Star Formation through the Chemical Lens

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Why star formation?

- One of the major open problems in astrophysics

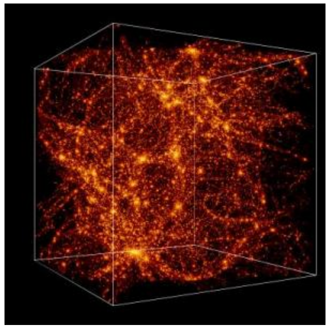
  Intensely interdisciplinary

  requires knowledge of different areas of physics:

  fluid dynamics, plasma physics, interaction of radiation with matter, condensed matter physics, atomic and nuclear physics

- Prerequisite for the understanding of galaxy formation/ evolution

  Connects luminous universe (stars) with dark/exotic sector (DM,DE)



- **"We are made of star stuff" Carl Sagan**

Stars Form in Molecular Clouds

- Massive
  (10^3–10^6 $M_\odot$)

- Cold
  ($T \approx 10K$)

- Molecular
  (mostly H_2,
  dust ≈ 1% by mass)

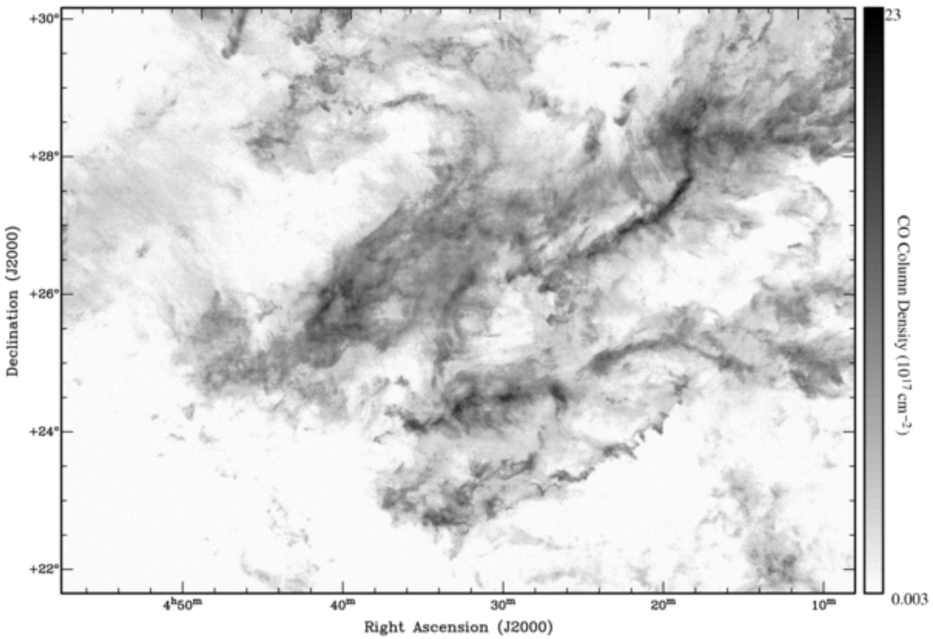
Taurus Optical ESO/Davide De Martin

- Turbulent & Magnetized

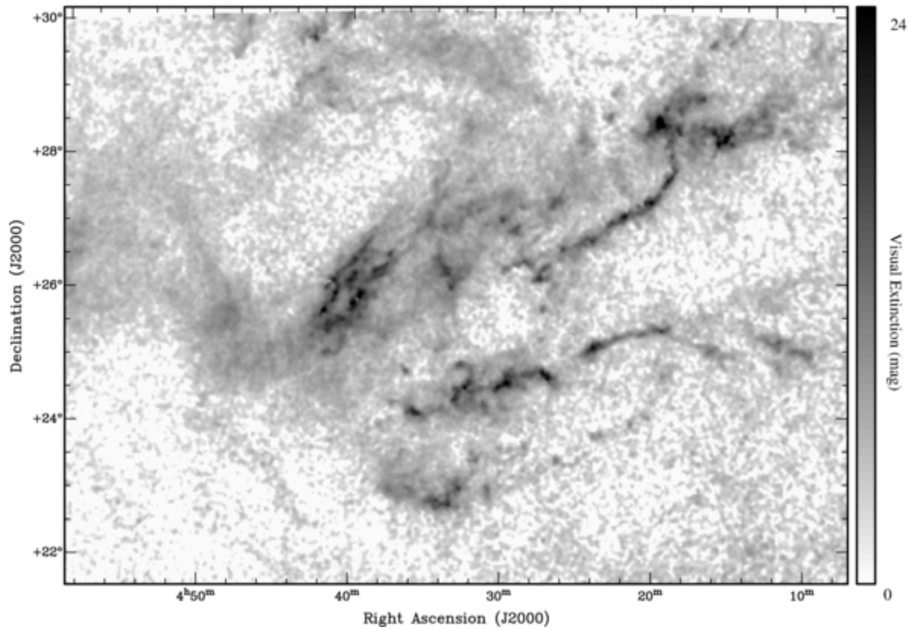
Too cold for H_2 emission. Most of the mass not visible.
MCs appear dark in the visible.

How are MCs observed?

CO emission



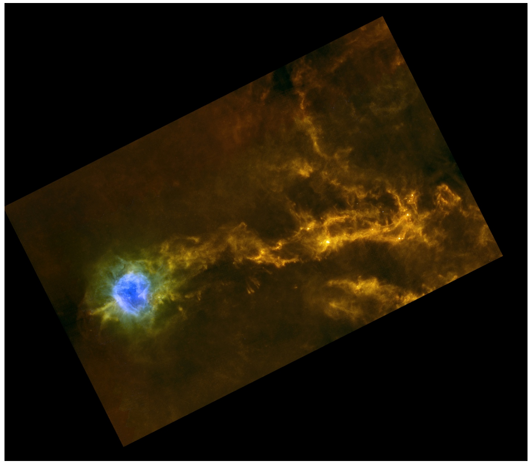
Dust Extinction



Pineda et al. 2010

How are MCs observed?

Dust Emission



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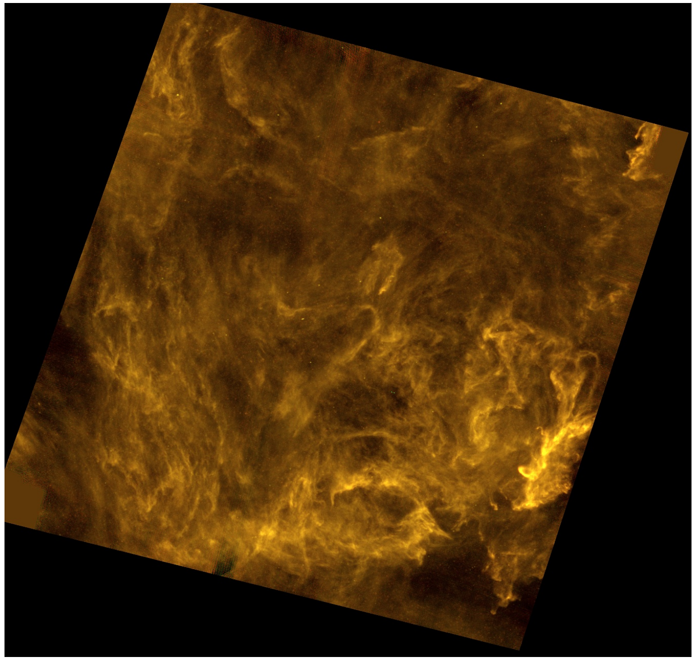
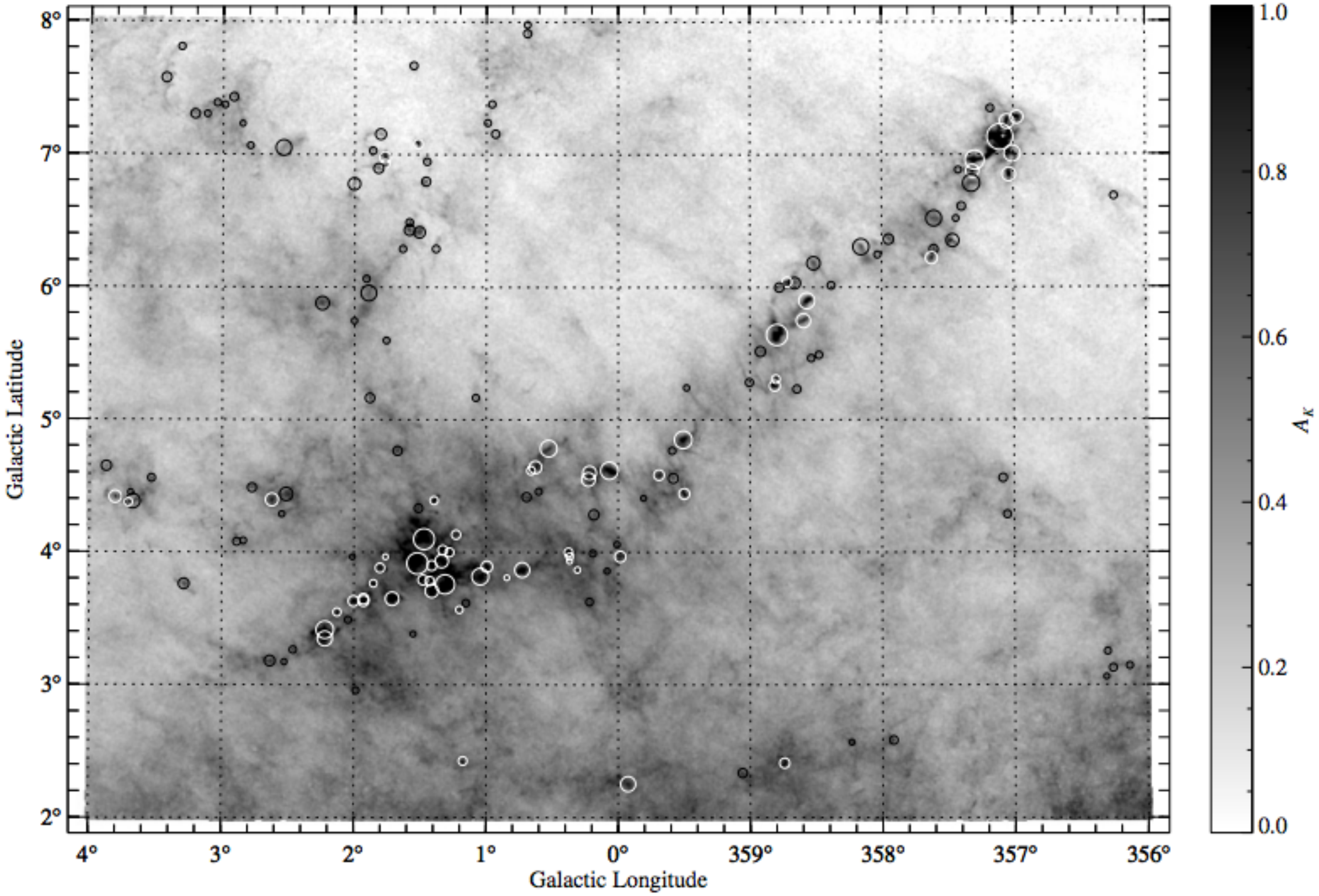


Polaris

Vela C

Herschel/ Gould Belt Survey Andre et al. 2010

Cores



Alves et al. 2007

How do cores form?

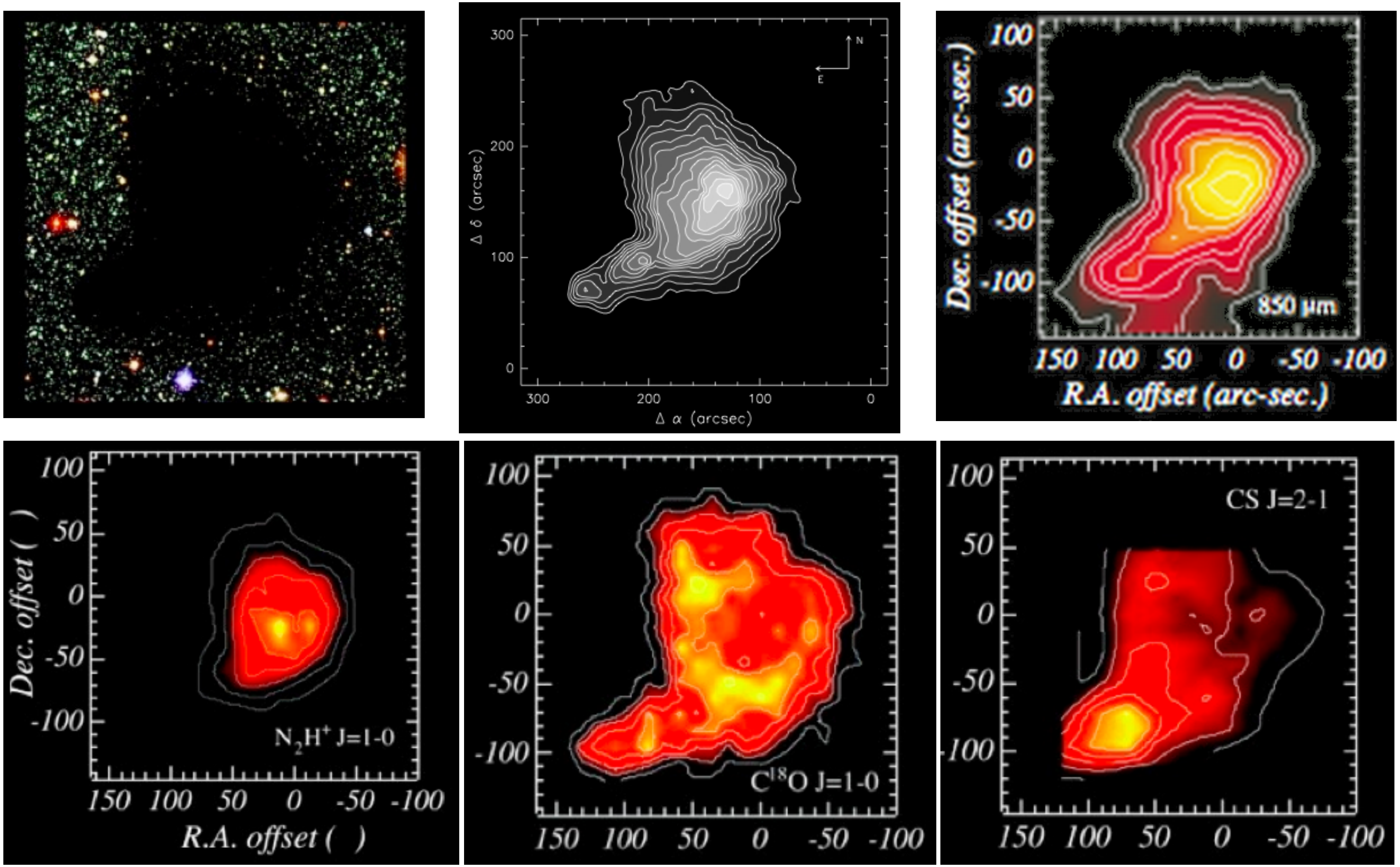
Weak B Field

- Molecular clouds supported by turbulence
- Turbulence (super-) Alfvenic magnetic fields weak
- Overdensities created by compression in converging flow regions
  - Some become jeans unstable (collapse)
  - Some reexpand (transient clumps)
- Eventually, hydrostatic protostars are formed in the collapsing cores

Strong B Field

- Molecular clouds mainly magnetically supported
- Turbulence (sub-) Alfvenic
- Ambipolar Diffusion
  - Damps MHD turbulence below a critical scale (cloud fragmentation)
  - Formation of **magnetically supercritical cores**
- Supercritical cores contract dynamically
- Eventually, hydrostatic protostars are formed

Looking Through the Chemical Lens



The Coming Flood of Molecular Line Data

SKA
SQUARE KILOMETRE ARRAY

ALMA

James Webb Space Telescope
JWST
NASA • ESA • CSA

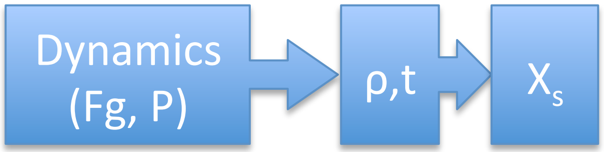
SOFIA
Stratospheric Observatory For Infrared Astronomy

The Plan: Produce Toolkit for Connecting Observations to Theories

- Chemistry + Dynamics + Radiative Transfer + Free Parameters + Projection Effects → **Observables**
- Produce database of observables from all combinations
- Make *freely available, easily accessible*
- Uses for such a database:
  - Identify observables that discriminate between theories
  - Design observing strategies, future observatories
  - Provide initial conditions for star and planet formation

Coupling of chemistry and dynamics

No B field



Chemistry affected by Dynamics but dynamics not affected by chemistry

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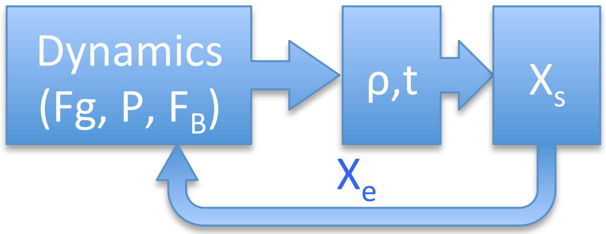
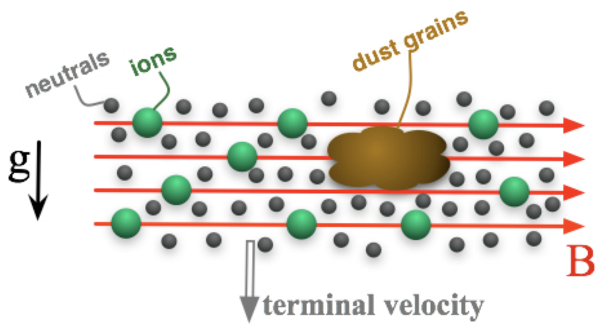
With B field





Chemistry affected by dynamics
and vice versa when B-field included

Ambipolar drift and other non-ideal
MHD phenomena depend sensitively on chemistry

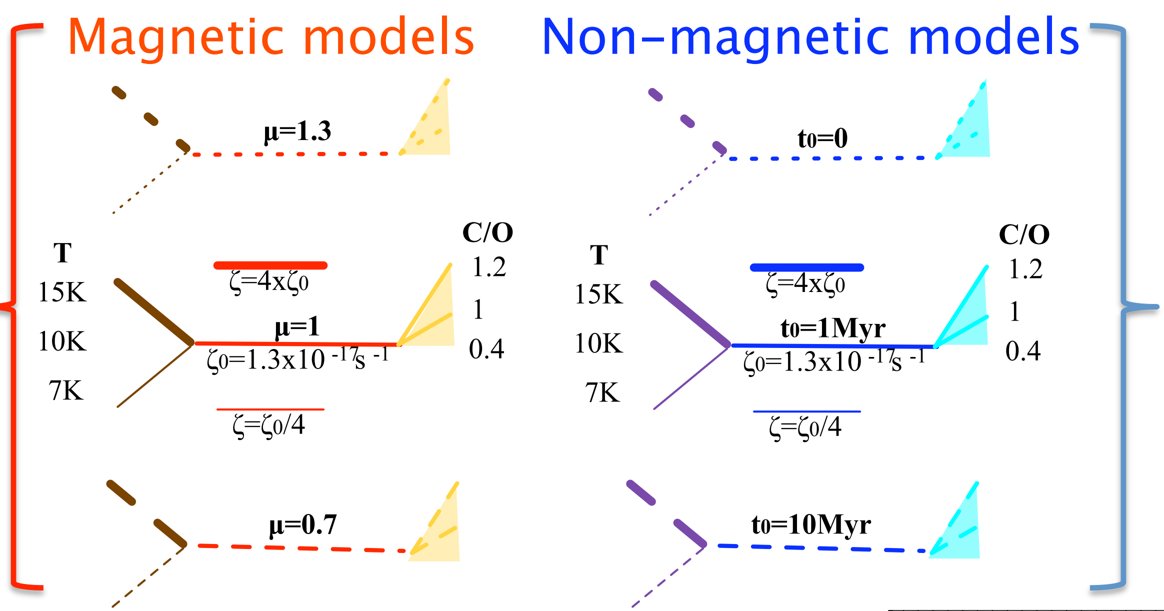
First Step: The Chemical Network

Gas-phase species															
H^+	H	H_2^+	H_2	H_3^+	He	He^+	C^+	C	CH	CH^+	CH_2^+	CH_2	N	N^+	CH_3
NH^+	CH_3^+	NH	NH_2^+	O	CH_4	CH_4^+	O^+	NH_2	CH_5^+	OH	OH^+	NH_3^+	NH_3	H_2O	NH_4^+
H_2O^+	H_3O^+	C_2	C_2^+	C_2H^+	C_2H	$C_2H_2^+$	C_2H_2	CN	CN^+	HCN^+	$C_2H_3^+$	HCN	HNC	Si^+	$C_2H_4^+$
H_2NC^+	Si	N_2	CO^+	$HCNH^+$	CO	N_2^+	HCO	N_2H^+	HCO^+	H_2CO	H_2CO^+	NO	NO^+	H_3CO^+	CH_3OH
O_2	O_2^+	$CH_3OH_2^+$	C_3^+	C_3H^+	C_2N^+	CNC^+	$C_3H_3^+$	CH_3CN	C_3H_2	CO_2	CO_2^+	HCO_2^+	HC_3N		
Grain mantle species															
H	C	CO	H_2CO	Si	C_2	O_2	CH	OH	NO	CH_2	H_2O	CO_2	CH_3	CH_4	HNC
C_2H_2	HC_3N	N_2	CN	NH	HCN	C_2H	NH_3	CH_3CN	CH_3OH	NH_2	N	O	H_2	HCO	C_3H_2
CH_2OH															

- 78 gas phase species + 33 grain ice mantle species (H, He, C, N, O, Si), 1553 reactions from UMIST
- Embedded cores ($A_v \geq 3$ mag), CO self-shielding
- Grains: MRN distribution of grains, negatively charged, fixed abundance, Grain Processes: freezeout, thermal desorption, cosmic-ray heating, & surface reactions
- Non-Equilibrium chemistry

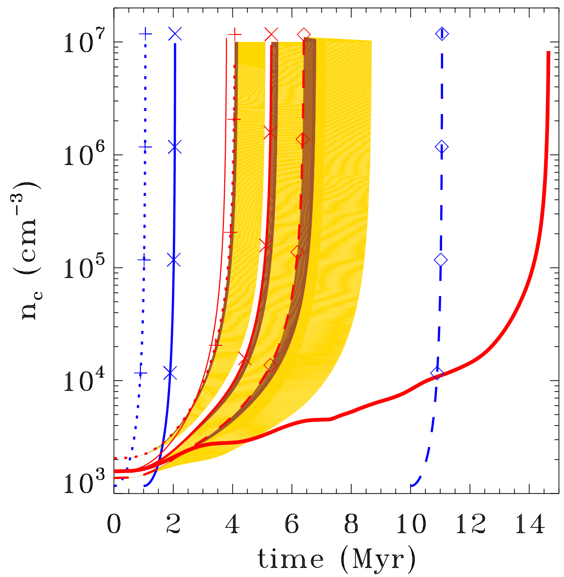
First Step: Collection of Models

Axially Symmetric 2fluid MHD



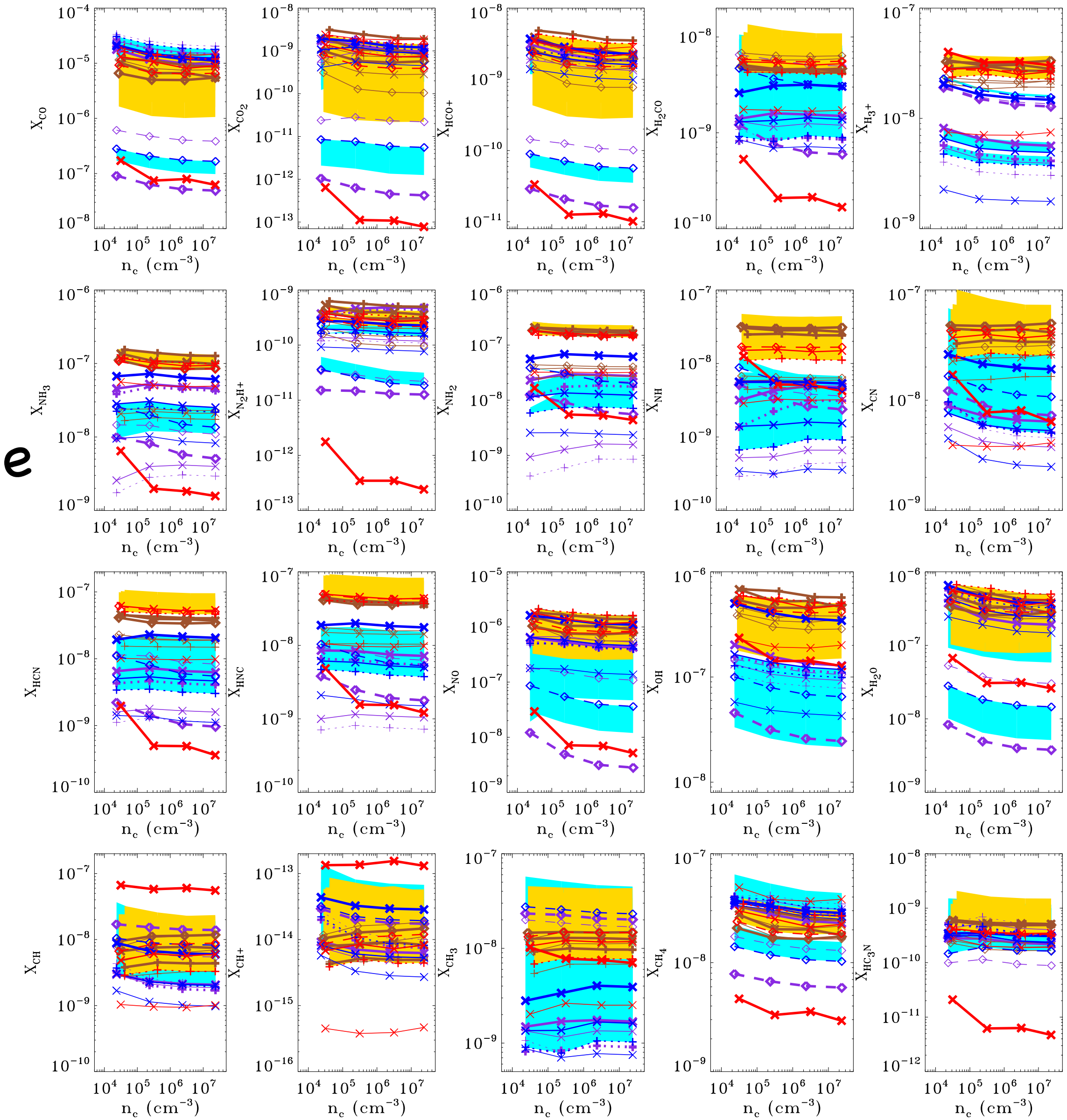
Spherical Hydro

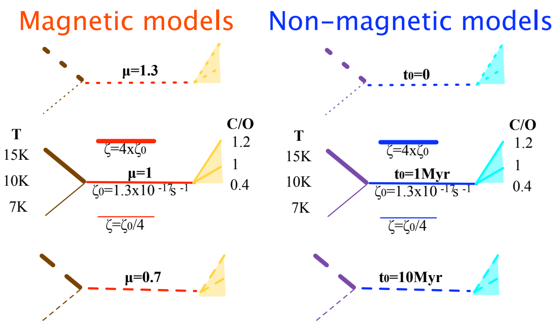
- ✓ Evolution Time:
- • M/Φ in magnetic models
- • Initial support phase in non-magnetic models
- ✓ CR ionization rate
- ✓ Elemental C/O
- ✓ Temperature



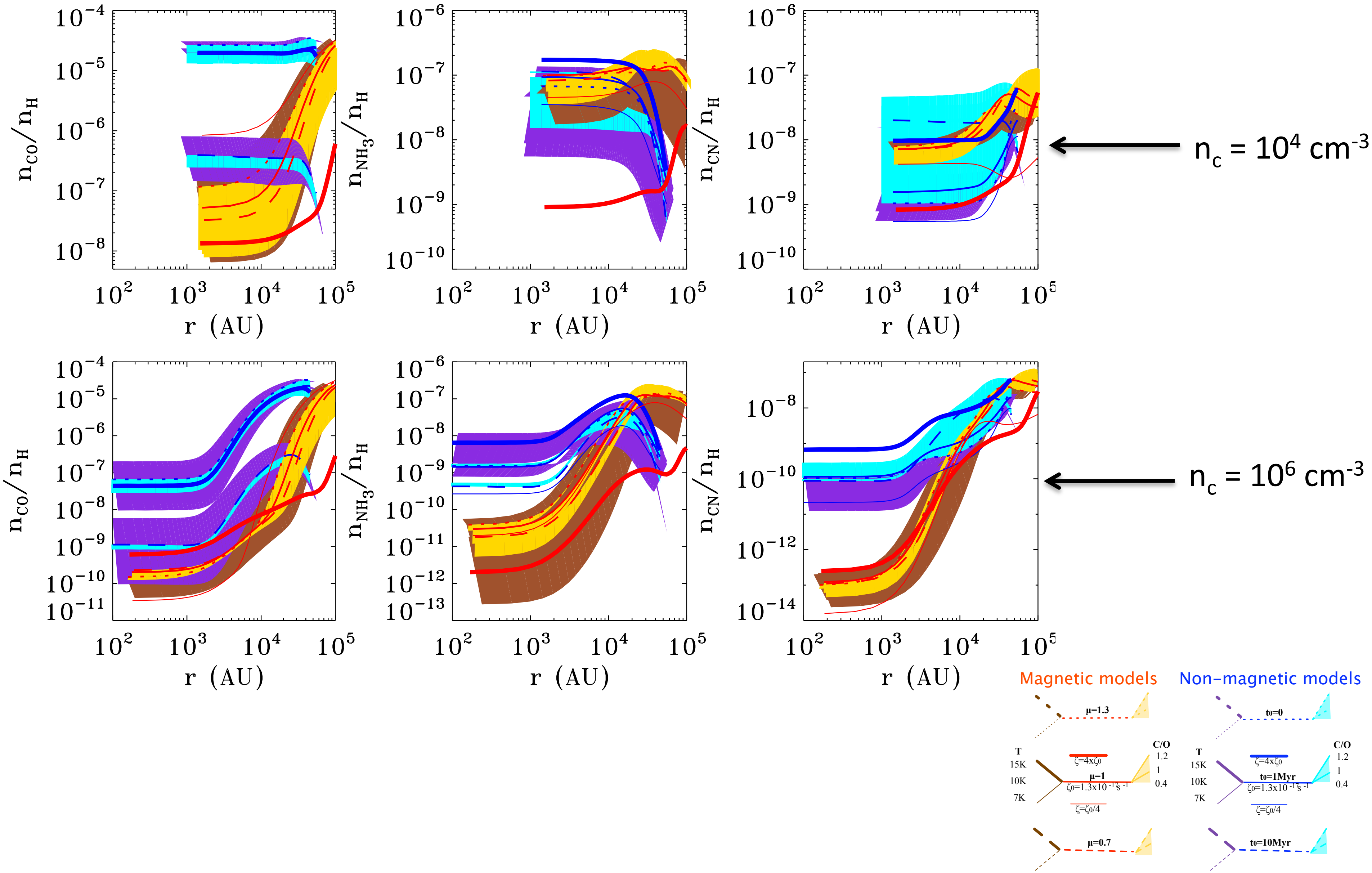
Degeneracies in Unresolved Cores

- Large chemical differentiation
- Large degeneracies
- Weak evolution: Average abundances dominated by the lower density outer parts





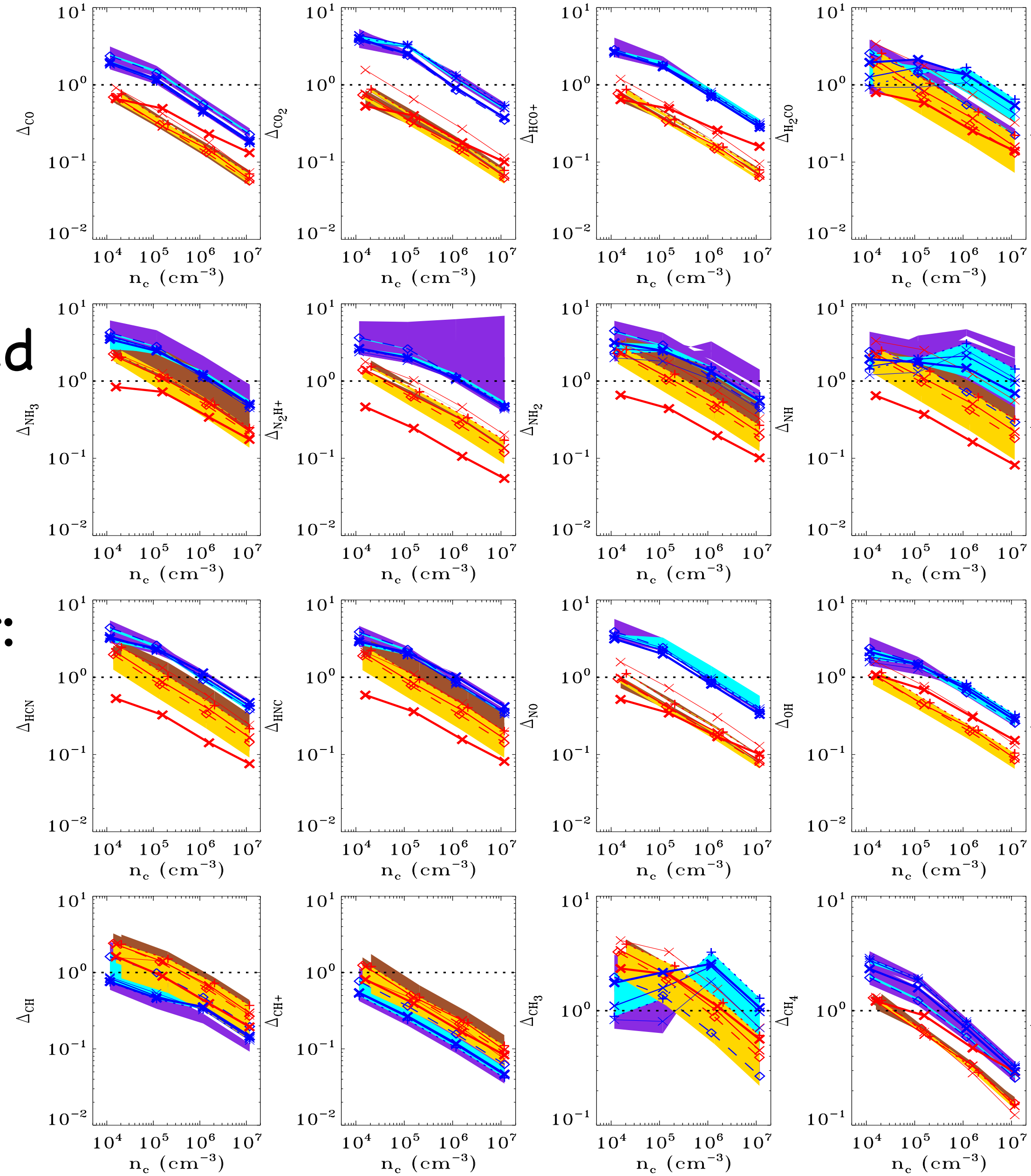
Central Parts Evolve

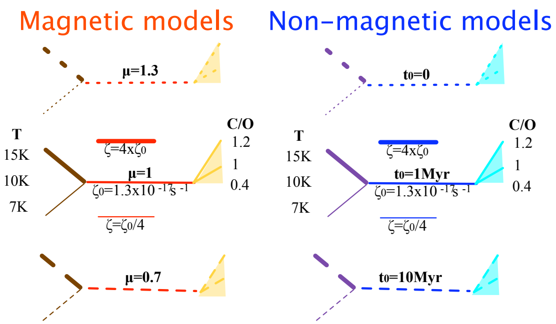


Depletion Measure

$$\Delta = \frac{\chi_{r=0.3R}}{\chi_{tot}}$$

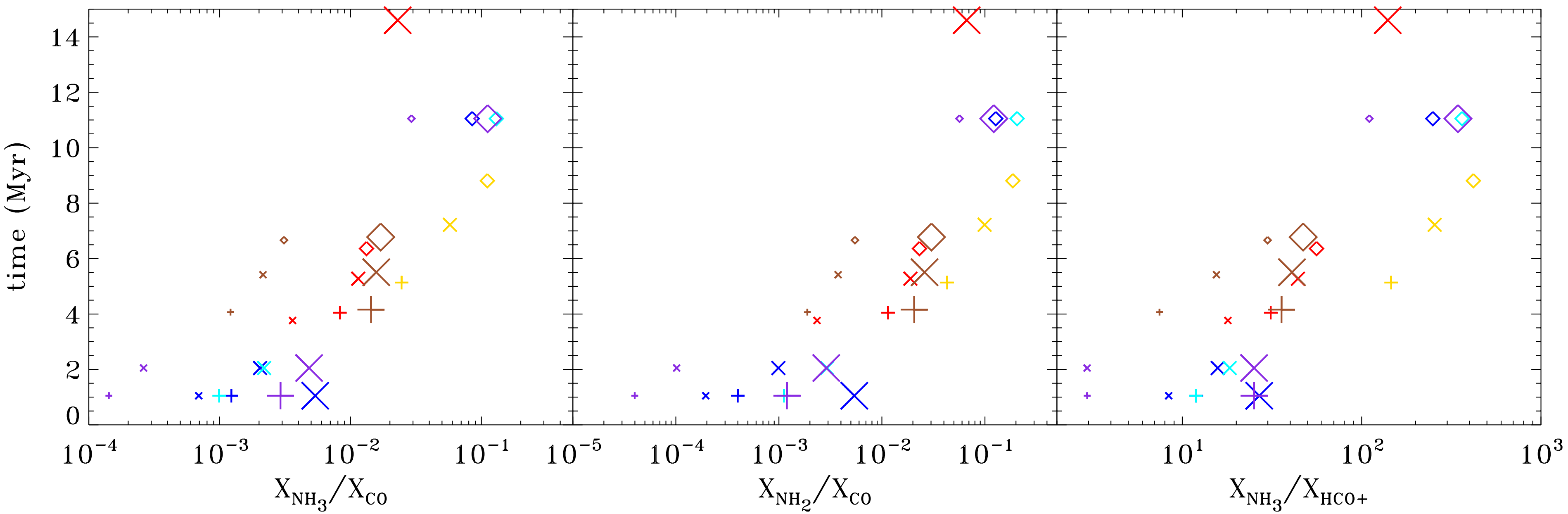
- Fast – Slow contraction models clearly separated for: CO, HCO^+, CO_2, NO, N_2H^+
- Model degeneracies for: CN, HCN, NH_3, H_2CO, CH

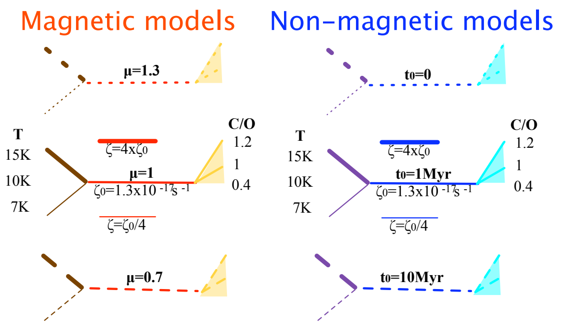




Interesting Abundance Ratios

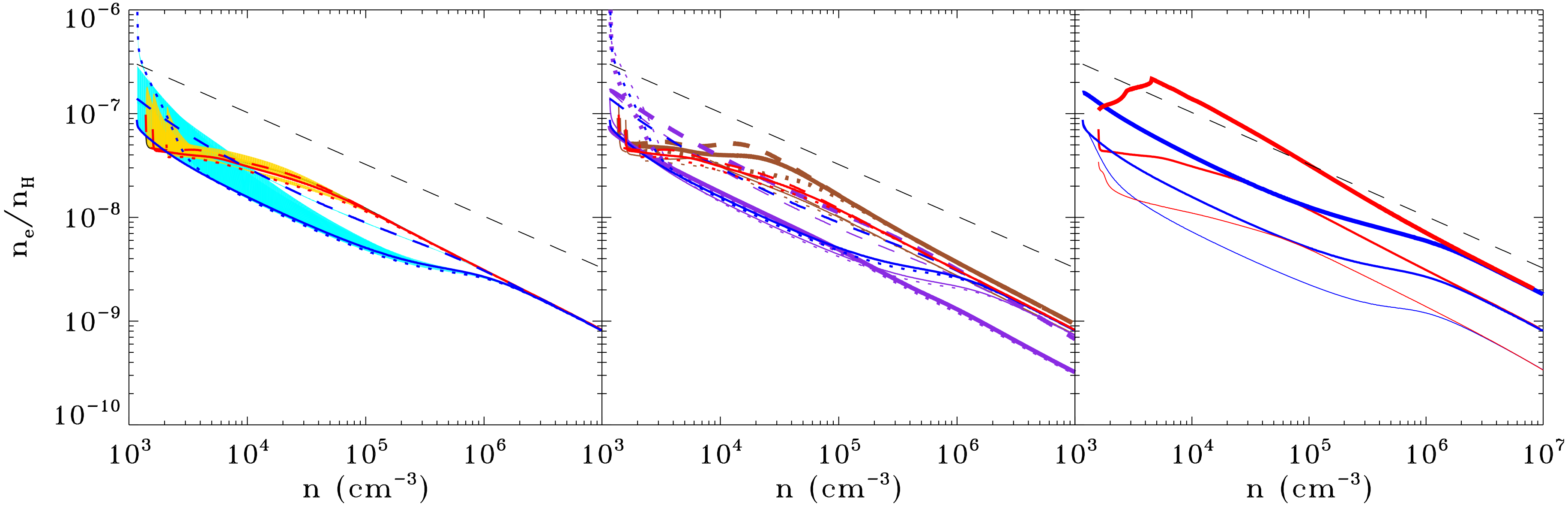
Chemical Chronometers?





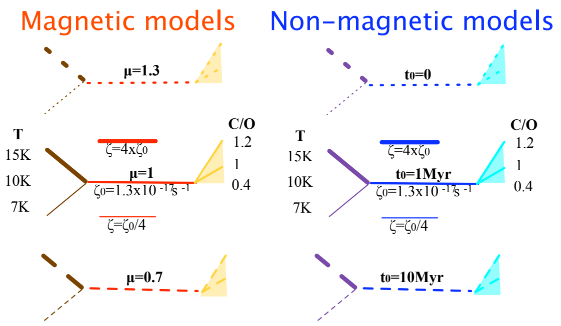
Tassis, Willacy, Yorke, & Turner 2012, ApJ, 753, 29

Degree of Ionization



$$\chi_e = 3 \times 10^{-8} \left(\frac{n}{10^5 cm^{-3}} \right)^{-0.5}$$

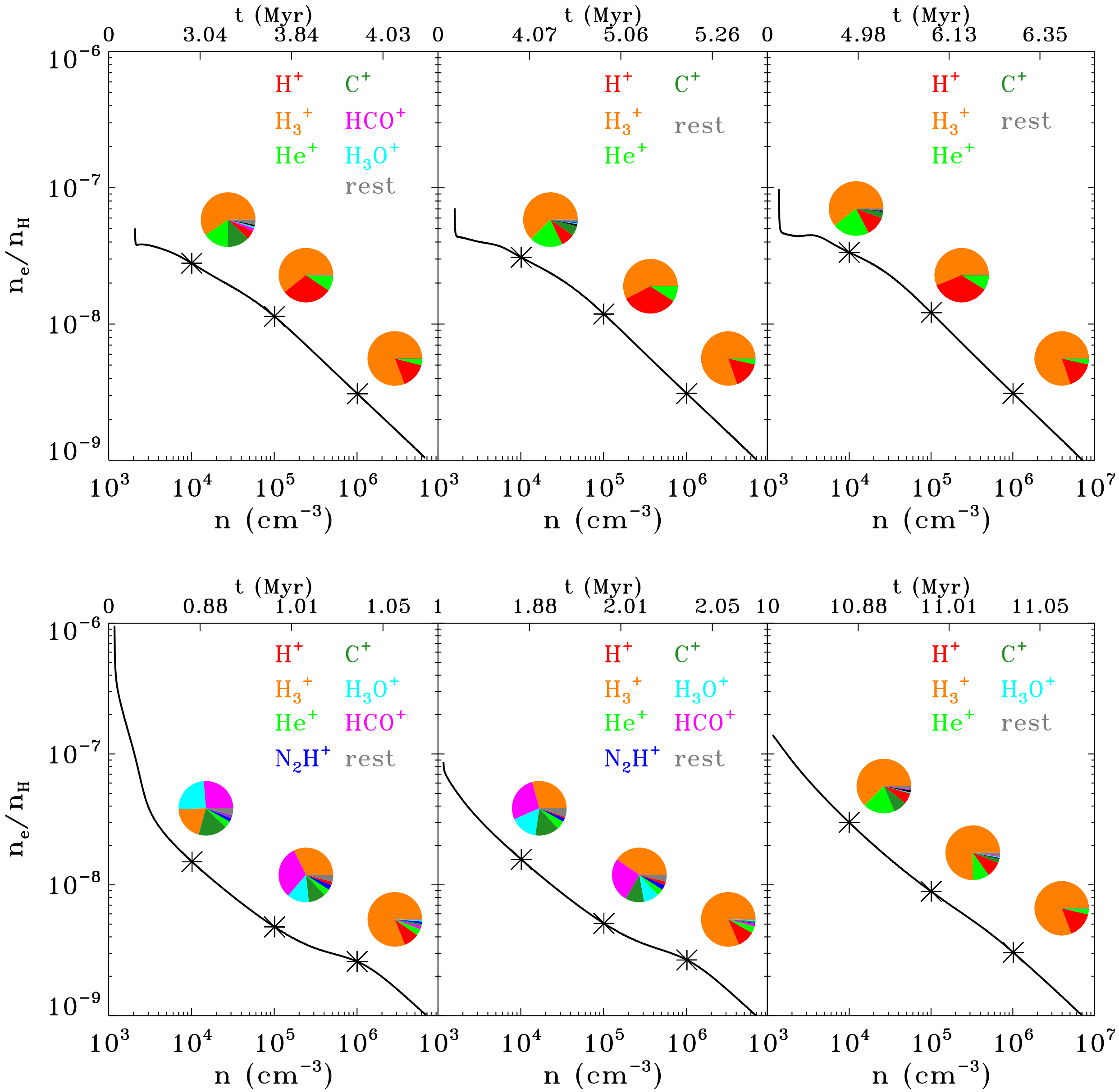
Elmegreen 1979, Nakano 1979

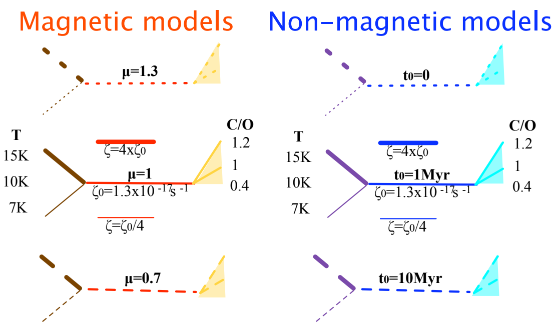


$$\chi_e \sim \left(\zeta^{1/2} T^{1/2} \right) n^{-0.6}$$

Tassis, Willacy, Yorke, & Turner 2012, ApJ, 754, 6

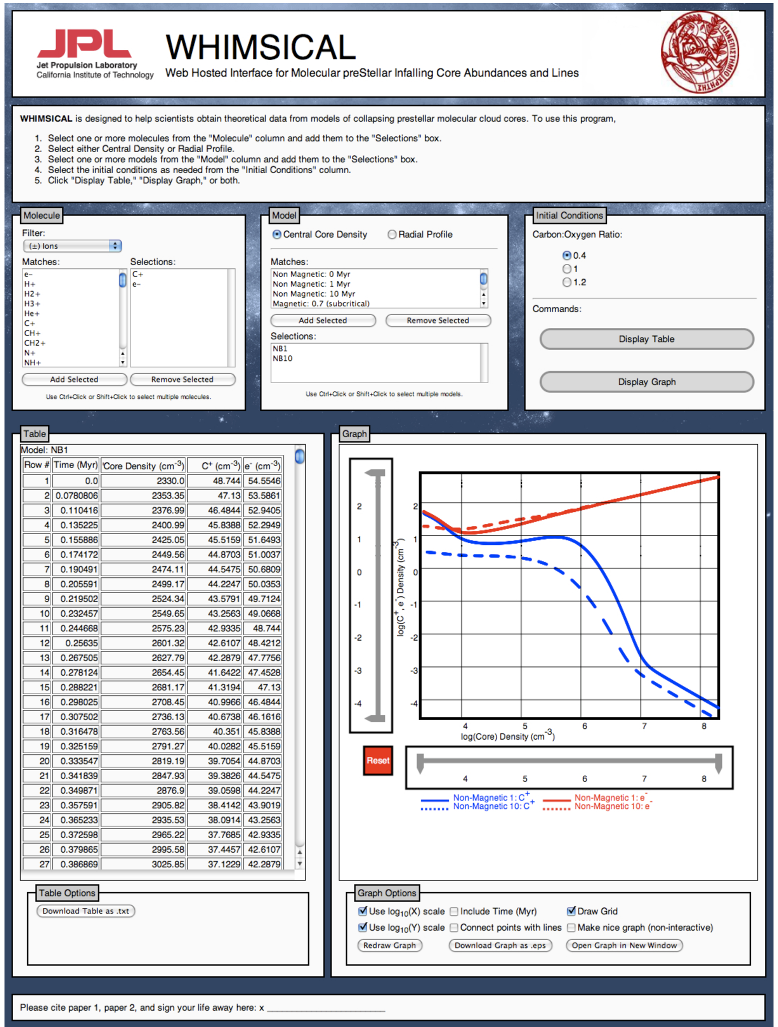
Dominant Ion?





The future

- Expand chemistry to include deuterated molecules, 10x reactions
- Advance to higher dimensionality models
- Predictions for line profiles (radiative transfer)
- Make results available online @ U. of Crete servers



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PEOPLE

MARIE CURIE ACTIONS

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Jet Propulsion Laboratory
California Institute of Technolc

NASA