Millisecond Pulsars Modify the Radio-SFR Correlation

Takahiro Sudoh

(University of Tokyo)

In collaboration with :

John Beacom (Ohio State), Tim Linden (Stockholm)

Millisecond Pulsars Modify the Radio-SFR Correlation

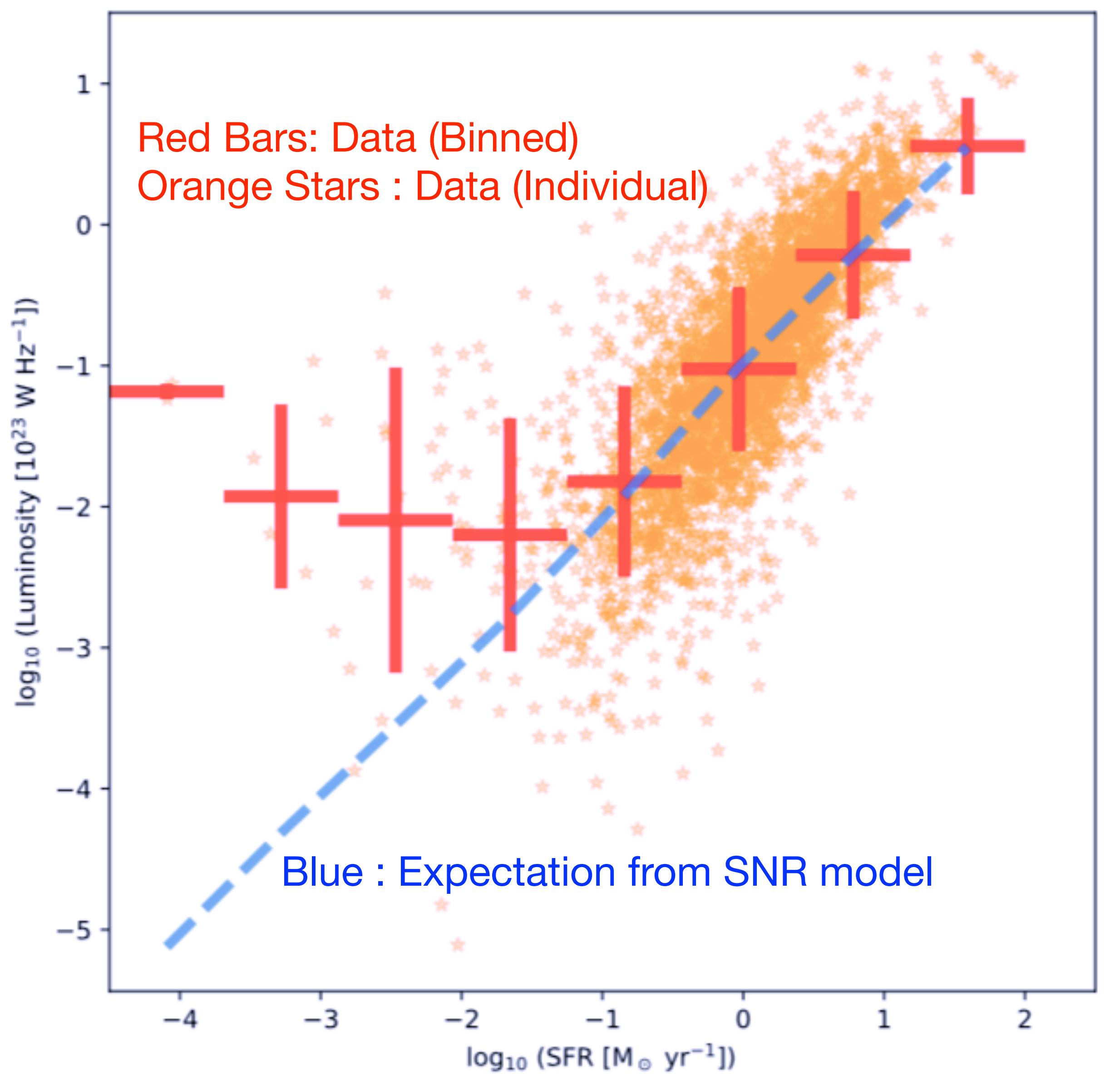
Takahiro Sudoh

(University of Tokyo)

In collaboration with :

John Beacom (Ohio State), Tim Linden (Stockholm)

Radio Excess in Low-SFR Galaxies



Data from Gürkan et al. (2018)

- Radio luminosities and SFRs are tightly correlated
- Interpretation : SNRs accelerate electrons, which produce radio emission
- Gürkan et al. studied this correlation in low frequency (150 MHz) and low SFR
- After removing AGN, they find an excess radio emission in low-SFR galaxies
- Excess emission is most prominent for massive galaxies

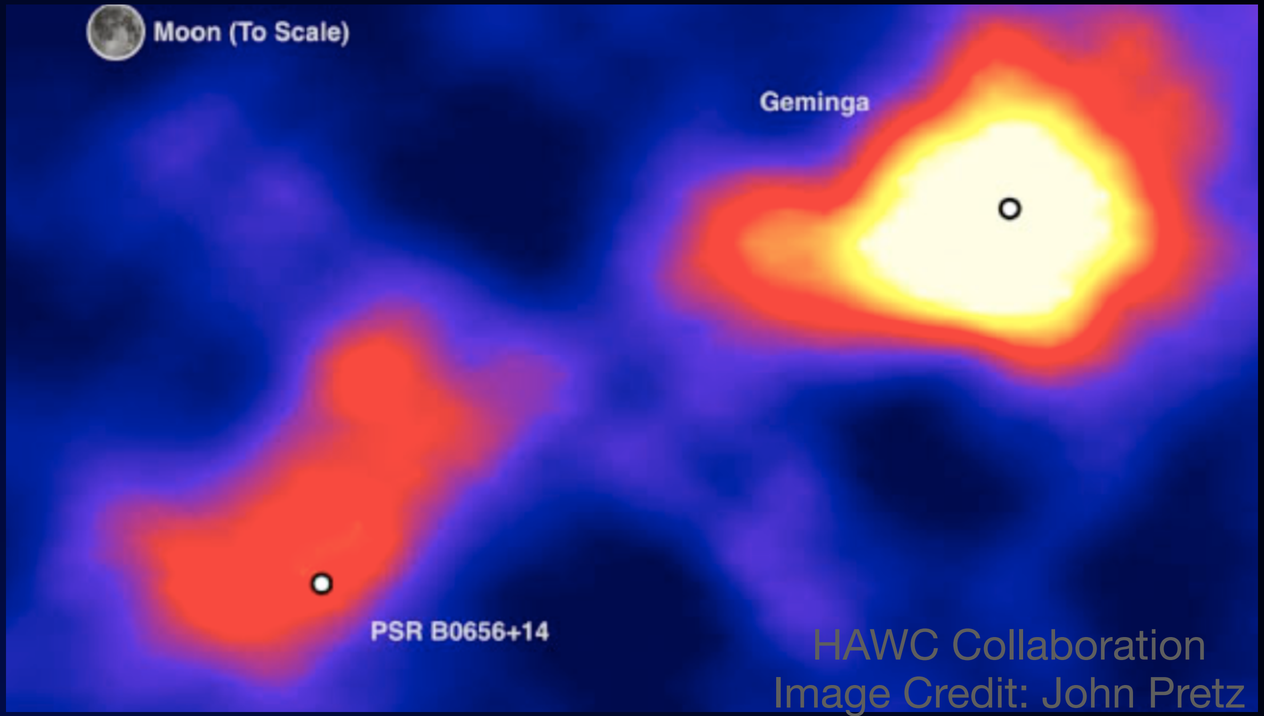
AGN?

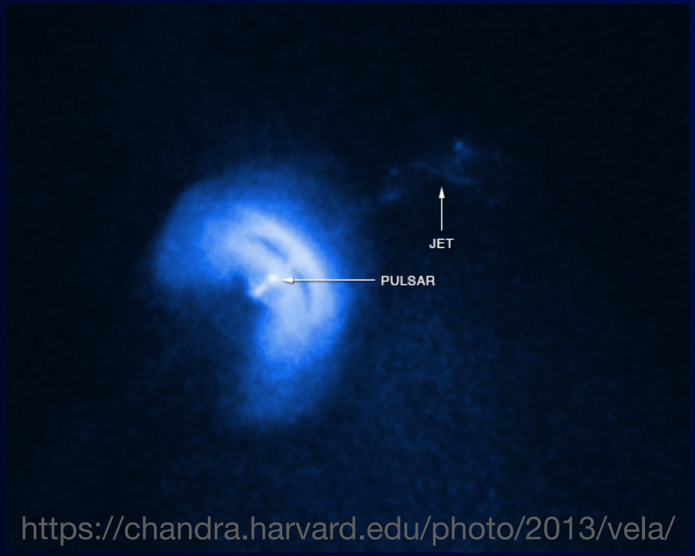
- Bright emission from low SFR galaxies
- If not SNR, then it must be AGN

AGN?

- Bright emission from low SFR galaxies
- If not SNR, then it must be AGN ?

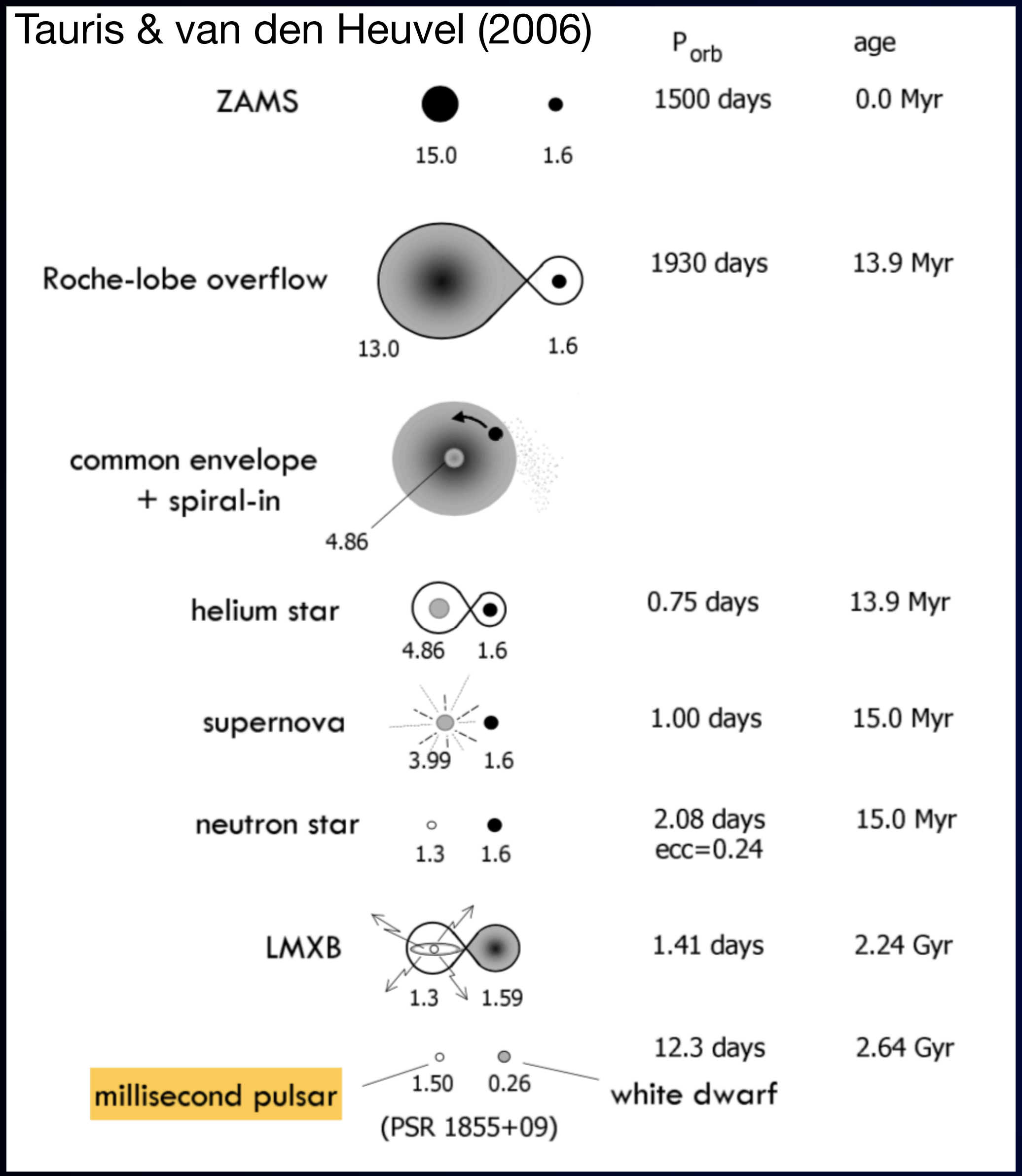
Pulsars!





- Pulsars accelerate cosmic-ray electrons, which can produce synchrotron radio emission

Millisecond Pulsars



- A normal pulsar is born at a core-collapse supernova, and will be inactive in ~ 10 Myr
- The dead pulsar accretes material from the companion star and spin up, becoming again a fast-spinning pulsar (= Millisecond pulsar, MSP)
- Time lag between star formation and MSP production
- MSPs may have a very long spindown time (~10 Gyr), i.e., long-lived
- $N_{\mathrm{MSP}} \propto M_*$ is naturally expected (instead of $\propto \mathrm{SFR}$)

MSPs as electron sources

- Normal pulsars release most of their spindown power as relativistic pulsar wind.
- Less is known about the pulsar wind from MSPs.
- Observations suggest an efficient production of cosmic-ray electron by MSPs
  - A few X-ray PWNe around MSPs (e.g, Lee et al. 2018)
  - Hint of TeV gamma-ray emission surrounding MSPs in the HAWC data (Hooper & Linden 2018), although also note that MAGIC reports non-detection of the globular cluster.
- We use GeV gamma-ray observations of MSPs to infer the total power in the galaxy.

Energy Budget

$$\text{SNR}, e \sim 5 \times 10^{38} \left(\frac{\text{SFR}}{M_\odot\ \text{yr}^{-1}} \right) \text{erg/s}$$

$$\text{MSP}, e \sim 2 \times 10^{37} \left(\frac{L_{\gamma,\text{MSP}}^{\text{MW}}}{10^{38}\ \text{erg/s}} \right) \left(\frac{\eta_\gamma}{0.1} \right)^{-1} \left(\frac{\eta_e}{0.1} \right) \left(\frac{M_*}{10^{10} M_\odot} \right) \text{erg/s}$$

Energy Budget

$$\mathrm{SNR}, e \sim 5 \times 10^{38} \left(\frac{\mathrm{SFR}}{M_\odot\ \mathrm{yr}^{-1}} \right) \mathrm{erg/s}$$

$$\mathrm{MSP}, e \sim 2 \times 10^{37} \left(\frac{L_{\gamma,\mathrm{MSP}}^{\mathrm{MW}}}{10^{38}\ \mathrm{erg/s}} \right) \left(\frac{\eta_\gamma}{0.1} \right)^{-1} \left(\frac{\eta_e}{0.1} \right) \left(\frac{M_*}{10^{10} M_\odot} \right) \mathrm{erg/s}$$

Total GeV gamma-ray luminosity of all MSPs in the Milky Way (uncertain by a factor of ~10, presumably from magnetosphere)

Energy Budget

$$\text{SNR}, e \sim 5 \times 10^{38} \left(\frac{\text{SFR}}{M_\odot \ \text{yr}^{-1}} \right) \ \text{erg/s}$$

$$\text{MSP}, e \sim 2 \times 10^{37} \left(\frac{L_{\gamma,\text{MSP}}^{\text{MW}}}{10^{38} \ \text{erg/s}} \right) \left(\frac{\eta_\gamma}{0.1} \right)^{-1} \left(\frac{\eta_e}{0.1} \right) \left(\frac{M_*}{10^{10} M_\odot} \right) \ \text{erg/s}$$

Total GeV gamma-ray luminosity of all MSPs in the Milky Way (uncertain by a factor of ~10, presumably from magnetosphere)

Fraction of the MSP power that go to gamma rays (relatively well known)

Energy Budget

$$\text{SNR}, e \sim 5 \times 10^{38} \left(\frac{\text{SFR}}{M_\odot \ \text{yr}^{-1}} \right) \ \text{erg/s}$$

$$\text{MSP}, e \sim 2 \times 10^{37} \left(\frac{L_{\gamma,\text{MSP}}^{\text{MW}}}{10^{38} \ \text{erg/s}} \right) \left(\frac{\eta_\gamma}{0.1} \right)^{-1} \left(\frac{\eta_e}{0.1} \right) \left(\frac{M_*}{10^{10} M_\odot} \right) \ \text{erg/s}$$

Total GeV gamma-ray luminosity of all MSPs in the Milky Way (uncertain by a factor of ~10, presumably from magnetosphere)

Fraction of the MSP power that go to gamma rays (relatively well known)

Total Power of all MSPs in the Milky Way

Energy Budget

$$\text{SNR}, e \sim 5 \times 10^{38} \left(\frac{\text{SFR}}{M_\odot\ \text{yr}^{-1}} \right) \text{erg/s}$$

$$\text{MSP}, e \sim 2 \times 10^{37} \left(\frac{L_{\gamma,\text{MSP}}^{\text{MW}}}{10^{38}\ \text{erg/s}} \right) \left(\frac{\eta_\gamma}{0.1} \right)^{-1} \left(\frac{\eta_e}{0.1} \right) \left(\frac{M_*}{10^{10} M_\odot} \right) \text{erg/s}$$

Total GeV gamma-ray luminosity of all MSPs in the Milky Way (uncertain by a factor of ~10, presumably from magnetosphere)

Fraction of the MSP power that go to gamma rays (relatively well known)

Fraction of the MSP power that go to electrons (unknown)

Energy Budget

$$\text{SNR}, e \sim 5 \times 10^{38} \left(\frac{\text{SFR}}{M_\odot \ \text{yr}^{-1}} \right) \text{erg/s}$$

$$\text{MSP}, e \sim 2 \times 10^{37} \left(\frac{L^{\text{MW}}_{\gamma,\text{MSP}}}{10^{38} \ \text{erg/s}} \right) \left(\frac{\eta_\gamma}{0.1} \right)^{-1} \left(\frac{\eta_e}{0.1} \right) \left(\frac{M_*}{10^{10} M_\odot} \right) \text{erg/s}$$

Total GeV gamma-ray luminosity of all MSPs in the Milky Way (uncertain by a factor of ~10, presumably from magnetosphere)

Fraction of the MSP power that go to gamma rays (relatively well known)

Fraction of the MSP power that go to electrons (unknown)

Total Power of Electrons from all MSPs in the Milky Way

Energy Budget

$$\mathrm{SNR}, e \sim 5 \times 10^{38} \left(\frac{\mathrm{SFR}}{M_\odot\ \mathrm{yr}^{-1}} \right) \mathrm{erg/s}$$

$$\mathrm{MSP}, e \sim 2 \times 10^{37} \left(\frac{L_{\gamma,\mathrm{MSP}}^{\mathrm{MW}}}{10^{38}\ \mathrm{erg/s}} \right) \left(\frac{\eta_\gamma}{0.1} \right)^{-1} \left(\frac{\eta_e}{0.1} \right) \left(\frac{M_*}{10^{10} M_\odot} \right) \mathrm{erg/s}$$

Total GeV gamma-ray luminosity of all MSPs in the Milky Way (uncertain by a factor of ~10, presumably from magnetosphere)

Fraction of the MSP power that go to gamma rays (relatively well known)

Fraction of the MSP power that go to electrons (unknown)

Assumption : $N_{\mathrm{MSP}} \propto M_*$

MW Mass : $6 \times 10^6 M_\odot$

Energy Budget

$$\text{SNR}, e \sim 5 \times 10^{38} \left(\frac{\text{SFR}}{M_\odot \ \text{yr}^{-1}} \right) \ \text{erg/s}$$

$$\text{MSP}, e \sim 2 \times 10^{37} \left(\frac{L_{\gamma,\text{MSP}}^{\text{MW}}}{10^{38} \ \text{erg/s}} \right) \left(\frac{\eta_\gamma}{0.1} \right)^{-1} \left(\frac{\eta_e}{0.1} \right) \left(\frac{M_*}{10^{10} M_\odot} \right) \ \text{erg/s}$$

Total GeV gamma-ray luminosity of all MSPs in the Milky Way (uncertain by a factor of ~10, presumably from magnetosphere)

Fraction of the MSP power that go to gamma rays (relatively well known)

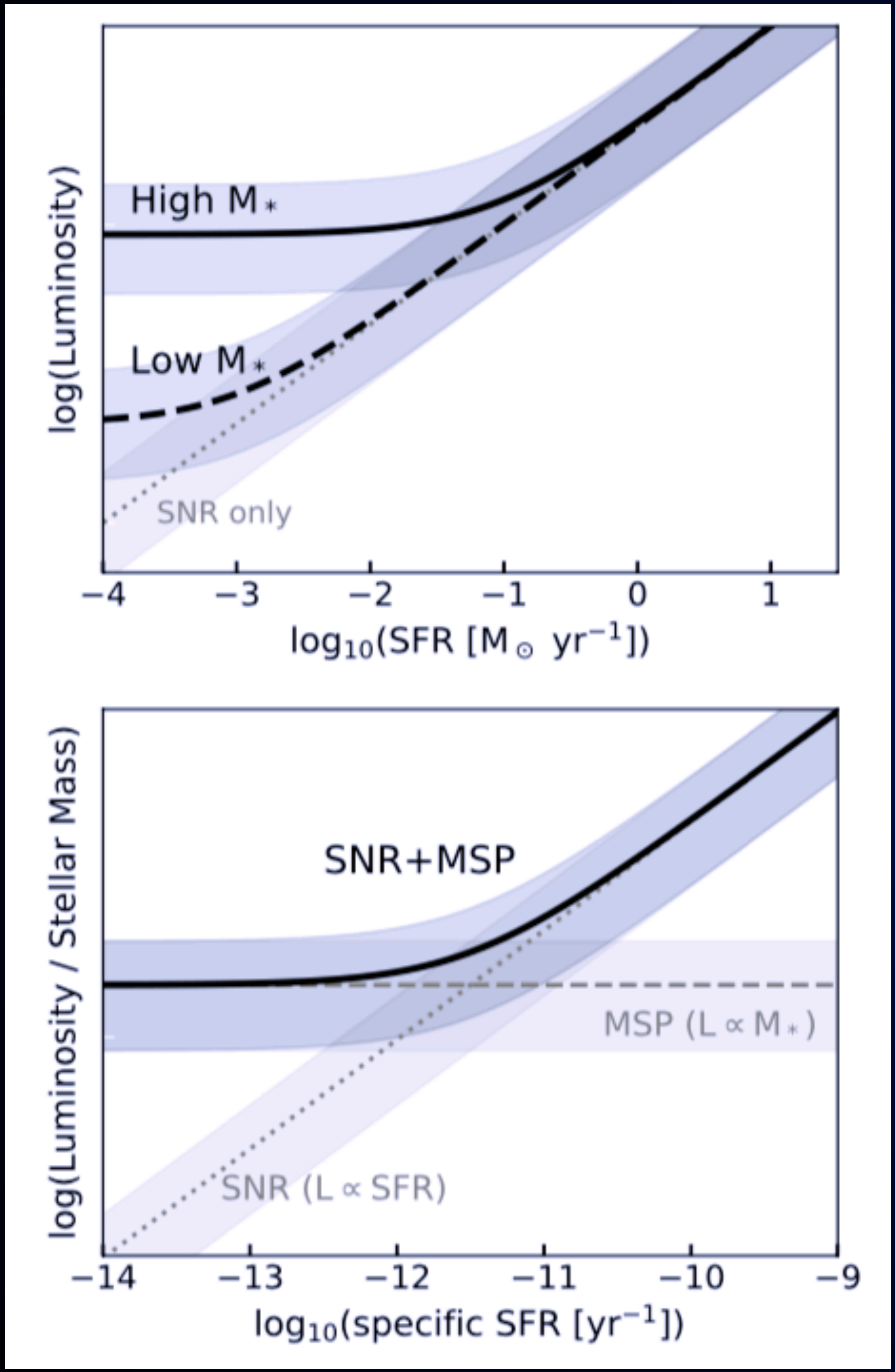
Fraction of the MSP power that go to electrons (unknown)

Assumption : $N_{\text{MSP}} \propto M_*$

MW Mass : $6 \times 10^6 M_\odot$

- Energy can be comparable for low-SFR and high-mass sources

Schematic Illustration



← Radio-SFR Correlation

← Normalized by mass

Modelling

- Model of galactic radio luminosity :
  - $L_{\rm radio}^{\rm model} = f_{\rm syn} \times [a_{\rm SNR,1}\psi + a_{\rm SNR,2}\psi^{1.18} + a_{\rm MSP}M_*]$
  - $f_{\rm syn} = (M_*)^{\beta}$: Efficiency of producing synchrotron

Modelling

- Model of galactic radio luminosity :
  - $L_{\rm radio}^{\rm model} = f_{\rm syn} \times [a_{\rm SNR,1}\psi + a_{\rm SNR,2}\psi^{1.18} + a_{\rm MSP}M_*]$

    SNR (Primary and Secondary)
  - $f_{\rm syn} = (M_*)^{\beta}$: Efficiency of producing synchrotron

Modelling

- Model of galactic radio luminosity :
  - $L_{\rm radio}^{\rm model} = f_{\rm syn} \times [a_{\rm SNR,1}\psi + a_{\rm SNR,2}\psi^{1.18} + a_{\rm MSP}M_*]$

    MSP
  - $f_{\rm syn} = (M_*)^{\beta}$: Efficiency of producing synchrotron

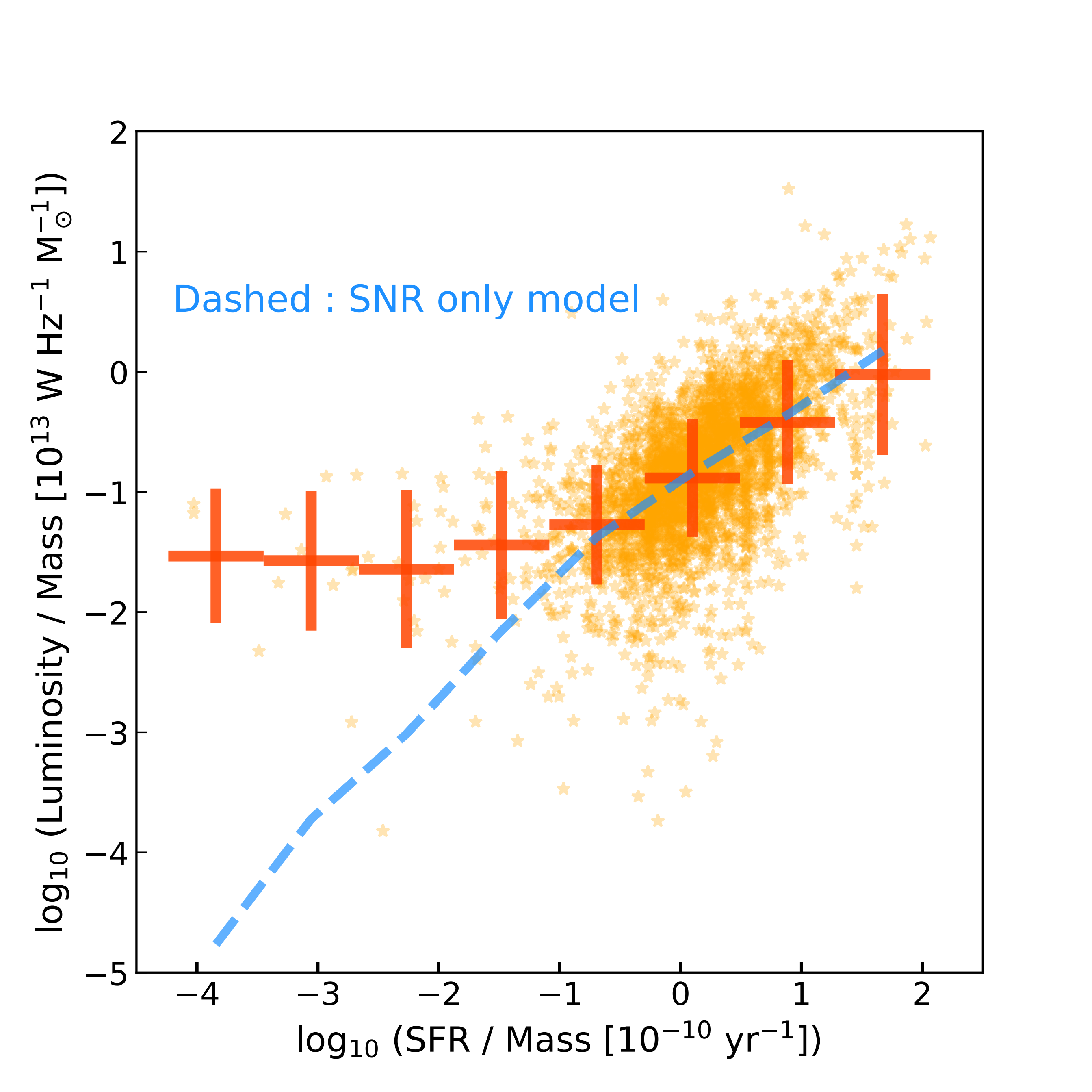
Modelling

- Model of galactic radio luminosity :
  - $L_{\rm radio}^{\rm model} = f_{\rm syn} \times [a_{\rm SNR,1}\psi + a_{\rm SNR,2}\psi^{1.18} + a_{\rm MSP} M_*]$
  - $f_{\rm syn} = (M_*)^{\beta}$: Efficiency of producing synchrotron
- Minimize likelihood to find the best-fit parameters :

$$P(L_{\rm radio}) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{|\log_{10} L_{\rm radio} - \log_{10} L_{\rm radio}^{\rm model}|^2}{2\sigma^2} \right)$$

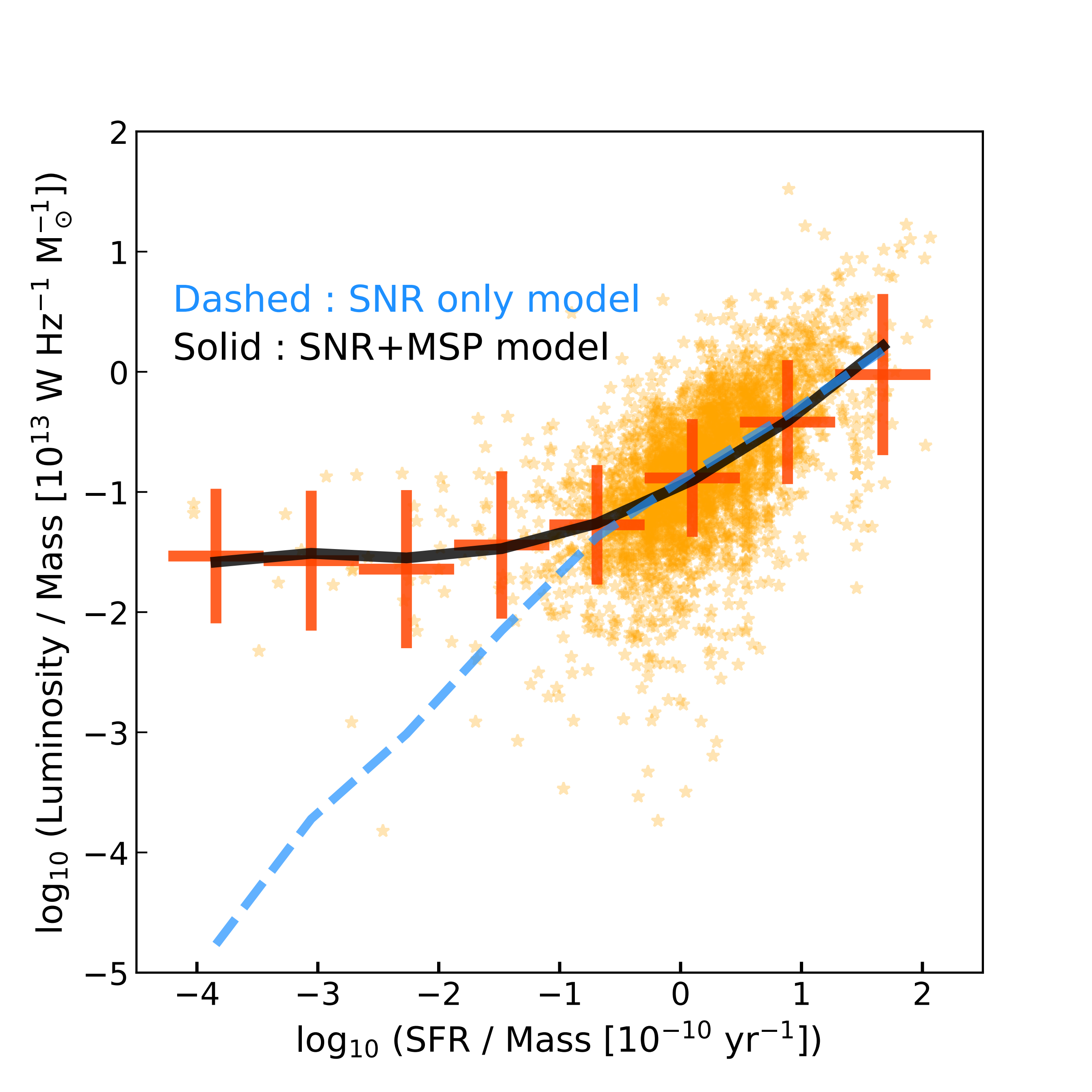
- We have tested several alternative approaches in our paper, but basic conclusions unchanged

Comparison to LOFAR data



- Bins are shown for illustration purpose.
- SNR-only model clearly fails to explain the data.

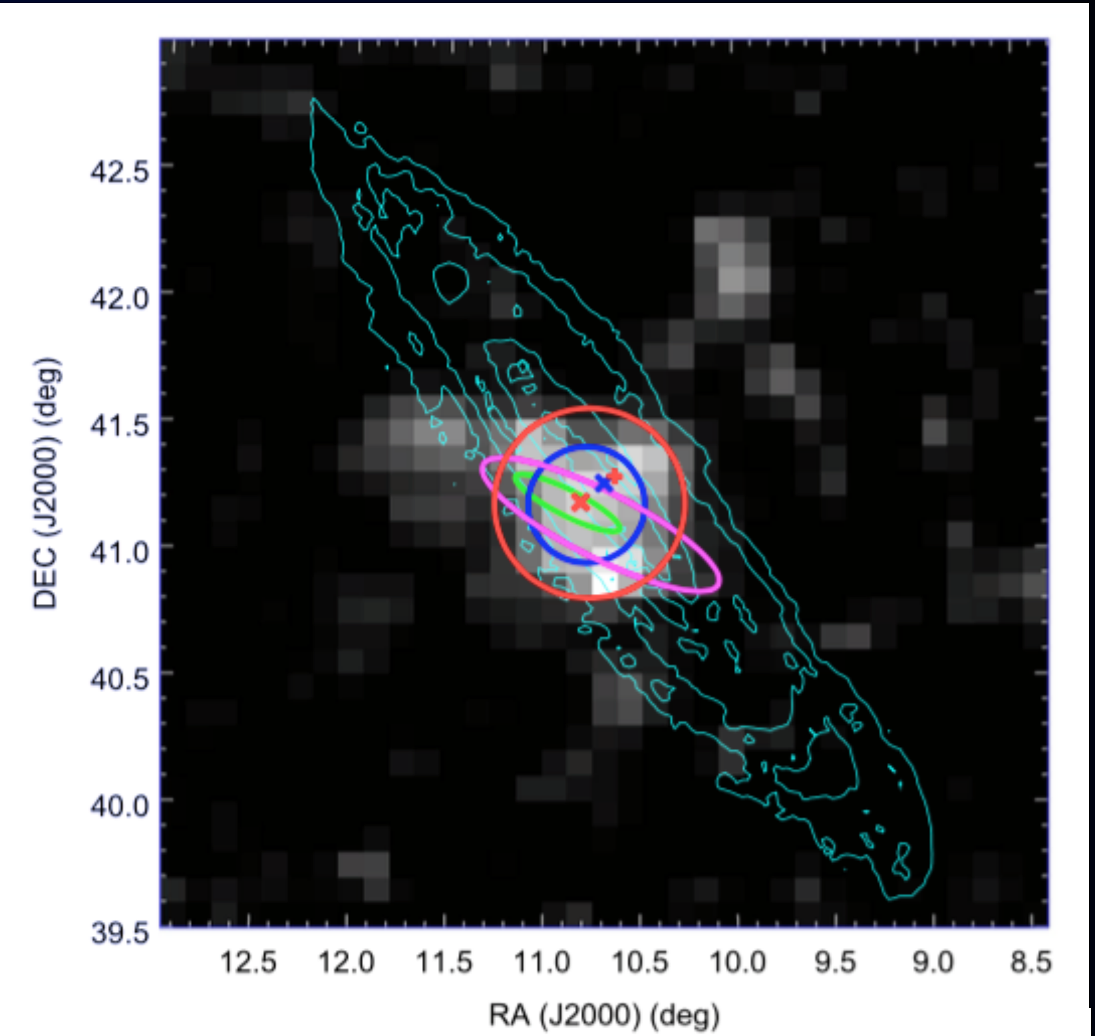
Comparison to LOFAR data



- Adding one parameter significantly improve the fit.
- The best-fit efficiency is :
  $\eta_e \simeq 1$
- It degenerates with a number of uncertainties and assumptions.
- MSPs may inject significant fraction of the power as cosmic-ray e+-.

Implications

- The center of Andromeda galaxy show bright radio and gamma-ray emission despite its low SFR
- Our best-fit model naturally explains the required cosmic-ray electron power
- Nearby galaxies will be good way to differentiate AGN contribution



Ackermann et al. (2017)

Summary

- Recent LOFAR observations find quiescent but radio-bright galaxies
- We argue that millisecond pulsars induces mass-dependence in the radio-SFR correlation, explaining the radio excess for massive low-SFR sources
- Observations of galaxies in radio may be important to study CR production in MSPs, which is relevant for observations of e+- and gamma rays.