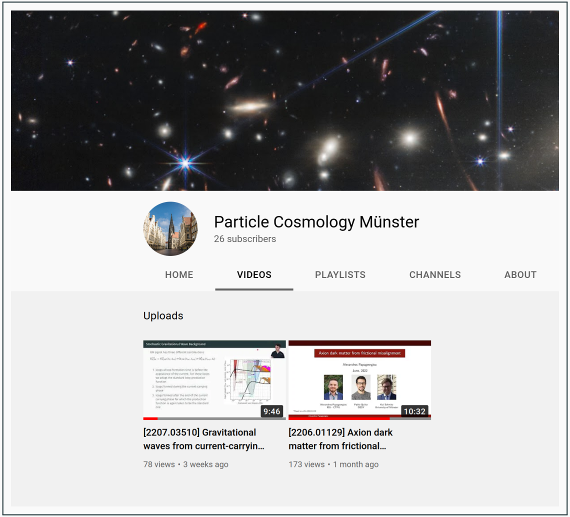
PTA Searches for Gravitational Waves from Cosmic Strings

Kai Schmitz
Junior professor at the University of Münster, Germany

MITP Scientific Program *"Probing New Physics with Gravitational Waves"*
MITP, Johannes Gutenberg University, Mainz | August 11, 2022

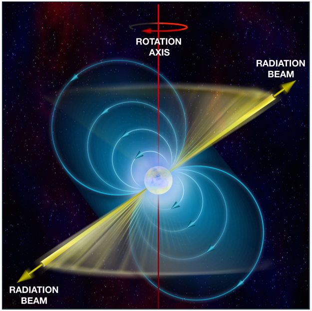
10-minute video abstracts on YouTube



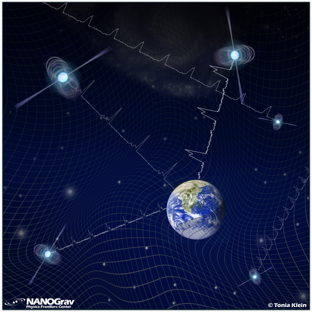
https://www.youtube.com/channel/UCanlXI7UvQsH77yDyj3-1uA

Pulsar timing arrays (PTAs)

Array of pulsars across the Milky Way → construct galaxy-sized GW detector!



[B. Saxton for nrao.edu]



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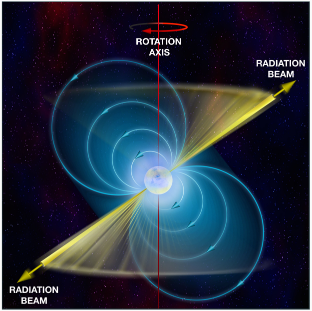

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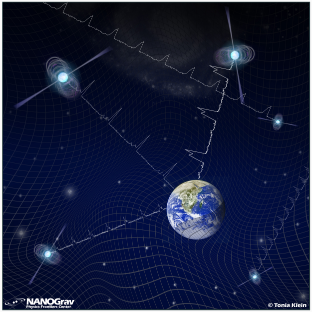

Pulsars: Highly magnetized rotating neutron stars, ultra-precise stellar clocks

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PSR J0437–4715 (173.7 rotations per second)

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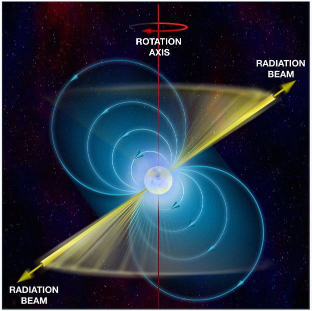

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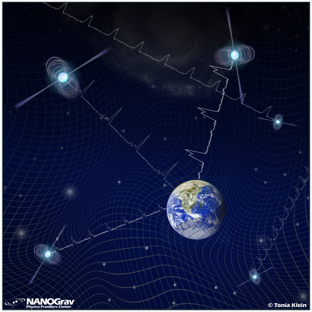

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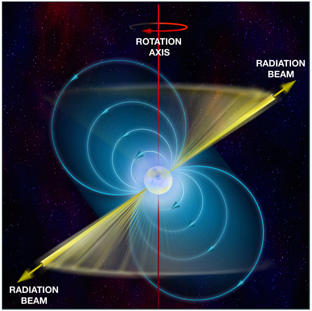

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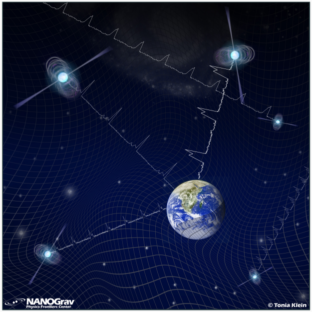

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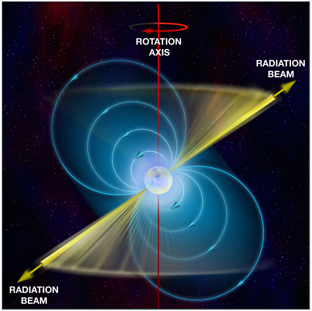

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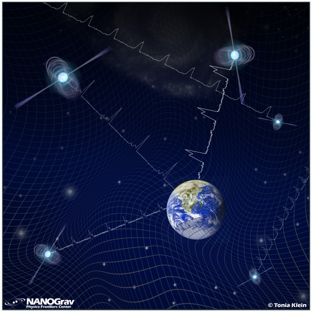

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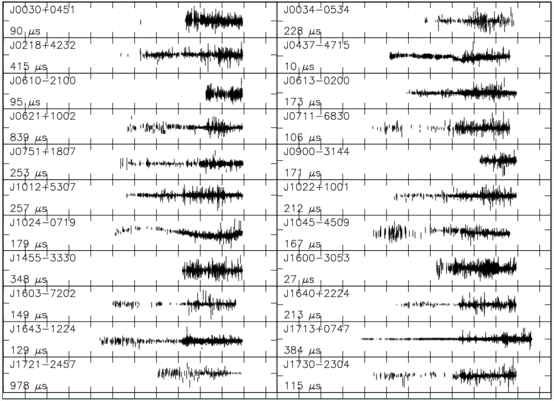
Look for tiny distortions in pulse travel times caused by nanohertz GWs

Residuals in pulse times of arrival (TOAs)

[IPTA Collaboration: 1602.03640]

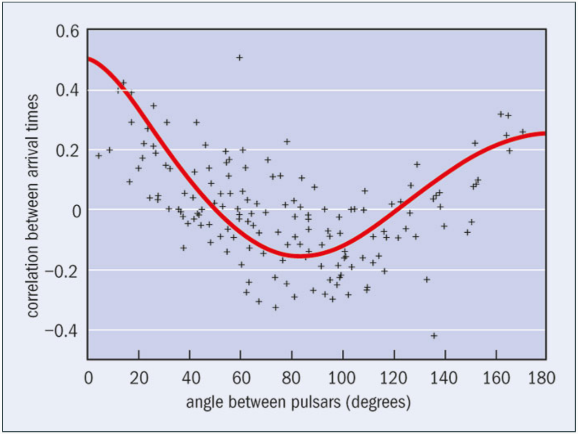


$$R^{(i)} = \mathrm{TOA}^{(i)}_{\mathrm{SSB}} - \mathrm{TOA}^{(i)}_{\mathrm{Model}}$$

- Measure TOAs and convert to TOAs at the solar-system barycenter (SSB)
- Compare to detailed timing model for each pulsar: pulsation frequency and derivatives, position, proper motion, binary dynamics, relativistic effects, ...

Hellings–Downs correlations

[physicsworld.com]



Hallmark signature of a stochastic gravitational-wave background signal:

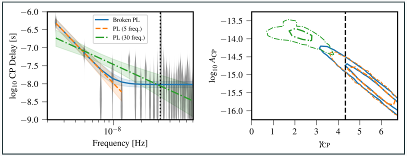
Quadrupolar correlations described by Hellings–Downs (HD) curve $\Gamma_{ij}(\psi)$

[Hellings, Downs: Astrophys. J. 265 (1983) L39]

First glimpse of a SGWB signal?

Strong evidence for a new stochastic *red process* in latest pulsar timing data

NANOGrav [2009.04496]



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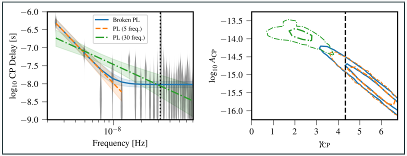
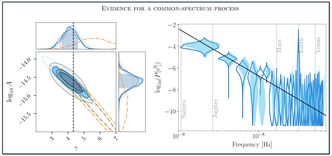


PPTA [2107.12112]



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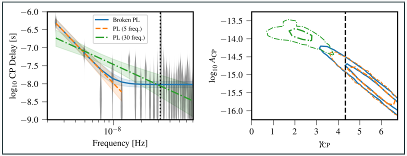

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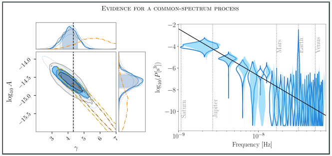

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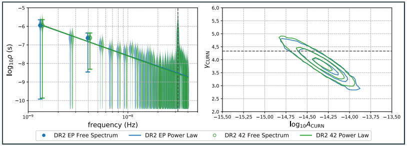

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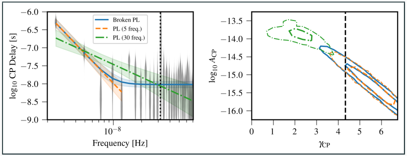

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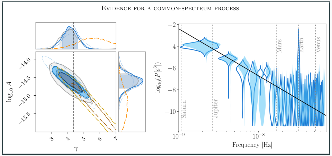

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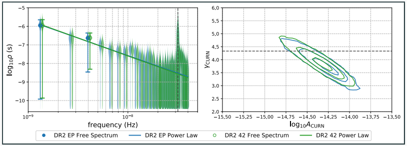

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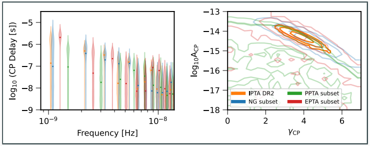

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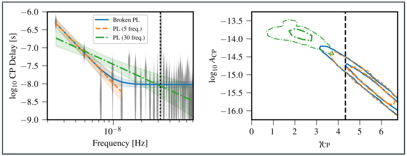

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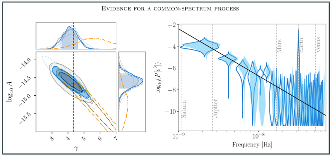

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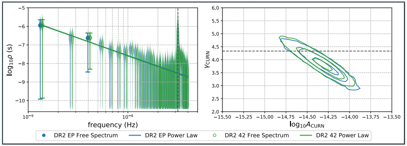

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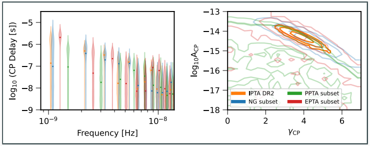
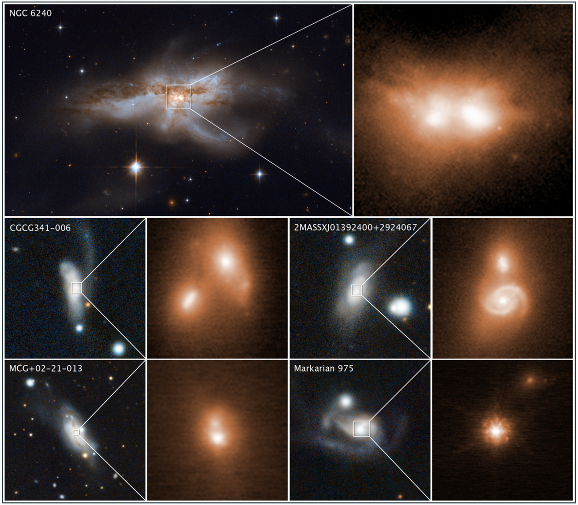


Not yet a detection, but consistent with interpretation in terms of GWs!

Astrophysical interpretation

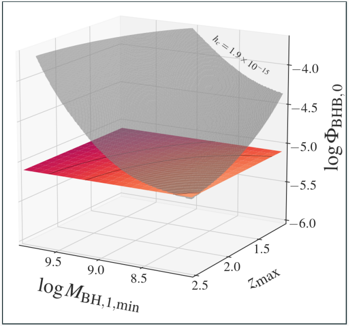
[hubblesite.org]



Mergers of supermassive black-hole binaries (SMBHBs) after galaxy mergers

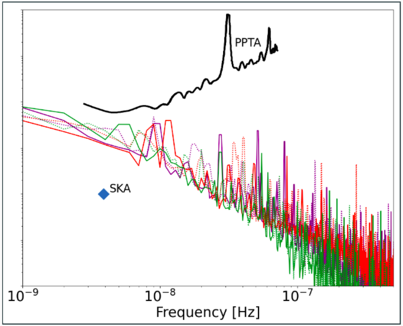
SMBHB models and simulations

SMBHB population model based on empirical quasar population



[Casey-Clyde et al.: 2107.11390]

Simulation based on SHARK galaxy evolution model (delay: 1 Gyr)



[Curyło, Bulik: 2108.11232]

- Left: $\Phi_{\mathrm{BHB},0}$ $\mathcal{O}(10)$ times larger than previous estimates, e.g., 1708.03491
- Right: Time delays of 100 Myr to 1 Gyr not enough to explain amplitude

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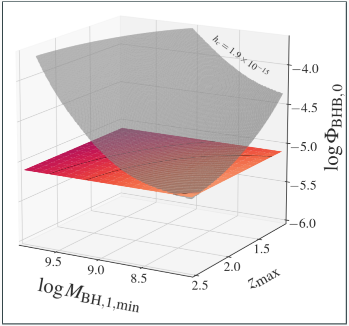

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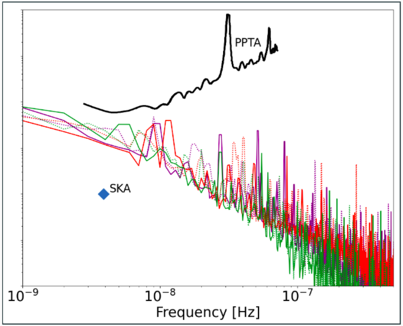

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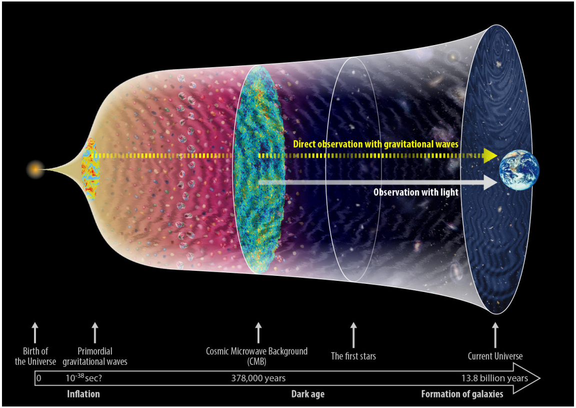
Might tell us something about our models, simulations ... or about the signal

Cosmological gravitational waves

[National Astronomical Observatory of Japan, gwpo.nao.ac.jp]

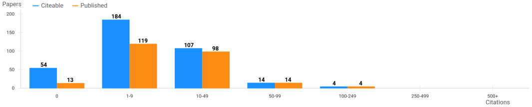


Viable possibility: Signal receives contributions from SMBHBs + X (or X only?)
→ Probe cosmology of the early Universe and particle physics at high energies

Cosmic strings [2009.06555, 2009.06607, 2009.10649, 2009.13452, 2102.08923] **Primordial black holes** [2009.07832, 2009.08268, 2009.11853, 2010.03976, 2101.11244] **Phase transitions** [2009.09754, 2009.10327, 2009.14174, 2009.14663, 2101.08012] **Audible axions and axion strings** [2009.11875, 2012.06882] **Inflation** [2009.13432, 2010.05071, 2011.03323] **Domain walls** [2009.13893, 2012.14071]

Overwhelming reaction in the particle physics community

Papers	363	248
Citations	4,001	3,702
h-index	30	30
Citations/paper (avg)	11	14.9



NANOGrav Data Hints at Primordial Black Holes as Dark Matter #1

V. De Luca (Geneva U., Dept. Theor. Phys. and Geneva U., CAP), G. Franciolini (Geneva U., Dept. Theor. Phys. and Geneva U., CAP), A. Riotto (Geneva U., Dept. Theor. Phys. and INFN, Rome and Geneva U., CAP) (Sep 17, 2020)

Published in: *Phys.Rev.Lett.* 126 (2021) 4, 041303 • e-Print: 2009.08268 [astro-ph.CO]

pdf links DOI cite — 136 citations

Has NANOGrav found first evidence for cosmic strings? #2

Simone Blasi (Heidelberg, Max Planck Inst.), Vedran Brdar (Heidelberg, Max Planck Inst.), Kai Schmitz (CERN) (Sep 14, 2020)

Published in: *Phys.Rev.Lett.* 126 (2021) 4, 041305 • e-Print: 2009.06607 [astro-ph.CO]

pdf links DOI cite — 121 citations

Cosmic String Interpretation of NANOGrav Pulsar Timing Data #3

John Ellis (King's Coll. London and CERN and NICPB, Tallinn), Marek Lewicki (King's Coll. London and Warsaw U.) (Sep 14, 2020)

Published in: *Phys.Rev.Lett.* 126 (2021) 4, 041304 • e-Print: 2009.06555 [astro-ph.CO]

pdf links DOI cite — 119 citations

Solar-Mass Primordial Black Holes Explain NANOGrav Hint of Gravitational Waves #4

Kazunori Kohri (INS, Tokyo and Tsukuba, Graduate U. Adv. Studies and Tokyo U., IPMU), Takahiro Terada (IBS, Daejeon, CTPU) (Oct 2, 2020)

Published in: *Phys.Lett.B* 813 (2021) 136040 • e-Print: 2009.11853 [astro-ph.CO]

pdf DOI cite — 103 citations

Gravitational Waves and Dark Radiation from Dark Phase Transition: Connecting NANOGrav Pulsar Timing Data and Hubble Tension #5

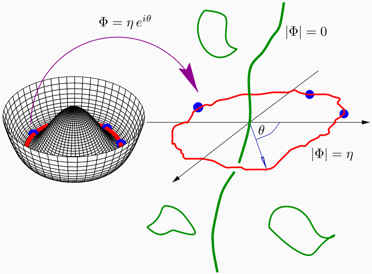
Yuichiro Nakai (Tsung-Dao Lee Inst., Shanghai and Shanghai Jiaotong U.), Motoo Suzuki (Tsung-Dao Lee Inst., Shanghai and Shanghai Jiaotong U.), Fuminobu Takahashi (Tohoku U. and Tokyo U., IPMU), Masaki Yamada (Tohoku U.) (Sep 27, 2020)

Published in: *Phys.Lett.B* 816 (2021) 136238 • e-Print: 2009.09754 [astro-ph.CO]

pdf DOI cite — 74 citations

NANOGrav 2009.04496: 423 citations and dozens of possible interpretations

Gravitational waves from stable cosmic strings

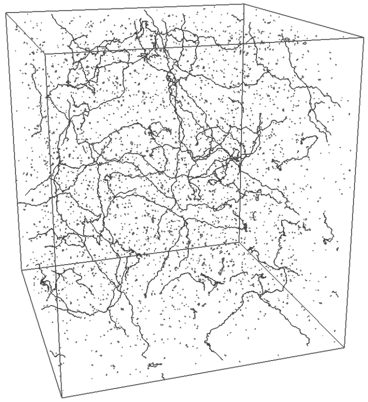


[Ringeval: 1005.4842]

Cosmic strings:

- Topological defects after $U(1)$ breaking in the early Universe

Gravitational waves from stable cosmic strings



[Allen, Martins, Shellard: ctc.cam.ac.uk/outreach]

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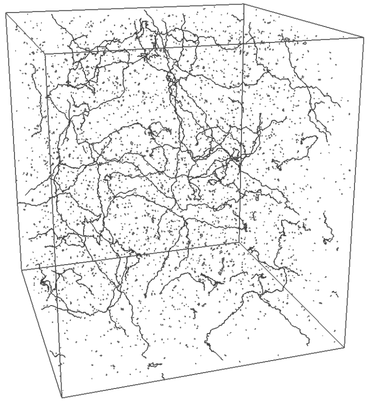
- Network of long strings and closed loops in scaling regime

Gravitational waves from stable cosmic strings



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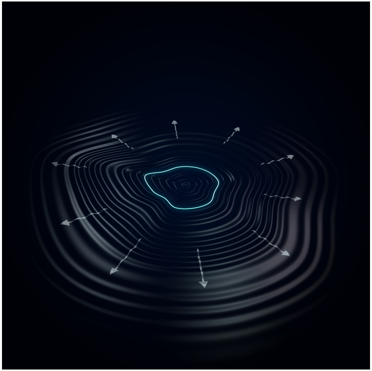

[CERN]

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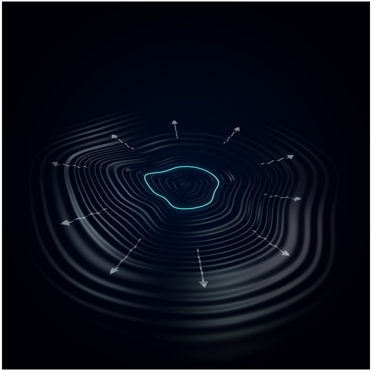

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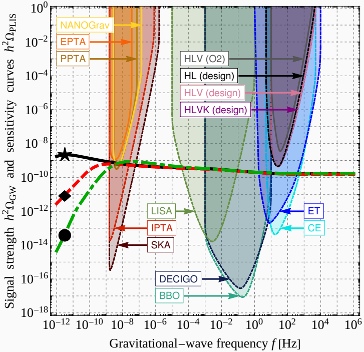
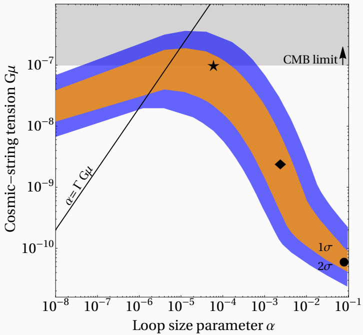
Assumption: Energy loss via particle emission off closed loops is negligible
[Matsunami, Pogosian, Saurabh, Vachaspati: 1903.05102] [Hindmarsh, Lizarraga, Urio, Urrestilla: 2103.16248]

Stable cosmic strings and NANOGrav

[Blasi, Brdar, **KS**: 2009.06607]
[See also Ellis, Lewicki: 2009.06555]





☺ Explain NANOGrav signal for $G\mu \sim 10^{-(10\cdots 11)}$ and $\alpha \sim 0.1$

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[Blasi, Brdar, **KS**: 2009.06607]
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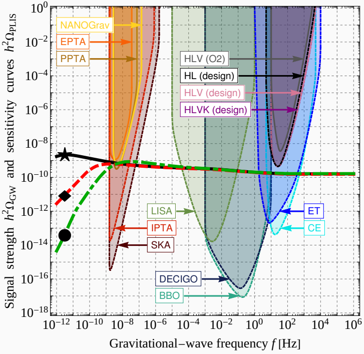

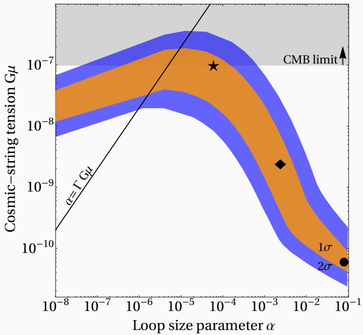

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☹ GUT scale $\Lambda \sim 10^{15\cdots 16}\,\mathrm{GeV}$ points to $G\mu \sim 10^{-(7\cdots 8)}$ (smaller α?)

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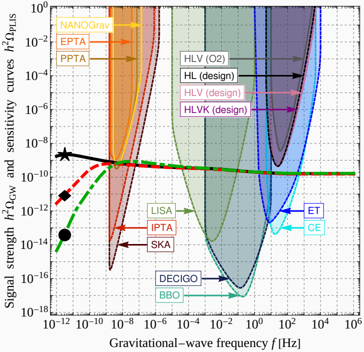

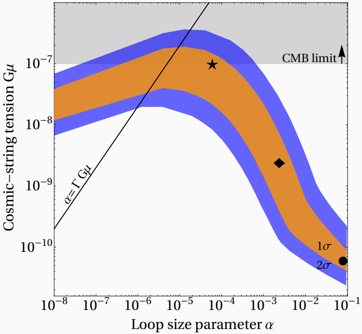

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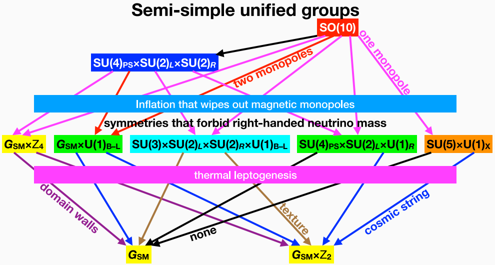
- ☹ Signal at higher frequencies too small for LIGO, Virgo, KAGRA

Cosmic strings and grand unification

[Dror, Hiramatsu, Kohri, Murayama, White: 1908.03227]
[See also King, Pascoli, Turner, Zhou: 2005.13549, 2106.15634]



UV embedding of the seesaw mechanism in GUT models:

Neutrino mass, leptogenesis, cosmic strings, GWs, proton decay

Cosmic strings and grand unification

[Dror, Hiramatsu, Kohri, Murayama, White: 1908.03227]
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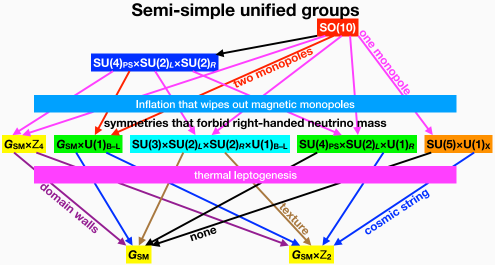
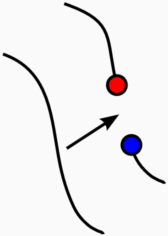


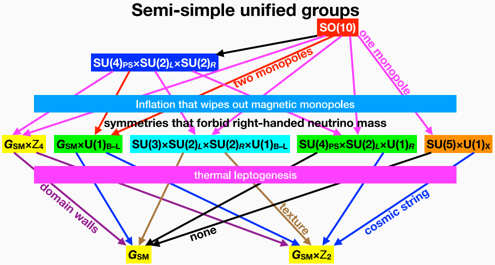


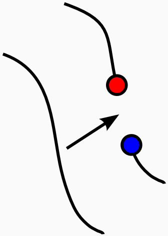
UV embedding of the seesaw mechanism in GUT models:

Neutrino mass, leptogenesis, cosmic strings, GWs, proton decay

Example: $G_{\rm SM} \times U(1)_{B-L} \to G_{\rm SM}$ results in *metastable* cosmic strings: quantum tunneling events lead to $SO(10)$ monopole pair production

[Dror, Hiramatsu, Kohri, Murayama, White: 1908.03227]
[See also King, Pascoli, Turner, Zhou: 2005.13549, 2106.15634]





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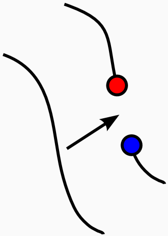
Assumption: Inflation dilutes monopoles; otherwise string–monopole gas

Monopole pair production



Decay rate per string length:
[Vilenkin: Nucl. Phys. B 196 (1982) 240]
[Preskill, Vilenkin: hep-ph/9209210]
[Monin, Voloshin: 0808.1693]

$$\Gamma_d = \frac{d\#}{dt d\ell} = \frac{\mu}{2\pi} e^{-\pi \kappa}, \qquad \kappa = \frac{m^2}{\mu} \qquad (1)$$

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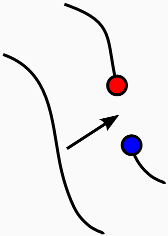

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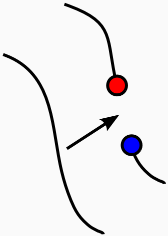

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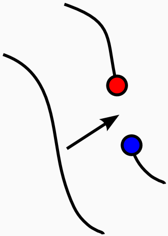

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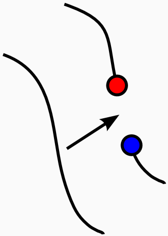

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Monopoles with and without unconfined magnetic flux:

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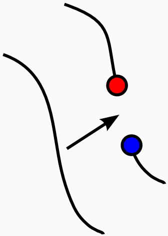

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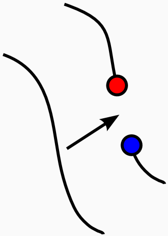

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Monopoles with and without unconfined magnetic flux:

- Unconfined flux: $M\bar{M}$ annihilation, emission of massless gauge bosons
- No unconfined flux: energy loss only via emission of gravitational waves

Possible scenarios

$$W_{B-L} = \lambda T \left(S\bar{S} - \frac{1}{2}\, v_{B-L}^2 \right) + \frac{h_i}{M_*} S^2 N_i^2 \tag{2}$$

$B-L$ phase transition after supersymmetric hybrid inflation:

- T: inflaton, S, $\bar{S}$: Higgs / waterfall fields, N_i: right-handed neutrinos

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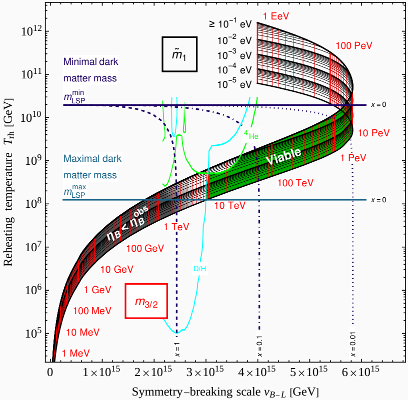

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[Buchmüller, **KS**, Vertongen: 1008.2355, 1104.2750]
[Buchmüller, Domcke, **KS**: 1111.3872, 1202.6679, 1203.0285]
[Buchmüller, Domcke, Kamada, **KS**: 1305.3392, 1309.7788]

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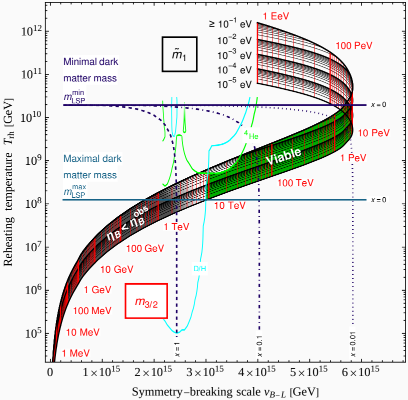

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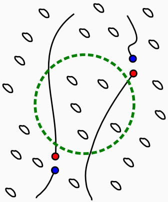
Minimal alternative: $SU(2) \times U(1) \xrightarrow{\text{triplet}} U(1) \times U(1) \xrightarrow{\text{doublets}} U(1)$
[Buchmüller: 2102.08923]

Strategy

End of scaling when long string segments begin to enter the horizon:
[Leblond, Shlaer, Siemens: 0903.4686]

$$\Gamma_d \, \ell \, t_s \sim \Gamma_d H^{-1} \, t_s \sim \Gamma_d t_s^2 \sim 1 \quad \Rightarrow \quad t_s \sim \frac{1}{\sqrt{\Gamma_d}} \tag{3}$$



Scaling regime, $t < t_s$

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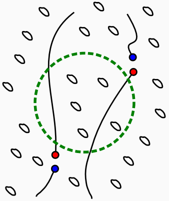

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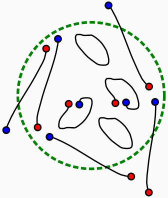

Decay regime, $t > t_s$

- Loops: emit GWs and decay into segments
- Segments from loops and long strings: emit GWs and decay into segments; no production of new loops

Formal description

Kinetic equation for the number densities of loops and segments, $\mathring{n}$ and $\tilde{n}$:

$$\partial_t \, n(\ell, t) = S(\ell, t) - \partial_\ell \left[u(\ell, t) \, n(\ell, t)\right] - \left[3H(t) + \Gamma_d \, \ell\right] n(\ell, t) \qquad (4)$$

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Challenge: Solve set of partial integro-differential equations in both the scaling and decay regimes, match solutions at $t = t_s$. (Plus, RD / MD.)

Number densities

Loop number density during the decay regime in the radiation era:

[Cf. Blanco-Pillado, Olum, Shlaer: 1309.6637] [Cf. Blanco-Pillado, Olum: 1709.02693]

$$\mathring{n}^{\mathrm{rr}}_{>}(\ell, t) = \frac{B\, e^{-\Gamma_d\left[\ell(t-t_s)+{}^{1}\!/\!{}_{2}\,\Gamma G\mu(t-t_s)^2\right]}}{t^{3/2}\left(\ell+\Gamma G\mu t\right)^{5/2}}\,\Theta\left(\alpha t_s-\bar{\ell}(t_s)\right)\,\Theta\left(t_{\mathrm{eq}}-t\right) \tag{5}$$

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because of new exponential suppression factor:

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Similar results for $\overset{\circ}{n}{}^{\mathrm{rr}}_{<}$, $\overset{\circ}{n}{}^{\mathrm{rm}}_{<}$, $\overset{\circ}{n}{}^{\mathrm{mm}}_{<}$, $\overset{\circ}{n}{}^{\mathrm{rm}}_{>}$, $\overset{\circ}{n}{}^{\mathrm{mm}}_{>}$, $\tilde{n}^{(s)\,\mathrm{rr}}_{<}$, $\tilde{n}^{(s)\,\mathrm{mm}}_{<}$, $\tilde{n}^{(s)\,\mathrm{rr}}_{>}$, $\tilde{n}^{(s)\,\mathrm{rm}}_{>}$, $\tilde{n}^{(s)\,\mathrm{mm}}_{>}$, $\tilde{n}^{(l)\,\mathrm{rr}}_{>}$, $\tilde{n}^{(l)\,\mathrm{rm}}_{>}$, $\tilde{n}^{(l)\,\mathrm{mm}}_{>}$. The integro-differential equation for $\tilde{n}^{(l)}_{>}$ is solved by an infinite series that needs be evaluated order by order.

Spectrum

Compute GW spectrum following the standard procedure:

$$\Omega_{\rm gw}\left(f\right)=\frac{G\mu^2}{\rho_{\rm crit}}\sum_k P_k\frac{2k}{f}\int_{t_{\rm ini}}^{t_0}dt\left[\frac{a\left(t\right)}{a\left(t_0\right)}\right]^5 n\left(\frac{a\left(t\right)}{a\left(t_0\right)}\frac{2k}{f},t\right) \tag{7}$$

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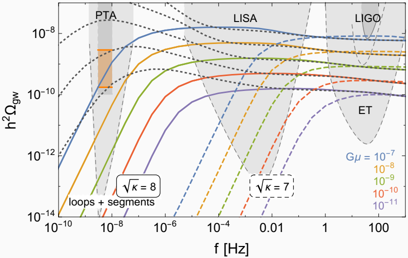

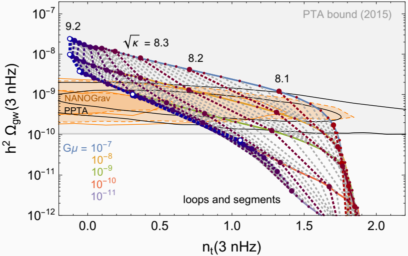

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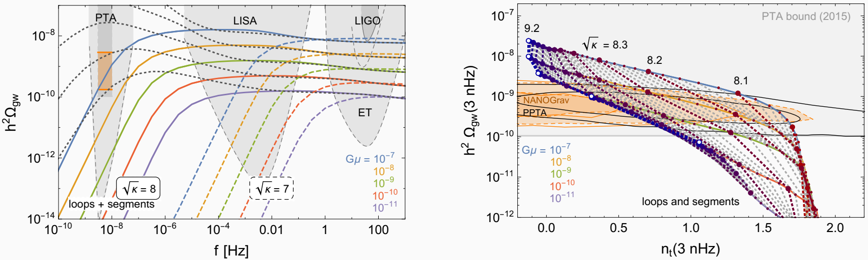

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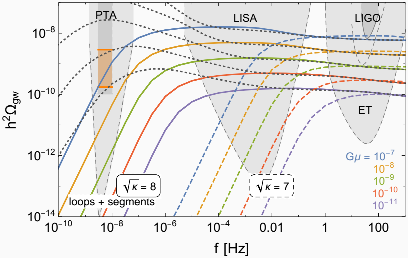

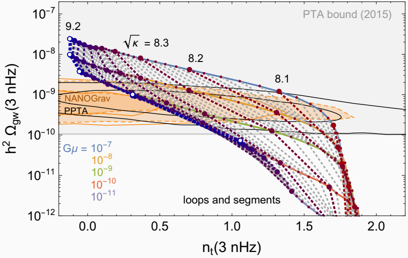

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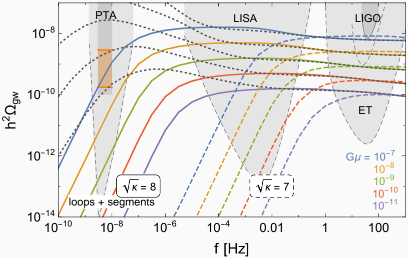

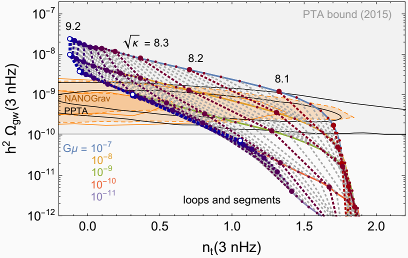

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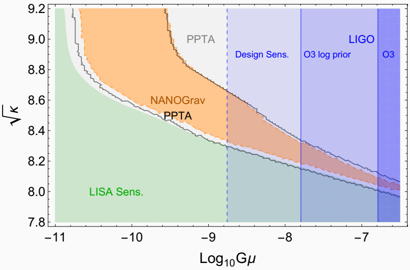
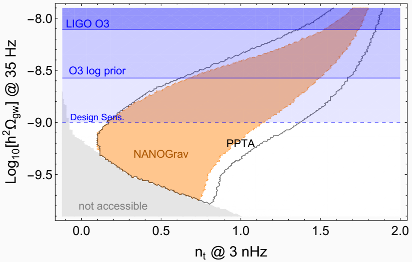
Observational prospects

Extrapolate spectrum to large f and compare with LIGO, Virgo, KAGRA:





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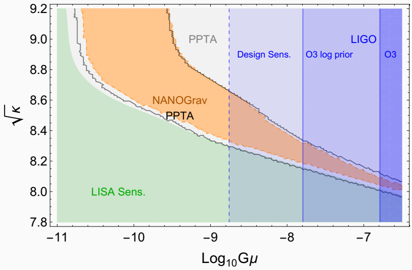

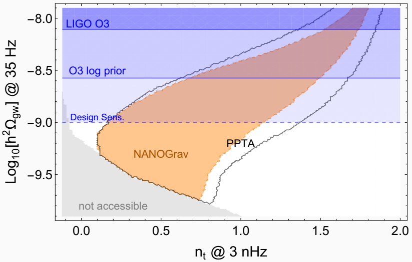

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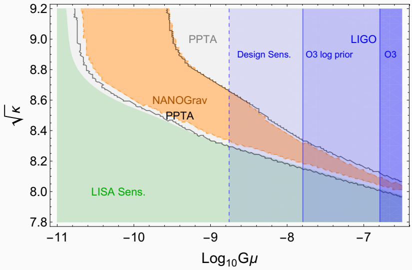

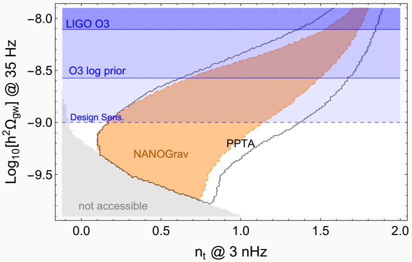

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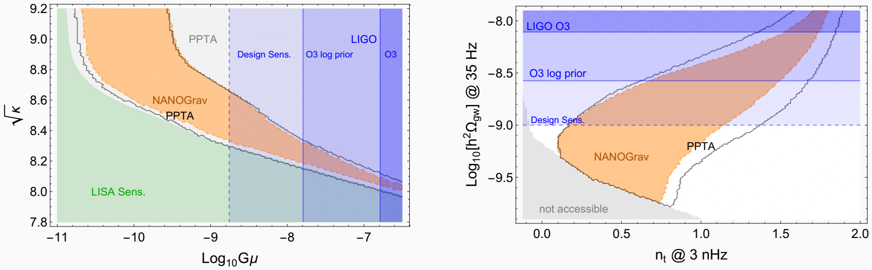

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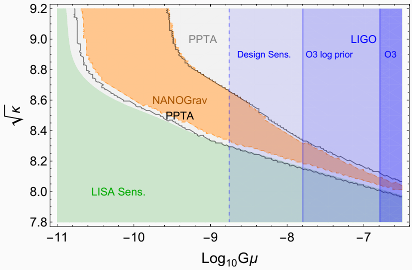

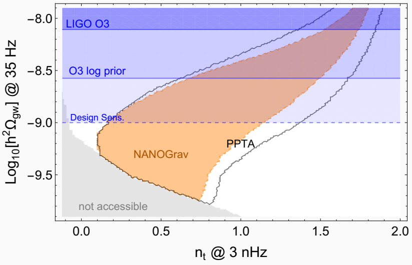

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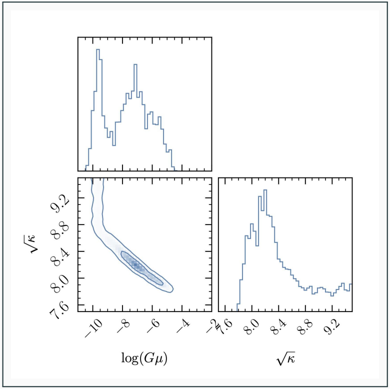
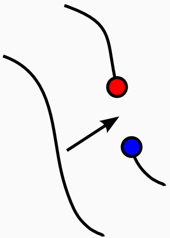
- LISA will probe the entire parameter space consistent with NANOGrav

Outlook

Preliminary results!!! IPTA DR2 search for metastable strings



Conclusions



Metastable cosmic strings:

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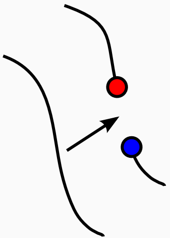

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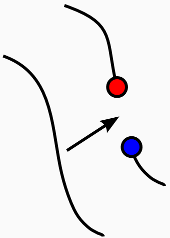

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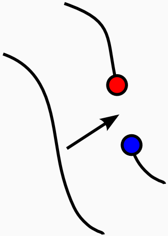

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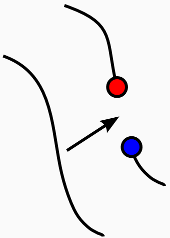

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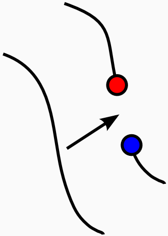

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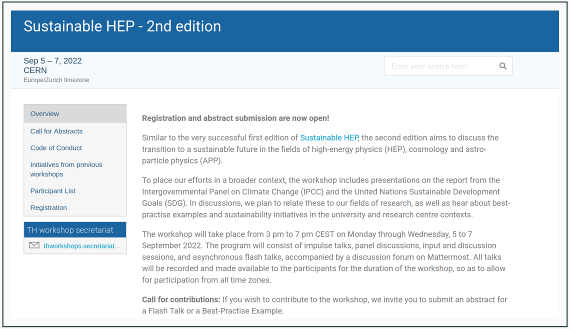
Thank you very much for your attention!

Workshop on Sustainable HEP



Sustainable HEP - 2nd edition

Sep 5 – 7, 2022
CERN
Europe/Zurich timezone

Enter your search term

Overview
Call for Abstracts
Code of Conduct
Initiatives from previous workshops
Participant List
Registration

TH workshop secretariat
thworkshops.secretariat...

Registration and abstract submission are now open!

Similar to the very successful first edition of Sustainable HEP, the second edition aims to discuss the transition to a sustainable future in the fields of high-energy physics (HEP), cosmology and astro-particle physics (APP).

To place our efforts in a broader context, the workshop includes presentations on the report from the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Sustainable Development Goals (SDG). In discussions, we plan to relate these to our fields of research, as well as hear about best-practise examples and sustainability initiatives in the university and research centre contexts.

The workshop will take place from 3 pm to 7 pm CEST on Monday through Wednesday, 5 to 7 September 2022. The program will consist of impulse talks, panel discussions, input and discussion sessions, and asynchronous flash talks, accompanied by a discussion forum on Mattermost. All talks will be recorded and made available to the participants for the duration of the workshop, so as to allow for participation from all time zones.

Call for contributions: If you wish to contribute to the workshop, we invite you to submit an abstract for a Flash Talk or a Best-Practise Example.

https://indico.cern.ch/event/1160140/

Remaining carbon budget for 1.5 degrees: $\mathcal{O}(2)$ tons per person per year

- How can HEP transition to a sustainable future?
- Lead by example, demonstrate best practices, amplify the voice of science