

Beyond BCS: Pairing Mechanisms, Material Families and the Contested Path to Ambient-Condition Superconductivity

Dr. Supriya Kumari

Assistant Professor, Department of Physics, Rajendra College, Chapra, Saran, Bihar

ABSTRACT

Superconductivity research has moved through an unusually crowded stretch over the last five to seven years, and that pace has forced a reconsideration of how tightly the field should still be tied to the Bardeen-Cooper-Schrieffer (BCS) picture of phonon-mediated pairing. Nickelates - first realised as infinite-layer thin films in 2019 and pushed into pressurised bulk Ruddlesden-Popper crystals from 2023 - have joined the cuprates and the iron-based compounds as a third correlated-oxide family with its own phase diagram and its own open questions. Hydrogen-dominant superhydrides, compressed inside diamond-anvil cells, keep raising conventional phonon-mediated T_c toward room temperature and, on two now-withdrawn accounts, past it; the credibility cost of those two retractions is addressed here directly rather than folded quietly into a general narrative of progress. A third, mechanistically distinct route has opened in twisted and proximitized graphene, where superconductivity appears without any parent magnetic order and can be dialled in through twist angle and proximity coupling alone. This review draws these threads together: it separates what is mechanistically established from what remains proposed, weighs the 2019-2026 record of major claims against how well each has actually been reproduced, and asks what stands between the present laboratory demonstrations and superconducting devices that could be deployed at scale. Results now confirmed by independent groups are treated differently from single-laboratory reports, and both are kept distinct from claims the literature has since withdrawn.

Keywords: *Superconductivity, BCS theory, Cuprate superconductors, Iron-based superconductors, Nnickelate superconductors, Superconducting qubits; Critical temperature*

Received : 10/7/2026 **DOI :** <https://doi.org/10.5281/zenodo.23031277> **Acceptance:** 15/8/2026

Introduction :

Kamerlingh Onnes watched the resistance of mercury drop to zero below 4.2 K in 1911 [1], and for forty-six years afterward no one had a theory that explained why. Bardeen, Cooper and Schrieffer supplied one in 1957 [2]: electrons near the Fermi surface are drawn together by a phonon-mediated attraction, condense into a coherent macroscopic state, and move without dissipating energy because an energy gap separates that state from anything they could scatter into. Extended into the strong-coupling regime by Eliashberg, the theory worked well for elemental metals and simple alloys, and it came with an implicit ceiling— nobody expected phonon-mediated pairing alone to push T_c much past 30 K. That ceiling stood until 1986, when Bednorz

and Müller reported superconductivity above 30 K in a lanthanum-barium-copper oxide [3]. The result did more than break a numerical limit; it showed that pairing could arise from something other than phonons altogether, and cuprate high-temperature superconductivity has occupied the field ever since. Finding a mechanism that is not tied to phonons and that might eventually work at or near room temperature has become one of condensed-matter physics's standing objectives.

What has changed in the past several years is less the refinement of established families than the arrival of entirely new ones. Iron-based superconductors, discovered in 2008, have by now matured into an applications-oriented subfield, with effort

concentrated on turning laboratory critical-current gains into cable and magnet technology (see §3.2 and §4.2). The cuprates, for their part, are no longer chiefly a discovery target: interest has shifted toward the pseudogap phase and toward the practical problem of manufacturing long YBCO-coated conductors for high-field magnets. The most consequential newcomer is the nickelate family. First observed in thin-film form in 2019 [5], it was extended in 2023 to bulk Ruddlesden–Popper crystals showing pressure-induced superconductivity near 80 K, a figure subsequently raised to 96 K in chemically substituted single crystals under pressure [6,31]. In parallel, hydrogen-dominant superhydrides compressed to hundreds of gigapascals have delivered transition temperatures that computation had anticipated years in advance [17–19] — alongside two claims of near- or above-room-temperature superconductivity that did not survive scrutiny and were subsequently retracted [20,25]. Most recently, twisted and proximitized graphene

heterostructures have demonstrated that superconductivity in a two-dimensional system can be switched on and off simply by adjusting twist angle and proximity-induced spin–orbit coupling, with no intrinsic magnetism required at all.

Three questions organise what follows. First, in each of these families, what is actually established about the pairing mechanism, as opposed to merely proposed? Second, of the headline results reported between 2019 and 2026, which have been reproduced by independent groups, which remain the property of a single laboratory, and which have been withdrawn? Third, what separates today’s laboratory demonstrations from superconducting technology that could actually be deployed — in quantum computing hardware, high-field magnets, power transmission, and precision sensing? The intent is not to catalogue every publication in the field (specialist reviews cited throughout do that job) but to give a critical, comparative account of where the evidence is solid,

Figure 1. Principal milestones in superconductivity research, 1911–2026

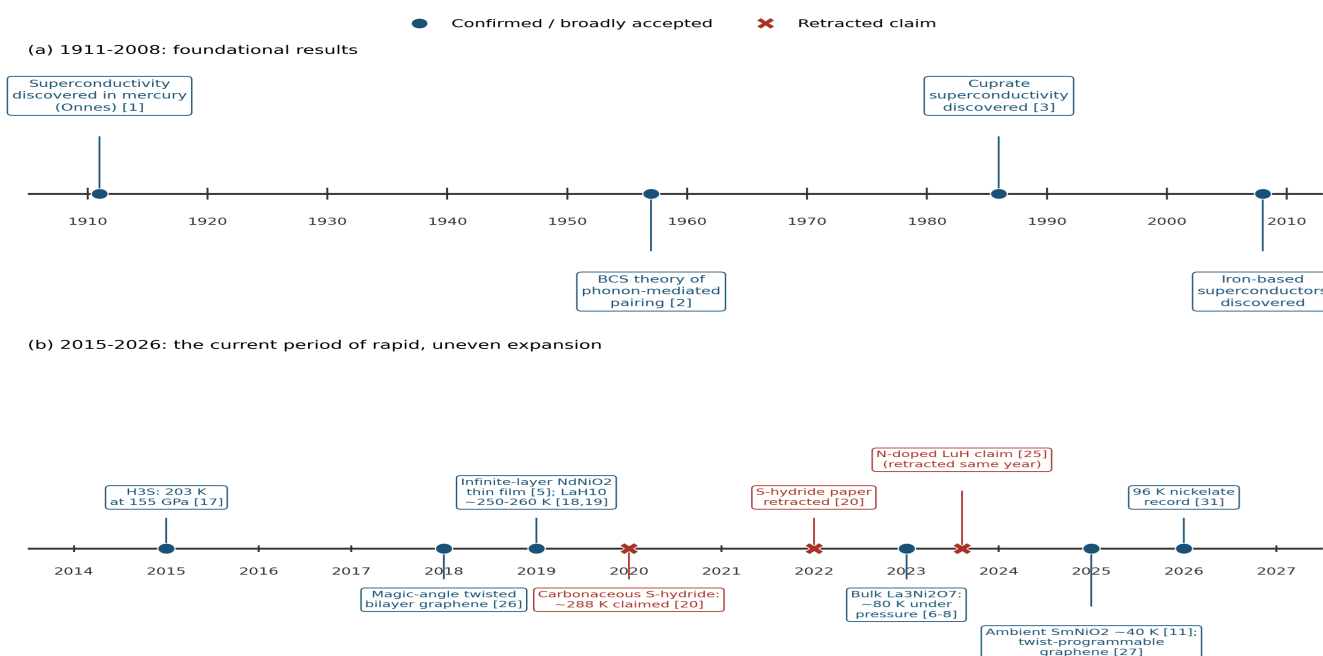


Figure 1. Principal milestones in superconductivity research, 1911–2026. Panel (a) shows the foundational period; panel (b) expands the crowded 2015–2026 interval. Circles mark confirmed or broadly accepted results; crosses mark claims that were subsequently retracted.

where it is genuinely still open, and where claims have run ahead of what the data support.

2. Theoretical Mechanisms

2.1 Phonon-mediated pairing and its limits

In the BCS picture, an electron passing through a lattice briefly displaces the surrounding ions, leaving behind a region of enhanced positive charge that draws in a second electron; the pair that forms condenses into a coherent ground state. Together with Eliashberg's strong-coupling extension, this mechanism remains a correct and essentially complete account of superconductivity in elemental metals, most alloys, and magnesium diboride. It is also what underlies the superhydride programme. Hydrogen's low mass produces unusually high phonon frequencies, and because T_c in the BCS/Eliashberg framework scales with that characteristic phonon frequency, hydrogen-dominant solids under extreme compression were flagged computationally — before anyone had synthesised them — as strong candidates for high phonon-mediated T_c [17–19]. That predictive success matters for what follows: it is precisely because the theoretical baseline in this family is so credible that the subsequent controversy over certain experimental claims carries the weight it does. The theory was never in doubt; particular experiments were.

2.2 Unconventional pairing: Correlation, spin fluctuations and order-parameter symmetry

Cuprates, iron-based pnictides and chalcogenides, heavy-fermion compounds, and now the nickelates all become superconducting out of a parent state that is antiferromagnetically ordered or otherwise strongly correlated; the superconducting dome appears once doping, pressure or strain has suppressed that order. The dominant theoretical account spin-fluctuation-mediated pairing, which was anticipated for the nickelates on theoretical grounds well before anyone made one [4] predicts an order parameter that changes sign across the Fermi surface: d-wave in the cuprates, $s_{\pm}$ -wave in most iron-based compounds. This picture is well supported qualitatively, but it is not a first-principles route to T_c : nothing in this class of theory currently predicts transition temperatures from microscopic parameters the way Eliashberg

theory does for phonon-mediated superconductors. That gap matters because it is largely why materials discovery in this space still proceeds empirically rather than by rational design.

The nickelates make the difficulty concrete. Inelastic-scattering and transport measurements point to some combination of magnetic correlations, orbital-selective correlation effects, and interlayer coupling operating in the bilayer and trilayer Ruddlesden–Popper phases, but which interaction actually does the pairing and how much weight the s - versus d -wave channels each carry remains genuinely contested; the comprehensive 2025–2026 reviews of the family are explicit that this is an open question, not a settled one [12–14]. Controlled-disorder experiments have become a useful way to discriminate between competing scenarios: electron-irradiation studies on nickelate compounds introduce well-characterised scattering and track how superconductivity responds to it [15], often constraining microscopic models more sharply than spectroscopy alone can. This complements pressure- and strain-tuning approaches and seems likely to become a standard part of the toolkit across unconventional families generally.

Twisted and proximitized graphene sits in a mechanistically separate category. Flat electronic bands generated either by a moiré superlattice potential or by proximity-induced spin–orbit coupling amplify the effective electron–electron interaction relative to the kinetic energy, and both correlated insulating and superconducting phases can emerge without any intrinsic magnetic order in the parent material. The scientific value of this system lies less in graphene superconductors becoming technologically important in their own right and more in how cleanly they can be tuned: twist angle, displacement field and proximity coupling can each be varied independently, which makes this a useful proving ground for theories of unconventional pairing that are hard to test cleanly in the correlated oxides, where several of these ingredients are always present at once.

Placing these four pictures side by side shows how unevenly the field's theoretical maturity is

actually distributed. Phonon-mediated pairing within the Eliashberg framework is quantitatively predictive, and for the superhydrides it anticipated experimental T_c values before synthesis of the four mechanisms discussed here, it is the only one capable of genuine forward prediction rather than after-the-fact rationalisation. Spin-fluctuation pairing in the cuprates and iron-based compounds rests on decades of spectroscopic and thermodynamic evidence, including phase-sensitive measurements that

Figure 2. Schematic comparison of the four pairing mechanisms discussed in the text

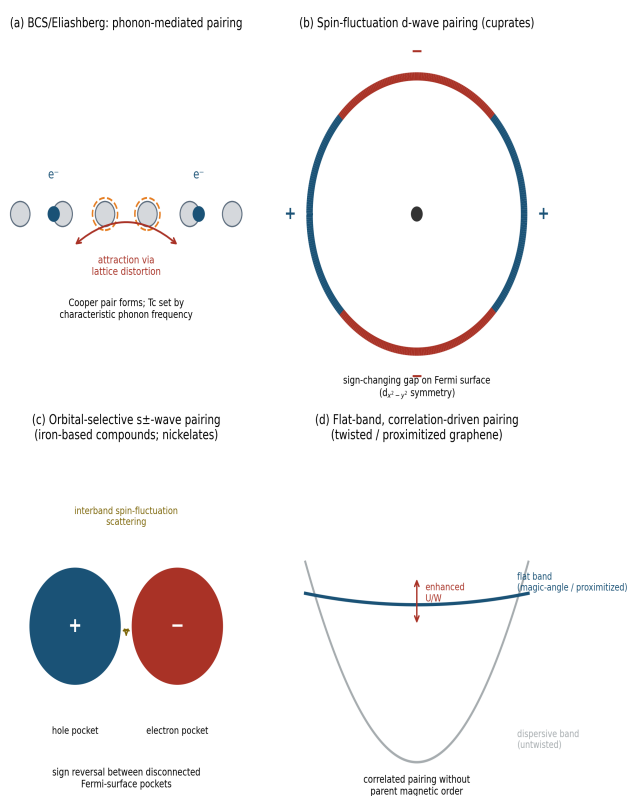


Figure 2. Schematic comparison of the four pairing pictures discussed in the text: (a) BCS/Eliashberg phonon-mediated pairing; (b) spin-fluctuation-mediated d-wave pairing in the cuprates; (c) orbital-selective $s_{\pm}$ -wave pairing in iron-based compounds and nickelates; (d) flat-band, correlation-driven pairing in twisted or proximitized graphene.

this hierarchy of evidentiary maturity rather than treated as though it applied uniformly across the field.

3. Advances Across Superconducting Material Families

The four families surveyed below differ not just in T_c but in crystal chemistry and dimensionality. Figure 3 lays out the four structural platforms perovskite-derived cuprates, infinite-layer/Ruddlesden Popper

establish d-wave order in the cuprates and $s_{\pm}$ -wave order in several iron-based compounds, but it still cannot deliver a quantitative T_c prediction. The nickelates inherit this same qualitative framework without having even settled the pairing symmetry, while the graphene systems are at an earlier stage still, where the correlated normal state itself rather than the pairing interaction remains the primary object of study. Any claim that a given family has a “settled” pairing mechanism should be read against

Figure 3. Schematic structures of the four material platforms discussed in this review

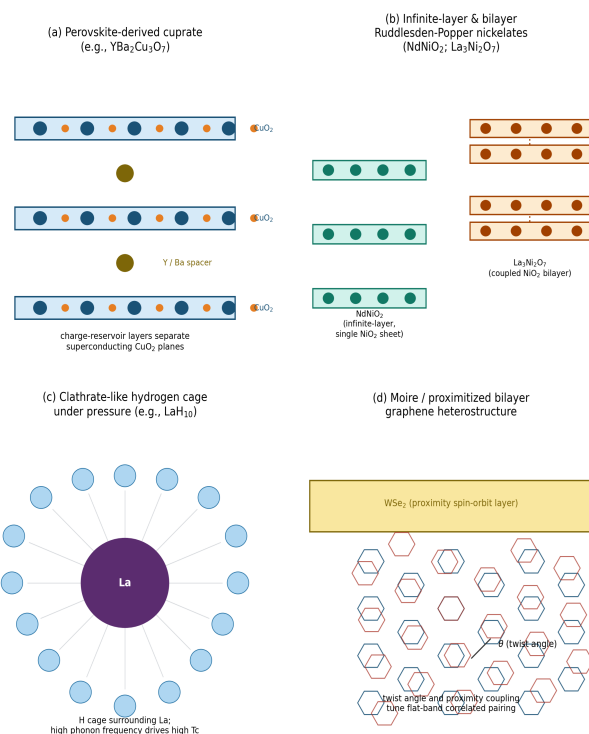


Figure 3. Schematic structures of the four platforms discussed in this review: (a) perovskite-derived cuprate unit cell (e.g., $\text{YBa}_2\text{Cu}_3\text{O}_7$); (b) infinite-layer and bilayer Ruddlesden–Popper nickelate structures (NdNiO_2 ; $\text{La}_3\text{Ni}_2\text{O}_7$); (c) the hydrogen sublattice of a representative clathrate-like superhydride under pressure (e.g., LaH_{10}); (d) a moiré or proximitized bilayer-graphene heterostructure, indicating twist angle and the adjacent spin–orbit-coupling layer (e.g., WSe_2).

nickelates, the clathrate-like hydrogen sublattice of the superhydrides, and moiré/proximitized graphene — within a single frame before the family-by-family evidence is discussed in turn.

3.1 Cuprates

Cuprate superconductors are still the highest- T_c materials at ambient pressure, with optimally doped compounds exceeding 130 K. The hunt for still-higher T_c within this family has been relatively quiet lately; attention has moved instead to the pseudogap phase, to the charge- and spin-density-wave orders that compete with superconductivity, and to the engineering problem of producing long, high-current YBCO-coated conductors tapes built from a thin epitaxial YBCO layer deposited on a flexible metallic substrate. Ongoing refinement of solution-based and vapour-deposition growth for these conductors is aimed at higher critical current density and lower manufacturing cost, which is the real bottleneck between cuprate superconductivity and wider deployment in magnets and grid applications, rather than any further search for a higher T_c .

3.2 Iron-based superconductors

The iron pnictides and chalcogenides, discovered in 2008, form the second major unconventional high- T_c family, reaching above 55 K in bulk compounds and considerably higher in monolayer FeSe grown on strontium titanate. Their upper critical fields and anisotropy are often more favourable than the cuprates' for high-field magnet work, which explains the sustained interest in wire and tape fabrication specifically, rather than any attempt to compete with the cuprates on peak T_c . Dedicated international workshops on applications of iron-based superconductors continued through 2025, including work aimed at collider and accelerator magnet technology; the broader trajectory here steady engineering progress on a material whose physics is already reasonably well understood offers a useful contrast with the nickelates discussed next.

3.3 Nickelates

The nickelates are the most consequential new family to have emerged in this period, and the sequence of results is worth laying out in some detail

because it illustrates both how fast the field has moved and how much of that progress is still provisional. Superconductivity first appeared in 2019, in thin films of hole-doped infinite-layer neodymium nickelate (NdNiO_2) [5], made by topotactic reduction of a perovskite precursor and following roughly two decades of theoretical prediction that the $3d^9$ electronic configuration of nickel oxides might reproduce cuprate-like physics [4]. A considerably more consequential development came in 2023: bulk single crystals of the bilayer Ruddlesden–Popper compound $\text{La}_3\text{Ni}_2\text{O}_7$ were reported to show superconductivity near 80 K under hydrostatic pressure [6]. Unlike some of the claims discussed in §3.4, this one has held up it was subsequently confirmed and extended by independent groups, including reports of a pressure-induced high-temperature phase in pressurised $\text{La}_3\text{Ni}_2\text{O}_7$ crystals [7] and bulk superconductivity in polycrystalline samples of the same compound [8], a degree of independent replication the hydride claims in §3.4 have largely lacked. Superconductivity has since been extended to the related trilayer compound $\text{La}_4\text{Ni}_3\text{O}_{10}$ and to strain-engineered thin films [9,10]. A later report pushed the onset further still, to a record 96 K in chemically substituted (La,Sm)-bilayer single crystals grown by an ambient-pressure flux method and made superconducting under pressure evidence that the bilayer/trilayer ceiling has not yet been reached and that chemical substitution, not just hydrostatic pressure, can raise T_c in this family.

A second, mechanistically distinct line of nickelate work targets ambient-pressure operation directly rather than chasing a higher T_c under pressure. Ariando and co-workers reported bulk superconductivity approaching 40 K in hole-doped samarium nickelate (SmNiO_2) at ambient pressure [11], achieved through substrate selection that markedly cuts residual resistivity and disorder. This is the first clear demonstration of Cooper pairing above 30 K in a cuprate-isostructural, copper-free oxide without any lattice compression, and it is a genuinely different achievement from the pressurised bilayer/trilayer results, since it removes the pressure

requirement altogether rather than raising T_c under pressure. Separately, strain engineering of thin-film $\text{La}_3\text{Ni}_2\text{O}_7$ has produced signatures of ambient-pressure superconductivity [16] by substituting substrate-induced compressive strain for hydrostatic pressure again a route toward ambient operation, but for the higher- T_c bilayer phase rather than the infinite-layer one, and one where fully unambiguous bulk superconductivity at ambient pressure has not yet been demonstrated to the same standard as the SmNiO_2 result. These are two distinct strategies converging on the same practical goal, and treating either single “ambient-pressure” result as evidence that the pressure problem has been solved generally would overstate where the field currently stands.

Comprehensive 2025–2026 reviews of the family [12–14] catalogue this expansion across the infinite-layer, bilayer and trilayer nickelate systems and are candid that several structural and mechanistic questions remain unresolved the role of oxygen vacancies and self-doped ligand holes [10], and the relative weight of s- and d-wave pairing channels, both under active investigation through nonmagnetic-impurity and epitaxial-strain studies. In roughly seven years, in other words, the nickelates have gone from a single thin-film report to a multi-member family with at least two independently confirmed high- T_c phases — but neither the microscopic pairing mechanism nor a reliable ambient-pressure route to the highest- T_c (bilayer/trilayer) members has yet been established.

3.4 Hydride superconductors under pressure

The superhydride programme has produced both the field’s most robustly established results and its most consequential retractions, and a critical review needs to keep those two categories clearly apart. On the well-established side, sulfur hydride (H_3S) was reported to superconduct near 203 K at 155 GPa in 2015 [17], and that result has since been widely reproduced. Lanthanum superhydride (LaH_{10}), which was predicted computationally before it was ever synthesised, was subsequently measured by independent groups to superconduct somewhere in the range of 250–260 K at pressures near 170–200 GPa [18,19]; this result too is broadly

accepted within the community. More recent theoretical work suggests that atomic quantum fluctuations help stabilise the high-symmetry, high- T_c structural phase of LaH_{10} at pressures somewhat below what earlier classical calculations predicted [24] a refinement of the phase-stability picture on paper, not a demonstrated reduction in the pressure actually required in the laboratory.

The contested and retracted side of the record diverges sharply from much of the popular coverage this field has received. A 2020 report of superconductivity near 288 K in a carbonaceous sulfur hydride at 267 GPa was presented, at the time, as the first genuine claim of room-temperature superconductivity. It did not survive scrutiny: after sustained questions about the background-subtraction procedure applied to the raw magnetic-susceptibility data, Nature retracted the paper in October 2022 [20], with the editors stating that non-standard, unspecified processing steps had undermined confidence in the published data a position the original authors disputed but that the journal maintained. A second, related episode followed in 2023, when the same research group reported near-ambient superconductivity (T_c up to 294 K at only ~ 1 GPa) in a nitrogen-doped lutetium hydride, a claim that drew considerable attention precisely because it combined a high T_c with an unusually low pressure. Independent groups could not reproduce the claimed transition, and the paper was retracted at the authors’ own request in November 2023, with Nature citing independently raised and substantiated concerns about the reliability of the electrical-resistance data. These are the two highest-profile hydride-superconductivity claims of the past six years, and both were withdrawn by the publishing journal; any assessment of where hydride superconductivity currently stands that leaves them out would be incomplete.

That said, the retraction of these two specific claims does not, on the evidence, indict the broader superhydride field. H_3S and LaH_{10} rest on an independently reproduced evidentiary base that is simply different from the retracted claims, and researchers working on flux-trapping and

magnetisation measurements in hydrides under pressure have continued to argue on separate, more conventional data that genuine high-temperature hydride superconductivity is reproducible across multiple compounds and laboratories, while explicitly distancing that argument from the retracted results [21,22]. Beyond the H3S/LaH10 core, ambient-pressure strain engineering of thin-film La3Ni2O7 nickelate which is not, despite occasional imprecise reporting, a hydride result at all has separately shown a route to lower-pressure operation for correlated-oxide superconductors [16]. On the hydride side specifically, first-principles calculations have identified hydrides built from quasi-molecular H2 units as a chemically distinct route to near-room-temperature Tc at pressures potentially lower than those required for the atomic-hydrogen sublattices of H3S and LaH10 [23]. This is a theoretical prediction rather than an experimental report, and its significance depends entirely on whether the predicted phases can actually be synthesised and measured a different, and at this stage considerably lower-stakes, kind of uncertainty than the data-integrity concerns behind the 2020 and 2023 retractions.

3.5 Twisted and proximitized two-dimensional superconductors

Two-dimensional van der Waals heterostructures offer a mechanistically distinct, and comparatively well-controlled, route to tunable superconductivity. Following the original discovery of correlated insulating and superconducting phases in magic-angle twisted bilayer graphene the phenomenology has since been extended to twisted trilayer graphene and to other moiré heterostructures. A 2025 result of particular interest demonstrated twist-programmable superconductivity in Bernal-stacked bilayer graphene proximitized by tungsten diselenide precise control of the twist angle between the two layers tunes the strength of induced Ising-type spin-orbit coupling, and as that coupling grows, superconductivity onsets at a higher displacement field and reaches a higher critical temperature p to about 0.5 K, with additional superconducting regions appearing once spin-orbit

coupling is strong. Because this system needs no moiré superlattice at all to generate flat bands the correlated physics here comes from proximity-induced spin-orbit coupling rather than a twist-induced periodic potential it offers an unusually clean platform for isolating the separate contributions of band flattening, spin-orbit coupling and interaction strength, something difficult to achieve in the correlated oxides, where these ingredients are always present together and hard to vary independently.

3.6 Cross-family comparative analysis

Read across these families together, three patterns stand out. First, evidentiary reliability tracks reported Tc only weakly: the two highest transition temperatures discussed in this review (~294 K and ~288 K) both belong to retracted claims, while several independently reproduced results H3S, LaH10, La3Ni2O7 under pressure sit at lower Tc but rest on a substantially firmer evidentiary base. A high headline Tc is, by itself, a poor proxy for scientific confidence. Second, pressure requirement and application readiness run inversely to one another across every family with a well-characterised phase diagram: the cuprates and iron-based compounds ambient-pressure and, among the families discussed here, mechanistically the best understood are also the only ones with an active, multi-decade engineering pipeline (coated conductors, magnet wire), while the nickelates and superhydrides, which need multi-gigapascal pressure for their highest-Tc phases, remain laboratory systems regardless of the measured Tc. Third, the degree of mechanistic consensus does not track the chronological order of discovery: the pairing symmetry in iron-based compounds (discovered 2008) is better constrained than in the nickelates (2019 onward), and both remain less settled than the four-decade-old cuprate case, where the pseudogap phase is still actively debated. Together these three patterns argue against equating “newer” or “higher-Tc” with “more promising,” and in favour of weighting replication status and pressure requirement at least as heavily as headline Tc when judging

Figure 4. Critical temperature versus pressure required, by family and replication status



by family, in the comparative table below.

4. Emerging Applications

Materials progress only becomes technological benefit alongside parallel advances in wire and device fabrication, cryogenic engineering and system integration, and the four application domains below sit at markedly different stages of that translation.

4.1 Quantum computing hardware

Superconducting circuits built around Josephson junctions remain the leading platform for large-scale quantum computing, largely because they are compatible with established microfabrication and support comparatively fast gate operations. Continued materials work on reducing two-level-system defect densities in niobium- and tantalum-based resonators, combined with better shielding and packaging, has steadily improved coherence times and multi-qubit gate fidelities incremental engineering progress on an already-mature platform rather than a new discovery. Separately, and at a much earlier and more speculative stage, researchers are exploring whether emerging superconductors, including proximitized two-dimensional systems, could support intrinsically protected, topologically nontrivial qubit designs; this line of work remains exploratory relative to conventional transmon

alternative to them.

4.2 High-field magnets

High-field superconducting magnets remain the dominant commercial application of superconductivity, underpinning MRI systems, NMR spectrometers and accelerator magnets. Ongoing improvements in YBCO-coated conductor manufacturing and in iron-based superconducting wire are aimed at higher achievable field strength and current-carrying capacity for accelerator- and fusion-relevant magnets; sustained engagement from the applied-superconductivity community, reflected in ongoing dedicated workshops, underscores continued demand for such magnets. High-temperature superconducting magnets are also central to the compact tokamak designs pursued by several fusion-energy ventures, which rely specifically on REBCO tape because it enables the high fields needed to confine plasma in a smaller reactor volume than conventional low-temperature superconducting magnets allow.

4.3 Power transmission

Superconducting cables capable of carrying very high current density without resistive loss

continue to be evaluated for grid-scale transmission, particularly in dense urban corridors where conventional cable capacity is constrained by available space. Cryogenic infrastructure cost remains the limiting factor for wide deployment, but pilot projects using cuprate and, increasingly, iron-based conductor technology continue to demonstrate feasibility over multi-kilometre distances a case where the materials science has, at present, outpaced the supporting economics.

4.4 Precision sensing

Superconducting quantum interference devices (SQUIDs) remain the most sensitive magnetometers available, used from magnetoencephalography to geophysical surveying and materials characterisation. Advances in thin-film fabrication of both conventional and unconventional superconductors continue to improve SQUID sensitivity and lower operating-temperature requirements, and superconducting nanowire single-photon detectors which exploit the sharp resistive transition of thin superconducting films have become an enabling technology for quantum communication and deep-space optical links.

5. Research Gaps, Unresolved Questions and Future Research Priorities

The issues below fall into three categories that review articles often blur together but that deserve separate treatment: methodological and evidentiary gaps in how claims get established; scientific questions that stay open regardless of data quality; and concrete directions that would plausibly narrow both.

5.1 Research gaps

Reproducibility standards in high-pressure measurement. The 2020 and 2023 retractions [20,25] were not simply cases of a disputed measurement; they involved disagreements over raw data, background-subtraction procedures and measurement protocol that, in the lutetium hydride case, were never resolved even after extensive independent replication attempts. Single-group, high-T_c, low-pressure hydride claims warrant the scepticism this history has earned without extending that scepticism, uncritically, to the independently

reproduced H3S and LaH10 results [17–19], which rest on an entirely different evidentiary base.

Pressure as a practical bottleneck.

The bilayer and trilayer nickelates, along with nearly all superhydrides, require substantial hydrostatic pressure to superconduct, which rules out large-scale application in their current form. Finding chemical substitutions, epitaxial strain, or alternative synthesis routes that stabilise these phases at ambient pressure the SmNiO₂ [11] and strained-La₃Ni₂O₇ [16] results are early, partial answers among the most consequential open materials-engineering questions in the field, arguably more so in the near term than the search for still higher T_c under pressure.

5.2 Unresolved scientific questions

No predictive microscopic theory for unconventional T_c. Spin-fluctuation and related pairing theories give a broadly consistent qualitative picture across the cuprates, iron-based compounds and nickelates, but none of them predicts T_c from microscopic parameters with anything like the reliability Eliashberg theory offers for phonon-mediated superconductors. Materials discovery in the unconventional families therefore stays largely empirical, and a new record T_c in these systems should be read as an experimental finding awaiting theoretical explanation, not as confirmation of any particular mechanism.

Pairing symmetry and pairing glue in the nickelates. Even for the best-characterised bilayer/trilayer phases, the relative weight of s- and d-wave channels and the identity of the dominant pairing interaction remain contested [12–15]; settling this is a prerequisite for any rational, rather than purely empirical, search for higher-T_c or ambient-pressure nickelate compounds.

How general is flat-band, correlation-driven pairing? Whether the mechanism behind superconductivity in twisted and proximitized graphene generalises to other flat-band or moiré systems with substantially higher T_c, or is intrinsically confined to the sub-kelvin range observed so far, is not yet known.

5.3 Future research priorities

Standardised replication and reporting protocols. Given the role that background-subtraction and data-processing choices played in both hydride retractions, community-agreed reporting standards for raw resistance and susceptibility data under high pressure including mandatory deposition of unprocessed datasets would lower the risk of a similar episode recurring and would speed up independent verification of genuine results.

High-throughput, computationally guided search for ambient-pressure phases: The predictive track record of structure-search calculations for the superhydrides [17–19] suggests that similar computational screening, paired with high-throughput thin-film and strain-engineering synthesis, could target ambient-pressure operation in the nickelates and related correlated oxides more systematically, rather than relying on incremental single-compound studies.

Discriminating experiments across families: Controlled-disorder methods such as electron irradiation, already informative for the nickelates [15], together with isotope-substitution and phase-sensitive measurements (Josephson interferometry, for instance), should be extended systematically across the cuprate, iron-based and nickelate families to test pairing-symmetry hypotheses on common experimental ground.

Engineering integration:

Wire fabrication, junction formation and cryogenic system integration determine how quickly a laboratory-scale T_c improvement turns into a usable magnet, cable or qubit; this translation takes years to decades even for well-understood materials such as the cuprates and iron-based compounds, and dedicated investment at this stage is likely to pay off sooner than continued discovery of new high- T_c phases.

Ranked by expected near-term impact, standardised reporting protocols and engineering integration are the lowest-risk priorities, since both act on materials and phenomena that are already established; discriminating experiments and computationally guided ambient-pressure searches

carry a higher scientific payoff but a longer and less certain timeline, since they depend on resolving the pairing-mechanism questions that remain open in §5.2. Framing the field's priorities this way rather than around the pursuit of a single higher- T_c record fits the evidentiary pattern identified in §3.6, where reported T_c alone turned out to be a poor predictor of either scientific reliability or translational readiness.

6. Conclusion:

Superconductivity research is going through an unusually diversified phase. Continued engineering refinement of cuprate and iron-based conductor technology sits alongside the rapid, largely well-substantiated growth of the nickelate family since 2019; a superhydride field whose core results (H₃S, LaH₁₀) remain solid even as two of its highest-profile recent claims have been formally retracted; and a comparatively new, cleanly tunable route to unconventional pairing in twisted and proximitized graphene heterostructures. Read across these families, the field is converging unevenly, and with real gaps still open on a picture in which strong electronic correlation, spin fluctuations, orbital physics, and lattice or interfacial engineering combine, in different proportions in different materials, to produce superconductivity well above the ceiling once assumed for phonon-mediated pairing alone. Getting from here to ambient-pressure, technologically deployable superconductors will most plausibly come not from a single breakthrough but from closer integration of high-pressure and thin-film synthesis, spectroscopic and scattering probes capable of discriminating between competing pairing scenarios, and a microscopic theory of strongly correlated electron systems that can eventually do for the unconventional families what Eliashberg theory did for the conventional ones. Applying, across the field as a whole, the replication standard now applied retrospectively to the hydride literature that extraordinary claims of high T_c at low pressure warrant independent replication before being treated as established physics would strengthen the discipline's evidentiary credibility going forward.

References:

- Onnes, H.K. (1911). The resistance of pure mercury at helium temperatures. *Communications from the Physical Laboratory of the University of Leiden*, 12, 120.
- Bardeen, J., Cooper, L.N., Schrieffer, J.R. (1957). Theory of superconductivity. *Physical Review*, 108(5), 1175–1204.
- Bednorz, J.G., Müller, K.A. (1986). Possible high T_c superconductivity in the Ba–La–Cu–O system. *Zeitschrift für Physik B Condensed Matter*, 64, 189–193.
- Anisimov, V.I., Bukhvalov, D., Rice, T.M. (1999). Electronic structure of possible nickelate analogs to the cuprates. *Physical Review B*, 59, 7901–7906.
- Li, D., et al. (2019). Superconductivity in an infinite-layer nickelate. *Nature*, 572, 624–627.
- Sun, H., Huo, M., Hu, X., et al. (2023). Signatures of superconductivity near 80 K in a nickelate under high pressure. *Nature*, 621, 493–498.
- Hou, J., Yang, P.T., Liu, Z.Y., et al. (2023). Emergence of high-temperature superconducting phase in pressurized $\text{La}_3\text{Ni}_2\text{O}_7$ crystals. *Chinese Physics Letters*, 40, 117302.
- Wang, G., Wang, N.N., Shen, X.L., et al. (2024). Pressure-induced superconductivity in polycrystalline $\text{La}_3\text{Ni}_2\text{O}_7$. *Physical Review X*, 14, 011040.
- Wang, N., Wang, G., Shen, X., et al. (2024). Bulk high-temperature superconductivity in pressurized tetragonal $\text{La}_2\text{PrNi}_2\text{O}_7$. *Nature*, 634, 579–584.
- Dong, Z., Huo, M., Li, J., et al. (2024). Visualization of oxygen vacancies and self-doped ligand holes in $\text{La}_3\text{Ni}_2\text{O}_7$. *Nature*, 630, 847.
- Chow, S.L.E., Luo, Z., Ariando, A. (2025). Bulk superconductivity near 40 K in hole-doped SmNiO_2 at ambient pressure. *Nature*, 642, 58–63.
- Wang, Y., Jiang, K., Ying, J., Wu, T., Cheng, J., Hu, J., Chen, X. (2025). Recent progress in nickelate superconductors. *National Science Review*, 12(10), nwaf373.
- Zhang, Y., Lin, L.-F., Maier, T.A., Dagotto, E. (2026). Superconductivity in Ruddlesden–Popper nickelates: a review of recent progress, focusing on thin films. *arXiv:2604.18385*.
- Nature Reviews Physics* (2025). Superconductivity in infinite-layer and Ruddlesden–Popper nickelates.
- Max Planck Institute for Chemical Physics of Solids (2025). High-energy electron irradiation reveals superconductivity mechanisms in nickelates.
- Ko, E.K., et al. (2024/2025). Signatures of ambient-pressure superconductivity in thin-film $\text{La}_3\text{Ni}_2\text{O}_7$. *Nature*, 638, 935–940.
- Drozdov, A.P., Erements, M.I., Troyan, I.A., Ksenofontov, V., Shylin, S.I. (2015). Conventional superconductivity at 203 kelvin at high pressures in the sulfur hydride system. *Nature*, 525, 73–76.
- Somayazulu, M., Ahart, M., Mishra, A.K., et al. (2019). Evidence for superconductivity above 260 K in lanthanum superhydride at megabar pressures. *Physical Review Letters*, 122, 027001.
- Drozdov, A.P., Kong, P.P., Minkov, V.S., et al. (2019). Superconductivity at 250 K in lanthanum hydride under high pressures. *Nature*, 569, 528–531.
- Snider, E., Dasenbrock-Gammon, N., McBride, R., et al. (2020). Room-temperature superconductivity in a carbonaceous sulfur hydride. *Nature*, 586, 373–377. [Retracted: *Nature*, 610, 804 (2022).]
- Hirsch, J.E., Marsiglio, F. (2022). Clear evidence against superconductivity in hydrides under high pressure. *Matter and Radiation at Extremes*, 7, 058401.
- Boebinger, G.S., et al. (2025). Hydride superconductivity is here to stay. *Nature Reviews Physics*, 7, 2–3.
- Liu, Z., Li, J., Zurek, E., et al. (2024). Emergence of near room-temperature superconductivity in hydrides with H_2 molecular units. *Physical Review B*, 109, L180501.
- National Institute for Materials Science, Tohoku University, University of Tokyo (2020). Record superconductor LaH_{10} sustained by atomic quantum fluctuations.

