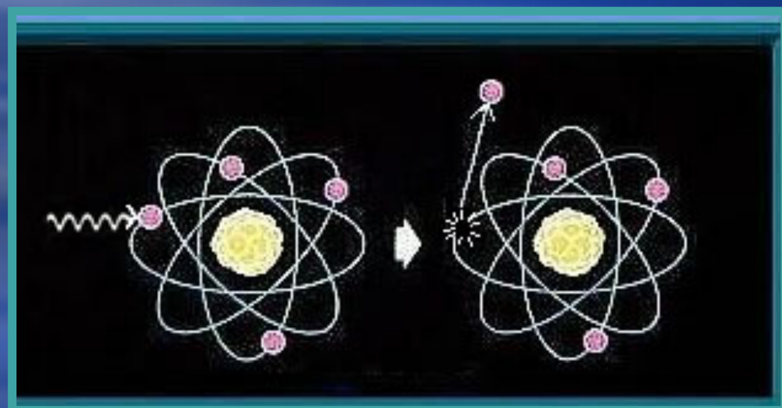
Ionization Processes in Star Formation and Young Stellar Objects

Fred C Adams – Univ. Michigan

Molecules and Dust as Fuel to Star Formation
KITP -- 23 June 2016



Ionization Effects

- Coupling of magnetic field
- Chemistry

- Magnetic braking in protostellar phase
- Location of dead zones for MRI
- Location of ice-lines (for varying species)
- Chemical make-up vs radial position
- Affects both star and planet formation

Ionization Sources

- Cosmic rays (CRs)
- Short-lived radioactive nuclei (SLRs)
- X-ray, EUV, FUV radiation from star
- X-ray, EUV, FUV radiation from cluster
- Collisions (in dense regions)

**FUV can ionize molecules (not hydrogen)

Ionization: State of the Art

- Cosmic rays (CRs)
  use canonical ISM rate $\varsigma \approx 10^{-17}\,\mathrm{sec}^{-1}$
- Short-lived radioactive nuclei (SLRs)
  use values for early solar nebula (or none)
- X-ray, EUV, FUV radiation from star
  included to good approximation
- X-ray, EUV, FUV radiation from cluster
  generally NOT included

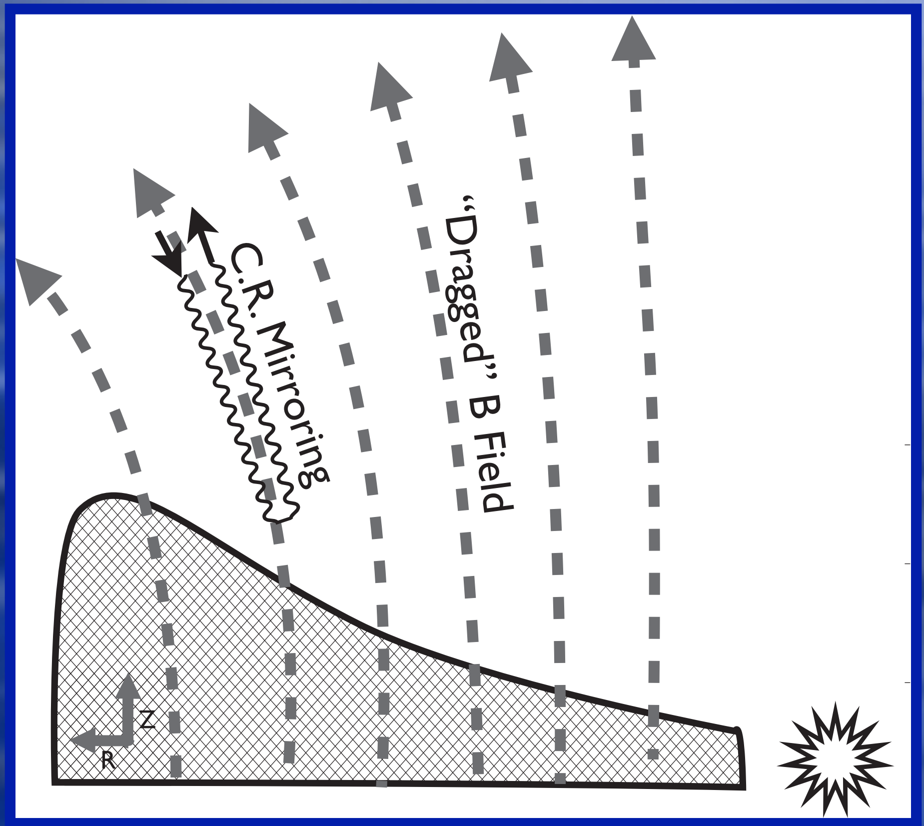
The Bottom Line

Ionization rates vary significantly from place to place and system to system

OUTLINE (complications)

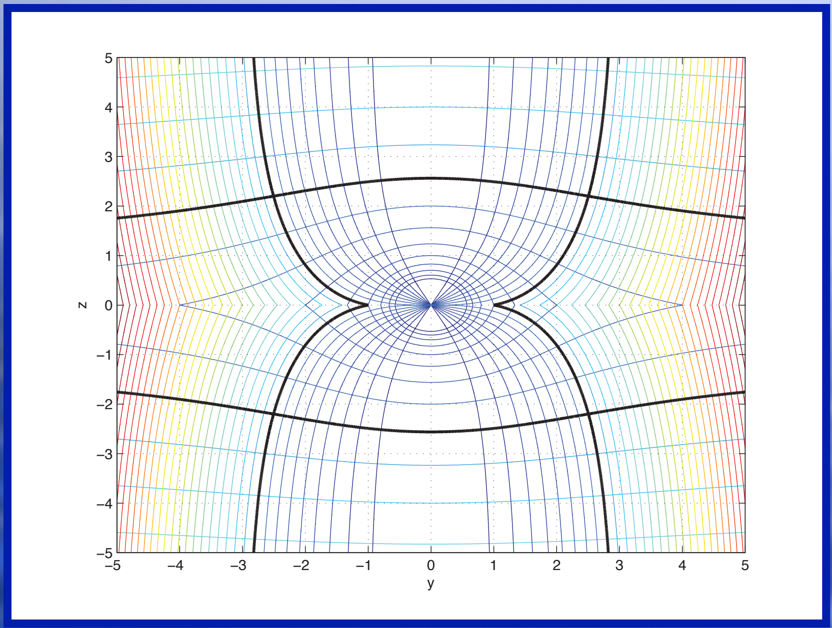
- CR magnetic mirroring w. turbulence
- CR enhancement in molecular clouds
- Enrichment of short-lived radionuclides
- Radiation backgrounds from clusters
- CR suppression by T-Tauriospheres
- Observational signatures and physical implications of varying ionization rates

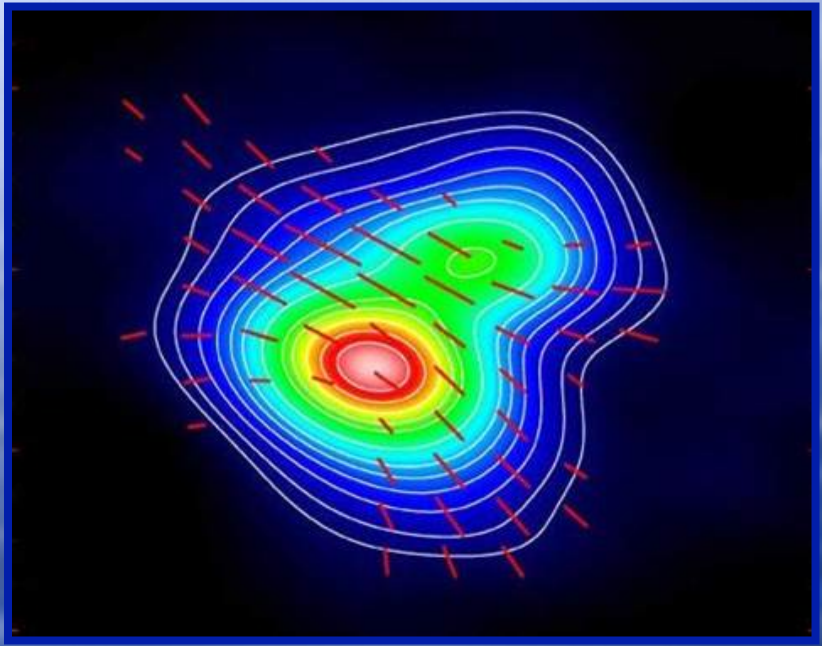
Effects of Turbulence on Cosmic Ray Propagation in Young Stellar Objects



Fred Adams
and
Marco Fatuzzo

Hour-Glass Field Shape

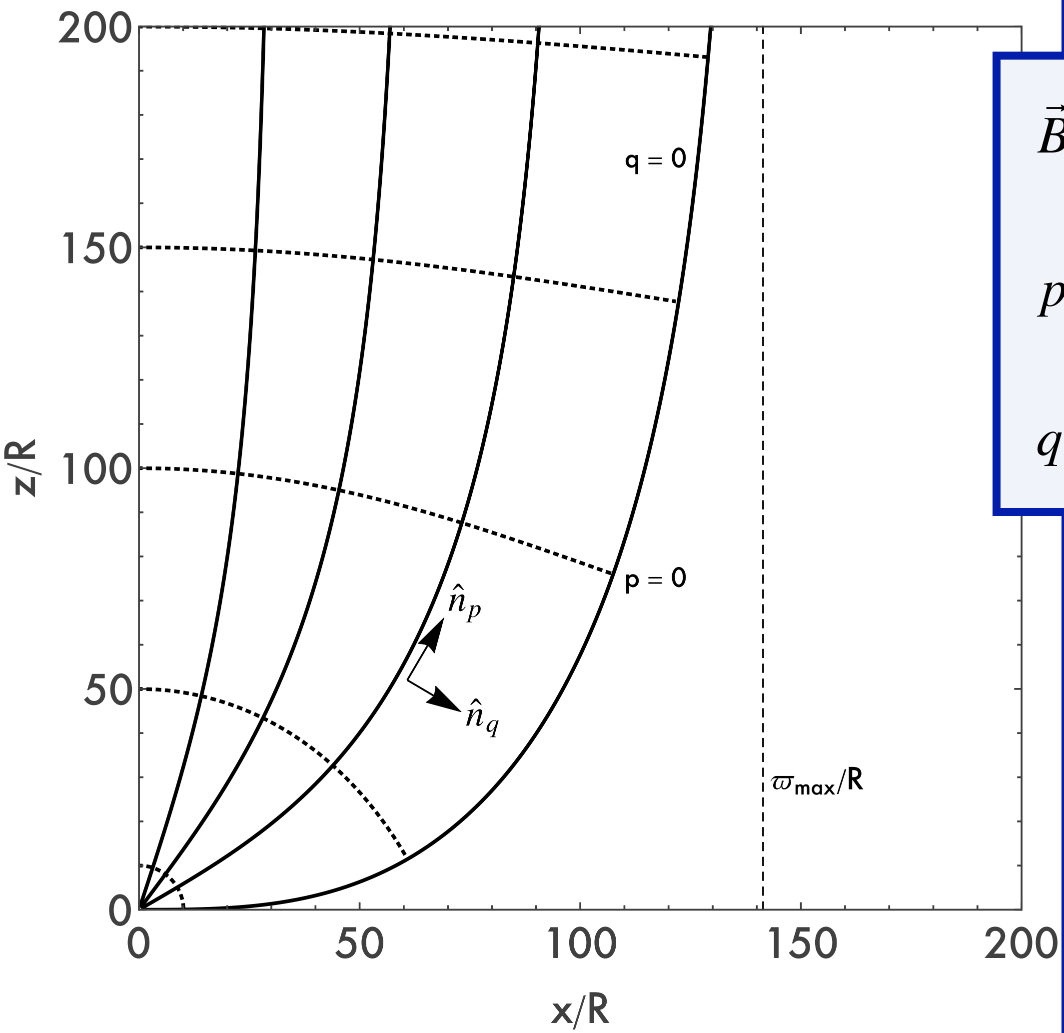




M. Warnez and
F. Adams (U. Michigan)

J. Girart (CSIC-IEEC),
R. Rao (ASIAA) and
D. Marrone (CfA)

Coordinate System



$$\vec{B}_0 = B_\infty \left[\frac{\varepsilon}{\xi^2} \hat{r} + \hat{z} \right] \quad \textit{where} \quad \xi = \frac{r}{R_d}$$

$$p = \xi \cos\theta - \frac{\varepsilon}{\xi}$$

$$q = \frac{1}{2} \xi^2 \sin^2\theta - \varepsilon \cos\theta$$

$$h_p = \left[1 + 2\cos\theta \frac{\varepsilon}{\xi^2} + \frac{\varepsilon^2}{\xi^4} \right]^{-1/2}$$

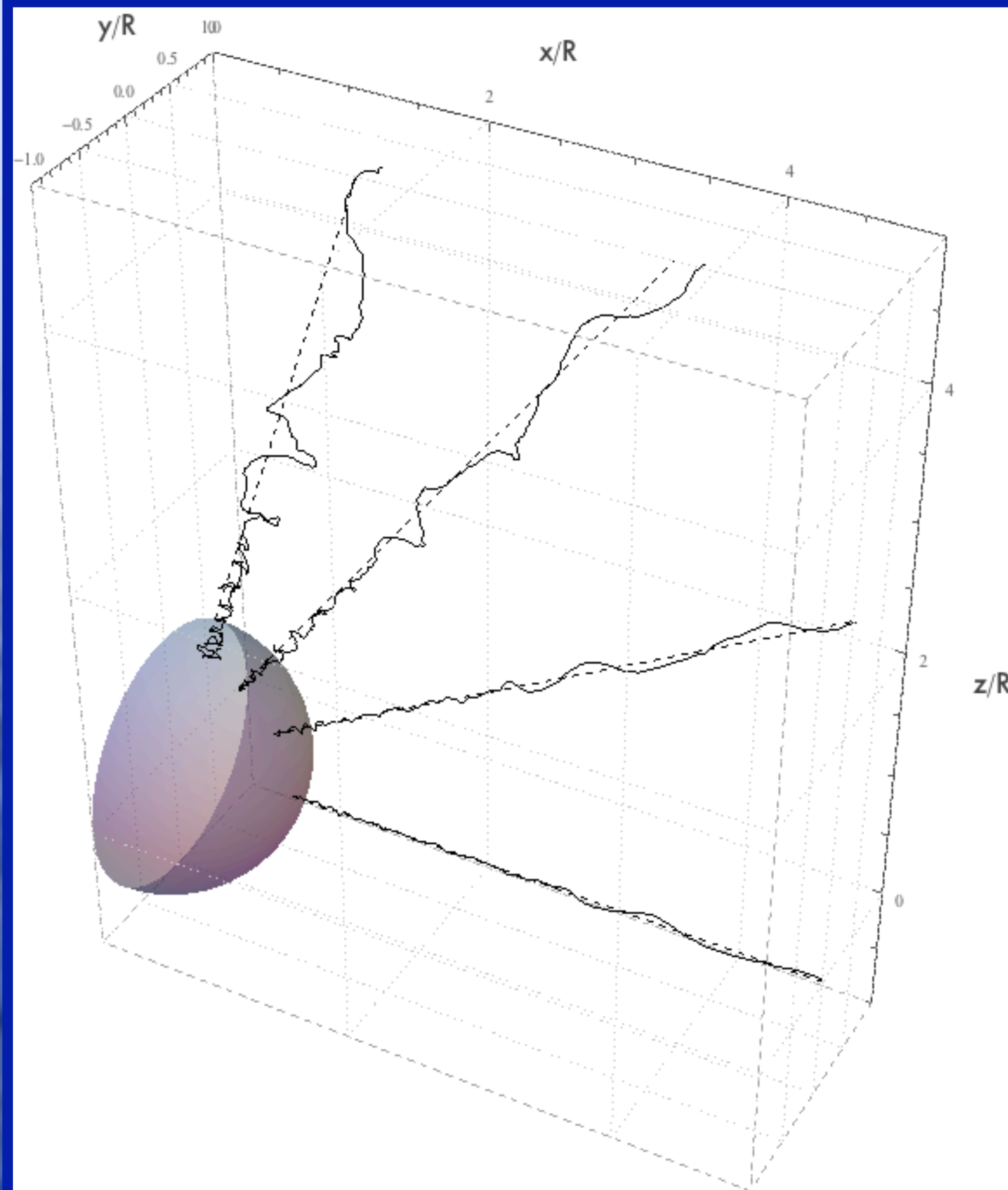
$$h_q = \frac{1}{\xi \sin\theta} \left[1 + 2\cos\theta \frac{\varepsilon}{\xi^2} + \frac{\varepsilon^2}{\xi^4} \right]^{-1/2}$$

$$h_\phi = \xi \sin\theta$$

Four different field lines with varying levels of turbulence

$$\eta = 1, 3, 10, 30$$

$$\eta \equiv \frac{\langle \delta B^2 \rangle}{B_0^2}$$

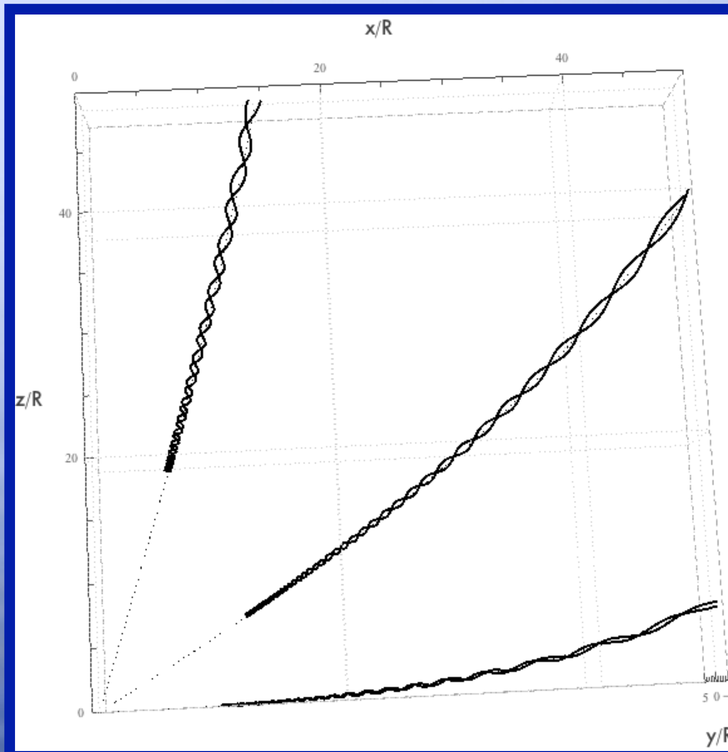


Three Particle Trajectories (w. different initial angles)

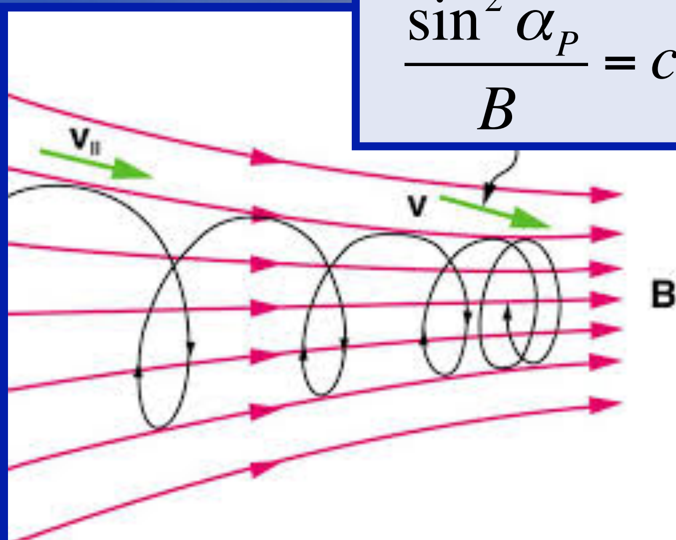
$\cos\alpha_p = 0.99 \ \ (left)$

$\cos\alpha_p = 0.99 \ \ (center)$

$\cos\alpha_p = 0.995 \ \ (right)$

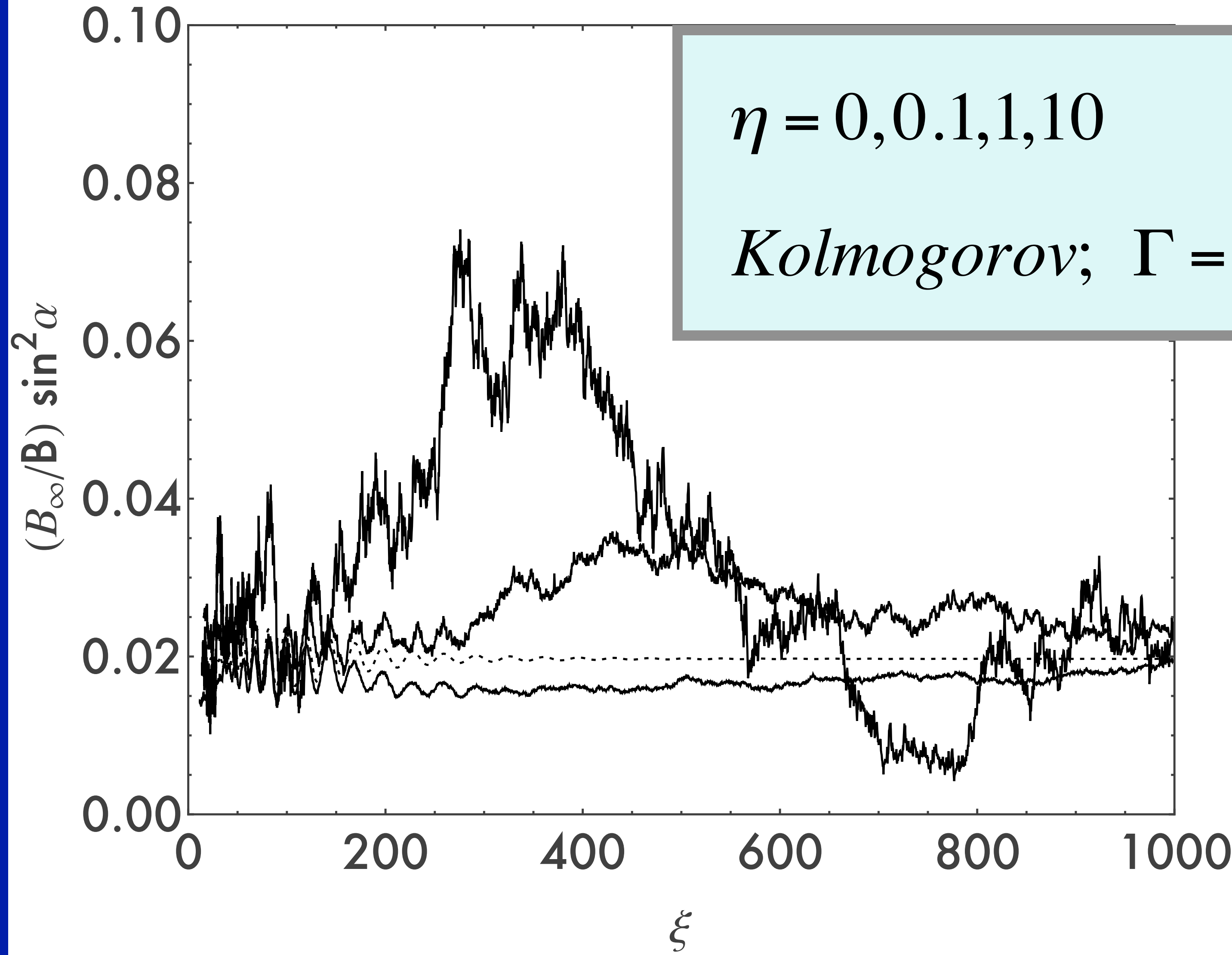


$$\frac{\sin^2\alpha_P}{B} = const$$



Mirroring and Funneling effects tend to cancel out

Effect of Turbulence

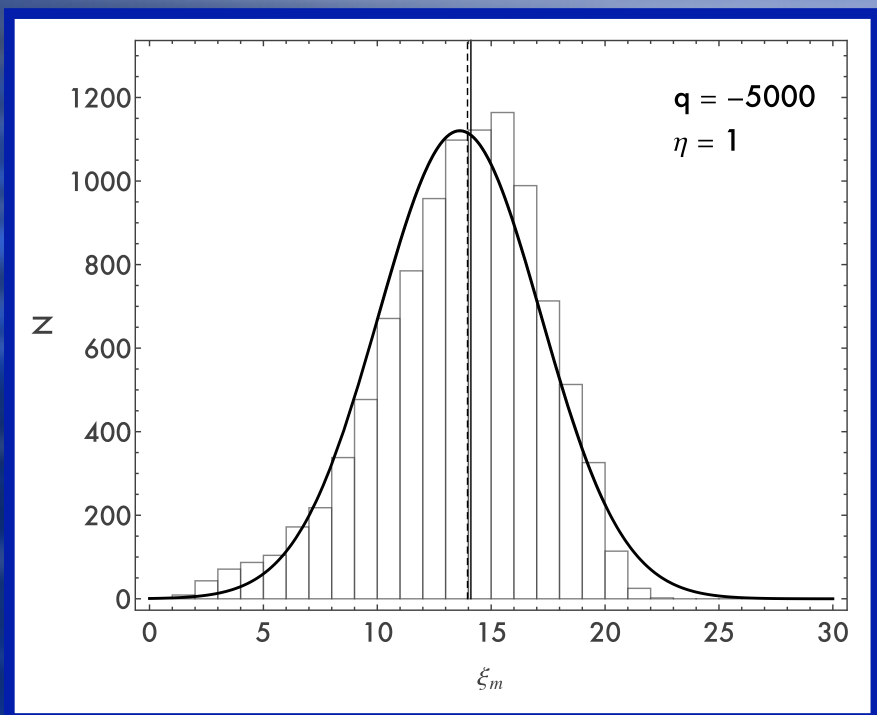


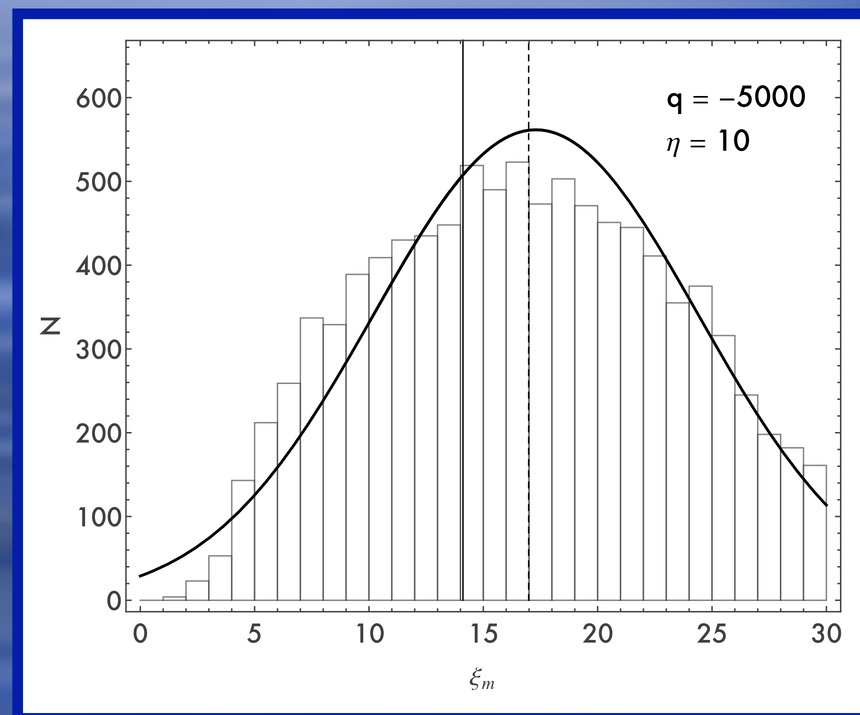
$\eta = 0, 0.1, 1, 10$

Kolmogorov; $\Gamma = 5/3$

Distributions of Mirror Radii

$$\gamma = 100, \quad \cos\alpha_P = 0.99 = const, \quad \eta = 1 \;\; and \;\; 10$$





CR Flux Enhancement from Supernovae in Molecular Clouds

Marco Fatuzzo, Fred Adams, & Fulvio Melia

Cosmic Ray Flux Variations

- [Ionization rate controls diffusion rate]
- [Cosmic ray flux controls ionization rate]
- Supernovae produce the cosmic rays
- SN often associated w. molecular clouds
- Cosmic rays injected into the clouds
- Molecular clouds have magnetic fields
- Cosmic rays must diffuse to get out

Cosmic ray flux can be enhanced in clouds compared to standard galactic value

Magnitude of the Effect:

- Cosmic Ray Energy Density can be enhanced by factor of 1000 (at most)
- Enhancement can be sustained over a Time Scale of few Myr
- Time Scale for Ambipolar Diffusion is increased by factor of 30
- Cosmic Ray Flux, Ambipolar Diffusion Rate, and Ionization rates will all vary with location and with time

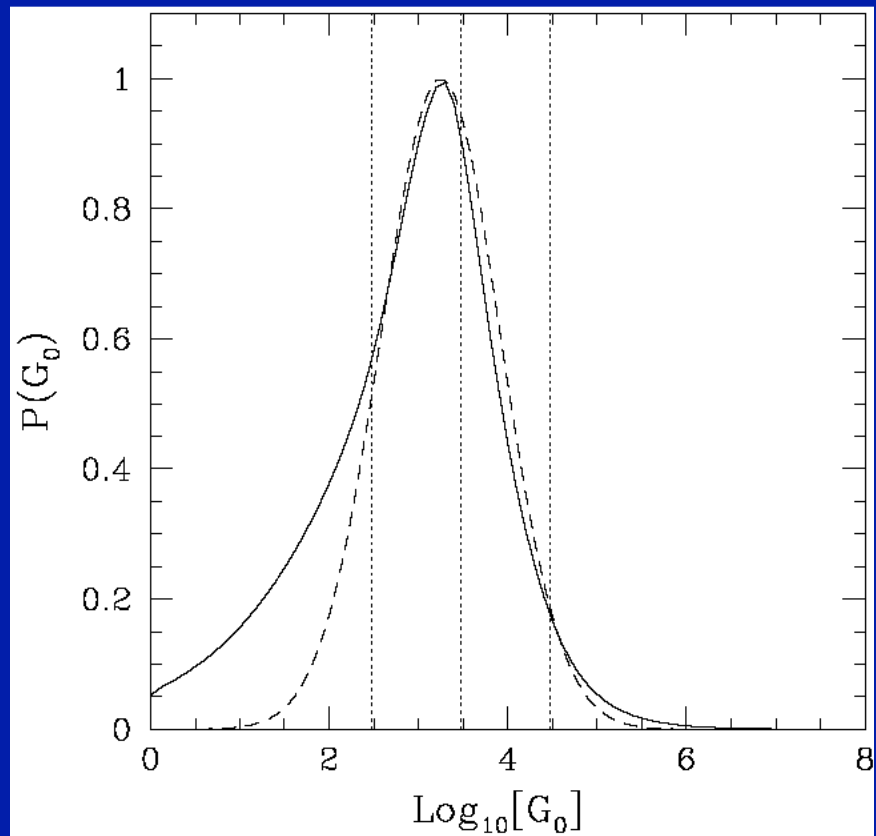
Fatuzzo, Adams, Melia, 2006, ApJ, 643, L49

Radiation Fields Provided by Background Cluster Environments: UV & X-ray

Composite Distribution of FUV Flux

FUV Flux depends on:
- Cluster FUV luminosity
- Location of disk within cluster

Assume:
- FUV point source at center of cluster
- Stellar density *ρ ~ 1/r*



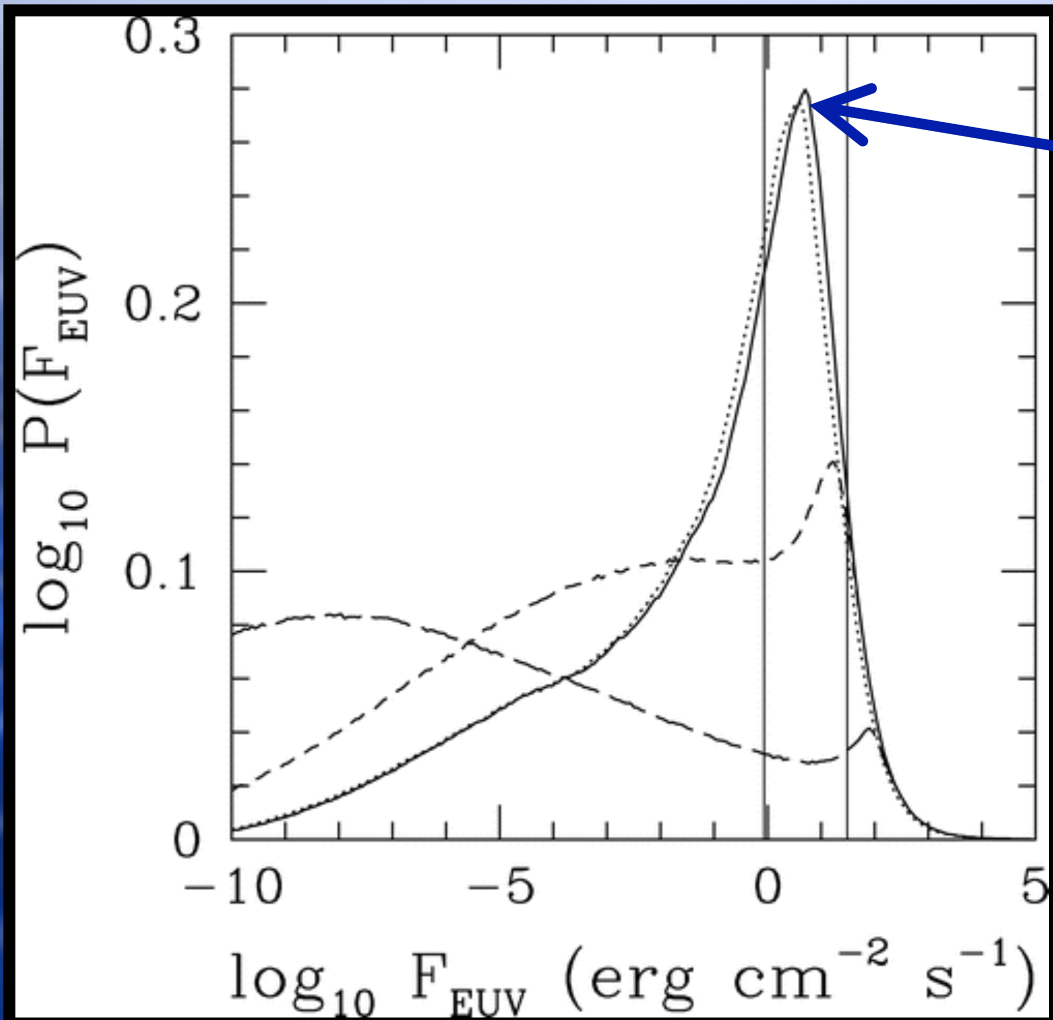
G_0 Distribution

Median	900
Peak	1800
Mean	16,500

G_0 = 1 corresponds to FUV flux 1.6 x 10^{-3} erg s^{-1} cm^{-2}

Adams et al. 2006, ApJ

Composite Distribution of EUV Flux



Peak value:

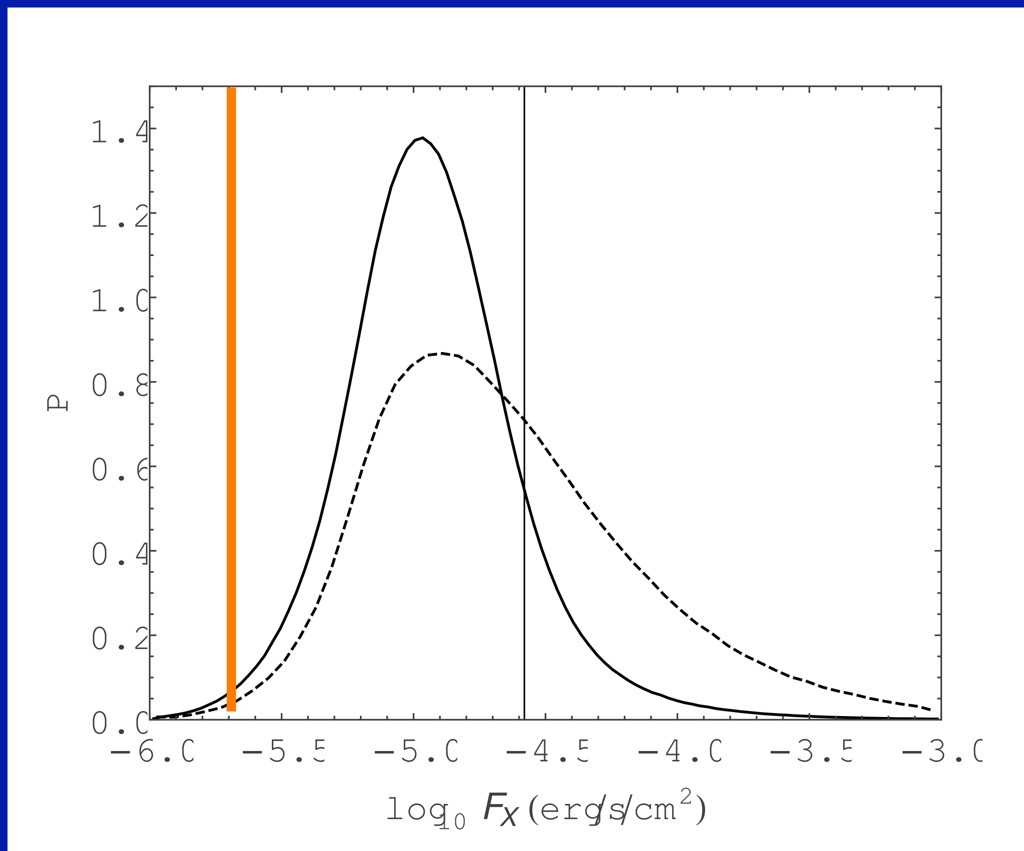
$$F_{EUV} \approx 10^{12}\ \gamma\ s^{-1} cm^{-2}$$

Using Lada/Lada cluster sample, standard IMF.

Peak value is comparable to TW-Hya flux @30AU with NO dilution;
If dilution included, Bkgrd >> stellar

Fatuzzo & Adams, 2008, ApJ

Composite Distribution of X-ray Flux



With NO dilution,
Stellar X-ray flux
Fx = 0.04 (cgs)
dominates bkgrd
If dilution included,
Bkgrd >> stellar
(@30AU)

$N_{max} = 3000$

$\rho \propto r^{-2}$ $(dashed)$

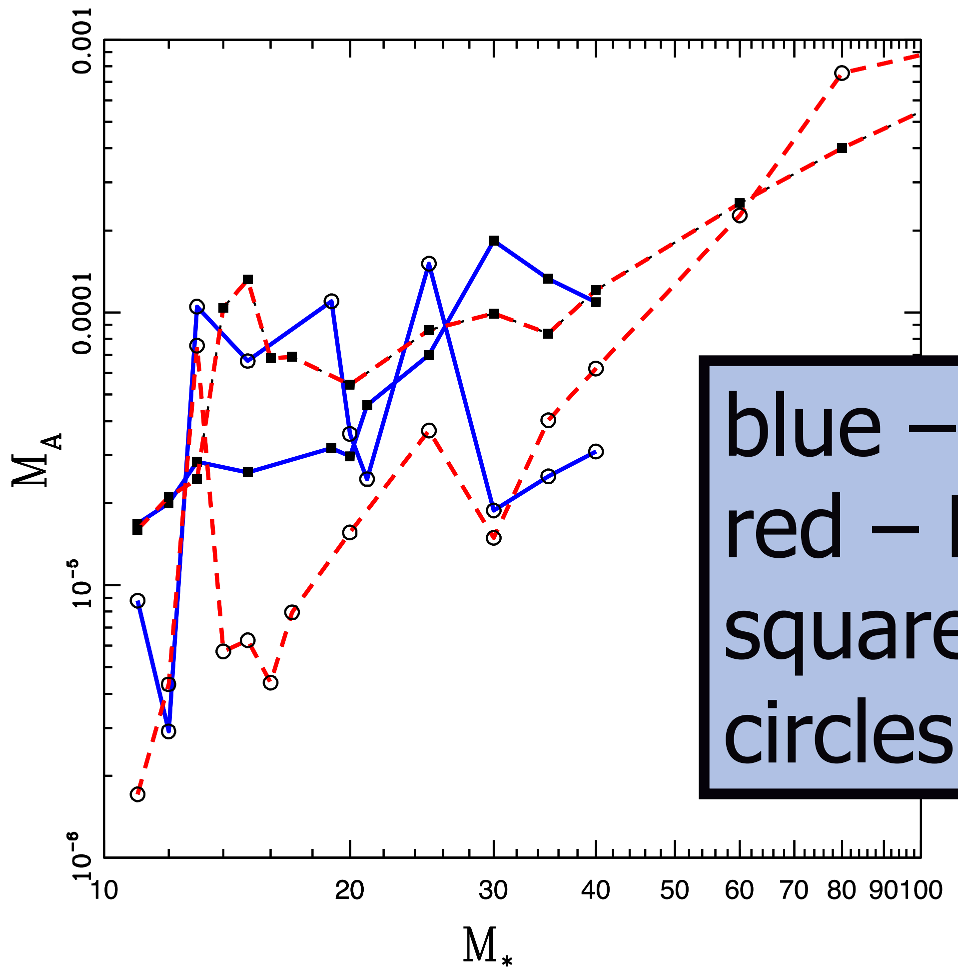
$\rho \propto r^{-1}$ $(solid)$

Adams et al. 2012, PASP

Distributions of SLRs Provided by Supernovae in Young Embedded Clusters

Fred Adams,
Marco Fatuzzo,
& Lisa Holden

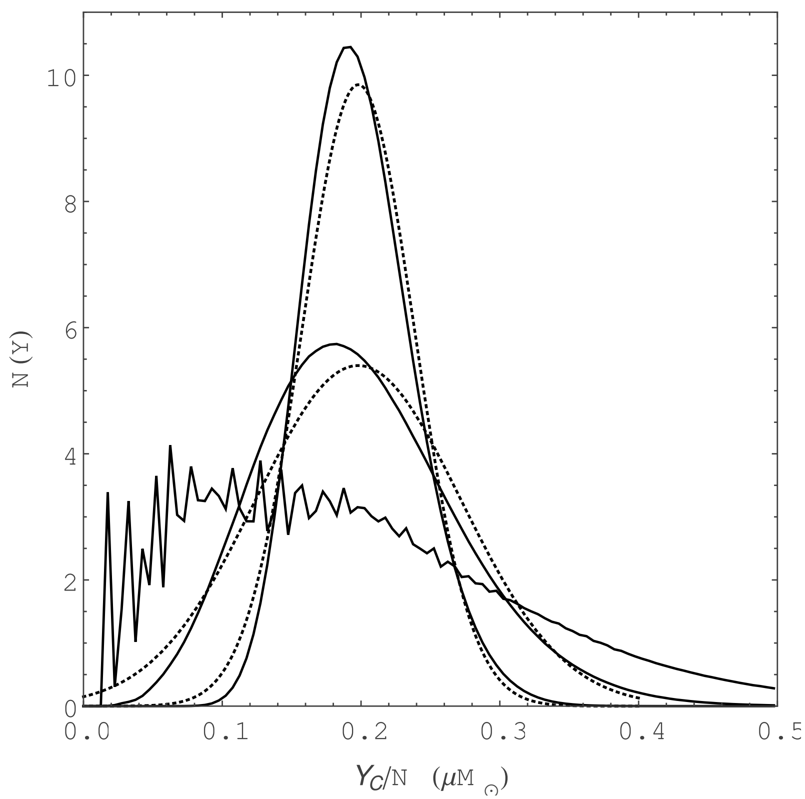
Nuclear Yields from Supernovae

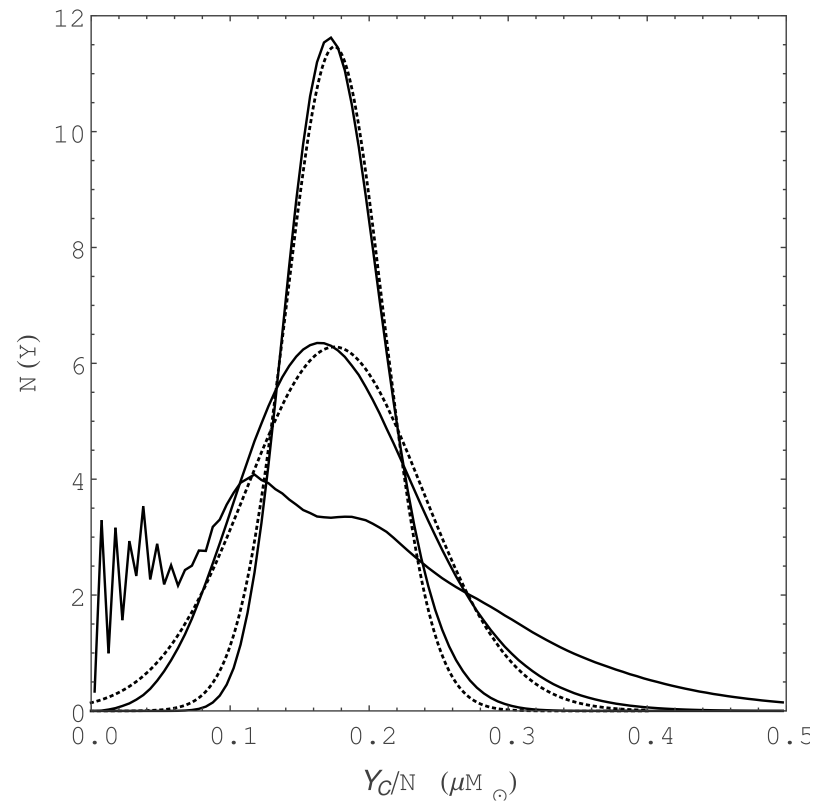


blue – Woosley+Weaver
red – Limongi+Chieffi
squares – 26Al
circles – 60Fe

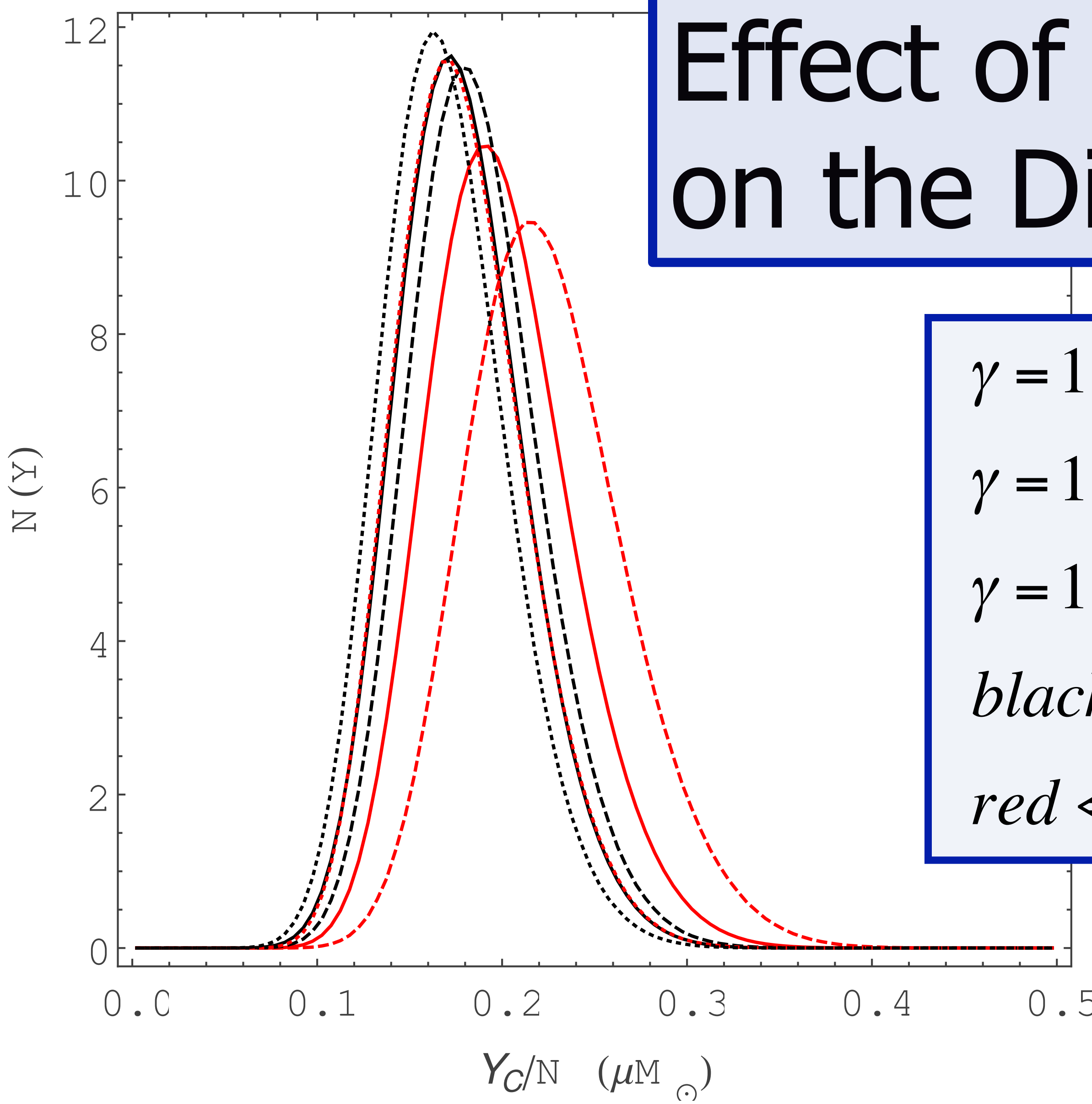
Nuclear Yields per Cluster: Distributions for 26Al and 60 Fe

$N = 1000,\ 3000,\ and\ 10{,}000$





Effect of Stellar IMF on the Distributions



$\gamma = 1.75$ (*dotted*)

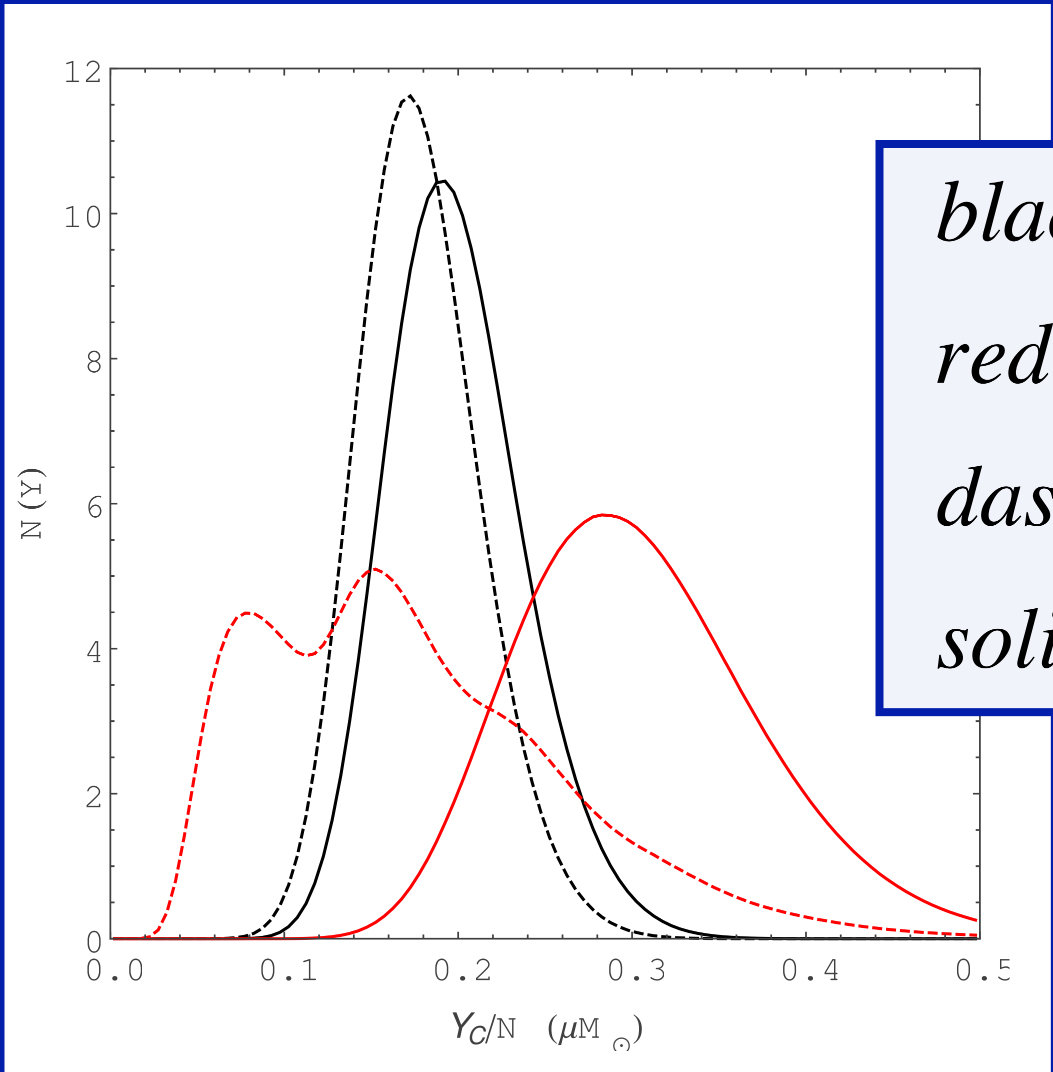
$\gamma = 1.50$ (*solid*)

$\gamma = 1.25$ (*dashed*)

black $\Leftrightarrow$ ^{60}Fe

red $\Leftrightarrow$ ^{26}Al

Comparison of WW and LC Models



black $\Leftrightarrow$ *WW yields*

red $\Leftrightarrow$ *LC yields*

dashed $\Leftrightarrow$ ^{60}Fe

solid $\Leftrightarrow$ ^{26}Al

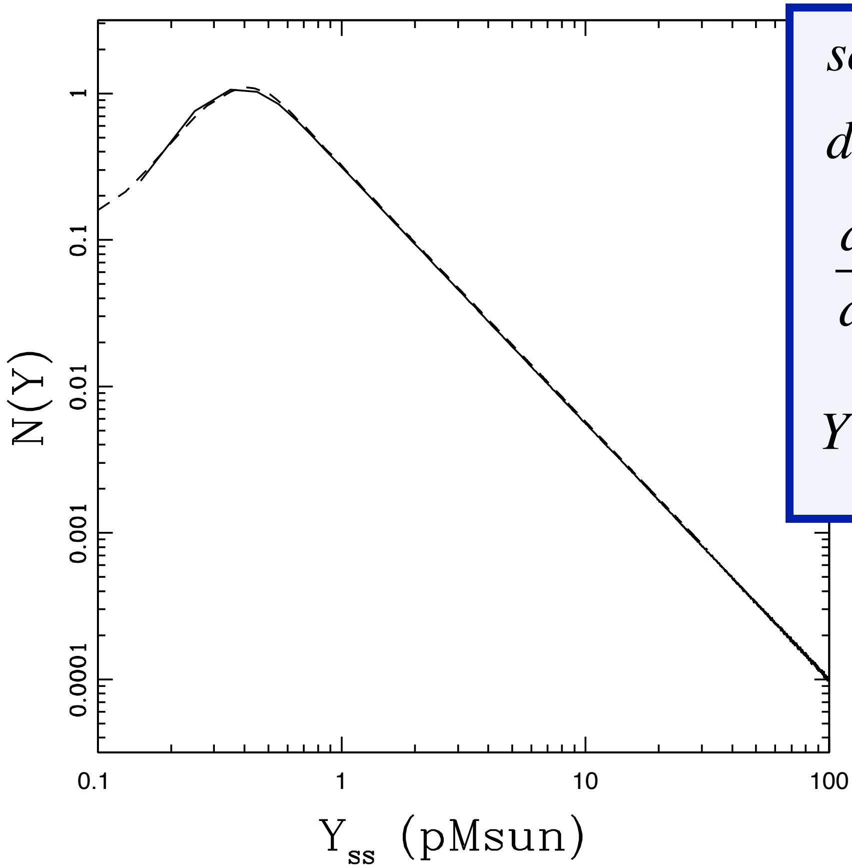
Analytic Form for Distribution of Nuclear Mass Delivered to Systems

$$\frac{dP}{dY} = (3-p)B_\lambda \int_0^1 d\xi\ \xi^{4-p} \exp\left[-\frac{(Y\xi^2-1)^2}{2\lambda^2}\right]$$

$$Y = M_0 X \quad \textit{where} \quad M_0 = \langle Y \rangle_C \frac{\pi r_d^2}{4\pi R_C^2}$$

$$Y >> 1 \ \Rightarrow \ \frac{dP}{dY} = C\ Y^{-(5-p)/2} \quad (power-law!)$$

26Al Delivered to Solar Systems



solid ⇔ *numerical sampling*

dashed ⇔ *analytic form*

$$\frac{dP}{dY} = (3-p)B_{\lambda}\int_0^1 d\xi\ \xi^{4-p}\exp\left[-\frac{(Y\xi^2-1)^2}{2\lambda^2}\right]$$

$$Y = M_0 X \quad where \quad M_0 = \langle Y\rangle_C \frac{\pi r_d^2}{4\pi R_C^2}$$

our solar system

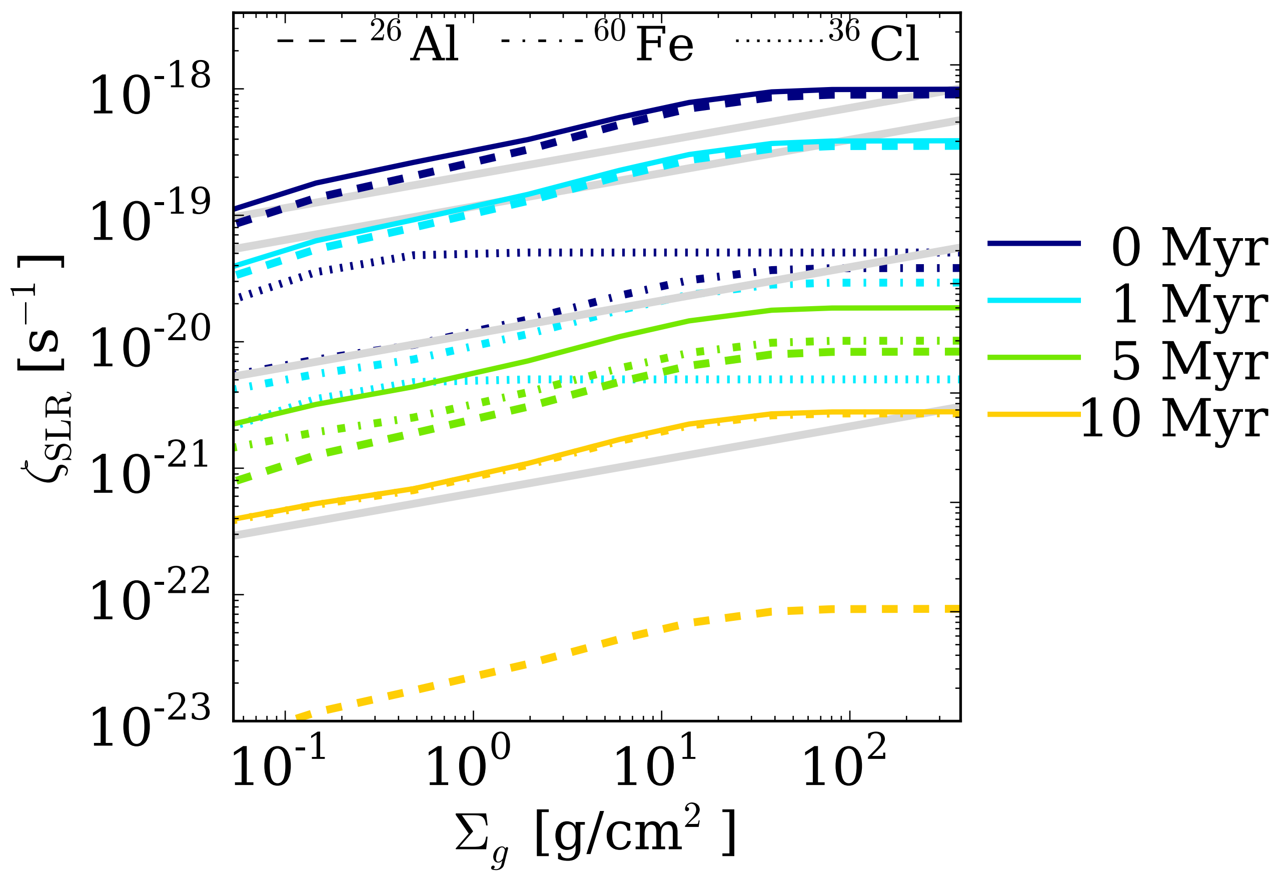
$$\Rightarrow Y = 100-200$$

$$P(Y>100)\approx 0.02 \quad (2\%)$$

Mass Scale Summary

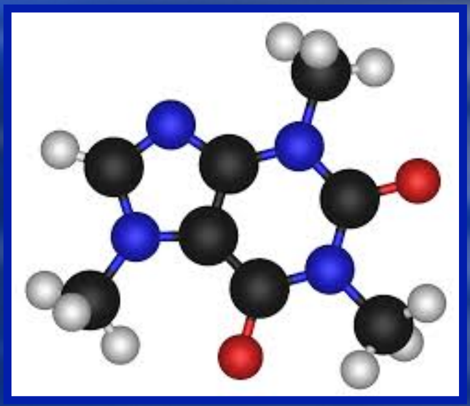
- Yields per supernova for important isotopes: 10 -- 100 microsun
- Yields per star (averaged over stellar IMF) : fraction of a microsun
- Yields per cluster (for N = thouands): millisuns
- Yields delivered to solar system disks fall in the range 1 – 100 picosuns
- Our Solar System received 100 picosuns

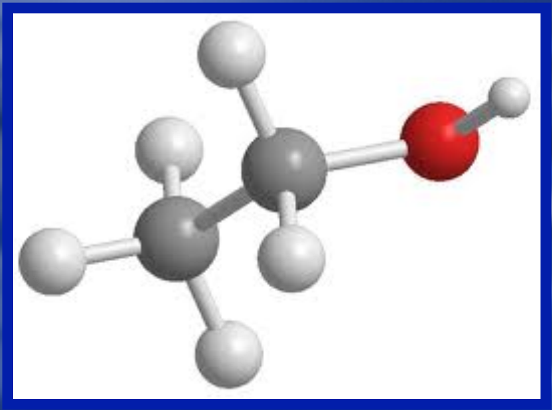
SLR Midplane Ionization Rate Including Losses and Decay

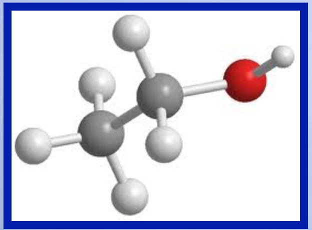


Protoplanetary Disks: Observational Signatures resulting from Different Ionization Scenarios

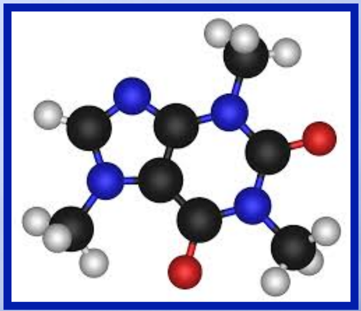
Ilse Cleeves, Fred Adams, Ted Bergin







Chemical Codes

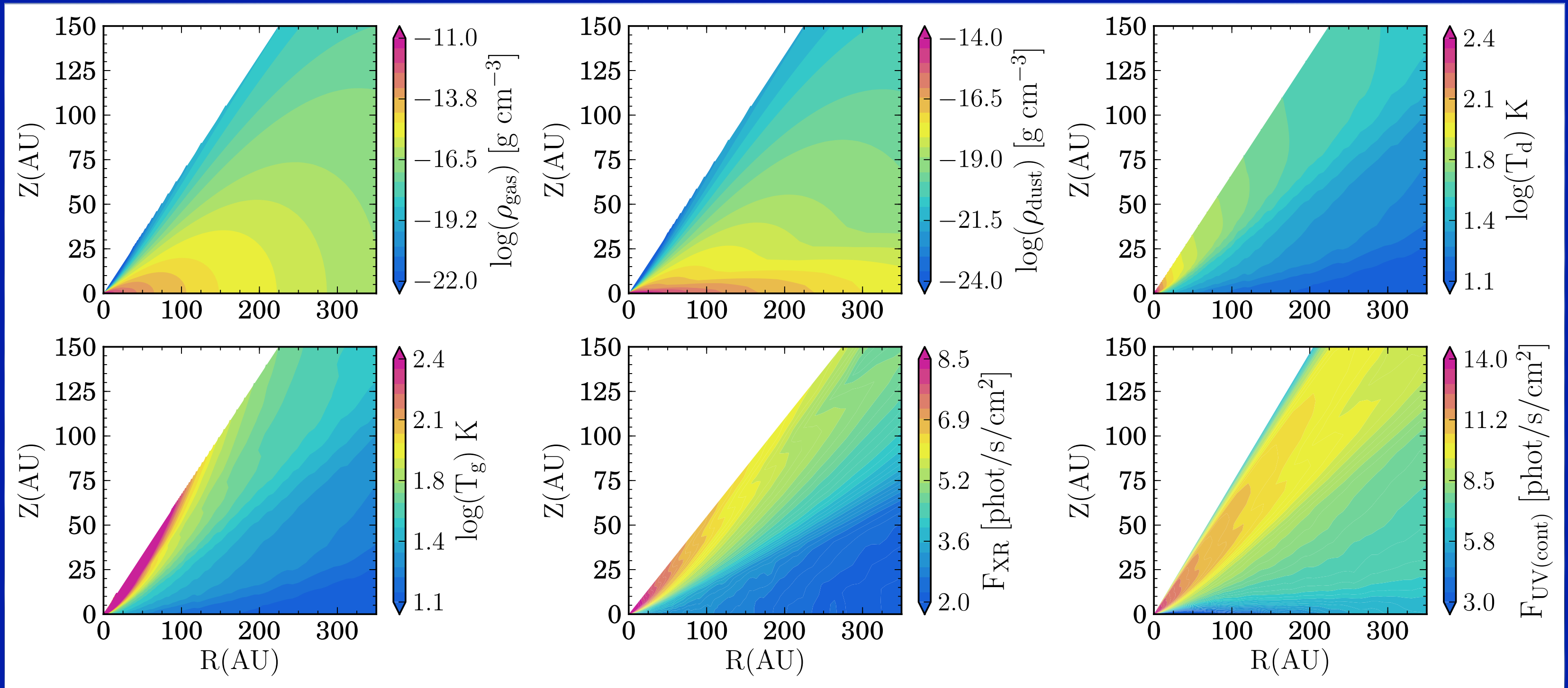


- 1+1D disk model for chemistry
- Disk density (power-law in r, gaussian in z)
- Use TW-Hya as template for UV, X-ray
- 2D Monte Carlo radiative transfer code
- 1000s of chemical reactions in network
- Coupling between gas and dust
- Predict abundances v. position of key species
- LIME 3D code to predict obs. signatures

Code References: Fogel et al. 2011; Cleeves et al. 2011, 2013; Bethell & Bergin 2012; Brinch & Hogerheijde 2011, etc.

Basic Disk Model

Gas density dust density dust temperature

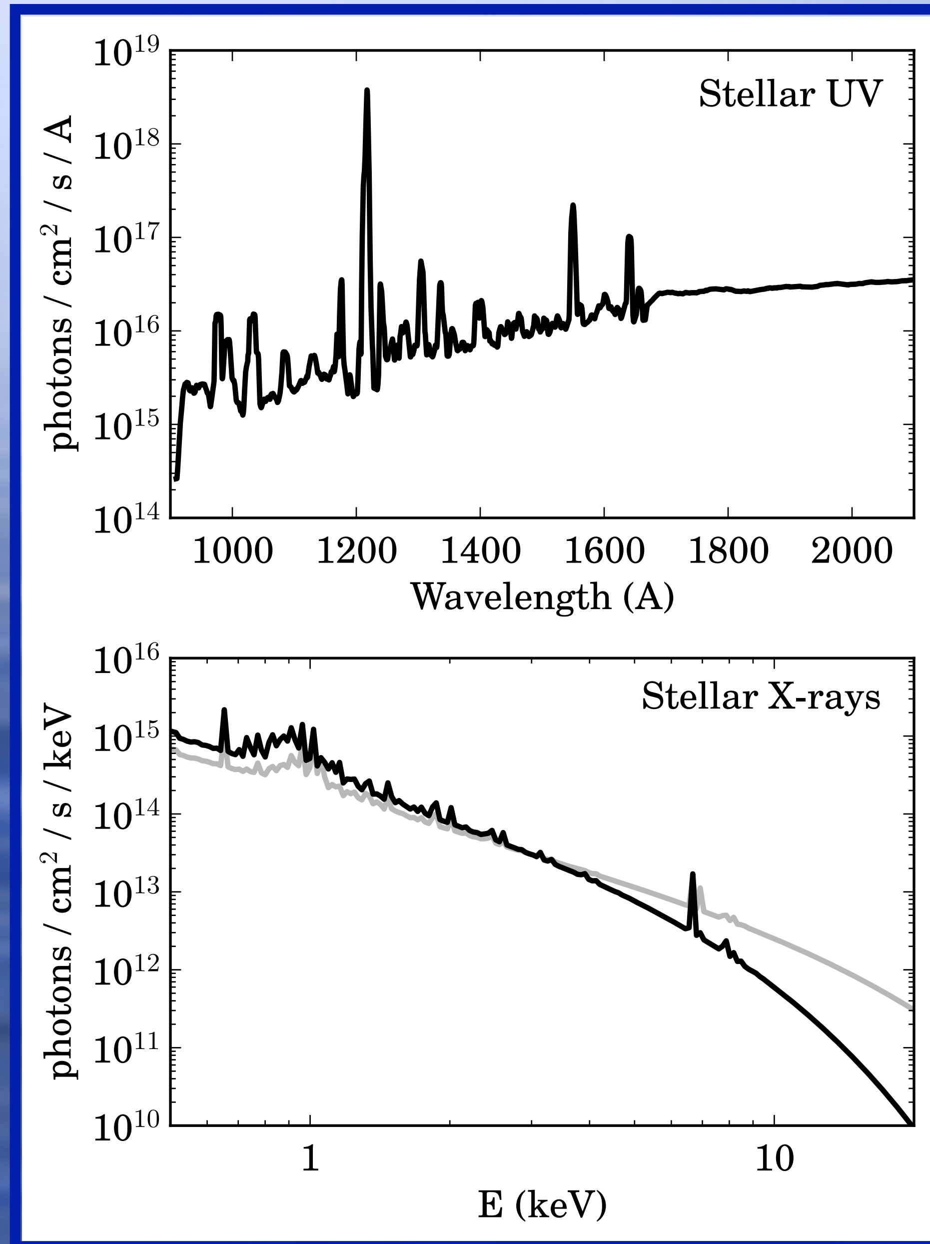


Gas temperature X-rays UV

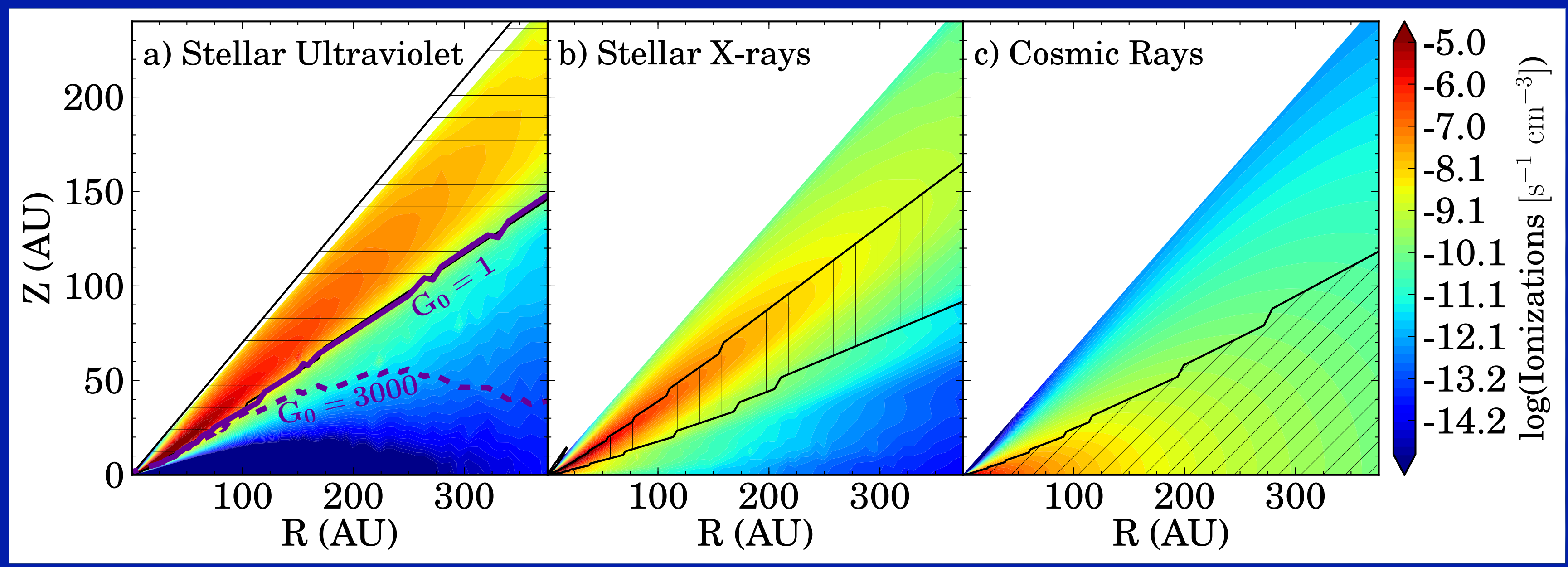
STELLAR RADIATION FIELDS

UV – from TW-Hya

X-ray `characteristic'

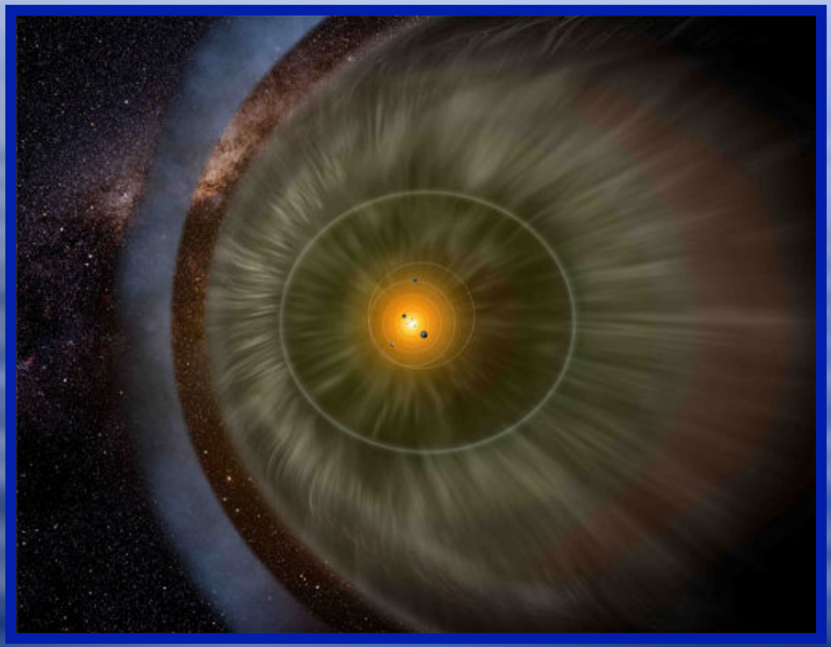


Relative Contribution of UV, X-rays, CRs to Disk Ionization



Hatched regions: more than 30% by given source

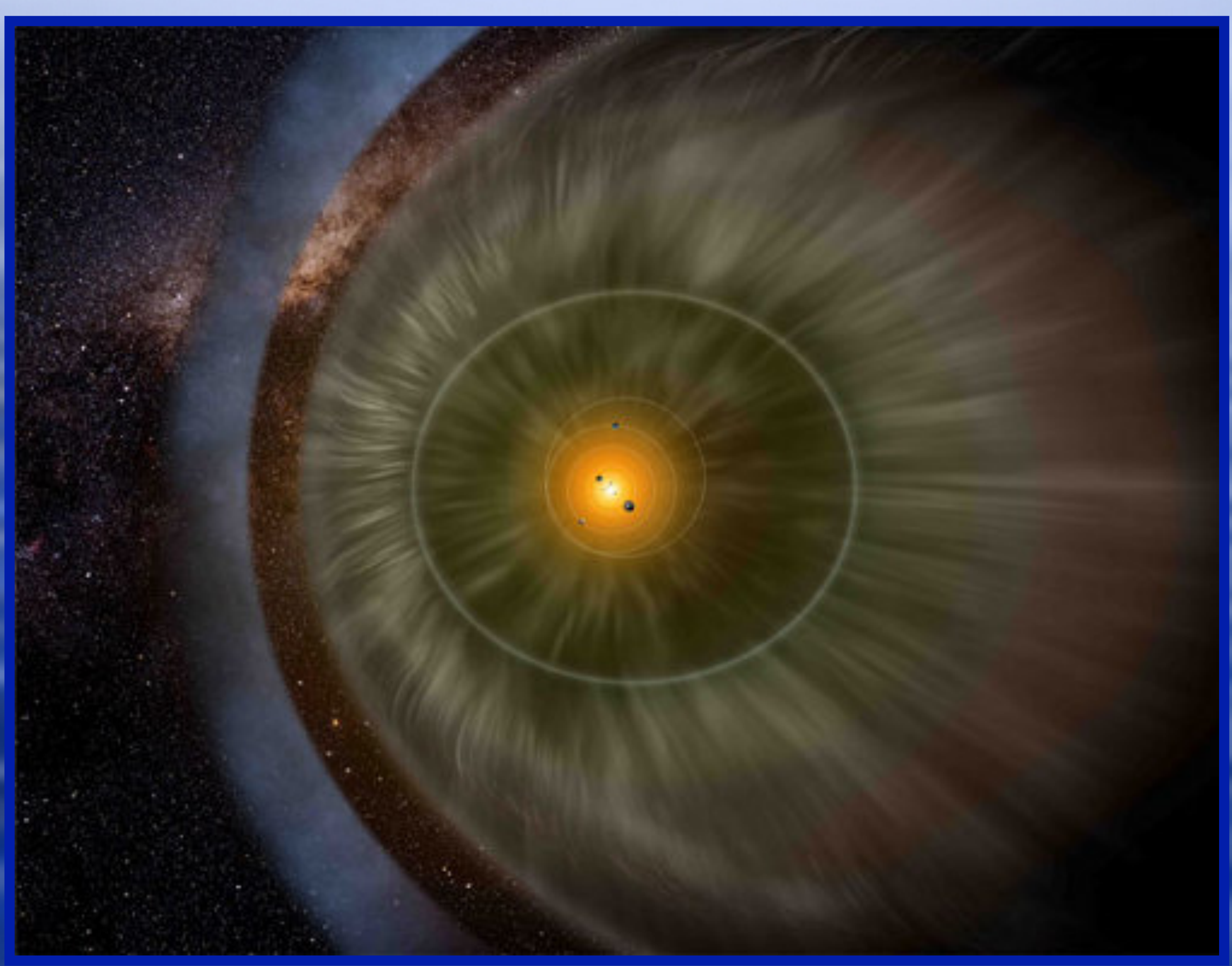
THE HELIOSPHERE



Graphic from IBEX Mission

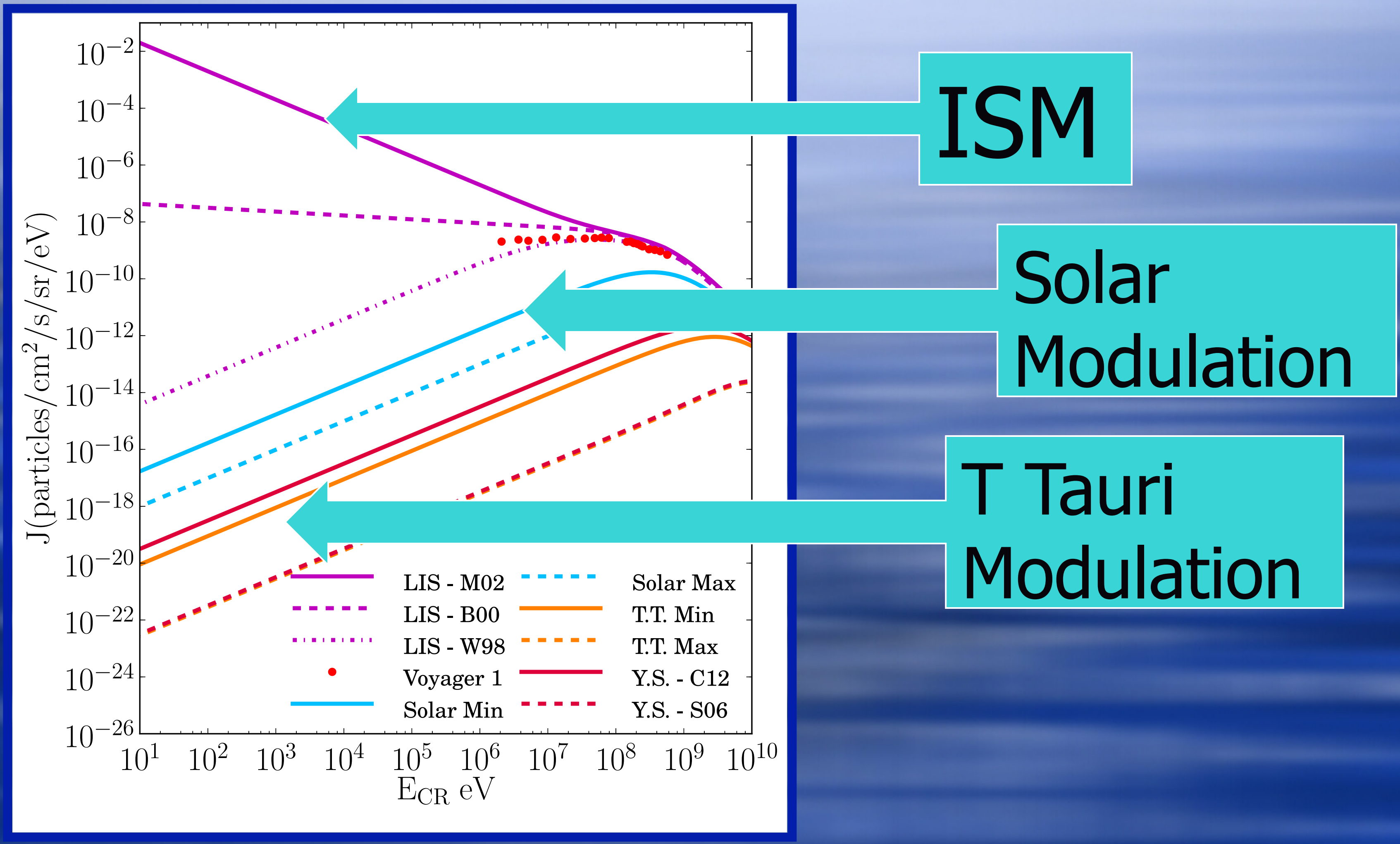
Reduces CR flux inside the Solar System

THE T-TAURIOSPHERE

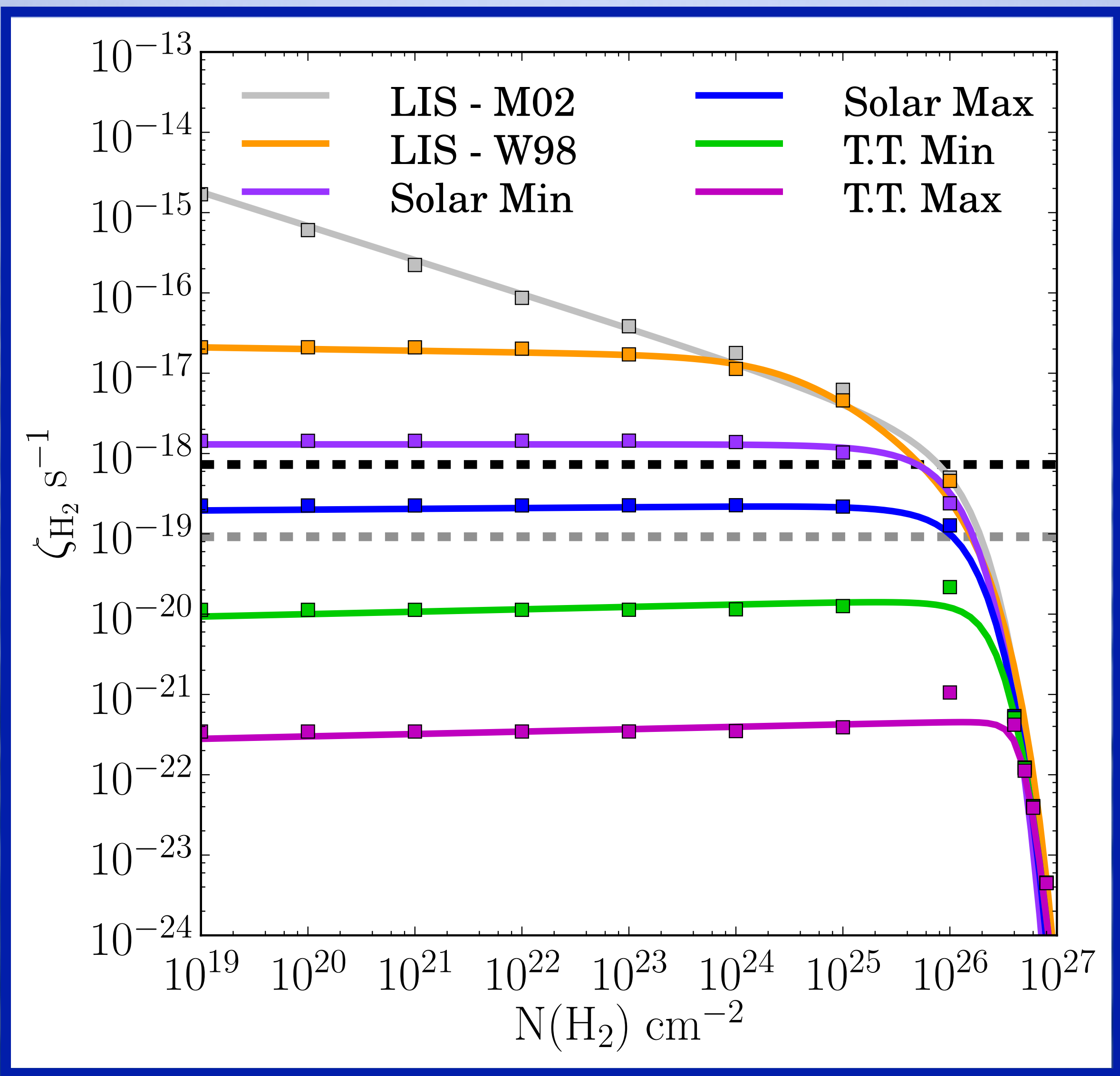


Reduces CR flux striking T Tauri Disks

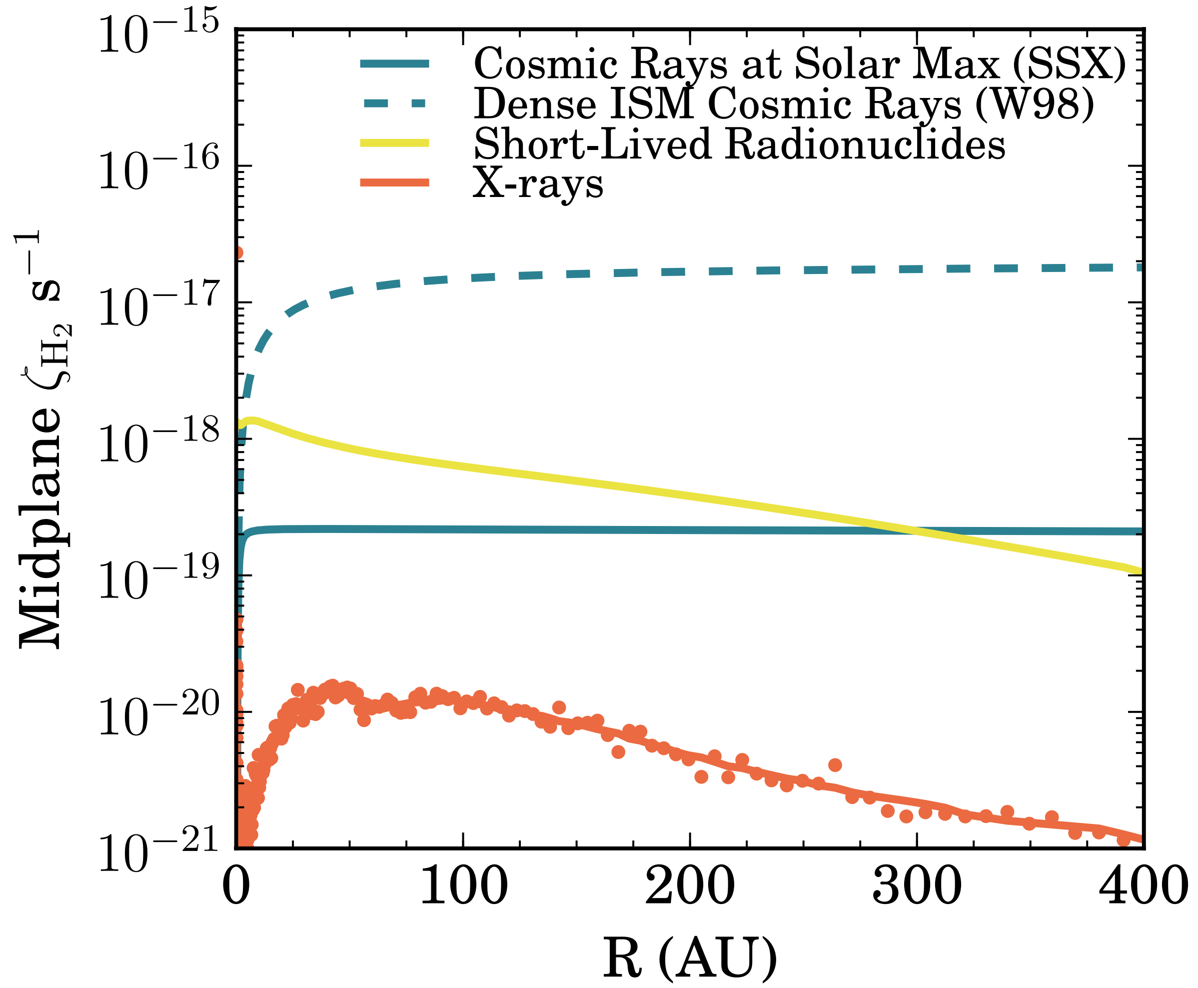
Modulated Cosmic Ray Fluxes



CR Ionization Rate vs Column



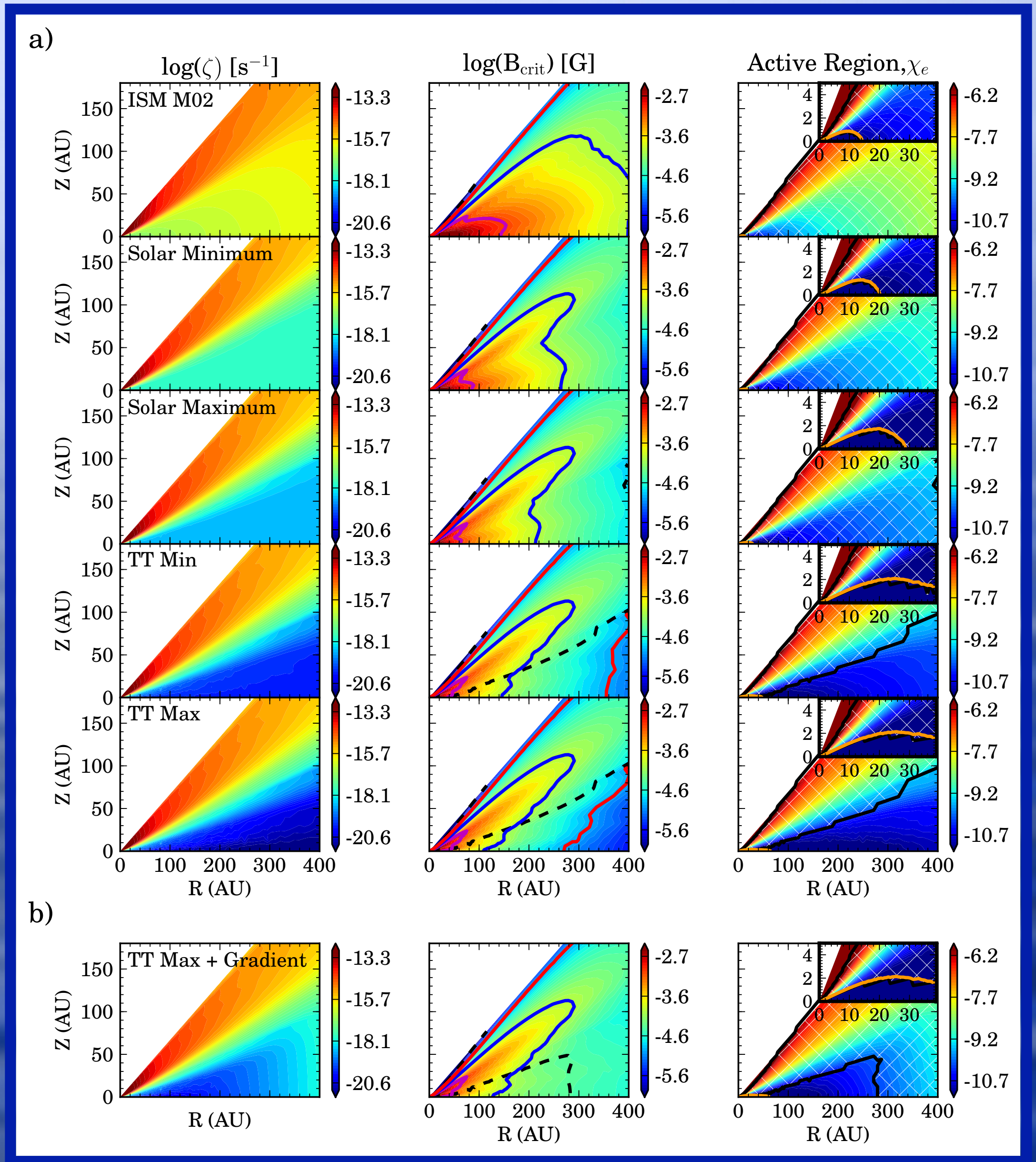
Mid-plane Ionization Rates



Index for Ionization Scenarios

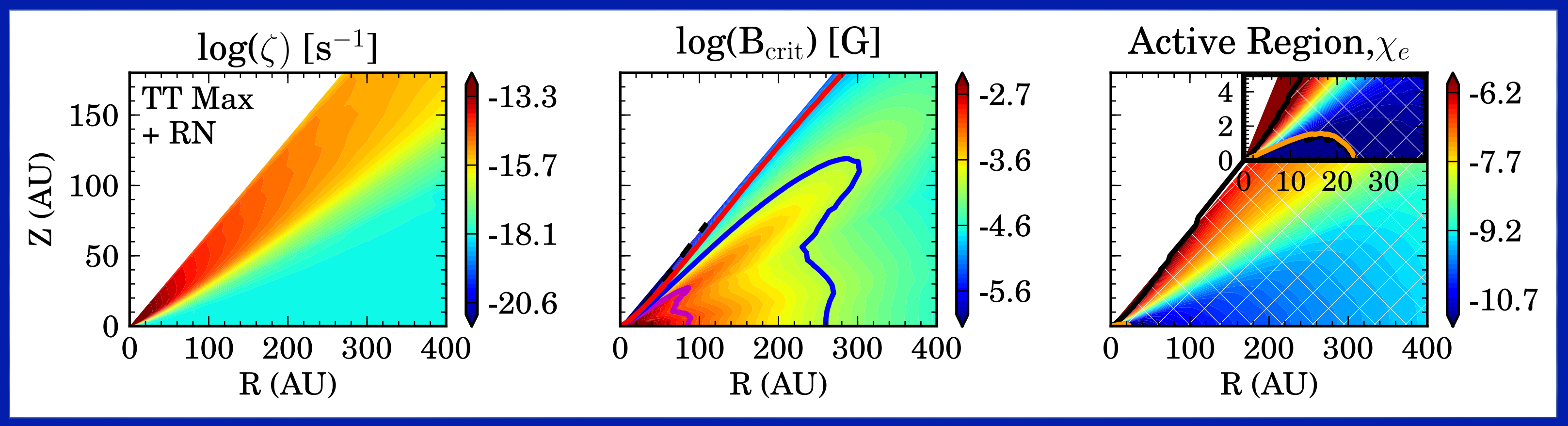
M02 (7×10^{-16} s^{-1})
W98 (2×10^{-17} s^{-1})
SSX (2×10^{-19} s^{-1})
TTX (3×10^{-22} s^{-1})
SSX+SLR ($\sim 1 \times 10^{-18}$ s^{-1})
TTX+SLR ($\sim 8 \times 10^{-19}$ s^{-1})

Ionization Rates and Dead Zones



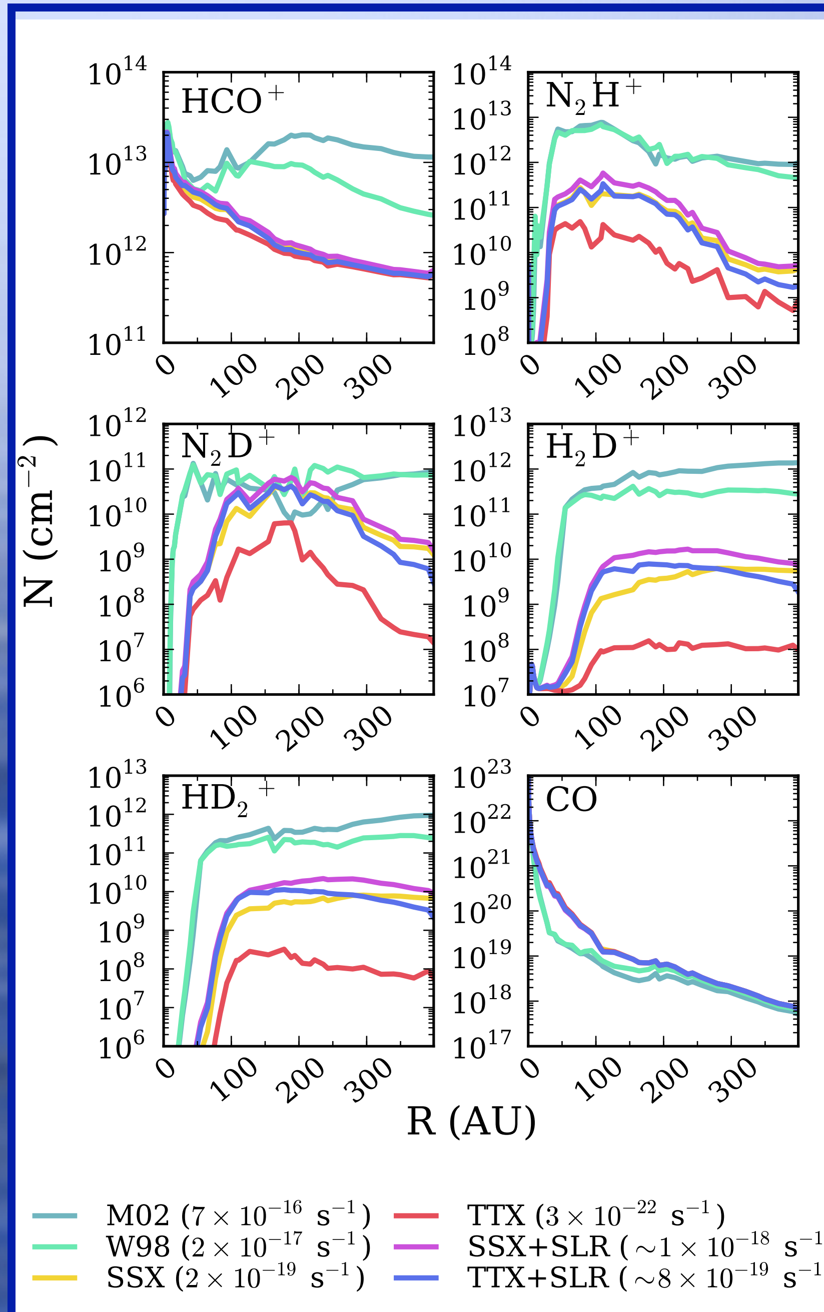
$$\zeta_{total} = \zeta_{CR} + \zeta_X \quad (only)$$

Include SLRS: Increase Ionization, Reduce Dead Zones

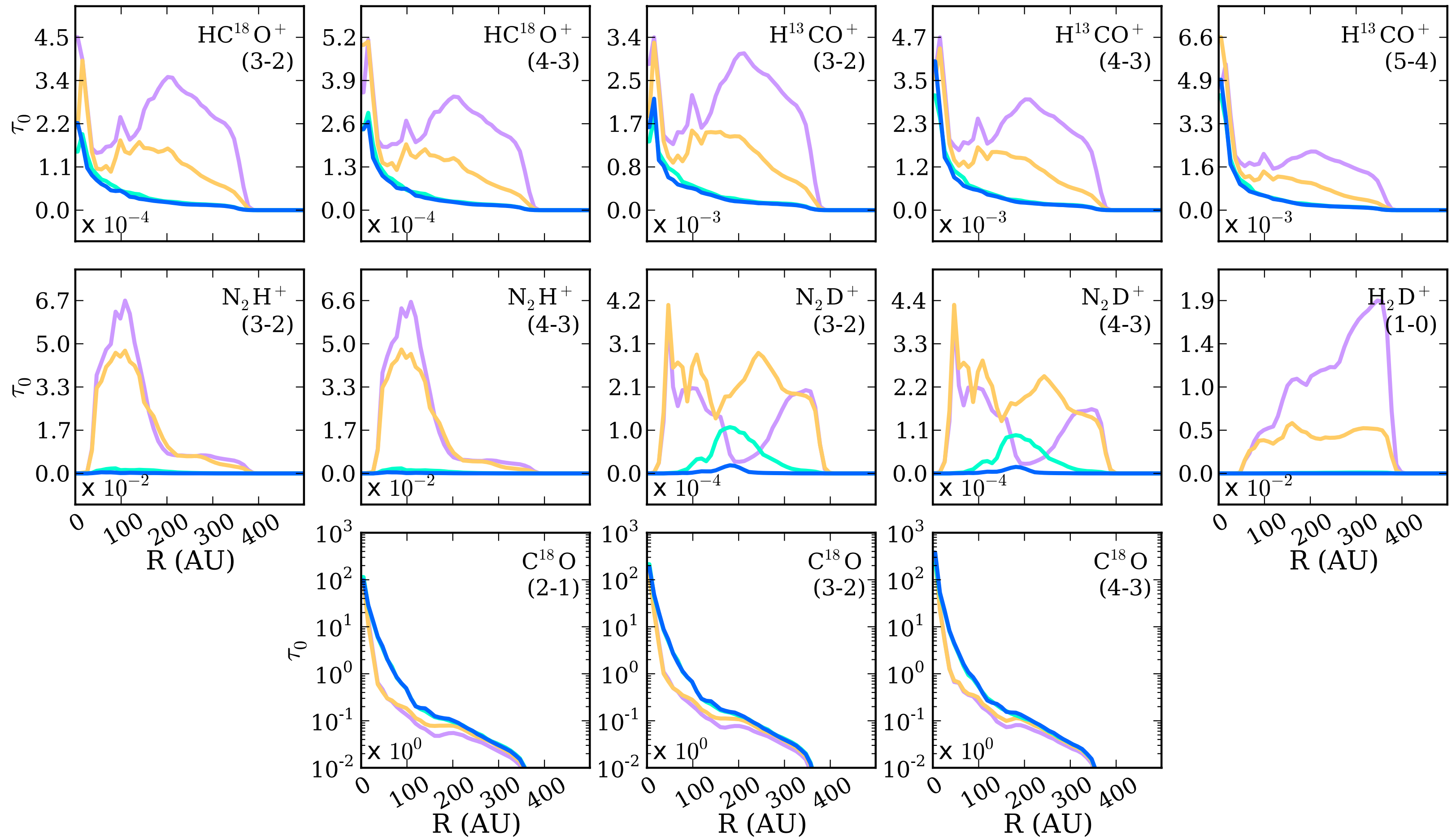


$$\zeta_{total} = \zeta_{CR} + \zeta_{X} + \zeta_{SLR}$$

Column Density Profiles



Face-on Line-center Optical Depth



M02: purple, W98: yellow, SSX: blue, and TTX: green

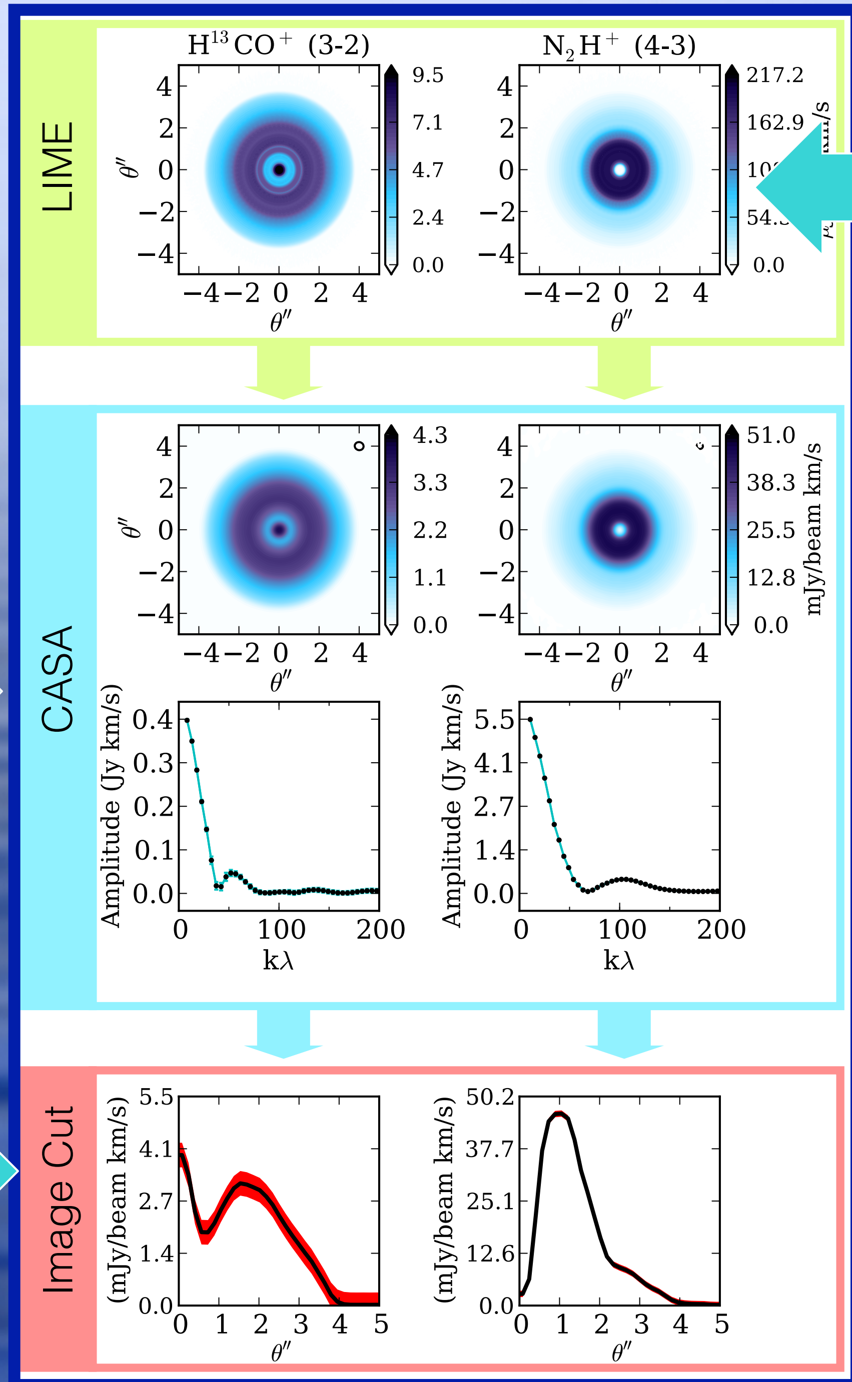
Schematic of Simulated Observations

(L.I. Cleeves)

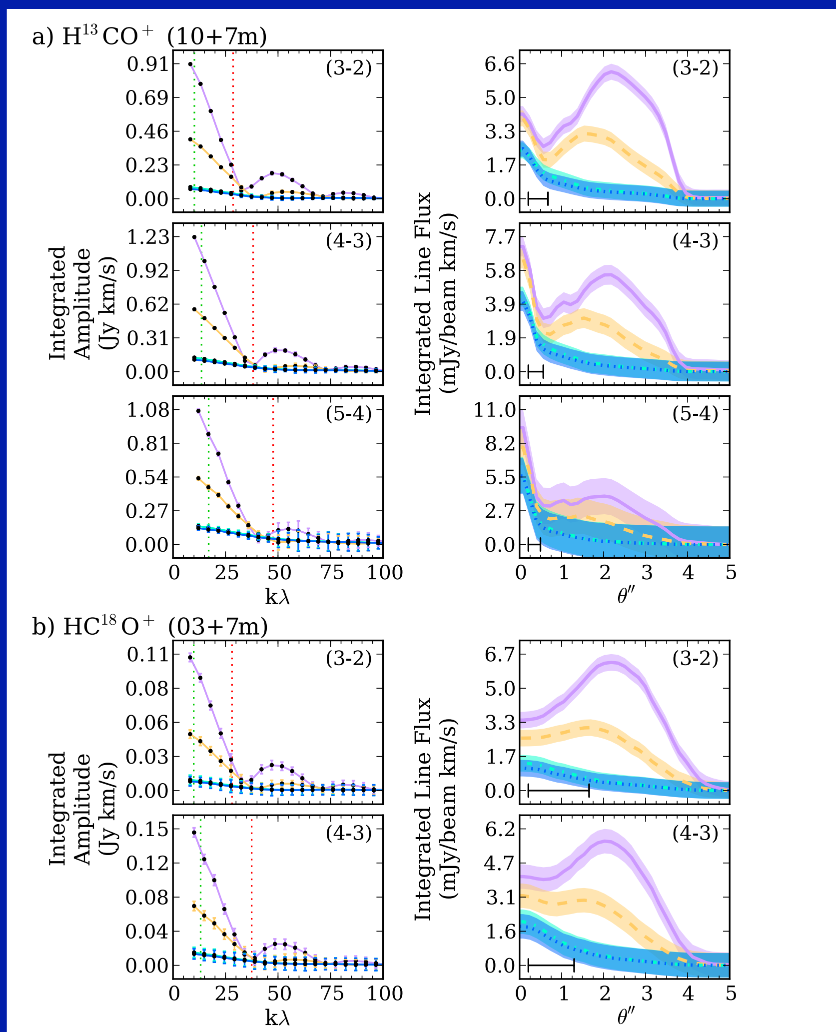
Simulated Observations w. Full array

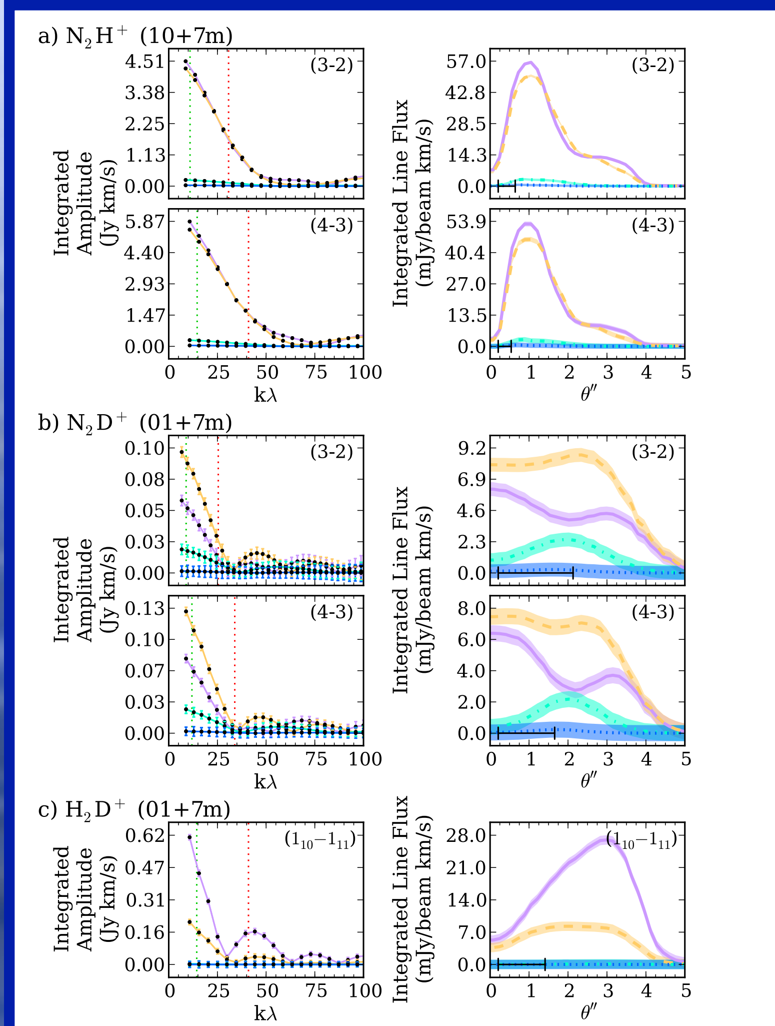
Cut across On-sky Emission Map

Radiative Transfer Output



Simulated ALMA Observations





MO2: purple, W98: yellow, SSX: cyan, TTX: blue

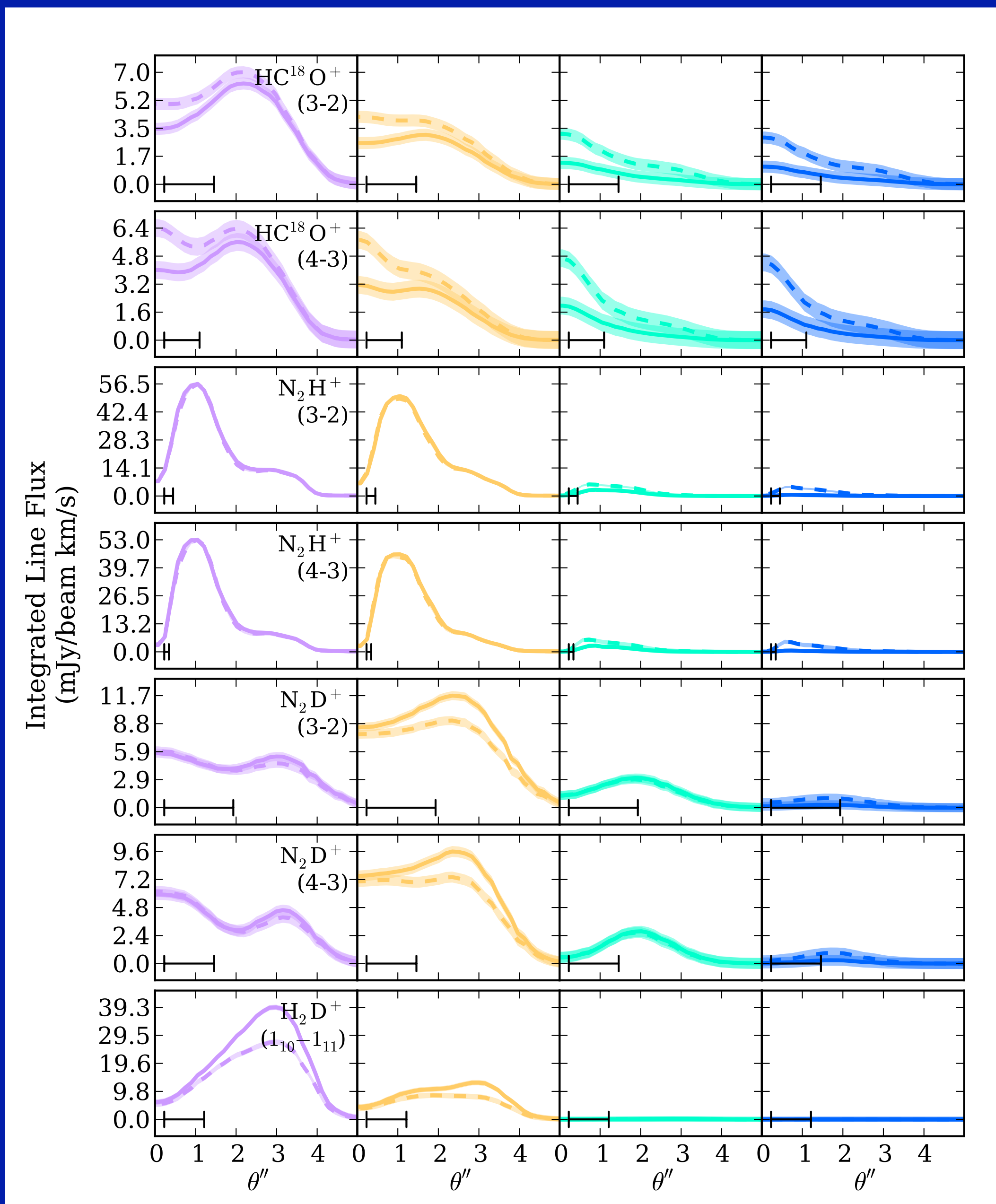
On-Sky ALMA Profiles

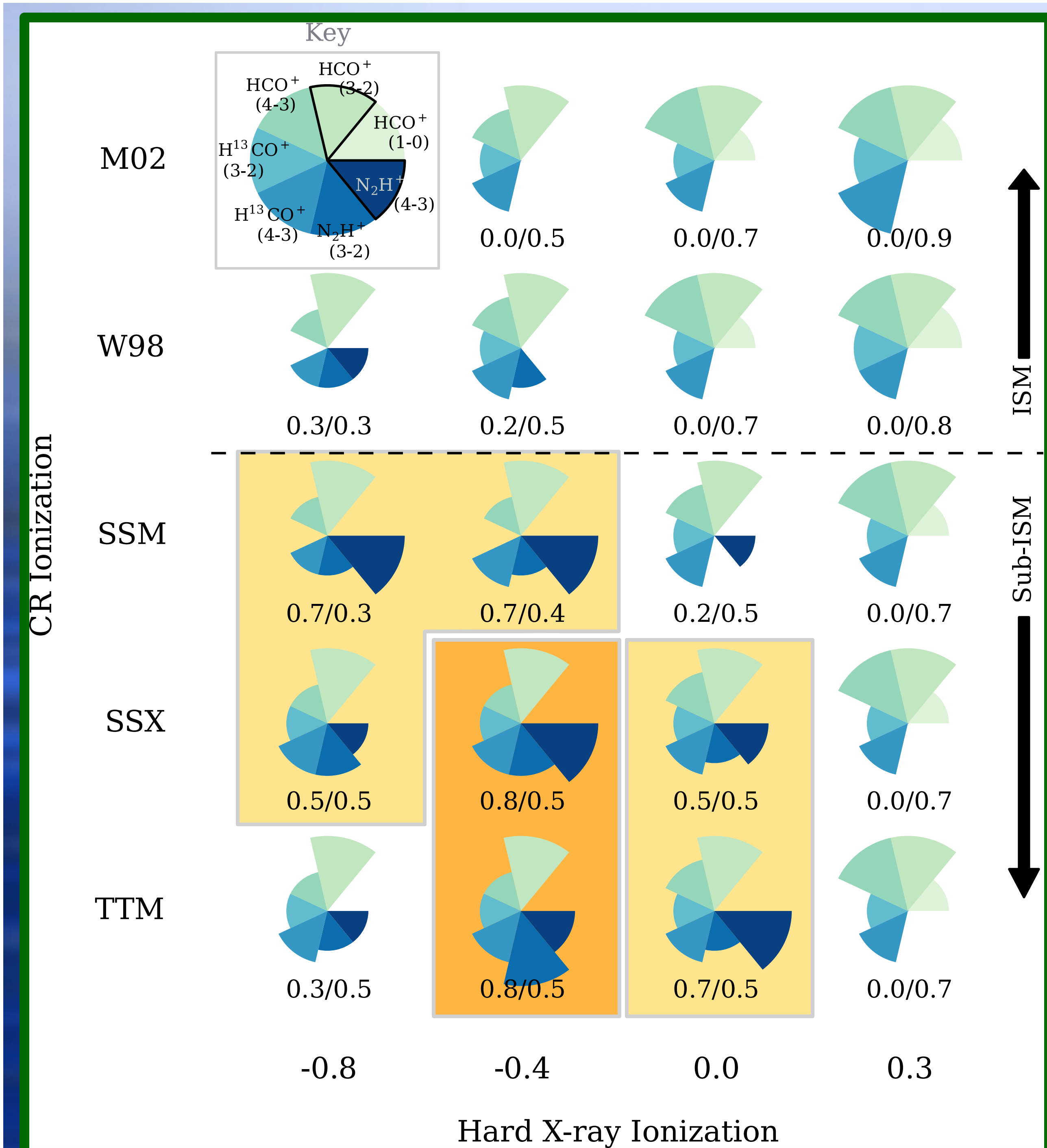
$Log_{10} L_X = 29.5 \ and \ 30.5$

$(in \ \ erg/\sec)$

$4 \ \ Cosmic \ \ Ray \ \ profiles:$

$M02, \ \ W98, \ \ SSX, \ \ TTX$





Goodness of Fit for Observed ALMA Lines in TW Hya

CR Flux is Low!

$\zeta_{CR} = 7 \times 10^{-21} s^{-1}$

$\zeta_{CR} << \zeta_{ISM}$

Cleeves et al. (2015)

SUMMARY

- Ionization rates vary significantly
- CR mirroring enhanced by turbulence
- CRs further suppressed by T-Tauriospheres
- CR fluxes can be enhanced by supernovae
- SLRs delivered to disks at picosun level
- Background radiation from clusters can dominate in some systems
- Effects of different ionization rates are now observable with ALMA (and others)

Every Sea has its Dragons

- How to mix and match ionization agents
- Time dependence of X-rays, backgrounds
- Dust settling affects SLR ionization
- Dust formation affects SLR capture
- Geometry of T Tauri winds
- Turbulent spectrum for magnetic fluct.

UNRESOLVED ISSUES

- Dead zones (turn off MRI, turbulence)
- Ice-lines (affect composition)
- Heating due to SLRs
- Dust settling
- Implication for planet formation

References

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