Relic Proto-Stellar Disks as an Origin of Circumstellar Interaction in Core Collapse SNe

(astro-ph/1004.4215)

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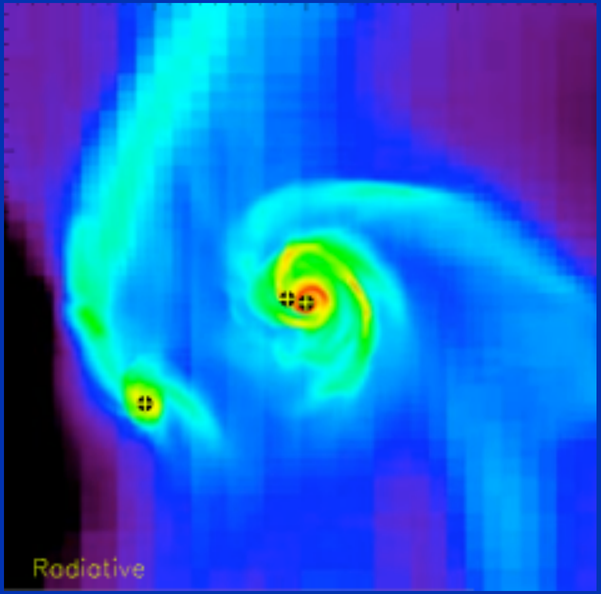
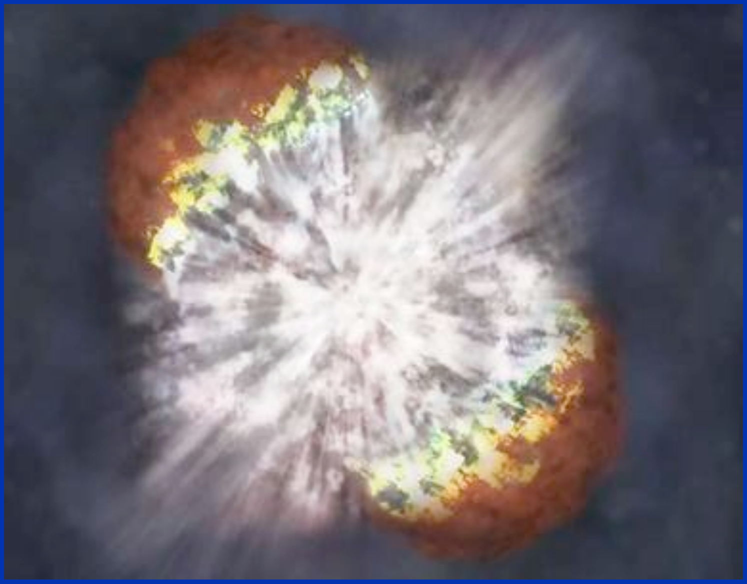
Krumholz et al. 2007





IAP Colloquium: “Progenitors & Environments of Stellar Explosions” 06.29.10

Very Luminous Core Collapse Supernovae

SN 06gy (Ofek+07; Smith+07,09,10), 06tf (Smith+08), 05ap (Quimby+05),
03ma (Rest+09), 07bi (Gal-Yam+09), 08fz (Drake+09), 08es (Gezari+09; Miller+09),
08iy (Miller+10), SCP 06F6 (Barbary+09), "PTF Events" (Quimby+09)

- **Bright:** Peak Luminosities (M_{peak} ~ -21 to -23)
- **Energetic:** E_{rad} up to ~ 10^{51} ergs
- Some (*but not all*) show **bright, narrow H emission** ("Type IIn")
- **Rare:** ~10^{-4} to 10^{-2} of Core Collapse SNe
- Related Oddballs? "Hybrid" Type I-IIn SN 2002ic (Hamuy et al. 2003) and 2005gj (Aldering et al. 2006; Prieto et al. 2007)
    - Type Ia into AGB-like Companion? (Livio & Riess 2003)
    - Type Ic Core Collapse into H-rich envelope? (Benetti et al. 2006)

Why so Bright?

Photon Diffusion Time

$$t_{\mathrm{diff}} \sim \tau R/c$$

=

Expansion Time

$$t_{\mathrm{exp}} \sim R/\mathrm{v}$$

Ideal Radius for Bright Emission

$$R_{\mathrm{peak}} \sim 100\ \mathrm{AU} \left(\mathrm{v}_{\mathrm{SN}} \big/ 10^{4}\ \mathrm{km\ s^{-1}} \right)^{1/2} \left(M_{\mathrm{SN}} \big/ 10 M_{\odot} \right)^{1/2}$$

Late-Time Energy Sources:

- Anomalously Large ^{56}Ni Yield

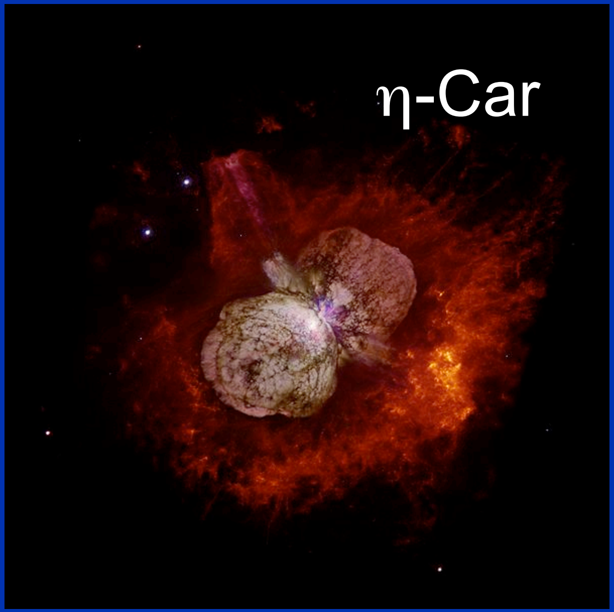
  (e.g. “hyper-novae” or pair instability Sne; e.g. Gal-Yam+ 09)
- Magnetar Spin-Down (Kasen & Bildsten 09; Woosley 09)
- **Circumstellar Interaction (Shock Heating)**
  - Very Luminous SNe require M_{CSM} ~1-10 $M_{\odot}$ at radii R ~ few hundred AU

Pre-Supernova Eruptions?

(e.g. Gal-Yam+05; Smith+07; Woosley+07)

- $\Delta T_{ejection}$ ~ 1-10 years
- Requires *Correlation* between Eruption and Core Collapse

⇒ 1) instability associated w late evolutionary stages or 2) delay btw pair instability pulsations (Woosley+07)



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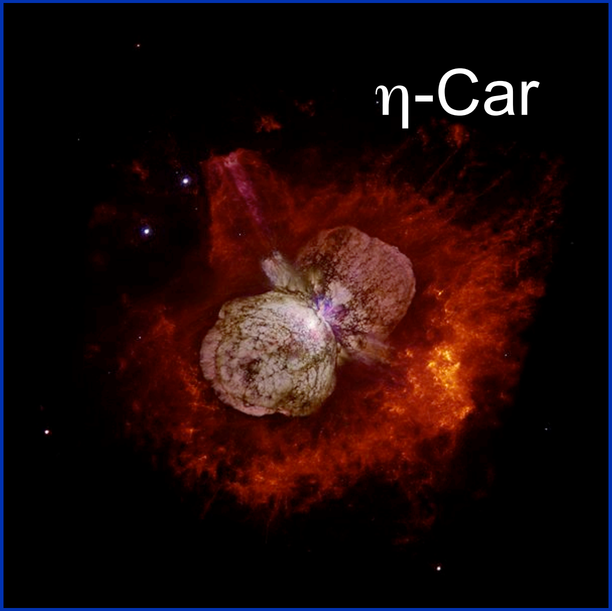

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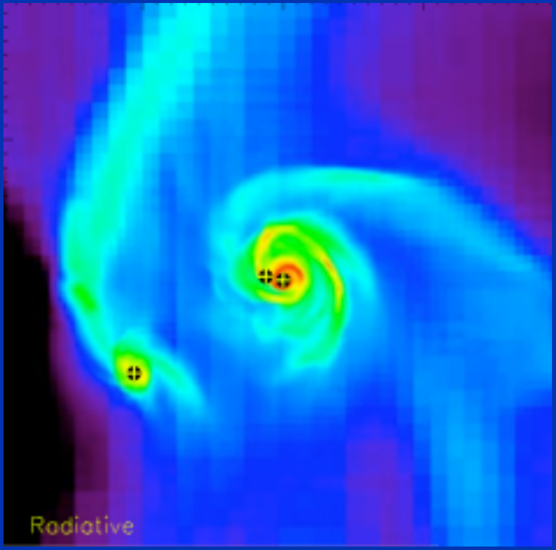
Relic Proto-Stellar Material?

(Lin & McCray 93)

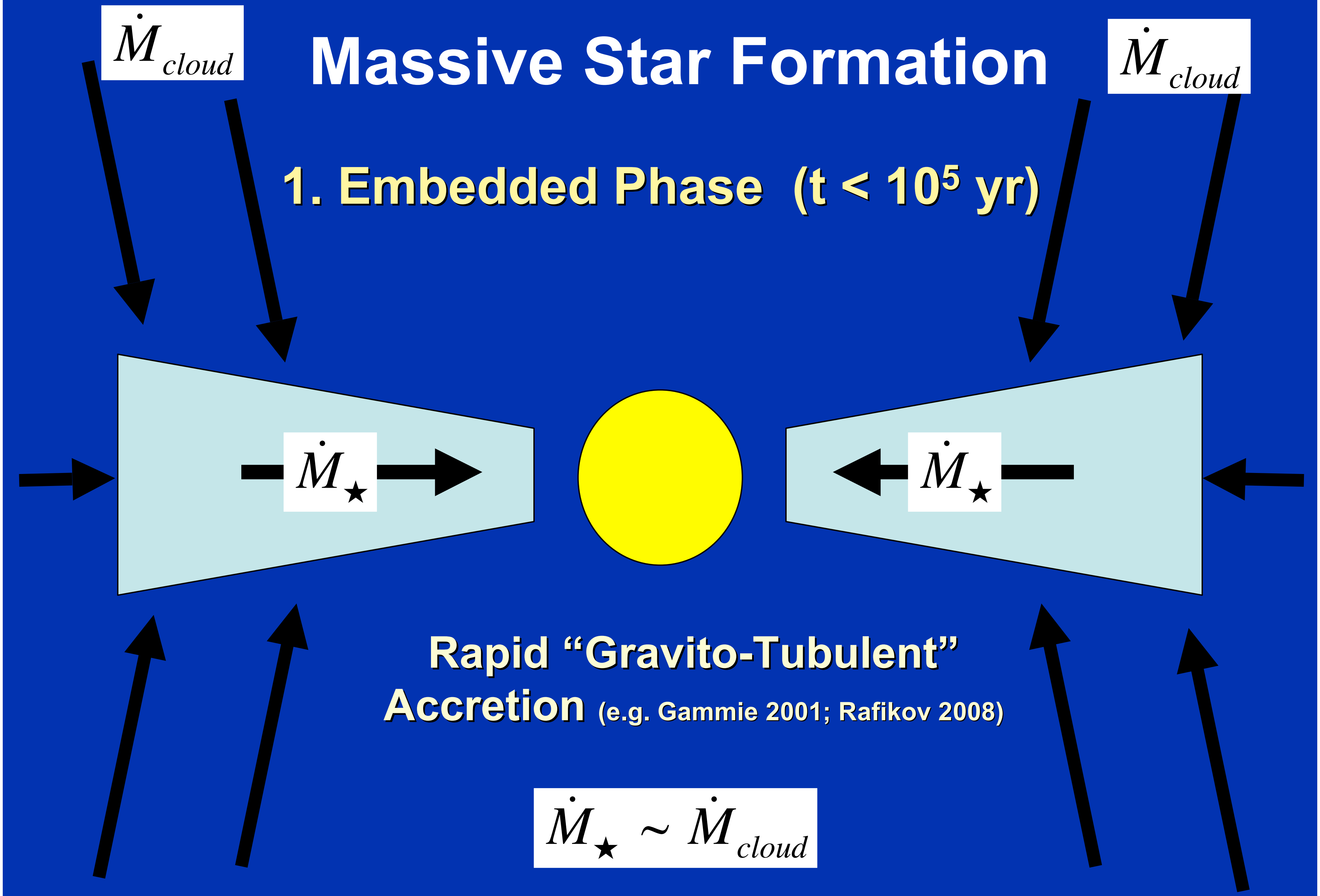
- Low mass proto-stellar disks live ~few Myr, similar to lifetimes of very massive stars
- Eliminates “coincidence” problem (CSM was *always* there)
- Hydrogen-rich CSM, even if progenitor not



Krumholz et al. 2007

Massive Star Formation

1. Embedded Phase (t < 10^5 yr)

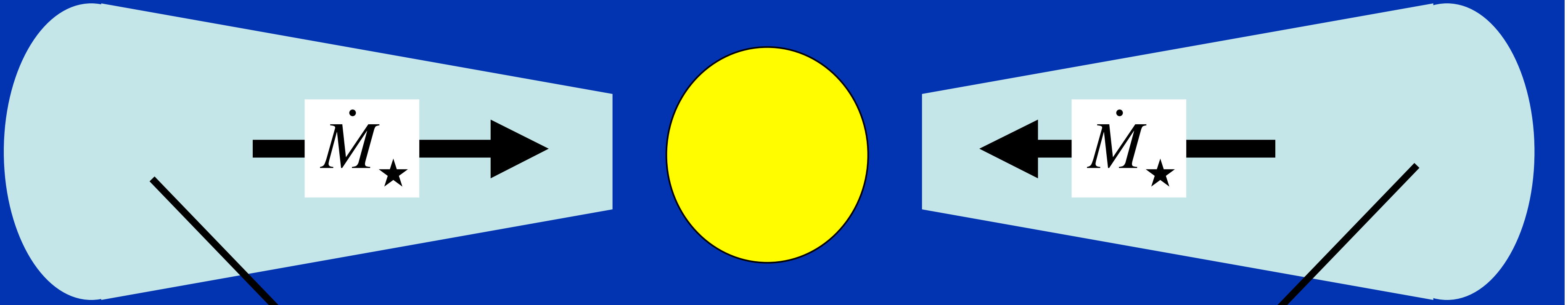


Rapid "Gravito-Tubulent" Accretion (e.g. Gammie 2001; Rafikov 2008)

$$\dot{M}_\star \sim \dot{M}_{cloud}$$

Massive Star Formation

2. Isolated Disk Evolution & Dispersal
(t > 10^5 yr)

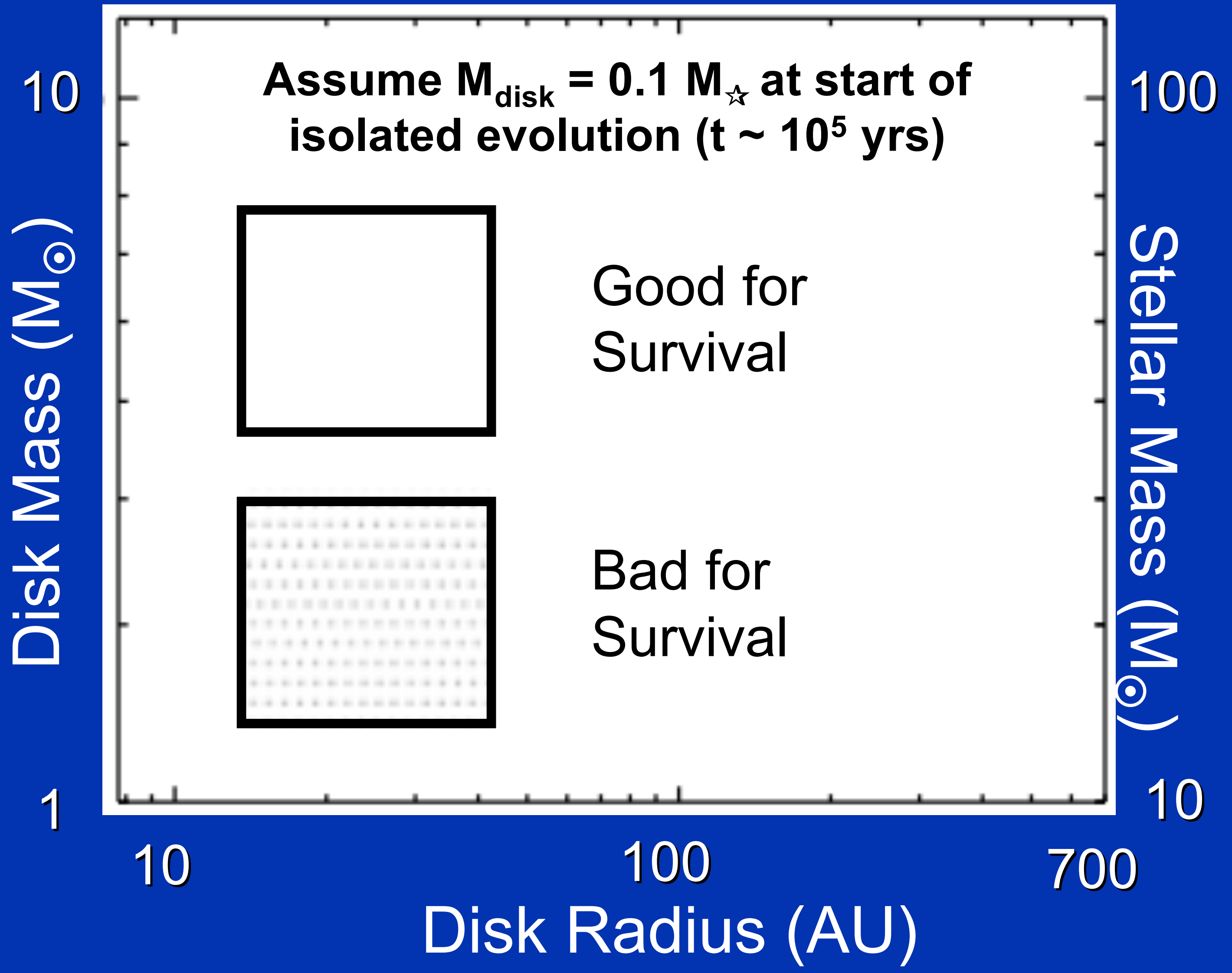


Gravitationally-Stable Accretion

$M_{disk} \sim 0.1 M_\star$

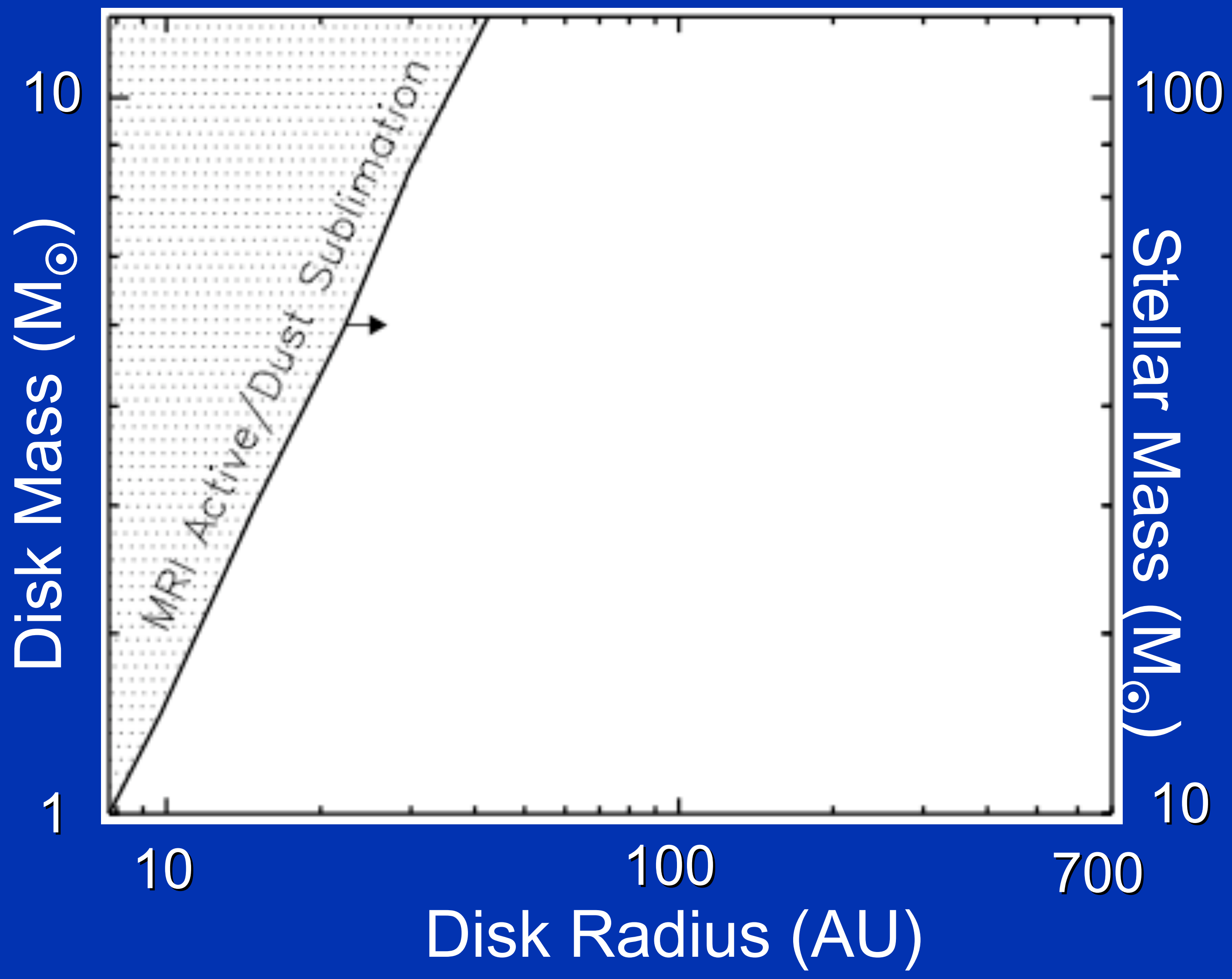
$R_{disk} \sim 10^2$-10^3 AU

Conditions for Disk Formation & Survival around Massive Stars (BDM 2010)



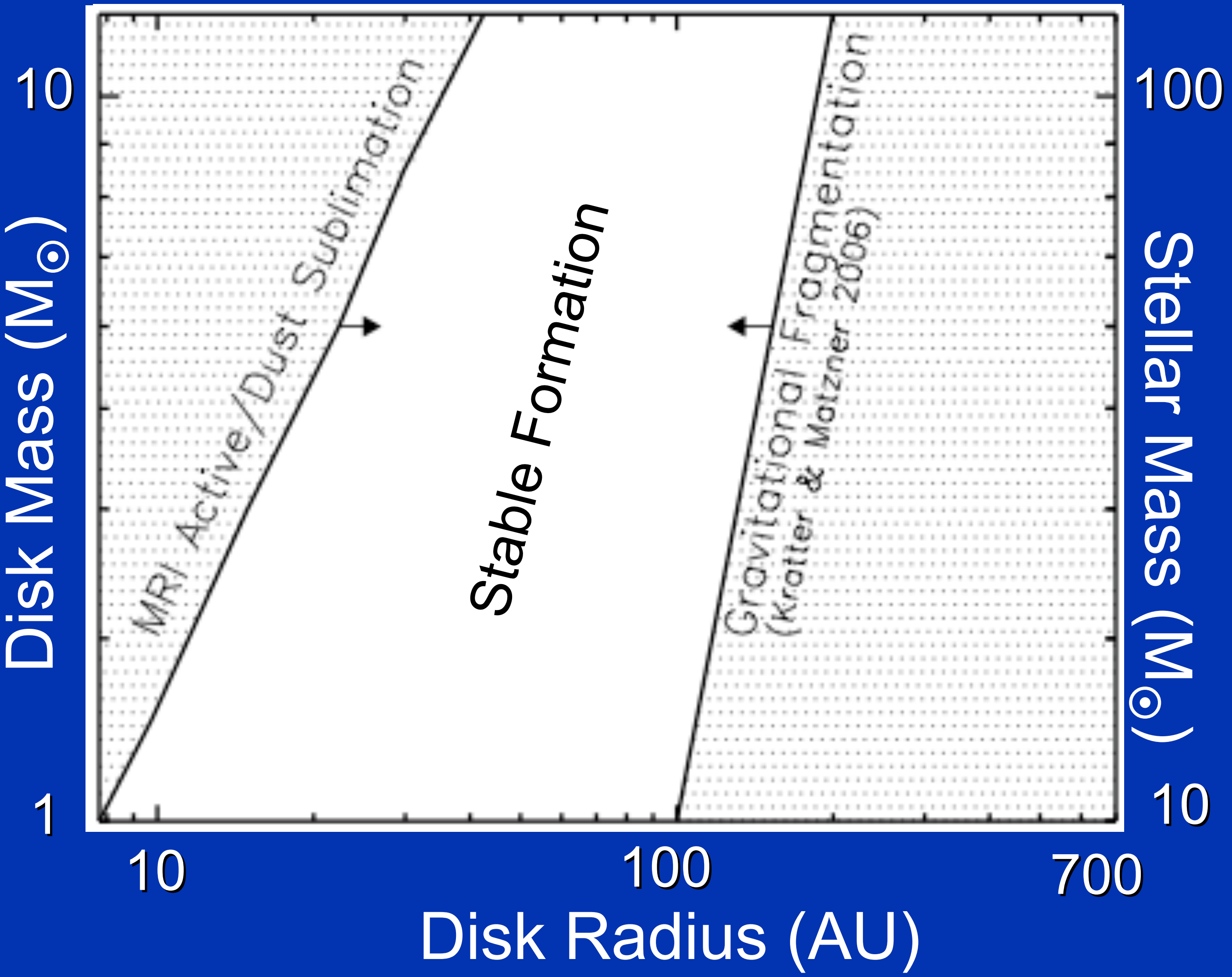
Assume $M_{disk} = 0.1\ M_{\star}$ at start of isolated evolution ($t \sim 10^5$ yrs)

Not Too Hot: T > 10^3 K ⇒ Dust Sublimation / Thermal-Ionization Activates MRI



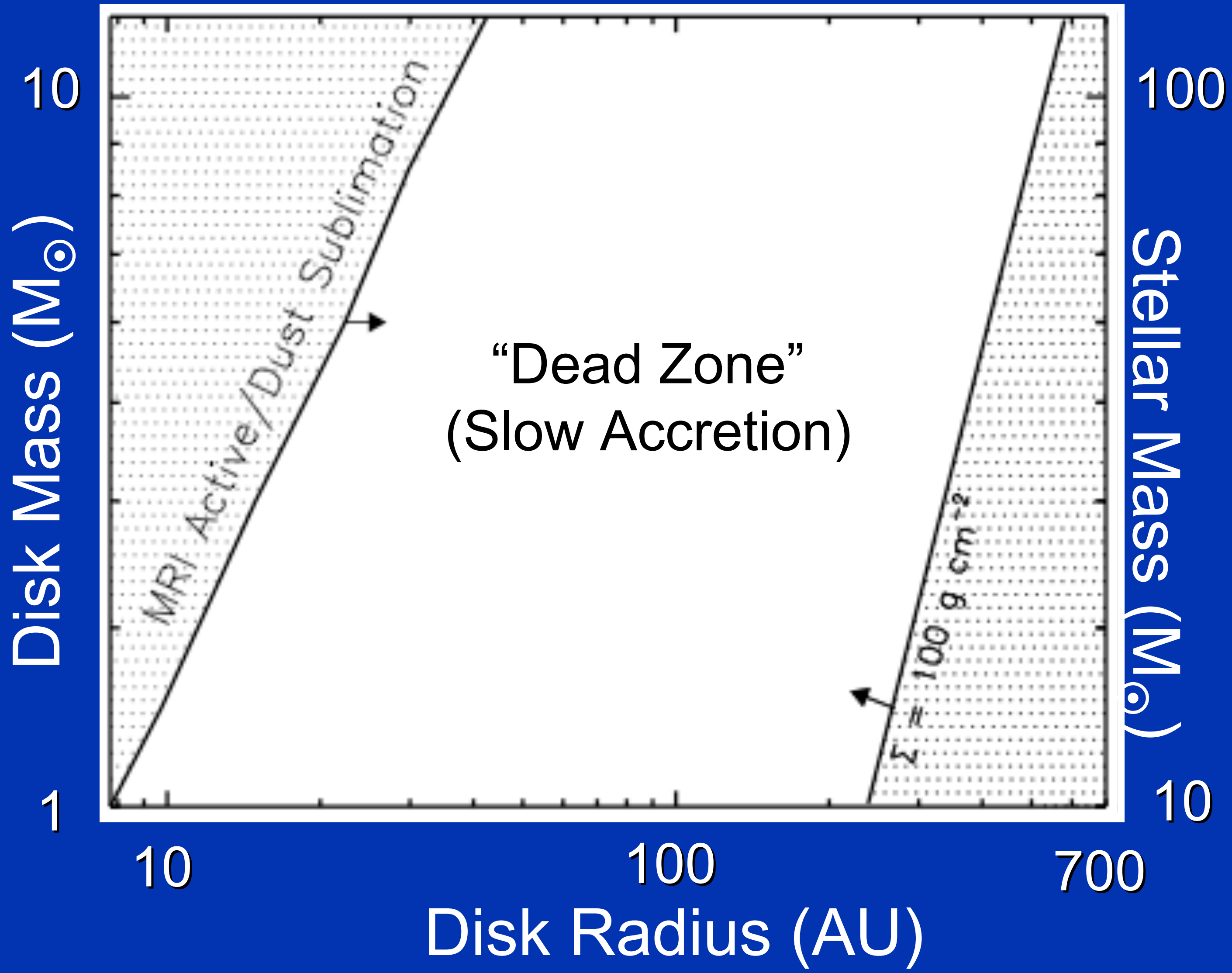
Not Too Cool: Gravitational Fragmentation

⇒Binary Companion(s) when $t_{cool} < \Omega^{-1}$ (Gammie 2001)



Ionization Shielding ($\Sigma > \Sigma_{cr} \sim 100$ g cm^{-2})

⇒ Magneto-Rotational Instability Suppressed



Accretion Time vs. Stellar Lifetime t_{life}~3-10 Myr

(for "suppressed" viscosity $\alpha = 10^{-3}$; Fleming & Stone 2003)

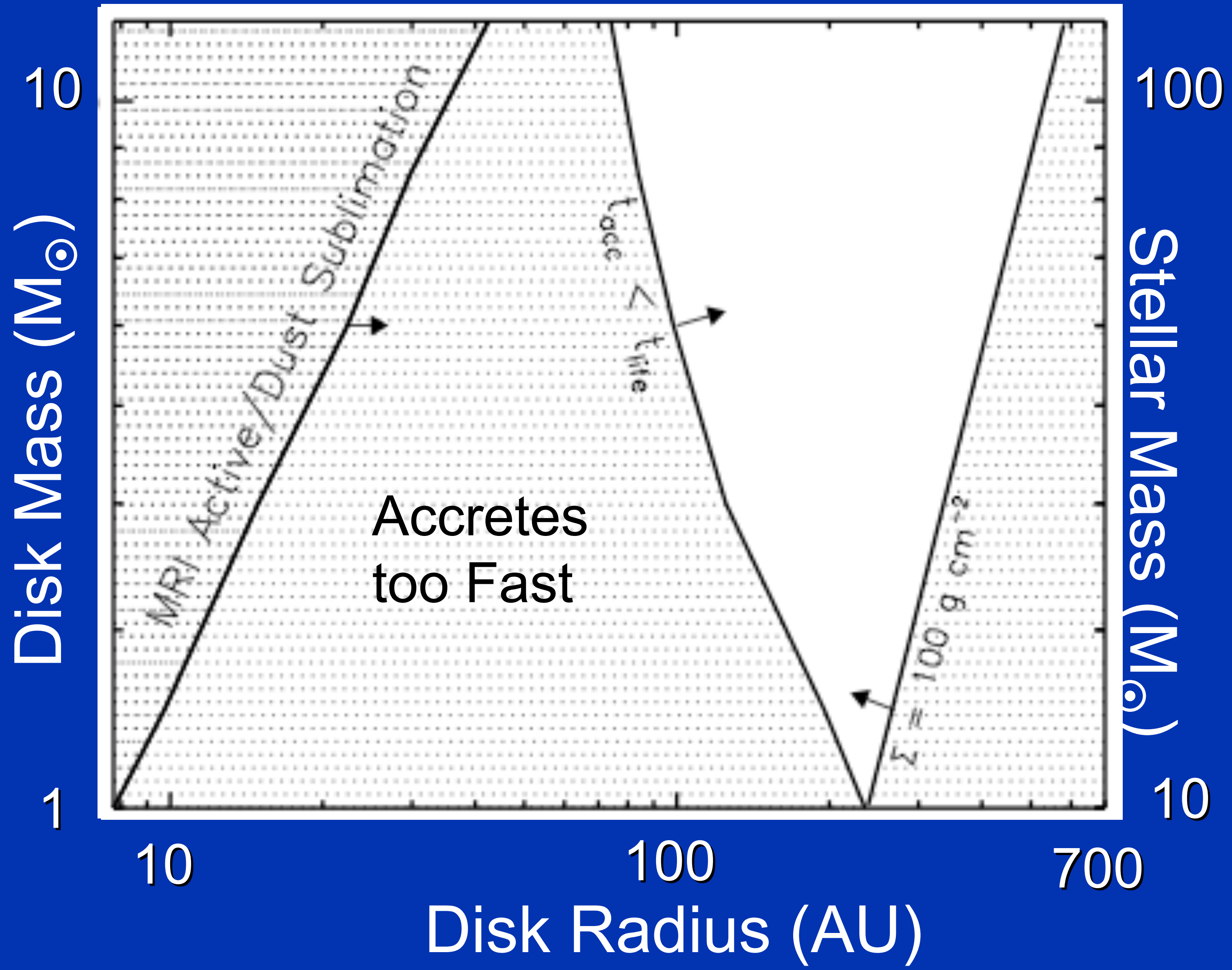
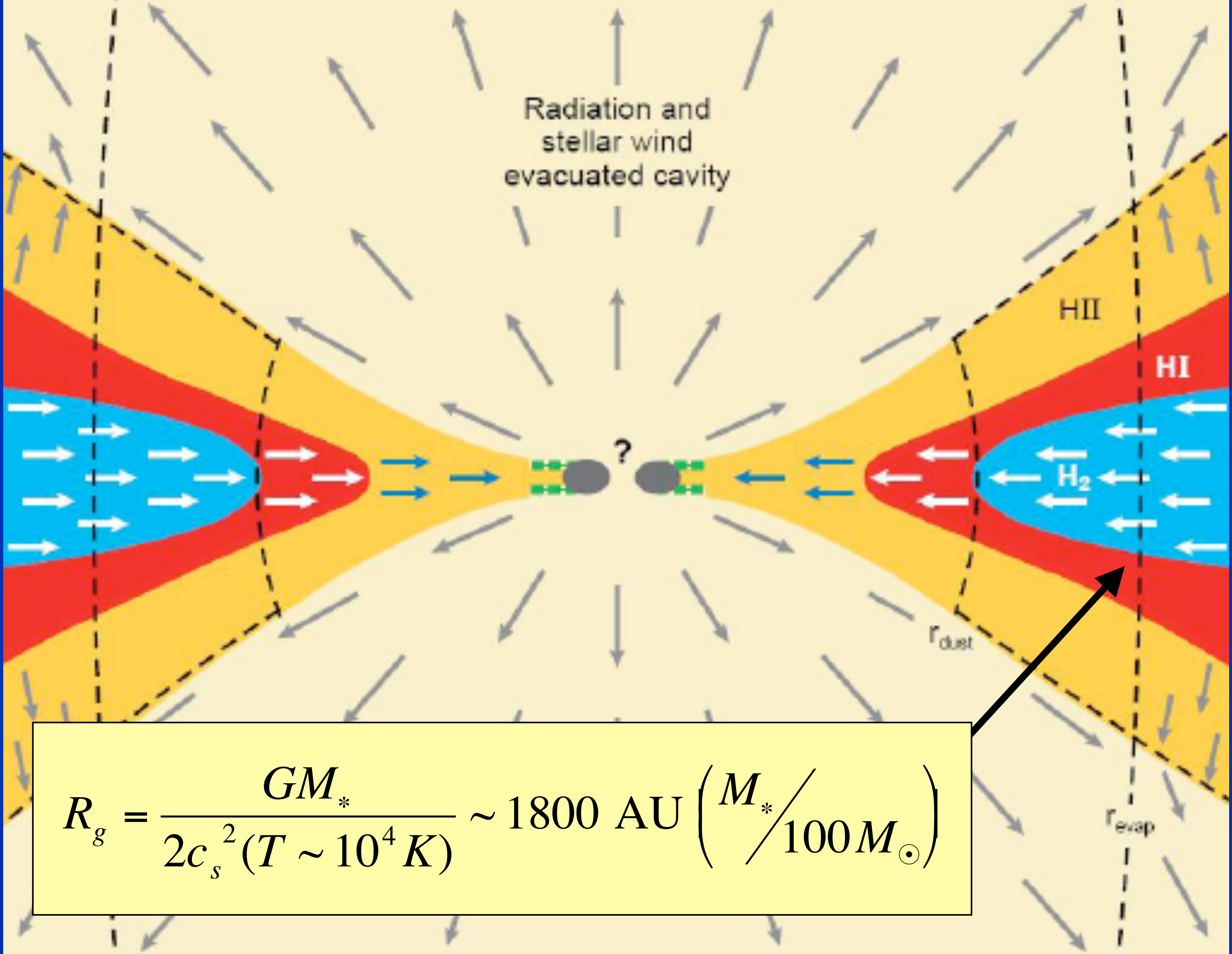


Photo-Evaporation (Hollenbach et al. 1994; Shu et al. 1993)



$$R_g = \frac{GM_*}{2c_s^{\,2}(T \sim 10^4 K)} \sim 1800 \text{ AU} \left({M_*}\big/{100 M_\odot} \right)$$

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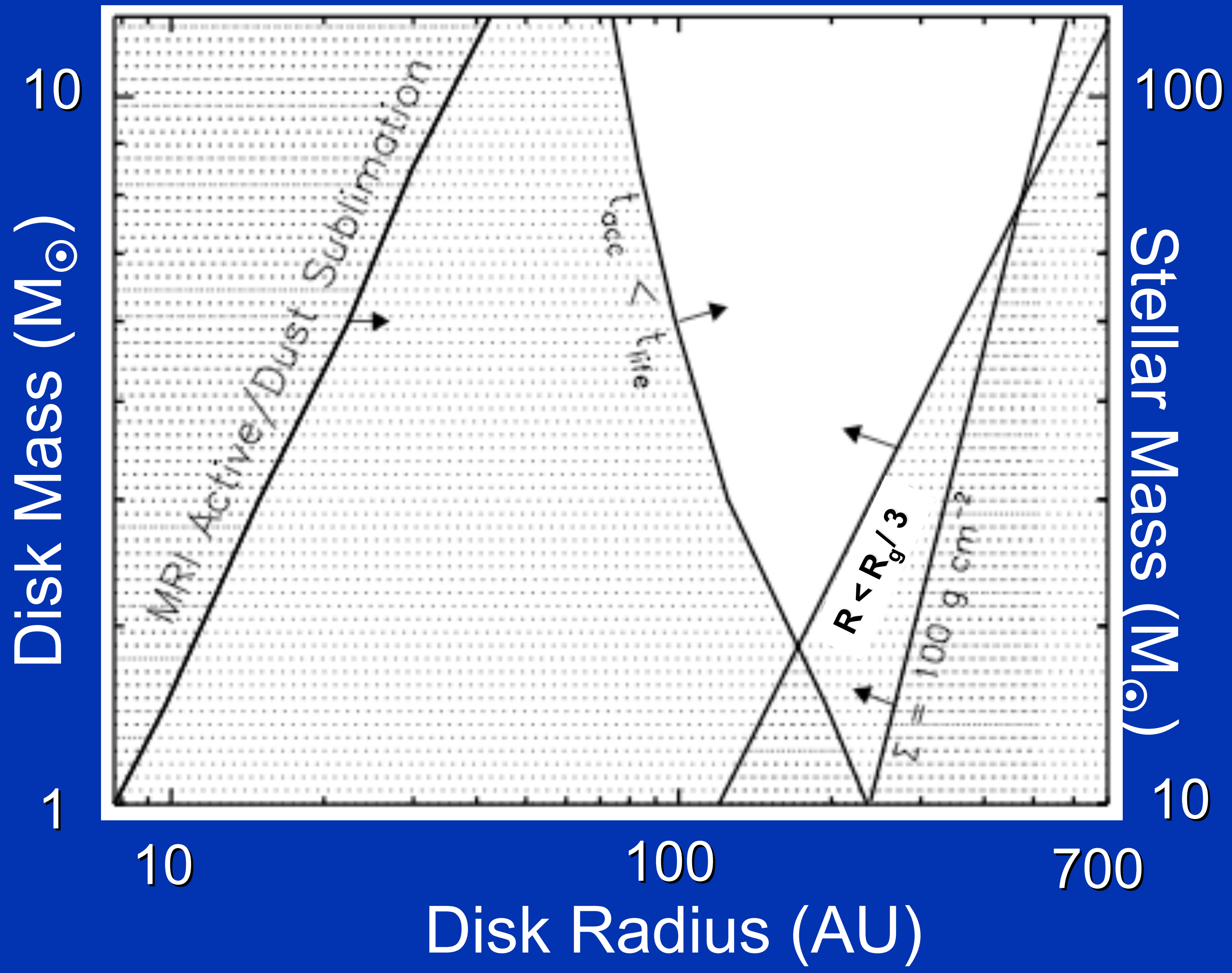
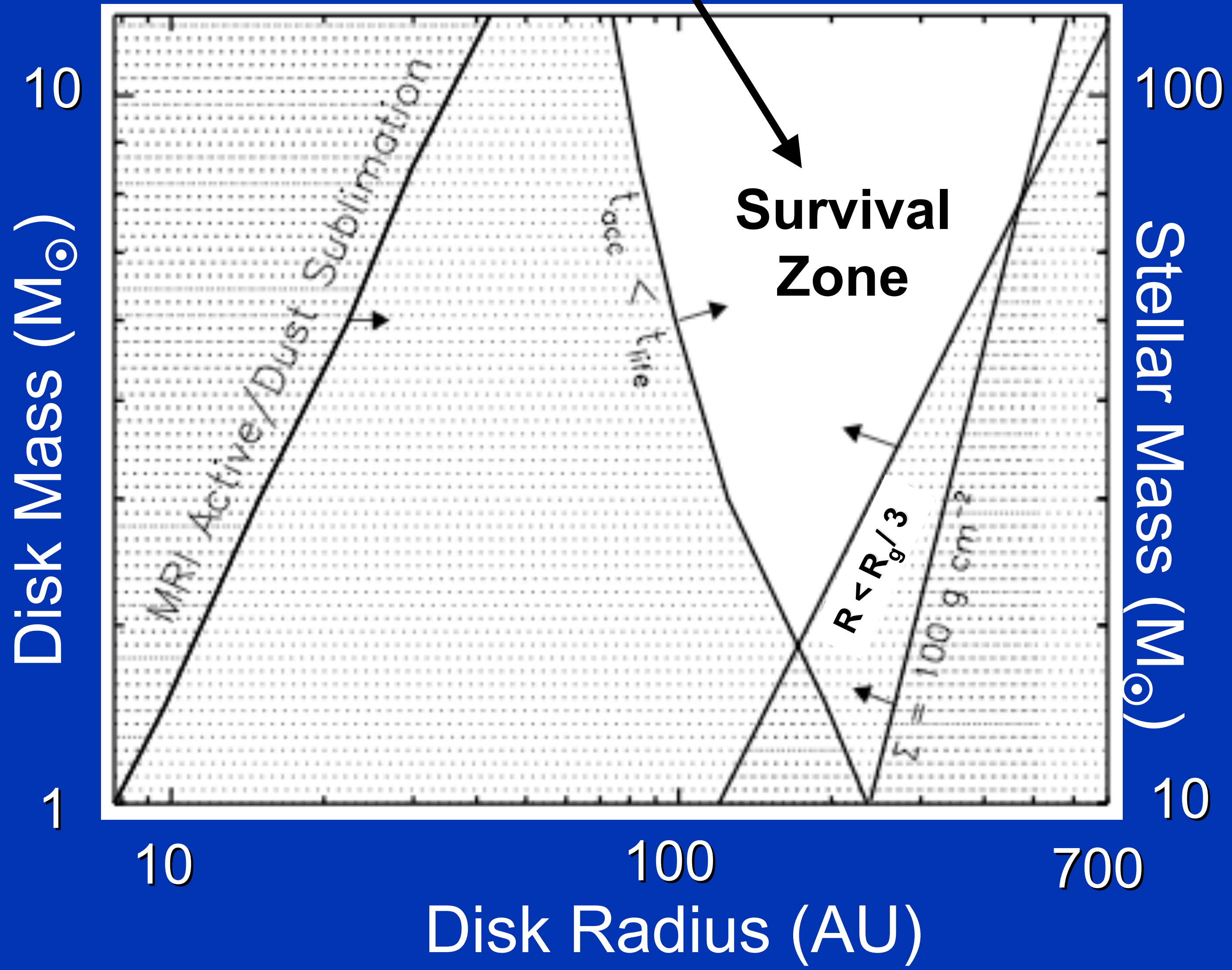


Similar to Inferred CSM Radii in VLSNe

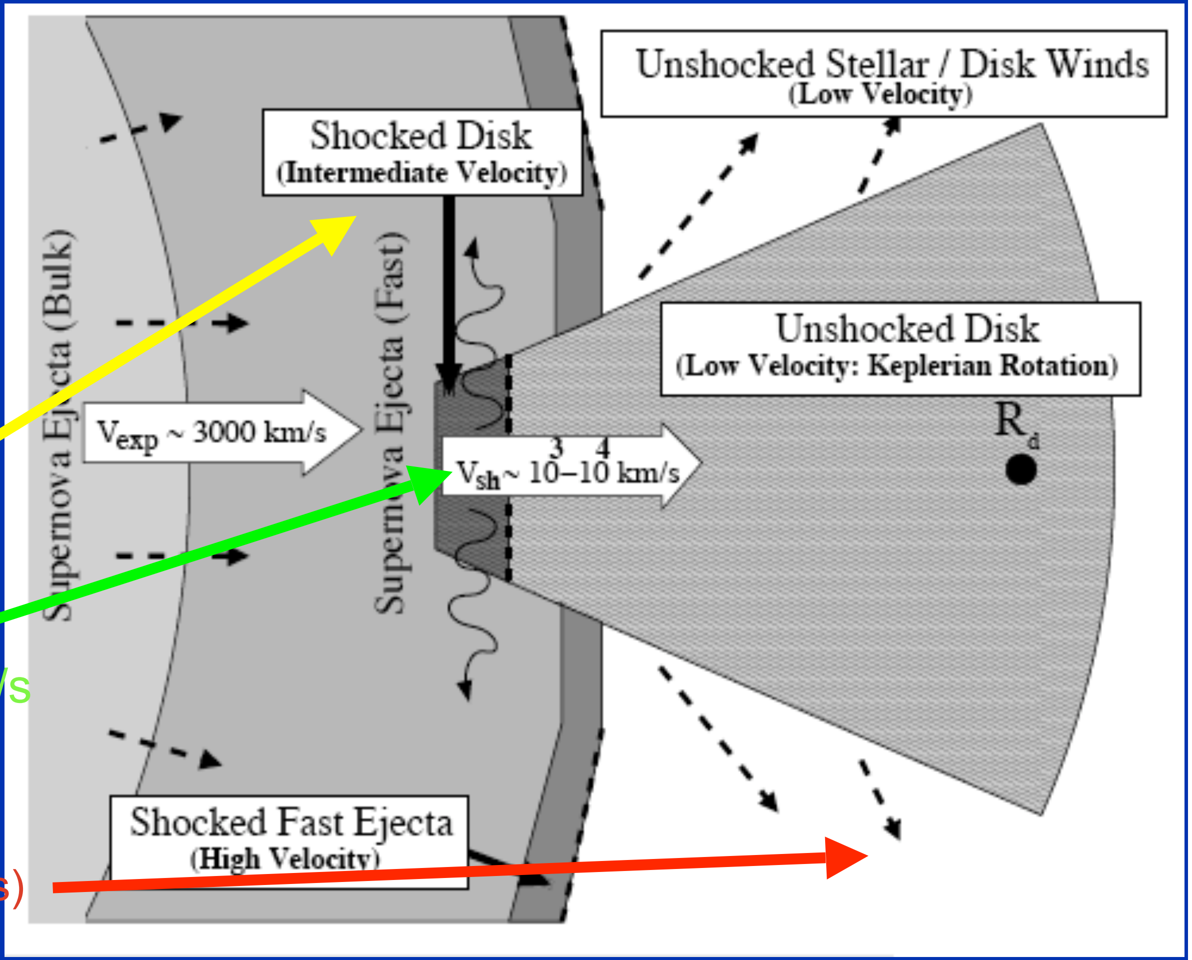
$$+R_{\mathrm{peak}} \sim 100\ \mathrm{AU} \left({}^{v_{\mathrm{SN}}}\!\Big/_{10^4\ \mathrm{km\ s^{-1}}} \right)^{1/2} \left({}^{M_{\mathrm{SN}}}\!\Big/_{10 M_\odot} \right)^{1/2}$$



Supernova Shock-Disk Interaction

- **Radiative Efficiency:** 10-20% (Disk Solid Angle)

- Velocity Components:
  - Broad ~ 10^4 km/s (SN Ejecta)
  - Intermediate ~ few 10^3 km/s (Shocked Disk)
  - Narrow ~ 10^2-10^3 km/s (Unshocked Disk & Stellar Winds)



(similar to model of Chugai & Danziger 1994)

Disk Photon Diffusion Vs. Ejecta Expansion Time
⇒ Bright Type IIn SNe Vs. *non*-IIn VLSNe

Prediction:
Long-Lived Disks around Very Massive Stars

- Relic disks should be observationally conspicuous
  - Luminous IR (and probably Hα) excess
- But in most systems, disk won't survive…
  - e.g. Binary companion, stellar collisions, etc.
  - Average compact HII region lifetime ~10% stellar lifetime (e.g. Churchwell et al. 1989; Churchwell 2002)
- Progenitors of Very Luminous SNe are rare
  - If VL-SNe constitute ~$10^{-3(4)}$ of CC SNe, then only ~3(30) progenitors alive now in Milky Way
  - Relic disks *not* the progenitors of all IIn (e.g. Yoon & Cantiello 2010)
- Local census of massive stars is incomplete
  - Observationally challenges (resolution, confusion, etc.)
  - How to distinguish "proto-star" from "evolved star + disk"

Conclusions

- **In most systems proto-stellar disk are dispersed, but survival may be possible for a subset of *the highest mass stars***
  - **Massive stars have short lifetimes**
  - **Massive star ⇒ massive disk ⇒ shielding from external ionization ⇒ slow accretion**
  - **Deep potential well ⇒ photo-evaporation ineffective**
- **If a disk does survive…**
  - **Likely to be massive with…**
  - **Typical radius ~ few 10^2 AU ⇒ Ideal for CSM interaction**
  - Several Potential Sources of Narrow Line Emission