Constraining the stellar energetic particle flux of T Tauri stars

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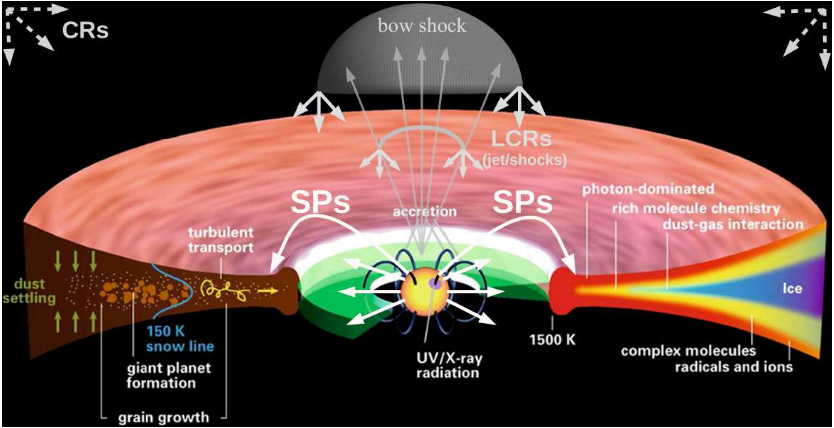
Cosmic Rays II - The salt of the star formation recipe
Florence, 10.11.2022

Energetic environment of planet-forming disks



Adapted from Henning & Semenov 2013

- **enhanced** stellar energetic particle **(SP) flux** in young solar like (T Tauri) stars?
- might be responsible for short-lived radionuclide anomalies observed in meteorites (e.g Gounelle+ 2006)
- **Goal:** characterize the contribution of SP to ionization and constrain the SP flux via molecular ion emission

Constraining ζ_{CR} in planet-forming disks

Reference	Disk(s)	Tracers	ζ_{CR} [s^{-1}]
Cleeves+ (2015)	TW Hya	HCO^+, $H^{13}CO^+$, N_2H^+	$\lesssim 10^{-19}$
Aikawa+ (2021)	MAPS (incl. IM Lup)	HCO^+, $H^{13}CO^+$, N_2H^+, N_2D^+	$\gtrsim 10^{-18}$
Seifert+ (2021)	IM Lup	$H^{13}CO^+$, N_2H^+	$\gtrsim 10^{-17}$, $r \gtrsim 100\,\mathrm{au}$ $\lesssim 10^{-20}$, $\mathrm{r} \lesssim 100\,\mathrm{au}$
Fujii & Kimura (2022)	(IM Lup)	–	$\approx 10^{-17} - 10^{-16}$, $\mathrm{r} > 100\,\mathrm{au}$ $\lesssim 10^{-18}$, $\mathrm{r} < 100\,\mathrm{au}$

What does this mean (my opinion) ?

- disks don't have one number for ζ (radial & vertical gradients)
- disks are diverse (mass, stellar properties, evolution, B field, environment ...)
- derived values are (very likely) model & tracer dependent (chemistry, disk model, ...)
- well ... it's complicated ... no complete picture yet

Sources of (solar) stellar energetic particles (SPs)

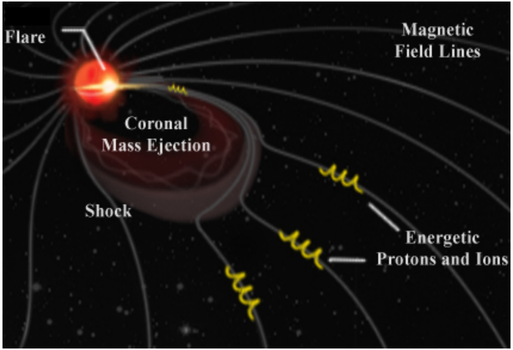
Impulsive SPs form in coronal layers during stellar flares:

- short duration (minutes)
- low max energy
- soft energy spectrum

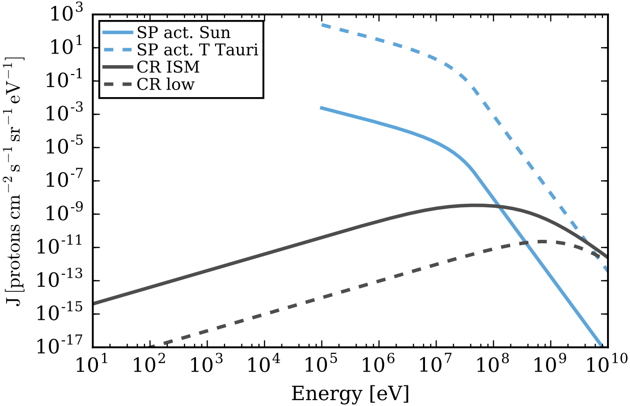
(Hu+ 2017; Fu+ 2019)

Gradual SPs are formed at Coronal Mass Ejection shock sites associated with stellar flares:

- long duration (days)
- high max energy (GeV)
- hard energy spectrum

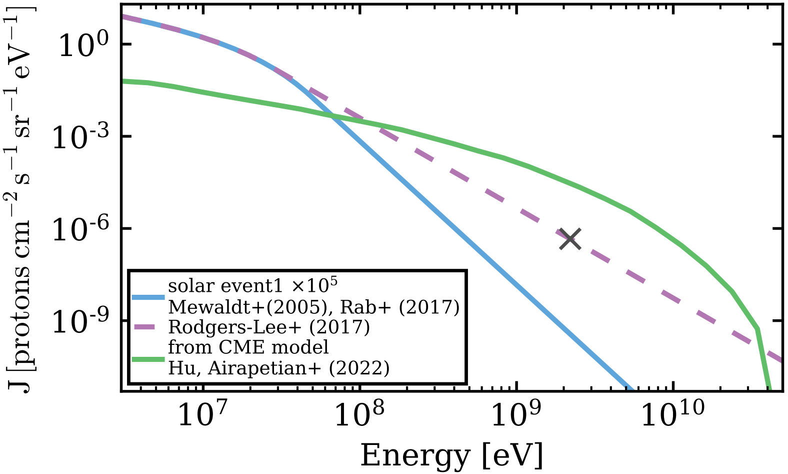


Stellar energetic particles (SP)



- **Active Sun:** averaged measurement of flare event (current Sun) (Mewaldt+ 2005)
- **Active T Tauri:** $\gtrsim 10^5$ higher; particle flux $\mathrm{F_p(E > 10MeV) \approx 150\,particles\,cm^{-2}\,s^{-1}}$ at 1 au (Feigelson+ 2002; Ceccarelli+ 2014; Gounelle+ 2006)
- **Assumptions:** SPs origin close to the star; they penetrate the disk; average/continuous flux (i.e. high flare frequency); treat them like galactic CRs for the chemistry; details: **Rab+ (2017b)**

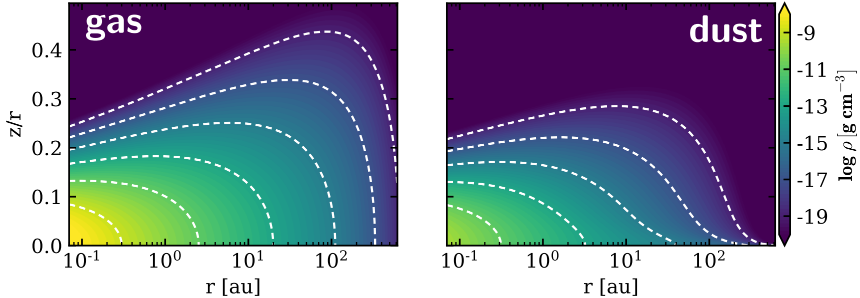
More stellar particle spectra



expect huge range of fluxes at GeV energies driven by super & mega flare events

ProDiMo - PROtoplanetary DIsk MOdel

Structure



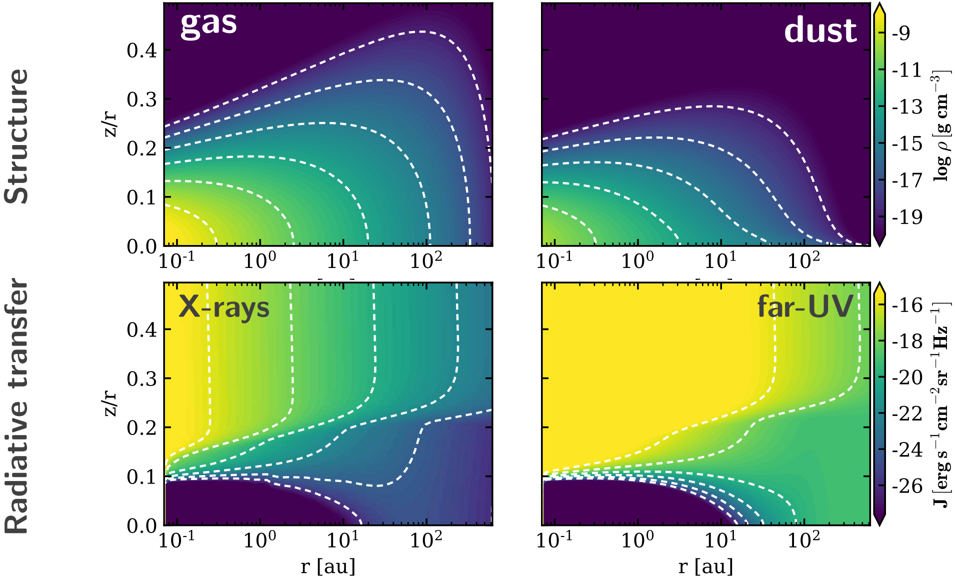
Representative T Tauri disk model

- **Stellar properties**
  $M_* = 0.7 M_\odot$
  $L_* = 1 L_\odot$; $T_{\rm eff} = 4000\,\mathrm{K}$
  $L_{\rm FUV} = 10^{-2} L_*$
  $L_{\rm X} \approx 10^{-3} L_* (= 10^{30}\,\mathrm{erg\,s^{-1}})$
- **Disk properties**
  $M_{\rm disk} = 10^{-2}\,M_\odot$
  total gas/dust= 100
  age $\approx 1 - 3$ Myr

https://prodimo.iwf.oeaw.ac.at

Woitke+ (2009); Kamp+ (2010); Thi+ (2011); Aresu+ (2011); Woitke+ (2016); Rab+ (2017b,a, 2018)

ProDiMo - PROtoplanetary DIsk MOdel



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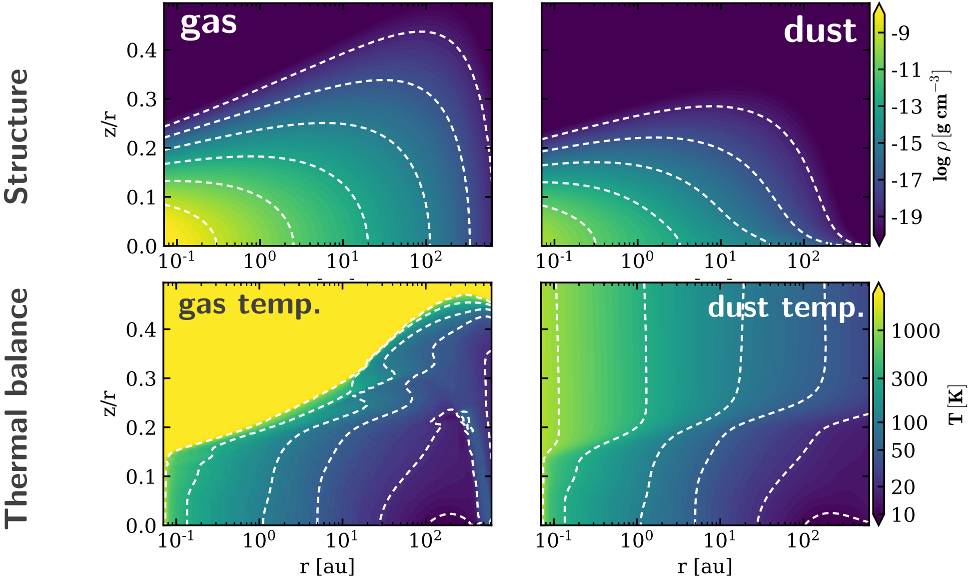

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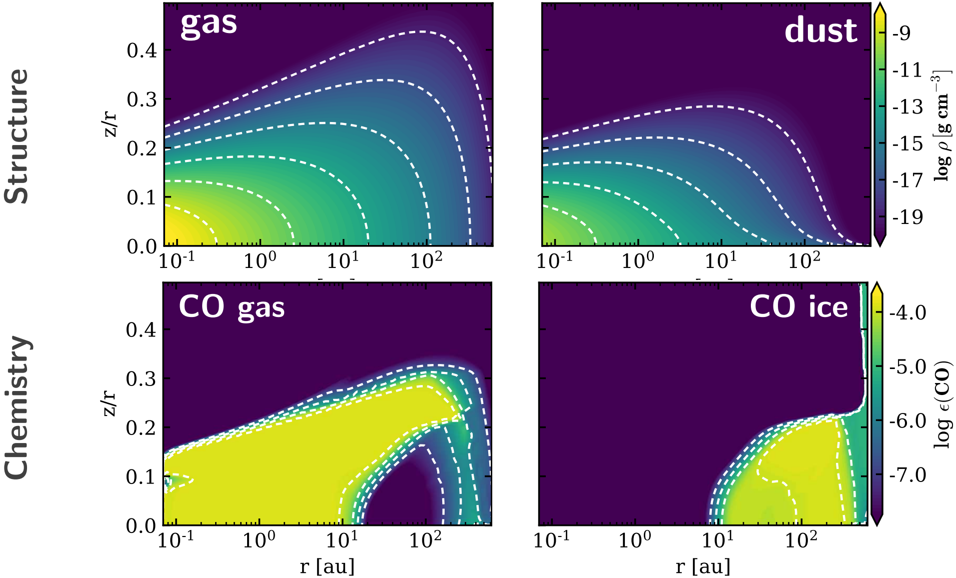

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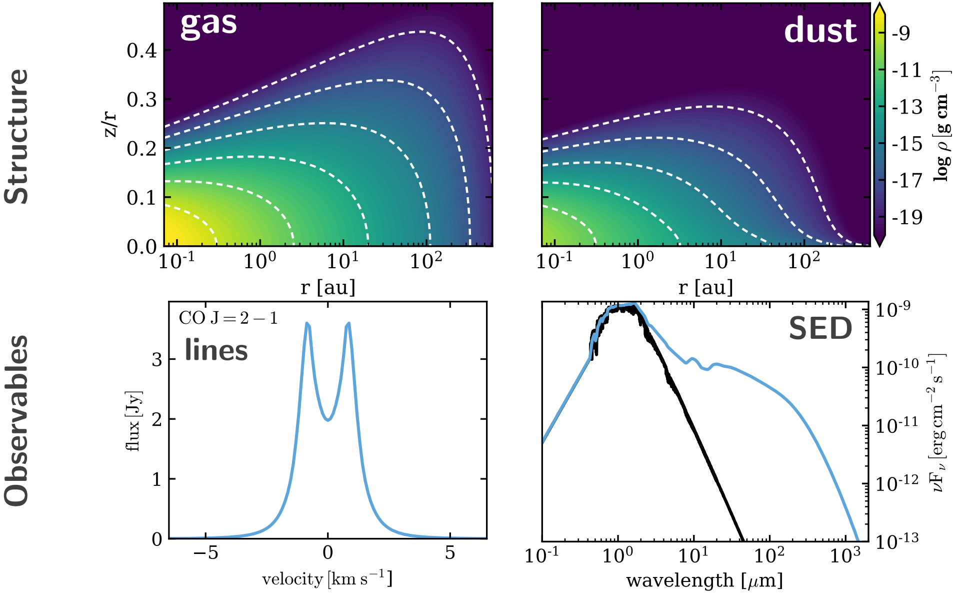

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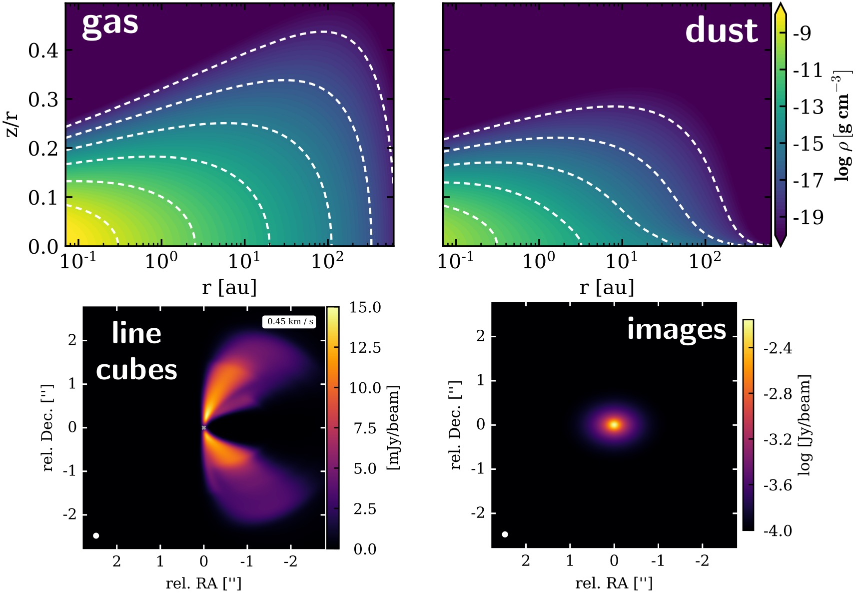
ProDiMo - PROtoplanetary DIsk MOdel

Structure

Observables



https://prodimo.iwf.oeaw.ac.at

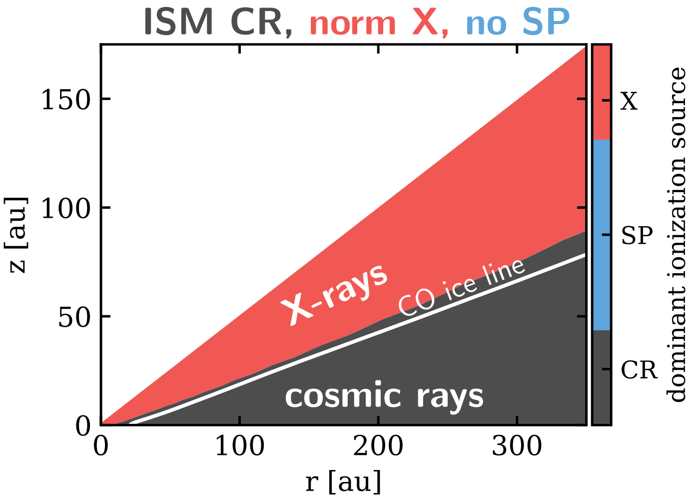
High energy ion. sources - H_2 ionization rates

several **high energy ionization sources** are able to ionize **molecular hydrogen**, the most abundant molecule in disks

- **X-rays**: X-ray RT with scattering, gas & dust opacities (see Rab+ 2018)
  normal: typical T Tauri spectrum ($L_X = 10^{30}\,\mathrm{erg/s}$)
  high: $L_X = 5 \times 10^{30}\,\mathrm{erg/s}$ and harder
- **Stellar Particles**: different transport methods and spectra (Hu+ 2022)
  ballistic model: continuous slowing-down approximation (e.g. Padovani+ 2009, 2018)
  diffusive model: considering magnetic fields (Rodgers-Lee+ 2017)
- **Galactic Cosmic Rays**: consider CR absorption
  ISM ($\zeta_{CR} \approx 10^{-17}\,\mathrm{s}^{-1}$): ISM like Padovani+ (2009)
  low ($\zeta_{CR} \approx 10^{-19}\,\mathrm{s}^{-1}$): modulated spectrum, "T-Tauriosphere" Cleeves+ (2013)

Dominant H_2 ionization source

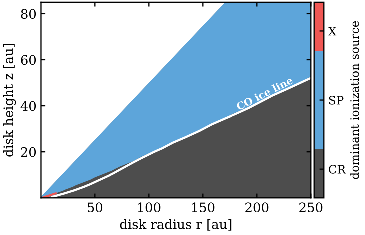
the transport models allow to calculate the H_2 ionization rate at each point in the disk and to determine the dominant H_2 ionization agent



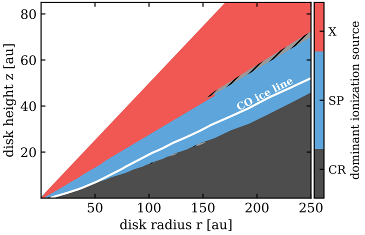
Impact particle transport models and spectra

- **"ballistic"**: continuous slowing-down approximation; no magnetic fields; two spectra: **"scaled"** and **"CME"**; $\propto 1/r^2$
- **"diffusive"**: propagation of particles due to magnetic field (Rodgers-Lee+ 2017) ; $\propto 1/r$
- **ISM CR, norm X**

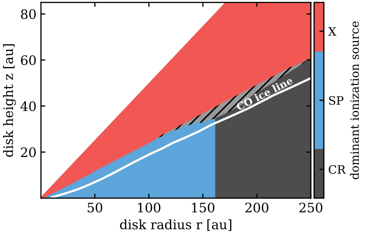
ballistic scaled



ballistic CME

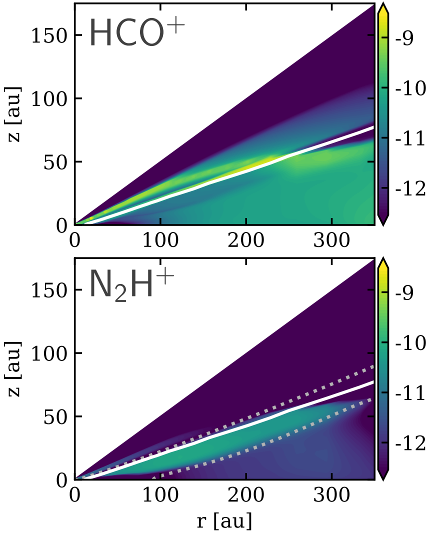


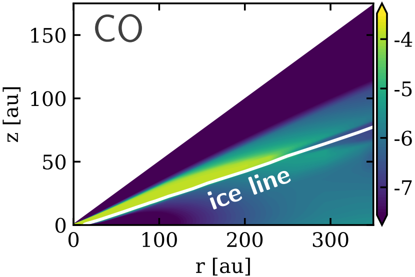
diffusive



Observational tracers - Molecules

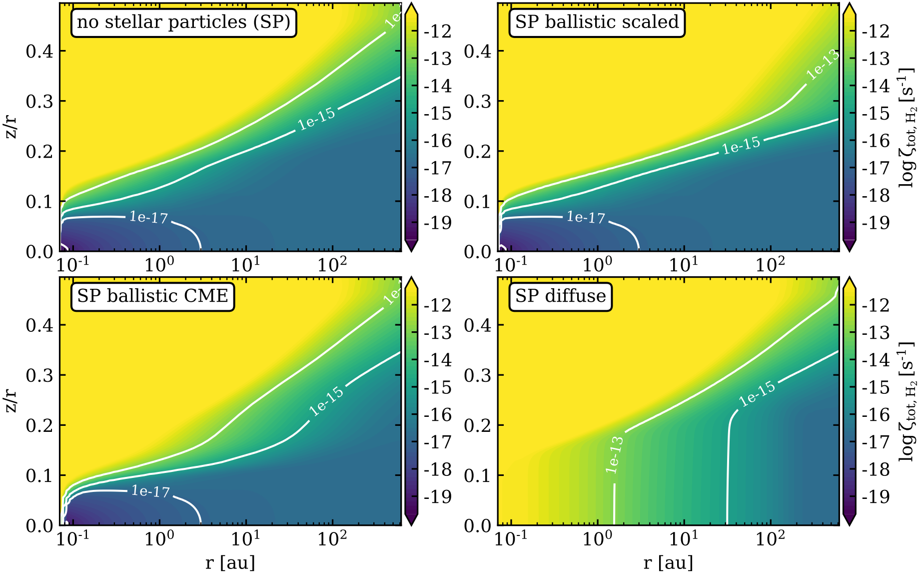
molecular abundance structure (ISM CR, norm X, no SP)



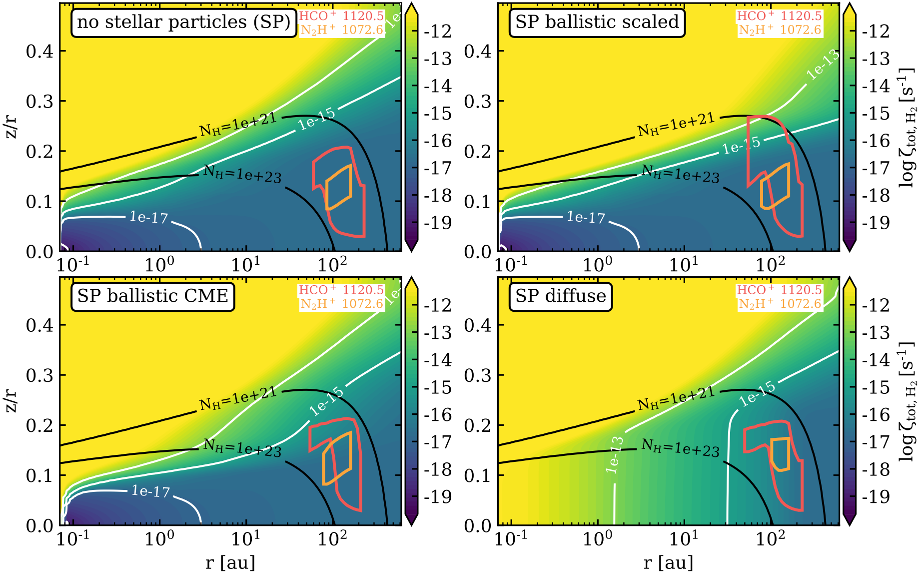


- molecular ion chemistry driven by high energy ionization of H_2
- HCO^+ & N_2H^+ common disk ionization tracers (observable)
- trace different regions of the disk as CO destroys N_2H^+
  (CO snow line tracer Qi+ 2013)

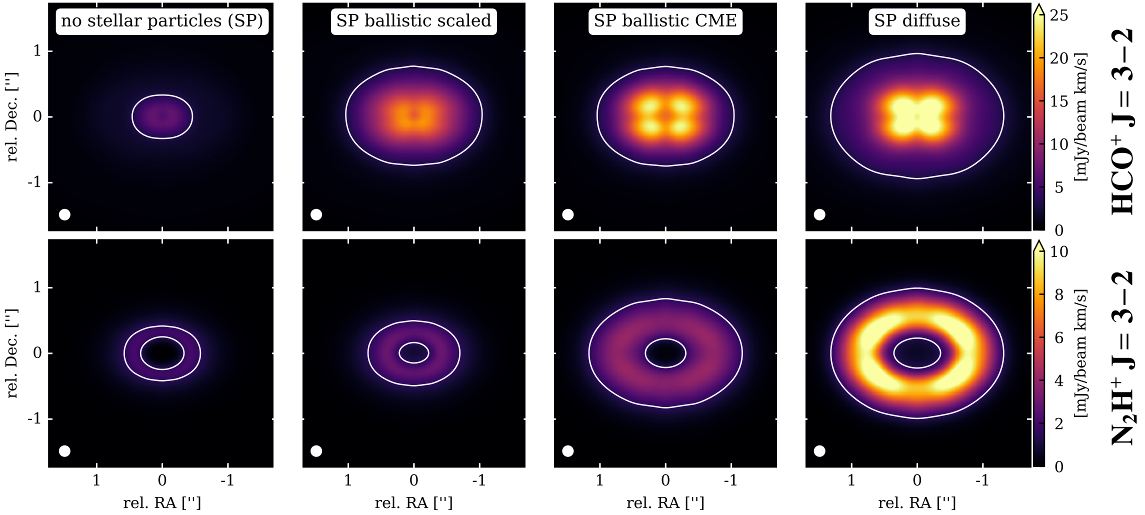
Tracing H_2 ionization rates (ISM CRs)



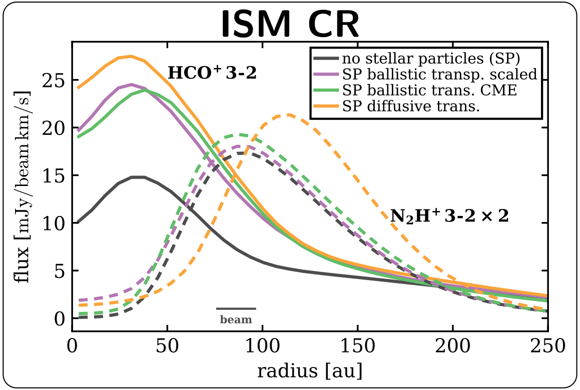
Tracing H_2 ionization rates (ISM CRs)

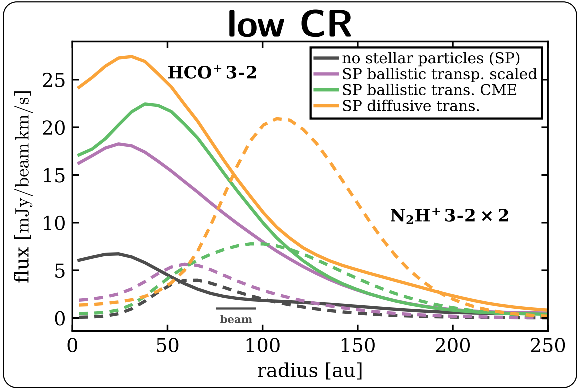


Observables (ALMA) - low CRs



Observables - transport models & spectra





- testing different particle transport models (and different input spectra) is crucial to improve observational constraints on the SP flux
- observations can provide constraints for the transport models (i.e. importance of magnetic fields)

Conclusions/Outlook

Conclusions

- impact of expected stellar particle flux observable in disks
- shape of particle energy spectrum and transport mechanisms are relevant
- models required to disentangle contribution of various ionization sources from observations

Outlook/ToDos

- impact form shock (Jets) accelerated LCRs
- modelling variability of flares and SP (i.e. time-dependent, observations)
- improved transport models, in particular the treatment of magnetic fields (e.g. structure)
- improved (chemical) models, model comparison
- impact on other molecules (e.g. hydrocarbons Favre+ 2018; Fontani+ 2017)
- impact on dust (e.g. Glauser+ 2009) and ices
- more embedded sources (Class I) ... have some toy models

Thank You for Your Attention!

References I

Aikawa, Y., Cataldi, G., Yamato, Y., Zhang, K., Booth, A. S., Furuya, K., Andrews, S. M., Bae, J., Bergin, E. A., Bergner, J. B., Bosman, A. D., Cleeves, L. I., Czekala, I., Guzmán, V. V., Huang, J., Ilee, J. D., Law, C. J., Le Gal, R., Loomis, R. A., Ménard, F., Nomura, H., Öberg, K. I., Qi, C., Schwarz, K. R., Teague, R., Tsukagoshi, T., Walsh, C., & Wilner, D. J. (2021). Molecules with ALMA at Planet-forming Scales (MAPS). XIII. HCO^+ and Disk Ionization Structure. *ApJS*, 257(1):13.

Aresu, G., Kamp, I., Meijerink, R., Woitke, P., Thi, W.-F., & Spaans, M. (2011). X-ray impact on the protoplanetary disks around T Tauri stars. *A&A*, 526:A163.

Ceccarelli, C., Dominik, C., López-Sepulcre, A., Kama, M., Padovani, M., Caux, E., & Caselli, P. (2014). Herschel Finds Evidence for Stellar Wind Particles in a Protostellar Envelope: Is This What Happened to the Young Sun? *ApJ*, 790:L1.

Cleeves, L. I., Adams, F. C., & Bergin, E. A. (2013). Exclusion of Cosmic Rays in Protoplanetary Disks: Stellar and Magnetic Effects. *ApJ*, 772:5.

Cleeves, L. I., Bergin, E. A., Qi, C., Adams, F. C., & Öberg, K. I. (2015). Constraining the X-Ray and Cosmic-Ray Ionization Chemistry of the TW Hya Protoplanetary Disk: Evidence for a Sub-interstellar Cosmic-Ray Rate. *ApJ*, 799:204.

Favre, C., Ceccarelli, C., López-Sepulcre, A., Fontani, F., Neri, R., Manigand, S., Kama, M., Caselli, P., Jaber Al-Edhari, A., & Kahane, C. (2018). SOLIS IV. Hydrocarbons in the OMC-2 FIR4 Region, a Probe of Energetic Particle Irradiation of the Region. *ApJ*, 859(2):136.

Feigelson, E. D., Garmire, G. P., & Pravdo, S. H. (2002). Magnetic Flaring in the Pre-Main-Sequence Sun and Implications for the Early Solar System. *ApJ*, 572:335–349.

Fontani, F., Ceccarelli, C., Favre, C., Caselli, P., Neri, R., Sims, I. R., Kahane, C., Alves, F. O., Balucani, N., Bianchi, E., Caux, E., Jaber Al-Edhari, A., Lopez-Sepulcre, A., Pineda, J. E., Bachiller, R., Bizzocchi, L., Bottinelli, S., Chacon-Tanarro, A., Choudhury, R., Codella, C., Coutens, A., Dulieu, F., Feng, S., Rimola, A., Hily-Blant, P., Holdship, J., Jimenez-Serra, I., Laas, J., Lefloch, B., Oya, Y., Podio, L., Pon, A., Punanova, A., Quenard, D., Sakai, N., Spezzano, S., Taquet, V., Testi, L., Theulé, P., Ugliengo, P., Vastel, C., Vasyunin, A. I., Viti, S., Yamamoto, S., & Wiesenfeld, L. (2017). Seeds of Life in Space (SOLIS). I. Carbon-chain growth in the Solar-type protocluster OMC2-FIR4. *A&A*, 605:A57.

References II

Fu, S., Jiang, Y., Airapetian, V., Hu, J., Li, G., & Zank, G. (2019). Effect of Star Rotation Rate on the Characteristics of Energetic Particle Events. *ApJ*, 878(2):L36.

Fujii, Y. I. & Kimura, S. S. (2022). Cosmic-Ray Ionization Rate in Protoplanetary Disks with Sheared Magnetic Fields. *ApJ*, 937(2):L37.

Getman, K. V. & Feigelson, E. D. (2021). X-Ray Superflares from Pre-main-sequence Stars: Flare Energetics and Frequency. *ApJ*, 916(1):32.

Glauser, A. M., Güdel, M., Watson, D. M., Henning, T., Schegerer, A. A., Wolf, S., Audard, M., & Baldovin-Saavedra, C. (2009). Dust amorphization in protoplanetary disks. *A&A*, 508:247–257.

Gounelle, M., Shu, F. H., Shang, H., Glassgold, A. E., Rehm, K. E., & Lee, T. (2006). The Irradiation Origin of Beryllium Radioisotopes and Other Short-lived Radionuclides. *ApJ*, 640:1163–1170.

Hu, J., Airapetian, V. S., Li, G., Zank, G., & Jin, M. (2022). Extreme energetic particle events by superflare associated cmes from solar-like stars. *Science Advances*.

Hu, J., Li, G., Ao, X., Zank, G. P., & Verkhoglyadova, O. (2017). Modeling Particle Acceleration and Transport at a 2-D CME-Driven Shock. *Journal of Geophysical Research (Space Physics)*, 122(11):10,938–10,963.

Kamp, I., Tilling, I., Woitke, P., Thi, W.-F., & Hogerheijde, M. (2010). Radiation thermo-chemical models of protoplanetary disks. II. Line diagnostics. *A&A*, 510:A18.

Mewaldt, R. A., Cohen, C. M. S., Labrador, A. W., Leske, R. A., Mason, G. M., Desai, M. I., Looper, M. D., Mazur, J. E., Selesnick, R. S., & Haggerty, D. K. (2005). Proton, helium, and electron spectra during the large solar particle events of October-November 2003. *J. of Geophysical Research (Space Physics)*, 110:9.

Padovani, M., Galli, D., & Glassgold, A. E. (2009). Cosmic-ray ionization of molecular clouds. *A&A*, 501:619–631.

Padovani, M., Ivlev, A. V., Galli, D., & Caselli, P. (2018). Cosmic-ray ionisation in circumstellar discs. *A&A*, 614:A111.

References III

Qi, C., Öberg, K. I., Wilner, D. J., D'Alessio, P., Bergin, E., Andrews, S. M., Blake, G. A., Hogerheijde, M. R., & van Dishoeck, E. F. (2013). Imaging of the CO Snow Line in a Solar Nebula Analog. *Science*, 341:630–632.

Rab, C., Elbakyan, V., Vorobyov, E., Güdel, M., Dionatos, O., Audard, M., Kamp, I., Thi, W.-F., Woitke, P., & Postel, A. (2017a). The chemistry of episodic accretion in embedded objects. 2D radiation thermo-chemical models of the post-burst phase. *A&A*, 604:A15.

Rab, C., Güdel, M., Padovani, M., Kamp, I., Thi, W.-F., Woitke, P., & Aresu, G. (2017b). Stellar energetic particle ionization in protoplanetary disks around T Tauri stars. *A&A*, 603:A96.

Rab, C., Güdel, M., Woitke, P., Kamp, I., Thi, W.-F., Min, M., Aresu, G., & Meijerink, R. (2018). X-ray radiative transfer in protoplanetary disks. The role of dust and X-ray background fields. *A&A*, 609:A91.

Rodgers-Lee, D., Taylor, A. M., Ray, T. P., & Downes, T. P. (2017). The ionizing effect of low-energy cosmic rays from a class II object on its protoplanetary disc. *MNRAS*, 472:26–38.

Seifert, R. A., Cleeves, L. I., Adams, F. C., & Li, Z.-Y. (2021). Evidence for a Cosmic-Ray Gradient in the IM Lup Protoplanetary Disk. *ApJ*, 912(2):136.

Thi, W.-F., Woitke, P., & Kamp, I. (2011). Radiation thermo-chemical models of protoplanetary discs - III. Impact of inner rims on spectral energy distributions. *MNRAS*, 412:711–726.

Visser, R., Bergin, E. A., & Jørgensen, J. K. (2015). Chemical tracers of episodic accretion in low-mass protostars. *A&A*, 577:A102.

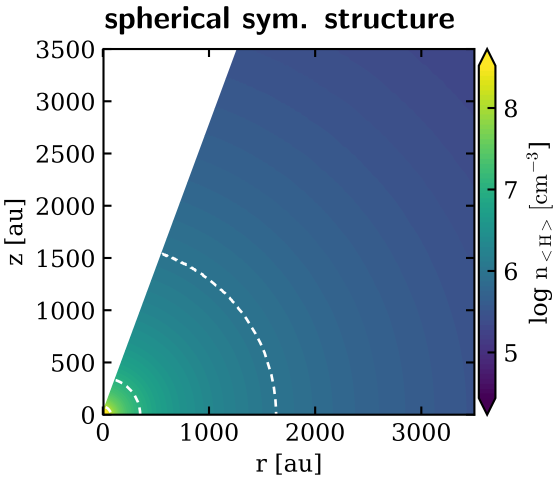
Woitke, P., Kamp, I., & Thi, W.-F. (2009). Radiation thermo-chemical models of protoplanetary disks. I. Hydrostatic disk structure and inner rim. *A&A*, 501:383–406.

Woitke, P., Min, M., Pinte, C., Thi, W.-F., Kamp, I., Rab, C., Anthonioz, F., Antonellini, S., Baldovin-Saavedra, C., Carmona, A., Dominik, C., Dionatos, O., Greaves, J., Güdel, M., Ilee, J. D., Liebhart, A., Ménard, F., Rigon, L., Waters, L. B. F. M., Aresu, G., Meijerink, R., & Spaans, M. (2016). Consistent dust and gas models for protoplanetary disks. I. Disk shape, dust settling, opacities, and PAHs. *A&A*, 586:A103.

Embedded sources - ProDiMo + Envelope

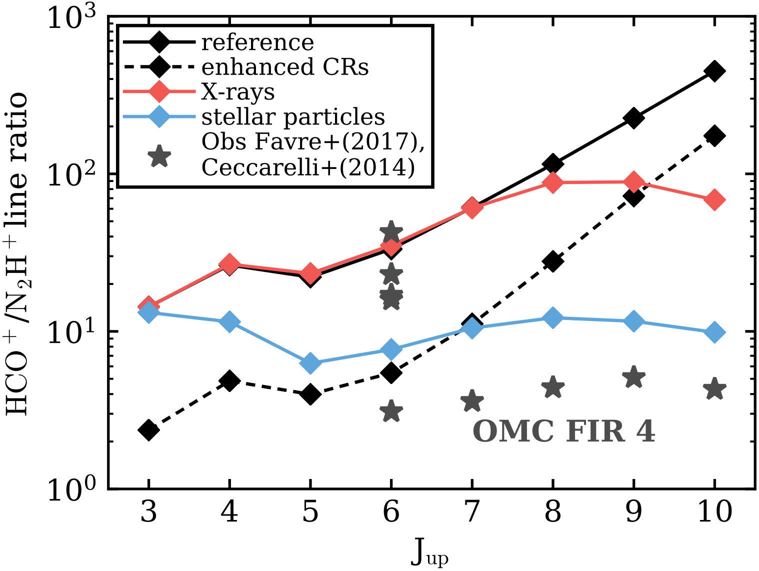
Motivation: low HCO^+/N_2H^+ line/abundance ratios, abundance of complex molecules in **OMC-2 FIR 4** → high ionization rates→ stellar energetic particles? (Ceccarelli+ 2014; Favre+ 2018)

- study impact of **X-rays**, **cosmic-rays**, **stellar particles**
- **ProDiMo** : Xray-RT (Rab+ 2018) stellar particles (Rab+ 2017b)
- based on 1D Class 0/I model of Visser+ (2015) (is not OMC-2 FIR 4)



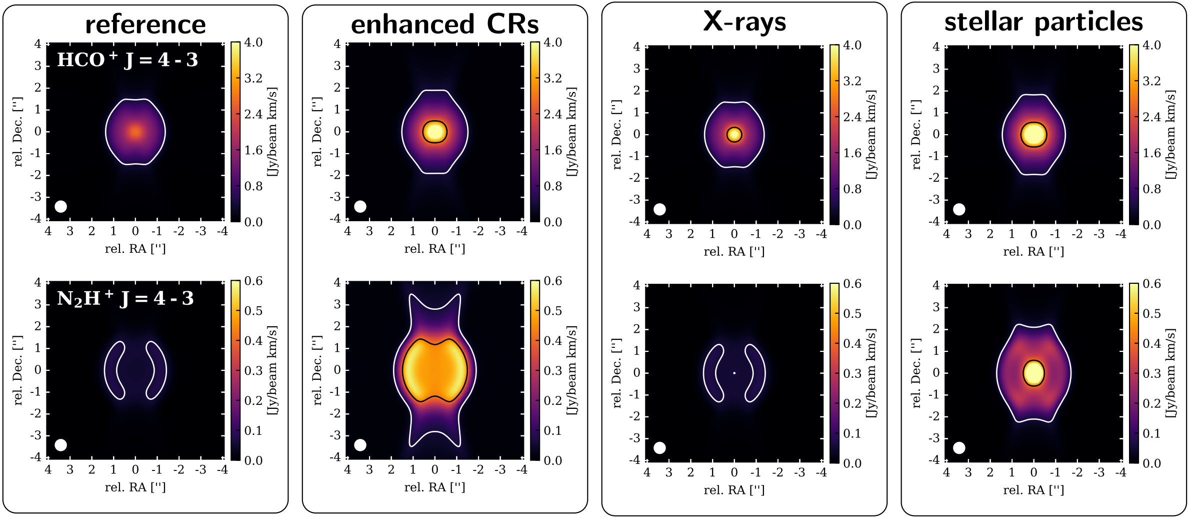
also rotating envelope model + disk is possible (Rab+ 2017a)

Embedded sources - HCO^+/N_2H^+ line ratios

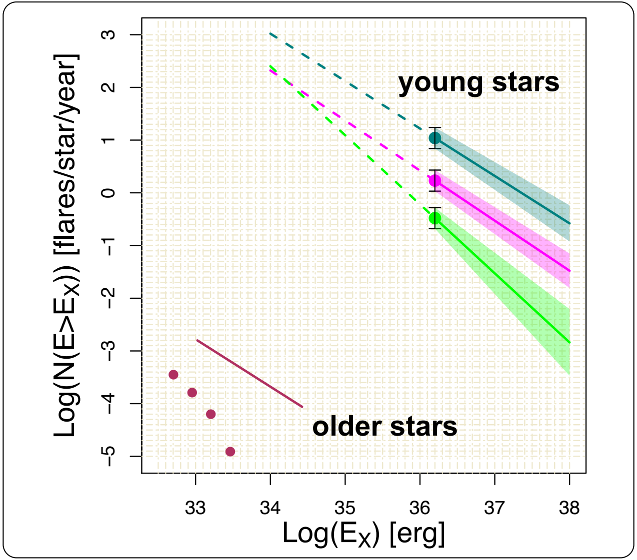


Embedded sources - images

Simulated **moment zero** maps for HCO^+ $J = 4 - 3$ and N_2H^+ $J = 4 - 3$



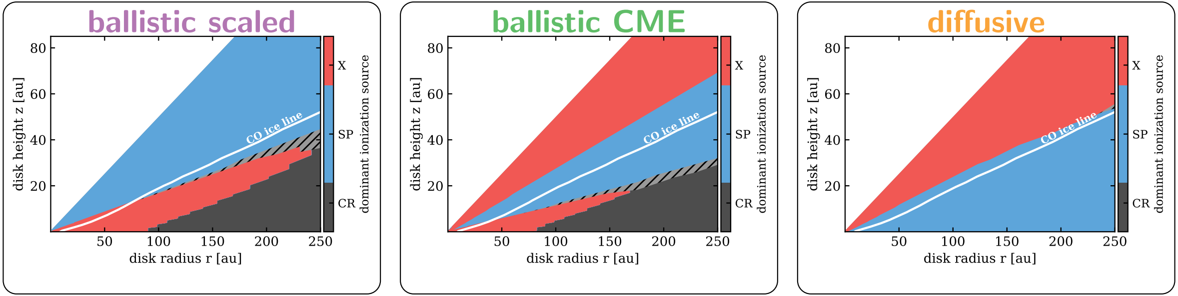
Frequency of super/mega X-ray flares



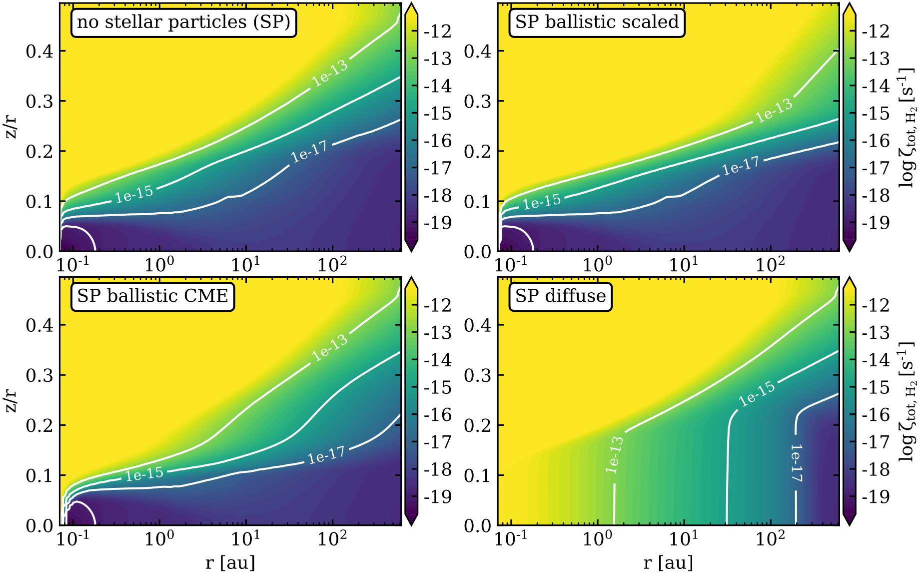
- **Getman & Feigelson (2021)**
- Chandra MYStIX and SFiNCs surveys, sample of 1,086 X-ray super-flares and mega-flares
- flares in young (PMS) stars are more energetic and more frequent by orders of magnitude than older (MS) stars

Impact particle transport models and spectra

- **"ballistic"**: continuous slowing-down approximation; no magnetic fields; two spectra: **"scaled"** and **"CME"**
- **"diffusive"**: propagation of particles; includes treatment of magnetic fields (Rodgers-Lee+ 2017)
- **low CR**, **norm X**



Tracing H_2 ionization rates (low CRs)



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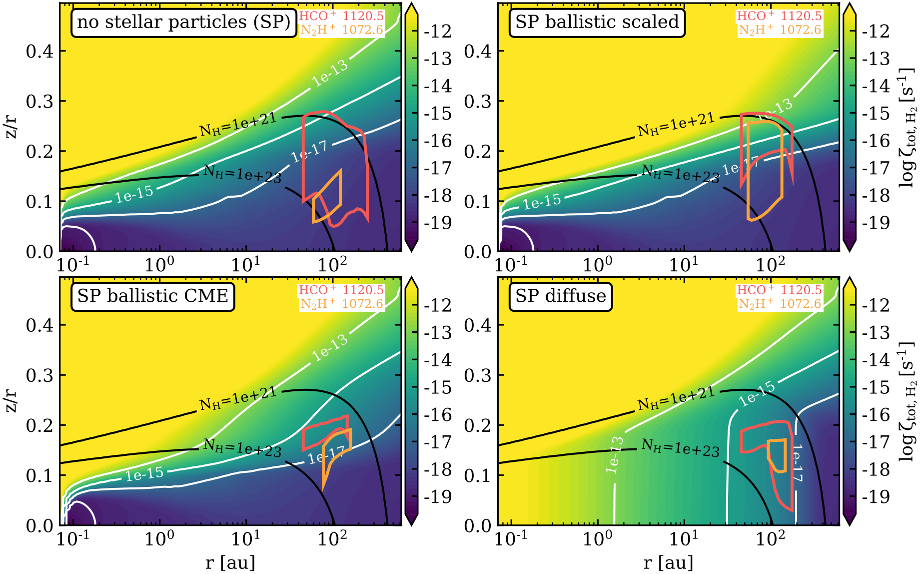
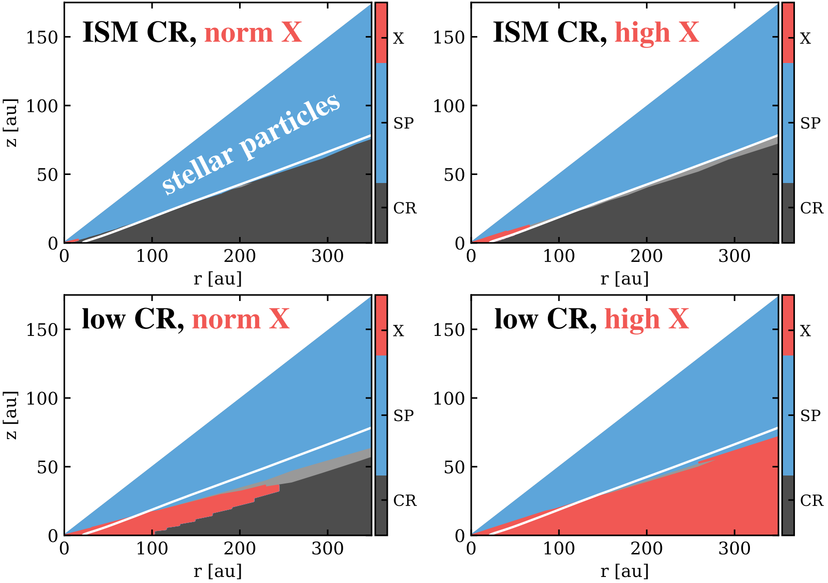


Dominant H_2 ionization source with SPs (ballistic)



Observables (ALMA) - ISM CR