Probing cosmic-ray particle acceleration in radio supernovae

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FELLOWS AT THE FRONTIERS 2016
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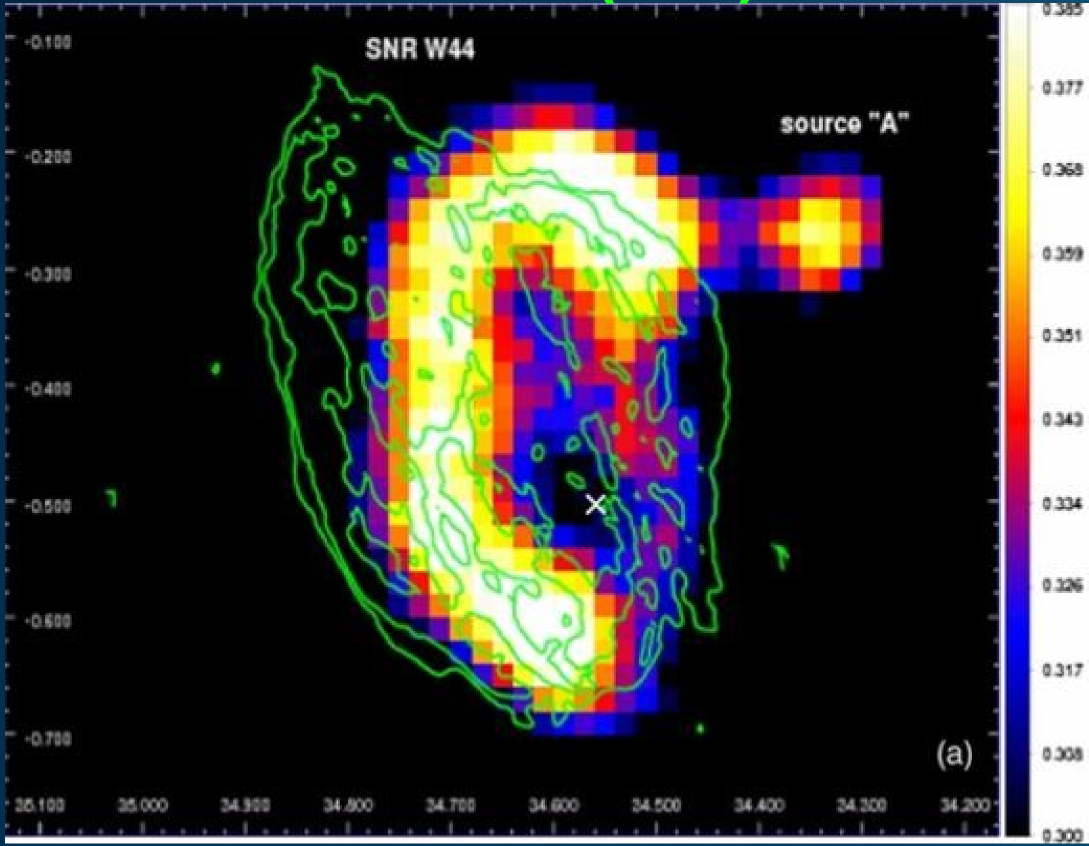
Motivation

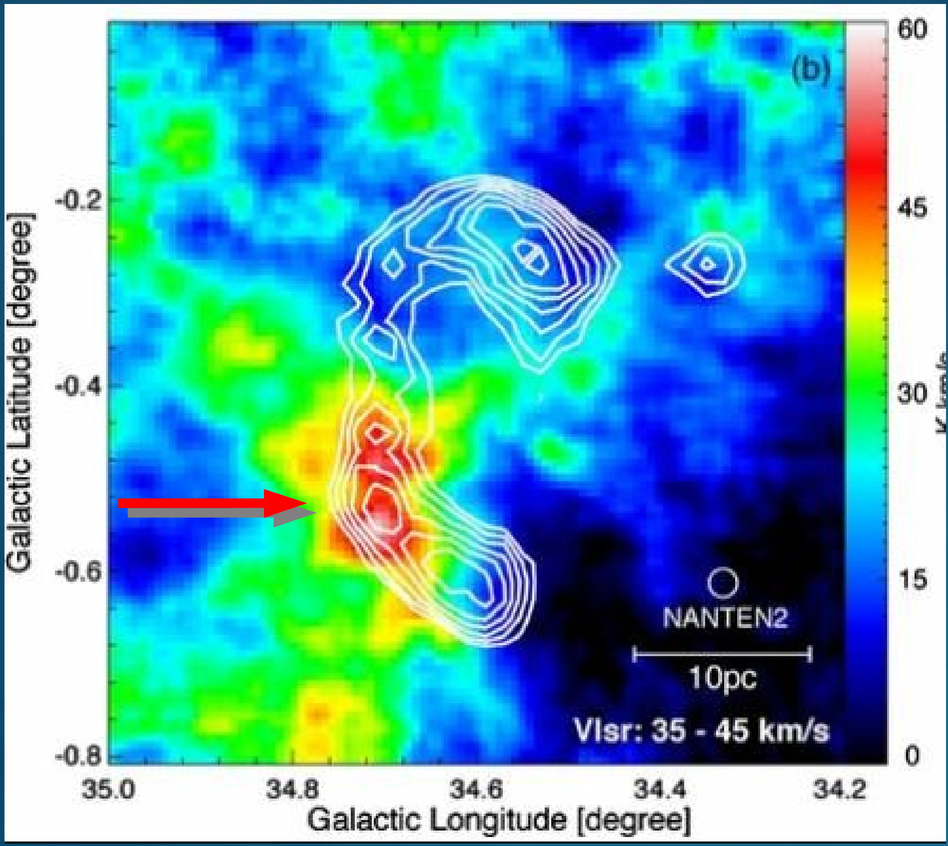
* Cosmic ray (CR) spectrum on Earth
* Evidence of CR acceleration in SNR

Color map: 400 MeV–3 GeV (AGILE)
Contours: 324 MHz (VLA)



Credit: Giuliani, 2011, ApJL, 742

Color map: CO (NANTEN2)
Contours: 400 MeV-3 GeV



Spatial correlation of dense molecular clouds & γ-rays

Probing CR acceleration

* Process? Inelastic pp collisions

* Probes? Emission from secondaries (γ-rays, electrons/positrons, neutrinos)

$$p + p \rightarrow p/n + \pi^{\pm} + \pi^{0}$$

$$\pi^{0} \rightarrow \gamma + \gamma$$

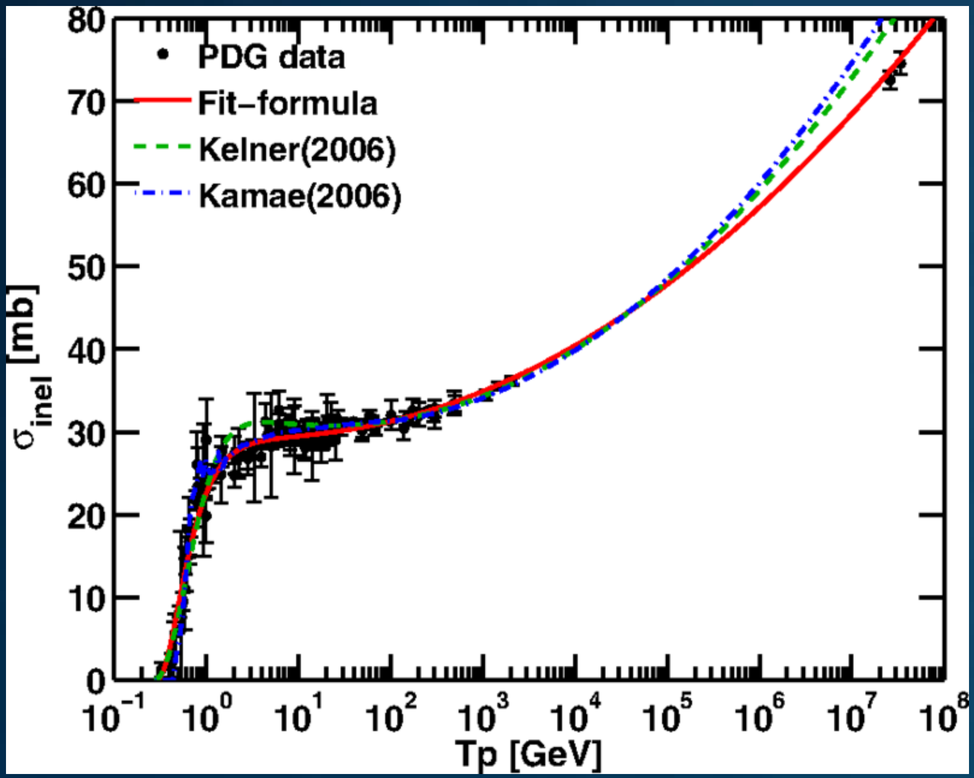
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}/\bar{\nu}_{\mu}$$

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{\mu}/\bar{\nu}_{\mu} + \nu_{e}/\bar{\nu}_{e}$$

* Requirements? Relativistic p and dense environments

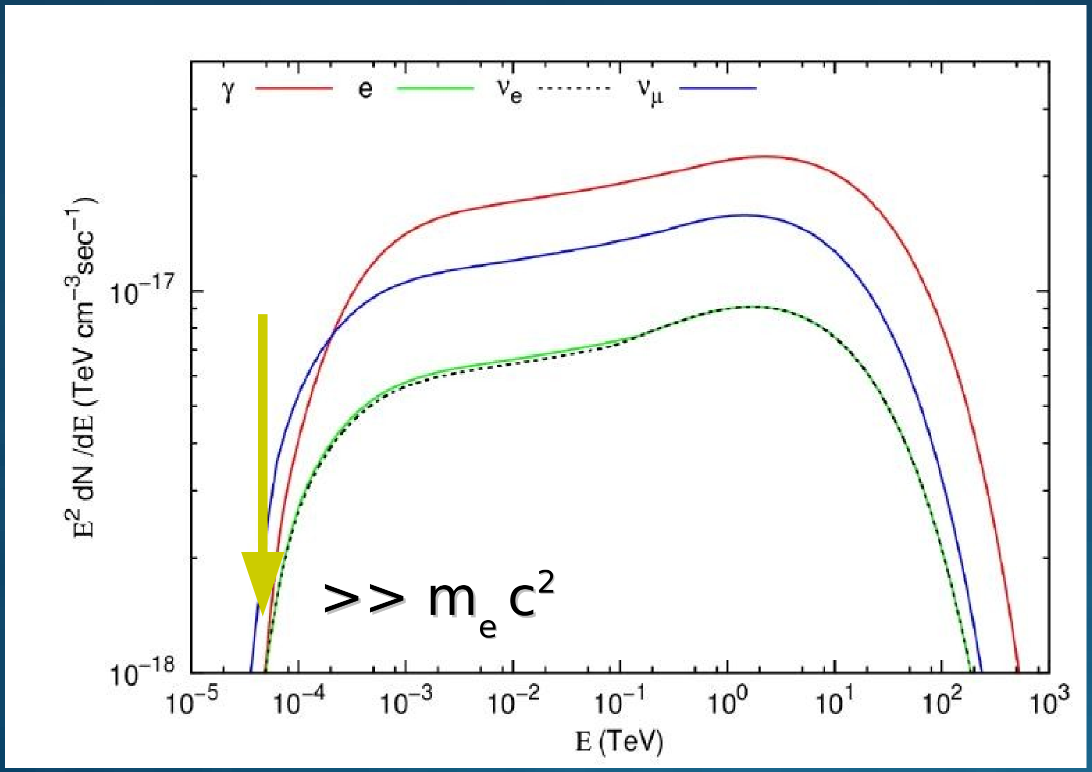
Pp collisions

Cross section << σ_T



Credit: Kafexhiu et al. 2014, PhysRevD, 90

Secondary particle energy spectra



Credit: M.Sc. Thesis by D. Kantzas

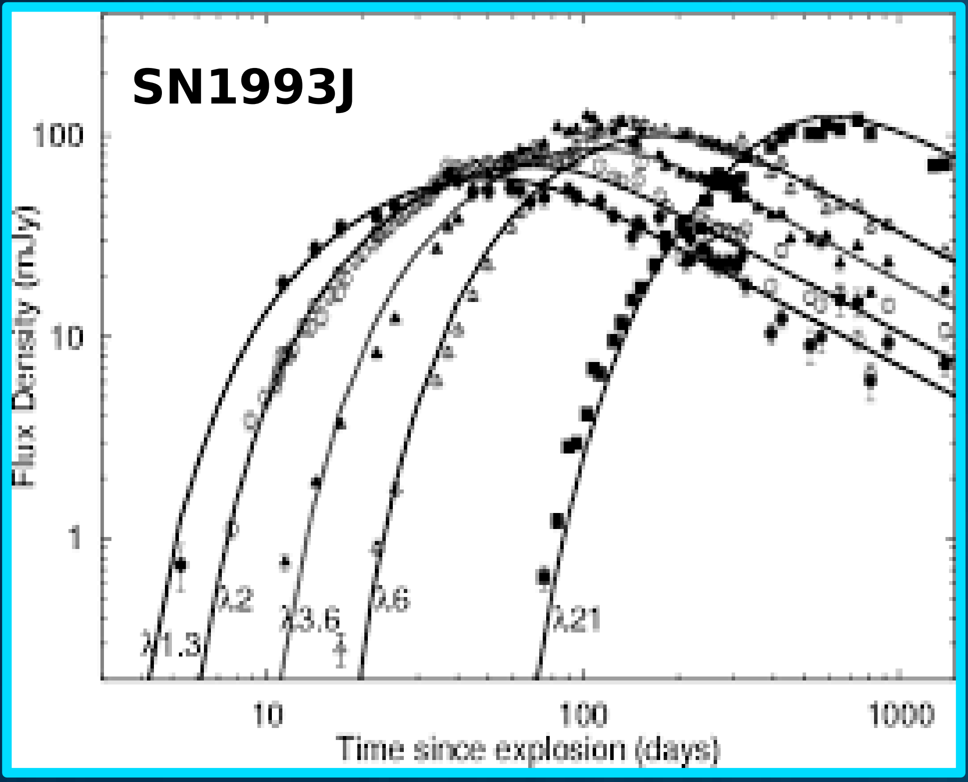
Optical depth for pp collisions:

$$\tau_{pp} = \frac{R\,\sigma_{pp}\,n\,c}{v_{sh}} \simeq 6 \left(\frac{A_w}{M_{sun}\,yr^{-1}}\right)\left(\frac{10^{14}\,cm}{R}\right)\left(\frac{5000\,km\,s^{-1}}{v_{sh}}\right)$$

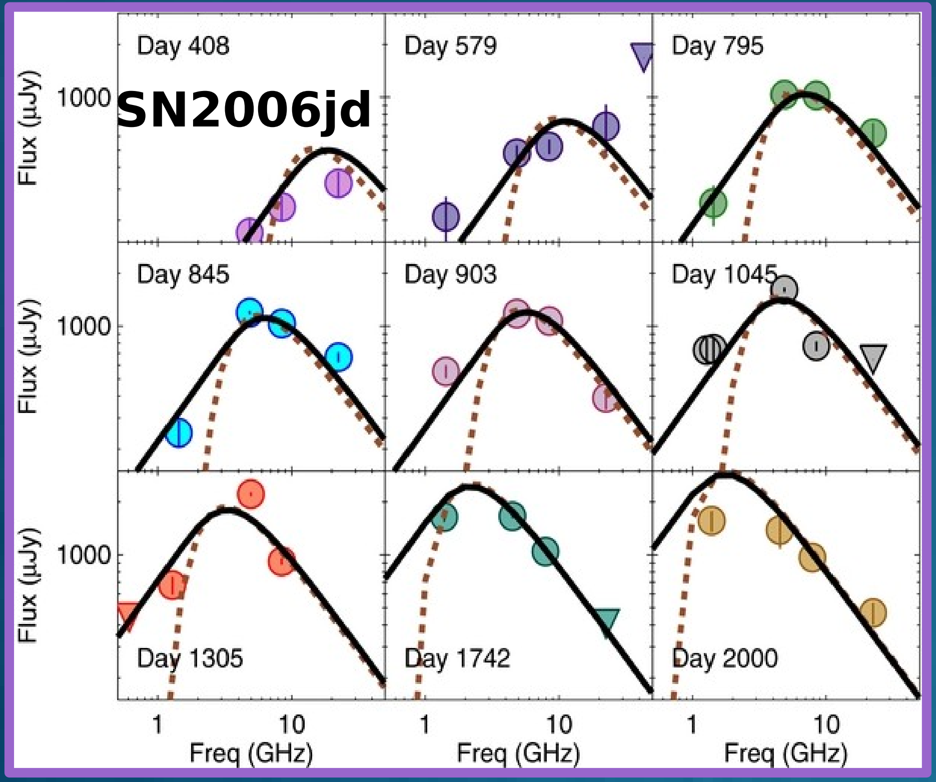
* **Dense CSM**
* **Slow shocks**

Radio SNe

- Interaction powered (e.g. Type IIn, superluminous SNe)
- Dense CSM (n>1e7 cc)
- Radio emission few 10-100 days after explosion
- Radio emission absorbed at early times



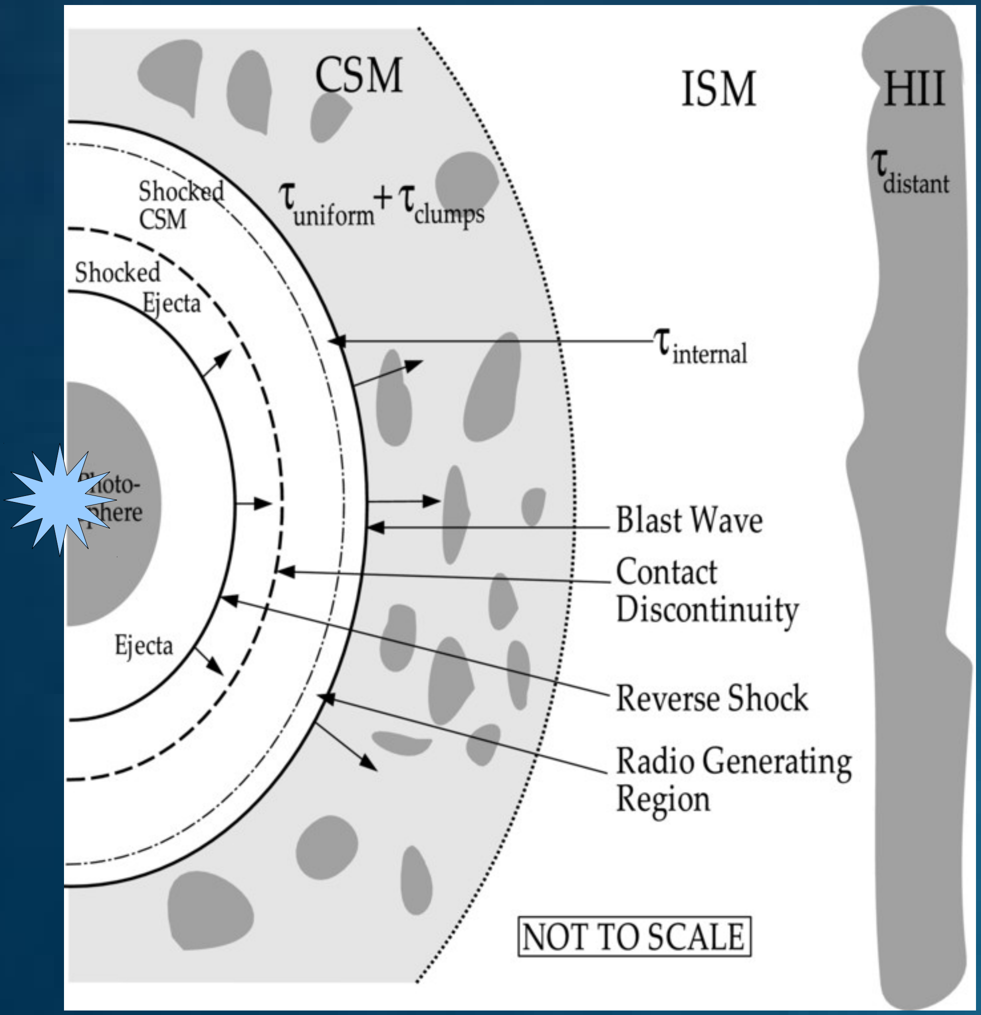
Credit: Perez-Torres et al. 2001, A&A, 374



Credit: Chandra et al. 2012, ApJ, 755

Radio SNe: current understanding

(Chevalier 1982, Chevalier 1998, Weiler 2001 +++)

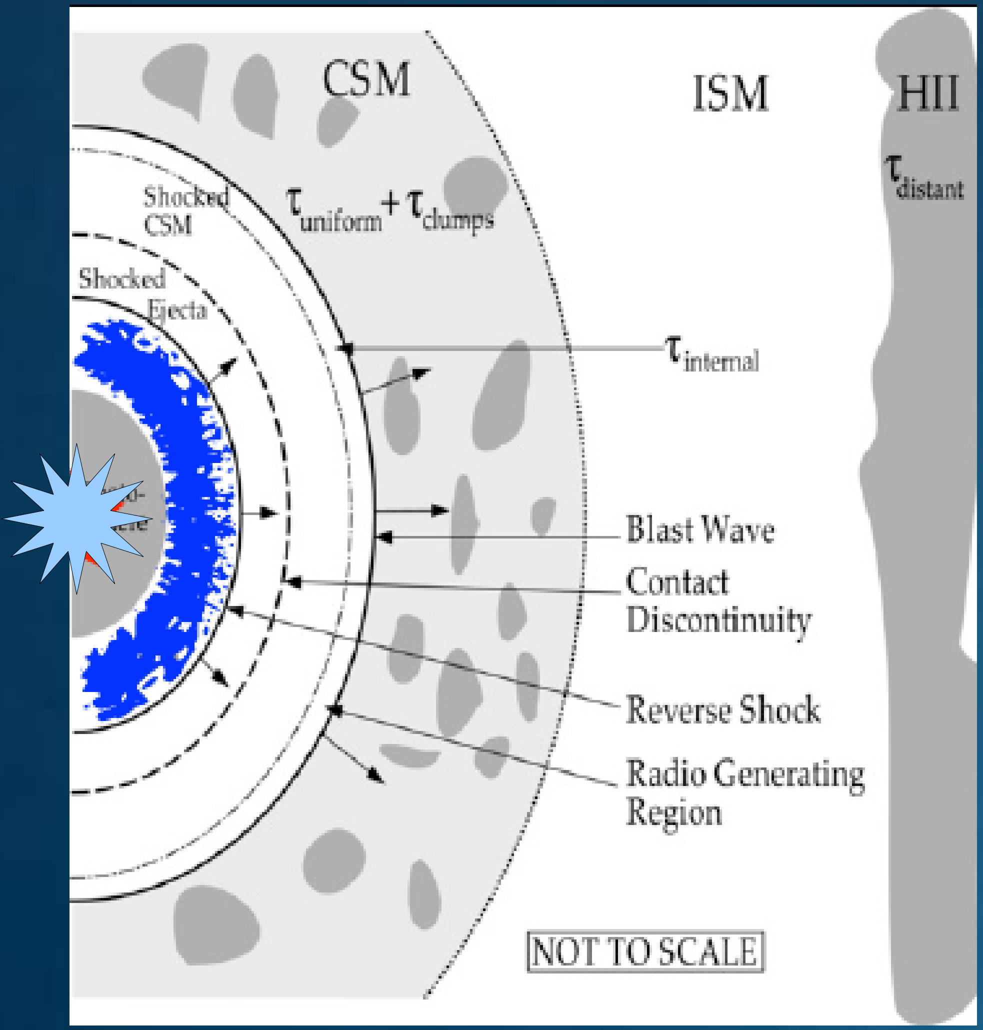


Credit: Weiler et al. 2002, ARA&A, 40

Radio SNe: current understanding

(Chevalier 1982, Chevalier 1998, Weiler 2001 +++)

Optical
emission
T ~ 6000 K



Credit: Weiler et al. 2002, ARA&A, 40

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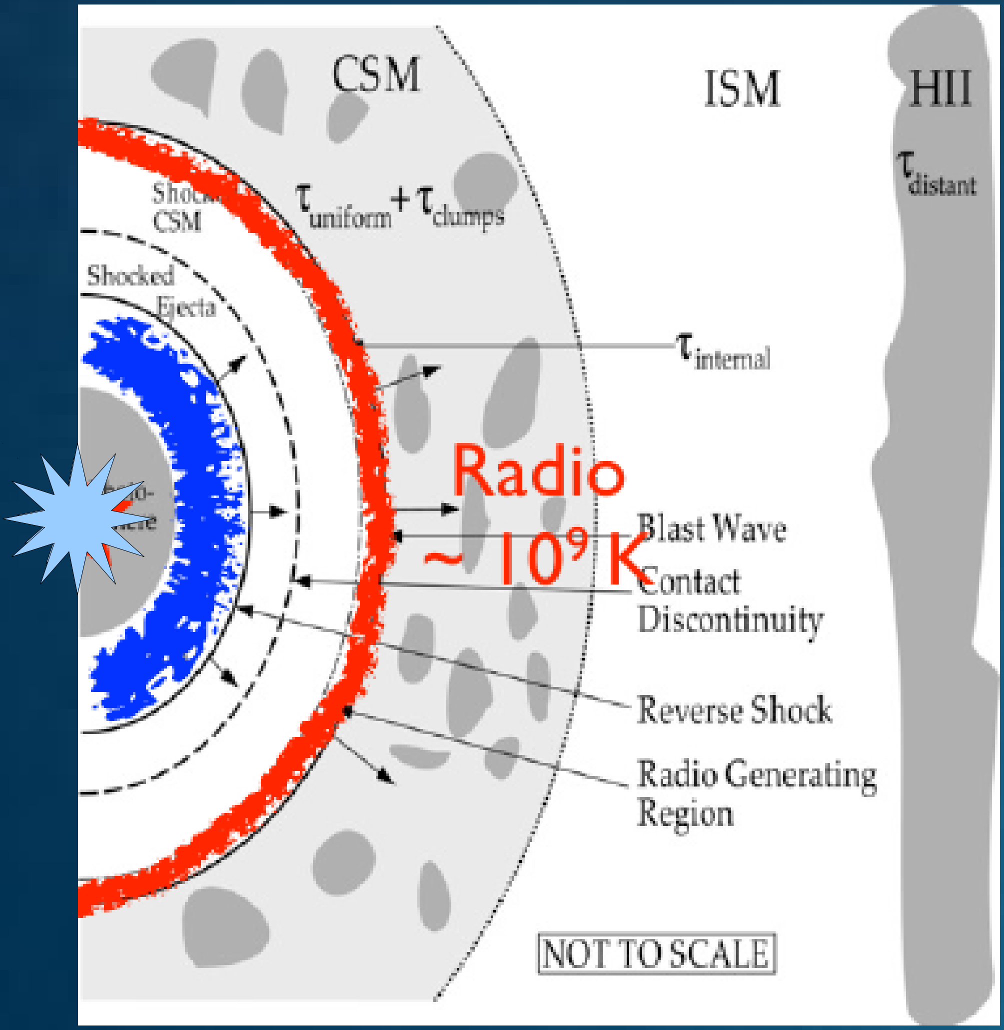
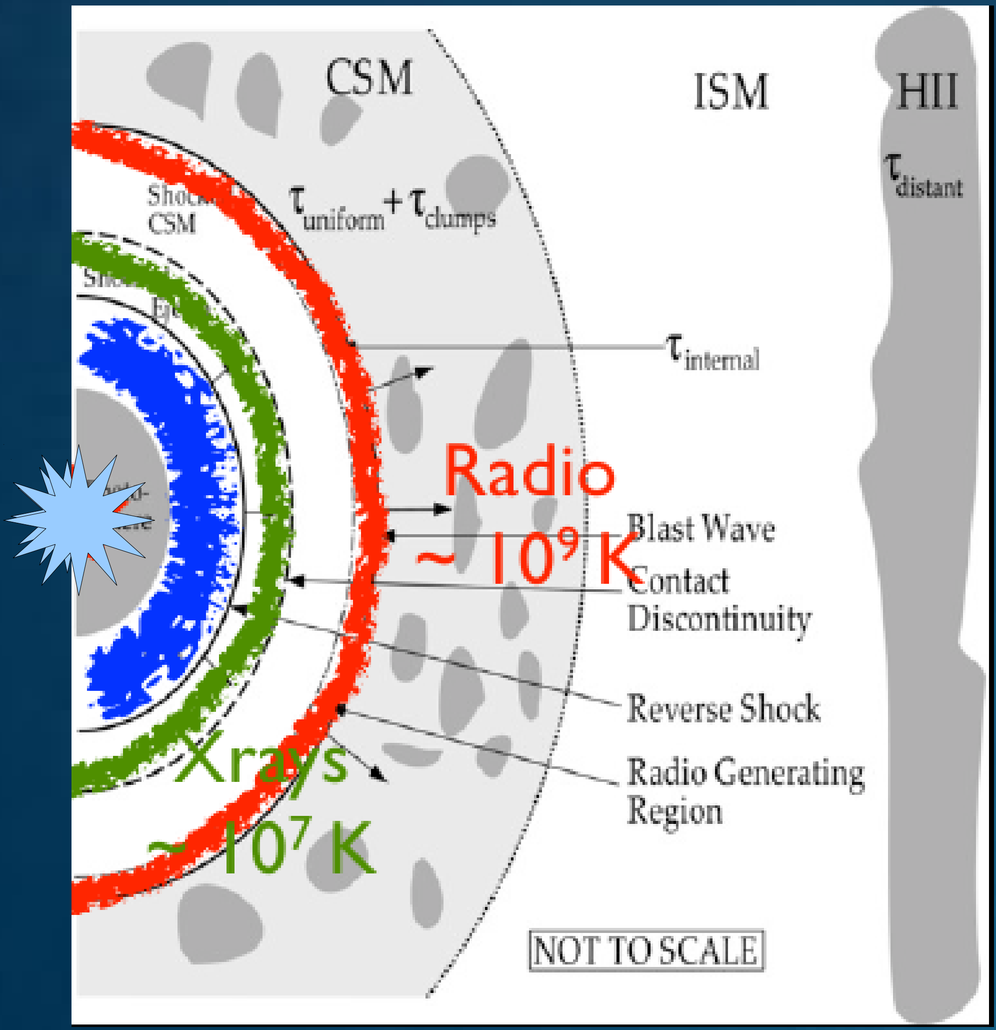


Credit: Weiler et al. 2002, ARA&A, 40

Radio SNe: current understanding

(Chevalier 1982, Chevalier 1998, Weiler 2001 +++)



Pp collisions in radio SNe ?

(Murase et al. 2014, MNRAS, 440)

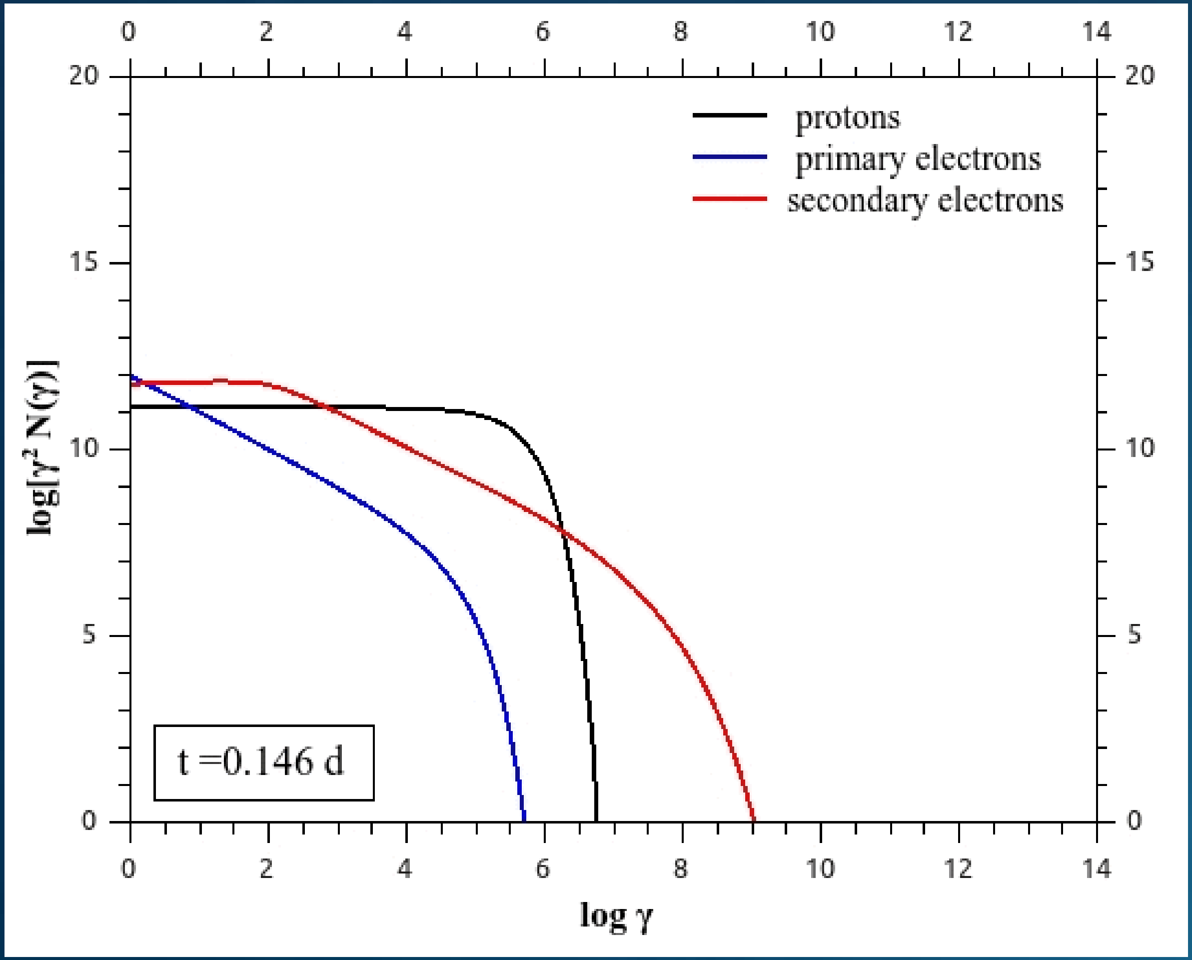
Credit: Weiler et al. 2002, ARA&A, 40

Model ingredients *(Petropoulou, Kamble, Sironi 2016, MNRAS)*

Novelty: Addition of secondary electrons from pp collisions → particle evolution → spectra & light curves

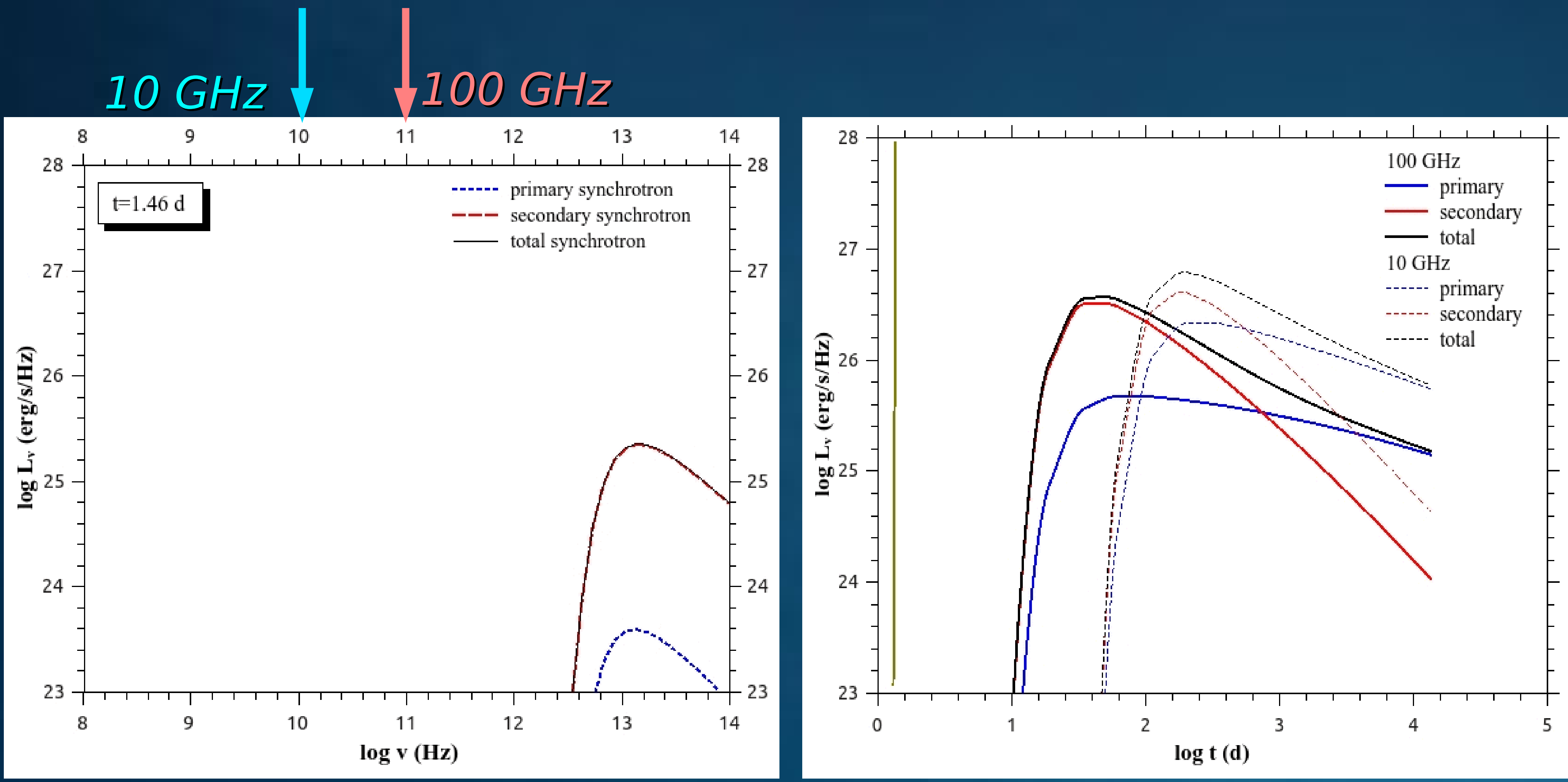
- **Shock dynamics:** free expansion (v_{sh}: shock velocity)
- **CSM:** power-law density profile *(A_w: mass loading parameter, w: power-law index, r_{bo}: shock breakout radius)*
- **Particle injection**: power-law distributions with exp. cutoff *(s: power-law index, K_{ep}: electron-to-proton ratio, ε_p: proton acceleration efficiency, E_{min}: minimum particle energy, E_{max}: maximum particle energy)*
- **Physical processes:** adiabatic expansion, pp collisions, synchrotron emission and absorption (SSA), free-free absorption (FFA)
- **Particle evolution:** injection + cooling processes

Evolution of particle distributions



Parameters: v_{sh}=9000 km/s, A_w=10^{16} gr/s (0.05 M_{sun} /yr), Mej=10M_{sun}, εB=0.01, εp=0.1, K_{ep}=0.001

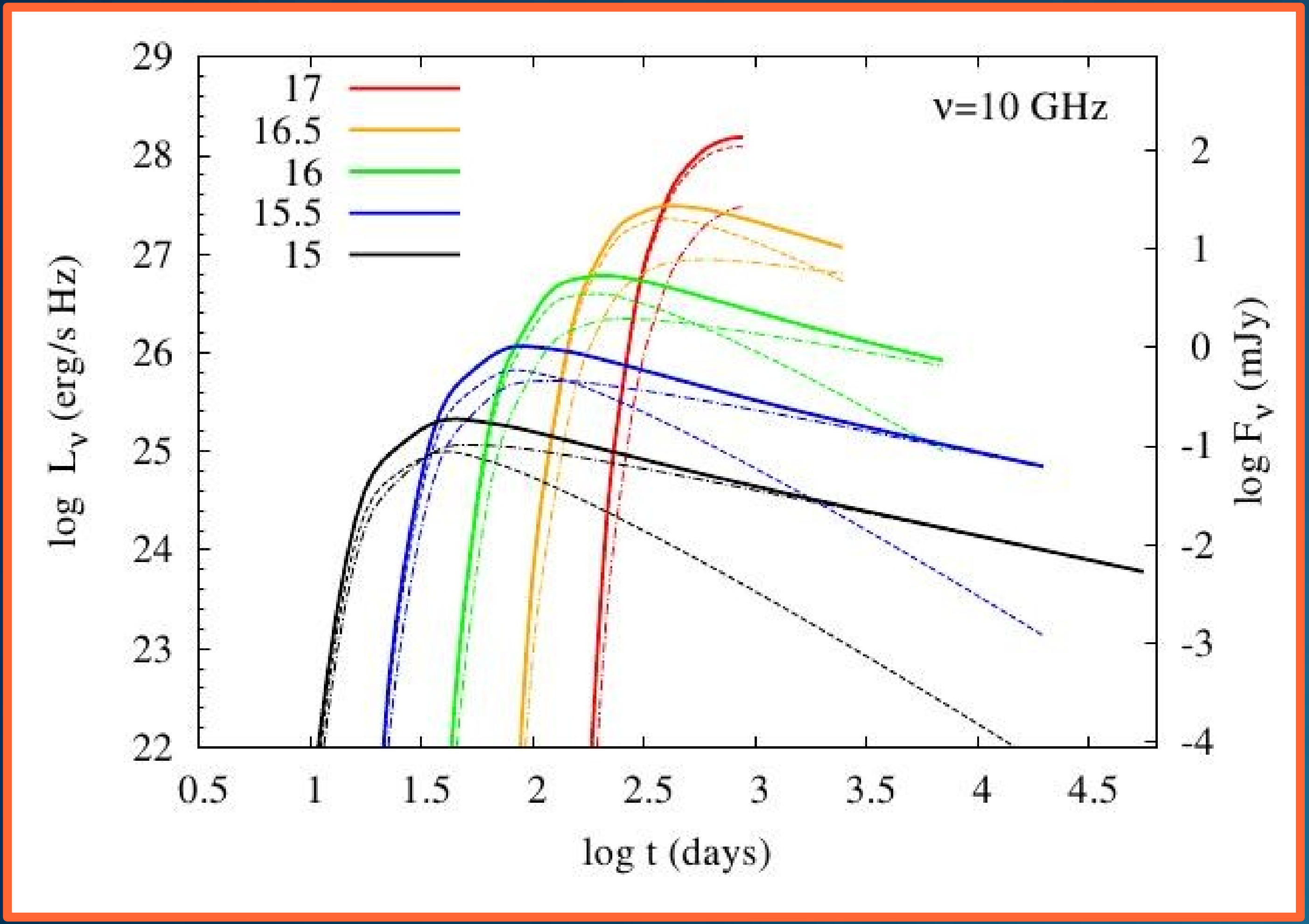
Radio spectra & light curves



Parameters: v_{sh}=9000 km/s, A_w=10^{16} gr/s (0.05 M_{sun} /yr), Mej=10M_{sun}, εB=0.01, εp=0.1, K_{ep}=0.001, T_e=10^5 K

Radio light curves

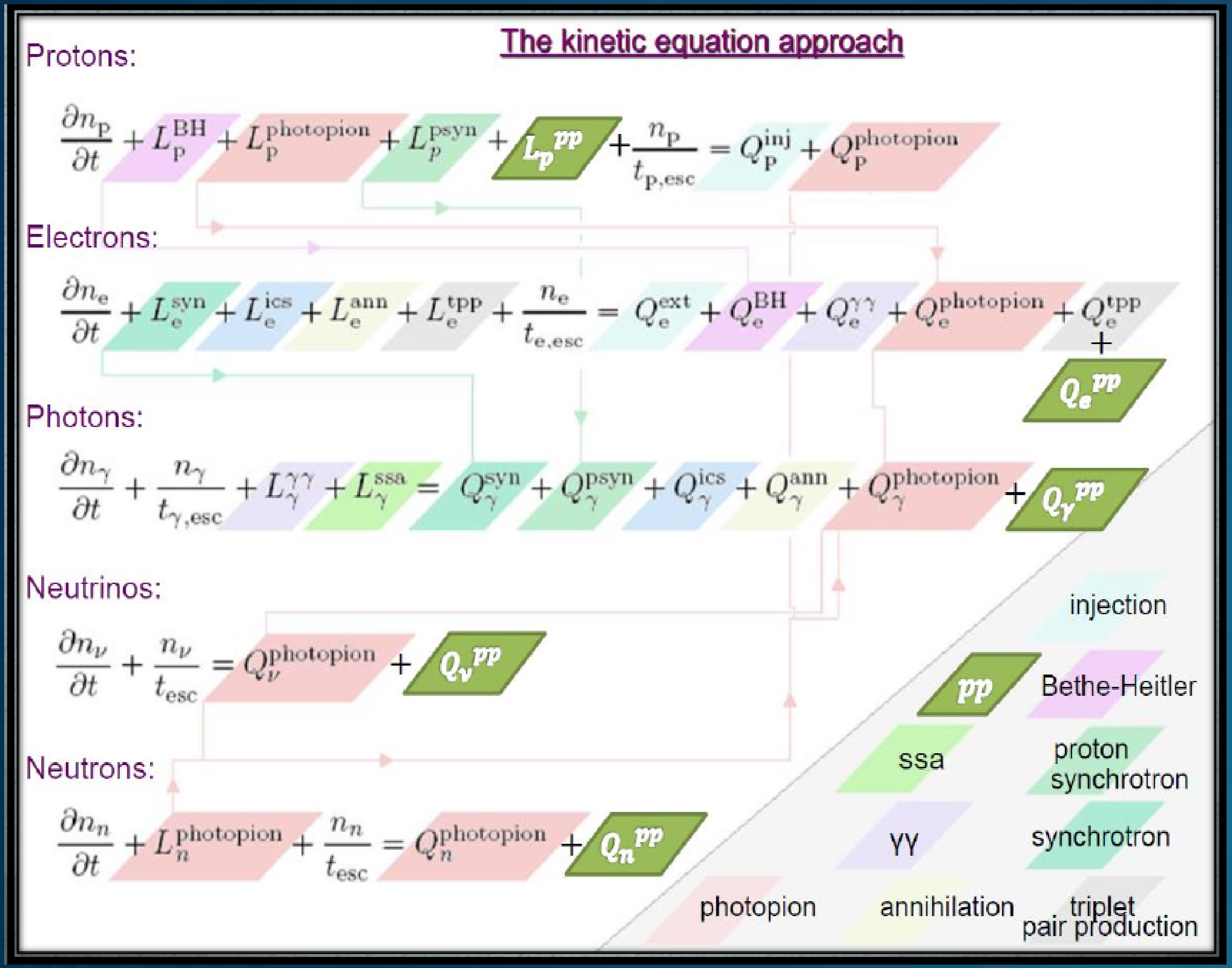
Role of CSM mass-loading parameter



Non-thermal broad-band spectrum

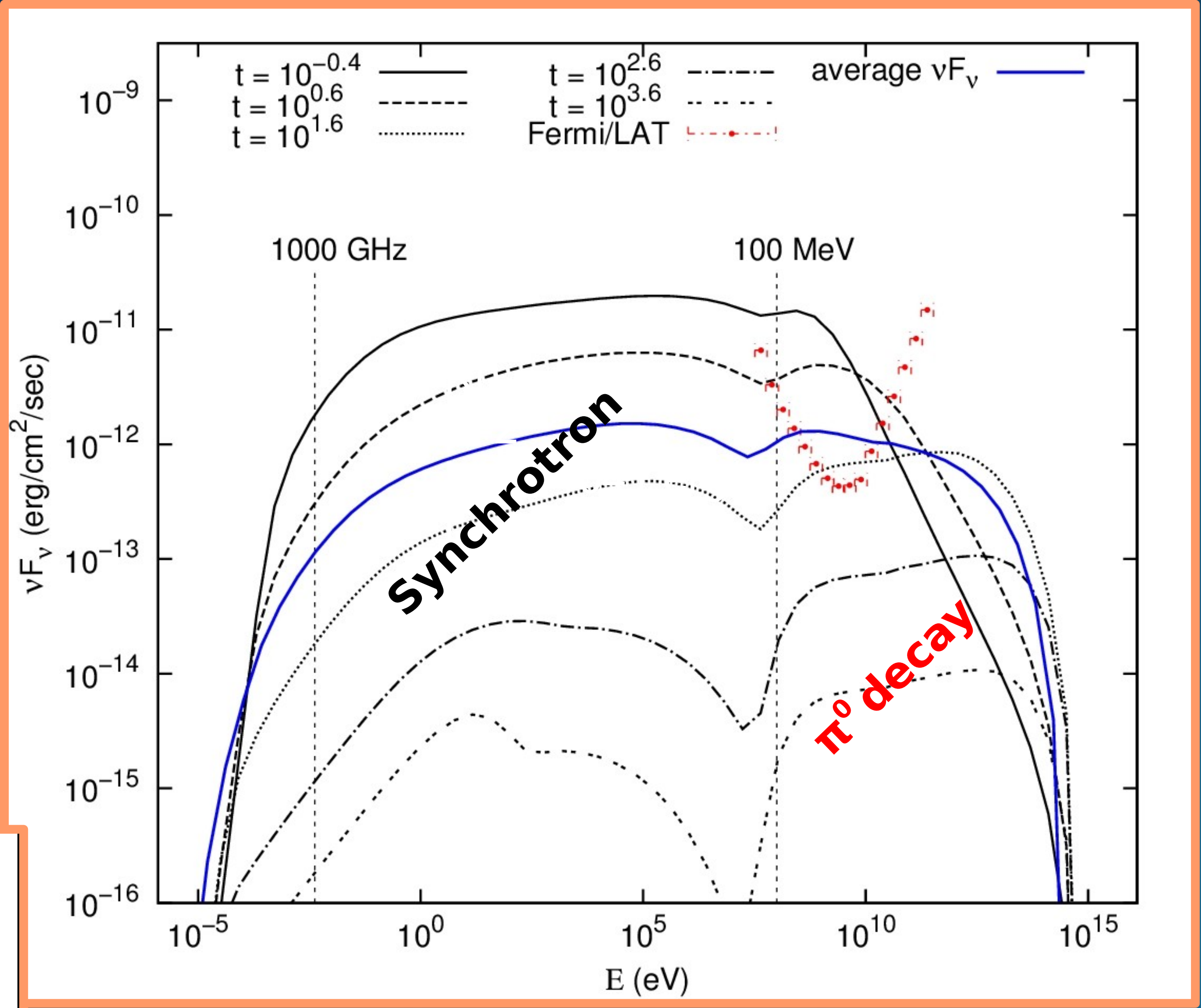
(M.Sc. Thesis of D. Kantzas, 2016, UoA)

Include pp collisions (Kelner et al. 2006) to numerical code for particle evolution (Mastichiadis & Kirk 1995, A&A; Dimitrakoudis et al. 2012, A&A)



Non-thermal broad-band spectrum

(Kantzas, Petropoulou, Mastichiadis 2016, arXiv:1607.05847; Petropoulou et al. 2016, in prep.)



$B_0 = 46\ G$

$\alpha_B = 1$

$v \approx 0.03c$

$d = 5\ Mpc$

CSM density: 5e11 cc

$R_0 = 10^{14}\ cm$

$p = 2$

$L_p = 10^{41}\ erg/s$

$L_e = 0.01\ L_p$

$[t] = days$

Conclusions

* Synchrotron emission from secondaries decay faster with time than that from shock-accelerated electrons

* A transition from secondary to primary dominated synchrotron radiation is indicated by a flattening of the light curve

* A higher electron-to-proton ratio decreases the contribution of secondaries to the radio emission

* γ-ray emission from nearby (<10 Mpc) and dense (>1e12 cc) Type IIn SN is detectable with Fermi

Future aspects

* Extension of the numerical code by adding:

- relativistic bremsstrahlung

- $\gamma\gamma$ absorption on optical SN photons

- $p\gamma$ interactions on thermal X-ray bremsstrahlung emission

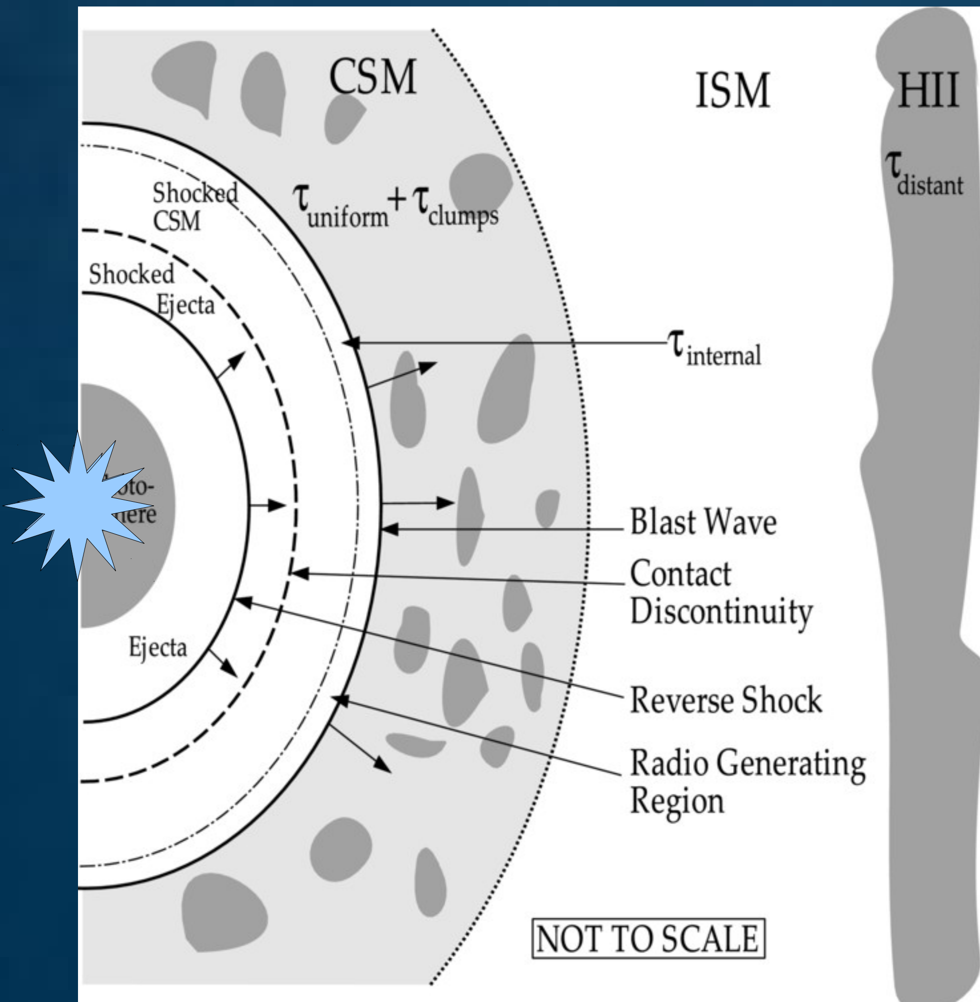
* Radio & γ-rays important for constraining microphysical parameters

* Application of the model to radio & γ-ray observations (upper limits)

THANK YOU

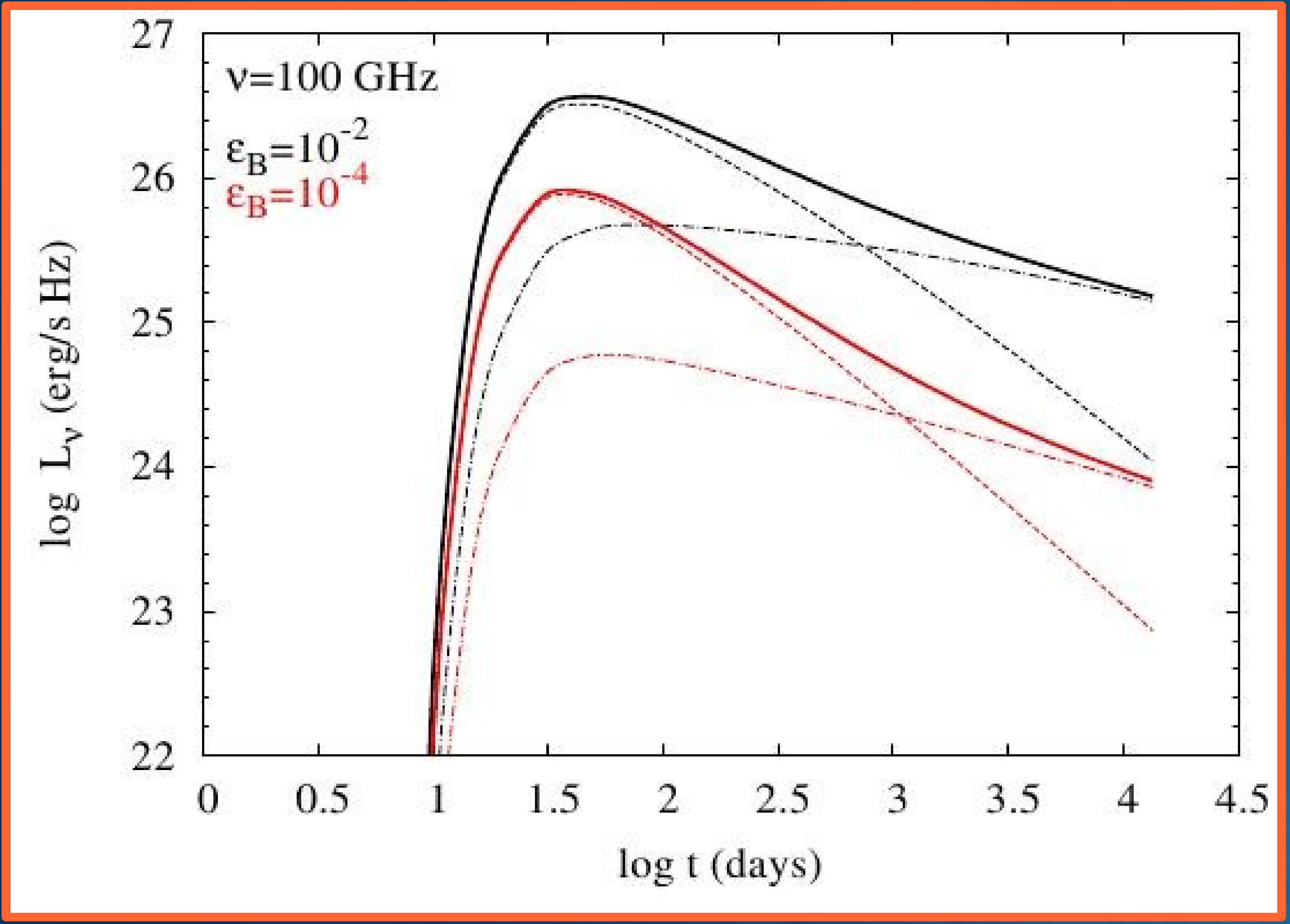
Radio SNe: current understanding

(Chevalier 1982, Chevalier 1998, Weiler 2001 +++)



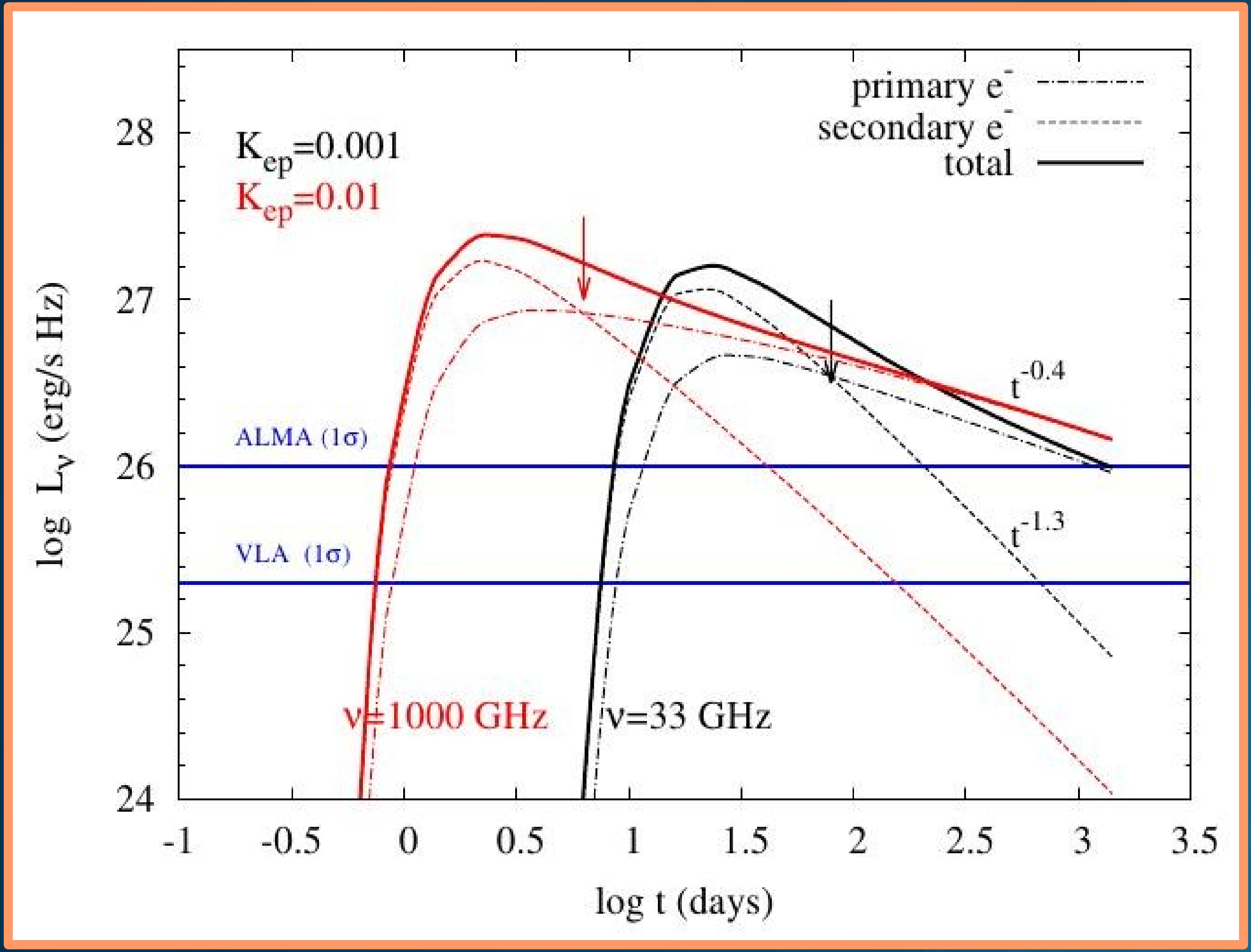
Radio light curves

Role of magnetic field strength



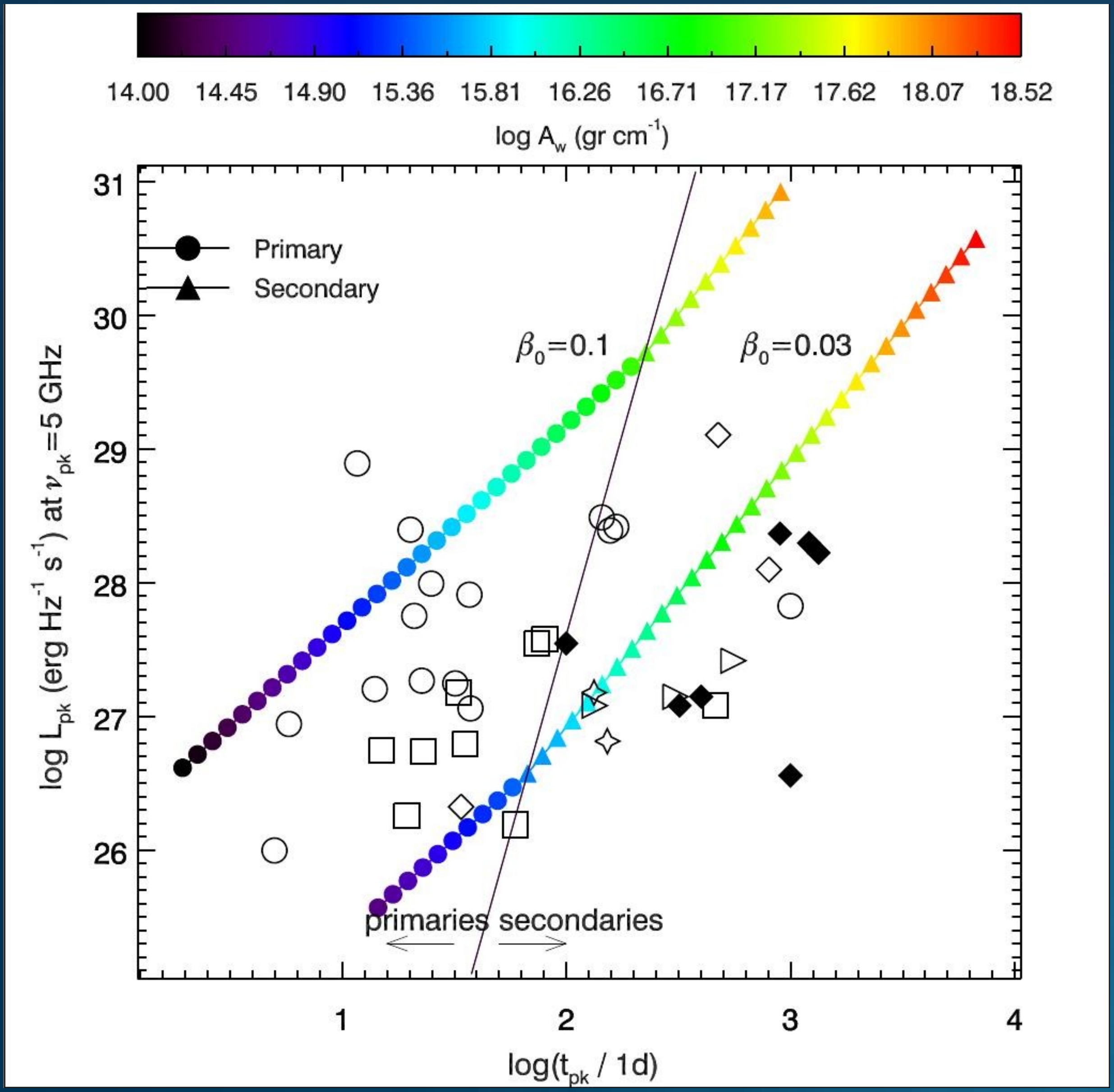
Radio light curves

Role of electron-to-proton ratio



Peak luminosity vs. Peak time

Peak luminosity at 5 GHz



Peak time (days)