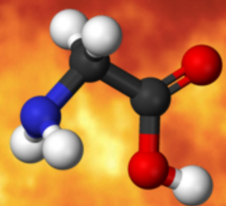
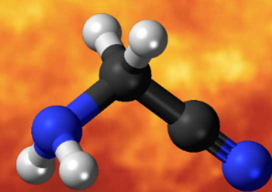
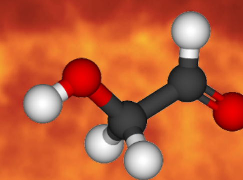
Science & Technology Facilities Council

Queen Mary University of London

The Formation of COMs in the ISM:
from Cold Cores to Galactic Center GMCs



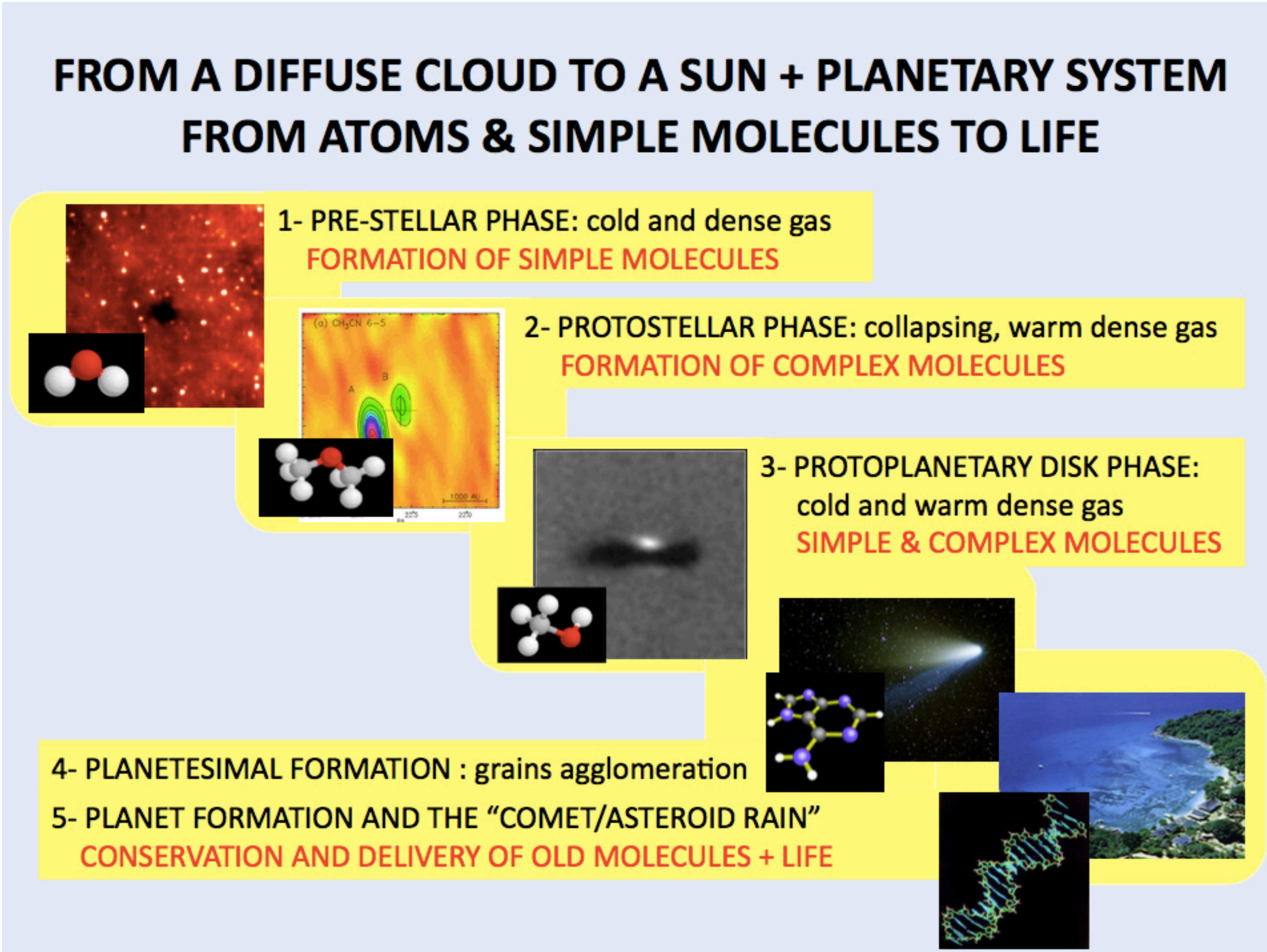




Izaskun Jimenez-Serra
(STFC Ernest Rutherford Fellow)

Shaoshan Zeng (QMUL), David Quenard (QMUL), Paola Caselli (MPE), Anton Vasyunin (MPE), Victor Rivilla (Arcetri), Jesus Martin-Pintado (CAB), Francesco Fontani (Arcetri), Serena Viti (UCL), Sergio Martin (ESO), Rafael Martin-Domenech (CAB), Leonardo Testi (ESO), Miguel Requena-Torres (JHU), Denise Riquelme (MPIfR), Nuria Marcelino (ICMM), Nicolas Billot (IRAM), Charlotte Vastel (IRAP), Bertrand Lefloch (IPAG), Rafael Bachiller (OAN), Rebeca Aladro (MPIfR)

From the ISM to the Origin of Life

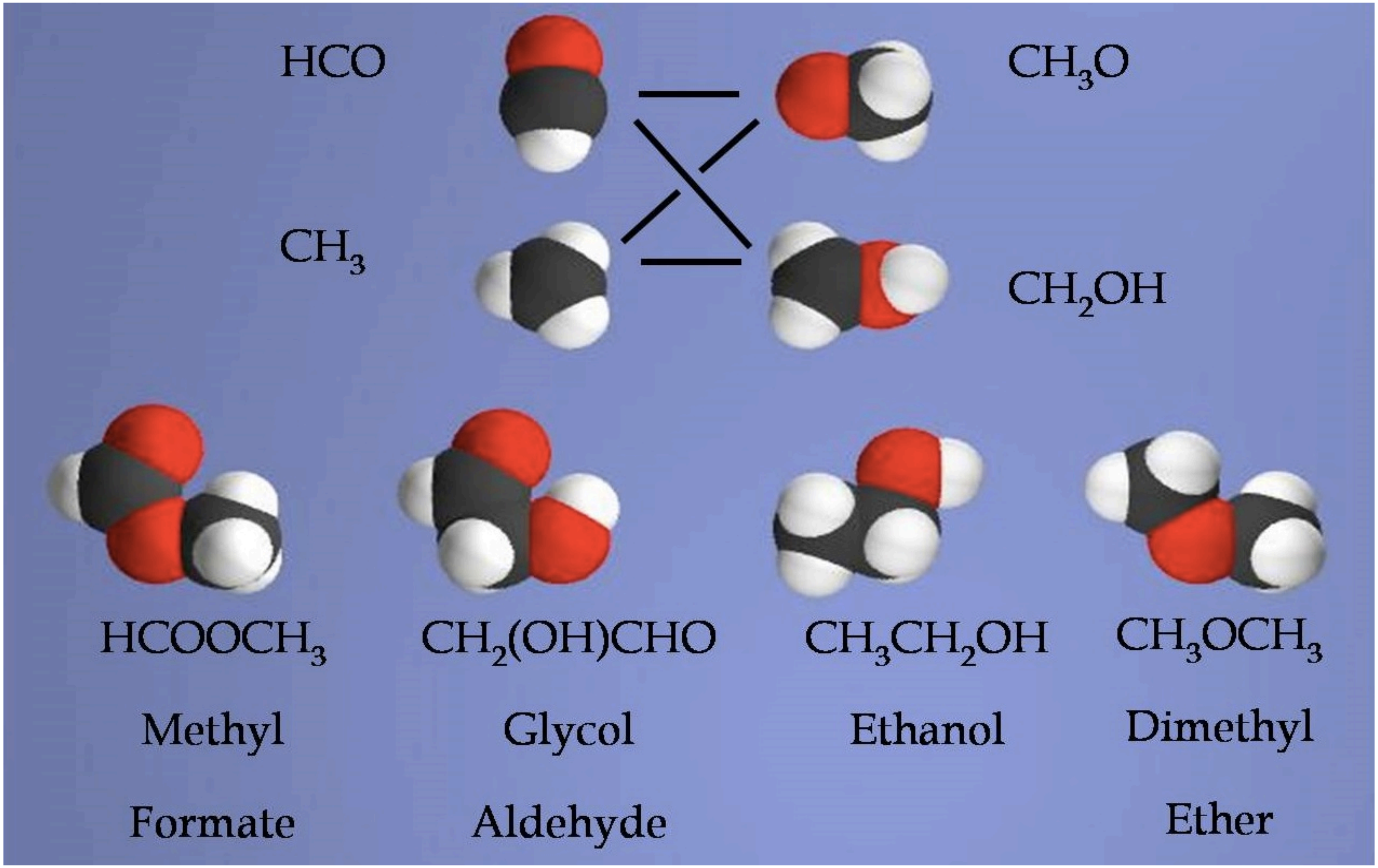


Caselli & Ceccarelli (2012)

Complex Organic Molecules (COMs) in Space

COMs are carbon-based compounds with >6 atoms

(Herbst & van Dishoeck 2009)



COMs: Carbon-based molecules with >6 atoms

(Herbst & van Dishoeck 2009)

- Star forming regions: Hot Cores and Hot Corinos
  (Hollis+2000,2004; Beltran+2009; Belloche+2016; Jorgensen+2012; Lykke+2017)

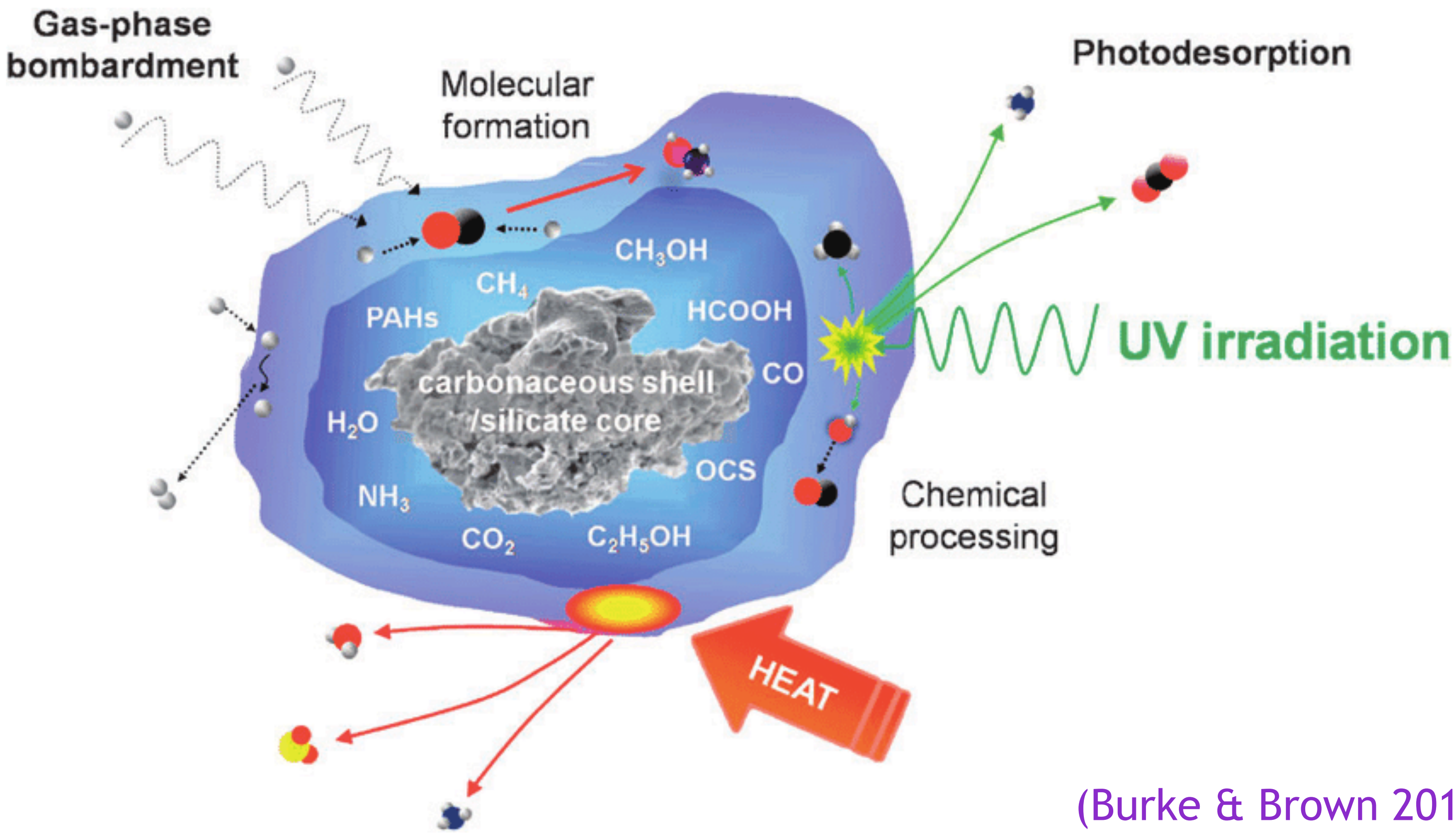
- Galactic Center Giant Molecular Clouds
  (Martin-Pintado+2001;Requena-Torres+2006,2008; Zeng et al. 2018)

- Molecular Outflows
  (Arce+2008; Codella+2015,2017)

COM formation in hot sources

COMs formed mainly via:

1. Hydrogenation (H addition; Charnley et al. 1997, 2001)
2. Radical-radical surface reactions (efficient at T>30 K; Garrod et al. 2008)



(Burke & Brown 2010)

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- Molecular Outflows
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- Radiation-Dominated Regions (UV photons and CRs)
  (Guzman+2013; Cuadrado et al. 2017; Fontani+2017)

- Starless Cores and Pre-stellar Cores
  (Marcelino+2007; Oberg+2010; Bacmann+2012; Cernicharo+2012; Vastel+2014; Jimenez-Serra+2016; Taquet+2017; Cordiner+2017; Soma+2018)

COMs: Carbon-based molecules with >6 atoms

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- Starless Cores and Pre-stellar Cores **(T<=10 K)**

Radical-radical surface formation inefficient at T<30 K

COM formation in cold sources (T=10 K)

Radical-radical surface formation inefficient at T<30 K

New mechanisms proposed:

1. Gas phase formation (Vasyunin & Herbst 2013; Balucani+15)
2. Non-canonical explosions induced by H_2 formation (Rawlings+2013)
3. Formation after H atom addition/abstraction on grains (Chuang+2016)

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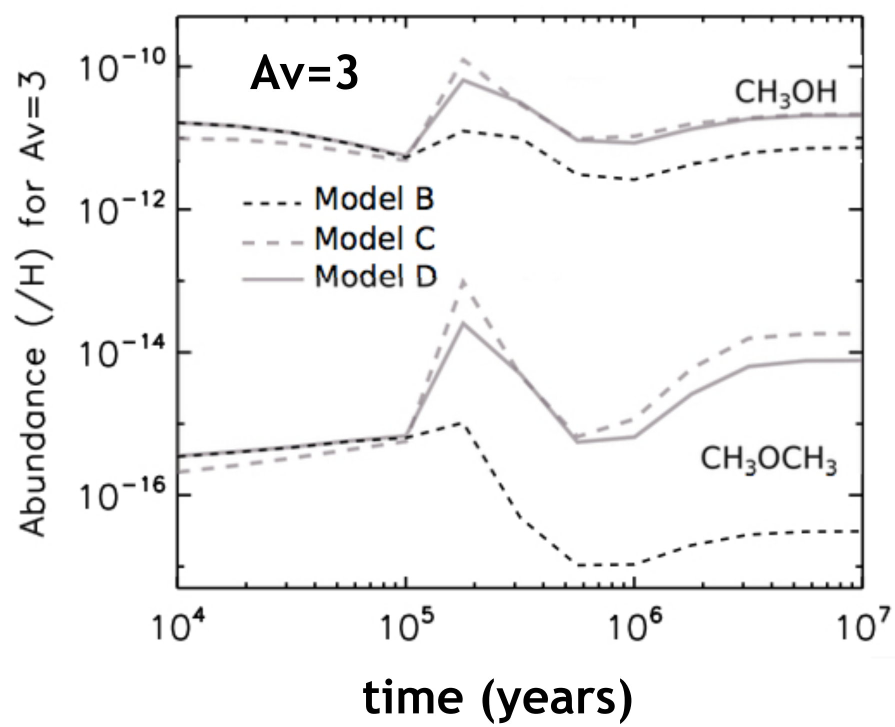

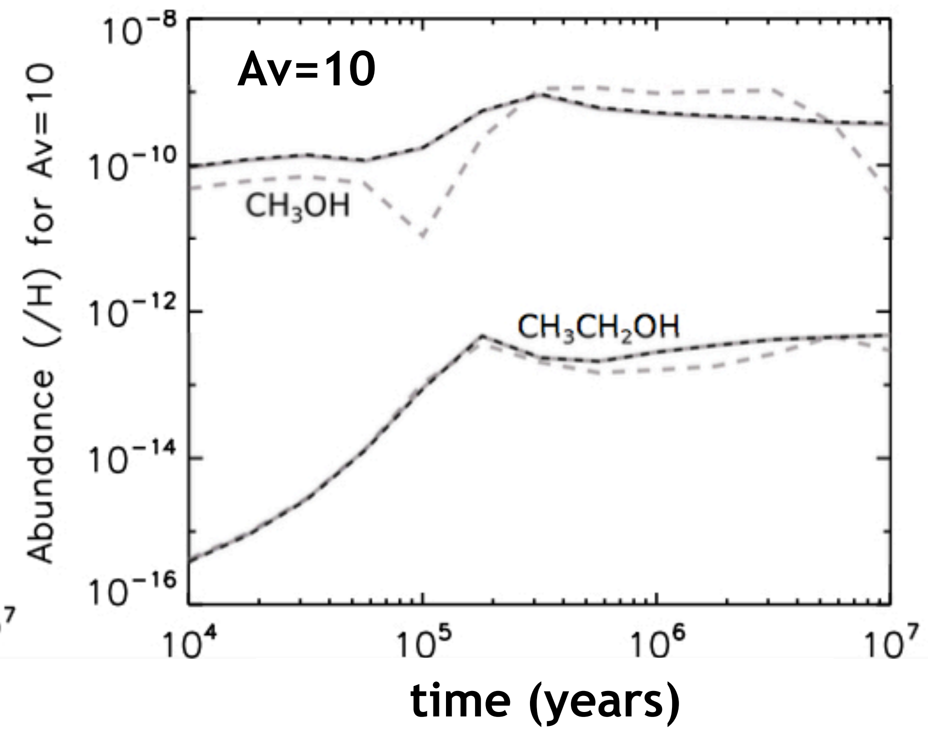

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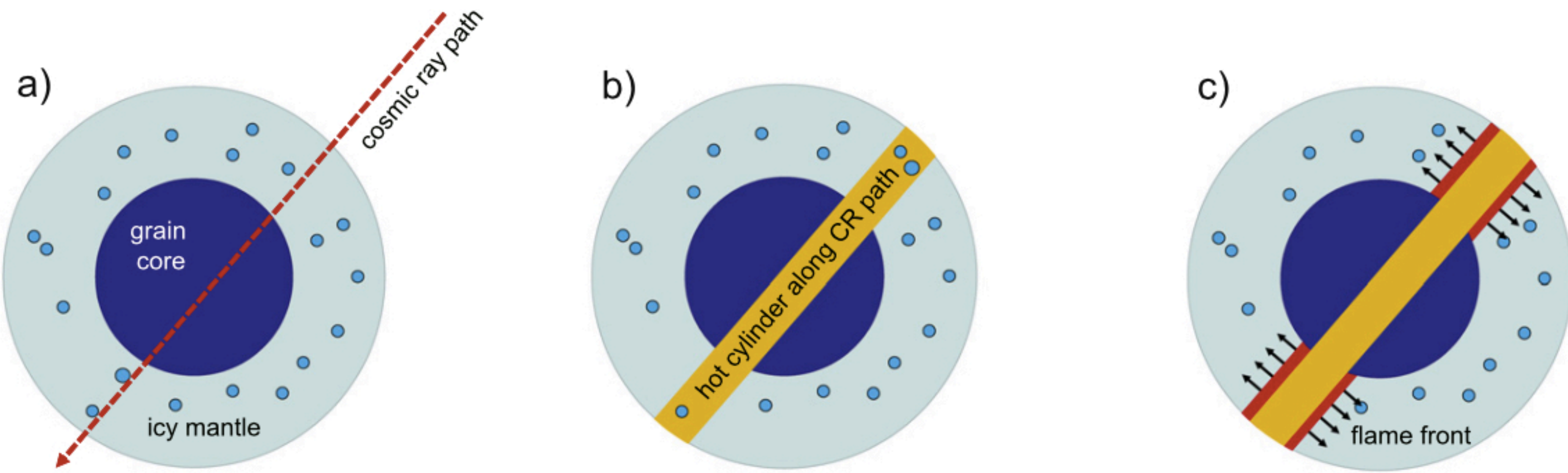
5. Impulsive spot heating and thermal explosion by CRs (Ivlev+2015)



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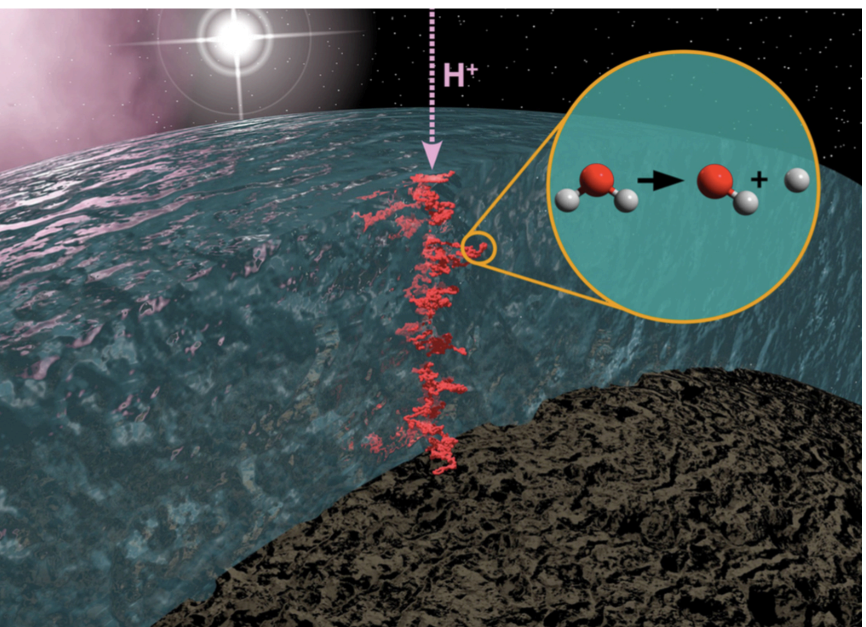
6. Radiation chemistry (radiolysis) on grains by CRs impacts (Occhiogrosso+11; Shingledecker+17)

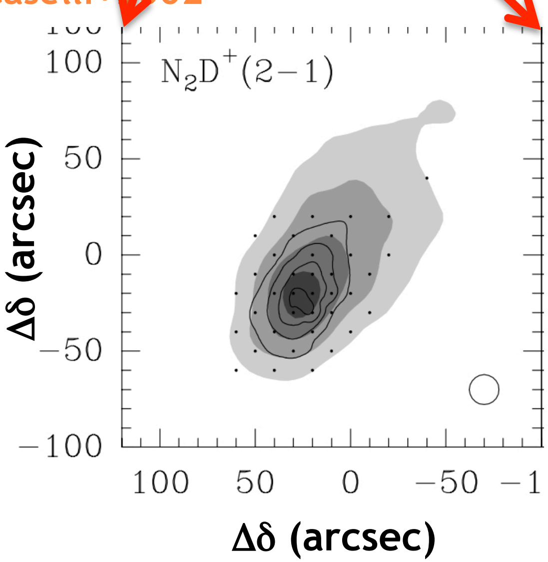


See experiments by e.g.

Kanuchova+16, Modica & Palumbo+10; Munoz-Caro+14; Rothard+17; Lafosse+06; Abplanalp+16; Cheng+18; Bergantini+18; Kaiser+13

Pre-stellar cores: Precursors of Solar-type systems

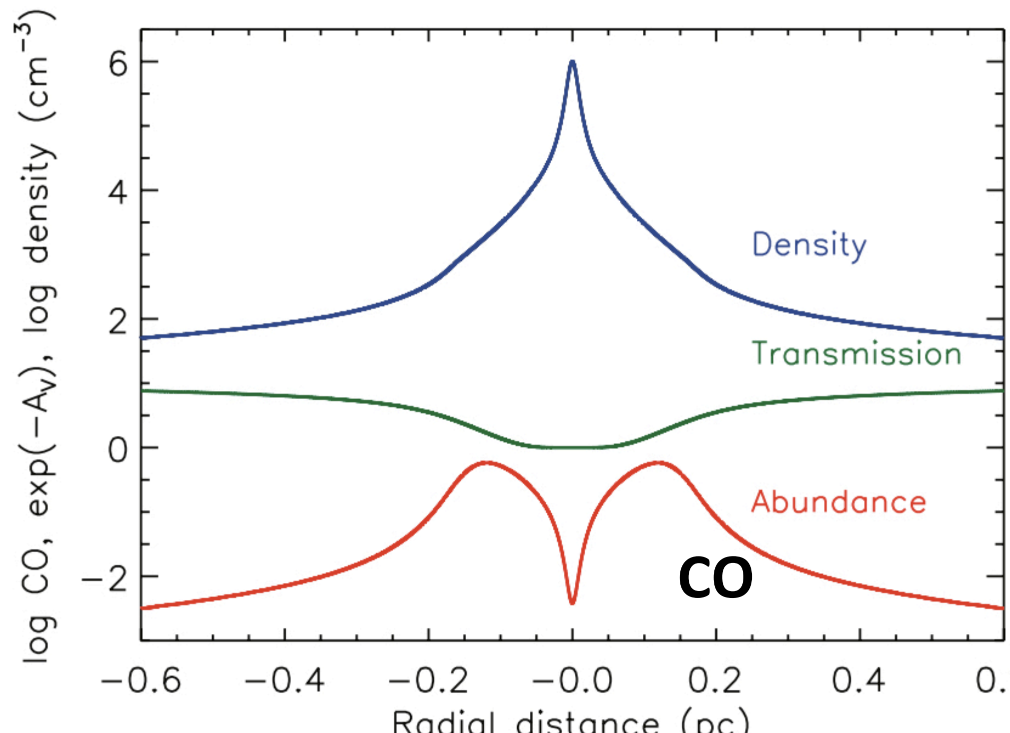
Caselli+2002



Pre-stellar cores:

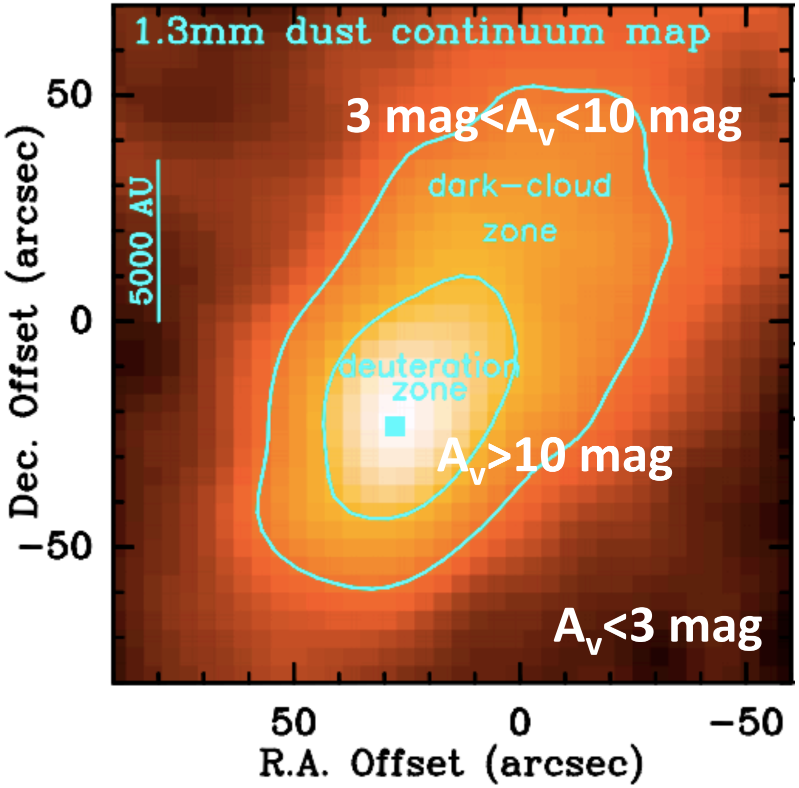
Cold and dense cores on the verge of gravitational collapse (no star inside yet)

Keto & Caselli 2008



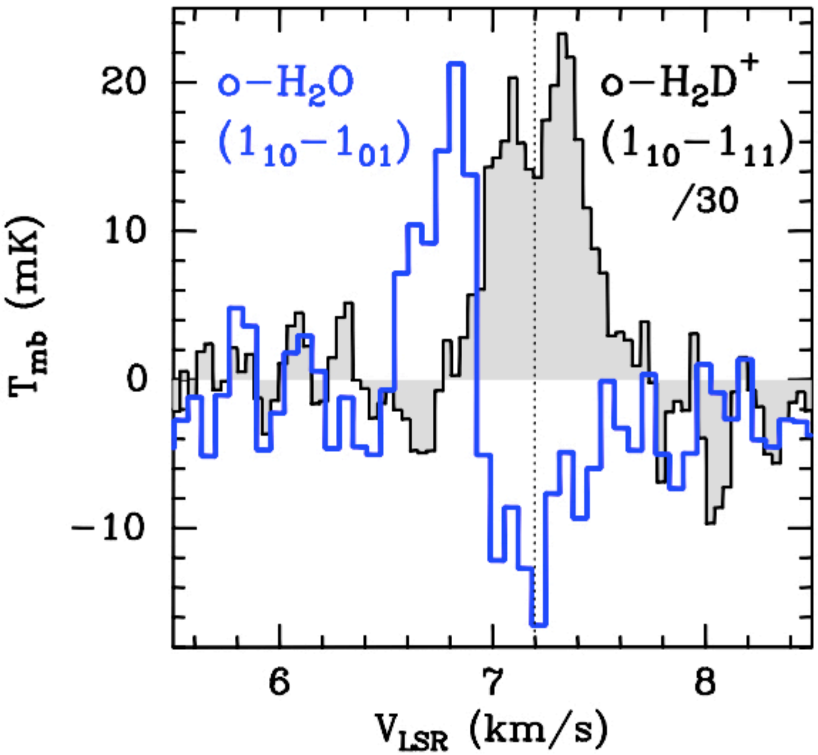
L1544 as a testbed

Caselli & Ceccarelli (2012)



Water vapour in L1544

(Caselli+2012)



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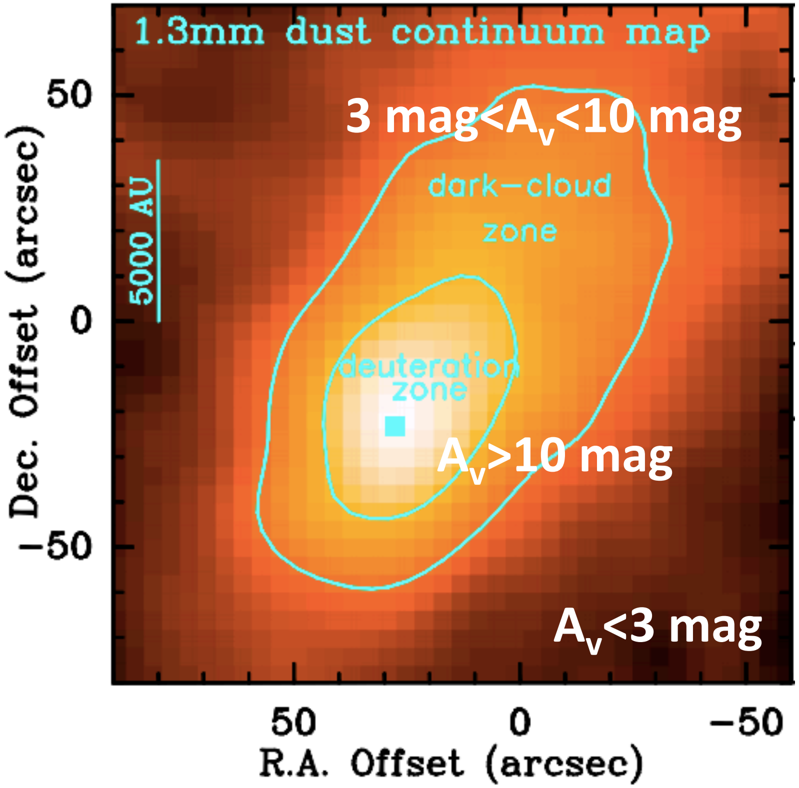

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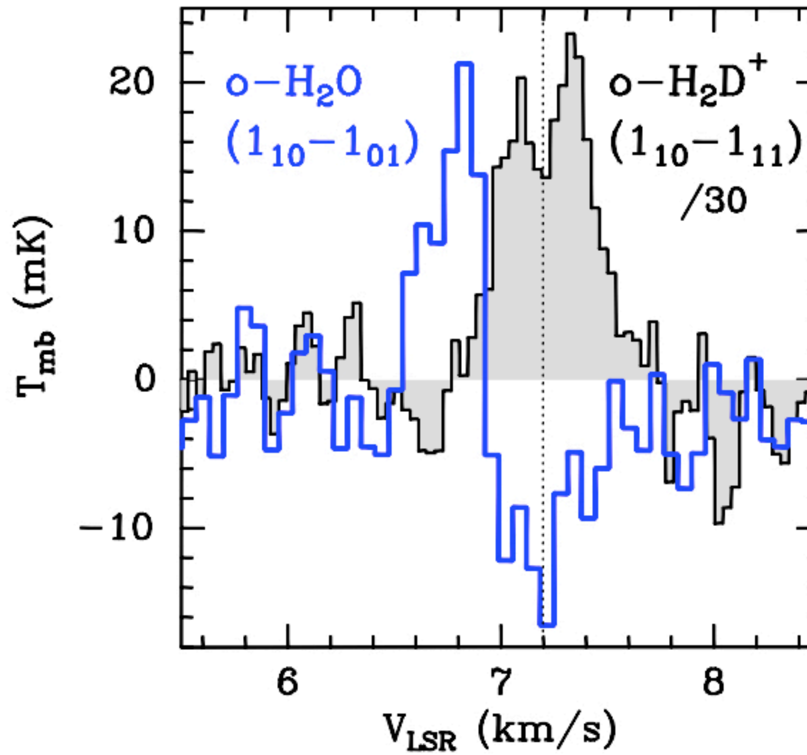
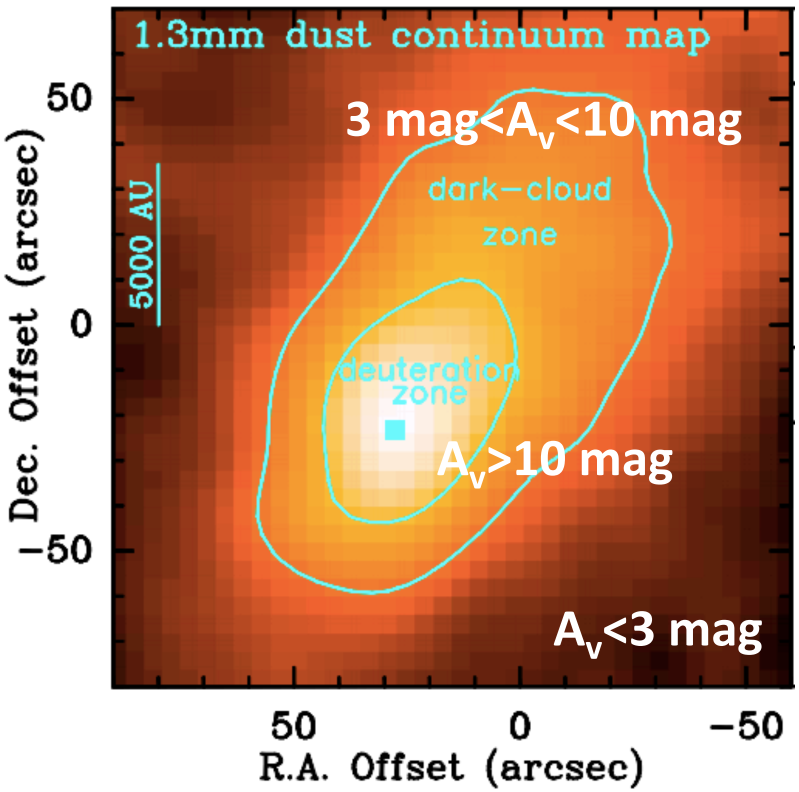


COMs(+precursors) expected to be released with H_2O

(C_3O, H_2CCO, HCOOH, CH_3CHO; Vastel+2014)

L1544 as a testbed

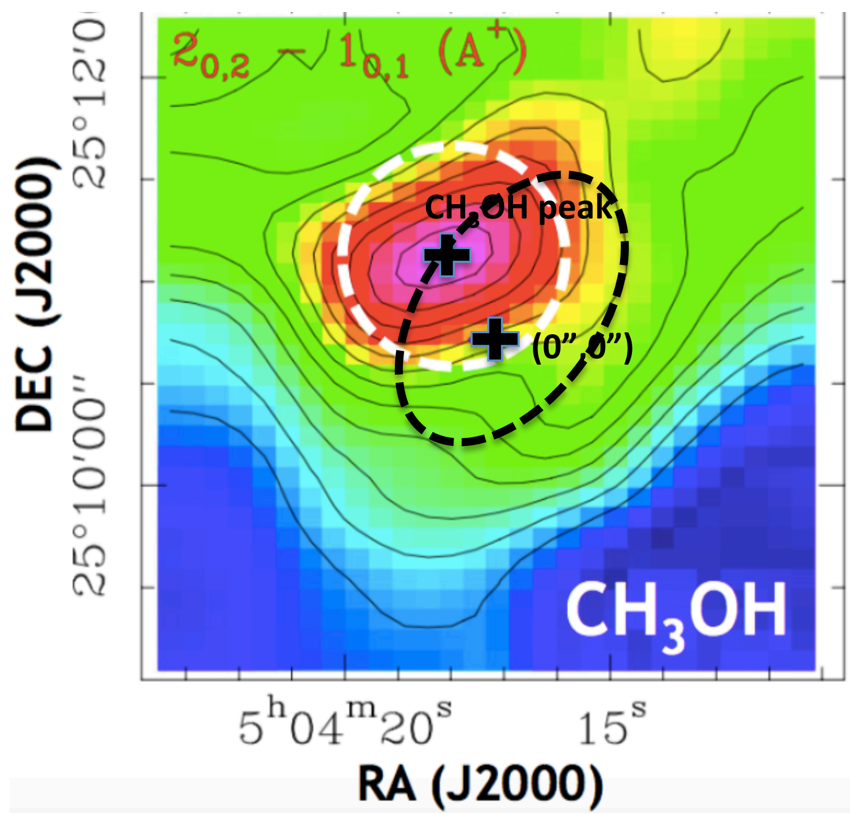
Caselli & Ceccarelli (2012)



CH_3OH-ring at r~4000 AU

intermediate density shell

interesting chemistry appears



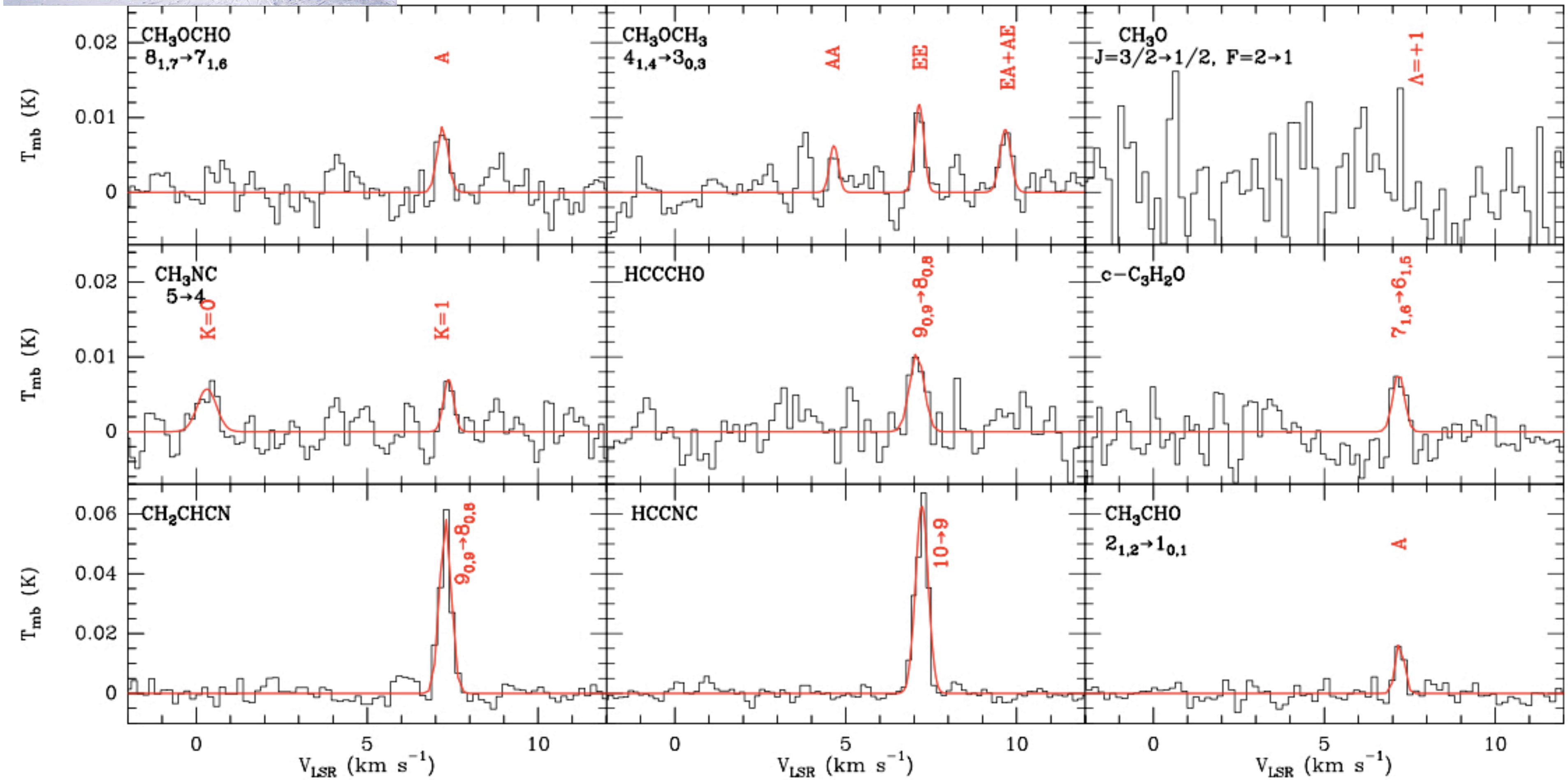
Bizzocchi et al. 2014

Detection of large COMs in L1544

CH_3OCHO, CH_3OCH_3, CH_3CHO, c-C_3H_2O, CH_2CHCN, CH_3NC, HCCNC, HCCCHO

(0,0)

Jimenez-Serra et al. (2016)

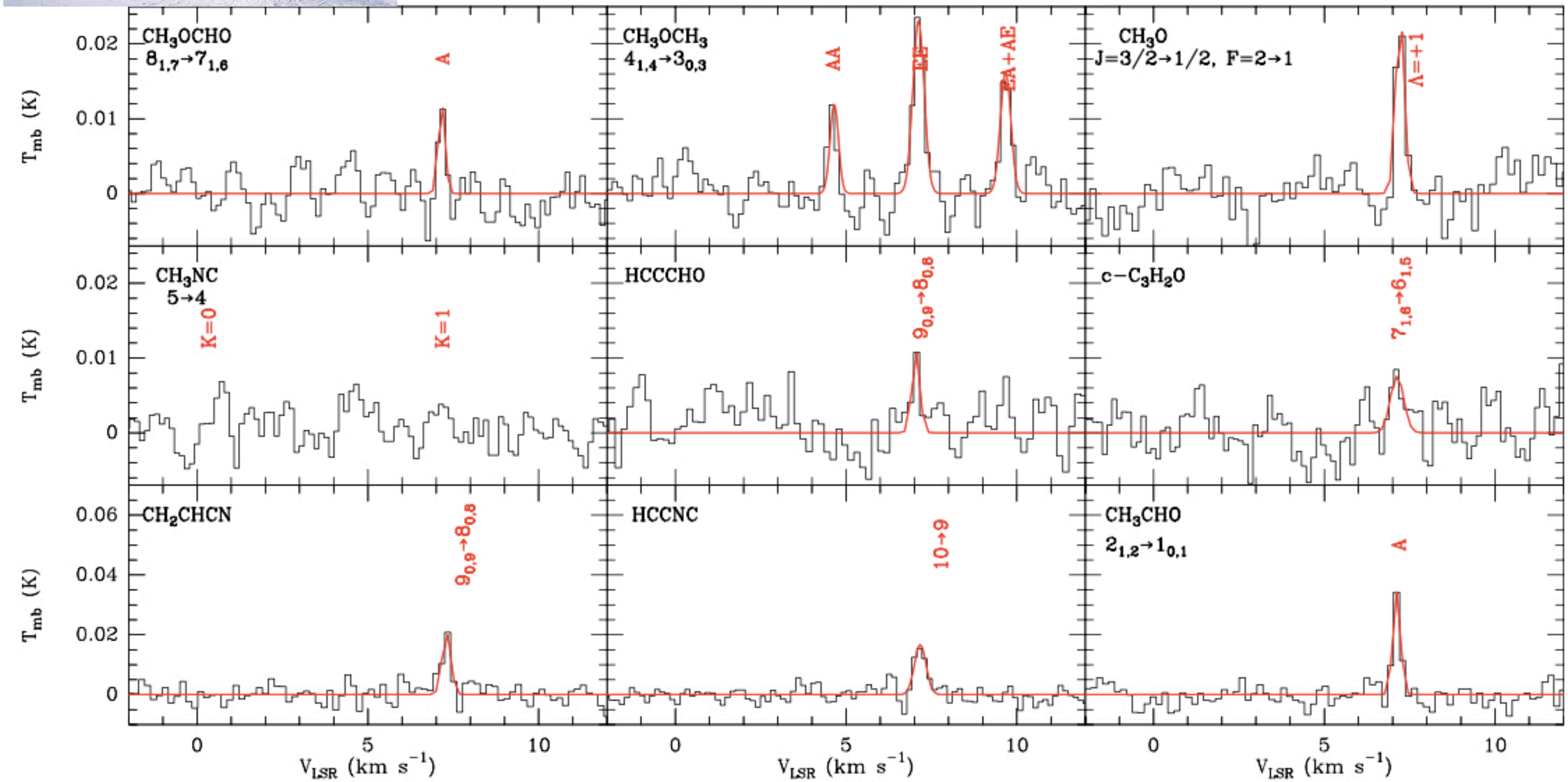


Detection of large COMs in L1544

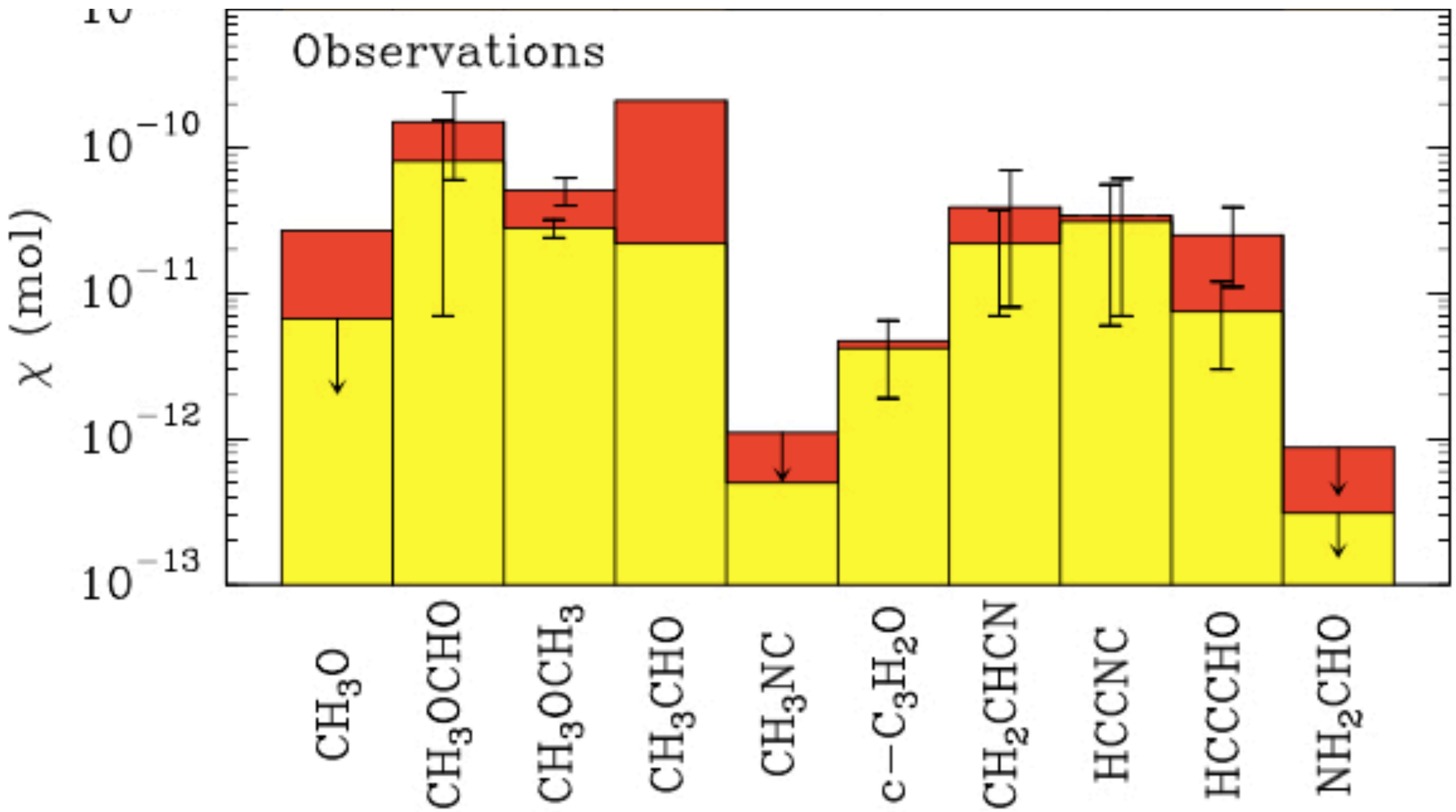
CH_3OCHO, CH_3OCH_3, CH_3CHO, $c\text{-}C_3H_2O$, CH_2CHCN, CH_3NC, HCCNC, HCCCHO

CH_3OH peak

Jimenez-Serra et al. (2016)



COM abundance profile in L1544



Jimenez-Serra et al. (2016)

CH_3O, CH_3CHO:

>6-10 x more abundant at r~4000 AU

CH_3OCH_3, CH_3OCHO and N-bearing COMs:

~2-3 x more abundant at r~4000 AU

O-bearing COM chemical modelling in L1544

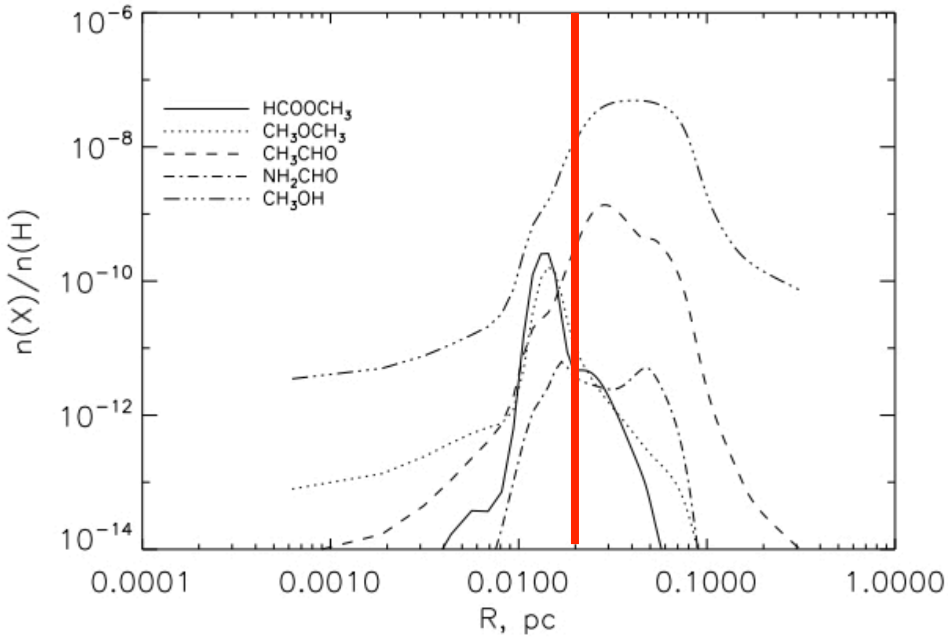
Gas-phase + dust grain model of Vasyunin & Herbst (2013)

COMs formed in gas-phase after precursors ejected by chemical reactive desorption

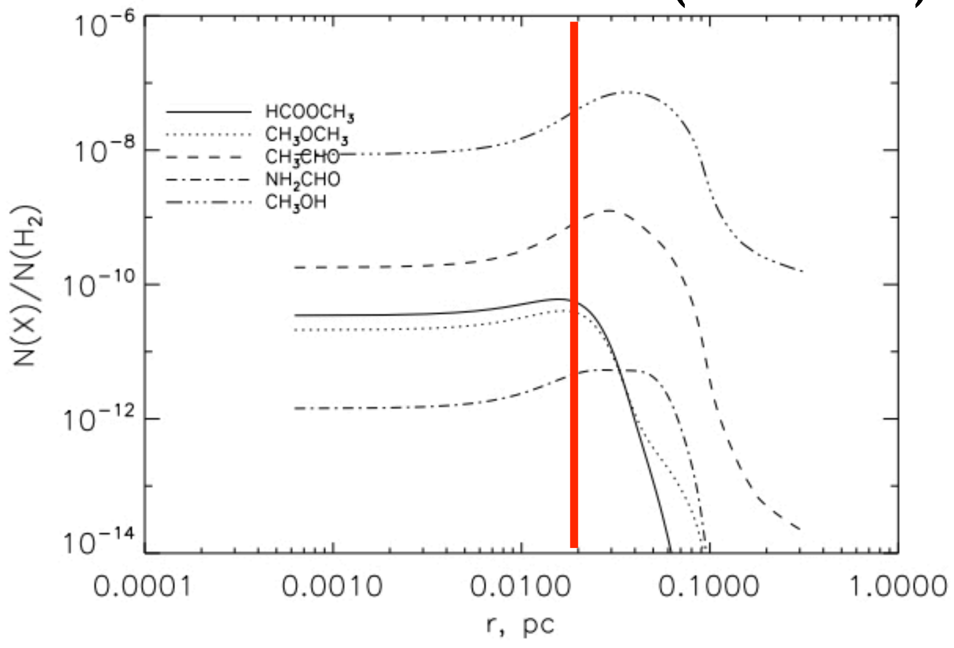
Updates:

- new multilayer treatment for the icy mantles of dust grains
- an advanced treatment for the reactive desorption (Minissale+2016)
- new neutral-neutral gas-phase reactions (Shannon+2013; Balucani+2015)

Pencil-beam Abundances

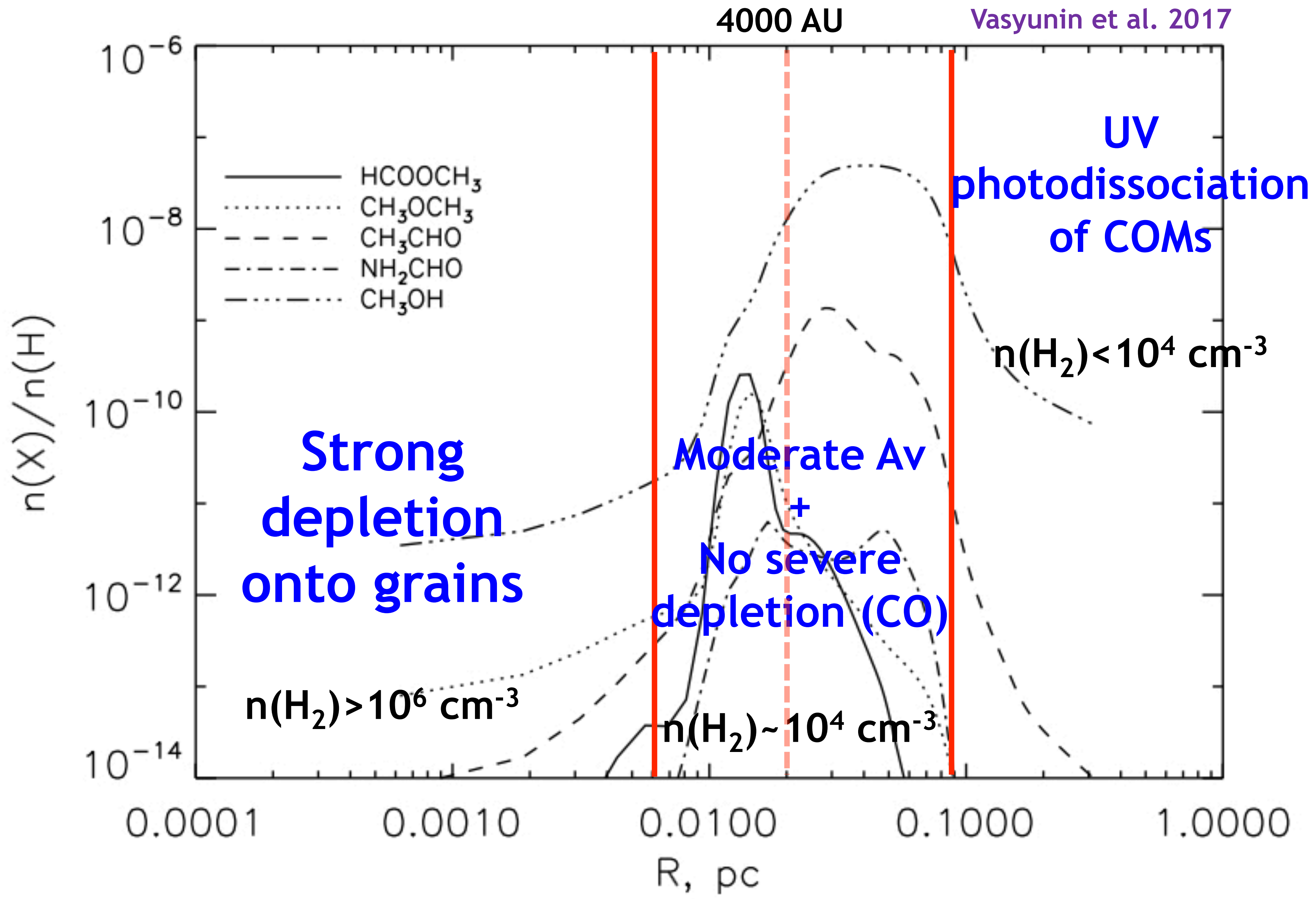


Convolved Abundances (26”-beam)



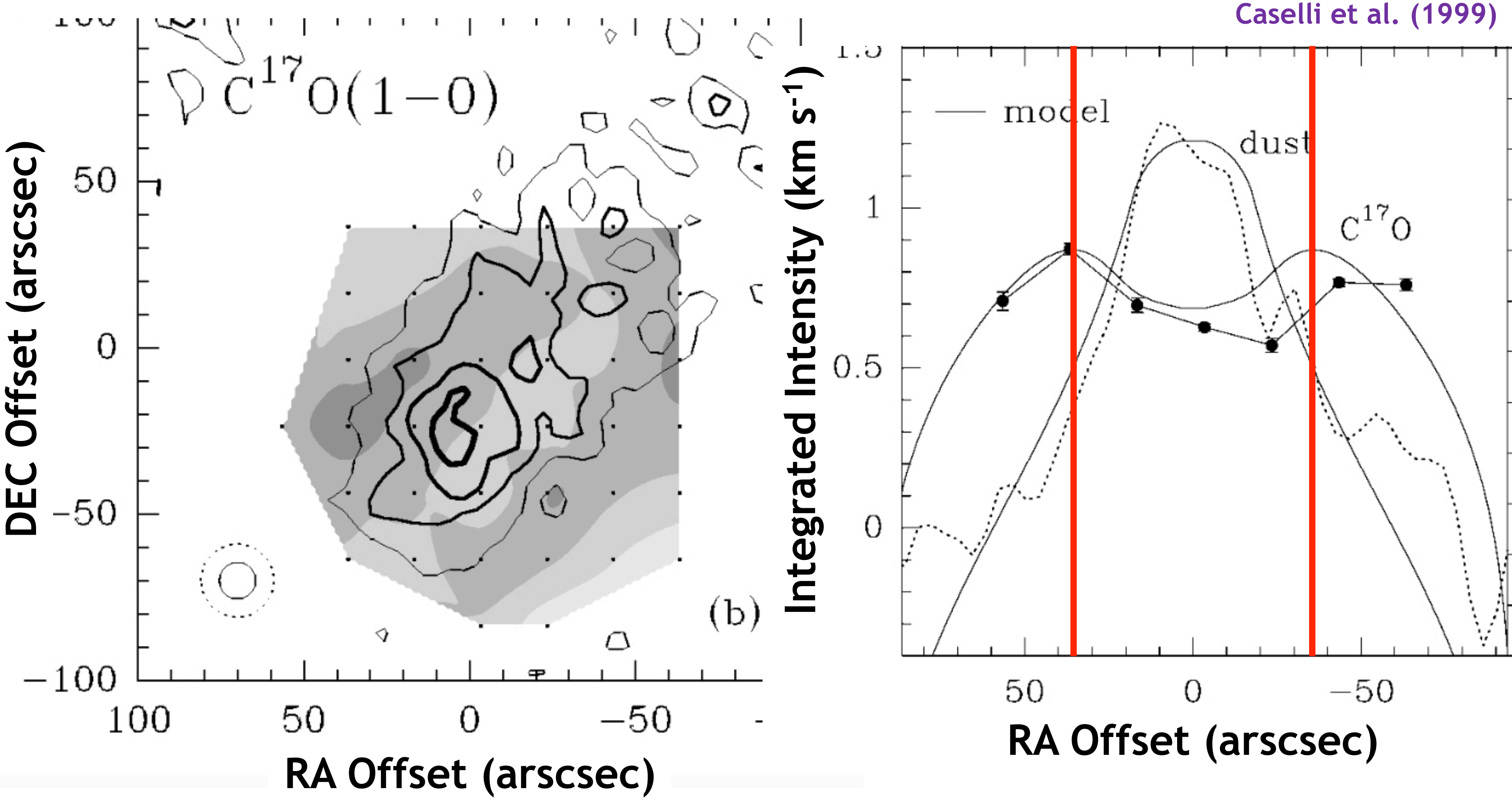
Vasyunin et al. (2017)

O-bearing COM chemical modelling in L1544



Where does CO depletion occur?

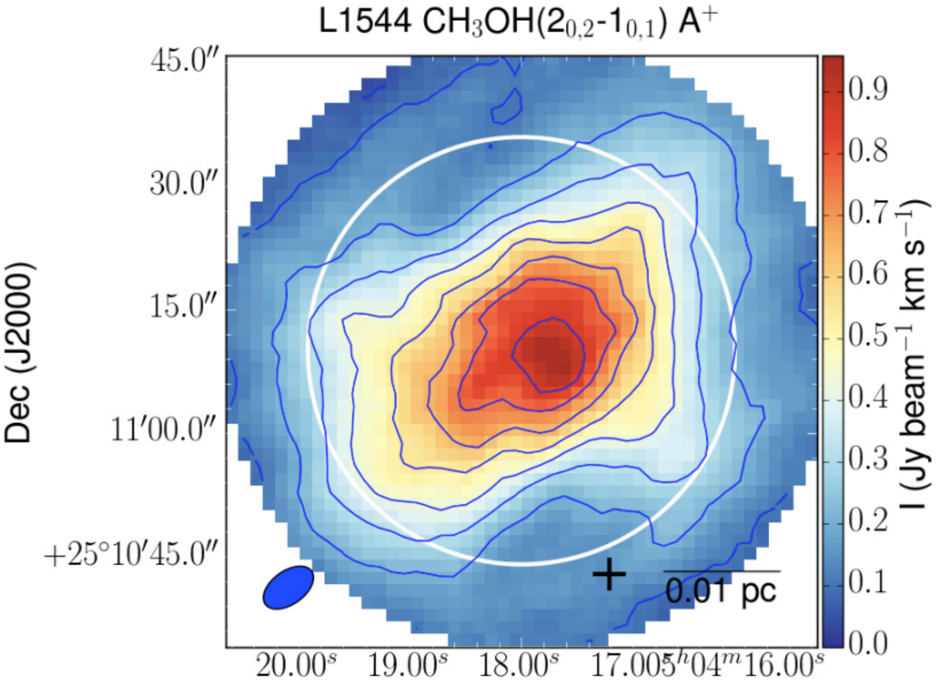
Caselli et al. (1999)



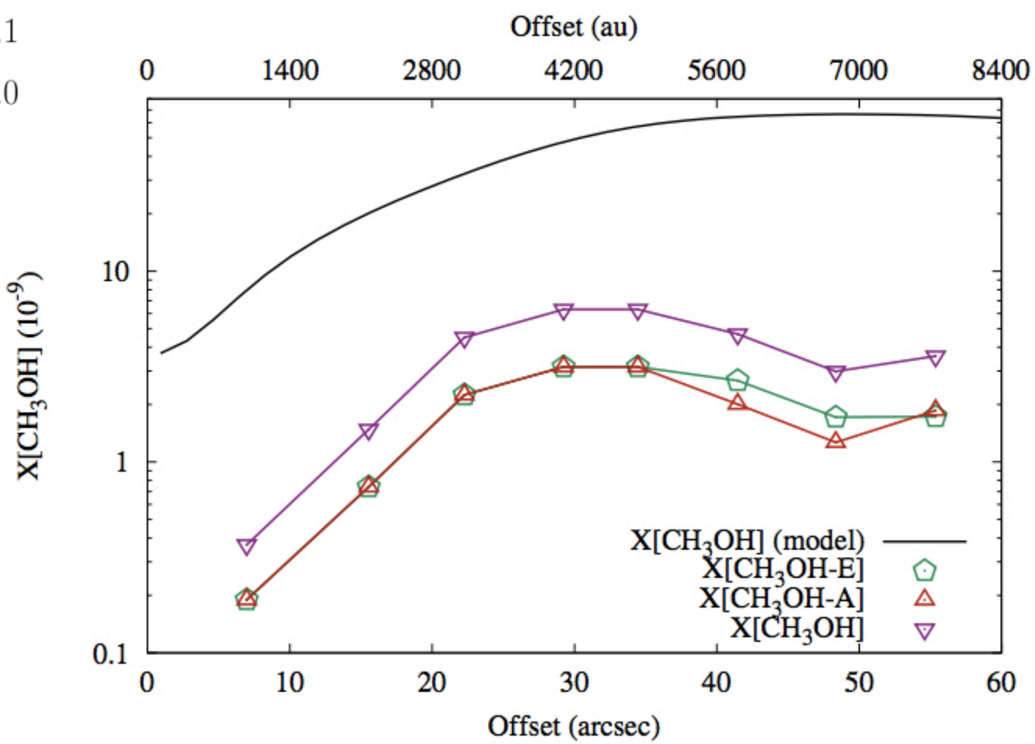
Catastrophic depletion of CO ➔

CO snow-line in pre-stellar cores

Small-scale structure of the CH_3OH peak



Punanova+18



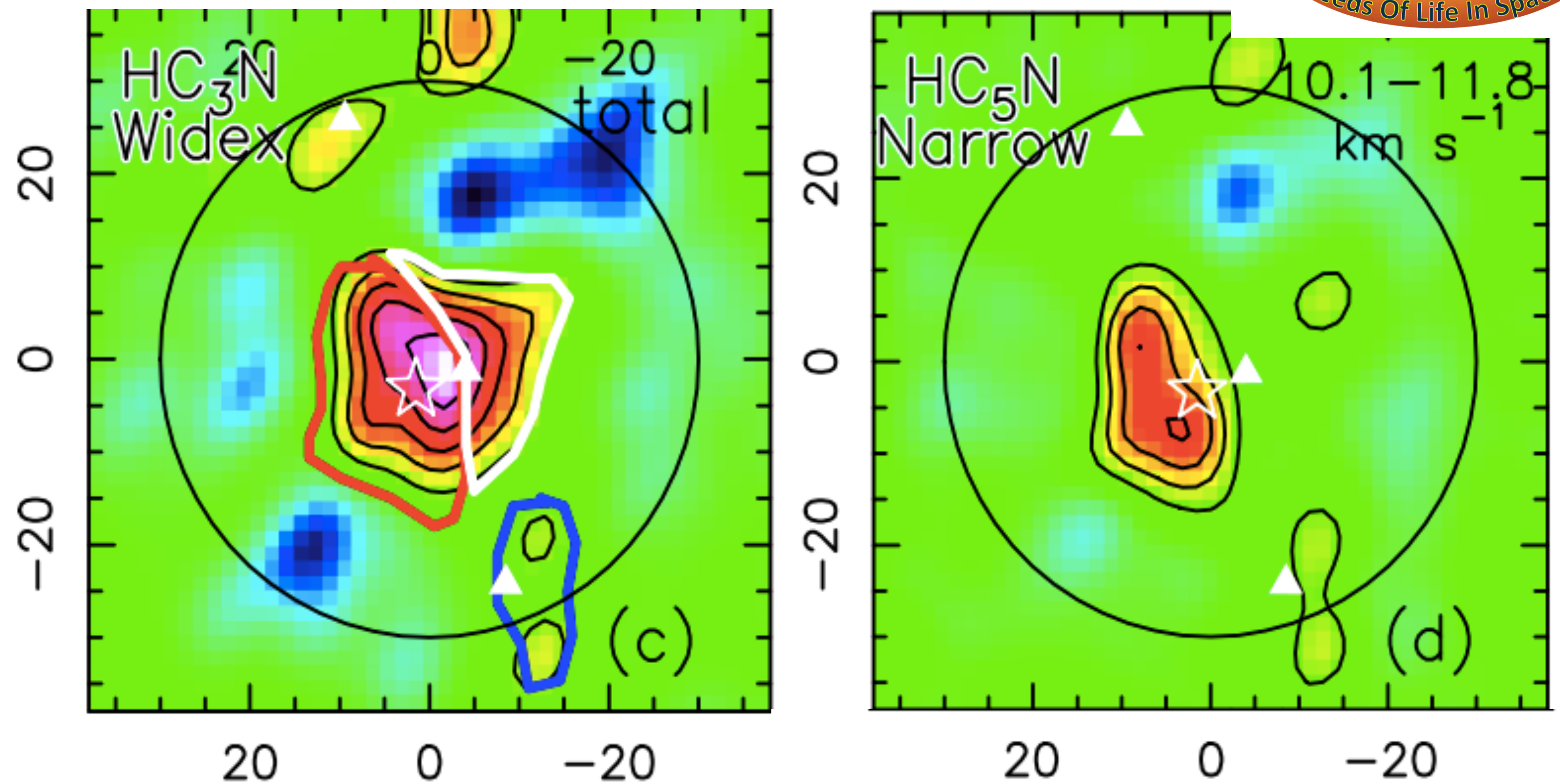
Large discrepancies for CH_3OH, CH_3O and CH_3CHO

New lab experiments and/or New formation routes for COMs (CRs?)

CR-induced chemistry in the OMC2-FIR4 cluster

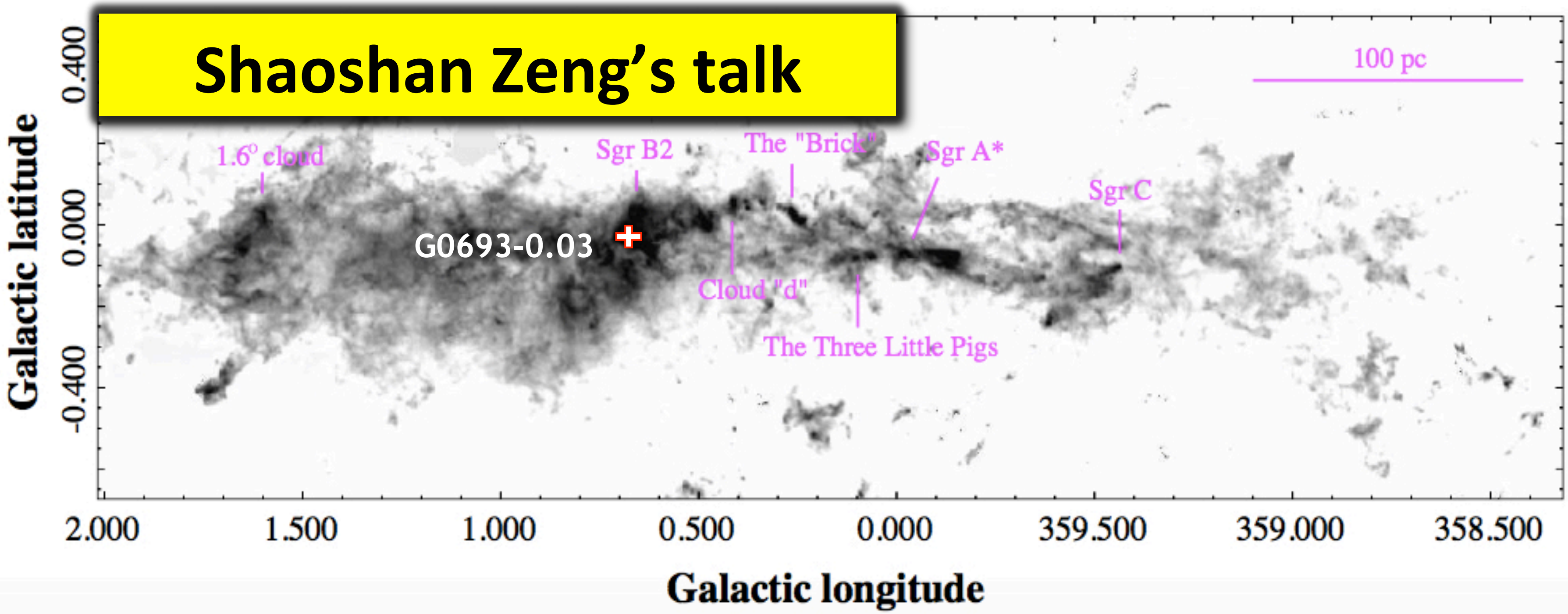
Herschel revealed an internal source of >10MeV particles (Ceccarelli+14)

Fontani+17



Smaller HC_3N/HC_5N ratios could be induced by enhanced CR ionization rate (~4×10^{-14} s^{-1})

Chemical complexity in the Galactic Center



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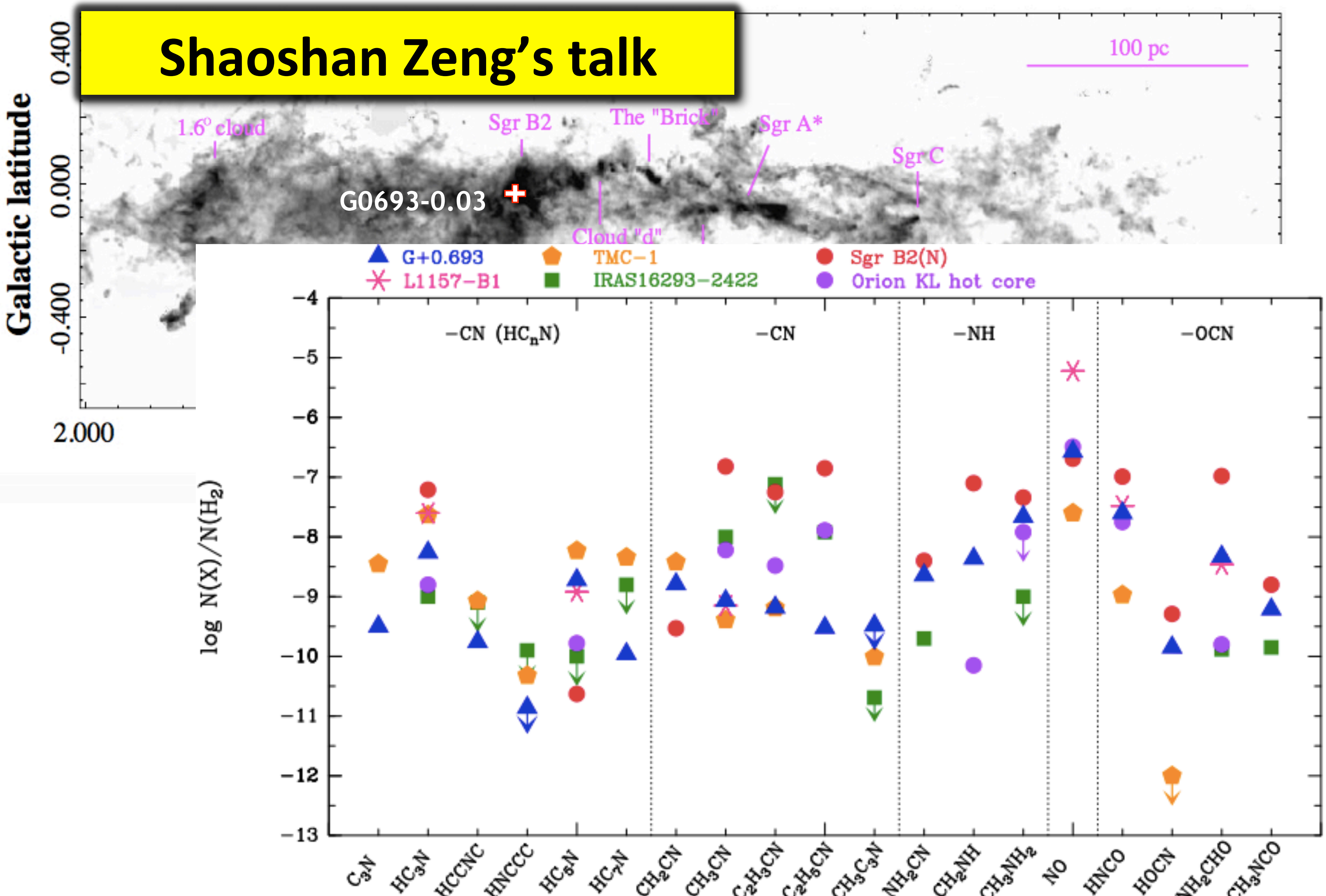
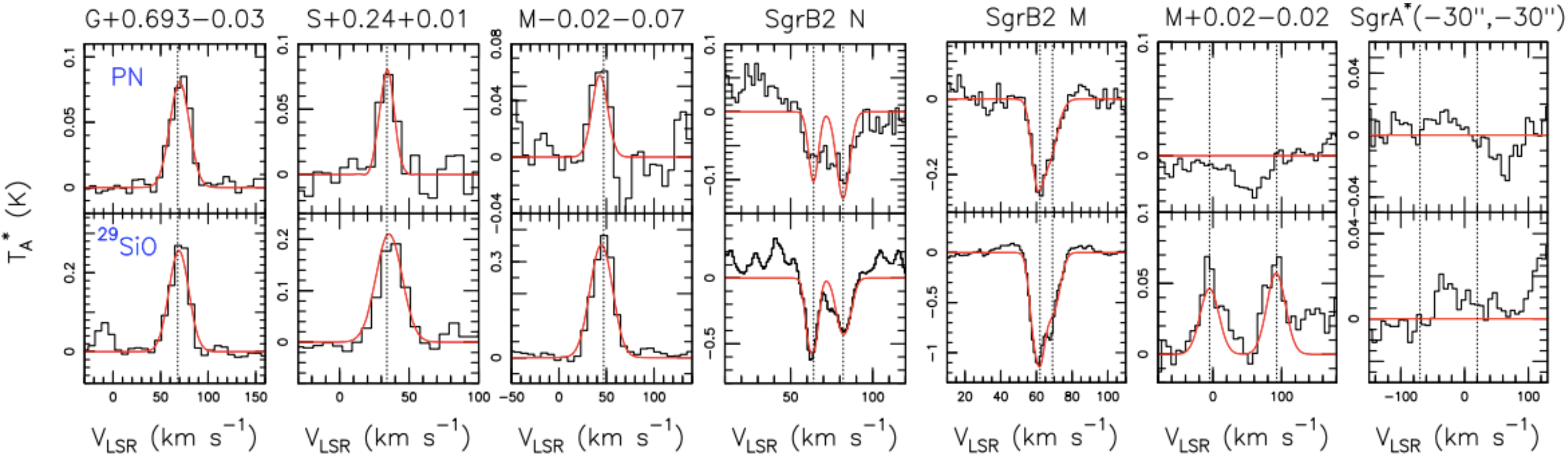


Chemistry of P under energetic phenomena



Victor Rivilla's poster

Rivilla et al. 2018

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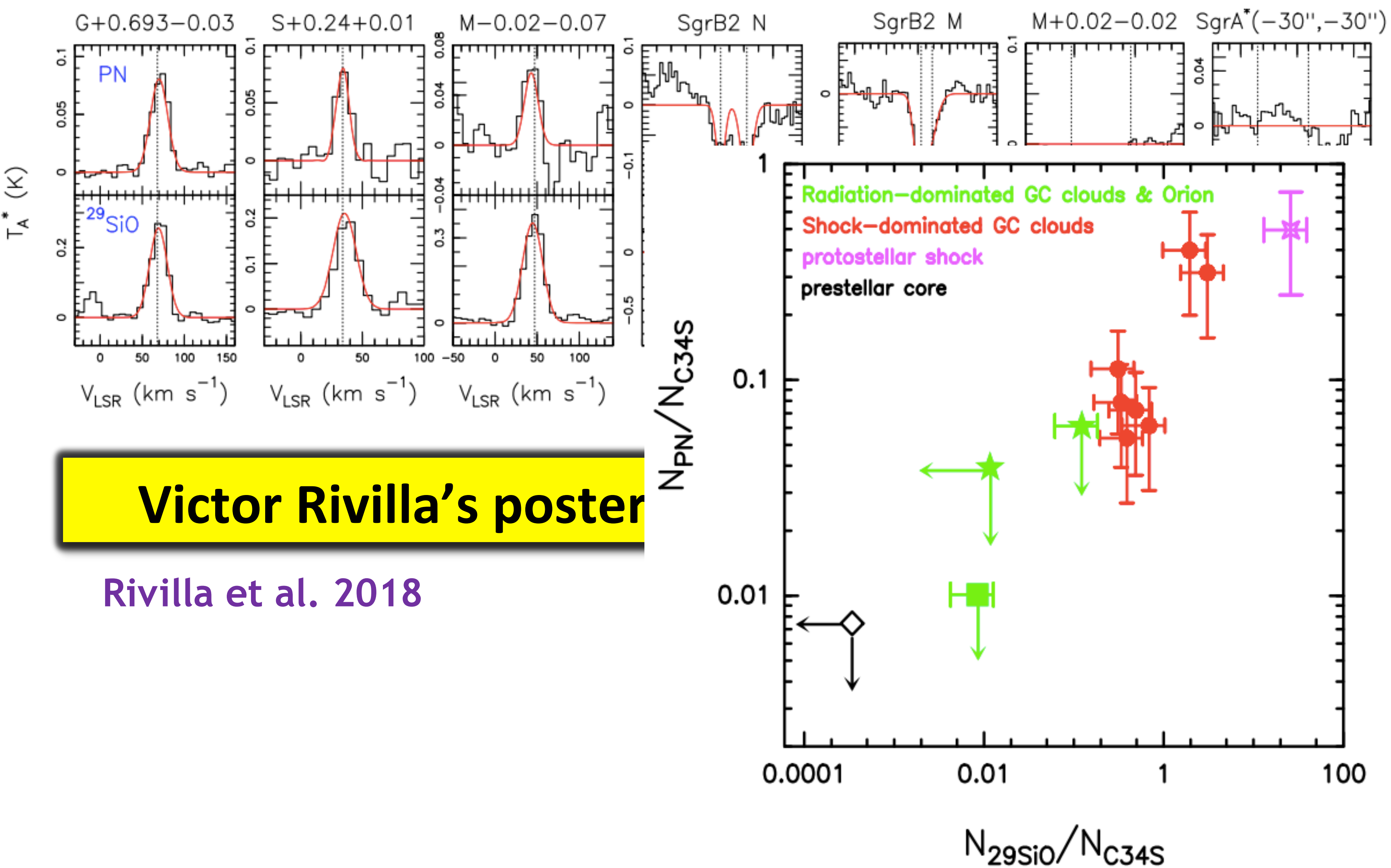

Victor Rivilla's poster

Rivilla et al. 2018

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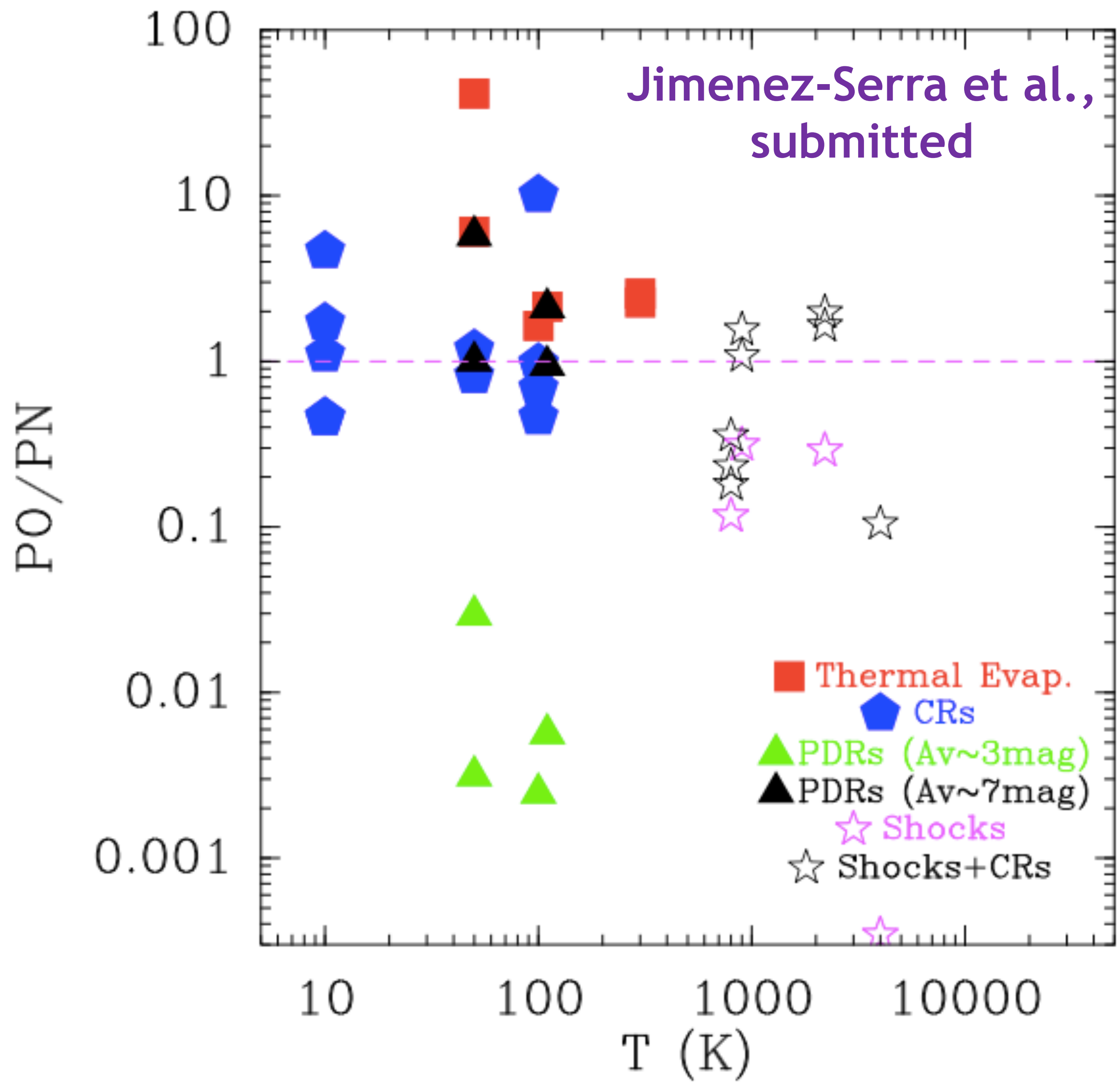

Conclusions

- New mechanisms proposed for the formation of COMs via the interaction of CRs. Non-trivial implementation in chemical models.
- COM abundance profile in pre-stellar cores *qualitatively* reproduced by chemical modelling
- However, discrepancies do exist for important COMs such as CH_3OH and CH_3CHO: new lab experiments and/or inclusion of new CR processes.
- CRs expected to play an important role in the chemistry of the ISM in star-forming regions and galactic nuclei.