

Title: Clusters of Galaxies in Microwave and X-Ray Spectral Bands

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Abstract:

PERIMETER INSTITUTE

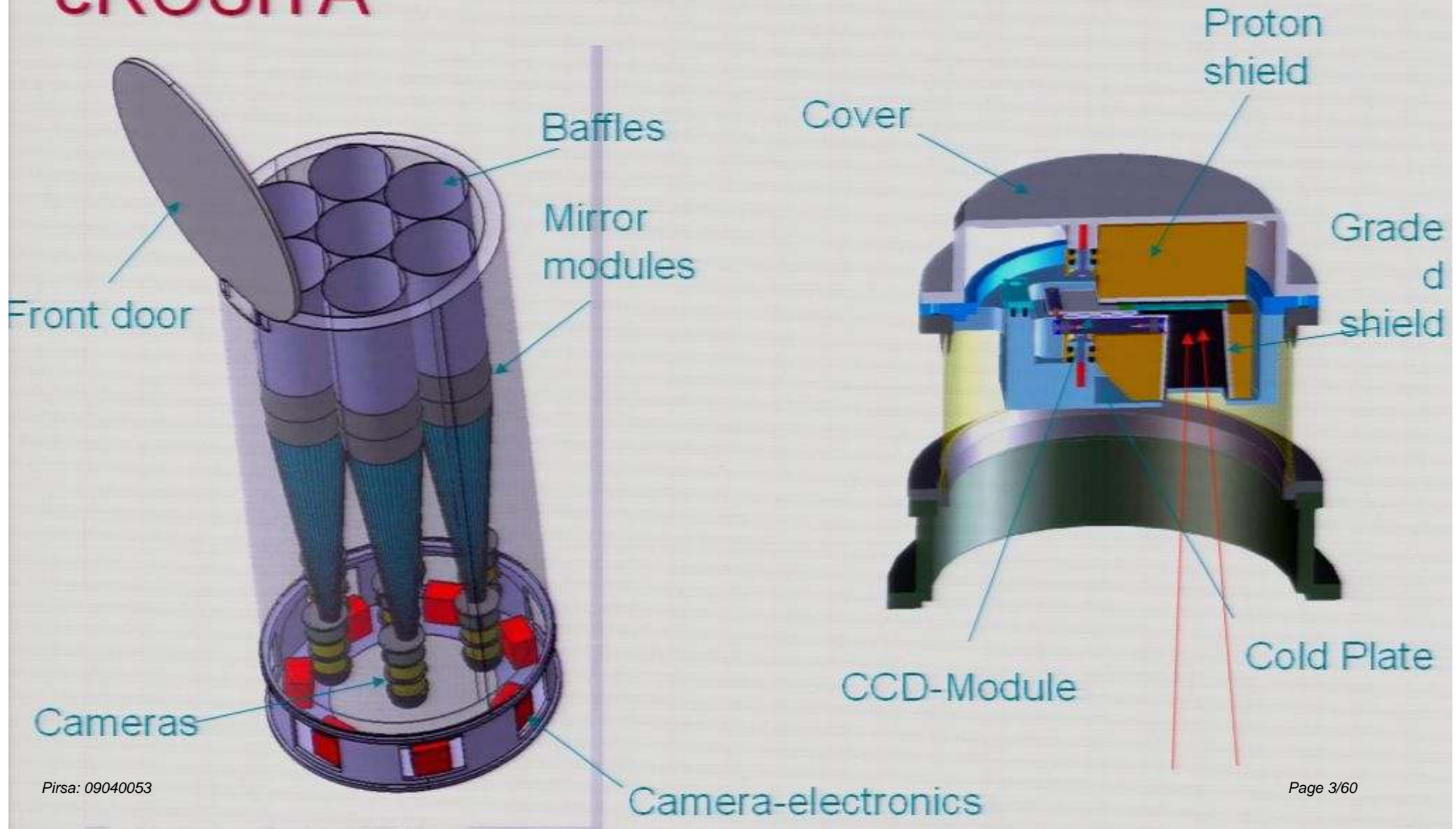
**Clusters of galaxies in Microwave and X-Ray spectral bands**  
*(spectroscopy and polarization)*

**Rashid Sunyaev**



*Max-Planck-Institut für Astrophysik  
and  
Space Research Institute  
of Russian Academy of Sciences*

# eROSITA



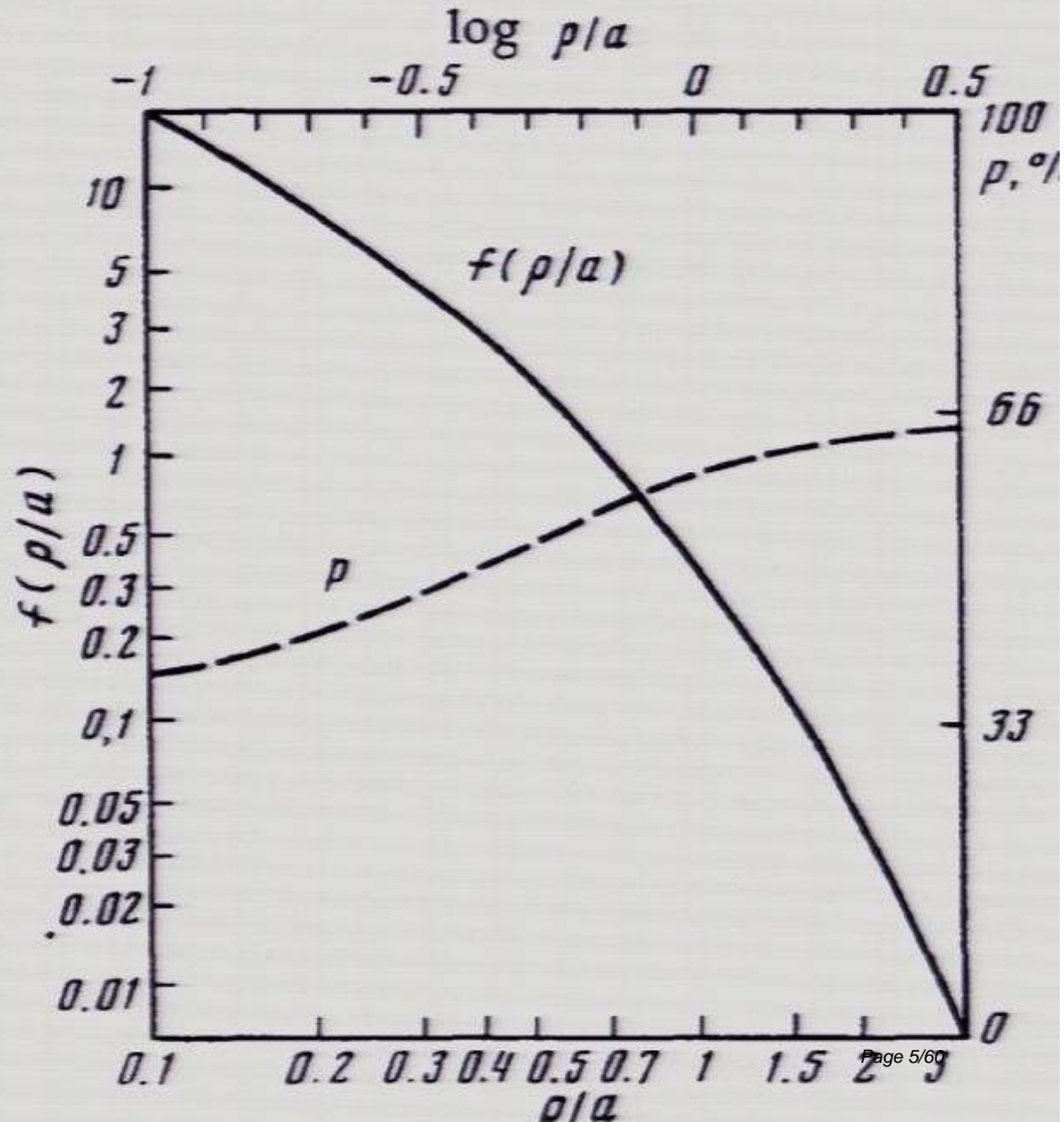
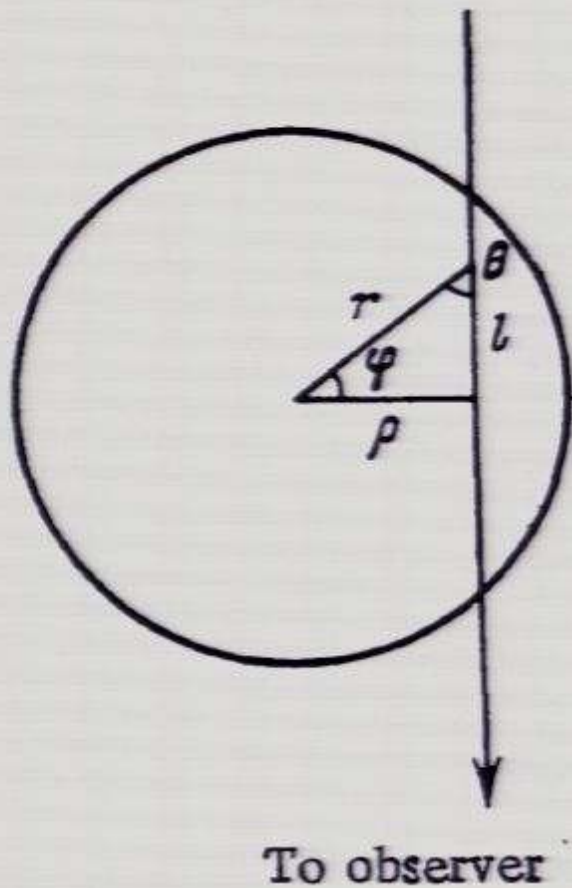
# SRG – observing strategy

<p>All-sky survey (41253 deg<sup>2</sup>): continuous scan with revolution around the axis tilted to Sun direction at ~30° per 96 minute (=orbit)</p>	<p>4 years</p>
<p>Deep Survey and pointed observations of individual objects</p>	<p>3–6 years</p>

# Bright source in the cluster

# Polarization of the scattered radiation

Scattering on free electrons



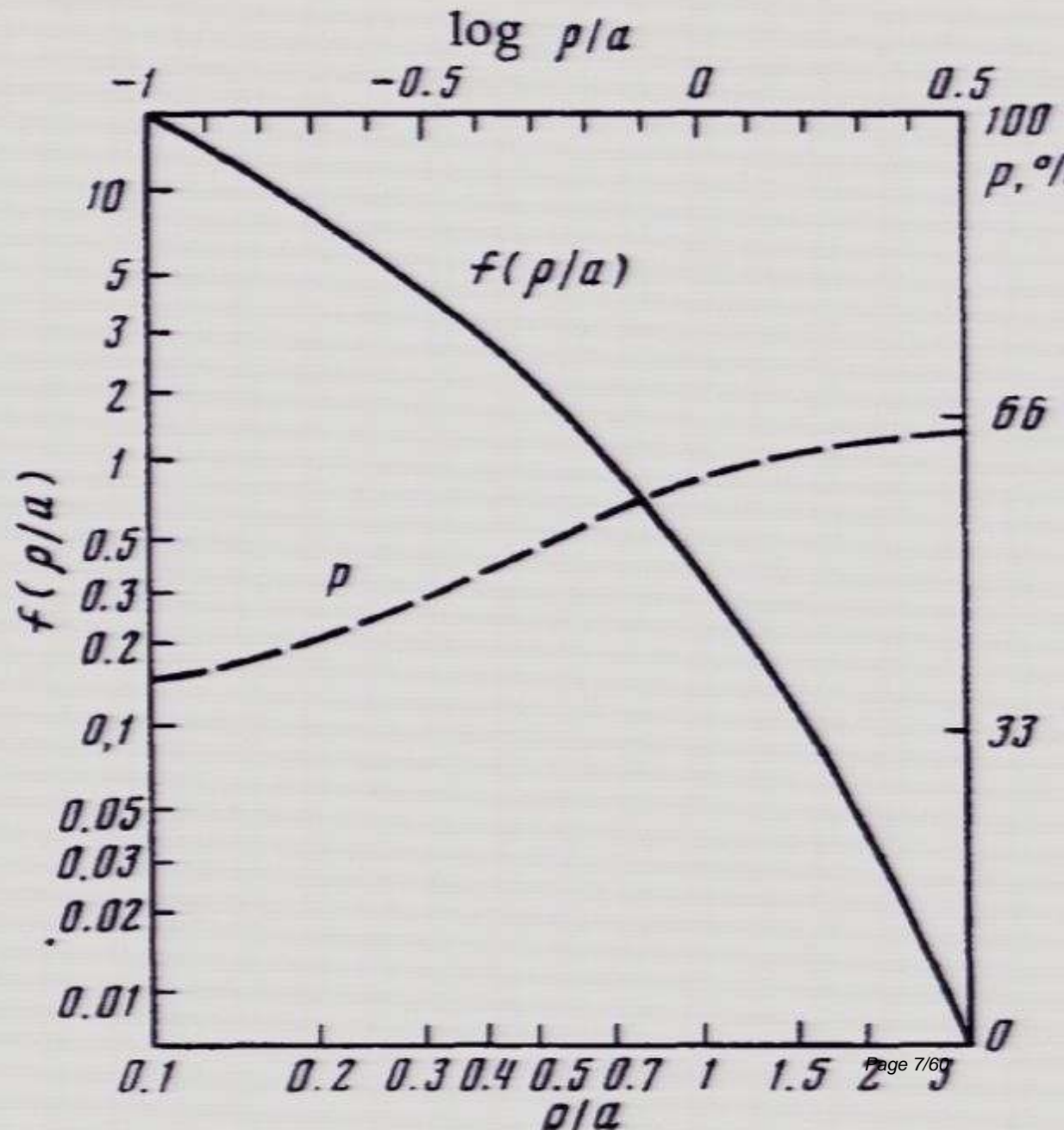
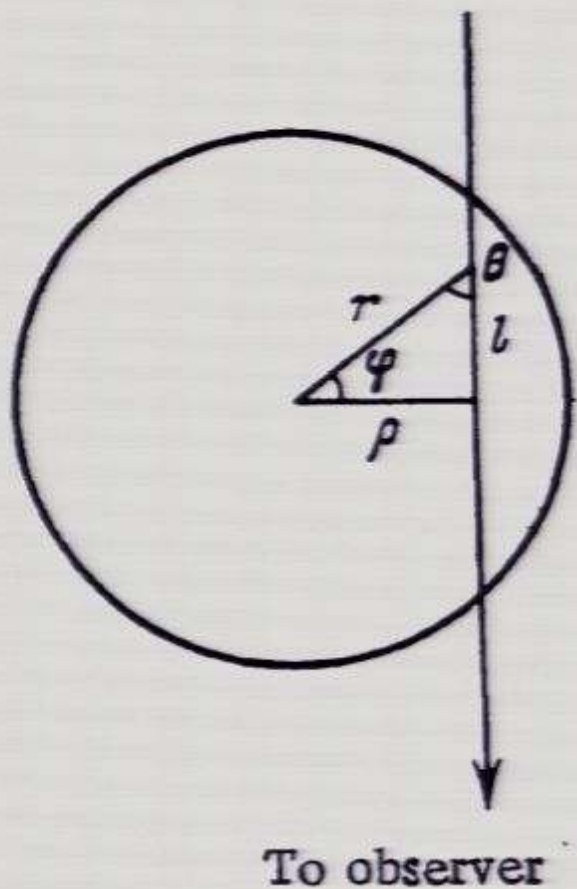
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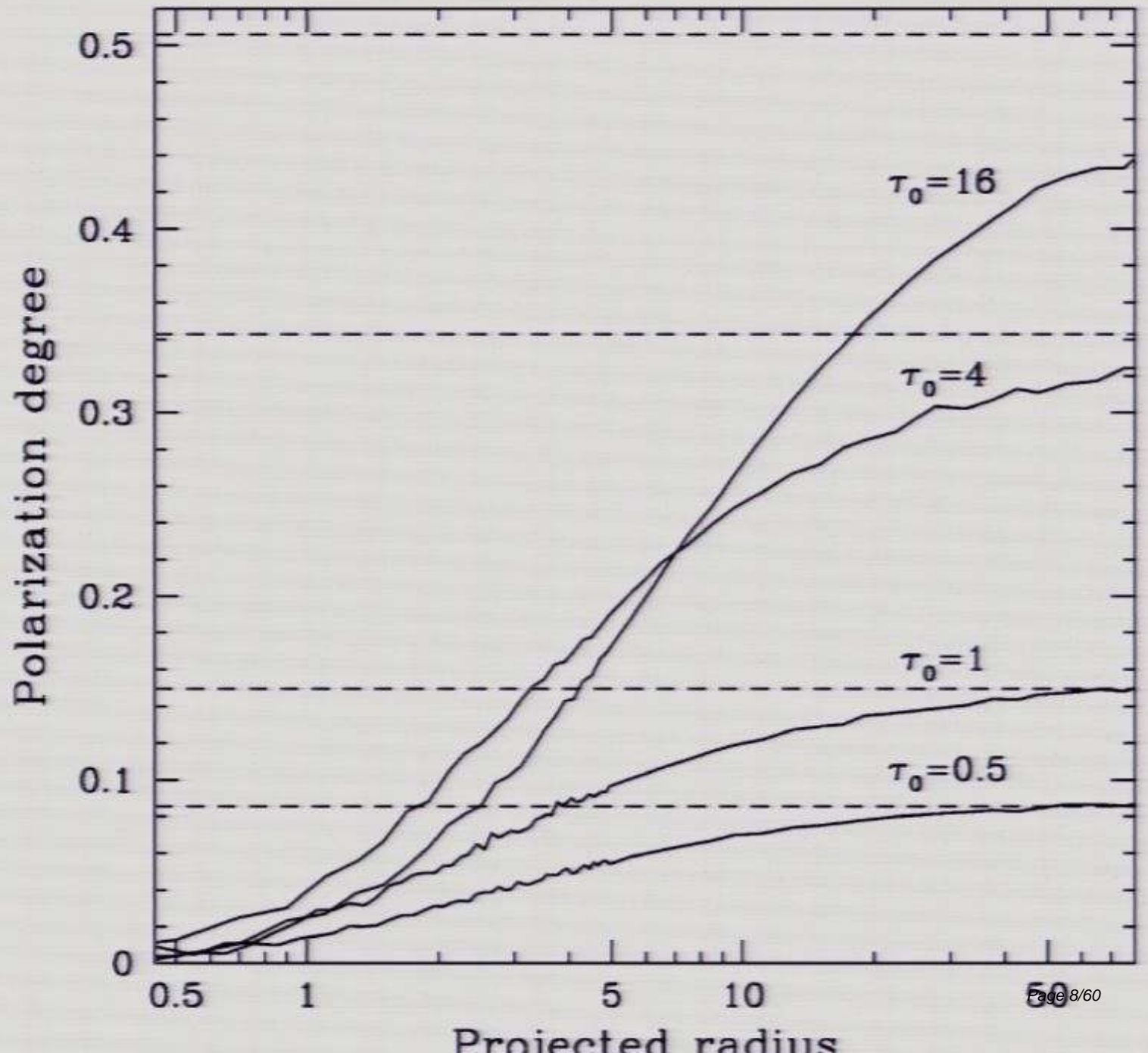
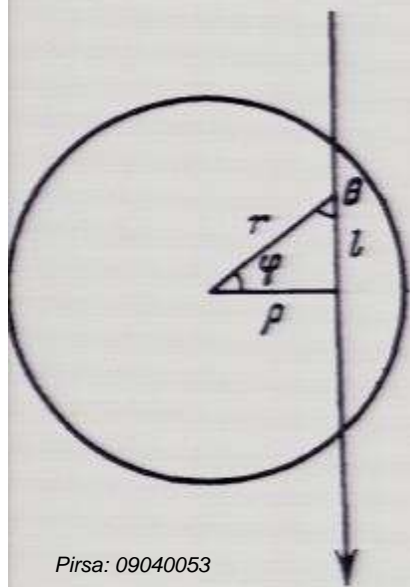
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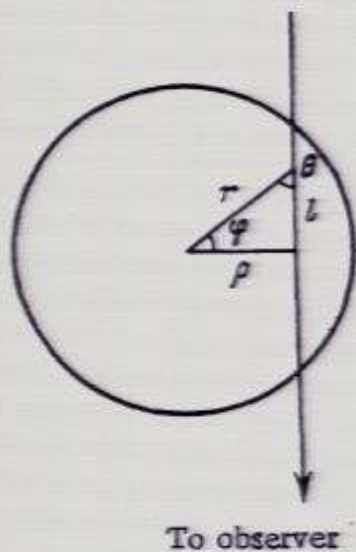
# Scattering in X-Ray resonant lines in the hot gas inside clusters



## Scattering in X-Ray resonant lines in the hote gas inside clusters

*X-Rays are emitted in the central part and scattered in the outer parts of the clusters*

**Table 2.** X-ray lines with large optical depth ( $\tau_0 > 0.5$ ) to resonant scattering: the Perseus cluster.

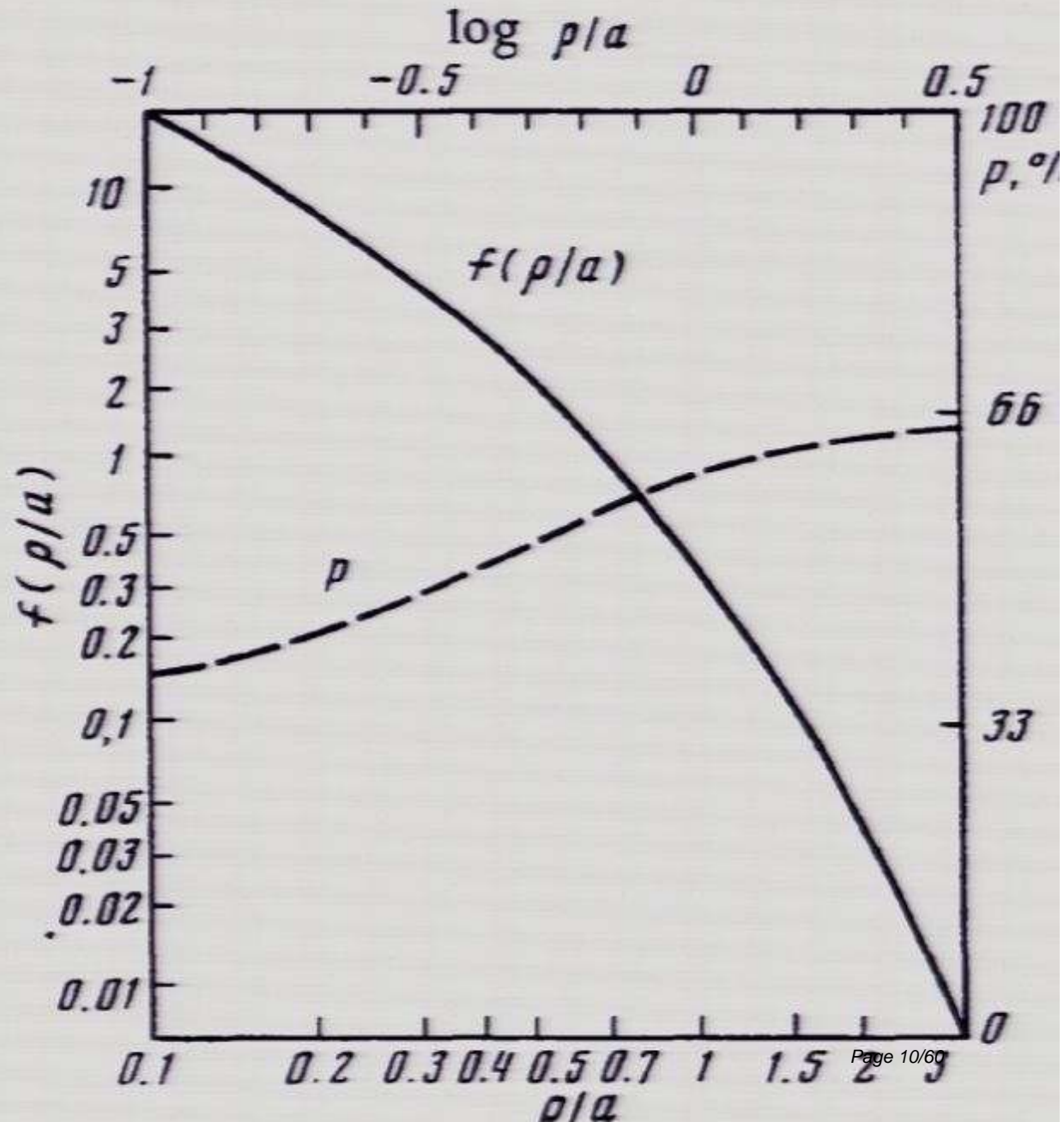
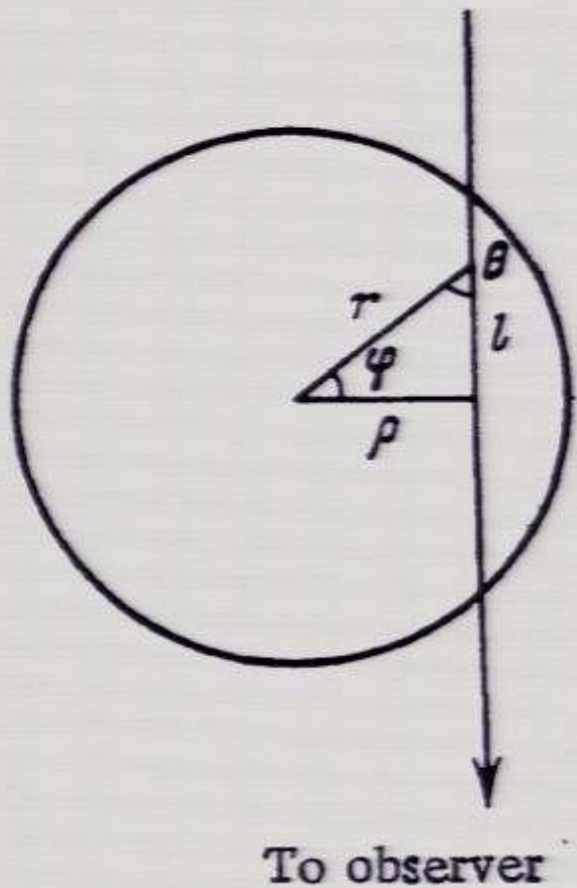


Ion	Energy (keV)	Optical depth	Weight of dipole scattering
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Fe XXV	6.700	3.3	1
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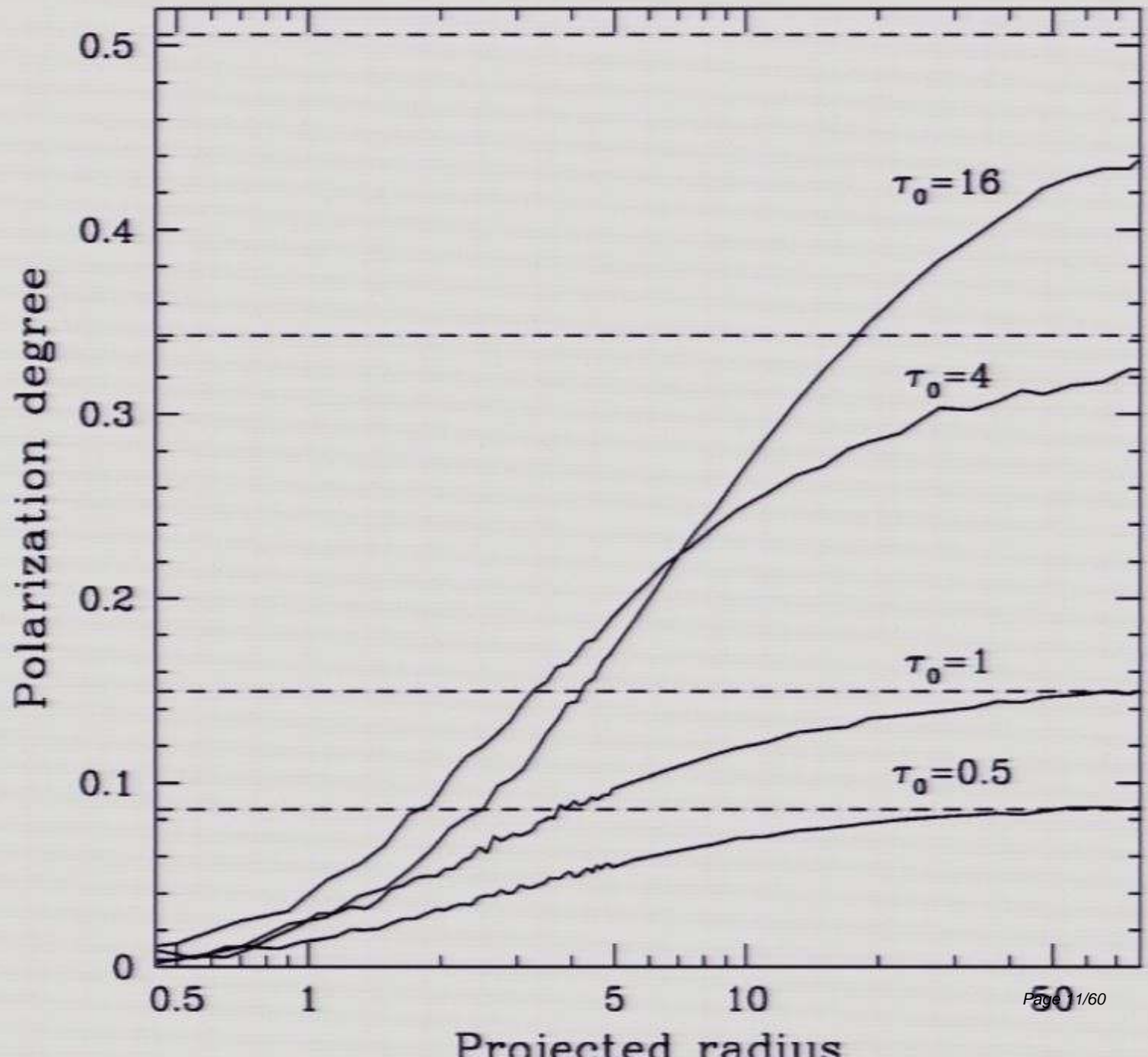
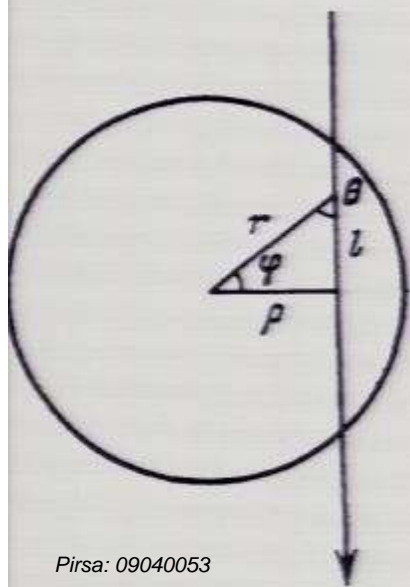
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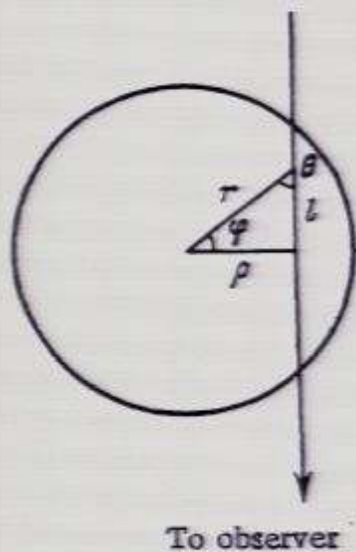
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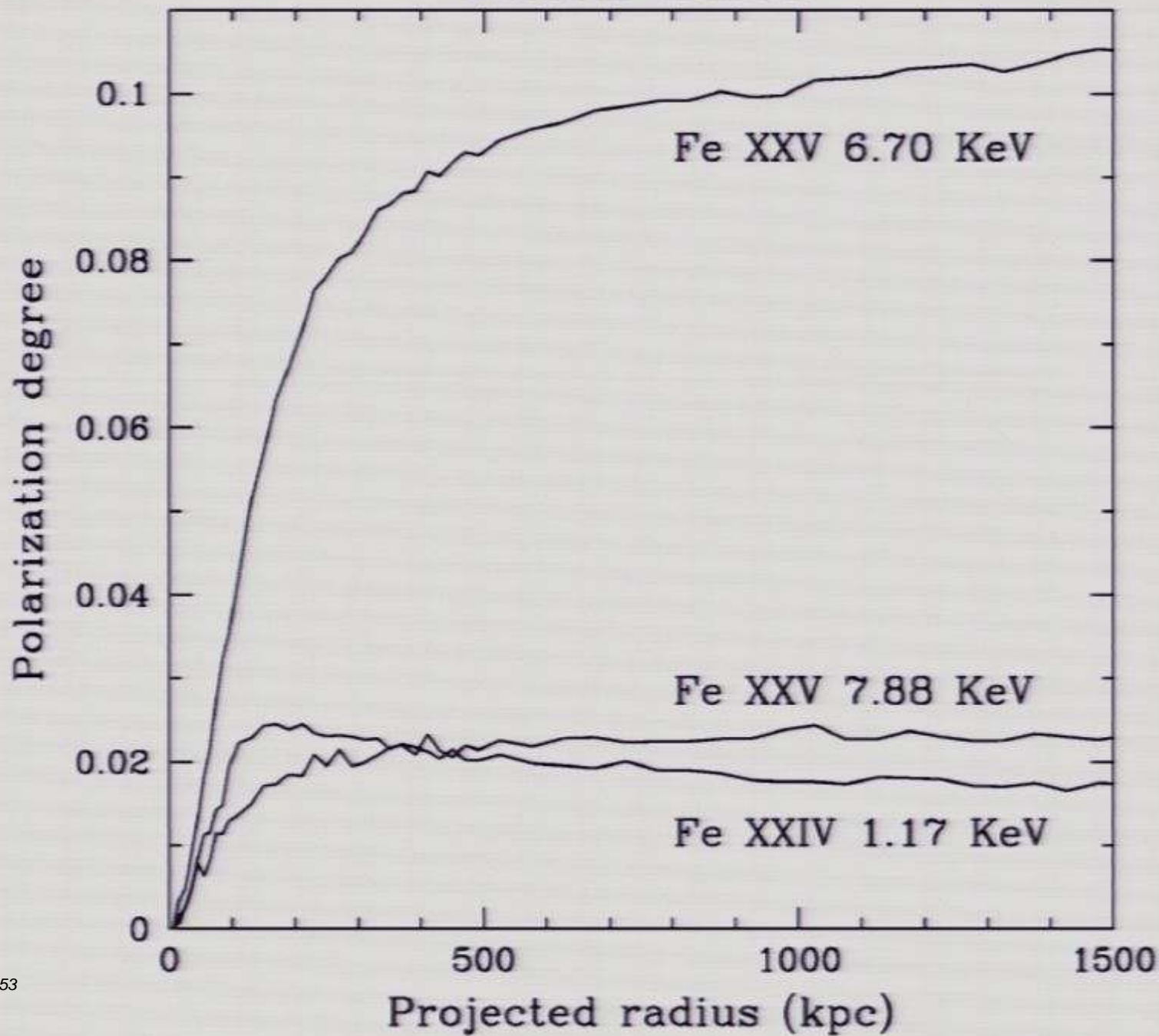
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# Perseus Cluster



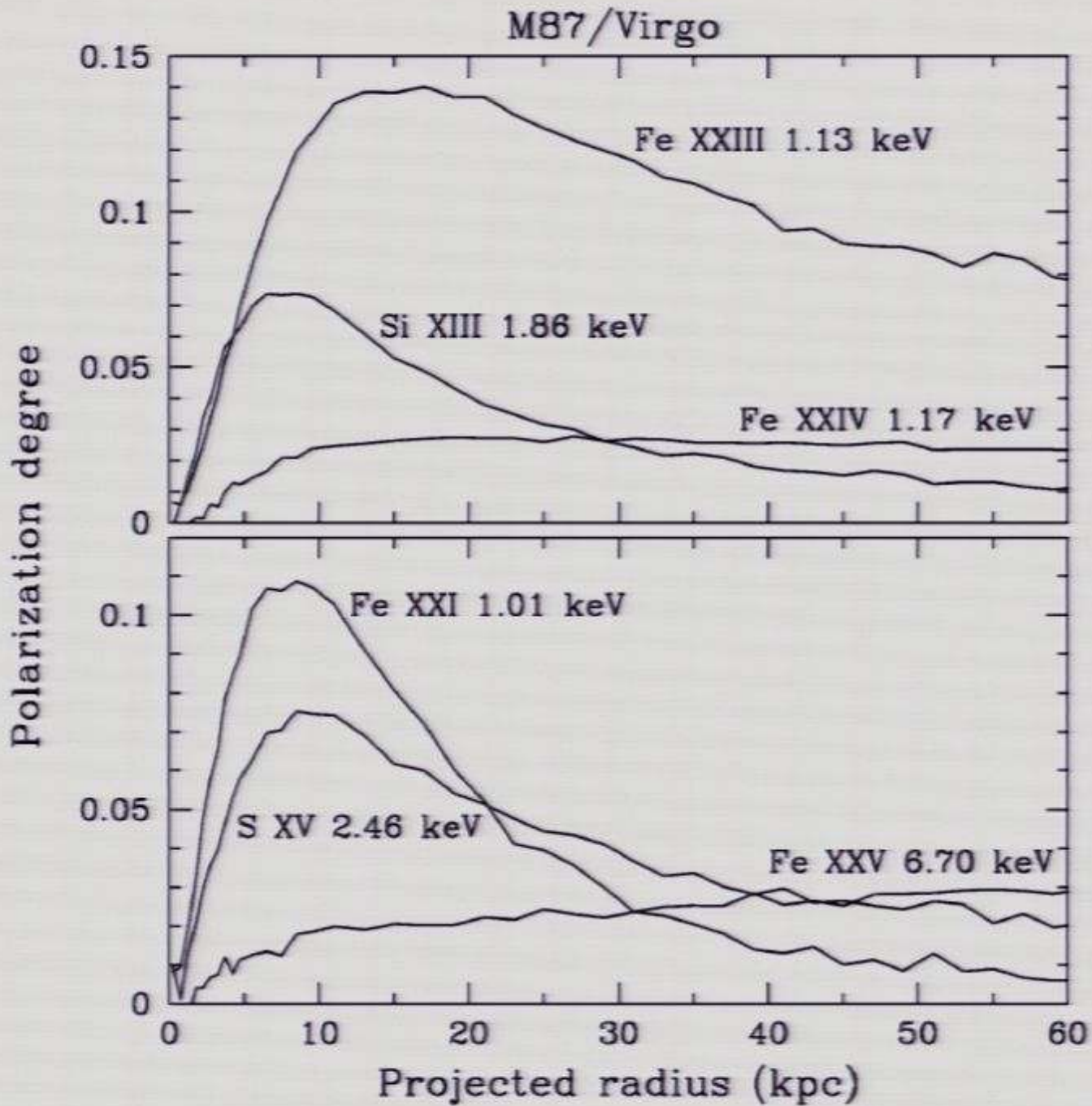
**Table 3.** X-ray lines with large optical depth ( $\tau_0 > 0.5$ ) to resonant scattering: the M87/Virgo cooling flow.

Ion	Energy (keV)	Optical depth	Weight of dipole scattering
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O VIII	0.654	0.7	0.5
Ne X	1.021	0.5	0
Ne X	1.022	1.0	0.5
Si XIII	1.865	2.1	1
Si XIV	2.004	0.8	0
Si XIV	2.006	1.7	0.5
S XV	2.461	2.5	1
S XVI	2.620	0.3	0
S XVI	2.623	0.6	0.5
Ar XVII	3.140	0.8	1
Fe XX	0.967	0.7	0.28
Fe XX	0.967	0.5	0.32
Fe XXI	1.009	2.3	1
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Fe XXIII	1.129	6.2	1
Fe XXIII	1.493	1.2	1
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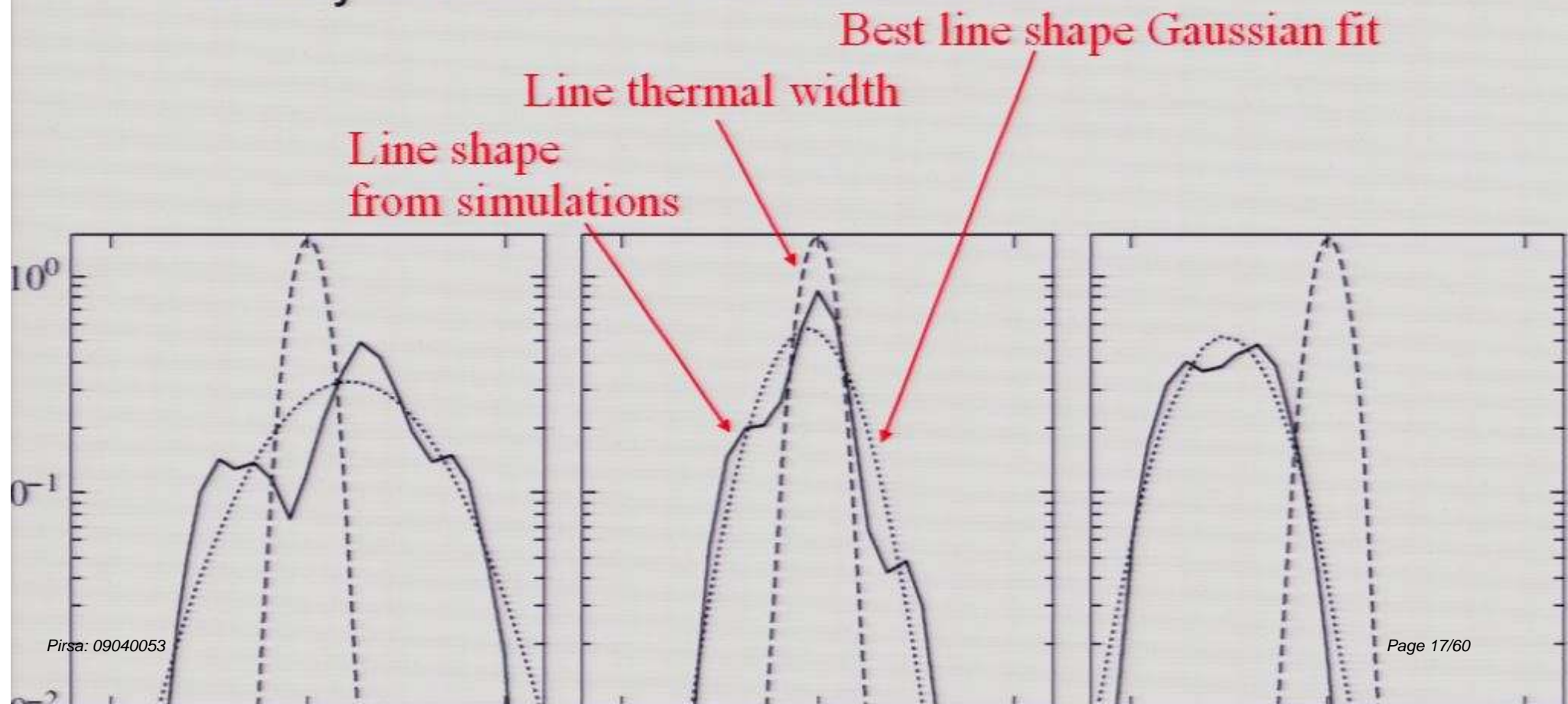
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# $^{57}\text{Fe}$ XXIV line: science

- Narrow Doppler profile
  - study turbulence and bulk motions



Electron is moving with velocity  $v$  in the CMB radiation field

$$T_0 = T_r \frac{\sqrt{1 - \beta^2}}{1 + \beta \mu_0}$$

Doppler

Quadrupole component

$$T_0 = T_r [1 - \beta \mu_0 + \beta^2 (\mu_0^2 - 1/3) + \dots]$$

Tangential component  
of velocity

$$p = 0.1 \tau \beta_t^2$$

Linear polarization

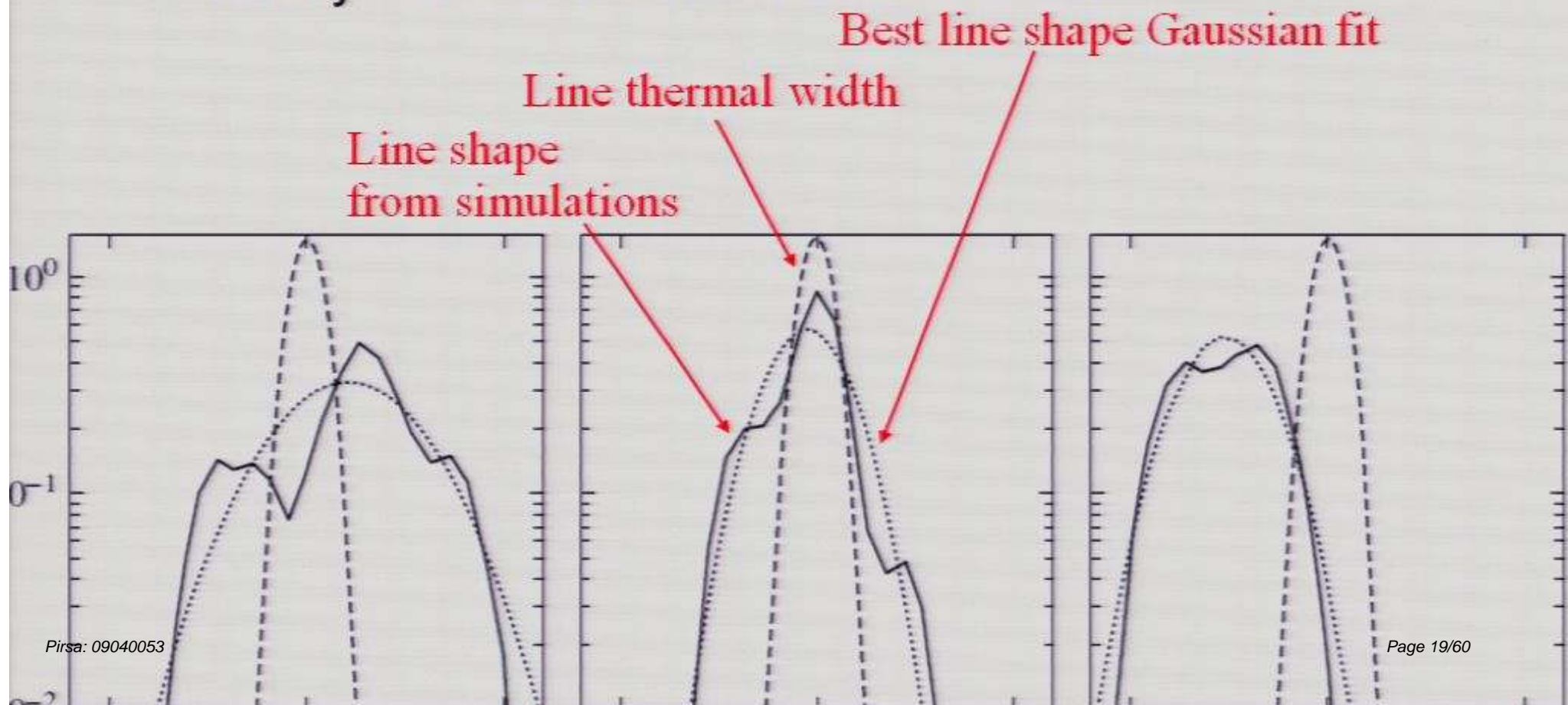
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Double scatterings also produce  
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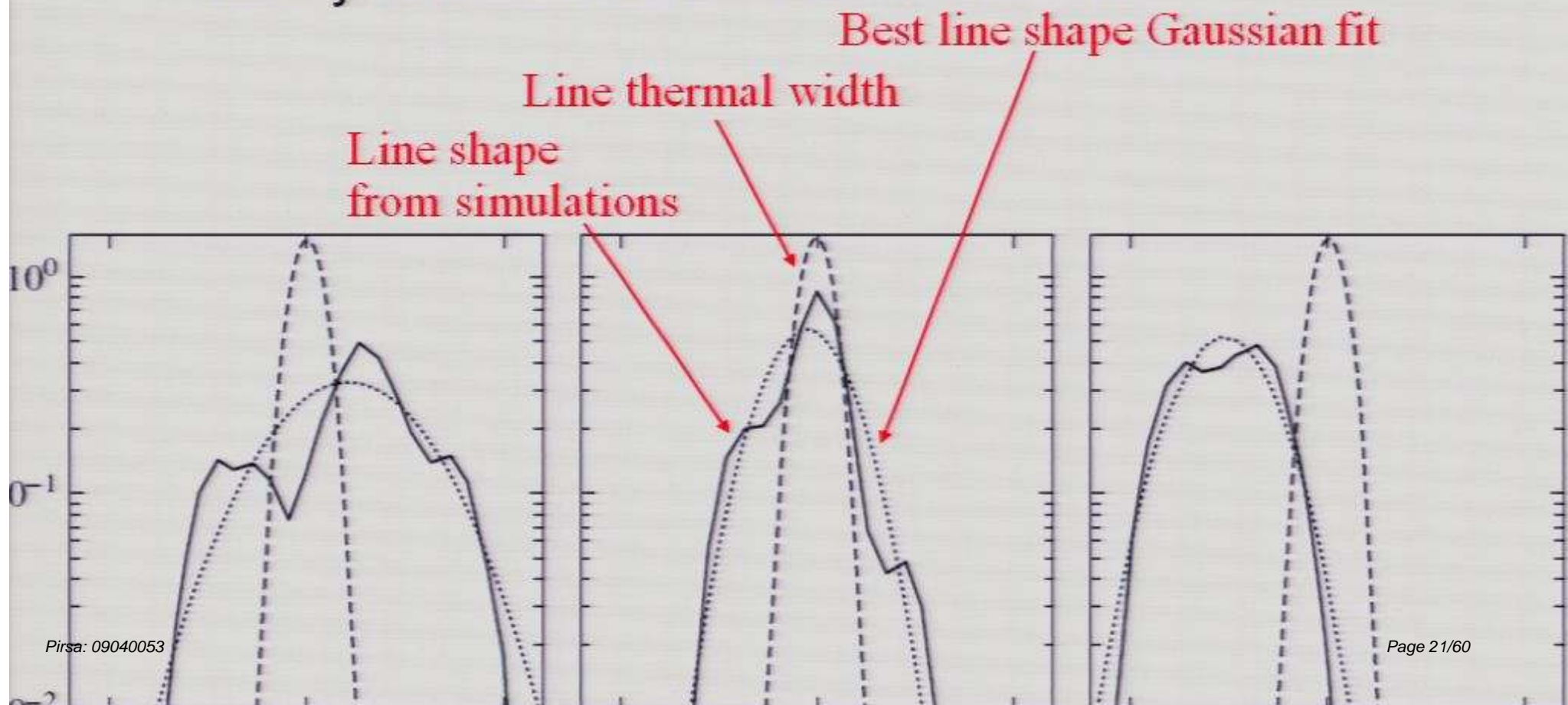
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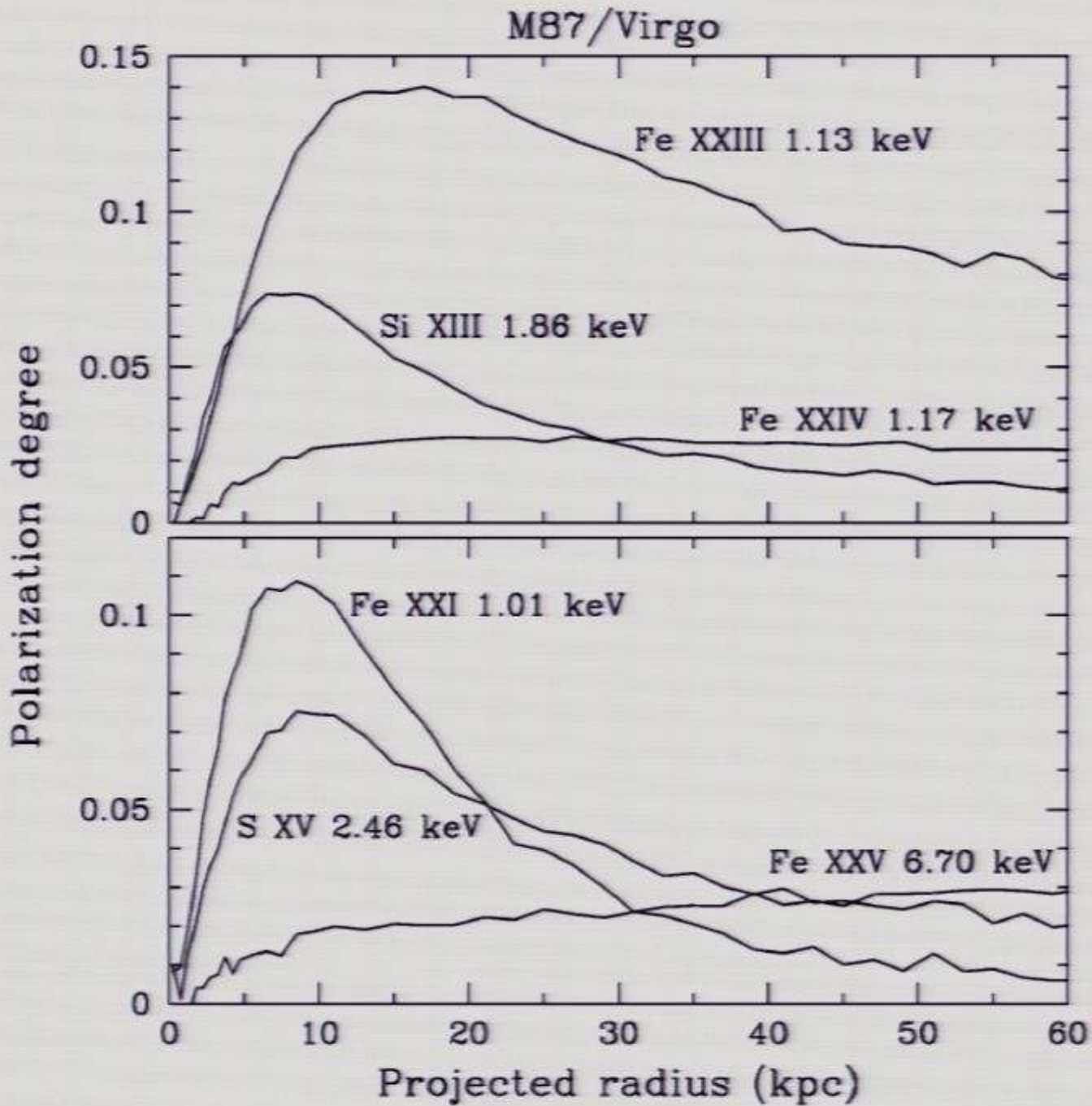
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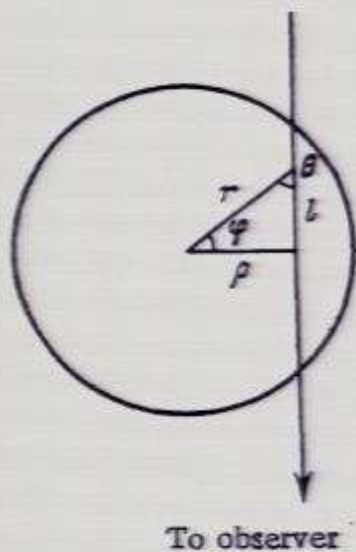




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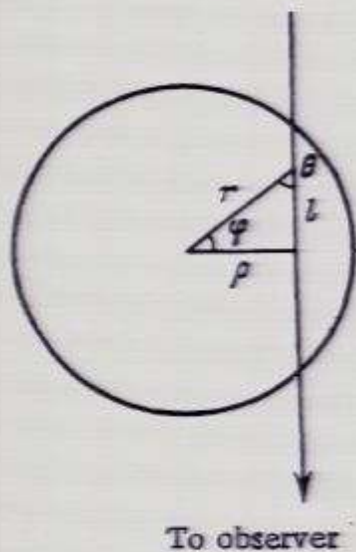
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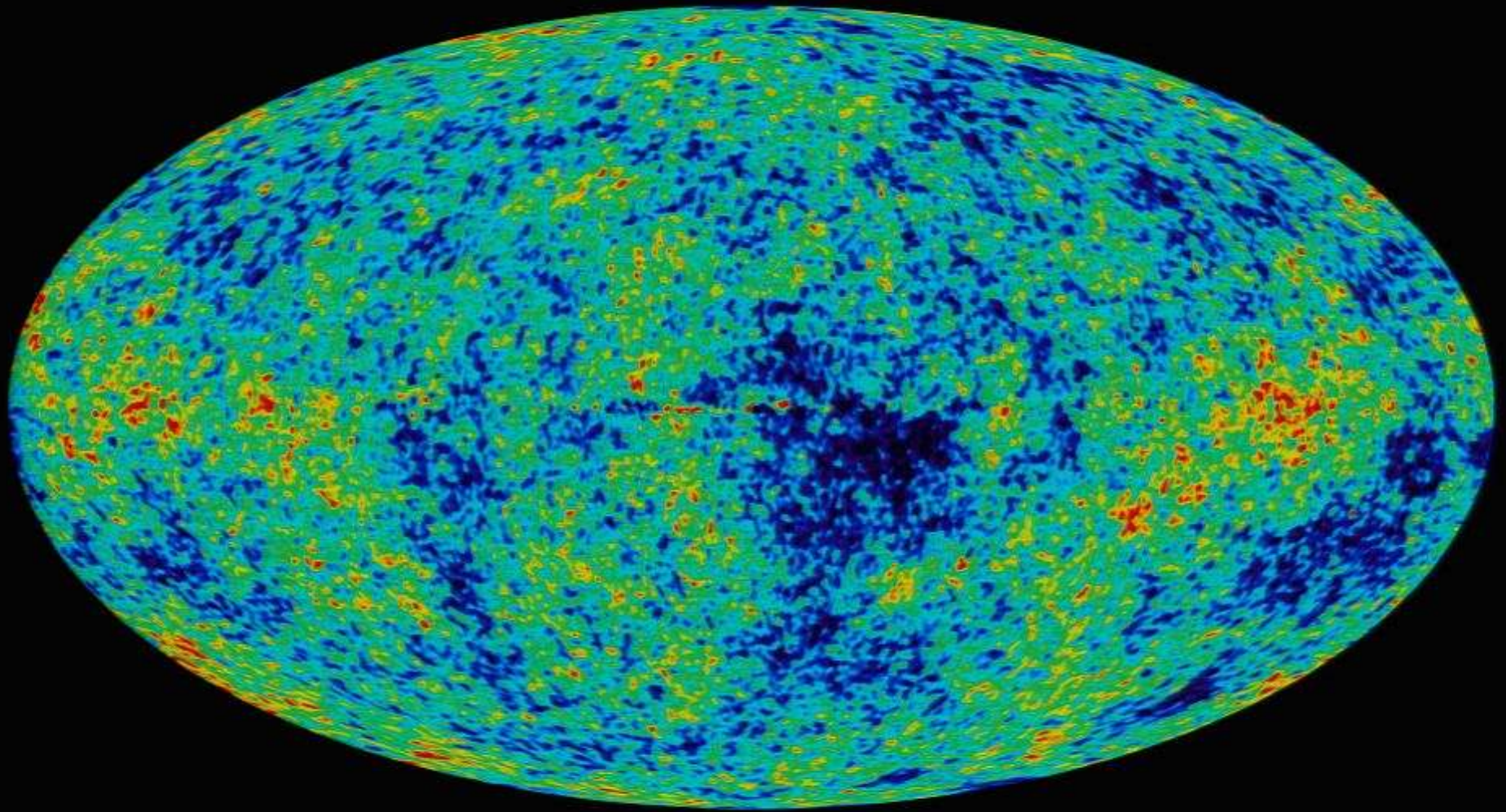
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# Microwave Sky seen by WMAP spacecraft



Dark blue -200 microK

Red +200 microK

CMB (Cosmic Microwave Background) - practically isotropic and has a black spectrum  
Tiny !!! primordial angular fluctuations are of interest

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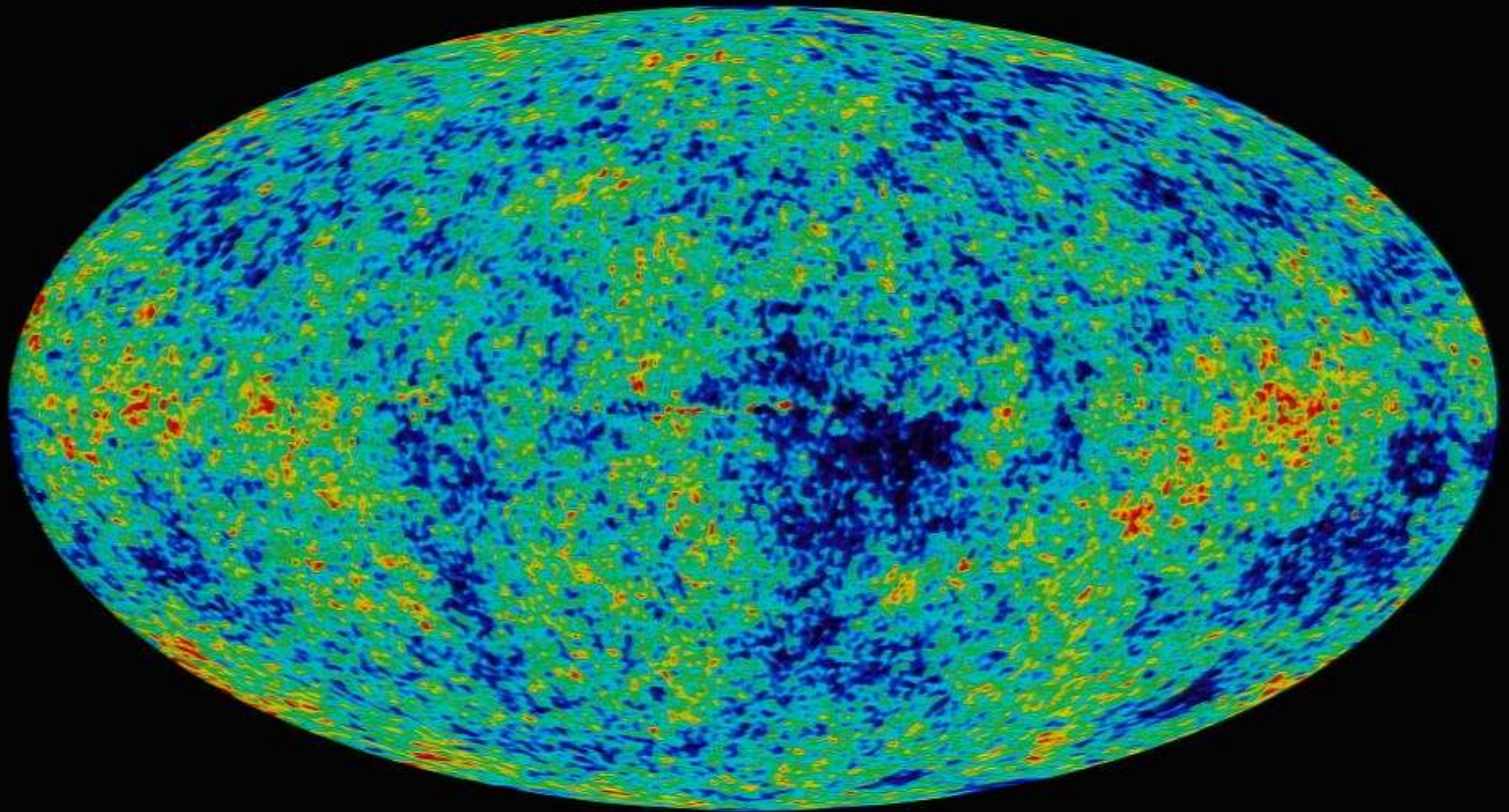
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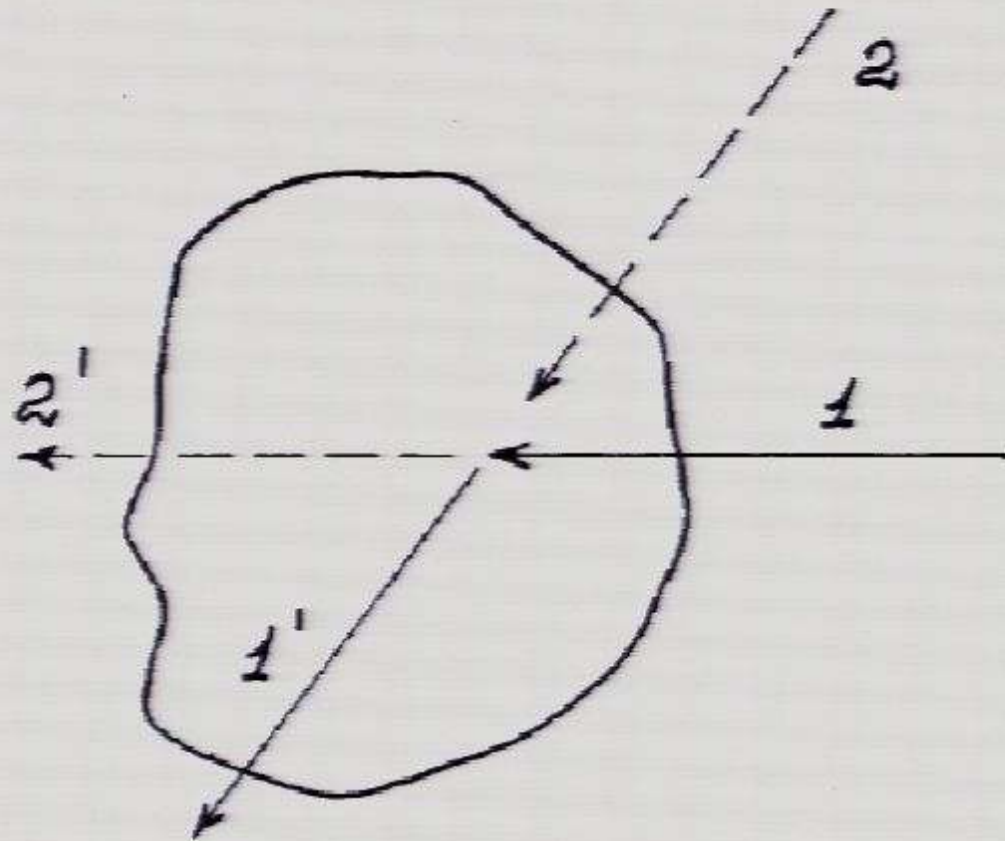


FIG. 2. The scattering of isotropic radiation field by the cloud of electrons.

Cloud is invisible

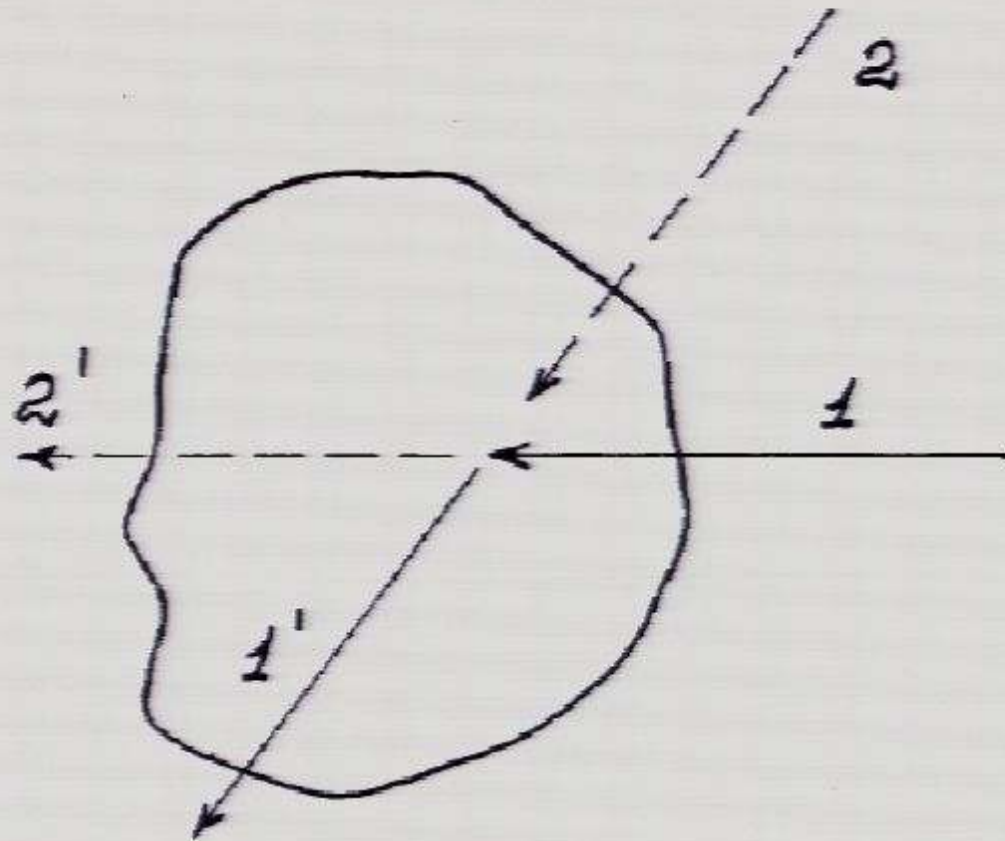
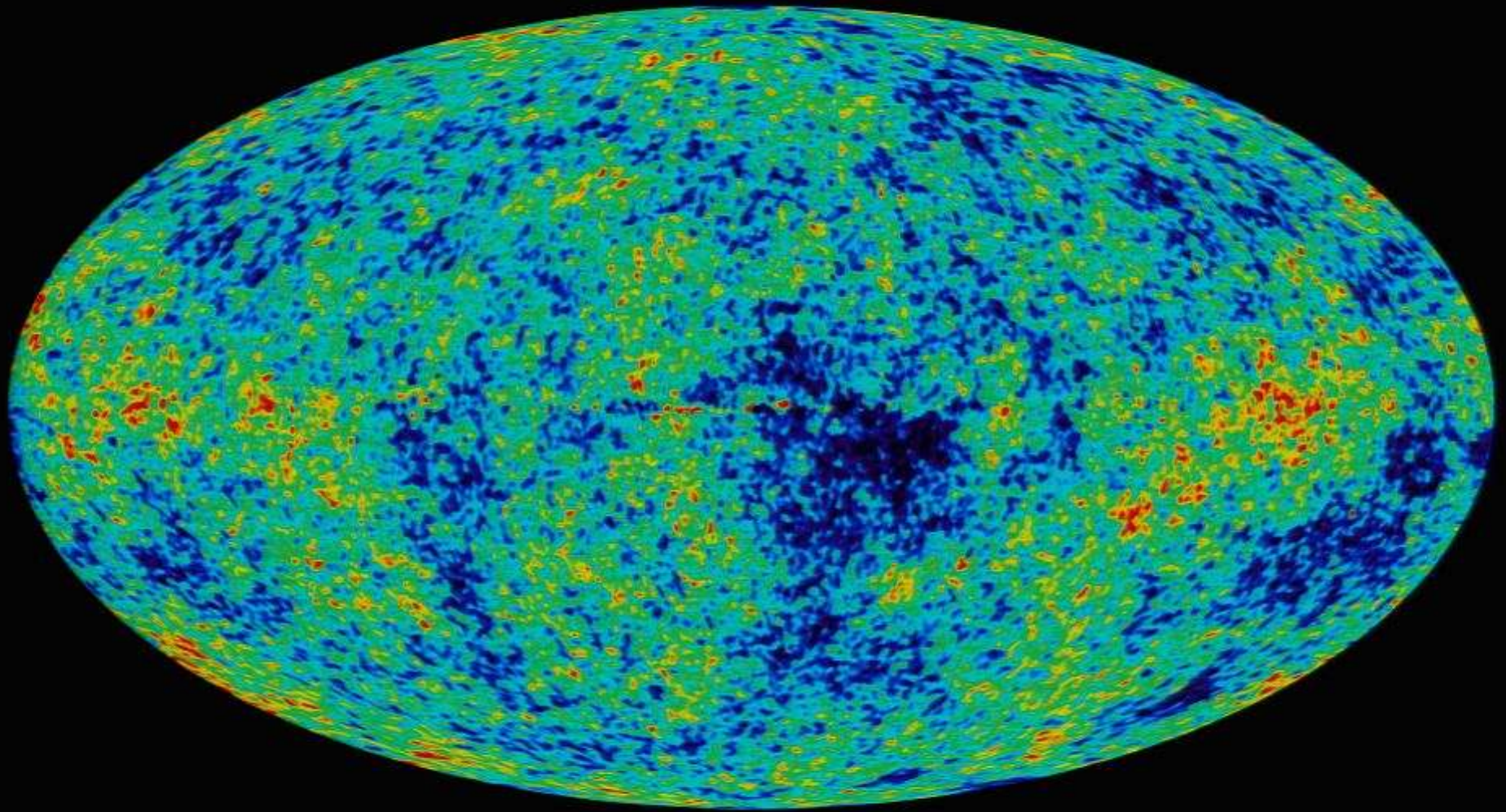


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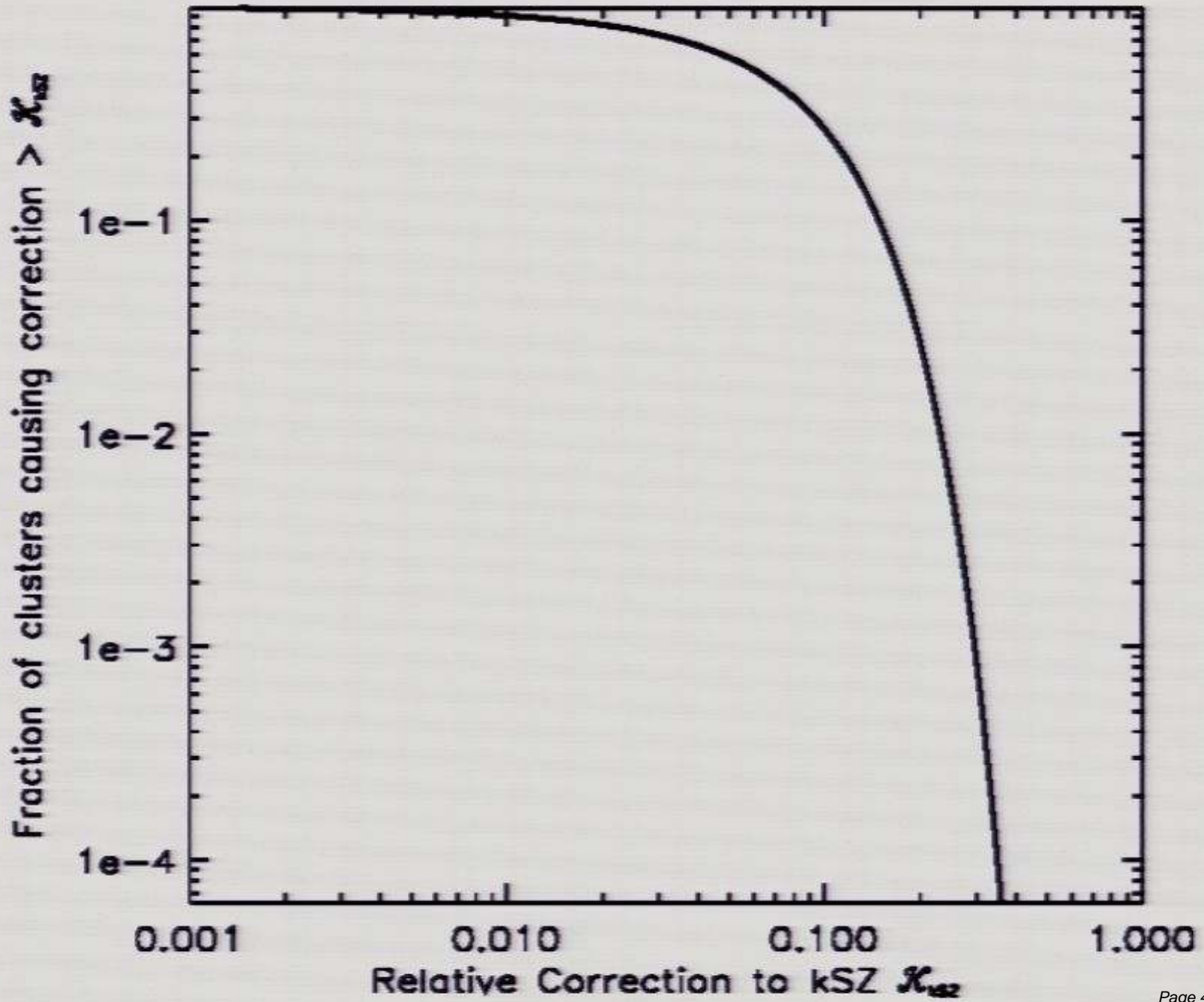
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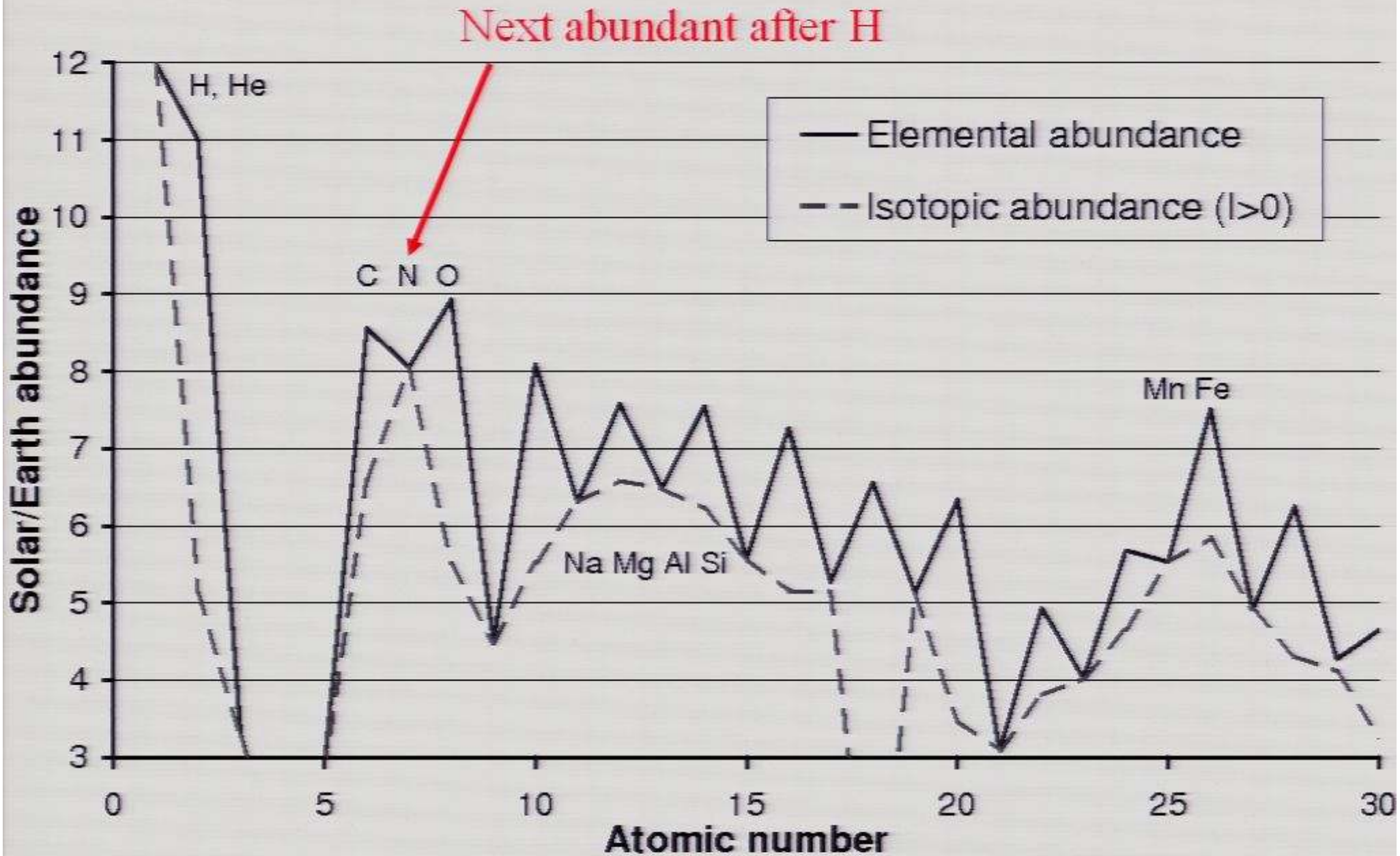


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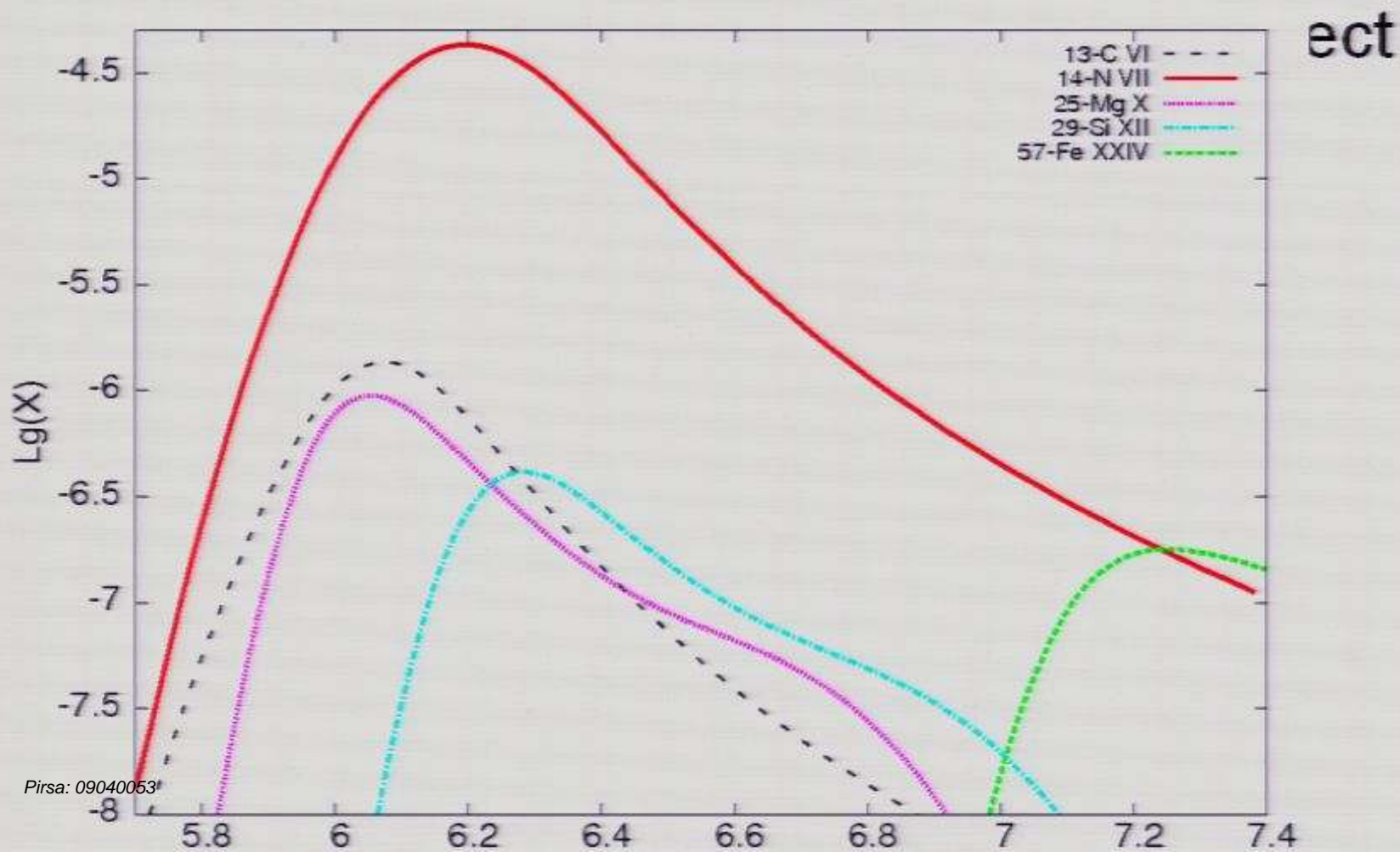
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- HFS transitions are possible only in
  - Isotopes with nuclear spin  $I > 0$ 
    - $^4\text{He}$  has zero nuclear spin
    - All  $\alpha$ -elements ( $^{16}\text{O}$ ,  $^{24}\text{Mg}$ , etc) have zero nuclear spin
    - Lines are especially sensitive to isotopes other than  $\alpha$ -elements
  - Ions with ground state electronic momentum  $J > 0$ 
    - Having one electron around nucleus (three, five etc.)

- Observations of a HFS line determine
  - Plasma temperature, due to ionic abundance
  - Isotopic composition



# Line parameters

- Frequency determined by nuclear charge  $Z$ , magnetic moment and spin  $l$ :

$$\Delta E_{HFS} = \frac{8 \mu}{3 I} \cdot \frac{\alpha^2 Z^3 m_e}{n^3 m_p} \cdot (I + 1/2) Ry$$

- Steep dependence on  $Z$  implies shorter wavelength for high- $Z$  ions

# Line parameters

- Spontaneous decay rate  $A$  is

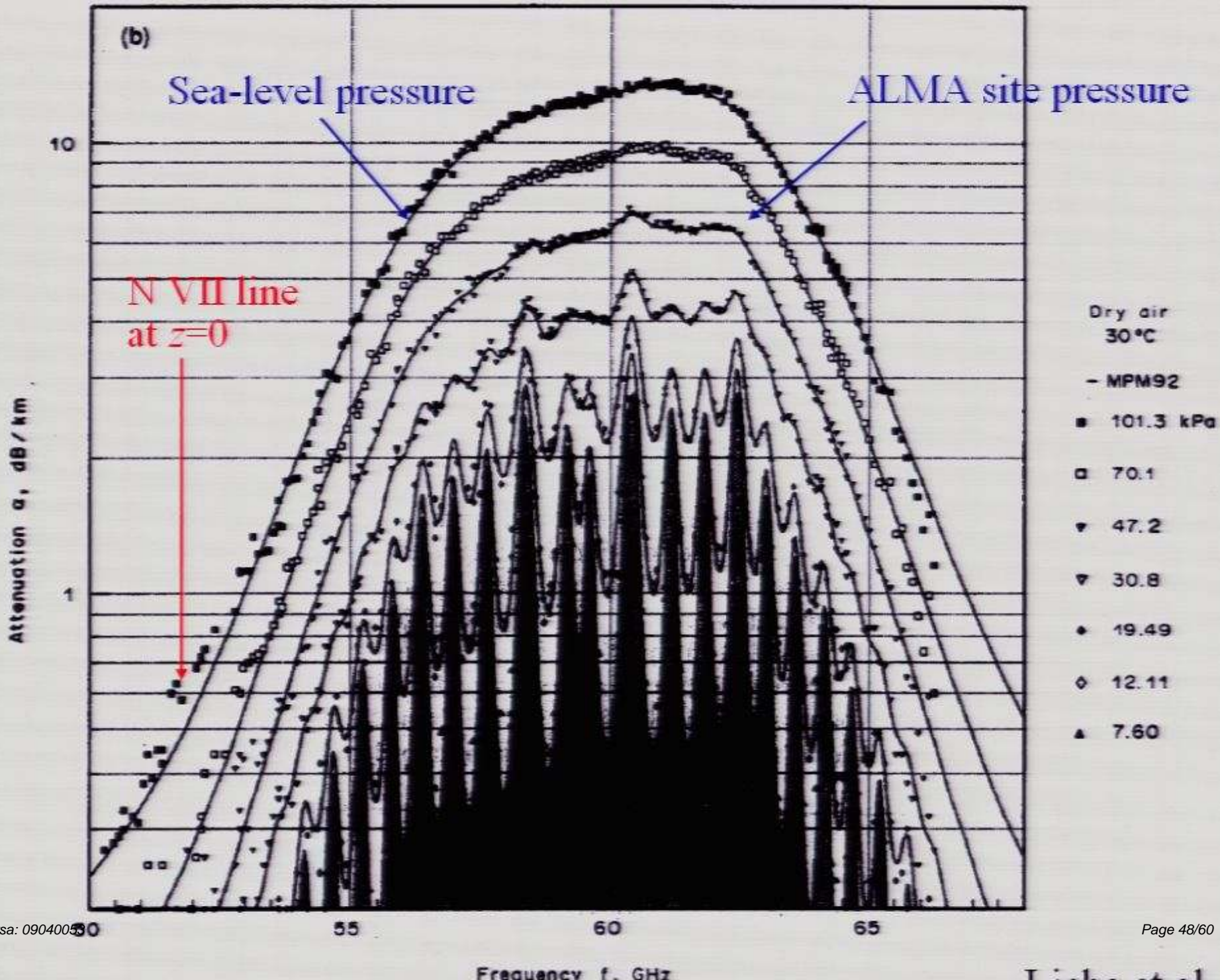
$$\begin{aligned} A(F \rightarrow F - 1) &= \frac{I}{I+1} A(F - 1 \rightarrow F) = \\ &= 1.0789 \cdot 10^{-7} \frac{I}{2I+1} \cdot \left( \frac{\lambda}{1 \text{ mm}} \right)^{-3} \text{ s}^{-1} \end{aligned}$$

- Meaning even sharper dependence on nuclear charge
- This makes high- $Z$  ion HFS lines competitive to the 21 cm line, despite much lower abundances

- Two ways to overcome this
  - Observe from height of ALMA (5100 m), where zenith transmission reaches 30-50%
  - Observe objects with redshift  $z > 0.15$   
(Sunyaev, Churazov 1984)
- Our initial motivation was to choose the latter way
  - To study if the HFS line of  $^{14}\text{N VII}$  may help in detection of the warm-hot intergalactic medium (WHIM)

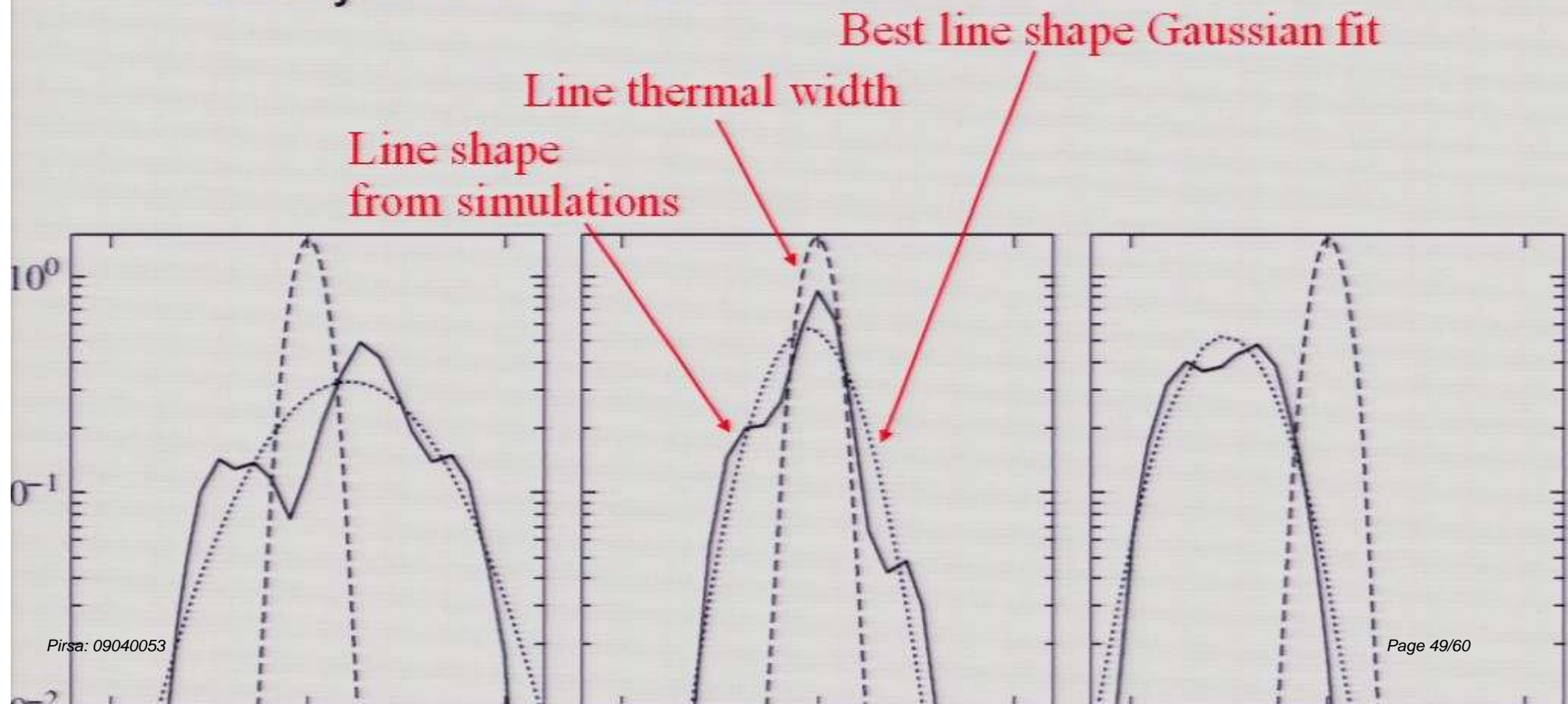
## Line brightness temperature, $\mu\text{K}$

Isotope	$\lambda$ , mm	N157B	CL
$^{13}\text{C}$ VI	3.8740(8)	4	13
$^{14}\text{N}$ VII	5.6519(11)	700	400
$^{17}\text{O}$ VIII	1.0085(2)	0.8	0.08
$^{25}\text{Mg}$ X	6.680(4)	15	14
$^{27}\text{Al}$ XI	1.2060(7)	50	40
$^{29}\text{Si}$ XII	3.725(2)	30	3.0



# $^{57}\text{Fe}$ XXIV line: science

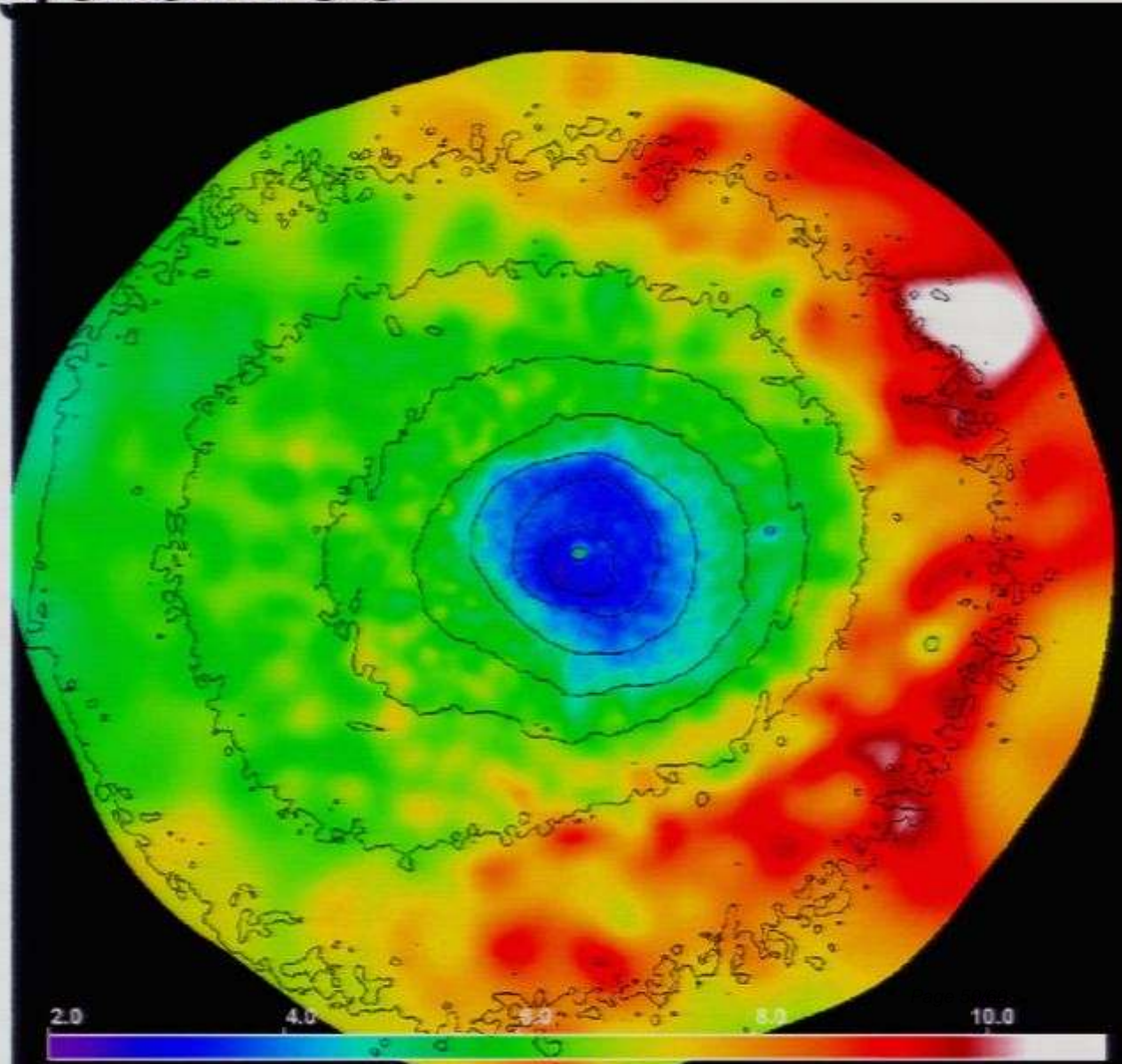
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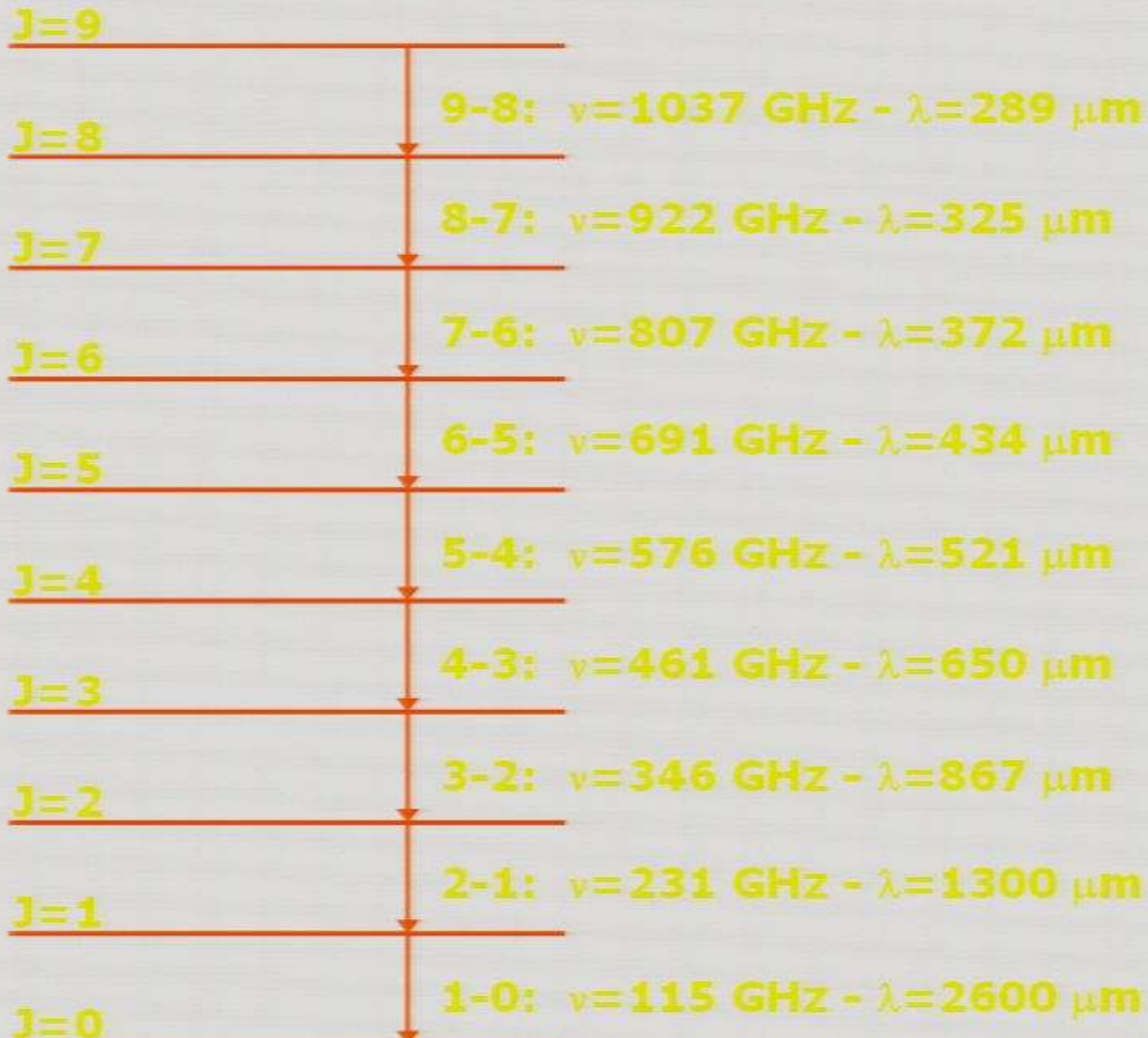
# $^{57}\text{Fe}$ XXIV line: clusters of galaxies

3.06 nm line

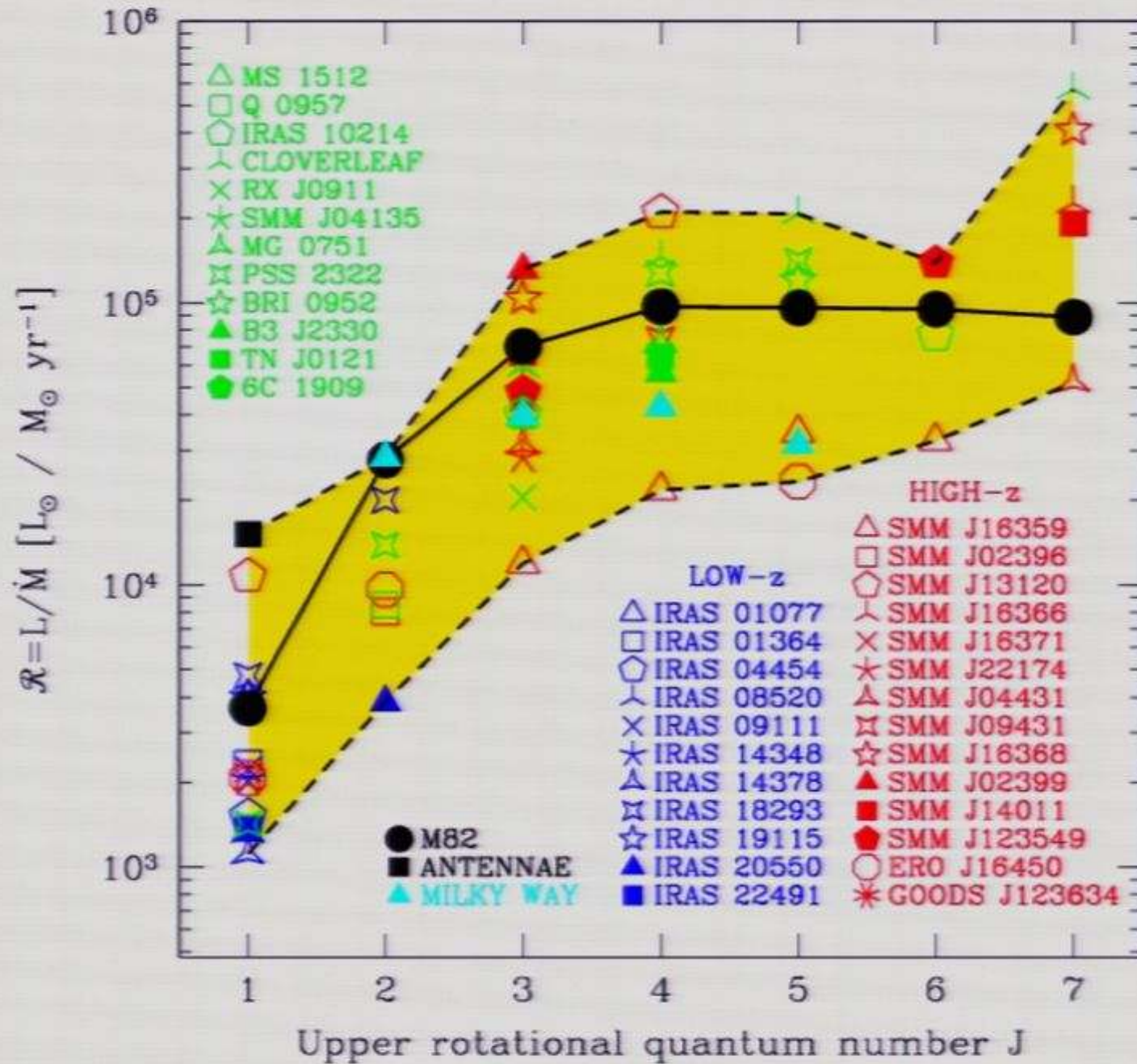
- Ion abundant at about 2 keV
- Temperature in intracluster medium
  - Central temperature decrement



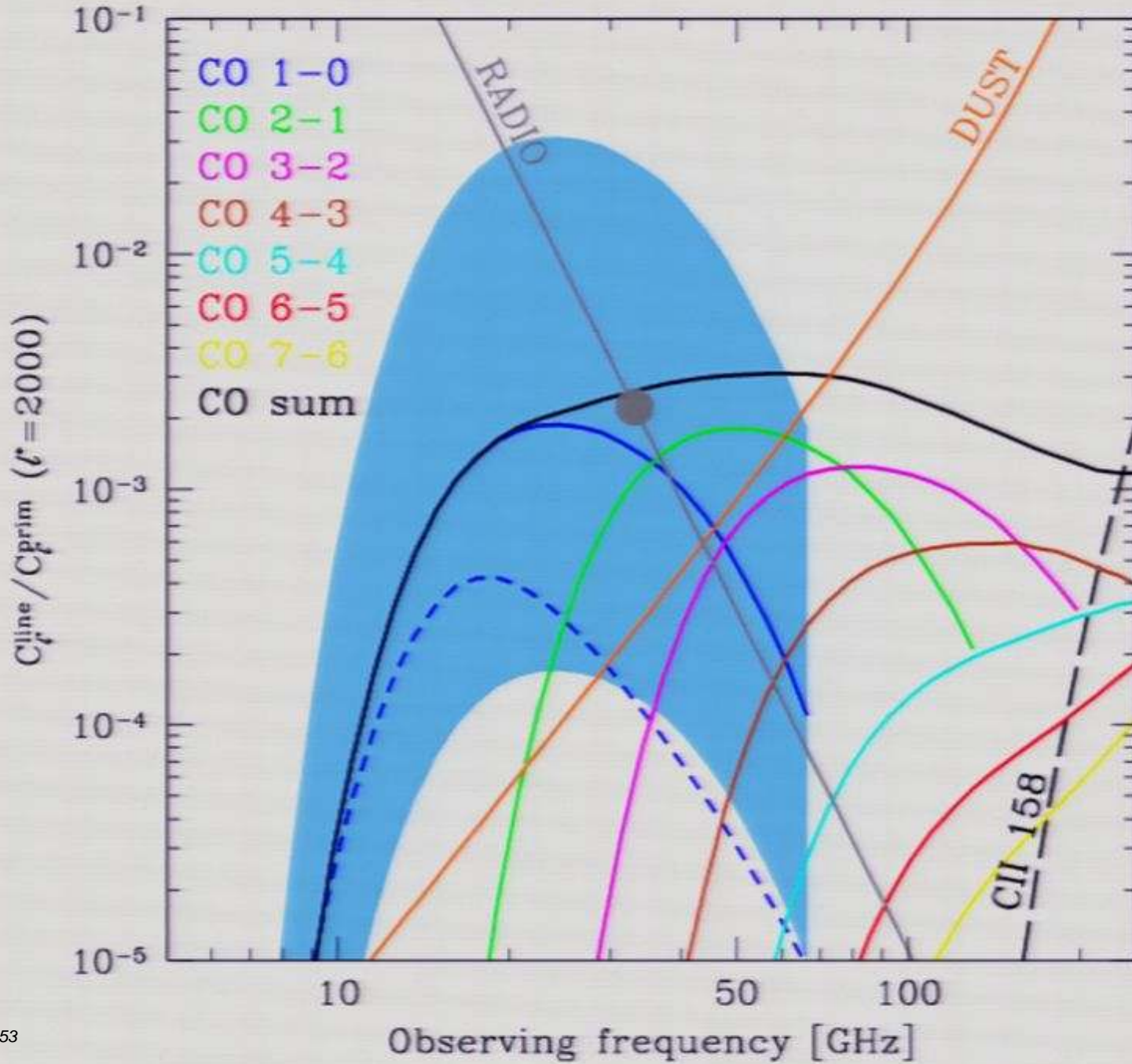
# CO rotational levels



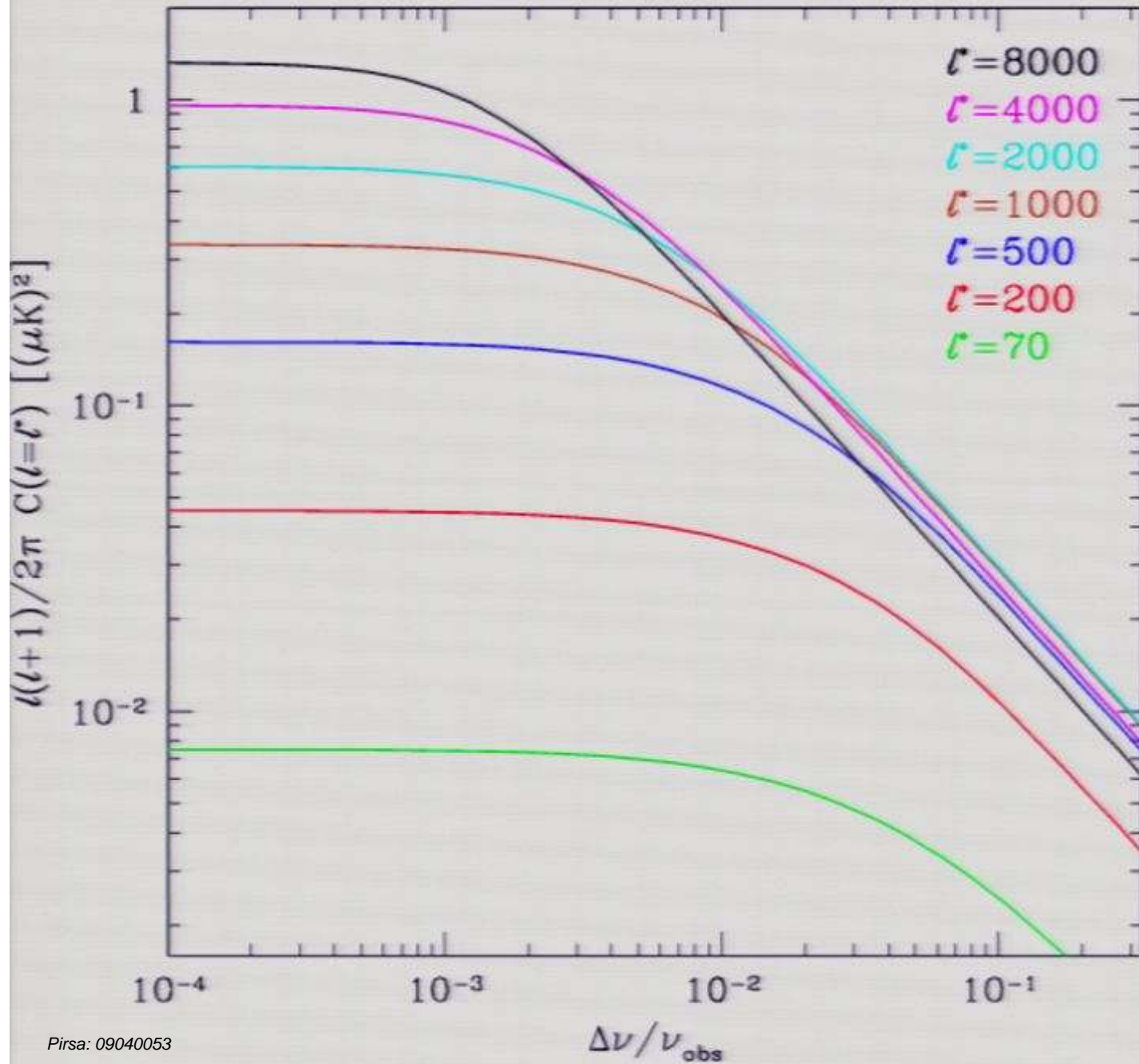
### Distribution of $\mathcal{R}$ ratios – CO lines

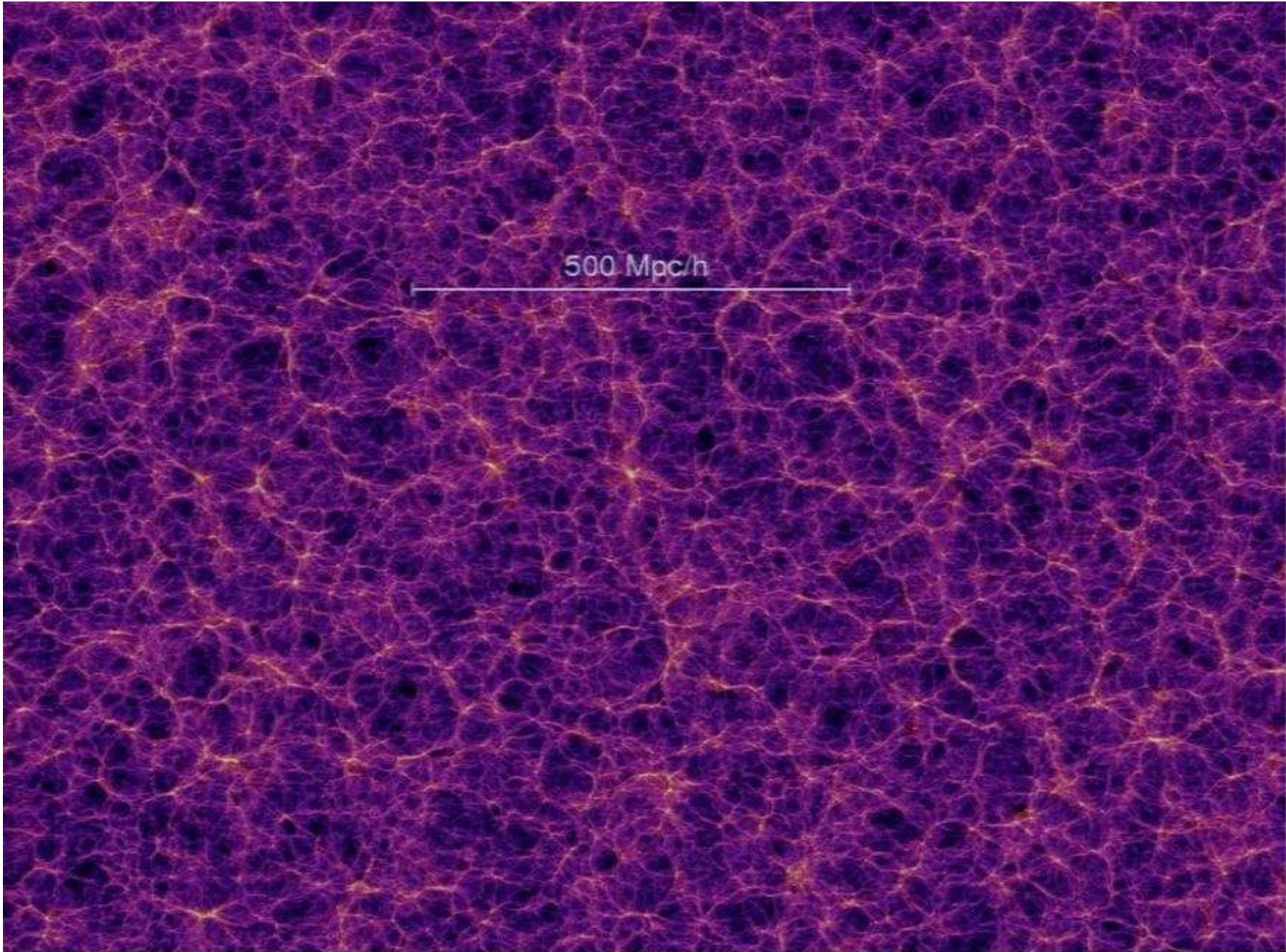


Frequency dependence -  $\Delta\nu/\nu_{\text{obs}} = 10^{-3}$

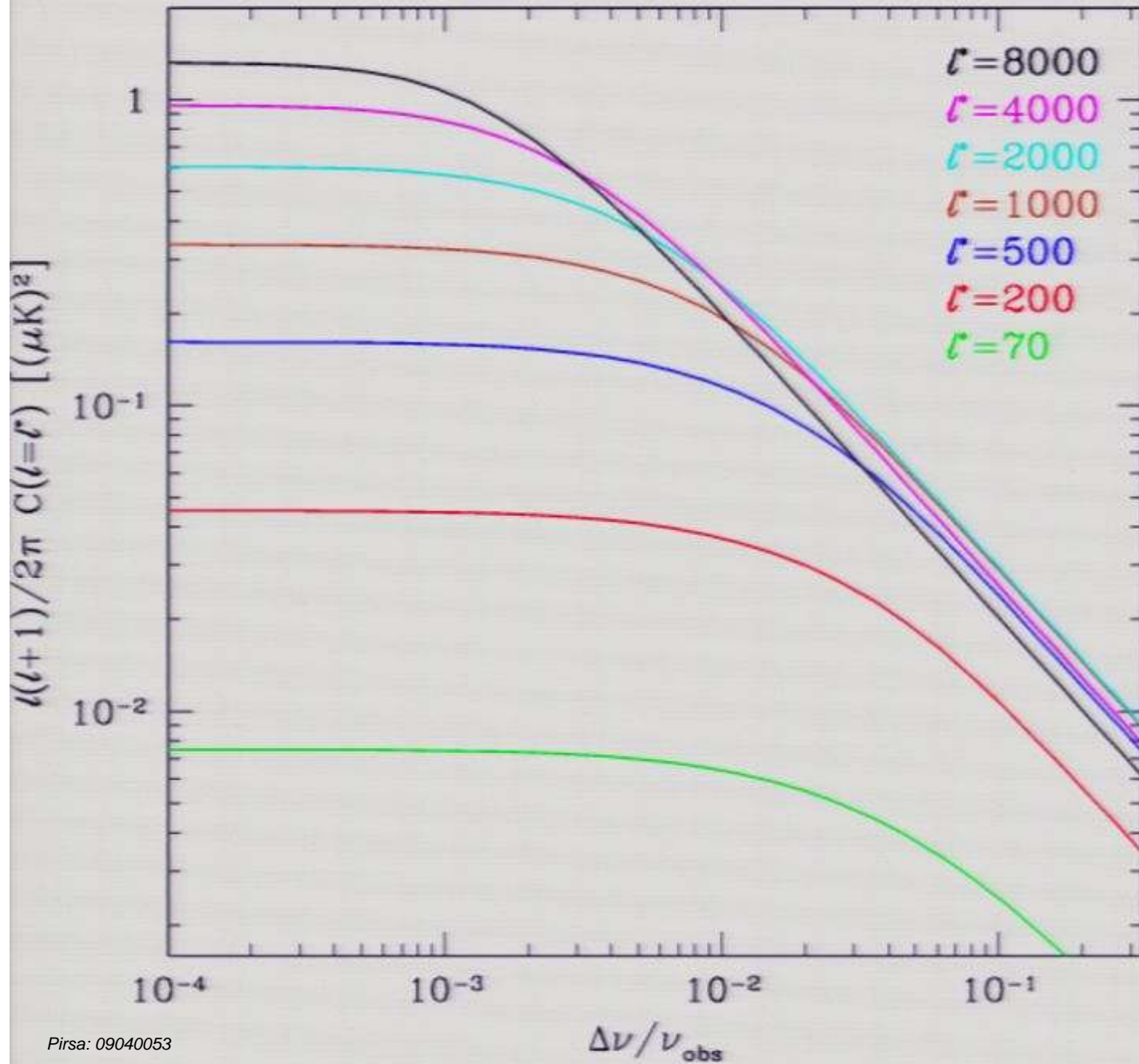


# Spectral resolution - CO 1-0 line - 30 GHz

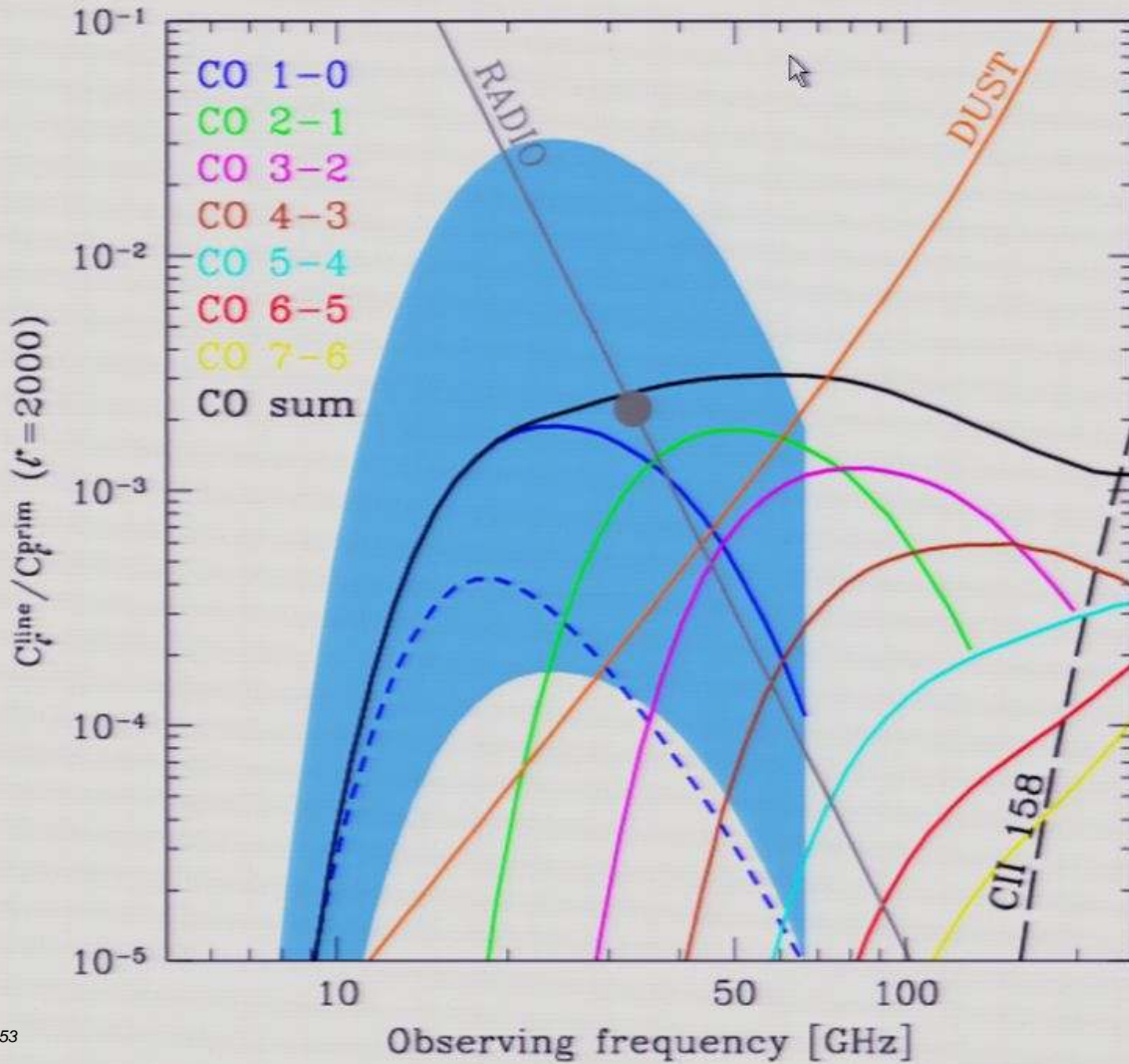




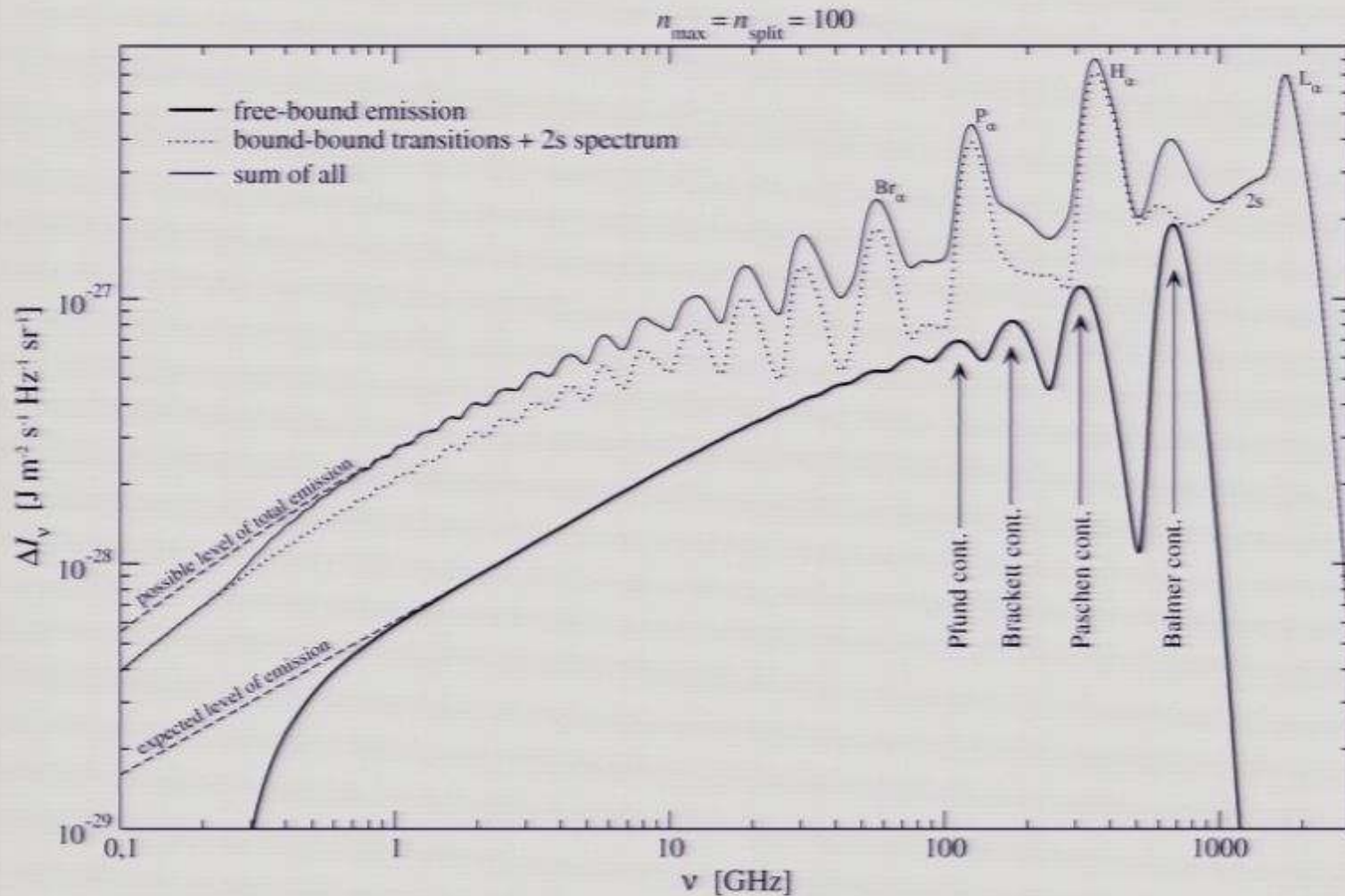
Spectral resolution – CO 1–0 line – 30 GHz



Frequency dependence -  $\Delta\nu/\nu_{\text{obs}} = 10^{-3}$



# 100-shell hydrogen atom and continuum CMB spectral distortions



## bound-bound & 2s:

- at  $\nu > 1$  GHz: distinct features
- slope  $\sim 0.46$

## free-bound:

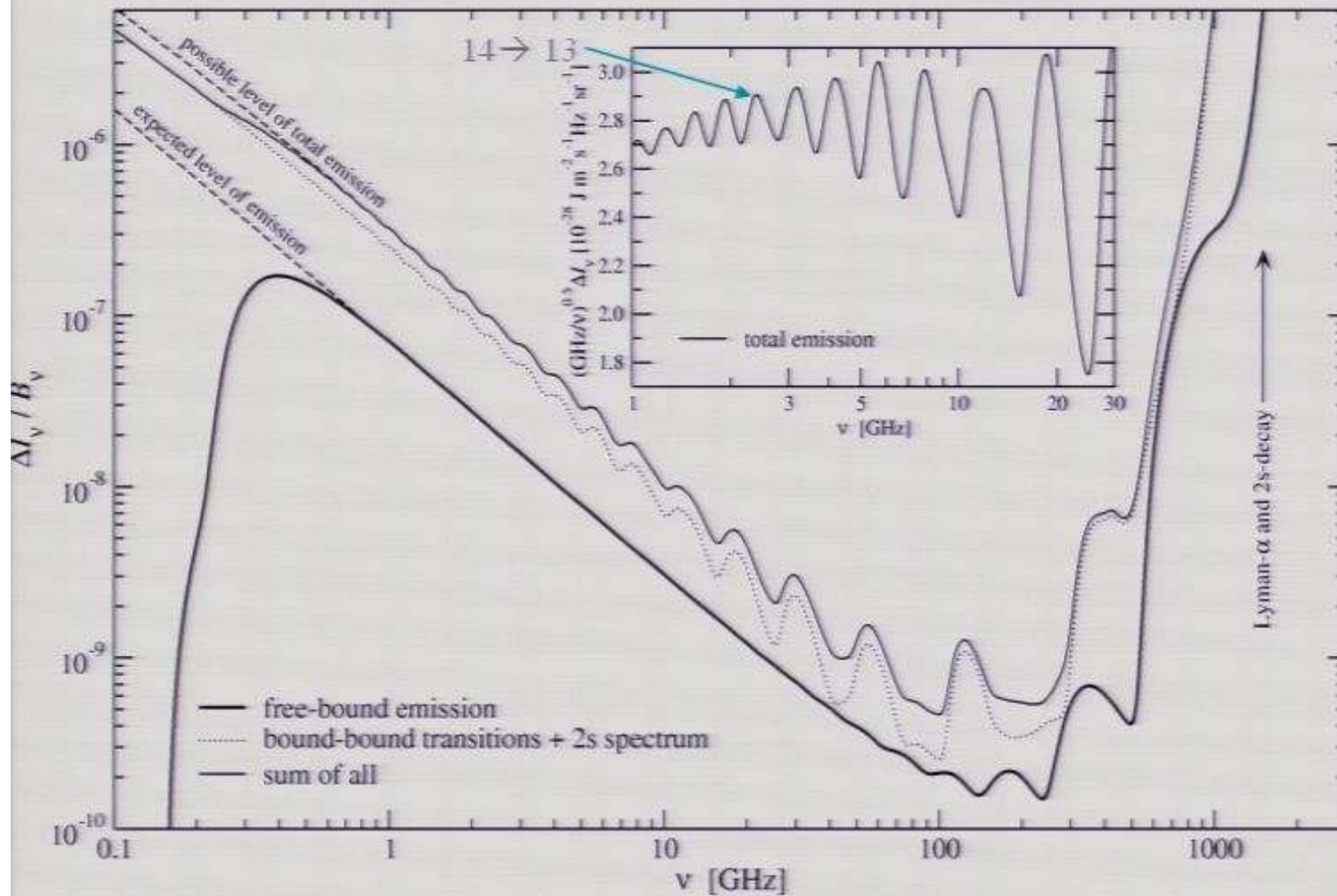
- only a few features distinguishable
- slope  $\sim 0.6$

## Total:

- f-b contributes  $\sim 30\%$  and more
- Balmer cont.  $\sim 90\%$
- Balmer:  $1\gamma$  per HI
- in total  $5\gamma$  per HI

# 100-shell hydrogen atom and continuum

## Relative distortions



### Wien-region:

- $L_\alpha$  and 2s distortions are very strong
- but CIB more dominant

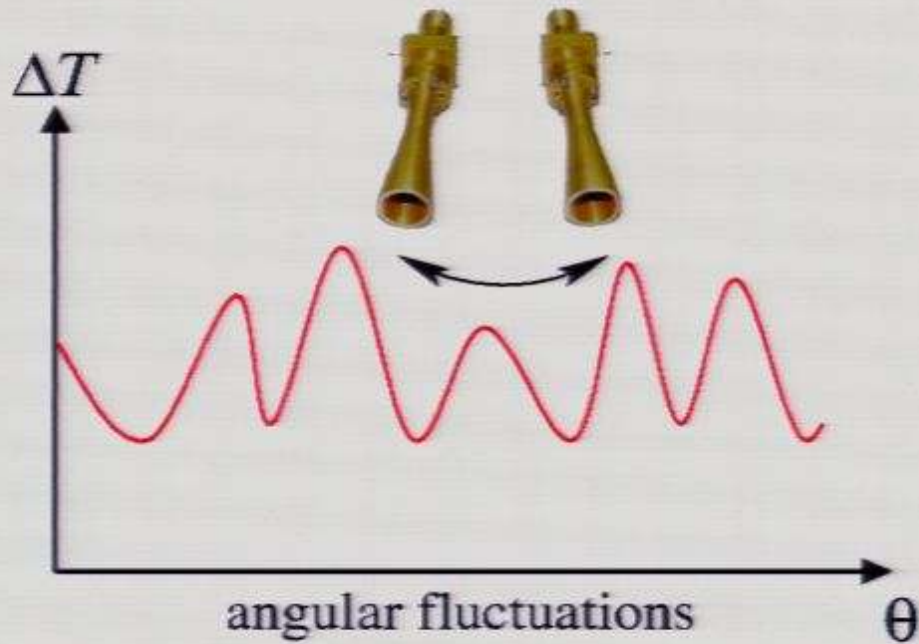
### @ CMB maximum:

- relative distortions extremely small
- strong  $\nu$ -dependence

### RJ-region:

- relative distortion exceeds level of  $\sim 10^{-7}$  below  $\nu \sim 1$ -2 GHz
- oscillatory frequency dependence with  $\sim 10$  percent-level amplitude:

*hard to mimic by known foregrounds*



**Scan over frequency  
instead of angular  
coordinate!!!**

