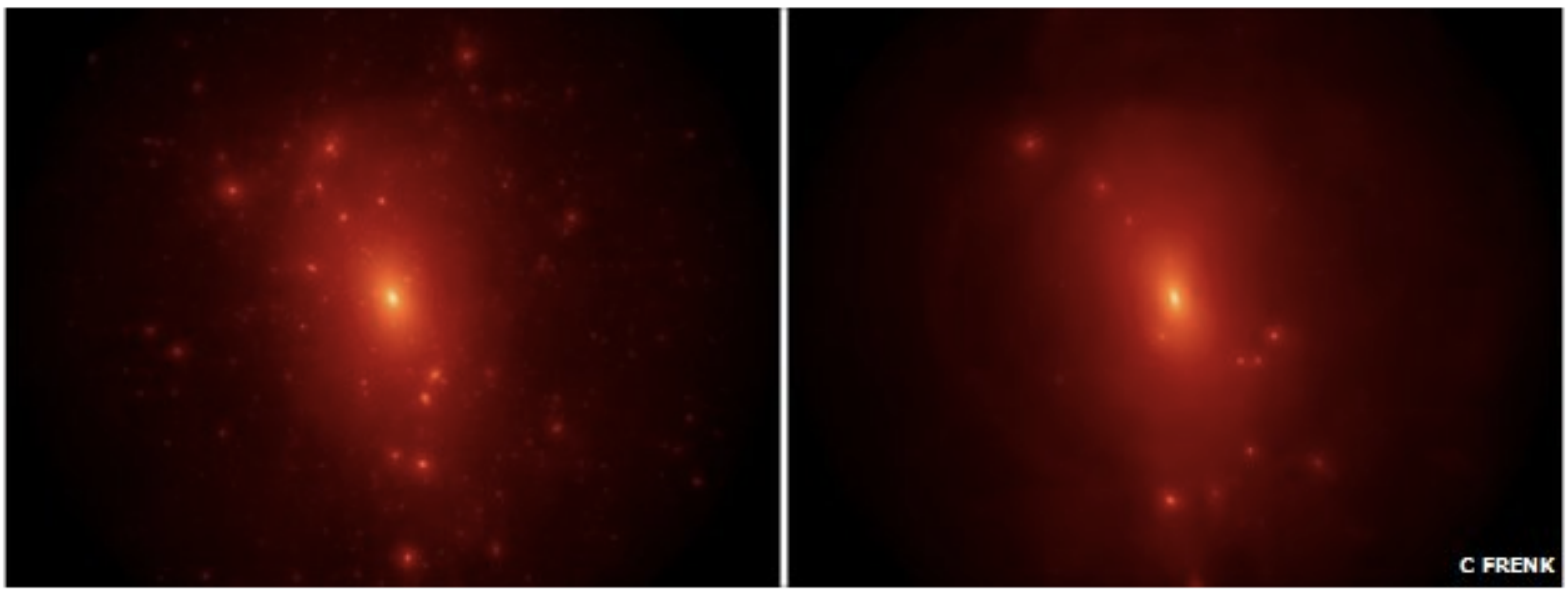
Malyshev, Neronov & Eckert 2014

# 8 New Cluster Detections at >2σ Reported in August Consistent with DM in FOV, with proper redshifting of line



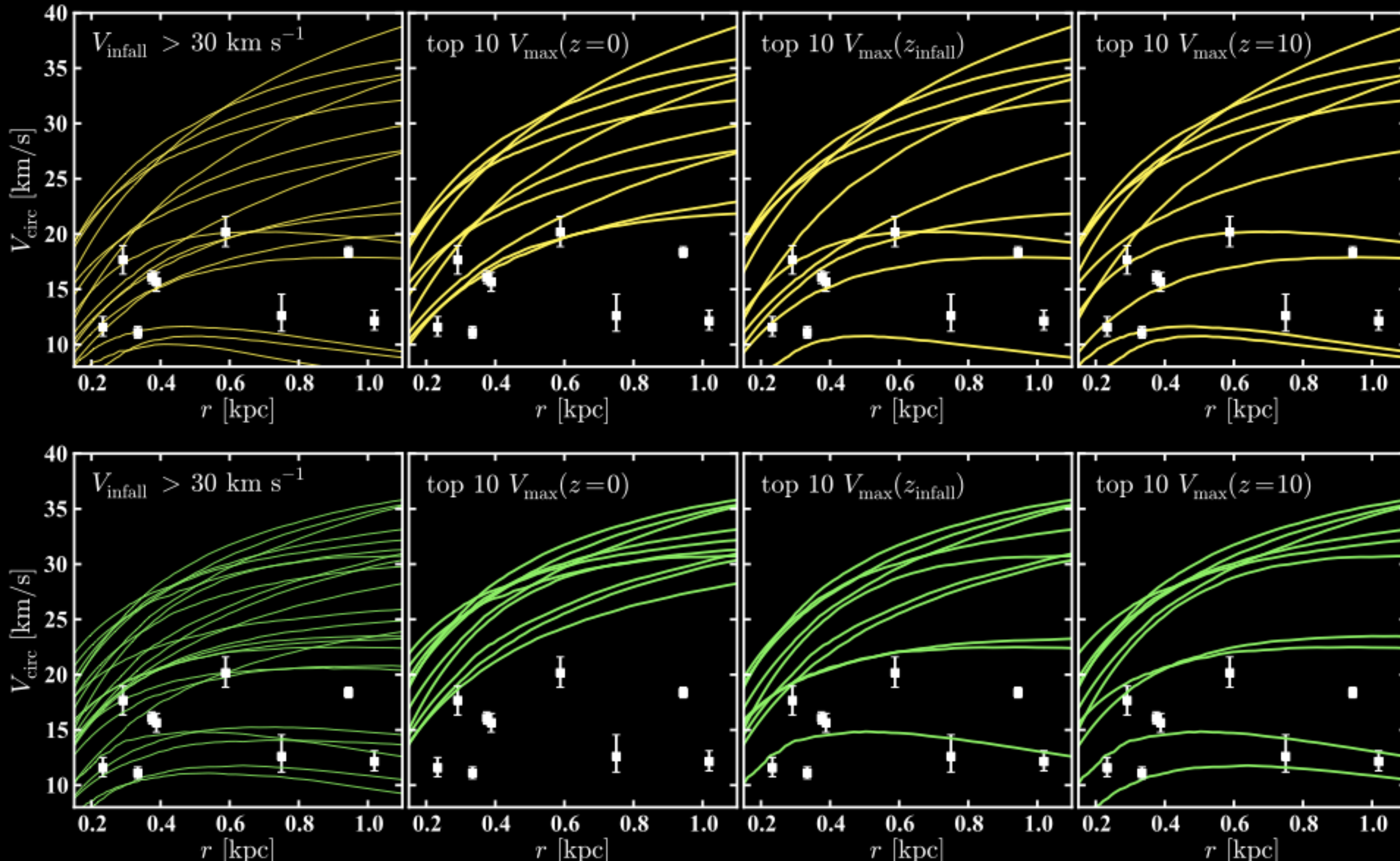

New clusters: Iakubovskyi+ 1508.05186

# Issues in Cosmological Small-scale Structure?




Dwarf galaxies around the Milky Way are less dense than they should be if they held cold dark matter

# Observed Dwarf Galaxy Concentrations are Much Too Low, While CDM Subhalos are "Too Big Too Fail"



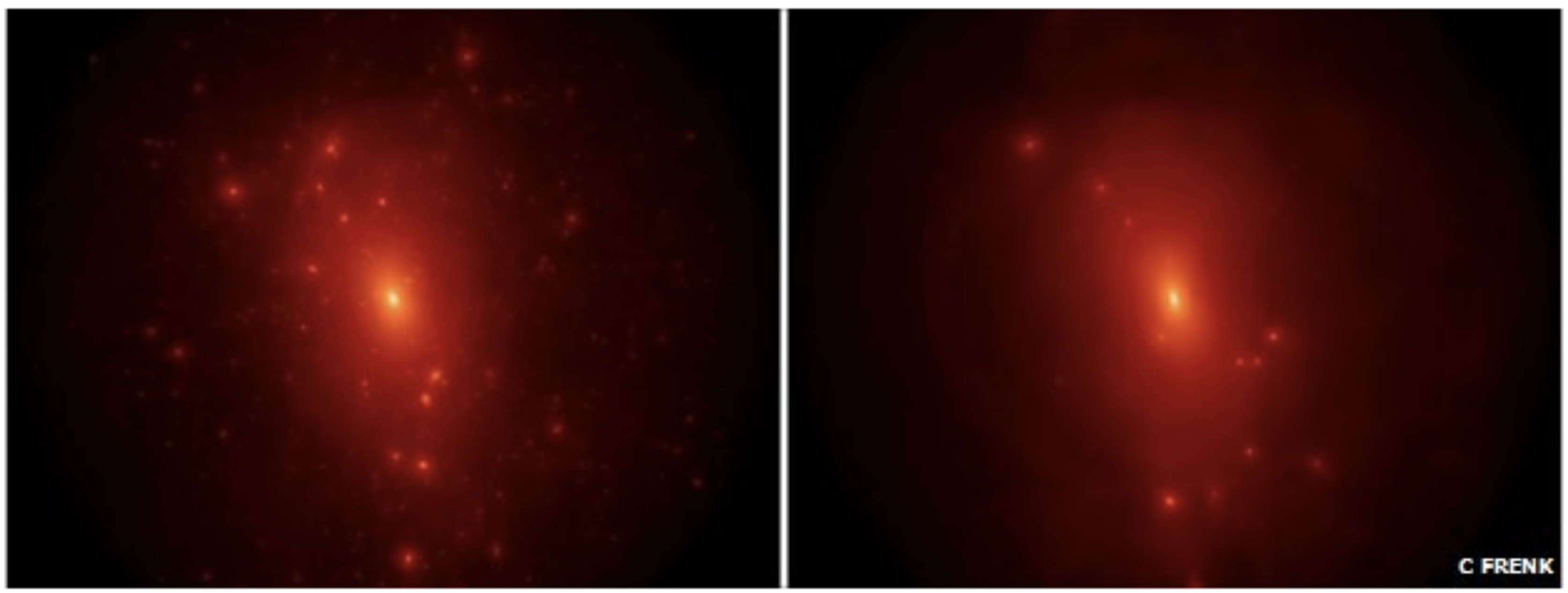

Boylan-Kolchin et al. 2011, 2012

**16 September 2011** Last updated at 13:47 ET



# Dwarf galaxies suggest dark matter theory may be wrong

**By Leila Battison**
Science reporter, Bradford




Dwarf galaxies around the Milky Way are less dense than they should be if they held cold dark matter

**Scientists' predictions about the mysterious dark matter purported to make up most of the mass of the Universe may have to be revised.**

Research on dwarf galaxies suggests they cannot form in the way they do if dark matter exists in the form that the most common model requires it to.

That may mean that the Large Hadron Collider will not be able to spot it.

Leading cosmologist Carlos Frenk spoke of the "disturbing" developments

**Related Stories**

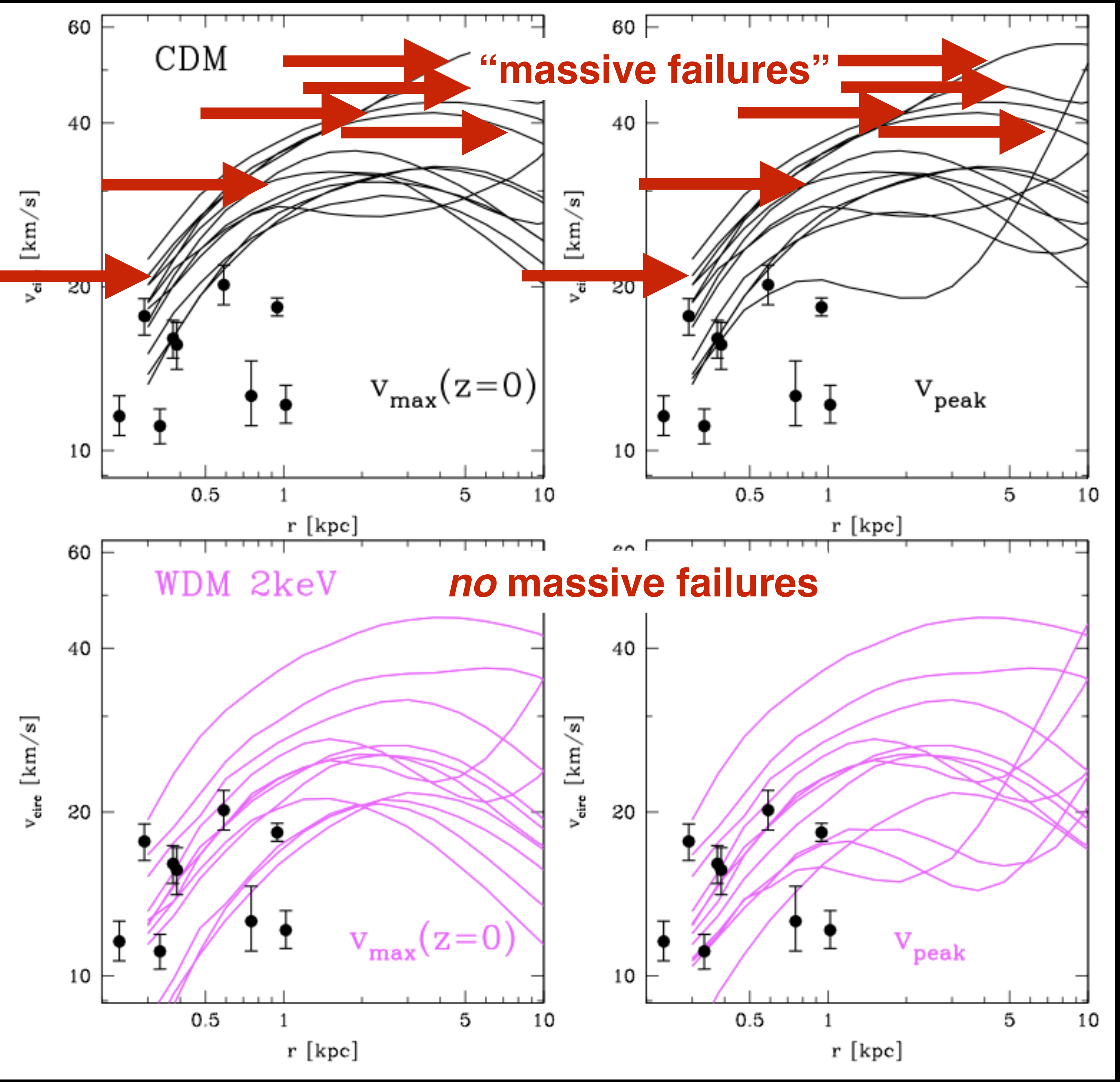
Dark matter hunters see 67 hints

Is LHC closing in on elusive Higgs particle?

'Filaments' hold dark matter test

Lovell et al. 2010

# WDM Solution to All Local Group Galaxy Properties?




Anderhalden et al. arXiv:1212.2967

*"It seems that only the pure WDM model with a 2 keV [thermal] particle is able to match the all observations" of the Milky Way Satellites: "the total satellite abundance, their radial distribution and their mass profile" (or TBTF)*

What is the relationship between particle mass and warm dark matter free streaming scale?

# Now: Sterile Neutrino Dark Matter Production

Quantum Field Theory + Statistical Mechanics

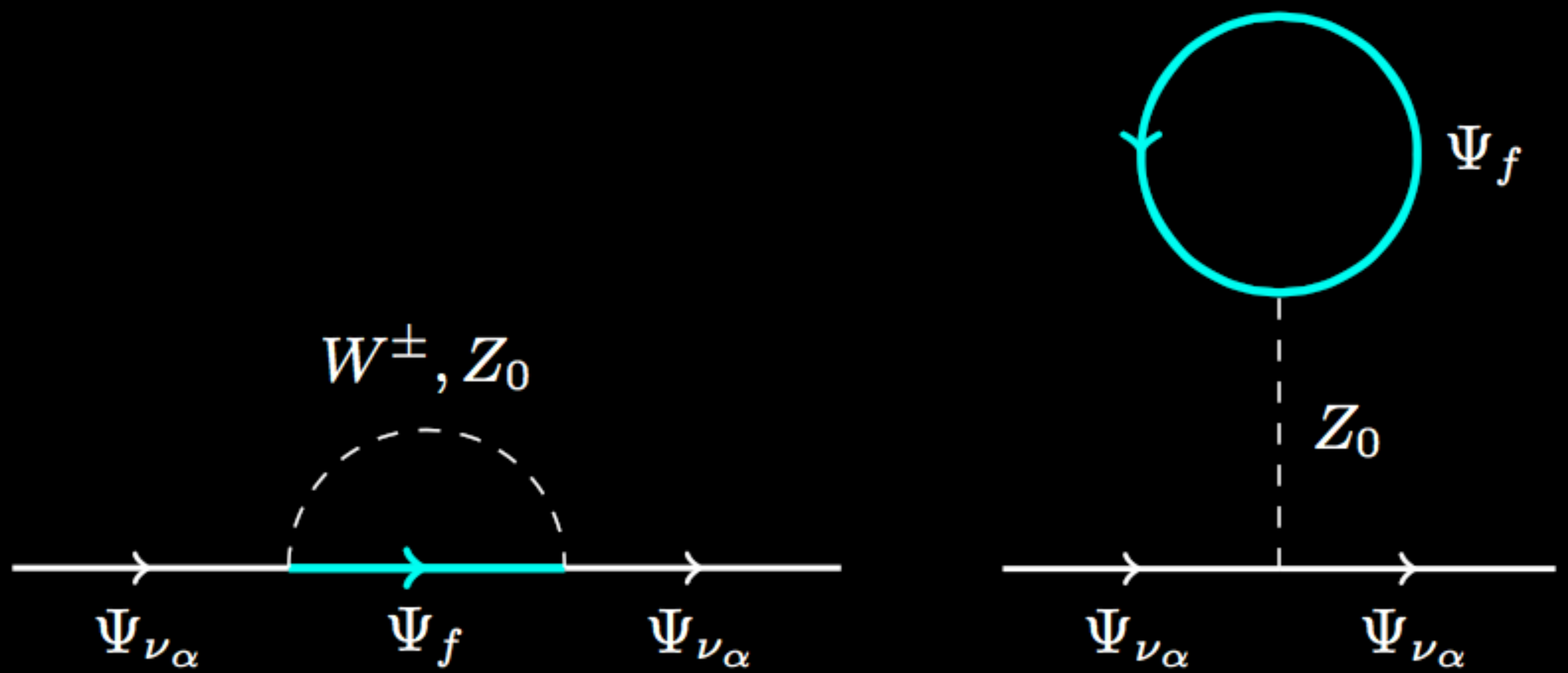
$$\rho(\epsilon, t) = \sum_{i,j} \rho_{i,j}(\epsilon, t)|\nu_i\rangle\langle\nu_j| \qquad \epsilon \equiv p_\nu/T$$

$$|\nu_\alpha\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_s\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

$$\dot{\rho}(\epsilon, t) = -i[H, \rho] \;\Rightarrow\; \rho(\epsilon, t) = \frac{1}{2}P_0(\epsilon, t)\left[1 + \mathbf{P}(\epsilon, t)\cdot\sigma\right]$$

$$\frac{\partial}{\partial t}\mathbf{P}(\epsilon, t) = \mathbf{V}(\epsilon, t) \times \mathbf{P}(\epsilon, t) + [1 - P_z(\epsilon, t)] \times \left[\frac{\partial}{\partial t}\ln P_0(\epsilon, t)\right]\hat{z} - \left[D(\epsilon, t) + \frac{\partial}{\partial t}\ln P_0(\epsilon, t)\right](P_x(\epsilon, t)\hat{x} + P_y(\epsilon, t)\hat{y})$$

# Thermal & Asymmetry Potentials: Neutrino Self-energy




(a) bubble diagram

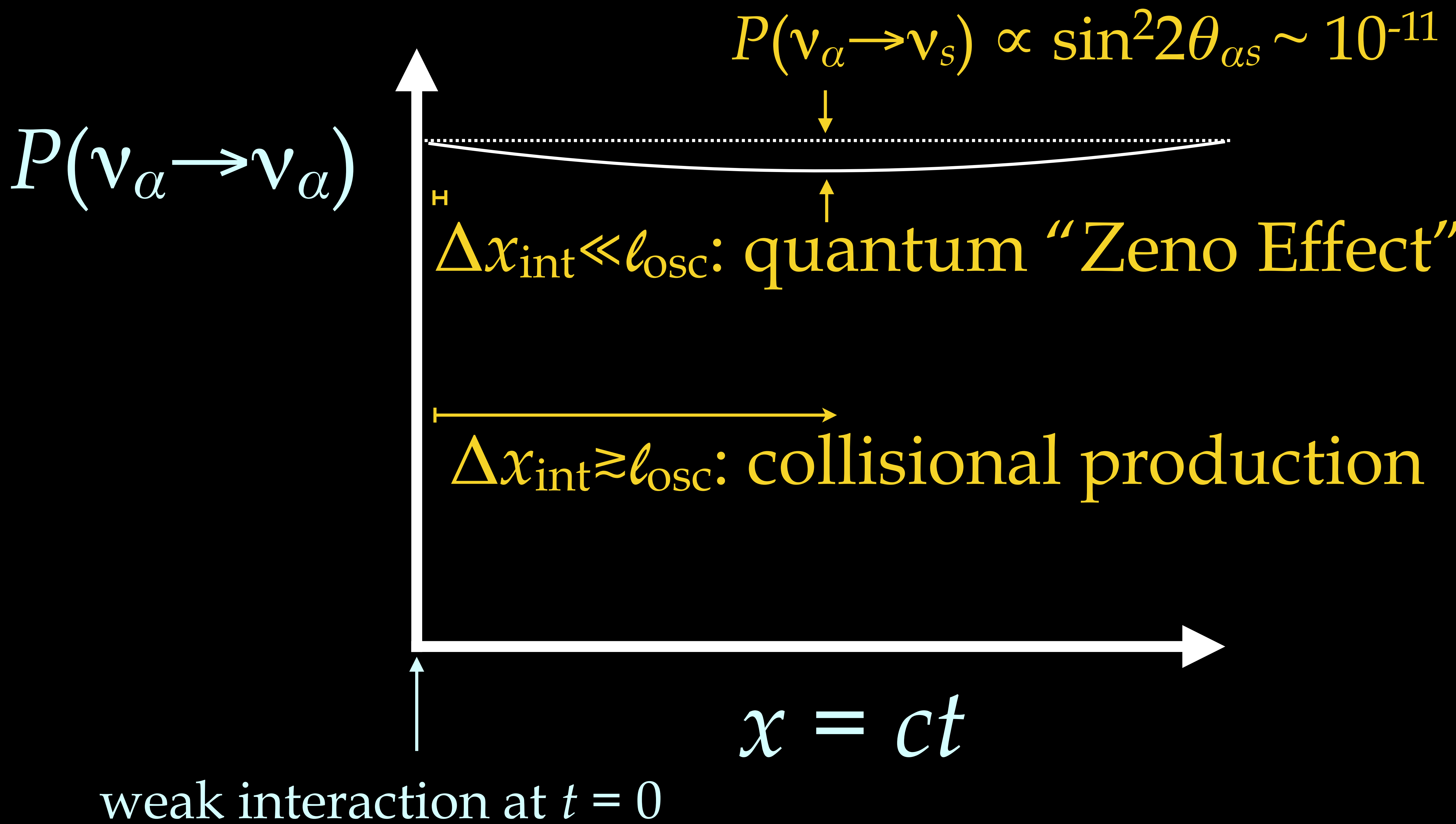
(b) tadpole diagram

Thermal & Asymmetry

Asymmetry

*⇒ Suppress active-sterile neutrino mixing at early times*

# A Simplified View of Sterile Neutrino Dark Matter Production



# Quasi-Classical Full Boltzmann Transport

$$0 = 0$$

$$\mathbf{L}[f] = \mathbf{C}[f]$$

$$\frac{\partial}{\partial t} f_{\nu_\mathrm{s}}(p,t) - H\, p\, \frac{\partial}{\partial p} f_{\nu_\mathrm{s}}(p,t) =$$

$$\sum_{\nu_x + a + \cdots \to i + \ldots} \int \frac{d^3 p_a}{(2\pi)^3 2E_a} \cdots \frac{d^3 p_i}{(2\pi)^3 2E_i} \ldots (2\pi)^4 \delta^4(p + p_a + \cdots - p_i - \ldots)$$
$$\times \frac{1}{2} \Big[ \underline{\langle P_\mathrm{m}(\nu_\mu \to \nu_\mathrm{s}; p, t)\rangle} \left(1 - f_{\nu_\mathrm{s}}\right) \sum |\mathcal{M}|^2_{i + \cdots \to a + \nu_\mu + \ldots} f_i \ldots (1 \mp f_a) \left(1 - f_{\nu_\mu}\right) \ldots$$
$$- \underline{\langle P_\mathrm{m}(\nu_\mathrm{s} \to \nu_\mu; p, t)\rangle} f_{\nu_\mathrm{s}} \left(1 - f_{\nu_\mu}\right) \sum |\mathcal{M}|^2_{\nu_\mu + a + \cdots \to i + \ldots} f_a \ldots (1 \mp f_i) \ldots \Big] .$$

# Sterile Neutrino Dark Matter Production

$\Gamma_\alpha(p) \sim G_F^2 p T^4 \sim T^5$

$\Delta^2 \sim p^{-2} \sim T^{-2}$

$$\Gamma(\nu_\alpha \to \nu_s) \sim \frac{\Gamma_\alpha(p)\Delta^2(p)\sin^2 2\theta}{\Delta^2(p)\sin^2 2\theta + D^2(p) + [\Delta(p)\cos 2\theta - V^L(p) - V^T(p)]^2}$$

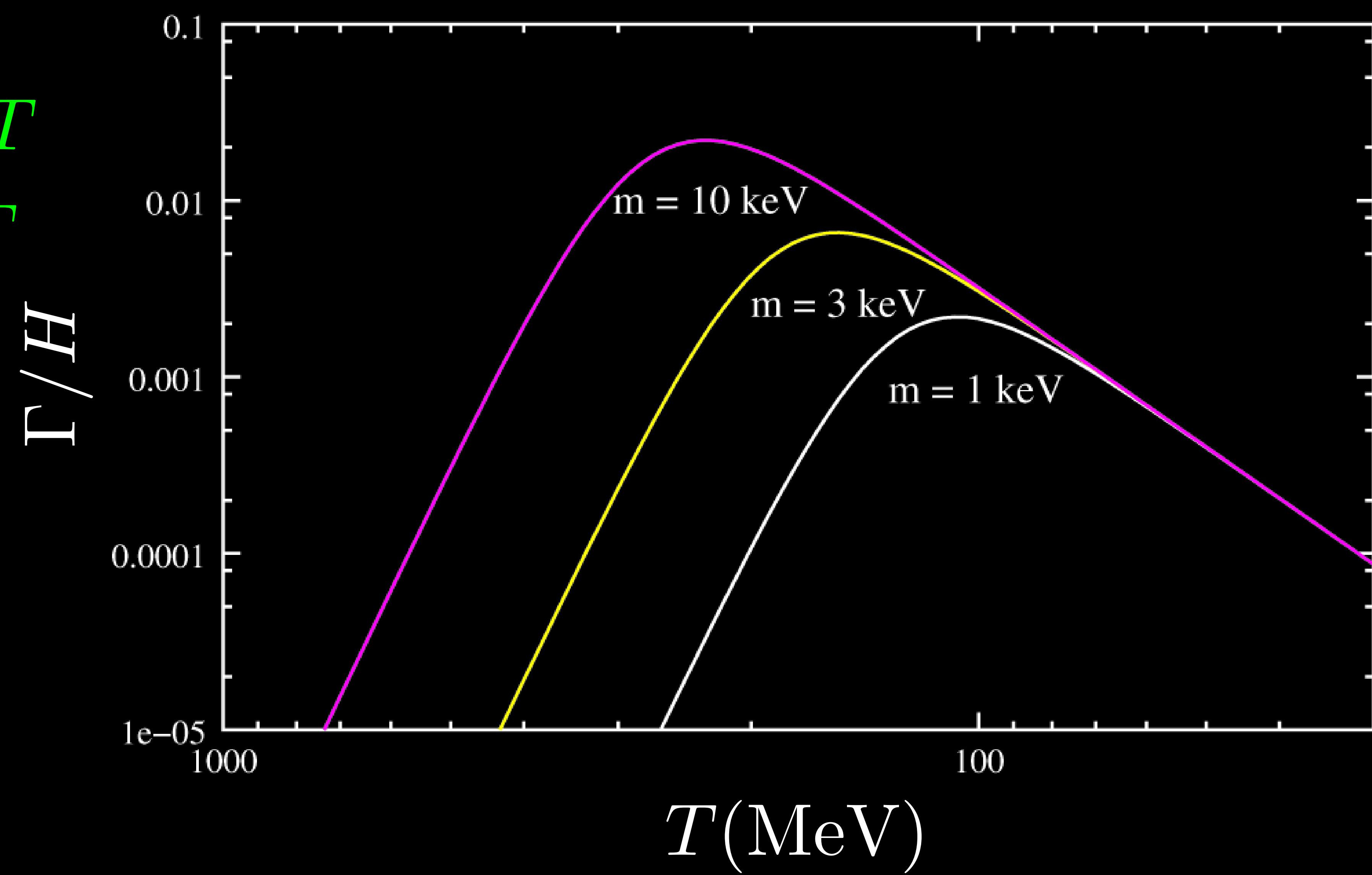
$D(p)^2 \sim T^{10}$

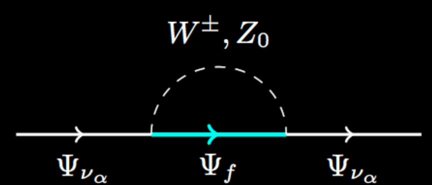
$[V^T]^2 \sim T^{10}$

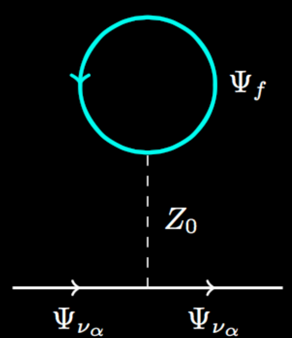
$$H^2 = \frac{8\pi}{3} G\rho \sim T^4$$

$$\frac{\Gamma}{H} \sim \begin{cases} T^{-9} & \text{High } T \\ T & \text{Low } T \end{cases}$$

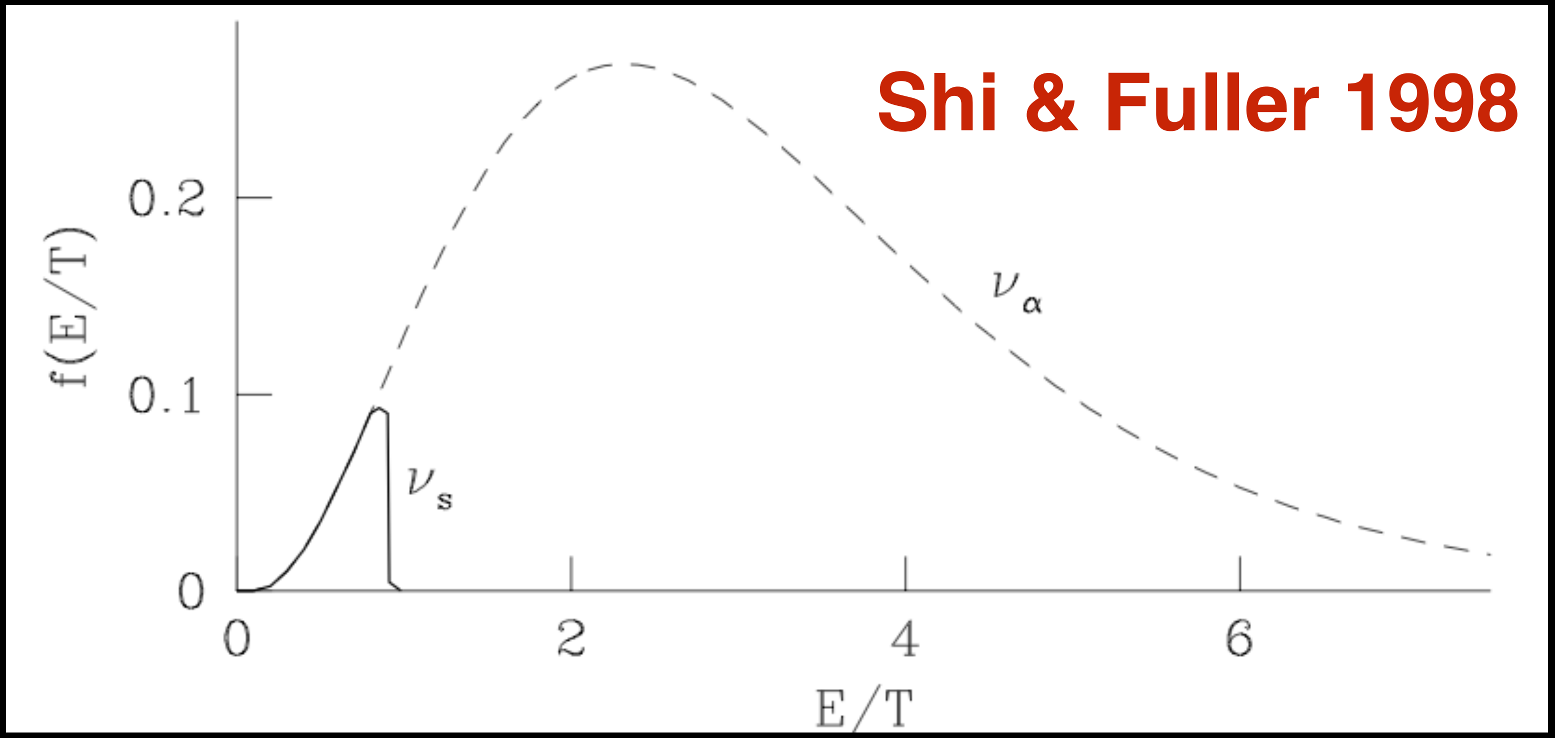
Never in Equilibrium!!



# Resonant Production




**Matter (thermal) mixing angle:**

$$\sin^2 2\theta_m = \frac{\Delta^2(p)\sin^2 2\theta}{\Delta^2(p)\sin^2 2\theta + [\Delta(p)\cos 2\theta - V^D - V^T(p)]^2}$$

$$\Rightarrow \qquad \epsilon_{\rm res} \approx \frac{\delta m^2}{(8\sqrt{2}\zeta(3)/\pi^2)G_{\rm F}T^4 L}$$

$$\approx 3.65\left(\frac{\delta m^2}{(7\,{\rm keV})^2}\right)\left(\frac{10^{-3}}{L}\right)\left(\frac{170\,{\rm MeV}}{T}\right)^4$$

# *New Physics in 2015: A tale of weak interactions in the strong coupling epoch*

Updated physics included in past year:

1. Redistribution of lepton asymmetry in collisional processes
2. More accurate inclusion of neutrino scattering on leptons, hadrons, quarks
3. Updated time-temperature evolution of the plasma, and more robust numerics

Teja Venumadhav, Francis-Yan Cyr-Racine, K. A., Chris Hirata, arXiv:1507.06655

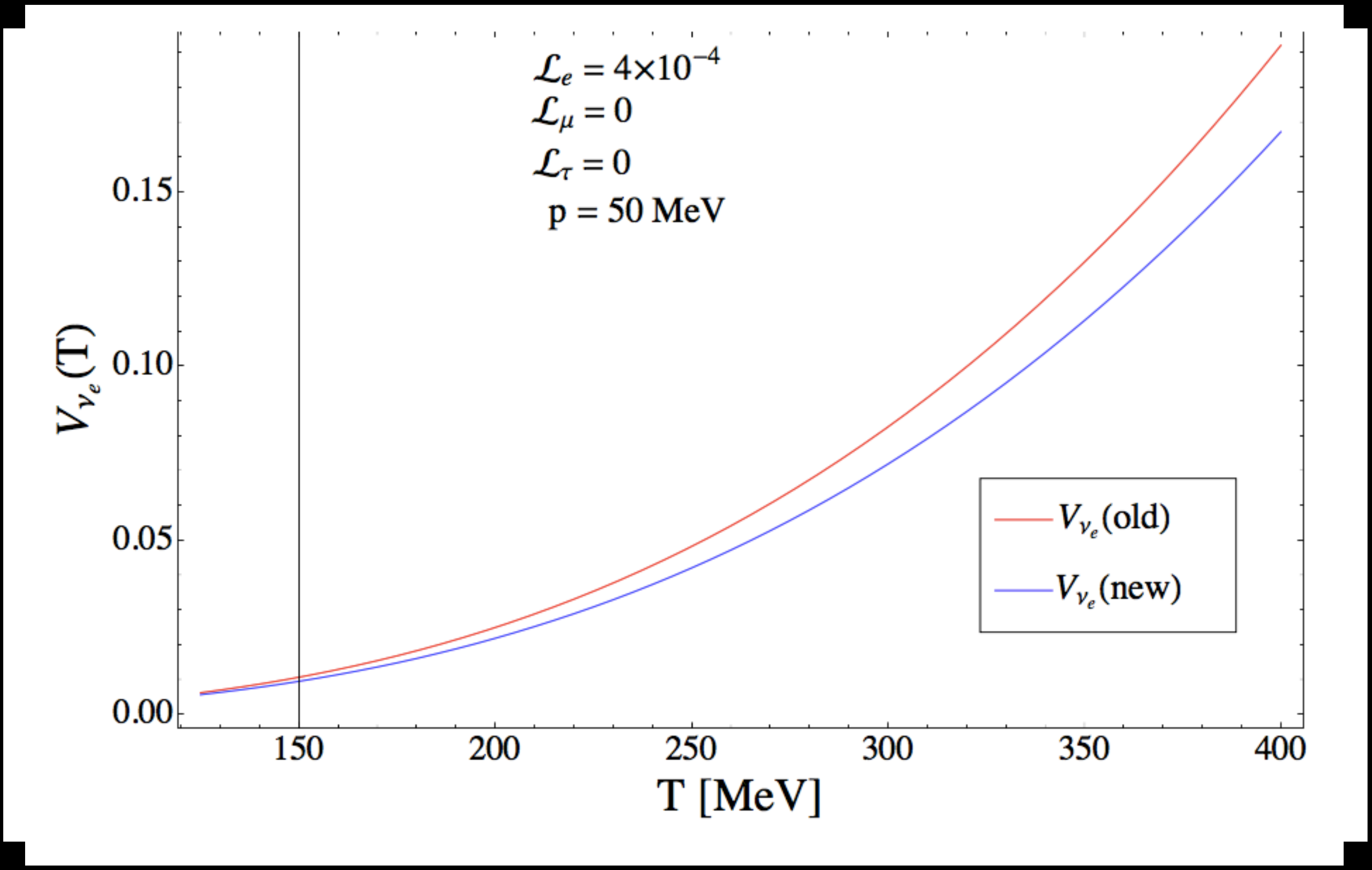
# *Redistribution of Lepton Asymmetries*

The following reactions redistribute lepton asymmetry among the charged leptons and neutrinos:

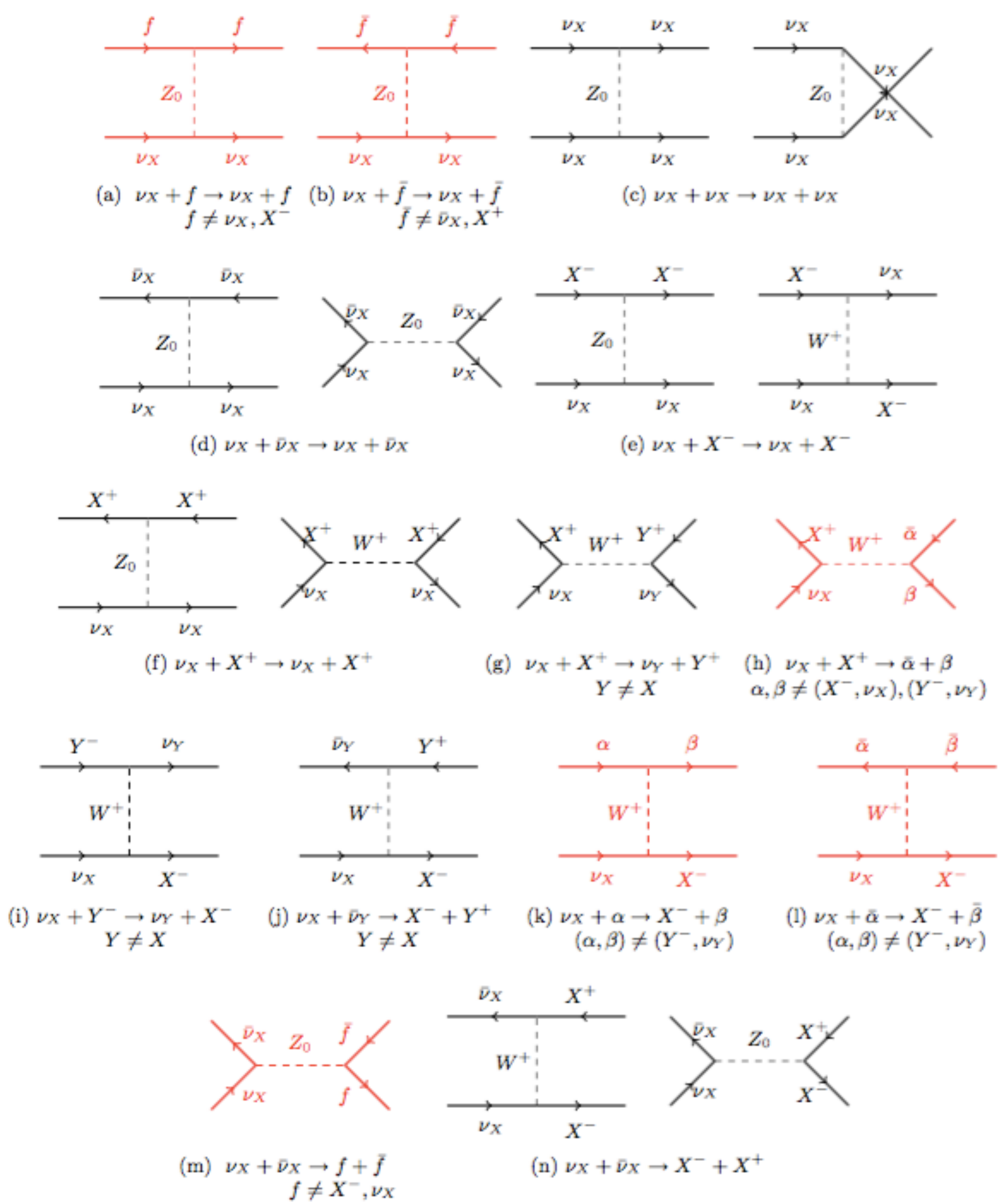
$$\nu_\mu + e^- \rightleftharpoons \nu_e + \mu^-$$
$$\nu_e + e^+ \rightleftharpoons \nu_\mu + \mu^+$$
$$\nu_e + e^+ \rightleftharpoons \underset{(u+\bar{d})}{\pi^+} + \text{stuff}$$
$$\nu_\mu + \mu^+ \rightleftharpoons \underset{(u+\bar{d})}{\pi^+} + \text{stuff}$$
$$\nu_e + e^+ \rightleftharpoons \underset{(u+\bar{s})}{K^+} + \text{stuff}$$
$$\nu_\mu + \mu^+ \rightleftharpoons \underset{(u+\bar{s})}{K^+} + \text{stuff}$$
$$\pi^+ + \pi^0 \leftrightharpoons K^+ + \text{stuff}$$

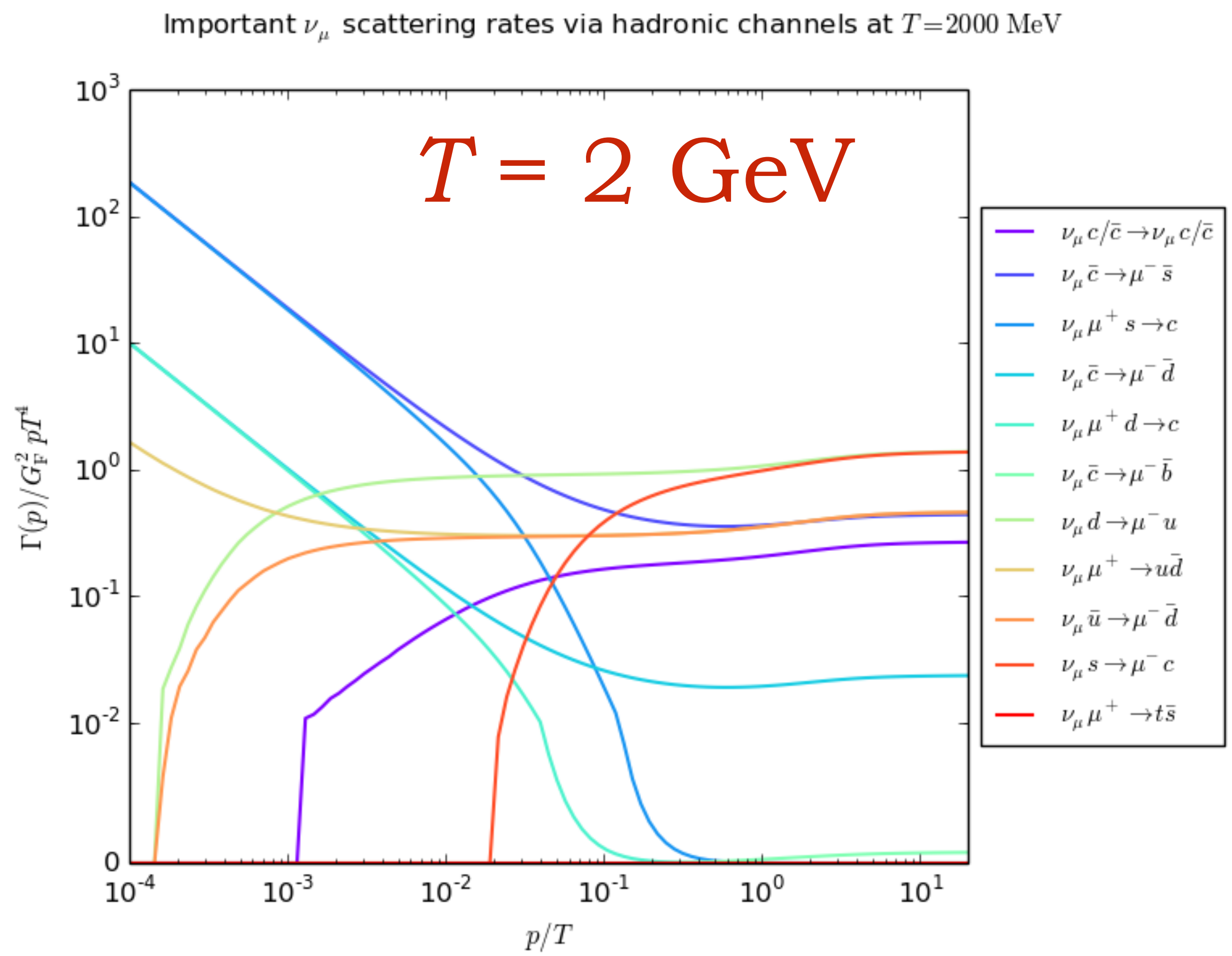
The quantum numbers are related to the chemical potentials via the susceptibility matrix

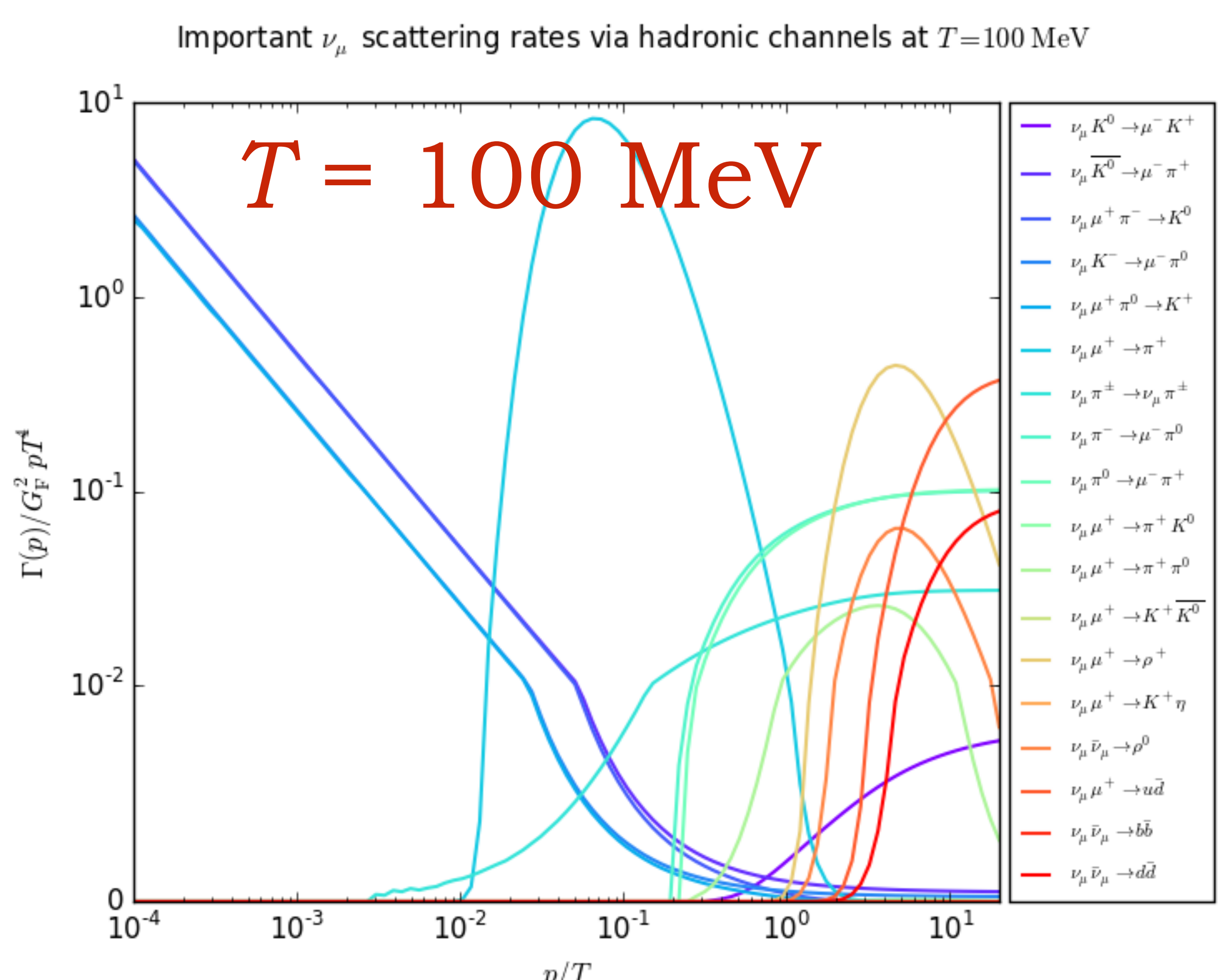
$$\begin{pmatrix} \langle Q \rangle \\ \langle B \rangle \end{pmatrix} = \begin{pmatrix} \chi_2^Q & \chi_{11}^{QB} \\ \chi_{11}^{BQ} & \chi_2^B \end{pmatrix} \begin{pmatrix} \mu_{Q,\text{sys}} \\ \mu_{B,\text{sys}} \end{pmatrix}$$



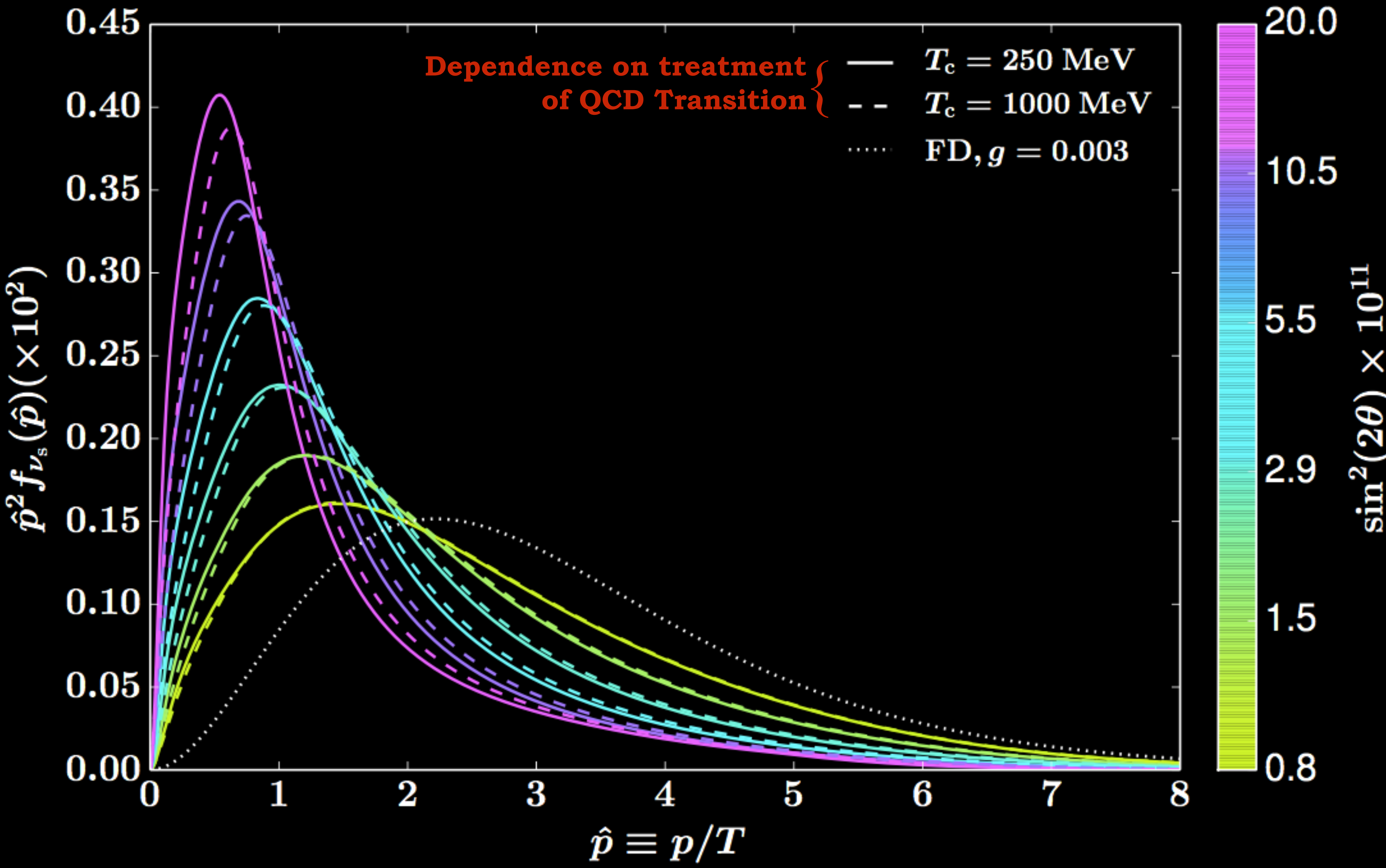
# *Exact neutrino scattering*



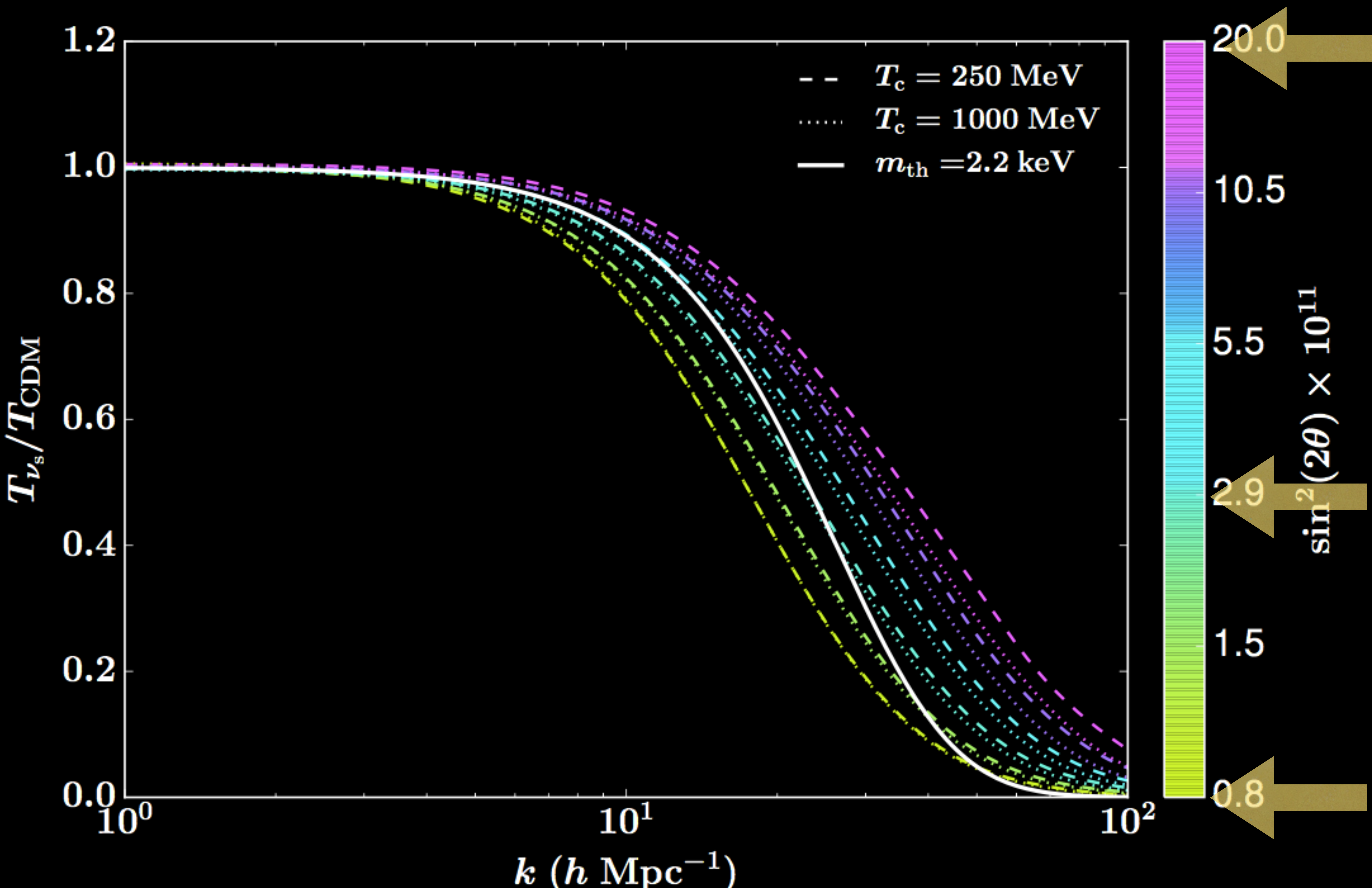



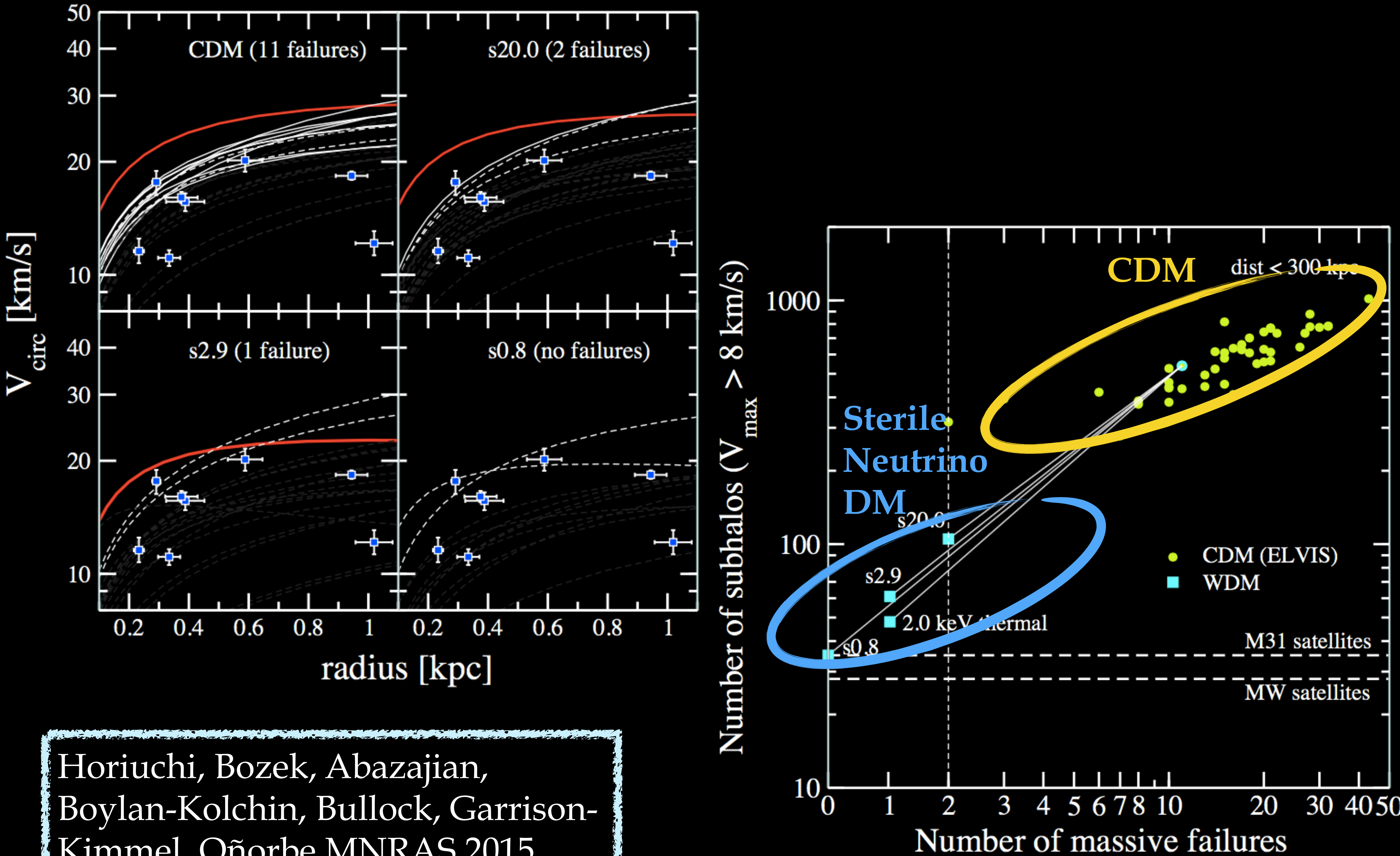
# *Final phase space density results*



# Structure Formation Transfer Functions

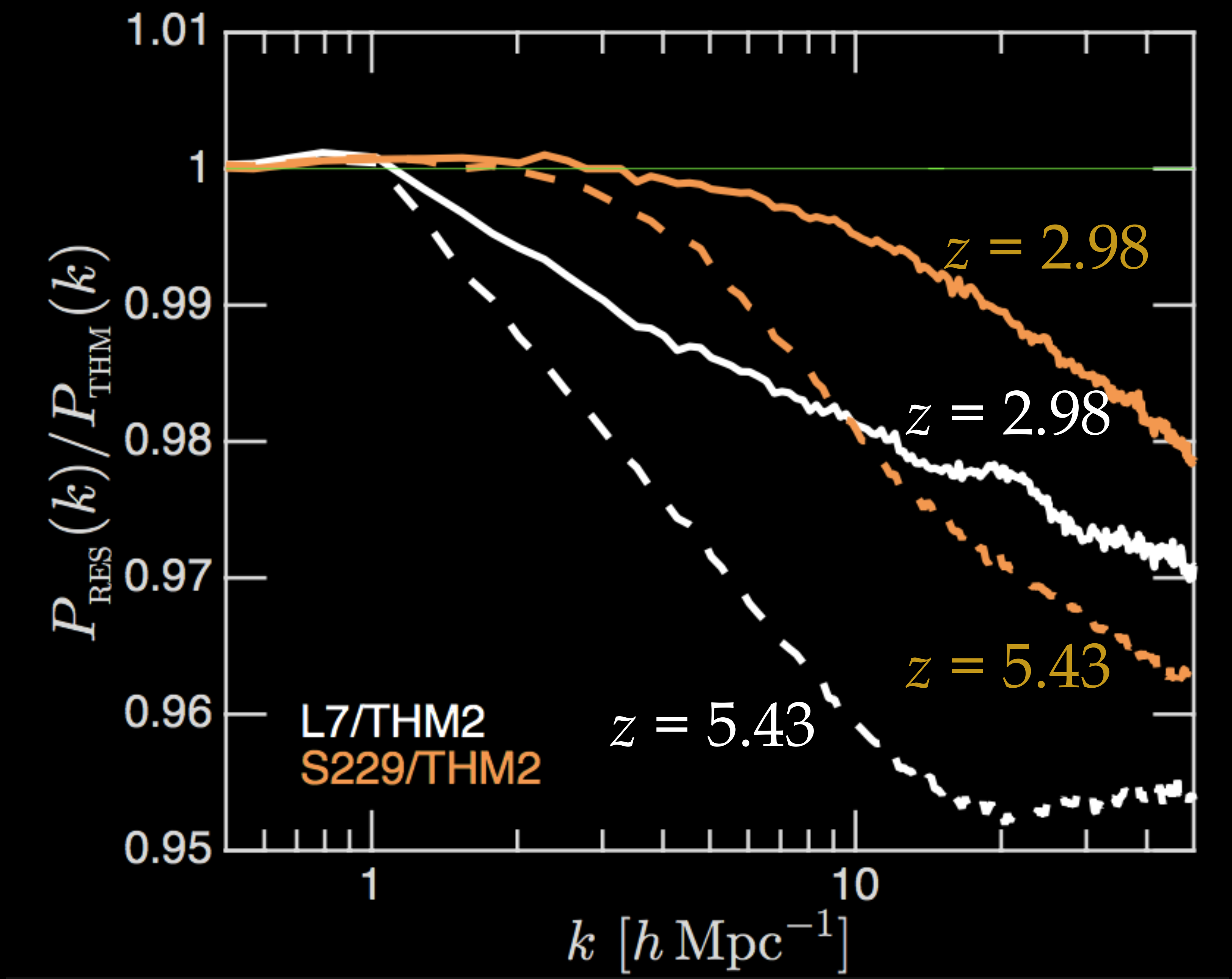


# *7 keV Alleviation of Too Big To Fail…*



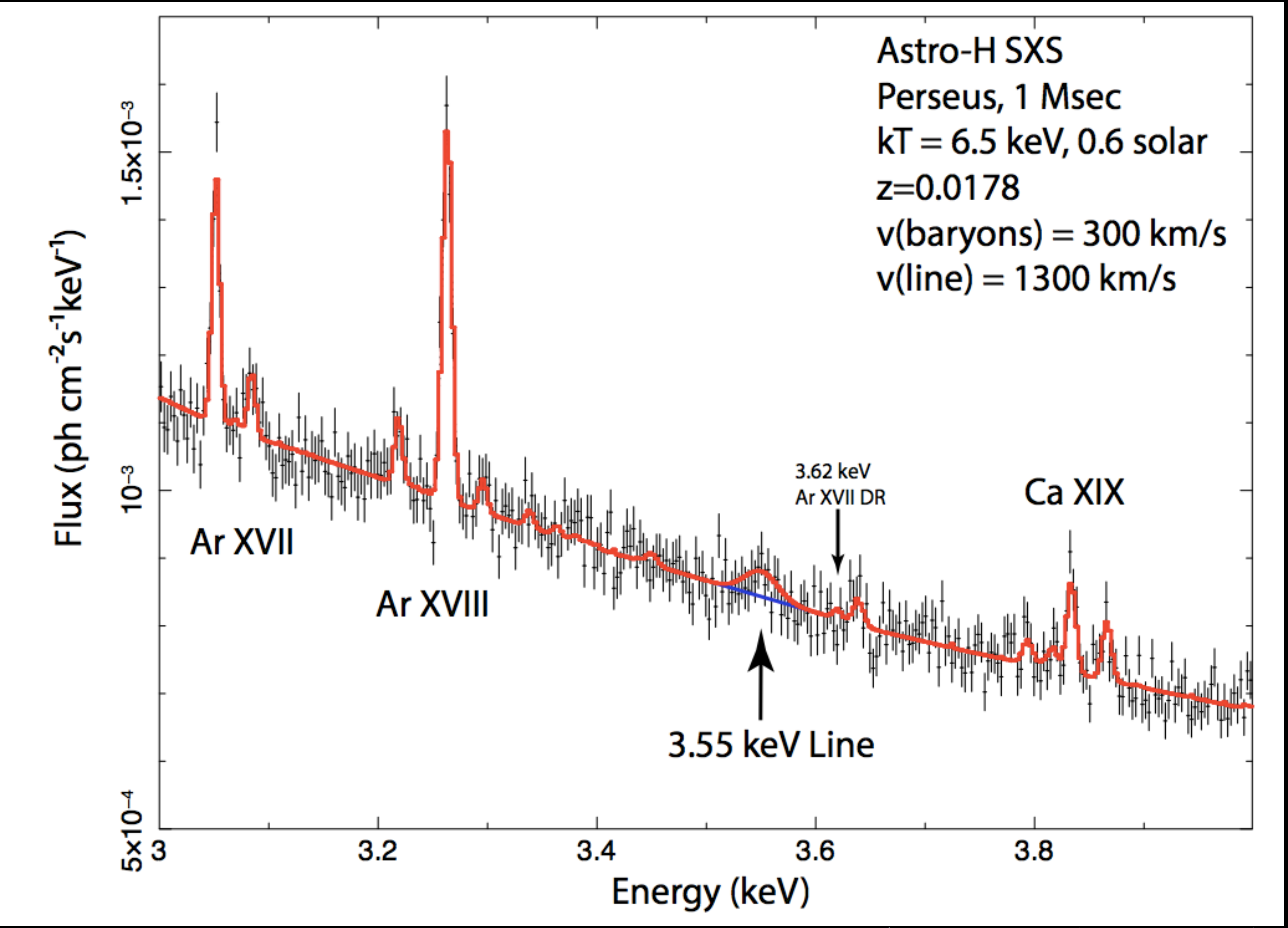

Horiuchi, Bozek, Abazajian, Boylan-Kolchin, Bullock, Garrison-Kimmel, Oñorbe MNRAS 2015

# *Features could be differentiable in future high-redshift measures*




Brandon Bozek, Michael Boylan-Kolchin, Shunsaku Horiuchi, Shea Garrison-Kimmel, Kevork Abazajian, James S. Bullock (2016)

# 3.5 keV Confirmation: Hitomi (Astro-H) X-ray Telescope



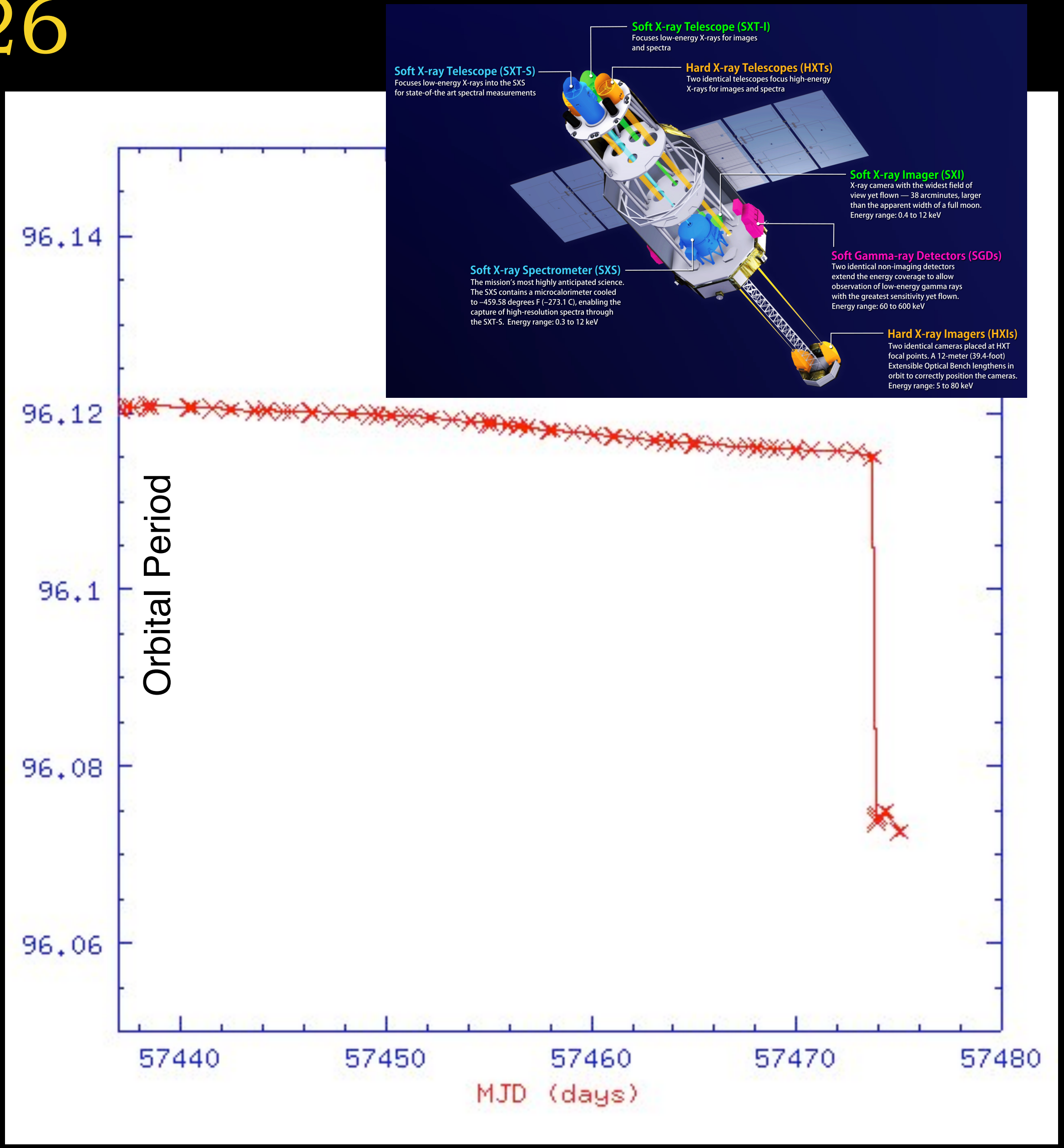

Bulbul et al. ApJ arXiv:1402.2301

# Confirmation: Hitomi (Astro-H) X-ray Telescope

# Communication anomaly of X-ray Astronomy Satellite "Hitomi" (ASTRO-H) - March 26

JAXA Press Releases:

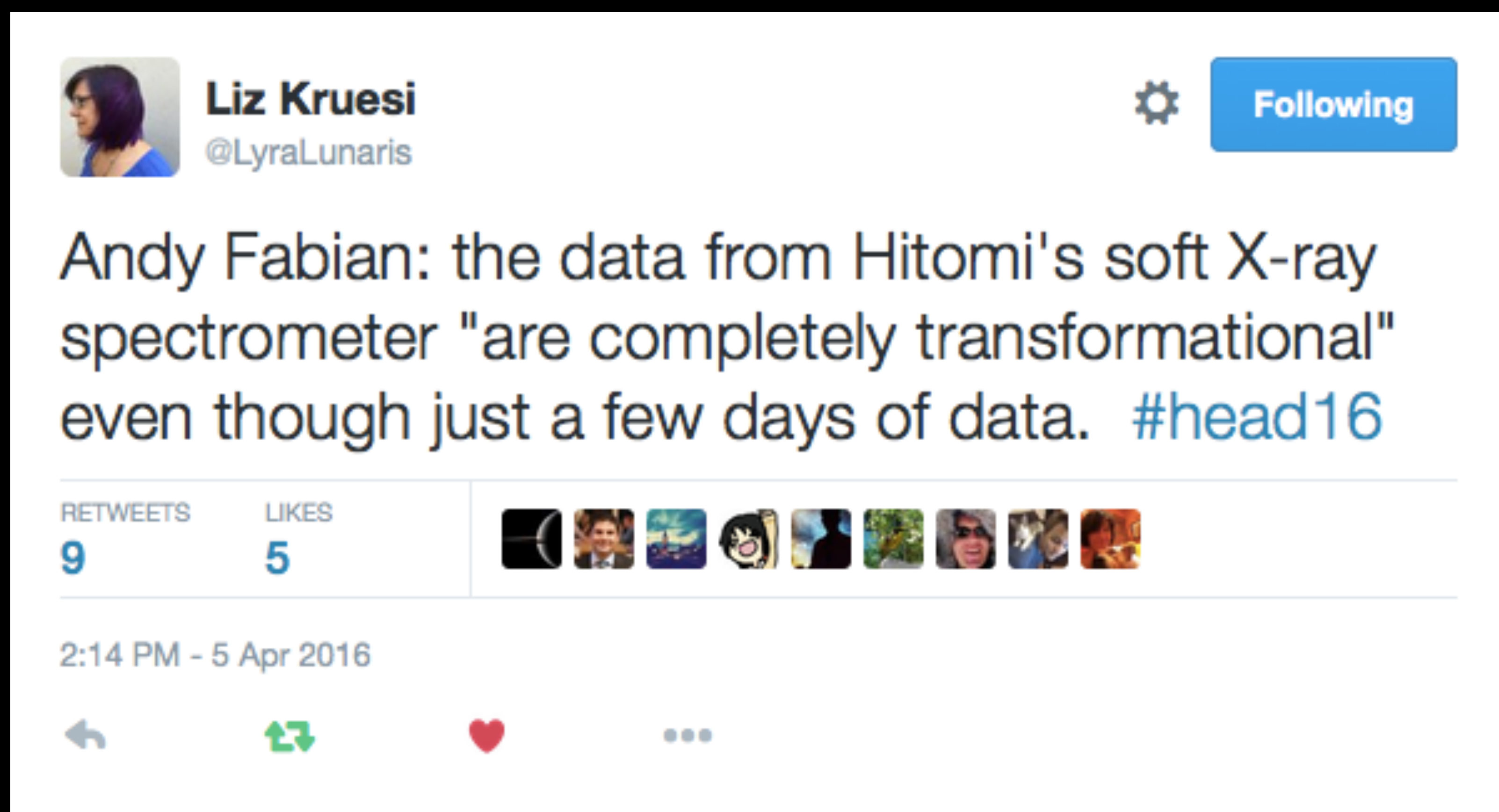
- loss of orbit altitude
- loss of communication
- debris reported by JSpOC (Joint Space Operations Center)
- estimated rotation period calculated from the light curve is about 5.2 seconds



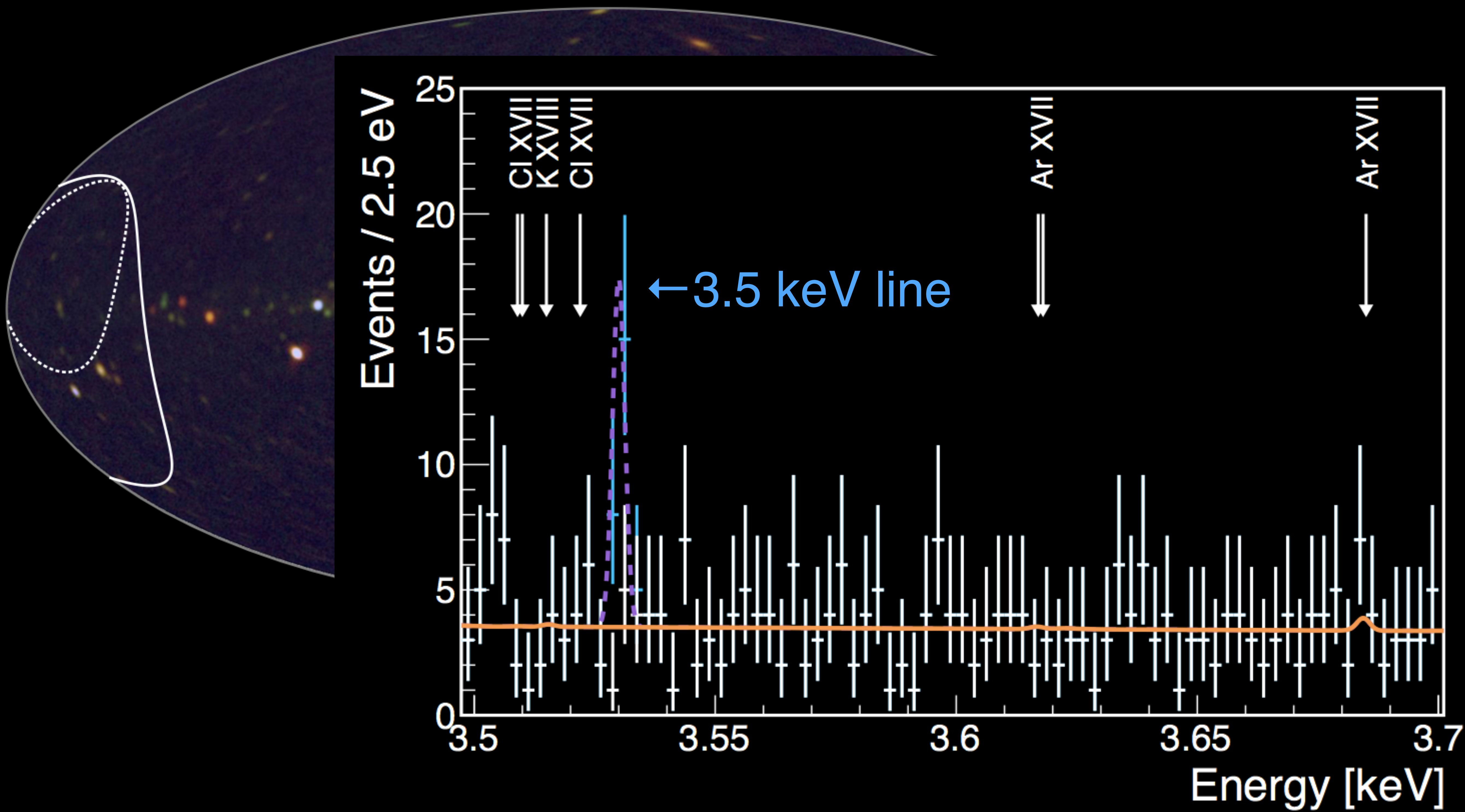

- JAXA: "cause for this fast rotations is anomaly in attitude control system. Based on information from several overseas organizations indicating the separation of the two SAPs from ASTRO-H, JAXA concluded that the functions of ASTRO-H could not be restored. Accordingly, JAXA ceased efforts to recover the satellite and turned to investigating the cause of the anomaly."

# *Hitomi (Astro-H) X-ray Telescope: Data?*

Jonathan McDowell (Harvard CfA):
"some of the data that's been returned is scientifically exciting" [Gizmodo March 30]

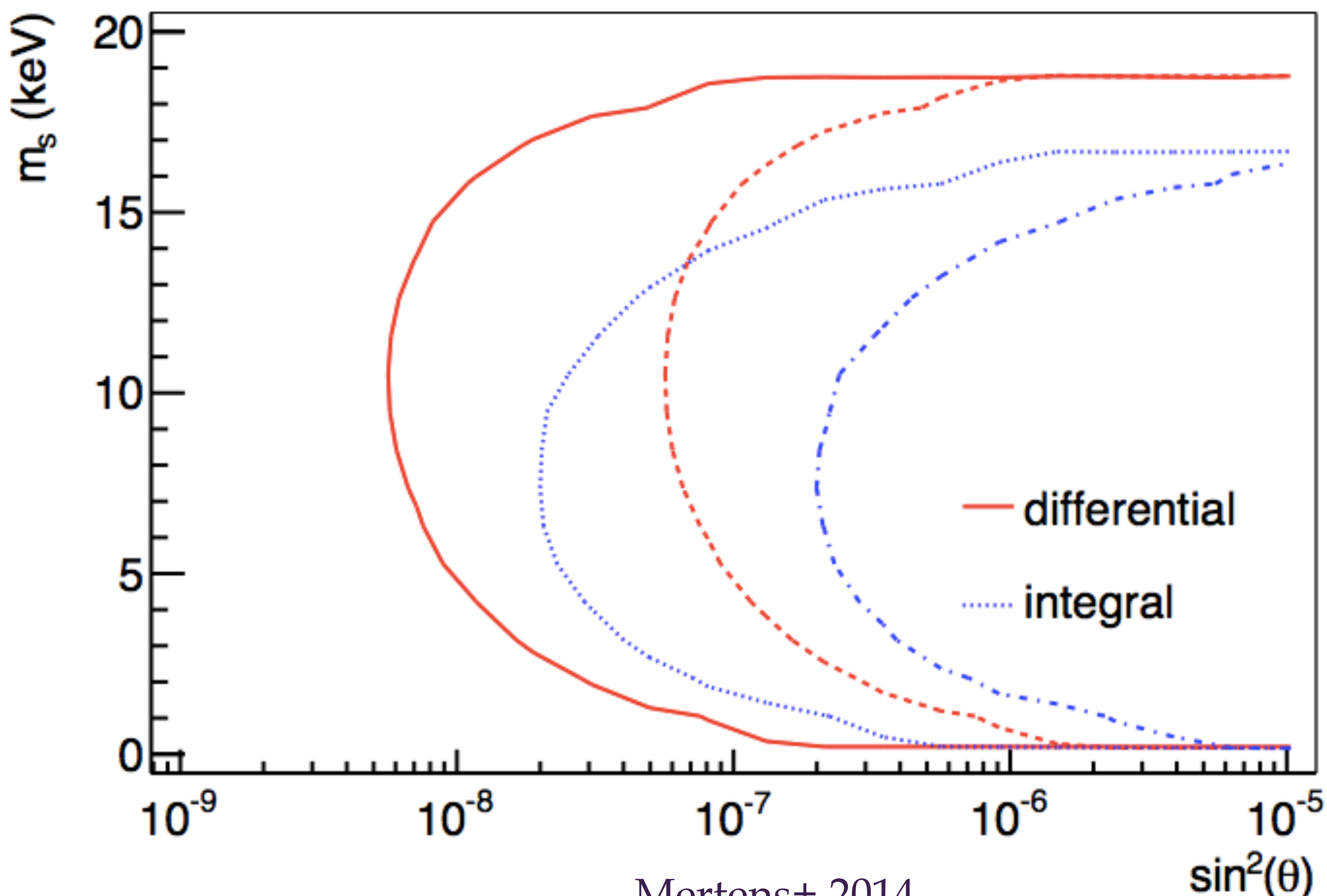


# Confirmation Method: #2 Sounding Rocket X-ray Observations: Micro-X & XQC



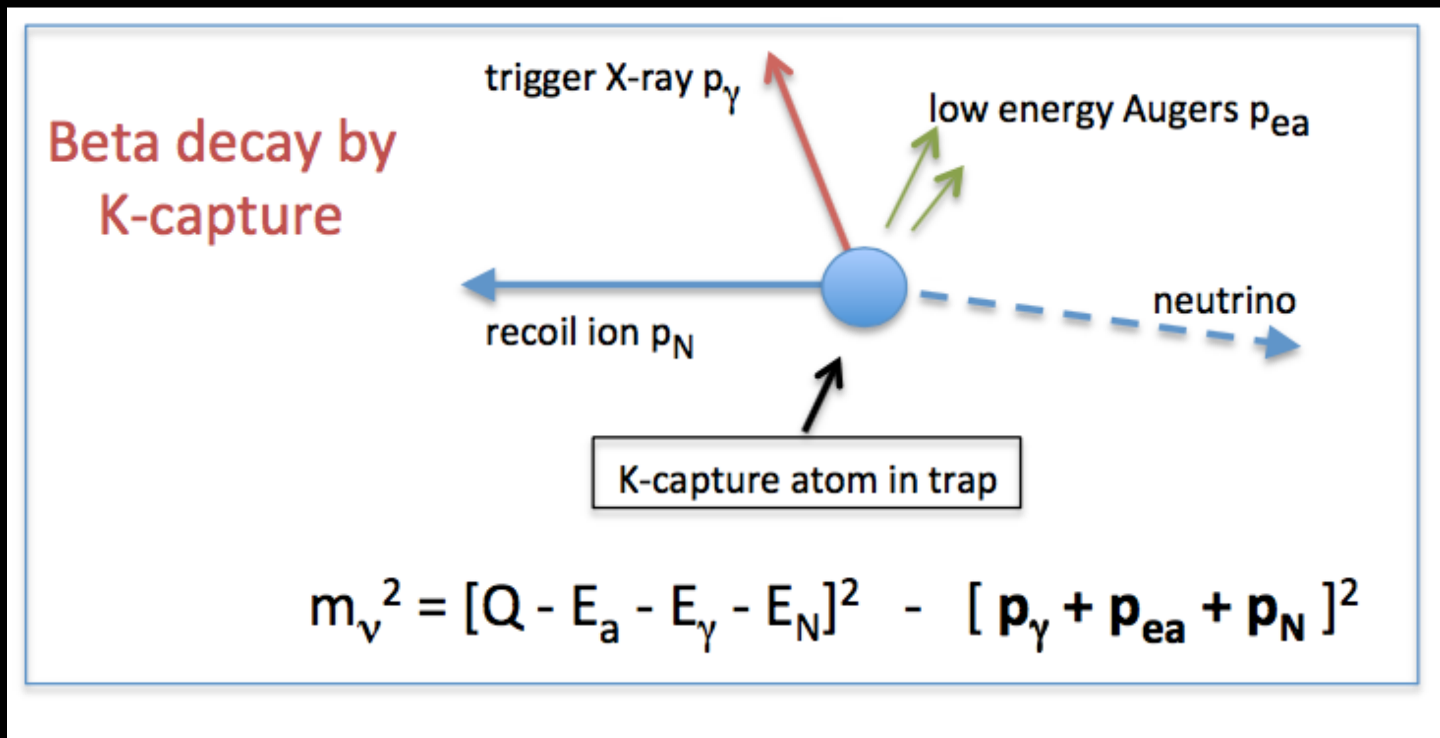

Figueroa-Feliciano+ 1506.05519

# *Confirmation Method #3: kinematic searches in nuclear β-decay*




Mertens+ 2014

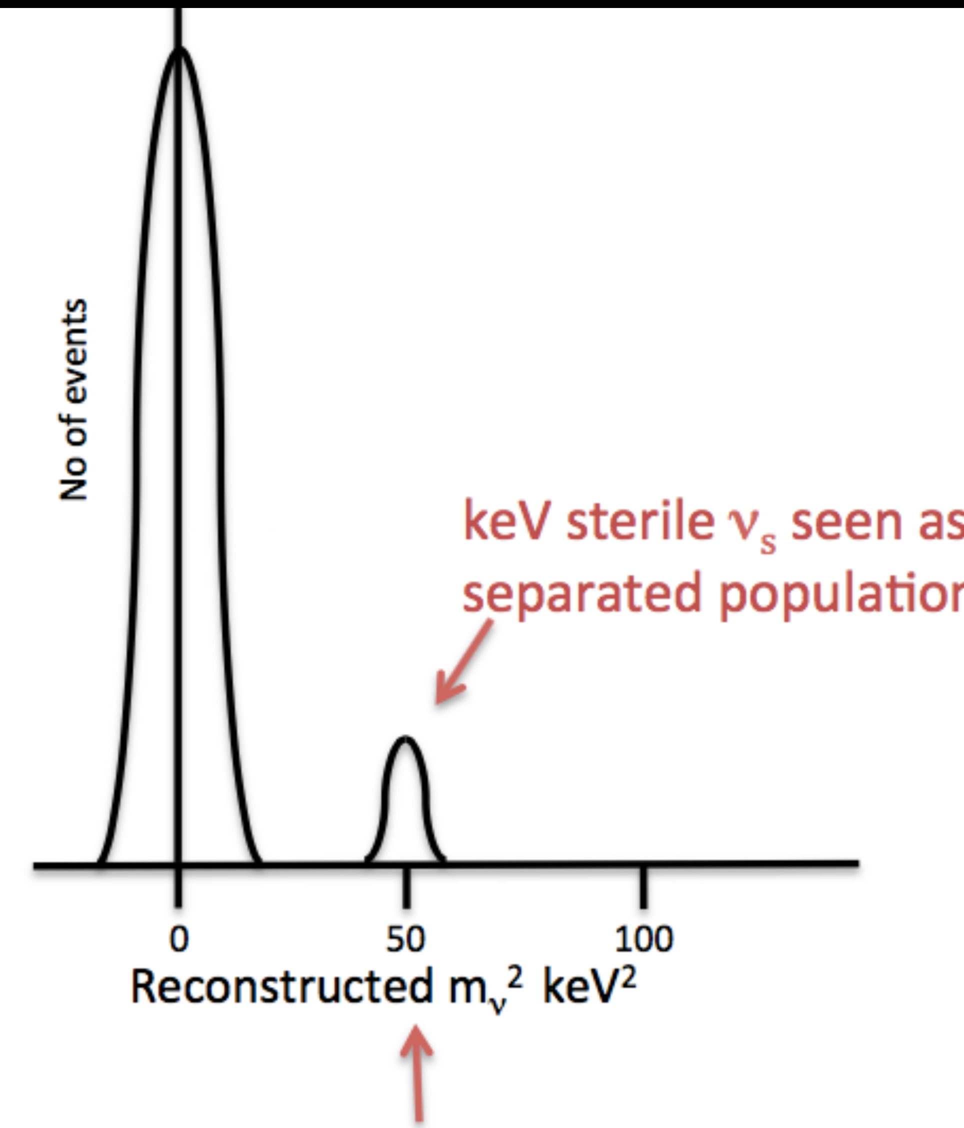
# Confirmation Method #4: full kinematic reconstruction of K-capture nuclear decay




Original studies: Finocchiaro & Schrock 1992

CACHE (Cesium Atomic-electron Capture with Heavy neutrino Emission)

$^{131}Cs$ Ion trap proposal:
Peter Smith at UCLA Dark Matter Conference, Feb. 2016
[Martoff, Napolitano, Hudson, Wang, Smith, Renshaw, Fuller, E Grohs]




High precision time of flight measurements needed to achieve 6σ separation from zero mass peak

Recent studies show this may now be feasible

# Summary

- An unidentified line has been detected at 4σ to 5σ in two independent samples of stacked X-ray clusters with XMM-Newton, with several subsamples showing the line. It is seen by the same group in the Perseus Cluster with Chandra data. (Bulbul et al. ApJ 2014)
- Within a week, an independent group reported a line at the same energy toward Andromeda (M31) and Perseus with *XMM-Newton*, with combined statistical evidence of 4.4σ. (Boyarsky et al. PRL 2014).
- Seen in 8 more clusters at lower significance. No consistent astrophysical interpretation exists.
- Follow up observations:
  - current: Hitomi (data implications uncertain)
  - 2017-2018: Micro-X, XQC
  - 2028+: ATHENA
- The simplest model for the signal is resonant sterile neutrino production with a cosmological *L*. The signal crosses a transition region from “cold” dark matter to “warm” dark matter, particularly at a small-scale structure cutoff scale of great interest in galaxy formation of the local group of galaxies, ~2 keV thermal WDM.