

Pulsar, pulsar timing array, and gravitational experiments

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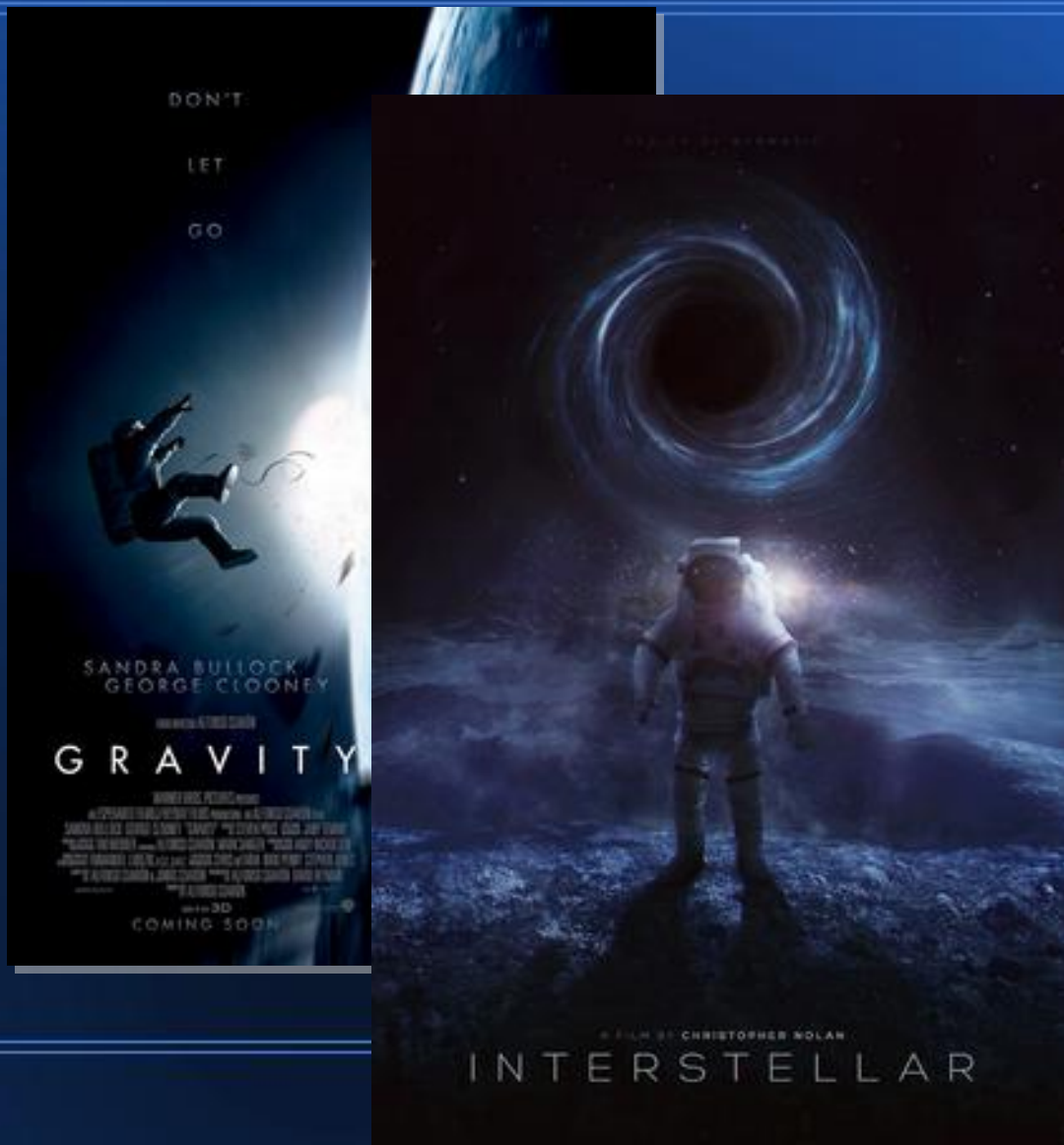
凡十一日没三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃速行經軒轅太星入太微垣掩右執法犯次將歷屏星西北凡七十五日入濁没明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十二日没至和元年五月己丑出天關東南可數寸歲餘稍没熙寧二年六月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天因元祐六年十一月辛亥出參度中犯掩側星壬子犯九游星十二月辛酉入奎至七年三月辛亥乃散紹興八年五月守



Outline

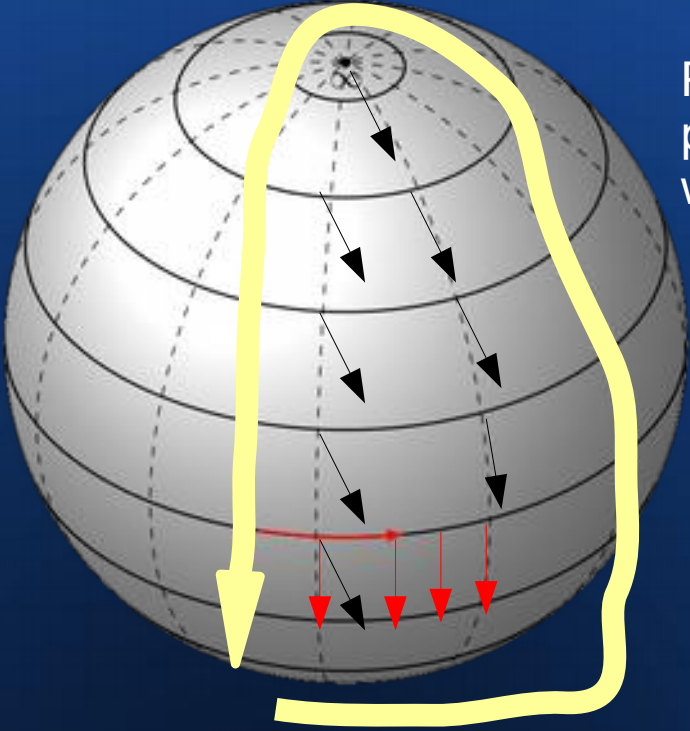
- Pulsars
- Gravitational wave
- Gravitational wave detection using pulsar timing array

Why we care about gravity theories?

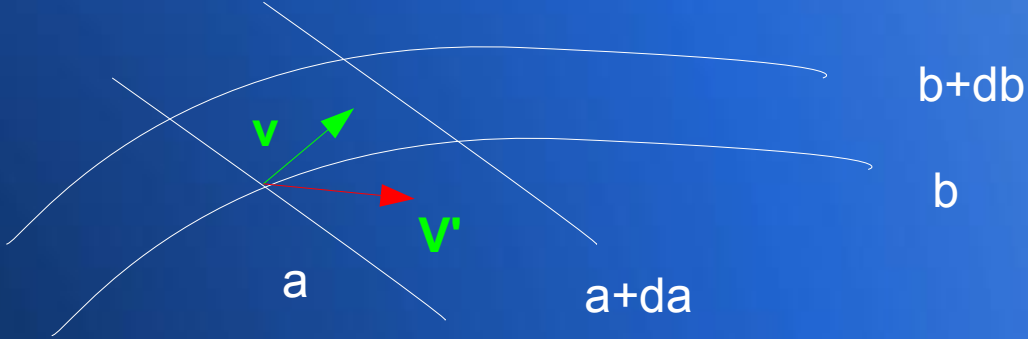


- Two **fundamental** philosophical questions
 - **What is the space?**
 - **What is the time?**
- Gravity theory is about the fundamental understanding of the background, on which other physics happens, i.e.
space and time
- Define the ultimate boundary of any civilization
- After GR, it is clear that the physical description and research of space time will be gravitational physics.
- But this idea can be traced back to nearly 300 years ago

$$F = ma = \frac{Mm}{r^2} \rightarrow \frac{a}{r} = \frac{M}{r^3} \rightarrow [T]^{-2} \sim \frac{M}{L^3}$$



Parallel transport. Locally, the surface is flat, one can define the parallel transport. However after a global round trip, the direction will be different.



$$\delta v^a = v^d \delta a^b \delta b^c R^a_{bcd}$$

The mathematics describing the **intrinsic** curvature is the Riemannian tensor.
 Riemannian = 0 \iff flat surface

The energy density is just the curvature!

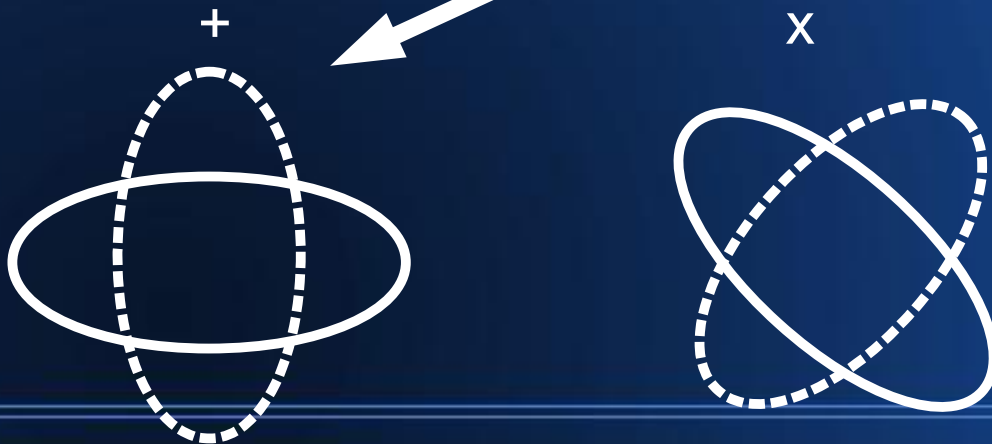
Gravity theory is theory of space and time!

Geometrical interpretation

$$\begin{pmatrix} h^+ & 0 & 0 \\ 0 & -h^+ & 0 \\ 0 & 0 & 0 \end{pmatrix} e^{i\omega t}$$

Transverse and traceless
i.e. conserve spatial volume
to the first order

$$\Delta = \begin{pmatrix} \Delta x & \Delta y & \Delta z \end{pmatrix} \begin{pmatrix} 1 + h^+ e^{i\omega t} & 0 & 0 \\ 0 & 1 - h^+ e^{i\omega t} & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \Delta x \\ \Delta y \\ \Delta z \end{pmatrix}$$



Generation of GW

$$h_{ij} = \frac{2\omega^2}{R} \left(Q_{ij} - \frac{Q_{ii}}{3} \right)$$

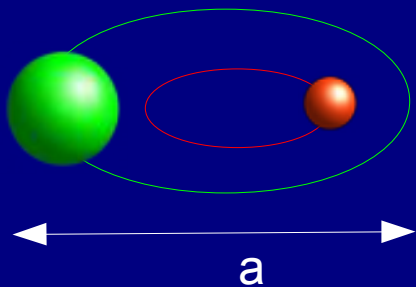
$$\omega^2 = \frac{(M+m)}{a^3}$$

$$Q \sim \mu a^2$$

$$\mu = \frac{mM}{m+M}$$

$$h \simeq \mu M_{\text{tot}}^{2/3} \omega^{2/3} R^{-1}$$

$$h \simeq M_c^{5/3} \omega^{2/3} R^{-1}$$



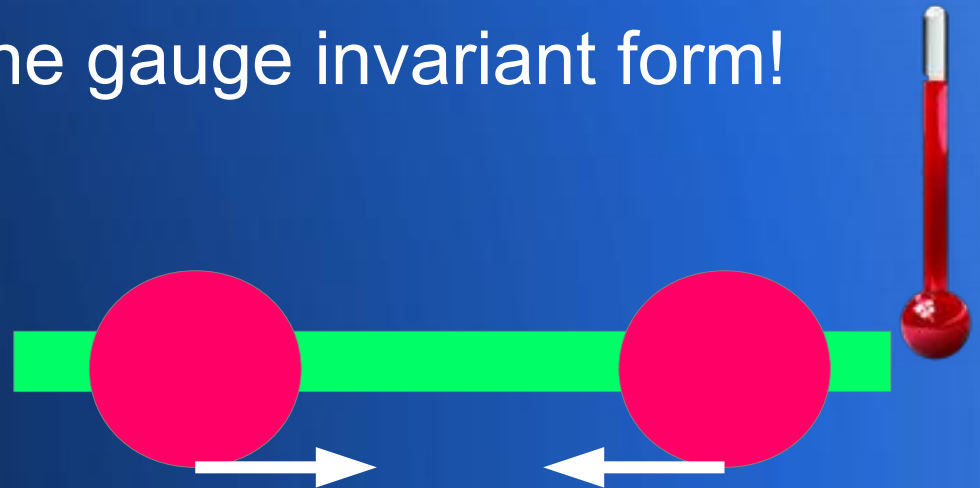
R



In GW astronomy, we are detecting $h \sim 1/R$. Increasing sensitivity by a factor of 10, the number of source is 1000 times. For other detector, they depend on energy flux, which goes as $1/R^2$, number of source increase as 100 times.

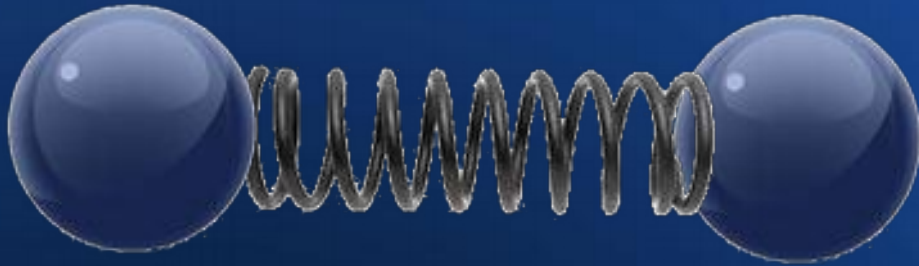
Is GW real?

- Does GW carry energy?
 - Bondi 1950s
- Can we measure it?
 - Yes, we can find the gauge invariant form!



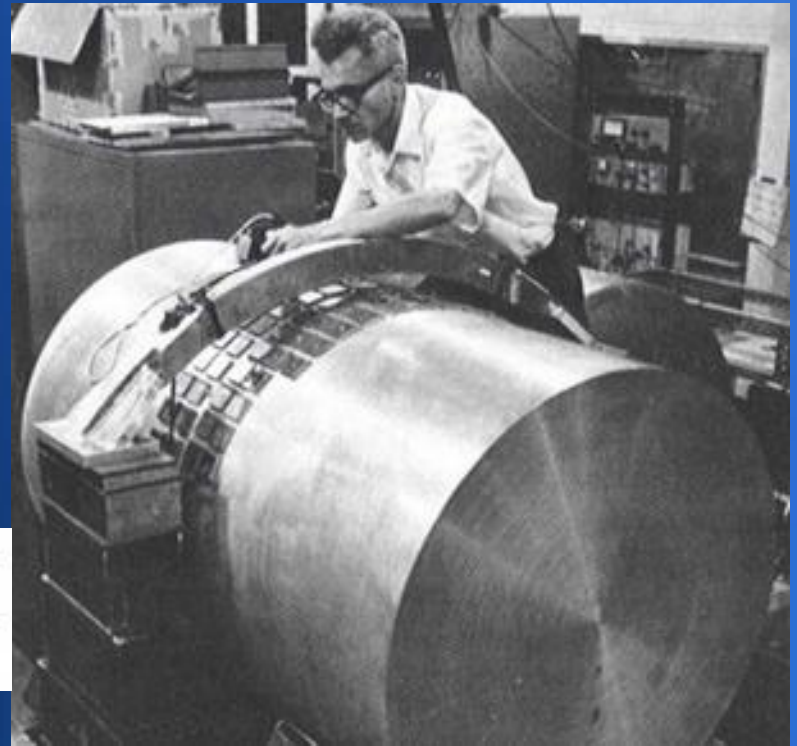
GW detector

- Bar detector



$$f = \frac{2L}{v_{\text{sound}}}$$

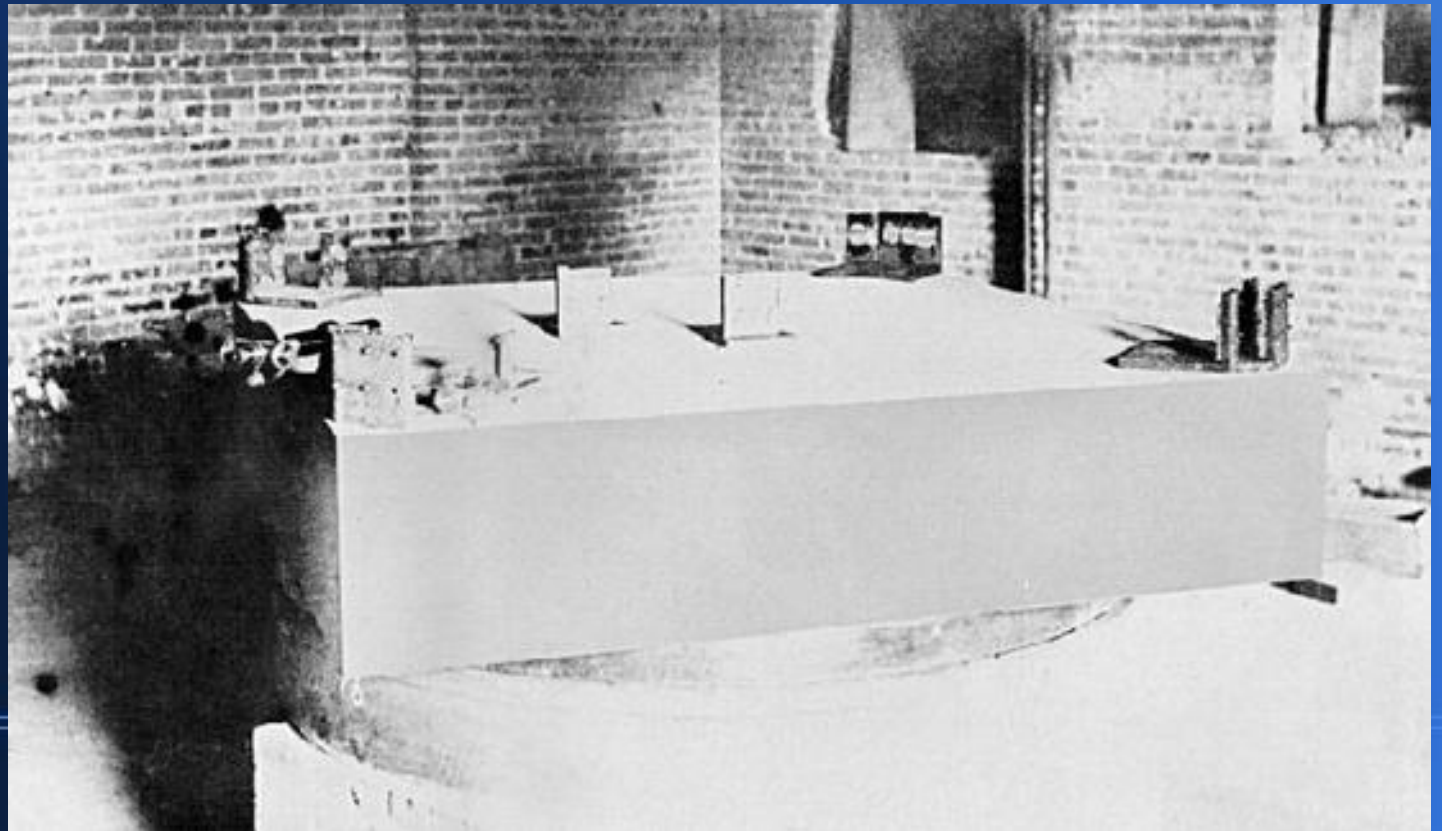
$$\frac{S}{N} \Big|_{\text{power}} = \frac{M_{\text{eff}} \omega^2 |\Delta x|^2}{2kT} = \frac{M_{\text{eff}} \pi f^2 h^2 \int \sigma df}{2kT}$$



Laser interferometer as GW detector

- Interferometer has long history.
 - Michelson-Morley experiment

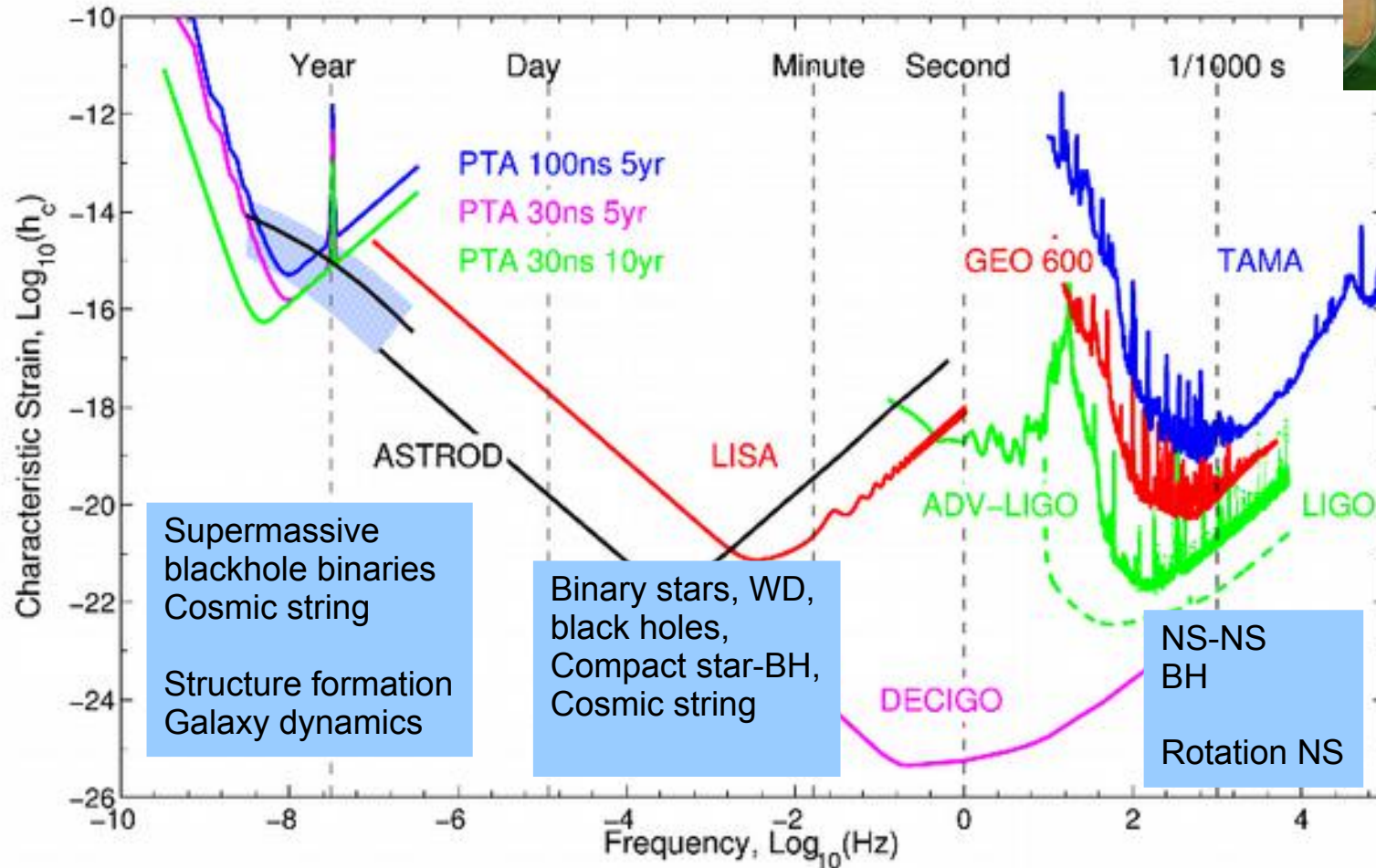
Key:
Multimirrors to amplify
signal
Vibration isolation.



Key idea

Compare the phase between two-way propagations

CMB...



Discovery of pulsars

- Little green man?

Source lies outside the solar system

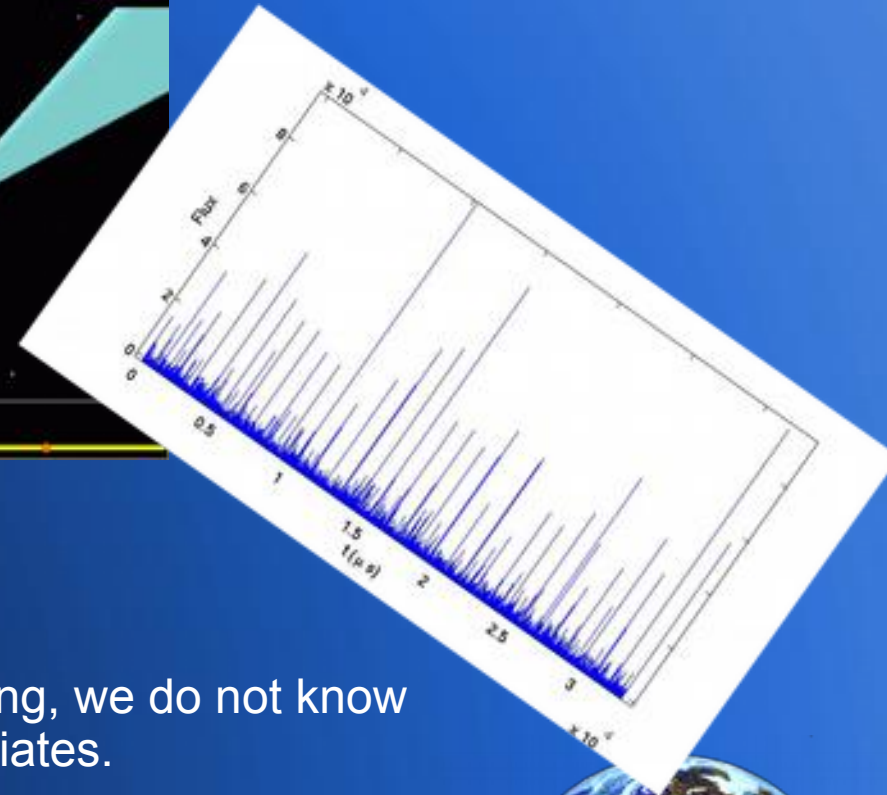
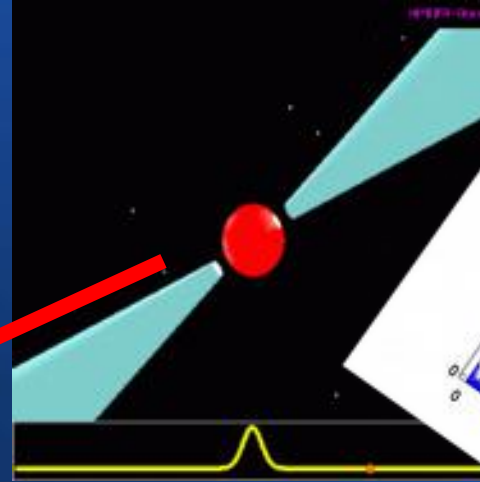
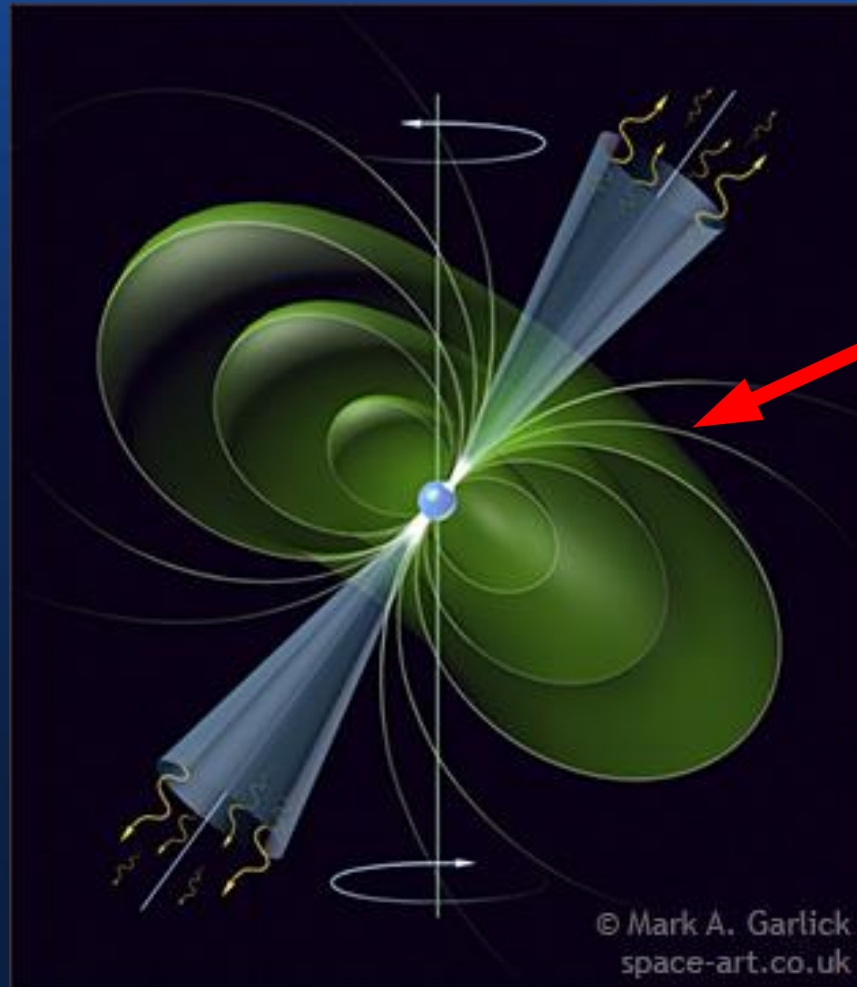
Distance is typical of stellar distances

Source must be very small. A white dwarf or neutron star?

Astrophysical origin, not ET



Phenomenology model

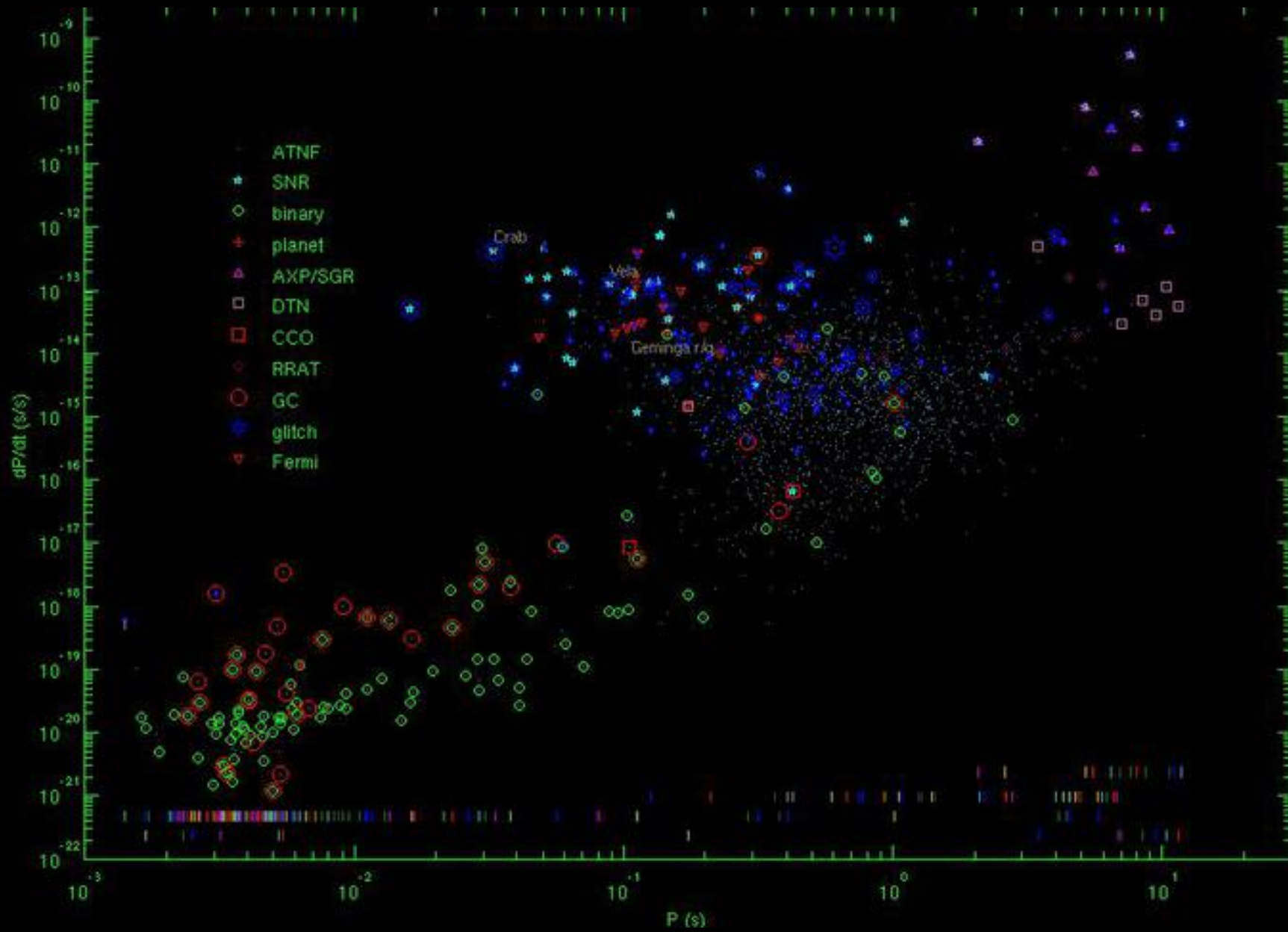


Frankly speaking, we do not know how pulsar radiates.

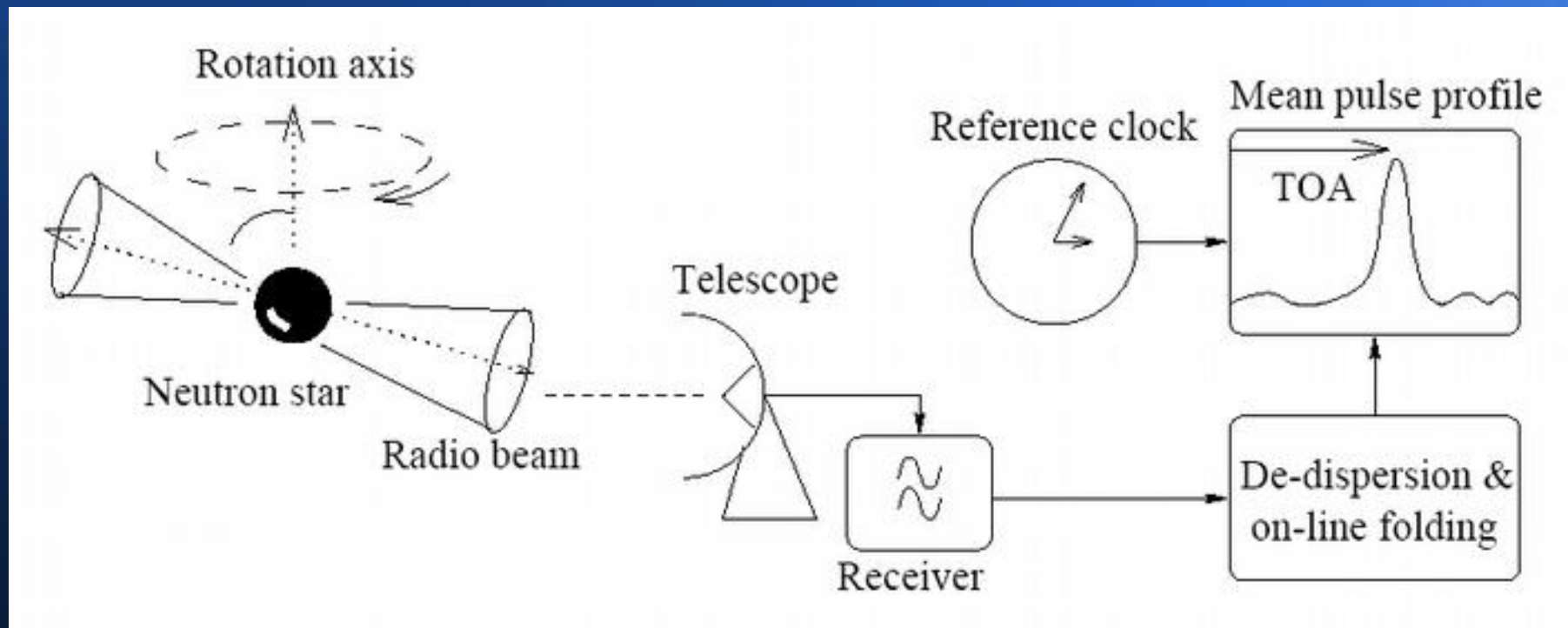




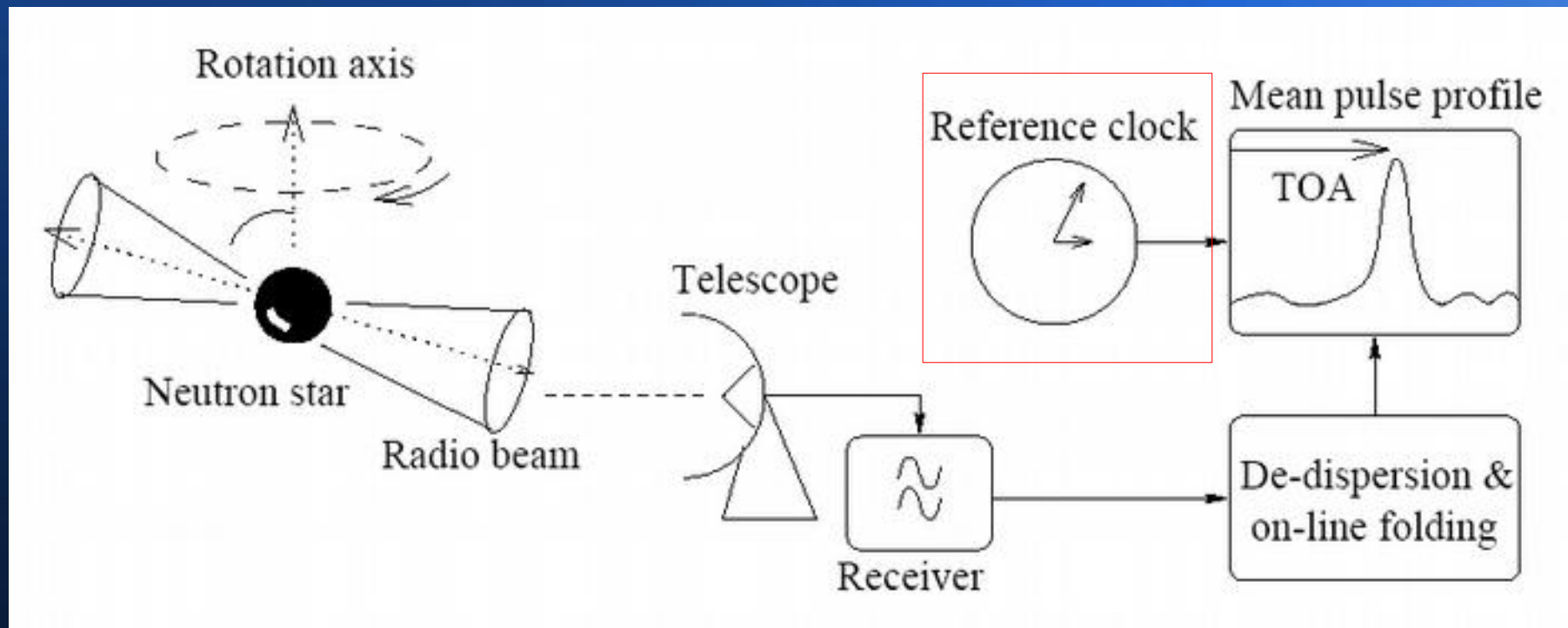
P-Pdot diagram for pulsars



Timing techniques



Timing techniques



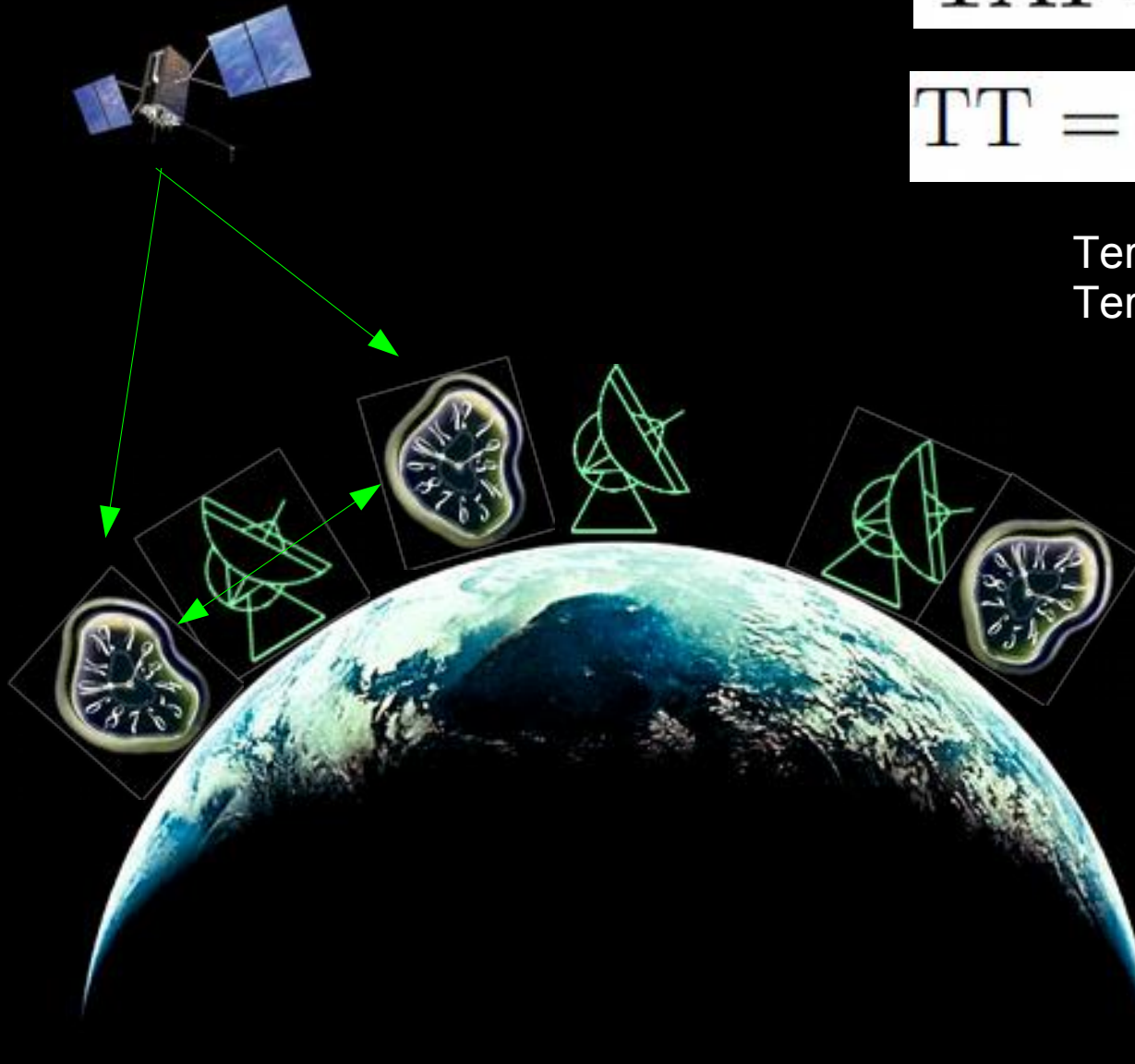


Time standard and transfer

$$\text{TAI} = \text{UTC} + \Delta T$$

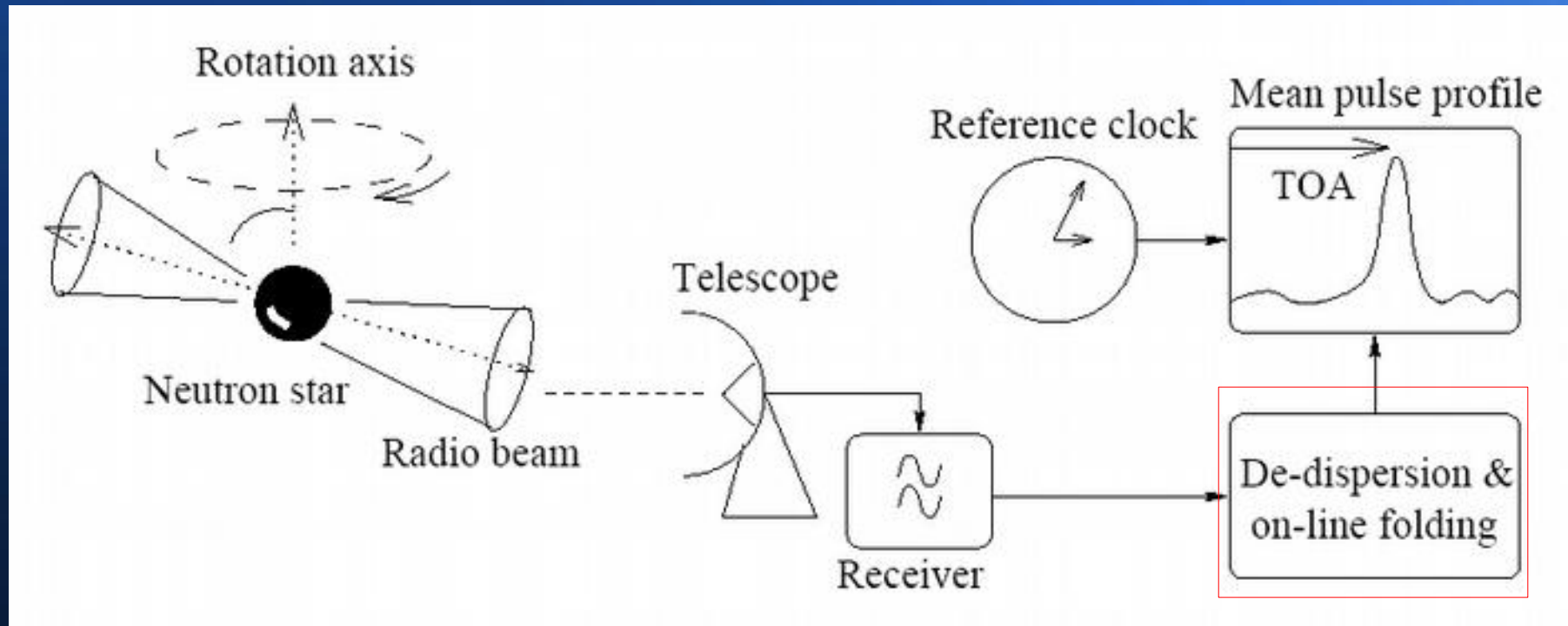
$$\text{TT} = \text{TAI} + 32.184 \text{ s}$$

Terrestrial Time: TT
Terrestrial Atomic Time: TAI

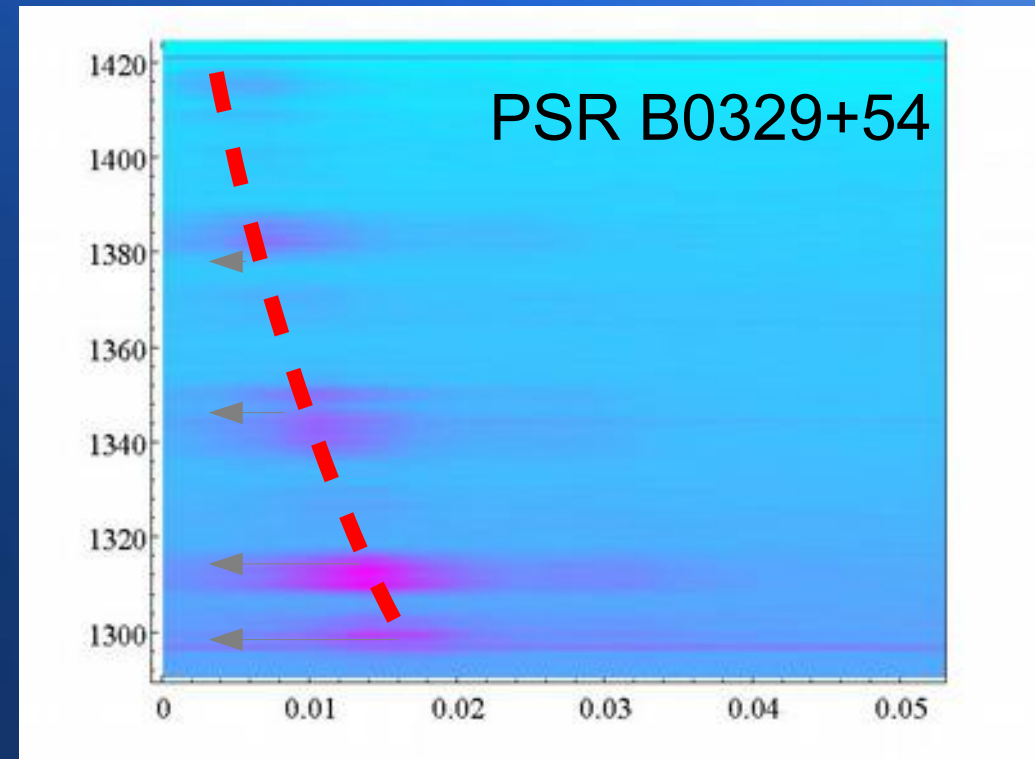
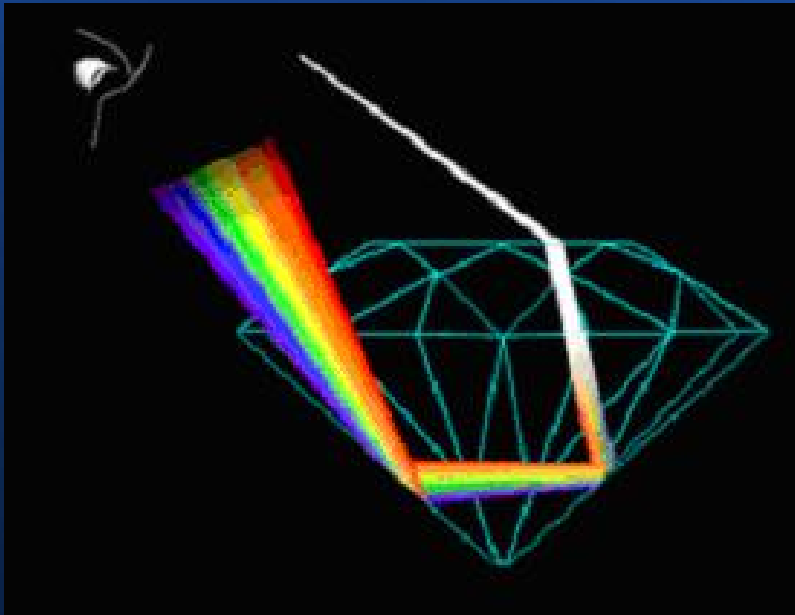


$\infty T < 10 \text{ ns}$

Timing techniques

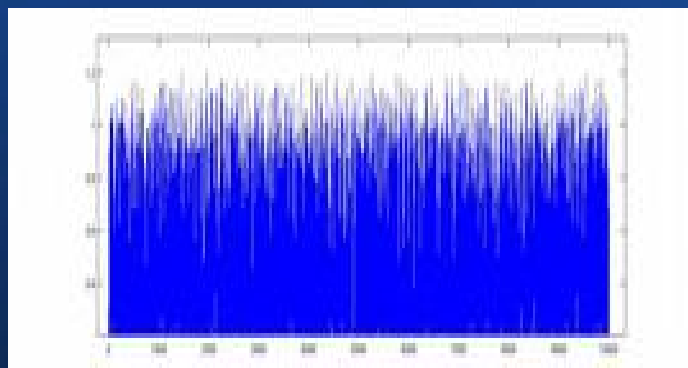


Dispersion

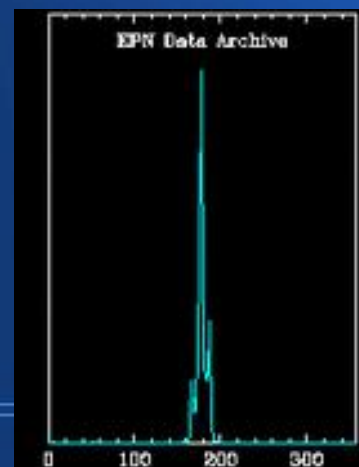
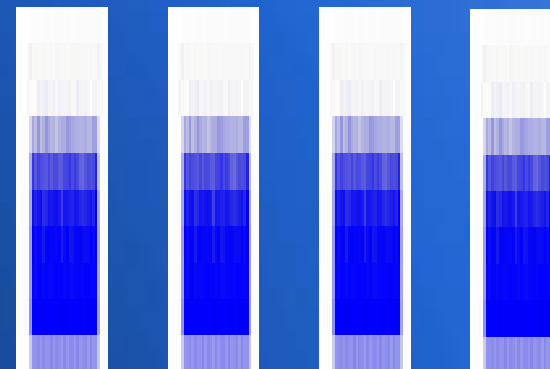


$$t_{\text{DM}}(f_1) - t_{\text{DM}}(f_2) = 4.15 \times 10^{-3} \text{ DM} \left[\left(\frac{f_1}{\text{GHz}} \right)^{-2} - \left(\frac{f_2}{\text{GHz}} \right)^{-2} \right] [\text{s}],$$

Folding



Raw data

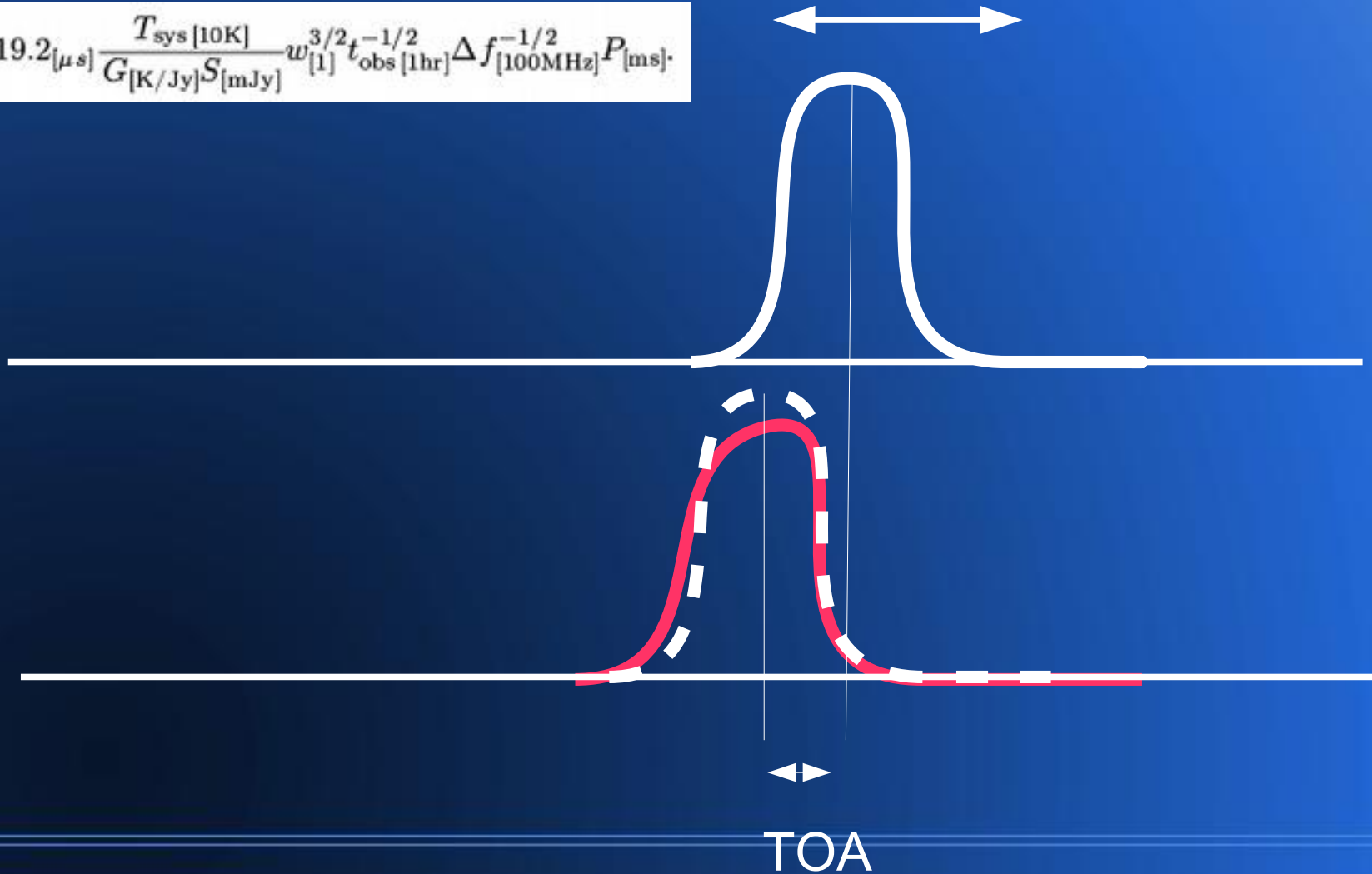




Determine the TOA

template matching

$$\sigma_{\text{TOA}} = 19.2_{[\mu\text{s}]} \frac{T_{\text{sys}} [\text{10K}]}{G_{[\text{K/Jy}]} S_{[\text{mJy}]}} w_{[1]}^{3/2} t_{\text{obs}}^{-1/2} \Delta f_{[100\text{MHz}]}^{-1/2} P_{[\text{ms}]}$$





Transfer to Solar Barycenter



$$t_{SSB} = t_{topo} + t_{corr} - \Delta D/f^2 + \Delta_{R\odot} + \Delta_{S\odot} + \Delta_{E\odot}.$$

$$\Delta_{R\odot} = -\frac{1}{c} \vec{r} \cdot \hat{s}$$

$$\frac{d\Delta_{E\odot}}{dt} = \sum_i \frac{GM_i}{c^2 r_i^E} + \frac{v_E^2}{2c^2} - \text{constant}$$

+Parallax + Solar wind + Atmospheric correction+....



Solitary pulsar

- Count the pulse
- Model the frequency with polynomial

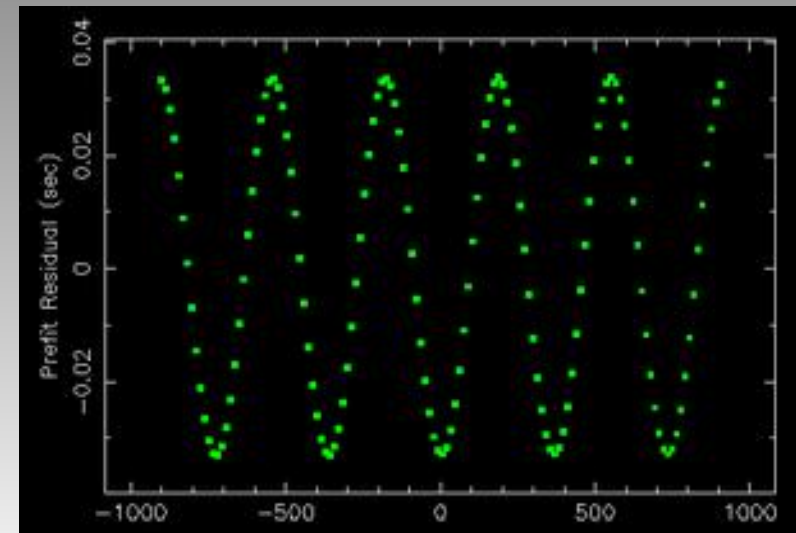
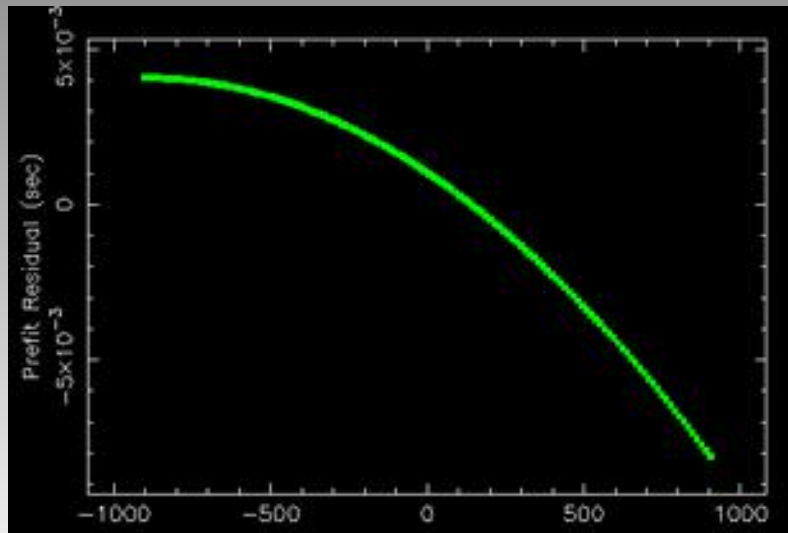
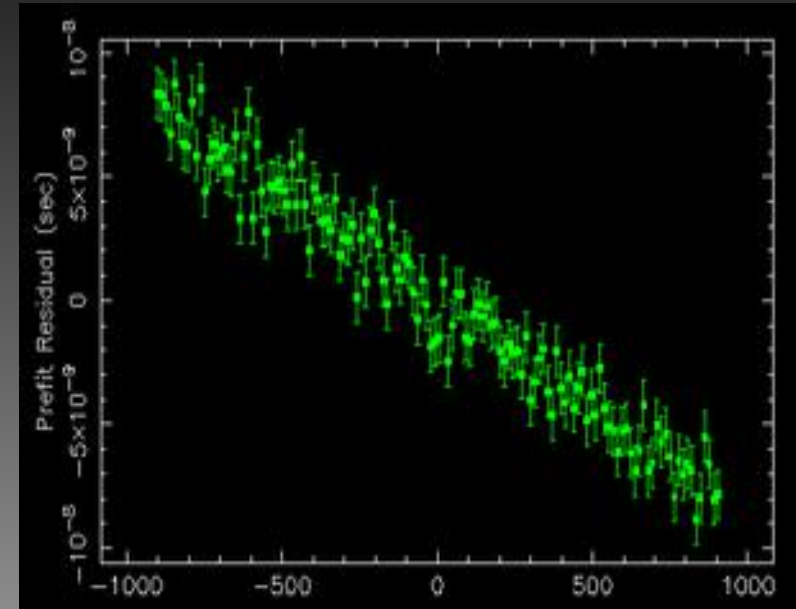
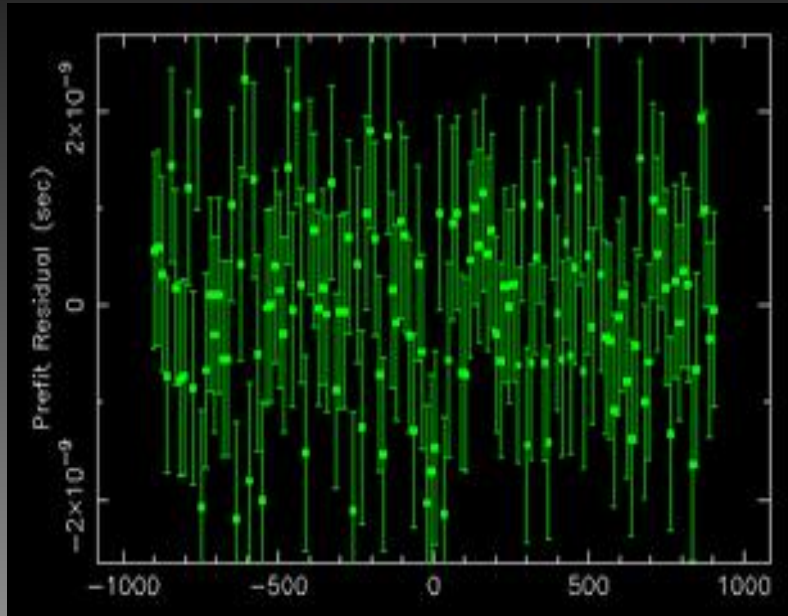
$$\nu(t) = \nu_0 + \dot{\nu}_0(t - t_0) + \frac{1}{2}\ddot{\nu}_0(t - t_0)^2 + \dots$$

$$N = N_0 + \nu_0(t - t_0) + \frac{1}{2}\dot{\nu}(t - t_0)^2 + \frac{1}{6}\ddot{\nu}(t - t_0)^3 + \dots$$

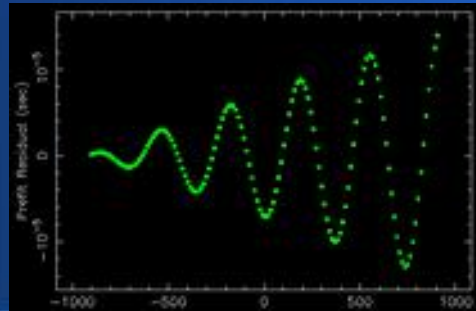
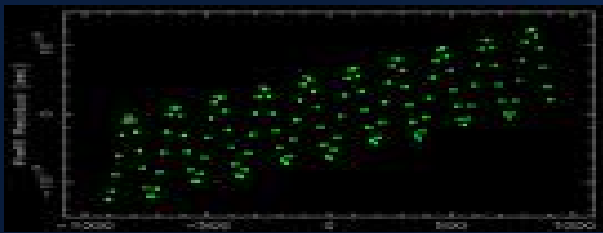
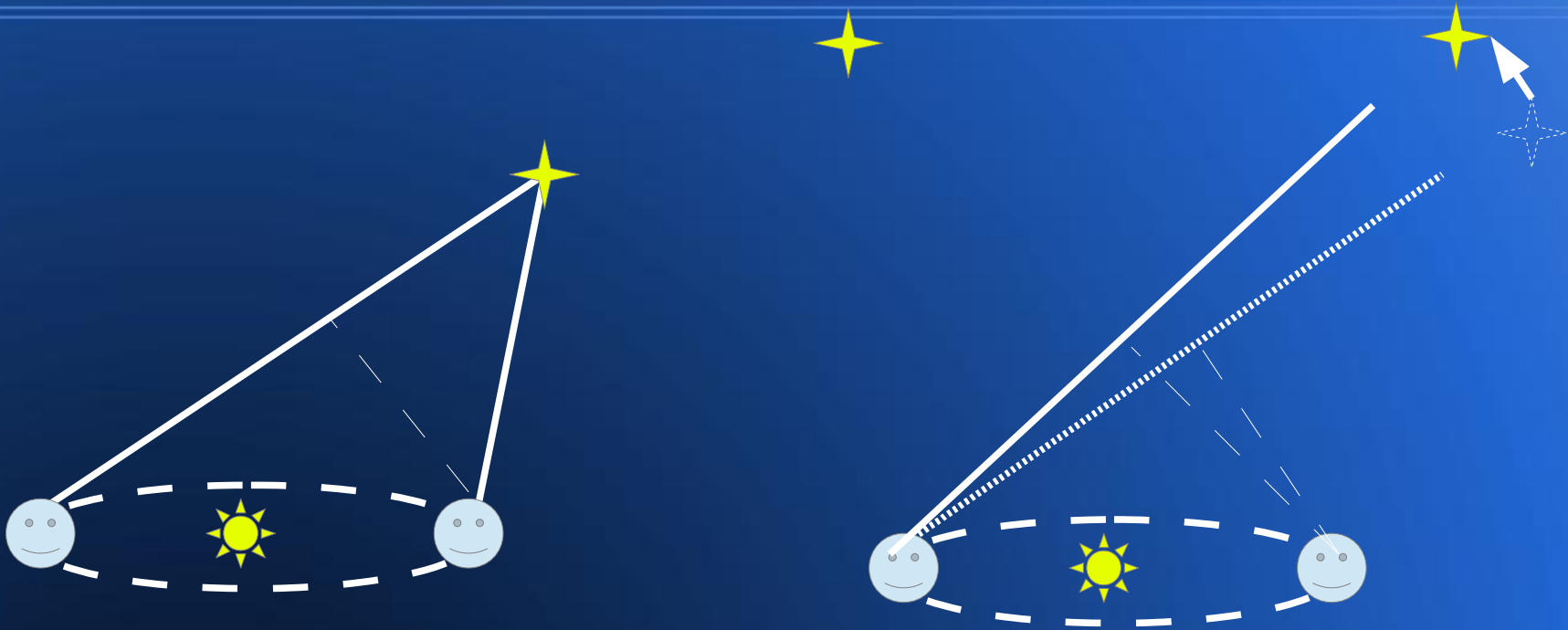
$$R[t] = \frac{N[t] - \text{Int}[N[t]]}{\nu_0}$$

Residual describe how data deviates from the model.

Examples

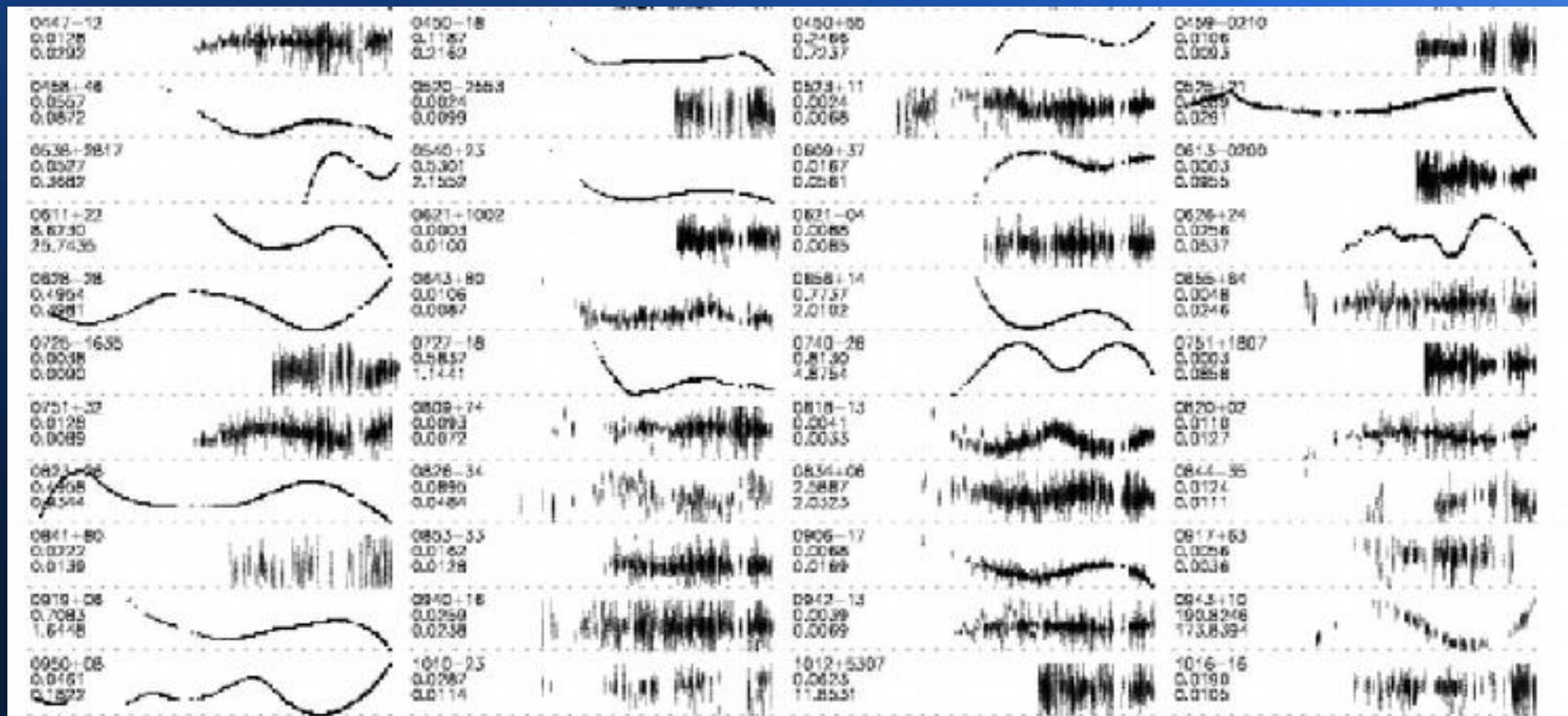


Timing parallax and proper motion

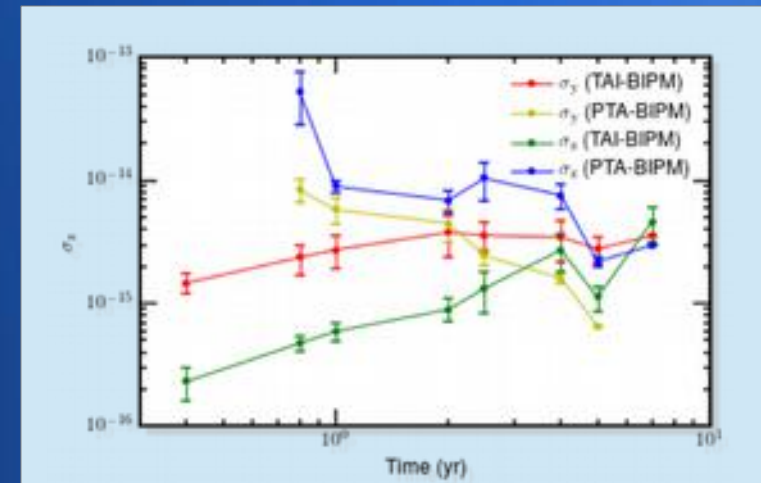
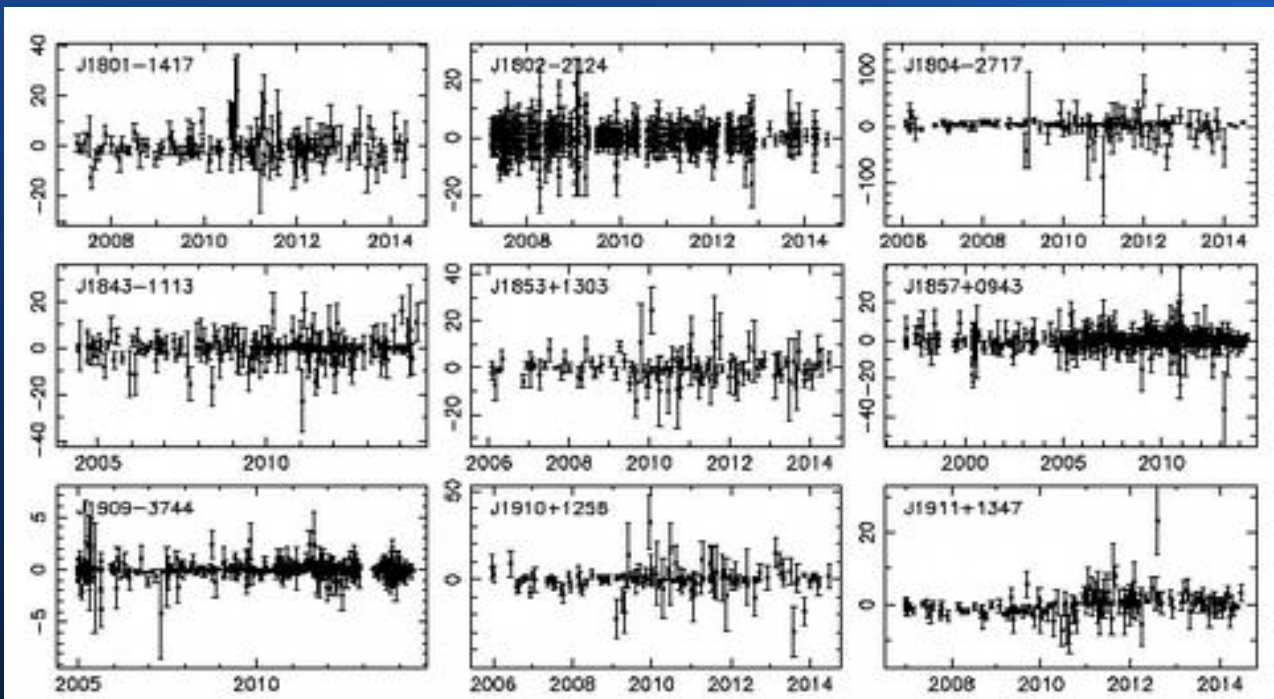


Timing behavior can be different

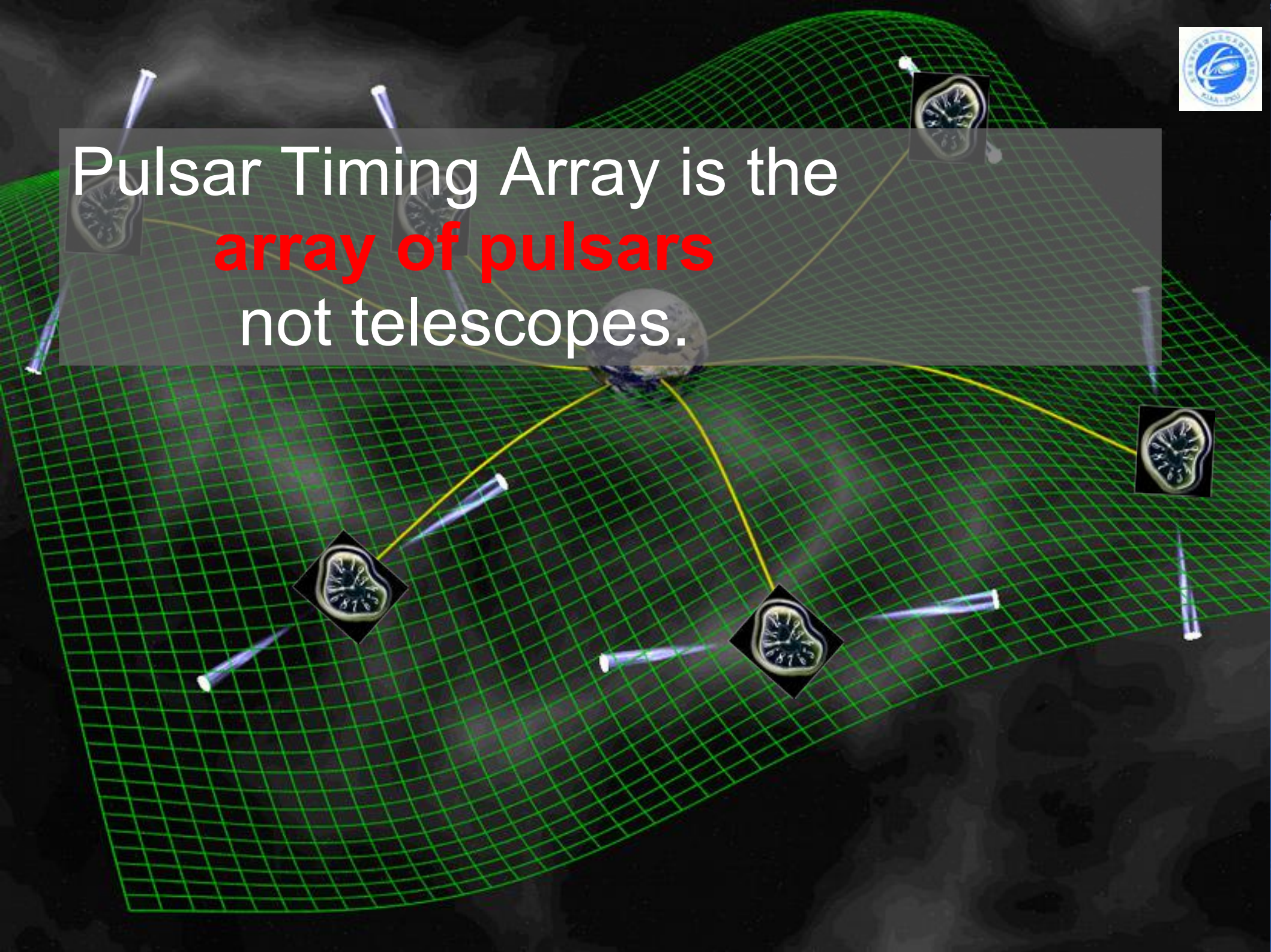
Young pulsars are noisy



Millisecond pulsar are stable



Pulsar Timing Array is the
array of pulsars
not telescopes.

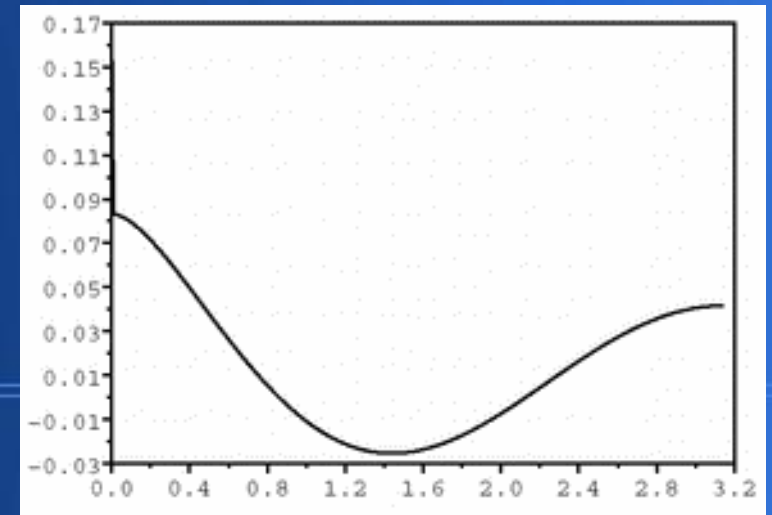
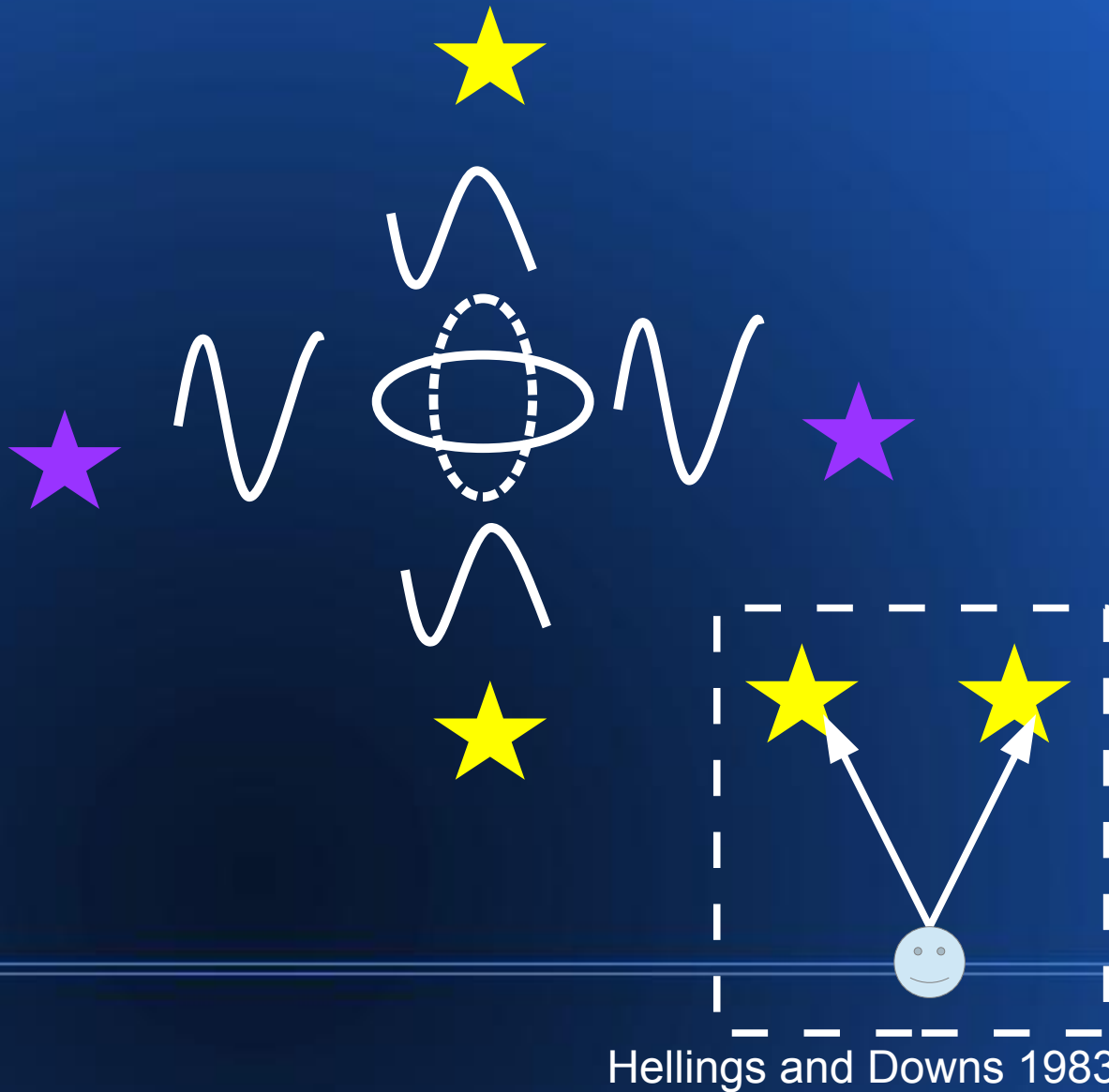


Question

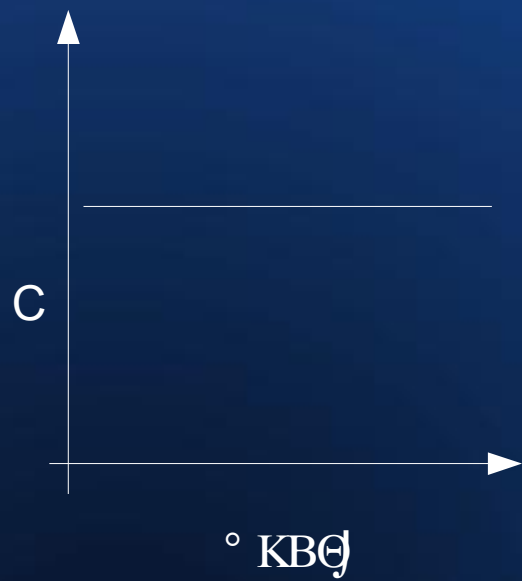
- What is the upper limit of the chirp mass of SMBHBs at redshift z with “observed orbital period of T ”, for a single pulsar timing with precision of 100 ns? How this scale with z ? Do you find surprise here?
- 2011MNRAS.414.3251L
- 2004ApJ...606..799J



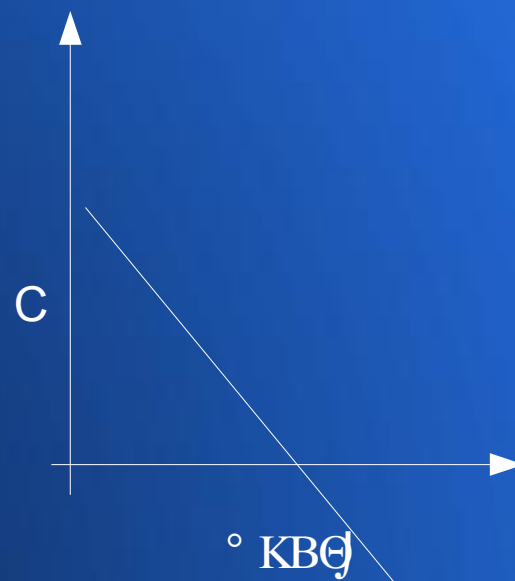
Identify Stochastic background



Mitigate noise

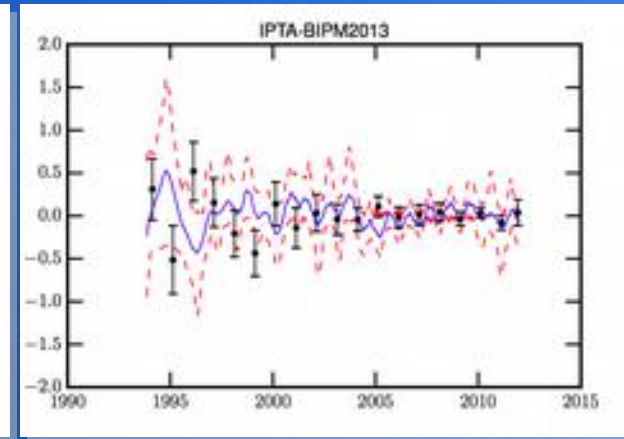
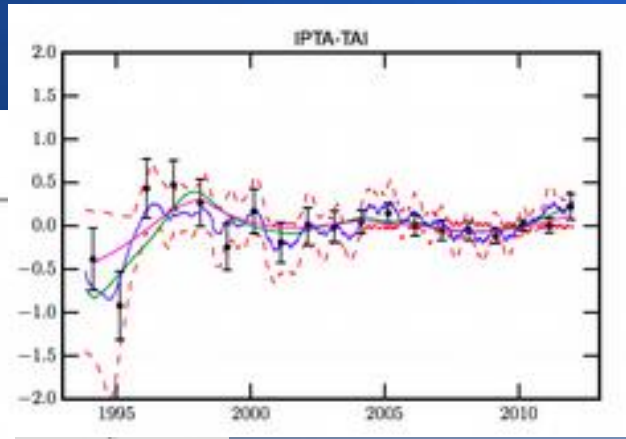
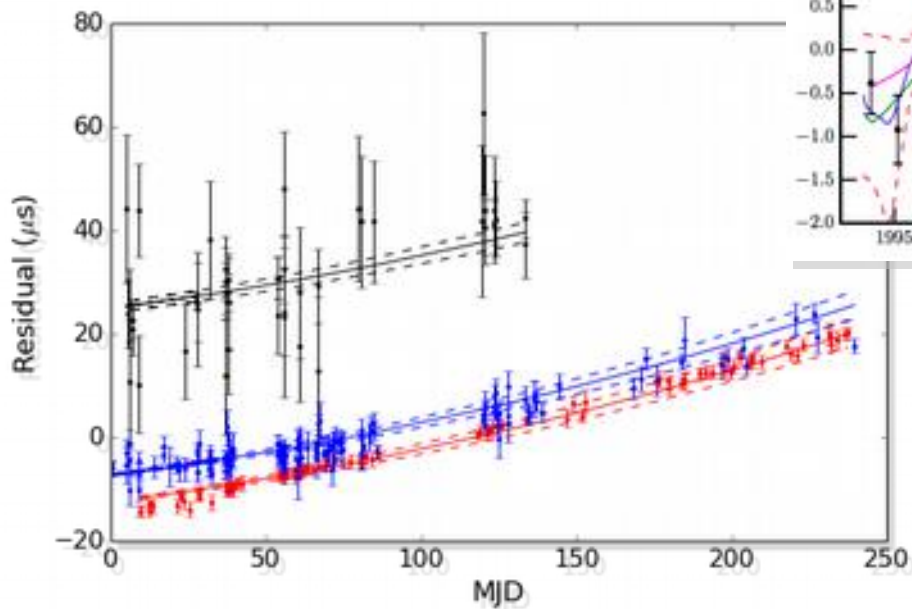


Clock noise



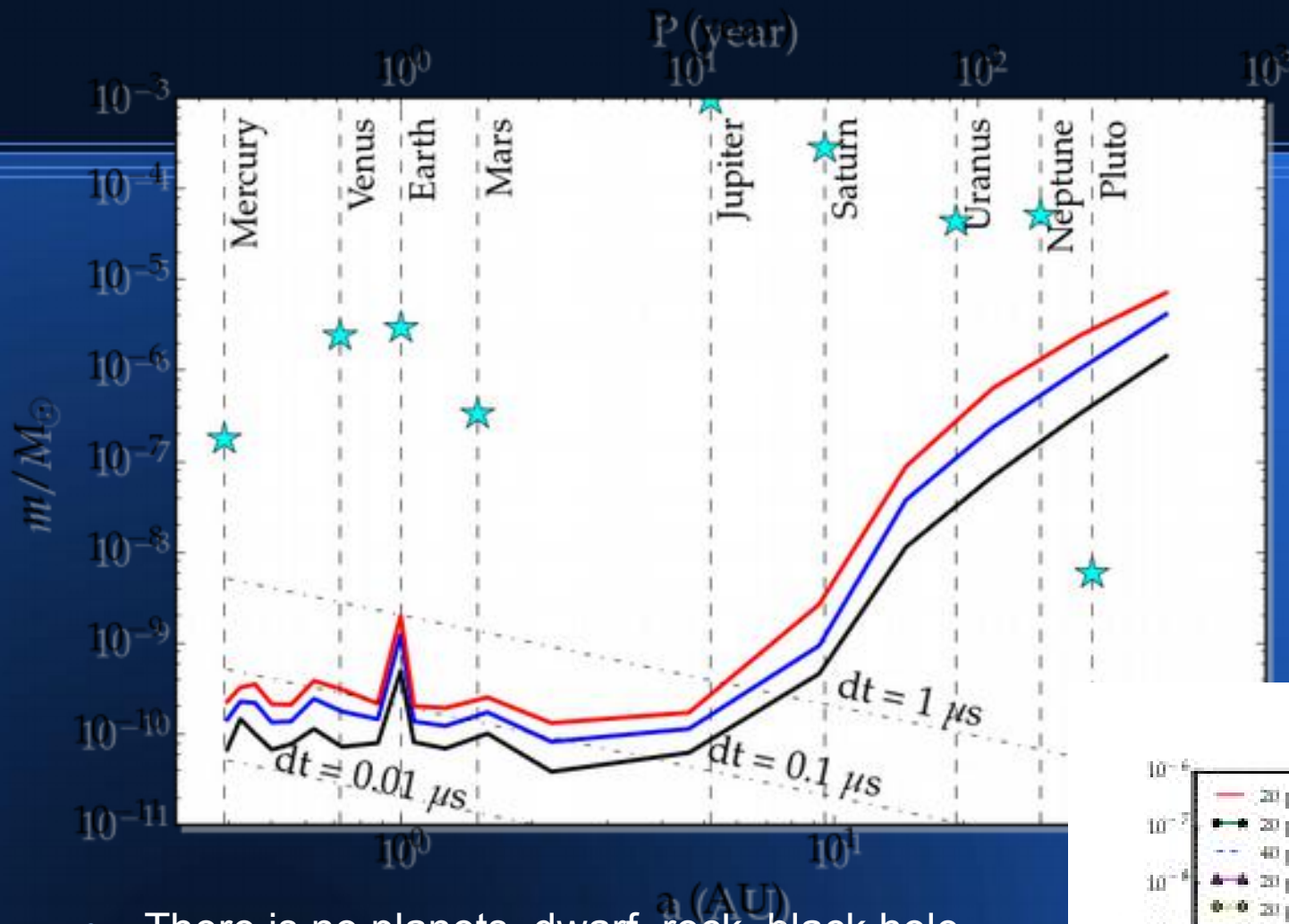
Planet ephemeris

Clock and paper time

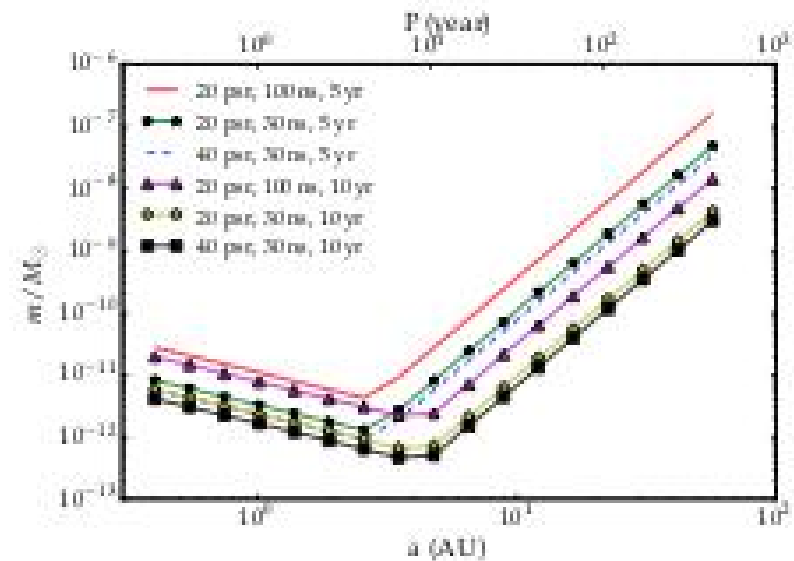


Hobbs et al., 2019

Know better for the Solar system



- There is no planets, dwarf, rock, black hole, cosmic string loop, ASP heavier than $1e20$ kg nearby (practically anything larger than 500km).





Most recent values

Current uplimit

EPTA $A < 6E-15$ (Van Haasteren et al. 2011)

NANOGrav $A < 7.2E-15$ (Demorest et al. 2012)

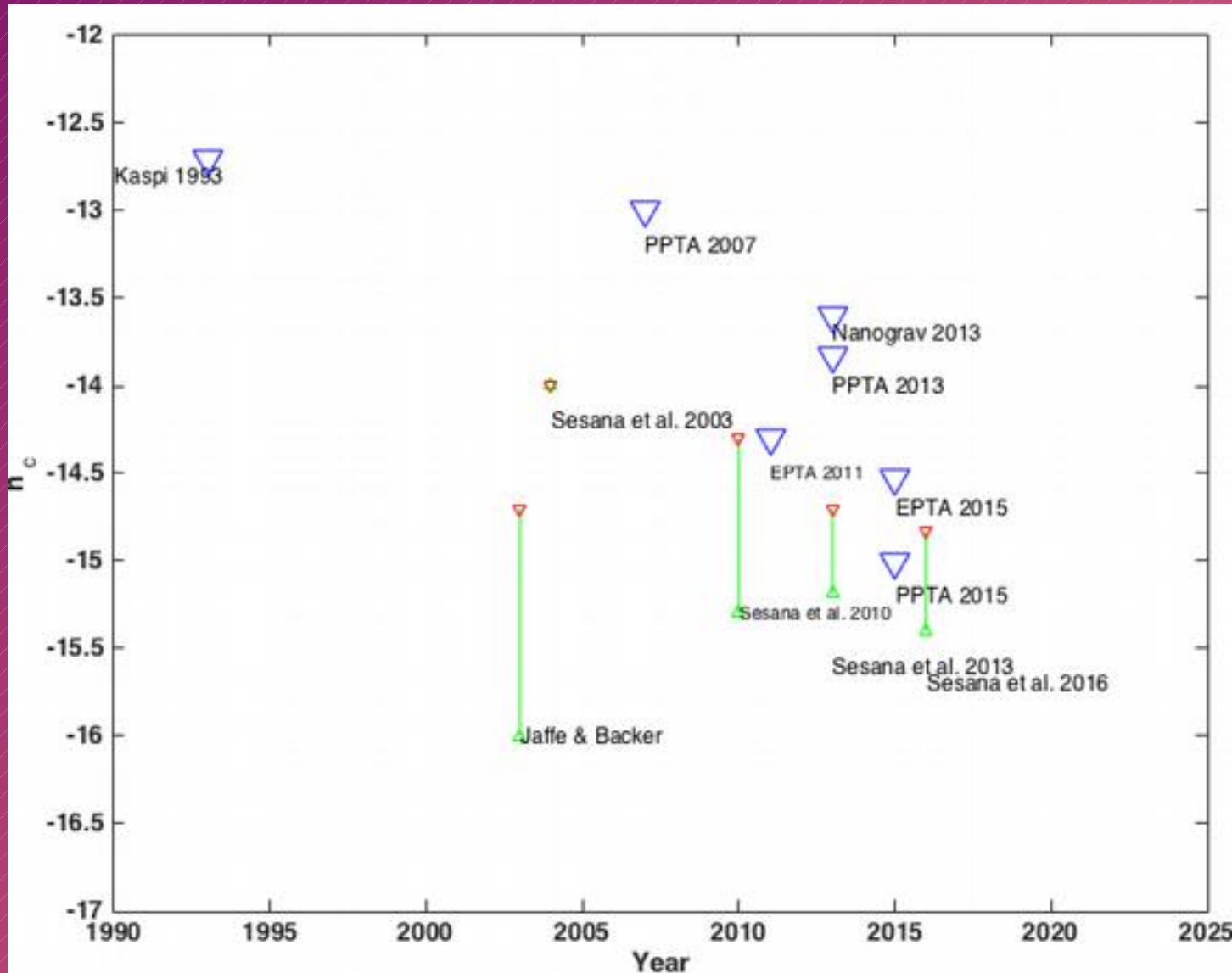
NANOGrav un-published value $2e-15$

PPTA $A < 2.4E-15$ (Shannon et al. 2012)

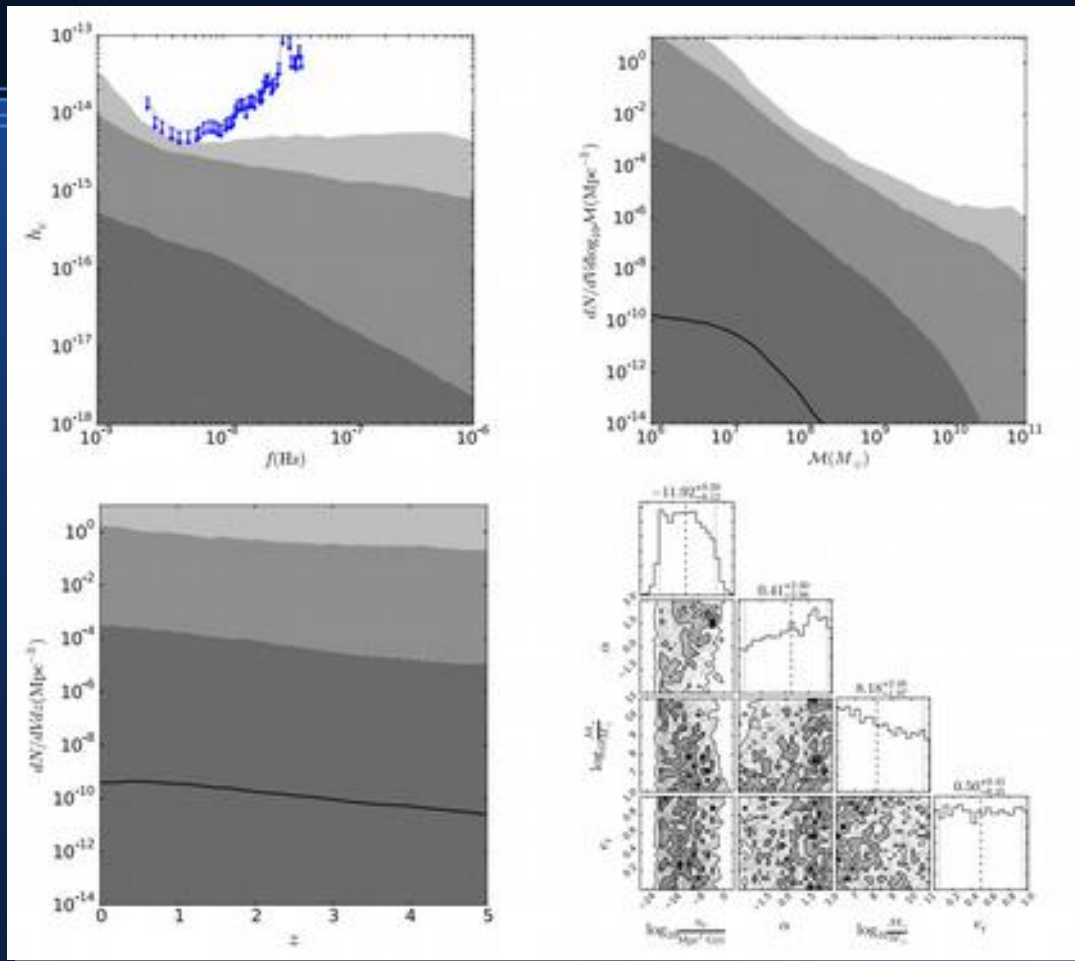
EPTA unpublished values: $A < 2.e-15$

Where we are now?

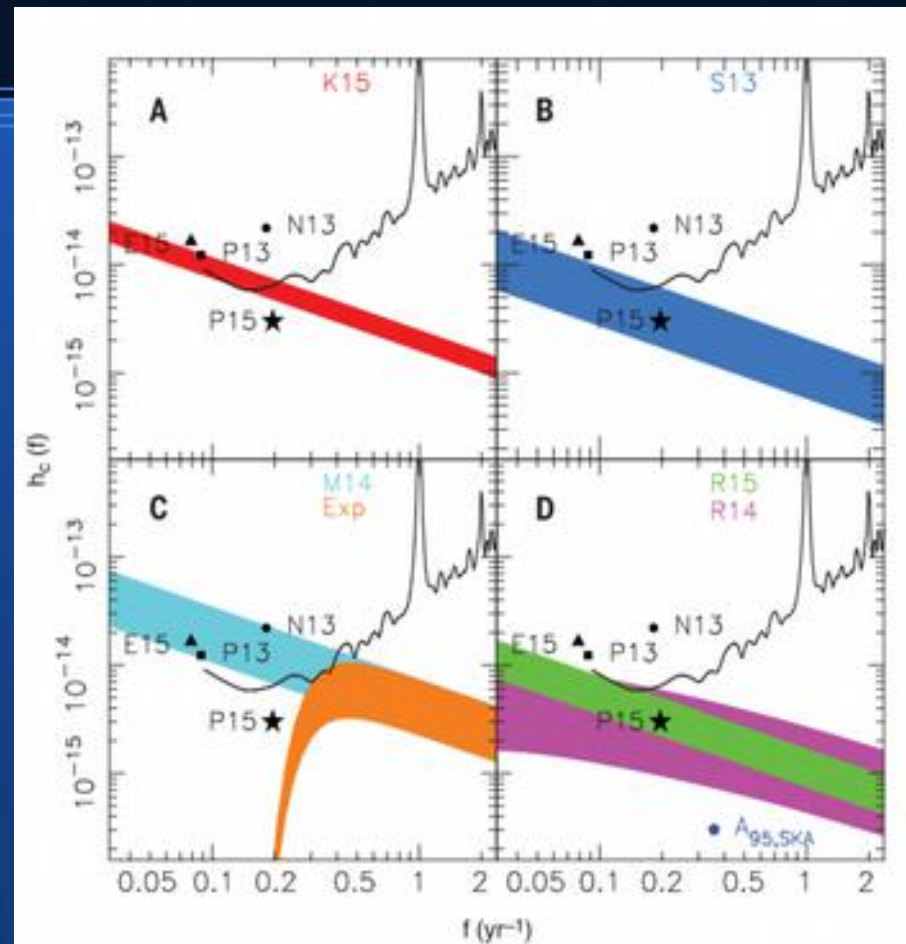
It is the best time, that we are reaching the interesting sensitivity.
It is the worst time, that theorists predicted lower and lower expectations.



Where we are now?



Chen et al., 2017



Shannon et al. 2015

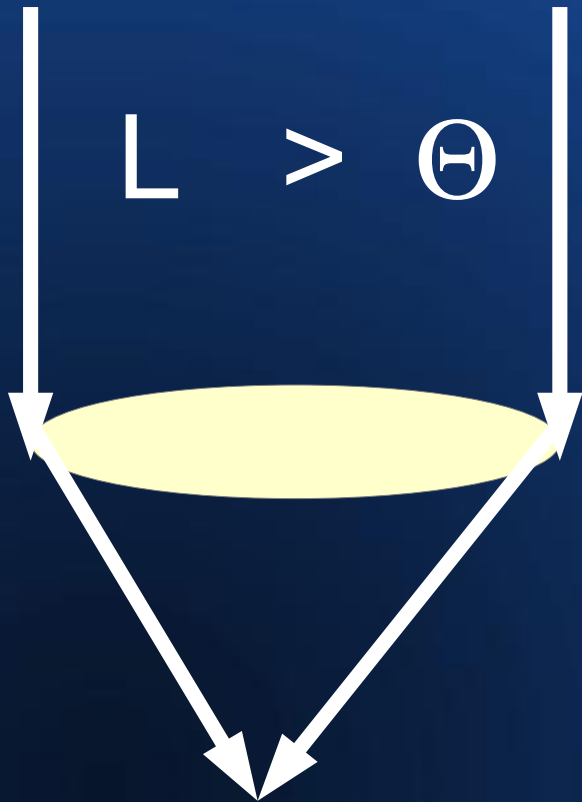


The eye not the ear



“See” the SMBH

- The size make big difference



See

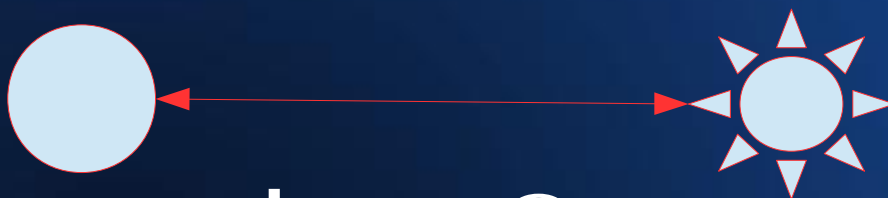


Hear

PTA as a short-wave detector

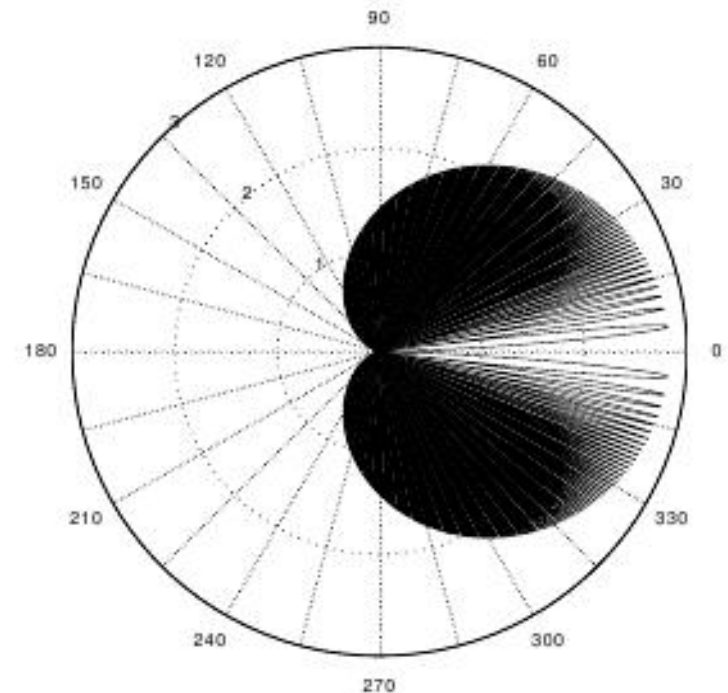
$$R(t) = T_0 + pt + \frac{1}{2}\dot{p}t^2 + \Delta_{\odot} + R_g(t) + R_{\text{par}}(t) + n(t|\sigma_n),$$

$$R_{\text{par}}(t) = \frac{\cos[2(\lambda_{\text{psr}} - \lambda_{\oplus}(t))] \cos^2 \beta_{\text{psr}} r_{\oplus}^2}{4D_{\text{psr}}},$$

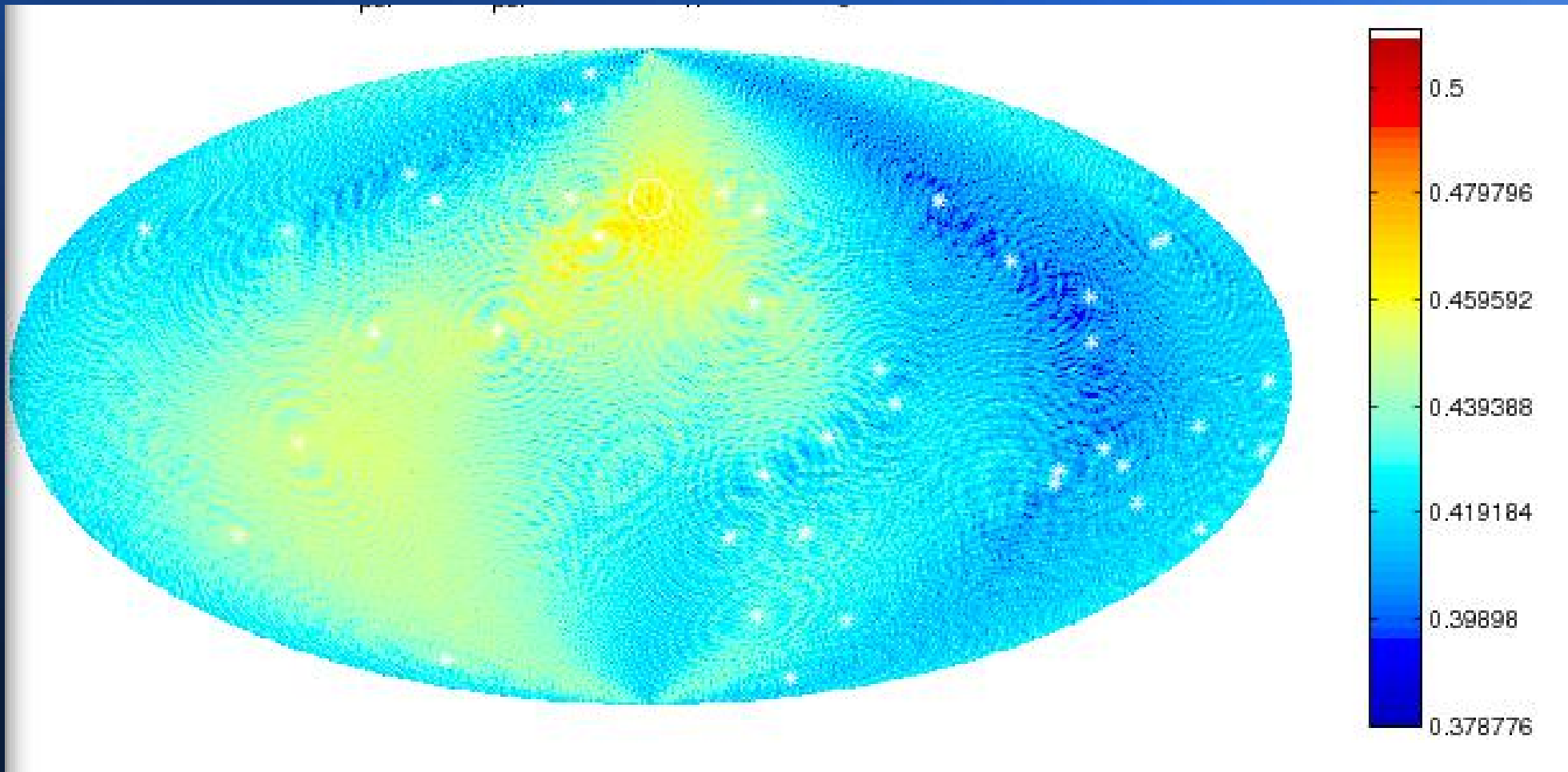


$$L \gg \oplus$$

$$N_{\gamma} \ll L$$

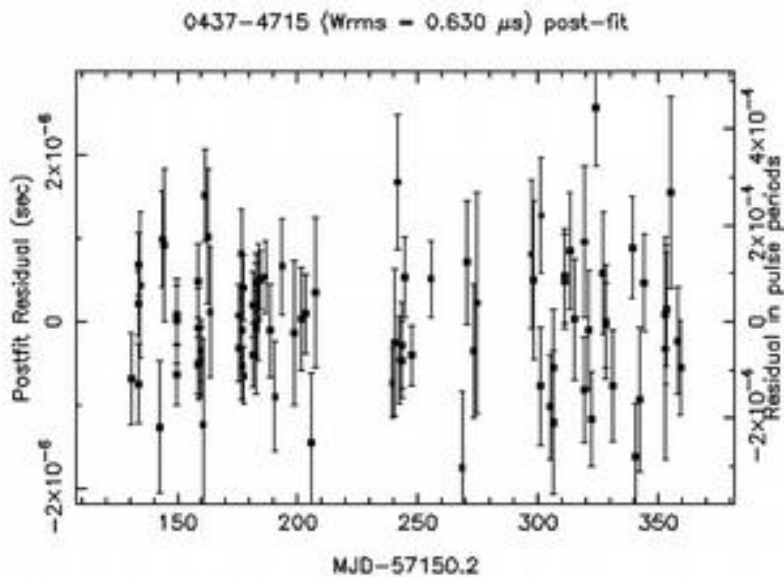


We can see more clearly



Timing

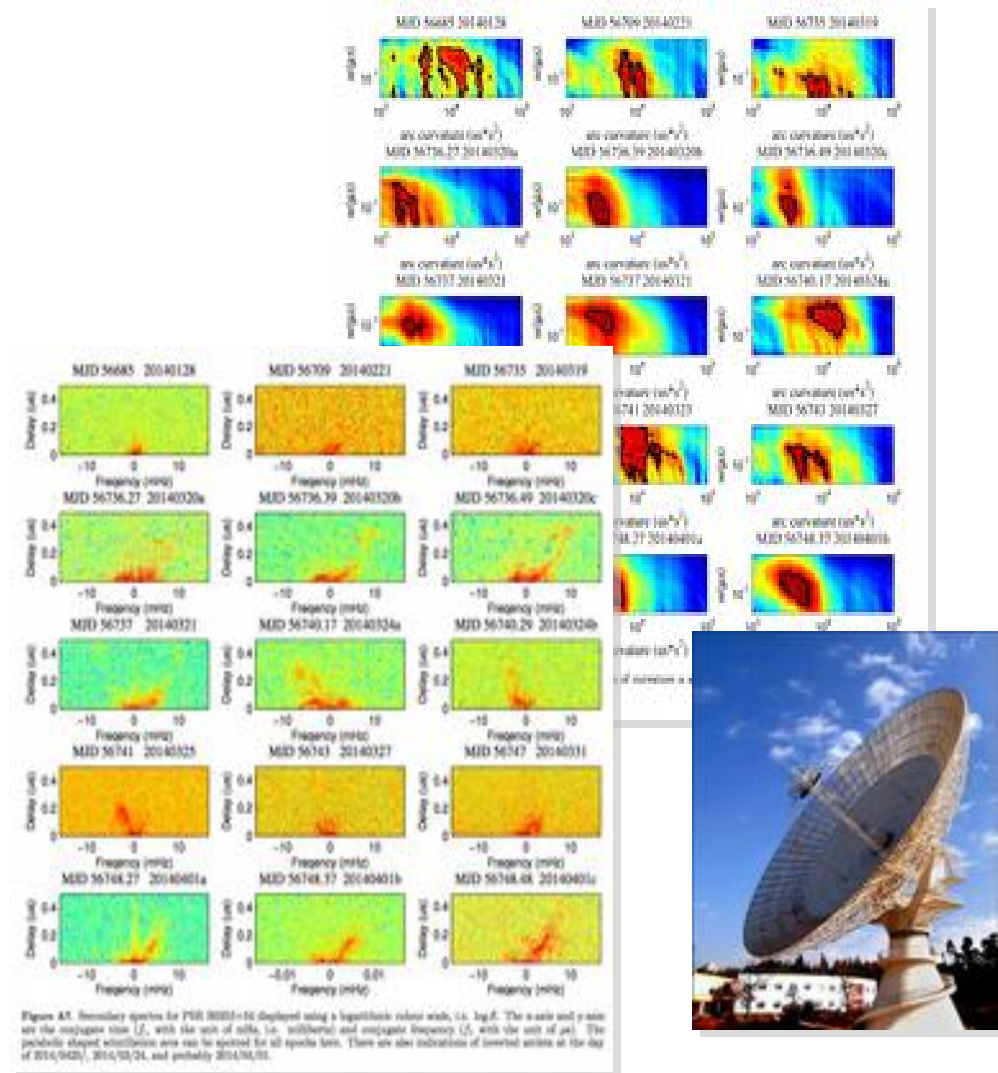
Utilize the Chinese telescopes resource which we can access to start high precision pulsar timing in China



Best Chinese timing precision so far using **Yunnan 40m**

Current upper limits: $\text{GW } A < 1e-13$
40 times worse than EPTA limits!

We started official timing array with 6 pulsar at S-band and C-band last month, ~20 hr observing time per day.



Detected scintillation arc and its variation for the first time.

Xu, Lee et al., submitted

Can we improve?

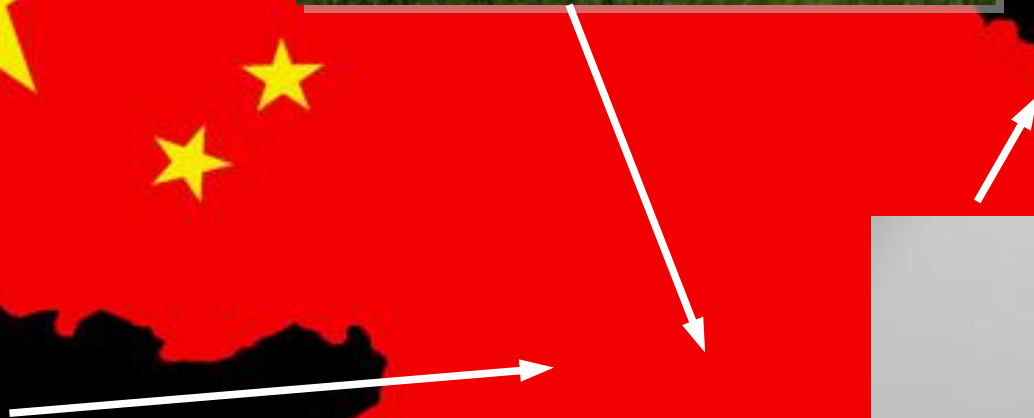
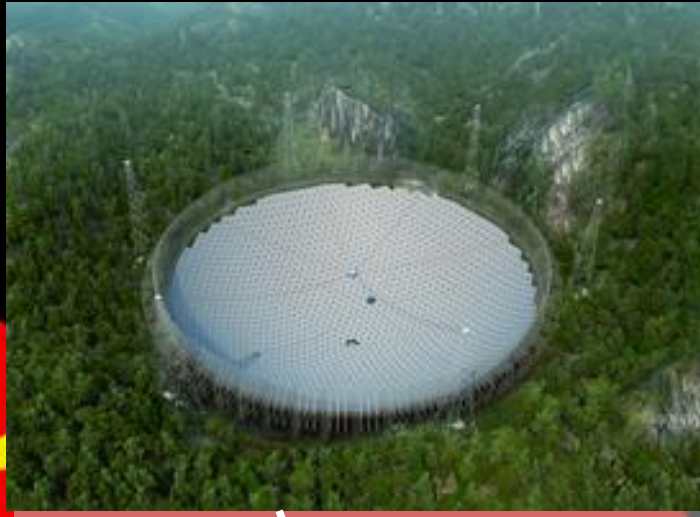
1. Radiometer noise dominated -----> Big improvement
2. Jitter noise dominated -----> Split the array,
reasonable improve.
3. ISM noise dominated -----> Go higher frequency
wider bandwidth
4. Intrinsic noise dominated -----> Find better pulsars

Improve the Radiometer noise

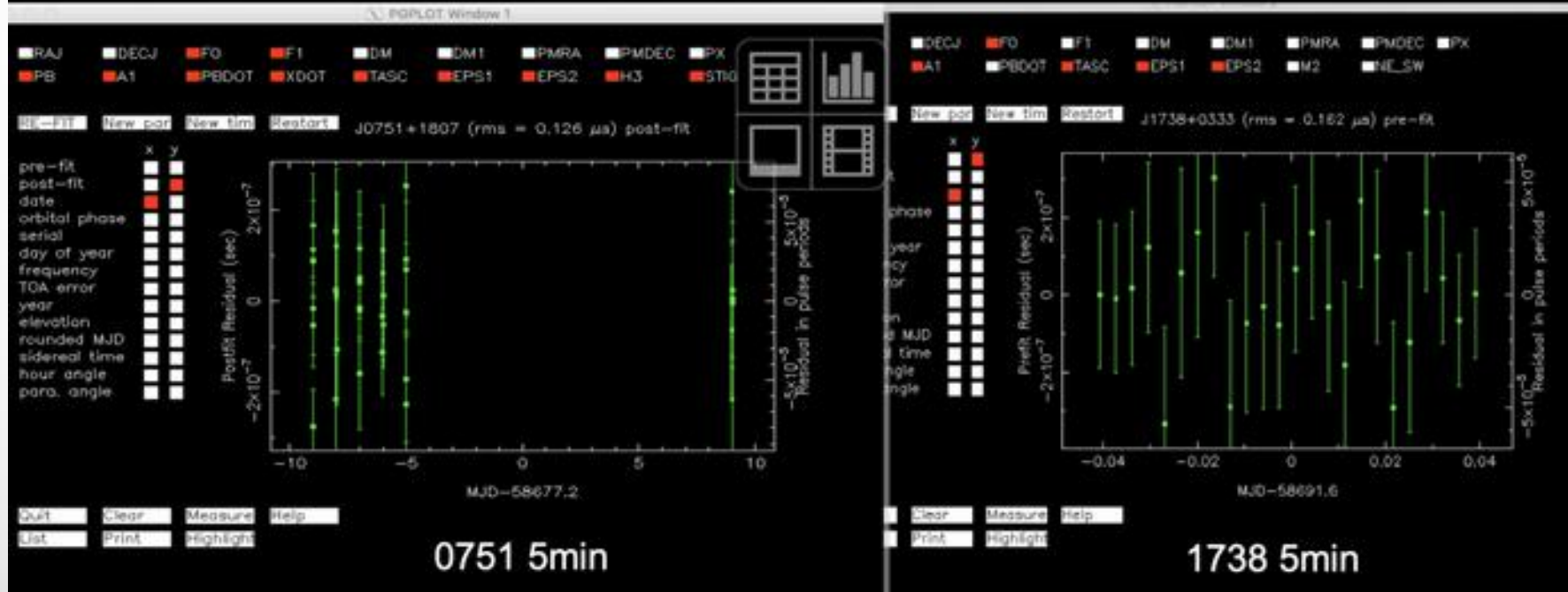
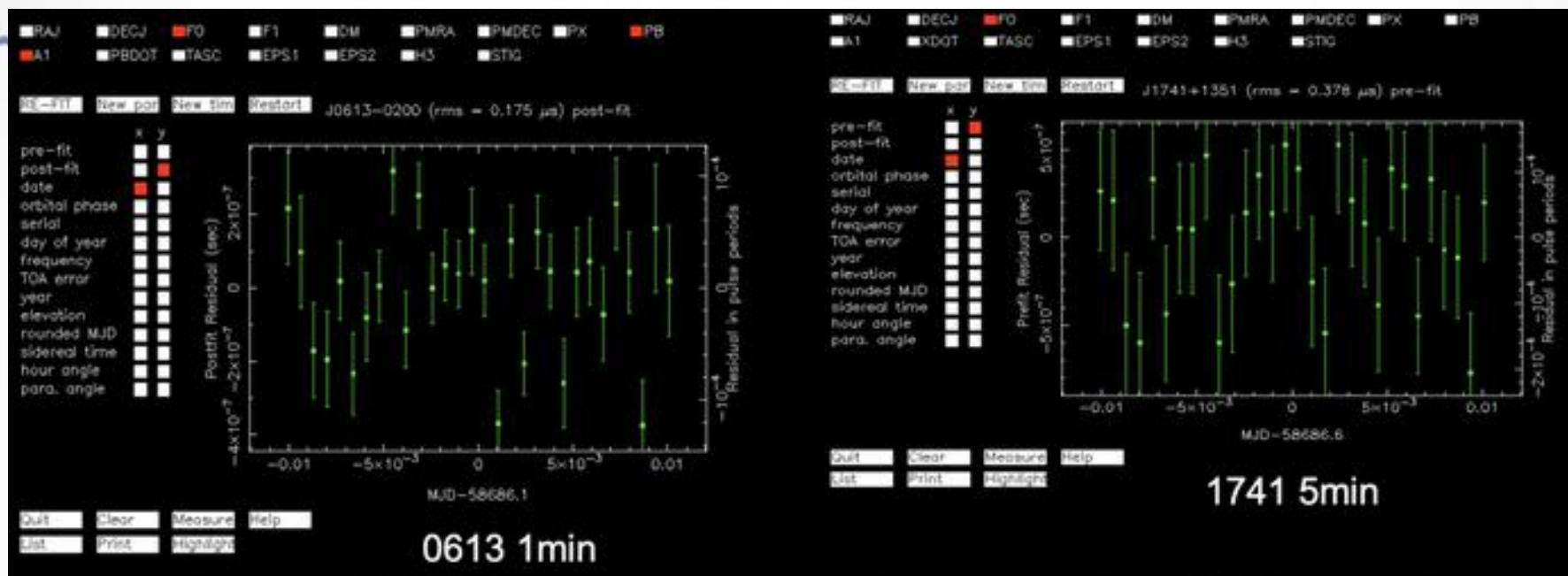
- Use stable MSPs
- Use big telescopes
- Use better electronics
- Get more telescope time
- Better calibration

$$\sigma_{\text{TOA}} = 19.2_{[\mu s]} \frac{T_{\text{sys}} [10\text{K}]}{G [K/\text{Jy}] S [\text{mJy}]} w_{[1]}^{3/4} t_{\text{obs}}^{-1/2} [\text{hr}] \Delta f^{-1/2} [100\text{M Hz}] P_{[\text{ms}]}.$$

Big telescope



Timing for strong pulsars immediately deliver great results at FAST. We can clearly see the effects of jitter, and measure the jitter parameters. For ~ 10 pulsar, we can **measure the jitter parameter to a good accuracy for the first time!**



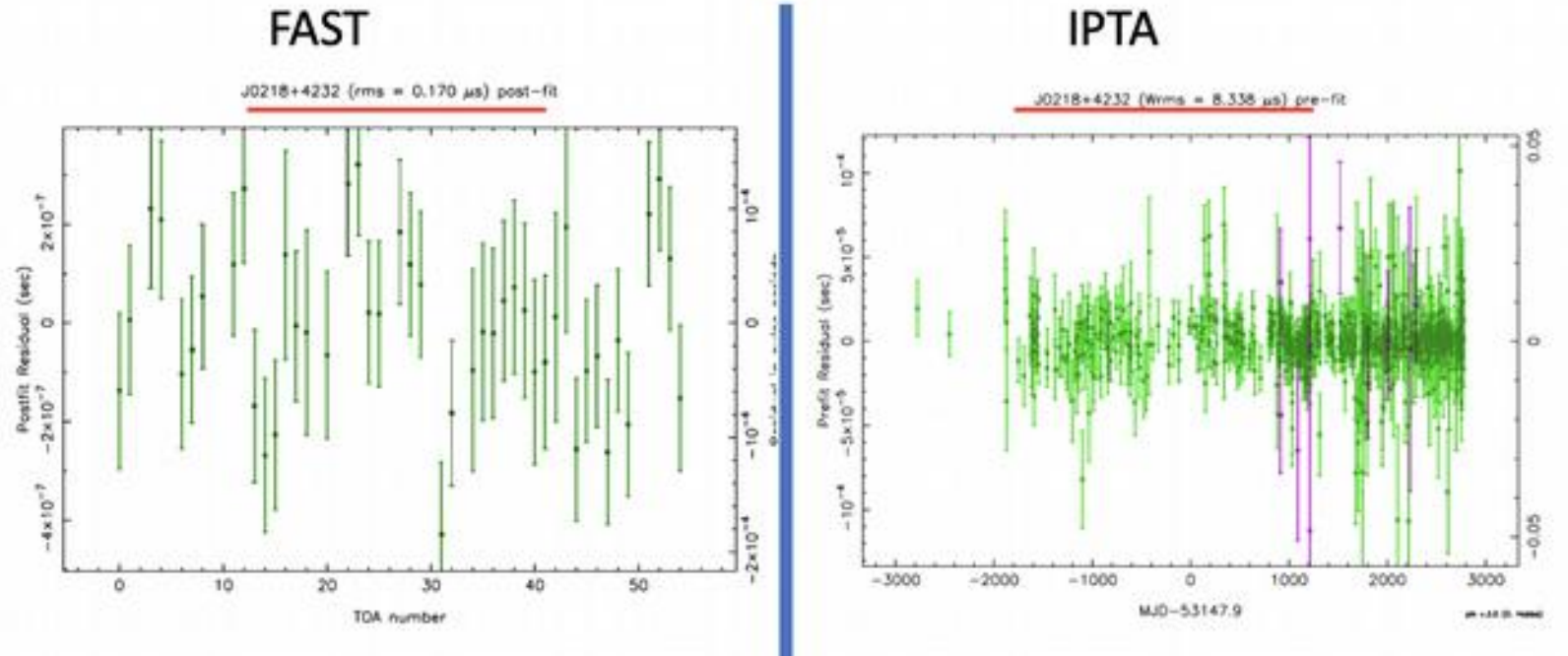
Timing for strong pulsars immediately deliver great results at FAST. We can clearly see the effects of jitter, and measure the jitter parameters. For ~ 10 pulsar, we can measure the jitter parameter to a good accuracy for the first time!

For reasonable PTA pulsars, FAST can achieve **100ns with 5-min** observation. A few-hour observation brings us down to 10ns level.

We will get very **competitive GW upper limit** with 2-3 year observation, and should **detect GW with 5-7 year** observation, if we get enough observation time.

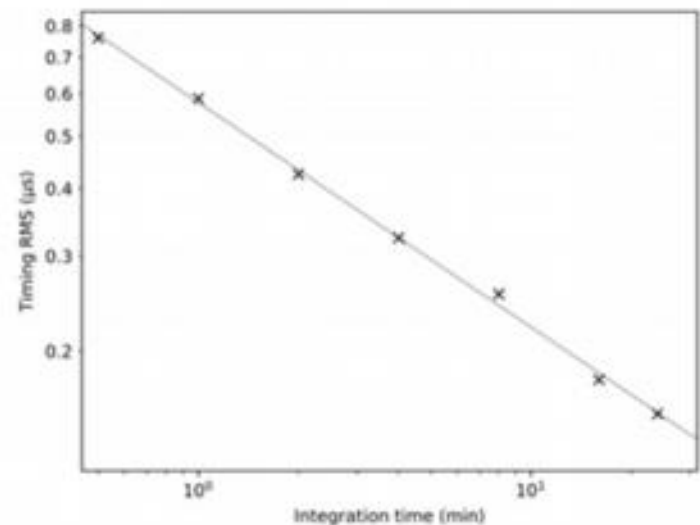
Weak pulsar timing

FAST is overwhelmingly powerful for weak pulsars.

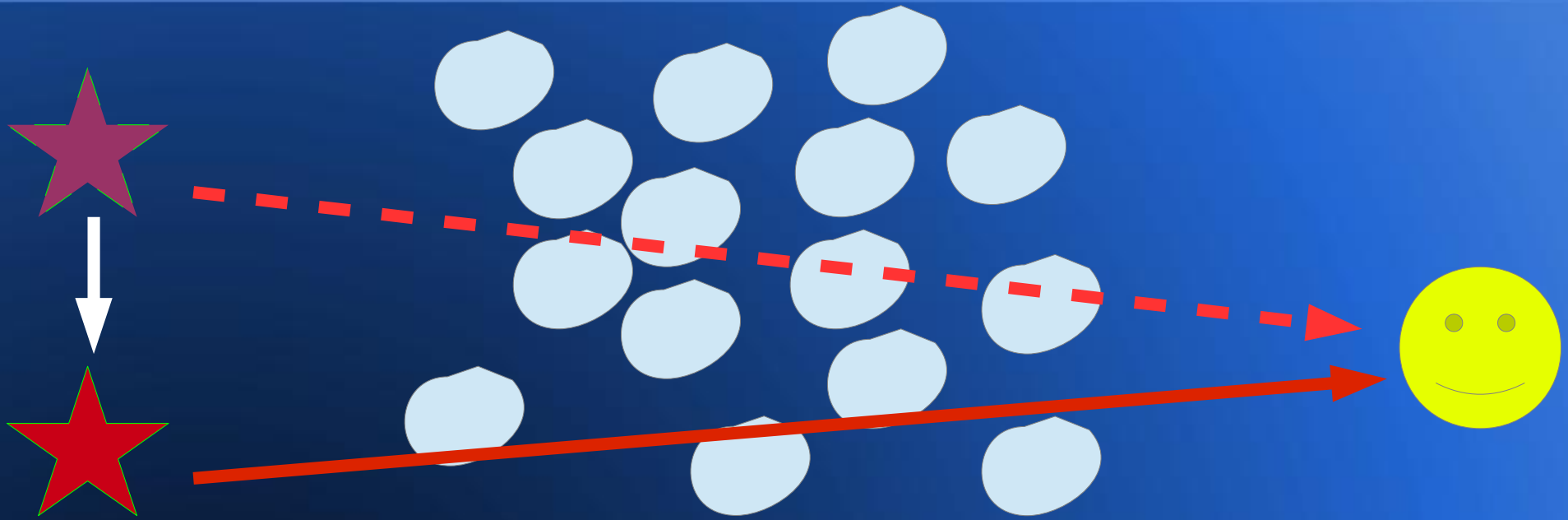


For weak pulsar, the high gain of FAST leads to a great improvement for timing precision. E.g., for J0218+4332, we can **achieve 48 times more precise measurement compare to the current IPTA.**

We see the perfect $1/\sqrt{T}$ law, even better timing can be achieved, if we have more observation time.



Red noise and DM noise

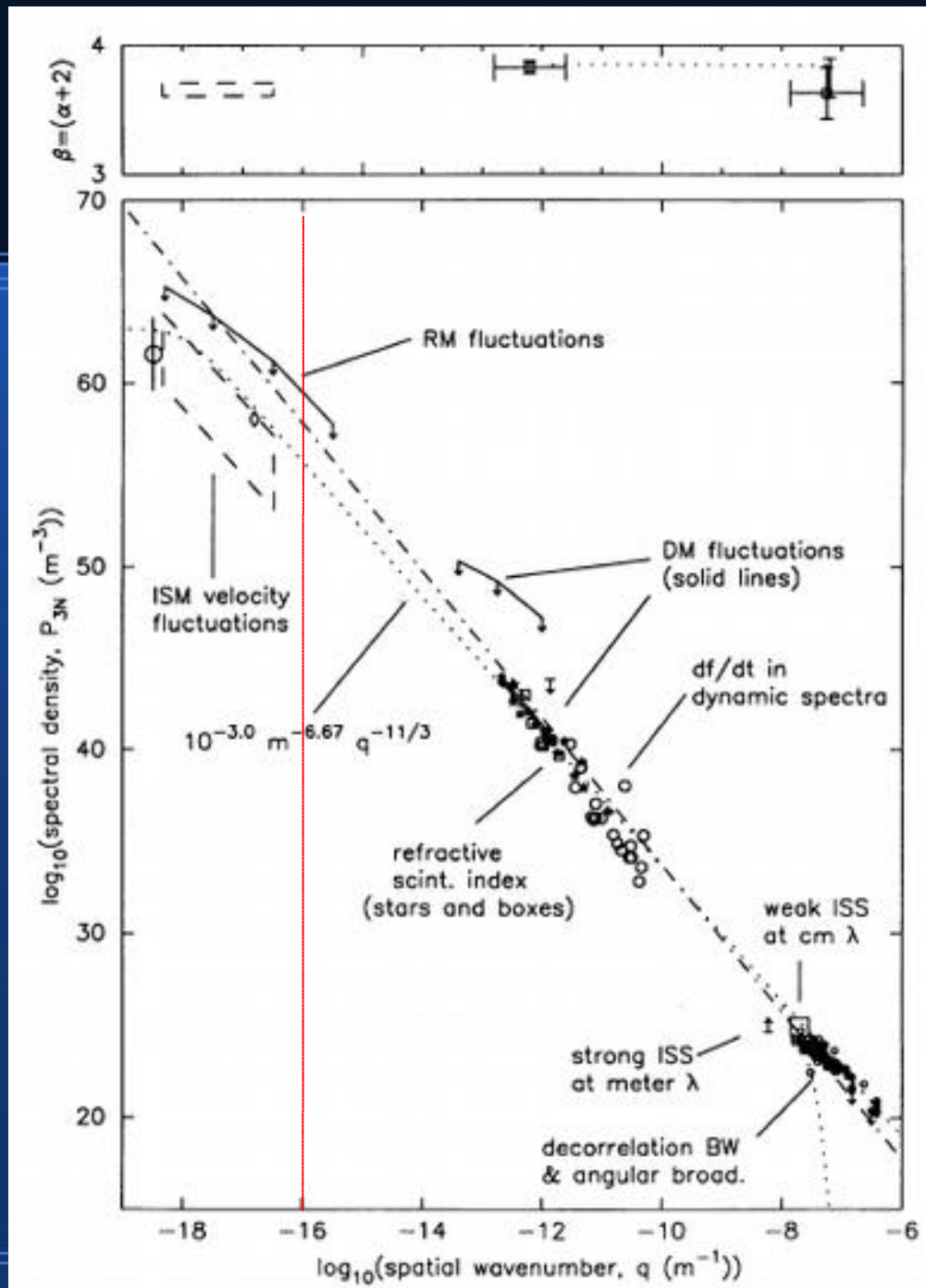
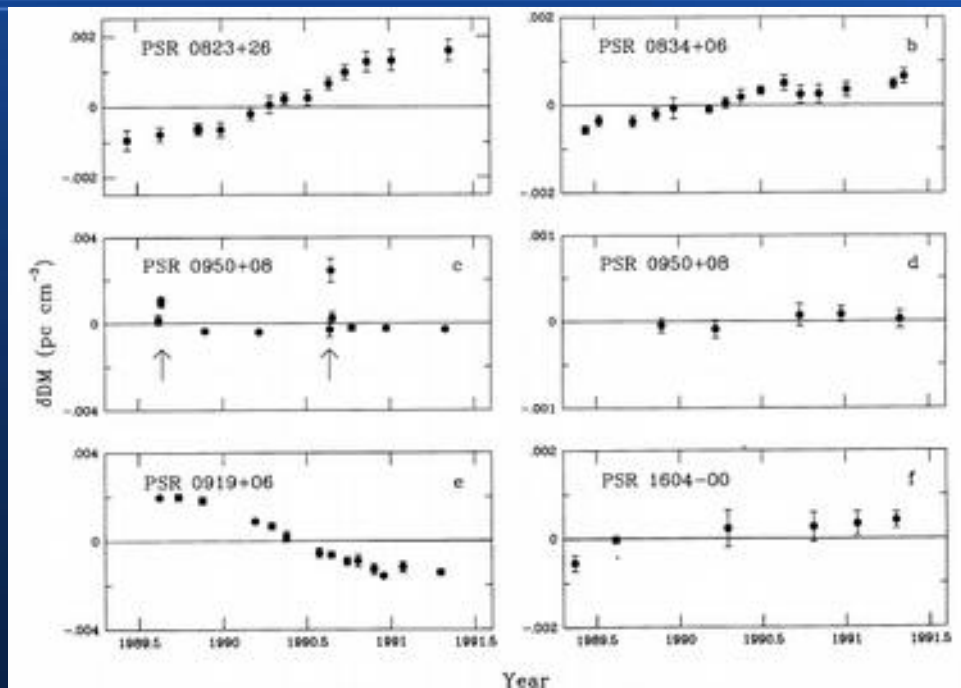


$$P(k) = C_N^2 k^{-\alpha}$$

$$S(f) \propto C_N^2 v_{\text{psr}}^\alpha f^{-\alpha}$$

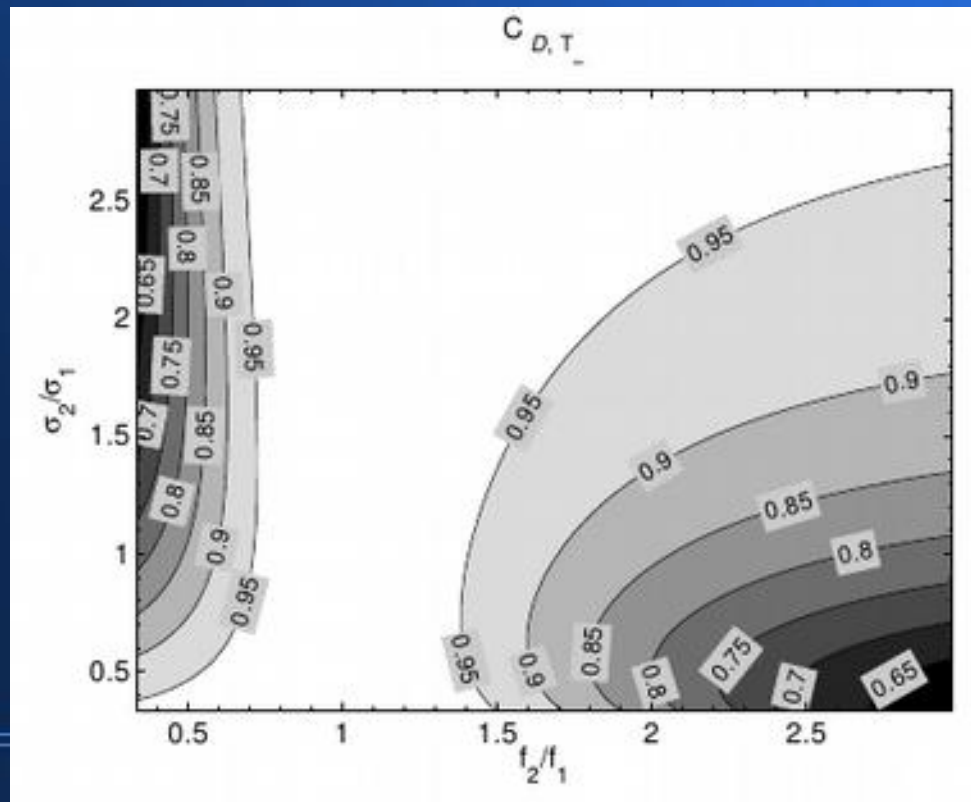
$$t_{\text{DM}}(f) - t_{\text{DM}}(\infty) = 4.15 \times 10^{-3} \text{DM} \left(\frac{f}{\text{GHz}} \right)^{-2} [\text{s}],$$

Electron density fluctuation spectrum

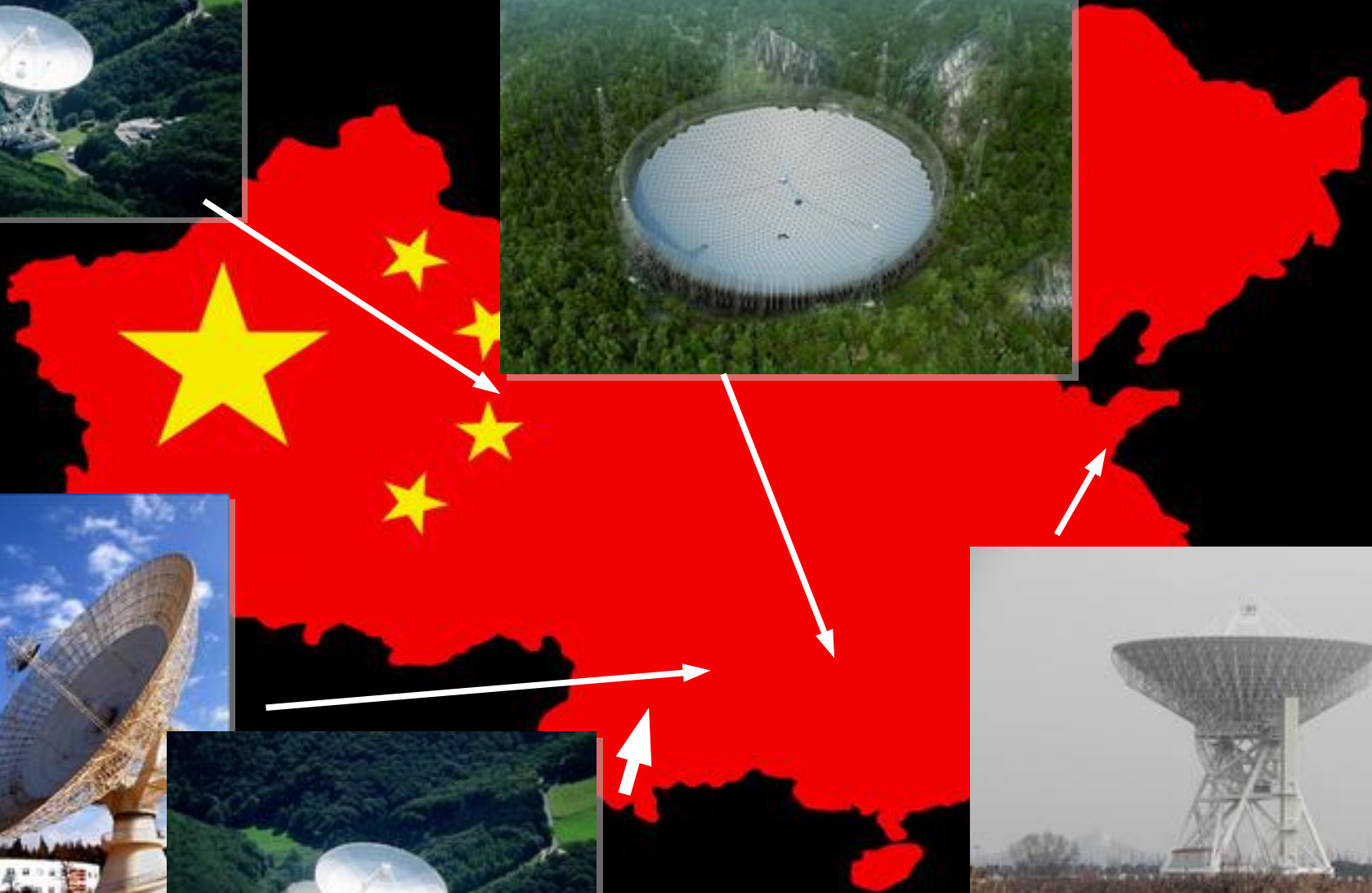


Need wideband system

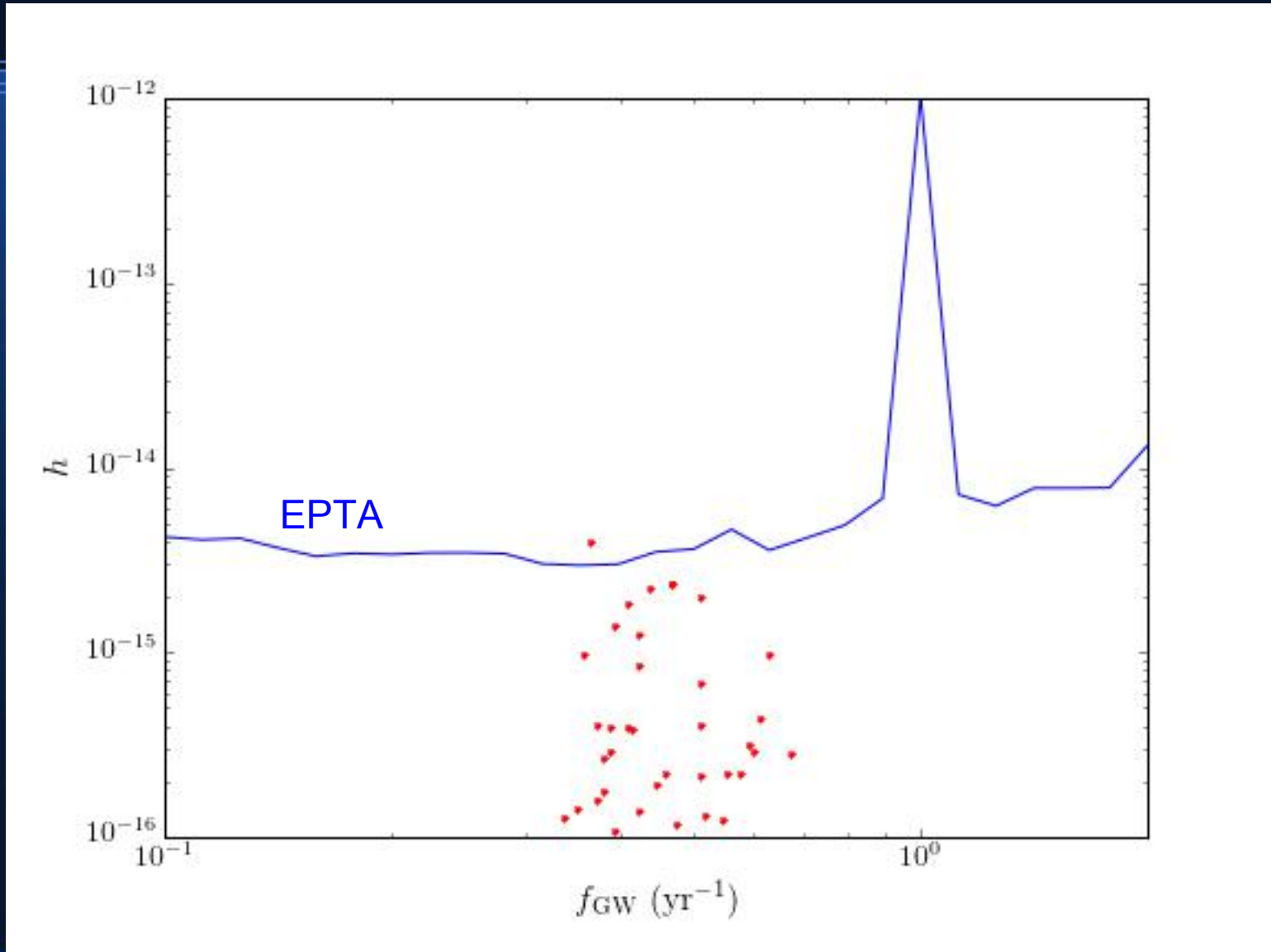
$$C_{D,T_\infty} = \frac{\langle \delta D \delta T_\infty \rangle}{\sqrt{\langle \delta D^2 \rangle \langle \delta T_\infty^2 \rangle}} = \frac{\sum_{k=1}^{N_f} \frac{1}{f_k^2 \sigma_k^2}}{\sqrt{\sum_{k=1}^{N_f} \frac{1}{f_k^4 \sigma_k^2} \sum_{k=1}^{N_f} \frac{1}{\sigma_k^2}}}$$



Big telescope

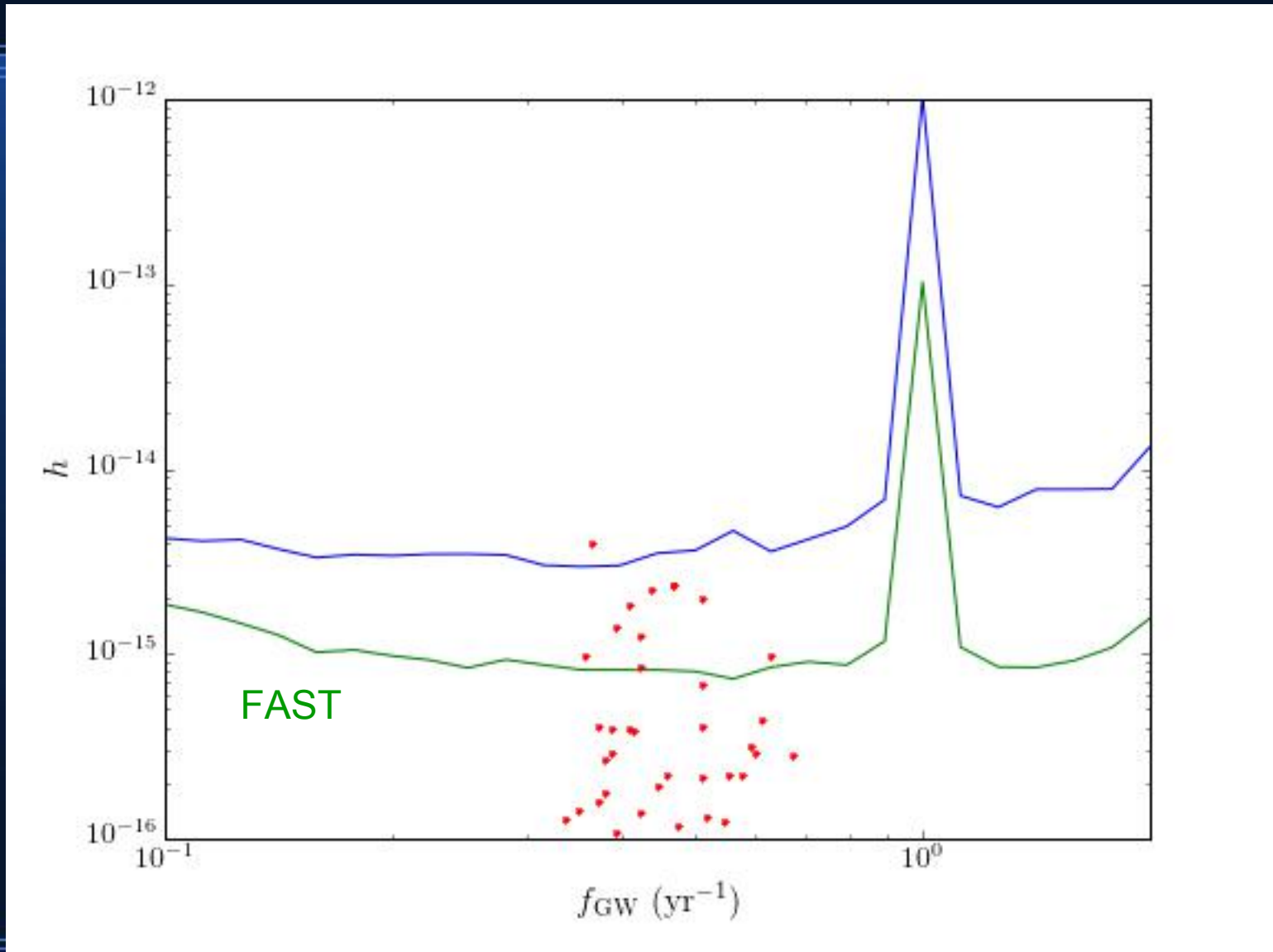


FAST and QTT—The future!

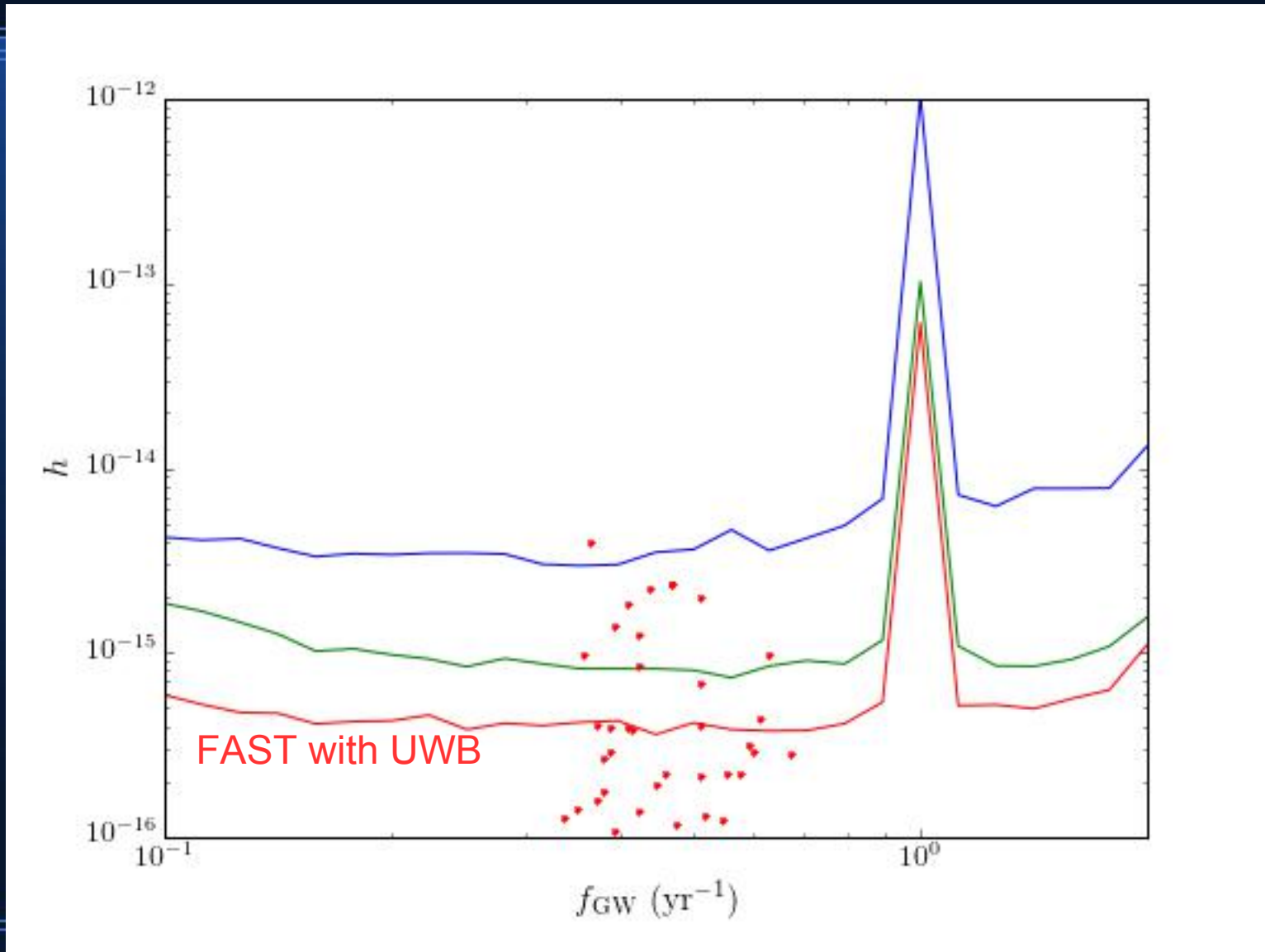


红点是已知的引力波源候选体

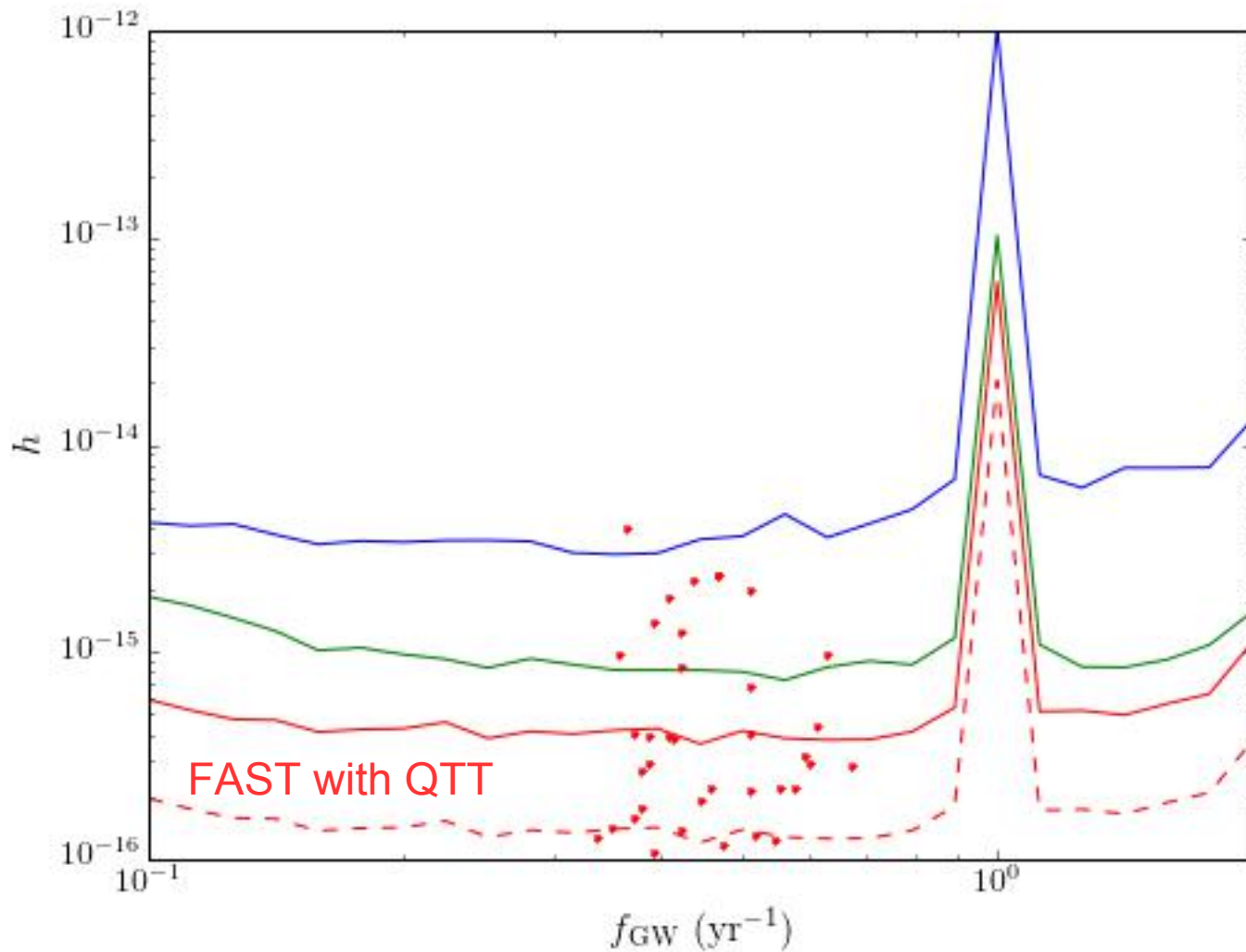
FAST and QTT—The future!



FAST and QTT—The future!



FAST and QTT—The future!



Summary

- We may detect gravitational wave in the near future using PTA and after the detection, we can
 - Study gravity theories
 - Polarization and graviton mass
 - Study the astrophysics
 - BH merger processes, mass function, cosmic structural formation
 - Locate the GW source and do other type of follow ups
 - Multi-messenger astronomy
- Extrapolate from current FAST observation data,
 - 3 year data → World leading nHz GW detector
 - 5 year data → 2-sigma indication
 - 7 year data → 3-sigma detection

Pulsars as laboratory

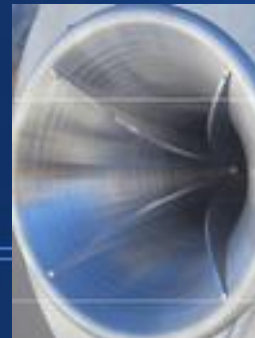
- The only place where The Four fundamental Interaction meets
 - Relativistic plasma physics
 - Relativistic fluid mechanics
 - Relativistic superconductivity and superfluidity
 - Nuclear density at zero temperature
 - Non-trivial neutrino opacity
 - Relativistic gravity
 -



Conclusion

Pulsars are very cool, and Pulsar Timing Arrays is no longer a Blunt Instrument for Gravitational Wave Detection!

- We need big telescope, more observing time, better electronics, and huge computers!
- Stay tuned!



Thanks

Questions: Please, do a survey and figure out what else can be studied via PTA?