

Exploring phase transitions with pulsar timing arrays.

QU Day 4/2023 – DM parallel session

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Based on work with Torsten Bringmann, Paul Frederik Depta,
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arXiv: [2306.09411], JCAP 11 (2023) 053

November 21, 2023



Outline of this talk.

1. The PTA signal
2. The null hypothesis:
astrophysics
3. Phase transitions vs.
precision cosmology
4. BSM or boring?



[DALL-E's interpretation of this talk's buzzwords]

In case you haven't heard the news.

At Last, There's a 'cosmic bass note'
A globe-spanning...
Astronomers detect 'cosmic bass note' of gravitational waves
Sound comes from the merging of supermassive black holes across the universe, according to scientists

Scientists 'hear' cosmic hum from gravitational waves
Scientists observed for the first time faint ripples caused by the motion of black holes that are gently stretching and squeezing everything in the universe
Gravitational waves finally 'heard' the chorus of gravitational waves that ripple through the universe

Black Holes in Space
Gravitational wave... at the center of the Milky Way

Scientists reveal how black holes come from cosmic collisions

The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find
Radio telescopes around the world picked up a telltale hum reverberating across the cosmos, most likely from supermassive black holes merging in the early universe.

of Low-Frequency Gravitational Waves
the waves, which... from pairs of merging supermassive black holes

Scientists 'hear' cosmic hum from gravitational waves
Scientists observed for the first time faint ripples caused by the motion of black holes that are gently stretching and squeezing everything in the universe.

A Background 'Hum' Pervades the Universe. Scientists Are Racing to Find Its Source
Astronomers are now seeking to pinpoint the origins of an exciting new form of gravitational waves that was announced earlier this year

Colossal gravitational waves—trillions of miles long—found for the first time
by studying rapidly spinning dead stars that create giant ripples of spacetime likely from merging supermassive black holes—

In a major discovery, scientists say spacetime churns like a choppy sea
The mind-bending finding suggests that everything around us is constantly being stretched and squeezed by gravitational waves

First Evidence of Giant Gravitational Waves Thrills Astronomers
For first time ever, scientists "hear" gravitational waves rippling through the universe
are tuning in to a never-before-seen type of gravitational wave spawned by pairs of supermassive black holes

Monster gravitational waves spotted for first time
Scientists discover that universe is a cacophony of gravitational waves

Gravitational waves produce a background hum across the whole universe
After decades of searching, astronomers have found a distinctive pattern of light, from scattering stars called pulsars, that suggests huge gravitational waves are creating gentle ripples in space-time across the universe
The results are... background, a hum of gravitational waves

Pulsar timing arrays.



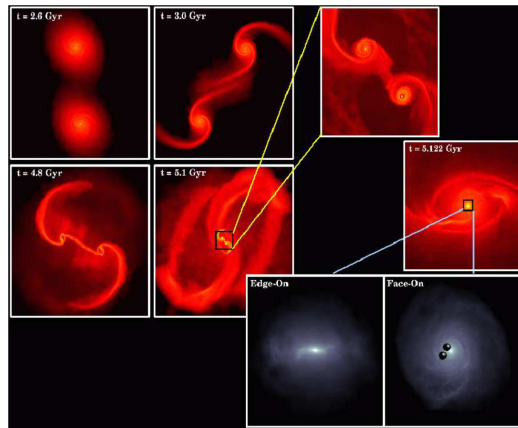
Millisecond pulsars emit radio pulses with an extremely stable frequency

- GWs affect propagation time \rightsquigarrow change observed pulse frequency
- PTAs monitor pulse frequency using radio telescopes on Earth
- Fourier decomposition of arrival times shows that pulse frequency modulations is due to GWs!

Merging supermassive black hole binaries.

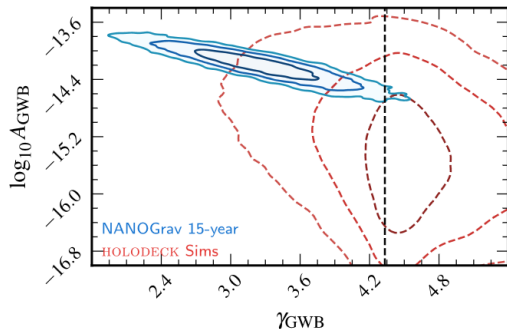
- Expect **supermassive black hole mergers** after galaxy mergers
- The resulting GW predictions can be well described by a power-law with amplitude A and slope γ :

$$\Omega_{\text{GW}}(f) \propto A^2 f^{5-\gamma}$$



[Mayer et al., 0706.1562; NASA/CXC/A. Hobart]


GW background from supermassive black hole binaries.



[NANOGrav collaboration, 2023]

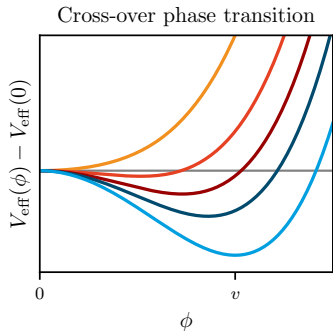
↪ Astrophysical simulations with realistic BH populations generate GW spectra that are in tension with the observed GW spectrum!

What other signal sources are thinkable?

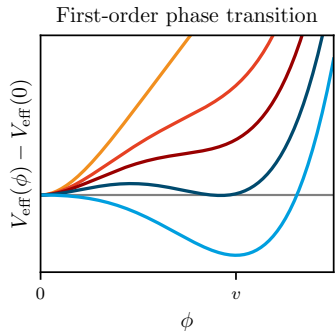
The background of the slide is a vibrant, abstract representation of the universe. It features a complex network of glowing filaments and numerous spherical structures that resemble bubbles or galaxies. The color palette is dominated by deep blues and purples, with bright, fiery oranges and yellows highlighting specific regions, possibly representing star formation or high-energy events. The overall effect is one of dynamic, swirling energy.

**Gravitational waves from dark
sector phase transitions.**

Cross-over and first-order phase transitions.



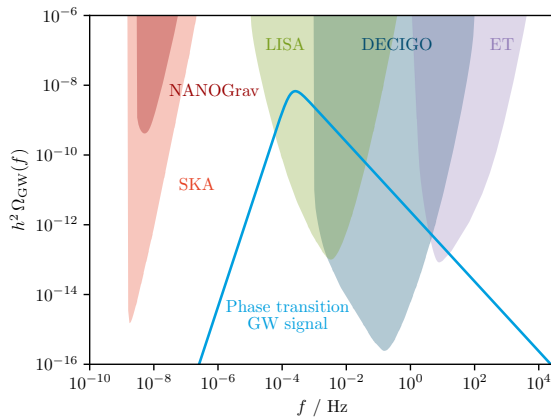
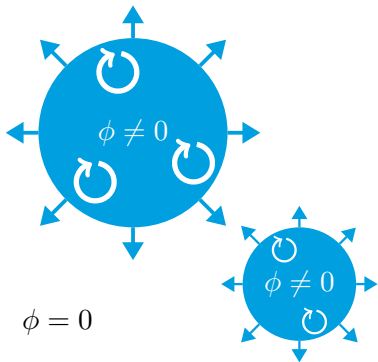
A scalar field “rolls down” from $\phi = 0$ to $\phi = v$, when the bath cools from **high temperatures** to **low temperatures**.



A scalar field tunnels to the true potential minimum ($\phi \neq 0$) to minimize its action (\sim free energy).

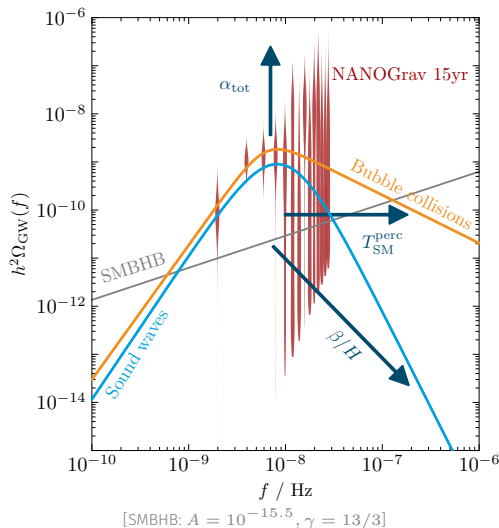
Gravitational waves from first-order phase transitions.

Bubbles of the new phase nucleate, collide and perturb the plasma...



... giving rise to a stochastic gravitational wave background which can be observed.

Parametrization of the GW signal.



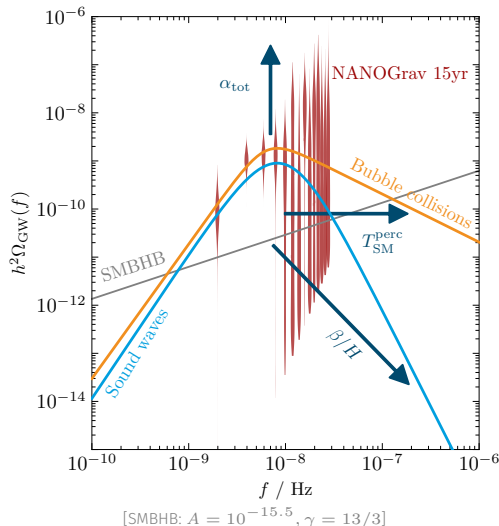
$$h^2 \Omega_{\text{GW}}^{\text{sw,bw}}(f) \simeq 10^{-6} \left(\frac{\alpha}{\alpha + 1} \right)^2 \left(\frac{H}{\beta} \right)^{1,2} \mathcal{S} \left(\frac{f}{f_{\text{peak}}} \right)$$

$$\text{with } f_{\text{peak}} \simeq 0.1 \text{ nHz} \times \frac{\beta}{H} \times \frac{T}{\text{MeV}}$$

To fit the **pulsar timing data**:

- Strong transitions, $\alpha \simeq \frac{\Delta V}{\rho_{\text{tot}}} \approx 1$
- Slow transitions, $\beta/H \approx 10$
- Percolation around $T \approx 10 \text{ MeV}$

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But there's no SM phase transition at 10 MeV?!

Let's put the transition in a dark sector.

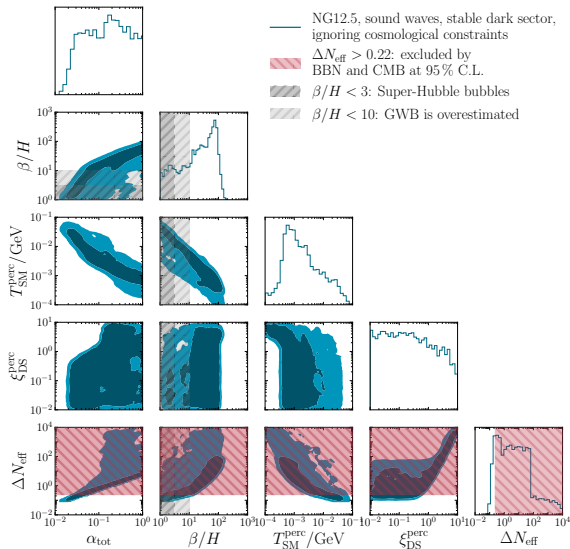
- **Stable dark sector:** additional DS energy density leads to larger Hubble rate, changing early element abundances and shifting CMB anisotropies through

$$\Delta N_{\text{eff}} \approx 6 \times \left(\alpha + \frac{1 + \alpha}{10} \xi^4 \right) \stackrel{!}{<} 0.22 \quad (@95 \% \text{ C.L.})$$

with the temperature ratio $\xi = T_{\text{DS}}/T_{\text{SM}}$ before the transition.

- **Decaying dark sector:** Energy transfer to the SM plasma, changing element abundances and CMB anisotropies. Constraints require $\tau < 0.1 \text{ s}$. [Depta, 2011.06519]

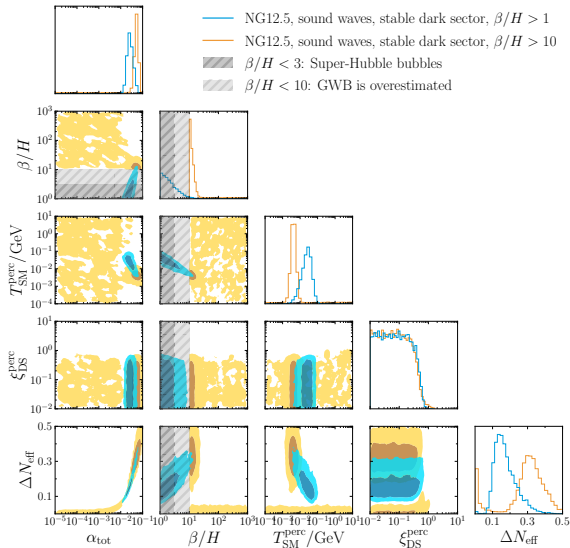
Stable dark sectors = strong tension between PTAs, CMB and BBN.



- Performed fit of the pulsar data with NANOGrav's own code **enterprise**

- ⚡ A good fit requires an enormous reheating of the dark sector: ΔN_{eff} can grow arbitrarily large
- ⚡ Bubble sizes would need to be super-Hubble to be okay with ΔN_{eff}
Causality ⚡ GW prediction ⚡

→ The tension cries for a global fit



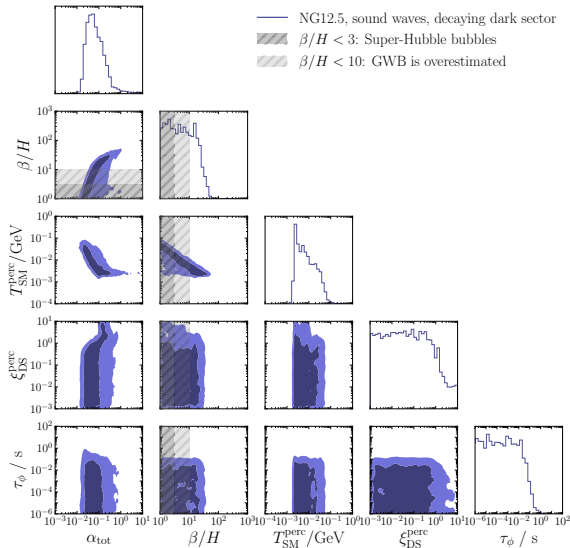
Global fit = compute global maximum of

$$\mathcal{L}_{\text{glob}}(\vec{\theta}_{\text{PSR}}, \vec{\theta}_{\text{PT}}) = \mathcal{L}_{\text{PTA}}(\vec{\theta}_{\text{PSR}}, \vec{\theta}_{\text{PT}}) \times \mathcal{L}_{\text{cosmo}}(\Delta N_{\text{eff}}(\vec{\theta}_{\text{PT}}))$$

Find:

- $\beta/H > 1$: would be a good fit, if the GW spectrum were reliable
- $\beta/H > 10$: $\mathcal{L}_{\text{glob}}$ starts preferring to not have a phase transition over violating BBN and CMB bounds!

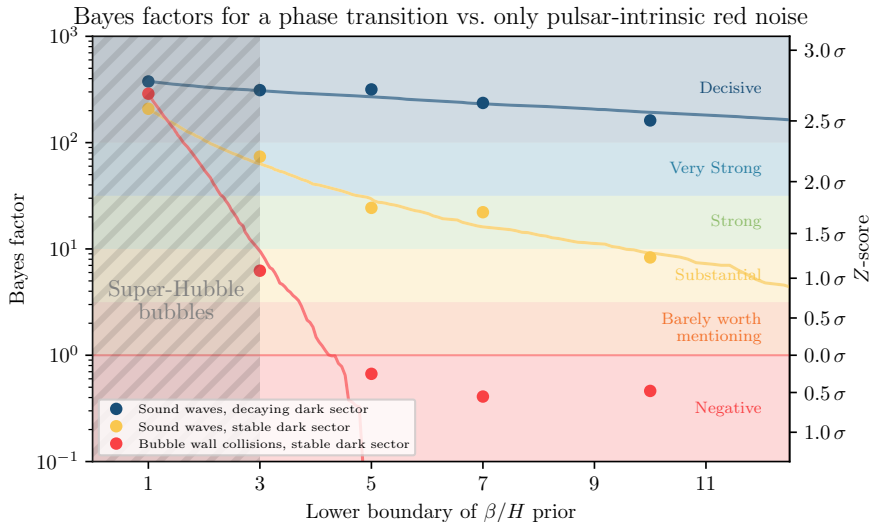
Decays to the rescue.



Decays save the fit...

... since more energy can be used to reheat the DS and emit GWs. They only need to happen before neutrino decoupling, $T_{\text{SM}} \gtrsim 2 \text{ MeV}$, corresponding to fast decays, $\tau \lesssim 0.1 \text{ s}$.

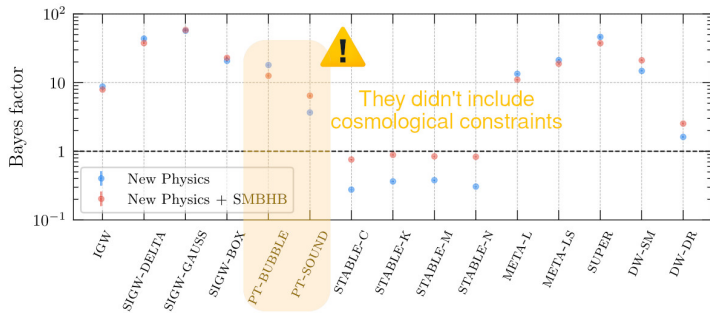
The evidence for a dark sector phase transition.





**So... what is the source of the PTA
signal?**

The evidence for new physics.



[NANOGrav collaboration, 2023]

- New physics matches spectra better
- BSM + SMBHB has highest Bayes factors
- We should perform global fits, including constraints & open astrophysical parameters

Still: As soon as a single merger or strong anisotropy is found in the data, all cosmological explanations will be dead.

Take-home messages.

- We are for the first time able to probe the early Universe before BBN!
- *Stable* dark sector phase transition explanations for PTA data are in tension with precision cosmology.
- *Decaying* dark sectors can compete with the SMBHB explanation and can even fit the data better
- Stay tuned for a follow-up incl. the latest PTA data

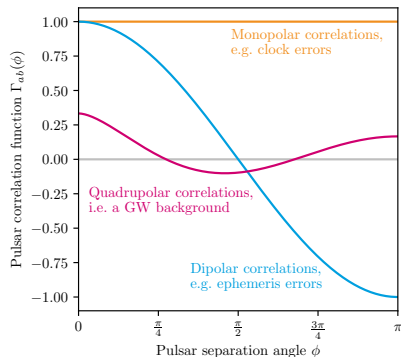
**Thank you very
much for your
attention!**

Do you have any
questions?



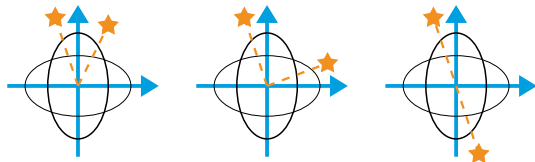
Backup slides.

How can we be sure it's actually gravitational waves?

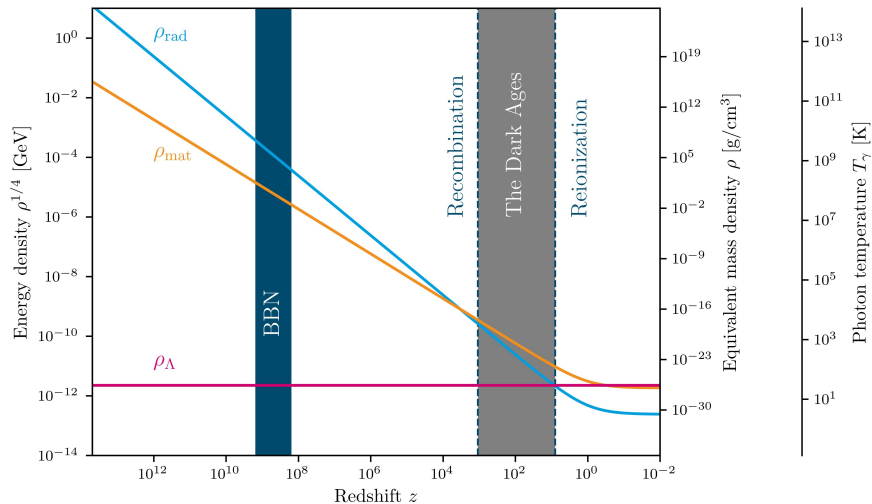


Red noise spectra can have many sources:

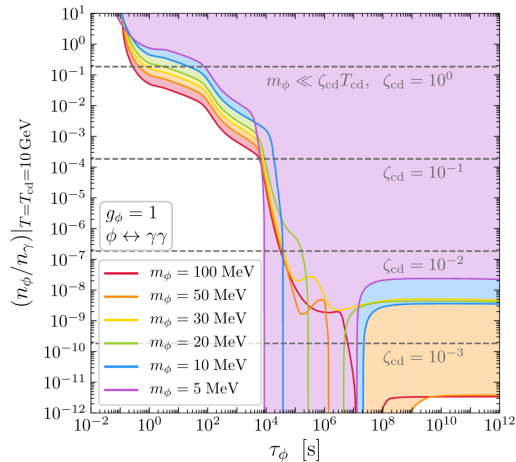
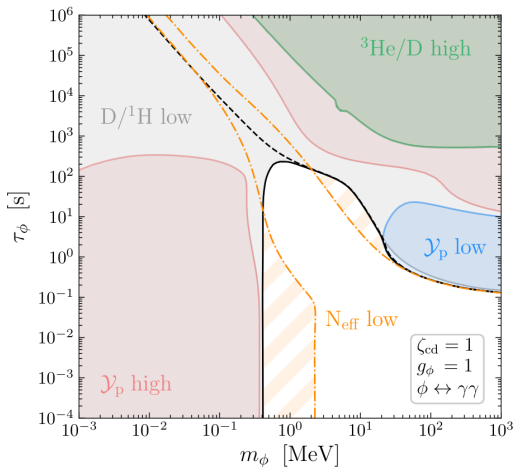
- Pulsars: no common red noise, $\mathcal{B} < 10^{-12}$
- Clock errors: **monopole**, $\mathcal{B} < 10^{-8}$
- Ephemeris errors: **dipole**, $\mathcal{B} < 10^{-7}$
- GWs: **Hellings-Downs curve**, $\mathcal{B} = 200 - 1000$
⇒ **Decisive evidence for GWs!** 🤖



A brief history of time: LCDM.

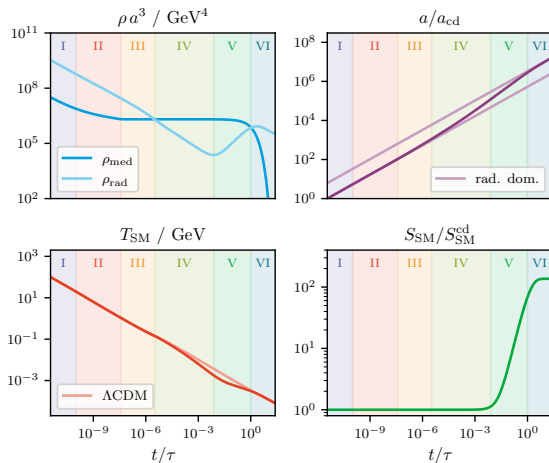


Electromagnetic scalar decays at MeV temperatures.



[Depta et al., JCAP 04 (2021) 011]

The out-of-equilibrium decay of a dark mediator.

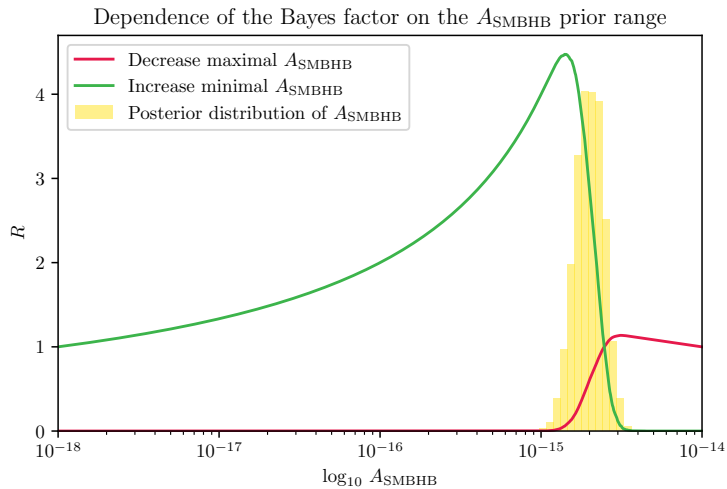


Energy densities $\rho_i(t)$ \rightsquigarrow Scale factor $a(t)$ \rightsquigarrow Temperatures $T_{\text{SM/DS}}(t)$ \rightsquigarrow Particle content $\rightsquigarrow \rho_i(t)$ \rightsquigarrow ...

Six phases:

- I Relativistic mediator
- II Cannibalistic mediator
- III Non-relativistic mediator
- IV Early matter domination
- V Entropy injection
- VI Mediator decay

How the choice of priors changes a Bayes factor.



Why violins shouldn't be used for fits including cosmological constraints.

