PROSPECTS FOR NEUTRINOS and ASTROPARTICLE PHYSICS

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Neutrino Oscillation Workshop – NOW 2022

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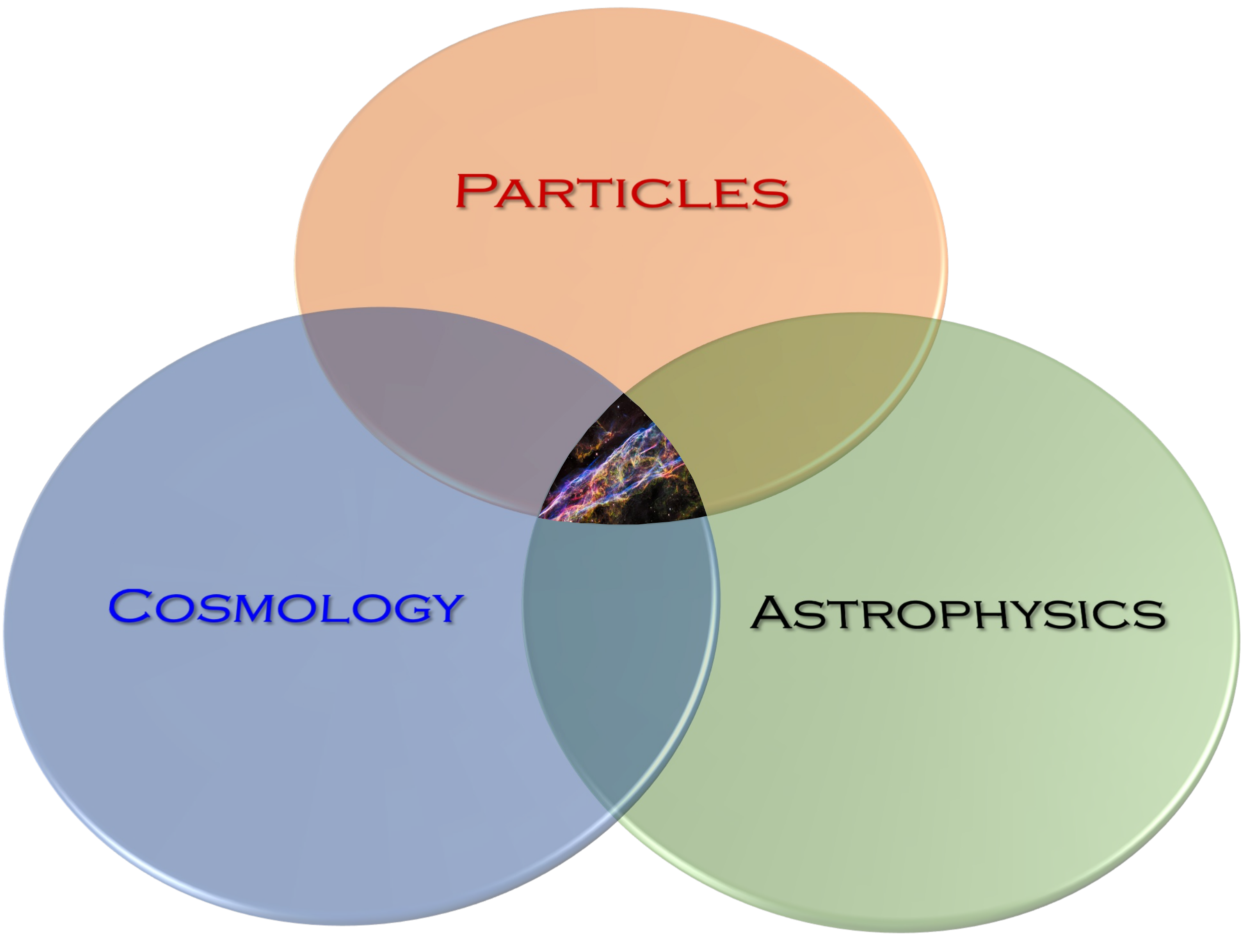
Astroparticle Physics in 2022

- Astroparticle Physics has grown to become a fundamental field of research which addresses most (if not all) of the most striking and fundamental questions in Nature
- The discoveries made in the past decades have radically changed our understanding of the Universe
- In some cases, we moved from pioneristic ideas and experiments to discoveries to a precision era (e.g. neutrinos); in others, discovery still awaiting but progress has been tremendous (e.g.: dark matter)
- The next 10-30 years promise to be equally exciting, thanks to a stream of new data from a variety of observational probes and wide range of theoretical ideas than can be put under deep scrutiny

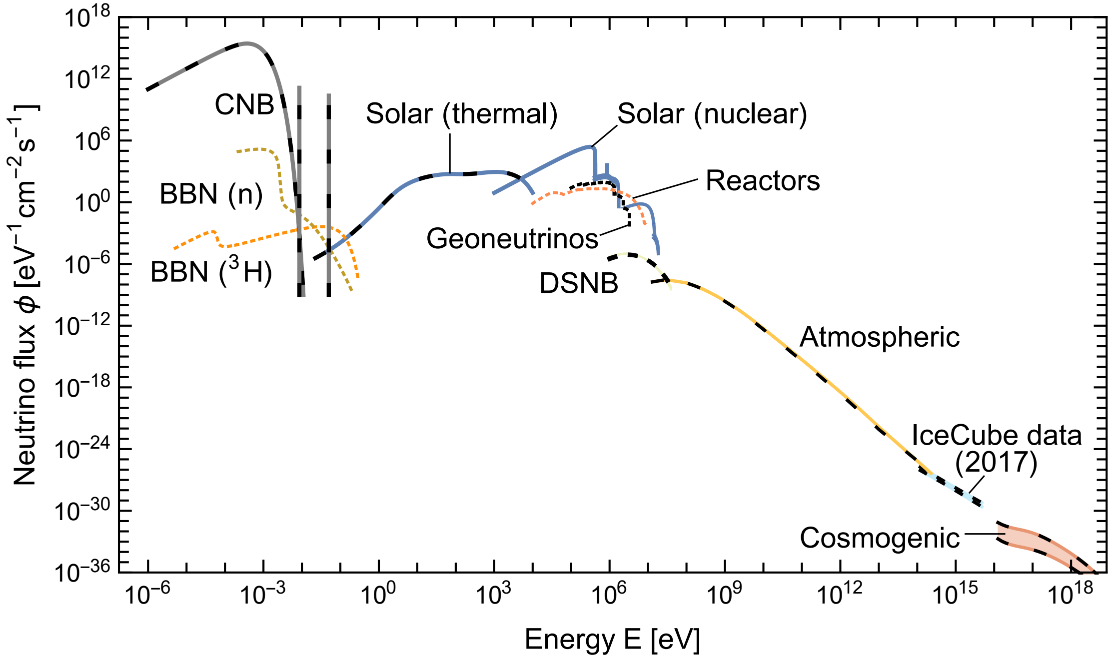
Very interdisciplinary and synergic field of research



Neutrinos
Dark Matter
Cosmic accelerators
Cosmic messengers
Dynamical spacetimes
Nuclear astrophysics
Particles in/from stars
Early Universe
Late Universe

Neutrinos

Fluxes and scales



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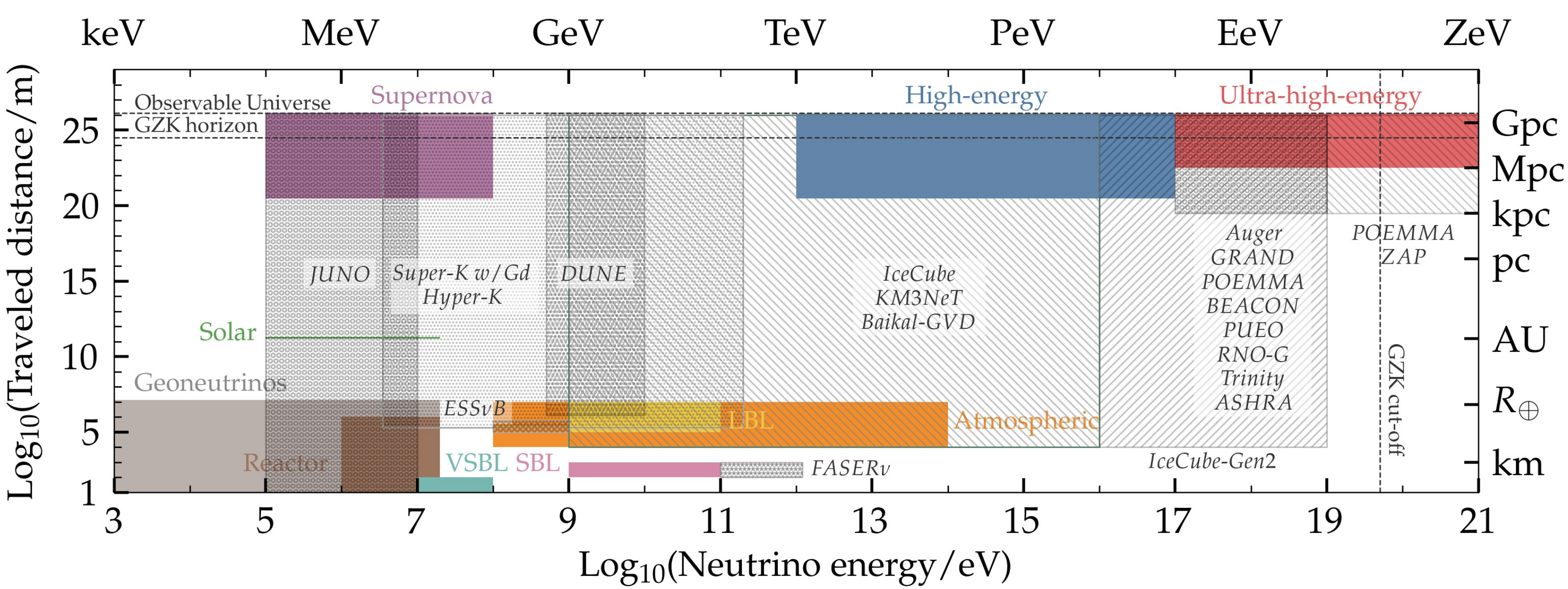


What is known

- Three active flavours
- Neutrinos oscillate: pattern well measured, both vacuum and matter effects observed
- (Two) squared mass differences Δm^2_{21} $|\Delta m^2_{31}|$
- Mixing angles

- Neutrinos observed in astrophysical environments:
  - Stars (Sun)
  - Earth (geoneutrinos)
  - Cosmic rays processes (atmospheric, astrophysical)
  - Supernova (SN1987, not yet DSNB)
- Cosmological neutrinos (indirectly)

What is not yet known

- Mass: origin, absolute masses, ordering
- CP phase
- Dirac or Majorana nature
  - If Majorana, implies: LNV, 2 additional phases
- Additional states (sterile)

- Direct observation of the CNB
- Diffuse SN background
- Cosmogenic
- Full role in supernova (thermo)dynamics

Mass

- Origin of mass
  - Mechanism similar to charged fermions (Higgs) or fundamentally different?
  - Sterile neutrinos have a role?
  - Scale of mass generation
- Absolute masses
  - Below 1 eV: much smaller than other fermions
- Pattern of masses and mixing
  - Very different from the quark sector (SM flavor puzzle)
  - Solution: dynamical, symmetry based?
- Ordering

Dirac or Majorana?

- All known fermions are Dirac: neutrinos might be the only (so far) Majorana particles
- Neutrinoless double-beta decay: key process
- Implications for Lepton number:
  - Dirac: Lepton number conserved
  - Majorana: Lepton number violation
    - Is Lepton number a fundamental symmetry of Nature? The answer could help in understanding the origin of neutrino masses and of their smallness
    - LNV is often a general feature of theories beyond the SM (unless a symmetry is imposed)
    - Matter (over antimatter) genesis?

Sterile neutrinos

- Hints from anomalies in observations, implications for particle physics, astrophysics, cosmology
- Sterile neutrinos can be easily accommodated as singlets in mild and minimal extensions of the SM: not very harmful, potentially very rich phenomenology (particle, astro, cosmo)
- The number and mass of sterile states in minimal settings are in general arbitrary (no fundamental symmetry “protects” them): in principle, they can span from sub-eV to (sort-of) Planck scale
- They can have a role in:
  - Explaining the smallness of neutrino masses
  - Generation of matter/antimatter asymmetry in the Universe
  - Explaining (all or part of) the dark matter in the Universe
  - (...)

Sterile neutrinos

- Mass at the eV scale: role in short baseline experiments
- Mass < MeV:
  - Cosmologically act as dark radiation, strongly bounded from N_{eff}
  - Can be constrained from cosmological probes (CMB, BAO, surveys)
- Mass at the KeV scale: can act as (warm-ish) dark matter, strongly constrained from astrophysical processes
- Mass above 10 MeV: can be searched in accelerator-based experiments

- Mixing needs to be (very small), otherwise unwanted consequences (oscillation patterns, cosmological radiation, astrophysical consequences)

- Matter/antimatter asymmetry
  - A dynamical solution requires B or L violation, CP violation (and non-equilibrium dynamics): Leptogenesis
  - LNV and CP violation in leptogenesis: possible links to mass generation modelling, light neutrino properties
- Neutrinos as DM
  - KeV scale sterile might work, but severely constrained
- Non-standard interactions: BSM physics
- Neutrinos and DE connection?
  - (DE density) $\sim$ (0.01 eV)^4 $\sim$ (nu density) $\sim$ $(m_{nu})^4$
- Probe for tests of fundamental symmetries
  - CPT, Lorentz symmetry, unitarity
- Quantum mechanics/QFT effects
  - Coherence and decoherence, collective phenomena in SN

Dark Matter

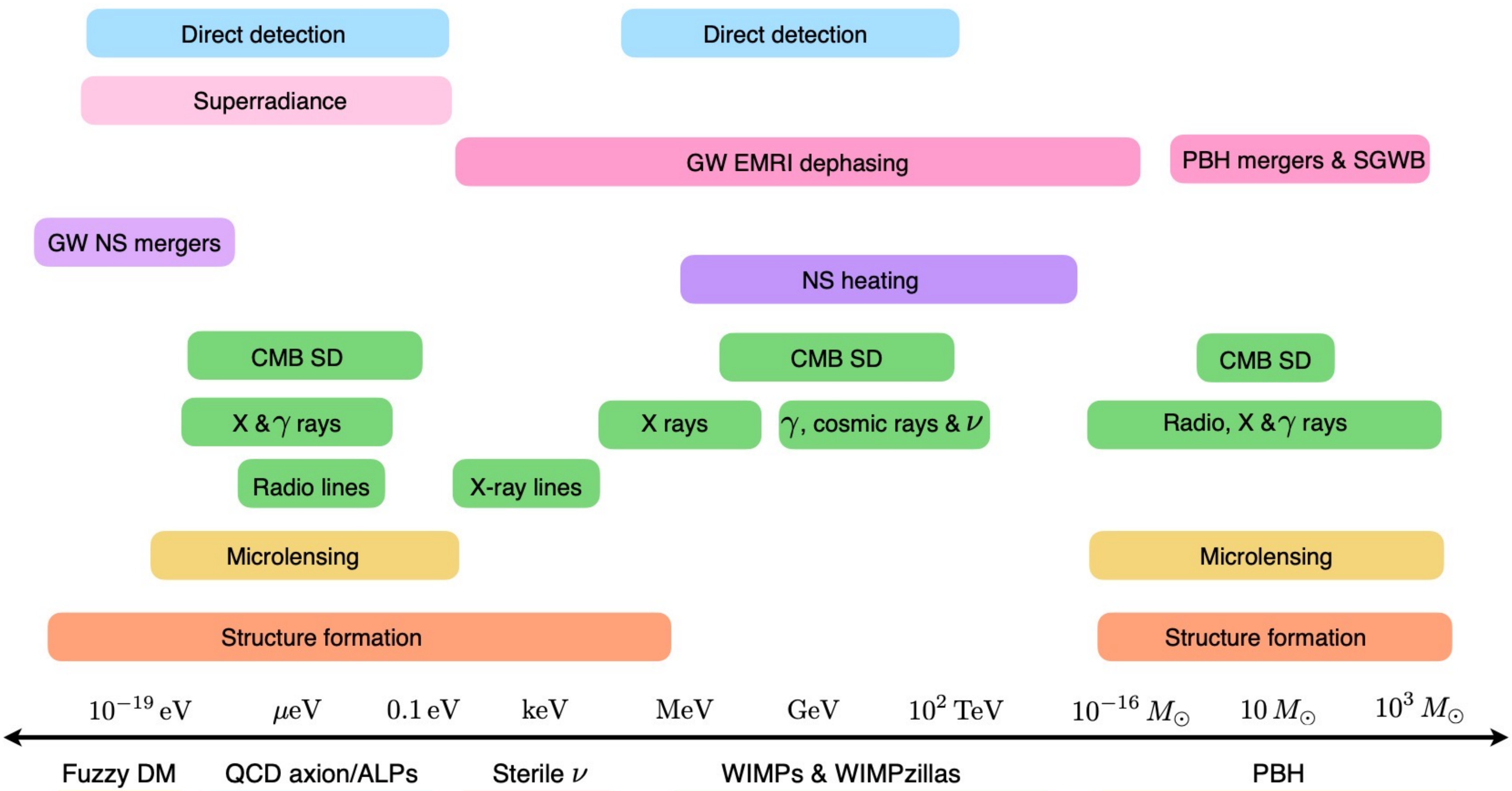
Fundamental Facts and Questions

- Overwheling evidence that majority of pressurless matter in the Universe is non-baryonic
- Gravitational inference clear, microscopic nature still a mistery
- What is Dark Matter?
  - If a particle, what are key parameters: mass, interaction types and strengths

What is (sort of) known

- Cosmic density about ¼ of the Universe total budget
  - CMB anisotropies, LSS
- Local density: 0.3-0.4 GeV cm^{-3} = 10^5 average density
  - Local stellar motions
- Local velocity dispersion: 200-300 km s^{-1}
  - Local stellar motions
- No preferred length scale
  - Galaxy clustering and evolution
- Behave as non-relativistic and pressurless (cold or cold-enough)
  - Structure formation
  - Excludes light neutrinos, implication for light scalars
- Early appearance: it had to be present way before CMB release, gravitational influence before 1 year from BB
  - Galaxy clustering
  - For light bosons, this sets the latest epoch of particle creation
- No significant interaction with ordinary matter or self-interaction
  - Darkness, Bullet cluster

What is unknown



Bosnic
Fluid
“Quantum”

Bosonic
(Thermal)
Non-thermal
Cold DM

Non-thermal
Warm DM

Thermal
Non-thermal
Cold DM

Primordial

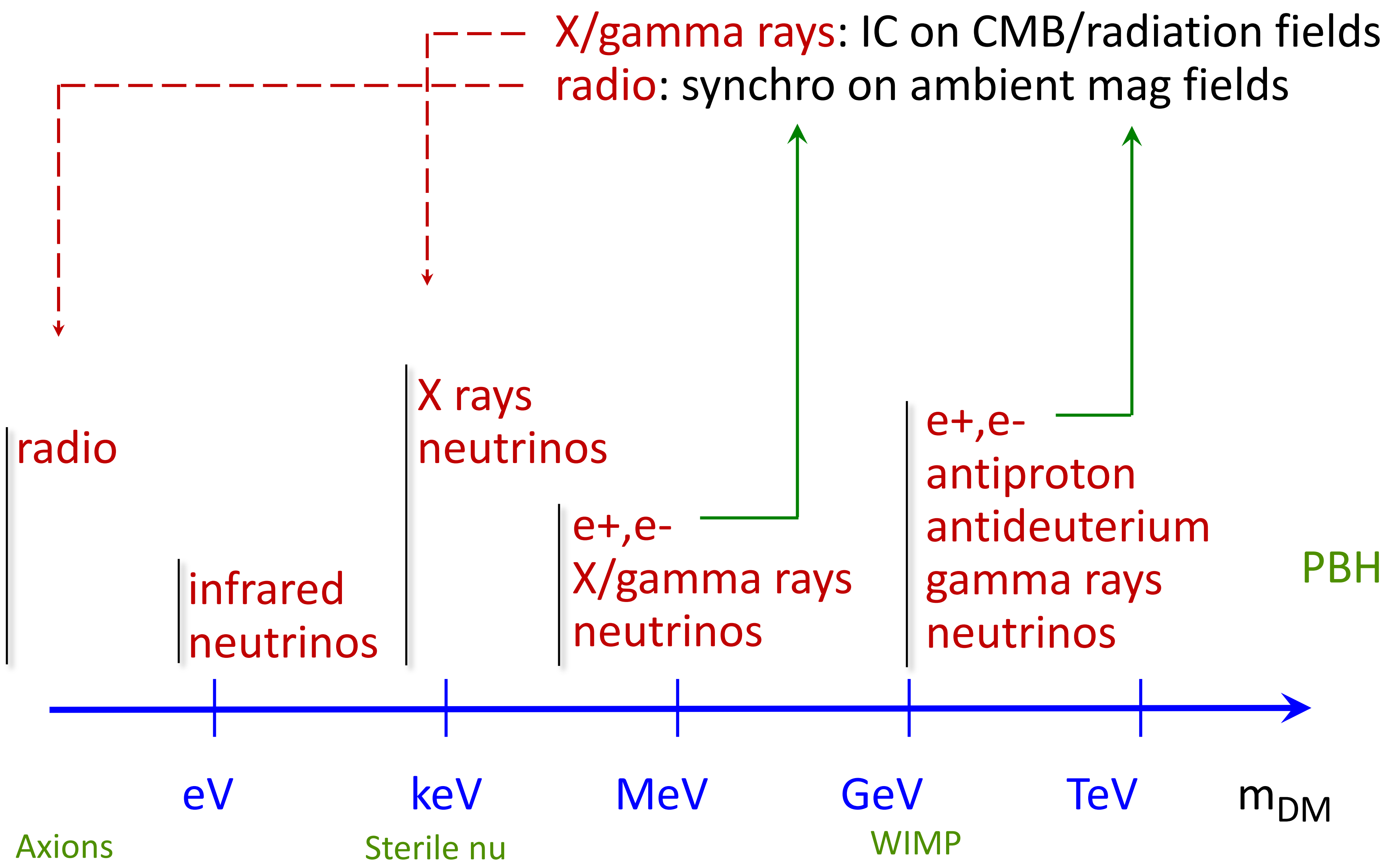
Tools at hand

- Cosmic surveys
    - Galaxies, clusters, voids – CMB, Ly-alpha, 21cm
    - Allow to test DM on different scales and at different times, deep test of clustering in the non-linear regime
    - Probe coldness, collisionless and pressurless hypotheses, wave vs particle, single vs multi-component, interactions with visible sector
    - Synergy with DE and Early Universe physics
- Effects induced on astrophysical systems
    - Sun, other stars, SN, NS, BH
- Experiments in the Lab
    - Passive but directly probe DM: direct detection
    - Active but indirect: production at accelerators

Tools at hand

- Cosmic messengers
  - DM can inject high-energy particles (messengers) into the cosmological environments (our Galaxy, external galaxies, clusters, filaments, voids)
    - Decay/annihilation if a particle
    - Evaporation or accretion if a PBH
  - Messengers might be reprocessed during the travel
  - Complex system of signals
  - Typically dominant astrophysical backgrounds
  - Probe DM interactions with itself and visible sector
  - Multi-messenger and multi-wavelength
  - Statistical correlations between signals; between gravitational tracers (galaxies, clusters, voids, cosmic shear, CMB lensing) and (one of more) messengers' emission

Tools at hand: cosmic messengers



- WIMPs: very rich phenomenology
- ALPs: very rich phenomenology, too

nev – peV	axion-photon conversion, oscillation, absorption of high-E photons	
μeV (QCD)	radio 100's MHz	
sub eV	CMB spectral distortions	
meV – eV	infrared	
KeV	X-rays	(sterile neutrinos, too)

Superradiance (BH, NS): dense axion cloud around BH with stimulated axion decay (ms bursts at GHz)

Microlensing: axion miniclusters

- PBH

radiative emission during accretion of gas

affects CMB, radio and X rays

astro uncertainties, PBH mass function

evaporation

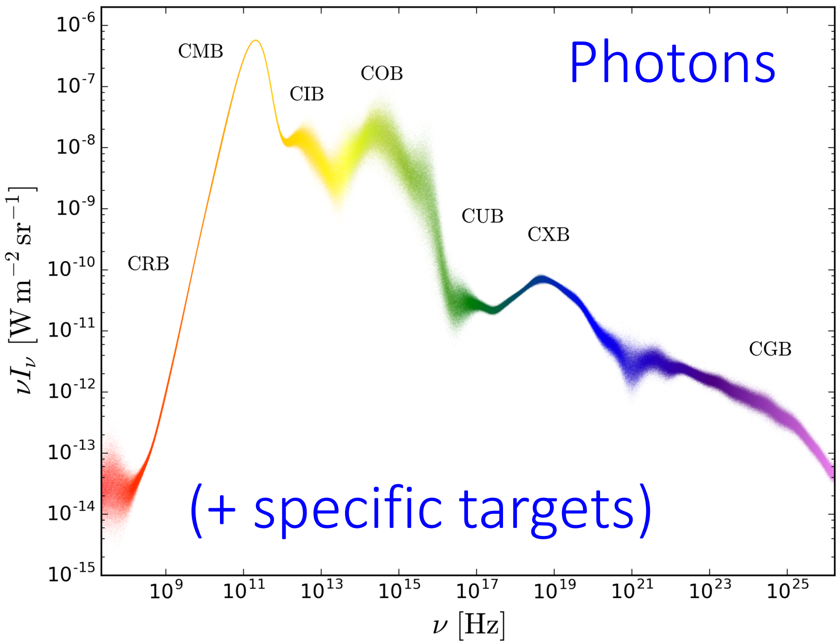
femto-, micro- lensing

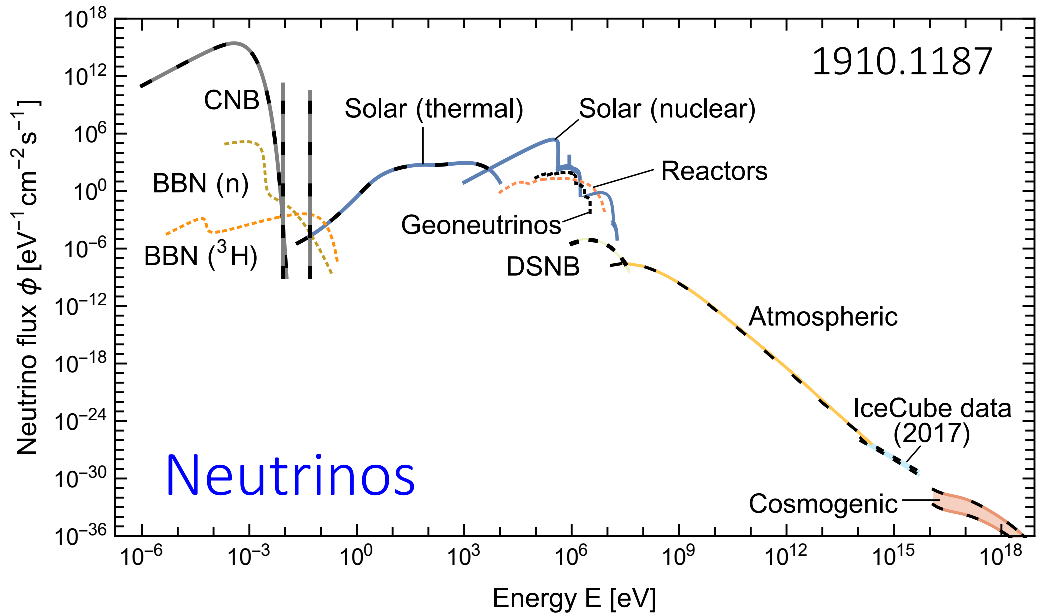
Connection to particle physics models

- Axion-like, wave (scalar, pseudo-scalar)
  - String theory?
  - Inflationary models?
  - Ad hoc?
- QCD axion (pseudo-scalar)
  - Strong CP-problem
- Sterile neutrinos
  - Very light, KeV, heavy
  - Neutrino mass models, leptogenesys models
- Dark photons
  - Gauge group extensions: U(1)’, SU(2)’
- Heavy (pseudo) scalars
  - Scalar sector extensions: singlets, 2HDM, triplets
- WIMPs
  - Supersymmetry
  - Extra dimensions
  - Minimal DM models
  - Leptogenesys models
- Very heavy particles
  - GUT
  - Leptogenesys

All of them require that DM “cosmological stability” is ensured (accidentally, through a symmetry)

Cosmic accelerators and Messengers


Photons
(+ specific targets)
CMB
CIB
COB
CUB
CXB
CRB
CGB
νI_ν [W m^{-2} sr^{-1}]
ν [Hz]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{9}
10^{11}
10^{13}
10^{15}
10^{17}
10^{19}
10^{21}
10^{23}
10^{25}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Neutrinos
CNB
Solar (thermal)
Solar (nuclear)
Reactors
BBN (n)
Geoneutrinos
BBN (^{3}H)
DSNB
Atmospheric
IceCube data (2017)
Cosmogenic
Neutrino flux ϕ [eV^{-1}cm^{-2}s^{-1}]
Energy E [eV]
10^{18}
10^{12}
10^{6}
10^{0}
10^{-6}
10^{-12}
10^{-18}
10^{-24}
10^{-30}
10^{-36}
10^{-6}
10^{-3}
10^{0}
10^{3}
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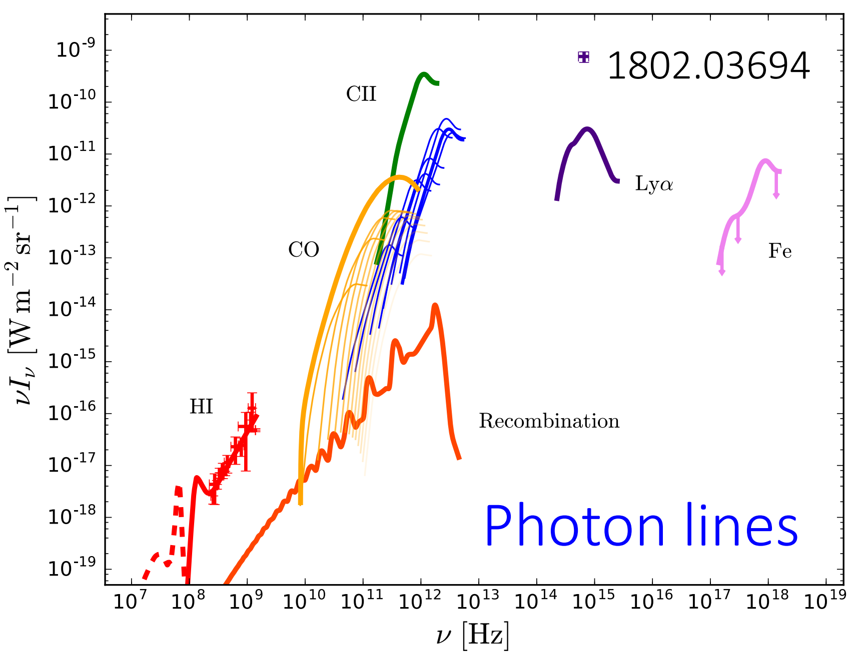
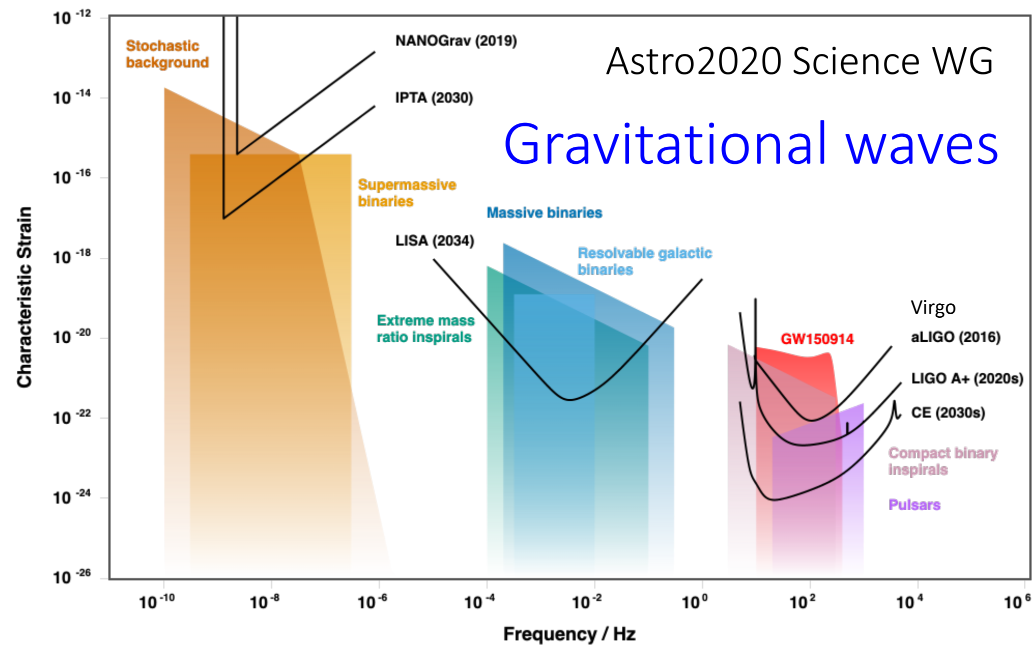
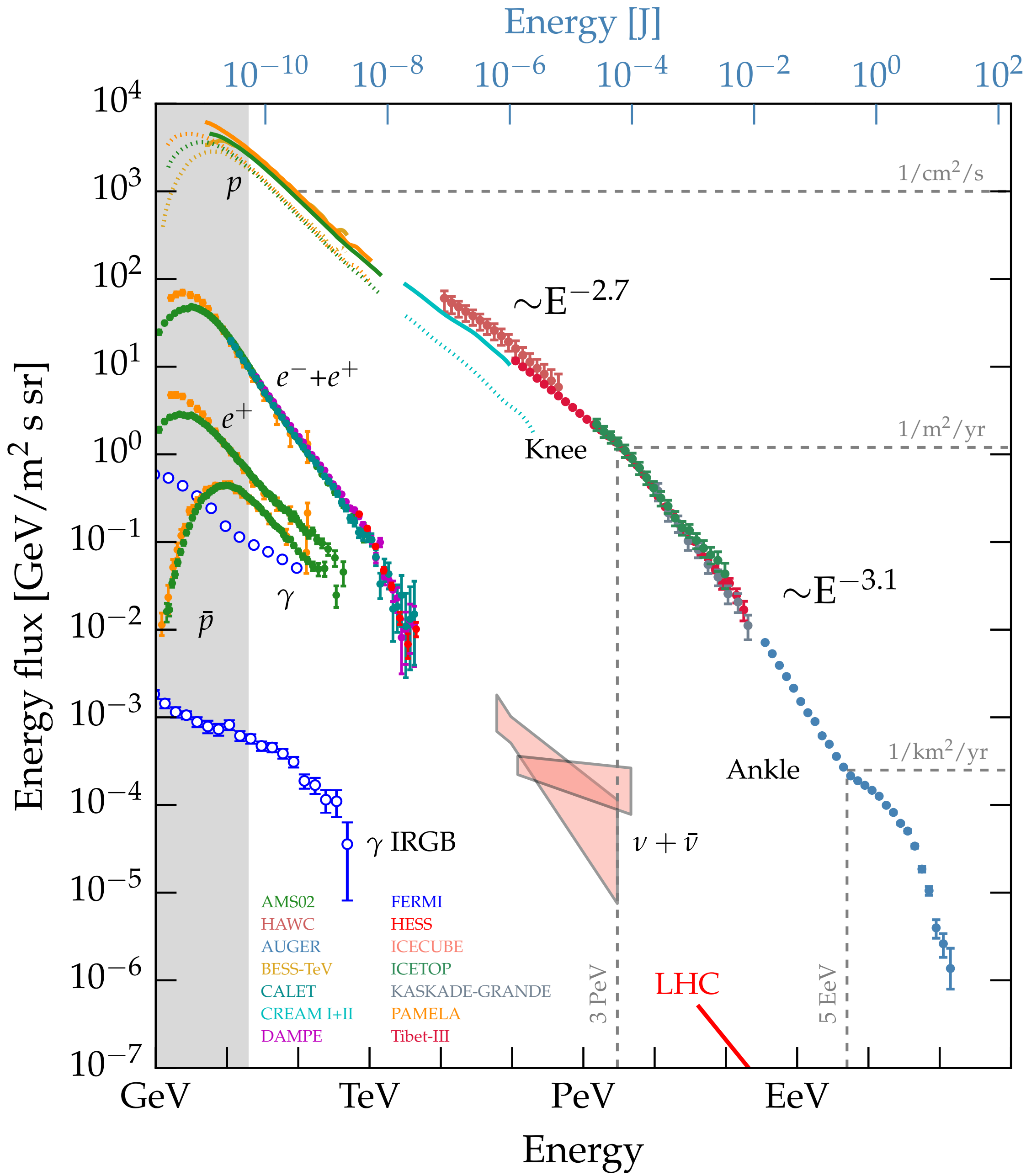
10^{9}
10^{12}
10^{15}
10^{18}


1802.03694
Photon lines
CII
Lyα
Fe
CO
HI
Recombination
νI_ν [W m^{-2} sr^{-1}]
ν [Hz]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}


Astro2020 Science WG
Gravitational waves
Stochastic background
NANOGrav (2019)
IPTA (2030)
Supermassive binaries
Massive binaries
LISA (2034)
Resolvable galactic binaries
Extreme mass ratio inspirals
Virgo
GW150914
aLIGO (2016)
LIGO A+ (2020s)
CE (2030s)
Compact binary inspirals
Pulsars
Characteristic Strain
Frequency / Hz
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}

Cosmic rays



+ nuclei

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Cosmic Accelerators and Messengers

- Some key questions:
  - Understading the sources (origin, mechanisms) of cosmic messengers
  - How accelerators work
  - What happens during the travel from the sources to us (depends on the messenger)

Cosmic Accelerators and Messengers

- Messengers:
  - Photons (from radio to HE gamma-rays)
  - Neutrinos
  - Charged particles (electrons/positions; [anti]nuclei)
  - Gravitational waves
- Sources:
  - Active Galactic Nuclei (relativistic jets)
  - Massive star clusters
  - Active galaxies
  - Tidal disruption events
  - Compact objects (e.g. PWN)
  - Mergers (galaxies, NS)
  - Bursts: GRB, FRB
  - SN explosions
  - Interactions during travel at different scales: ISM, CGM, IGM, ICM; IRF, CMB; magnetic fields
- Microphysics of CR (kinetic approach, effective model, simulations)
- Feedback of CR on star formation
- CR propagation near their sources
- Arrival directions and tracing

Dynamical Spacetimes

- Cosmology
    - Background, perturbative and non linear-regime
    - Beyond GR

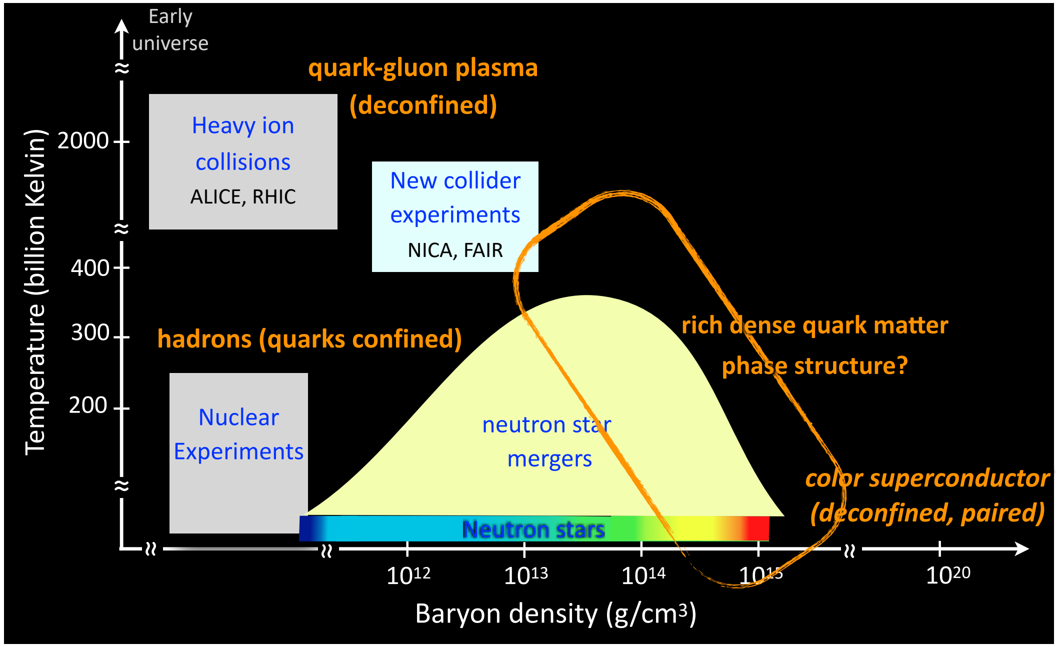
- Gravitational Waves
    - Mergers: BH, NS
    - Pulsars
    - Stochastic Background
    - General Relativity tests
    - Dark Matter: PBH, halos of DM can affect mergers

    - Post Newtonian/Minkowskian expansions
    - Numerical Relativity

    - Multiwavelength correlations

Nuclear Astrophysics

- Neutron stars, binary mergers, kilonovae
- Core-collapse supernovae (neutrinos, GW)
- Origin of elements
- Multiwavelength
- QCD phase diagram



Particles in/from Stars

- Sun
  - Neutrinos
    - Standard and non-standard energy generation (astrophysics) or non-standard neutrino interactions
    - Solar core composition
    - Metalliticity
  - Light particles (axions, ALPs, DM): energy transfer mechanisms
  - Dark matter
  - Hadronic interactions at the solar photosphere

- Evolved stars
  - He core and internal temperature: sensitive to neutrino production, other light particles (axions), neutrino dipole moment

- White Dwarfs
  - New Physics affects energy-losses (cooling): axions, neutrino magnetic moment, magnetic monopoles, dark matter particles, dark forces
  - GW from WD mergers
- Supernovae
  - 3D simulations, progenitors, magnetic fields, neutrino dynamics
  - GW from SN
  - Neutrinos and GW as early warning for e.m. signal
  - Diffuse Supernova Neutrino Backgrouns
  - BSM in Supernovae
- Neutron stars
  - Eq. of state
  - Mergers: GW, neutrinos, multiwavelength counterpart
  - Kilonova and nuclear processes
  - Test for DM around NS
- Black holes
  - Test of GR in the strong regime
  - Boson stars, gravistar, etc: ultra light ALPs, DM
  - Superradiance

Early Universe

- Open questions
  - What happened in the very first seconds
  - Matter/energy and physical laws governing the very early Universe before thermalization
  - Origin of primordial fluctuations
  - Origin of matter/antimatter asymmetry
  - Nature of DM, generation, imprint on late Universe
- Primordial inflation
  - Data are compatible (although not a proof, yet)
  - Probes dynamics sensitive to UV physics
  - Tensor modes: imprint on CMB polarization, not a guaranteed signal, foreseen reach for scala-to-tensor ratio at 1/1000
  - Stochastic GW background
  - Non gaussianities: scalar fields content, their interactions
  - Origin of primordial fluctuations: quantum vs classical

Early Universe

- Reheating and preheating
  - Tests prturbative and non-perturbative physics
  - Can produce or have impact for isocurvature perturbations, stochastic GW, non-gaussianities, PBH, topological defects, primordial mag fields, matter/antimatter asymmetry
- Thermal and non-thermal relics
  - Dark matter
- Baryo/Lepto-genesis
- BBN as a tool for New Physics
- Phase transitions
  - QGP, EW, BSM (e.g. GUT, PQ symmetry)
  - Typically produce a stochastic background of GW

Late Universe

- Dark ages and Reionization
  - CMB, HI, Ly_{alpha}, SZ
  - Test for background evolution, for dark matter
- Structures in the Universe
  - Halos, filamens, voids
  - Test for dark matter, dark energy, dark radiation, GR
  - Emission of messengers from structures
- Dark Energy
  - Mechanism: cosmological constant vs scalar dynamics
  - Test for gravity theories beyond GR, scalar fields dynamics, quantum effects

Astroparticle Physics in 20 years

- Astroparticle Physics has fantastic opportunities of steady growth toward a further deepening of fundamental questions in Nature
- Open problems are outstanding and quite fascinating: they will require a strong, coordinated and synergic effort from experiment, observations, theory, data analysis, numerical approaches
- Many of these problems are (potentially) intertwined or connected: solution to one might offer opportunitites of understanding to others
- The future looks bright, quite worthwhile the great effort required to solve the many open problems