EXCITING CO IN MRK 231:

BLACK HOLE ACCRETION OR STAR FORMATION?

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Sterrewacht Leiden

outline

- What is HerCULES?
- Why CO?
- Markarian 231
  - CO excitation
  - chemistry
- Conclusions

what is HerCULES?

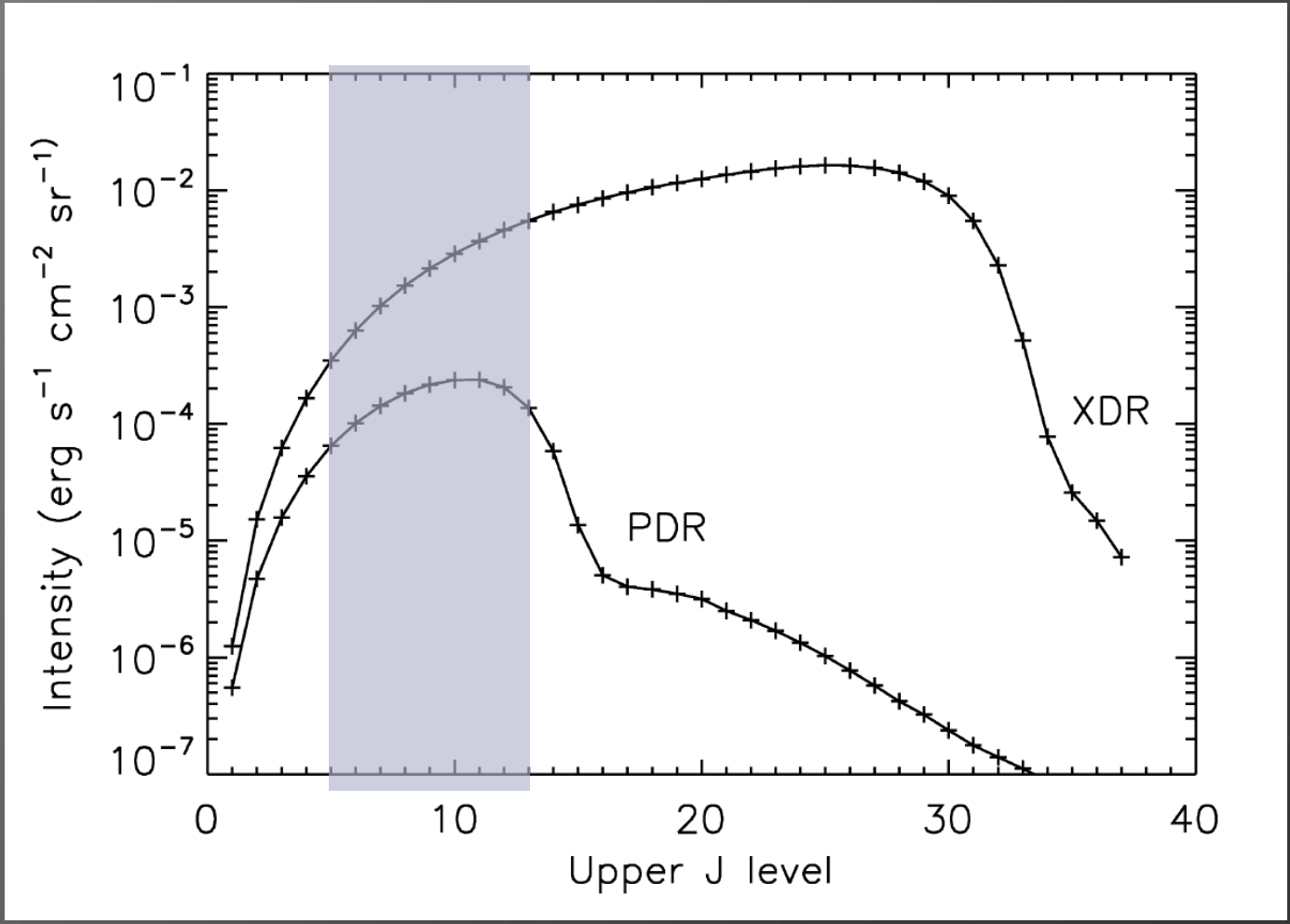
- Herschel Comprehensive ULIRG Emission Survey
- Inventory of gas cooling lines in 29 (U)LIRGs:
  - SPIRE: High resolution FTS
  - PACS: [CII] 158μm, [OI] 63 and 146 μm
- More in Plenary Session 7 @ 14:40 by Paul van der Werf
- Poster P1.57 by Eduardo González Alfonso

why CO?

- Most abundant molecular species
- CO ladder reflects the excitation of the gas

- Only low-J lines (<6) observable from ground
- SPIRE: J=5-4 up to J=13-12
- Differentiation between UV and X-ray excitation:

why CO?

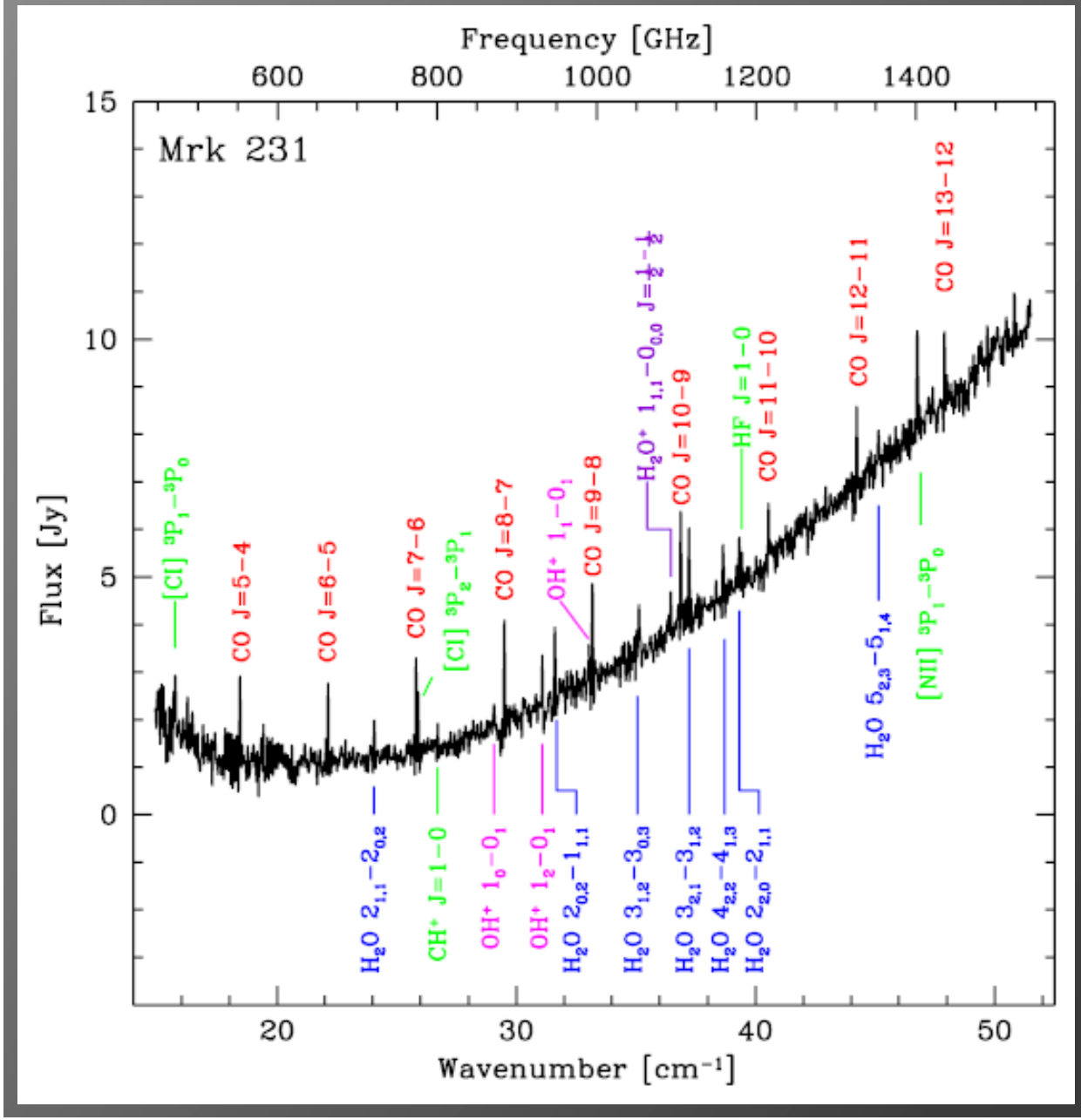


[Rowin Meijerink, 2006 PhD Thesis]

Markarian 231

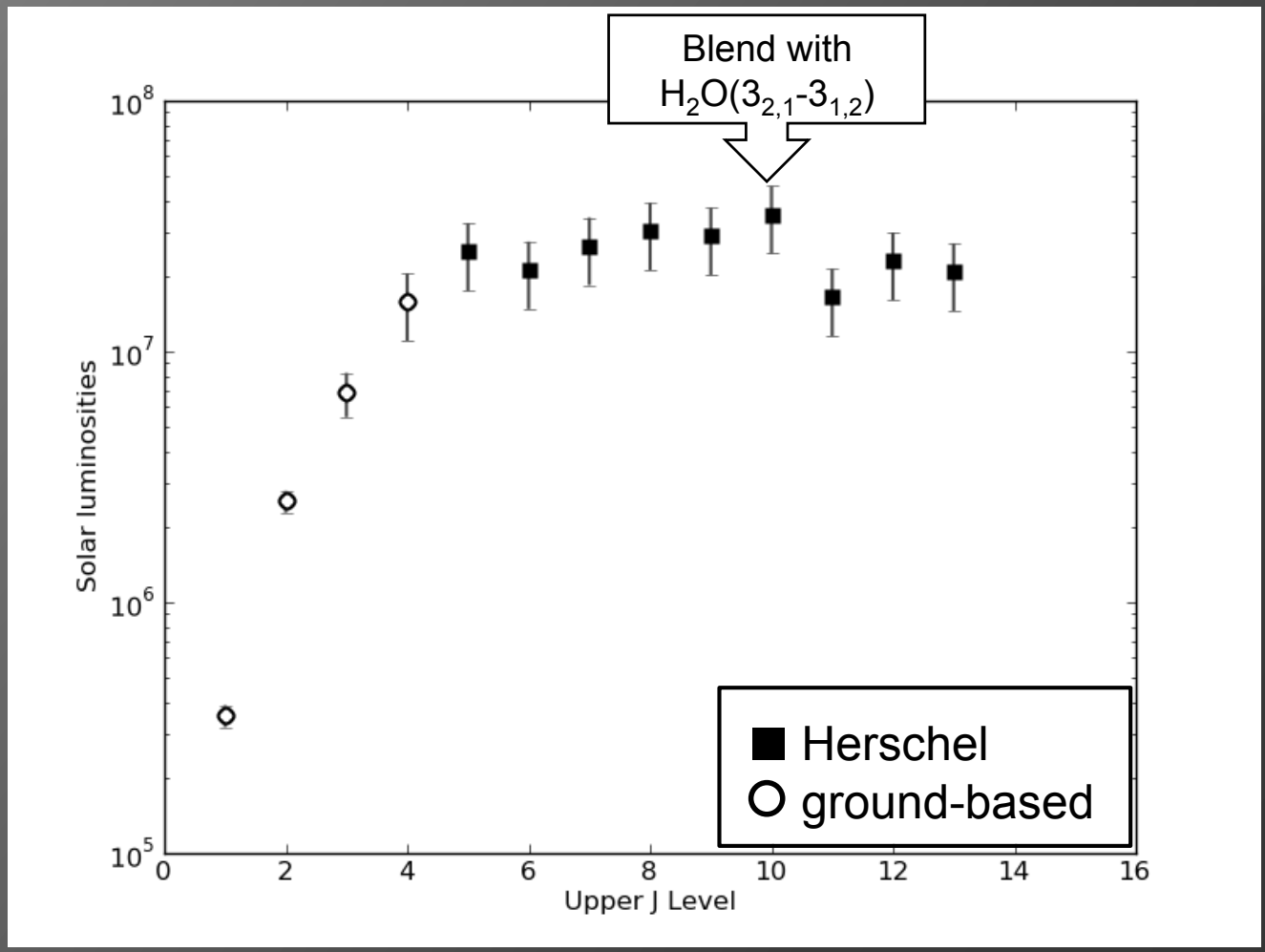
- Perfect test case:
  - Brightest ULIRG in sample ($L_{IR} = 4x10^{12}\ L_o$)
  - Optically visible AGN [Boksenberg et al., 1977]
  - 100-1000 pc star formation disk [Taylor et al., 1999]
- Observed during SDP:
  - SPIRE high resolution in both bands
  - Total on source time: ~2 hrs
- Which resulted in a beautiful spectrum:

Markarian 231



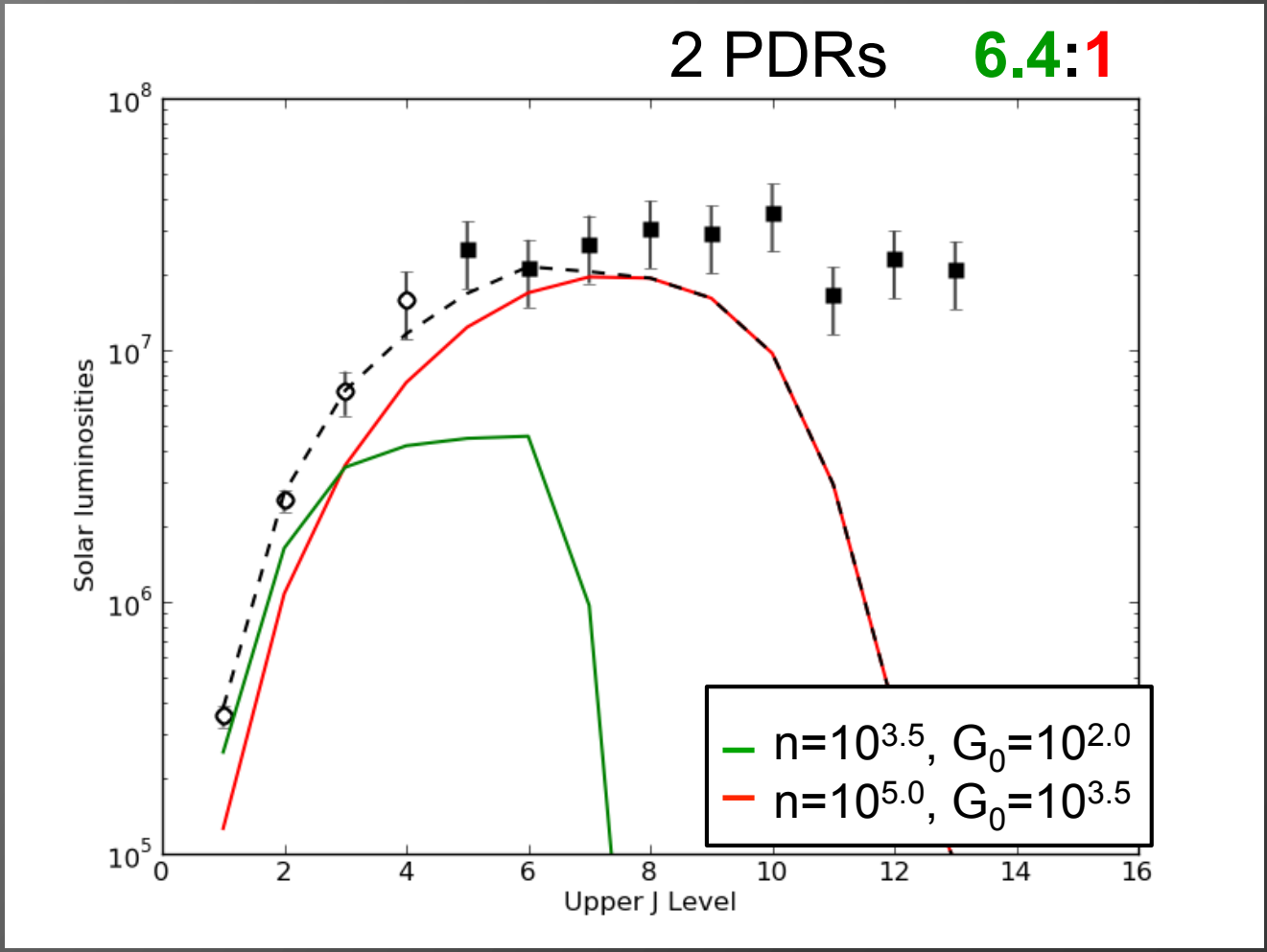
- 25 lines:
  - 9x CO (5-4 to 13-12)
  - 7x H_2O
  - 3x OH^+
  - H_2O^+
  - CH^+
  - HF
  - 2x [CI]
  - [NII]
- More coming?

CO excitiation

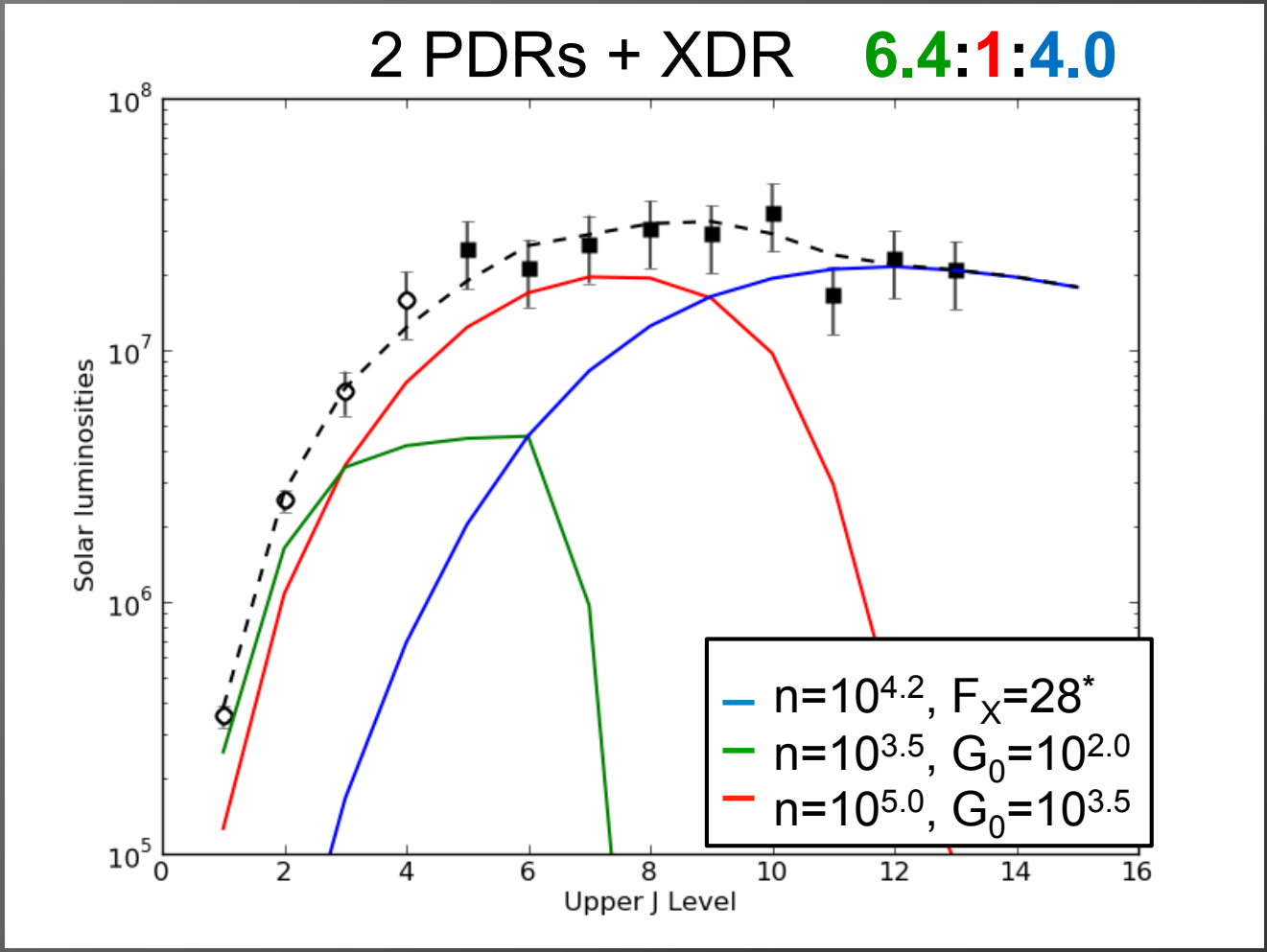


[ground-based data: Papadopoulos et al., 2007]

CO excitiation

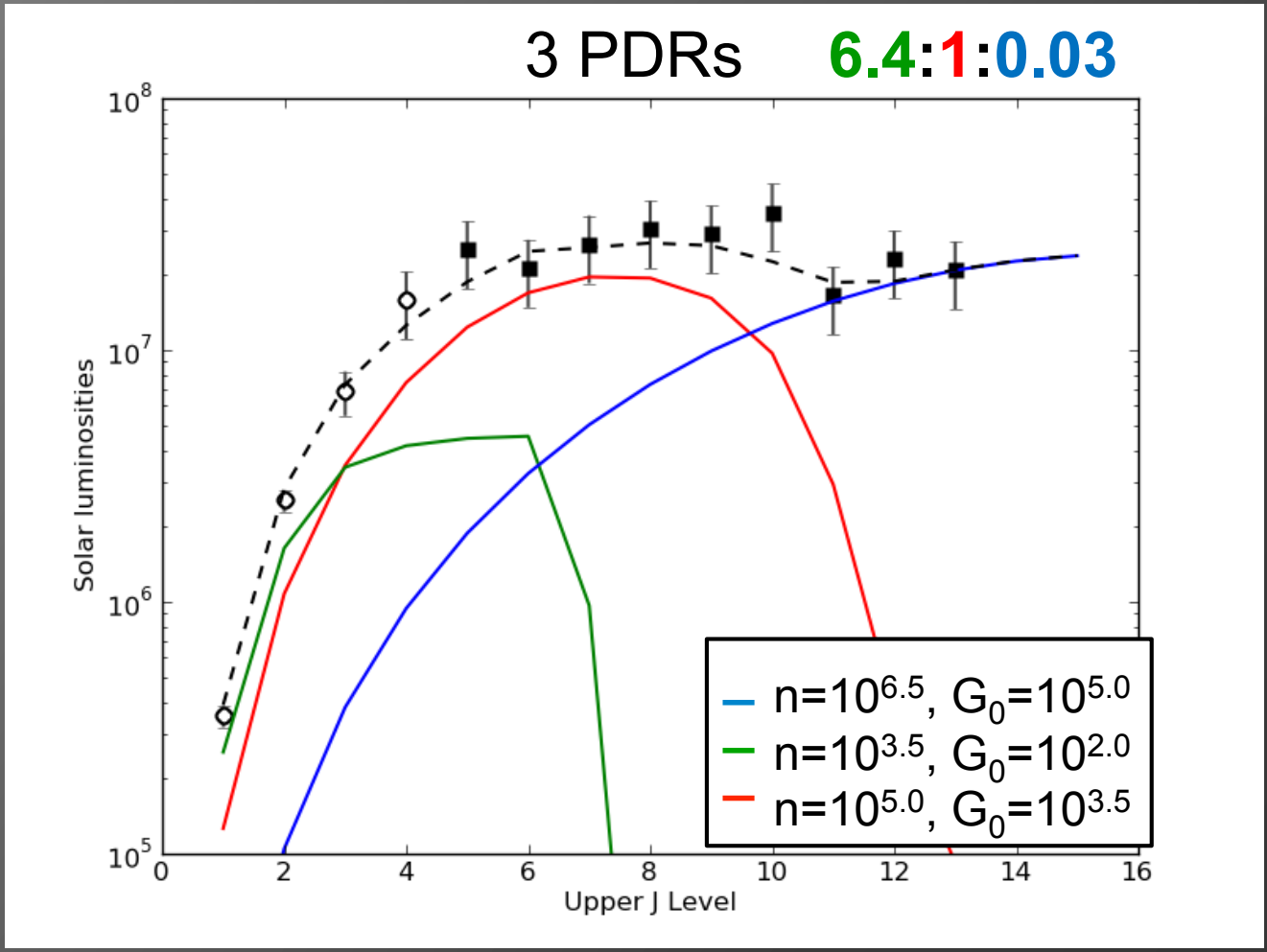


CO excitiation



* 28 erg cm^{-2} s^{-1} → $G_0=10^{4.2}$

CO excitiation



CO excitiation

High excitation PDR or XDR?

- High excitation PDR:
  - About same mass as intermediate PDR
  - But, G_0 only <0.3 pc of O5 star → <1% of volume
  - → 50% of mass in <1% of volume?

  - HE PDR also contains 50% of the dust
  - Typical temperature: 170K [Meijerink & Spaans, 2005]
  - IR SED shows not more than 20% hot dust

CO excitiation

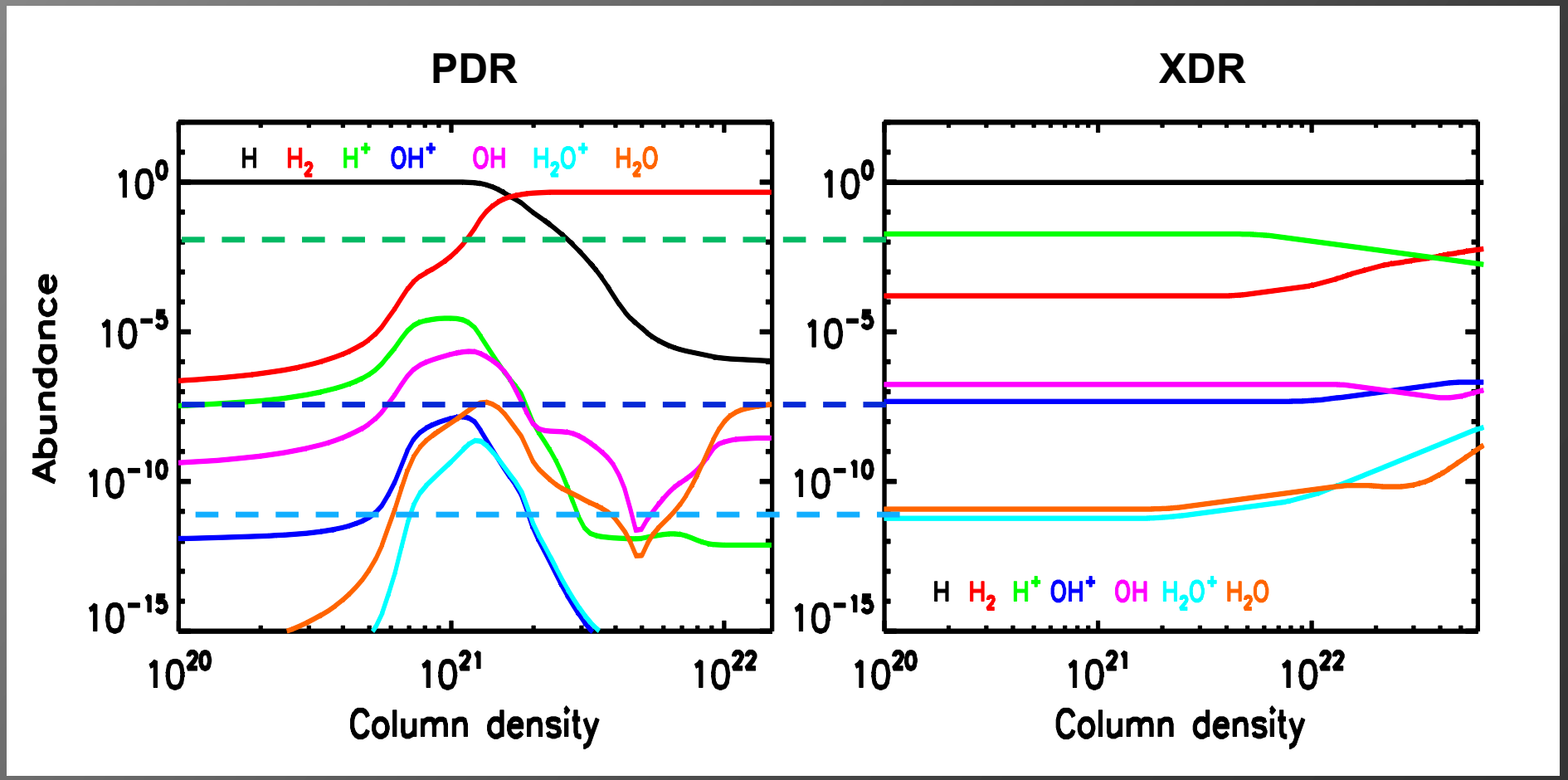
High excitation PDR or XDR?

- XDR:
  - XDR also contains significant fraction of mass
  - But F_X can be produced up to ~160 pc from core
  - XDR produces lower T_{dust}: ~70K [Meijerink & Spaans, 2005]
- XDR far more likely for high-J CO

chemistry

- Extraordinary bright OH^+ and H_2O^+:
  - Only factor 2 – 3 weaker than CO
  - Comparison: no detection in SPIRE spectrum of Orion Bar [Habart et al., 2010]
- Key species in formation: H+
  - Requires efficient ionization

chemistry


PDR
XDR
H H2 H+ OH+ OH H2O+ H2O
Abundance
10^0
10^-5
10^-10
10^-15
10^20
10^21
10^22
Column density

chemistry

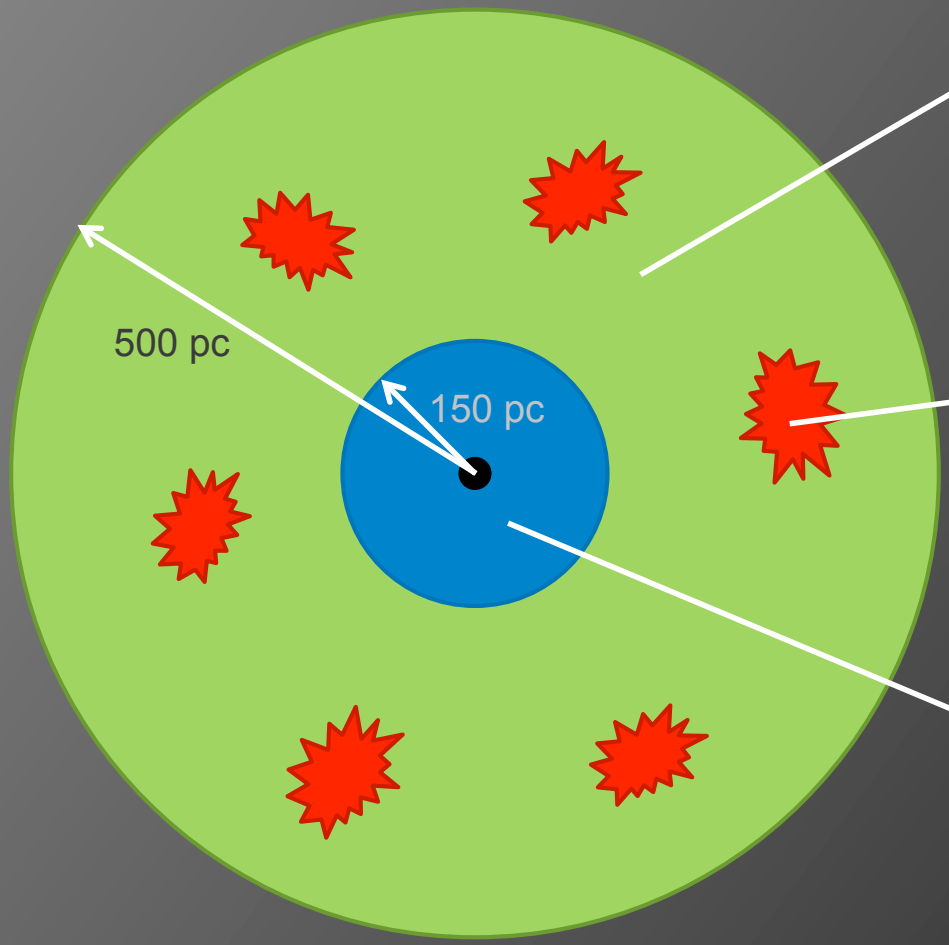
- Extraordinary bright OH^+ and H_2O^+ :
  - Only factor 2 – 3 weaker than CO
  - Comparison: no detection in SPIRE spectrum of Orion Bar [Habart et al., 2010]
- Key species in formation: H+
  - Requires efficient ionization
  - ~ 3 orders more abundant in XDR than HE PDR
  - Also OH+ and H2O+ more abundant in XDR

conclusions

- ISM components in Mrk 231:
  - Extended, low density PDR
  - Small scale, dense PDR
  - High excitation component
- High excitation PDR or XDR?
  - Both XDR and HE PDR can reproduce CO ladder
  - But IR SED and chemistry rule out PDR
  - → Third component is XDR

conclusions

"Model" of Mrk 231



- PDR 1:
  - $n=10^{3.5}$, $G_0=10^2$, r~500pc
  - Large scale molecular gas
  - → Low-J CO lines
- PDR 2:
  - $n=10^5$, $G_0=10^{3.5}$
  - Small, dense SF clumps
  - → mid-J CO lines
- XDR:
  - $n=10^{4.2}$, $F_X=28$, r~150pc
  - Circum-nuclear disk
  - → High-J CO, OH^+, $H2O^+$

final conclusion

Future of HerCULES is very exciting!