Catastrogenesis

Dark Matter and gravitational waves from ALP cosmic string-wall system annihilation

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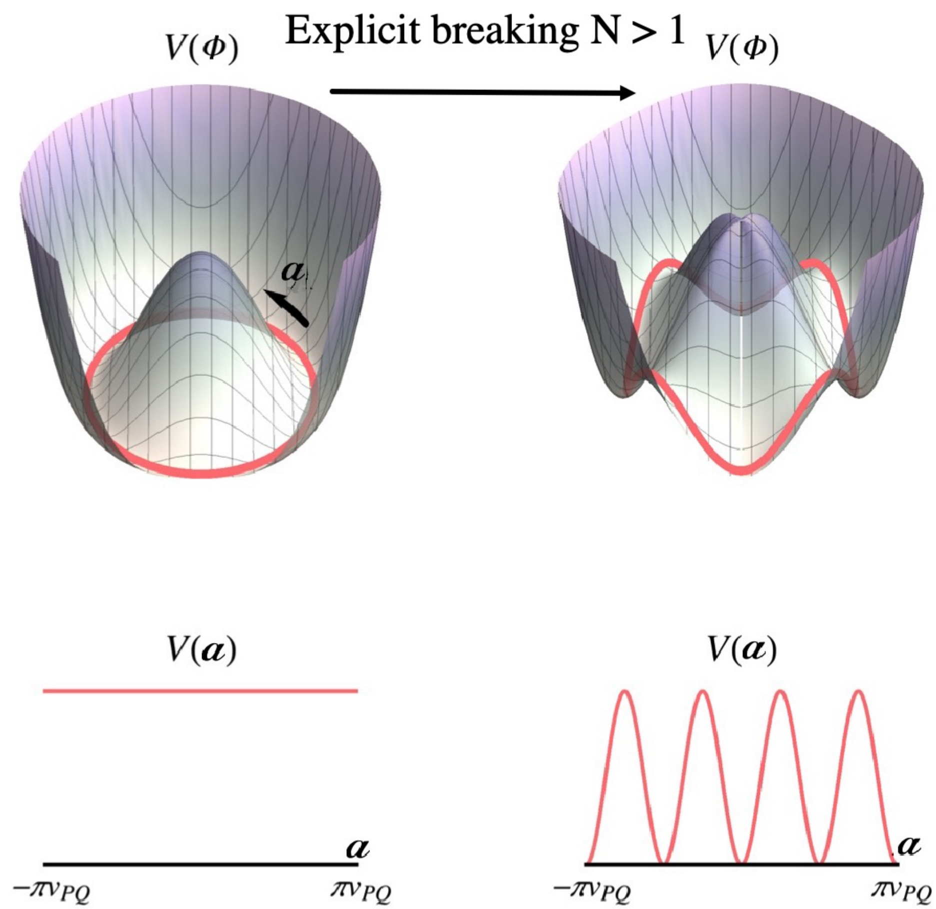
Here "ALP" = "U(1) pseudo-Nambu-Goldstone boson"

- Nambu Goldstone Boson (NBG) due to a U(1) global symmetry spontaneously broken at a scale V is the field component a along the orbit of degenerate minima $\phi = Ve^{\theta}$, phase $\theta = a/V$.

- The symmetry is also explicitly broken at a scale $v << V$- leads to one $(N = 1)$ or more $(N > 1)$ true minima along the previous orbit of degenerate minima (discrete symmetry Z_N) gives mass to the pseudo-NGB $m_a \simeq v^2/V$.



(Fig. adapted from Armengaud et al 1904.09155)

Many particle models of this type

- Original axion model (Peccei and Quinn 1977; Weinberg 1978; Wilczek 1978)
  $U(1)_{PQ}$ - Explicit breaking due to QCD instanton effects $V > v \simeq \Lambda_{\rm QCD}$, $N = 6$

- Invisible axion (also called QCD axion) models (Kim 1979; Shifman, Vainshtein and Zakharov 1980; Zhitnitsky 1980; Dine, Fischler and Srednicki 1981)
  $U(1)_{PQ}$ - Explicit breaking due to QCD instanton effects $V >> v \simeq \Lambda_{\rm QCD}$,
  KSVZ $N = 1$ or $N > 1$, DFSZ $N = 6$.

- Generic axion-like particle (ALP) models (Jaeckel and Ringwald 2010)
  Ad-hoc $U(1)$ and explicit breaking for ALPs to be dark matter $V >> v$, $N = 1$ or $N > 1$

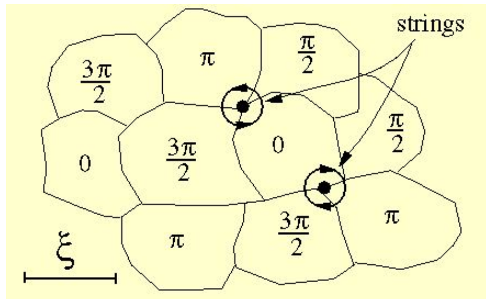
- Singlet Majoron models (Chikashige, Mohapatra and Peccei 1981; Rothstein, Babu and Seckel 1993; Gu, Ma and Sarkar 2010)
  $U(1)_L$ - Explicit breaking due to gravitational effects, $N = 1$ or $N > 1$

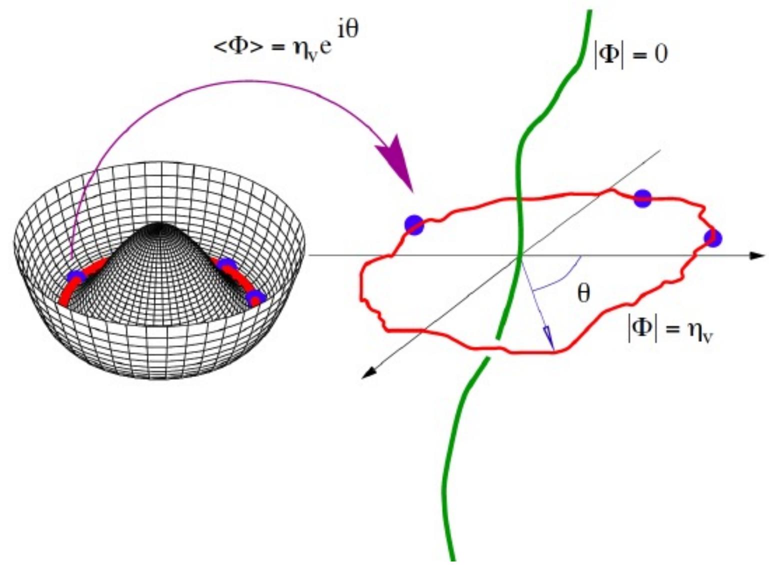
- ...

Complex cosmology

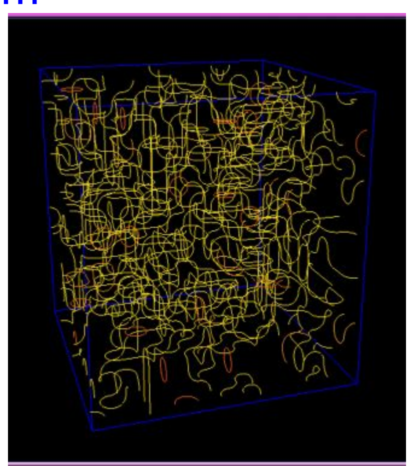
- Spontaneous breaking at scale V: creates domains with different field phase. If inflation happens after, at end of inflation the Universe is in only one domain.
- We assume a POST-INFLATION scenario then cosmic strings appear

(Kibble Mechanism 1976)





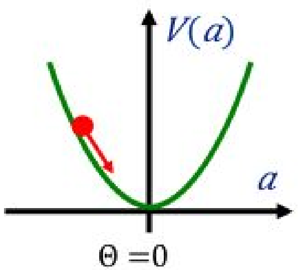
constituting a string system

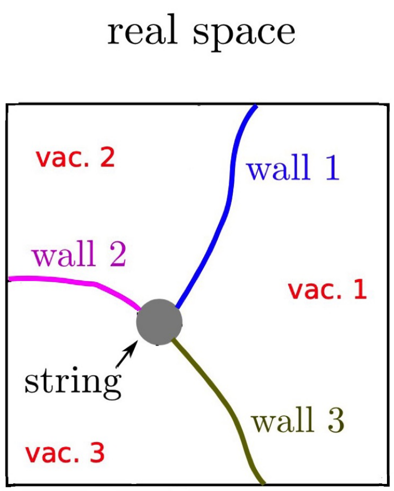


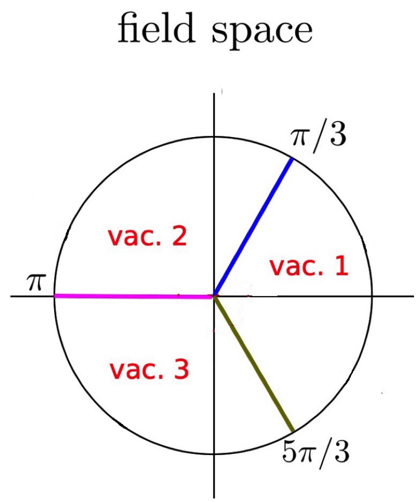
Complex cosmology

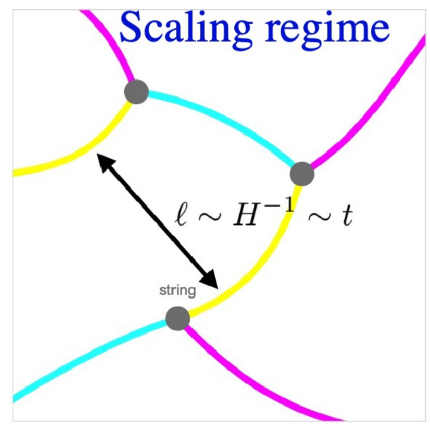
Eq. of motion $\ddot{a} + 3H\dot{a} + V(a)' = 0$, $V = (m_a^2 a^2)/2$ damped oscillator.

- Field is driven towards closest Z_N minimum when $3H \simeq m_a \simeq v^2/V$ ($t \simeq$ oscillation period m_a^{-1}): cosmic walls appear joined to the strings. E.g. for $N = 3$









- N=1 unstable system: "ribbons" bounded by strings shrink and annihilate fast

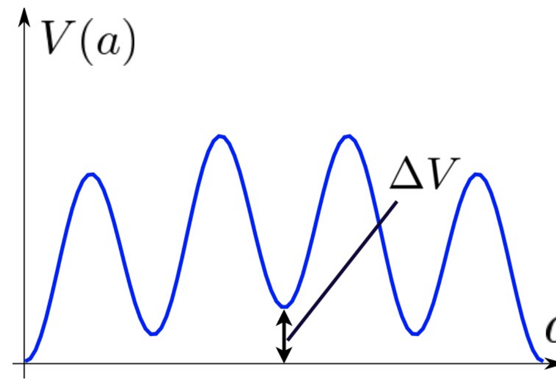
- N>1 stable string-wall system: each string attached to N walls - Soon reaches a "scaling regime" in which linear size $\simeq$ cosmic horizon t (Press, Ryden, Spergel 1989)

Complex cosmology of $N > 1$ stable wall system

- Energy density of system $\rho_{\text{wall system}} \simeq \sigma/t$ ($\sigma \simeq v^2 V$: energy per unit area), while for radiation or matter domination $\rho \sim 1/t^2$ decrease faster with time. Thus stable walls would get to dominate the energy density of the Universe, leading to an unacceptable cosmology.

- Zeldovic, Kobzarev and Okun (1974) realized this problem and proposed as solution: a small breaking of the Z_N so that only one true vacuum remains.

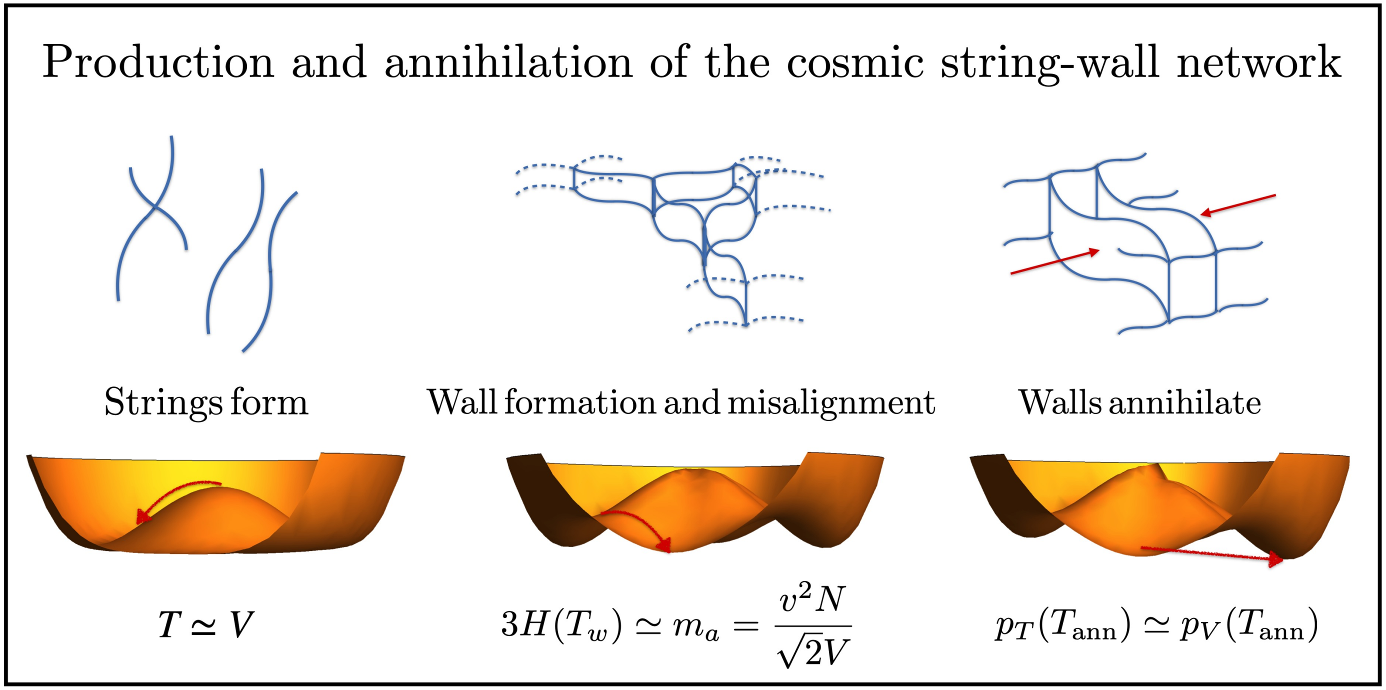
- This introduces a "bias", i.e. an energy difference or volume pressure $\Delta V = p_V \simeq V_{\text{bias}}$ between the false and the true vacua.



- Initially $V_{\text{bias}} \ll p_T \simeq \sigma/t$, the tension pressure.

- As p_T decreases with time, when $V_{\text{bias}} \simeq \sigma/t$, walls accelerate away from the true vacuum leading to the annihilation of the string-wall system: $t_{\text{ann}} \simeq \sigma/V_{\text{bias}}$

Complex cosmology of $N > 1$ stable wall system



At annihilation, all the string-wall system energy goes mostly into ALPs, and some into gravitational waves (GW) and possibly Primordial Black Holes (PBH). We dub this “CATASTROGENESIS” from the Greek for “overturn” or “annihilation” καταστροφή

Generic potential includes

$$V(\phi) \supset \boxed{\frac{\lambda}{4}\left(|\phi|^2 - V^2\right)^2} + \boxed{\frac{v^4}{2}\left(1 - \frac{|\phi|}{V}\cos\left(N\theta\right)\right)} - \boxed{\epsilon_b v^4 \frac{|\phi|}{V}\cos(\theta - \delta)}$$

Spontaneous symmetry breaking — Explicit breaking — Bias

Explicit breaking **U(1)** $\to Z_N$

Bias term as introduced by Sikivie, PRL 48 (1982) 1156 for QCD axions, assumed to be $\ll$ explicit breaking term, i.e. here $V_{\rm bias} \simeq \epsilon_b v^4 << v^4$, i.e. $\epsilon_b \ll 1$

ALP production in these models via three mechanisms:
1)- misalignment, 2)- emission by strings and 3)- catastrogenesis.
For small enough bias catastrogenesis is the dominant mechanism of ALP production, and could be tested by GW measurements

A bit of history of topological defects

- Hot subject in 1980's-90's. Were an alternative (produce isocurvature or isothermal perturbations) to inflaton quantum fluctuations (produce adiabatic or curvature perturbations) as LLS seeds.

- Lost appeal when CMB anisotropy spectrum proved dominant perturbations are adiabatic.

- Continued being studied because of axion cosmology e.g. Hiramatsu et al 1207.3166; Kawasaki, Saikawa and Sekiguchi 1412.0789; Gorghetto, Hardy and Villadoro 2007.04990 and because cosmic strings appear in many particle models (e.g. string models).

- Recently interest in GW produced by cosmic strings in $N = 1$ ALPs models
e.g. Chang and Cui 1910.04781; Gouttenoire, Servant and Simakachorn 1912.02569; Gorghetto, Hardy and Nicolaescu 2101.11007

and by cosmic walls, from discrete symmetry e.g. Saikawa 1703.02576 and in $N > 1$ ALP models e.g. GG, Simpson and Vitagliano 2103-07625 and 2207-07126; GG, Hyman, Simpson and Vitagliano 2207-07126; Gorghetto and Hardy 2212.13263, GG and Hyman 2307.07665

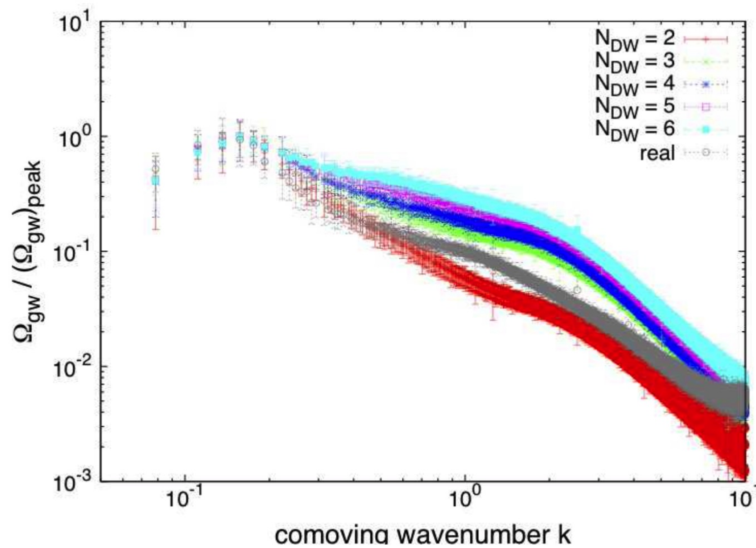
Gravitational Waves from Catastrogenesis

Amplitude:

- Quadrupole formula for the power emitted in GWs $P \simeq G\dddot{Q}_{ij}\dddot{Q}_{ij}$, where $Q_{ij} \simeq E_w t^2$ and $E_w \simeq \sigma t^2$. Thus $\dddot{Q}_{ij} \simeq \sigma t$, and $P \simeq G\sigma^2 t^2$.
- The energy density emitted per Hubble time is $\Delta\rho_{\rm GW} = Pt/t^3 = G\sigma^2$ independently of the emission time t, and is redshifted to the present, thus
- the peak GW amplitude, corresponds to the latest emission time $t = t_{\rm ann}$, $\rho_{\rm GW}|_{\rm peak} \simeq G\sigma^2 \left(a(t_{\rm ann})/a_0\right)^4$.

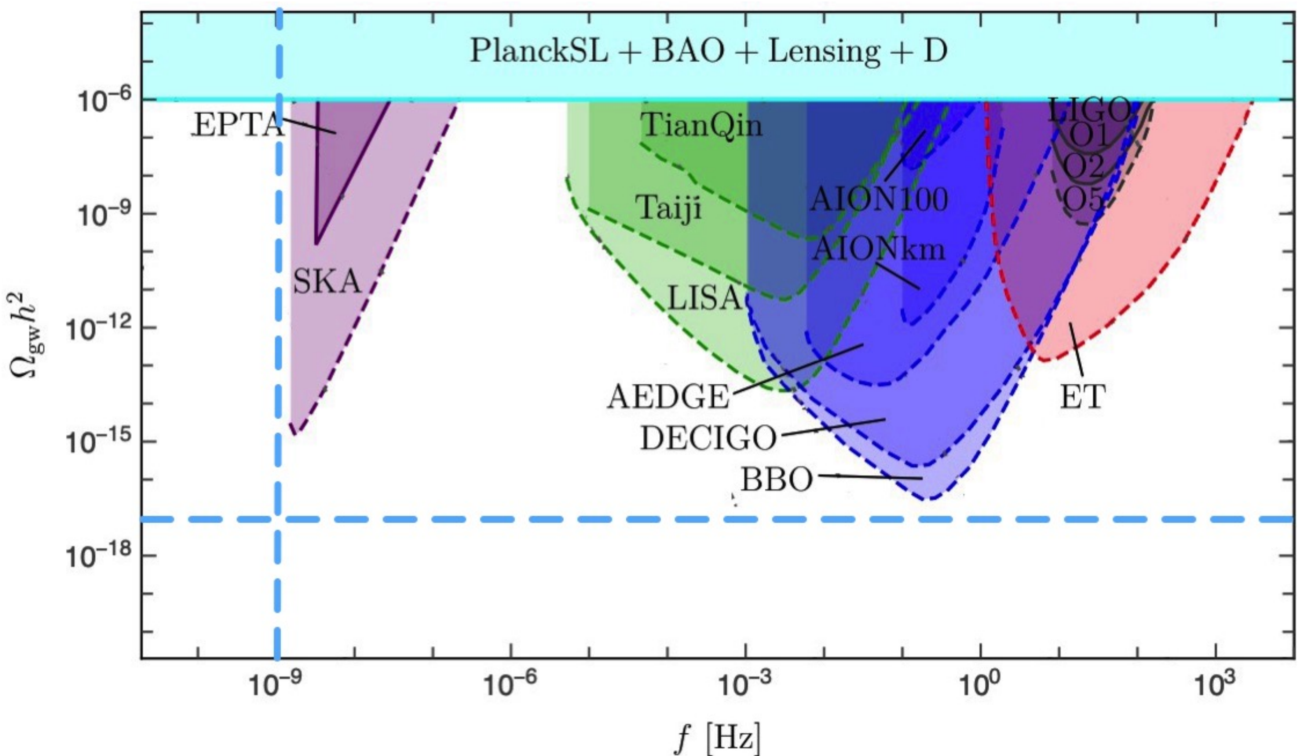
Spectrum:

- Peaked at inverse of the horizon size at annihilation: $f_{\rm peak} \simeq H(t_{\rm ann})a(t_{\rm ann})$
- $f < f_{\rm peak}$: f^3 (white noise) super-horizon wavelengths, absence of causal correlations (Caprini et al 0901.1661])
- $f > f_{\rm peak}$: f^{-1} from simulations (plot) (Hiramatsu et al [1207.3166]



Gravitational Waves from Catastrogenesis for Stable ALPs

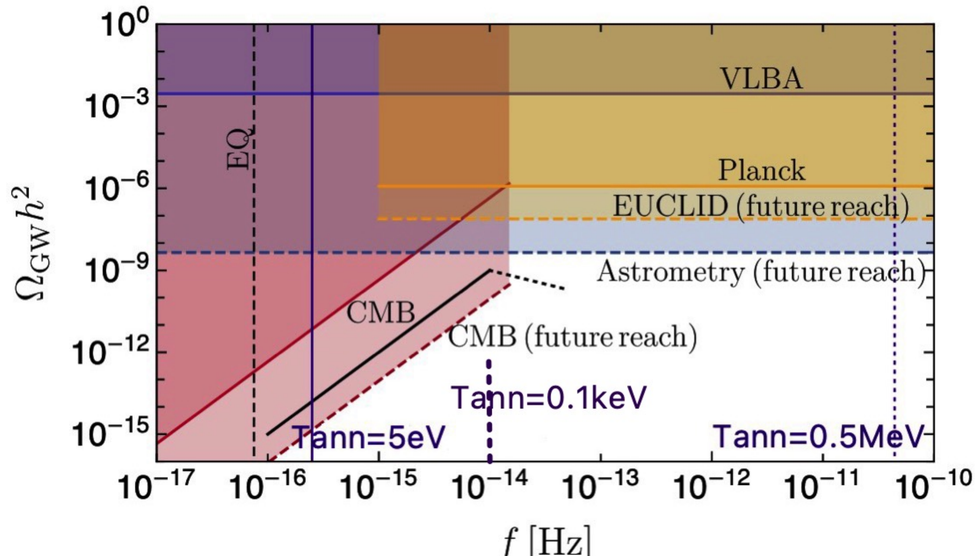
Our allowed observable window is at frequencies below the range of direct GW detection $\Omega_a h^2|_{\rm catastrogenesis} < \Omega_{\rm DM} h^2 \simeq 0.12$ implies $\frac{\Omega_{\rm GW} h^2|_{\rm peak}}{10^{-17}} \left(\frac{f_{\rm peak}}{10^{-9}{\rm Hz}}\right)^2 < 10^{-2}$



E.g for future astrometry reach $\Omega_{\rm GW} h^2 \simeq 10^{-9} \implies f_{\rm peak} < 10^{-14}$ Hz ($T_{\rm ann} < 10^2$ eV)

Gravitational Waves from Catastrogenesis for Stable ALPs

Could be detected by future CMB and astrometry measurements for $m_a \supset 10^{-16}$eV -1 MeV



- Astrometry: apparent distortion of the position of background sources. Present: Very Long Baseline Array (VLBA) catalog. Future: optical satellites or SKA. - $N_{\rm eff}$ at CMB emission. Present: Planck. Future: EUCLID

- CMB polarization. Present Planck, BICEP/Keck Array. Future: LiteBIRD, PICO, CORE.

Low $T_{\rm ann}$ <100eV: structure formation limits not well understood may impose $\Omega_a/\Omega_{DM} < 1$ (Gorghetto and Hardy 2212.13263 find observation of GW in $N > 1$ models in tension with the limits they derive from isocurvature perturbation upper bounds)

Gravitational Waves spectrum from cosmic strings

Entirely different from catastrogenesis.

- Quadrupole formula for the power emitted in GWs $P \simeq G\dddot{Q}_{ij}\dddot{Q}_{ij}$, where $Q_{ij} \simeq \; E_s t^2$ and $E_s \simeq \mu t$. Thus $\dddot{Q}_{ij} \simeq \mu$, and $P \simeq G\mu^2$.

- The energy density emitted per Hubble time is $\Delta\rho_{\rm GW}(t) = Pt/t^3 = G\mu^2/t^2$ at the emission time t, which redshifted to the present by $[a(t)/a_0]^4 \simeq t^2/t_0^2$ makes an almost constant contribution

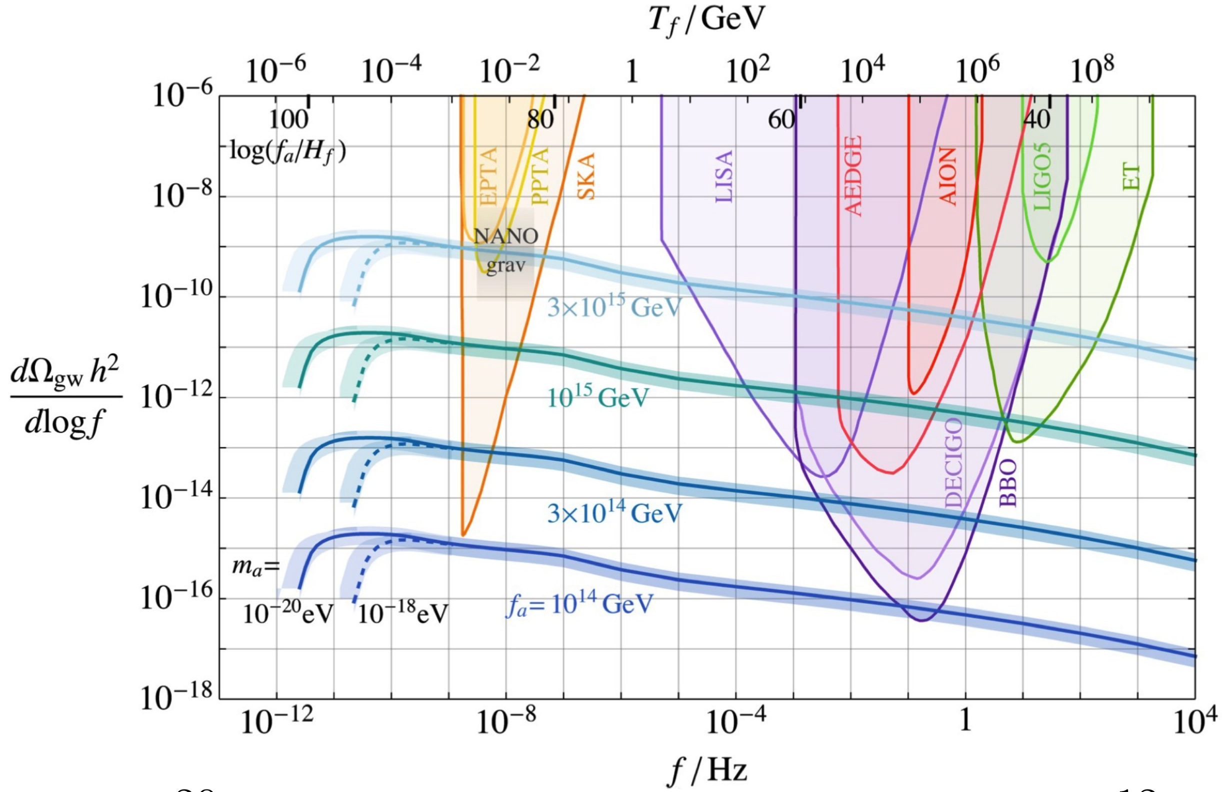
- thus the spectrum is almost flat in frequency at present except for a logarithmic correction coming from a log dependence in μ

(recall that the frequency depends on the inverse of emission time $f \sim 1/t$)

Gravitational Waves spectrum from cosmic strings

Entirely different from catastrogenesis. Emission ends when walls appear $H \simeq m_a \simeq f_{\rm cutoff}$

Gorghetto, Hardy and Nicolaescu 2101.11007: GW observable for $V > 10^{14}$ GeV

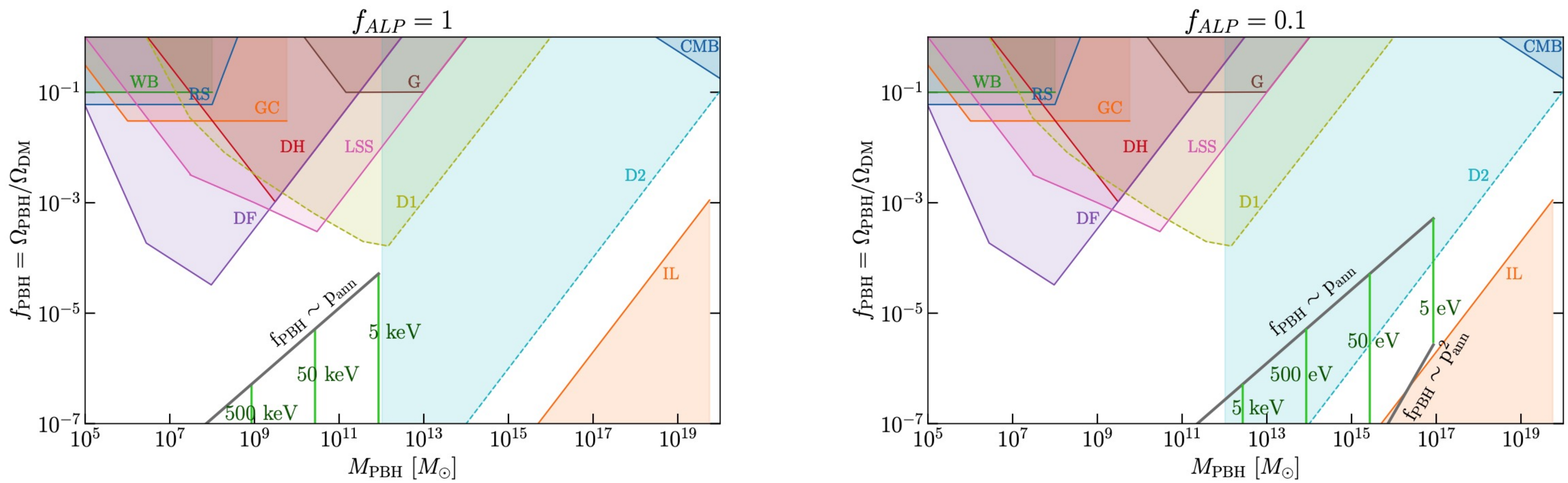


Ly-α: $m_a > 2 \times 10^{-20}$ eV, so walls formed before 5.3 keV and $f > 10^{-12}$ Hz

Could PBH form from Catastrogenesis?

After the annhilation process starts, if the linear size of walls continues growing with t, figure of merit $p = R_s/t \sim V_{\rm bias} t^3/t \sim t^2$ grows for $t > t_{\rm ann}$ and could becomes 1 signaling BH formation (R_s: Schwarschild radio) (Ferrer, Masso, Panico, Pujolas and Rompineve, 1807.01707)

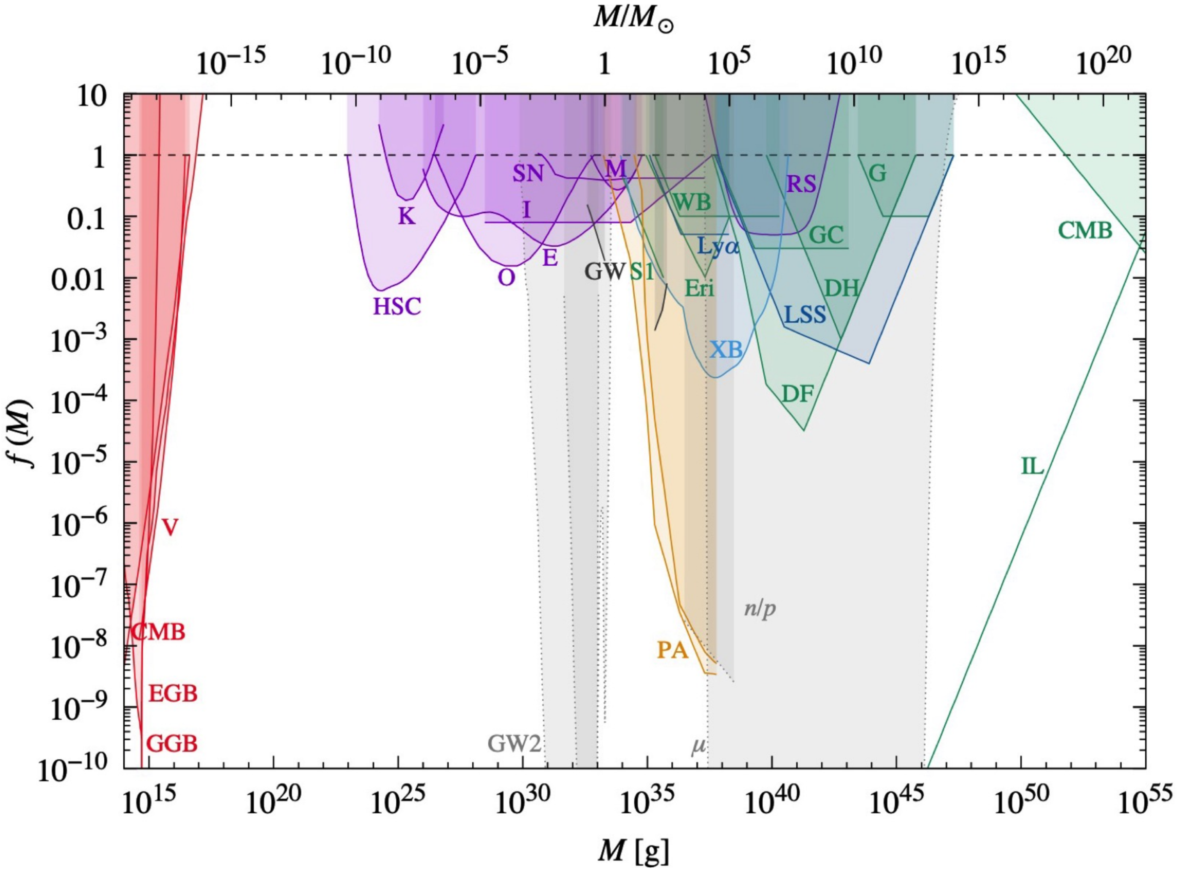
It depends on details of the collapse that need to be tested with simulations!!!
(only existing Kawasaki, Saikawa and Sekiguchi 1412.0789)



Vertical lines are $T_{\rm ann}$ - are very low. Thus is PBH are formed, they are "Stupendously Large". since horizon very large. (D2: discovery limits CMB spectrum μ-distortion, Deng 2106.09817)

Could these models produce PBH of much lower mass?

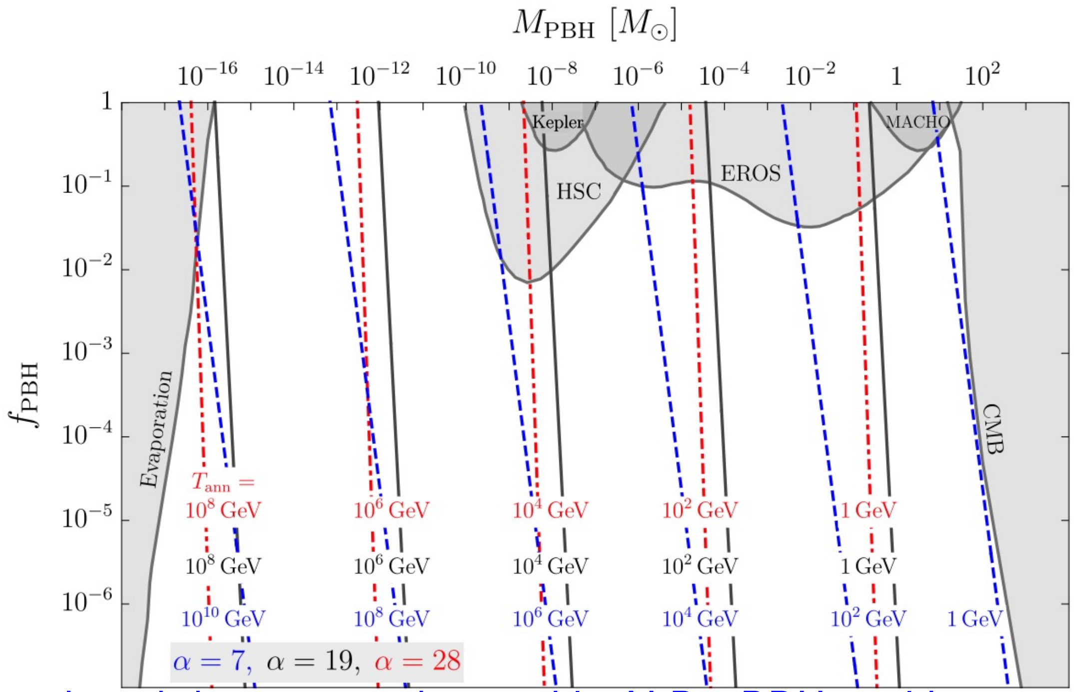
In the "asteroid mass" range 10^{-16} $M_\odot$ to 10^{-10} $M_\odot$ PBH could be all of the DM. (Carr and Kuhnel 2021, Green and Kavangh 2020)



Yes- for unstable ALPs which decay very early in the history of the Universe. Assume ALPs are heavy enough to have escaped laboratory constraints and decay into products that thermalize (thus they are not part of the DM).

PBH from Catastrogenesis for Unstable ALPs

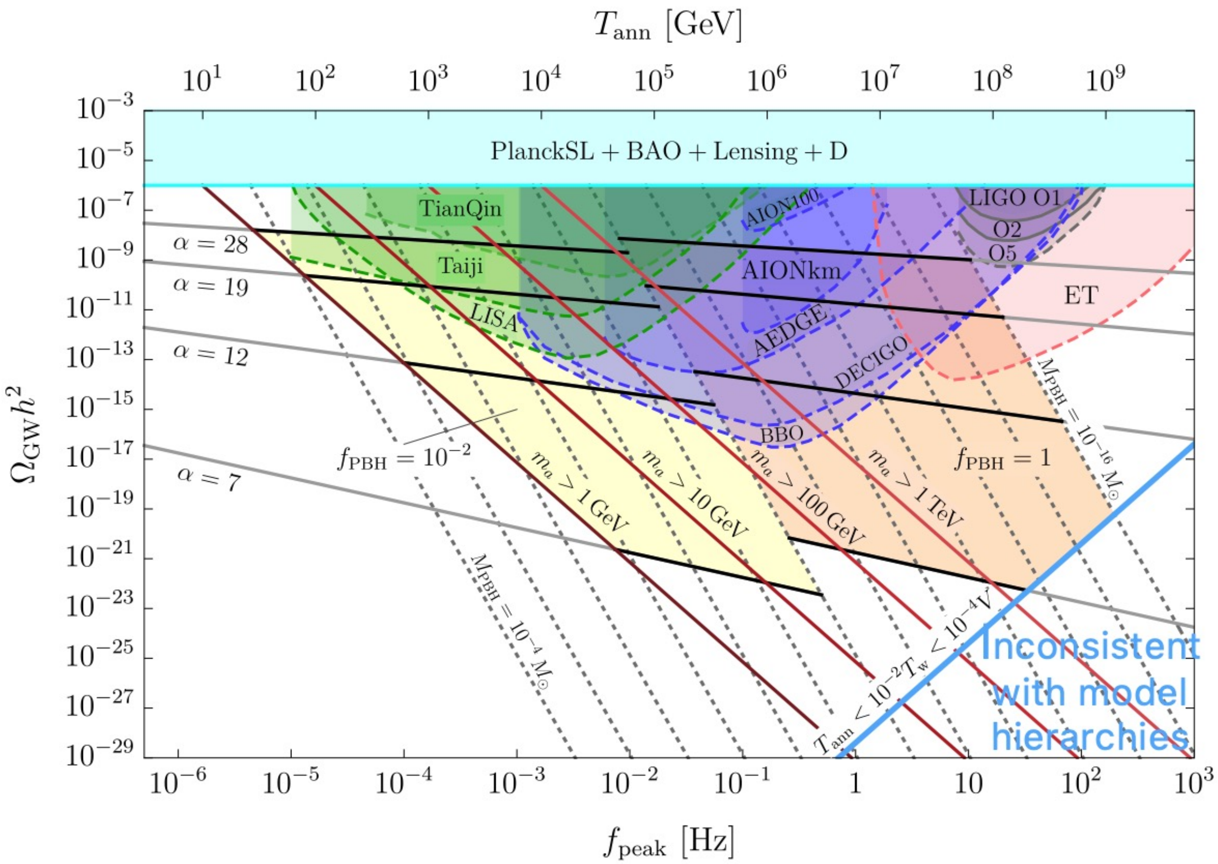
From available simulations Kawasaki, Saikawa and Sekiguchi 1412.0789) $T < T_{\rm ann}$, $\frac{\rho_{\rm wall-system}(T)}{\rho_{\rm wall-system}(T_{\rm ann})} \simeq (T/T_{\rm ann})^{\alpha}$ power α parameter has large error (from only two data points)



If PBH can be formed, with heavy enough unstable ALPs, PBH could constitute all of the DM, for $T_{\rm ann}$=10^4–10^9GeV And GW would be at observatories frequencies...

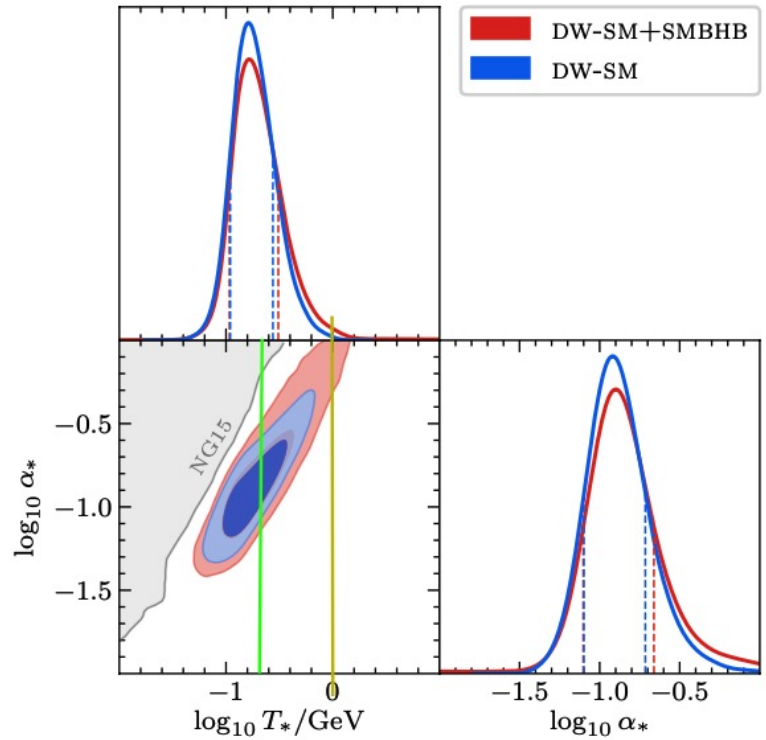
GW from Catastrogenesis for Unstable ALPs

Signal amplitude may be too small, unless evolution parameter is very large!



NANOGrav 15 yr GW signal (2306.16213)

"North American Nanohertz Observatory for Gravitational Waves" 15 yr data (67 pulsars) shows 3.5-4σ evidence for a GW background at $f \simeq 10^{-8}$ Hz). One type of "new physics" that could produce this signal is Domain Walls annihilating into SM products "DW-SM" (2306.16219)

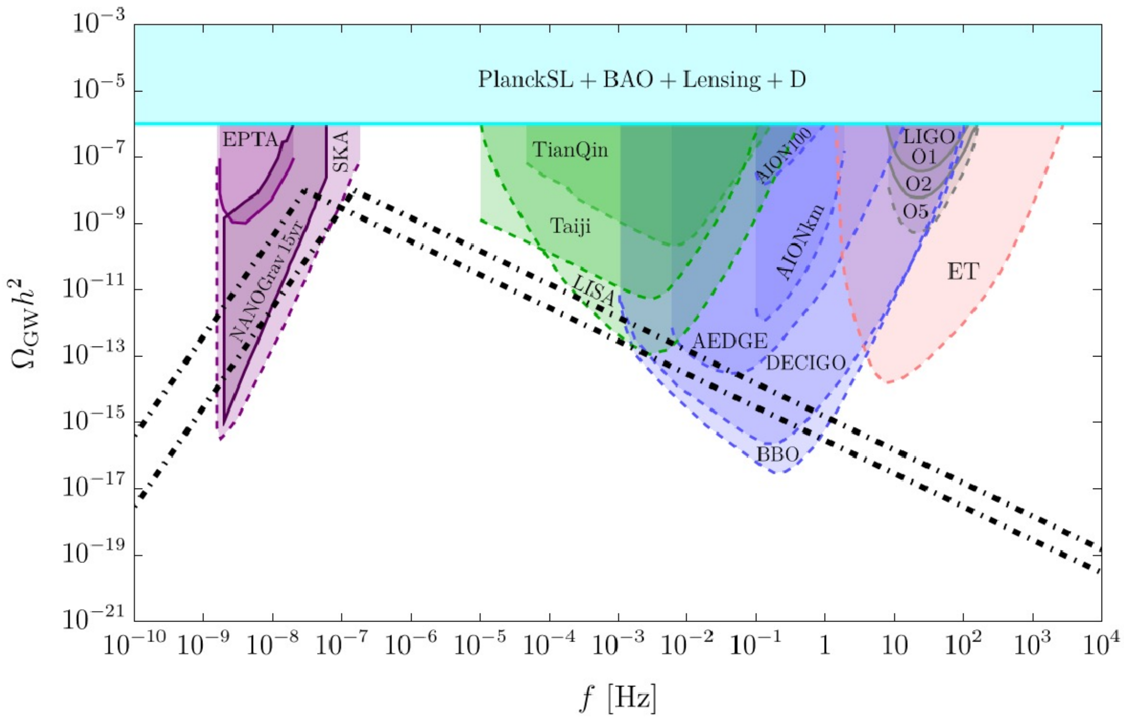


NANOGrav GW signal (Gelmini and Hyman, 2307.07665)

Catastrogenesis can explain it with $a \to \gamma\gamma$, if PBH do NOT form

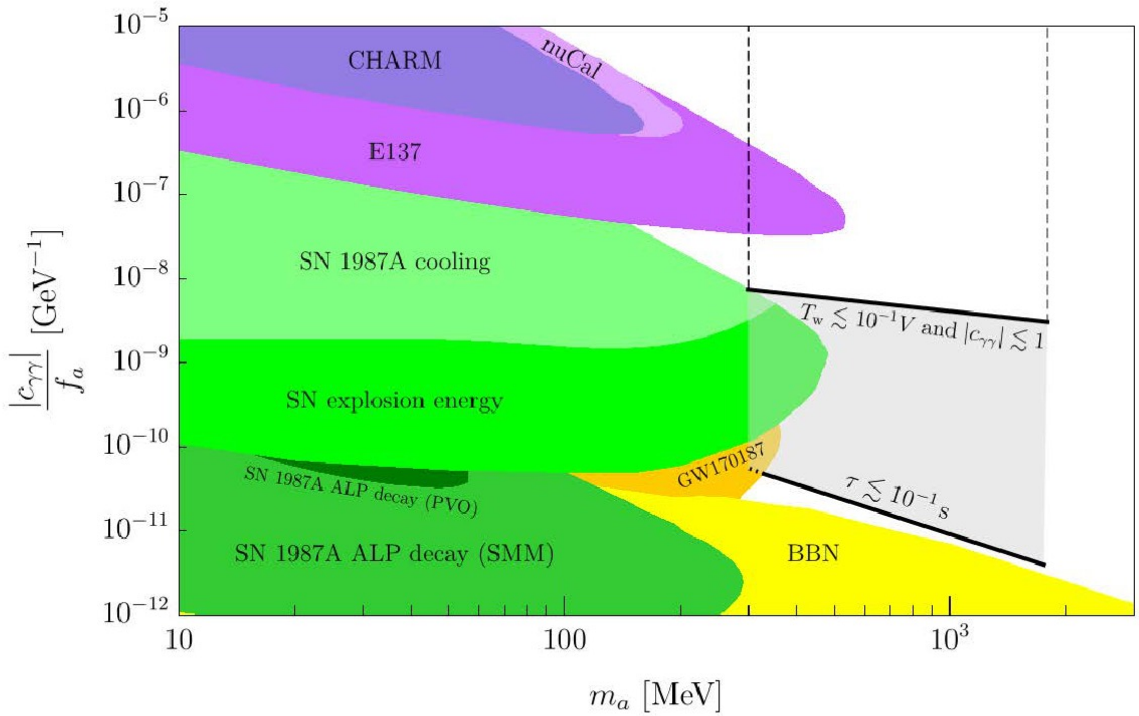
NANOGrav DW-SM fit: $T_{\rm ann} \lesssim$1GeV $\Rightarrow m_a \lesssim$1.8GeV-

ALPs limits: $m_a \gtrsim$300MeV $\Rightarrow T_{\rm ann} \gtrsim 0.2$GeV. Thus 2.9×10^{-8}Hz$<f_{\rm peak}<1.5 \times 10^{-7}$Hz



NANOGrav 15 yrGW signal Catastrogenesis can explain it with ALPs decaying into photons before BBN, if PBH do NOT form (gray region)

Requires $|c_{\gamma\gamma}| >$ in simplest QCD models (which is $\simeq \alpha_{\rm EM}/8\pi \simeq 2.9 \times 10^{-4}$) (Gelmini and Hyman, 2307.07665)



Conclusions

We studied the generation of particles, GW and possibly PBH at annihilation of the string-wall system of a post-inflationary $N > 1$ U(1) pseudo-Goldstone bosons (ALPs) scenario, which we dubbed "catastrogenesis"
a minimal particle model with amazingly rich cosmology!

Our calculations are only estimates, need to be tested by numerical simulations!

Stable ALPs: could be the DM. GW with distinctive peaked spectrum could be detected through CMB and astrometric measurements. If PBH are formed, they would be supermassive.

Unstable "heavy" ALPs: PBH in the "asteroid" range could be produced and be the DM. GW frequency would be in GW detectors range, but amplitude is very uncertain. Could explain NANOGrav data if PBH do not form, e.g. with ALPs decaying into photons $a \to \gamma\gamma$.

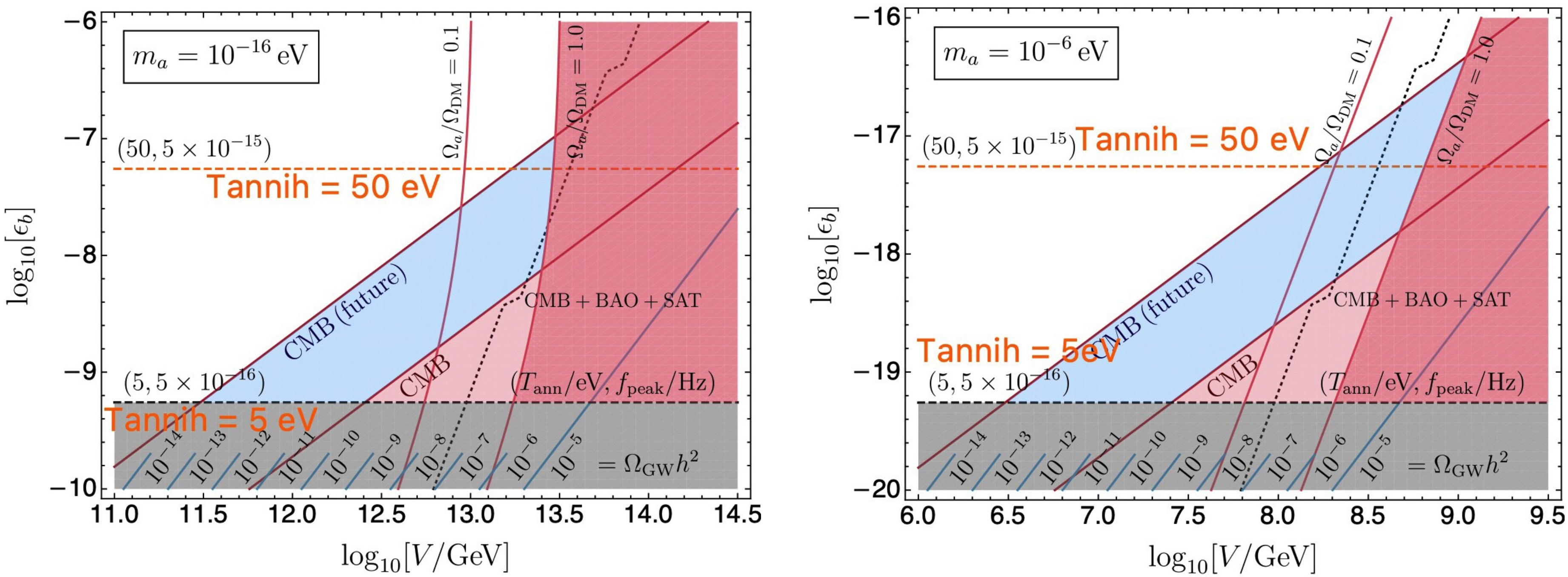
Main message: **Catastrogenesis potentially very interesting mechanism usually overlooked, badly in need of new numerical simulations!!!**

.

EXTRA SLIDES

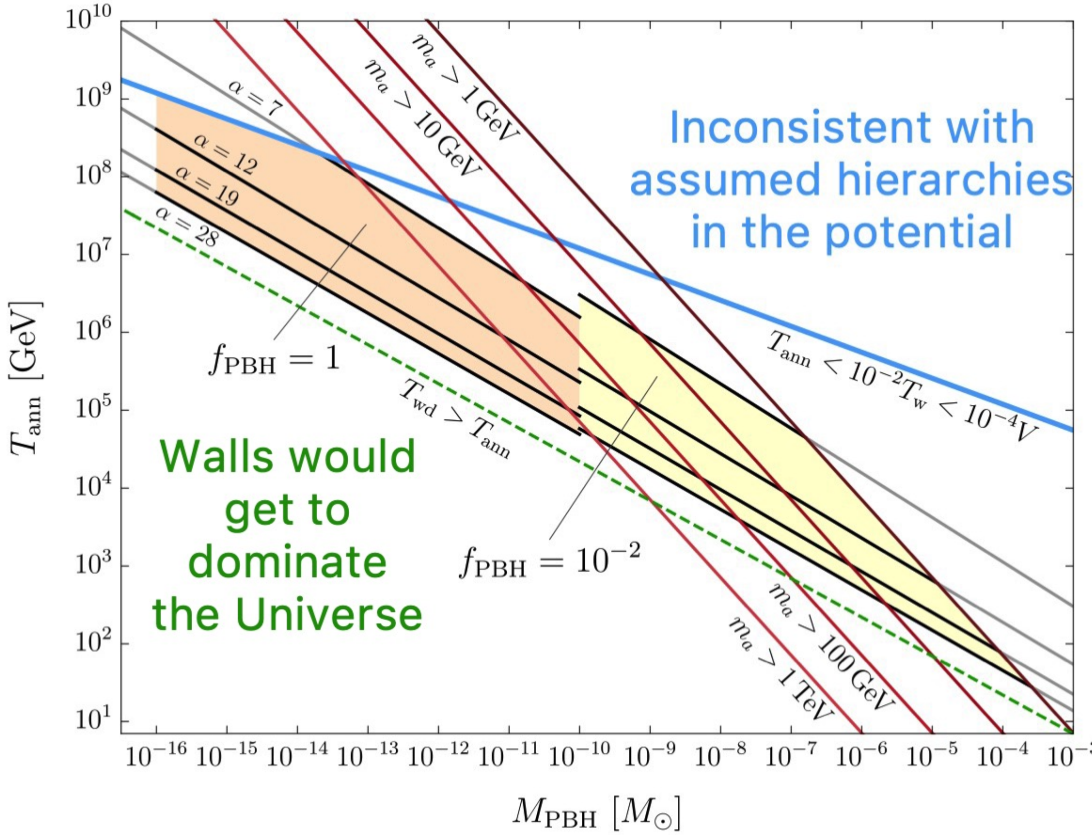
Gravitational Waves from Catastrogenesis for Stable ALPs

Observable window translates in parameter space for 10^{-16} eV$<m_a<$1 MeV GW mostly from walls, and avoid Black Hole superradiance limits at low end; self consistency $v < 0.01V$ at high end



Structure formation limits not well understood may restrict $\Omega_a/\Omega_{DM} < 1$ in observable window (Gorghetto and Hardy 2212.13263 find observation of GW in $N > 1$ models in tension with the limits they derive from isocurvature perturbation upper bounds)

PBH from Catastrogenesis for Unstable ALPs



If PBH can be formed from the collapse of a wall system, in heavy unstable ALP models PBH could constitute all of the DM! And GW would be at observatories frequencies...

GW from Catastrogenesis for Unstable ALPs

If observable, spectrum would be very characteristic... string emission could be observable too